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SENSORS

Editorial .... G. Harsányi 1

Application of thin-films in thermal sensors .... T. M. Berlicki, S. J. Osadnik and E. L. Procióv 2

A capacitive pressure sensor fabricated by a combination of SIMOX (SOI) substrates and novel etching techniques .... A. Medler, C. Patel and J. Butcher 6

Thick film PTC thermistor .... J. Hormadaly, J. R. Larry and S. Mergui 9

CMOS compatible temperature sensors .... V. Székely 13

Semiconductor gas sensor .... J. Mizsei 18

Hybrid technologies in sensors .... L. Pércsi, Cs. Császár, Zs. Keresztes-Nagy, R. Dobay and G. Harsányi 22

Business – Research – Education

Sensor story in Hungary .... E. Hahn 27

Practical education in semiconductor process technology at TU Budapest .... T. Kormány and V. Timár-Horváth 29

About NEXUS organization (network of excellence in multifunctional microsystems) .... V. Timár-Horváth 30

News – Events

Communication Technology '96 Budapest 32

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EDITORIAL

In the second half of the 20th century, the interest in the development of electric sensing devices, called sensors, has considerably increased. The scientific research was followed by an emerging demand from many fields of life. Various material structures are applied in sensors, depending on the nature of the quantity to be measured. Their spectrum ranges from single crystals through amorphous polymers to living cells. The sphere of various sensor types means also a broad spectrum from the mechanical and acoustic sensors to the measurement of electrochemical, chemical and biological quantities, including the conventional electric sensing transducers and even the new family of fibre optic sensors. Although the practical application of the sensors has been developing rapidly, the theoretical background of their operation is often a subject of discussion.

Integrated circuits and systems have changed many aspects of our life in the last decades. Moreover, while the microelectronics revolution has been spreading, the IC technologies have been gradually transforming the way of thinking of today's engineers and scientists about sensing devices.

The microprocessor is deaf, dumb, and blind without suitable sensors to provide input from the surrounding world of physical and chemical variables, such as pressure, acceleration, flowrate, temperature, humidity, concentration of chemical and biological compounds, etc. Without actuators, it is powerless to carry out control functions.

The wide-spread application of microprocessors and related memory units which are able to handle and store signals (the carriers of information) has created the need for low cost, high performance, high volume sensors and actuators. These devices that can be produced using similar IC batch processing techniques as the one used to manufacture microprocessors, memories and/or interconnecting systems, are finding their way into a myriad of new applications.

Conventional application fields of sensors are measuring and test of different physical and chemical quantities, the industrial process control, and/or automation. The new areas are mainly from the consumer field (e.g. domestic and automotive electronics, household, safety, comfort and pleasure) and from the highly advanced scientific areas (e.g. medicine, environment protection, research, etc.). The former need low cost, while the latter high reliability sensors.

Sensorics is a multidisciplinary territory and needs skills from many areas. Eastern and Central European countries are suffering from the problems of economical changes nowadays, however, the research, development and production of various sensors seem to survive. As an acknowledgement, several big international conferences have been held in Budapest, such as EUROSENSORS VII in 1993 and a NATO Advanced Research Workshop on "MCM and Sensor Technologies" recently in 1995.

The aim of the present issue is to promote and continue international cooperation, with giving the possibility for selected NATO-ARW participants to publish their newest results. The papers of Hungarian, Eastern and Western European, as well as US authors demonstrate an international conversation that might mean a start of future collaboration.

G. HARSÁNYI

Gábor Harsányi graduated in electrical engineering from the Technical University of Budapest in 1981 and received a doctorate in electronics technology from the same University in 1984. He then joined the Hungarian Microelectronics Company and conducted research and development of thick film sensors. Since 1984, he has been a member of the research and teaching staff of the Department of Electronics Technology, Technical University of Budapest, in the position of associate professor. His main research interests are the construction and technology of integrated circuits, electronic assemblies and microelectronic sensors. Recent key topics are: reliability, physics of high density electronic interconnection systems, polymers in sensorics, sensing film structures in fibre optic sensors. At present, he is head of the Sensors' Laboratory, TU, Budapest. In 1992, he received a Ph.D. from the Hungarian Academy of Sciences. He was 1993/94 President of the Hungarian Chapter of ISHM (International Society for Hybrid Microelectronics). He received the Best Paper of Session Award at the 1991 International Symposium on Microelectronics at Orlando, Fl, USA. He is also member of the Technical Program Committee of ISHM-Europe. He has an international reputation in the field of Microelectronics and Sensorics. His publishing activity is mainly in connection with IEEE, ISHM and Eurosensors conferences. He is a member of the Editorial Board of the journal "Hybrid Circuits". He has conducted several successful research projects both for industrial companies and for government funds. His scientific research, publication and related coordinating activity is supported by several Hungarian institutions such as the National Committee for Technological Development (OMFB), the National Scientific Research Fund (OTKA) and the Foundation for the Hungarian High Education and Research. He was involved in several international projects, e. g. PHARE-ACCORD. In 1994 and 1995 he co-chaired two NATO Advanced Research Workshops organized together with ISHM. Recently, he published a book "Polymer Films and Sensor Technologies" (Technomic Publishing Co., Inc., Lancaster, Basel).

APPLICATION OF THIN FILMS IN THERMAL SENSORS

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Examples of some thermal sensors based on thin film Ni, NiCr and NiCu made by the authors are given along with some basic relations describing the heat exchange in such devices. These are batch fabricated by using the method known in microelectronics. Examples of measurement results of some parameters of those constructions are presented.

1. INTRODUCTION

Utilizing thermal interactions provides the possibility of measuring of several quantities like gas and liquid flow rate, gas composition, concentration of solution, infrared radiation, pressure, humidity and many others [1]–[7]. Generally, it is assumed that the sensor output voltage can be expressed by the relation:

$$U = aZ_TP, \qquad (1)$$

where **a** is the sensitivity of an element sensitive to temperature changes, Z_T is thermal impedance (or thermal resistance R_T in the steady state conditions), P is the power supplied to the element.

Such kind of sensor can also be used for measurement of microwave power and non-sinusoidal signals as well as infrared radiation.

Utilizing the changes in Z_T value, which depend on the ambient thermal properties, it is possible to measure quantities like the rate of medium movement, changes in composition and pressure.

2. SENSOR DESIGN AND THE BASIC RELATION

Thermal sensors can be manufactured in a form of a single element, predominately thermoresistor, which simultaneously plays a double role as an element supplied with power and a sensor for temperature measurement. Such elements can be used both for power measurement as well as for measurement of thermal parameters of the medium. They are featured with simple design, small dimensions and relatively low price. Necessary protection against the harmful effect of environment can be realized by deposition of oxide layer (for example SiO_2) or by covering with glass foil.

The power balance for such type of element can be expressed in a form

$$P = \alpha A(T_e - T_a) + \frac{1}{R_L}(T_e - T_a) + Q_r, \qquad (2)$$

where **a** is the coefficient of heat transfer, A is the sensor surface, T_e and T_a are temperatures of the element and medium, R_L is the thermal resistance of leads, Q_r is the power dissipated by thermal radiation. Coefficient α depends on the medium parameters and on heat transfer mechanism (natural or forced convection, conduction to the package).

In the case of natural convection [2]

$$\alpha = C\lambda(Gr\ Pr)^n, \qquad (3)$$

where λ is the heat conductivity, Gr and Pr are Grashof and Prandtl numbers

$$Gr = \beta g(T_e - T_a)\frac{L^3}{\nu^2} \qquad Pr = \frac{\mu}{\lambda}C_p,$$

where β is the coefficient of volume expansion, g is the acceleration of gravity, is the sensor dimension, $\nu = \mu/\rho$, μ is the coefficient of dynamic viscosity, ρ is the density, C_p is the specific heat, C and n are constants.

In case of the forced convection

$$\alpha = C_1\frac{\lambda}{L}Re^{1/2}\ Pr^{1/3}, \qquad (4)$$

where L is the sensor dimension along the fluid flow path, Re is Reynolds number, $\mathrm{Re} = vL/\nu$ and v is the flow rate of medium [2].

In many applications it is advantageous to separate the element for power supply from the element for temperature measurement. In such case the input element, where power is supplied, is made in a form of resistor, whereas changes in temperature are measured with a thermoelement or thermoresistor.

Typical designs of such elements are shown in Fig. 1.

Glass foil or SiO_2 membrane made on silicon are the most common substrates for the sensors fabrication. The materials are featured with low thermal conductivity, ensuring high value of thermal resistance of the sensor, which is a condition of its high sensitivity. In case of the design shown in Fig. 1, power transfer takes place through the medium and substrate material. For the circular geometry Fig. 1a [4]

$$P = \alpha\pi r_e^2(T_e - T_a) +$$

$$+(T_e - T_a)\frac{I_0(kr_a)K_1(kr_e) + K_0(kr_a)I_1(kr_e)}{I_0(kr_a)K_0(kr_e) - K_0(kr_a)I_0(kr_e)}, \qquad (5)$$

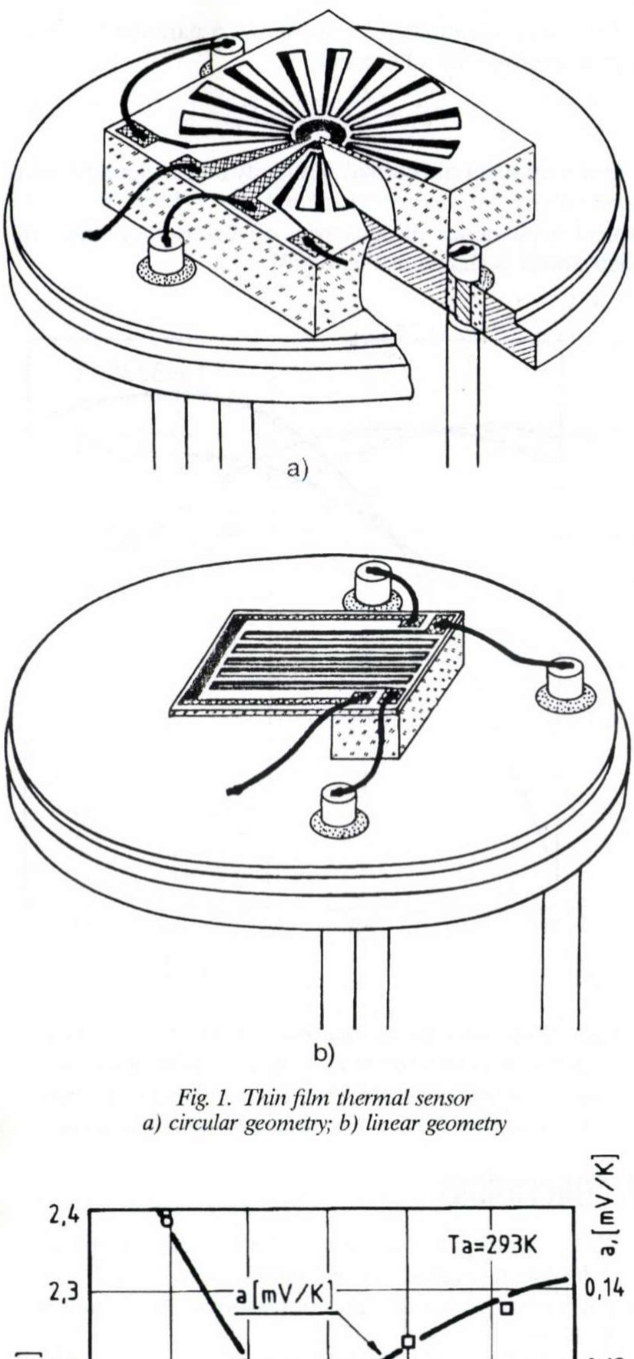
where r_e is the radius of heating resistor, r_a is the outside radius of the thermoelement, I_0, I_1, K_0, K_1 are the modified Bessel functions, d is the substrate thickness and

$$k = \sqrt{\frac{\alpha}{\lambda d}}.$$

In case of linear geometry, shown in Fig. 1b

$$P = \alpha w w_e(T_e - T_a) + \frac{1}{w\sqrt{\alpha\lambda d}}\tanh[L - w_e)\sqrt{\frac{\alpha}{\lambda d}}], \qquad (6)$$

where w is the width of the chip and w_e is the width of heating resistor.



a)

b)

Fig. 1. Thin film thermal sensor
a) circular geometry; b) linear geometry

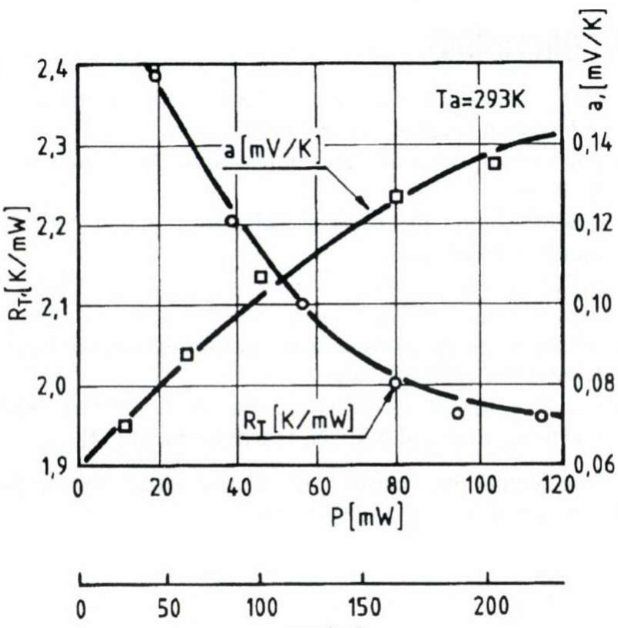


Fig. 2. Sensitivity of the thermopile and thermal resistance of the linear sensor on TO-5 base (Fig. 1b)

Coefficient of heat transfer α depends on thermal parameters of surrounding medium. The dependence of thermal resistance $R_T[R_T = (T_e - T_a)/P]$ of a sensor with dimensions $1.62 \times 2 \times 0.1$ mm, mounted on TO-5 package, on supplied power is shown in Fig. 2. Decrease in substrate thickness causes an essential increase in R_T value.

3. SENSORS

Thermoelements and thermoresistors are commonly used as the elements which respond to temperature difference changes in a sensor. Thermoresistors can be made of metal layers (the typical ones are Ni or Pt) or semiconducting layers. Ni and Pt layers have high value of the coefficient of thermal resistance (TCR) and simultaneously have good time stability.

The authors deposited Ni layers both by evaporation as well as by magnetron sputtering methods and obtained high TCR values and good stability at temperatures below 250°C [8], [9]. The authors examined also the doped Si and Ge layers featured with high negative value of TCR [10]. A typical dependence of TCR on temperature for Si layers doped with B is shown in Fig. 3. Si was deposited by magnetron sputtering. The material is featured with good adhesion to the substrate and high time stability.

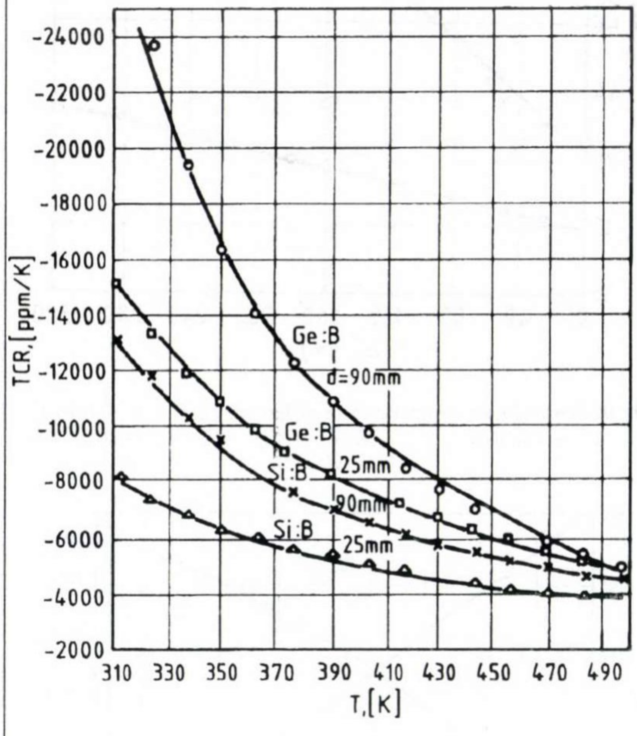


Fig. 3. TCR versus temperature for Si and Ge layers (d = distance between target and substrate during the deposition)

Investigations of several material sets for multilayer thermoelements have also been performed. There were examined both metal layers: NiCr, NiCu, Ni as well as layers doped with germanium [10]–[12]. Metal layers were deposited by magnetron method. The method gives the possibility of good reproduction of the alloy composition. However, when magnetic materials like Ni, NiCr are deposited it is advisable to design an appropriately shaped target or use the magnetic fields with high strength in order to avoid short-circuiting of magnetic field by the target.

Typical characteristics of sensitivity of the metal thin film thermoelements are shown in Fig. 4. Much higher values of sensitivity can be obtained in case of thermoelements made of semiconductor materials. It is however at the cost of much higher resistivity of those layers. Typical characteristics of resistivity and sensitivity **a** on temperature of Ge layers doped with Au is given in Fig. 5. Ge layers doped with Au can be deposited by evaporation as well as by magnetron sputtering methods. In the first case similar evaporation temperatures of Ge and Au guarantee the good reproducibility of composition for this method of deposition.

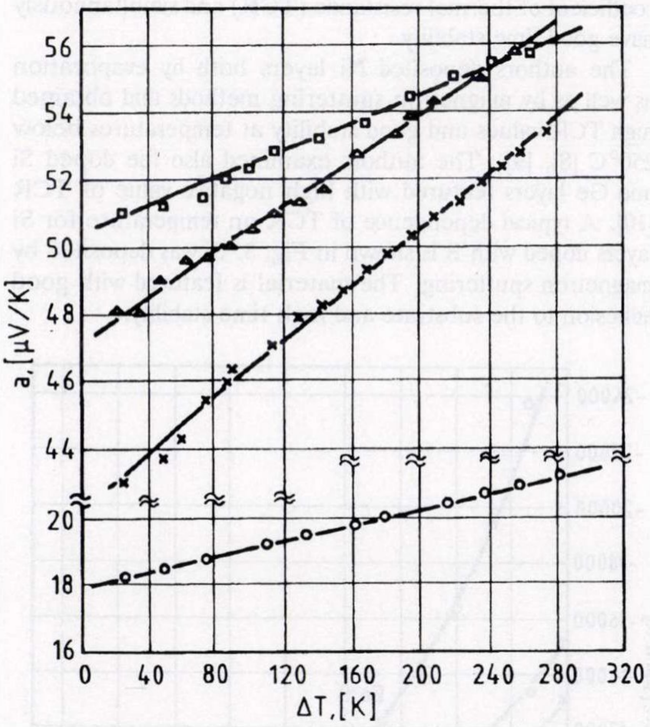


Fig. 4. Sensitivity versus temperature difference ($\Delta T = T - 300$ K):
□ – *CuNi-Fe;* Δ – *CuNi-NiCr;* X – *CuNi-Cu;*
○ – *NiCr-Ni*

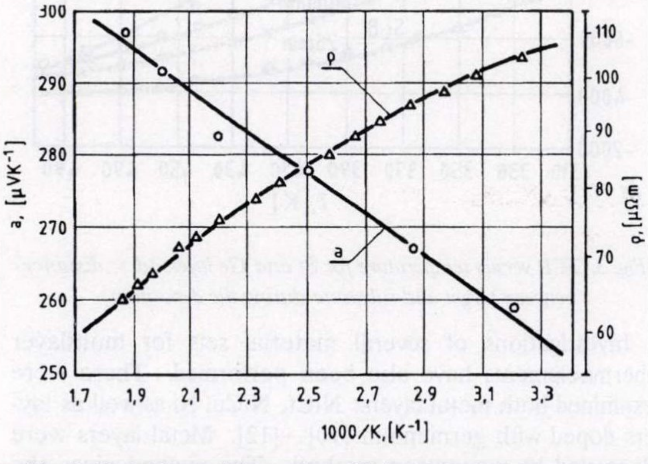


Fig. 5. Resistivity and thermal sensitivity of GeAu 2.2at. layer (0.5 µm) working with CuNi as thermocouple

From the relationship (1) it follows a parameter, which is characteristic for all sensors

$$S = \frac{U_{\text{out}}}{P} = aZ_t. \qquad (7)$$

It is a quotient of thermal sensitivity of the element measuring changes in temperature and thermal impedance. A typical dependence of sensitivity of a sensor on the supplied power is shown in Fig. 6 [13].

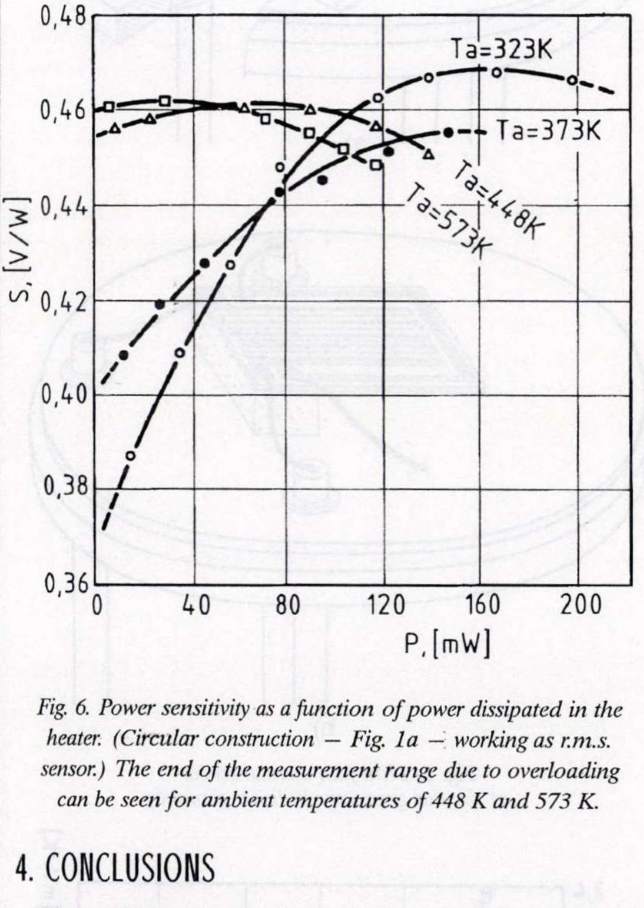


Fig. 6. Power sensitivity as a function of power dissipated in the heater. (Circular construction – Fig. 1a – working as r.m.s. sensor.) The end of the measurement range due to overloading can be seen for ambient temperatures of 448 K and 573 K.

4. CONCLUSIONS

The authors, on the basis of the mentioned materials and designs fabricated several types of sensor:

- flow-sensor, consisting thermoresistor of Ni [8] and Si + Ta layers;
- flow-sensor on the basis of NiCr resistor and NiCr-Ni thermoelement [14];
- high-frequency power transducer (r.m.s.) with NiCr resistor and NiCr-Ni thermoelement [15];
- psychometric humidity sensor (thermoelements of NiCr-Ni and NiCr-NiCu) [16];
- pressure sensor (from 0.1 MPa to 1.5 MPa) NiCr thermoresistor and NiCr-Ni thermoelement [17].

The mentioned sensors are characterized by simple design, good stability and reliability.

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Stanislaw J. Osadnik graduated in electronics engineering in 1960 and received a doctorate in electronics engineering in 1966, both from the Technical University of Wroclaw. In 1970-1971 he joined Pennsylvania State University, USA, for postdoctoral research. After additional research on thin film materials at the Technical University in Wroclaw, he received a doctorate in sciences in 1976. Since 1976 he has been a professor at the Institute of Electron Technology in Wroclaw. He is the head of the Hybrid Microcircuits Group currently involved in research on thin film materials for microsensors.

Eugeniusz L. Prociów obtained an M.Sc. degree in electronics engineering in 1973 from the Technical University of Wroclaw. In the same year he joined the Institute of Electron Technology at the same university. During 1990 and 1991 he was in Kassel, Germany, engaged in a joint research program on ion and plasma deposition; then he rejoined the Institute of Electron Technology, where he is at present a Ph.D. candidate. His recent work has involved studying the performance of thin metal-semiconductor films and their application to thin film thermal sensors.

A CAPACITIVE PRESSURE SENSOR FABRICATED BY A COMBINATION OF SIMOX (SOI) SUBSTRATES AND NOVEL ETCHING TECHNIQUES

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Silicon technology has been employed for several years for the manufacture of pressure sensors for the vast world-wide market. However many popular designs suffer from process induced stresses. The structure described in this paper, has been designed from silicon on insulator (SOI) material. In addition to avoiding these traditional problems, circuitry can be readily incorporated due to the use of standard processing steps. The monocrystalline silicon diaphragm is expected to display improved performance over more common materials used for the sensing element. The fabrication process begins with the opening of a window in the top silicon by wet or dry etching. Through this opening, with the surrounding silicon acting as a mask, buffered hydrogen fluoride is used to isotropically etch the buried silicon dioxide to form a cavity. When a pressure is applied to the device, the diaphragm deflects, detected by an increase in the capacitance between the diaphragm and substrate. By avoiding back etching, chip size and etch time are reduced while mechanical strength is increased. The pressure sensor is designed to measure in the range 0–250 mmHg and to achieve this many single diaphragms are interconnected in a matrix arrangement. This novel fabrication technique can be applied to the manufacture of many microstructures for other sensing and actuating applications.

1. INTRODUCTION

Many pressure sensors exist with various measurement ranges and applications. Silicon technology has been successful in the precision and low cost (low accuracy) sectors of the market. The total pressure sensor sales in Western Europe are predicted to be 35.7 million units by 1977 [1]. There has been a recent trend towards capacitive devices [2], away from piezoresistive designs for several reasons including their inherent difficulties with long term stability, low pressure measurements, temperature drift and low yield [3]. Common methods for fabrication of capacitive pressure sensors include boron doping, silicon direct wafer bonding or bonding to pyrex substrates. The high boron doping acts as an etch stop but can result in high stress which is problematic for suspended structures. Silicon wafer bonding can cause diaphragm warping, require high temperature and the resulting films can have unbounded areas and trapped bubbles [7]. Pyrex bonding can lead to a mismatch in thermal expansion coefficients between diaphragm and substrate at high and low temperatures resulting in stress [6]. The undoped structure designed here does not suffer from these process induced stresses and allows the incorporation of circuitry in the structures [4], [5].

The design described below avoids these processing problems and incorporates a monocrystalline silicon diaphragm which has improved performance over polysilicon, silicon nitride and other material layers common in sensing elements. Further design benefits are provided by the SIMOX material producing a thin diaphragm and small cavity depth — both well controlled; resulting in high stability and reproducibility and the provision of natural etch stops without necessitating implantation for high doping levels or electrochemical control.

The fabrication procedure is simple, using few masking steps and front side only processing. This increases the mechanical strength of the chip and reduces the size and process time over back, or front and back etched designs. The metal contacts and bonding pads can be formed using aluminium deposition. A window is then dry etched through the top silicon layer and using the same photoresist mask this is then underetched to form a diaphragm suspended above a cavity. This is achieved by the removal of a section of the buried silicon dioxide in buffered hydrogen fluoride, using etch time to control the diaphragm diameter and ultimately pressure measurement range.

The production of this performance pressure sensor demonstrates the feasibility of SIMOX technology. The significance is increased by the applicability of this technology to the fabrication of other microstructures for sensing and actuating applications.

2. FABRICATION AND DISCUSSION

The simple process sequence from the initial SIMOX wafer is shown in Fig. 1. A small window is etched through the top silicon layer to expose the buried oxide, using a photoresist mask. For this, a silicon etchant with a slow etch rate and with silicon:silicon dioxide selectivity was required. Both wet and dry (RIE) etching procedures have been investigated for this step and currently a potassium permanganate based wet etch has been implemented.

The buried oxide is then etched from below the silicon to form a cavity. A number of possible etchants were investigated and an appropriate solution and etching procedure was determined and characterized for the controlled lateral etching of silicon dioxide. The important criteria being a high etch rate and high selectivity over silicon to minimize effects on the silicon top layer. There is a linear relationship between etch time and underetch distance, which is independent of the size of the etch window within the experimental range used.

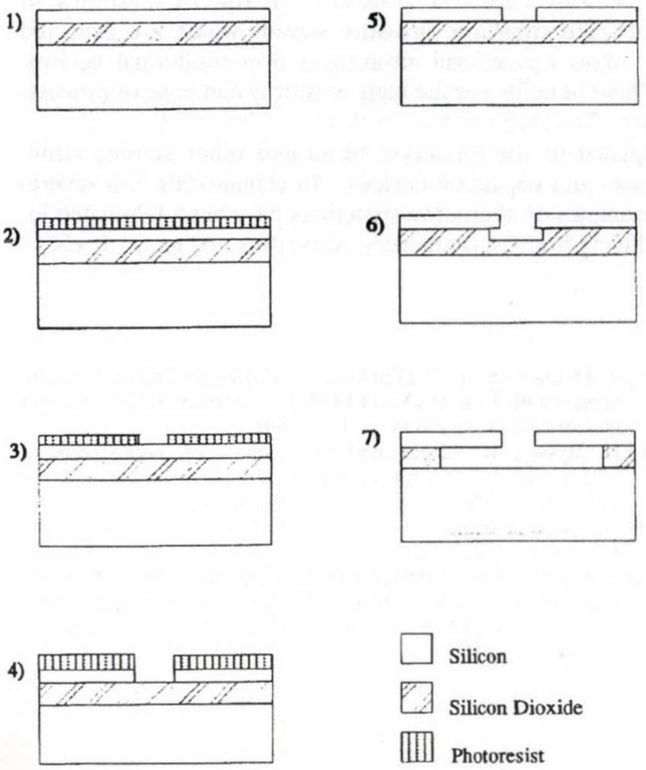

Fig. 1. The fabrication procedure

The challenge of retaining metallization through a long hydrogen fluoride etch, was addressed and overcome either by using a thick metallization layer which could be retained unprotected through etching or by application of the metal as a final step, subsequent to diaphragm formation and protection. In either case the metal layer is deposited by magnetron sputtering and defined by photolithography and etching. It is then sintered to form interconnects and contact pads.

The access window and therefore, diaphragm are circular, this increases sensitivity and eliminates cracking from stress concentration at sharp corners of the access windows, a problem which was initially experienced. A series of low surface tension rinses was developed to reduce the likelihood of stiction, another common cause of diaphragm collapse and therefore device failure, often seen in early fabrications [8]. Stiction is common in microstructure fabrication. It is an effect thought to be caused by a combination of van der Waals and other forces which pull the suspended element into contact with the substrate where it becomes stuck, ultimately resulting in device failure. This occurs as the rinse water, trapped under or inside a structure dries following etching. Finite element modelling has been used to confirm the feasibility of this structure and aid its design. Results indicate that the maximum diaphragm stress occurs around the central etch window but is well below the fracture stress for silicon.

A single diaphragm device was then successfully fabricated using the optimized fabrication routine described above (Fig. 2). To increase the device output with respect to parasitic capacitances, an interconnected matrix of these single diaphragms has now been designed and fabricated. The matrix comprising of 2500 single sensing membranes has an expected full scale capacitance change of 10 pF. It is believed that single device failure will be relatively insignificant (Fig. 3).

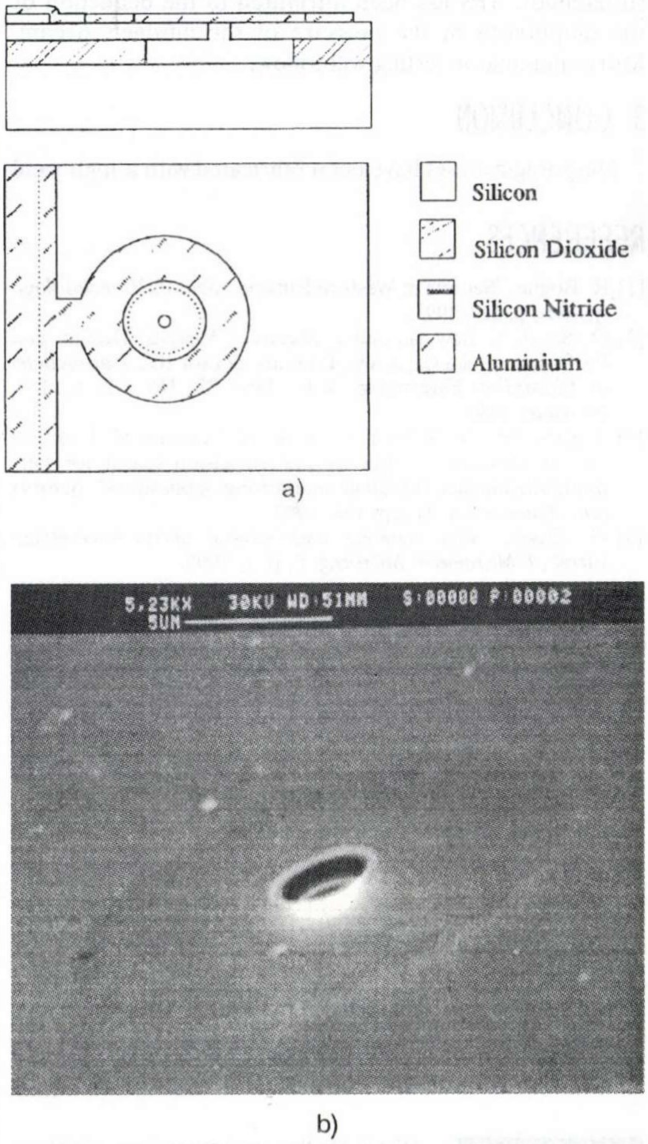

Fig. 2. The single diaphragm design
a) Device design with interconnection; b) SEM image of a device

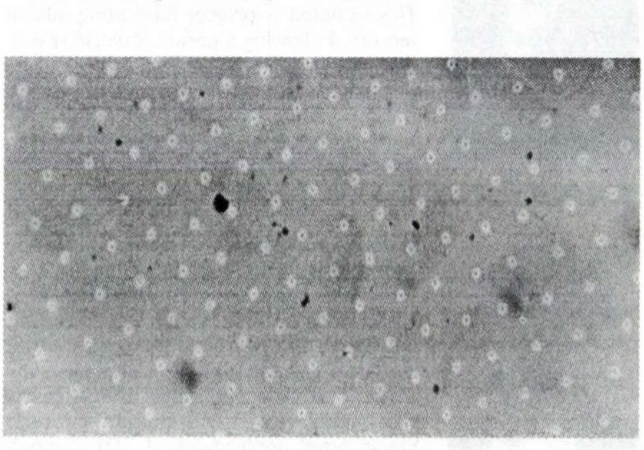

Fig. 3. A matrix of devices

Simple 'functionality' tests were then carried out using a nitrogen stream directed at the diaphragm. A small change in capacitance could be detected, coinciding in time with the application of flow and not present in the absence of nitrogen flow or with virgin SIMOX sample (unetched). This has been attributed to the deflection of the diaphragms by the pressure of the nitrogen stream. More quantitative testing will follow.

3. CONCLUSION

Diaphragm arrays have been fabricated with a high yield (98 % in 2500 membranes successfully manufactured). This demonstrates that it is plausible, using conventional processing steps in conjunction with SIMOX substrates, to fabricate capacitive pressure sensors which are expected to show operational advantages over traditional devices. These benefits include high sensitivity and ease of processing. Furthermore this method of fabrication can also be applied to the formation of various other sensing structures and capacitive devices. To demonstrate this several examples of alternative structures have been fabricated including bridges, cantilevers, resonators and gear wheels.

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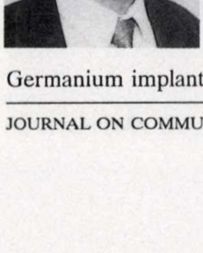

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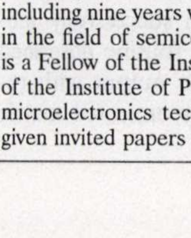

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THICK FILM PTC THERMISTOR

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Electrical properties of DuPont thick film PTC thermistors 5091, 5092, 5093 and 5393 have been studied as a function of temperature, frequency and voltage. Resistance variations are essentially linear with temperature down to 100 K. Measurements performed at extended range 4–300 K show no resistance minimum and suggest the use of these materials for cryogenic temperature sensing. Lack of resistance minimum is discussed in connection with the published conducting mechanisms of thick film resistors. Sensitivity to voltage pulsing increases with resistance. Dependence of resistance has been obtained in the range of DC to 100 kHz. Resistance is essentially independent of frequency.

1. INTRODUCTION

Positive temperature coefficient (PTC) thermistors are usually [1] separated into two categories, switching PTC thermistors such as $BaTiO_3$ and elemental PTC thermistors such as silicon, germanium and platinum. Thick film PTC thermistors are a relatively new addition to the PTC thermistors. DuPont compositions 5091, 5092, 5093 and 5393 are based on ruthenium pyrochlore chemistry and display unique properties [2]−[4]. These compositions have a high positive temperature coefficient of resistance (TCR), of the order of 3000 ppm/°C, which is typical for metals. Detailed electrical properties concerning process sensitivity to peak firing, profile and compatibility with various thick film conductors were reported in a previous NATO workshop [2].

The 5091, 5092, 5093 and family of 5393 thick film PTC thermistors displays a unique combination of properties: a large resistance range spanning 10 $\Omega/\square$ to $\sim$ 3000 $\Omega/\square$ high positive TCR, outstanding stability after laser trimming, linear dependence of resistance on temperature in a fairly broad range, compatibility with Ag, Ag/Pd and Au conductors, ease of processing, and fairly low process sensitivity for the low end members. This combination of properties allows high reproducibility and interchangeability, which are very important in thermistor applications [5], [6]. Besides the obvious advantage of having high positive TCR and linear dependence of resistance on temperature, these PTC thermistor compositions are also interesting from a theoretical point of view: typical thick film ruthenium based compositions are resistors with a small TCR and a resistance minimum. This resistance minimum usually occurs at room temperature and can be shifted by the inclusion of semiconducting oxides known as TCR drivers. Previous studies [3], [4] have shown that these PTC thermistors do not have a resistance minimum in the temperature range of liquid nitrogen to $\sim 250°$C.

The aims of this paper are to present resistance measurements at lower temperatures for location of the resistance minimum when such a minimum exists and to assess the use of these PTC compositions as cryogenic thermal sensors. In addition to the above, resistances were measured as a function of applied voltage (ESD) and as a function of frequency in the hope of shedding more light on the conduction mechanism of these PTC compositions.

2. EXPERIMENTAL

Four commercially available thick film PTC sensor compositions, DuPont 5091, 5092, 5093 and 5393, were studied. This series is based on ruthenium pyrochlore chemistry and spans a resistance range of 10 $\Omega/\square$ to $\sim$ 3000 $\Omega/\square$. Electrical connection to the sensors was through prefired thick film metallizations; although these compositions are compatible with Ag, Ag/Pd and Au thick film conductors, a DuPont 7484 Ag/Pd was selected for this study. Sensors were prepared by standard thick film processing: 7484 Ag/Pd was printed on 96 % Al_2O_3 substrates and fired according to a short Birox® profile (30 minutes cycle with 10 minutes at peak temperature of 850°C). Subsequently, PTC sensor pastes were printed on the metallized substrates, dried and fired according to recommended protocol. A short Birox® profile was used for the PTC paste compositions. The dried thicknesses of the PTC compositions were generally $25 \pm 3\ \mu$. Standard thick film techniques were used to measure the voltage response of the fired compositions; an ESD test was used for this purpose. Sensors were subjected to a voltage pulsing in the range of 500 to 5000 V. A two-probe technique was used in the ESD measurements.

Resistance as a function of temperature was measured in a cryostat for very low temperatures. The compositions were measured at FIU, where the low temperature range was 30K. The two-probe technique was used for all compositions. 5393 was measured down to liquid He temperature at the DuPont experimental station. Three compositions (5091, 5092, and 5093) were measured in the frequency range of DC to 100 kHz. These measurements were done at room temperature and down to 30 K using a two-probe technique.

3. RESULTS AND DISCUSSION

3.1. Resistance as a function of temperature

Figs. 1 to 4 present the variation of resistance with temperature for 5091, 5092, 5093 and 5393 respectively. All four compositions show a similar behaviour: resistance is essentially linear with temperature down to $\sim$ 100 K, and below K the slope of resistance decreases. Figs. 1−3 show no resistance minimum down to $\sim$ 30 K. Fig. 4

(5393) shows no resistance minimum even when the temperature range is extended to 4 K. Fig. 4 (5393) represents the most sensitive composition, because 5393 contains the lowest volume fraction of pyrochlore conductive. Based on the behaviour of 5393, one would expect the more metallic compositions 5091, 5092 and 5093 to show similar behaviour to 5393. Although the slope of resistance decreases in the temperature range of 4 – 100 K, the change in R versus T is still sufficiently large for cryogenic temperature sensing.

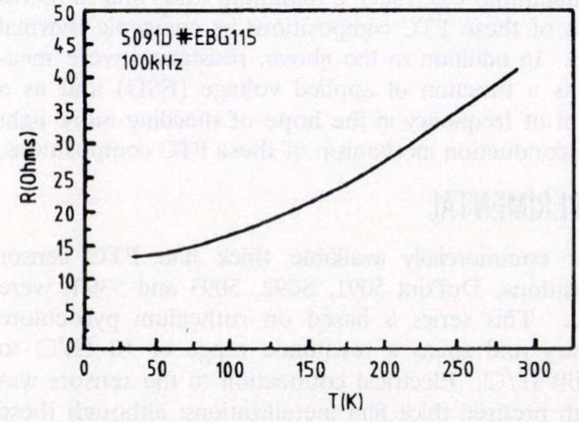

Fig. 1. Resistance as a function of temperature, 5091

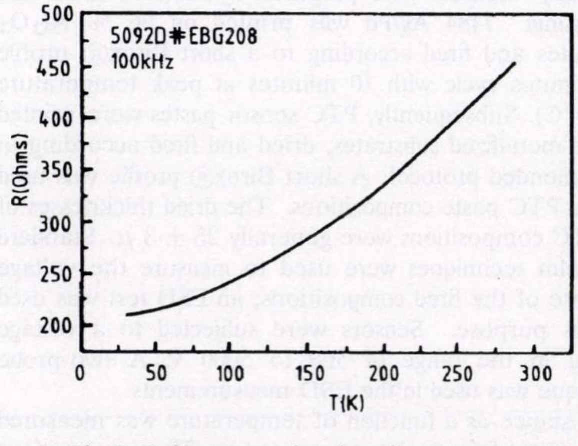

Fig. 2. Resistance as a function of temperature, 5092

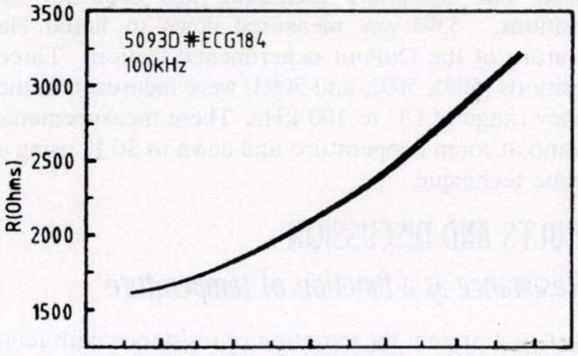

Fig. 3. Resistance as a function of temperature, 5093

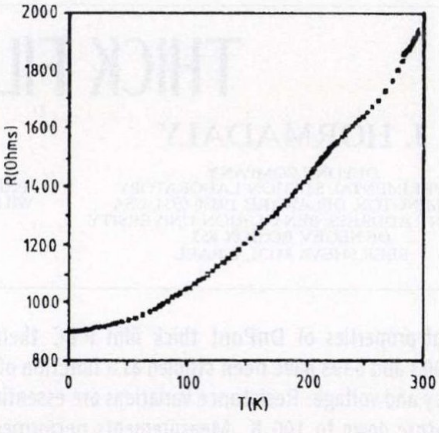

Fig. 4. Resistance as a function of temperature, 5393

The lack of a resistance minimum in the fairly broad temperature ranges 4 – 300 K (this study) and 77 – 523 K [3] raises questions about the conduction mechanism of these compositions and of thick film resistors in general. The compositions are very similar to typical thick film resistors in that they contain ruthenium pyrochlore conductive, glassy phase and fillers. However, in their electrical properties (R versus T) they are very different from thick film resistors. Seager & Pike [7] in their detailed study of thick film resistors accounted for the resistance minimum by assuming a mechanism of tunnel barriers with impurities in the barrier (glass). These impurities assist conduction by acting as resonant tunnelling centers. A combination of metallic, metal insulator metal and particle charging energy [7] equation was derived to describe the behaviour of thick film resistors. This equation is given below:

$$R(T) = \frac{R_{0'}}{2}\left(\frac{\sin aT}{aT}\right)[1+\exp(E/kT)]+R_0'(1+bT),$$

where R_0, R_0', a, b are constant and E is one half of the charging energy (E_c). The electrical behaviour of the PTC thermistors, namely, the lack of resistance minimum, suggests that the conduction mechanism in disordered systems such as the present system and the related thick film resistors, results from the strong interaction of ruthenium pyrochlore with the glassy phase and possibly from reorientation of the conducting particles (as such and conducting particles such as RuO_2, which are a result of this interaction [3]).

3.2. ESD Tests

Voltage pulsing results are given in Table 1. and Fig. 5. Both show that the low end members 5091 and 5092 are essentially insensitive to voltage pulsing up to 5000 V. This behaviour is typical of thick film resistors with a fairly high volume fraction of conductive phase. The volume fraction of the conductive phase in the PTC thermistors is given qualitatively by: 5393<5093<5092<5091.

Compositions 5093 and 5393 are sensitive to voltage pulsing, sensitivity increasing as the volume fraction decreases, i.e. in the order 5093<5393. This behaviour may be accounted for by assuming continuous paths of metallic particles in the fired sensor, the number of these paths increasing with the volume fraction. By application of sufficiently high voltage pulsing, some of these paths become open and cause the increase in resistance. This effect is very small for compositions with a high volume fraction (and hence many conducting paths) such as 5091 and 5092.

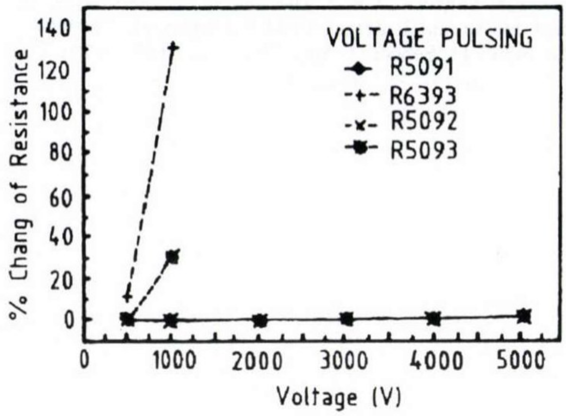

Fig. 5. Resistance change as a function of voltage

Table 1. Voltage pulsing (ESD of 5091, 5092, 5093 and 5393)

Pro-duct	Lot #	% Change of Resistance at					
		500 V	1000 V	2000 V	3000 V	4000 V	5000 V
5091	DEG-053	-0.118 (0.41)*	-0.161 (0.33)	-0.129 (0.58)	-0.189 (0.56)	-0.182 (0.49)	-0.252 (0.47)
5092	DDG-048	-0.041 (0.20)	+0.017 (0.27)	-0.28 (0.40)	-0.27 (0.16)	-0.012 (0.36)	0.028 (0.15)
5093	DIH-105	3.52 (0.36)	113.0 (30.0)	–	–	–	–
5393	E81217-66A	22.1 (11.0)	692.0 (130.0)	–	–	–	–

* Values in parenthesis are standard deviations
5 resistors were measured for each composition

3.3. Frequency Dependence

Variation of resistance with frequency was measured in the DC range up to 100 kHz. Results of log-log plotting are given in Fig. 6 for 5091, 5092 and 5093. In this plot the resistance is independent of frequency in the range studied. When the resistance is plotted on a linear scale versus frequency on a log scale, it becomes clear that the resistance decreases slightly with frequency. The decrease in resistance with frequency is typical to disordered systems [8]; usually the conductivity (σ) follows: $\sigma(\omega)\alpha\omega^S$, where ω is the frequency and S is a constant.

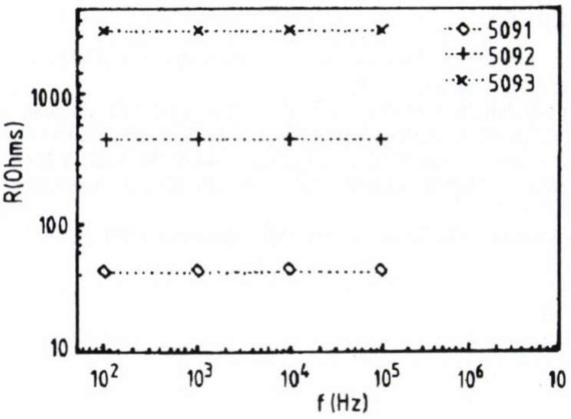

Fig. 6. Resistance as a function of frequency for 5091, 5092 and 5093

4. SUMMARY

Electrical properties of DuPont 5091, 5092, 5093 and 5393 thick film PTC thermistors have been measured as a function of temperature, voltage and frequency. Resistances are linear with temperature for a fairly broad temperature range. No resistance minimum was found for these compositions in a broad temperature range. This unique behaviour of materials which are chemically thick film resistors suggests a conduction mechanism that does not involve tunnelling barriers. The data also suggest a key role for the interaction of the conductive phase with the glassy matrix. We believe that this interaction controls the conducting mechanism. These compositions have sufficient resistance change at low temperature to make them candidates for cryogenic temperature sensing. Sensitivity to voltage pulsing increases with resistance; low end members 5091 and 5092 are essentially independent of voltage pulsing in the range of 500 – 5000 V. Members with a smaller volume fraction of conductive phase (5093 and 5393) are sensitive to voltage pulsing and show increase in resistance. This increase may be accounted for by assuming a small number of metallic conducting chains, which become nonconducting by application of voltage.

Frequency dependence of resistance in the DC-100 kHz range has been obtained. The PTC compositions are essentially independent of frequency in the range studied. Log-log plotting shows independence of resistance with frequency. Semilog plotting reveals a slight decrease of resistance with frequency. This decrease of resistance with frequency is typical of disordered systems.

5. ACKNOWLEDGEMENTS

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CMOS COMPATIBLE TEMPERATURE SENSORS*

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The application of MOS — especially CMOS — circuits is becoming more and more dominant in integrated circuit technology. This explains the increasing interest in CMOS realizations of monolithic temperature sensors lately. We pay special attention to a specific application of temperature sensors namely when the aim is to check the integrated circuit chip itself and prevent its overheating. The outlined sensor arrangements will be qualified upon whether they are suitable or not for the above purpose. Architectural problems of built-in thermal test circuits will be examined in detail. In the paper a few of the possible realizations are discussed.

1. INTRODUCTION

The application of MOS — especially CMOS — circuits is becoming more and more dominant in integrated circuit technology. This explains the increasing interest in CMOS realizations of monolithic temperature sensors lately. We pay special attention to a specific application of temperature sensors namely when the aim is to check the integrated circuit chip itself and prevent its overheating. The outlined sensor arrangements will be qualified upon whether they are suitable or not for the above purpose. Architectural problems of built-in thermal test circuits will be examined in detail.

2. PTAT SENSORS

A typical temperature sensing solution in bipolar technique is to exploit the temperature dependence of the forward biased diode. The ideal diode equation is

$$I = I_s\left(e^{\frac{qV}{kT}} - 1\right), \qquad (1)$$

where the I_s saturation current is also temperature dependent:

$$I_s(T) = const \cdot T^3 \cdot e^{-\frac{qU_g}{kT}}. \qquad (2)$$

(U_g is the bandgap voltage, $k = 1.38 \cdot 10^{-23}$ VAs/K is the Boltzmann constant while $q = 1.6 \cdot 10^{-19}$ As is the elementary charge.) Since the absolute temperature T appears in three different terms of (1) and (2) this yields a quite complicated temperature dependence. Luckily, however, driving the diode by a constant forward current results in a more-or-less linearly temperature dependent diode voltage:

$$V(T) = T\left(\frac{V_0}{T_0} - \frac{U_g}{T_0}\right) - 3\frac{k}{q}T \cdot \ln T/T_0 + U_g. \qquad (3)$$

It gives a temperature sensitivity between -1 mV/K and -2 mV/K, which is a reasonable value. T_0 is an arbitrary reference temperature and $V_0 = V(T_0)$. The forward characteristics of a pn junction is stable, barely dependent on the inaccuracies of the fabrication process — thus a sensor with acceptable features can be built using a single diode.

The nonlinear effects can be eliminated using the principle explained in Fig. 1. We use two diodes driven by the same current but the cross-sectional area of diode "B" is n times larger than that of diode "A" (in an exact realization diode "B" consists of n diodes of size "A" connected in parallel). The output voltage is the difference of the voltages of the two diodes. This can be calculated as:

$$V_{out} = \frac{kT}{q} \cdot \ln n. \qquad (4)$$

V_{out} is obviously proportional to the absolute temperature. This is why such circuits are called PTAT (Proportional To Absolute Temperature) sensors [1], [2]. This way we can obtain a sensor with completely linear characteristics which is an indisputable advantage. The sensitivity is very stable since it depends only on physical constants (k and q) and on n, the number of diodes forming diode "B". On the other hand it is a disadvantage that this sensitivity is quite low: e.g. 0.12 mV/K for $n = 4$.

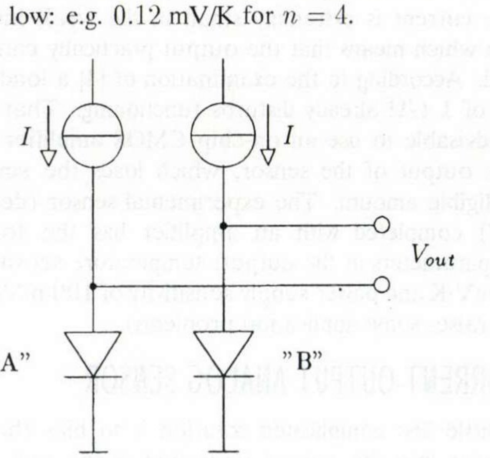

Fig. 1. Principle of a bipolar PTAT sensor

The idea of the PTAT sensor can also be implemented in MOS realization. One possibility is to use pn diodes (or bipolar transistors) within the MOS circuit. The technology usually enables this though with certain limitations. The other possibility is to use the MOS transistor in a region where its characteristics is of exponential nature. The MOS transistor has such a characteristics in the weak inversion region. The exploitation of this region for sensing is mentioned in [1], a possible realization integrated into a constant current source design is presented in [3]. A similar solution was published in [4] as a stand-alone temperature sensing cell.

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The block-scheme of the solution can be seen in Fig. 2a. The two MOS transistors have the same current. Since they are of different size (W/L ratio), their V_{GS} voltages are also different. The difference of these two voltages appears on the output node. While operating in the subthreshold region the output voltage is proportional to the absolute temperature due to the exponential transistor characteristics

$$V_{out} = V_{GS1} - V_{GS2} = \frac{kT}{q} \ln\left(1 + \frac{(W/L)_2}{(W/L)_1}\right). \quad (5)$$

Thus we have a PTAT sensor, again. Since the output voltage is quite low several of such sensors should be connected in series — a simple solution is outlined in Fig. 2b.

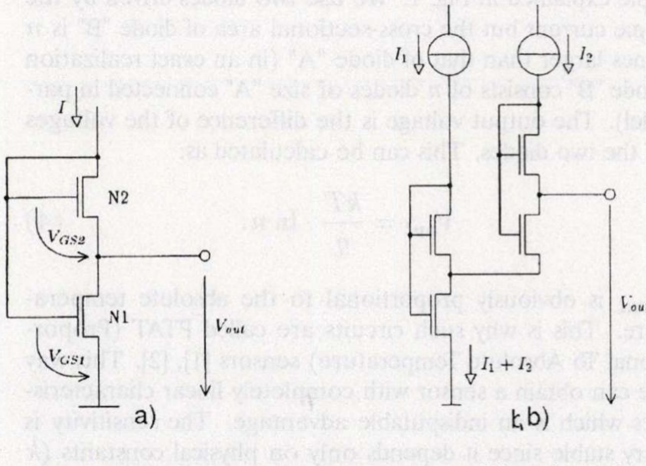

Fig. 2. MOS PTAT sensor operating in the weak inversion region a) single stage; b) two stacked stages

The current is extremely small in the weak inversion region which means that the output practically cannot be loaded. According to the examination of [4] a load in the order of 1 $G\Omega$ already disturbs functioning. That is why it is advisable to use an on-chip CMOS amplifier circuit at the output of the sensor, which loads the sensor in a negligible amount. The experimental sensor (described in [4]) completed with an amplifier has the following main parameters at the output: temperature sensitivity of 1.32 mV/K and power-supply sensitivity of 100 mV/V (the latter raises some application problems).

3. CURRENT-OUTPUT ANALOG SENSOR

A little less complicated solution is to bias the MOS transistor into the normal operation region and exploit the temperature dependence of the two most important constants of the characteristics, namely the threshold voltage V_T and the gain factor β. These dependences are in order of

$$\frac{\Delta V_T}{\Delta T} \approx -1.5 \text{ mV/K} \quad (6)$$

$$\frac{1}{\beta}\frac{\Delta \beta}{\Delta T} \approx -0.5 \text{ \%/K}. \quad (7)$$

It is advisable to find an arrangement where the addition of these two effects can be obtained. A suitable solution is shown in Fig. 3. The voltage of node X is:

$$V_X = V_T \frac{2 - s}{1 - s}, \quad (8)$$

where

$$s = \sqrt{\frac{\beta_5}{\beta_2}}\left(\sqrt{\frac{\beta_1}{\beta_3}} + \sqrt{\frac{\beta_1}{\beta_4}}\right). \quad (9)$$

So V_X shows a temperature dependence proportional to the threshold voltage. The output transistor is controlled by this voltage and has a current of

$$I_{out} = \beta_6 V_T^2 \frac{1}{(1-s)^2}, \quad (10)$$

with the temperature dependence of

$$\frac{\Delta I_{out}}{I_{out}} = \left(\frac{1}{\beta_6}\frac{d\beta_6}{dT} + \frac{2}{V_T}\frac{dV_T}{dT}\right)\Delta T. \quad (11)$$

This equation considering the data of (6)-(7) yields a ca. -0.9 %/K change in the current.

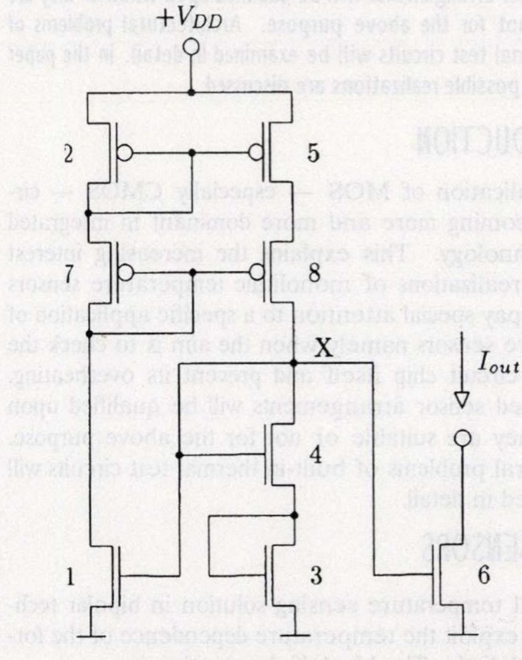

Fig. 3. CMOS temperature sensor with analog current output

The advantage of this circuit arrangement is that it is quite simple and its output current is in the suitable range (1 – 10 μA). It is important that the value of the voltage V_X and the current I_{out} are practically independent of the power supply due to the circuit scheme. Simulation shows a dependence of 0.24 %/V in the output current. The disadvantages are the not exactly linear temperature-current characteristics and that the sensitivity depends on process-dependent parameters, not on physical constants.

The first design of the sensor in Fig. 3 was finished in our Department at the end of the last year and it is under realization at the moment.

4. FREQUENCY-OUTPUT SENSORS

Those VLSI MOS circuits which may need the continuous control of the internal temperature belong almost exclusively to the digital family. For this reason a sensor with digital output signal would be the most suitable to such circuits. An excellent solution in many aspects is when this signal is a square-wave output of an oscillator whose frequency carries the temperature information. The evaluating circuitry (using a counter) can easily convert it into binary data.

4.1. The programmable ring oscillator

An interesting example of frequency-output sensors is the solution published in [5]: a ring oscillator which is slowed down deliberately. An elementary inverting delay cell of the oscillator is shown in Fig. 4. The stage can be configured: using the *TG1* and *TG2* transfer gates either the upper or the lower branch can be switched into the circuit. In the upper branch the n-diffusion resistor *R* and the *C1* and *C2* excess capacitors cause the slowing. In the lower branch the increased channel length of the n-type transistor and again the *C1* and *C2* capacitors cause the slowing. The frequency of the oscillator depends strongly on the power-supply and temperature in both cases. Since these dependencies are different, after measuring the frequency in both configurations both the supply voltage and the temperature can be calculated.

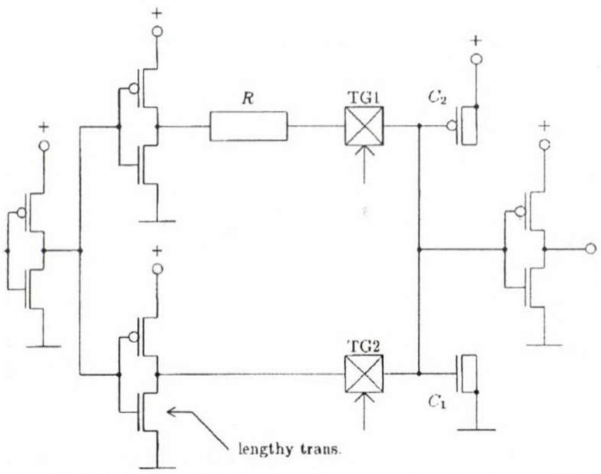

Fig. 4. A single delay cell of the temperature measuring ring oscillator

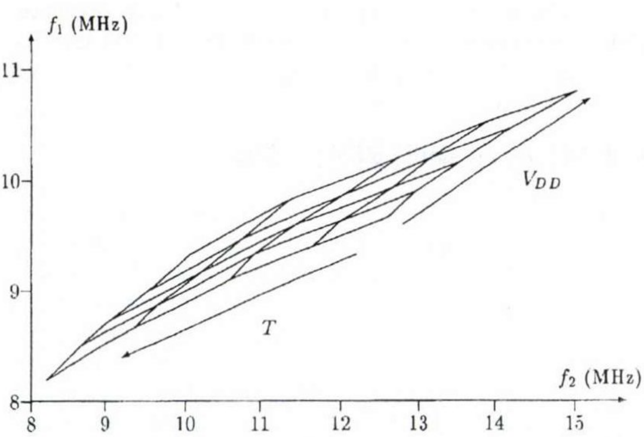

Fig. 5. Evaluation diagram for the temperature dependent ring oscillator

It has to be mentioned that this calculation cannot give a result of high accuracy since although the temperature dependence of the two configurations are not the same, they are very similar. The temperature and supply voltage for the two measured frequency values can be determined using the diagram in Fig. 5. Considering the compressed shape of the diagram it is not surprising that the accuracy in the experimental results is 3°C. This accuracy is however sufficient for the given purpose (monitoring of the internal overheating of the chip).

The authors designed the circuitry described above in a form of a cell that can easily be inserted into any digital design — and they propose to do so in case of thermally delicate circuits. A certain problem is that this cell uses a relatively large silicon area ($\approx$ 1 mm^2 using 2 micron technology).

4.2. Current-frequency converter

We can easily build a frequency-output sensor using the analog current-output sensor in Fig. 3 as well. We can use the I_{out} output current and its "copy" generated by a current mirror to charge and discharge the capacitor C (Fig. 6). The signal of the capacitor is led to a differential amplifier the V_{ref} reference voltage of which is switched between two different levels (V_{r1} and V_{r2}). The resulting frequency is

$$f = \frac{1}{2}\frac{I_{out}}{C(V_{r1} - V_{r2})}. \tag{12}$$

Attention has to be paid to the two reference voltages, they (or at least the difference $V_{r1} - V_{r2}$,) should be supply voltage independent. Considering the $3 - 5$ μA output current of the analog sensor a convenient frequency range of $0.5 - 1$ MHz can be obtained by using a $C = 1 \div 2$ pF capacitor. The chip area required by the above circuitry is ca. 0.02 mm^2 with 1 micron technology — this is an appropriate value.

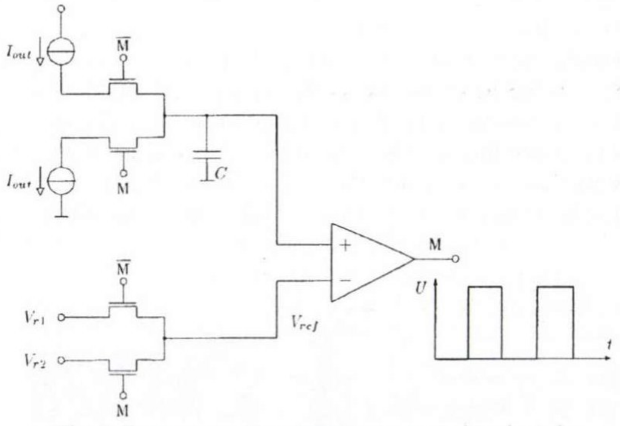

Fig. 6. Frequency-output temperature sensor based on the current-output cell of Fig. 3

4.3. The thermal-feedback oscillator

A novel principle temperature sensor is under development at our department [6]. It is the thermal feedback oscillator (TFO). It is also a frequency-output solution.

This approach is based on measuring the internal thermal diffusion constant of the silicon for temperature sensing as it was already proposed earlier in [7], [8]. The thermal diffusion constant is defined as:

$$D_{th} = \lambda / c, \tag{13}$$

where λ is the thermal conductivity and c is the unit-volume heat capacitance. This diffusion constant shows a reasonably large ($-0.57\ \%/^\circ\mathrm{C}$) temperature dependence in silicon.

In order to measure this diffusion constant we use oscillating circuits in which the frequency-determining feedback element is realized by a thermal time-delay line. This circuit is the thermal-feedback oscillator. If the feedback element is a thermal two-port (thermal delay line) then the frequency of the oscillator is directly related to the thermal diffusion constant and thus shows similar temperature dependence as the thermal diffusion constant. When the output signal is squared this becomes a truly digital signal whose frequency carries the temperature information. For the further evaluation a simple time-window counting is needed only. Using an on-chip counter the binary-coded output becomes possible.

This solution has considerable advantages:

(i) This sensor is compatible with standard IC technologies. This means that the sensor and the joined signal processing circuitry can be realized on the same chip.

(ii) The thermal diffusion constant is an intrinsic material parameter of the silicon whose value is fairly independent of process tolerances and has no time instability. So this quantity may serve as a nearly absolute measure of the temperature without scaling and calibration.

(iii) The thermal diffusion constant shows a reasonably good temperature dependence in silicon — enabling to obtain a temperature resolution of about 1 degree centigrade.

In the last year we developed several versions of the thermal feedback oscillator circuit. The thermal delay line is a small localized area on the silicon chip surface (Fig. 7). The dissipating (input) element is a MOS transistor while the output temperature sensors are temperature gradient sensing resistors with silicon-metal contacts. The latters have a temperature sensitivity of about 1 mV/K. Four series-connected sensors are used in order to enhance the overall sensitivity. The appropriate arrangement of the sensor elements assures the suitable time-response. Careful shielding has to be used in order to avoid capacitive couplings between the input and the outputs. The SEM-photograph of the thermal delay line is shown on Fig. 8.

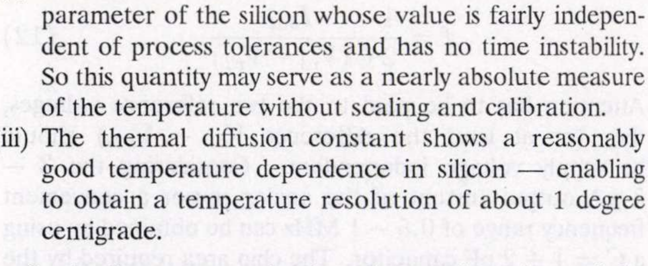

Fig. 7. Thermal delay line
T1 — dissipating transistor; S1, S2 — temperature gradient sensors

The circuit works accurately with 5 V supply voltage. The measured temperature dependence of the frequency is shown on Fig. 9. The frequency of the oscillation corresponds well to the expectations based on simulation. The supply voltage dependence of the frequency of the recent design is quite good: about ±0.4 % in the 4.8 – 5.2 V supply voltage range.

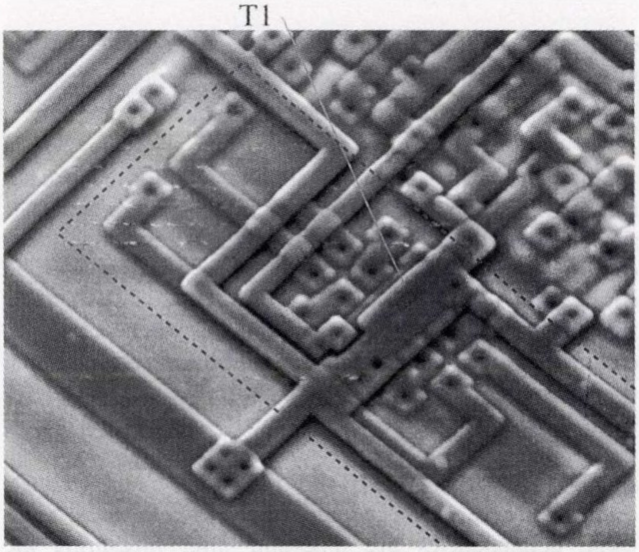

Fig. 8. SEM photograph of the thermal delay line

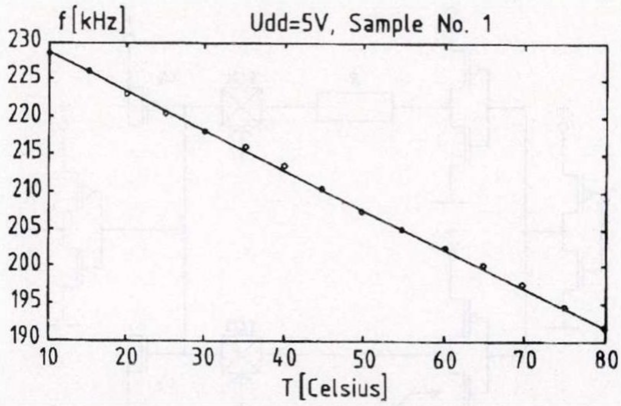

Fig. 9. Frequency versus temperature diagram measured on an experimental TFO circuit

The circuit was fabricated with an $1.2\ \mu\mathrm{m}$ standard CMOS process with the following components: 31 transistors, 2 low-value capacitances and the thermal delay structure. The required silicon area is 0.012 mm^2.

5. ASPECTS OF IMPLEMENTATION

In this section we discuss possible solutions for the internal thermal self-checking of VLSI ICs. Considering the ever increasing device density and thermal problems, it has a growing importance to place additional circuitry onto the chip to ensure continuous temperature control (thermal monitoring). We have also been working on the general aspects of this problem lately [9]. We have suggested that thermal testing aspects have also to be considered at the design of large ICs. As an extension of the well-known DfT (Design for Testability) principle we proposed the idea of Design for Thermal Testability (DfTT) with certain practical suggestions. These can be summarized as follow:

The minimum requirement of DfTT is — which on the other hand in most cases is already sufficient - that the temperature of each main region (chip, functional area, etc.) of the system could be measured.

This requires the following excess circuitry:

(i) a temperature sensor on each chip or region;

(ii) circuitry by which each sensor can be addressed and the temperature information read out.

This excess circuitry provides the following advantages:

- The manufacturer can carry out careful outdoor thermal testing, in order to find the chips which operate on higher temperatures than their normal operating temperature — this way discovering possible mounting defects, considerably increasing the overall reliability of the system.
- The built-in thermal sensors enable life-time thermal monitoring of the system as well. The system itself can carry out the regular thermal testing of the system units, in order to warn for the danger of overheating in advance.
- Continuous on-line testing is possible, when the system, parallel with system operation observes the temperature of the components as well and interacts in case of danger.

6. CONCLUSION

The common application of CMOS circuits has been raising an ever increasing demand for MOS-compatible temperature sensors. A basic field of application of these sensors is thermal monitoring of VLSI circuits. There are numerous CMOS-compatible temperature sensor arrangements being researched/developed, an overview of typical solutions has been given in this paper. We can conclude that no well-accomplished solution exists at the moment but there are a lot of promising approaches among those under development.

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SEMICONDUCTOR GAS SENSOR

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In this paper the theoretical and practical background of the realization and application of highly sensitive and selective semiconductor gas sensors is discussed. The basis of this discussion are the literature, and some experimental results. Most important items are the quality of the semiconductor surface, the role of the additives (catalytically active materials), the size of crystals or the layer thickness compared to the Debye length of the semiconductor, the quality of the interface between semiconductor crystals, and interface between the semiconductor and the grain of doping material (potential barriers). All of listed factors depend on technology, some of them depend on temperature, as well as the characteristics of the realized sensor or sensor system. Some examples for application are also given in this article.

1. INTRODUCTION

Since the first demonstration of the chemical sensitivity of the semiconductor surface, intensive and fruitful research have been carried out to lay the foundation of the theory and practice of semiconductor gas sensors.

The purpose of this work is to give a short review of these research, the results concerning the background of the semiconductor gas sensors. Other type of the gas sensors (lambda sensors, electrochemical cells) are not included into this subject.

A resistor-type semiconductor gas sensor usually contains a heating resistor and another resistor for sensing the gas. The most commonly used materials for this sensing purpose are semiconducting metal oxides (like SnO_2) containing some catalytically active dopants.

2. BASIC PHENOMENA

It is known from the theory of adsorption, that the surface coverage

$$\theta = \frac{(ap)^{1/i}}{1+(ap)^{1/i}} \tag{1}$$

is usually proportional to work function changes ΔV_s due to adsorption. In Eq. (1) p is the partial pressure, a and i are constants ($i = 2$ for the case of H_2 adsorption). For the high concentration θ is high, probably $\theta = 1$, and for low partial pressure θ is proportional to the square root of the concentration.

The basic principle of the operation is the control of the surface and/or interface potential barriers by adsorbed radicals (surface charge or work function change).

The random potential barrier network is the general model of homogeneous semiconductor gas sensors. This system has been analyzed by Sinkkonen [1], and Lantto et al. [2].

The electrical conductivity can be expressed in simple form as

$$G = G_0 \exp(-V_s/kT), \tag{2}$$

where G_0 is the conductivity at zero V_s potential barrier (Morrison, [3]).

In the semiconductors the extent of the space charge layer (which controls the electrical conductivity processes) depends on Debye length:

$$L_D = \sqrt{\frac{kT\varepsilon}{q^2 n}}. \tag{3}$$

Here k, T, q, ε, and n are the Boltzmann constant, absolute temperature, electron charge, dielectric constant, and charge carrier concentration.

For semiconductors the order of magnitude of L_D is in the micrometer range, and comparable to characteristic extent of the structure (grain size of the thick films or the layer thickness of the thin film), see Fig. 1.

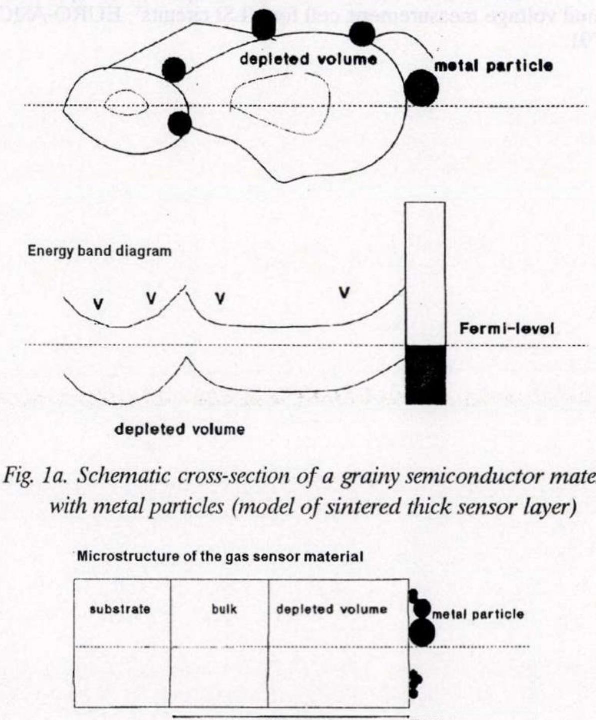

Fig. 1a. Schematic cross-section of a grainy semiconductor material with metal particles (model of sintered thick sensor layer)

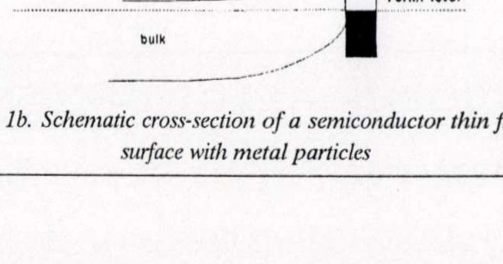

Fig. 1b. Schematic cross-section of a semiconductor thin film surface with metal particles

In the case of insulators L_D is very big, because of the very low value of the charge carrier concentration. Moreover, it is not an easy job to measure the conductivity of the insulators: the measured data depend on many unreproducible parasitic factors. For this reason the insulating materials are not suitable as gas sensitive resistors.

In the degenerated semiconductors and the metals L_D is comparable with atomic dimensions, thus only ultrathin layers can give sensitive device. The ultrathin layers have some problems connected with technology, physical and chemical stability [11].

3. SILICON AND COMPOUND (OXIDE) SEMICONDUCTORS

Broad range of materials have been tested for gas sensor application: monocrystalline elementary semiconductors [4], [5], polycristalline compounds [6] and oxides [7], [8], high temperature superconductor ceramics [9].

Silicone was applicable for gas sensor purpose only as a part of a MOS system [4], [5), (MOS tunnel diode or capacitor, MOS transistor). The metal-silicon Schottky barrier was gas insensitive due to the Fermi-level pinning effect. This phenomenon is the consequence of the high surface and interface trap density in the forbidden band, near to the Fermi-level.

The best results were connected with high value of surface index. This parameter shows the correlation between the height of the metal-semiconductor Schottky barrier and the value of the work function of different metals [10]:

$$s = \frac{\delta V}{\delta W}. \qquad (4)$$

For elementary semiconductors (with covalent bonding) s is usually near to zero. This means, that the barrier height is almost independent of the work function of the surface additives.

For compound semiconductors (with ionic bonding) s is near to one, the barrier height follows the change in the work function. As the work function is very sensitive to surface adsorption process, the system must be also gas sensitive.

4. ACTIVATION

For improving the sensor characteristics the most exciting possibility is the surface and interface doping by catalytically active materials [12], [13]. For example Pt and Pd makes the surface selective for H_2, *Cu* [14], and Ag [15] is useful activator for H_2S, while for methane the Rh is effective [16].

The usefulness of activation is clearly demonstrated on the Fig. 2. Two types of SnO_2 thin film sensors were inserted into the same gas chamber and their resistivity plotted simultaneously. The sensors were made by the same technology (details are described later), only the final (activation) step was carried out by different materials i.e. palladium (Fig. 2a) and silver (Fig. 2b). As it can be seen from the Fig. 2., the system is extremely selective and sensitive for the H_2 and H_2S.

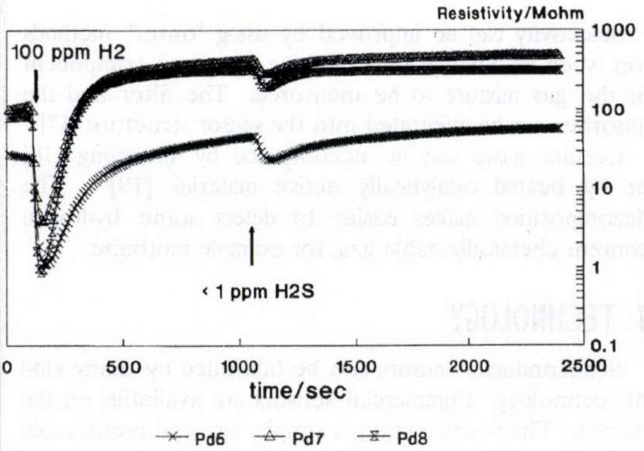

Fig. 2a. Resistivity response of the Pd doped sensors for 100 ppm H_2 and 1 ppm H_2S concentration pulse

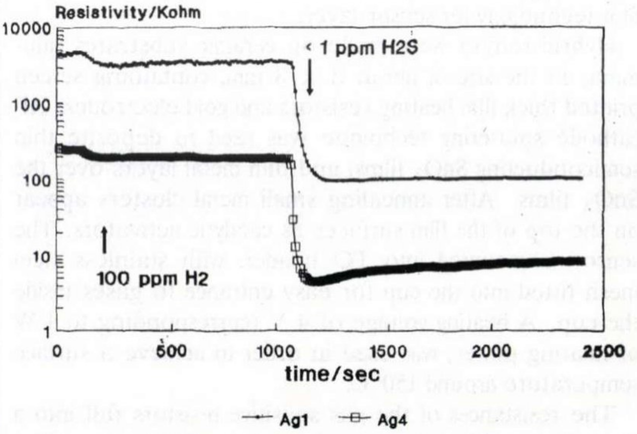

Fig. 2b. Resistivity response of the Ag doped sensors for 100 ppm H_2 and 1 ppm H_2S concentration pulse. The time interval is too short, thus the full recovery is missing.

5. TEMPERATURE

The temperature of the sensor surface is one of the most important parameters. First of all, the adsorption and the desorption are temperature activated processes, thus dynamic properties of the sensors (response time, recovery) depend exponentially on the temperature. The surface coverage, co-adsorption, chemical decomposition or other reactions are also temperature dependent, resulting different static characteristics at different temperature.

On the other hand, the temperature has effect on the physical properties of the semiconductor sensor material (charge carrier concentration, Debye-length, work function). For example at higher temperature the charge carrier concentration (and the conductivity) increases, the Debye-length decreases. This is one possible reason of decreasing sensitivity at higher temperatures. At the low temperature most of gas sensor materials (metal oxides) are rather insulator than semiconductor.

6. OTHER POSSIBILITIES FOR IMPROVING THE SELECTIVITY

Selectivity can be improved by using "outer" methods too, such as filtering, or absorbing out some component of the gas mixture to be measured. The filter and the absorber can be integrated into the sensor structure [17].

Certain gases can be decomposed by sparkling [18] or by heated catalytically active material [19]. The decomposition makes easier to detect some hydrogen content chemically stable gas, for example methane.

7. TECHNOLOGY

Semiconductor sensors can be fabricated by many kind of technology. Commercial sensors are available on the market. Their construction is simple: sintered metal-oxide thick film on ceramic pipe, containing a heating wire inside (see photo in [24]).

Our semiconductor gas sensor were fabricated by hybrid technology for unification of advantages of the thick film technology for heating resistor, and advantages of the thin film technology for sensor layer.

Hybrid sensors were made on ceramic substrates (alumina) in the size of about 3 × 3 mm, containing screen printed thick film heating resistors and gold electrodes. RF cathode sputtering technique was used to deposite thin semiconducting SnO_2 films, and thin metal layers over the SnO_2 films. After annealing small metal clusters appear on the top of the film surfaces as catalytic activators. The sensor is mounted into TO header, with stainless steel mesh fitted into the cup for easy entrance to gases inside the cup. A heating voltage of 4 V (corresponding to 1 W of heating power) was used in order to achieve a surface temperature around 150° C.

The resistances of the gas sensitive resistors fall into a range from a kiloohm up to about a megaohm, depending on the temperature, the surface activation material and process, and composition of ambient atmosphere. A selective sensor system has been developed using different surface activator materials and temperatures. More detailed information about technology of these sensors and experiments can be found in [15], [21] and [23].

8. APPLICATION

Semiconductor sensors are used as the active part of gas and fire alarm systems, as well as for measuring or detecting the concentration of combustibles or other gas in the air (see Fig. 2). Other examples for application are presented in the Figs. 3 and 4.

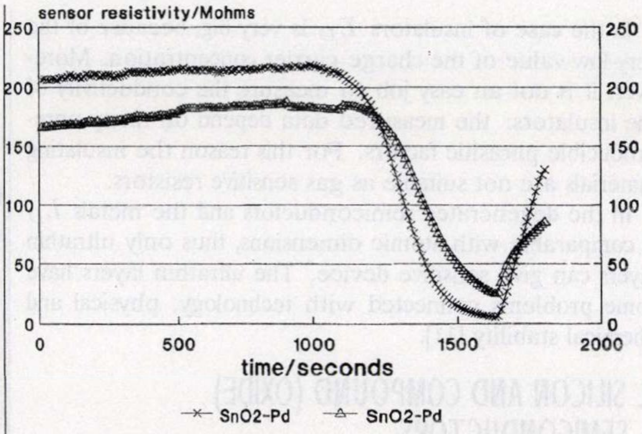

Fig. 3. Result of active NH_3 filter test: the decreasing of the sensor resistivity shows the saturation of the filter

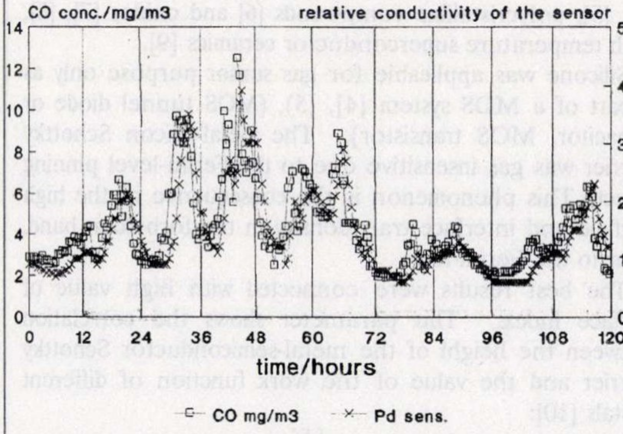

Fig. 4. Air pollution monitoring with commercial gas analysing system (CO concentrations), and semiconductor sensor. Results were collected from one of the most overcrowded main road of Budapest. Good correlation exists between sensor conductivity and CO concentration. Morning and afternoon rush hours can clearly be recognized.

9. CONCLUSION

Sensitive and selective semiconducting gas sensors can be made by fulfilling the next requirements:

- compound (oxide) semiconductor [10] with characteristic extent comparable to the Debye-length [1] – [3];
- or elementary semiconductor with well ordered interface (MOS structure with low interface trap density [4], [5]);
- appropriate temperature range for the quick response time;
- appropriate temperature range for the semiconducting behavior of the gas sensor material or the semiconductor substrate;
- doping the sensor surface (interfaces) by catalytically active materials [12] – [16] and [21];
- modification of the gas mixture to be measured (filtering, absorbing some component [17], converting or decomposing [18], [19]).

An up to date data collection is presented in [20] and [22] (oxide semiconductor gas sensor materials, structures, technologies, temperature ranges and gas sensitivities).

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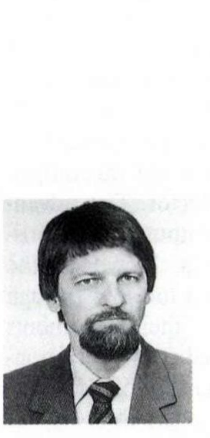

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HYBRID TECHNOLOGIES IN SENSORS

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This paper gives a survey about the research work in the Sensor's Laboratory at the TU Budapest. The results are originating from the work of students of different level: ranging from undergraduate to Ph. D. Four research areas will be highlighted:

- **a thick film laser power detector;**
- **a polymer thick film pressure sensor;**
- **a fibre-optic pressure sensor;**
- **thick film based enzymatic biosensors.**

The individual areas are under research and development, and the results demonstrated here are not always complete. This paper should be observed with this consideration in mind.

1. THICK FILM LASER POWER DETECTOR

In recent years, laser trimming, soldering, engraving and micromachining are widely used in microelectronics technologies where the power of the laser beam is the most important parameter. Thus there is a demand for detectors to measure it directly. Various laser power detectors have already been developed. Conventional laser power detectors for low power measurements are made of semiconductor or pyroelectric materials. Some types use thin film technologies. These detectors are of high reliability and accuracy but they do not have wide power measurement range enough required for the high laser power of micromachining. The cause of this is that the surface of the sensors can easily be damaged with the high power laser beams [1].

Detectors on ceramic substrate made by thick film technology are relatively cheaper and can be used for high power levels but their accuracy and reliability were not proper, or their production was too complicated for the industrial use. Generally, these types were very sensitive to measuring conditions, that means the eccentricity and position of the laser beam. If the output signal of the sensor depends on the position of the point of impingement, high effort is necessary to adjust precisely the laser beam axis to the detector centre. In unfortunate cases, the failure of the measurement may be considerable.

There are several different types of detectors which can be produced by thick film technology and are suitable to measure laser power [2]. One of them is the thermopile and the other is the thermistor based detector. The advantages of both detectors are that their output characteristics are nearly linear with small hysteresis. However, the output level of the thermopile detector is too low though it can be increased by connecting a lot of thermoelements in series [1]. In this case, the complicated construction increases the cost of the device. The advantage of the thermistor detector is that its output level is larger than that of the thermopile detector by three orders of magnitude. The reason of this is that the thermistors are usually used in a Wheatstone-bridge arrangement where the small change in the resistor values results a big output signal. On the other hand, its disadvantage is that a small change in the measuring conditions can also cause a big measurement error because of the big position sensitivity.

Recently, a detector has been developed by W. Smetana and J. Nicolics [3], [4] on the basis of a new mathematical verification. The sensor consists of a circular copper target enclosed by a ring-shaped cooling duct on an alumina substrate carrying two concentric circular Pt-thick film resistors. The Pt-resistors are acting as temperature sensors. The active area is within a circular sector with the radius of the inner sensor ring and is coated by a high absorptive varnish. A laser beam positioned on this area causes a radial heat flow in the direction to the cooling duct. The temperature differences are detected by the circular sensor elements. It can be demonstrated that due to circular layout of the resistors, the sensitivity does not depend on eccentricity and the position of the laser beam. This is very important result because the laser beam of a high power laser is often characterized by an asymmetrical intensity distribution which affects the accuracy of the power detection.

Our new thick film laser power detector combines the advantages of the different sensors: the circular shapes and the thermistor materials. The layout of the sensor is shown in Fig. 1.

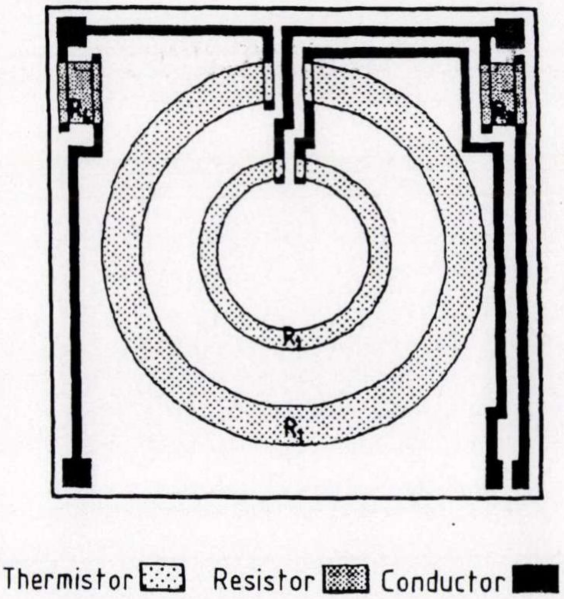

Fig. 1. Layout of the thick film laser power detector

Essentially it consists of an alumina substrate (96 % Al_2O_3) carrying two concentric ring-shaped high negative thermal coefficient thick film thermistor resistors, and two other resistors on the same substrate made of a small thermal coefficient thick film paste. The four resistors are connected into Wheatstone-bridge arrangement and each resistor is of the same nominal value in order to get the easiest zero adjustment possibility. The thermistor resistors are ring shaped in order to exploit the eccentricity independence of the circular layout. The active area is within the inner sensor ring and is coated by a high absorptive varnish in order to increase the sensitivity. A cooling duct is built under the outer circular resistors. All the resistors of the bridge are on the same substrate, thus just an external high precise potentiometer is necessary for the balance adjustment of the bridge.

The samples were produced by traditional thick film technology. The films were printed using 200 mesh stainless screens for each layer. The layers were dried at 150°C for 15 minutes and fired in air in a conventional belt furnace, at a standard 850°C profile, over a 60 minutes total cycle time. The time at peak temperature was approximately 10 minutes. The conductor layer was fired separately from the resistor layers. The parameters of the materials used are shown in Table 1.

Table 1. The parameters of the pastes

Paste type	Product name	R_S	TCR [ppm/°C] (at $25 \ldots 125$°C)
Thermistor	Remex 4993	1500 $\Omega/\square$ ± 15 %	NTC, $\beta = -7000$
Resistor	Remex 8051	100 k$\Omega/\square$ ± 10 %	± 50 %
Conductor	Remex 2014 Pd-Pt-Ag	80 m$\Omega/\square$	—

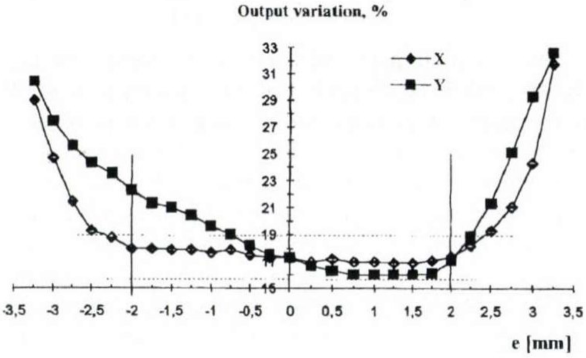

Fig. 2. Normalized output voltage — eccentricity characteristic of the detector. The diameter of the active area is 8 mm and that of the impingement is about 4 mm.

According to the measurement results, a maximum sensitivity ($\Delta U_{\text{bridge}}/U_{\text{supply}}P$) of 2,3 mV/VW of the bridge could be reached with optimising the varnish material and thickness. The linearity of the detector is about 0.5 % and the hysteresis is below 1 % in every case.

One of the measurements was the determination of the eccentricity dependence when the laser power is constant. Fig. 2 shows the normalized output voltage as a function of the eccentricity in the direction of X and Y. Since the diameter of the active area is 8 mm and the diameter of the laser beam about 4 mm, the maximum deviation between the centre of the laser beam and the boundary of the active area can be about 2 mm in any direction. The sensitivity change of the detector is within ± 10 % until the point of impingement has been on the active area with the exception of $-Y$ direction. In this direction the maximum deviation is about 30 % the cause of which might be that the resistors are not full circles. The output conductors may strongly modify the ideally circular thermal distribution which could be avoided by using a more sophisticated structure.

2. POLYMER THICK FILM PRESSURE SENSOR

In recent years, several types of piezoresistive elements have been developed and applied to realise pressure sensors using various materials and fabrication technologies, e.g. diffused or implanted semiconductor resistors, thin and thick film elements, polymer composites. Both bulk and membrane based types have been developed.

Piezoresistive pressure sensors have been made by using thick film technology for more than one decade [5]. This sensor types have several advantageous properties such as low cost, good reproducibility, relatively low thermal drift, compatibility with signal amplifier and converter units, etc. However, thick film piezoresistive pressure sensors have relatively low sensitivity. Supposing an optimal layout and geometry as well as an optimal arrangement of the piezoresistive elements, the sensitivity is determined by the ability of the substrate to deformation and the sensitivity of the resistors to strain (Gauge factor). Since the gauge factor of the thick film resistors is in the range from 10 to 15, only slightly depending on type and sheet resistivity, the sensitivity of the sensor is limited mainly by the properties of the alumina substrate [6].

One possibility to improve the sensitivity is to increase the deformation of the substrate at a given pressure. The idea of applying Polymer Thick Film (PTF) technology is based on the possibility that a wide range of substrates, even flexible ones, can be used.

The sensing element of a thick film pressure sensor is generally a membrane with four resistors on it, connected into a Wheatstone-bridge configuration. The pressure difference between the two surfaces of the substrate causes a deformation and a change in the resistance values, so the bridge becomes unbalanced. The output signal is measured on the unbalanced bridge. This was also used in our new PTF pressure sensor.

During the realization, several technological problems had to be overcome. The first problem arises in connection with the screen printing. Because of the small thickness of the flex substrate, the original tools and methods cannot be used. Conventional positioning in a suitable cavity on the working table of the screen printing machine, which is often used for alumina substrates, cannot be used in the case of the thin, flexible substrates. Fixing those on a flat surface one by one using double sided adhesive tape is not good for industrial use. We fixed the substrates to suitable shaped frames, which have enough thickness to position those on the table of the screen printing machine. In the course of curing the thin, flexible substrate with films on it may be easily deformed. The above mentioned frame can prevent the deformation. Connecting and soldering on alumina or rigid FR4 substrates has no problems. Using flexible substrate, this technological step becomes much more difficult. When applying high pressures to the sensor, the force deforming the membrane is much greater than that the effect of the leads which can therefore be neglected. Using flexible membrane, the forces generated by the leads can modify the deformation of the membrane. That is the reason why the leads must be fixed near to the inactive part of the membrane. Another problem is how to make a proper solder joint on the membrane. At high temperature, the membrane can be damaged easily. That is why we replaced the soldering with conductive glue.

Table 2 contains the main parameters of the sensors comparing them with sensors made by conventional cermet thick film technology [7].

Table 2. Main parameters of the thick film pressure sensors

PARAMETER	CERMET	PTF on flexible substrate
Gauge factor	10	10
Substrate material	alumina	polyester
Young-modulus, 10^4 N/mm^2	33	1.4
Substrate thickness, mm	0.6	0.25
TCR, ppm/°C	50	500
ΔTCR_{max}, ppm/°C	10	50
Sensitivity ($\Delta U_{br}/U_{su}p$), mV/VkPa	$5 \cdot 10^{-3}$	1
Pressure range, kPa	10^3	5
Full scale output (FSO), mV/V	5	5
Additional temperature failure, %FSO/°C	0.05	0.08
Long term drift (1000 h, 85°C)	<0.5 %	<0.2 %

Piezoresistive pressure sensors fabricated by polymer thick film technology on flexible membranes have extremely high sensitivity and very low cost. The problem of the PTF technology based on epoxies may be the poor long term stability. On the basis of the experimental investigations on this sensor, studies with other materials will be conducted in order to improve the long-term stability and the working temperature range of the device.

3. FIBRE-OPTIC PRESSURE SENSOR

Every fibre-optic pressure sensor construction where the propagated light intensity is modified by the variation of applied pressure is called fibre-optic intensity pressure sensor. This type of sensors can be intrinsic and extrinsic: the main difference between them is that in the first type the optical fibre simply conducts the light from the source to the photodetector and the variation in parameters of the transmitted light is caused by an effect located outside the fibres. In the other case, the effects are inside the fibre itself which cause the change in the propagated light intensity during the sensing process [8].

This paper give a description about a newly developed fibre-optic pressure sensor which contains a flexible and combined membrane. This membrane enables the sensor to measure extremely low and high pressure. The cross-section of a conventional membrane based extrinsic fibre-optic pressure sensor structure is shown in Fig. 3. It contains a flexible membrane covered by reflective material which can be deformed under pressure difference. The transmitted light intensity between the input and output fibres is modulated by the deformation of the membrane, as illustrated in the magnified part.

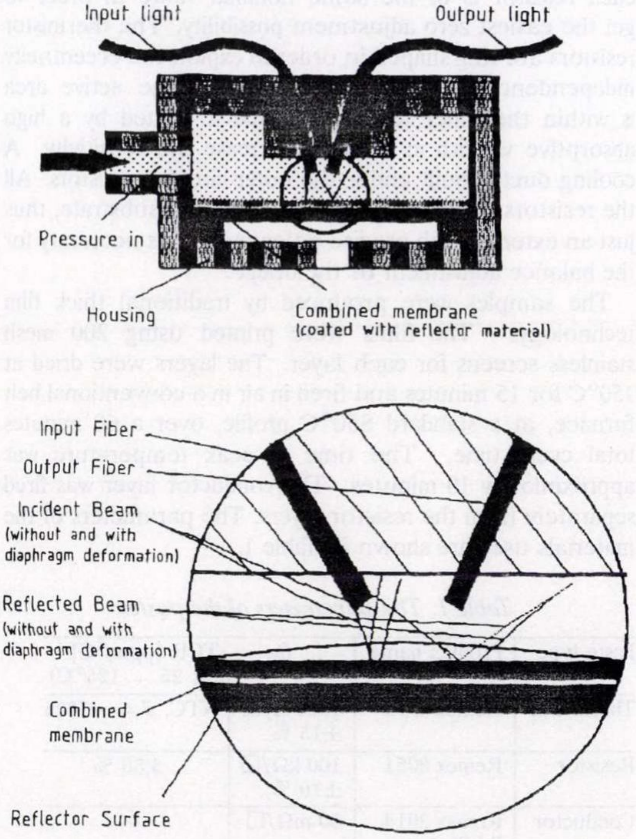

Fig. 3. The cross-section of the flexible membrane fibre-optic intensity pressure sensor

The operating pressure range is determined by the geometry and by the flexibility of the used membrane. Rigid membranes can be operated for wide pressure ranges with low sensitivity, while flexible ones with high sensitivity for very limited ranges. There is a lack of pressure sensors which have high sensitivity at low pressures but lower sensitivity at higher pressure ranges and can operate in wide ranges. Our paper shows an interesting solution for this problem. A possible method is to create a special multilayer hybrid membrane structure where different materials are integrated into one membrane. Fig. 4 shows this multilayer type membrane solutions.

During the operation of the sensor, the measured or monitored pressure is acting here on the top of the membrane. In this situation, at first the rubber membrane covered with aluminium thin film is deformed. This deformation causes the intensity change in the transmitted (reflected) light which is processed by the photodetector. If the pressure is higher, the rubber starts to impress to the second, more rigid membrane. In our experiments, the applied material was Kapton® polymer. This polymer was applied in several pressure sensor types [9]. Certainly, the scale of the membrane deformation is smaller in the function of the increasing pressure than it was in case of rubber. The characteristic of this operation has a typical pressure-deformation function that should be optimized by the thicknesses and geometry. The same effect is continued when the double membrane system reaches the third one made of steel.

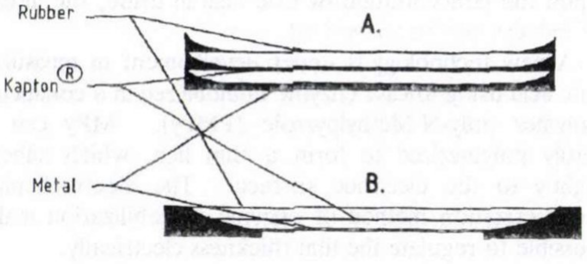

Fig. 4. Multilayer pressure sensitive flexible membranes using different frames

In the experiments, the measuring optical wavelength was 660 nm. The applied optical waveguides were made of PMMA [Poly(methyl-metacrylate)] with a diameter of 1 mm. The measured pressure range was 1 kPa . . . 1 MPa (0.01 . . . 10 bar). The detector output which is closely correlated with the transmitted optical intensity is shown in Fig. 5 as a function of the applied pressure.

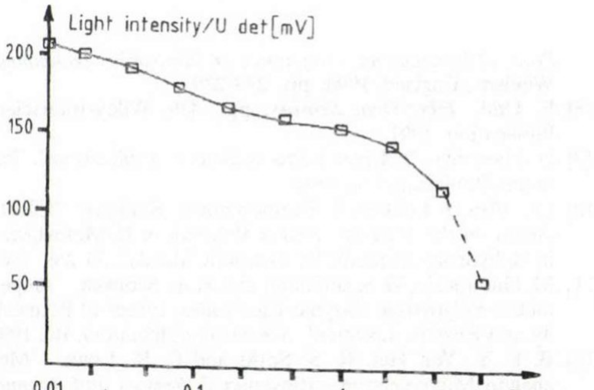

Fig. 5. The measured pressure-light intensity curve in case of the multi-layer membrane

4. AMPEROMETRIC BIOSENSORS ON THICK FILM BASIS

In the last few years, significant research efforts have been concentrated on the development of sensors for the detection and monitoring of key analyses in healthcare and veterinary medicine, bioprocessing, agrochemical industry, environmental monitoring, and defence. Electroconducting conjugated polymers appear very attractive for sensor applications either as sensitive components or as matrices for immobilization of specific substrates. This is due to their intrinsic properties and that ionic species can be included by doping, very similar to the behaviour of inorganic semiconductor materials. The doping reaction enables to modulate the conductivity reversibly over several orders of magnitude via redox reactions [9], [10].

Enzymatic biosensors were developed on several substrates for example: glass or ceramic substrates, Si wafers, etc. [11], [12]. Our new method under development is based on the use of conventional thick film technology to make a general sensor structure applicable in enzymatic biosensors.

The application of eletcroconducting conjugated polymers in biosensors seemed to be the most promising area for immobilising bioactive compounds. Biosensors are suitable for indicating and quantitative measuring of psychologically significant, biologically active substances. These components are very sensitive and their analytical measurement is based on selective reactions. The determination of the substances is realized by enzymatic reactions, the redox enzymatic reaction being the most important of these. The conclusions referring to the quantity of the substance to be measured, should be drawn from detecting the electron transfer during the reaction.

The greater part of research studies on enzymatic biosensors described the immobilization of GOD (glucose oxidase) in a polymer matrix for the determination of glucose concentration in the blood [13], [14]. The reaction, using oxygen mediator, goes according to Fig. 6.

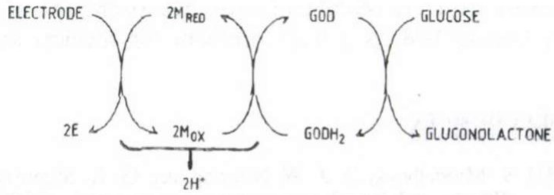

Fig. 6. Electrical wiring of a redox enzyme; flow of electrons from the electrode through a monoelectronic relay ($M_{\mathrm{ox}}/M_{\mathrm{red}}$) to the glucose oxidase enzyme

The direct amperometric detection of the oxidation current of the produced H_2O_2 (in the case of oxygen mediator) is the conventional sensing mechanism. In this case the potential difference between counter and reference electrode is controlled, and the current flowing through the working and the counter electrode is measured.

A general amperometric thick film structure has been developed using three electrodes. The electrode layout of the sensor can be seen on Fig. 7. For the substrate of the sensor alumina was used. The 5.08×5.08 cm (2" × 2") ceramic substrate was divided into 4 strip shaped parts. On one unit (5.08×12.7 mm), there are 3 sensor elements and an auxiliary conducting layout which connects the sensors into a group and helps in making connection to the power supply during the subsequent electrochemical deposition processes necessary for the polymer/enzyme matrix deposition. The actual size of one sensor element is 25.4×4.23 mm.

Three electrode layouts were designed for the amperometric measurement. Pd-Pt-Ag paste was applied for the working and counter electrodes, Ag/AgCl for the reference electrode. For the first step all the three electrodes were screen printed from Pd-Pt-Ag paste. After drying (15 min, 150°C) the base structure of the sensor has been fired according to the usual 850°C profile. Ag paste was printed onto one of the Pd-Pt-Ag electrodes to build up Ag/AgCl reference electrode. AgCl was made by electrochemical chloridization.

To avoid application of further firing, solder pads were used instead of firing multilayer structures in the interconnecting part. Soldering paste was printed onto the surface of these pads by means of dispenser. Cu wires insure the connections between the pads which were fixed using soldering.

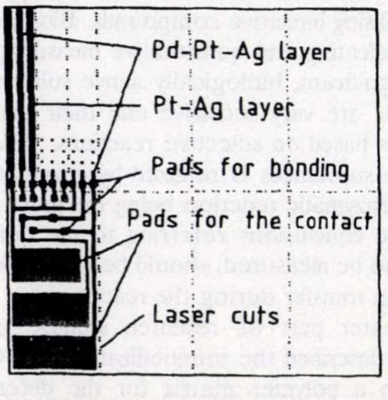

Fig. 7. The electrode structure of the biosensor

A new type of enzyme is planned to be used for the sensor structure described above. Measuring the uric acid in human body is a hard problem for medical science. There were sumptuous methods (spectroscopy, enzymatic reaction) to determine the concentration of uric acid in blood or in urine. Measuring the concentration of uric acid in blood is important, because it encrusts at the knuckles causing gout. Above the highest normal value upon the concentration of uric acid in urine, the disease of kidneys can be recognized.

A new technology is under development in measuring uric acid using uricase enzyme immobilized in a conducting polymer poly-N-Methylpyrrole (PMPy). MPy can be easily polymerized to form a thin film, which adheres tightly to the electrode surface. The electrochemical polymerization method of enzyme immobilization makes possible to regulate the film thickness electrically.

Uricase catalyses uric acid oxidation, producing allantion and hydrogen peroxide. The change of concentration of hydrogen peroxide (H_2O_2) can be electrochemically detected:

$$\text{Uric Acid} + O_2 + 2H_2O \Longrightarrow \text{Allantion} + H_2O_2 + CO_2.$$

The electrodeposition and the immobilization of the enzyme is under development and the results are to be published in later issues.

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Róbert Dobay is student at the Technical University of Budapest. At present, he is working on his final project at the Department of Electronics Technology, and will finish studies in 1996. He is a candidate of future Ph.D. student. His research area is the fabrication of biosensors.

Gábor Harsányi's biography and photo see on page 1.

SENSOR STORY IN HUNGARY

1. INTRODUCTION

Information is becoming the key word in many issues. Our work and our life are increasingly dependent on information.

The amount of information to be handled has significantly increased over the past two decades. The handling of information can no longer be accomplished through mechanical means and "human" processing. The objective processing needs a chain of electronic instruments. The chief parts of the chain can be divided into four stages. The information must originally be obtained through a transformation of physical quantities into electrical signal. This stage is the input transducer or "*sensor*". The second stage is the processor unit in which the signal is modified (amplified, filtered, converted into a digital signal). The modified signal is transmitted to the output terminal then the third stage is the transmission-line. Finally, the transmitted signal can be applied to present the result on a display, a computer, or an output transducer. The output transducer transforms the electrical signal into a mechanical one. The output transducer is called "*actuator*".

The number of nonelectrical quantities is very large and we can imagine that the kind of sensors is infinite. But it is evident that all the quantities may be derived from 5 different types: mechanical, thermal, radiant, magnetic and chemical quantities.

Most of modern sensors are discrete or integrated solidstate devices produced by monolithic or hybrid IC technology.

The advantages of the IC technologies are: decreasing dimensions, uniformity of the production, moderate prices, possibility of integration of sensors and electronic circuitry on the same chip or on ceramic plate ("*smart sensors*").

The advancements, which are the results of heavy investments in research and production justify the current broad interest in silicon sensors. Large number of physical and chemical effects, which transform nonelectric signals into electrical ones, have been identified in silicon. For preparing certain sensors the thin and thick film technologies are very attractive to be used.

In Hungary the sensor story starts from '50s, parallel with rapid development of optical and electronic industry. For infrared spectroscopy and technics, the Research Institute for Optics and Fine Mechanics (OKL) had developed a family of infrared detectors: a modified Golay-cell ("electropneumatic-cell"), a semiconductor thermopile based on chalcogenid silver compounds and a photo-electromagnetic InSb detector [1].

The publicity of these developments was very poor. The sensors have very attractive characteristics but the industrial backround was unsuitable for producing.

The Research Institute for Electronics (HIKI) was the base-institution for the technology of Ge and Si electronic devices and Si IC-s.

2. PHOTO SENSORS

A line of research was the development of photosensors. It was produced a family of self supported planar-diffused photovoltaic cells.

These sensors were utilized in Zeiss-Jena and in the Hungarian Optical Company (MOM). The electronic characteristics were excellent, especially, the very low dark current.

The "high tech" of photosensors is the avalanche photodiode. The HIKI-type was a planar-diffused Si diode with a guard-ring to prevent the local break-down in p-n junction. The device has a multiplication-factor of 200–500 and a response time about 10^{-11} s.

The avalanche diode is a very expensive device, but it is indispensable in optical telecommunication systems as a detector of high frequency modulated light-beam.

3. PRESSURE SENSORS

Another line of HIKI-s sensor-program was the R+D of pressure sensors for industrial and medical applications. The sensor is a full active 4 arme bridge from piezoresistors. The resistors are produced in an n type silicon diaphragm by ion implantation. If a pressure acts on the diaphragm so that it is deflected the result is a change in resistance on the basis of the piezoresistive effect.

Today the INTERBIP Ltd. manufactures pressure sensors from 0.1 bar to 600 bar. They are suitable for absolute, relative and differential pressure measurement. The applications of sensors include gas and liquid pipe line systems, measurement of blood pressure, technological processes etc. The characteristics of these pressure sensors are excellent, comparable with the best products.

On the basis of thick film technology a capacitive and resistive sensor and a gas sensor was developed. The capacitive sensor is an interdigital capacitor made on ceramic substrate with an isolator film as sensitive element.

The materials of resistive sensors are gas sensitive semiconductor compounds such a SnO_2 [14]–[21].

4. TEMPERATURE SENSORS

Metallic resistors made from Ni and Pt have been the preferred elements for measuring temperatures. They are reliable and can be used in a broad temperature range but have two disadvantages: low sensitivity and relatively large mass (large heat capacity).

Silicon "spreading-resistance" sensor is more sensitive and achieve virtually the close tolerances and the reproducible characteristic of the metallic sensors. For compensating nonlinearity a series temperature independent resistor is utilized.

Sensor topic is recent field of research at the *Department of Electrical Engineering of the Technical University of Budapest.*

Department of Electronic Devices. A large spectrum of chemical sensors was developed on semiconductor basis. The first one was a H_2 sensitive MOS transistor with Pd gate-electrode.

In cooperation with the University of Oulu a large number of papers were published about the investigation and application of SnO_2 thin film as H_2, H_2S detector [2] – [13].

Department of Electronics Technology. The theoretical and practical activities in thick film technologies resulted in new sensor principles and materials as well as new application possibilities.

The conduction mechanism of thick film resistors was investigated and extended to the piezoresistivity. It was established that Ruthenium-oxid based resistors have a high guage-factor dependent on sheet resistance of the layer.

The resistors connected in bridge were utilized on a ceramic diaphragm as very stable pressure sensor from 1 bar to 200 bar.

A thermal "quality-factor" was introduced for characterization of thermal behaviour of the sensors offset and FSO. The most attractive results were received with sensors made by polymer thick film technology on plastic diaphragm [14] – [21].

Other types of sensors: Si and thick film temperature sensor, a semiconductor (Si) dew-point sensor laser power detector made by thick film technology [22] – [30].

Institute for Physics. The research work on sensor was concentrated on investigations and development of metal oxid gas sensors in cooperation with the Siemens Co. The effect of oxidizing and reducing gases on the sensor characteristics was studied. The favourite material is the Ga_2O_3 in thin film form [31] – [35].

Department of Process Controll. The topics of the research-works are the theoretical interpretations of some mechanical sensors and development of a new magnetoelastic Force-sensor [36] – [40].

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PRACTICAL EDUCATION IN SEMICONDUCTOR PROCESS TECHNOLOGY AT TU BUDAPEST

The paper gives a brief description on the practical education in semiconductor process technology at the Department of Electron Devices of TU Budapest. After a short review of this activity in the eighties and in the first half of this decade the present situation is discussed with special respect to the challenging microsystem age.

1. INTRODUCTION

The Department of Electron Devices has the possibility since twenty five years to run a laboratory for the education of basic semiconductor process technology. The laboratory equipment was modernized last time in the early eighties and was supplemented with material and technology characterizing facilities in the late eighties. The laboratory is able in its present form not only to demonstrate the very basic process steps of monolithic IC preparation but gives also the possibility for the students to perform manually these steps from the characterization of the wafer to the last measurement on the packaged device.

The laboratory has two four-tube diffusion furnaces, one mask aligner up to 3 inches in wafer diameter, 5 laminar boxes, a vacuum evaporator, an RF sputter machine and a couple of characterizing instruments as: Talystep surface profiler, DLTS equipment for determination of contamination and inner crystal defects, C-V measuring equipment and spreading resistance meter for quality measurements of dielectric layers and doping profiles, scanning electron microscope for surface investigations, an ellipsometer, an IR Spectrometer and other smaller electrical measuring instruments.

2. SOME PAST EXAMPLES

In recent years the significance of the knowledge of process technology was declared as a necessary contribution to the professional competence of a student when he (she) graduates and becomes an electrical engineer. The knowledge of microelectronics means the knowledge of circuit design, device realization, testing and the application of integrated circuits. Better understanding of the device fabrication gives better choice of appropriate circuits. Teaching processing means to give a deep theoretical background in process steps and to show during practical exercises the relations between technology parameters and the desired electrical performance data.

To fulfill the above mentioned requirements students had to produce for many years an SSI level p-channel digital MOS circuitry with measuring and evaluating its characteristics. The complexity level was very low not only because of the technical background (e.g. lack of a 'clean room' facility and of expensive and dangerous processing equipment like ion implanter, CVD, dry etching equipment etc.) but of didactical reasons — every process step could be evaluated easily in its completeness and explained in details.

This laboratory exercise was done during one semester and more skilled students could continue their activity in the following 1-2 semesters with a freely chosen individual course project and finally the diploma work. The best students were involved in the R&D activity of the laboratory: they took part in the development of different sensors (SnO_2 gas sensors, Ta_2O_5 gate ISFETs, humidity and temperature sensors and of their measuring devices or computer controlled measuring systems as well).

By the end of the last decade — due to the University course programm — the number of students involved in this form of education became too high, the energy of our staff and the financial support of the Department became too low. Thanks to the helpful contribution of the Research Institute for Material Sciences and the Research Institute for Technical Physics a large spectrum of highly developed processing and measuring techniques could be presented for 50–60 students every year.

To evaluate this age it is a great pleasure to mention that not only the previously existing Hungarian industrial need was fulfilled by our highly skilled graduates but many of them were invited to make Ph.D. research at different European universities and even in Japan.

3. PRESENT SITUATION

In order to achieve a more economical wide-range technical education, since 1991, the curricula of electrical engineering is being reformed. The basic comprehensive courses are given for all students and the specialization takes place only in the 6. term. The new education program of the Electrical Faculty of TU Budapest unfortunately omitted the education of microelectronics technology. A short presentation of the process steps have been 'hidden' into the subjects Material Science in the 1. term and Microelectronics in the 5. term. Students visit only the semiconductor laboratory and investigate IC lay-out — as illustration to the theory — using optical and scanning electron microscopy.

But the technology education still has not been cancelled in the semiconductor laboratory: this time interest has been grown at the Faculty of Natural and Social Sciences of TU Budapest. Some students of the branch 'engineering physics' are highly motivated to get familiar with the basic semiconductor process technology steps and they do the laboratory exercises in the form of an elective subject. The aim of the branch is to give not only deep theoretical background in material science, solid state physics, surface physics, optics and solid state electronics but also well-based practical knowledge and skills, that is why the characterization of the materials used and deposited during the process steps for these students is more obvious.

The Department of Electron Devices together with the Department of Electronic Technology follows the new trends in the world: a new educational branch has just been developed entitled 'Microsystems and Modular Circuits'. Students are involved in the development of microsystems during their course projects and final reports using the upgraded CAD tools of the Department of Electron Devices. The circuits are realized in ASM technology in Grenoble, TIME Laboratory as a result of an ESPRIT cooperation. In the THERMINIC COPERNICUS project students work together with their tutors on thermal characterization of microsystems.

To evaluate this period it is worth mentioning that besides this low intensity technology education even now there are three Ph.D. students in the semiconductor laboratory dealing with sensor technology development and investigation.

4. THE FUTURE

In authors opinion all respective Hungarian institutions have to keep searching for the connection points to join the main European revolution-like development in the microsystems area either in design or in measurements, tests and characterization of basic materials and ready-made parts. The joint research needs appropriate human resources. Presently this is still existing. But later?

It will not depend upon our willingness... We are ready to work together with universities abroad and with different research laboratories either abroad or in Hungary. The Department of Electron Devices recognized the high importance of the microsystems in the very near future and from this reason joined first in Hungary the pan-European "Network of Excellence in Multifunctional Microsystems" (NEXUSPAN). This department serves as the National Contact Point for information dissemination.

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ABOUT NEXUS ORGANIZATION (NETWORK OF EXCELLENCE IN MULTIFUNCTIONAL MICROSYSTEMS)

Microsystem technology (MST) is considered to be a highly innovative field providing miniaturized micro-mechanical/micro-electronic devices for a variety of applications in areas like medicine, biology, automotive industry, environmental control, industrial process control, robotics and telecommunication. Microsytem technology offers new opportunities for the development of miniaturized integrated systems including sensors, microelectronics and actuators. MST combines a large number of technologies, which are applied in the system design and fabrication. The integration of these technologies leads to improved performance and lower costs for existing products and to completely new products. MST will have a significant impact on all industrial levels, similar to the impact of microelectronics in recent years.

European industry provides powerful system solutions, but it will become more difficult in the future to keep the present-day shares of the world market in microsystem technology. In order to maintain Europe's competitiveness in MST and to support the co-operation between researchers in the field of MST and between industrial users and developers the 'network of excellence NEXUS' was founded in 1992 in Western Europe. This network addresses the exchange of information and to co-ordination of MST research efforts in the European Union.

Filial networks NEXUSEAST and NEXUSPAN were founded in 1994 and 1995, respectively to supplement and expand the activity of the successful NEXUS organization towards co-operation with an integration of the countries of Central and Eastern Europe (CEE) and the New Independent States (NIS) of the former Soviet Union. NEXUS and its supplementary activities including NEXUSEAST/NEXUSPAN have the objective of pro-active support of MST research, development and exploitation throughout Europe. It is expected that NEXUSPAN will shortly include and co-ordinate up to 100 members from all CEE/NIS countries, leading to close links and co-operation between East and West Europe in the field of MST.

First member from Hungary in the NEXUSEAST network was the Department of Electron Devices at TU Budapest. Later the NEXUSEAST/NEXUSPAN community expanded with additional two entries from Hungary: Department of Electronics Technology of the Technical University of Budapest and Research Institute for Material Sciences in the Central Research Institute for Physics.

The first task in the NEXUSPAN project was the compilation of an almanac "Who is Who in Eastern European MST" to supplement the almanac "Who is Who in NEXUS". The almanac provides a base for reference for MST researchers and users looking for partners in Eastern Europe. The first version included descriptions of 30 laboratories from nine countries based on a questionnaire circulated to all known MST labs in Central and Eastern Europe. The almanac was distributed to all NEXUS and NEXUSPAN members. It is currently being expanded primarily to include descriptions from laboratories in the NIS.

Further activities of NEXUSPAN include the support of visits of Eastern European researchers to MST labs and training courses in the West and the build up of a communication network. NEXUS has just established an on-line information service via WWW. The acronym is EMSTO: European MicroSystems Technology Online. Everyone is kindly invited to visit the EMSTO homepage (http://www.vdivde-it.de/it/emsto).

In order to fulfil the tasks NEXUSPAN set up a number of National Contact Points (NCP), whose purpose is to provide local support to the NEXUS office, to collect information on MST activities in the perspective countries and to serve as a contact point for institutions looking for partners in these countries. NCPs are responsible for information dissemination in their countries about NEXUS events as well. NCPs should establish in the near future WWW homepages containing country specific information, the description of NEXUSPAN members from their country and links to the other NCPs, to NEXUS and EMSTO. Hungarian NCP is found at the Department of Electron devices, TU Budapest. The contact person is Ms. V. Timár-Horváth.

Another approach of NEXUSPAN is the organization of workshops in Eastern Europe to provide a frame for members to present their MST activities to interested participants from research and industry from both Eastern and Western Europe. The workshops include an overview of the state-of-the-art in MST and an introduction to NEXUS, in addition to presentations of local activities. Visits to local laboratories are also included. These workshops are connected to major related conferences and are financed by NEXUS.

The first NEXUSEAST/NEXUSPAN workshop on microsystem technologies was held in Sinaia (Romania) on 14. October 1995. It was attended by 69 participants from 15 European countries. Invited talks on the state-of-the-art in MST, the NEXUS concept, industrial perspectives and various R&D aspects were given by speakers from Belgium, Germany, England, France and Switzerland. Moreover, short presentations were given on national MST activities in Bulgaria, Georgia, Hungary, Moldavia, Poland, Romania and Slovakia. In a poster session 23 working groups, mainly from Eastern Europe presented their MST related R&D activities.

The second NEXUSEAST/NEXUSPAN Workshop on Microsystem Technologies will be held in Szczyrk, Poland on 17. May 1996 as a joint-workshop to the IV. Polish Conference on Optoelectronic and Electronic Sensors (13—16 May). Invited papers will be submitted by leading European specialists, a poster session will present results of research teams from Poland and other CEE countries and a round table discussion will summarize the results. The participation in the workshop is free.

NEXUS organization publishes his own periodical review entitled 'mst news'. Every NEXUS node is welcome to contribute and present his newest results! Readers may obtain continuously information on the European projects regarding MST and the realization facilities in technology centres.

Membership in NEXUSPAN is open to all European companies and institutes intending to contribute expertise in areas relevant to microsystem technology.

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■ COMMUNICATION TECHNOLOGY '96 BUDAPEST

From April 10 to 12 a three days conference and exhibition was organized by Communication Expos International France and the Scientific Society for Telecommunications Hungary. The conference program included an intensive *Public Policy and Strategy Program* and a subsequent *Technology Applications Program*. At the exhibition leading product manufacturers and service suppliers were present.

Opening the Public Policy and Strategy part of the conference *Prof. G. Gordos, President of the Scientific Society for Telecommunications, Hungary* expressed his pleasure to welcome the conference participants representing manufacturers, service providers, regulators and also users of telecommunications. In a special presentation *H. Chasia, Deputy Secretary General, ITU* addressed the conference. He emphasized the significant results of Hungary in the development of telecommunication in the last six years. He appreciated the steps of liberalization, and the introduction of market economy conditions in Hungary. The Keynote Address of *K. Lotz Minister of the Ministry of Transport, Communication and Water Management* was conveyed by Deputy Secretary of State I. Bölcskei. In the message the recent privatization of the Hungarian Telecommunications Company, MATÁV was outlined and the establishment of local operators was discussed. He emphasized that in the development of infrastructure and regulations the adjoining to the EU is in the center point. The second Keynote Address was given by *E. Straub, CEO of the MATÁV*. He highlighted the main impacts of the privatization of the company: the financial stability and the access to the know-how. Both are provided by the two leading telecommunications companies Ameritech and Deutsche Telekom, the owners of MATÁV. As a third important consequence of privatization he mentioned the change of thinking within the company. MATÁV's development is characterized by almost 2 million lines, the digitalization of the switching capacity is close to 60 %, the backbone network is covering all the needs, international connections are well developed. Important developments are made in business communication services, ISDN was introduced in Budapest. VSAT services, managed leased lines are operating. In the near future MATÁV has to prepare itself for the competition.

The title of the first session was *Cooperative and Competitive Development, I. Bölcskei Deputy Secretary of State* outlining the market situation, stated that in all branches of telecommunications — except the conventional telephone service — competition is present. In the telephone service MATÁV is the principal operator with 80 % share of the market, the remaining 20 % is divided among several local telephone operators. In the telephone service the monopolistic situation is valid until 2001 for MATÁV and 2002 for the LTOs. Recently the OECD report on Hungarian telecommunications raised the possibility of shortening this period, to make Hungary more competitive on the international market. According to Mr. Bölcskei the valid concessional agreements are obligatory for both sides, however the agreements can be reconsidered. Speaking about the objectives of the development plans he mentioned that until 1997 telecommunications network and services in Hungary will be corresponding to the development level of the country, the respective demands being satisfied in completeness. From 1997 the development strategy has to be changed. Instead of quantitative development the improvement in quality will be of critical importance. Business communications will be in the focus, alternative services will be introduced, the significance of mobile communications will be increased. *M. Salamon from OECD* presented some points of the OECD report on Hungarian telecommunications. He emphasized the need for a telecommunications statement of the government accepted by the Parliament with accompanying regulations expressing the needs of the users also *S. Krupanics, President, Communications Authority of Hungary* discussed the relation between the regulations and the market. He expressed that the development reaches a new phase when the private, foreign ownership is over 50 % in telecommunications. In this case an independent regulatory structure is necessary. This situation has been arrived in Hungary. The emphasis in the regulations should be changed from the technology aspects to the economic regulations. As an example he mentioned the price regulations where the present rules are not in full accordance with the needs of market competition and the needs of the users.

Session two discussed the topic *Alternative Service Providers P. Tölösi, Chief Officer of MATÁV* discussed the financial difficulties that would be faced by an alternative service provider in Hungary. The only candidates for this role might be operators having a nation-wide network in service, such as closed private networks, the broadcasting company Antenna Hungaria, or the mobile operators. Directors of the mobile operators *E. Gussi, Pannon GSM, M. Papp , Westel 450, A. Sugár, Westel 900* emphasized the unexpectedly large penetration of mobile services. They mentioned that almost everything that is provided by the wire-bound network can be reached by the mobile network also. *Antenna Hungaria* having a monopoly in broadcasting services can also be a candidate for alternative service provider. Future development is depending on the results of privatization.

The third session entitled *International Integration of Hungary's Communication Network* dealt with economic questions. *F. Kraemer, Senior Engineer, EBRD* expressed the opinion that Hungary has a telecommunications policy which makes the country attractive for investments and there is encouraging perspective for Hungary to be a regional communication hub. *Ray Stewart, Chief Financial Officer of MATÁV* commented the process of developing a cohesive management team for the company. Now there are eight members of senior management: CEO, two executive directors, five chief officers. From these four are Hungarians, two Germans and two Americans. The results of the company are remarkable. 1.5 billion USD has been invested. At the middle of 1997 the telephony market will be a supply market. ■

THERMINIC WORKSHOP

INTERNATIONAL WORKSHOP ON THERMAL INVESTIGATIONS OF ICS AND MICROSTRUCTURES

September 25–27, 1996
Budapest, Hungary

The first THERMINIC Workshop was held in Grenoble in 1995, it gathered together about 90 attendees from Europe, USA, Japan. The second THERMINIC Workshop will be held in Budapest, September 25–27, 1996. THERMINIC Workshops are a series of events to discuss the essential thermal questions of microelectronics and microstructures. These questions are becoming more and more crucial with the increasing element density of deep submicron downscaling of integrated circuits necessitating thermal simulation, monitoring and cooling. The high element density of MCMs and the mobile parts of microsystems raise newer and newer thermal problems to be solved in the near future. Thermal effects on the other hand can be used as as bases of sensor or other functional structures. The Workshop intends to deal with all aspects of thermal design, investigation and measurement of microcircuits and microsystems.

The Workshop is sponsored by the IEEE Computer Society, Test Technology Technical Committee, in cooperation with the BARMINT 8173 ESPRIT and the THERMINIC 00922 COPERNICUS Projects.

Areas of interest:

- Thermal and Temperature Sensors
- Thermal Simulation
- Electro-thermal Simulation
- Thermal Modelling and Investigation of Packages
- Evaluation of Thermal Measurements
- Thermography

Speakers are required to prepare full length papers for the Workshop. Submitted materials will be included in Workshop Proceedings.

- Submission deadline (5 copies): **15 May 1996**
- Notification of acceptance: **14 June 1996**
- Submission of manuscripts for distribution at the Workshop: **31 August 1996**

Special Issue of the IEEE Transaction of VLSI Systems:

A Special Issue of the IEEE Transactions on VLSI Systems will appear as a follow-up to the Workshop. The deadline for submission will be 31 October 1996, the authors being notified about their papers by 31 December 1996. Details will be published later.

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