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Advances in Materials Technology: MONITOR

Issue No. 14 August 1989

INDUSTRIAL SENSORS

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Dear Reader,

This is number 14 of UNIDO's state-of-the-art series in the field of materials entitled Advances in Materials Technology: Monitor. This issue is devoted to Industrial Sensors.

In each issue of this series, a selected material or a material-related technology as in this Monitor, a group of materials is featured and an expert assessment made on the technological trends in those fields. In addition, other relevant information of interest to developing countries is provided. In this manner, over a cycle of several issues, materials relevant to developing countries could be covered and a state-of-the-art assessment made.

The leading article for this issue was prepared by Messrs. R.F. Wolffenbuttel, S.A. Audet, P.J.A. Munter and P.P.L. Regtien, all four of them are professors at the Delft University of Technology, Department of Electrical Engineering in Delft, The Netherlands.

We invite our readers also to share with us their experiences related to any aspect of production and utilization of materials. Due to paucity of space and other reasons, we reserve the right to abridge the presentation or not publish them at all. We also would be happy to publish your forthcoming meetings (please see section "Past Events and Future Meetings").

We would be grateful to receive your opinion on possible subjects for our forthcoming issues. In this way we expect to have a dialogue with our readership to establish the feedback which will allow us to effectively monitor the developments in the field and better serve our readers, especially in the developing countries.

For the interest of those of our readers who may not know, UNIDO also publishes two other Monitors: Microelectronics Monitor and Genetic Engineering and Biotechnology Monitor. For those who like to receive them please write to the Editor, Microelectronics Monitor; and Editor, Genetic Engineering and Biotechnology Monitor.

Industrial Technology Development
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CONTENTS

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SENSORS: MATERIALS, TECHNOLOGY, STATE-OF-THE-ART AND FUTURE TRENDS

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1 Introduction

A sensor is a device that is responsive to the value of a physical quantity or parameter. It converts information from one physical domain into another. Such sensors, or transducers, play an important role in instrumentation and control. A general feature of modern industrial plants is the increased number and diversity of sensors installed for controlling the processes for reasons of economy, safety or reduction of environmental pollution. Because of the availability of electronic data-processing equipment, nowadays sensors will provide an electrical response to a mechanical, thermal, radiant, chemical or magnetic stimulus. This article will first briefly discuss some sensor technologies along with a number of state-of-the-art sensors. As sensors will usually require electronic signal-conditioning before processing by a computer, special emphasis will be put on silicon sensors. The material compatibility gives silicon sensors the intrinsic possibility of integrating the sensor with the signal conditioning circuits and the data processor. In the future trends a few examples will be given of such smart integrated silicon sensors. Moreover, some special silicon sensor processing steps that will disclose a new range of new sensor applications will be discussed. Another present trend that will be discussed concerns the existence of the so-called sensor foundries.

2 Sensors and materials

For the discussion of the state-of-the-art in sensors and the associated sensor technologies, a division of the sensor field will be made into five non-electrical energy domains. These domains are magnetic, thermal, radiant, chemical and magnetic. In some of these domains a special material is used because of its specific advantage in dealing with a signal in that domain. Such a special material will be discussed. However, silicon will be shown to be a good compromise in almost all of the domains and its properties with respect to signals of a particular domain will, therefore, always be discussed in the associated section.

2.1 Sensors and materials for mechanical quantities

The sensors in this section respond to quantities with dimensions length and force, or combinations thereof, and their time derivatives. They are categorized according to the underlying physical principle. Table 1 contains some general characteristics of sensors with a mechanical input quantity.

2.1.1 Inductive mechanical sensors

Inductive sensors are based on changes in self inductance, mutual inductance or magnetic resistance. The changes are primarily caused by displacement of a movable part of the sensor construction. Therefore, such sensors are suited to the measurement of displacement, angular velocity and flow. Some examples of inductive displacement sensors are a coil with a moving core and the eddy-current sensor. These types have a relatively small range and a strong nonlinearity. Sensors based on variable mutual inductance are the LVDT (linear variable differential transformer), the RVDT (rotational version of the LVDT) and the synchro (of which the resolver is a special type). The LVDT is for linear displacements, and the others for angular displacements. They are available in a wide variety of measurement range, sensitivity and physical dimensions (table 1). A displacement sensor can also be used as a force sensor (with spring) or an accelerometer (with mass). A disadvantage is the necessarily large displacement. Velocity data and acceleration data can also be obtained by (electronically) differentiating the displacement signal. Angular velocity is simply measured by detecting a passing piece of metal or magnetic material attached to the turning object, using an inductive sensor. In this way, also flow (gas or liquid) can be measured, by inserting a free running propeilor into the stream (turbine flow meter and cup anemometer).

2.1.2 Capacitive mechanical sensors

Capacitive sensors are based on changes in the capacitance of a set of electrodes, according to the basic formula $C=\epsilon G$, where G is a geometrical factor. For a flat-plate capacitor, $G=A/d$ when stray fields are neglected. Examples of capacitive sensors are the LVDC (linear variable differential capacitor), with a structure similar to that of the LVDT, and the capacitive accelerometer with feedback. The latter consists of a differential capacitor with a movable center plate, connected to an electromagnetic driving system. The output signal is the current that is required for maintaining the movable plate in the center position. This type enables the measurement of static acceleration.

2.1.3 Resistive mechanical sensors

Sensors in this category utilize changes in the electrical resistance due to mechanoresistive or piezoresistive effects. Potentiometers and strain gauges belong to this group. Potentiometric transducers are available as linear or angular position sensors. There are wired types (with a finite resolution) and film types (having an infinite resolution). Some disadvantages of potentiometers are the wear on the slider and the contact resistance. Strain gauges are used for the measurement of forces, torsion, strain, pressure, etc. They are small devices, and can easily be mounted at almost any place on a construction. The resistance change is proportional to the strain. Their material is metal or semiconductor, the latter having a much larger sensitivity. Many modern pressure transducers contain a silicon diaphragm, with integrated strain gauges.

2.1.4 Piezoelectric materials and sensors

Piezoelectricity is the ability of a material to develop an electric charge proportional to an applied mechanical stress. It is a reversible effect: an applied voltage produces a proportional strain. Piezoelectricity can be described by the following expressions: $d = D/T = S/E$, where D is the dielectric displacement, T the stress, S the strain and E the electric-field strength. The constant d is the piezoelectric constant. As d may differ along different axes of the crystalline material, it is generally expressed in tensor form. Piezoelectric materials are usually also pyroelectric, which means that an electric charge is generated proportional to temperature due to the thermal expansion of the material.

Characteristic for a piezoelectric crystal is the existence of at least one polar axis or the absence of a centre of symmetry. The most well-known single-crystal piezoelectric material is quartz, widely used as an electrical or mechanical resonator, or as a basic sensor material. Polycrystalline materials, like ceramics, may also show piezoelectricity, if they are ferroelectric, that is the presence of a spontaneous electric dipole moment that can be changed in orientation upon applying an electric field. Normally, the electric dipoles in a ceramic are randomly oriented so there is no external dipole moment. Above the ferroelectric curie temperature the dipole moments can be oriented in a preferred direction by applying an electric field. This process, called poling, results in a permanent macroscopic dipole moment at temperatures below the curie temperature.

Popular ceramics are barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), lead zirconate ($PbZrO_3$), potassium niobate ($KNbO_3$), sodium niobate ($NaNbO_3$), potassium tantalate ($KTaO_3$)

and sodium tantalate ($NaTaO_3$). For transducer applications, mixtures of these materials are used, such as lead titanate zirconate, $Pb(Ti,Zr)O_3$. Such compounds show optimal piezoelectric properties at certain mixing ratios.

Piezoelectric ceramics are manufactured by a standard method. The raw material is milled and mixed, after which a treatment in a calcining furnace follows. Calcination removes water, carbon dioxide and other impurities, and allows thermochemical reaction of the constituent oxides. After grinding the material into a 1 to 10 μm powder, piezoelectric bodies of almost arbitrary shape can be produced by pressing, where an organic binder is used. These bodies are fired at elevated temperatures, varying from 1200 to 1450 °C, depending on the material. The flat surfaces are then polished and supplied with electrodes, mostly silver. Poling occurs by applying a short high DC voltage at an elevated temperature.

The properties of piezoelectric ceramics are temperature and time dependent. Most parameters vary approximately logarithmically in time. A typical decay rate is -1% per time decade.

Some polymeric films show piezoelectric properties after poling. Of all known polymers, polyvinylidene (PVDF) has the highest piezoelectric activity. PVDF is a semi-crystalline (50% crystalline and 50% amorphous) polymer whose structure is a chain of $-CH_2-CF_2-(CH_2-CF_2)^n-CH_2-CF_2-$. After fabrication of the films, its dipole moments are randomly oriented. By poling, however, a reasonably stable piezoelectric film is obtained. This piezoelectricity shows a thermally induced mechanical relaxation, resulting in a temperature dependent decay of the piezoelectric properties, especially at higher temperature. Figure 1 shows an example. Such a decay is also typical for poled piezoelectric ceramics. Piezofilms are available in several thicknesses (from a few to several hundreds of μm), and with or without a metallization on both sides (nickel or chromium). Unlike ceramics, piezoelectric films are flexible, pliant, tough and lightweight. They can be laminated into bimorphs, increasing the deflection of the film at an applied voltage.

Table 2 shows some piezoelectric properties of several materials. The low acoustic impedance of PVDF makes it very useful for ultrasonic transducers in air. A piezoelectric mechanical sensor is constructed as a capacitor: according to the expression $Q = CU$, the output signal is a voltage proportional to the force. Such sensors can also be used for the measurement of pressure and acceleration. There are no moving parts. Therefore, the sensors are very robust. Some disadvantages of piezoelectric sensors are the temperature sensitivity (due to the pyroelectric effect), the leakage resistance of the crystal, which excludes static measurements, and a sharp resonance peak in the frequency characteristic.

2.1.5 Mechanical sensors based on an optical system

An optically coded strip or wheel (encoders), placed inbetween a light source and a light-sensitive detector, enables the measurement of linear and angular displacements, respectively. The binary output (light or no light) makes the system independent of the intensity and sensitivity of the optical devices and insensitive to contamination. As shown in figure 2 there are two types of encoders: absolute and incremental. Their resolution is determined by the width of the slots and the size of the encoder, but can be improved by adding a fixed encoder with a slightly different pitch (Moiré-pattern). The combination of a narrow beamed light source and a PSD (position sensitive detector) can also be used for linear or angular displacements. When a light spot falls on the active area of a PSD, a photocurrent is generated, which splits up into two directions, in a ratio depending on the position of this spot. The distance to the source or a reflecting object can be calculated from the spot position and geometrical constants by triangulation techniques. Instead of a PSD, also an array of photodiodes can be used in this application, giving a discrete output signal but with less resolution. Arrays are available with up to 1024 diodes on a few cm.

2.1.6 Glass fibre sensors

Another material that has recently become popular as a sensor material for, amongst others, mechanical quantities is the glass fibre. Glass fibre systems were originally developed for communication, however, the transmission of the radiant energy through the fibre is affected by temperature and mechanical loading of the fibre. Also the reflection of light from a free tip is affected by external influences. The glass fibre and the photodetector act as tandem transducers. These properties make the glass fibre suitable as a sensor in an explosive environment.

2.1.7 Acoustic principles

There are four physical effects that can be utilized for electroacoustic transduction: the electrostatic, electromagnetic, piezoelectric and magnetostrictive effects. All these effects are reversible, so they can be used for transmitting as well as for receiving acoustic signals. For ultrasonic applications, only the piezoelectric and the electrostatic effects are of interest. Piezoelectric transducers are constructed as a capacitor. For acoustic applications in air, an acoustic impedance converter is mounted on the piezoelectric crystal, to optimize energy transfer and to obtain a better directivity. Piezoelectric transducers have a small frequency band, because they behave as a mechanical vibrating system with high quality factor. Popular types have resonance frequencies of 40 or 200 kHz.

An electrostatic transducer basically consists of a flat-plate capacitor with one fixed plate, which is grounded, and a movable plate, which is charged with a constant charge Q. Upon moving this plate (by air molecules) an output voltage change $U = Q/C$ is generated, proportional to the displacement. Electrostatic transducers have a wide frequency band, and can be realized with an upper frequency of several MHz.

Distance measurements with acoustic sensors are based on the time-of-flight of a pulse or burst, or on the frequency shift of an FM signal. They can also be used for flow-measurements (gases and liquids), utilizing the Doppler effect.

2.1.8 Mechanical sensors based on a thermal tandum transduction

Some mechanical quantities can be measured by a thermal sensor as an intermediate. The hot-wire anemometer is an example of such a sensor. A heated wire is plunged into the gas stream, by which it is cooled depending on the flow velocity. The electric current required for maintaining a fixed temperature of the wire is a measure for the flow velocity.

2.1.9 Silicon micromechanical sensors

For a number of reasons, single-crystal silicon is very useful as a construction material for a variety of mechanical sensors. The material can be refined to a high purity; it can easily be shaped (addition of material by deposition of thin layers; removing material by etching; see section 3.2) and it offers the possibility of batch production, using photographic techniques. Furthermore, single-crystal silicon has some favourable mechanical properties. For instance, its Young's modulus, expressing the material's elasticity, equals 1.9×10^{11} Pa, which is almost the same as that of steel. The stiffness-to-weight ratio is higher than of other common construction materials like steel. The tensile yield strength (7.10^{9} Pa) is about three times that of stainless steel. Silicon does not show any measurable plastic flow (at low temperatures), which means that there is no loss of calibration after high stress.

Examples of silicon sensors for mechanical quantities, that are presently available, are pressure or force sensors, accelerometers and flow meters based on thermal principles. There are two basic mechanical sensing principles in use. The first employs the static elastic deformation of a thin silicon beam or membrane. The deflection of the membrane or beam is measured either capacitively or by using the piezoresistive properties of silicon. The other principle is based on resonant structures.

Figure 3 shows the structure of a capacitive pressure sensor. The silicon diaphragm is etched isotropically or anisotropically from wafer thickness down to 10 micrometers, using etch stop techniques. The diaphragm is mounted on a glass substrate using anodic bonding, leaving a gap of 1 to 5 micrometers. The sensitivity of such capacitive sensors depends mainly on the dimensions of the membrane. The capacitive technique also allows the construction of a matrix of such miniaturized pressure sensors, suitable for tactile sensing in robotic applications.

The bending of a beam or membrane, produced by an applied force, can be measured by silicon strain gauges, integrated in the silicon structure on the sites of maximum strain. The gauge factor of such strain gauges depends on doping type, doping concentration and crystal orientation, and may vary from -100 (for n-type Si) to 200 (for p-type Si).

Resonating type pressure sensors are shaped as vibrating beams or membranes. Such a structure can be made by standard etching techniques, similar to the capacitive type of sensors. The resonating part is excited at its resonance frequency, that changes when the strip is stressed or bent by an applied force. A typical frequency shift at maximum stress is about 10% from the zero pressure frequency. The resolution of resonating sensors can be very high, up to 10^{-6}. The resonant structure can also be used for the construction of an accelerometer, by fixing a mass on the vibrating part.

Silicon flow sensors are mainly based on the thermal principle, similar to the anemometer.

Instead of a heated wire, a heating resistoe or transistor in the centre of a silicon chip heats this chip to a controlled temperature above the gas temperature. An air flow along the device generates a temperature difference between the upstream and the downstream ends of the chip. The temperature difference is rather small, because silicon is a good thermal conductor. The sensitivity of the device as a sensor for temperature differences can be improved by thermal isolation (generally performed by a cantilever shaped area as shown in figure 4), reduction of the thickness of the sensitive part (by etching) and by applying thermopiles instead of a single thermocouple. Excellent thermal isolation can be obtained through the use of silicon membranes, cantilever beams and bridges. This aspect is particularly important for thermal sensors, as the thermal conductivity of a thermopile detector fabricated on a silicon membrane or cantilever beam will be reduced, which allows the sensitivity of the device to increase significantly. High-sensitivity thermal detectors have been developed using micromachining techniques (figure 4). Many micromachined pressure sensors are now available for the measurement of absolute, differential, vacuum and acoustic pressure, shear stress, flow acceleration, resonant frequency and blood pressure for applications in fields of science ranging from automotive, aviation and process control to medicine. In addition, these techniques have also opened new possibilities for device-dimension limitation, which is a necessary requirement for chemical sensors designed for implantable medical applications. The micromachining of grooves and holes within the silicon wafer or within thinned silicon membranes has permitted the fabrication of unique and creative micromechanical structures. Fascinating micromechanical tools and devices have recently been presented. Micromechanics may imminently see as bright a future as that of microelectronics.

2.2 Sensors and materials for thermal sensing

The temperature is a measure of the amount of heat stored in a system or in a medium. Temperature sensors are either of the contact type, in which the sensor comes into thermal equilibrium with the substance whose temperature is being measured, or non-contact type, in which the temperature is measured using the radiation laws. The latter category will be considered as infrared sensors and will be discussed in the section on radiant sensors.

A key issue in contact type of temperature sensors is the measurement error introduced by the heat capacity of the sensing device itself. In the case of temperature sensing in a system with a small heat capacity the equilibrium temperature will be determined by the original object temperature, by the original sensor temperature and by the ratio between their heat capacities, as the amount of heat stored in the object will be redistributed in the system comprised of object plus sensor and might give rise to a substantial measurement error. Another mechanism that leads towards an extra non-reproducibility error in temperature measurements is the heat leakage to the surroundings introduced by the sensor. Therefore, for temperature sensing in small systems a small temperature sensor and an effective isolation from the surroundings is mandatory.

Temperature sensors can be classified in sensors that utilize a different intermediate signal domain; a tandem transducer and thermal sensors that directly provide an electrical output signal. Usually the mechanical domain is used in thermal tandem transducers. The largest and most-common group in the tandem transducers category is that of the expansion type of temperature sensors utilizing the linear expansion due to temperature in solids (bimetals), liquids (liquid-in-glass thermometer) or gasses (gas thermometer).

2.2.1 Expansion-type of thermal sensors

Different metals usually reveal different mean thermal expansion coefficients. By connecting two different metals, a bimetal is realised in which one of the metals will expand or contract with a higher rate than the other when the temperature is changed. When holding one end of the bimetal in a fixed position the deflection of the opposite end of the bimetal can be used for indicating the temperature or for triggering an alarm.

The liquid-in-glass thermometer is a well-known representative of the temperature sensor based on the volumetric expansion of liquids. A glass bulb is filled with a liquid, usually mercury. However, for low temperature applications also alcohol (> -110 °C) or pentane (>-200 °C) is used. A tandem transduction from mechanical to electrical can take place using a resistive, capacitive or LVDT displacement sensor.

Gas thermometers are based on the ideal gas law, which states that for such gasses the product of volume and pressure varies proportional with temperature. A typical gas thermometer consists of a bulb containing a gas with nearly ideal properties, such as helium, nitrogen, argon and others. Usually the constant volume measurement method is used, in which a change in temperature is measured using a pressure transducer. The last type of temperature sensor in which a tandem transduction is required is the vapor pressure thermometer. This sensor utilizes the temperature dependence of the pressure of a saturated vapor with a volatile liquid. The pressure can be measured using a pressure transducer. This method can only operate in a small temperature range.

2.2.2 Direct temperature sensors

The direct temperature sensors reveal as a common property the direct change of an electrical property due to temperature. The electrical resistance of a metal increases with temperature due to the increased interaction between electrons and atoms. For covering a wide operating range a stable material should be used with a constant temperature coefficient in this entire operating range. The best performance is observed with platinum resistance thermometers. The sensitivity is equal to 0.39 Ω/K at 300K and the specified range is from -200 °C to 850 °C (IEC 751 standard). Nickel and copper are also sometimes used. For the read-out of these resistive transducers usually a Wheatstone bridge is applied. Nickel sensors reveal a poor linearity. A disadvantage of copper sensors is their low resistivity, which creates the need for fine gauged wire. General disadvantages of the resistive thermometers is the large volume and the associated high heat capacity and long response times. The self-heating due to the current flowing through the sensor supplies extra heat to the measurement system. This gives an error in a 100 Ω Pt resistor, depending on the construction, of around 0.1 K/mW. Low current operation is, therefore, required for minimising this error.

A doped semiconductor reveals a negative temperature coefficient due to an increasing mobility of charge carriers at an increasing temperature. The sensitivity of such a thermistor depends on the doping concentration and is typically 1%/K in a temperature range extending from -50 °C to 150 °C.

Another class of direct temperature sensors utilises the Seebeck effect. Such a thermocouple is comprised of a closed electrical circuit of two different metals in which a potential is generated proportional to the temperature difference between the two junctions. An output voltage can be measured proportional to the temperature diffence. Typical performances are 35 μV/K up to 1000 °C temperature difference for a chromel-constantan thermocouple. A disadvantage that remains is the fact that only a temperature difference is measured, so one of the junctions should be connected to a reference temperature for absolute temperature measurement. The sensitivity can be enlargend by alternatingly placing several thermocouple leads in series for realising a thermopile as shown in figure 5.

Silicon reveals a Seebeck coefficient, depending on the doping level, of up to about 1 mV/K. A large number of Si-Al junctions can be realised in series using lithographic techniques and sensitivities exceeding 100 mV/K are feasible. An advantage of thermopile temperature microsensors in silicon is their relatively small heat capacity.

A pn junction in a semiconductor can also be used for direct temperature sensing. The current voltage characteristic in silicon diodes reveals a temperature coefficient equal to -2 mV/K. A suitable circuit for integration of a temperature sensor in silicon is the PTAT current source, which provides an output current Proportional To Absolute Temperature.

2.3 Sensors and materials for radiant quantities

The sensors in the radiant signal domain are designed to respond to e.m. radiation in a particular part of the spectrum, which basically extents from radio frequencies up to high-energy radiation. Two different radiant properties are usually of interest: intensity and energy or wavelength. The e.m. spectrum is usually subdivided into a number of subranges: radio (< 1 GHz), microwave (1-100 mm), infrared (1-1000 μm), visible (350-750 nm) and ultraviolet and nuclear(> 10 eV). Microwave devices are often used for the measurement of mechanical quantities, such as distance (radar) and velocity (Doppler).

Radiation detectors usually fall into two categories: thermal detectors and photon detectors. The former being a tandem transducer using the thermal domain and the latter being a direct transducer to the electrical signal domain.

2.3.1 Thermal radiation detectors

The spectrum emitted by a blackbody at a certain temperature is described by the Planck radiation law. Similarly, a blackbody temperature is raised by absorbing radiation. Therefore, a thermopile can be used as a radiation detector when one of the junctions is covered by an absorbing layer. This category of radiant sensors is also referred to as non-contact temperature sensors or pyrometers. Similarly, by placing an absorbing layer on a resistive thermometer a bolometer is obtained. Also the pyrodetector can be classified in this category. A pyrodetector uses the pyroelectric effect and a surface charge is generated due to the polarisation of the material when heating the sensor. Such a material is usually also piezoelectric and a strain will also generate a charge. Also in the case of a thermopile an output signal will be generated at a static temperature gradient. For preventing such effects from deteriorating the response of thermal transducers a chopping of the radiant signal is usually required and temperature changes can then be detected.

For evaluation and comparison of radiant detectors a figure of merit, the so-called area-normalised detectivity D^* (m $\sqrt{}$ Hz /W), is used rather than the sensitivity, as the meaningful sensitivity is determined by the noise level. D^* is defined as $\sqrt{A_d}$ / NEP, where A_d denotes the detector area and NEP denotes the Noise Equivalent Power. The NEP is equal to the radiant power required to bring about the same output voltage as the noise voltage and is thus the lower threshold of the radiant signal. A higher value of D^* denotes a better performance. Typical values for D^* in both thermopiles, pyrodetectors and bolometers are in between 5.10^7 and 5.10^8 cm $\sqrt{}$ Hz/W. Responsitivities in the order of 10 V/W are common for these devices.

A radiation detector for very small radiation levels is the Golay cell, which is a gas expansion temperature sensor. The gas pressure is detected using the deflection of a mirror mounted on a flexible membrane in the sensor housing. Responsitivities in excess of 10^6 V/W are possible.

In integrated silicon infrared detectors a micromachined structure is used for maximising the response (silicon is a good thermal conductor) and minimising the response time. For etched-membrane silicon thermopiles a $D^*=10^8$ and a response time smaller than 100 msec is observed.

2.3.2 Photon detectors

The second category of radiant detectors consists of the photon detectors, where charge carriers are generated by incident photons. Detectors in this category are realised in a semiconductor material. As the charge generation is proportional to the number of incident photons the optical intensity can be measured. The operation is determined by the bandgap of the material and a smaller bandwidth is usually observed compared with thermal detectors. Only the incident photons that carry an energy in excess of the bandgap energy are able to produce an electron-hole pair. This wavelength dependence makes it possible to split-up the spectral range in the infrared, visible and high-energy radiation part and to discuss the materials that are commonly applied in that particular part of the spectrum.

For infrared detection, materials such as Ge (E_g=0.66 eV) or PbSe (E_g=0.2 eV) can be used. The bandgap makes the detectors based on those materials suitable for infrared detection in respectively the 1-1.5 μm and 2-7 μm wavelength range. Other lead salts that are often used are PbS and PbTe. A typical figure of the detectivity is $D^*=1.10^{11}$ cm $\sqrt{Hz}$/W. Silicon can not be used for photon-based infrared detection, however performs quite well in the visible part of the spectrum because of the indirect bandgap at 1.1 eV. This property allows a reasonable quantum efficiency for wavelengths in between 400 and 900 nm.

Based on the effect of the generated electron-hole pairs, there are two types of radiant detectors in silicon: the photoconduction detectors and the photojunction detectors. In photoconductors the excess generated charge carriers cause a change in the resistivity. A convenient property of such a device is the topologically-determined gain factor. The inverse proportionality of this gain with the square of the distance between the contacts has resulted in the commonly used interlaced finger structured sensor.

Another semiconductor photon detector is the junction diode. A short circuited pn junction acts as a self-generating radiant detector (a solar cell). The detector operates in the photovoltaic mode. A voltage is available across the terminals, which is determined by the difference in Fermi level between the p- and n-type layers. Operation in the current mode is possible using a reverse voltage across the diode and results in an enhanced collection efficiency. As the charge carriers are separated by internal fields a sub-nanosec response is obtained. An improved efficiency over a larger wavelength range can be obtained using a PIN diode connected to a high reverse voltage. The large very low doped I-type layer is depleted giving a large absorption layer in which the charge carriers are collected. A photon detector reveals a high detectivity. Typical values of D^* lie between 10^{12} and 10^{14} cm $\sqrt{Hz}$ /W. A disadvantage is the wavelength-dependence of the response, which makes conversion tables necessary in radiometric applications. For silicon photodiodes the operation is restricted to a range between 400 nm and 1100 nm. The advanced silicon processing techniques have led to the realisation of large two-dimensional imaging arrays of optical photon detectors.

For the fabrication of high-energy radiation detectors a material with a high atomic number is required in order to provide a sufficient stopping power and, therefore a reasonable efficiency. Practical detectors are often based on GaAs, HgI_2 or CdTe. Silicon is less suitable in this respect. However, due to the more mature processing technology associated with silicon and the availability of silicon-based integrated electronics, a large amount of research is currently aimed at the realisation of silicon x-ray detectors.

Nuclear-particle radiation consists of high-energy electromagnetic radiation and charged particles. When electromagnetic radiation enters and interacts through the photoelectric effect within a silicon p^+-n junction detector, electron-hole pairs are created (figure 6). The amount of charge produced, Q, is dependent on the energy of the incident electromagnetic radiation. For photons in the x-ray and gamma photon regions, this charge is given by the formula $Q = E/\epsilon$, where E is the energy of the incident radiation and ϵ is the mean energy required to create one electron-hole pair (3.6 eV in silicon). Conversely, charged, high-energy nuclear particles, i.e. minimum-ionizing particles, tend to traverse entirely through the silicon wafer and react with the silicon lattice mainly by means of the Coulomb interaction. This results in the creation of a narrow tube (radius < 1 μm) of electron-hole pairs centered around the particle's track. Minimum-ionizing particles create approximately 85 electron-hole pairs per micron.

Detection of the incident radiation is based on the collection of this generated charge. Fast and efficient collection is assured by reverse biasing the detector. Due to the high internal electric field, the charge carriers will separate and drift to their respective contacts (holes to the p^+- and electrons to the n^+-contact). When 4 kΩ-cm silicon is used as the starting material, typical collection times for a path of 300 μm are 10-20 nsec. As the detector has a capacitive impedance, this charge can be quantified by measuring the height of the detector's output pulse. The signal is then amplified and electronically processed. Since the photoelectric absorption coefficient decreases exponentially as the photon energy increases, deep-depletion depths are necessary if soft x-rays in the energy range of approximately 1 - 33 keV are desired to be imaged. Minimum-ionizing particles, due to their high energy, barely interact while they are traversing through the silicon lattice. Therefore, a depletion depth of a few hunderd micrometers is necessary in order to obtain a satisfactory signal-to-noise ratio. Therefore, nuclear radiation-sensors are fabricated on high-purity silicon. Radiation sensors capable of one- and two-dimensional position resolution of incident radiation have been realized through the integration of diode arrays together with passive multiplexing readout schemes on high-purity substrates.

2.4 Sensors and materials for chemical quantities

In this section, only the devices that are immersable in a substance (gas, liquid, solid or mixtures thereof) are considered. Such sensors should have a selective response to the molecular or ionic concentration of a specified component in that substance. The main types of chemical sensors are:

(1) potentiometric sensors, generating an electrochemical potential related to the concentration of the material in solution;

(2) amperometric sensors: these produce an electric current due to an electrochemical reaction, that is proportional to the concentration of the material in solution;

(3) electrical admittance sensors;

(4) catalytic sensors, with which the heat liberated in a controlled chemical reaction is measured;

(5) mass sensors, that measure the mass of a gas or liquid that is absorbed by a specific absorbant.

2.4.1 Measurement of ionic concentration

If the type of ions in a solution is known, the ion concentration can be derived from a conductivity measurement. The sensor consists of a pair of Pt electrodes, connected to an AC-impedance meter. The accuracy of this method is about 1%. The ionic concentration can also be measured by an ion-selective electrode, that developes an electrical potential proportional to the logarithm of the activity of the ion in solution. Most ion-selective electrodes consist of glass that is permeable to a specific ion only. The electrical connection is made by a metal electrode (Ag-AgCl or Hg-HgCl) and an HCl solution inside the glass electrode as an intermediate.

Except for the HN electrode, used for the measurement of the alkalinity or acidity (pH) of a solution, electrodes are available for a wide variety of ions (Na^+, K^+, Mg^+ etc.). The sensitivity of such electrodes is given by the Nickolski equation, and depends on the ion charge and activity. The sensitivity of a pH electrode is about 60 mV per pH unit at 25 °C. A potentiometric measurement requires a reference electrode, for which a calomel (Hg-HgCl) or an Ag-AgCl electrode is used. These electrodes contain a saturated KCl solution as an intermediate, that is in contact with the test solution through a glass membrane or a very narrow channel. With a glass electrode, a pH range from 0 to 14 is covered, and an accuracy of 0.03 pH can be attained. Covering the electrodes by certain enzymes makes them sensitive for organic substances such as urea, glucose, amino-acids and penicillin. The stability of such electrodes is only several weeks, response time is several minutes, and the range varies from 10^{-4} to 10^{-2} mole/l. The high impedance of the electrode (exceeding 100 MΩ) requires a very high input impedance of the measurement circuit. Other electrode systems, such as the antimony electrode, have a much lower impedance, but their range and accuracy are strongly limited. Organic substances can also be detected by enzyme-based amperometric sensors, and are useful for medical applications, food production processes and pollution control. For biological applications, very thin electrodes are developed (0.5 μm). CHEMFETs or ISFETs are newly developed ion-selective sensors based on silicon technology. Their structure is identical to a junction or MOS FET, except for the gate electrode, that consists of an Si_3N_4 layer that is sensitive to H^+ ions. Such semiconductor electrodes have a high input impedance, a low output impedance and a small size.

2.4.2 Measurement of gas concentration

The concentration of flammable gases (such as hydrocarbons, but also CO) can be measured with catalytic devices. Such transducers consist of a catalyst (to sustain the reaction at reasonable temperatures), a temperature sensor (to measure the temperature rise due to the reaction heat) and a heater (to maintain the catalyst at the operating temperature). Common catalysts are platinum and palladium. Operating temperatures are high (typically 500 °C). Catalytic sensors are not gas specific. Mass sensors for gas detection are based either on a vibrating crystal or on surface acoustic waves, both coated by a gas-specific gas absorber.

Oxygen concentration can be measured by a potentiometric sensor at high temperatures (800 °C), with ZrO_2 as an ion conductive material. The sensitivity of such a sensor is about 53 mV/decade; the measurement range varies from about 1 to 25 volume %. Gas sensors based on solid-state technology are under development. Many silicon gas sensors are currently reported in literature. It is expected that a large number of new gas sensors will become available within the next two decades. The main problem is the reproducibility and the selectivity of such sensors.

2.4.3 Humidity and moisture sensing

An important class of humidity sensors is that based on the absorption of water from the substance under test. Such absorption sensors use the relation between a characteristic property of hygroscopic materials and the amount of absorbed water at absorption equilibrium. Measurement quantities may be changes in mass (detected by a vibrating piezoelectric crystal with a hygroscopic coating) or electrical parameters (the dielectric constant or resistivity of a hygroscopic material). The most popular material for use as an absorption sensor is Al_2O_3. When aluminium is electrochemically oxidized (anodization), a porous layer of Al_2O_3 is created on the aluminium surface (figure 7). Exposed to a humid atmosphere, this layer absorbs water molecules, partially filling the pores with liquid water by capillary condensation. Both resistivity and dielectric constant of the layer change according to the amount of absorbed water, which is, in turn, related to the relative humidity (figure 8). The construction of a sensor is completed by the deposition of a metal layer on top of the Al_2O_3 (mostly gold for its chemical resistivity) thin enough to allow water molecules to penetrate into the pores. The structure acts either as a capacitor or as a resistor, both varying with relative humidity.

Some polymers have a relative permittivity that changes with water absorption and can, therefore, be used as a dielectric material for capacitive humidity sensors. The most investigated polymers for this purpose are cellulose acetate buthyrate (CAB) and polyimide. The sensors are produced as flat capacitors, mounted on a glass or ceramic substrate. The top electrode consists of a very thin metal layer or has a digitated structure, to allow the uptake of water by the polymer film. Figure 9 shows a photograph of such a sensor.

Current research on absorption sensors is directed to the use of other porous ceramics and compounds (for instance $MgCr_2O_4$-TiO_2) and other polymers. Major goals are the reduction of the response time, the hysteresis and the sensitivity to other gases. Furthermore, there is a trend towards the integration of the sensitive materials with electronic circuits or even with electronic devices, such as MOSFET's.

Some other types of humidity sensors are the electrolytic hygrometer and the dew-point sensor. The electrolytic type makes use of Faraday's law. The output is the electric current required for complete dissociation of water, absorbed by a dessicant (in particular P_2O_5).

Accurate measurement results are obtained with the dew-point method. This method is based on maintaining equilibrium between evaporation and condensation of the water on a cooled surface. This equilibrium occurs, by definition, at the dew-point temperature, which is uniquely related to the water-vapor content of the test gas. Optical dew detectors use a polished metal mirror. Dew on the cooled mirror is detected by an electrooptical system, responding to scattering of a light beam by the dew drops. Capacitive dew detectors consist of a flat body with an electrically isolating top layer, (for instance oxidized silicon) on which a pair of interdigitated electrodes is deposited (for instance aluminium or tantalum). The capacitance between the electrodes rises sharply at the onset of dew, due to the high dielectric constant of liquid water. The highest accuracy is achieved when the amount of dew is kept constant, by controlling the cooling power up to a fixed reflection or capacitance change. Typical characteristics of the most popular humidity sensors are listed in Table 3.

2.5 Sensors and materials for magnetic fields

2.5.1 Thin magnetic-field-sensitive films

Both ferromagnetic and metal thin films can be used for magnetic field sensing. They operate however, on different measurement principles. Ferromagnetic materials are characterized with a permanent magnetization with a preferential direction, the so-called easy axis, with respect to one of the crystal axes (see figure 10) and with the presence of various small regions in the material with different magnetization orientations, the magnetic domains, which tend to align with magnetic fields. The response of the ferromagnetic thin film devices to an in-plane magnetic field can be a quadratic resistivity change or a linear pseudo-Hall voltage variation (figure 10). The characteristics of suitable metal films are a high mobility, a high resistance and a small temperature dependence. The output signal of metal films to magnetic fields perpendicular to the plane of the film is a Hall voltage.

The ferromagnetic films used can consist of any binary or ternary alloy of Ni, Fe and Co, but permalloy (Ni_xFe_{1-x}, $x = 0.81$) is used most frequently. The magnetic hardness, which indicates the influence of demagnetizing effects (e.g. the characteristics of soft materials are significantly influenced by demagnetizing fields) can be tuned, to a certain extent, by adjusting this ratio. The film should have a high magnetoresistivity (magnetic field induced change in resistance), a small anisotropic field (this is the applied field along the hard axis needed to rotate the magnetization over 90 degrees, the sensitivity is inversely proportional to this field), a small geometric demagnetization (magnetic poles at the edges of the film partly reverse the magnetization of the film in the opposite direction, negligible for circular or square shaped films), zero magnetostriction (no response of the material to stress or stress changes), a small temperature dependence and long-term stability. The film can not be thinner than the mean-free path of the carriers, for in that case the high recombination rate at the surface will start to dominate, resulting in a sensitivity drop. The galvano-magnetic properties of thin films can be determined by first calculating the orientation of the magnetization caused by the applied in-plane magnetic field, followed by evaluating the resistivity anisotropy resulting from this magnetization orientation. The thin films are mainly sensitive to the in-plane magnetic fields in the direction of the hard axis (perpendicular to the easy axis).

Indium Antimonide (InSb) thin films have a very high mobility and are, therefore, extremely suited for the fabrication of Hall plates (Hall plates will be explained later on). The high mobility yields a high bias-current dependent sensitivity. Unfortunately, the material shows a rather poor temperature behavior with respect to silicon Hall plates due to the temperature dependence of the carrier concentration at 300 K. The Hall plates are sensitive to fields perpendicular to the plane of the chip. The resolution of metal Hall plates, about 0.1 μT, is two orders of magnitude lower than the resolution of permalloy thin film devices.

A design aspect of ferromagnetic films is the need for a bias field to reduce the Barkhausen noise and to set the magnetization in a specified direction. The resistivity response can be linearized by rotation of the magnetization direction or the current direction. Configurations used include (see figure 11) a biased sensor (a single rectangular sheet of resistive material with a bias field), which shows a high harmonic distortion, a sensor with inclined elements (two resistors inclined at an angle, with or without a bias field), which is a relatively simple structure, which has the highest sensitivity and offers the highest resistance and a barber-pole sensor, which rotates the current by means of slanted stripes of good conductivity and offers the best linearity and the least distortion. These configurations can all be used in a bridge circuit. The sensor with inclined elements can best be used for low magnetic field measurements, the barber-pole sensor for low and medium fields.

Metal films can be rectangular or square in shape. The short-circuit of the Hall voltage by the contacts should be minimized. A crucifix shape demonstrates the most linear response and a minimal short circuit by the current contacts.

Ferromagnetic films can be fabricated with vacuum deposition techniques on flat substrates at low temperatures, while a magnetic field to fix the easy axis needs to be present. The vacuum deposition can be either thermal evaporation or cathode sputtering with a low deposition rate to prevent any film failures. The film should be deposited onto a flat substrate to prevent deterioration of the uniform magnetization. The edge profile of the film introduces a strong (geometric) demagnetization which can be minimized by trying to make the edge profile (originally square shaped) as close to ellipsoidal shaped as possible using different processing techniques. The temperature during deposition can be anywhere between 25 and 300 °C. Higher temperatures will lead to major changes in structure and magnetic properties such as domain splitting. The magnetic field present during the deposition should be several milli Teslas in order to set the easy-axis direction. The permalloy is adversely affected by most chemicals and oxidizes easily. Polyimide insulation layers which enclose the permalloy film and additional $Si\,N_3$ or $Si\,O_2$ interlayers provide a good protection against environmental influences. Aluminum can be used as contact material since gold may corrode the permalloy. However, a thin molybdenum interlayer may be needed to prevent the diffusion of aluminum into the permalloy. Finally, an annealing step at 300 °C for several hours reduces the specific resistance and the anisotropy field, both resulting in a higher sensitivity. This annealing has little influence on domain splitting.

The ferromagnetic thin films can be used to sense very small fields: 1 nT - 100 μT. The devices can be made very small due to the thin film used. In magnetic heads both ferromagnetic films and metal films can be used. The sensor can be in the airgap of the yoke in the case of lateral recording or a special configuration can be used in vertical recording. An advantage of solid-state magnetic-vector sensors compared to inductive coils is the constant signal amplitude, which is independent of bit density and rate. Magnetic stripes can be read with a low resolution thin-film stripe geometry. The position of a cog in a cog wheel uses the in-plane field measurement capabilities of permalloy films. The sensor is put in between the cog wheel and a permanent magnet and the stray field at the edges of the cogs can be detected by a field-strength or gradient sensor (the latter in case of small cogs). Bubble memories can be read using so-called expanders (see figure 12): the bubble domain is increased in size and read with a chinese character sensor or a chevron stretcher structure. Fluxgate magnetometers can be used for earth magnetic field measurements (about 40 μT - see figure 13). In this case, the complexity of the sensor structure (two coils, perpendicular oriented around the permalloy film) introduces the most problems.

Future trends in magnetic materials research are pulled by the increasing demand for high density magnetic recording. The applications to sense the position of a cog wheel can be used in automotive applications. The earth-magnetic field sensor can be used in navigation systems for vessels and vehicles. A disadvantage of permalloy films is the sensitivity of the magnetic-film parameters to the production process.

2.5.2 Silicon magnetic field sensors

Silicon is a very suitable material for the fabrication of magnetic sensors, despite its relatively low mobility in comparison to Indium Antimonide (InSb) and Gallium Arsenide (GaAs).

The drawback of InSb is the small bandgap between the valence and conduction band, resulting in an almost intrinsic behavior at room temperature. GaAs can be operated up to 250 °C, silicon up to 150 °C, but silicon is a much better choice in terms of dissipated power. Another advantage of silicon over GaAs and InSb is the more mature fabrication technology, which determines the practical possibilities of integration of electronic circuits on the same chip.

The principle of operation of silicon magnetic sensors is based on the Lorentz force: the deflection of charge carriers in a direction perpendicular to both the current and the magnetic field is proportional to the product of the velocity of the charge carriers and the magnetic field strength. The classification of magnetic sensors can be made according to the underlying mechanism determining the sensitivity, i.e. the Hall effect or current deflection. A voltage is measured in the Hall effect devices. The direction of the current is fixed and the applied magnetic field will rotate the electric field vector. At current-deflection measuring devices, the electric field direction is fixed and the current direction rotates dependent on the applied magnetic field. The Hall effect is well known from the Hall plate devices, but there are also some magnetotransistors (magnistors) using this principle to modulate the current injection into the collector.

A Hall plate is a rectangular sheet of resistive material with four symmetrically positioned contacts at the plate boundaries (see figure 14). Numerous variations in shape and size are possible. A magnetotransistor (magnistor) is a transistor structure (BJT or FET) modified such that the deflection of the current in either the base, collector or channel can be measured (see figure 14). There are, however, Hall plate-alike structures measuring the current deflection (the split-drain magnistors) and magnistors operating on a combination of the Hall effect and current deflection. Finally, there are some additional structures like the carrier-domain magnetometer and the magnetodiode (see figure 14). The magnetic-field sensitive current domain in carrier-domain magnetometers moves continuously through the device, resulting in a frequency dependent output signal. Charge carriers in magnetodiodes are deflected to or from a high recombination area, resulting in magnetic-field dependent diode-characteristics.

Standard IC processes, like bipolar or CMOS, are used to make magnetic sensors. Non-standard processes are avoided where possible, for the cost per sensor would increase drastically. Sometimes, a more accurate alignment is desirable to minimize offset.

The optimum device for a specific application has to be determined for each individual case. The highest sensitivity can be obtained with split-drain magnistors, while the lowest noise can be obtained at low frequencies with magnetotransistors and at higher frequencies with bulk Hall plates. Low offset can be obtained with orthogonally switched Hall plates and high resolution can be obtained with bipolar multi-collector magnistors. When the Hall plate is driven from a current source, it demonstrates a linear response and a good temperature behavior and it enables the use of a high operating frequency. The not-commercially available carrier-domain magnetometers and magnetodiodes are thwarted by poor reproducibility.

Applications of magnetic sensors are found in: contactless switching, angular/linear displacement detection, current detection and field mapping and measurement. Contactless switching as used in keyboards and brushless d.c. motors is the major mass production application of magnetic sensors (see figure 15). Low cost and low offset are prerequisites for these devices, which usually consist of a bulk Hall plate integrated together with on-chip electronics. The Hall plates used in keyboards have a build-in hysteresis and are triggered by the movement of the small permanent magnet in the button. The angular/linear displacement sensor is usually composed of a Hall plate with a small permanent magnet at the back of the package, which is put in front of the metal object that needs to be measured. Current detection uses the effect that a current through a wire generates a magnetic field proportional to its magnitude. The output of the Hall plate, which is positioned close to the wire is proportional to the current in the wire. The Hall plate can be used to multiply two signals when both the magnetic field and the supply voltage of the plate are used as variable inputs. In power measurement, the output signal is the product of the voltage across the plate and the current through the wire. The three-dimensional magnetic-field-sensitive magnetotransistor can be used to map highly divergent magnetic fields due to the device's high resolution. Measurement of magnetic patterns on credit cards can make use of lower resolution devices.

Future trends involve the integration of electronics on the same chip to realize a smart sensor. This general feature of silicon sensors is discussed in section 4.2. Only recently, significant progress has been made concerning the offset of Hall plates by switching two or more plates orthogonal to another. Sensors, which are sensitive to more than one component of the magnetic field vector, have been reported, making the positioning of the sensor less critical. The properties of a few realised silicon magnetic sensors are listed in table 4.

2.5.3 Compatible magnetic-field-sensitive structures

The most sensitive magnetic sensors are based on the ferromagnetic effect. Unfortunately, silicon itself is not ferromagnetic . A compatible structure such as ferromagnetic thin film on top of a silicon substrate combining the properties of ferromagnetic materials and the availability of integrated circuits in silicon can lead to very interesting devices. The incentives to deposit thin magnetic films on top of silicon includes the possibility to select both the optimum thin-film material and the optimum IC technology. The advantage is that the often very very small output signals are amplified on the spot, thereby minimizing the influence of environmental disturbances and increasing the resolution of the device. The silicon can be used at the same time for temperature compensation by measuring the temperature directly underneath the device. One of the largest financial advantages is that only one package is needed instead of a thick film substrate and a larger package. Possible drawbacks of this technique are that the heat dissipation in the silicon wafer and the stresses between the various layers might adversely affect the total device performance. The technologies have to be compatible as well, for the deposition of the thin film should not change the characteristics of the underlying electronic components. However, permalloy films can be made non-magnetostrictive and the magnetic films used can be isolated from the substrate by a simple silicon dioxide layer. As indicated in the section on thin magnetic films, the permalloy is sensitive to numerous etchants and similar precautions have to be taken to prevent the deterioration of the thin film.

Several devices have been made using this technique, including a Nickel-Cobalt ($Ni_{.76}Co_{.24}$) magnetoresistor bridge with a differential amplifier. Here, a standard IC process was used and the resistances were deposited on the silicon wafers using electron-beam evaporation, followed by aluminum deposition to interconnect the IC parts internally as well as the IC part to the sensing part (see figure 16). A magnetic compass can be made using a highly sensitive permalloy flux-gate magnetometer. The silicon can be used to integrate the bias electronics and signal processing. In conclusion, the deposition of a thin magnetic film on top of a silicon wafer appears to be very promising and commercially devices based on this principle should be available in the near future.

3 Silicon sensor technology

3.1 Silicon general properties

Silicon is currently employed in the fabrication of more than 98 % of all commercial semiconductor devices sold worldwide. The initial efforts in the development of semiconductor fabrication technologies in the 1930's and 1940's were concentrated on the semiconductor germanium (Ge). The electron and hole drift mobilities at 300 K are more than twice as high in pure, defect-free Ge (3900 and 1900 cm^2/Vs, respectively) than in pure, defect-free silicon (1500 and 475 cm^2/Vs, respectively). However, due to the relatively narrow bandgap of Ge (0.66 eV), devices fabricated in Ge display high junction-leakage currents and therefore must be operated at low temperatures.

Devices fabricated in Si (bandgap 1.12 eV) can be operated at higher temperatures. In addition, Si is an abundant element in nature, rendering it a low-cost starting material, and Si readily lends itself to surface-passivation techniques, which produce oxides unparalled in their dielectric and interfacial properties. Therefore, Si inevitably replaced Ge as the dominant material for semiconductor device fabrication.

Silicon is not the optimum semiconductor in every respect. Gallium arsenide (GaAs) for example has an electron drift mobility (8500 cm^2/Vs) approximately six times higher than that of Si at 300 K, which allows the fabrication of devices with improved frequency responses and smaller electric fields. It is also a direct-bandgap semiconductor, permitting the fabrication of many electro-optical devices that can not be made with silicon technology. However, as it is a compound semiconductor, GaAs growth, purification and processing technologies are more complicated than those of Si. Silicon therefore, is currently the principal material used in the fabrication of most semiconductor integrated circuits, devices and sensors. The magnetic permeability and piezoelectric coefficients of silicon are however, negligible. In order to compensate for this, magnetic and piezoelectric thin-film deposition techniques have been developed, which are compatible with silicon integrated-circuit technology.

Silicon belongs to the cubic class of crystals with the zincblende structure. As it is an elemental semiconductor, Si is further catagorized into the degenerate form of zincblende crystal structures with the diamond lattice. Other properties of silicon are listed in table 5.

3.2 Silicon processing

Silicon planar technology is currently the primary processing method used in the fabrication of most semiconductor integrated circuits and devices. There are presently two basic silicon device technologies; bipolar and Metal-Oxide-Semiconductor (MOS). Both classes of devices are realized through the use of silicon planar technology. A brief, qualitative overview of the basic silicon planar-fabrication technologies is given below.

Silicon processing begins with crystal growth and wafer preparation techniques. Silicon planar-processing technologies are then utilised. These procedures include epitaxial growth, thermal oxidation, lithography, wet-chemical and dry etching, diffusion, ion-implantation, dielectric, polycrystalline and amorphous silicon deposition and metallisation. Several of the processing techniques, i.e. lithography and etching procedures, are performed many times during device fabrication. Circuit testing follows the completion of the fabrication process. Working devices are then mounted in packages, bonded and encapsulated.

A substantial percentage (80-90%) of the silicon crystals prepared for integrated-circuit fabrication are grown by the Czochralski (CZ) method. This process involves the melting of electronic-grade silicon (EGS) in a quartz-lined graphite crucible, and is depicted schematically in figure 17.

The crucible is surrounded by radio-frequency heating coils, which establish and control the temperature of the melt to that near the solidification point of silicon. A seed crystal pre-cut with the desired crystallographic orientation is attatched to a holder, dipped into the melt and raised with a certain speed and rotation. The growing material crystallises at the solid-liquid interface with the same crystallographic orientation as the seed. Dopants, most commonly boron or phosphorous, can be added to the melt in the form of highly doped powders in order to obtain p- or n-type silicon. The diameter of the resulting crystal is controlled by the pulling rate, the rotation speed and the melt temperature, as well as by the amount of dislocations and crystal faults created in the growing crystal. Demands for silicon crystals with high resistivities must be satisfied through floating-zone (FZ) growth or refining techniques.

Epitaxy is a process of preserved, ordered growth of a thin mono-crystalline layer upon a crystalline substrate. Silicon epitaxial layers, 2 to 20 microns thick, serve in bipolar and some MOS technologies as regions of proper resistivity and conductivity, within which the device is fabricated.

The silicon substrate serves as the seed crystal for the epitaxial growth and as a mechanical support. The epitaxial layer is typically doped opposite to that of the substrate for insulative purposes. Dopants can intentionally be incorporated into epitaxial layer during its deposition. Hydrides of the impurity atoms are generally used as the dopant sources. The growth of crystalline silicon from the vapor phase is called vapor-phase epitaxy (VPE) and is the most common form of epitaxial growth in silicon planar processing. VPE systems consist of a quartz reaction chamber into which the gasses are pumped and a susceptor for support of the wafer.

Other methods of mono-crystalline silicon growth from a silicon substrate include liquid-phase epitaxy (LPE) and molecular-beam epitaxy (MBE).

Upon exposure to air, the surface of silicon becomes covered with a 15-20 Å thick layer of native silicon dioxide (SiO_2), which will increase to approximately 40 Å in time. The thermal oxidation of silicon in quartz furnace tubes at temperatures between 700-1200 °C in an atmosphere of oxygen (dry oxidation) or water vapor (wet oxidation) allows relatively dense, adherent, trap-free layers of SiO_2 to be grown with relative ease. These films serve as masks for diffusion and ion-implantation steps, as gate-oxide films, as dielectrics and as passivation layers.

Silicon is oxidised at its surface. The growth of a thermal oxide film with a thickness of d, involves the consumption of a layer of silicon $0.44d$ thick. Wet oxidation is usually carried out by allowing a carrier gas to flow through a water bubbler maintained at 95 °C (for the production of water vapor) into a quartz diffusion tube in which the silicon wafer is placed (figure 18). Wet oxidation is a rapid process, but results in relatively porous films (ρ = 2.18 g/cm^3). It is used to grow thick films for masking purposes. Dry oxidation is a slower process involving only oxygen, but it produces oxide films with higher densities (ρ = 2.28 g/cm^3) and with relatively low concentrations of traps and interface states. Dry oxidation procedures are used in MOS technologies to fabricate gate oxides.

Lithography is the process of transferring geometrical patterns from one surface to another and was developed for the semiconductor industry in the early 1960's. In this sphere, one surface is the silicon wafer, the other surface is a photosensitised glass plate or mask and the geometrical patterns on the mask define sections of the device under design, i.e. diffusion windows, polysilicon or metal interconnections, etc. As the fabrication of the device is a sequential process, the features of each mask are transferred level by level through a lithographical procedure onto the surface of the wafer. This procedure first entails the coating of the silicon wafer, which has been fabricated so as to encompass the film to be etched (figure 19(a)), with a polymer called (positive or negative) resist (figure 19(b)). The resist is sensitive to a specific region of the electromagnetic spectrum, i.e. the ultra-violet light or x-ray region, or to an incident ion or electron beam. The mask is then placed over the wafer surface and exposed to the electromagnetic radiation or to the beam (figure 19(c)). This is followed by the development of the (negative) resist (figure 19(d)). Etching techniques will then uncover the pattern that was desired to be transferred (figure 19(e)) and the resist is then removed (figure 19(f)). Positive resist allows the transfer of a pattern exactly opposite to that of negative resist. Optical lithography utilises ultra-violet light as the radiation source while x-ray, electron-beam and ion-beam lithographies utilise x-rays, electron and ion beams respectively. Optical lithography is currently the most widely used lithographical process and is capable of resolutions of less than 1 μm. Electron-beam lithography is generally used for the manufacturing of low-volume custom or semi-custom devices, while x-ray and ion-beam lithographies are still in their developmental stages.

Various etching techniques are used in silicon planar technology, most of which fall into the catagories of wet-chemical or dry-etching methods. The etch rate is defined as the vertical etch depth divided by the time of etching. Etchants are termed anisotropic or isotropic depending on their vertical and lateral etch rates. Within the time limits of the etching procedure, if the vertical etch rate greatly exceeds the lateral, a vertical edge profile coincident with the mask pattern will be produced and the etchant is termed anisotropic (figure 20(a)). Isotropic etchants tend to be independent of direction or crystal orientation and have vertical and lateral etch rates on the same order of magnitude, which generally results in underetching of the mask pattern (figure 20(b)).

Wet-chemical etching techniques involve the exposure of the wafer to chemical solvents in order to provoke the conversion of the unprotected material into soluble compounds, which can be dissolved by the chemical etchants. The essential steps in such an interfacial reaction include the transport of the reactants to the reacting surface, the surface reaction itself and the transport of the subsequent products away from the surface. Dry-etching procedures became very popular after the discovery of their highly anisotropic potential, which in turn makes high-resolution pattern transfer and smaller feature sizes realizable. These procedures include several techniques for film removal including plasma etching, reactive-ion etching, sputter etching and ion-beam milling.

The diffusion of impurity atoms in a material at elevated temperatures will occur if a concentration gradient exists. Diffusion as a fabrication step in silicon planar processing is an important method for the introduction of a predetermined concentration of impurity atoms into a specific region of the silicon lattice so as to alter its conductivity. Common n-type dopants used include phosphorous (P), arsenic (As) and antimony (Sb), while boron (B) is the most widely used p-type dopant. Diffusion is performed through window openings in a (silicon dioxide) mask, which overlies the silicon substrate. Diffusion systems are most frequently performed in open-tube systems, similar to thermal oxidation systems, where wafer insertion is performed at one end of a quartz diffusion tube and dopant introduction occurs at the other end.

Ion-implantation is an alternative technique for the introduction of impurity atoms into the silicon substrate in order to alter its electrical properties. In this technique, an ion-implanter is used to first convert neutral dopant atoms into ions. These ionised impurity atoms are then purified, collimated into an ion beam and accelerated to an energy between 15-500 keV. The ion beam is then directed at the silicon surface and subsequently deflected so as to scan the wafer surface. The energy of the beam is chosen so that it is sufficient to implant the ions somewhere between 10-10,000 Å below the silicon surface, wherever it is not protected by a sufficiently thick isolating mask. The collision of the implanted ions with the substrate atoms causes material damage. A process of thermal annealing must occur in order to restore the crystal structure and to activate the implanted carriers.

Currently, the most commonly used deposited thin films include polycrystalline and amorphous silicon and dielectric materials, i.e. silicon dioxide and silicon nitride. These films are deposited by various chemical-vapor deposition techniques including atmospheric-pressure (CVD), low-pressure (LPCVD) and plasma-assisted (PCVD). Amorphous silicon is used in the fabrication of solar cells, while polysilicon is used in the fabrication of gate electrodes in the self-aligned gate technology of MOS devices. Silicon deposited below approximately 600 °C is generally amorphous in crystal structure. Above this temperature, polycrystalline silicon results. The dielectric films function as insulators between conducting films and as passivation layers.

Aluminum and aluminum with 1-2 % silicon are the metal films most widely used in silicon planar technology and are obtained through vacuum evaporation, sputtering or electron-beam systems. They provide highly conductive interconnections between device contacts and external terminations. Other metals with well-developed deposition technologies include Au, Al-Si-Cu alloys, Ti-Al, Ti, Ti-W, Mo, Pd, Pt and Ta.

Bonding pads will normally be placed around the edges of a design in order to allow easy circuit bonding and testing. Initial testing of each chip on a finished wafer is performed with a wafer prober prior to bonding. Those chips passing the initial testing are then mounted in packages generally with epoxy cement, bonded with aluminum or gold wires and encapsulated for protection purposes. Final tests are then performed on the finished integrated-circuits.

3.3 Special silicon sensor processing

The development of advanced, inexpensive instrumentation systems for a wide range of fields has been stimulated by the availability of superior microelectronics. A great demand therefore exists for the development of inexpensive sensors and actuators, as they are the weak link in the total system. Advancements made in silicon processing technologies designed for the manufacture of silicon integrated circuits have promoted the development of silicon sensors.

Although there have been many successful silicon sensor designs manufactured with standard bipolar or MOS processing sequences, the fabrication of silicon sensors usually follows, in some form or other, nonstandard processing sequences. Additional processing steps must often be added during the fabrication of many sensor designs, i.e. the deposition of piezoelectric or magnetic thin or thick films.

More recently, a specialized controlled-etching technology called micromachining has been developed to selectively remove silicon and numerous other films used in silicon planar processing in the fabrication of high-performance sensors. The bonding and encapsulation of silicon pressure and chemical sensors still remains a great problem and an impeding obstacle to further development. All these nonstandard procedures cause the device turnaround time to increase and the yield to decrease. As a result, although the development of silicon sensors has remarkably progressed through the knowledge acquired from the sophistication of silicon integrated circuits, numerous challenges still exist.

Methods for the deposition of conductive, insulative, piezoelectric and magnetic thin films have developed concurrently with silicon planar processes so that they are not only compatible technologies, but complementary. Several deposition technologies have been developed to meet the demands of the industry. The particular method of thin-film deposition used will determine the film microcomposition and microstructure. These characteristics will in turn influence the physical and chemical properties of the film and the functional operation of the fabricated devices.

The available deposition methods can be divided into evaporation processes and chemical- and physical-vapor deposition processes. In evaporation processes, vapors are produced from the source material by increasing its temperature through various discharge methods, i.e. direct-resistance, electron-beam, laser beam or arc discharges. The material vapors will condense on the desired substrate when it is kept at a low temperature and potential. Evaporation processes are usually carried out under vacuum conditions so as to limit the number of material collisions with the background gas species, to prevent the incorporation of the background gas species within the film and to prevent the subsequent reaction with residual gasses.

Chemical-vapor deposition processes include atmospheric pressure (CVD), low pressure (LPCVD) and plasma-assisted (PCVD) technologies. Physical-vapor deposition processes include various sputtering and plasma processes and ion-beam methods.

Sputtering processes involve the ejection of atoms from a target through its bombardment with energetic particles, followed by the condensation of the ejected atoms onto a substrate. The number of ejected species per incident ion is termed the sputtering yield, which increases with the energy and the mass of the bombarding ions. The principle sputtering methods include glow-discharge sputtering and ion-beam sputtering. Other sputtering processes include direct-current, radio-frequency, reactive, reactive-magnetron and planar-magnetron sputtering. A partially ionized gas is termed a plasma and can be composed of electrons and ions, as well as a variety of neutral species. The densities of the electrons, ions and neutral species are the most important deposition parameters. Other parameters include the discharge voltage, gas pressure and gas type. Plasmas are used in dry-etching methods as well as in thin-film deposition techniques. Different ion-beam PVD methods include ion-beam sputtering deposition, ion-beam deposition and ion-cluster-beam deposition. The main advantage of ion-beam sputtering methods is that relatively low processing pressures can be maintained (i.e. below 10^{-6} Torr).

The effective inclusion of ZnO thin-film deposition technologies within the otherwise standard processing sequences of silicon sensors demonstrates its success as a technology compatible with silicon planar technology. A number of techniques are available for the thin-film deposition of ZnO including ion plating and chemical-vapor deposition, as well as direct-current, radio-frequency, reactive-magnetron and planar-magnetron sputtering. The most important material parameters to be characterized are the piezoelectric and pyroelectric coefficients. Other general characterization studies often performed include measurements of the material composition, resistivity and absorption spectra and investigations of the crystal structure. The application of ZnO-thin films in pressure, mechanical and surface-acoustic wave sensors is based on its piezoelectric properties. Thin-film ZnO layers have also been utilized in the realization of optical and chemical sensors, which are based on pyroelectric as well as the piezoelectric effects.

Thick-film materials have been used since the early 1960's to fabricate circuit components and hybrid circuits. Thick-film technology is based on the silk-screen film deposition and high-temperature firing of conductive, resistive and insulative pastes and inks onto ceramic or insulating substrates. This technology currently plays an essential role in the electronics industry and has become a solid-state sensor technology in itself. Recently however, thick-film technologies have been developed that are compatible with silicon planar technology. Thick-film depositions are mainly used as protective layers in the fabrication of silicon integrated devices, but they are beginning to play an important role in the bonding and packaging of silicon circuits. Bonding techniques are also available, which connect separately fabricated silicon integrated circuits to thick-film networks through metal-film conductors in the formation of hybrid integrated circuits. Future prospective applications of thick-film materials in integrated silicon designs are found in the potential realisation of complex three-dimensional circuits and networks.

Micromachining pertains to the use of specialised fabrication techniques for the controlled, selective etching of silicon and numerous films used in silicon planar processing. Early etching methods employed wet-chemical isotropic etchants. Anisotropic-etching technologies were sought to overcome the problems associated with precision, sensitivity and temperature dependence.

Isotropic wet-chemical etch solutions show no preferential etch rate to any crystallographic orientation, and usually consist of a mixture of hydrofluoric, nitric and acetic acids. Problems with isotropic etchants are found in the areas of etch control, selectability and precision. Anisotropic wet-chemical etchants differ from isotropic etchants in that they are orientation dependent. They are known to selectively etch the <100> and the <110> crystal orientations, leaving the <111> orientation relatively free from attack (etch rates are typically 50 times slower in the <111> direction than in either the <100> or <110> directions). The use of anisotropic etchants with <110> silicon substrates results in openings with vertical sidewalls, while sidewalls set at an angle of 54.7° with respect to the surface are produced in <100> silicon. The most commonly used anisotropic wet-chemical etchants include potassium hydroxide (KOH) and ethylene diamine pyrocatechol water (EDP).

The dry etching in radio-frequency or electron-cyclotron-resonance generated plasmas of silicon, polysilicon, silicon dioxide, silicon nitride, resist, aluminum and other films used in silicon planar technologies has become a well-accepted alternative to conventional wet-chemical techniques. Greater control over the etching procedure is available with dry-etching techniques. Dry-plasma etching can also be isotropic or anisotropic (i.e. orientation independent or dependent, respectively). The directionality of the etching, the absolute-etch rates, the etch-rate ratios, as well as the amount of polymer deposition and the degree of radiation damage, are all determined by such procedural and instrumental parameters as the composition, temperature and flow rates of the reactant gasses, the pressure and the power density of the plasma, the voltage between the substrates and the plasma and the wafer temperature.

Dry etching can occur by different mechanisms; mainly categorised by ion-etching techniques (i.e. sputter etching and ion milling), and reactive-etching techniques (i.e. plasma etching and reactive-ion etching). Etching occurs primarily by physical means such as ion bombardment in ion-etching techniques. In the reactive-etching techniques, a radio-frequency or electron-cyclotron-resonance generated plasma produces neutral atoms, neutral molecules and radicals that react with the films to produce volatile compounds. Common gasses used for dry etching include freon (CF_4) and chlorine gasses such as carbon tetrachloride (CCl_4) and Cl_2. Atomic fluorine and chlorine are produced in the respective plasmas, which react to produce the volatile compounds SiF_4 and $SiCl_4$, respectively.

In order to fabricate precisely dimensioned micromechanical structures such as cantilever beams, diaphragms and bridges, the etching procedure must be so controllable that it can be completely stopped at a predesignated point. Predetermination of the etch rate followed by the timing of the etch procedure is the most common method of termination, but due to such factors as the etch-rate sensitivity to agitation and temperature, as well as processing parameter and substrate thickness variations, this method in not satisfactory in the fabrication of microstructures. Satisfactory etch-rate reduction methods employed include the boron etch stop and electrochemical etch (ECE) stop procedures.

In a number of applications, if the anisotropic etchants KOH or EDP are used, the boron etch stop technique can be utilised. When these anisotropic etchants are applied to the n-regions of structures with p^+-n junctions, the etch rate becomes significantly reduced at the interface of the n-region to the heavily-doped p^+-region (boron impurity greater than approximately 5×10^{19} cm^{-3}). This procedure cannot be used in all applications. Considerable mechanical strain is introduced with such a high-impurity level, which makes the growth of a high-quality epilayer on top of this p^+-layer very difficult. In addition, the high boron doping level also prohibits the direct fabrication of microelectronics within this layer.

Although more difficult to use, anisotropic ECE etch-stop procedures offer significant advantages in this area. The etching will terminate at the epitaxy/substrate interface of an n-type epitaxially layer grown on a n^+- or p-substrate with a doping level standardly used in microelectronics fabrication. The microelectronic or sensor devices can be fabricated in the epilayer with standard processing techniques followed by the use of the ECE etching procedure to define the microstructures. Cantilever beams, bridges, floating membranes and micromechanical structures have been fabricated with these techniques from silicon as well as from such films as polysilicon, amorphous silicon, silicon dioxide, silicon nitride and polyimide.

The first well-established plasma-etching techniques were isotropic and nonuniform in nature, occurring primarily through the formation of volatile compounds and practiced in low-voltage barrel type reactors. These instruments are still widely in use for applications where high resolution is not required in order to etch numerous films used in silicon planar technology i.e. photoresist removal. Highly directional etching is now performed by reactive-ion etching in parallel-plate reactors. Etching in these systems also occurs primarily through the formation of volatile compounds, but ion bombardment also plays an important role. The reactors are similar to sputter-etching instruments. Vertical etch rates that greatly exceed lateral etch rates result with reactive-ion etching procedures, but the etch selectivity is reported to be poor due to the nonselective sputtering.

The bonding of the silicon sensor to a package substrate is necessary in order to provide the sensor with mechanical support, as well as thermal and electrical conduction paths. For proper design function however, the standard organic adhesives used in integrated-circuit bonding are often unacceptable for bonding certain sensors to their packages, in particular high-performance pressure sensors, i.e. piezoresistive and capacitive pressure sensors, as well as multi-ion (ISFET) chemical sensors. Chemical sensors require in addition that the bond be highly resistant to harsh-environmental conditions, while allowing for the separation of multiple ions. The types of bonding techniques for microsensors in general include eutectic, epoxy, polyimide, nonuniform-press, thermocompression-metallic, room-temperature compression-metallic, electrostatic (or anodic) and low-temperature glass bonding, as well as ultrasonic, seam and laser welding. Anodic bonding closely approximates the ideal bonding technique, i.e. that technique which utilizes an infinitely-thin adhesive so as to glue the sensor onto a substrate with a thermal expansion identical to that of silicon's (3.2×10^{-6}/°C). This procedure can be made compatible with silicon planar technology with the concurrent maintenance of the quality of all the existing integrated electronic components during the procedure. The quality of the seal does not deterioate with time and glass is also highly resistant to chemical attack.

A sensor converts a measurand by means of a physical or chemical effect typically into an electrical signal. The encapsulation and packaging of the sensor and any associated on-chip microelectronics must be performed in such a way as to allow the interaction between the sensor and the measurand to take place in a satisfactory manner. Encapsulation and packaging solutions have been developed for the radiant, thermal, magnetic and mechanical sensors, which allow the feasible interaction of external physical variables with the silicon sensor. Such solutions however, are still being sought for the chemical sensors.

Unlike the other catagories of microsensors, chemical sensors must come into direct physical contact with the substance being measured. This requirement often demands that the sensor be submerged into harsh-chemical environments. Encapsulation and packaging solutions must be developed simultaneously with the sensing device, which will allow the chemical substance to be measured to come into direct contact with the microsensor without causing degradation due to the harsh chemicals. The sensing device must first be designed so that only the actual sensing components come into direct contact with the medium. Any on-chip electronics must be kept completely isolated from the medium. For signal transfer between the chemically sensitive part of the device and its associated electronics, a technique has been introduced called the coated-wire method. Methods of encapsulation of several types of membranes have also been investigated. One successful method involves the drilling of a cavity partially through a glass substrate into which the chemical sensor is anodically bonded. Pores in the cavity ceiling then provide enviromental contact with the sensor to take place. Improvement in device performance is directly related to improvements in encapsulation and packaging considerations.

4 Future trends

4.1 Sensor foundries

The demand to small and rugged sensors has led to the development of silicon strain-gauges and pressure sensors, both utilizing the piezoresistive effect in the early 60's. Nowadays, a great variety of silicon sensors is available to measure any physical or chemical effect or quantity. The sensors are usually relatively cheap and, therefore, a good alternative for non-silicon devices (Hall plates cost $0.30 and pressure sensors as low as $5). The price of sensors made in silicon technology can be low only when made in mass production and sold in large quantities. Sometimes, when the present non-silicon sensors used are very expensive and large, a silicon version can be introduced which is not made in mass production, but is still cheap compared to the conventional product and offers some distinct advantages. In this chapter we will take a look at the markets for silicon sensors, the sensor-producing companies, financing and several production issues. These companies and the way they market their product will determine the availability of integrated sensors and will, thus, affect the future trend in sensors.

There are two ways to categorize the market for silicon sensors. The market can be segmented according to the measured physical parameter: pressure sensors, Hall effect devices, temperature sensors, chemical sensors, accelerometers, flow sensors, etc. Annual growth of each market segment over the next decade is expected to be 10 to 15 %, and the annual growth for new products, such as improved pressure sensors, chemical sensors and silicon accelerometers will be even higher. Each category contains smart sensors, the 'smart' part of the sensor varying from hybrid TC compensated sensors to sensors with on-chip electronics.

The market can also be categorized according to the type of customer: The consumer electronics, automotive industry, the process industry, the medical sector, etc. The automotive industry is an almost ideal target for low cost sensors. Here, there is a need to measure almost any parameter under various circumstances. In addition, house-hold appliances, consumer electronics and computers can also make good use of cheap silicon sensors. The process industry and medical applications are the traditional markets for pressure sensors. Silicon sensors, which are not mass produced, are usually used only in highly specialized products, e.g. airplane and military industry.

A wider application of sensors in all parts of the industry is thwarted by the huge variety of sensing principles offered, with no standardization whatsoever with respect to the output signal and the signal source. Computers need standardized bus-compatible sensors with a digital output. Sensors with an intrinsic digital output are, therefore, extremely important. Generally, low cost, rugged and reliable sensors compatible with computer systems will become increasingly important, as will be discussed in the next chapter on smart sensors. New sensors will include multi-function sensors, and those featuring higher levels of on-chip signal conditioning, which offers improved performance and greatly simplified use.

Most sensor producing companies are divisions of multinationals. The major producers for pressure sensors are: Delco, Motorola and Sensym and for Hall sensors: Sprague, Texas, Honeywell and Siemens. Temperature sensors are mainly produced by Valvo and Siemens. Chemical sensors are made by various companies. Novel silicon accelerometers are made by a number of smaller companies specialized in micromachining. Recently, Honeywell started a new family of semiconductor humidity and air flow sensors. These sensors are also being made by several smaller companies. The large companies produce most of the mass-made sensors for internal use, while small companies are interested mostly in non-mass production or special products. The small sensor companies, such as ICSensors, Novasensor (USA) and Xensor

Integration (The Netherlands) exist by offering specific knowledge and exclusive products. Usually, small companies will not have the facilities to mass produce at all or at least not as economically as large companies. They are, therefore, limited to only low-volume special products. The huge variety of available sensing principles allows this approach to be successful in those cases.

Financing of new sensor products can be done in two ways. The first option is to arrange a contract with a customer to develop a new sensor and use the knowledge to develop and improve one's own products at a later stage. The other option is to use the profits of the present products to develop new products. This last approach does not present any problems with respect to customers who might be interested in patents for the work performed on their account. Payment of the development can be done beforehand (dedicated financing) or after delivery of the prototypes. The ever remaining high costs of the initial batches of silicon-sensor prototypes results in only large sensor-producing companies being able to start new sensor projects. Companies can develop and test the new devices themselves or have the customer perform on-site tests on the products developed on their behalf. Small customers have to wait for the product to become standard and hence will be too late to obtain a large segment of the market using that sensor as a part of a total system.

A high priced sensor can sometimes be acceptable to customers due to the lack of an alternative or due to the high costs and exceptionally large dimensions of the alternative. This makes costly micromachining steps and/or specialized packages viable even for mass sensor production. However, micromachining processing steps and packaging should be standardized even further and at least be automated to minimize production costs.

The production of silicon sensors begins with the wafer fabrication, with standard processes, as well as with micromachining and Si-on-Si wafer bonding techniques. Once the sensors themselves have been made, they have to be put in a package. The die-down should use an epoxy, which is selected for its thermal behavior, flexibility, creep, etc. Bonding is very expensive and the number of bond-wires needed should be minimized. Usually, there is not enough volume for an economic accountable automated bonding procedure. The encapsulation is usually a very critical step in the process since it undermines the good performance of the die itself. Encapsulation problems can be solved but usually require more attention (e.g.

non-magnetic, stress-free, low heat capacity, transparent windows, etc.). A large part of the total cost of sensors is the packaging (the die is, usually, only a small part of the total cost). The packaging problems are often overlooked in sensor research. The price of the packaging is very sensor dependent, e.g. surface-mount pressure sensors can be produced at a relatively low cost with respect to the high pressure resistant stainless steel sensor housing. Testing of the parts can be very labor intensive and complicated when mass volumes of the sensor are not being made. The problem occurring here is that a piezoresistive pressure sensor might be very package stress sensitive when a flexible package has been used in combination with a faulty die-down technique. Basically, the new sensor types should be controlled with respect to their sensitivity to virtually all possible variables in their application environment. Shipping of the often non-standard packages, sometimes with small cables attached, requires special handling and also higher expenses. Generally, further standardization and automation should result in a reduction of the production costs.

It can be concluded that the future prospects for silicon sensor producers are very good. The demand for sensors over the next ten years is expected to increase drastically, resulting in very good opportunities for the foundation of new sensor companies. However, the companies will probably not produce high quantities, but highly specialized products. Broader standard product ranges and improved accessibility to the customers are important aspects for successful sensor companies.

4.2 Smart sensors

The widespread availability and increasing performance of electronic information processing equipment has reduced the role of electro-mechanical calculators to that of an obsolete museum exhibit, in which the pre-war culmination of precision mechanical craftsmanship is displayed. The rapid growth of microelectronic technology has been the main promotor of this change from bulky mechanical precision equipment to microprocessor-based systems, as it allowed an increasing on-chip density and, thus, an increased number and complexity of integrated functions. As a result, high volume production of digital and analog building blocks can be realised at a price unattainable for non-electronic systems. Therefore, no extensive research efforts are to be reported on alternative techniques. Exceptions are the increasing popularity of research on electro-optics for high-speed switching applications and the pneumatic processing systems, which are often used for safety reasons in applications with a high explosion- and/or fire risk, such as chemical plants.

Despite the large number of sensing effects in silicon, mentioned already, that can be utilized for the sensing of non-electrical quantities, such a complete transition from expensive precision mechanical structures to microelectronics has not yet been established for sensors. There are basically three reasons for this reluctant acceptance of silicon sensors in commercial products for the instrumentation and control industry. Firstly, integrated circuits and sensors reveal a high initial production cost and a small added cost per sample, which makes the economic competitivity strongly dependent on the market volume. For digital integrated circuits a huge market was already available at the introduction of such devices. For sensors a substantial market can be developed at a favourable price setting, however a realistic estimation of the present market size will result in only a moderate production volume of integrated sensors. Secondly, most of the presently available silicon sensors fail to provide a direct microprocessor compatible output signal and, therefore, require extra signal conditioning circuits. This common practice strongly undermines the claimed advantage of silicon viz. manufacturing the sensor in the same material in which the signal conditioning and information processing circuits are realised. Finally, there some operating limitations that prevent the application of silicon sensors in harsh environmental conditions. The limited field of applications, such as military and space research, where the latter is essential and where a high reliability is prescribed under extreme environmental conditions is not likely to be penetrated by silicon sensors because of its limited temperature range. Moreover these applications feature small production series of highly specialized sensors with costs as a secondary priority. This starting-point does not fit the highlights of silicon sensors at all and makes the implementation of integrated silicon sensors in such applications unlikely irrespective of future developments. In contrast, a glamourous future seems feasible in consumer products and in the instrumentation and control industries. These application areas impose less extreme environmental requirements, are very keen on product costs and constitute a large market. These boundary conditions fit the silicon sensor, as it is relatively inexpensive in mass production and it can easiliy comply with the operating range requirements in consumer products.

A limitation of present silicon sensors that, so far, precludes a breakthrough in this market originates from the inability of the integrated silicon sensor industry to exploit the, often mentioned and rarely implemented, intrinsic advantage of silicon sensors (its processing compatibility with microelectronic circuits) to full advantage. Present integrated silicon sensors reveal a poor price/performance ratio compared to other microelectronic components. These sensors still supply an output signal that is strongly sensor-type oriented and not of a standard format; e.g. a Hall sensor will generate a small voltage at an applied magnetic field and a piezoresistive sensor will give a resistivity change when applying a pressure. Another property of current sensors, that contribute to its less user-friendly ring, results from the presence of undesirable characteristics (such as offset, drift and non-linearity) at the output. Again, silicon integrated sensors have the potential to overcome these general drawbacks by adding on-chip integrated compensation circuitry. These two inadequacies of sensors forces a prospective designer of a system with such sensors to acquire either an intimate knowledge of the sensing element before being able to implement it or to purchase a complete sensor system. The former is in strong contrast with the digital and analog building blocks, for which the transfer functions can be well characterized without the user having to become familiar with the details of the internal operation of the building block. This feature was one of the prime reasons for the smooth penetration of these building blocks in all the levels of the systems market and the rapid acceptance by systems engineers.

A system engineer is usually reluctant to go into detail in the underlying sensor operation and is, therefore, inclined to resort to an expensive sensor system or to use a known conventional sensor rather than implementing an innovative silicon sensor. This threshold seriously hampers the breakthrough of silicon sensors and forces the sensor research community to actually exploit the long cherished intrinsic advantage of integrated silicon sensors and to use the compatibility with the signal processing circuitry to realise an output signal of a standard format and to compensate in the package for undesired characteristics. It is generally believed that a sensor boom is to be expected as soon as such thresholds are removed. Sensors complying with such characteristics are referred to as 'smart sensors' or 'intelligent transducers' and, as a consequence of the above-mentioned advantages, a considerable research effort is aimed in the direction of the development of such smart sensors.

The research in smart sensors can be classified according to the extend in which the properties of a genuine smart integrated silicon sensor have been realised. The pursued objectives are listed in order of increased complexity of the smart sensor and involve sensor chips that incorporate:

(1) direct on-chip amplification of the sensor signal and/or conversion to a different analog signal carrier,

(2) in addition to (1); a multiplexing of several sensors and a compensation for sensor non-idealities,

(3) in addition to (2); an analog to digital conversion,

(4) in addition to (3); an interface for connection to a standardized digital sensor interface bus and automatic sensor calibration.

An essential remark that has to be made with respect to smart sensors in all these categories is the possible occurrence of interference of the nonelectrical signal with the performance of the signal condition circuits . If proper operation of an integrated sensor can only be maintained by using extra processing steps for shielding the electronics or when serious compromises have to be made in the sensor performance to obtain the required compatibility between the circuit elements and the sensor, it might be opportune to resort to a hybrid realisation.

The first step has already been set for a wide range of sensor types and usually the signal level and the output impedance of the smart sensor are such that the SNR is not susceptible to noise added to this output. Also a conversion of resistance change in resistive transducers to a signal voltage is, as a rule, performed using a Wheatstone-bridge configuration. Also the second milestone has often been reached. The compensation of sensor non-idealities using a second identical sensor that is not subjected to the non-electrical quantity to be measured is already common practice. The CCD camera is perhaps the most impresssive example of a matrix sensor with on-chip multiplexing. Current state-of-the-art sensor research can be situated somewhere between the second and the third milestone. We will therefore focus on the problems that will arise when proceeding with the third objective

Apart from a few exceptions, an integrated sensor with an analog-to-digital conversion (ADC) is not yet customary. Various reasons cause the integration of the ADC with a sensor that is already integrated with analog signal condition circuitry to be a less trivial task than obvious considerations would suggest. The specifications of sensors with respect to accuracy very rarely forces the use of an ADC with a resolution exceeding 12 bit. In addition, the bandwidth of transducers does usually not impose severe demands on the converter speed. Converters complying with such demands can be well constructed using relaxed processing specifications, as present state-of-the-art ADC research is involved in 16-bit resolution ADCs and thus nothing seems to impede a direct implementation of the thoroughly tested 12-bit ADCs and the associated technology. However, at least three boundary conditions, that are inherent to integrated silicon sensors, seriously complicate the matter.

The first originates from the required processing compatibility. Most of the available ADC concepts are optimised for realisation in a CMOS process, whereas most silicon sensors have an affinity to bipolar processing. The second cause for the mismatch between sensor research and the available types of ADCs results from the disproportion between inaccuracy and dynamic range that is often encountered in sensors. As an example; a silicon PIN photodiode can easily cover a dynamic range exceeding 5 decades of incident light intensities with good linearity, whereas the inaccuracy is limited to about 1% due to temperature dependences and to remaining errors in the spectral uniformity after correction in a look-up table. The resolution results in a 16-17 bit ADC, which is rather superfluous when considering the inaccuracy of the sensor. Such characteristics strongly favour the implementation of a nonlinear ADC, whereas state-of-the-art ADC research is more involved in linear ADC. A third problem that hampers the integration of an ADC in a smart sensor of the second category has to do with industrial yield. Both the increased chip area needed per device and the possible extra processing steps needed for the ADC (e.g. laser-trimming for accurately-matched resistors) reduce this yield and thus affect the economical motivation for addition of the ADC in the smart sensor in a negative sense. These boundary conditions make future research of ADCs that are especially suited for integrated sensors necessary.

As a result, an increasing effort in current smart sensor reseach is aimed at the realisation of special types of ADCs. In those ADCs only a moderate resolution is pursued, whereas a large emphasis is put on the simplicity and compatibility with standard processing. At the same time special attention is being paid to sensors that provide a signal in a kind of intermediate form in between analog and digital, such as a pulse width modulation or a frequency output. The information is still in analog form. However, the selected representation strongly simplifies the ADC in the information processing system (viz. using the pulse width signal as a counter enable respectively a counting of the frequency). This step is only an intermediate one and can be situated inbetween the second and third milestone. An on-chip ADC will, of course, be more attractive, however, additional research is needed.

The compatibility and yield issues mentioned above also have an impact on the feasibility of realising the sensor interface bus mentioned in the fourth objective. This checkpoint stresses the importance of realising an on-chip interface and reflects the general feeling that a sensor should provide a signal in a prescribed digital format, a transmission along a standard digital bus for maintaining maximum flexibility and user-friendliness. Unfortunately, there are almost as many different sensor buses as there are manufacturers of sensor systems and a genuine sensor bus standard is not available. Generally, there is a pronounced preference for a serial bus structure with a minimum number of wires. There is a strong motivation, especially among the main users of sensors, such as the automotive industry, to come to a standard protocol. An improvement in this situation is to be expected within a reasonably short period.

Finally, the state-of-the-art of integrated silicon smart sensors will be described from three typical examples reported in literature.

The first concerns a silicon colour sensor in which colour information is extracted from an incident visible spectrum using the wavelength dependence of the absorption coefficient in silicon instead of dyed colour filters deposited on top of the photosensitive surface. Due to this wavelength dependence the short wavelength parts of the incident spectrum are absorbed relatively close to the silicon surface, while the long wavelength components penetrate deep into the silicon. The sensor operation is based on the reverse biasing of a shallow p+n junction in order to deplete the lower doped n-type epilayer down from this junction. Concurrently, the remaining non-depleted part of this epilayer is depleted using the substrate voltage. In this way an electronic control of the width of the upper charge collecting layer can be realised. This sensor structure is compatible with bipolar processing when the epilayer is used as the n-type layer. As the short wavelength components in the spectrum are absorbed shallowly, all the blue light has already been absorbed at very thin collecting layers. Therefore, when illuminated with light with predominantly short-wavelength components, the perceived photocurrent remains almost constant at an increasing width of the upper depleted part of the epilayer associated with an increasing reverse voltage. However, when illuminating with long-wavelength light the detected photocurrent increases with this layer width. The depletion of the lower part of the epilayer prevents the existence of a neutral layer in which charge carriers generated beyond the depleted region could otherwise diffuse upwards and contribute to the photocurrent in the upper junction. An essential aspect of this sensor is the solving of the relation I_{ph}=f(wavelength, intensity) by switching between several values of the reverse voltage. This principle is, therefore, implemented in the smart sensor shown in figure 21. Output signals are available for direct driving of a dual-slope ADC, thus, giving a direct microprocessor-compatible output signal.

A second example stresses the advantage of on-chip multiplexing in an array sensor. This 9 row by 9 column capacitive tactile imaging sensor is realised in a 28x28 mm integrated circuit, which contains 81 aluminium electrodes, as well as the addressing logic for each element. This sensor is intended for robotic applications. Placing such a sensor in a robot gripper makes automatic assembly possiole. The operation involves the measurement of the indentation pattern of an isolating rubber layer caused by the pressure distribution acting on the sensor surface.

The capacitance between a selected electrode and a common conductive rubber layer is measured and an image is formed by scanning all the electrodes. The capacitance changes are in the fF range and are converted into a phase shift of the driving sinewave using a special read-out method. From this phase angle a pulse-width-modulated output signal can be obtained to drive a counter for ADC as described above. A photograph of one tactile element with its neighbours is shown in figure 22 and the complete sensor before coverage with the rubber layers is shown in figure 23.

The last example of a smart sensor design is the so-called flip-flop sensor. Developments in this sensor type have led to flip-flop sensors suitable for sensing many different physical parameters. The sensor consists of a flip-flop in which a circuit element is sensitive to the desired measurand. The sensing action consists of alternately bringing the flip-flop into an unstable state and observing the stable state to which it switches by counting the number of ones and zeros. A nonzero value of the physical quantity results in a flip-flop imbalance and thus in a deviation in the ratio of ones and zeros from unity. The advantages of such a flip-flop sensor include the possible integration of the sensor with the ADC in a simple structure and the intrinsic digital output. Flip-flop sensors can also easily be combined to a matrix sensor using addressing techniques similar to those used in static RAMs. A realisation is shown in figure 24.

These examples clearly demonstrate that much is already possible. Implementation of the smart sensing principle in many other signal domains is to be expected on a short term.

5 Conclusions

As shown in the first part of this article, a wide range of sensors, realised in several competitive sensor technologies, is available for sensing almost any of the non-electrical quantities. The choice for a particular sensor technology is, therefore, usually determined by additional requirements that result from the application, such as the ability to withstand a high operating temperature or whether the sensor needs to be chemically inert. Silicon has been shown to be a suitable sensor material that is susceptible to a large number of physical effects. Silicon is not ferromagnetic or piezoelectric, however, when using compatible structures the transductions based on these properties can be implemented as well.

Another desirable property of a sensor is the ease of operation. This implies that:

(1) no intimate knowledge of the internal sensor operation should be required,

(2) the sensor should operate with a minimum amount of maintenance and

(3) the sensor should provide an output signal in a standard digital output format for direct microprocessor interfacing that is not affected by interfering quantities.

These characteristics are met in a smart silicon sensor, in which the intrinsic advantage of having a sensor in the same material in which the signal processing circuits are integrated is fully exploited. Smart silicon sensors are, therefore, likely to become the major future trend in sensor research. Sensor foundries are discussed as a factor that also affects the future trend in sensors, as these specialised sensor manufacturers largely determine the accessability of the sensor as a commercial product.

The advances made in the research on special silicon processing steps, such as micromachining and sputtering of compatible structures as well as the progress made in smart sensors and the expected improvement in the industrial yield thereof and the sensor packaging is likely to result in an increased impact of sensors in many aspects of the instrumentation and process-control industries.

Figure captions

Figure 1. Decay of piezoelectricity.

Figure 2. (a) Absolute and (b) incremental optical encoders.

Figure 3. Basic structure of a silicon pressure sensor.

Figure 4. Cantilever beam, useful for thermal and resonating sensors.

Figure 5. Al-Si thermopile integrated in silicon.

Figure 6. Schematic of a basic high-purity silicon radiation sensor.

Figure 7. Structure of porous Al_2O_3.

Figure 8. Structure and responses of an Al_2O_3 based humidity sensor.

Figure 9. Photograph of a polymer film humidity sensor.

Figure 10. a) Geometry of a simple magnetoresistive sensor and b)characteristics when used as magnetoresistive or planar Hall sensor [K.Petersen, Magnetfeldsensoren und magnetische positionsgeber, NTG Fachberichte 93, 1986, pp. 186-191].

Figure 11. Ferromagnetic sensor configurations. a) Biased sensor, b) sensor with inclined elements and c) barber-pole sensor.

Figure 12. Bubble memory expanders: a) Chinese character sensor and b) the Chevron stretcher structure [S.Middelhoek et al., Physics of Computer Memory Devices, London, Great Britain, Academic Press, 1976].

Figure 13. Fluxgate magnetometer principle.

Figure 14. Silicon magnetic field sensitive sensors: a) Bulk Hall plate, b) bipolar dual-collector

magnetotransistor, c) Rotating carrier-domain magnetometer and d) magnetodiode.

Figure 15. a) A non-contact switch and b) a Hall plate used to measure the position of the permanent magnet rotor.

Figure 16. Structure of a compatible magnetic sensor combining electronics and a thin magnetic film.

Figure 17. Schematic of the Czochralski crystal growing method.

Figure 18. A thermal oxidation system.

Figure 19. The lithographic procedure; (a) silicon wafer including the film to be etched, (b) application of the resist, (c) application of the mask and exposure to the radiation or beam, (d) development of the resist, (e) etching of the film, (f) removal of the resist.

Figure 20. (a) An anisotropic edge profile and (b) an isotropic edge profile.

Figure 21. Photograph of the integrated silicon smart sensor.

Figure 22. Photograph showing a detail of the tactile imaging sensor.

Table captions

Table 1. Characterization of some mechanical sensors.
* denotes dependency on signal conditioning circuitry

Table 2. Comparison between some properties of piezoelectric materials.

Table 3. Typical specifications of humidity sensors for air.

Table 4. Characteristics of selected silicon magnetic sensors. In the column on directional sensitivity, B_z means that the sensor os sensitive to a component of the magnetic-flux density perpendicular to the chip surface. B_x and B_y indicate a sensitivity to one of the in-plane components.

Table 5. Properties of Si at 300K

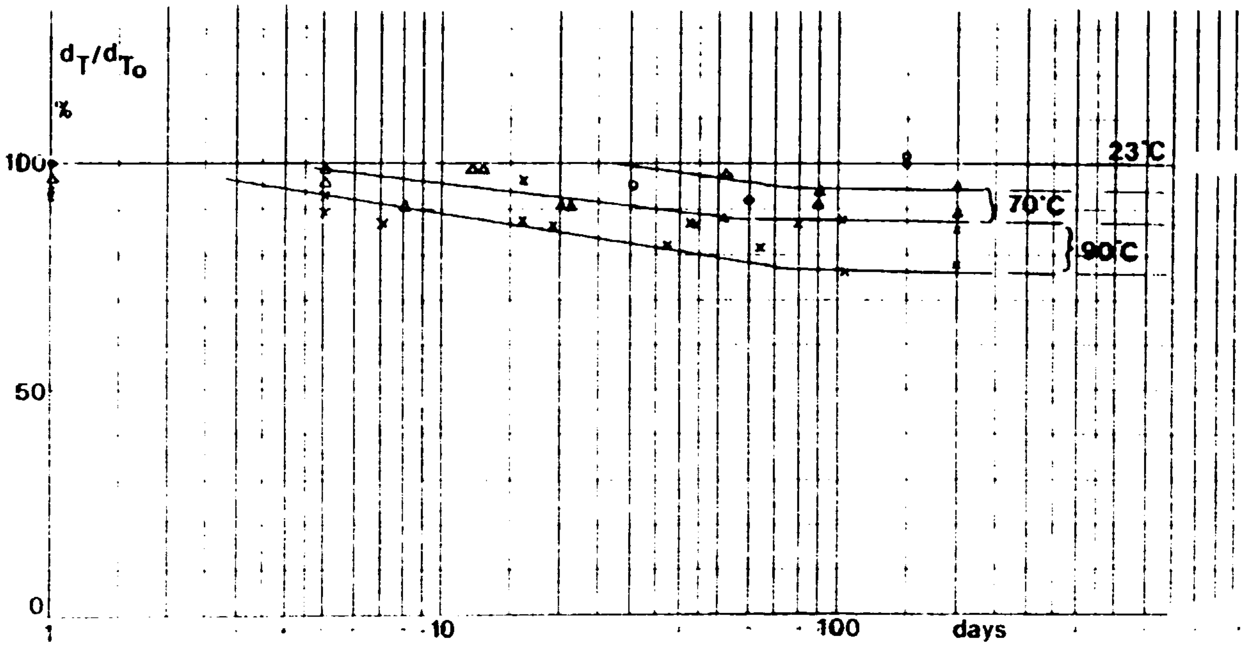
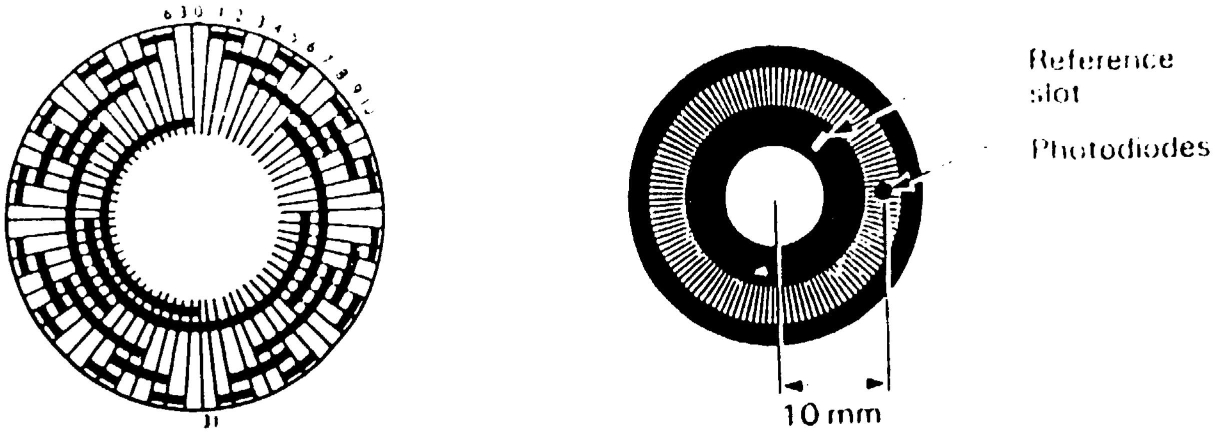


Figure 1



(A)

(B)

Figure 2

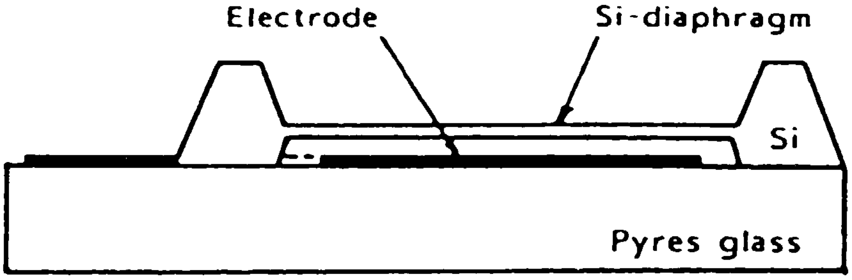
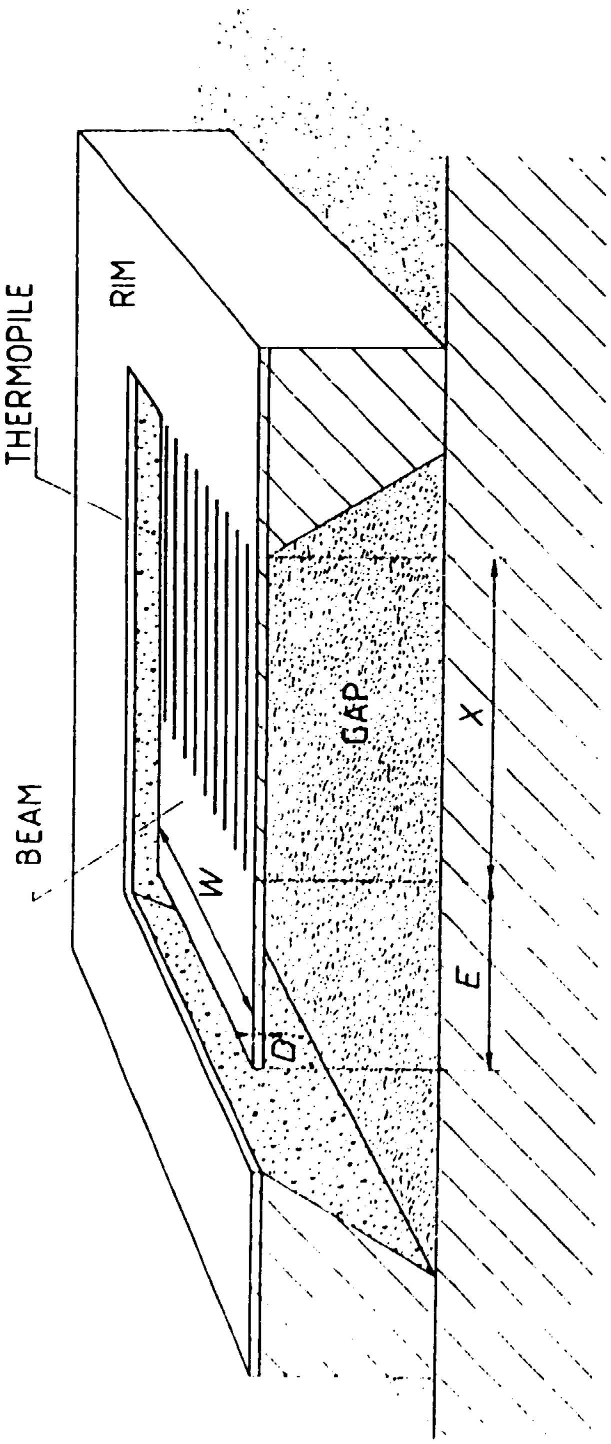


Figure 3



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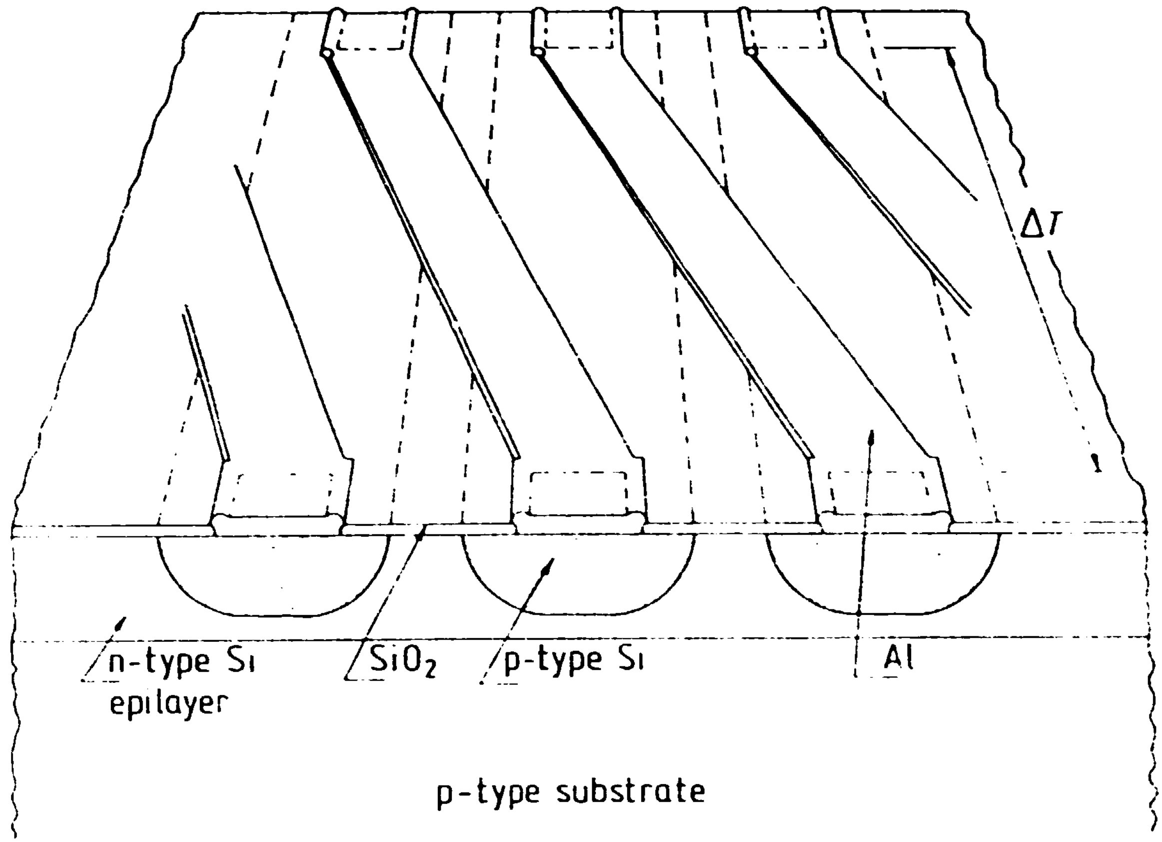
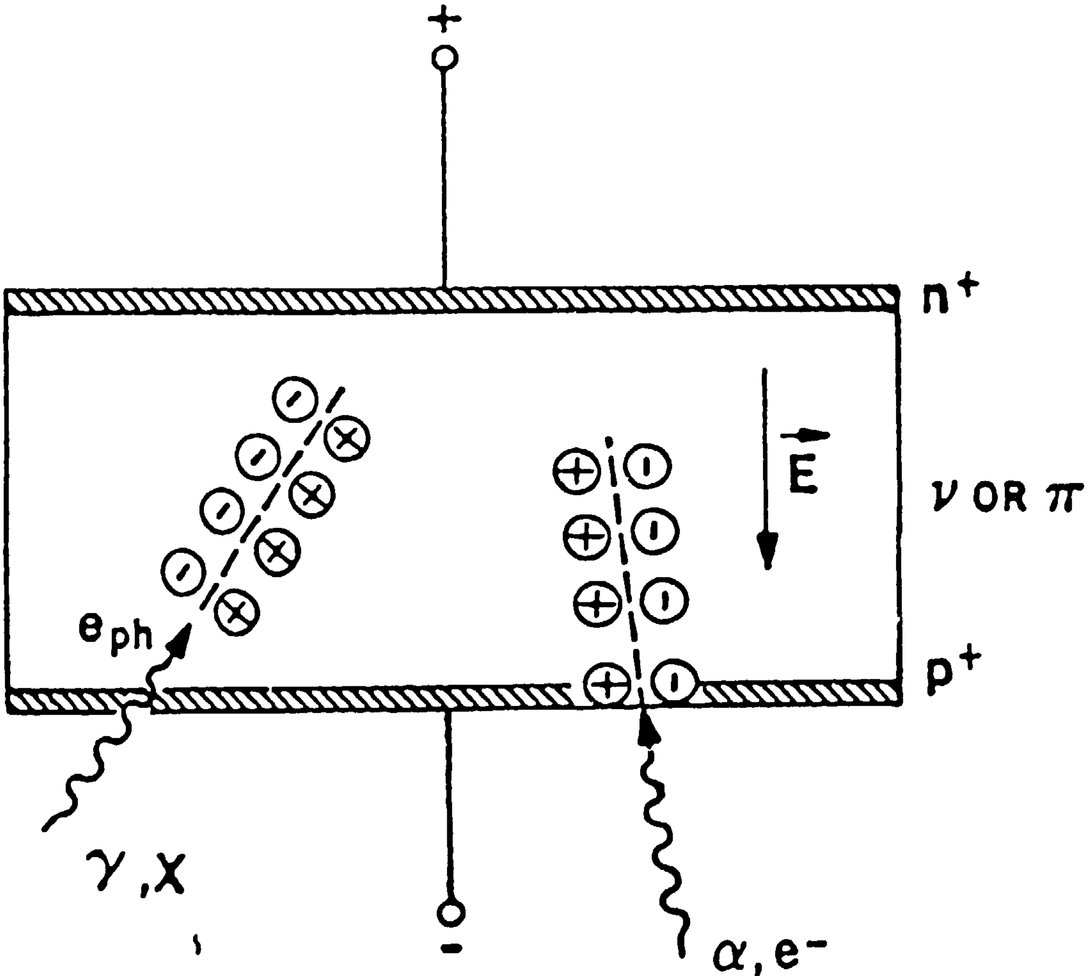


Figure 5



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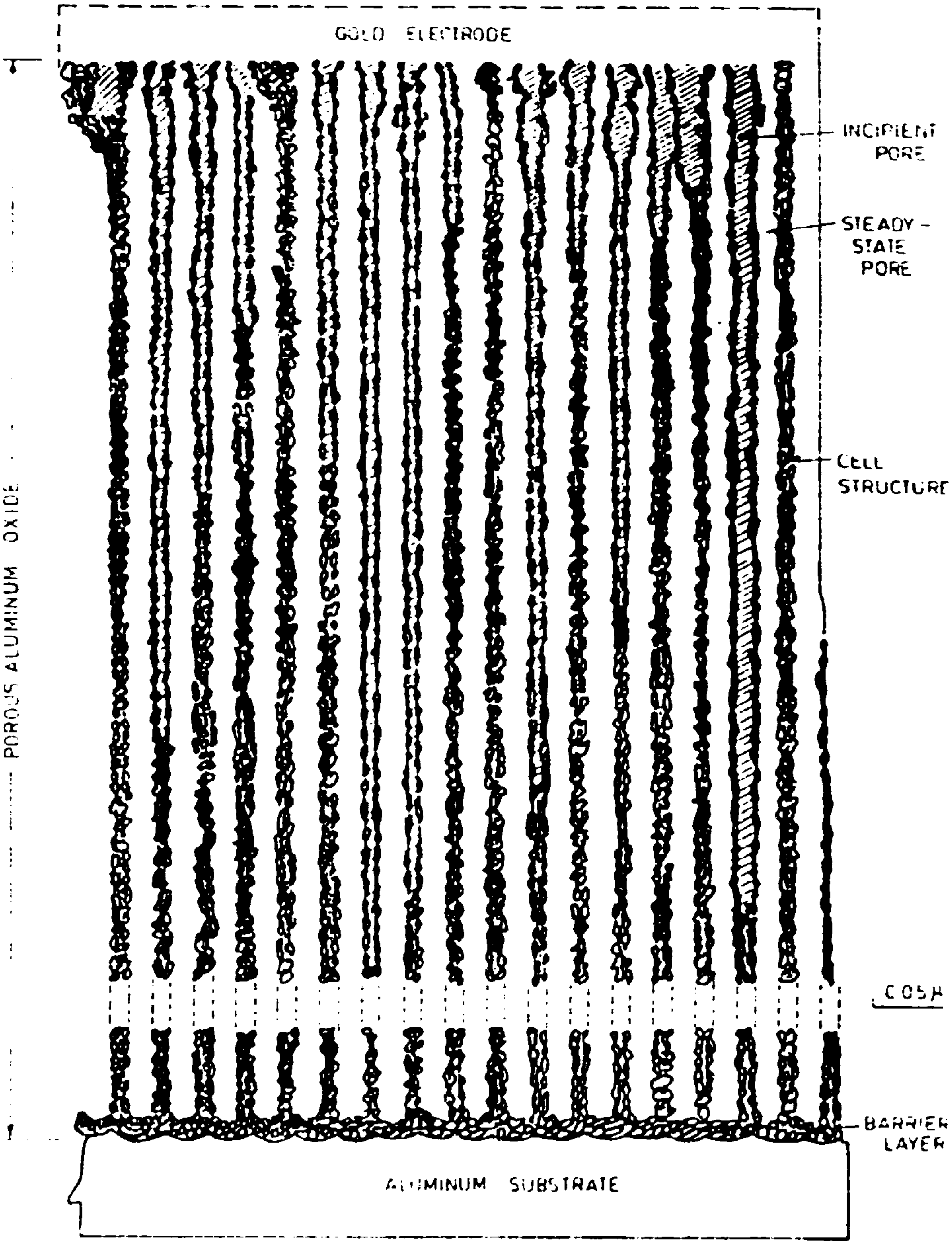

GOLD ELECTRODE
POROUS ALUMINUM OXIDE
INCIPIENT PORE
STEADY - STATE PORE
CELL STRUCTURE
C 05 µ
BARRIER LAYER
ALUMINUM SUBSTRATE

Figure 2

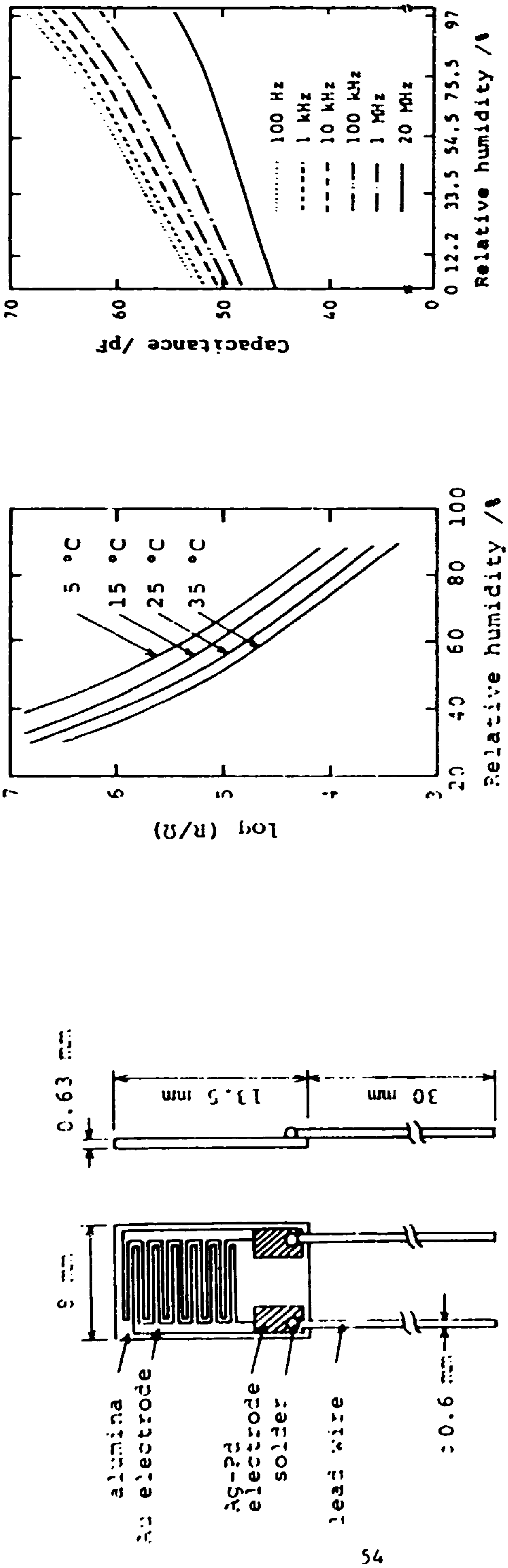

alumina
Au electrode
Ag-Pd electrode
solder
lead wire
φ0.6 mm
8 mm
0.63 mm
13.5 mm
30 mm
log (R/Ω)
3
4
5
6
7
20
40
60
80
100
Relative humidity /%
5 °C
15 °C
25 °C
35 °C
Capacitance /pF
0
40
50
60
70
0
12.2
33.5
54.5
75.5
97
Relative humidity /%
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
20 MHz

Figure 8

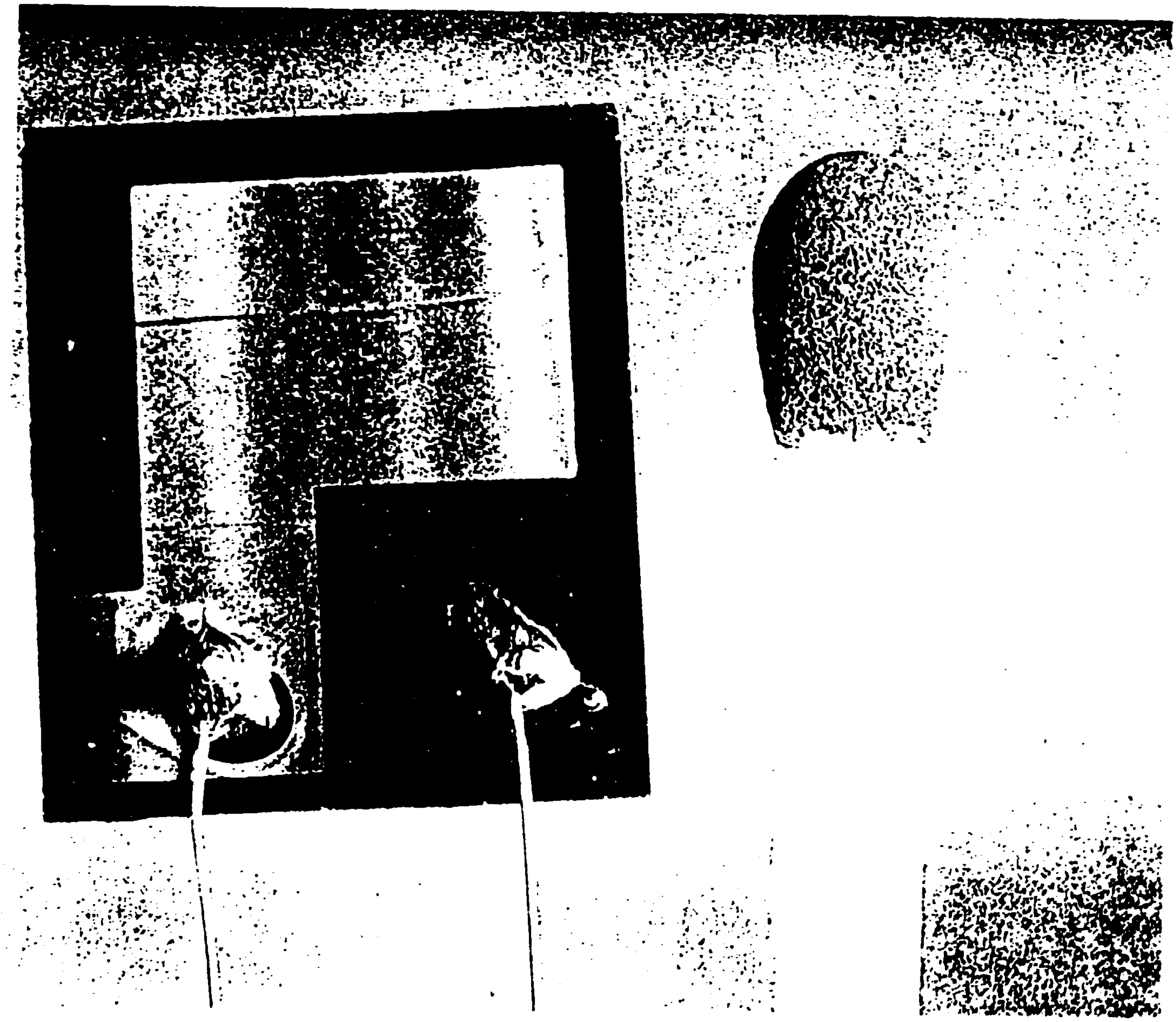
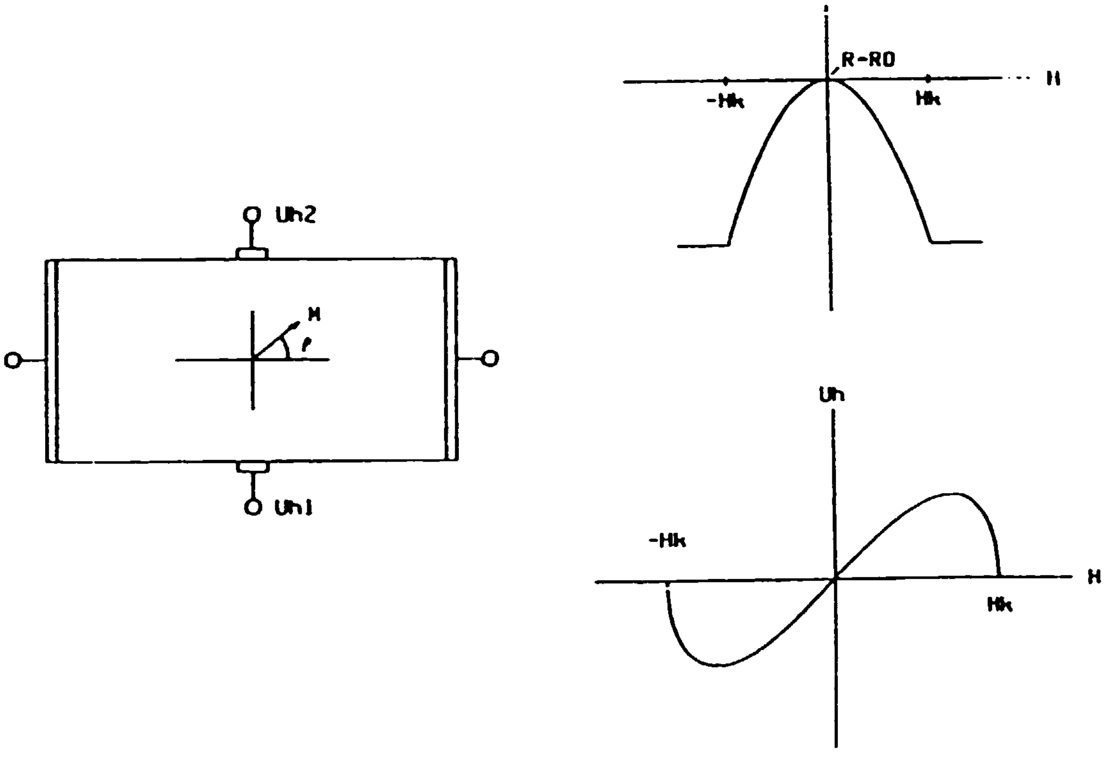


Figure 9



(A) (B)

Figure 10

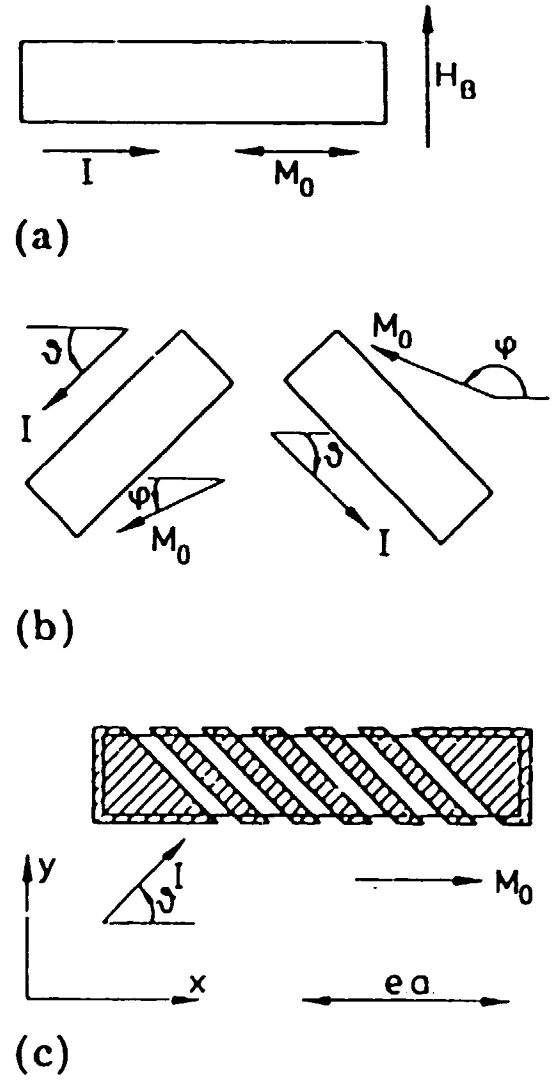


Figure 11

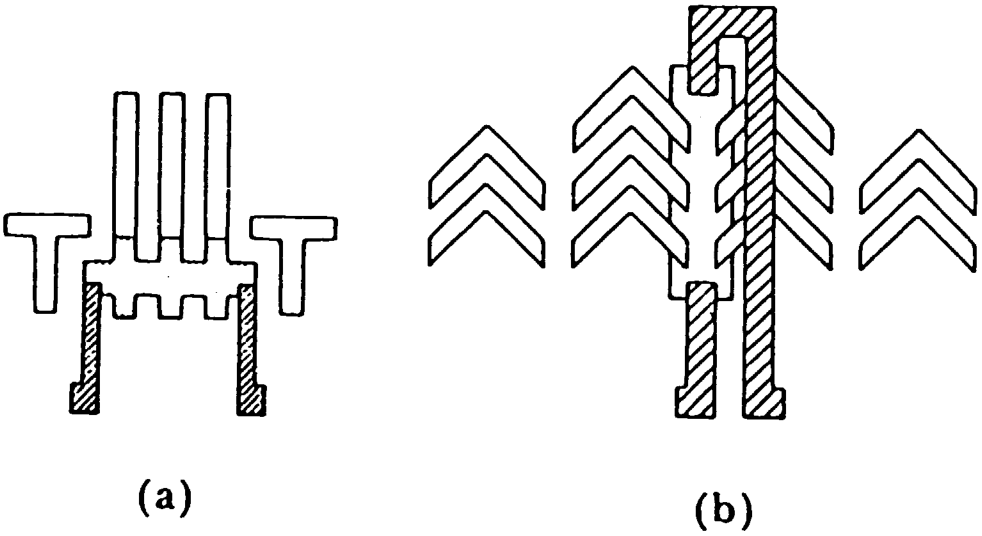


Figure 12

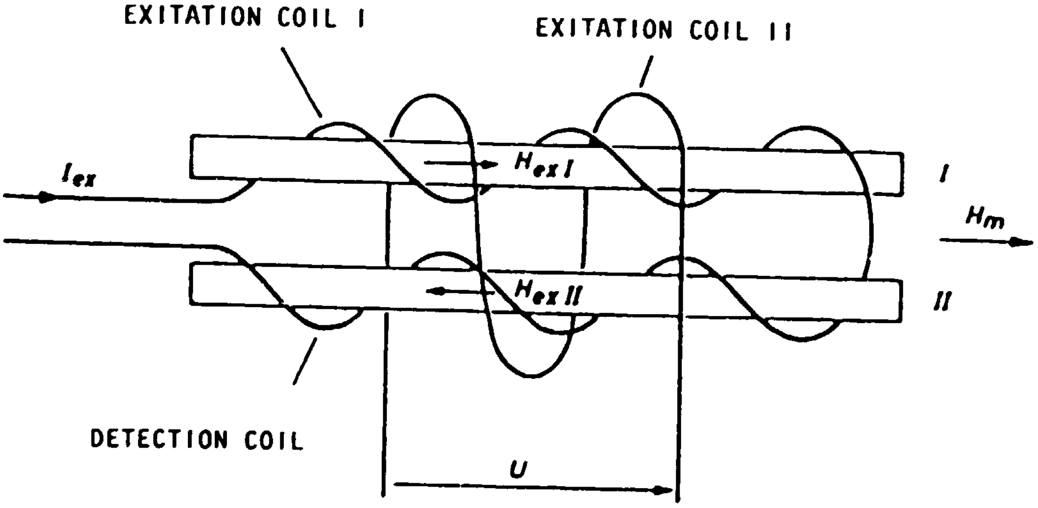


Figure 13

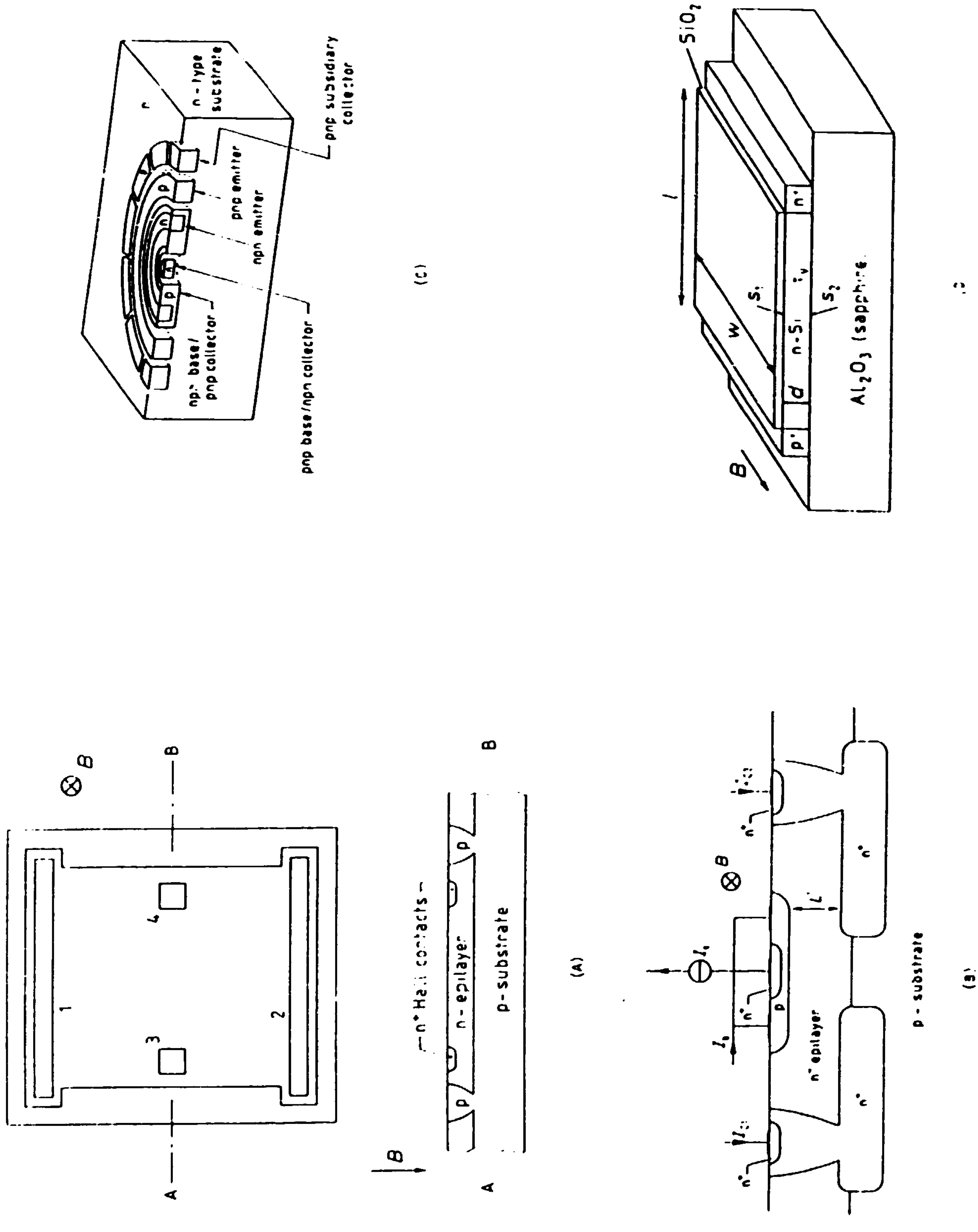
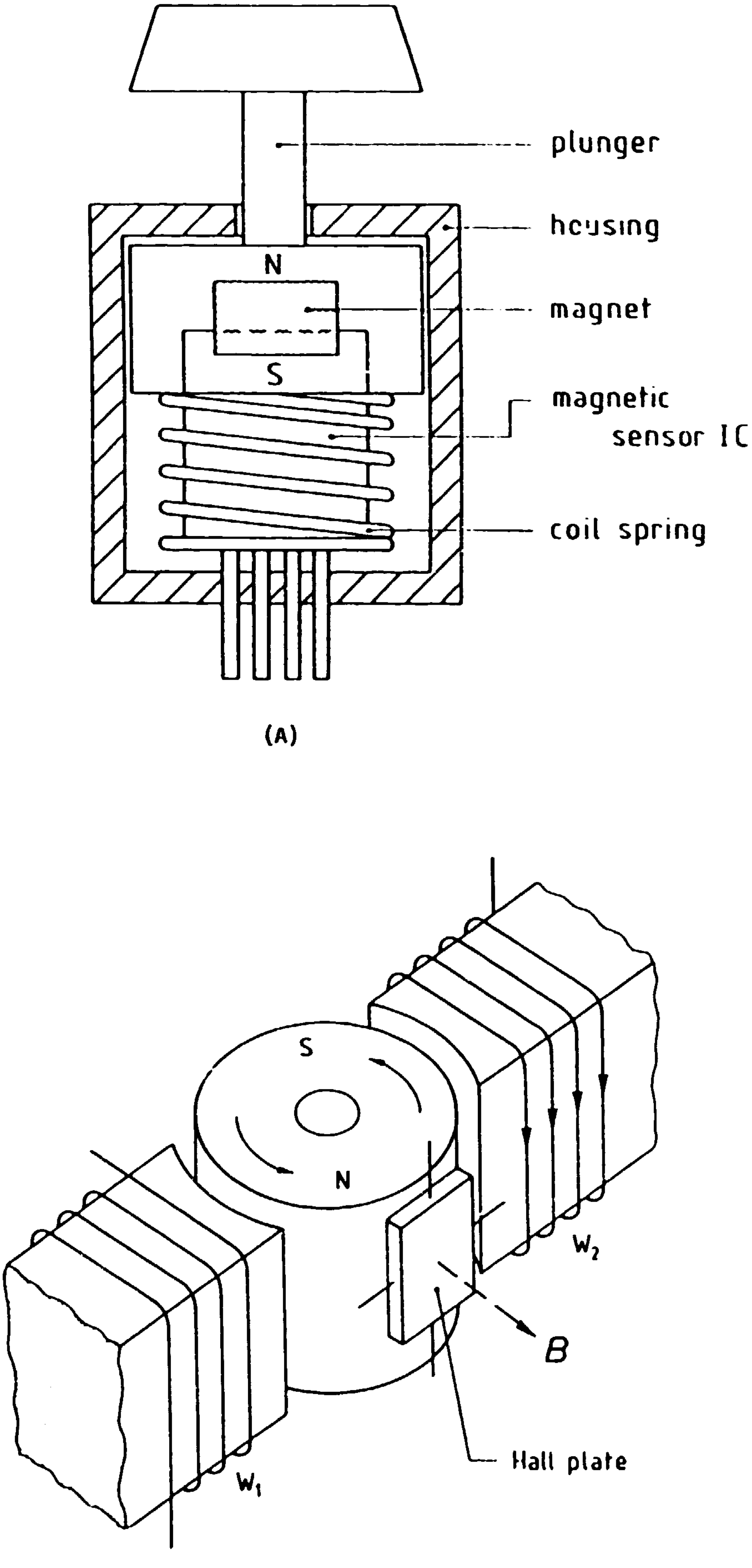

A
B
1
2
3
4
n⁺ Hall contacts
n - epilayer
p
p - substrate
(A)
n⁺
p
n⁺ epilayer
p - substrate
I_x
L'
(B)
n - type substrate
n
pnp subsidiary collector
pnp emitter
npn emitter
npn base/ pnp collector
pnp base/npn collector
(C)
SiO_2
l
w
d
S_1
S_2
n-Si
p⁺
n⁺
Al_2O_3 (sapphire)
B

Figure 14


plunger
housing
N
magnet
S
magnetic sensor IC
coil spring
(A)
S
N
W_2
B
Hall plate
W_1

(B) Figure 15

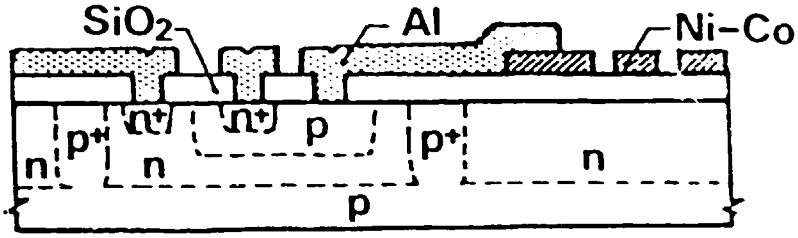


Figure 16

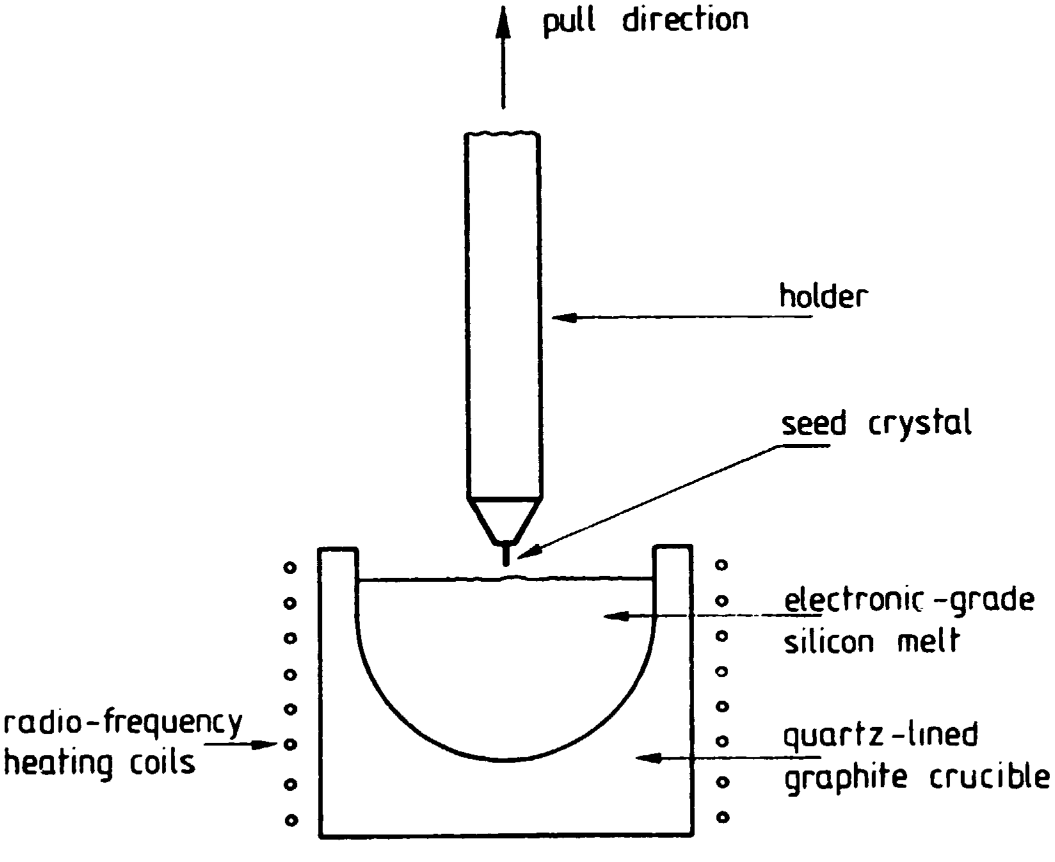


Figure 17

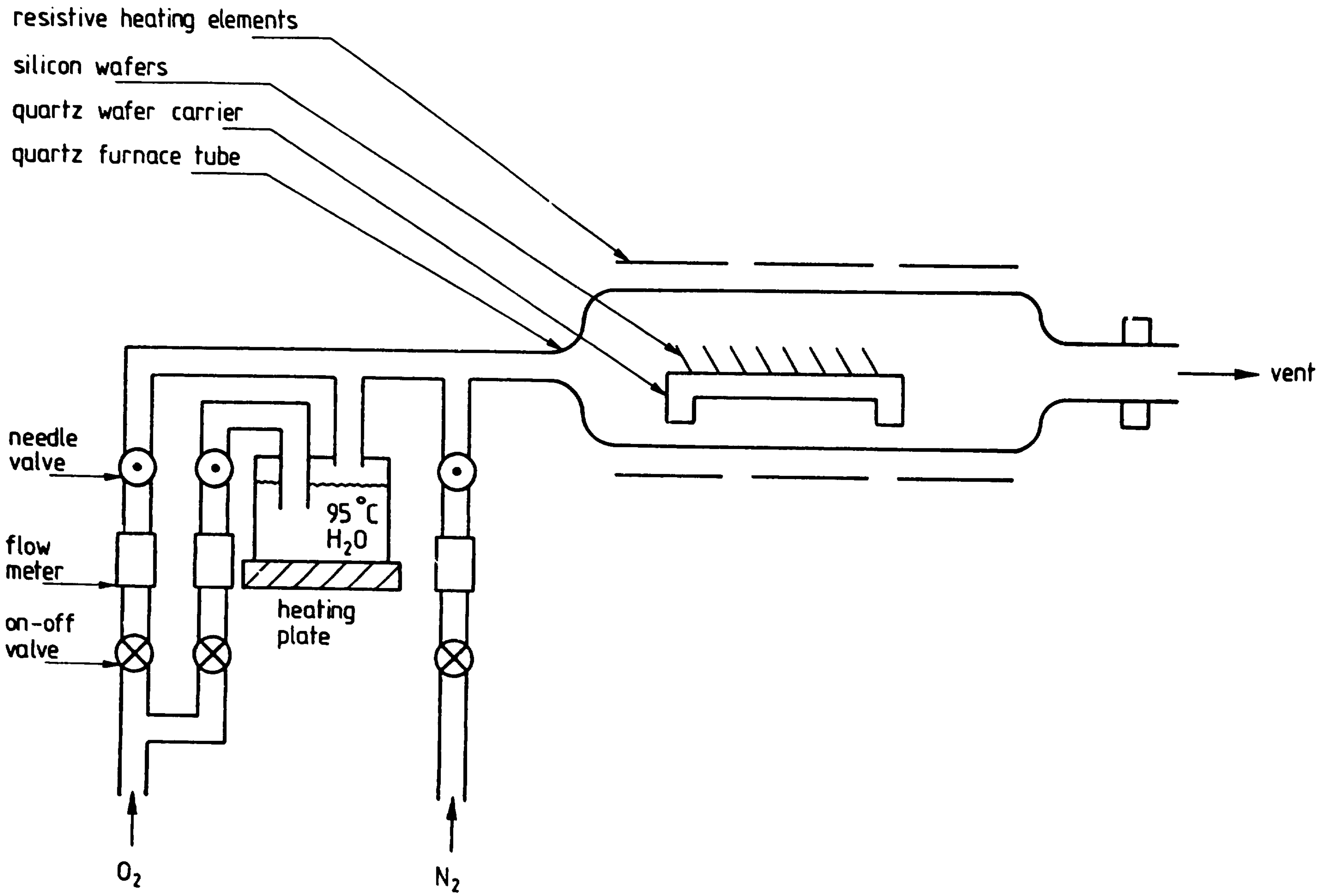

resistive heating elements
silicon wafers
quartz wafer carrier
quartz furnace tube
vent
needle valve
flow meter
on-off valve
95 °C
H_2O
heating plate
O_2
N_2

Figure 18

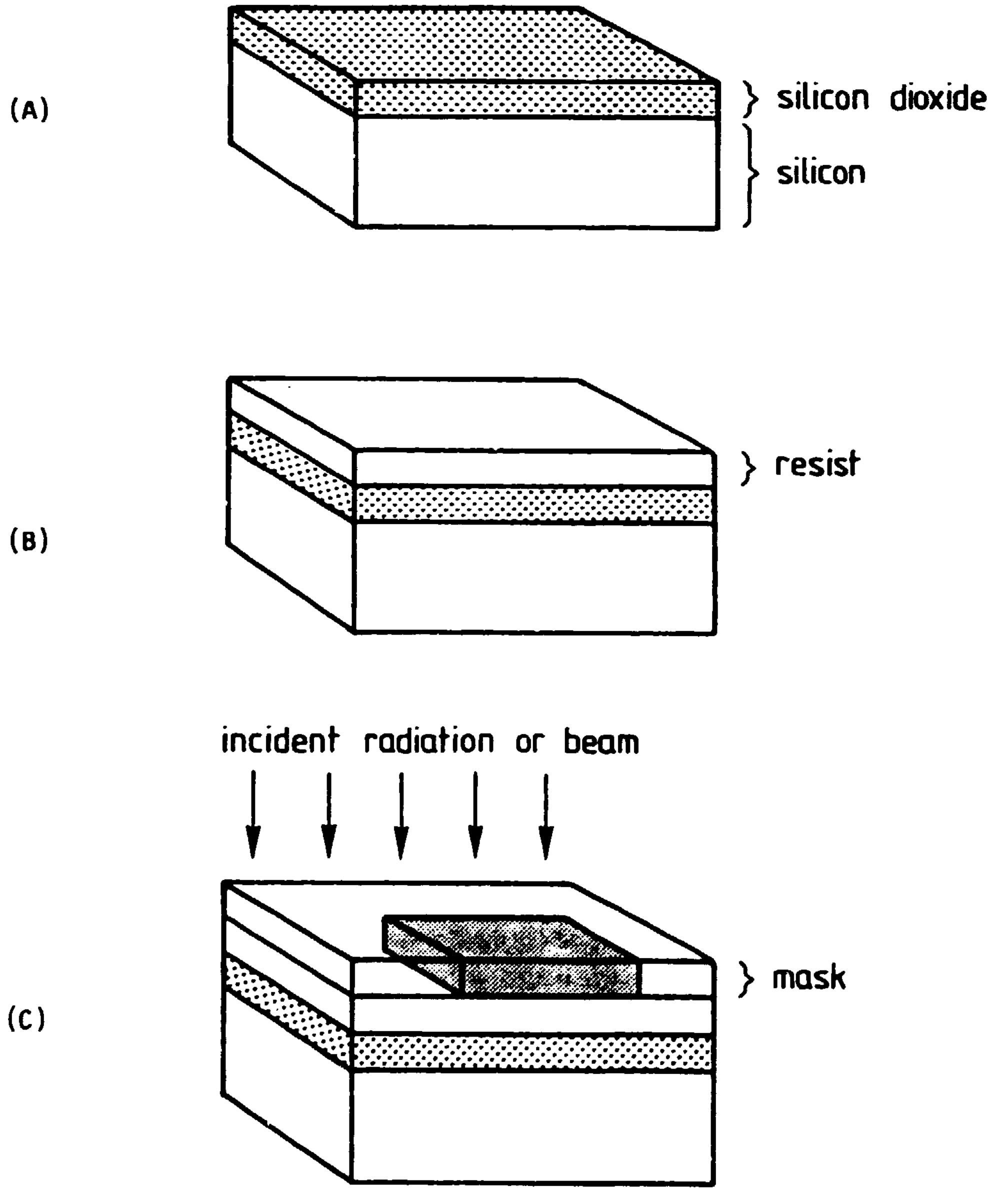


Figure 19 (A, B, C)

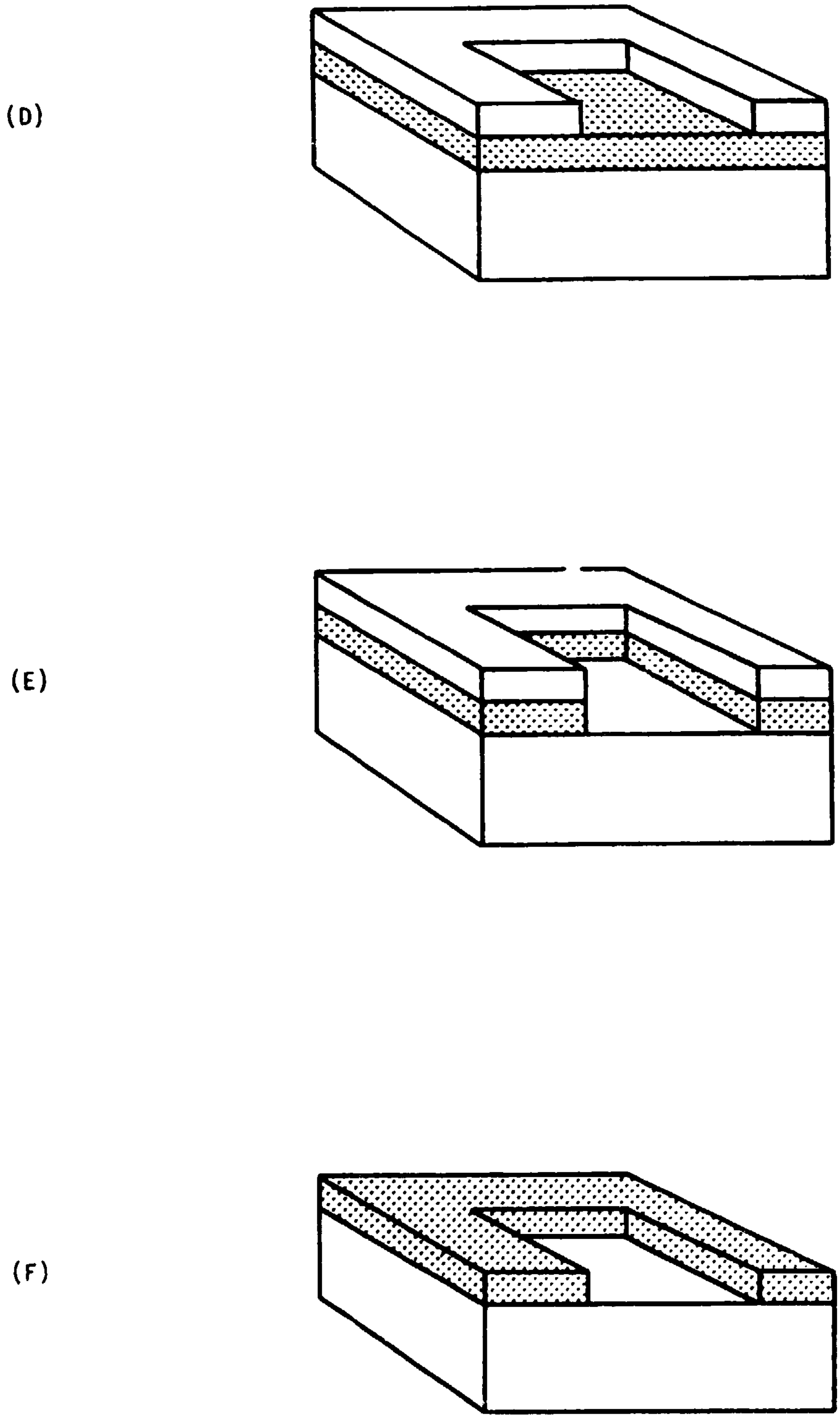


Figure 19 (D, E, F)

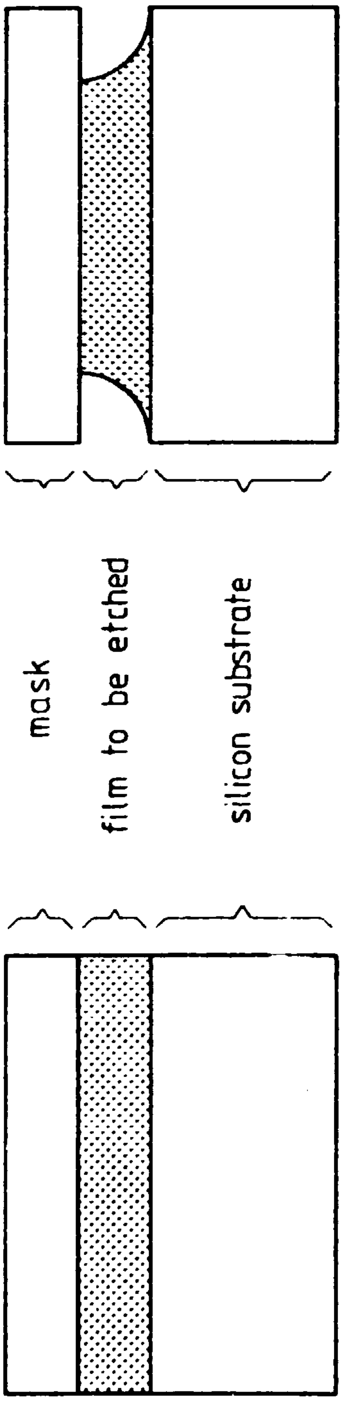


Figure 20

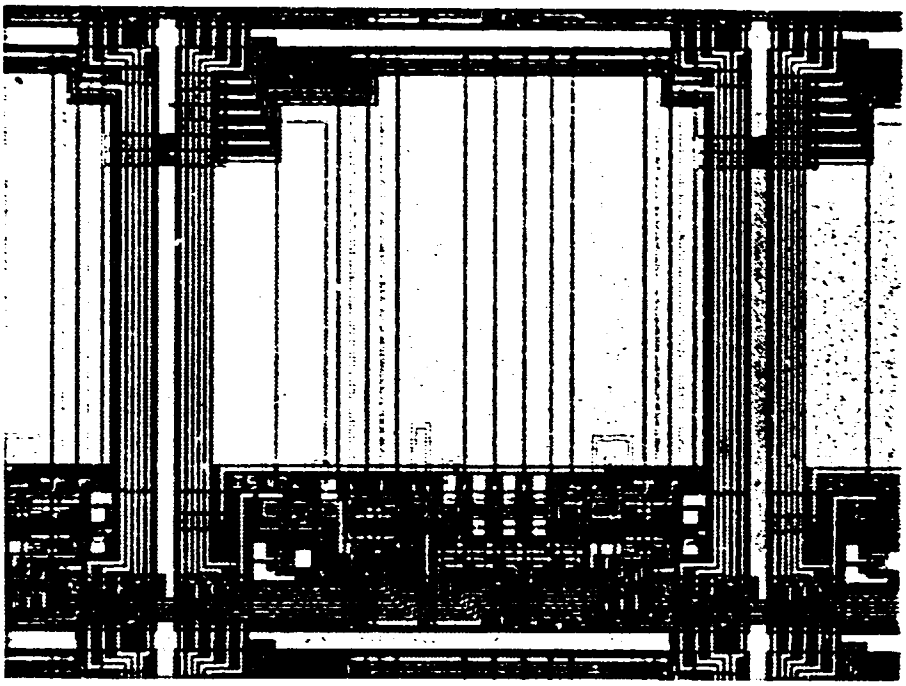


Figure 21

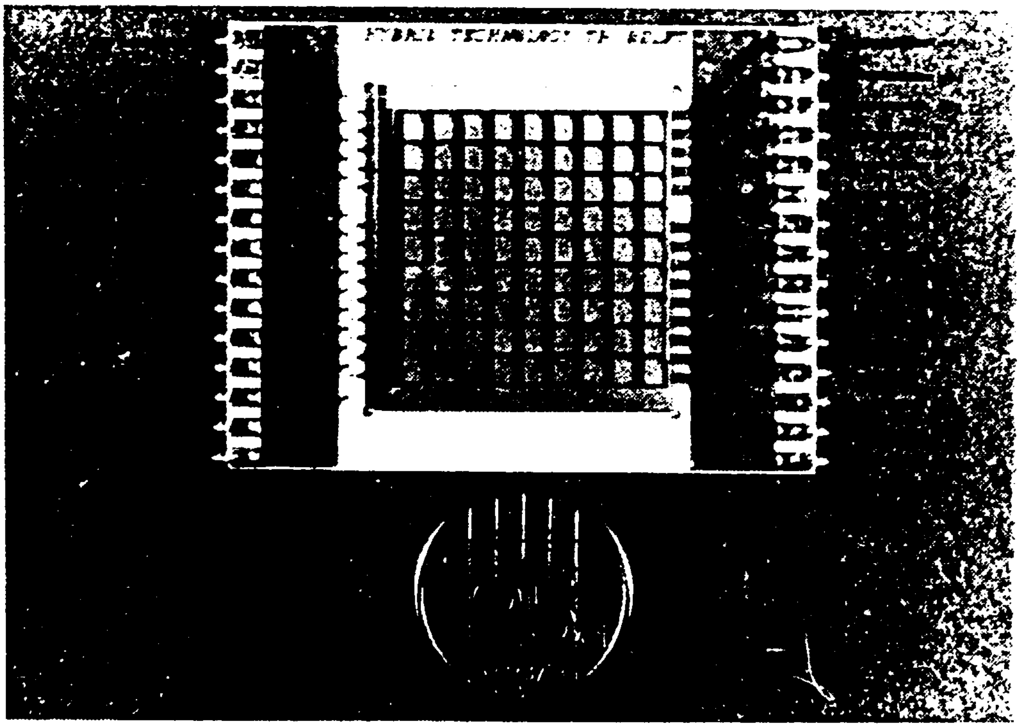


Figure 22

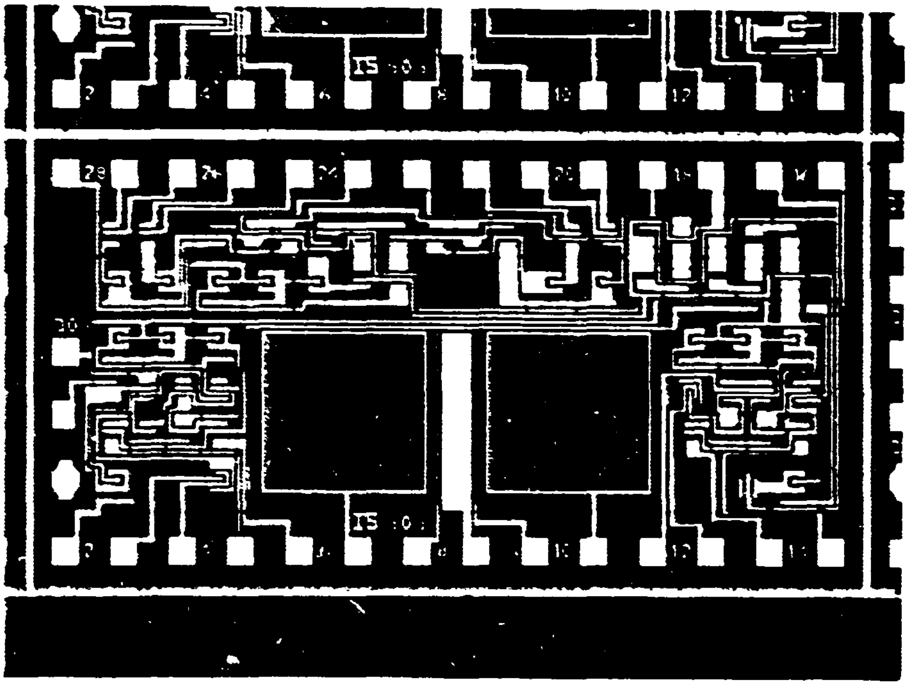


Figure 23

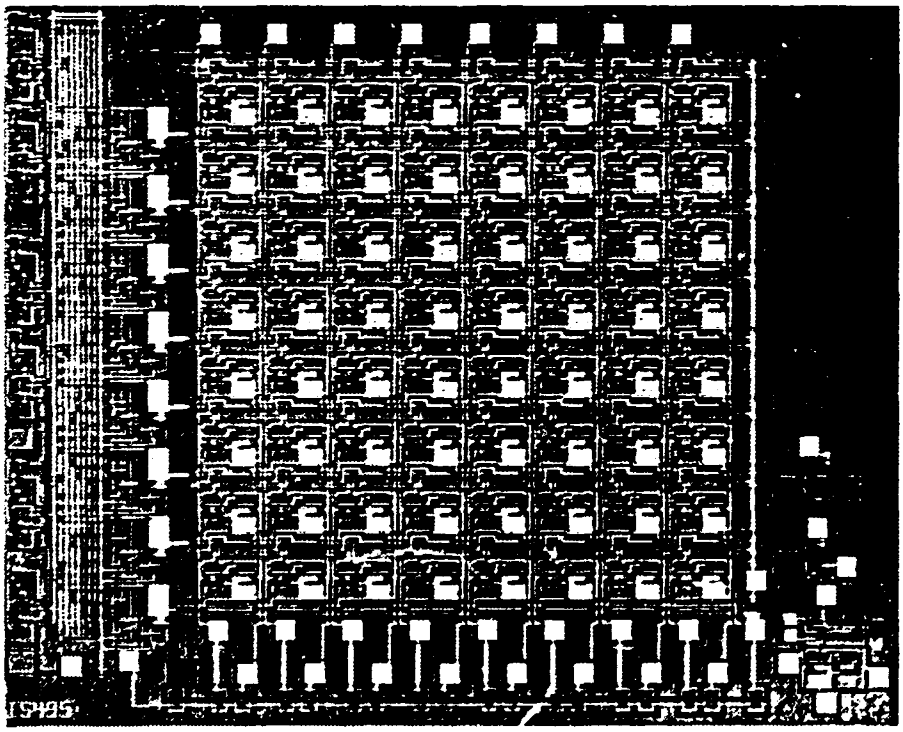


Figure 24

Principle; type	**measurement range** (full scale)	**sensitivity**	**nonlinearity** (±% full scale)	**max. temp** (°C)
Inductive:				
LVDT	±1 mm to ±30 cm	10 to 200 mV/(mm.V)	0.25	500
RVDT	+40 deg.	5 mV/(deg.V)	0.5	500
Synchro	2π	2π/revolution	0.5	
Eddy current	.1 mm to 60 mm	0.1 to 5 V/mm	0.5	300
Turbine flow	1 to 10^4 l/min	3 to 10^4 rev./l	0.25	260
Cup anemometer	75 m/s	10 Hz/(m/s)		50
Capacitive:				
LVDC	2.5 mm to 250 mm	•	0.01	80
RVDC	70 deg.	•	0.01	150
Servo accel.	2 to 100 g	0.1 to 5 V/g	0.03	125
Resistive:				
lin. potentiometer	10 mm to 1.2 m	•	0.1	125
ang. potentiometer	2π to 40x2π	•	0.1	125
strain gauges	5000 microstrain	2 to 100 %/%	1	350
id., for accel.	±5 to ±5000 g	0.01 to 30 mV/g	1	120
id., for pressure	10^4 to 10^8 Pa	•	0.25	150
Piezoelectric:				
acceleration	10^3 to 10^6 ms^{-2}	0.1 to 50 pC/(m/s^2)	•	500
force	10^2 to 10^6 N	2 to 4 pC/N	•	300
pressure	10^7 to 10^8 Pa	20 to 800 pC/MPa	1	200
Optical:				
lin. incr. encoder	1 cm to 3 m	80 lines/mm		80
ang. inc. encoder	2π	2000 lines/2π		80
P.S.D.	30 to 300 cm	•	•	50
Acoustic:				
distance	1 cm to 10 m	0.003 s/m	•	
flow (doppler)	to 20 m/s	0.3 %/(m/s)	•	
Thermal:				
gas flow meter	0.005 to 7000 l/min	•	•	70

Table 1

Material	density (kg/m^3)×10^3	ϵ_r	d_{33} (m/V)×10^{-12}	acoustic impedance (kg/m^2.s)×10^6
quartz	2.65	4.5	2	14.3
$BaTiO_3$	5.7	1700	78	30
PXE5	7.6	1800	384	30
PVDF	1.78	10 - 12	20 - 30	2.5

Table 2

Sensor type	range			inaccuracy	gas temperature		gas pressure
	lowest	highest	unit	±(minimum)	min. (°C)	max. (°C)	max. (bar)
Al_2O_3	-110	60	°C dp	1 °C	-70	100	350
polymer	0.5	100	% rh	2.5 %	-50	125	
vibr.crystal	0.02	1000	ppm	5 %	-18	52	1 (controlled)
LiCl	-45	130	°C dp	0.5 °C	-45	130	40
electrolytic	1	3000	ppm	2 %	0	80	7
dew point	-90	170	°C dp	0.2 °C	-40	170	220

Table 3

Device	sensitivity	directional sensitivity	offset	spatial resolution (μm^3)	on-chip electronics
bulk Hall	7.6 %/T	B_z	< 10 mT	200×200×10	no
orthogonal Hall plate	13 V/T	B_z			yes
multi-collector magnistor	S_x = 1.4 %/T S_y = 2.2 %/T S_z = 0.3 %/T	B_x, B_y and B_z		60×10×16	no
carrier-domain device	250 kHz/T	B_z	0	500 diameter	no
magnetodiode	25 V/T	B_x			no

Table 4

Atoms/cm^3	5×10^{22}
Atomic weight	28.09
Breakdown field strength	~ 3×10^5 V/m
Crystal structure	Diamond
Density	2.328 g/cm^3
Dielectric constant	11.9
Distance between neighboring atoms	2.36 Å
Energy gap	1.12 eV
Lattice constant	5.431 Å
Intrinsic carrier concentration	1.45×10^{10} cm^{-3}
Melting point	1412 ^{0}C
Mobility, drift	
Electrons	1500 cm^2/Vs
Holes	475 cm^2/Vs

Table 5

2. CERAMICS FOR SENSORS

Sensors come in a wide variety of shapes, sizes and materials. They are important in many manufacturing processes for detecting temperature, gases, humidity, and pressure, to name just a few. In fact, the sensor market is expected to grow between 10 and 30 per cent annually, according to one expert at Battelle-Frankfurt. Battelle has started a multi client study to evaluate the numerous manufacturing techniques available for making sensors. The study will include analyses of application areas and markets, as well as a survey of the state of the art of sensors and integrated signal processing.

One segment of the market includes sensors made of ceramic materials. This segment alone has a wide range of applications. For instance, at the 89th American Ceramic Society Annual Meeting, a session devoted to sensors included papers describing improved materials and processes: titania oxygen sensors; tin oxide thin films for gas sensing devices; and barium titanate thermistors.

Thermistors for temperature

A thermistor is a temperature dependent resistor that can be used as a temperature sensor, flow meter, or protection device against current or voltage surges. Doped $BaTiO_3$ ceramics have a large positive temperature coefficient (PTC) and are widely used. However, fabrication is often difficult because small variations in composition or processing affects the electrical properties. Alfred University characterized several $BaTiO_3$ materials and showed that slight changes in baria and titania content could change the grain-size distribution.

For protecting electrical components or devices, low resistance at room temperature is required because PTC thermistors usually are connected in series with the device to be protected. Conventional disc thermistors make it difficult to reduce the resistance of the ceramic indefinitely. Pennsylvania State University developed a fabrication method that arranges the PTC elements in a multi-layer structure consisting of four $BaTiO_3$ layers. The room temperature resistance is reduced to 1/16 that of the disc thermistor.

Another study at Alfred University produced a self regulating, flow through $BaTiO_3$ heater with a connected, open pore structure. Structures ranging from 10 to 100 pores per linear inch (ppi) were evaluated by determining the back pressure across the sample as a function of flow rate. The slope of this data increased with increasing ppi. A 20 ppi foam structure was tested in a reducing atmosphere, with oxygen introduced at various temperatures. Resistance increases with an increase in temperature, indicating an oxygen diffusion controlled effect.

By combining $BaTiO_3$ with $BaSnO_3$ (BTS), multifunctional ceramic sensors can detect temperature, relative humidity, and such gases as propylene, acetylene and ethylene at ambient temperatures and pressures. These sensors have the advantages of high sensitivity, fast response time, and high stability.

Researchers at Tsinghua University (People's Republic of China) also studied the microstructure of these materials, which have a porous structure. The grains are interconnected by necks, and the pores are channelled at the grain edges. The porosity provides a large exposed surface area to the adsorbing gas and provides surface channels with low conduction barriers for charge carrier flow across the particles. The bare necks usually have similar properties to that of the bulk material; however, the total capacitance and conductivity are determined by the amount of these bare necks. The necks can act as barriers to conduction between particles.

Tsinghua also characterized the pore size and shape of the BTS materials. Pore systems (in average width) fall into three categories: micropore, 2 nm; mesopore, 2 to 50 nm; and macropore, 50 nm. The average pore size of material with 31.4 per cent porosity was 300 nm with 10^{13} necks. With an increase in porosity to 39.5 per cent, the pore size jumped to 4,500 nm, with a decrease to 10^9 necks. The decrease in necks corresponds to a decrease in sensitivity by a factor of 10. Mesapores are assumed to be mainly intergranular and are linked through the macropores, forming a network described as capillary pipes forming a tree-like pore system in three dimensions. The ratio of meso to macro pores can be controlled by the amount of pore-forming additives.

Composites go both ways

$BaTiO_3$ thermistors have several limitations: they have relatively high room temperature resistivity (100 ohm.cm) and high manufacturing costs. Alternatives include composites consisting of carbon black or transition metal-oxide filler (such as TiO, VO_2, V_2O_3) in a polymer matrix. Carbon-black loaded crystalline polymers (such as polyethylene) show a modest PTC as well as low room-temperature resistivity (1 to 52 ohm·cm).

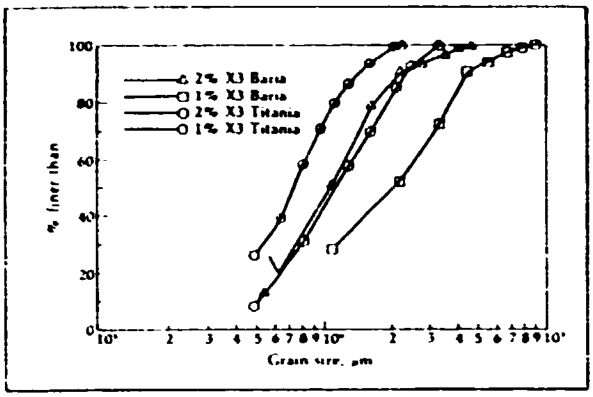
Researchers at Pennsylvania State University have studied composites of V_2O_3 with elastomers (flexible epoxy and polyurethane) as well as crystalline polymers like polyethylene and poly (butylene terephthalate). Both negative temperature coefficient (NTC) and PTC resistance effects are observed in all powder polymer systems. The position and intensity of the NTC transition is independent of the type of polymer matrix; on the other hand, the location of the PTC transition is determined by the choice of polymer, whether amorphous or crystalline. All composites have low room temperature resistivities.

The behaviour of such metal insulator composites can be described by percolation. The change in resistivity is a function of the volume per cent filler. In other words, there is a specific volume per cent where the resistivity starts to decrease. This is called the percolation threshold at which filler particles begin to form conductive paths. As the concentration of filler increases, more conductive paths are formed, and large PTC effects are seen. Once the polymer becomes saturated with these conductive paths, low resistivities occur.

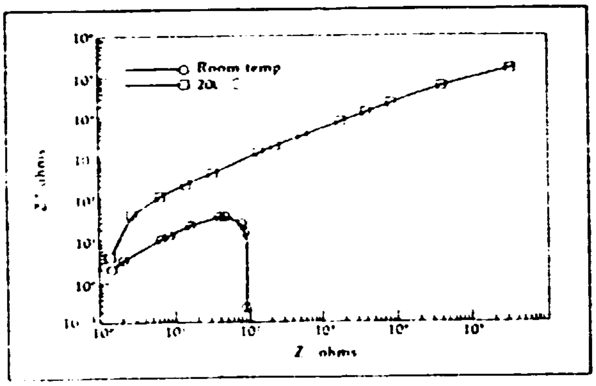
When crystalline polymers are used, the PTC phenomenon is generally observed at the polymer melting point. At this temperature, thermal expansion occurs and the magnitude of this volume change is a function of the degree of crystallization. At room temperature, the filler particles are in contact, producing a low resistivity. As the temperature increases, the polymer expands more quickly than the conductive particles, separating the grains. A rapid increase in resistivity of between one and eight orders of magnitude is observed. For amorphous polymers, on the other hand, there is some indication that the PTC temperature corresponds with the glass transition temperature.

The NTC behaviour of the polyurethane and epoxy composites follows that of transition metal oxides.

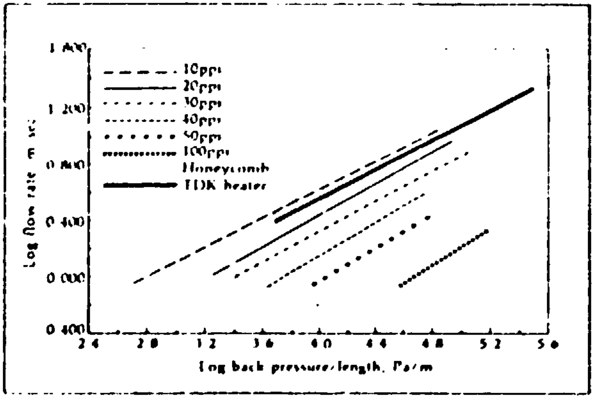
For V_2O_3, there is a semiconductor to metal phase transition at -148°F (-100°C) due to a change in lattice shape and delocalization of the electrons. Though the location of the NTC is similar for both polymers, Penn State researchers found there is a difference in magnitude. In addition to the low-temperature NTC, an NTC effect also is observed at temperatures above the PTC transition. This decrease in resistivity follows a path similar to that of the pure polymers.



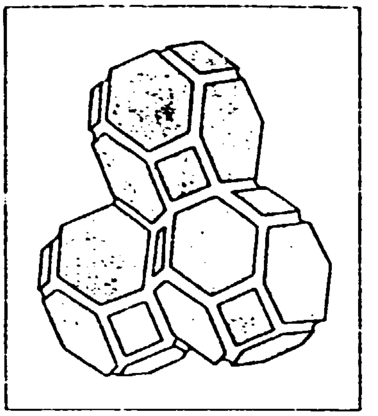
A characterization study at Alfred University shows that slight changes in composition of $BaTiO_3$ thermistors can affect such properties as grain size distribution which, in turn, can change the electrical behaviour.



The impedance behaviour of a $BaTiO_3$ thermistor at two different temperatures as determined by researchers at Alfred University.



The amount of pores in a connected open cell structure of $BaTiO_3$ can change the flow properties of a flow through heater as seen by the increase in slope. Decreases in Y intercept are also observed. Courtesy, Alfred University.



A schematic of the $BaTiO_3$-$BaSnO_3$ structure as depicted by Tsinghua University (China) researchers. The grains are interconnected by necks and the pores are channelled at grains. The shape of the grains is dubbed "tetrakaidecahedron" and the cylindrical pores coincide with three grain edges.

Once again Japan

According to a joint two-year multi-client study recently started by IIT Research Institute and Yanase and Associates, Japan has made significant strides in applying worldwide technology to producing sensors of all types. However, unlike other industrial products, few of these are exported. IITRI's objective is to transfer this technology to the US.

A preliminary analysis by the multi-client study indicates that an estimated 400 companies in Japan produce sensors. Approximately 20 per cent are large electric and electronic firms that produce sensors for their own specific needs. The remaining 80 per cent are small and medium-size specialized firms with limited sensor product lines aimed at Japanese domestic products.

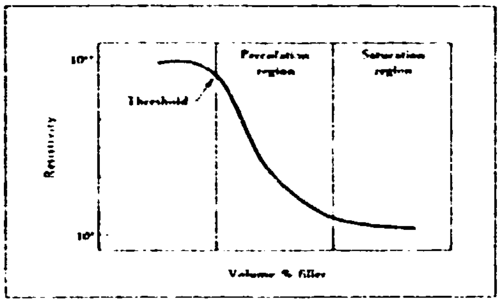
Of the 400 companies, an estimated 130 are involved in temperature and heat sensors and 80 in physical density and biochemical sensors. Fujikura Ltd., an electric wire and cable manufacturer, developed a oxygen sensor capable of measuring the gas in minute quantities. Based on partially-stabilized zirconia (PSZ), lattice defects in the crystal structure, caused by the calcia or yttria stabilizers, allow oxygen ions to move from one vacancy to another in the atomic lattice.

The mobility of these ions produces an electric current in the material. Increase in current flow reaches a saturation level, as the oxygen ions fill holes. By measuring this saturation value, oxygen levels can be measured instantly. According to Fujikura, their oxygen sensors can be made much smaller and more durable - up to 10 times - than conventional sensors.

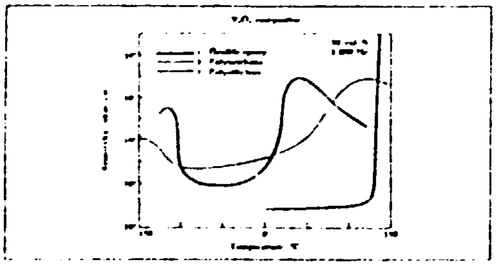
Several other Japanese companies have applie' integrated-circuit thick-film technology to manufacturing oxygen sensors. Hitachi Ltd. has developed a zirconia air-fuel ratio sensor with a heater for the three-way catalytic converters. The sensor consists of two zirconia plate cells, a stoichiometric cell, and a lean cell, laminated on the plating heater as one body.

The sensing principle is based on the rate-determining diffusion of oxygen molecules at a gas diffusion aperature. By applying a voltage to the lean cell, the oxygen molecules are reduced at the cathode, and are trasferred to the anode as oxygen ions through the zirconia. At the anode, they oxidize into oxygen molecules, which are released in exhaust gas through the protection layer in the outside electrode. A balance is maintained between the oxygen molecules being pumped out of the gas diffusion chamber and those being transferred through the aperature unit. The amount of these oxygen molecules is measured by the pumping current.

The advantages of the sensor include its compact size and simple structure which is a result of using the thick film technology. No temperature compensation is required because the sensing part is precisely controlled by the platinum heater. In addition, the sensor has: a wide measurement range; high accuracy even with large temperature and pressure changes; quick response and short starting times; requires no reference gas; and has low heater electric power.



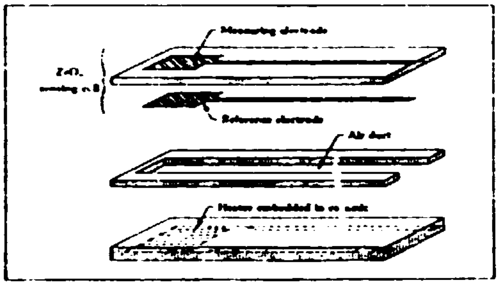
A percolation curve shows resistivity as a function of volume per cent filler for metal-insulating composites. The percolation threshold occurs when the filler particles begin to form conductive paths. As the concentration of filler increases, so do the number of conductive paths, producing large PTC effects. As the saturation region is reached, low sensitivities occur. Courtesy, Materials Research Laboratory, Pennsylvania State University.



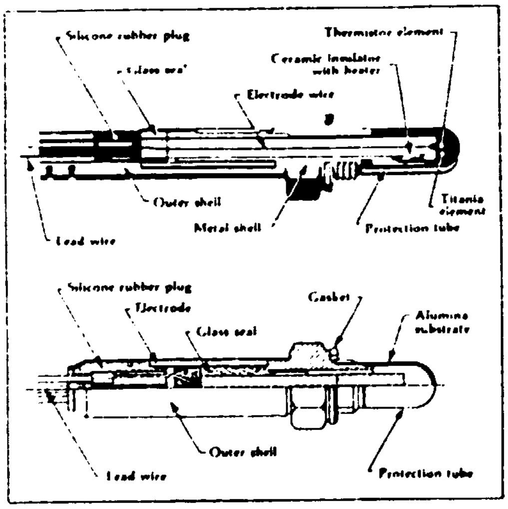
The resistivity/temperature behaviour is a function of polymer type as determined by Pennsylvania State University. For the epoxy composite, the PTC is more "dramatic", occurs near room temperature, and has an intensity of five orders of magnitude. The room temperature resistivity is relatively high, which occurs within the PTC transition. The resistivity at temperatures less than 0°C is considerably larger than polyethylene composites of the same volume fraction.

NGK Insulators Ltd. has developed a similar heated zirconia sensor based on the same oxygen pumping principles, as well as thick-film technology. Though such heated sensors have better operating performance at low temperatures, and are more durable and stable than unheated sensors, there is one disadvantage. The ceramic heater's location inside the sensor leads to a complex structure requiring extended electrical connectors, and thus, higher costs.

NGK's design consists of two electrochemical cells, one ceramic heater sheet, a gas-diffusion control gap between the cells, and an air duct installed between the cell and the ceramic heater. Each electrochemical cell consists of yttria-partially stabilized zirconia between porous platinum electrodes on both sides. An insulated layer is placed between the cells. A printed pattern made from metal powder paste is embedded into a ceramic layer to form the heater. The platinum electrodes exposed to the exhaust areas are protected by thin layers of porous ceramics.



An exploded view of the NGK Insulator's sensor element, which consists of three zirconia green sheets fabricated by tape casting. The measuring platinum electrode is screen-printed on one side of the top sheet, and the reference platinum electrode is printed on the other side. An air duct is punched in the middle sheet. A resistor for heating the element is screen-printed on one side of the bottom sheet. The green sheets are laminated together by hot pressing and sintered to form a complete single chip. Courtesy, SAE.



The pellet-type titania sensor, above, is being replaced with the thick film titania sensor, below. Titania thick film is coated on the multilayered alumina substrate composed of four layers. Pt thick film for the heating element and the electrode is printed on the base layer. Courtesy, SAE.

Titania is better

NTK Technical Ceramics Division and NGK Spark Plug Co. Ltd. have designed a thick film titania sensor which has several advantages over zirconia sensors. The zirconia sensor has several problems: phase transformation of the material can cause deterioration; air flow through the gap allows moisture penetration into the internal cell (as from road splash); the internal electrode can be contaminated with vaporized gas from rubber elastic, which requires expensive fluorine-rubber elastic; and lead poisoning can severely reduce response time as well as the sensor life itself.

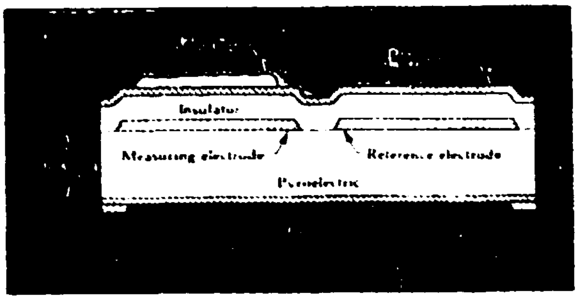
Titania, on the other hand, is a n-type semiconductor, and behaves as a catalyst for CO oxidation. The mechanism is based on the chemical equilibrium between oxygen-related lattice defects and oxygen gas in the surrounding area. Therefore, if the environmental temperature is constant, the sensor resistance is only dependent on the oxygen concentration. Hence, referenced external air is not required for this sensor, which allows the terminal portion to be submersible. The titanium sensor can be installed downstream of the exhaust pipe.

With regard to lead poisoning, titanium acts as a catalyst against the exhaust gas and can be operated above 1,292°F (700°C) without requiring a precious-metal catalyst (operation at lower temperatures may require a catalyst). The catalyst, usually needed for zirconia sensors, deteriorates with contamination by leaded fuel. Titania sensors also are normally of the stable crystalline structure, rutile, which shows no phase transformation from low temperatures up to its melting point. In addition, titania has a thermal expansion coefficient similar to that of the alumina substrate and platinum electrode, and is insoluble in water, dilute acids, and dilute alkalis.

Similarly, Allied Automotive's Autolite Division is marketing a titania sensor using the same technology. A thick-film platinum heater pattern is printed onto one side of a flat alumina substrate. This heater has a high positive temperature coefficient of resistance and thus is used as a single-valued compensating resistor. The titania can be heated to nearly the highest exhaust temperature and held in a 122°F (50°C) band near this temperature. A porous thick-film layer of TiO_2 is applied to the other side of the substrate.

In tests comparing their TiO_2 sensor to ZrO_2 sensors, Autolite found that titania sensors have faster switching times from rich-to-lean, lean-to-rich air/fuel ratios. Heat-up times also are up to eight times shorter. In other words, the sensor becomes functional very early in the engine warm-up cycle. Other advantages are: the sensor maintains stability after engine aging (up to 50,000 miles (80,000 km) or more); provides more uniform control over the entire exhaust-temperature range; has location flexibility; can maintain closed-loop control during prolonged engine idling.

For optimum sensor performance, high interconnected porosity, small particle size, and small grain size are required. More porosity on the sensor surface prevents a continuous glassy phase from forming. This glassy phase is produced when fine lead particles are deposited on the sensor surface. The exhaust gas flow is restricted to the sensor surface area and the resulting glassy phase can penetrate into the element when overheated. The surface of the titania sensor contains small particles and has a larger volume of porosity compared to the zirconia sensor. Thus, the titania sensor is more resistant to lead poisoning than zirconia.



Shown is a schematic of an integrated scanning pyroelectric microcalorimeter. The $LiTaO_3$ pyro electric chip contains a heater element which is a Ni-Cr film. Courtesy, University of Pennsylvania.

More fundamental research is needed to understand the basic sensing mechanisms, which depends on microstructural (porosity) development. Complete models must be developed based on thermodynamics, reaction kinetics, and solid state physics. Hence, Ohio State University scientists are studying the oxidation-reduction kinetics of porous titania. By sintering TiO_2 in HCl atmospheres, vapor phase transport is enhanced and grain-growth kinetics can be measured. This information is used to develop various sintering cycles to alter the microstructure so that its effect on the response time can be determined.

After measuring conductivity changes in the titania, asymmetry was observed between the oxidizing and reducing cycles. The voltage drops during reduction are generally faster with increasing temperature and porosity and with decreasing grain size. The conductivity changes during oxidation are more complex. However, response times of less than one second occur under certain conditions, even without a catalyst. Ohio State researchers are trying to explain the asymmetry with a grain-boundary preferred oxidation/reduction process.

From thick to thin

Various semiconducting ceramics including tin, zinc, and iron oxides, are used to measure or detect combustible and toxic gases. In a recent study by Charles River Associates, world sales totalled several million dollars per year for these devices, with Japan dominating. Sales are expected to increase to between \$90 and 160 million by 1990 without expansion into other applications, which is a 20 to 30 per cent annual growth rate. If new applications are developed, sales will even be higher; between \$260 and 430 million, which is an average annual growth rate of 40 to 50 per cent. However, for ceramic gas sensors to expand into new applications, their problems of nonselectivity, instability, poor reproducibility, and high operating temperatures must be solved.

Scientists at General Motors Research Laboratories have developed a gas-sensor device using thin film technology that solves the problems of nonselectivity and reproducibility. They use a metallo-organic deposition (MOD) technique for tin oxide thin films that has several advantages over conventional methods. MOD is accurate in process control and is compatible with microelectronic processes, unlike chemical reaction and precipitation methods. MOD also is inexpensive compared to vacuum deposition which requires costly equipment. Because of the latter, materials cannot easily be modified with additives as with MOD. Therefore, MOD can be used for both single sensor devices and the newer integrated sensor design.

The GM researchers found that the gas sensitivity of the films can be modified by various additives. Thin, pinhole-free films of 0.1 to 0.3μm were formed by spinning metallo-organic inks containing tin (II) 2-ethylhexanoate onto silicon wafers. Additives of antimony, tantalum, silver, or platinum were added to the ink. The sensitivity to reducing gases (C_2H_5OH and H_2S) is depressed by donor-type additives (Sb or Ta), but enhanced by an acceptor type additive (Ag). The platinum additive enhances the sensitivity to reducing gas as well as oxidizing gases (NO_x).

A more conventional method, chemical vapour deposition (CVD) is used at Case Western Reserve University to fabricate an integrated solid state ion-sensitive field-effect transistor (ISFET). Such a device can be used as a biomedical chemical sensor for measuring pH. After oxidation of the silicon sensing area, called a gate, CVD of alumina (a pH sensitive dielectric) takes place. The wafers are then heated up slowly to avoid thermal shock. At the deposition temperature, a hydrogen annealing step is performed prior to CVD.

The operating principle of the gate is based on surface association and dissociation. As the solution ionic concentration varies, the surface-charge density at the sensing area also changes. In turn a change in channel conductance occurs, which can be measured as a variation in voltage or current output. Alumina is used because the dielectric material must have low solubility and its fabrication must be compatible with solid state technology for batch processing. Another advantage is that the sensing area can be quite small, 13 X 450μm or less, which reduces the overall sensor size to 2,200 X 1,900μm or less. Thus, these microsensors overcome the size limitations of conventional sensors and can be used for <u>in vivo</u> monitoring.

However, Case researchers discovered that alumina's microstructure will change under different processing conditions. These differences in turn will alter the surface properties which affect the sensing ability. For instance, after post annealing at 2,150°F (1,175°C), thickness decreases indicated an increase in both film density and refractive index. Furthermore, the dielectric strength decreases as the post-annealing time or temperature increases. At the deposition and annealing temperature of 1,562°F (850°C), the film appears as an amorphous gamma phase with a small amount of fine grains. As the temperature increases to 1,832°F (1,000°C) the structure is more crystalline, with both gamma and alpha phase, indicating the beginning of the phase transition. An annealing temperature of 2,150°F (1,175°C) shows a crystalline structure with both phases, but with a much wider range of grain size.

ISFETs also may have potential application as gas sensing devices. Unlike conventional transistors, ISFETs are exposed to the ambient atmosphere; therefore, their properties change according to the presence and level of various gases in the environment. However, even though the devices have the advantages of low manufacturing costs and can operate at room temperature, they lack sensitivity and selectivity of gases, as indicated by Case Western's study. This problem may limit ISFETs to pH or humidity detectors since other ceramic materials have better gas-sensing properties.

<u>Thermal sensors for chemical processes</u>

Pyroelectric materials, such as $LiTaO_3$, or $PbTiO_3$, have generally been used in optical sensors or as thermal bolometers for infrared measurements. More recently, these materials have been used for measurement of gas flow and chemical detection by thermally programmed enthalpimetry. Because $LiTaO_3$ has a Curie or phase transition temperature of 1,130°F (609°C), the pyroelectric coefficient along the c-axis is virtually temperature independent up to the 572°F (300°C) level. In other words, the induced current in the electronic circuit will be independent of ambient temperature and will be a function only of the time rate of change of the pyroelectric element temperature. The induced current is a measure of the change in the total energy stored in the pyroelectric material. Therefore, the $LiTaO_3$ crystal can be used as a thermal flux detector having great sensitivity. Extremely small temperature changes less than 2 X 10^{-6}°F (10^{-6}°C) can be measured.

$LiTaO_3$ can be made into chips smaller than 50μm in thickness. Thus it has found application as an integrated differential scanning microcalorimeter, with sensitivities in the submicrocalorie range, and as a high sensitivity microenthalpimeter for monitoring catalytic processes. Both devices are made using standard microfabrication technology, with a NiCr heater element directly integrated onto the $LiTaO_3$ chip. The entire assembly is mounted on a ceramic substrate.

The pyroelectric calorimeter structure has several advantages over conventional differential scanning calorimetry. The latter requires the calorimeter and sample to be placed in a furnace, whose large mass can often limit the heating rate. Because the pyroelectric calorimeter has the heater element integrated directly on the device, small increases in thermal energy are possible by controlled pulses of electrical power to the heater film. Thus, the average temperature of the calorimeter can be incremented during the measurement run in predetermined amounts. (Source: <u>Advanced Materials and Processes</u>, September 1986, article written by Laurel M. Sheppard, Associate Editor)

It makes sense with ceramics

Sensor category	Typical ceramic material	Sensing mechanism	Applications
Piezoelectric devices	Lead-zirconate-titanate	Converts mechanical energy to electrical energy	Ignitors, photoflash actuators, resonators, beepers in paging devices, ultrasonic devices
Negative temperature coefficient thermistors	Complex systems of nickel, manganese, cobalt, and copper oxides	Coefficient of resistivity varies inversely with temperature	Control of nonlinear circuits, temperature measurement, automobile sensors, medical thermometry
Positive temperature coefficient resistors	Combinations of barium titanate with either strontium or lead titanate	Electrical resistivity varies positively with temperature	Self-regulating heating devices, current limiters, sensors for temperature, airflow, and liquid level
Varistors	Zinc oxide	Voltage — dependent resistors with nonlinear electrical properties due to electrical junctions at grain boundaries. Electrical properties are essentially temperature-independent	Protect electronic equipment from voltage images: TV receivers, microwave ovens, automotive electronics
Oxygen sensors	Zirconia stabilized with yttria or magnesia, titania	Zirconia: an electromagnetic field is produced in response to the equilibrium partial pressure of oxygen Titania: *n*-type semiconductor-chemical equilibrium between oxygen-related lattice defects, oxygen gas in surrounding area	Controlling exhaust emissions in automobiles, process control for steelmaking, combustion control, gas manufacture Mainly automotive — controlling exhaust in 3-way catalytic converter
Humidity sensors	Magnesia-chrome-titanium, or alumina	Resistance is a formation of relative humidity of the environment through chemical adsorption, dissociation of water	Microwave ovens, air conditioners, industrial operations
Combustible and toxic gas sensors	Various semiconducting oxides including tin, zinc, and iron oxides	Electrical conductivity responds to changes in gas concentration — (*n*-type: flow of negatively-charged electrons conduct electricity: *p*-type: conducts by flow of positively-charged electron holes)	Environmental monitoring, gas leak detection, process control, energy management
Chemical sensor (ion-sensitive field-effect transition (ISFET))	Alumina, silica, silicon oxynitride, silicon nitride	Surface charge chemistry at gate sensing area varies with the solution ionic concentration which changes voltage or current output	Biomedical chemical sensor for measuring pH, humidity detectors
Thermal sensors (pyroelectric)	$LiTaO_3$, $PbTiO_3$	Current output is a function of the change in the total energy in pyroelectric material	Optical sensors, thermal bolometers for infrared measurement, gas flow measurement, enthalpimetry, calorimetry

Sources: Case Western Reserve University, University of Pennsylvania, Charles Rivers Associates/National Bureau of Standards: A Case Study of Ceramic Toxic and Combustible GAs Sensors (NBS GRC 84-470-5).

3. SENSOR TECHNOLOGY AND APPLICATIONS IN EUROPEAN SCIENCE

Sensor technology in Europe was reviewed at the Third European Conference on Sensors and Their Applications (EUROSENSORS '87) convened in Cambridge, UK. The meeting was organized by the Institute of Physics (UK) and supported by the Commission of European Communities under the plan "for the transnational development of the supporting infrastructure for innovation and technology transfer". (The citation may sound pompous, but the European effort to focus on research and development in crucial high-technology areas is very real!) Several UK scientific and engineering institutes acted as co-sponsors. The lectures (and the exhibition) were hosted by the Cavendish Laboratory of classical fame.

There were three workshops:

- Sensors in the Syllabus
- European Funding of Sensor Research
- Software for Sensor Systems.

The scientific talks of EUROSENSORS '87 were grouped as follows:

- Silicon sensors
- Metrology
- Sensors in industry
- Chemical sensors
- Optical sensors
- Flow sensors
- Biosensors
- Magnetic sensors
- Physiological sensors

Following are the highlights of a few selected talks taken from sessions on silicon sensors, chemical sensors, and optical sensors.

Silicon sensors

S. Middelhoek (Delft University, the Netherlands) characterized the area of silicon sensors as one which is full of promises and also pitfalls. The main point is that silicon, as a sensor material, permits the integration of a sensing element and a signal processing circuit on a single chip. But in order that this attractive concept can be realized for a given measurement, it is necessary, not only that the silicon shows a suitable physical or chemical effect and that a sensor can be designed based on this effect but also that the sensor is compatible with the desired circuit technology. The possible effects and sensor applications were grouped as follows:

- Light detectors (especially CCD's, colour sensitive photodiodes, nuclear radiation sensors, IR detectors based on integrated thermopiles)
- Sensors for mechanical signals (such as vacuum sensors, tactile imaging sensors, integrated optical potentiometers)
- Sensors for thermal signals (specifically, integrated thermopiles)
- Sensors for magnetic signals (including three dimensional magnetic field sensors)
- Chemical sensors.

Subsequently, Middlehoek talked about the need for developing "smart sensors", which should have a standard output and where unwanted cross-sensitivities should be compensated. In addition, for these smart sensors, offset, drift, and other hard-to-handle effects should be minimized. Self testing should be possible. All these needs require integration. While hybrid structures are possible, the most elegant solution is obtained when the sensor and the signal processing circuit are made from the same material and integrated on the same substrate. Silicon technology appears suitable to achieve this goal. Special examples in this line were mentioned; these included: a piezoelectric pressure sensor with a current to frequency converter, a capacitive pressure sensor based on a square-wave oscillator, a pressure sensor based on a two-ring oscillator with a frequency ratio output, flip flop sensors, and sensors with bus compatible outputs. In concluding the presentation, the speaker pointed out that many difficulties connected with the development of silicon sensors (especially smart ones) have been often grossly underestimated. However, recent developments are more encouraging and the industry should pursue smart silicon sensors with great perseverence, patience, and adequate budgets.

J.C. Greenwood (Standard Telecommunications Laboratories [STL], Harlow, UK) talked about resonant silicon sensors, an idea which he proposed in 1969 and which, by now, has reached true maturity. Resonant sensors consist of a mechanical resonator supported so that the force to be measured changes the tension in the resonator in such a way that it modifies the restoring force and therefore the natural frequency. The most advanced geometry currently under investigation at STL is an altimeter, capable of resolving measurement to within a few centimetres of height. More specifically, this silicon-based resonant absolute pressure sensor has a resolution better than one part in 10^{-6}, and has a drift less than 0.04 per cent per year. This sensing technology is now adapted to measure other quantities, such as differential pressure, acceleration, and temperature. Optical, magnetic, thermal, and electrostatic excitability of resonant silicon sensors has been also demonstrated, opening up the way to a family of sensors suitable for use in harsh environments.

Chemical sensors

G. Horner and colleagues (Technical University, Munich, Federal Republic of Germany), reviewed significant improvements of the selectivity of a gas sensor system, achieved by the use of an array of sensors. Horner recalled that, in the past two years, it has been clearly demonstrated that sensor elements can be successfully grouped to a sensor array and that their signals can be evaluated and correctly interpreted by pattern recognition methodology. In this way, one can identify substances which could be identified only by much more sensitive (often unavailable) individual sensors. In recent experiments, the Munich researchers used an array of up to four metal oxide gas sensors. A computer controlled the calibration, the measuring, and the scavenging procedures. Using mixtures of known substances, calibration vectors were computed and their mean values stored in the computer. In the testing procedure of a single unknown gas, the computer then compares the test vector with the calibration vectors in the memory, using either pattern recognition or correlation algorithms. As a practical example, results for gas mixtures of CO and CH_4 were presented.

Another imaginative presentation was given by V. Dibbern, on behalf of the Philips Research Laboratory, Hamburg, Federal Republic of Germany. Dibbern reported that by using a silicon substrate, thin film processes, photolithography, and anisotropic etching, it was possible to fabricate a miniaturized gas sensor based on semiconducting tin oxide. Not only size but also power consumption and costs were thus reduced. Indeed, the crucial problem in this effort was to secure excellent thermal insulation, since, in view of the high (about 300°C) operating temperature, power must not exceed 100 mW. This goal was achieved by a membrane technology. The active part of the device is situated in the centre of a thin membrane, etched into <100> silicon. In the prototype device chip, membrane, and active area are squares with edge lengths of 2,700, 1,350, and 450μm, respectively.

W. Göpel (University of Tübingen, Federal Republic of Germany) gave an overall review of solid-state chemical sensors. He gave a thorough treatment of adsorption, absorption, and transfer reactions, then described experimental approaches to the study of interface reactions and recounted experimental results on prototype inorganic, as well as organic, sensors. He concluded with a review of future trends, including comments on new materials and new technologies, microstructured devices, and even complex tasks involved in evaluating sensor data (such as pattern recognition).

Optical sensors

The numerous contributed talks in this area were proceeded by a topical survey talk on novel optical fibres for sensor applications. This comprehensive and analytical review was presented by W.A. Gambling (University of Southampton, UK). He concentrated on recent considerable advances in this area, achieved by appropriate selection of core and cladding materials, and by novel fibre structures and designs. In particular, he explained that, by spinning the preform during fibre drawing, a high degree of circular birefringence can be introduced while, at the same time, linear birefringence becomes negligible. Such fibres are eminently suitable as sensors of magnetic fields and of electric currents. On the other hand, fibres caused to have a high linear birefringence, are best suitable for fibre gyroscopes measuring angular rotation. As another example, he pointed out that the introduction of rare-earth materials into the core of a fibre produces absorption bands with steep edges, which have a strong wavelength selectivity to change in temperature - this, in turn, provides the basis for constructing distributed sensors that cover a wide range of temperatures.

Two contributed papers touched on topics of immediate concern to naval needs. The first, a report by P.W. Porder (University of Kent, UK) described research done at his institute in co-operation with the Royal Signals and Radar Establishment (Malvern, UK). This work concerned laser velocimetry using fibre optics with diode sources and detectors. The researchers designed and constructed fibre-based dual-beam Doppler difference laser anemometer systems suitable for use in a wide variety of fluid dynamics studies. The primary concern was the development of a compact and portable system. A probe-type optical configuration was developed, in which the laser source, modulators, and detectors form one assembly, joined to the transceiver optics in a second (passive) assembly by a cable of fibres. Two single-mode fibres were used, together with one multi-mode receiving fibre.

The second paper directly addressing naval needs described the development of a laboratory prototype fibre-optic velocity hydrophone. It was presented by T.R. Empson, on behalf of Cambridge Consultants Ltd., Cambridge, UK. Velocity hydrophones respond to the particle velocity field, rather than simply to the pressure field associated with the acoustic signal (as conventional hydrophones do). Hence velocity hydrophones have an inherent directionality, independent of frequency - this makes them particularly useful for passive sonar applications. The sensor head, developed by Cambridge Consultants with the support of the UK Ministry of Defence, is an all-optical device, sensing the movement of a mechanical "leaf" which is coupled into the acoustic wavefield. The structure of the sensor head is illustrated in figure 1. The head is linked to a transceiver unit by two optical fibres. The operating principle of the head is based on a dual-wavelength displacement sensor, earlier developed for other (non-underwater) purposes. The transceiver launches light at two operating wavelengths alternatingly into the input fibre. At the sensor head, mechanical movements of the "leaf" in the field are converted into changes in the relative light-intensities at the two wavelengths. The modulated light-signal then returns (along the output fibre) to the transceiver unit, where the vane displacement and velocity are determined from the output of the optical detector by the processing electronics. Studies were conducted (with both simulation and experiments in a water tank); further development aims at improving performance, primarily by replacing the current p-i-n detector with an avalanche photodiode.

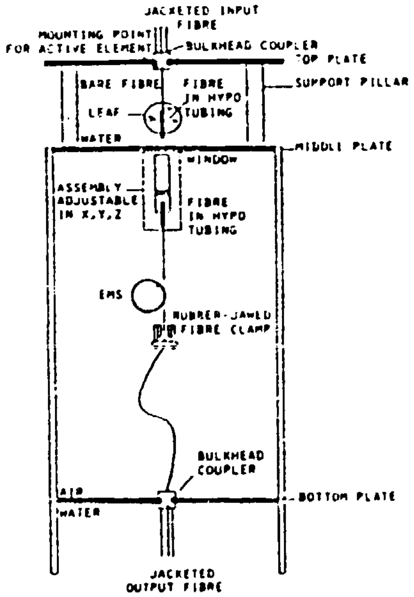


Figure 1. Schematic of the sensor head. EMS: electromagnetic sensor.

An interesting, innovative paper, describing recent research at the rather new Sowerby Research Centre of British Aerospace (Bristol, UK) was read by D. Hickman. It described research toward the development of an optical sensor based on temporal coherence properties. In conventional optical detector systems, a single detector is usually insufficient whenever one wants to detect a signal that is both less intense and has a spatial frequency content similar to that of background objects (clutter). This is so, because only time averaged intensity is measured - hence information concerning coherence and polarization is lost. The British Aerospace scientists pursued an alternative approach, which is based on selectively modulating the various signals by using their characteristic coherence or polarization properties prior to the detection stage. This approach can be expected to give significant improvements in both the signal-to-clutter ratio and the signal-to-noise ratio. The principle of the system is represented in figure 2. Experimental results are encouraging: for filtered white light against white-light background a gain of 10^3 in the signal-to-clutter ratio has been obtained, without additional filtering. For white light versus laser discrimination the gain was greater than 10^5.

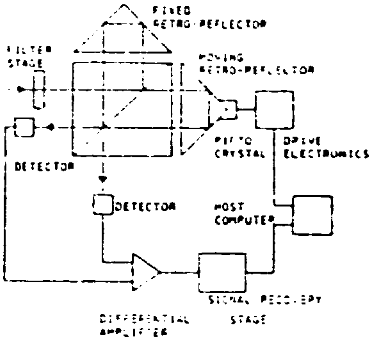


Figure 2. Schematic of the temporal coherence sensor

P. Nellen, on behalf of the Swiss Federal Institute of Technology, Zurich, Switzerland, reported on experiments with grating input couplers on planar waveguides. This device can be used, for example, as a sensor for the absorption of molecules out of a liquid on the waveguide surface, or as a differential refractometer. The clever device is shown in figure 3, and its function is self-explanatory. The s- and p-polarized He-Ne laser beams (λ=632.8nm) are incident on the film waveguide (in most experiments, made of SiO_2/TiO_2 on glass substrate, 160nm thick), under different angles chosen in such a way as to permit excitation of the TE_0 and TM_0 modes. This was achieved by rotating the rotation stage on which the waveguide was mounted. Very small rotation angles are required. The effective refractive indices of the two modes could be determined with an accuracy of $\Delta n \gtrsim 5 \times 10^{-5}$. (This required a careful measurement of the optimum incoupling angles for the two modes).

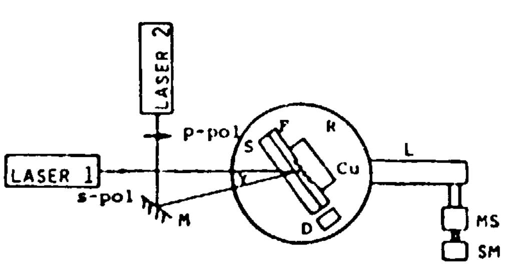


Figure 3. Schematic of the grating input coupler. M: mirror; S: substrate; F: waveguide film with grating; Cu: cuvette with sample; D: photodetector; R: rotation stage; L: lever arm; MS: micrometer screw; SM: stepping motor

When the device was used for actually measuring adsorption of a (biologic) substance from a solution, the molecules adsorped on the waveguide surface caused effective refraction index changes for the two modes - and these were then determined from the angular shifts of the two resonance incoupling curves. "Continuous" measurements with 1000 points could be taken in a 2 second scan over 1.25°. Scans can be repeated every 20 seconds.

Concluding remarks

The conference and the exhibition clearly demonstrated growing awareness in Europe of the need to step up efforts toward more rapid development of sensor-related research and industrial development. It has been well recognized that the "sensor scene" is more multidisciplinary than it ever was, ranging from basic physics, chemistry, solid-state devices, optoelectronics, microelectronics, micromechanics, and computerization to materials-technology, and so on. The conference underscored that the trend today is toward miniaturization and toward distributed "intelligent" (or "smart") instrumentation. In more practical terms, some speakers pointed out that, whereas "technology push" is strong, "market pull" is ill-defined. Others emphasized that a far higher percentage of R&D funds should be used to improve design aids and to investigate manufacturing methods. Finally, the need for increased government- and industry-supported technical education and training was pointed out. (Source: European Science Notes Information Bulletin, April 1988, article written by Dr. Paul Roman)

4. DEVELOPMENTS IN INTELLIGENT OR SMART SENSORS AND SYSTEMS

(a) Intelligent sensors in Neubiberg

The rather new Institute for Measurement and Control Technology is a self-managed unit of the Electrical Engineering Division of the West German Armed Forces University of Munich. The University's modern and pleasant campus is in Neubiberg, a southeastern suburb of Munich. The Director of the institute is Professor Dr. H.R. Tränkler. He has only about nine research associates, but receives much technical support by the institute's close co-operation with industrial research laboratories, including those of Siemens and Karl Thomae. In addition to undergraduate and graduate level teaching and fundamental and applied research, the institute also maintains a technology-transfer and advisory function, co-operating with the appropriate Bavarian governmental agencies.

The institute's work in the area of metrology focuses on intelligent ("smart") sensor systems. The main research targets are as follows:

1. Drafting and testing algorithms for sensor-specific signal processing and data evaluation. This work concerns linearization of sensor characteristics and static error correction; dynamic error correction and adaptive sensors; and finally, recognition of complex measurement signals (this includes pattern recognition, both spatial and temporal).

2. System design studies of microelectronic measuring systems. The research in this subfield comprises not only the integration of diverse sensors, electronic and logic components, and data fusing, but also the system-aspects and problems of both the "process"-environment (from where the measurands and other data are taken) as well as of the human interface (at the final level of the entire system).

3. There is additional research done to invent, design, and fabricate prototypes of new sensors and partial sensor-systems (transducers). This work has entailed, so far, only electromechanical devices (not optical, optoelectronic, or microelectronic-semiconductor sensors), but a broadening of scope is in progress.

The research and design laboratory of the institute has very fine equipment and instrumentation. This includes a DX990/10 computer (dedicated to microprocessor programming), development systems for Intel microprocessors, IEEE-bus-controlled test and calibration tools (for a wide variety of measurements, ranging from mechanical entities through electrical data to gas chromatography, density and concentration measurement instruments), as well as a number of personal computers and peripheral calculation equipment.

General considerations about intelligent sensors

In the true tradition of German academia, Tränkler approaches the institute's programme from a philosophical viewpoint. Physics and technology, he explains, determine the quality and applicability of sensors and transducers. Theory of measurement produces the algorithms which are necessary for static or dynamic correction of sensor signals - similar algorithms are needed to devise intelligent measuring systems. The physics, technology, and mathematics aspects are so interwoven that only a well-focused, well-directed, concentrated research programme has the chance to come up with widely applicable, properly accurate, and relatively inexpensive systems. Contrary to often-heard overoptimistic promises, Tränkler believes that the ideal physical effect (on which a sensor is based) is generally not realizable on the level of design and manufacture, not even if intolerable fabricating expenses are taken into account. Instead of stable linear and influence-free characteristics of measuring components, we get, in the output, unwanted arithmetic operations and combinations with external perturbing influences. Tränkler, following other pioneers in "smart" microprocessor-controlled measurement systems, says that, instead of "fighting" the inevitable, one must use "brains". For example, by application of reference input signals (or by a separate measurement of the perturbing influences) the static characteristic of a sensor can be corrected. In practice, this requires the systematic use of algorithms, as well as a knowledge of the approximation model function.

Here is where intelligent sensor systems (IS) become the "operative idea". Even though the field is still in a formative period, Tränkler finds it important to coin precise definitions. He emphasizes that all ISs are based on sensor-specific measurement-signal processing. He distinguishes between ISs in the broader sense and in the narrower sense. ISs in the broader sense simply enhance the usable information-content to a required level. ISs in the narrower sense gain usable information stemming from a number of individual informations which - taken by themselves - have only a small, and hence insufficient, information content.

ISs in the broader sense may be used, for example, to improve static or dynamic transference characteristics. But for the determination of complex measurands (such as recognition of spatial or temporal patterns), ISs in the narrower sense must be used.

Thus, ISs allow the determination of quantities almost entirely free from physical or technical sensor-quality limitations and from perturbing external influences; moreover, they permit the determination of complex features which previously could not be measured by sensors at all. In addition, it is now possible to combine smart sensors with sophisticated evaluating processors on one chip, and these "single chip sensors" are becoming increasingly important. The single chip IS can be considered as a natural outgrowth of elementary sensors in the classical sense, through stages of the transducer and digital sensor. This is illustrated in figure 1. Even more impressive is the graphical representation of the historical development of "sensors", showing now, gradually, the sensor element, analog signal preprocessing, converter, and microcomputer components of a measurement system became integrated (figure 2).

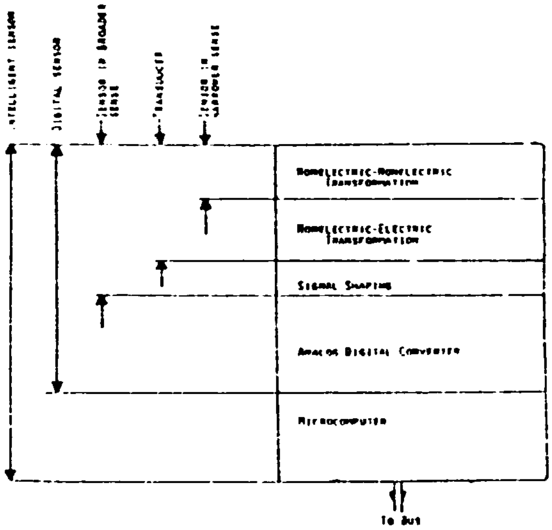


Figure 1. Scheme of an intelligent single-chip sensor

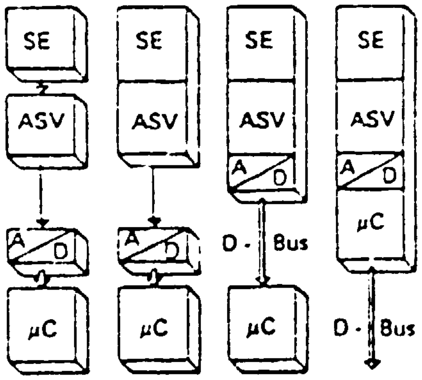


Figure 2. Development of modern measuring systems. (SE = sensor element; ASV = analog signal processing; A/D = analog/digital converter; mC = microcomputer; D-Bus = data bus.)

Tränkler emphasized that, in his opinion, for the realization of high-performance intelligent sensors it is absolutely necessary to assign a dedicated microcomputer to each sensor path. These permit both the computation of static, adaptive, and dynamic corrections, as well as the determination of complex features. Furthermore, in order to increase the integrity of the signal transmission, and also to increase clarity and economics of the system, it is necessary to use sensor-specific signal forms and serial bus systems.

Tränkler concluded the interview with sketching his vision of an entire microelectronic system of the future (see figure 3). On one side, we have the "process" which is monitored by sensors and acted upon by actuators. On the other side, we have the "human operator", who receives output from the huge system and can influence or control the process by appropriate inputs. In between we have the intelligent sensor systems and intelligent actuator systems, with appropriate signal specific processing. To each microperipheral component there is assigned a dedicated microcomputer. The individual components communicate through a digital data bus. For successful operation, it is necessary to employ specific signal processing procedures (adapted to each element), so as to minimize data traffic on the bus.

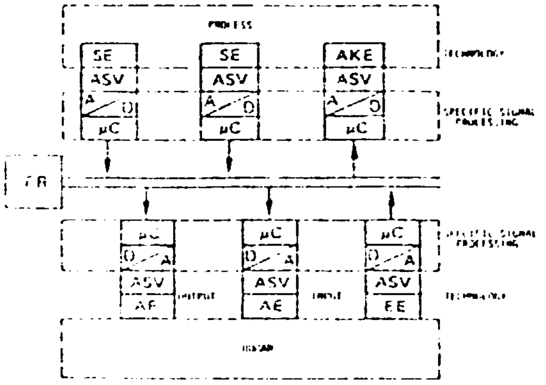


Figure 3. A complete microelectronic system of the future. (SE = sensor element; ASV = analog signal preprocessing; A/D = analog/digital converter; C = microcomputer; FR = controlling computer; D/A = digital/analog converter; AE = output interface; EE = input interface.)

Examples of current research

Trankler's philosophy is well illustrated by an industrial multi sensor system, recently designed, built, and tested at the institute (and transferred to users). The multi-purpose system is symbolized in figure 4. A coil spring or a printed coil sensor element or some other micromechanical sensor element (not shown) responds to force, displacement, pressure, mass flow, or liquid level values in the "technical process". Temperature in the "process" is also sensed (by locally developed spreading resistance-effect sensors) - but of course, temperature parameters also influence and perturb the reading of the other measurand. The inductive sensor controls the frequency of an inductive-capacitive oscillator that operates at around 1 MHz. The temperature sensor controls a resistive-capacitive oscillator. The signals of the oscillators are electronically multiplexed together, and transmitted (via a two wire line, a coaxial cable, or a fibre-optic link) to a demultiplexer at some distance away. Frequency analog mode of transmission is used. After frequency-digital conversion, a microcomputer linearizes the sensor output and corrects for temperature perturbations The processed output of the intelligent sensor is calibrated by the programme when the system is installed, and the calibration results are stored in the microcomputer's memory. The microcomputer has a keyboard/display peripheral, and is connected to a "sensorbus" by a suitable interface. The sensorbus combines data from a large number of intelligent sensors. Incidentally, the microcomputer (in each IS path) can also easily be its own watchdog and report any sensor problems.

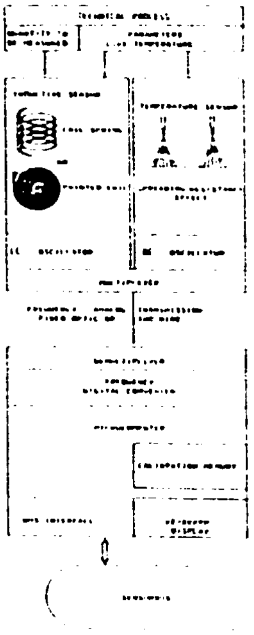


Figure 4. Microcomputer - oriented intelligent sensor system scheme

A second project, recently concluded at the institute, illustrates the algorithm designing activities of the researchers. In the past, one did not have inexpensive sensors that could selectively determine the individual component concentrations in a gas mixture. The reason is that, for any individual sensor for a particular component, there always is some cross-sensitivity to the other components. Hence, the individual component concentration values can be ascertained only by using several sensors for each component - any single one has, naturally, a different cross sensitivity to the "alien" gas components. With such a multi-sensor system a multidimensional analysis can be performed, provided that with the use of sensor-specific signal processing one succeeds to determine the n measurands $X_1, \ldots, X_n$ from the m sensor output signals $Y_1, \ldots, Y_m$. This is what the scientists of the institute did. The coefficients of the system of equations were determined by a regression procedure, based on a large of measurements on systems with known composition. However, the equations with the established coefficients allow an easy solution for an unknown set of concentration values only if the system is linear. (Then, for n=m, matrix inversion gives the answer). In real life, the system is nonlinear, so that the superposition principle does not apply. The scientists developed stochastic-deterministic search procedures and also, on an even more sophisticated level, they developed algorithms for pattern recognition. With these methods, quick solution of the equation system - i.e., efficient and simultaneous determination of the individual gas component concentrations - became feasible.

After developing the algorithms, the researchers also did the experimental and construction work: they built a complete workstation with elaborate and flexible calibration and testing facilities and used it to develop prototype gas analyzers. Later, these were transferred to governmental and industrial users.

A third aspect of the institute's research profile is exemplified by the development of signal processing and algorithmic methods for use with intelligent sensors designed for recognizing complex features. Using only simple IS methodology, it is now possible to discover and map faults with ultrasound echo analysis in bulk matter samples. But to improve the distance resolution up to an acceptable level it is necessary to separate very clearly the partial echoes. The institute's researchers achieved this by using convolution algorithms that calculate and display correlations. Figure 5 illustrates the success of this research. The top line shows the actual echo-profile, as captured by the sensor (piezoelectric transducer). The second line is a norm-echo, automatically produced by the measuring system. The bottom line shows the result of convolution: the resolution of the echoes is now excellent.

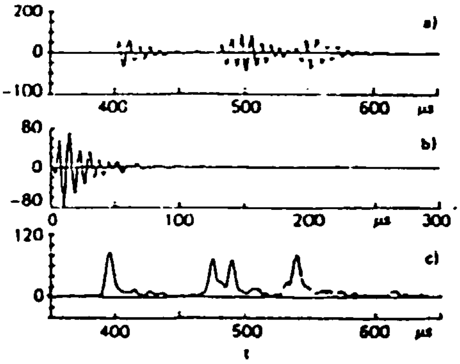


Figure 5. Separation of partial echoes by convolution

<u>Some data-handling research</u>

As is obvious from the introductory discussion, in modern microelectronic measuring systems the sensor signals must be available in a digital form. However, up to now, only in very few cases do we have sensors which give directly a digital output. Therefore, one must be satisfied (for the time being) with "digital-friendly" sensors. Among these, Tränkler thinks, sensors with a frequency-output are foremost, allowing a simple digitalization of the raw output. One reason is that sensors of this class can be manufactured with high accuracy and inexpensively, and the use of expensive analog-digital converters becomes unnecessary.

Frequency-analog sensors or control sources are well known. They range from the tuning fork quartz oscillator to resistive sensors (Si or Pt resistance thermometers, or magnetosensitive field-plates), capacitive sensors, and inductive sensors. Tränkler notes that even voltage-outputting sensors (such as modern Hall-elements) allow for an easy conversion of voltage to frequency.

Here, then, is the first research in this area which was tackled successfully at Neubiberg. For efficient use of frequency output sensors, it is important to have extremely good oscillators. This is so because the Q-value of, let us say, an inductive sensor element is usually low and, in addition, varies with the measurand. In order to have a multi-purpose oscillator with extreme frequency stability, the institute developed a modified Franklin oscillator (see figure 6). Here the needed 180° phase-rotation is achieved not with passive components, but via a second amplifier stage which has a high input resistance, a low output resistance, and a low and widely frequency-independent input- and output-capacitance. In this way, the output frequency of the oscillator coincides to great precision with the resonance frequency of the oscillating circuit. Apart from high stability, this also reduces substantially the usual warm-up time. Using this modified Franklin oscillator with inductive sensors, in the particular case of a conical spring displacement sensor a resolution of 9 Hz/µm was achieved in the entire range from 1.3 MHz to 2.2 MHz. The standard deviation of the output signal was below 2Hz. Current experiments study the use of the oscillator with capacitive sensors. As a matter of fact, the institute went beyond this oscillator development work, and has now developed an even more stable modified Pierce oscillator.

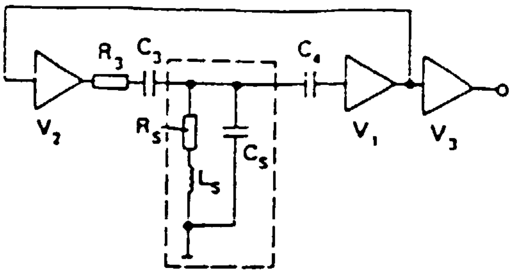


Figure 6. Circuit diagram of the modified Franklin oscillator

Once a good-quality frequency signal is obtained, the ne[illegible] ep is to combine it (using locally develop[illegible] ic-circuits) with the output of a standard RC-[illegible] tor that is linked to the output of a t[illegible] e sensor which monitors the temperature of [illegible] ironment.

Eventually [illegible] ter demultiplexing), the frequency-digital conversion (i.e., frequency measurement) must be taken care of. For this step, the researchers of the institute developed known counter techniques to suit the specific requirements of ISs. They found that by using a microprocessor, one can effectively arrange for a synchronized gating time. As figure 7 shows, three counters are used in the Neubiberg converter-system. Z1 (in figure 7) captures the pulses at the input, Z2 measures the synchronized gating time, and Z3 is used as a programmable time-divider supplying the gating time. The quality of this converter system is illustrated by the experimental result that using, for example, a 10-MHz reference frequency, a 10-ms gating time setting guarantees a resolution of about 16 bits, completely independently of the input-signal's frequency. In the conceptual framework of IS work, a further advantage of the Neubiberg-converter is that the gating time can be automatically adjusted so as to suppress system-induced perturbations. In other words, the counter "contains" an integrated filter.

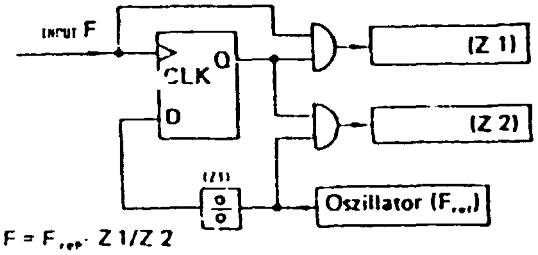


Figure 7. Block diagram of the frequency/digital converter

Plans for the future

The institute's future plans continue the present preoccupation with sensor-specific methods for measurement-signal processing, and the development of IS systems that allow for high-demand requirements while aiming for price-effectiveness, ruggedness, and simplicity as well. (Source: European Science Notes Information Bulletin, June 1988, Article written by Dr. Paul Roman)

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(b) Advanced Sensor Research at Siemens

In 1986 the Federal Republic of Germany cornered 45 per cent of Europe's market in semiconductor-based sensors. No wonder then that the largest German electrical, electronics, dataprocessing, and telecommunications firm, Siemens AG, recently accelerated its research and prototyping of novel sensors, which also include on one chip important parts of the processing microelectronics. Two main lines are reviewed here.

Intelligent MOS-Transistor Sensors

Siemens developed a class of miniaturized metal oxide semiconductor (MOS) devices suitable for the modern, normalized and self-calibrated measurement of mechanical entities such as pressure, flow, vibration, and acceleration. They are based on the well-known pressure-dependence of the MOS-transistors' channel-conductivity. Actually, the sensor system determines the detuning of a ring-oscillator circuit which contains several field effect transistors (MOSFETs). The transistors and resistances, capacitances, etc. are carefully arranged on a thin-film membrane. Additional built-in microelectronic circuits provide on-chip correction of temperature effects. Of course, the output is an easily digitized frequency.

While well-developed methods of silicon technology make the fabrication of such sensors feasible, there are also a number of unusual micromechanical fabrication steps involved. Research toward these problems has been completed in the Erlangen laboratories of Siemens, where also a new clean room fabrication facility was opened up for production.

Chemical sensors for liquids and gases

Ion-sensitive field-effect transistor sensors, ISFETs (a subclass of more general, chemically sensitive field-effect transistors, ChemFETs) are a focal effort of Siemens. In such devices, the gate-electrode of the well-known MOSFET is replaced by a chemically sensitive (in the present case, ion-sensitive) membrane. When the concentration of a specifically defined ion in a liquid (or gas) changes, the charge distribution on the surface of the membrane will change. The resulting potential difference then controls the channel resistivity.

In the Siemens devices for liquids, the crucial part of the sensor consists of a flow cell with a sandwich-like structure. This contains two ISFETs with identical membranes. For calibration of the zero level, both are moistened with some liquid. In the course of the actual measurement, one of the ISFETs stays in contact with the calibrating liquid, the other with liquid to be tested. The ensuing voltage differential depends on the sample's ion concentration.

On the other hand, for gaseous samples Siemens developed an entirely new methodology. Here the researchers used a phototransistor which is preceded with an optical filter so devised that it changes its transparency in the presence of certain gases or vapours. Such devices turned out to be particularly superior to other chemical sensors when the measurand is a polar molecule, such as alcohol or ammonia. Sensitivities down to a few thousandths of a percent (i.e., 10^{-5}) have been recently achieved.

These sensors have been produced also with a gas-transmitting encapsulation. These devices may be inserted into liquids for measuring gas concentrations of dissolved agents.

All chemical sensors developed at Siemens are strictly specific for only one chemical. By developing suitable membranes, current work focuses on extending the range of measurands.

The chemical sensor research at Siemens is done in co-operation with the Technical University of Munich. (Source: European Science Notes Information Bulletin, September 1989, article written by Dr. Paul Roman)

5. CURRENT AWARENESS

T° sensors

Temperature sensor probes resist corrosion

A British manufacturer of temperature sensor probes has developed a version specifically for use with corrosive materials.

Designed for a long working life in such applications as plating and in anodizing vats, the sensor probes are supplied complete with a one-piece PTFE well. This has a precision-fit, finely threaded screwed cover, and a nut-and-olive gland to give a positive seal around the PTFE sleeved sensor leads.

Intended as a positive solution to the problem of short sensor life in such applications (conventional probes with protection on only the immersed portion are not always satisfactory because they are vulnerable to splashes or vapour condensation) the well protects the sensor itself from attack by corrosive and intrusive liquids and low-surface-tension materials.

As usual in this branch of industry, the company manufactures sensors tailored to meet the requirements of individual applications. They can be fitted with either thermocouples or resistance temperature detectors, and can be connected to temperature controllers or indicators.

This temperature sensing probe is specifically designed for use with corrosive, intrusive, low-surface-tension liquids where the life of sensors is usually very short. Sensors, tailored to the particular applications, can incorporate either thermocouples or resistance temperature detectors. (Nulectrohms Ltd., Meppershall, Shefford, Bedfordshire, England SG17 5LX) (Source: Maintenance, Vol. VII, No. 4, January-February 1988)

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Battelle Memorial Inststitute has developed a new metal temperature sensor. The new sensor has been successfully tested and may be able to help steel producers considerably cut energy costs and enhance productivity, according to the American Iron & Steel Institute The American Iron & Steel Institute and the National Institute of Standards & Technology selected Battelle Memorial Institute to develop the sensor at the Energy Deptartment's Pacific Northwest Laboratory. The sensor will be able to monitor the internal temperature of hot steel at different stages of the production process. The process works by determining the speed with which ultrasonic waves move through hot steel. Enhancements in manufacturing techniques accomplished by technologies like the sensor are needed to help US steel producers to compete with foreign manufacturers who rely on government subsidies, according to DM Boyd, Battelle's Applied Physics Centre. (Source: Am Mtl Mkt, 22 November 1988)

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High-temperature sensor

Trans-Met Engineering, Inc., has developed a new high-temperature Dew-Point Sensor that operates on a patented concept to measure dew point in industrial drying systems. The system sensor is based on detecting the exothermic heat of condensation when moisture forms on a surface. The system utilizes two matched Trans-Met heat flow sensors mounted in a cooled block with one sensor running slightly cooler. Air samples are drawn through the dew-point sensor with either a fan or an air ejector. As moisture collects on the cooler of the two detectors a sudden change in the balance signal occurs indicating a dew point. This temperature is displayed on the panel in digital form.

The control unit is mounted in a NEMA enclosure with a digital readout of dew point and provides a 4 to 20-milliamp analog output for both dew point and air temperature. The Dew Point 9000 is insensitive to environmental fouling and will operate to 500°F. (Source: Iron and Steel Engineer, November 1988)

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Low-temperature wireless thermal sensor: A wireless thermosensor developed in Japan measures temperatures ranging from near 0 K to 100°C with a resolution of about 0.01°C. Unlike metal resistance sensors, it is almost completely unaffected by even extremely high magnetic fields.

A radiowave of about 10.6 MHz is transmitted to a 7-mm ring-shaped antenna, causing a quartz oscillator (similar to quartz clock movement) to resonate at a specific frequency. Because resonance frequency varies slightly with the temperature, frequency reading gives temperature.

(Electrotechnical Laboratory, Agency of Industrial Science & Technology, 1-1-4, Umezono, Tsukuma-shi. Ibaraki-ken 305, Japan) (Source: Inside R & D, 7 December 1988)

New sensor coupling device for cutting tools

Professor I. Inasaki, Department of Mechanical Engineering, Keio University, has developed a new device for detecting the cutting process.

This new sensor coupling device is for milling machines, drilling machines and for the machine centre. Within the industry there has always been the need for a practical application of the sensor coupling device to detect the cutting process-related signals from the "tool side". A mounting device which enables the sensor to be fixed close to the rotating multipoint cutting tool has been developed to meet this need. Thus a more practical method for detecting the tool fracture of twist drills and/or tool chipping of an end mill cutter becomes possible. The machining process associated signals are high-frequency acoustic emission (AE) signals detected from the spindle top of the machine being used. In this study, two kinds of AE signals have been compared. The first are those detected from the spindle housing. The second are signals detected from the spindle top using the newly developed sensor coupling device.

'Throughout various experiments it has been proved that the detection of AE signals associated with the cutting tool state is possible from the "cutting tool side". The introduction of the coupling device allows for the detection of the AE signals transferred from the rotating spindle of a machining centre to the non-rotatable part of the spindle head with a very low damping.

Construction problems concerning, for example, the vaporization of the magnetic liquid, have to be solved. Additionally, the best location of the developed coupling device along the spindle has to be determined.

The idea of transferring AE signals through a liquid medium from a rotating part to a non-rotating part allows for the application of monitoring systems in new technical fields. Signals which are difficult to detect due to a low accessibility of the signal source for a sensor can be recorded using this idea.

The developed monitoring algorithm which determines tool fracture or tool chipping in multipoint cutting tools reliably supervises the multipoint tool state. (Faculty of Science and Technology, Keio University, 14-1 Hiyoshi 3-chome, Kohoku-ku, Yokohama City, Kanagawa Pref.) (Source: JETRO, December 1988)

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Chemicals detection

Surface acoustic wave (SAW) sensors for new generation of chemicals detection devices

In a joint project with the Delft University of Technology, the TNO Prins Maurits Laboratory has developed a surface acoustic wave (SAW) sensor for detecting NO_2. This sensor may be considered an important step towards a new generation of chemical microsensors for detecting chemicals in the atmosphere.

The TNO Prins Maurits Laboratory has been working for a number of years on the development of chemical microsensors. Chemical sensors can be used to transduce chemical signals (the presence of concentration of a certain substance) into suitable electrical signals. They are used for the identification of toxic, corrosive and explosive compounds (alarm and detection), or for the checking of process variables in chemical processes. In the last decade, much research has been conducted into miniaturization for the production of microsensors. Chemical microsensors are mostly based on IC technology, where the sensor and the electronics are integrated on the same silicon chip. Apart from the fact that they are small and use little energy, microsensors have the advantage of being robust and reliable. Furthermore, the fact that they can be mass-produced means that they are low in price.

Surface acoustic wave (SAW)

After an extensive analysis of the various existing sensor systems which could be used in miniaturized alarm and detection systems, the TNO researchers decided to work on the basis of surface acoustic wave (SAW) technology.

An alternating electrical field is generated on a piezo-electric substrate material (quartz) with the aid of two interdigital aluminium electrodes. A synchronous mechanical deformation of the substrate material is thus produced. If the correct crystallographic direction of the piezo electric material is used, an acoustic wave is created which, under certain conditions, is restricted to the surface of the substrate material - the surface acoustic wave. The second identical set of electrodes, at a distance of approximately 8 mm, acts as a receiver. The combination of the transmitter, receiver and the wave path which lies between them is called a delay line.

Any change in the wave path between the transmitter and receiver affects the propagation speed of the wave and this can be measured very accurately as a frequency change. Such a change may manifest itself as a change in mass. Use is made of this phenomenon by means of a so called SAW sensor.

The surface between the transmitter and receiver has a chemically reactive layer, which selectively adsorbs a specific particle from the atmosphere, thus causing a change in mass. The reactive interlying area is called the chemical interface. One requirement is that the gas is released again as soon as the atmosphere is clean. Heavy demands are placed on the choice of material due to the selectivity referred to above as well as the stability and reversibility required.

The advantage of the acoustic principle is that a simple change in mass, which happens with almost every chemical interaction, is sufficient to form a signal. Thus, each chemical interaction which gives the desired selectivity, etc. is suitable, and a choice can be made from a range of chemical and biological substances when developing the chemical interface.

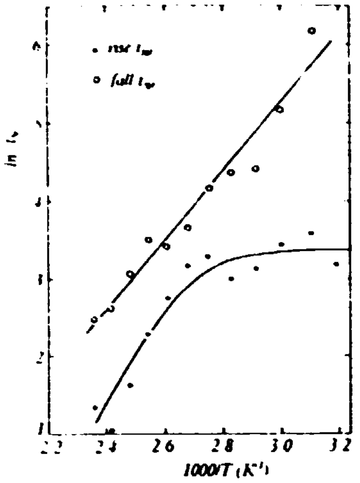
Joint venture

The TNO Prins Maurits Laboratory is developing the chemical (micro) sensors in co-operation with the Delft University of Technology. The chemical work on the sensor, the selection and application of the chemical interface is carried out by TNO, while researchers at the university are studying the underlying sensor technology. These researchers recently succeeded in placing the sensor, together with the processing electronics, onto a small chip.

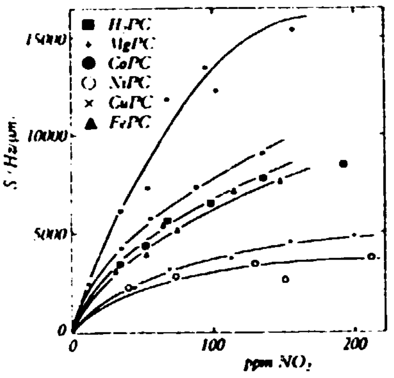
NO_2 sensor

In order to become familiar with the know-how of this new generation of sensors, work was first carried out on a sensor for nitrogen dioxide (NO_2). For this sensor, which has been patented, phtalocyanines were used as a chemical interface. Various aspects of the sensor were examined, such as selectivity, speed, stability, the effect of the way in which the chemical interface was applied, the thickness of the chemical interface and chemical changes in the phtalocyanines, as well as the effect of temperature and frequency.

The sensor appeared to be selective with regard to NO_2 in the presence of a number of other gases such as methane, carbon dioxide, carbon monoxide, water, sulphur dioxide, ammonia and toluene. The researchers also found that, in the application of the chemical interface, chemical bonding is to be preferred to physical application (smearing, spraying, steaming) because of the eventual stability and speed achieved. Sensitivity does decrease, but this can be compensated by selecting a higher sensor frequency.



Relation between ln(t80) and 1000/T for the rise and fall times of the sensor



Response per layer thickness (Hz/μm) as a function of the NO$_2$ concentration at 150°C

(Extracted from Applied Research, February 1989/23)

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Tactile and pressure sensors

New sensor said able to act as robots' fingertips

A new sensor designed to improve robots' sense of touch has been developed at Sandia National Laboratories. Primary developer Bert Tise says the work shows that tactile sensors can be made small enough to serve as fingertips on robotic hands.

The sensing area of the new digital tactile sensor (DTS) is about 0.5 inch square, roughly the size of a human fingertip. In the sensing area are 256 sensing elements arrange in a 16 by 16 pattern. Their resistance varies with mechanical load, and the array can sense forces ranging from 1 oz to about 1,000 lb.

The package for the DTS is 0.8 inch square and 0.25 inch deep. It also contains the microcircuitry that scans the 256 sensing elements and provides digital output for analysis by the computer that tells the robot what to do.

The sensing elements, called force-sensing resistors, are made of a proprietary, thick-film, piezoresistive polymer; their performance depends in part on the mechanical configuration. The elements are supplied by Interlink Electronics, Santa Barbara, Calif., and Sandia developed the microcircuitry and interfacing. The electrical resistance of the sensing elements declines as the mechanical load increases; resistance changes rapidly with loads smaller than 16 lb, but less rapidly and approximately linearly with larger loads.

The new DTS is at the working prototype stage. Further development is needed before a production model can be designed. Sandia meanwhile is using the prototype in research on dexterous manipulation.

Sensors will be tested by mounting them on fingers of a commercial robotic hand. The devices, protected by Mylar film, will be wrapped around the fingers like bandages. As the hand handles objects, data from the sensors will help the guiding computer decide how the grasp should be adjusted. Tactile data will also be integrated with data from other types of sensors, such as vision sensors, to keep the robotic system's attention on the overall task. (Reprinted with permission from Chemical and Engineering News, American Chemical Society, 2 May 1988.)

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Colour-mark sensors

Series 1720-4300 colour-mark sensors are used for positioning by direct reflection of red, black, brown, blue, green, and other coloured register marks. Radiant source for the fully self-contained sensors is a modulated green or red LED. Series includes a 2-m pre-wired lead cable, mounting holes with bracket, and operating indicator lamp. (Electrical/Electronic Div., McGill Mfg. Co., 102 N. Campbell St., Valparaiso, IN 45383, USA.) (Source: Machine Design, 8 December 1988)

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Low-cost pressure sensor

Model PT11 pressure sensor is for use as a primary-control component in hydraulic systems, engine monitoring, robots, and industrial-control systems. The low-cost device senses from 0-100 to 0-10,000 psi with combined error of ± 0.5 per cent average across the line and a minimum burst pressure exceeding 500 per cent of range. An integral housing assembly is incorporated. Sensor with 1-in. hex base consists of two parts (element and gauge patch) which are bonded together. (Revere Corp. of America, Box 56, Wallingford, CT 06492, USA) (Source: Machine Design, 9 February 1989)

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Sensor module plugs into standard I/O panels

Fibre-optic photoelectric sensor module is for OEMs that use microprocessor-based control systems in material-handling and packaging equipment. The 100-μ high-speed FiberPak control module plugs directly into standard panel-mounted microprocessor bus used by I/O module makers such as Opto 22, Gordos, Grayhill, and Potter Brumfield. Device interfaces through plastic fibres to fibre-optic accessories, and can be used in PB4, PB8, and PB16 single-channel I/O mounting racks. Four sensing modes are offered: through-beam, proximity, and true and polarized reflex. Input module and photoelectric control are combined, simplifying installation and reducing costs. Unit is unaffected by electrical noise in adjacent wiring or equipment. (Opcon Inc., 720 80th St. SW, Everett, WA 98203, USA) (Source: Machine Design, 8 December 1988)

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Sensor integrates punch press, laser

The Touch Probe Sensor (TPS) from Mazak Nissho Iwai Corporation (Schaumburg, Ill. USA), offers an alternative to a punch-press/laser machine by integrating press and laser via hardware and software.

The touch sensor is mounted on the laser-machine cutting head to manually or automatically measure dimensions and angles between reference holes with positioning accuracies of ±0.0008 in. Any linear or angular inaccuracies are then adjusted automatically.

The TPS also measures the cut of a reference hole while the software calculates the necessary beam offset and adjusts the laser program to obtain the best cutting tolerances.

The touch-sensor function is used to process single- or multiple-piece sheets of ferrous, non-ferrous, or non-metallic materials. (Source: American Machinist, February 1989)

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Radiation-based sensors

The National Institute of Standards and Technology is evaluating a non-destructive sensor system for process control during formation of thin-film ceramic coatings on metals. Photothermal radiometry is used to monitor the surface uniformity of materials and measure the thermal resistance of ceramics applied to metal substrates. A modulated laser beam heats a thermal "hot spot" on the surface of the ceramic coating. The thermal wave is partly reflected by the metal substrate. An IR sensor directed at the hot spot detects temperature fluctuations and measures the thermal resistance of the ceramic coating. Ceramic coatings of nitride, boride, oxide and carbide materials only several micrometers to 1 mm thick can support temperature differentials of several tens to several hundreds of degrees Celsius. The thermal conductivity of the ceramic coatings depends on the materials and the deposition method. (Source: C & E News, 9 December 1988)

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All-silicon infrared sensor

Infrared (IR) sensors are normally made of such materials as mercury, cadmium, and tellurium because it is tough to detect low-energy IR radiation with silicon pn-junctions. Now researchers at Japan's NEC have fabricated an IR sensor that uses only silicon, but has a wave-length sensing range that can be adjusted by varying the distribution of dopants and the voltage applied across the n-type layer. IR rays ranging from 1 μ to 12 μ wavelength (at temperatures of 50 K to 77 K) are sensed. The advantage of all-silicon device, of course, is that it can be mass-produced at fairly low cost. This should extend use of IR sensing.

In the new sensor, a low-concentration p-type layer and high-concentration n-type layer are stacked on an n-type silicon substrate. Free electrons in the high-concentration n-type layer absorb IR rays and undergo a change in energy state. These excited electrons pass through the p-type layer (a barrier) to the n-type substrate, generating electrical signals. Although the device is still relatively low in sensitivity, this will be improved by adding layers. (Nippon Electric Co. Ltd., 5-33-1, Shiba, Minato-ku, Tokyo 108, Japan) (Source: Inside R&D, 22 February 1989)

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Manufacture of sophisticated radiation sensors planned

Brazil will be the first third world country to mass-produce sensors for measuring gamma and X-ray radiation. To make this possible, the National Commission for Nuclear Energy (CNEN) will, by 1991, invest 60,000 OTNs [National Treasury Bonds] in Mittec Materials and Components, a company established in Sao Carlos (Sao Paulo) which has for 10 years been studying the sodium iodide monocrystal, an essential component for this type of equipment.

Mittec is comprised of a group of scientists from the University of Sao Paulo's Institute of Chemistry and Physics, and MC Minicom, a software house, devoted to computer programs for the financial sector. The first results appeared in early 1987, with the introduction of relative humidity capacitive sensors. This was followed by other equipment which, based on the experience from over 10 years of research, would culminate in the sodium iodide monocrystal.

Measuring and characterizing the radiation, based on this material a sensor manages to detect lower radiation levels which would probably not be picked up by a Geiger counter. It can be used in nuclear medicine, laboratories, agriculture, astronomy, etc. The project, to be carried out at Mittec's new facilities in Sao Carlos, is divided into four phases. The first one will produce sensors with a 1 inch diameter and length which, during the following phases will have a proportion of 2 by 2, 3 by 3, and 3 by 3 with a shaft (a hole that allows for analyses in test tubes).

Mittec's aim is to complete the project by the beginning of 1991, exporting as well as meeting the national demand satisfactorily. (Extracted from O Estado de Sao Paulo, 29 March 1988)

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Ultrasonic sensors expand sensing capabilities

Opcon Inc. (Everett, Washington, USA), a supplier of photoelectric sensors and machine vision products, introduced the UC60 Series of ultrasonic sensors to provide its customers with expanded non-contact sensing capabilities.

In utilizing high-frequency sound waves to determine the precise distance from an object, ultrasonic sensors provide application capabilities where photoelectric would not be the best solution. An example of this would be determining the fill level of containers. In range-sensing applications ultrasonic sensors provide a linear analog response to an object's distance that is independent of a material's colour or composition.

The series is made up of the UC60-LN1A, an analog output level sensor, and the UC60-ZD1A, a switched output zone detection sensor. Both sensors include adjustable sensing zone features, stainless steel case, extended temperature operation, built-in temperature compensation, short-circuit/transient-protected outputs and 10-30 VDC operation.

Designed for use in analog monitoring or feedback systems, the UC60-LN1A sensor outputs distance as an analog voltage or current. Typical applications include controlling a pump to maintain a liquid level in a tank or controlling the speed of a motor to maintain preset infeed loop depth.

The UC60-ZD1A produces a switched output when an object enters a present zone. Typical applications are empty carton certification, empty bin check on automatic storage and retrieval systems and height sorting.

The built-in temperature compensation allows the sensor to maintain a consistent reading over its operating range. In addition to outputs, each sensor also provides separate output lines which interface to remote modules and panel meters, further expanding sensing capability.

For environments exceeding the sensor's operating temperature limits of -20°C to +55°C, waveguide adapters are available to remove the sensor from extreme temperatures and direct the sensing path to the desired target. Waveguides may also be used to guide the sensing path around any bends or obstructions. (Source: Food Engineering International, February 1989)

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Optical and fibre-optic-based sensors

A humidity sensor that uses an optical IC has been trial produced according to sources at the Faculty of Engineering Science at Osaka University, Japan. The sensor includes a waveguide that is part of a lithium niobate crystal wafer. A beam of light directed into the waveguide is directed into two paths, one of which is isolated from the surrounding environment, while the other is exposed. The paths are maintained at a set temperature; thus, the temperature of the path subjected to any enveloping gas will decrease. The sensor is 1 mm thick; the wafer is 3 cm long and 2 cm wide, and consists of 3 waveguides. (Source: NewTeJa, May 1988)

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Fibre optic sensor

LS 1000 and LS 1200 liquid level switches incorporate a single filament optical fibre instead of bundled fibres for higher performance. The compact sensors utilize a U-shaped glass sensing element made with proprietary glass structure to sense liquid presence. The sensor fibre resists ultra high amounts of shock and vibration. Electrical circuitry can be located as far as 100 ft. away from the sensing probe and liquid. These switches are well suited for hazardous or explosive environments. (Gems Sensors Div., IMO Delaval Inc., Cowles Road, Plainville, CT06062, USA) (Source: Machine Design, 1988)

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Use of fibre-optics in a sensor requires choice of the right fibre and the right wavelength, as reviewed by J.F. Wahl of Corning Telecommunications Products Division Properties exploited by fibre-optic sensors are subtle. A force sensor compresses a fibre between complementary mini-sawtooth surfaces, causing at the many bends light losses that increase as the force presses the sawteeth together; multimode fibre and special coatings can enhance this effect. A current sensor measures rotation of polarization caused in the fibre by the magnetic field of the current, but requires a fibre of low birefringency. Preservation of signal versus noise can be enhanced in some applications by polarization maintenance through highly birefringent fibres. Interferometry can measure very slight pushes and pulls, such as in passive sonar systems, but must be at a wavelength short enough to provide good accuracy - typically shorter than the long wavelengths the telecommunications industry prefers to minimize scattering losses. Laser gyros, now primarily a military technology, have many potential applications from cars to robots, but must be sold to those industries. (Source: Photo Spec., December 1988)

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Optical-fibre sensors

FS/FU Series optical-fibre photoelectric sensors detect objects as small as 0.015 mm in diameter. Sensors recognize objects every 0.5 ms or detect 2,000 objects/s. With three types of LEDs, the light source of amplifier is selectable, allowing options of plastic, glass, spiral stainless steel, coaxial, and micro lens for mounting in close juxtaposition. The heat-resistant units can operate at ambient temperatures to 200°C. (Keyence Corp. of America, 20610 Manhattan Place, Suite 132, Torrance, CA90501, USA) (Source: Machine Design, 24 November 1988)

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Tokyo Aviation Instruments develops light pressure sensor

Tokyo Aviation Instruments recently developed a "light pressure sensor" using optical fibres and a semiconductor laser. It appears that fly by light (FBL) will be introduced into the pilot systems of future aircraft. For this reason, one in which the output of the sensor itself can be obtained from direct light is favoured.

The light pressure sensor developed by Tokyo Aviation Instruments mechanically detects changes in pressure and reads it using optical fibre and a semiconductor laser. The changes in pressure which are detected using a diaphragm are mechanically enlarged and transmitted to a linear encoder. The linear encoder vaporizes a chrome reflector film on a glass substrate into "bar code" form and the existence of the reflector film is read by optical fibre and a semiconductor laser. A "self-combining effect" is used for this purpose in which the output of the semiconductor laser is increased when the light generated by the semiconductor laser is returned to the laser by a mirror.

A special feature of this test-manufactured light pressure sensor is that the detector part will function even if separated from the sensor output part. In tests detection was possible using an optical fibre 500 metres long. There is no electrical system in the detector and it is resistant to electromagnetic interference and heat. Another special feature is that it is superior in stability since signal readout is by the digital method. Its performance matches that of conventional electrical detection methods.

The final output in this test-manufactured part will be electrical, but it is also possible to create a direct output by light using this method. For this reason, the company believes that it will be used as an FBL sensor. (Extracted from NIKKEI AEROSPACE, 7 December 1987)

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Marketing - miscellaneous

Smart sensor market grows

The US industrial sensor market will be dominated by smart sensors in the near future, according to a report from Technical Insights Inc., a firm that tracks world-wide macro- and micro-technology trends. The $2.5 billion sensor market is experiencing a 10 per cent growth rate, with smart sensors predicted to account for 80 per cent of that market by 1992.

Smart sensors merge electronic data processing, a function normally handled by external processing units, and sensing into single IC chips. New technology will enable sensors to have vastly improved sensitivity, linearity, accuracy, and resistance to interference. The report says there will also be a standardization of output and signal formats, a reduction in the number and size of components, and lower costs. (Source: Machine Design, 26 May 1988)

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Bio-sensors

Plessey is teaming up with Cambridge University in Britain and Fisons Scientific Equipment Division to research, manufacture and market bio-sensors in a move to create a lead in the field of organic electronics. The consortium maintains that bio-sensors have the potential to create a multibillion pound market in the 1990s and beyond, as a diagnostic and analytical technique.

However, the success of bio-sensors will depend very much on the development of technology linking the chip with biotechnology. (Source: AMT [Advanced Manufacturing Technology], Vol. 2, No. 6, December 1988/January 1989)

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First 3D intelligent image sensor

The report from Sharp's Central Research Laboratory is that a prototype intelligent image sensor using 3D integration has been created. It is significant: parallel processing is easily accomplished in 3D-IC because the logical structures are implemented in the physical structure - you use vertical direction for data flow. Also you do not have to use syncronous clocks for serial data processing, so the system incorporates both parallel processing and asynchronous sensing.

The prototype character-recognition system built and tested includes about 10,000 transistors and 3,000 diodes implemented with laser-recrystallization technology. In the top layer, the sensor block, 210 pixels transfer their data in parallel to the middle layer, the converter block. The bottom layer, the comparator block, compares 35 data items from the middle with ROM data to find matches with one or another of 64 characters. Comparison time is 10 times quicker than similar serial processors.

The prototype's capabilities are limited and progress could still be slow towards the goal of creating a truly accomplished intelligent image-sensor chip. This would have 10, not 3, layers. (Source: Inside R&D, 18 January 1989, Vol. 18, No. 3)

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Krupp Widia (FRG) has developed a plastic composite magnetic material for use in rotor and sensor magnets. The firm said the material is made by placing magnetic neodymium-iron-boron powder in plastic. The magnets, made via pressing and injection moulding, have such benefits as they are stronger versus sintered magnets and the plastic material makes handling and more processing easier. The plastic magnets, offered in high- and low-coercivity types, can be made to close tolerances so that usually no machining is needed. (Source: Am Mtl Mkt, 23 November 1988)

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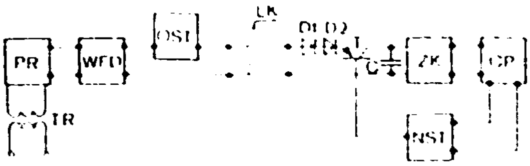
Spark-proof feeding of sensors

The patented electrical system is designed for the spark-proof day feeding of sensors installed underground, remote display of measuring results being employed. This system can feed a measuring sensor distant a long way off with a current of the order of 200 mA at a voltage of 7 V. No batteries are necessary for sensor feeding. The electrical system has been applied for the stationary-type multifunctional fire damp detector that has been specially conceived for that particular system.

The voltage of the secondary windings of the network transformer TR is rectified by the rectifier PR, and converted into a direct current in the high-resistance low-pass filter WFD. That filter is connected with the cable line LK through a receiver of remote measurement control signals OST. The other end of the line is connected to the input of the keyed feeder ZK via two diodes D1 and D2 and the keying transistor T which is controlled from the output of the remote measurement control signals transmitter NST in the form of coded or time-base signals. The capacitor C is connected in parallel with the keyed feeder input. Terminals of the measuring sensor CP supply circuit controlling the operation of the transmitter of the remote measurement signals are connected to the output of the keyed feeder.



(Source: Polish Technical Review, 4 178/1988)

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Sensor measures everything

Work is being done on Lamb-waves at the University of California, Berkeley. The sensors they are developing are sensitive to many measurands and can operate as a biosensor, chemical vapour or gas detector, scale pressure sensor, densitometer, radiometer, thermometer, or microphone. More important than this versatility is the convenience of operating in the low MHz frequency range, and the capability of operating while immersed in a liquid. The fact that the Lamb-wave device is highly sensitive to changed mass per unit area of surface is useful in biological and chemical sensors.

The microsensor being developed at Berkeley is based on a planar sheet or film with a thickness much smaller than the wavelength of the ultrasonic waves propagating in it. The thin plate also has a low heat capacity, so a rapid thermal response. Changes of oscillator frequency indicate magnitudes of the variable sensed.

Many inexpensive quasi-digital sensors could be based on the simple structure. Add electrodes or a ferromagnetic film and you can sense electric and magnetic fields as well. (Berkeley Sensor and Actuator Centre, Dept. of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA) (Source: Inside R&D, 21 September 1988)

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Long-wave infrared sensor promises more co-ex control

Increased accuracy of multilayer gauging is opening up a whole new area of control for the co-extruded barrier package, in which new ways of adjusting throughput and feeding extruders are expected to play an important role. According to instrument manufacturer Measurex International, Slough, England, the advent of true spectroscopic analysis in measuring individual layers of a moving co-extruded web will make it possible not only to increase barrier-layer integrity at lower resin cost, but also to develop better-performing barrier products at a fraction of today's expense.

Measurex's introduction, in early 1988, of what it claims to be the first on-line multilayer sensor to use Fourier transform infrared (FTIR) spectroscopy to distinguish among different resins in a multilayer web, laid a foundation for new closed-loop technology in multilayer thickness gauging and control. With the continuously reliable readings of individual layers permitted by fast spectroscopic web analysis, it will be possible to fine-tune individual extruder throughputs in response to thickness or weight variations in each layer.

Faster response. Most current process control strategies for co-extrusions are based either on gravimetric feeding or on changes in hauloff speeds. The disadvantage of the former method is its slow response to changes in individual layer weight or thickness: by the time materials flow is modified in the hopper of an extruder, hundreds of feet of off-spec product may have been run. And changing hauloff speed influences only overall thickness of the web, without controlling the gauge of the most-critical layers, including barrier.

With the more-accurate gauging methods of on-line spectroscopy, it will be possible instead to control individual extruder screw speeds (or auxiliary gear pumps) to modulate the flow of different polymers into the extrusion die. One reason this approach has now become practical is said to be the ability of new FTIR sensors to measure all co-extrusion layers simultaneously, and thus to eliminate time lags in the response of different extruders that could create greater layer imbalances.

Another key to this type of precision control of individual layer melt flows is the claimed ability of FTIR sensors to distinguish more reliably among different types of resins. Earlier multilayer sensors used the low region of the infrared light spectrum - from wavelengths of 1 to 3 micron - in which most of the standard polymers used for co-extrusion, including PE, PP, and polyvinylidene chloride (PVdC), only generate overtones or "echos" of their presence in the upper part of the spectrum.

The FTIR sensor is the first on-line gauging device to successfully use the upper part of the infrared spectrum (2.5 to 25 micron) in order to track the more clearly defined source of such echos, and to be able to tell the differences between, for example, low-density and high-density polyester.

The task of bringing spectroscopic individual layer analysis out of its long-term site in the testing laboratory into the real world of production measurement began about two years ago, with Measurex's acquisition of Advanced Systems Design Corp., Newton, MA, USA. ASD had developed an FTIR sensor that was potentially capable of measuring individual co-extrusion layers in real-time; what remained to be done was (1) to "ruggedize" it for the production floor, and (2) develop computer processing methods to handle the "denser" information the FTIR sensor is capable of generating.

Effectively isolating the vibration sensitive instrument involved mounting it on a fast-traversing scanner frame with a complex series of shock attenuators and dampers tuned to eliminate vibration frequencies that could affect instrument performance. Then the raw detection signals had to be converted into information meaningful to the user on the basis of complex calibrations for each resin likely to be involved. The result is a fully practical instrument in terms of being able to perform usefully fast cross-web scans (30 s or less per scan) with the ability to make one or more complete multilayer measurements per second.

In addition to the improved control possibilities it may bring to multilayer production lines, another prime use of FTIR technology targeted by Measurex is in development of new co-extruded products. (Measurex International, Measurex House, Datchet, Slough, Berkshire, SL3 9AJ, England) (Source: Modern Plastics International, December 1988)

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6. PUBLICATIONS

Intelligent sensors: the merging of electronics and sensing

The Merging of Electronics and Sensing, a timely state-of-the-art report covering all aspects of this new technology. You'll learn what smart sensors are ... how they work ... what they can do ... how they affect major industries ... and how you can use them. (Technical Insights, Inc., P.O. Box 1304, Fort Lee, N.J. 07024, USA)

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Sensors and instruments

New 16-page brochure describes line of industrial sensors, analyzers, and systems for process control, combustion efficiency, pollution abatement, and quality assurance. Teledyne Analytical Instruments, City of Industry, California, USA.

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Sensors

This single-page data sheet provides an overview of sensors and detectors for improving efficiency, quality and process control in a wide range of applications. Among the units discussed are the Micro-Fuel Cell sensor for trace and percent analysis of oxygen in gases. Teledyne Analytical Instruments, City of Industry, California, USA.

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Sensors and controls in the analysis of distributed systems (El Jai, A. & A.J. Pritchard)

NY: Halsted Pr, 1988, 125p
003 QA402.5 87-33919 ISBN 0-470-21023-0

Relation between various notations underlying the analysis of systems and the choice of controls and sensors. Optimization of the parameters of a control. Hyperbolic and non-linear systems. Index

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Noncontact sensors

Standard inductive proximity sensors, ultrasonic units, weld field immune sensors, and plug-in sensors with miniature connectors are new products listed in the 1988/1989 version of this catalogue. Reference guide, model number index, and cross reference simplify the reference and selection process. ISSC Division, Honeywell, Box 934, York, PA 17405, USA.

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Update for Fibre Optic Sensors Study

ERA is planning to update the highly successful first edition of "Fibre Optic Sensors: Market Opportunities and Technology Trends to 1990" (ERA Report No. 83-013u/3).

Since 1983 when the study took place research into fibre optic sensors has progressed considerably. There are now more than 200 types of optical sensor available commercially and more advanced types are under development. Furthermore, the applications and markets for these sensors are expanding rapidly.

It is anticipated that the new edition of the study will, like the first, be produced in three parts:

Technology Review: This will be in two volumes: Fibre Optic Sensor Engineering - covering all aspects of fibre optic sensor techniques, performance limitations, components and systems; and Fibre Optic Sensor Applications - providing a comprehensive literature and patent review coupled with an extensive programme of face-to-face interviews covering sensor research, development and commercial manufacture from 1983 onwards. The review will be structured according to sensor type (i.e. temperature, pressure, flow, etc.) and by market sector (i.e. aerospace, medical, etc.).

Market survey: The market survey will concentrate on two main areas: Fibre Optic Markets - current and future markets analysed by measurand and market sector; Competing Technologies - the role of fibre optic sensors examined in relation to existing competitive technologies and newcomers such as biosensors, supercondutors and advanced semiconductor (smart) sensors.

The new survey "Fibre Optic Sensors - Update on Technology and Markets" will be funded on a joint-sponsored basis. (Source: ERA News Technology Supplement, September 1988, ERA Technology Ltd., Cleeve Road, Leatherhead, Surrey KT22 7SA, UK)

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Plasma processing and synthesis of materials: symposium held from 21 to 23 April 1987, Anaheim, California, USA

Edited by Diran Apelian and Julian Szekely.
Pittsburgh: Materials Res, 1987. 435p.
(Materials Research Society Symposia Proceedings; Vol. 98) 621.044 TA2005
87-31534 ISBN 0-931837-65-0

Advances in plasma processing have implications for commercial applications in melting and refining, extractive metallurgy, near net shape manufacturing, composite materials processing, and electronic materials processing. Presents 52 papers falling into four categories: plasma fundamentals, plasma diagnostics, thermal plasmas for materials processing, and cold plasmas for processing of electronic materials.

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The American National Standards Institute (ANSI), New York, NY, has issued a revised version of the Catalog of American National Standards. The 1988 edition features a subject index intended to simplify the search for needed standards. The catalogue (176 pp) lists over 8,000 standards for acoustics, construction, electronics, image technology, information technology, measurement and automatic control, and mechanics. Sections on how to use the catalogue and how to purchase standards have been revised, making the catalogue easier to use.

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Norex USA Inc., Washington, DC, has made available the 1987/1988 AFNOR Catalogue, listing English translations of French standards. Published in January 1987, the listings in the catalogue (softcover, indexed, 358 pp) include translations of over 4,500 French standards. Each listing includes the standard's number, date of publication in the original version, and title. Coverage ranges from metallurgy and aeronautics to textiles and packaging. The catalogue includes an introduction, a list of European standards available in English, and information for ordering standards.

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Engineering materials

UK materials information sources 1989 provides over 650 sources of data and advice on engineering materials in the UK, including consultancies and commercial firms. The directory is available from The Design Council, 28 Haymarket, London SW1Y 4SU.

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Japan Directory of Materials is published by Technical Information Service, 2-20, Nishihara 5 chome, Tanashi-shi, Tokyo 188, Japan. It gives names, addresses, and telephone numbers of about 1,500 raw materials manufacturers, machinery makers, processors, and users in the Japanese plastics industry, plus information on about 100 national and public research institutes, and about 200 academic institutes and societies.

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European Directory

The 1988/1989 edition of Advanced Composite Materials: Directory of European Activities has been published by Metra Martech. Information on polymer, ceramic and metal composites has been gathered from 250 organizations in 16 countries. The directory gives details of materials and technology suppliers and composites manufacturers, as well as research, testing and consulting organizations and relevant academic institutions. In addition, there is a reference listing of the activities of 550 companies with known interests in advanced composites.

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Elsevier Applied Science Publishers Ltd., Essex, UK, has made available Mechanical Behaviour of Composites and Laminates, the proceedings of the September 1986 European colloquium 214, Kupari, Yugoslavia. Edited by W.A. Green and M.V. Micunovic, the book (293 pp, hardcover) consists of 30 papers dealing with the behaviour of composites and laminates and is arranged into five topical divisions: edge effects, impact damage, strength, and fracture criteria; dynamics theory; homogenization; nonlinear, inelastic, and thermal behaviour; and numerical methods and optimization. An index of contributors and a subject index are included at the end.

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Engineering and design expertise, composite production processes, and specialty materials are the focus of this colourful 20-page manual. Abrasive water-jet cutting, blow molding, injection molding, thermoforming, and other production methods are highlighted. Photographs and text survey possibilities for transparent plastic fabrication, stretched acrylic, composites and laminates, advanced composite fabrication, protective and optical coatings, and other products. Aerospace, automotive, and industrial uses are featured. Texstar Inc., Box 534036, Grand Prairie, TX 75053, USA.

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US consumption of advanced composites was worth $312 million in 1987 and, with the market expanding at 13 per cent a year, it should be worth $840 million within five years. During this time market volume should almost double while the consumption of carbon fibres is expected to triple. A study of this market is available from Skeist Inc., 375 Route 10, Whippany, New Jersey 07981, USA.

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Environmental Effects on Composite Materials, volume 3, edited by Dr. George S. Springer, presents 30 technical studies on performance characteristics of advanced composite materials under various temperature, moisture, and radiation conditions. The reports provide new experimental and analytical results related to mechanical, physical, thermal, and chemical properties of composite materials. Hundreds of tables and graphs are included. Tables of contents for volumes 1 and 2 are included as a reference. 498 pp. Technomic Publishing Co. Inc., 851 New Holland Ave., Box 3535, Lancaster, PA 17604, USA.

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Advances in Polymer Blends and Alloys Technology by Technomic Publishing Co., Inc., Lancaster, PA. An anthology of papers, the book (188 pp, soft-cover) gives technologies for tailoring polymer structures to produce blends and alloys and covers all aspects of blends and alloys, including thermosets and thermoplastics, elastomeric blends, analysis of blends, polyurethane blends, thermodynamic compatibility theory, and production economics. New technical developments of high-temperature, high-stress applications polymers are detailed, such as polyurethanes, silicones, polycarbonates, and sulfonates. Many of the papers discuss new structures that are important to the development of whole new families or specialty polymers offering desirable physical properties and cost advantages. Polymer producers and processors seeking new applications in specialty polymers will find this volume helpful.

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High-temperature superconductors: extended abstracts

Edited by D.U. Gubser and M. Schluter,
Pittsburgh: Materials Res, 1987. 280p

Consists of the extended abstracts from talks contributed at a symposium organized to bring together leading researchers working on the new superconducting oxide ceramics. References are included, as are illustrations and data presentations.

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High-temperature superconducting materials: the latest developments

This in-depth 190-page report describes advances in Japan and surveys the situation worldwide. Japanese materials developments and tests are covered, and also the actions of Japanese governmental agencies. To order, or for more information, contact:
Margaret Corbin, ASM International, Metals Park, OH 44073.

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Superconductivity: the threshold of a new technology (Mayo, Jonathan L.)

Blue Ridge Summit: TAB Bks, 1988. 144p.
621 3 QC612 88-1880 ISBN 0-8306-9122-7

Introducing superconductivity. Application of superconductivity. Superconductivity: today and beyond. Index.

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Introduction to fine ceramics: applications in engineering

Edited by Noboru Ichinose. Translated
from Japanese by Keizo Histake and
Charles G. Aschmann. NY: Wiley, 1987. 160p.
666'219 TP807 86-32484 ISBN 0-471-91445-2

Fundamentals of ceramics: questions and answers. Structural ceramics: questions and answers. Electronic ceramics: questions and answers. New technology of ceramics: questions and answers. Index.

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Introduction to the principles of ceramic processing (Reed, James Stalford)

NY: Wiley, 1988. 486p.
666 TP807 87-25310 ISBN 0-471-84554-X

Ceramic raw materials. Material characterization. Processing additives. Beneficiation process. Forming processes. Drying, surface processing, and firing. Index.

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Raw materials for the glass and ceramics industries. Edited by G.M. Clarke & J.B. Griffiths

Metal Bulletin plc, Worcester Park, Surrey.
1987. Pp. 210.

This is the fifth in a series of Industrial minerals' surveys of mineral-consuming industries and supersedes the Raw materials for glass survey published in 1977. It contains 20 articles on individual raw materials, two on the glass and ceramics industries respectively, and a guide to producers of the main raw materials world-wide. All the review articles have appeared previously in various issues of Industrial minerals magazine but have been specially updated for this collection.

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Ultrastructure processing of ceramics, glasses, and composites. Edited by L.L. Hench & D.R. Ulrich

John Wiley & Sons, Chichester. 1984. Pp. 564.

The present book contains the proceedings of a conference held in February 1983 at Gainesville, Florida. It comprises 42 papers and is divided into six sections covering such topics as sol-gel processing, organometallic precursors, micromorphology-based processing, phase transformation-based processing, and characterization.

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Advanced ceramics. Solving problems and cutting costs. By V. Mitchell

Financial Times Business Information Ltd.,
London. 1987. Pp. 111.

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Current Topics in Photovoltaics, Volume 2

T.J. Coutts and J.D. Meakin, eds.: published
by Academic Press, New York, 1987; 208 pp.

This book is essential reading for all those involved in research and development of solar cells. The authors and the editors are to be congratulated on producing such authoritative reviews on topics of great current interest, and the third volume promises to maintain the same high standard.

7. PAST EVENTS AND FUTURE MEETINGS

"Sensor 88"

"Sensor 88", a comprehensive biennial West German event in the area of sensorics, took place in Nuremberg, 3-5 May 1988. As on the preceding three occasions, the activities were initiated by the German Society for Transducer Technology (AMA), and co-sponsored by six other international organizations.

Following is a summary of a few talks:

Some new methods and materials

The keynote address in this area was given by K.-W. Bonfig (University of Siegen, FRG) who described vividly the merits of direct digital measurement (DDM) techniques. DDM allows the precise determination of an entity by a measuring device, with high noise suppression and a minimal number of device or system components. This is made possible by the use of microprocessor technology. Tolerance of the metering circuit, influence of offsets, drifts, etc. are largely eliminated. Focusing on his colleagues' recent experiments, Bonfig explained that a microprocessor is used to generate an auxiliary signal with digital, pseudo-random time-behaviour. This auxiliary signal is combined with the output of the measuring device, whose analogue signal is read by the microprocessor, using an analogue-to-digital converter. The components of the final signal that originate from the known auxiliary signal are then filtered out by correlation analysis, and thus the true measureand can be determined, free of many disturbances.

The next two talks described the use of novel materials.

D. Halvorsen (Pennwalt Corporation, Edinburgh, UK) talked about the use of new piezoelectric and pyroelectric plastic films made from poly-vinylidene fluoride (PVDF). This material lends itself to a large number of control and monitoring applications. PVDF is distinguished by ease of fabrication, and devices based on it are lightweight and shatter-resistant. One of the most exciting uses of PVDF sensors is in the area of hydrophones. Pressure sensors for shockwave studies, infrared sensors, vibration sensors, switching devices, robotic tactile sensors, and medical monitors are other promising areas of application.

M. Piso and colleagues (Research and Development Institute for Electrical Engineering, Bucharest, Romania) talked about the application of magnetofluidic materials. Actually two areas, only vaguely related, were covered in the talk. A microcomputer-controlled magnetofluidic passive three-axis accelerometer was one topic; general considerations on the use of magnetofluidic systems as an active medium for sensors (including an accelerometer) was discussed in the second half of the exposition.

Chemical sensors

W. Neu, representing a group of researchers from the University of Tübingen (FRG) opened the session with a review of recent work concerning studies of prototype inorganic and organic solidstate chemical sensor materials used for gas detection. Their research employed a "multimethod interface analysis" technique, which combined phenomenological and spectroscopic approaches, and used both ultrahigh-vacuum and high-pressure environments. As a result of these studies, the researchers produced and optimized an SnO_2 sensor for NO_2 detection. Other in-depth studies aimed at the understanding of the gas-sensing mechanism involving phtalocyanin (used for O_2 and NO_2 detection). In a related experiment, phtalocyanin was used to coat ionic conductors (like AgJ); in this manner, new sensors of remarkable properties were produced.

Another talk on chemical sensors was given by G. Gauglitz, also from the University of Tübingen. Unlike the usual talks on chemical sensing, this work presented a dynamical study of photochemical processes in thin layers of photoresists. The crucial element in the research was the development of a suitable reflectance-spectroscopy measurement system. Apart from shedding light on the photochemistry in thin layers, this method can be used to improve present (entirely empirical) industrial procedures for microstructuring circuit boards and semiconductor wafers.

Pressure measurement

Shi Jinshan (Yan Shan University, People's Republic of China) reported on the development of a new, very high sensitivity pressure transducer with optical fibre data link. "The ingenious design" of the transducer (as the speaker referred to it) uses a flat diaphragm of sensing differential capacitors, whose capacitance changes the width of the pulsed signal. Pulse position modulation is employed, so as to avoid instability effects.

A new family of silicon pressure sensors was described by H. Kuisma (Vaisala OY Company, Helsinki, Finland). Actually, the Vaisala researchers developed two basic structures:
(1) a vacuum-isolated absolute pressure sensor consisting of a silicon diaphragm and a glass-covered silicon support-plate, and
(2) a more complicated structure, consisting of a diaphragm, a cover plate on one side, and a base plate with a stationary electrode on the other side of the diaphragm. Both types can be scaled well from very low to medium pressures. The second type can be configured so as to act as an absolute, a gauge, or a differential pressure sensor.

Optical sensors and measurement techniques

The keynote address, a tutorial introduction reviewing technologies for the fabrication of integrated-optics devices on a glass substrate, was presented by A. Brandenburg (Fraunhofer Institute for Measurement Technology, Freiburg, FRG). He gave a very clear description of both the thermal and the ion-exchange methods for waveguide formation, and concluded with some applications of such devices as sensors or as sensor-components.

A group of researchers from the University of Paderborn (FRG), represented by W. Sohler, described an interesting computer-controlled system for optical gas analysis. The system uses optical fibres for remote sensing. An integrated optical parametric oscillator (IOPO) serves as a source for near-infrared radiation (between 1.0 μm and 1.6 μm). Differential absorption spectroscopy accomplishes the determination of various gas components (mainly methane and HCl were used in the experiments). The IOPO is continuously tunable; it has a spectral linewidth less than 0.7 cm^{-1}, and an output of several mW. The detection limit and the selectivity of optical gas analysis will be much improved by use of this system since the luminous power density of this advanced integrated optical device exceeds that of a light-emitting diode by several orders of magnitude.

A very careful discussion of signal processing for optical fibre Fabry-Perot (FFP) sensors was presented by H. Wölfelschneider from the Freiburg Fraunhofer Institute. He paid particular attention to the transmission-line-insensitivity problem of the evaluation methods. He concluded by indicating that his studies may serve an important role in the future development of multiplexed signal processing systems, suitable for simultaneous handling of several FFP-based sensors, even if these ascertain different measurands.

H. Höfler (also from the Freiburg Institute) described a diode-laser-based interferometer, suitable for supersensitive measurement of displacements. The major problem in the use of a diode laser in the interferometer was its stabilization. The usual thermal- and current-stabilizing methods were found inadequate, and the difficulty was overcome by the use of a simultaneous index-of-refraction compensation technique. (Extracted from European Science Notes Information Bulletin, 88-08.)

Meetings on Materials

1989

APRIL

Amsterdam	12th World Conference for Nondestructive Testing (WCNDT) (International Committee for Nondestructive Testing, c/o Organisatie Bureau Amsterdam bv, Europaplein 12, 1078 GZ Amsterdam, Netherlands)
1-6 Houston, TX	World Congress on Superconductivity (P.O. Box 27805, Houston, Texas, USA)
3-7	6th International Conference on High Temperature: Chemistry of Inorganic Materials (89 National Institute of Standards and Technology, Bldg. 223, Gaithersburg, MD 20899, USA)
4-6 Torquay, UK	Manufacture of Advanced Thermoplastic Composites (Plymouth Polytechnic, Department of Mechanical Engineering, UK)
4-7 Swansea, Wales	Annual Convention of the Institute of Ceramics (Ceramic Technical Group, MDD B552, Harwell Laboratory, UKAEA, Oxon OX11 ORA, UK)
7-9 Austin, TX	Second International Symposium on Polymer Analysis and Characterization (Du Pont Co., Experimental Station, PO Box 80228, Wilmington, Du Pont, Del. 19880-0228, USA)
9-13 Denver, CO	Wear of Materials-89 (IBM Corporation, Box 6, Endicott, NY 01360, USA)
9-14 Dallas, TX	General Meeting, American Chemical Society (American Chemical Society, 1155 16th Street NW, Washington, DC, 20036, USA)
10-12	International Workshop on Ion Beam Modification and Processing in High-Tc Superconductors: Physics and Devices (Harwell Laboratory, Oxfordshire OX11 ORA, UK)
10-13 Oxford, UK	Sixth Oxford Conference on Microscopy of Semiconducting Materials (The Royal Microscopical Society, 37/38 St. Clements, Oxford OX4 1AJ, UK)
10-13 Davos, Switzerland	Recycle 89 (Maack Business Service, CH-8804 Au/near Zurich, Switzerland)
16-20 San Diego, Calif.	Structural Plastics '89 (Society of Plastics Industry, 1275 K Street, N.W., Washington, DC 2005, USA)
17 April London	Automotive Materials Conference (Shearson Lehman Hutton and American Metal Market, 7 East 12th Street, New York, NY 10003)
17-19 University of Surrey	Metals and Materials '89 (The Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB)
17-21 New Orleans, La.	Annual International Conference on Corrosion (NACE, PO Box 218340, Houston, Texas 77218, USA)
17-21 San Antonio, Texas	Inter-American Conference on Materials Technology(Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78284, USA)
19-21 Paris	European Composite Congress (Centre de Promotion des Composites, 65 rue de Prony, 75017 Paris)
24-26 Basle, Switzerland	Advanced Composites in Aircraft Structures: Quality Control Systems and Repair Considerations (Technomic Publishing AG, Elisabethstr. 15, CH-4051 Basle, Switzerland)
24-29 San Diego, Calif.	Materials Research Soc. Spring Meeting (Materials Research Society, 9800 McKnight Road, Pittsburg, PA. 15237, USA)

MAY

22-26 Les Emblez, France	Second International Symposium on High Temperature Corrosion of Advanced Materials and Coatings (Colloque Corrosion à Haute Temp., Univ. de Provence, Caisse 26, 13331 Marseille, Cedex 3, France)
24-26 Lakewood, Colorado	9th Solar Energy Research Institute Photovoltaic Advanced Research and Development Project Review Meeting (Solar Energy Research Institute, 1617 Cole Blvd., Golden, Colorado, USA)
24-26 Strasbourg, France	COMPU-PLAST 89 International exhibition and seminar on plastics engineering and technology (IDEXPO, 21 ave. de l Division Leclerc, 94230 Cachan, France)
10-11 Montpellier	First European Technical Symposium and Polyimides (Lab. Polymer Science and Advanced Materials, USTL, Place Bataillon, 34060 Montpellier, Cedex 1, France)
31 May - 2 June Milan, Italy	Evolution of Advanced Materials (AIM, 2 Piazzale R. Morandi, I-20121 Milan, Italy)

JUNE

Budapest, Hungary	SILICONF '89 (Scientific Association of the Silicate Industry, Anker köz 1-3, H-1061 Budapest, Hungary)
8-12 Guangzhou	Ceramics China '89 (Guangdong International Trade and Exhibition Corporation, Guoji Road, Sanyuanli, Guangzhou, People's Republic of China)
11-14 San Diego, Calif.	Powder Metallurgy Conference and Exhibition (Metal Powder Industries Federation and the American Powder Metallurgy Industry)
12-14 Pittsburg, PA, USA	International Symposium on Alloy 718 Metallurgy and Applications (The Metallurgical Society, 420 Commonwealth Dr., Warrendale, PA 15086, USA)

12-16 Augustine, Florida	Advanced Materials Chemistry Conference (Dept. of Chemistry. University of Florida, Gainesville, FL 32611, USA)
19-23 Denver, CO	SOLAR '89 - The National Solar Energy Conference (American Solar Energy Society, 2400 Central Ave., B 1 Boulder, Colorado 80301, USA)
19-23 Maastricht	First European Ceramic Society Conference (MECC, P.O. Box 1630, 6201 BP Maastricht, Netherlands)
25-29 Jerusalem, Israel	International Conference on Composite Materials for High Temperatures: Fundamental Principles and Performance (Ministry of Science and Development, P.O. Box 18195, 91181 Jerusalem, Israel)
26-29 Johannesburg	21st Annual Symposium: Improved Ceramic Materials (South African Ceramic Society, P.O.B 13702, Northmead, 1511 Benoni, RSA)
26-28 Petten, NL	European Colloquium: High Temperature Corrosion of Technical Ceramics (HIC/1-89, J.R.C, P.O.B 2, 1755 ZG Petten, Netherlands)

JULY

2-7 Leningrad, USSR	XV International Congress on Glass (I.V. Grebenschikov Institute of Silicate Chemistry, Academy of Sciences of the USSR, ul Odoevskogo, 24 kor 2 Leningrad, 199057, USSR)
3-5 Oxford, UK	7th BNF International Conference: The Materials Revolution through the 90's - Powders, Metal Matrix Composites, Magnetics (BNF Metals Technology Centre, Wantage Business Park, Oxfordshire OX12 9BJ, UK)
5-9 Bangkok, Thailand	POLYTECH '89 (Preecat Sananvatananont Trade Exhibition and Conference Company, 254/15 16 Pradipat Road, Phayathai, Bangkok 10400, Thailand)
10 July Birmingham, UK	Bonding and Repair of Composites (Rapra Technology Ltd., Shawbury, Shrewsbury, Shropshire SY4 4NR, UK)

AUGUST

23-26 Bad Windsheim, FRG	High Temperature Superconductors Physics and Materials Science (Applied Research Laboratory, Pennsylvania State University, Box 30, State College, PA 16804, USA)
20-24 Halifax, Nova Scotia Canada	28th CIM Annual Conference of Metallurgists (Centre de Recherchas Minerales, 2700 rue Einstein, Sainte Foy (Quebec) G1P 3W8, Canada)
28 August - 1 September Neuchatel, Switzerland	Third International Conference on Surface Modification Technologies (Metallurgical Society of AIME and Centre Suisse d'Electronique et de Microtechnique S.A., Neuchatel, Switzerland) (Dr. T.S. Sudarshan, Materials Modifications, Inc., P.O. Box 4831, Falls Church, Va. 22044, USA)

SEPTEMBER

2-6 Taipei, Taiwan	TAIPEI PLAST '89 (CETRA Exhibition Department, P.O. Box 109-865, Taipei, Taiwan)
5-7 Sheffield, UK	Interfacial Phenomena in Composite Materials (Butterworth Scientific Ltd., P.O. Box 63, Westbury House, Bury Street, Guildford, Surrey GU2 5BH, UK)
6-8 Kingston-upon Thames, UK	Meeting on environmental aspects of polymer degradation and stabilization: recycling, conservation and industrial applications (Department of Chemistry, Manchester Polytechnic, Chester Street, Manchester M1 5GD, UK)
6-10 Bangkok, Thailand	Thai Plas '89 (SHK International Services Ltd., 22/F, National Mutual Centre, 151 Gloucester Road, Hong Kong)
11-29	Workshop on Materials Science and Physics of Non Conventional Energy Sources,
and	
25-29 Trieste, Italy	Workshop on Interaction between Physics and Architecture in Environmental Conscious Design (Prof. G. Furlan, ICTP, P.O.B. 586, I-34100 Trieste, Italy)
18-20 Islamabad, Pakistan	International Symposium on Advanced Materials (Pakistan Institute of Metallurgical Engineers and Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB)
20-21 London, UK	Plastics recycling - future challenges (Plastics and Rubber Institute, 11 Hobart Place, London SW1W 0HL, UK)
25-27 Lisbon, Portugal	Second International Seminar on Surface Engineering with High Energy Beams. (International Federation for Heat Treatment and Surface Engineering (IFHT) - Centre of Mechanics and Materials of the Technical University of Lisobn, Ed. I.S.T., 1096 Lisbon Codex, Portugal)
25-29 Freiburg, FRG	9th European Photovoltaic Solar Energy Conference and Exhibition (WIP, Sylvensteinstrasse 2, D-8000 Munich 70, FRG)
25-29 Limoges, France	International Forum of Ceramics (Comité Regional d'Expansion Economique du Limousin, 27 Blvd. de la Corderi, 87000 Limoges, France)

OCTOBER

2-4 Bournemouth, UK	Third European Electric Steel Congress (Institute of Metals, 1 Carlton House Terrace, London SW1Y 5DB, UK)
2-5 Indianapolis, IN	Symposium on Textures in Non-metallic Materials (ASM International Materials Week, Materials Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, USA)
2-4 Cleveland, Ohio	High Temperature Polymers and their Uses (Ferro Corporation Technical Centre, 7500 E. Pleasant Valley Road, Independence, OH 44131, USA)
4-5, Turin, Italy	Plastics in Automobiles and Industrial Vehicles (SNC, Via F. Romani 25, 10131 Turin, Italy)
24-25 Chicago, USA	Degrada Pak '89 - Conference on Degradable Packaging Materials (Degrada Pak, P.O. Box 345, Milltown, N.J. 08850, USA)
26, London, UK	Structural and Mechanical Aspects of High Temperature Oxidation - Oxidation and Advanced Materials - (The Institute of Metals, Conference Department, 1 Carlton House Terrace, London SW1Y 5DB)

NOVEMBER

17-20 Beijing, People's Republic of China	IPCONEX Food and Pharmaceutials Packaging Exhibition (SHK International Services Ltd., 22/F, National Mutual Centre, 151 Gloucester Road, Hong Kong)
22-24 Aachen, FRG	European Conference on Advanced Materials and Processes (The Federation of European Materials Societies [comprising of the Deutsche Gesellschaft fuer Metallkunde, the Institute of Metals, the Société Française de Metallurgie and the Schweizerische Verband fuer die Materialtechnik] - DGM-Informationsgesellschaft mbH, Adenauerallee 21, D-6370 Oberursel, FRG)
20-23 Kobe, Japan	International Conference on Evaluation of Materials Performance in Severe Environments (The Iron and Steel Institute of Japan, Keidanren Kaikan, 1-9-4, Otemachi, Chiyoda-ku, Tokyo 100, Japan)
28-30 Canberra, Australia	Fifth National Space Engineering Symposium (Institution of Engineers Australia, 11 National Circuit, Barton, ACT 2600, Australia)
28 November-1 December Chiba, Japan	New Materials and Processes for the Future. First Japan International SAMPE Symposium and Exhibition (Japan Chapter of SAMPE, Meguroeki Higashiguchi Bldg., 3-1-5 Kamiosaki, Shinagawa-ku, Tokyo 141, Japan)

DECEMBER

4-7, Zürich, Switzerland	Polythylene and Polypropylene Copolymers and Compounds in Food and Technical Packaging (Maack Business Services, Seestr. 308, 8804 Au/near Zürich)

1990

JANUARY

15-18 Bombay, India	ICACM-90. International Conference on Advances in Composite Materials (ASM International India Chapter, Bombay, India) (ICACM-90, Prof. P. Ramakrishnan, Dept. of Metallurgical Engineering, Indian Institute of Technology, Powai, Bombay - 400 076, India)

UNIDO Meetings

In close co-operation with the Chinese hosts (Chinese Silicate Society, Bai Wan Zhuang, Beijing, People's Republic of China), UNIDO is preparing the Second World Congress on Non-Metallic Minerals to be held in Beijing from 17-21 October 1989. Organizers are UNIDO, Chinese Silicate Society, Yugoslav Union of Engineers and Technicians, Miners, Geologists and Metallurgists, and Industrial Minerals, Part of Metal Bulletin Journals Ltd. of London, UK and New York, USA.

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Issue No. 1 - STEEL

Issue No. 2 - NEW CERAMICS

Issue No. 3 - FIBRE OPTICS

Issue No. 4 - POWDER METALLURGY

Issue No. 5 - COMPOSITES

Issue No. 6 - PLASTICS

Issue No. 7 - ALUMINIUM ALLOYS

Issue No. 8 - MATERIALS TESTING AND QUALITY CONTROL

Issue No. 9 - SOLAR CELLS MATERIALS

Issue No. 10 - SPACE-RELATED MATERIALS

Issue No. 11 - HIGH TEMPERATURE SUPERCONDUCTIVE MATERIALS

Issue No. 12 - MATERIALS FOR CUTTING TOOLS

Issue No. 13 - MATERIALS FOR PACKAGING, STORAGE AND TRANSPORTATION

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Readers' comments

We should appreciate it if readers could take the time to tell us in this space what they think of the 14th issue of Advances in Materials Technology: Monitor. Comments on the usefulness of the information and the way it has been organized will help us in preparing future issues of the Monitor. We thank you for your co-operation and look forward to hearing from you.