OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

19193

United Nations Industrial Development Organization

Distr.
LIMITED

ID/WG.519/2(SPEC.)
17 September 1991

ORIGINAL: ENGLISH

Expert Group Meeting on
Processing and Application of
New Materials

Vienna, Austria, 4-6 November 1991

SENSOR MATERIALS FOR POLLUTION CONTROL AND OTHER APPLICATIONS*

Prepared by

V. Kravchenko**

---

* The views expressed in the document are those of the author and do not necessarily reflect the views of the Secretariat of UNIDO. Mention of the names of firms and commercial products does not imply endorsement by the United Nations Industrial Development Organization (UNIDO). This document has not been edited.

** Institute of Radio Engineering, Academy of Sciences of the USSR.

V.91-28879

Introduction

Sensors are devices which give us knowledge about the external world (and to some extent about the internal state of a man as well). They are widely used in industry, home appliances, medicine etc. Sensor world market in 1990 exceeded 15 billion US dollars and it is growing at around 8,8% annual rate to reach appoximately 30 billion $ in 2000 (fig.1). Main producers of sensors are developed countries of West Europe, USA and Japan (fig.2) [1]. In 1987 more than 140 million different sensors were produced only in Europe [2]. Developing countries produce only very small part of the total number of sensors which can be regarded as a substantial problem in developing modern industrial, medicine and consumer facilities and in proper pollution control. General trends of sensor development and application of new materials and technologies in the field are described briefly in the report. It is certainly impossible to give a detailed analysis of the situation because many hundreds of special books and reviews are devoted to the field which has already obtained special name of "sensorics" or "sensoelectronics". Some most important for our treatment references are given at the end of the report. Many references to earlier publications can be found in these sources. Some general Conferences devoted to the subject such as "Eurosensors", "Sensors and actuators", "Transducers" and more specialized ones are held regularly and proceedings of these meetings are important to understand the latest results. Some specialized journals such as "Sensors and actuators", "Sensor Magazine", "Sensor review", "Sensor Trend Intern.", "Sensors", "Fiber optics" as well as more general "Electronics", "Technisches Messen", "Elektronik", IEEE Transactions etc publish many hundreds papers on the subject annually.

Present state-of-the art of sensor materials for different applications, some constraints, new technologies of sensor materials and possibilities of their implementation in developing countries are reviewed consecutelely in the report, main attention being given to inorganic materials for sensors and their technologies, which are used in solid-state sensors.

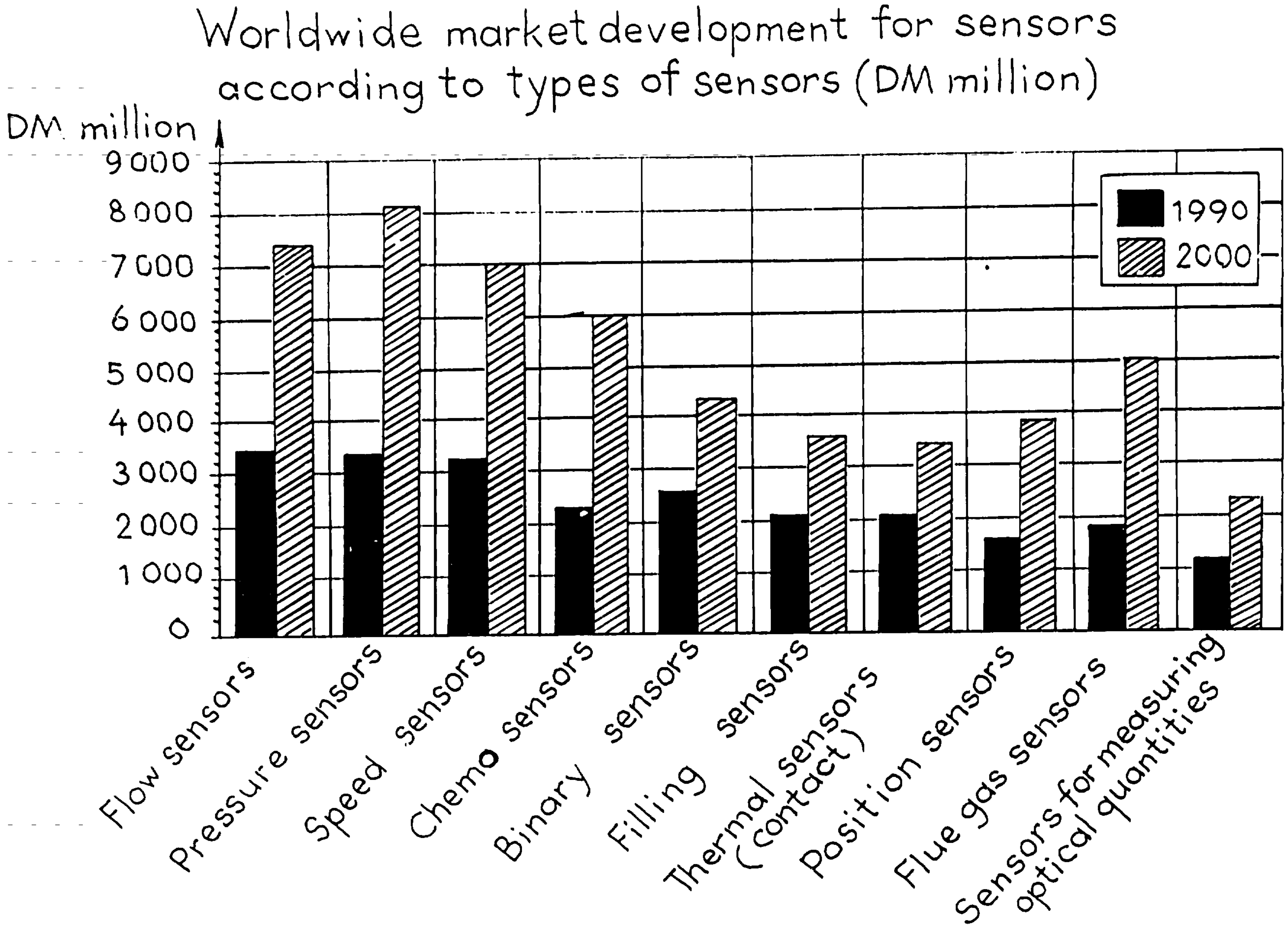

Worldwide market development for sensors according to types of sensors (DM million)
DM million
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1990
2000
Flow sensors
Pressure sensors
Speed sensors
Chemo sensors
Binary sensors
Filling sensors
Thermal sensors (contact)
Position sensors
Flue gas sensors
Sensors for measuring optical quantities

Fig. 1

Worldmarket development of sensors according to individual regions

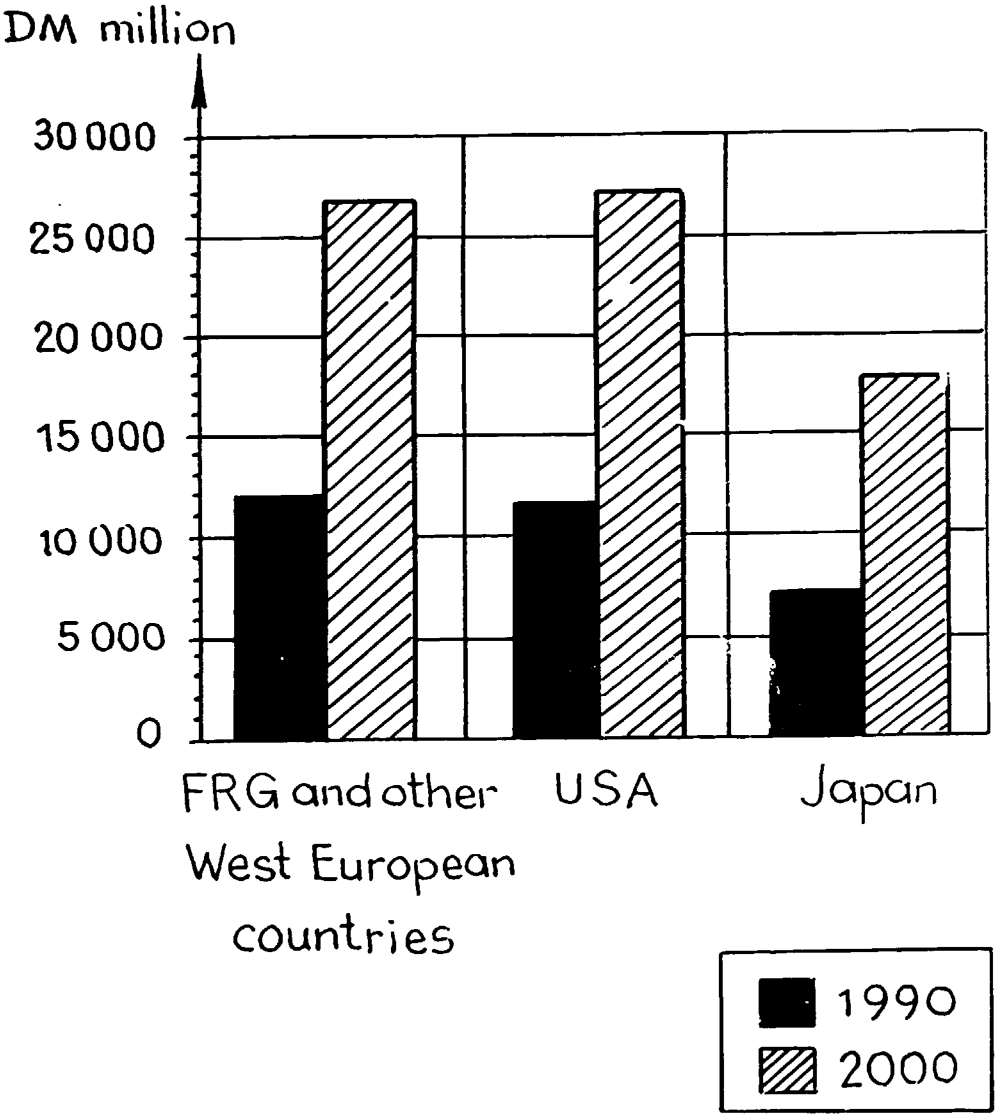


Fig. 2

1. Present state-of-the art of solid state sensors.

Most phenomena can be discovered and investigated using 6 main signal domains: radiant, mechanical, thermal, electrical, magnetic and chemical signals. Table 1 shows most important physical and chemical parameters which can be used in these signal domains [3]. More detailed description of different sensors and effects they use can be given (see, for instance, [3,4]). Fig.3 shows some simple devices converting one kind of signals (or energy) to another one [3]. The sensors correspond to some extent to human senses, and table of correspondence is given in annex (table A1 [5]).

Table 1.

The six signal domains [3].

Signals	Properties and phenomena
radiant	Right intensity, wavelength, polarization, phase, reflectance, transmittance.
mechanical	Force, pressure, torque, vacuum, flow, volume, thickness, mass, level, position, displacement velocity, acceleration, tilt, toughness, acoustic wavelength and amplitude
thermal	Temperature, heat, specific heat, entropy, heat flow,
electrical	Voltage, current, charge, resistance, inductance, capacitance, dielectric constant, electric polarization, frequency, pulse duration
magnetic	Field intensity, flux density, moment, magnetization, permeability
chemical	Composition, concentration, reaction rate, toxicity, oxidation-reduction potential, pH.

out in	rad.	mech.	therm.	elect.	magn.	chem.
rad.	optical filter	Golay cell detector	solarimeter	solar cell		photographic process
mech.	flint	gearbox		electric generat.		
therm.	temp. sensit. LCD	bimetal	heat exchange	thermocouple		
elect.	LED	loud speaker	cooling element	MOSFET	coil	battery
magn.	magneto optic modulat	magn. clatch	adiabatic demagn.	Hall plate	magnetic circuit	
chem.	candle	explos. motor	gas heater	pH meas. cell		chem. process

Fig. 3 Six-by-six matrix showing some devices for signal or energy conversion [3]

But certainly sensors cover much broader field of external signals including those which are far beyond usual human senses such as electrical and magnetic signals, high energy radiation etc.

These were remarks concerning sensors in general. Solid-state sensors which are most important for applications are based on different solid-state materials (see table 2). The materials are applied in different forms: silicon devices of different design, thin and thick inorganic films, sintered ceramics, polymer foils, metal wires, glasses and fibers etc. Each variety has its own advantages and drawbacks. Fig. 4 shows an example of relations between different kinds of sensors [3].

Table 2.

Different materials used for sensing elements
of solid state sensors [6]

Material	Example	Application for measurement
Metals	Pt, Ni, alloys	temperature, elongation, strain etc.
Intermetallic compounds	Nb_3Ge	magnetic flux
Semiconductors	Si, GaAs	pressure, temperature, emission
Other inorganic materials	$LiTaO_3$, glass fiber, ceramics	temperature, strain, liquid level
Polymers		emission, humidity, oil
Binary and triple oxides with dopents	RhO_x, Cu_2O, $SrTiO_3$	
Optimized catalysts systems, solid state electrolites		(Bio)chemical parameters
Metal-organic compounds	Phtalocyanines porfirines	
Ferments	Glucose, oxidazes	
Microorganisms	Microbs-reaction	

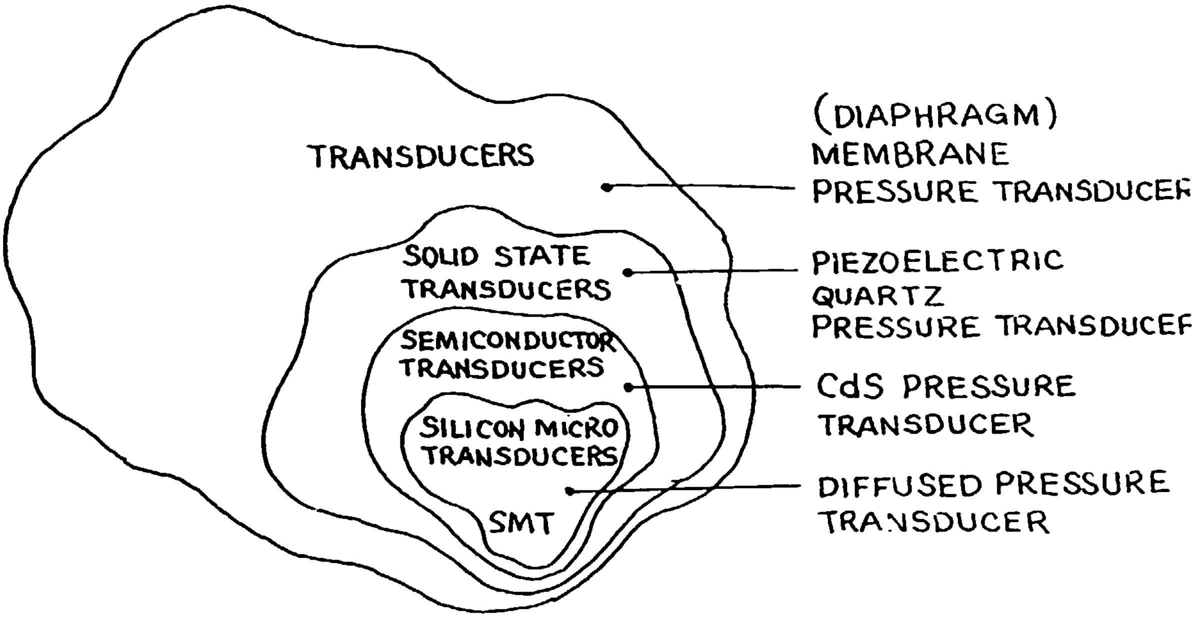


Fig.4 Transducers and technology [3]

Different materials and effects can be used almost in every case, and one must consider many sides of problem to make a good choice. Some examples of different applications and technologies mainly in enviroment control are given below.

1.1. Humidity sensors.

Humidity sensing and measurements are of great importance in various industrial process applications, such as food processing, manufacture of plastics, electrical insulating materials, petrochemical products, solvents, building construction materials, paper and pulp production, gas control for semiconductor industry (oxygen, argon, nitrogen, helium), atmosphere control in buildings, for instance, in grain-elevators. Solid-state humidity sensors are usually rather simple and are based on changes of physical properties of materials resulting from interaction with water vapors. Some polymers and semiconductors change drastically their resistance under influence of water. Resistance of polystyren-sulfonate decreases three order of magnitude when humidity increases from 10% to 97-98% [7]. The polymer materials are simple to prepare but their properties change with time under atmosphere action and some hysteresis also takes place during water absorption and desorption processes althogh their properties are constantly improving. One more effect used to measure relative humidity RH is surfase acoustic wave (SAW) frequency change under influence of water. Voltage output for broad-band SAW delay line made on Lithium niobate piezoelectric crystal changes one order of magnitude when RH changes from 89 to 98%, so 0,1% RH sensitivity can be obtained in this RH interval. Resistance of some semiconducting oxide ceramics can also change with RH and these ceramics can be used as sensing elements, especially, at elevated temperatures. The compositions include $MgCr_2O_4$-TiO_2, ZrO_2-MgO, TiO_2-SnO_2 and others. The sensors can work at temperatures from -20 to 650 C and do not change their properties after some hundred thousands measurements [8]. Typical size of sensing element is 4x4x1 mm. And certainly a number of RH sensors was developed on silicon basis [3,9].

1.2. Automotive industry.

A lot of different sensors are used in cars. Table 3 shows some ceramics sensors used in Toyota automobiles production [10]. Special conferences were devoted to the sensors applied in the industry (for instance, [11]). May be it is interesting to mention the most important sensed parameters in the car engine and their use [12]:

- crankshaft angle position, which indexes ighition timing (and injection timing for electronic fuel injection systems), yields angular velocity for ignition and fuel control, and from which an engine roughness signal can be derived;
- manifold absolute pressure, which is a primary parameter for speed/density fuel control systems;
- manifold vacuum, for ignition control and load sensing;
- ambient absolute pressure, for exhaust-gas recirculation;
- air flow, for mass-air flow-fuel-control systems;
- oxygen partial pressure, for air/fuel ratio control to ensure exhaust gas compositions within stoichiometric - ratio "window" which can be handled efficiently by three-way catalysts, and possibly for lean-limit control;
- knock, for retarding ignition timing during knock-inducing conditions;
- fuel flow, for optimizing engine economy;
- coolant temperature, for cold start;
- air temperature, for air-density correction;
- throttle position, for power command and its time derivative, and for idle shutoff on coast-down;
- oxides of nitrogen partial pressure in exhaust, for diesel engine emission control;
- exhaust gas flow for exhaust-gas-recirculation systems

and some others. Besides the engine control sensors some other sensors are used in cars, such as air RH and temperature sensor to control atmosphere inside the car, accelerometer, sensors of rotation, pressure, acceleration and velocity for antilock braking, position sensor for steering, velocity/proximity microwave sensors for safety and so on.

Table 3.

Some ceramics sensors used in Toyota automobile production

Oxygen sensor (ZrO)
Knock sensor (PZT)
Backup sensor (PAT)
Electric buzzer (PZT)
Thermal sensor of water temperature (Fe_3O_4-$CoMn_2O_3$-NiO)
Thermal sensor for exhaust gas (Al_2O_3-Cr_2O_3)
Fuel level switch (Al_2O_3-Cr_2O_3)
Light-emitting diode (GaP)

---

* piezoelectric zirconate-titanate
** piezoelectric alumina titanate

Main sensor materials for the applications include different silicon devices and ceramics in form of sintered samples, thin and thick films. GaAs Gann diodes, GaP light-emitting diodes, ZnS electroluminescent devices are also used as parts of sensors. It is necessary to note that many automobile sensors work in harsh enviroments (temperatures from -60 to +150°C, sometimes even up to 700°C, dust, high humidity, thermal and mechanical shocks, vibrations etc.), so high requirements exist to stability and packaging of these sensors [12, 13]. Some sensors for automotive industry can also act as pollution control sensors (such as sensors of oxygen partial pressure, oxides of nitrogen partial pressure etc.), which is very important because cars are one of the main sources of pollution. Total automotive sensors' market in the world is around 6 Billion DM and is expected to reach 20 Billion DM to the end of the century. Number of sensors in one BMW car is around 30 now and can reach 80 in luxury cars [14]. The sensors together with small on-board computer can enable "Smart car" concepts where the car driver can obtain full information of car's behavior and his own functions can be partly replaced by computer, with highly increased safety.

1.3. Chemical sensors.

Many chemical substances are considered as polluting agents and their concentration in air, water and soil must be well controlled to be kept is under certain limiting values. Chemical and food industry, agriculture and many other areas also need control of chemical substa nces present. The control can be done using different chemical sensors. The main materials used for commercial gas or water sensors include silicon (different variants of field-effect transistors, FET) and semiconducting ceramics - SnO_2, In_2O_3 or Fe_2O_3 for reducing agents, $Sn\ O_2$ or WO_3 for H_2S sensor, different oxide materials for air-to-fuel ratio and humidity sensors already discussed [3,8,15]. Silicon-based sensing elements include so called ion-sensitive field effect transistor (ISFET), Pd-gate MOSFET (Metal-oxide FET)hydrogen detector, ISFET with some additional ion-permeable layers on oxide surface (so called CHEMFET) and some devices using silicon together with metal oxide or polymer layers (tin-oxide gas sensor on silicon substrate, chemdiodes etc.)[3,15]. Main disadvantage of FET-based sensors is a necessarily close contact between the sensor and the fluid and gases to be analyzed, so protection (encapsulation) of the electronic functions from the often corrosive environment is necessary. Other problems include instability of electronic materials exposed to gas or liquid environment (eg. the hydrolisis of gate dielectrics), instability problems due to contamination, poor selectivity, short lifetime, unavalaibility of multispecies sensors, the lack of mass fabrication method (because of the lack of compatibility between depositing different ion-selective membranes and integrated circuits technology) [15]. So more detailed researches are necessary in the field.

Ceramics-based sensors are much more stable and rather cheap, but at the same time need further improvement in stability, selectivity and sensitivity. About 20 million such sensors are already commercially produced and used each year and extensive investigations are carried out to increase the scope of ceramic materials used and improve sensor's perfomance [15,18]. Many ceramic sensors use semiconductor oxide ceramics or solid electrolytes. Some materials used for gas detection are listed in tables 4 and 5 (following [15-18]).

Table 4.

Semiconductor gas combinations [15,16].

Semiconductor	Gas
SnO_2	O_2, H_2, CO, alcohols, H_2S, HC, NO_x
SnO_2, In_2O_3, WO_3	H_2S
TiO_2	O_2, CO
Ti/Nb/Ce oxide	Air-to-fuel (A/F) ratio
CoO	O_2, CO
Co_3O_4	CO
Nb_2O_5	A/F ratio
$Co_{1-x}Mg_xO$	A/F ratio
$LaCO_3$, $NdCO_3$, $SmCO_3$, $EuCo_3$	CO
Fe_2O_3	C_4H_{10}
WO_3	HC, alcohols, H_2S, C H
Ag_2O	CO
ZnO	CO, HC, O_2
$ZnGeO_yN_z$	NH_3
Organic semiconductors:	
Polyphenylacetylene	CO, CO_2, CH_4, H_2O
Phtalocyanine	NO_x, NO_2, chlorinated HC
Polypyrrole	NH_3
Polyamide, polyimide	NO_2

Table 5.

Some Solid-Electrolyte-Based Sensors ([15-18]).

Cell	Temperature, °C	Analyte
Ref/ZrO_2-Y_2O_3/MM,O_2	500-800	O
Ag/$SrCl_2$-KCl-AgCl/Pt,Cl	100-450	Cl
Ag/Li_2SO_4-Ag_2SO_4/Pt,SO +SO +air	500-750	SO_x
Ref/CaS-Y_2S_3/Pt,S	600-900	S_x
Ag/$Ba(NO_3)_2$-AgCl/Pt,NO_2	500	NO_2
Ag/KAg_4I_5/Pt,I_2	40	I_2
Na(vap)/β"Al_2O_3(Na)/Na(vap)	200-300	Na
Al,Cr/LaF_3/Au+Ag,O_2,CO_2,SO_2,NO,NO_2	R.T.	O_2, CO_2, SO_2, NO, NO_2
Au,CO_2,O_2/K_2CO_3,CO_2,ZrO_2-CaO/Au,O_2,CO_2	700	CO_2

Ref-Ref.electrode, MM-metals, vap-vapours.

The tables though not exhaustive show how many inorganic materials can be used as solid-state sensing elements in chemical sensors. The elements' technology is condiderably simple and flow chart for the preparation of tin oxide paste used for production of many sensors is shown in fig.5 as an example.

Chemical sensors have many applications, some of which are listed in table 6.

One can see that the scope of their applications is extremely wide and includes many sides of industry and everyday life. We shall discuss in the second chapter some new possibilities connected with modern trends in sensor development.

1.4. Summary of existing technologies.

One can see from some examples discussed above that basic technologies used for sensor production include different materials and technologies.

Silicon and usual technology of IC production together with a new technology of micromashining (see chapter 2) are used widely. The sensors have small size, are compatible with data processing systems and can be produced on mass scole. Production costs being rather high at the begining owing to complexity of technology are

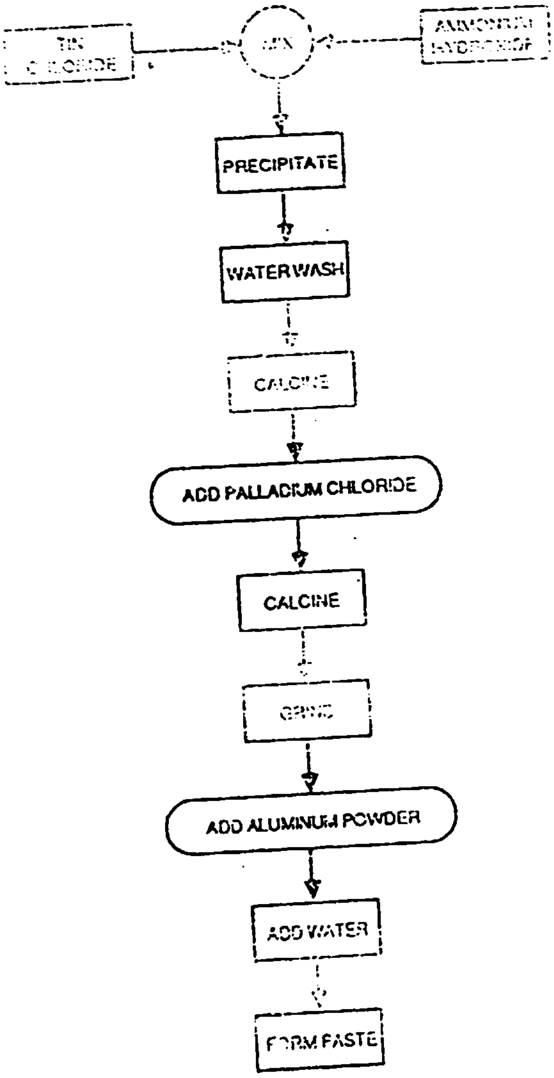


Figure 5 Flow chart for tin oxide paste preparation

Table 6

Application of chemical sensors in various fields [18]

Field	Sensor target	Aim
Consumer electric products and home appliances	humidity, dew turbidity gas species (O_2, hydrocarbons) ionic species (or electrolytes)	convenience, comfort high quality high function safety energy conservation
Automobile, etc.	humidity, dew, smog ets. gas species (O_2, CO, NO, organic, air to fuel ratio etc.)	comfort, high quality high function, safety pollution control energy conservation
Chemical and Metallurgical industry (including petroleum ind. fermentation ind. food-stuff ind. etc.)	solute components (organic or inorganic) pH, turbidity, ionic species (or electorolytes) solvent components gas species (organic, inorganic)	process control labor saving, automatic security system in plants pollution control resources saving energy conservation
Labor environment (underground, oil field, coal mine, ship, gas stand big building, etc.)	volatile solvent gas species (O_2, CO_2, organic etc.) hazzard substances (CH_4, H_2S, etc.) others	security system disaster prevention fire prevention

Living environment Office environ.	humidity gas species (town gas, LP gas, H_2 etc.), fire, smog, etc.	safety, comfort offensive smell, combustion control energy saving, fire prevention gas poisoning prevention
Health, Medical care	blood components (pH, O_2, Na^+,K^+, blood sugar, etc.) uric components (ions species, bio-chemical compounds) other bio-related compounds microorganism	health control diagnosis inspection medical engineering remote diagnosis medical treatment artificial organs
Agriculture Forestry Fishery	humidity, water content freshness gas species (CO_2, O_2,etc) moisture, pH, electrolytes,	facilitate agriculture or horticulture cultivate fishery freshness inspection fresh storage
Meteorology Oceanography	humidity, salinity turbidity environmental gas species	unmanned observation station telemetry
Energy Atomic power Natural resources	gas species (CO_2, hydrocarbons) metal elements, metal ions humidity, pH	steam power plant combustion control mineral resource searc mines, energy concervation
Community in city	gas species (H_2, NO, etc.) smog, electrolytes or soluble substances poisonous substances pH, turbidity	pollution control disaster prevention safety control automatic monitoring

constantly going down following the technology improvements. At the same time the sensors have distinct fields of applicaions and can be used only to small extent in such important fields as chemical sensing and pollution control. Great initial investments are necessary. The personnel qualification and requirements to equipment maintenance must be very high as it is usual for semiconductor industry.

Ceramic sensors based either on semiconductor oxide materials or on solid electrolites are much easier to produce as it was discussed in section 1.3. Technological problems of reliability and reproducibility exist and additionnal efforts to solve the problems and to improve sensitivity and selectivity of the sensors are necessary but for many applications the sensors'production can be organized with much lower costs and lower manpower qualification as compared with silicon-based technology. One must keep in mind that size and weight of sensing elements themselves are rather small. There are no serious resourse constraints for this production and usual infrastructure requirements concering materials, energy, water and communication systems exist for the production units.

But it is necessary to note that sensor production in any country needs preliminary investigation of local and international market because one can't forecast in advance which kinds of sensors will find a niche in existing industrial and consumer production. In reality new sensor manufacturing is a high-risk undertaking and may be the reasonable way to reduce the risk is to use international cooperation and technology transfer. It refers also obviously to new developments in sensors and sensor materials which will be discussed in the following chapter.

2. New technologies of sensors and sensor materials.

Most important newly developed and emerging technologies to be described here include sensors based on optoelectronic and piezoelectric materials, micromashining technology, search for new materials and "smart" or intelligent sersors.

2.1. Optoelectronic and piezoelectric sensors.

These new varieties of sensors have some advantages as compared with usual sensors discussed in chapter 1. Optoelectronic sensors include non-invasive detection, vision and pattern recognition and fiber-optic sensors. The last kind of sensors is developing very quickly. Fiber-optic sensor includes light source (usually laser diode or laser), optical fiber line and optical receiver (photodiode). The sensing element can use the fiber itself (for instance, fiber with magnetic coating) or, more often, some additional substance or material, placed either between two fibers, or on fiber tip or bare fiber core. The material can be in form of single crystals, thin films (including integrated optics circuits), membranes, pastes, solution etc. The sensors using optical fibers are insensitive to external electromagnetic interference (EMI), have good resistance to corrosion and chemical attack, high sensitivity; the sensing element can be situated very far from the main processing device. At present the number of fiber-optical sensors produced amounts to 5-10% only of total sensor quantity [2] but these sensors are usually most sophisticated and most expensive. Some examples can be given. In our laboratory fiber-optic sensor of electric field strength is developed. The sensor can measure electric field strength from 30 V/m up to 200 kV/m at d.c. and at frenquences up to some hundreds MHz at any given point and is insensitive to EMI on fiber line. It can be used to control high-voltage equipment and high-power electric stations. A number of optical sensors to control hazardous gases (ammonia, organophosphonate, sulfur compounds) are described in [19]. Fiber-optic sensors were developed for continuous monitoring of pH, CO and penicillin [20]. Environment investigations and detection of small quantities of ground water contaminants such as trichlorethylene and chloroform are described in [21]. Precise body temperature monitoring during hyperthermia cancer treatment by microwave and radio-frequency, blood pressure measurements "in vivo", blood glucose measurement, cholesterol monitoring and so on are very important new fiber-optic sensor applications in healthcare [22]. Many other technical applications of the sensors include thermometers for measurements of very low and very high temperatures, "distributed" temperature sensors, electric current sensors, optical gyroscopes and fiber-optic hydrophones, liquid level sensors etc [23,24]. Barriers still existing in fiber-optic sensors'development include problems of reproducibility and rather high price which is connected with prices of optoelectronic components. But this industry is developing quickly. Total optoelectronic components'market in Europe was estimated as 2187 Million US $ with rise to 4147 Million $ by 1995. Fig.6 show European optoelectronic component market by country, Germany helding the biggest market. World optoelectronic component market was 5232 Million Dollars in 1990 and is expected to be 16120 Million Dollars in 1995 with annual growth rate 22,2% in 1989-1996 [25]. Component prices are going down with this rapid market growth. Fiber-optic sensor market is estimated to be 164 Million Dollars in 1990 and is estimated to reach $ 935 Million by 1996 [26]. Promising variety of sensors is connected with utilization of piezoelectric resonators and surface acoustic waves (SAW) devices. The resonance frequency of these devices depends on external factors. For instance, temperature can be measured using this method with accuracy 10^{-5} °C [27]. When a film or membrane is applied to resonating quartz crystal plate or to SAW device the frequency changes which can be measured with very high accuracy. Using very thin, some tens of Angstroms, polymer films (so called Langmuir-Blodgett films) as a coating of piezoelectric crystals one can obtain odor sensors which can detect ppm-ppb odor levels in air or nanogram levels [28]. Some prototypes of drog detecting sensors are developed using these principles.

2.2. Micro-machining technology.

Semiconductor technology widely used for IC production was applied to prepare mechanical components of very small dimensions (sometimes only a few microns). Deposition, lithography and etching technique are used to produce three-dimensional mechanical structures. The main material is silicon, which can be anisotropically wet ectched to produce highly accurate almost atomically smooth planes. As a semiconductor silicon offers the opportunity of integrating into one piece a mechanical sensor and electronic circuitry [29,30]. The most impressive example of

EUROPEAN OPTOELECTRONIC COMPONENT MARKET BY COUNTRY: 1989

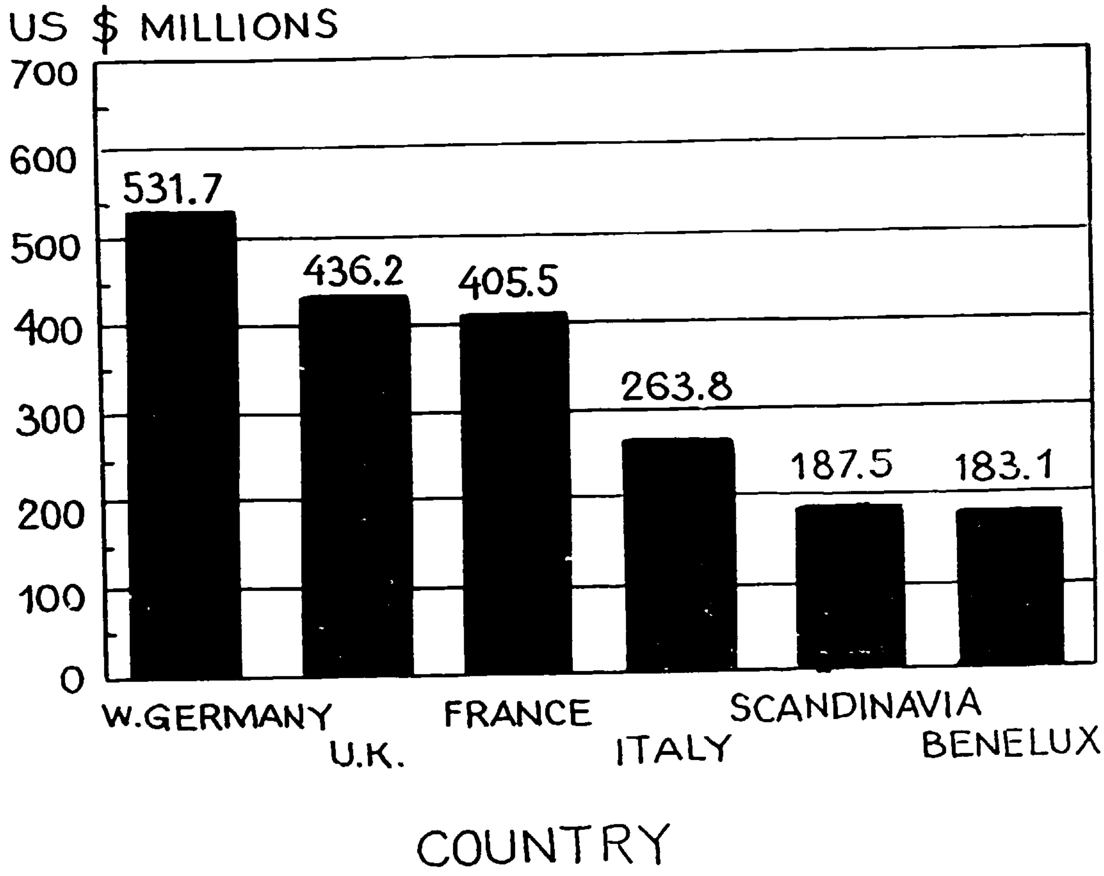


Fig. 6

sensor produced by this technique was integrated gas chromatograph [31] where all the mechanical parts of small sensing cell were made of locally etched silicon. The size of the elements can be as small as 1-2 micrometers in one dimesion with up to 1 mm in other dimensions. There is a huge variety of micromechanical sensor device types but the commonest basic types are as follows:

- membrane devices, usually, pressure sensors, where a thinner membrane is supported by a thicker frame;
- beam devices usually flow sensors or accelerometers, in which an unsupported structure is deflected to act as a sensor.
- surface machined devices where mainly passive parts of sensing devices are produced.

One more material which can be subjected to this micro-mechanical treatment is piezoelectric quartz, and very delicate sensing structures were made using these crystals.

The technological problems connected with this technique include development and application of new technological methods, combination of micro-mechnical structures with electrical and optical systems and improvement of packaging methods [30].

2.3. New sensor materials.

Besides application of well-known materials already discussed in Chapter 1 intensive researches of new materials are carried out. These new materials include inorganic materials, polymer materials, ferments and some others. Only ceramic materials will be briefly discussed here. The improvement of ceramic materials goes in some directions [32]. First, it is development of technology of thin and thick films instead of sintered bulk materials to decrease response time. Second, it is improvement of existing materials, which can reside on choice of new catalyst, new dopant or dopant combination in a known material, new electrode configuration on material etc. For instance, in [33] V-Mo-Al_2O_3 catalyst added to doped ZnO ceramics enabled detection of halogenated hydrocarbons at 500 ppm level. Now freon gas detector is proposed that senses 100-1000 ppm of freon -133, -22 and 11. Third, it is search of new materials. For example, now a new ceramic material exists which enable freon gas sensitivity at 0,05 ppb level. Ag-βAl_2O_3 solid electrolyte was found to detect arsine AH_3, a dangerous compound used in semiconductor industry [34]. Fourth, it is development of new multicomponent or multilayer structures or reasonable combination of existing materials to go from single substance detection to multicomponent analysis (for instance, [32,35-37]). Fifth, investigations are carried out to combine ceramic sensors with IC to obtain so called "smart" or intelligent sensors which will be discussed in the next section.

2.3. Intelligent sensors.

Usual sensor detects and measures some physical or chemical quantity and converts it into an electrical signal. But nowdays the electric signals are to be processed by some more complicated device, for instance, by computer. The computer needs a singal which would be free from unnecessary noise, corrected for some additional or random declinations and mistakes and preferably converted into digital form. The computer can do all these functions of signal transformation itself but its action would be slower in this case, so better to do all this preliminary signal treatment in a special device connected with the sensing element and such a combination is called "smart" or intelligent sensor. So practically it is a sensing element combined with special IC or microprocessor [38]. Now only a few per cent of all sensors produced can be regarded as intelligent sensors but their production is increased and they can be regarded as a main way of future sensor industry. From the point of view of materials mainly silicon is used now in electronic part of smart sensors. Some problems of sensing element interaction with electronic circuitry exist in case of elements made from different materials but they do not practically depend on material properties and can be overcome by sensor design. One can distinguish different kinds of intelligent sensors: hybrid sensors, where sensing element and IC or microprocessor are separated, then sensors <u>on</u> silicon and sensors <u>in</u> silicon (three-dimensional structures) [38]. Most smart sensors used in pollution control and chemical monitoring belong to hybrid type.

Smart sensors can find very wide applications in many areas: predictive maintenance and process control in industry, in robotics, expert systems, automotive industry, space and aircraft, consumer products etc. Only two impressing examples of future possibilities of intelligent sensors will be given below.

The first one is smart sensor application in automotive industry. Some possibilities were discussed in chapter 1. Now consumer demands exist for greater safety and performance as well as goverment-mandated regulations concerning auto safety and emission control standards. As a result intelligent performance, safety and security equipment, elements of navigational system, active suspension control, communication equipment will grow very fast in the future. The ultimate "smart" car will incorporate sensing and control capability which will interact more directly with driver"s environment and that integrates functions. The ideal of system integration is so-called "networked car", in which distinct computer-controlled systems and subsystems cooperate with each other to maximize vehicle performance and safety. Some new steps in the industry include development of a system to change pressure in tyres to deflate them on rough roads for a smoother ride and to reinflate them again on smooth roads, then construction of "intelligent highways" which may enable autos to steer themselves in 100 miles per hour "convoys" with 2-3 times greater density of traffic on each highway and high safety. The system can use internal and external guidance methods: inertial guidance, radio signals and sensors for internal types, various combinations of beacons, computer networks, buried copper strips and sensor interrogator devices located along the highway. Some international projects in the field exist, for instance, european "Prometheus" program on smart cars [39]. Certainly this is future but it is a foreseeable future based on already existing sensor systems.

Another future possibility is a "smart house" concept. Fig. 7 shows future intelligent house with most important sensor and actuator systems [40]. In addition to fairly common sensing applications - automatic lighting, air conditioning, energy supply and distribution - there are important security arrangements. Various sensors are involved including person-identification sensors and body-heat sensors which restrict access to private houses or to offices after business hours, smoke and gas detectors,"prescnce control" with smart sensors which may detect when a person enters an office during working hours and how long he or she stays here. All sensor readings are trasmitted to

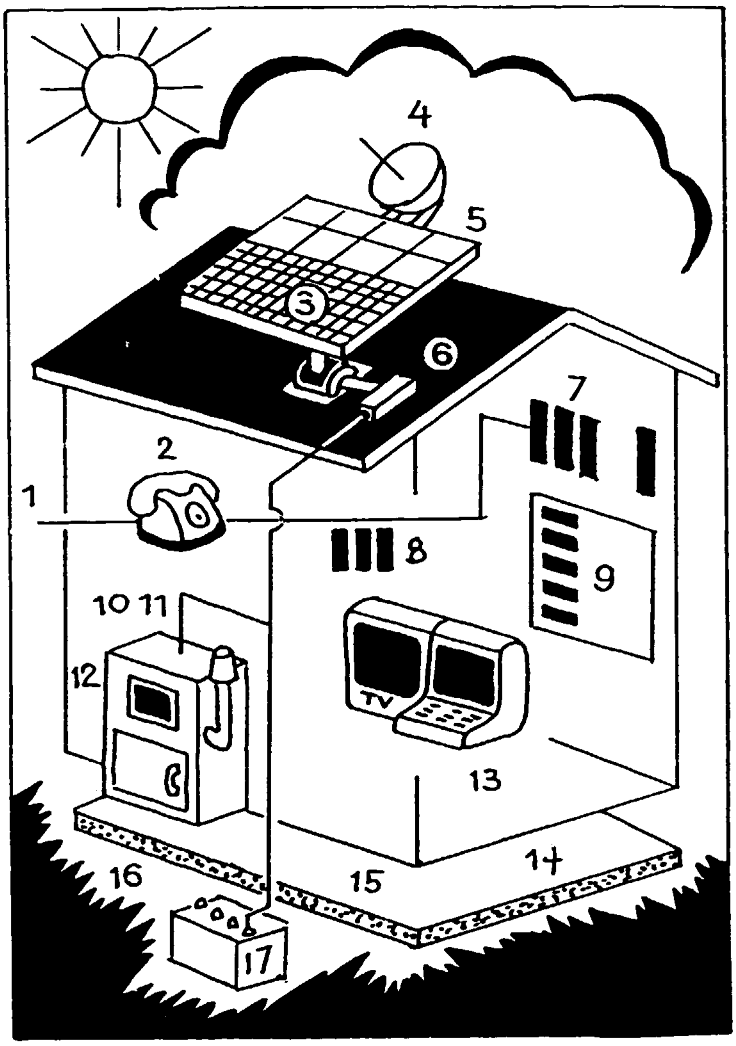


Fig. 7. "Smart house" with sensor and actuator systems [40]. 1. watch signal; 2. solar energy concentrator; 3. solar battery; 4. antenna; 5. sun movement sensor; 6. outside temperature sensor; 7. security sensors (fire, gas, intrusion in broad zone, intrusion through window); 8. comfort sensors (temperature, humidity, conditioning); 9. caring sensors (blood pressure, pulse rate, height, weight, fatiguability etc); 10. heating system temperature sensor; 11. water level sensor; 12. boiler; 13. computer system of internal information; 14. ground temperature sensor; 15. heat accumulator; 16. battery; 17. battery charge sensor.

personal computer and for control also outside the house. Such smart buildings and smaller prototype flats and offices are already starting to appear in United States, Japan, Scotland and also in newly industrialized countries like Republic of Korea, for instance.

III. Conclusions and recommendations.

Sensor industry is considered by experts as one of key technologies of present and future time. For instance, W. E. Morrow. Jr., director of Lincoln Lab at MIT, USA, includes in eight "High Leverage Technologies" passive sensors, sensitive radars, photonics, machine intelligence and robotics, signature control, the second group "Core Technologies" includes data fusion and the third group "Emerging Technologies" includes "Low-power, high-speed electronics for sensor signal processing and recognizers". All the mentioned technologies are parts of sensor development industry and science and passive sensors and photonics depend critically on materials and technologies'development. So all the countries must have their own policy in the field.

The problems of developing countries are connected with choice of scientific and industrial directions in each coutry. On the market there are many sensors produced on industrial scale. Only in Europe more than 1500 companies are offering problem solution in more than 50000 type of commercially available sensors for about 100 measurement parameters [39]. Following the preceeding chapter it is possible to say that at least some kinds of sensors are applicable in each country: chemical sensors for industrial application and pollution control, sensors for home and industrial appliances such as humidity and temperature sensors and different medical sensors for health care. Most of these sensors are based on inorganic sintered ceramics, thin and thick films and some polymer materials. The technology of the materials is relatively simple and although some technological barries exist no serious resource or infrastructure constraints can be foreseen at the moment.

The problems existing are connected to manpower, to development and production ozganization and financing. Usually it is necessary to have some scientific background and reseach facilities and teams which are engaged in sensor materials problems and are able to support industrial developments. Not in all developing countries such teams exist so international cooperation, help in education and organization of internationally recognized centres of excellence seem to be necessar y. The sensor technology field is unique, in that many developments still come from small companies and even one man company, the inventory basis plays an important role and in many cases technology transfer or joint ventures'organization will facilitate the establishment of new production line.

A big problem exists that the sensor markets in many cases are invariably small niches which, even if successful, would provide healthy but not outstanding profits [42]. As a result sensor technology even in western countries has not enjoyed a high level of enthusiasm from many possible investors. And the same situation will probably take place in developing countries. The probable solution may be administrative and financial programme of industry development made with help of state planning organizations.

One more problem is connected with the fact that end user customer does want cost effective solutions to a range of problems, albeit solutions that take account of the communication and computing elements as well as sensor needs. The sensor must remain but one component in system terms, and sensor materials even more constitute only a part of the sensor. So sensor materials development by itself is of small practical use, it must be tightly connected with sensor production and companies that are active in sensor technology must be prepared to either offer customers a complete solution with all other elements included or specialised applications consultancy services. And this cooperation may be greatly facilitated by some joint state program. It is necessary to hote that such state programmes exist in western countries, for instance, "Advanced Sensors Technology Transfer Programme" in United Kingdom [43], as well as some international programmes, for instance, "Prometheus" mentioned above. Certainly for developing countries better to establish such programmes and projects using possibilities of international organizations like UNIDO and the meeting on new materials may help to do this.

References

1. Forschung und Anwendung modernen Sensorsysteme. Sensor Magaz, 1990, No 4, p. 4-6.
2. Kistler J. Entwicklungstendenzen der Sensorentechnik. Technica, 1987, B. 15, No16, s. 9-16.
3. Middelhoek S., Audet S. A. Silicon sensors. London et. al.: Academic press, 1989.
4. Wada S., Kawai S., Furuia M. Modern state and development prospects of sensors. Nihon hakue kikan gakkaisi, 1988, v. 23, No 2, p. 166-174.
5. Wiegleb G. Sensortechnik. Ubersicht, Application, Anwendungen. Franzis-Verlag, GmBH, Munchen. 1986.
6. Richter W., Haase K.-H. Sensortechnik. Radio Fernsehen Electronik, 1988, v. 37, No 9, p. 554-557.
7. Huang P. H. Humidity sensing, measurements, and calibration standards. Sensors, 1990, No 2, p. 12-20.
8. Nitta T. Development and application of ceramic humidity sensors. In: Chemical sensor technology. Ed. T. Seyama Tokyo-Amsterdam et. al., Kodansha-Elsevier, 1988, vol. 1, p. 57-78.
9. Szulce A. Czujniki wieikosci nieelektrycznych. Wiadomosci Elektrotechniczne, 1985, v. 53, No 15-16, p. 350-354.
10. Frankhouser W. L. Advanced processing of ceramic compounds. Dynamic Compaction Technology. Self-propagating High-Temperature Synthesis, Plasmochemical Technology. Park Ridge, N. J. USA, Noies Data Corp., 1987.
11. Sensors for automotive systems: Congress and exhibition. Detroit, 1980, Soc. of Automotive Eng, SP-458, Warrendale, P. A. 1980.
12. Wolber W. G. Automotive engine control sensors'80. In [11], paper 800121.
13. Sieck R. E. Sensors and switches for harsh industrial environments. Sensors, 1990, No 11, 41-44.
14. Sensorik im Automobil heute und morgen. Sensor Magazin, 1991, No 1, p. 6-7.
15. Madou M. J., Morrison S. R. Chemical sensing with solid-state devices. Boston: Academic Press, 1988.
16. Kulwicki B. M. Ceramic sensors and transducers. J. Phys. Chem. Solids, 1984, vol. 45, No 10, p. 1015-1031.
17. Warrel W. L. Solid-electrolyte sensors for SO_2 and/or SO_3. In: Chemical sensor technology. Ed. T. Seyama. Tokyo-Amsterdam et. al: Kodansha-Elsevier, 1988, vol. 1, p. 97-107.
18. Seyama T. Chemical sensors-current state and future outlook. In: Chemical sensor technology. Ed. T. Seyama. Tokyo-Amsterdam

et. al.: Kodansha-Elsevier, 1988, vol. 1, p. 1-13.

19. Guilani J. F. Optical waveguide chemical sensors. In: Chemical sensors and microinstrumentation. Ed. Murray R. W. at. al. Washington, ACS symp. series 403, 1989, p. 364-379.

20. Walt D. K., Munkholm Ch., Yuan R. et. al. Design, preparation and applications of fiber-optic chemical sensors. In: Chemical sensors and micro-instrumentation. Ed. Murray R. W. et. al. Washington, ACS symp. series, 403, 1989, p. 252-272.

21. Angel S. M., Ridley M. N., Langry K. et. al. New developments and applications of fiber-optic sensors. In: Chemical sensors and microinstrumentation. Ed. Murray R. W. et. al. Washington, ACS symp. series, 403, 1989, p. 345-363.

22. Jones K. Caring sensors. Sensor Reiew, 1990, July, p. 111-114.

23. Krasiuk B. A., Semenov O. G., Sheremetiev A. G., Shesterikov V. A. Fiber optic sensors. Moscow, Mashinostroenie, 1990 (in Russian)

24. Busurin V. I., Nosov Ju. R. Fiber-optic sensors. Moscow, Energoatomizdat, 1990 (in Russian).

25. Mixed fortunes forecast for optoelectronic components. Electro Optics. March 1991, p. 11.

26. Market for sensors will reach $ 935 M by 1996. Electro Optics, March 1991, p. 29.

27. Muramatsu H., Suda M., Ataka T. et. al. Piezoelectric resonator as a chemical and biochemical sensing device. Sensors and Aetuators. 1990, vol. A21-A22, p. 362-368.

28. Viens M., Cheeke J. D. H. Highly sensitive temperature sensor using SAW resonator oscillator. Sensor and Actuators, 1990, vol. A24, p. 209-211.

29. Wilson P. Silicon micro-machining. Sensor Review, 1990, v. 10, p. 178-181.

30. Jordan G. R. Sensor technologies of the future. GEC Review, 1987, vol. 2, No 1, p. 23-32.

31. Solid state sensors, actuators and interface electronics. IEEE Trans. on ED, 1979, vol. ED-26, No 12, p. 1861-1946.

32. Sensors. A comprenensive survey. Vol. 1 Fundamentals and general aspects. ED. W. Gopel, J. Hesses, J. N. Zemel. VCH, 1989.

33. Shiratori M., Katsura M., Tsuchia T. Halogenated hydrocarbon sensor. Proceed. of the 1st International Meeting on Chemical sensors, Fukuoka, Japan, Sept. 19-22 1983, p. 119-123.

34. Kirchnerova J., Bale C. W., Skeaff J. M. Ag-β Al_2O_3 solid

electrolyte for sensing arsine, AsH . Sensors and Actuators, 1990, vol.B2, No 1, p.7-10.

35. Sherbaum K.D., Weimar U., Göpel W. Multicomponent gas analysis: an analytical chemistry approach applied to modified SnO sensors. Sensors and Actuators. 1990, vol.B2, No 1, p.71-72.

36. Ichinose N. New developments in ceramic sensors. Erekuturonikusu, 1986, v.31, No 8, p.31-34.

37. Tsukada K., Miyahara Y., Shibata Y., Miyagi H. An Integrated chemical sensor with multiple ion and gas sensing. Sensors and Actuators, 1990, vol.B2, p.291-295.

38. Hellman H. Intelligent Sensors: The Merging of Electronics and Sensing. Englewood/Fort Lee (NJ) Technical insights, 1988.

39. Tshulena G.R. Die Sensorindustrie in Europa. Sensor Magazin, 1991, No2, p.7.-10.

40. Kako H., Yamane Y. Sensors and microcomputers. Tokyo, 1983.

41. Sensor Technology, 1991, January, p.5.

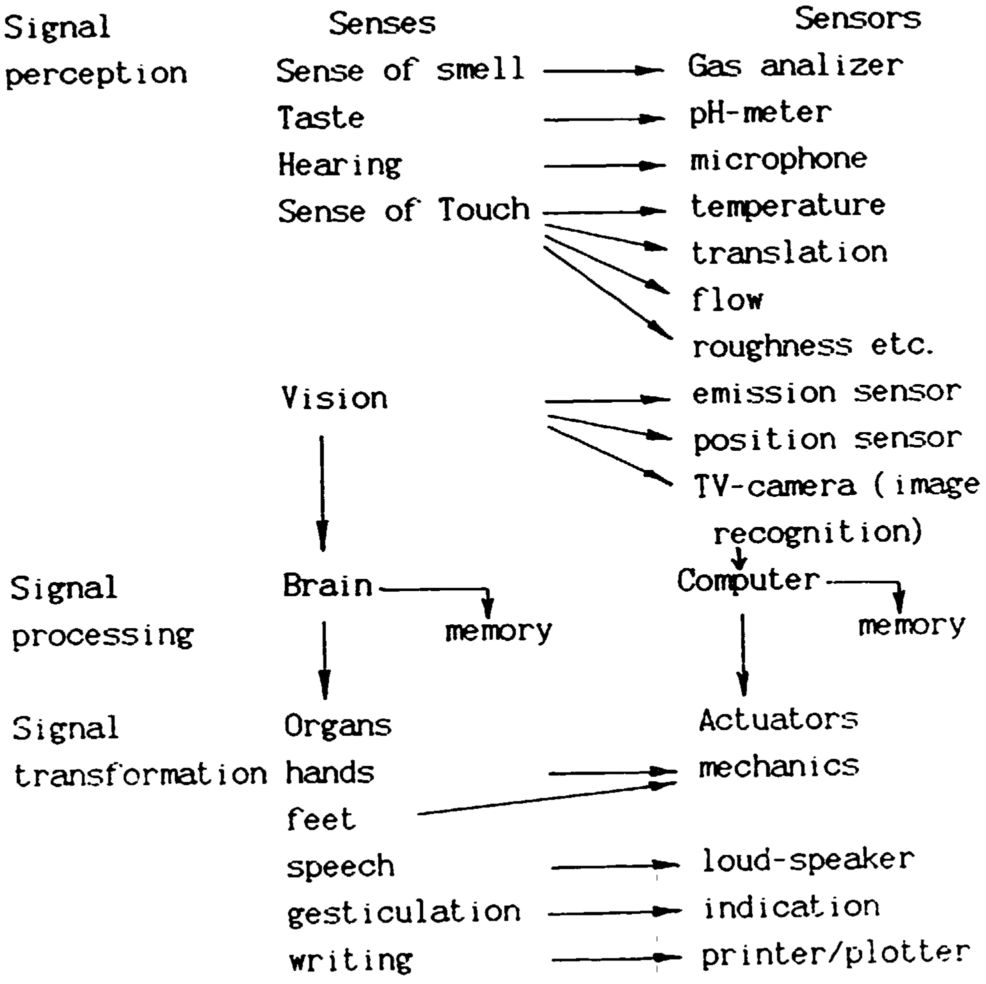
42. Mc Clelland S. Were are the opportunities? Sensor Review, 1990, January, p.22-24.

43. Bogue R. Sensor resea$\overset{r}{\vee}$ch-ripe for exploitation. Sensor Review, 1990, April, p.63-65.

Annex 1.

Correspondence between processes of signal perception, processing and tranformation for biological system (a man) and technical automatic system [5].

Biological system (man) Technical automatic system



Signal perception
Senses Sensors
Sense of smell → Gas analizer
Taste → pH-meter
Hearing → microphone
Sense of Touch → temperature
Sense of Touch → translation
Sense of Touch → flow
Sense of Touch → roughness etc.
Vision → emission sensor
Vision → position sensor
Vision → TV-camera (image recognition)

Signal processing
Vision → Brain → memory
TV-camera (image recognition) → Computer → memory

Signal transformation
Brain → Organs
Computer → Actuators
hands → mechanics
feet → mechanics
speech → loud-speaker
gesticulation → indication
writing → printer/plotter