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Silicon: a Promising Material for Sensors

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Silicon integrated-circuit technology offers exciting possibilities for the fabrication of integrated sensors. In this paper the advantages and some problems of using silicon for sensors are discussed and some examples are presented.

Die Siliziumtechnologie der integrierten Schaltungen bietet interessante Möglichkeiten für die Herstellung integrierter Sensoren. Die Vorteile sowie einige Probleme der Siliziumsensoren werden besprochen und an Hand verschiedener Beispiele näher erläutert.

La technologie des circuits intégrés au silicium nous offre des possibilités très intéressantes pour la fabrication de capteurs intégrés. Dans cet article les avantages et certains problèmes de l'utilisation de silicium pour les capteurs sont discutés à l'aide de quelques exemples.

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1. Introduction

The past 30 years have been a period of a continuous microelectronic revolution. Since 1959 the integrated-circuit (IC) complexity has been doubling every year. At the same time the performance—price ratio has shown a dramatic increase: a factor of 10^{18} for digital signal processing and 10^{12} for analogue circuits. In comparison, if the aircraft industry had made the same progress today's Boeing 767 would be able to fly around the world in 20 min while consuming only 20 l of fuel; at the same time the aircraft would cost only $500 [1].

This tremendous improvement in the performance—price ratio has made the proliferation of microelectronics into non-electronic products and industries possible. Today, as a result of the unprecedented, rapid development of microelectronics, electronic watches, games, sewing machines, personal computers, etc. are a commonplace. The advent of microelectronics into traditionally non-electronic industries is, however, seriously impeded by the lack of appropiate input transducers (or sensors) having a performance—price ratio comparable to the microelectronic circuits [2]. With the exception of military and professional applications where the cost aspect does not seem to be of primary importance, in the vast majority of the consumer goods in which information is processed electronically the input side of the system is usually formed by very simple sensors such as pushbuttons. The fact that a large number of products such as mechanical scales, clinical thermometers, rotating vane flow meters, etc. still do not use any form of electronic information processing indicates that there is still a lot of room for innovation and new products. However, the lack of cheap, dependable and mass-produced sensors which are at the same time immune to hostile environments and do not exhibit significant drift of the characteristic is a problem which should be solved before further penetration of electronics into more traditional markets can take place.

The field of consumer goods is not the only one in need of appropriate sensors. The performance capabilities of robots, robot systems and control systems in general are to a large extent dependent on the sensors with which they are equipped [3].

In the above applications the interface formed by sensors between the information-processing circuitry and the outside world is a bottleneck which justifies the current interest and effort in the field of sensors and silicon integrated sensors in particular.

2. Information-processing systems

In figure 1 the three components which invariably form a measurement or a control system are depicted. The input transducer, usually called a sensor, transforms the input signal of interest into a signal suitable for the in-

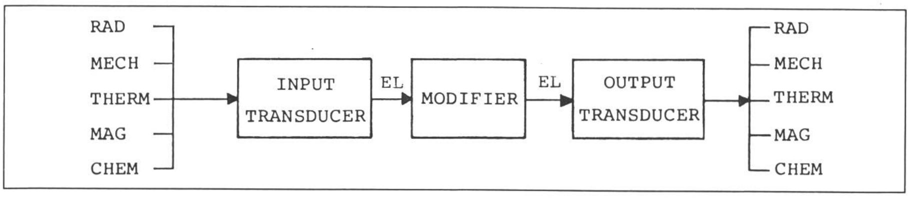

Fig. 1 Functional block diagram of a measurement or a control system

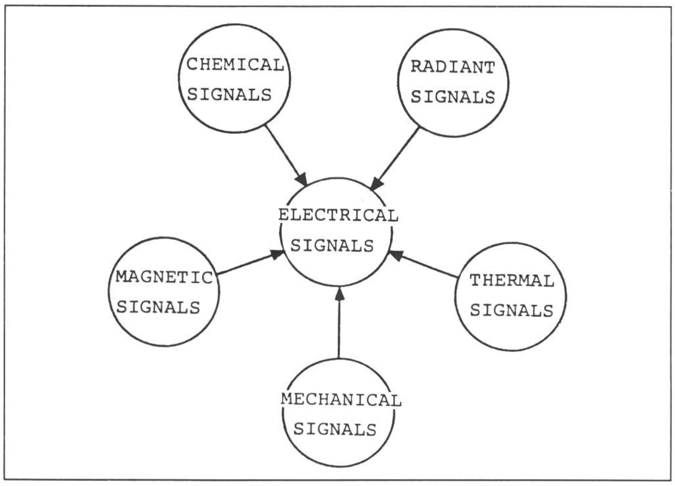

Fig. 2
The five possible signal conversions to the electrical domain

formation-processing unit. This signal need not be an electrical signal as there are still measurement and control systems which internally do not use electronic information processing. An example is the ordinary mercury thermometer in which the thermal input signal is transformed into a mechanical expansion of mercury which is then processed mechanically in the glass capillary tube. However, the distinct advantages of electronic signal processing such as flexibility, low power consumption, speed, reliability, low cost, low weight, etc. are the reasons that this form of information processing has become the most attractive one. As a consequence, sensors which transform the signal of the measurand into an electrical signal suitable for electronic information processing are becoming increasingly important, and we will concentrate on these only.

There are five possible signal types which the input transducer may transform to an electrical signal, i.e. radiant, mechanical, thermal, magnetic and chemical signals (fig. 2). Electrical-to-electrical signal conversion has been omitted because of its triviality. Another important distinction can be made between self-generating and modulating sensors. A self-generating sensor needs no auxiliary energy sources to produce the output; an example is the solar cell. As a contrast, in the modulating transducers the input signal modulates an energy source to yield an output signal; a Hall plate is a good example.

The second block in the measurement and the control-system chain (fig. 1) is formed by the information-processing unit (digital and/or analogue). At this stage the signal from the sensor is modified (filtered, amplified, etc.) in such a way that the appropriate signal can be sent to the third stage – the output transducer. The output transducer converts its input signal into a form that can be perceived by one of our senses, or it performs an action. In general, the output transducer is the inverse of the input transducer since it converts an electrical signal into one of the five possible signal forms [4; 5].

3. Silicon-integrated sensors

As a result of the enormous efforts devoted to perfecting integrated circuits over the past thirty years, a dependable, diverse, commercially oriented and sophisticated silicon IC technology is available nowadays. Silicon has shown itself to be the best material for this technology. Moreover, a whole range of modulating and self-generating effects is available in silicon which may be used for sensing purposes [5]. In table I a few examples are given of physical and chemical effects in silicon which may be used in self-generating and modulating transducers. If an effect such as for instance piezo-electricity cannot be found in silicon, a whole range of compatible technologies exists in which it is possible to produce layers of materials having the desired properties on top of a silicon substrate (ZnO piezo-electric layers or NiFe magnetic layers, for instance).

Batch silicon technology fabrication offers the possibility of producing large quantities of sensors, thereby reducing their price. These sensors can have very small dimensions and they will not significantly disturb the measurand, their power consumption can be very small and their frequency response is good. Arrays of sensors are also possible for simultaneous, distributed measurements (CCD video cameras).

Silicon also has very good mechanical properties. For example, it has a higher limit of elasticity than steel. It also exhibits no hysteresis if subjected to repeated stress. Micromachining of 3-dimensional structures is feasible [6; 7], and in terms of their chemistry, Si and SiO_2 are inert in many hostile environments.

Another very important advantage of using silicon as the material for sensors is that the sensor and the signal-processing electronics (or a part of it) may be integrated on the same chip (to obtain the so-called smart sensor). In

Some physical and chemical effects to be used in transducers Table I

Signal Domain	Effects for self-generating Transducers	Effects for modulating Transducers
Mechanical	–	Piezoresistance
Thermal	Seebeck Effect	Temperature Dependence of Resistance
Radiant	Photovoltaic Effect	Photoconductivity
Chemical	Galvano-electric Effect	Ion-sensitive Field Effect
Magnetic	–	Magneto-Resistance

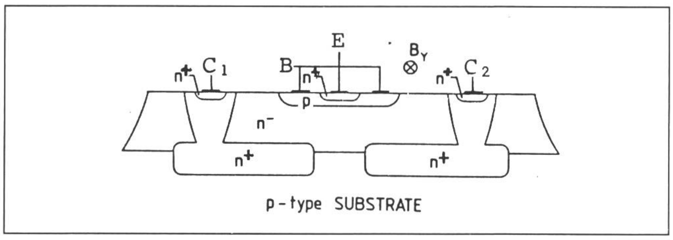

Fig. 3
Cross section of the dual collector magnetotransistor

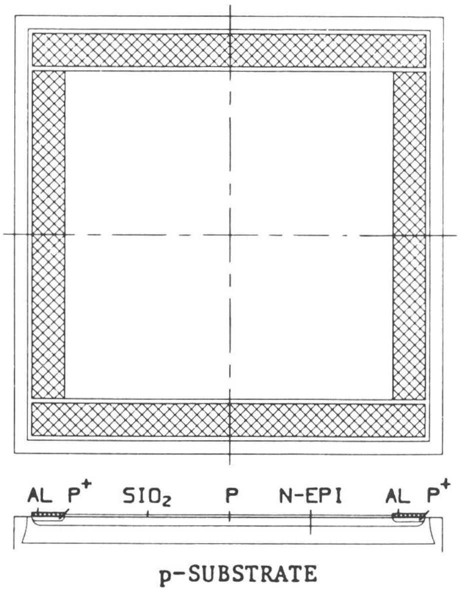

Fig. 5 Top view and cross section of the light spot position-sensitive device

this way the problem of long connections which are susceptible to noise can be alleviated by amplifying the sensor signal or by encoding it on the chip, and subsequently transmitting it to the central signal processor. Power-supply stabilisation and reference voltages can be integrated along with the circuitry to compensate for non-linearities and temperature dependence of the sensor output. In this way the central signal processor can be somewhat relieved of its load. When an array of sensors is required, a multiplexing circuit may be integrated with the sensors, which would reduce the number of connections to the outside world.

But not all problems have been solved yet. Drift of the sensor characteristics may be a problem in some sensors, in which case calibration of the sensor must be performed from time to time. Other sensors have the problem that the production yield is not high enough, which increases the sensor price. The present price of $5 to 10 for solid-state pressure transducers, for example, is still too high for the home appliances market [8]. The cost of development and processing requires large quantities to be produced and sold. The production yield must be reasonably high to keep the price low. Packaging may present other difficulties. The sensor may have to operate in a hostile environment in which the usual IC encapsulation is inadequate.

In some cases the technological requirements for the sensor may be incompatible with the signal-conditioning circuit technology if a smart sensor is desirable. Where a smart sensor can be realized, unwanted feedback loops may be created (temperature feedback for example). Silicon can also be used between -50 °C and +150 °C only, and a smart sensor will always need a power supply.

These problems are the reason why silicon sensors have not yet flooded the market and why at present there is intensive research in the field of silicon-integrated sensors.

4. Some examples of silicon sensors

In the following the possibilities and limits of silicon sensors are illustrated by discussing a few sensors which were developed at the Delft University of Technology.

4.1 The magnetotransistor

Both the Hall plate and the magnetotransistor make use of the Lorentz deflection of the charge carriers by the magnetic field for sensing purposes. Contrary to the Hall plate, which is sensitive to magnetic fields perpendicular to the chip surface, the magnetotransistor is sensitive to in-plane magnetic field [9]. Figure 3 shows that in the absence of a magnetic field the current injected by the emitter into the base and subsequently into the epitaxial *n*-region will be evenly distributed between the two collectors. The difference in the two collector currents I_{c1} and I_{c2}, which is the output signal, will be zero in this case. In case the magnetic field is not zero, the current will be deflected toward one of the collectors and an imbalance between the two collector currents will be created which is linearly proportional to the applied magnetic field. This device can be fabricated in standard bipolar IC technology and can be used as a contactless proximity sensor in keyboards.

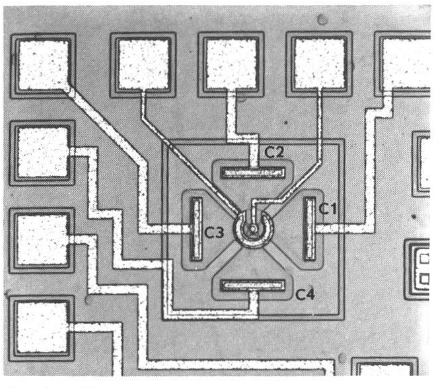

Fig. 4 Microphotograph of the four collectors magnetotransistor

Another application is the brushless electromotor in which the magnetic sensor is used to determine the position of the rotor with respect to the stator and in such a way make an accurate electronic commutation possible [10].

The four-collector version of the magnetotransistor as shown in figure 4 is capable of performing an in-plane magnetic-field vector measurement. Collectors C1 and C3 are sensitive to the *x* component of the magnetic-field vector, while collectors C2 and C4 sensitive to the *y* component. This configuration makes a solid-state compass feasible.

Like all modulating transducers, magnetotransistors are plagued with offset which is an additive error in the output of the sensor responsible for a non-zero output signal when the measurand is zero. Currently a sensitivity-variation offset reduction method is being developed which should deal with this problem in a satisfactory manner [11].

4.2 Solid-state humidity sensor

An example of a commercially available silicon sensor is the humidity sensor. In this case the silicon chip is being cooled off until water vapour starts to condense on the aluminum capacitor structure on top of the chip. The condensed water changes the dielectric constant of the capacitor. The change of the capacitance is detected and the temperature of the chip is recorded. Knowing the temperature at

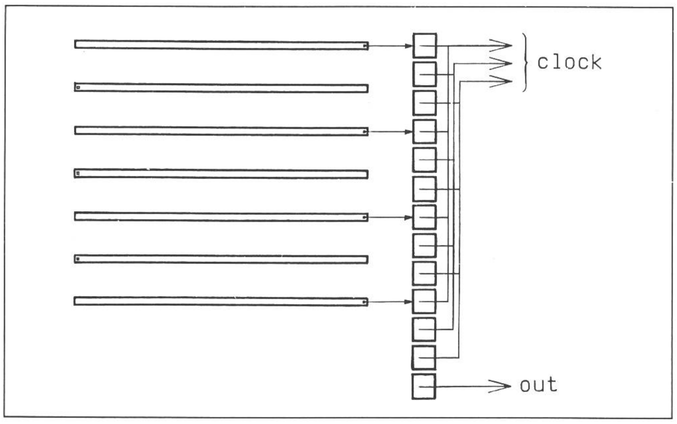

Fig. 6 Schematic representation of the nuclear particle detector with CCD readout

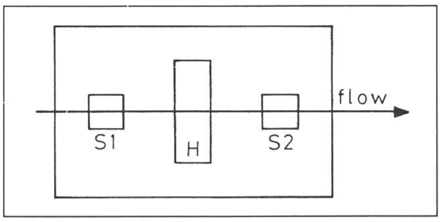

Fig. 8 Diagram of the monolithic flow sensor

which water vapour condenses as well as the ambient temperature is enough to determine the air humidity with 1% inaccuracy [12].

4.3 Light-spot position-sensitive detector (PSD)

A position-sensitive detector is capable of measuring the x and y coordinates of a light spot on the surface of the detector. A PSD is formed by a p-type diffusion in an n-type substrate forming a large-surface pn-diode (fig. 5). A light spot generates a photo-current which is collected by the contacts in the n-type and the p-type layers. The amount of current collected by the contacts is a measure of the distance between the centre of the light spot and the particular contact. If the currents drawn by the opposite contacts are compared to each other for each pair of contacts, the x and the y position are obtained. PSDs of 6×8 and $15 \cdot 15$ mm^2 in area have been made which have a non-linearity of less than 0.5% and a resolution better than 1 µm [13].

An example of a compatible technology solution of the shortcomings of silicon as a material is given in [14]. Silicon as a material is not sensitive to x-rays. In order to be able to use the PSD as an x-ray position detector, a layer of phosphor (which is sensitive to x-rays) has been applied to the surface of the PSD to convert x-rays into light photons.

4.4 Silicon micro-strip detector

As a result of cooperation with CERN in Geneva a silicon micro-strip detector has been developed which is capable of detecting the place of incidence of a passing elementary particle. The detector is made of a series of p-type strips which are diffused in a 2-kΩ n-type substrate. The pitch of the strips can be as low as 20 µm. An elementary particle passing through a pn-diode strip will generate a pulse in that strip. If the signals from the adjacent strips are also processed, the resolution of the measurement can be as high as 3 µm.

One drawback of the micro-strip detector is the large number of output connections. An elegant solution to this problem is described in [15], where a junction CCD is used to read out the strips serially. This greatly reduces the number of bonding wires (fig. 6).

4.5 Silicon thermopile

The old-fashioned thermocouple is a good example of a self-generating transducer where a temperature difference between the junctions of two different materials is transformed into a voltage difference. This transformation occurs directly and no auxiliary power source is needed.

Silicon planar technology offers the possibility of integrating a large number of thermocouples in series on one chip to obtain a thermopile. This connection scheme increases the sensitivity to temperature differences across the chip with respect to a single thermocouple. In [16] a thermopile is described which consists of 152 p-type silicon aluminum thermocouples yielding an output voltage as high as 76 mV/°C (fig. 7). The thermopile occupies an area of 3.8×1.5 mm^2 and the strips are 1.5 mm long. The thermopile has a total resistance of 250 kΩ and a maximum output current of 0.3 µA per degree of temperature difference. The construction of such a thermopile using a conventional lumped-element method would be very labour-intensive, so that this example illustrates still another advantage of the silicon planar technology: integration of repetitive structures requires a minimal amount of effort and does not increase the price of the chip significantly.

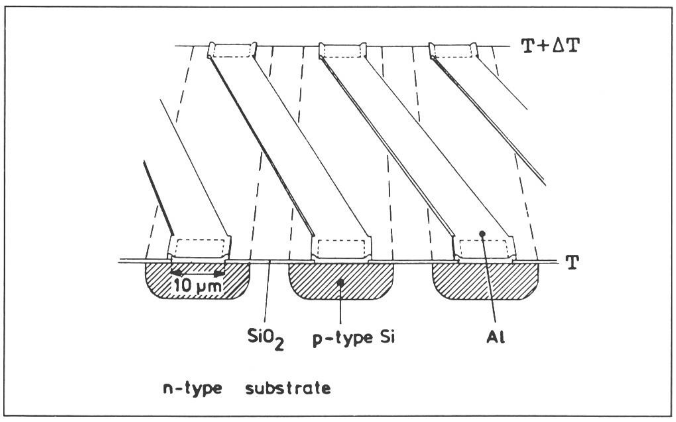

Fig. 7 Part of the aluminum p-type silicon thermopile

4.6 Silicon flow meter

The silicon flow meter is based on the transfer of heat which is enhanced by a flowing medium. The structure is shown in figure 8. H represents the heat source formed by a dissipating bipolar transistor, while $S1$ and $S2$ are two temperature-sensing transistors. In the absence of flow there will be no temperature difference between $S1$ and $S2$. Consequently, the output signal (temperature difference) will be zero. The presence of a flowing substance over the chip surface will, however, create an imbalance in the temperature distribution as the medium boundary layer is heated up. Because the medium is moving the temperature of the sensor downstream from H will be higher than the temperature of the

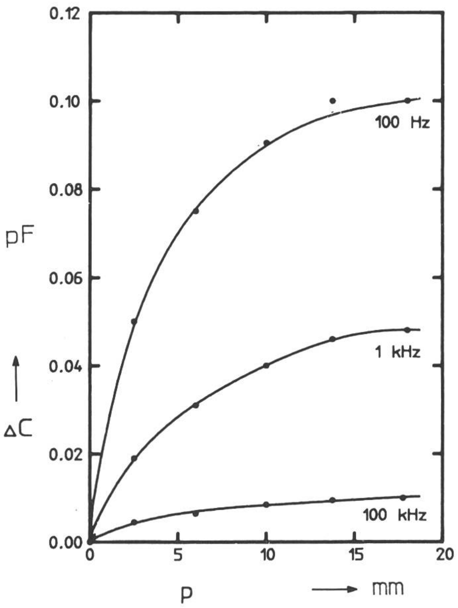

Fig. 9 The change of capacitance in pF as a function of the CO pressure in mm Hg

upstream sensor. The output signal depends on the square root of the flow velocity and is generally a complicated function of the thermodynamics of the boundary layer. A simple linear relation between the flow velocity and the output signal may be obtained if the temperature difference between the sensors is small and if a constant temperature difference is maintained between the chip and the flowing gas or a fluid [17; 18].

4.7 The gas sensor

In the case of a gas sensor an interdigitated electrode structure is covered with polyphenylacetylene (PPA) [19]. PPA's permitivity changes slightly upon absorption of gases and a change in capacitance can be observed. The device consists of a substrate with 40 pairs of 0.35-µm-thick aluminum electrodes on top. The total area of the device is 1.6×1.2 mm². A 0.77-µm-thick polymer (PPA) is applied to the top of this structure, resulting in capacitance values of around 3pF.

In figure 9 the change of the capacitance is given as a function of the carbon-monoxide pressure. The device is also sensitive to CO_2 and CH_4 so that it is not possible to use the structure when these gases are present simultaneously. An additional difficulty is presented by the dependence of the output signal on the relative humidity.

4.8 Integrated temperature sensor

If two bipolar transistors are biased in such a way that the ratio of their emitter currents is a constant, the difference in their emitter-base voltages is proportional to the absolute temperature (PTAT). This property is used in a single-chip temperature transducer. A simple example of a PTAT circuit is shown in figure 10. The collector current ratio of T1 and T2 is kept at a constant by the current mirror formed by transistors T3 and T4. In that case the output current I_0 is proportional to the absolute temperature [20].

If this PTAT current circuit is combined with a band-gap voltage reference and a resistor network a transducer is obtained with the output signal on a Celsius, Fahrenheit or any other scale.

5. Conclusion

As the above examples show, the advantages of silicon and the problems encountered in silicon sensors together explain the reason why at the present time an intensive research is being conducted in the field of silicon integrated sensors.

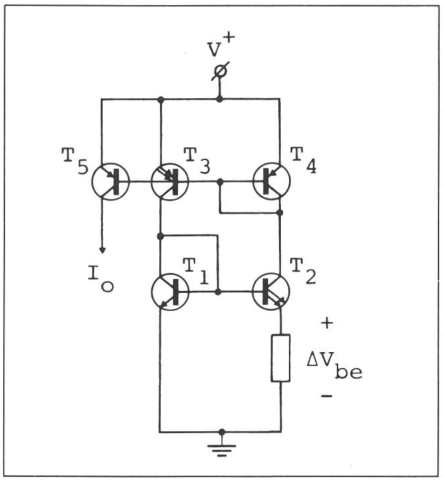

Fig. 10 Schematic representation of a current source, in which I_0 is proportional to the absolute temperature (PTAT)

Bibliography

[1] *A. Gupta* and *H.-M. D. Toong:* The special issue on personal computers. Proc. IEEE 72(1984)3, p. 243...245.
[2] *S. Middelhoek:* Integrated sensors. Proceedings of the third Sensor Symposium, Tsukuba City/Japan, 1983: p. 1...10.
[3] *A. Dumbs* and *J. Hesse:* Sensor problems in robotics. Sensors and Actuators 4(1983)4, p. 629...639.
[4] *S. Middelhoek* and *D. J. W. Noorlag:* Three-dimensional representation of input and output transducers. Sensors and Actuators 2(1981/82)–, p. 29...41.
[5] *S. Middelhoek* and *D. J. W. Noorlag:* Silicon microtransducers. Journal of Physics E: Scientific Instruments 14(1981)12, p. 1343...1352.
[6] *S. Middelhoek, J. B. Angell* and *D. J. W. Noorlag:* Microprocessors get integrated sensors. IEEE Spectrum 17(1980)2, p. 42...46.
[7] *J. B. Angell, S. C. Terry* and *P. W. Barth:* Silicon micromechanical devices. Scientific American 248(1983)4, p. 36...47.
[8] *R. Allan:* Sensors in silicon. High Technology 4(1984)9, p. 43...50.
[9] *V. Zieren:* Integrated silicon multicollector magnetotransistors. Thesis of the University of Technology, Delft, 1983.
[10] *Y. Kanda* a. o.: Silicon Hall-effect power ICs for brushless motors. IEEE Trans ED 29(1982)1, p. 151...154.
[11] *S. Kordić, V. Zieren* and *S. Middelhoek:* A magnetic-field-sensitive multicollector transistor with low offset. International Electron Devices Meeting, Technical Digest (1983), paper 28.2, p. 631...634.
[12] *P. P. L. Regtien:* Solid-state humidity sensors. Sensors and Actuators 2(1981/82), p. 85...95.
[13] *D. J. W. Noorlag:* Lateral-photoeffect position-sensitive detectors. Thesis of the University of Technology, Delft, 1982.
[14] *O. M. Sprangers* and *D. J. W. Noorlag:* Linear silicon position-sensitive detector for the measurement of x-ray and electron-beam positions at room temperature. Sensors and Actuators 3(1982/83)–, p. 335...372.
[15] *W. R. T. ten Kate* and *C. L. M. van der Klauw:* A new readout structure for radiation silicon strip detectors. International Electron Devices Meeting, Technical Digest (1983), paper 28-6, p. 647...650.
[16] *G. D. Nieveld:* Thermopiles fabricated using silicon planar technology. Sensors and Actuators 3(1982/83)–, p. 179...183.
[17] *A. F. P. van Putten* and *S. Middelhoek:* Integrated silicon anemometer. Electronics Letters 10(1974)21, p. 425...426.
[18] *R. W. M. van Riet* and *J. H. Huijsing:* Integrated direction-sensitive flowmeter, Electronics Letters 12(1976)24, p. 647...648.
[19] *E. C. M. Hermans:* CO, CO_2, CH_4 and H_2O sensing by polymer covered interdigitated electrode structures. Sensors and Actuators 5(1984)3, p. 181...186.
[20] *G. C. M. Meijer:* An IC temperature transducer with an intrinsic reference. IEEE J. Solid-State Circuits 15(1980)3, p. 370...373.