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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 [1]. 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 propellor 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 [2]. 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 [3].

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). In [4], a comparison is made between silicon piezoresistive and capacitive pressure sensors, with respect to sensitivity, maximum range, time stability and temperature coefficient.

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) [5]. 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 [4]. 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 [5]. 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) [1].

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 diffence 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 [1]. 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 $\sqrt{\text{Hz}}$/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 $\sqrt{\text{Hz}}$ /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 [5].

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 [6][7]. 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 [8]. 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 [9]. 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 [10]. 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) [11] [12]. 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 [13]. 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 [14]. 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 [15]. 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 (0.6[illegible] 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. Galium 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 [15].

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 [15][16].

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 0.44*d* 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 [17]. 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, as listed in [17], 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 ($3.2 \times 10^{-6}/^{\circ}C$). 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 [17]. 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) [18]. 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 [19]. 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 [20]. 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 [21] or a frequency output [22]. 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 [23]. 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 possible. The operation involves the measurement of the indentation pattern of an isolating rubber layer caused by the pressure distribution acting on the sensor surface (24). 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 (25). 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.

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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 [9].

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 [14].

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

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.

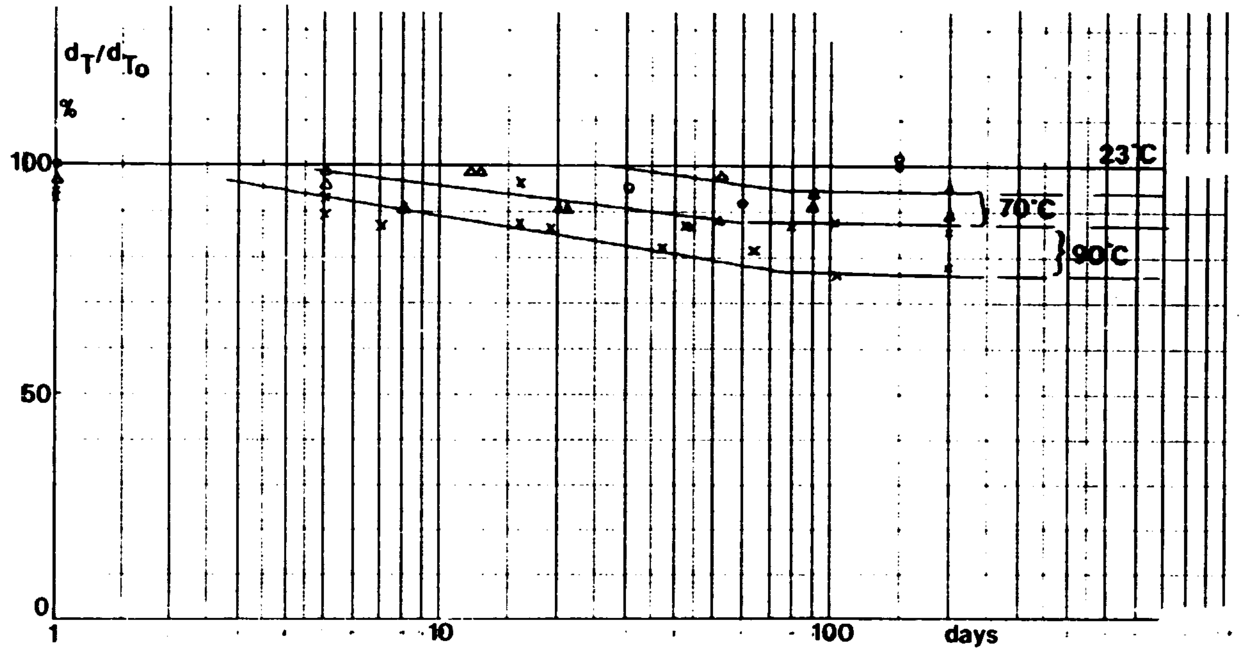
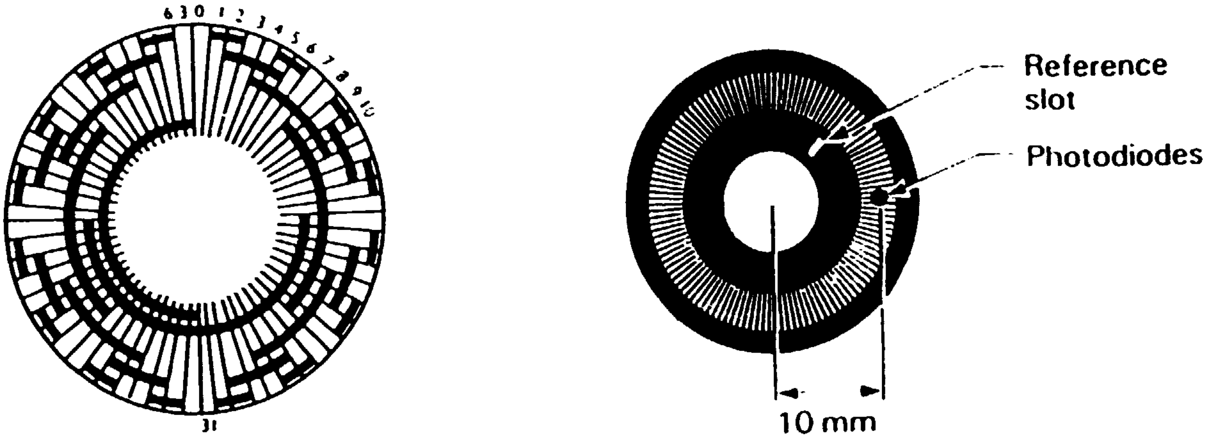
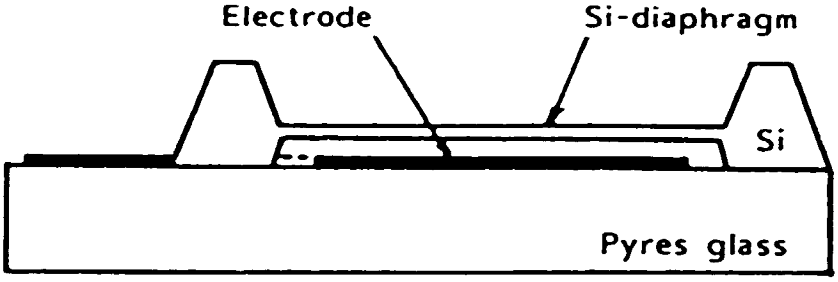
d_T/d_{T_0}
%
100
50
0
1
10
100
days
23°C
70°C
90°C

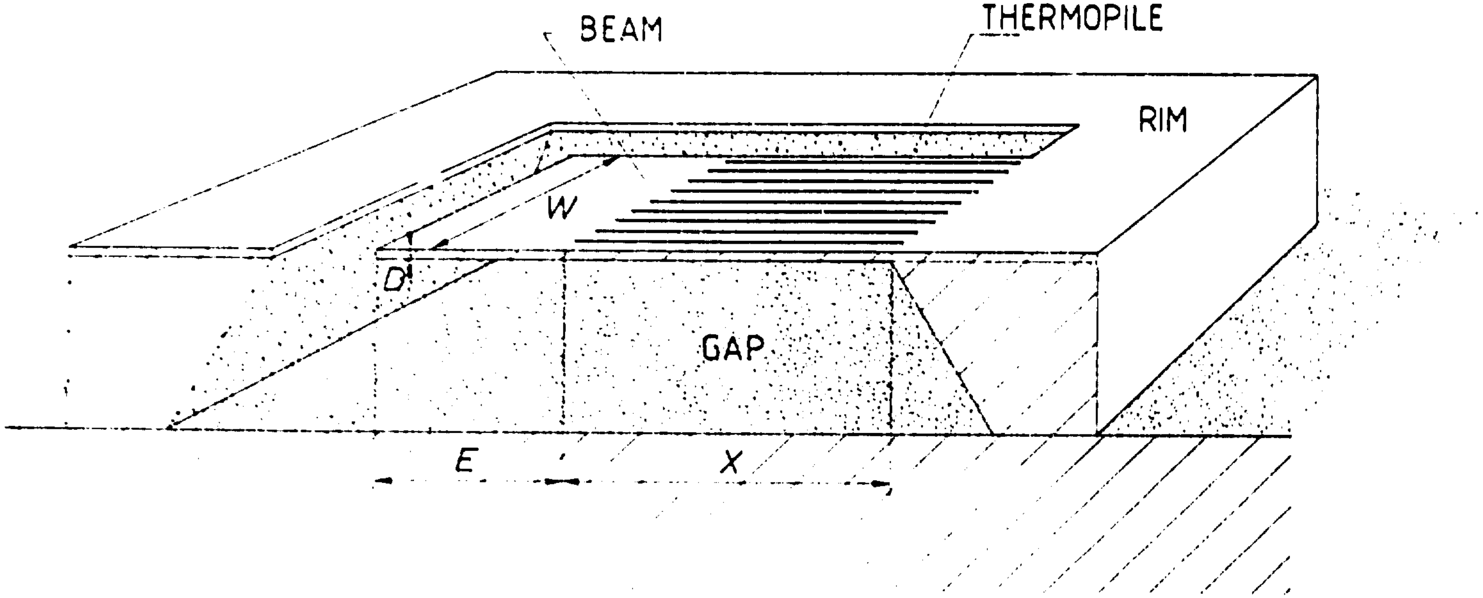
Figure 2.



(A)

(B)


Electrode
Si-diaphragm
Si
Pyres glass



4

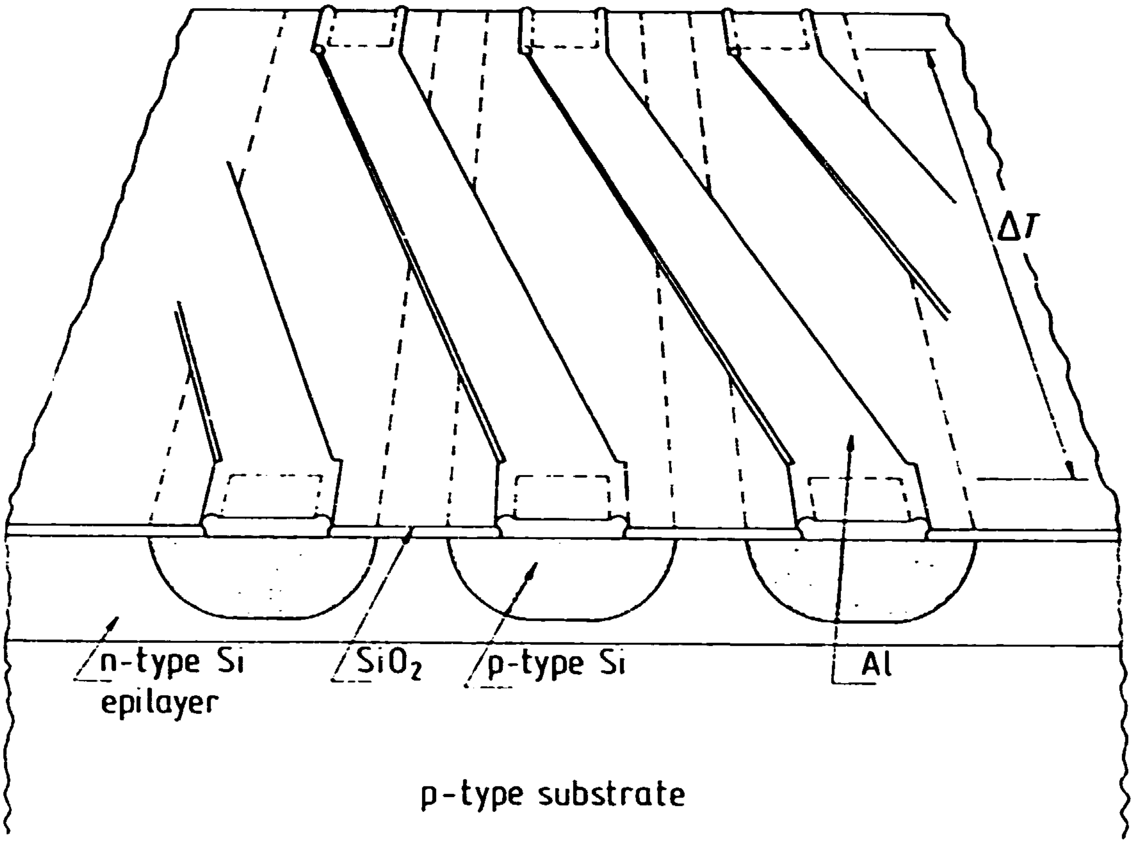
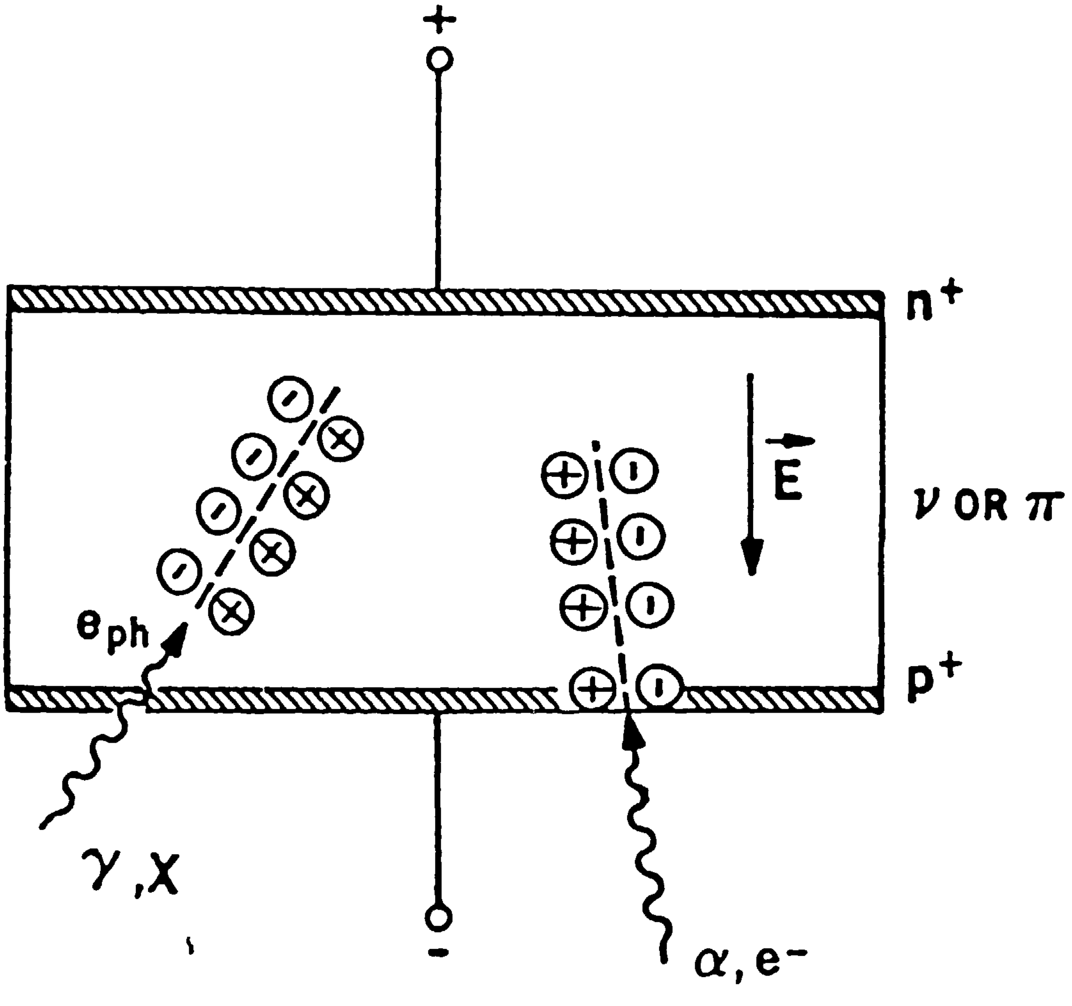
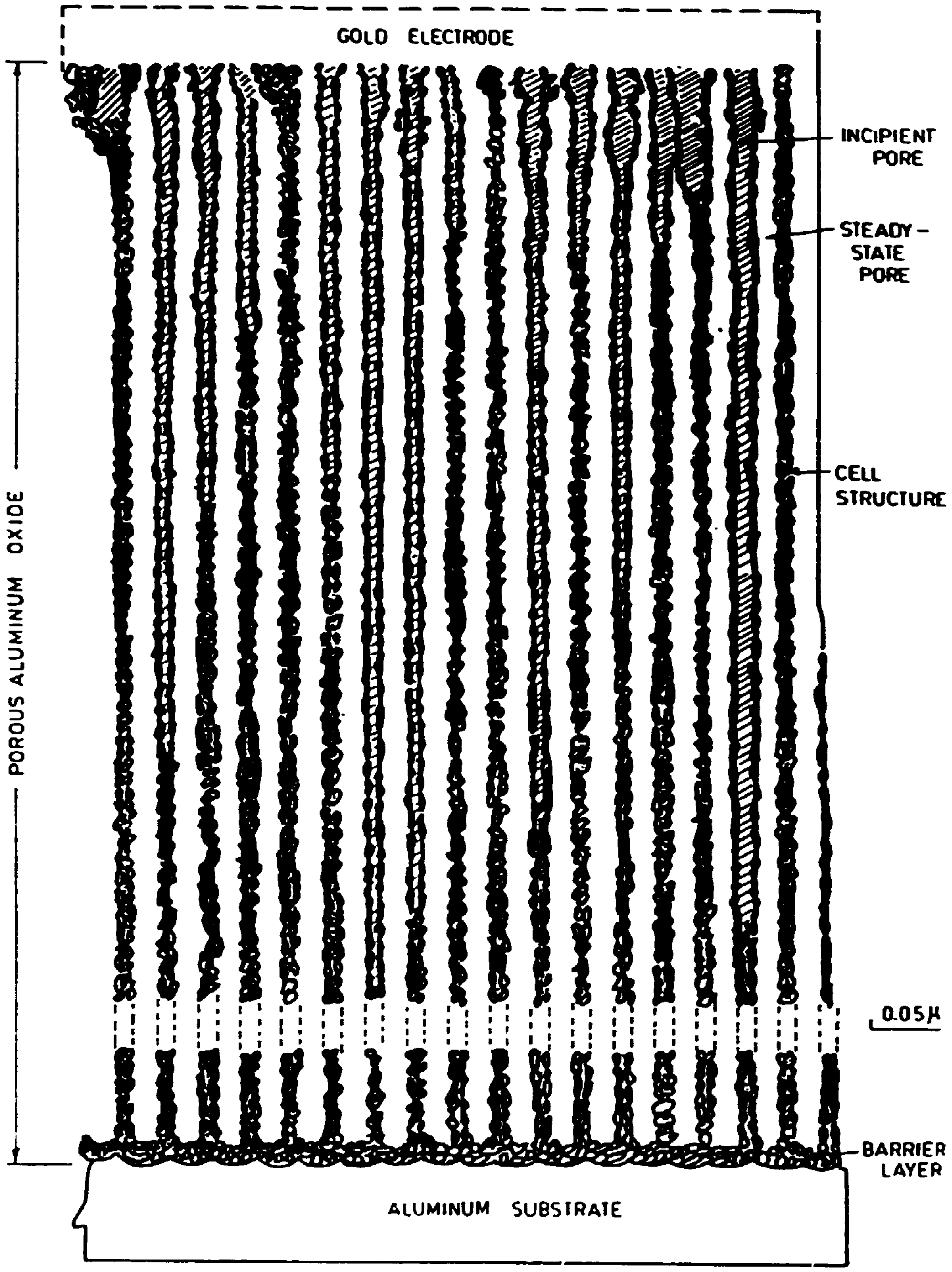
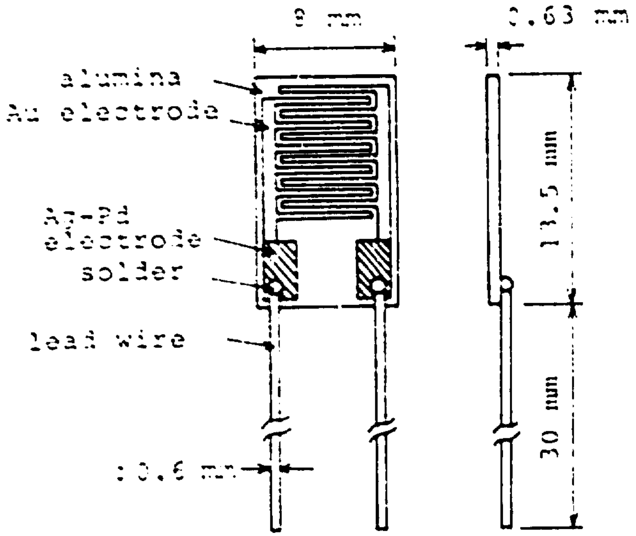
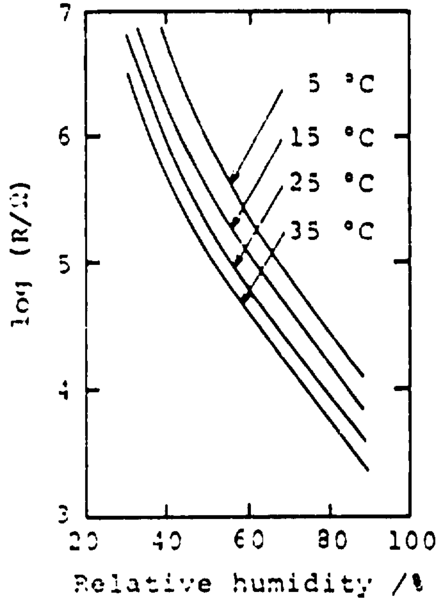

ΔT
n-type Si
epilayer
SiO_2
p-type Si
Al
p-type substrate

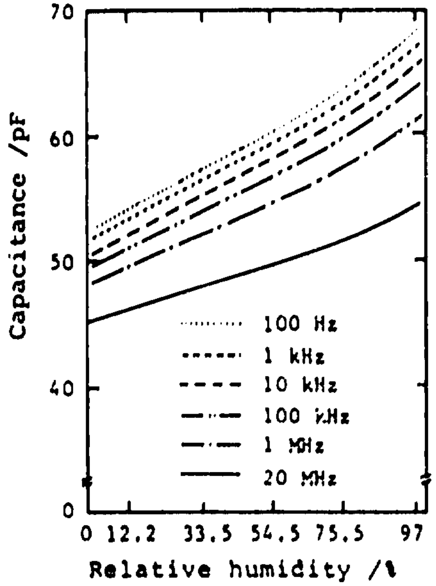
figure 6

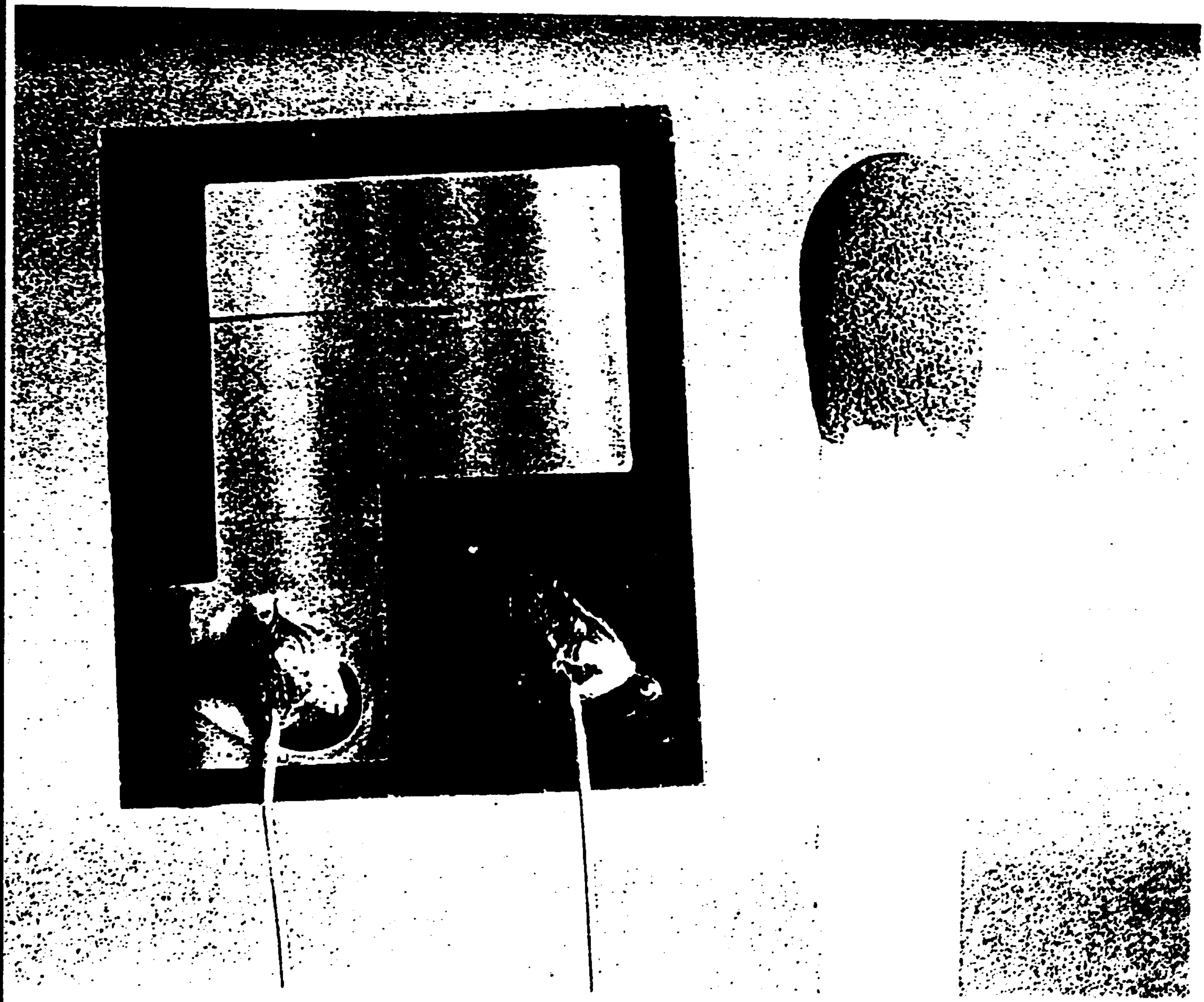


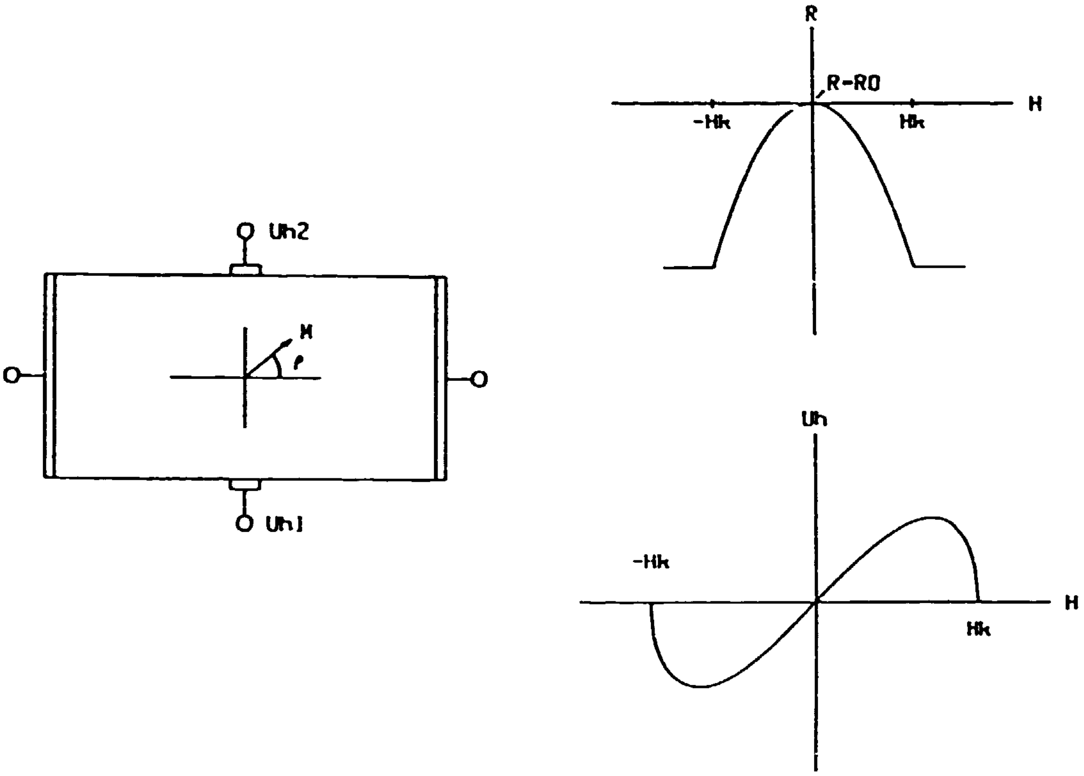

GOLD ELECTRODE
POROUS ALUMINUM OXIDE
INCIPIENT PORE
STEADY-STATE PORE
CELL STRUCTURE
0.05μ
BARRIER LAYER
ALUMINUM SUBSTRATE


9 mm
0.63 mm
alumina
Au electrode
Ag-Pd electrode
solder
lead wire
13.5 mm
30 mm
ϕ0.6 mm


log (R/Ω)
7
6
5
4
3
5 °C
15 °C
25 °C
35 °C
20
40
60
80
100
Relative humidity /%


Capacitance /pF
70
60
50
40
0
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
20 MHz
0
12.2
33.5
54.5
75.5
97
Relative humidity /%





(A)

(B)

Figure 10.

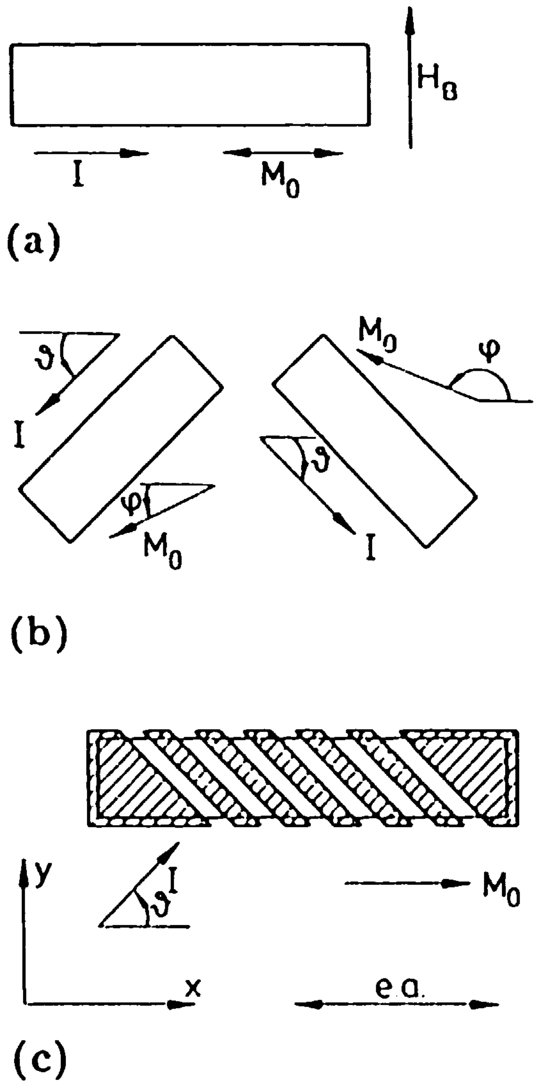
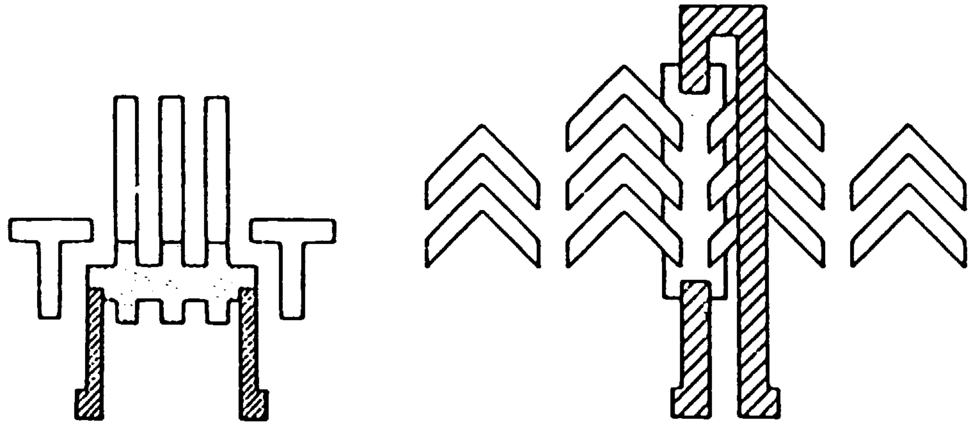
H_B
I
M_0
(a)
ϑ
I
φ
M_0
M_0
φ
ϑ
I
(b)
y
I
ϑ
M_0
x
e.a.
(c)

Figure 11.



(a)

(b)

Figure 12.

figure 13

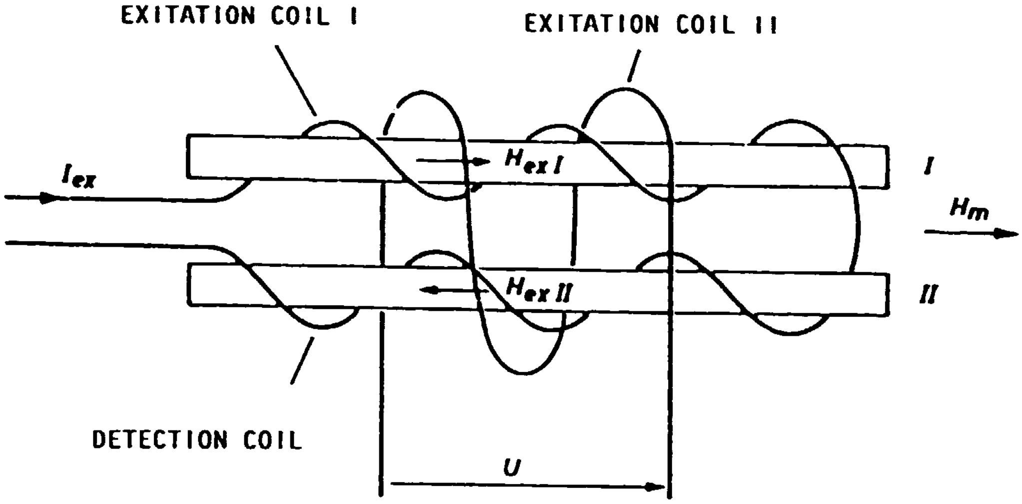
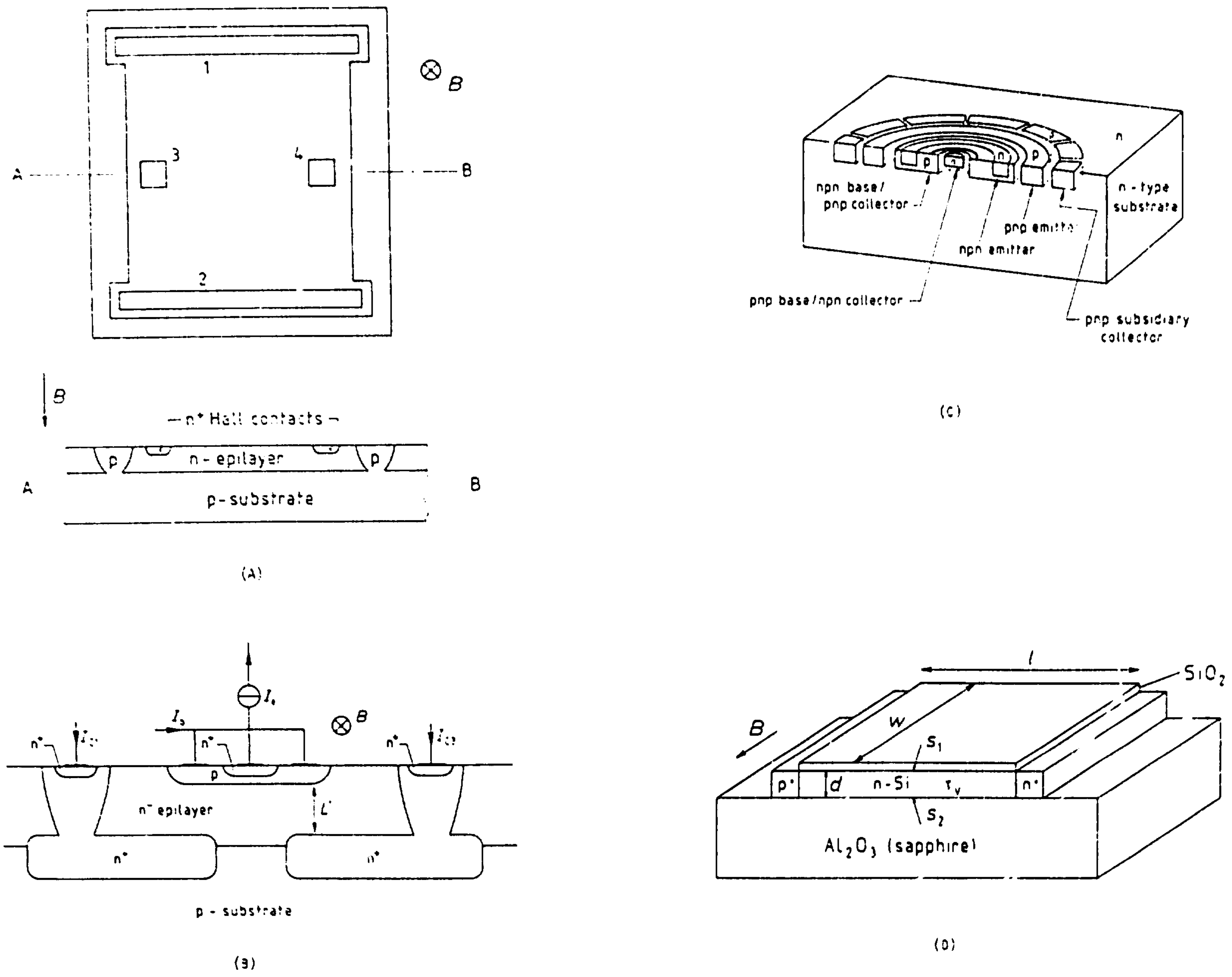
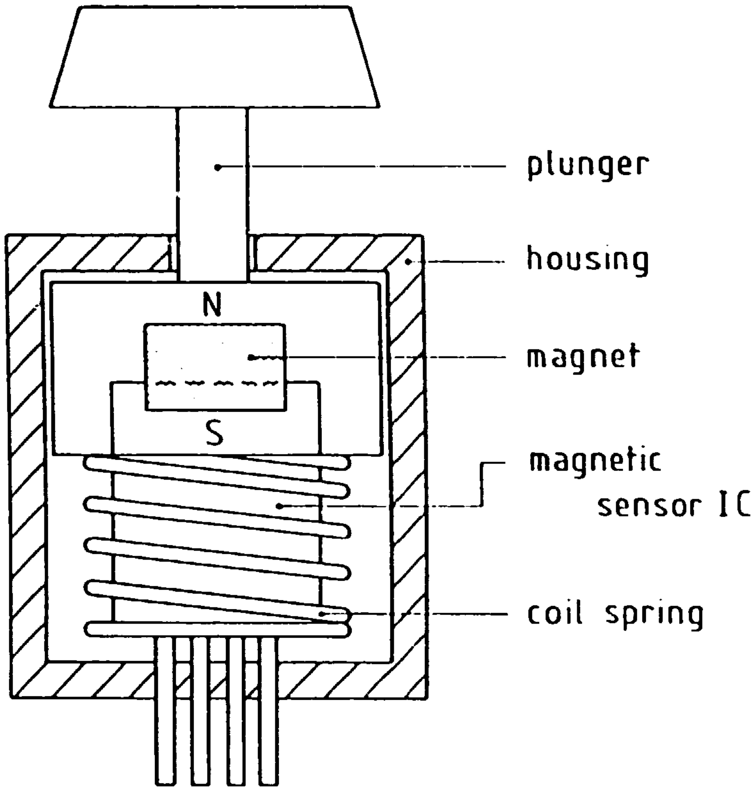


Figure 13.

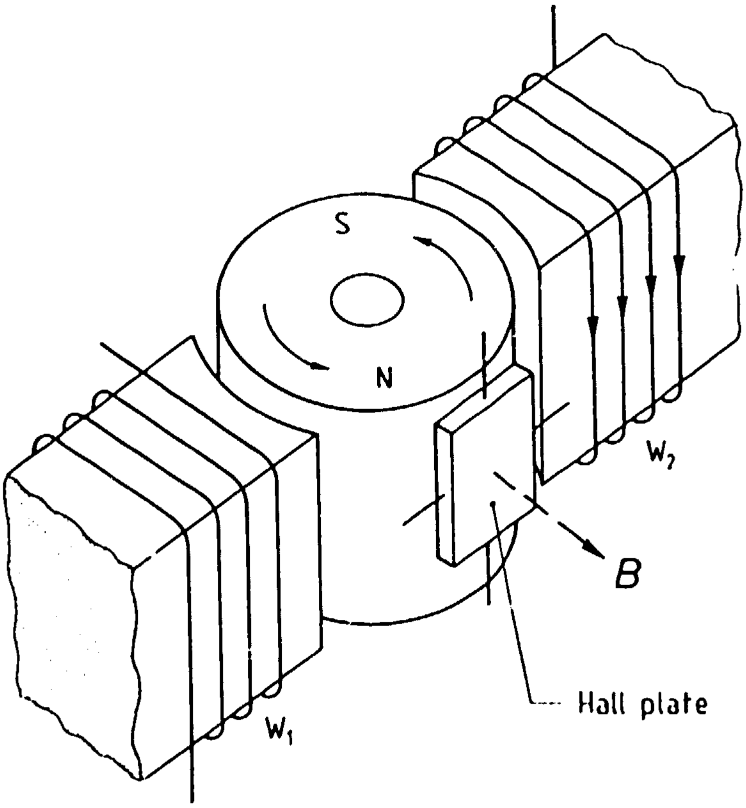


(A) (B) (C) (D)

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.

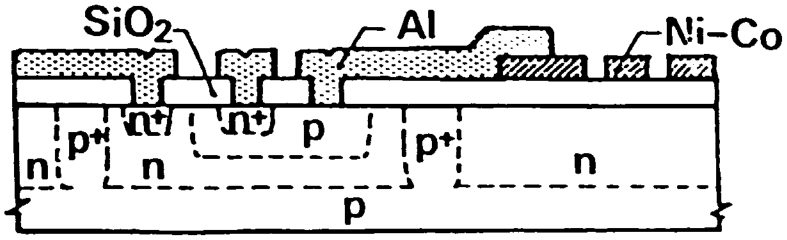
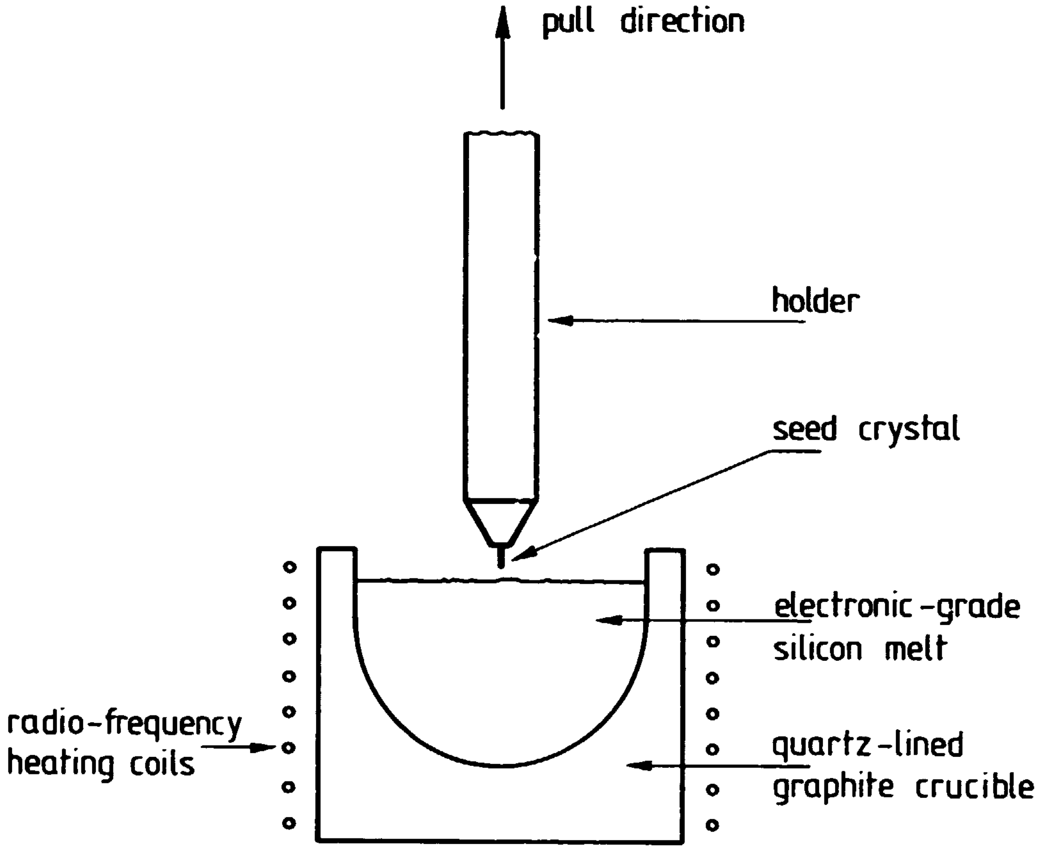
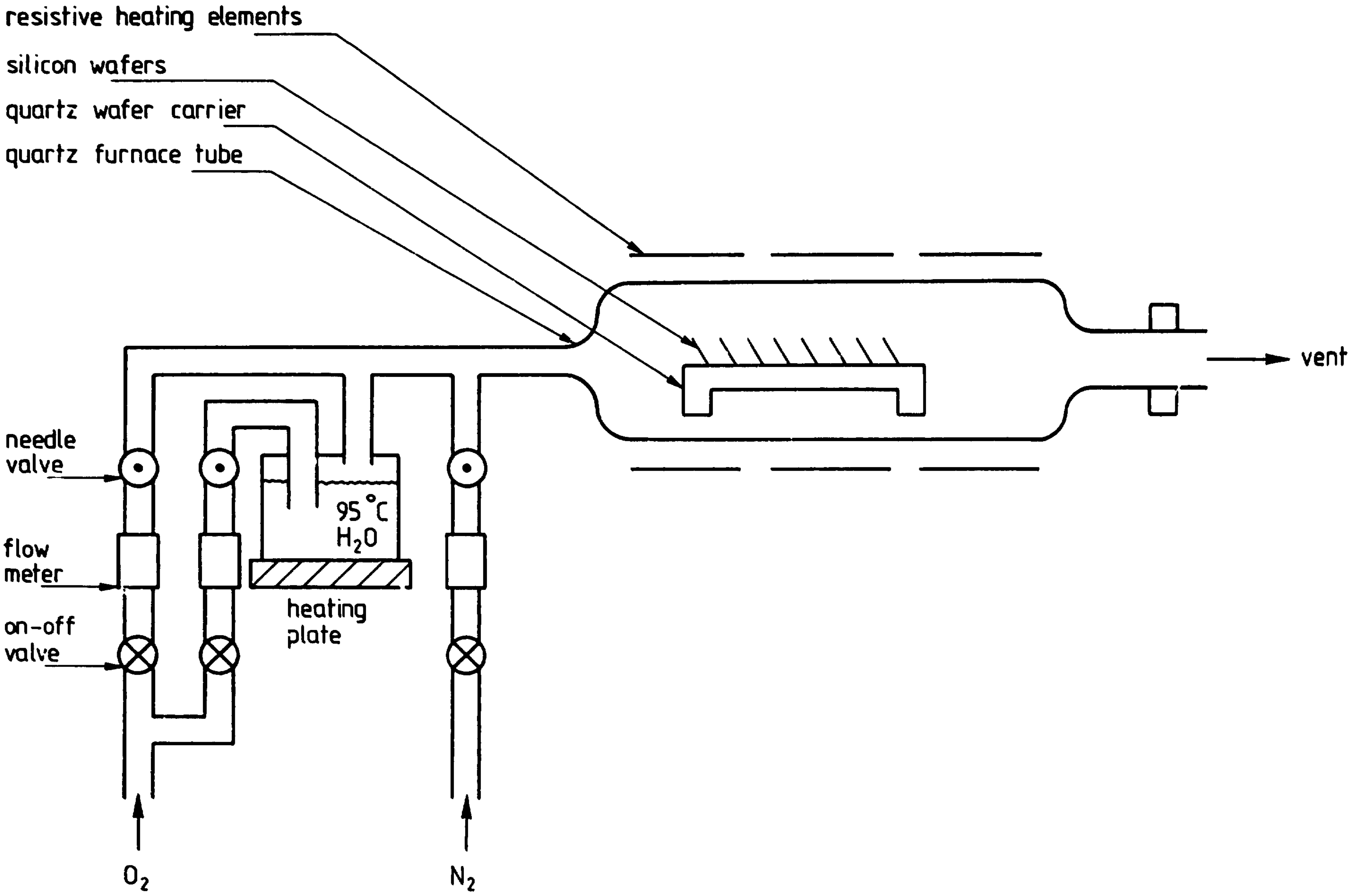
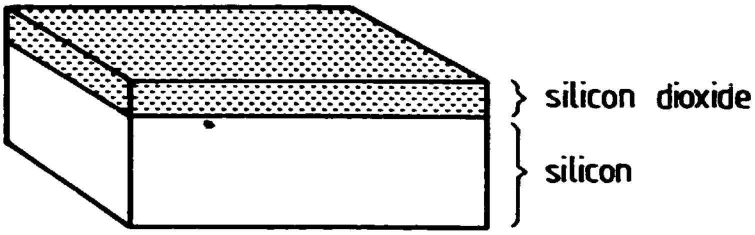


Figure 16.

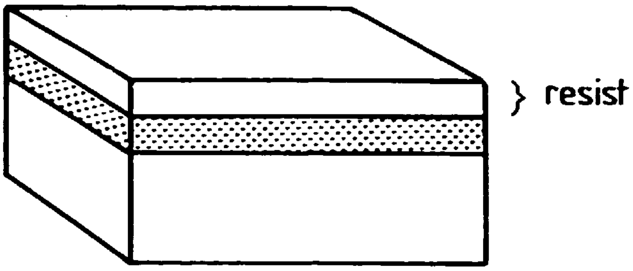

pull direction
holder
seed crystal
electronic-grade silicon melt
radio-frequency heating coils
quartz-lined graphite crucible


resistive heating elements
silicon wafers
quartz wafer carrier
quartz furnace tube
vent
needle valve
flow meter
on-off valve
95 °C
H2O
heating plate
O2
N2

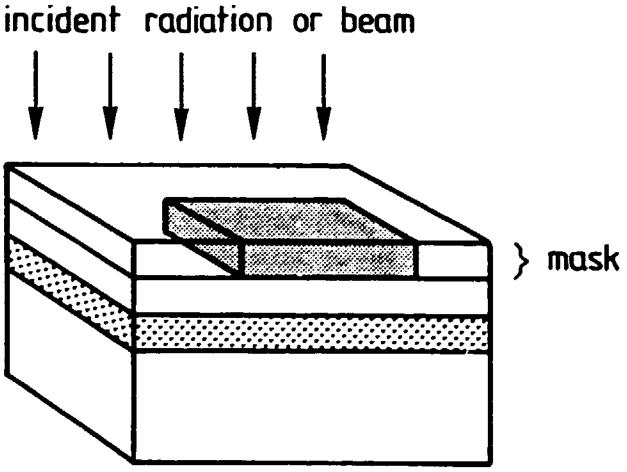
(A)


silicon dioxide
silicon

(B)

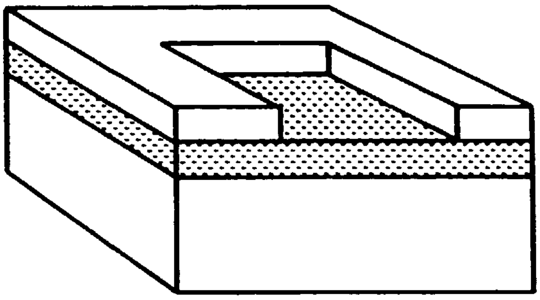

resist

(C)

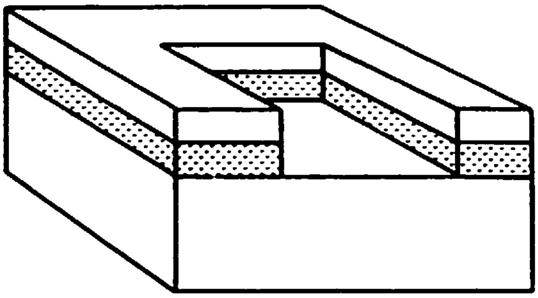

incident radiation or beam
mask

d-f

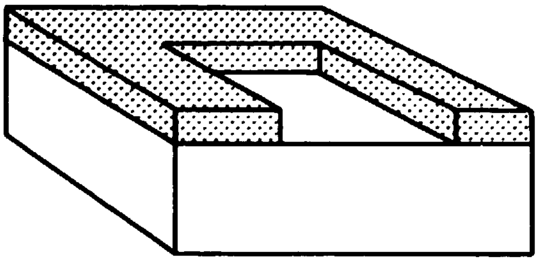
(D)

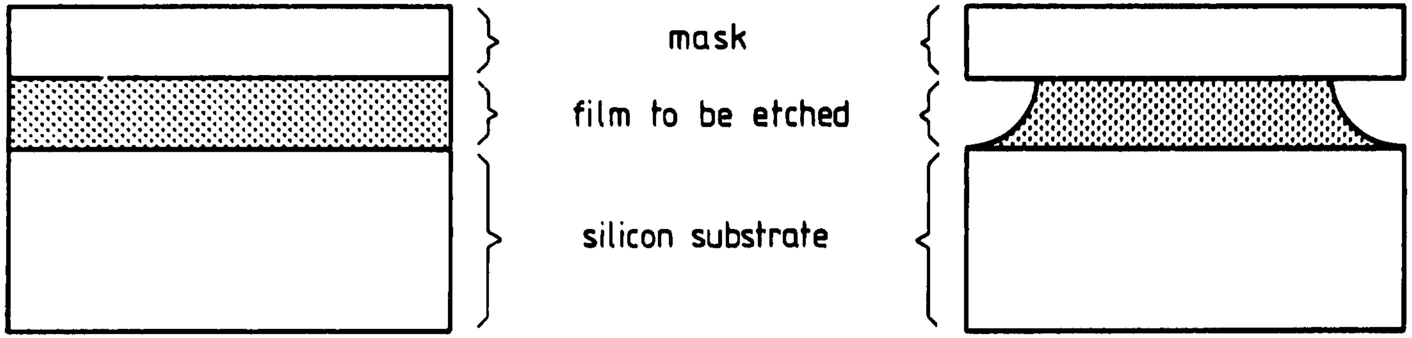


(E)



(F)




mask
film to be etched
silicon substrate

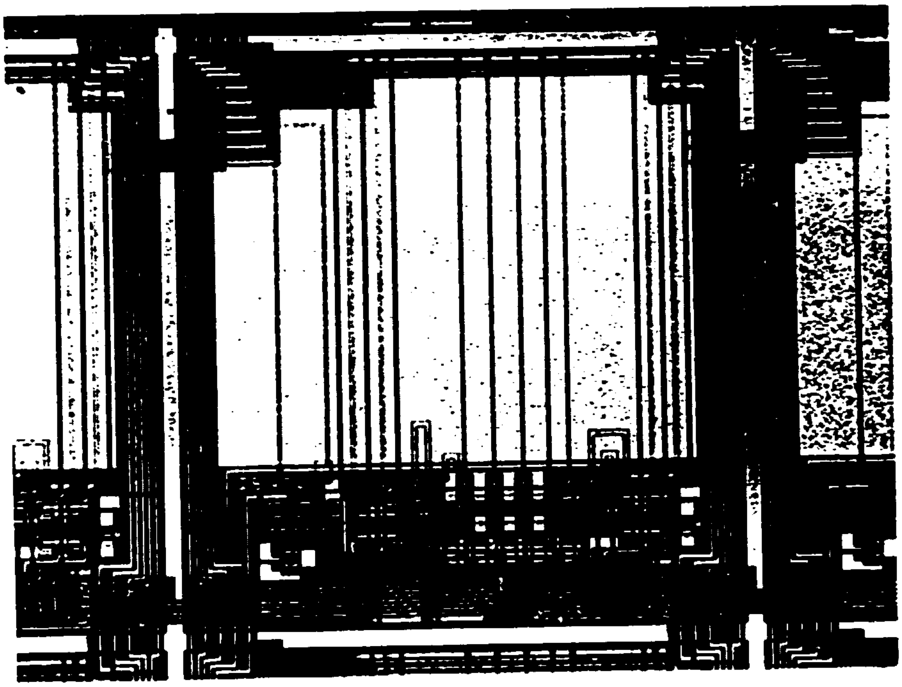
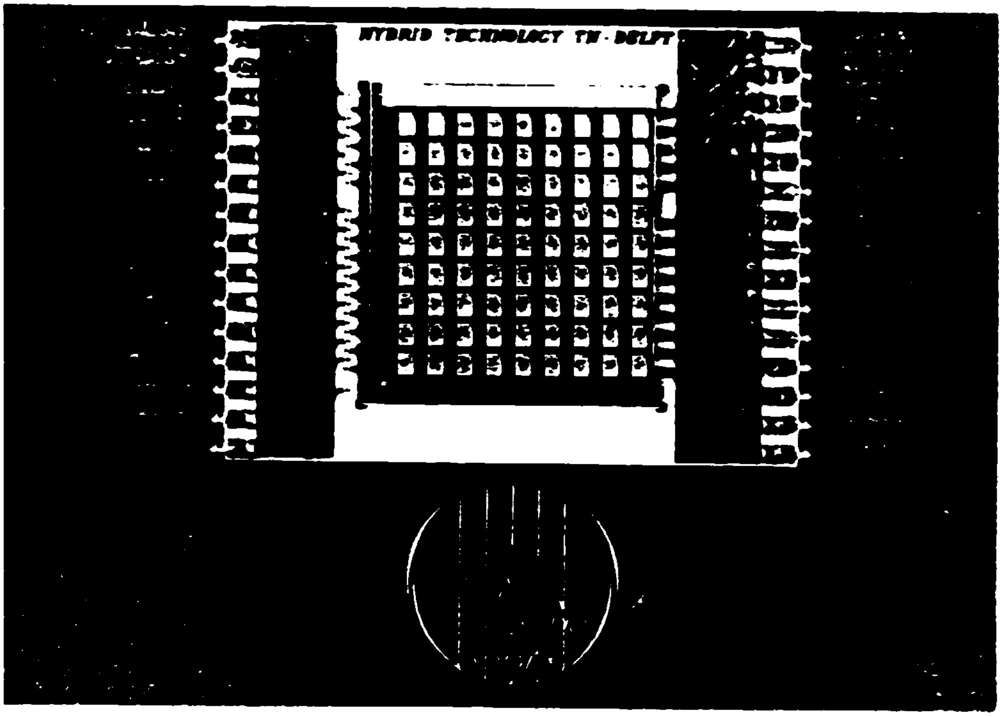
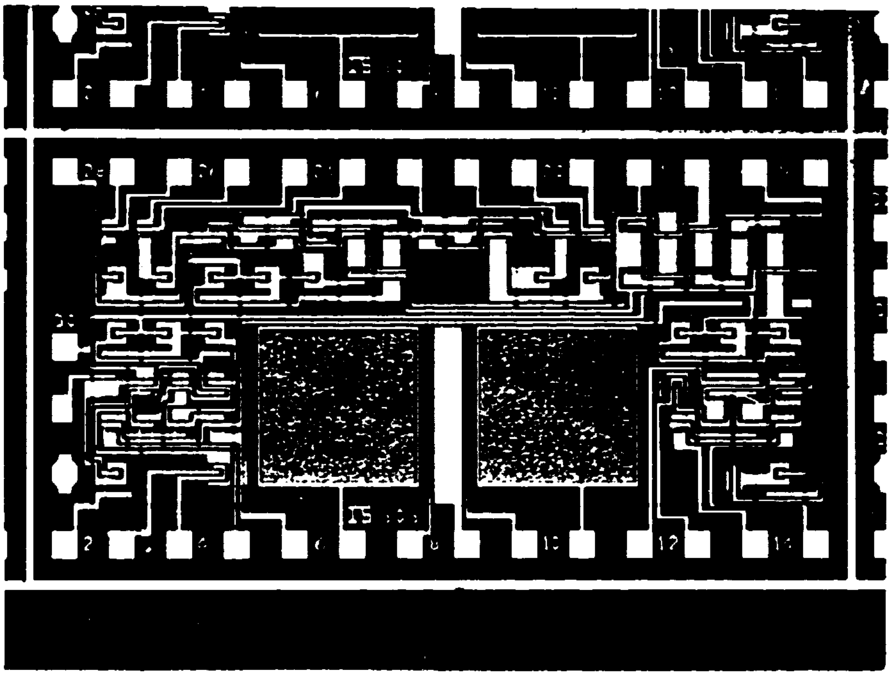
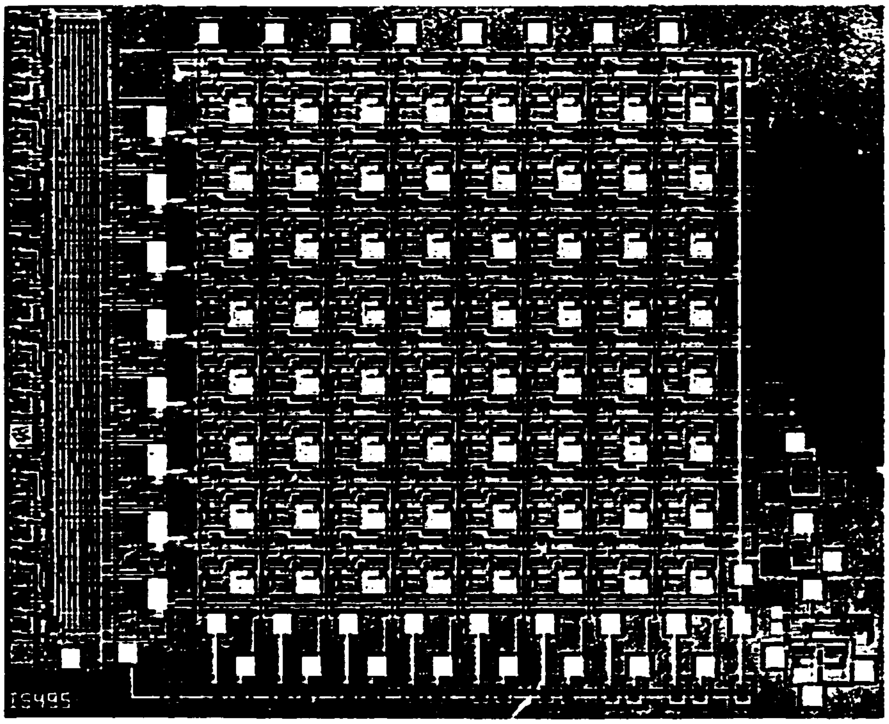


figure 22




2
4
6
8
10
12
14


IS495

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 $40\times2\pi$	*	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 $(kg/m^3)\times10^3$	ϵ_r	d_{33} $(m/V)\times10^{-12}$	acoustic impedance $(kg/m^2.s)\times10^6$
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. (^{0}C)	max. (^{0}C)	max. (bar)
Al_2O_3	-110	60	^{0}C dp	1 ^{0}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	^{0}C dp	0.5 ^{0}C	-45	130	40
electrolytic	1	3000	ppm	2 %	0	80	7
dew point	-90	170	^{0}C dp	0.2 ^{0}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	$\sim 3 \times 10^5$ 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.