UDK621.3:(53+54+621+66), ISSN0352-9045 Informacije MIDEM 32(2002)4, Ljubljana

INTRODUCTION TO SENSORS

S.Amon, D.Vrtačnik, D.Resnik, U.Aljančič, M.Možek

Laboratory of Microsensor Structures - LMS
Faculty of Electrical Engineering, Ljubljana, Slovenia

POSVET O SENZORJIH V ZAVODU ITC SEMTO
15.03.2002, FE Ljubljana

Key words: sensors, actuators, MEMS, micromachining, sensor parameters, transduction principles, smart sensors

Abstract: An overview of basic definitions and properties related to sensors is given. Key sensor classifications and definitions of some relevant sensor properties such as transfer function, sensitivity, accuracy, resolution, selectivity, noise, nonlinearity and other are emphasized. Some recent applications based on silicon standard and micromachining technology available in Laboratory of Microsensor Structures (LMS) are presented, such as research and development of silicon devices, sensors and microelectromechanical systems (MEMS) as well as integration of sensors and electronics resulting in smart sensor solutions.

Osnovne značilnosti senzorjev

Ključne besede: senzor, aktuator, MEMS, mikroobdelava, parametri, principi pretvorbe, inteligentni senzor

Izvleček: Uvodoma bodo predstavljene nekatere osnovne definicije s področja senzorjev in pomembnejši ključi razdelitve senzorskih družin. Podrobneje bodo razložene izbrane senzorske lastnosti kot so npr. prenosna funkcija, občutljivost, točnost, ločljivost, selektivnost, šum, nelinearnost in drugo. Shematsko bo predstavljen tudi princip zajemanja podatkov na osebnem računalniku. V nadaljevanju prispevka bo predstavljena raziskovalno - razvojna dejavnost na področju mikrosenzorskih struktur v LMS. Poudarek bo na predstavitvi postopkov mikroobdelave in aplikacijah, ki so bile v Laboratoriju zasnovane. Na koncu bomo podali pregled lastnosti inteligentnih senzorjev, ki predstavljajo eno izmed glavnih smernic razvoja modernih senzorskih struktur.

I. INTRODUCTION

Sensor applications today are wide spread and constantly growing, mainly due to the increasing amount of data which is acquired from environment. The data is mainly intended for further computer processing. This giant stride of sensor applications is expected to be continuous at least for five more years and at least proportional to the technological development. Future development will be concentrated in the field of three dimensional (3D) microsensor structures, based on classical microelectronic processes and up-to-date micromachining processes. The preferences for microelectronic approach are evident from the well-known story of integrated microelectronic circuits. Therefore, modern sensors main benefits are: price, quality, mature technologies, miniaturization and compatibility with existing integrated circuits design processes, which leads to integrated sensor designs with smart sensor features that represent today's absolute peak of sensor technology.

II. BASIC TERMS

In this section some basic terms will be discussed which are commonly used in practice, nevertheless their exact definition is often not so evident.

SENSOR: Sensor is defined as a (electronic) device which produces an (electrical) output signal in explicit relation to the value of sensed quantity on its input.

Example: Pressure sensor

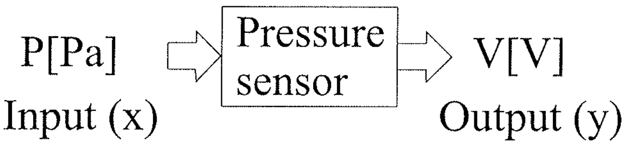


Figure 1: Pressure sensor.

Remarque: Beside original term "sensor", there are also other common names in use for sensor devices such as detector (e.g. photo-detector), meter (e.g. thermo-meter), element (e.g. thermo-element) etc.

ACTUATOR: Actuator is often defined as a (electronic) device which produces an output in the form of mechanic or information signal, which is in explicit relation to the value of (electrical) quantity on its input.

TRANSDUCER: Transducer is often defined as a common name for both sensors and actuators.

III. OVERVIEW OF SENSING PRINCIPLES

Operation of a sensor is always based on a transduction of sensor input signal energy into sensor output signal energy. This transduction, performed in sensor, is one of the basic natural phenomena. Today there are over 350 known types of transduction between various forms of energy, and their number is still increasing. Based on this variety of transduction principles, many types of sensors can be realised.

Example: Photosensor transduces input light energy into output electrical signal energy, based on the principle of photoeffect which is performed inside photosensing element.

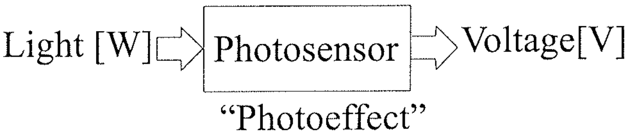


Figure 2: Transduction in photosensor.

Remarque: The term transduction is sometimes replaced by well-known synonyms such as effect, law etc.

Transduction principles are usually classified by the type of input energy. Based on this criterion, sensors are sometimes classified as mechanical, temperature, electrical, magnetic, irradiation, chemical, biological etc.

IV. OVERVIEW OF SENSOR CLASSIFICATIONS

Various sensor classifications are met in the literature, each one having its unique advantages. Brief overviews of some standard sensor classifications are given in Tables 1 - 7. Classification by the conversion phenomena is commonly used for educational purposes, since it emphasizes a conversion principle for various sensor applications. Classification by the output quantity is appropriate for systems designers who need to use sensor output in a particular project. Classifications by the type of input stimulus, price or field of use serve mainly to the end user. Classifications by fabrication technology or sensor material are appropriate for manufacturers.

Physical	Thermoelectric	**Chemical**	Chemical transformation	**Biological**	Biochemical transformation
	Photoelectric		Physical transformation		Physical transformation
	Photomagnetic		Electrochemical process		Effect on test organism
	Magnetoelectric		Spectroscopy		Spectroscopy
	Electromagnetic		Other		Other
	Thermoelastic				
	Electroelastic				
	Thermomagnetic				
	Thermooptic				
	Photoelastic				
	Other				

Table 1: Sensor classification by the conversion phenomena

Resistance	Capacitance	Inductivity	Voltage	Current	Other

Table 2: Sensor classification by the output quantity

Acoustic	Wave amplitude, phase spectrum, wave velocity, other
Biological	Biomass, other
Chemical	Components, other
Electric	Charge, current, potential, voltage, electric field, conductivity, permitivity, other
Magnetic	Magnetic field, conductivity, permitivity, other
Optical	Wave amplitude, phase spectrum, wave velocity, refractive index, emmisivity, reflectivity, other
Mechanical	Position, acceleration, force, stress, pressure, strain, mass, density, moment, shape, stiffness, viscosity, other
Radiation	Type, energy, intensity, other
Thermal	Temperature, flux, specific heat, thermal conductivity, other.

Table 3: Sensor classification by the type of stimulus (input quantity)

Thick film, thin film, bipolar, unipolar, micromachined, other
Semiconductor/silicon, metallic, insulator, ceramic, biological, (in)organic, solid, liquid, gas, other

Table 4: Sensor classification by the fabrication technology and by sensor material

Agriculture	Automotive
Civil engineering	Space
Distribution	Domestic
Energy, power	Environment
Medicine	Information
Military	Marine
Scientific measurement	Other

Table 5: Sensor classification by the field of application

biological	radioactivity and radiation
chemical	heat and temperature
electric, magnetic or electromagnetic	mechanical

Table 6: Sensor classification by the detection means

sensitivity	stimulus range (span)
stability (long and short term)	resolution
accuracy	selectivity
speed of response	environmental conditions
overload characteristics	linearity
hysteresis	dead band
operating life	output format
cost, size, weight	other

Table 7: Sensor classification by some special specification

V. BASIC SENSOR CHARACTERISTICS AND PARAMETERS

In this section some significant sensor definitions, properties and parameters will be reviewed /1/. In the definition of sensor characteristics we will refer to sensor as a "black box" with its stimulus input x (i.e. measured input quantity) and (electrical) sensor response (output quantity) y (Fig. 3).

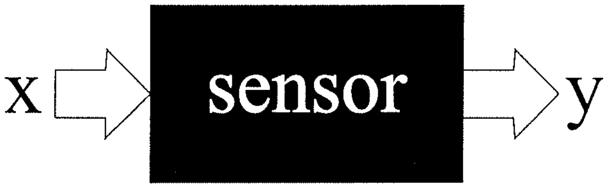


Figure 3: General presentation of a sensor.

Transfer function: is the relationship between input x and output y of a sensor. This function establishes dependence between the electrical signal y and stimulus x. (Fig. 4)

$$y = y(x) \tag{5.1}$$

Input stimulus x range is from x_{min} to x_{max}, output electrical signal y range is from y_{min} to y_{max}.

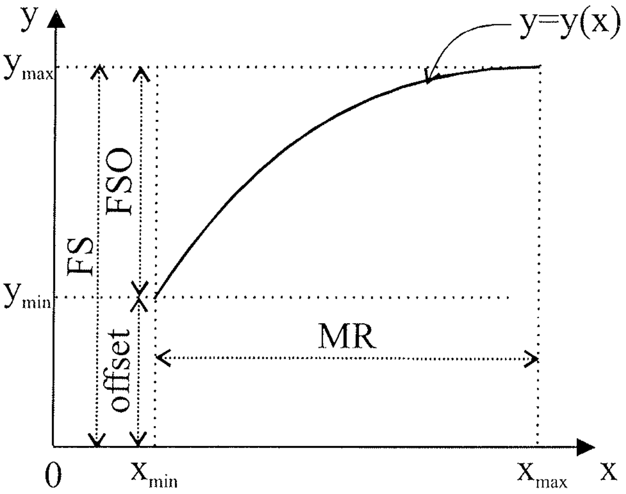


Figure 4: Transfer function of a sensor.

Measured Range (MR), also **Span:** is a dynamic range of stimuli which can be applied to a sensor.

$$MR = x_{max} - x_{min} \tag{5.2}$$

Full Scale (FS): is maximal range for sensor output quantity, given by y_{max}

Full scale output (FSO): is the difference between the electrical output signals y_{max} and y_{min}, measured at minimum applied stimulus x_{min}

$$FSO = y_{max} - y_{min} \tag{5.3}$$

Sensitivity S: is the ratio of the change of sensor output Δy and a according small input stimulus variation Δx (Fig. 5). Therefore sensitivity S can be mathematically expressed as a first order derivative of the output y to stimulus x

$$S(x) = \left.\frac{dy(x)}{dx}\right|_x \tag{5.4}$$

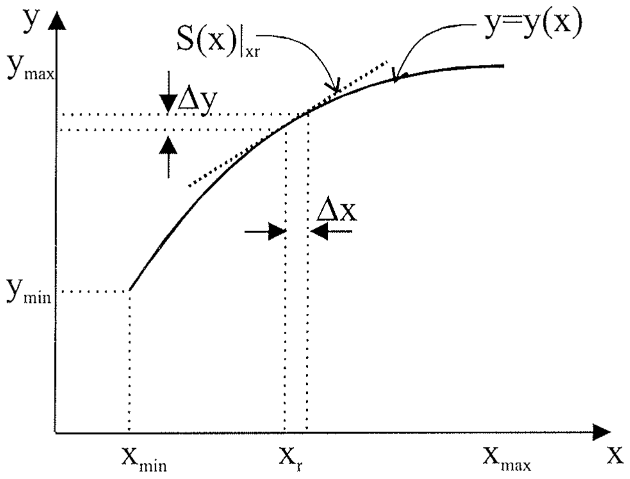
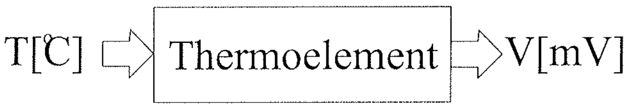


Figure 5: *Sensitivity.*

Example: Thermoelement sensitivity



$$S = \frac{dV(x)}{dT}\left[\frac{mV}{^{o}C}\right]$$

Offset y_{min}: is the value of transfer function *y(x)* at minimum stimulus x_{min}

$$y_{\min} = y(x)\,\big|_{x=x_{\min}} \qquad (5.5)$$

Accuracy ε: is the difference between the value of measured input stimulus x_m, obtained from sensor transfer function y_m and the true value x_t of the same stimulus, obtained from high accuracy reference sensor (Fig. 6). Accuracy is usually normalized to the measured range *MR* and then expressed in percent.

$$\varepsilon\ [\%] = \frac{x_m - x_t}{MR}\cdot 100 \qquad (5.6)$$

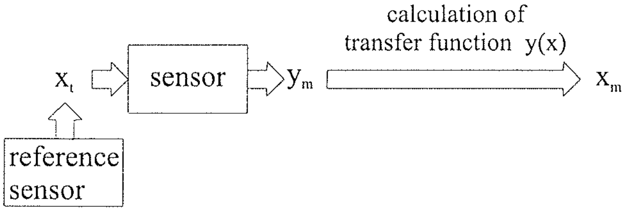


Figure 6: *Accuracy determination.*

In modern sensor design, accuracy is being replaced by much wider term *uncertainty*, which combines systematic and random errors (see below).

Resolution R: is the smallest change in input stimulus Δx_{min}, which already produces a measurable change in output Δy_{min}. Resolution is often normalized by *MR* and then given in percent.

$$R[\%] = \frac{\Delta x_{\min}}{x_{\max} - x_{\min}} 100 \qquad (5.7)$$

Selectivity S_α: is defined as sensitivity of a sensor to the variations of different unwanted input environment parameters x_α such as temperature, humidity, light etc.

$$S_\alpha = \frac{\Delta y}{\Delta x_\alpha} \qquad (5.8)$$

Obviously, an ideal sensor has selectivity $S_a = 0$!

Remarque: Other names for selectivity are also drift, instability, cross sensitivity etc.

Noise N: is the RMS (root - mean - square) value of the sensor output signal, measured at minimal stimulus x_{min} on sensor input.

Minimal Detected Signal MDS: is the minimal value of the input stimulus x_{min}, which yields an output response equal to the noise level (S/N ratio=1). Therefore input values below *MDS* cannot be distinguished from noise, and are hencefore not measurable!

Nonlinearity NL: is the deviation of a real transfer function from the ideal linear response (y_{NL}, Fig. 7). There are several ways how to specify nonlinearity, depending on how the approximating ideal linear line is superimposed to the transfer function. Approximating line can be drawn through minimal and maximal characteristics points (terminal points line). Another best-fit line can be obtained by drawing a parallel line through the terminal points and then choosing a best-fit line at the midway of those two lines. The nonlinearity is then calculated as a maximum deviation from the midway line. The type of approximation used dictates a value calculation algorithm, which is performed by signal processing electronics in smart sensors. With prevalent use of microprocessors one can implement more complex value calculation algorithms such as least squares fit which minimizes the square area between approximating line and the transfer function.

Hysteresis H: is the deviation Δy_{HYST} of a sensor when the entire measurement range is scanned in the direction from x_{min} towards x_{max} and opposite (Fig. 8).

Repeatability Rep: is the deviation Δy_{Rep} of the sensor outputs when the entire measurement range is scanned repeatedly in the direction from x_{min} towards x_{max}. So repeatability is similar to hysteresis, only the measurement range is scanned in the same direction (Fig. 9).

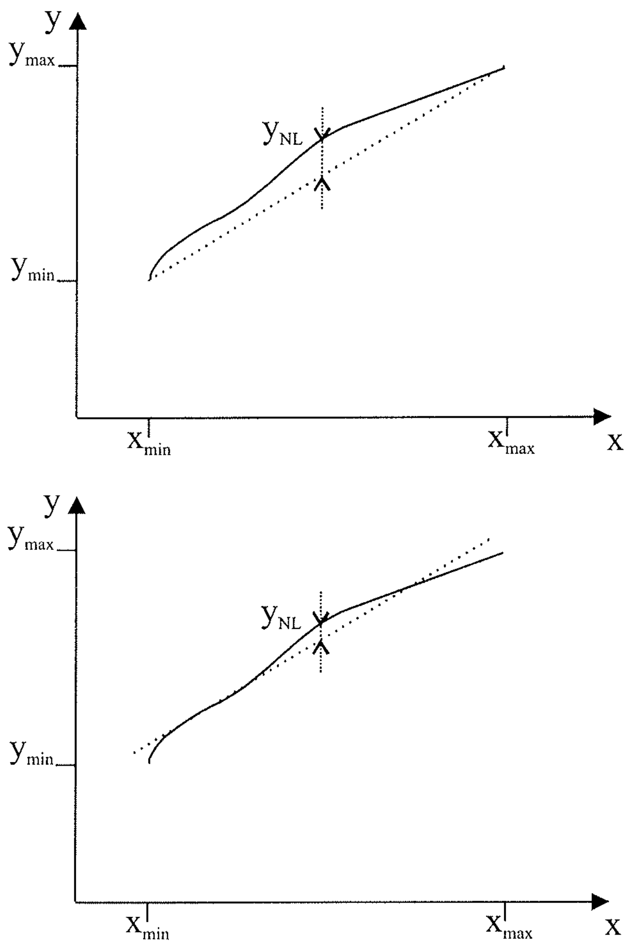


Figure 7: Nonlinearity calculation methods.

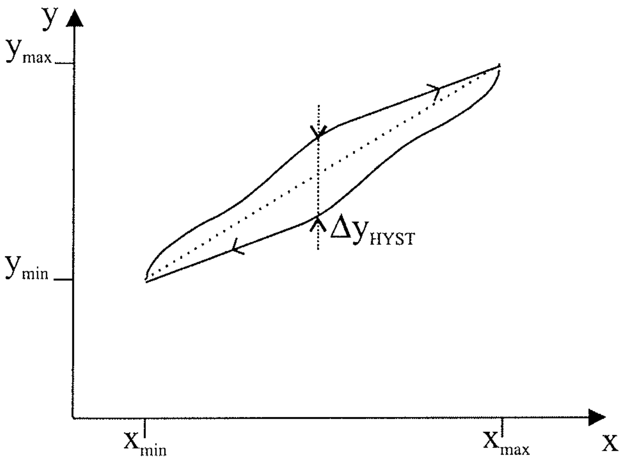


Figure 8: Hysteresis.

Temperature zero drift or **error**, also **offset drift:** is the change of sensors output y_{min}, when the temperature range is scanned from T_{min} to T_{max} with minimum stimulus x_{min} at the input (Fig. 10). Similarly, temperature drift error is sometimes measured at maximum stimulus applied.

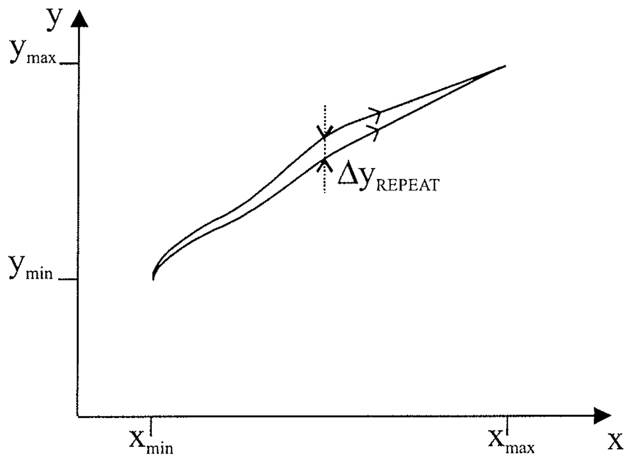


Figure 9: Repeatability.

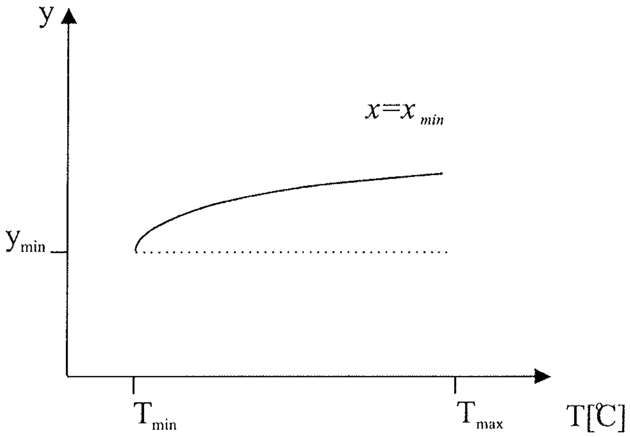


Figure 10: Temperature zero error.

Overrange (also **overload) characteristics:** is the maximum permissible limit of the input stimulus, which can be applied to a sensor for a certain period without causing permanent degradation of sensors characteristic.

Recovery time: is the time required for a sensor to regain specified characteristics after being exposed to overload.

Response time: is the time required by a sensor output to reach 90% of the final steady- state response value upon exposure to a step stimulus.

Long-term stability: is given as the maximum deviation in sensor response Δy_{STAB} after longterm operation at constant specified operating conditions (Fig. 11).

Uncertainty: is obtained from an error estimation procedure which considers statistical error sources and error sources that can be determined by measurement or other means. Statistical errors are described by standard deviation s_i and variance u_i. Standard uncertainty (u_i=s_i) represents each component that contributes to the measurement result. Other types of errors can be obtained from previously acquired set of measurements, calibration reports etc. Both sources are associated in combined standard uncertainty by means of RSS method (Root of the Sum of the Squares):

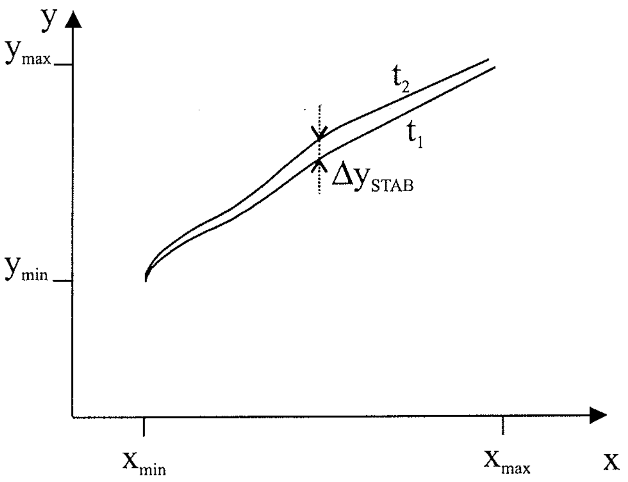


Figure 11: *Long-term stability.*

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + ... + u_n^2} \qquad (5.9)$$

VI. SENSOR TECHNOLOGIES

Technologies which are prevalent in modern microsensor structures design and fabrication are commonly divided into two major categories:

1. *Classic microelectronic technologies*, which incorporate standard integrated circuit process technologies such as thick and thin - film technologies and semiconductor technologies (diffusion, implantation, oxidation, photolithography, metal and dielectric layer deposition ...)
2. *Micromachining* is a collective name for a group of modern processes which are devoted to fabrication of 3D microstructures. Some more important micromachining processes are:
   - Etching (dry, wet; isotropic, anisotropic)
   - Laser micromachining
   - EDM (Electro Discharge Machining)
   - Sacrificial film processing
   - Film lift-off method
   - LIGA (Lithographie-Galvanoformung-Abformung)
   - Hole sealing
   - Wafer bonding etc.

Silicon has prevailed as the fundamental material for microelectromechanical systems (MEMS) fabrication due to its excellent electrical, optical and mechanical properties such as:

- Mature and well known microelectronic technology
- Excellent electrical properties (doping, semiconductor properties...)
- Excellent optical properties (photoelectric and photovoltaic effect ...)
- Excellent chemical properties (isotropic, anisotropic etching ...)
- Excellent mechanical properties (Young modulus is comparable to stainless steel, without practically any plastic deformation - devices operate or break)
- Other interesting features (piezoelectricity, piezoresistivity, Hall and Seebeck effect ...)

VII. SIGNAL CONDITIONING

Digital signal conditioning is crucial for a good sensor application. In this section we give a brief review of basic electronics involved.

A typical sensor system with basic building blocks for signal conditioning is shown in Fig. 12. As an example, output signal from temperature sensor is a small voltage in the range of milivolts. This signal is amplified by a high input impedance amplifier, such as instrumentation amplifier. Signal from the amplifier is led to a low pass filter, which removes unwanted high frequency components in sensor signal. Low frequency spectrum of a signal is then presented to the sample & hold circuit for signal discretization. The digital result from A/D converter is then further elaborated, often by a personal computer. In modern sensor systems the signal conditioning circuit is normally integrated with sensor. This arrangement is referred to as "system on chip" (SOC) or "microsystem" (MS) /4/.

VIII. SENSOR ACTIVITIES AND APPLICATIONS IN LMS

Activities in Laboratory of Microsensor Structures at the Faculty of Electrical Engineering, University of Ljubljana consist of basic research in the field of micromachining

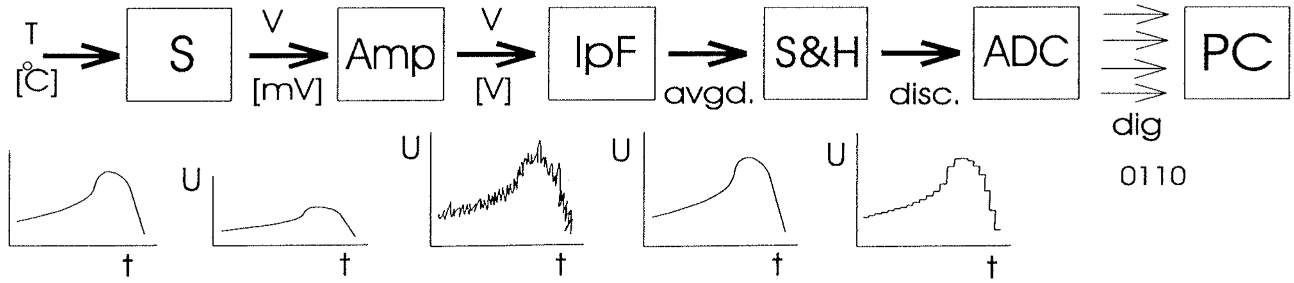


Figure 12: *Typical sensor system with basic building blocks for signal conditioning.*

and development of different advanced sensor and actuator 3D microstructures and devices. In this section we present a short survey of some results and developed devices.

An/isotropic etching of silicon:

Anisotropic properties of silicon are of utmost importance in micromachining by wet anisotropic etchants such as KOH, EDP, TMAH and others (Fig. 13). These etchants etch different crystal planes by distinct etch rates, which are significantly influenced by etchant concentration, etch bath temperature. Both parameters also strongly influence surface quality of microstructures.

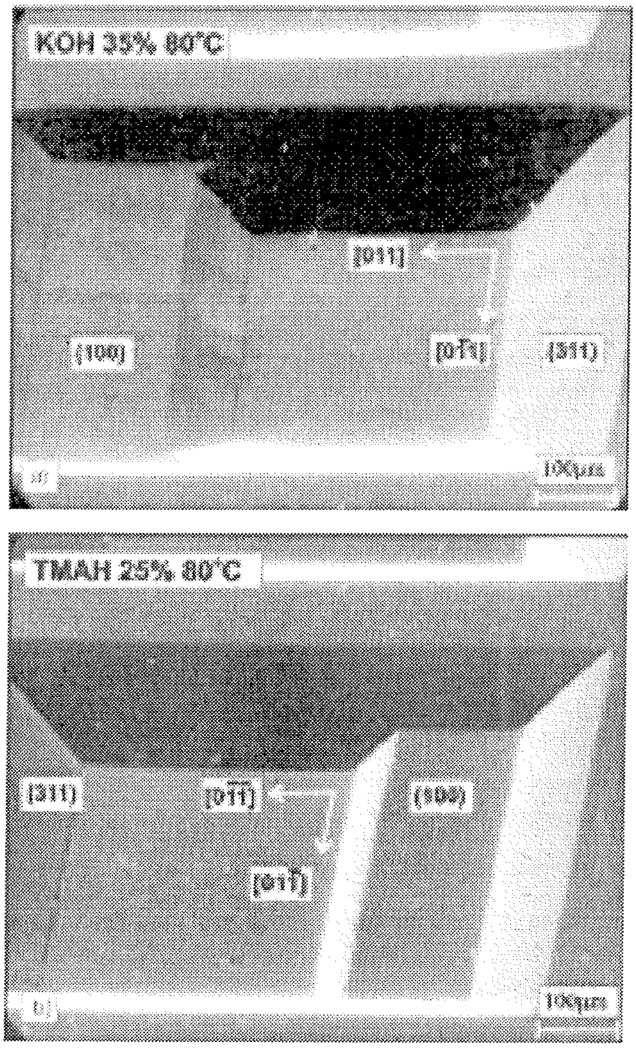


Figure 13: *Anisotropic etching of silicon.*

Study of compensation structures:

In wet micromachining of silicon microstructures fast etching of high-index crystal planes occur at convex corners. By utilizing different shapes and/or size of compensation structures this effect can be mitigated to a great extend (Fig. 14).

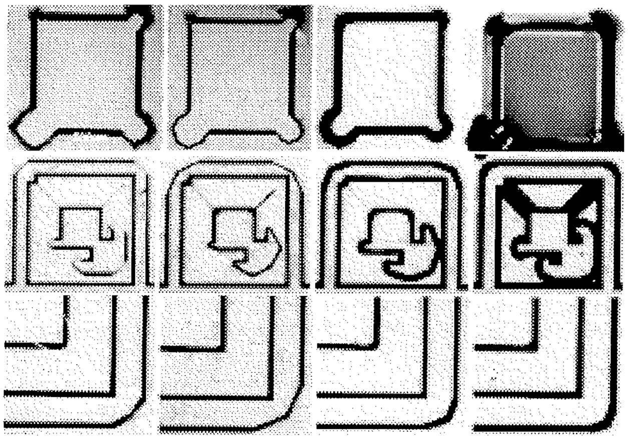


Figure 14: Convex corner compensation technique.

Compensation of convex corners in realization of 3D structures /bossed diaphragms/

In case of bossed diaphragm /5/, used in low-pressure measurement devices, there is a need for proper design of compensation structures that will occupy small footprint and effectively compensate convex corner undercutting to depths beyond 300μm. Various approaches have been studied (Fig. 15).

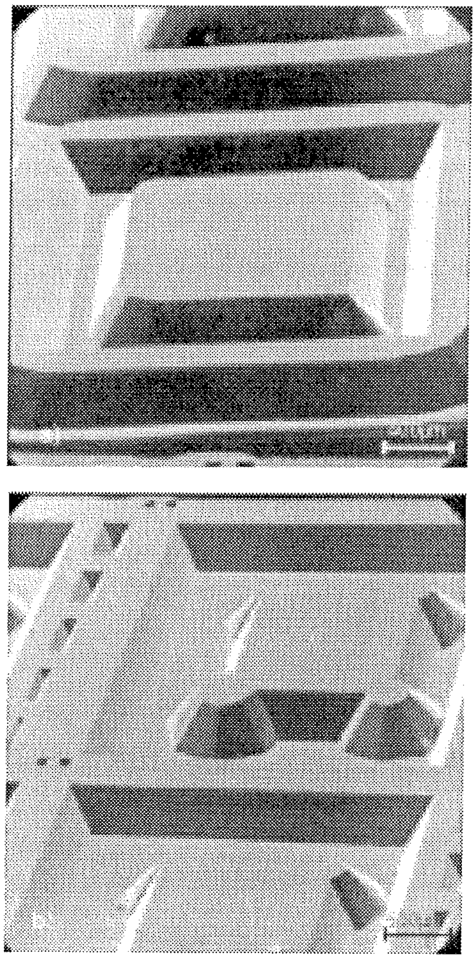


Figure 15: Compensation of convex corners in realization of bossed diaphragms.

Identification of silicon crystal planes:

Recognizing various crystal planes in silicon micromachining is of great importance, because of etch rate dependency (anisotropy). This enables proper microstructure lateral mask design and predictive final shape and size of the microstructure (Fig. 16). Most often, <100> crystal oriented silicon wafers are used, with known orientations of relevant crystal planes.

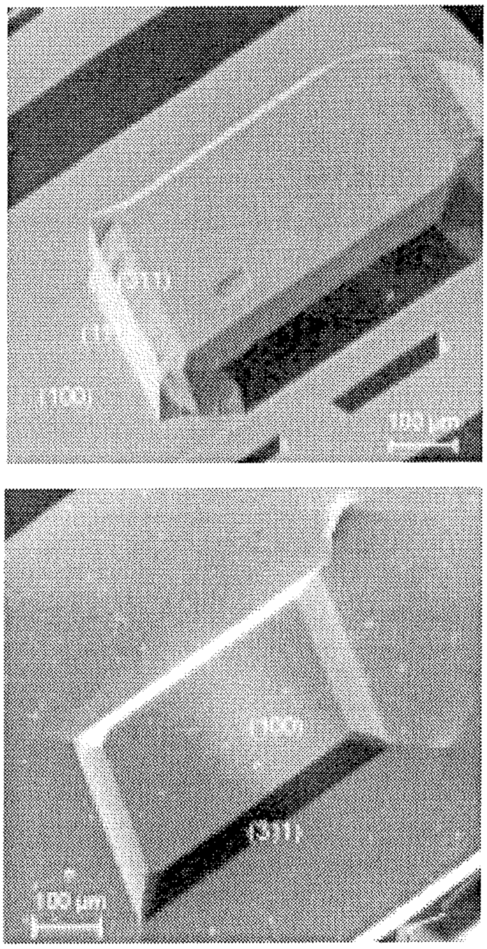


Figure 16: Identification of silicon crystal planes.

Silicon micromachining of microtips for AFM (Atomic Force Microscopy) and FED (Field Emission Displays)

By aid of an/isotropic etching (wet or dry) it is possible to perform very precise etching of silicon micropyramides or cones with apex radius bellow 20nm (Fig. 17). These microtips are successfully used for research and investigating the material physical surface properties in AFM. When fabricated as an array and electrically connected they act as point sources of electrons for light generation, thus realizing an optical display (FED).

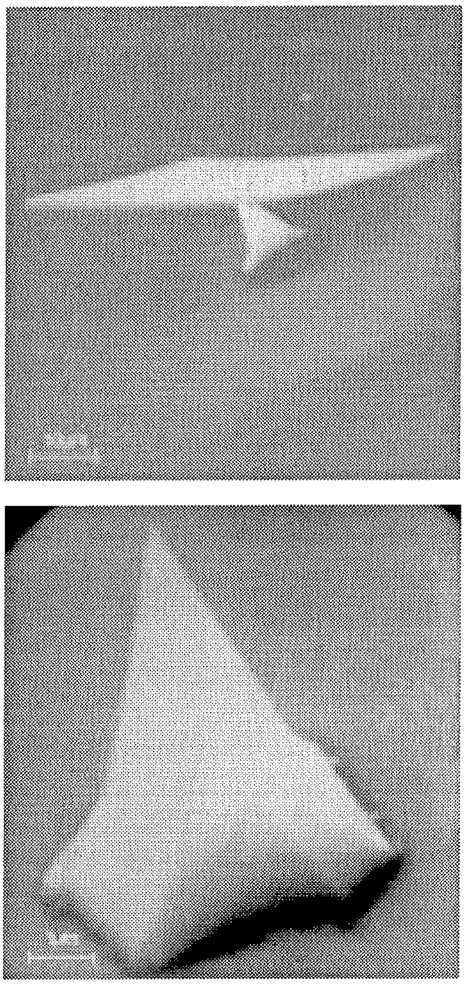


Figure 17: Silicon micromachining of microtips.

Piėzoresistive pressure sensor:

In this microstructure /6/ four resistors are diffused on the membrane and connected into the Wheatstone bridge for temperature compensation (Fig. 18). Besides, there are additional resistors diffused outside membrane region, which is important for compensation in smart sensors for accurate pressure measurements.

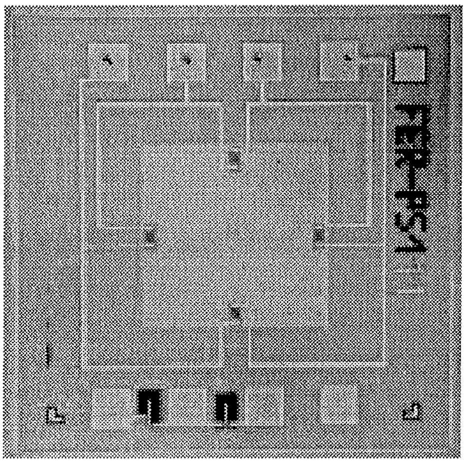


Figure 18: Piezoresistive pressure sensor.

Silicon photosensor: Phototransistor

In LMS designed and fabricated silicon phototransistor is dedicated to specific application requiring fast response and switching times. Besides, it allows high amplification of incident light signal (Fig. 19).

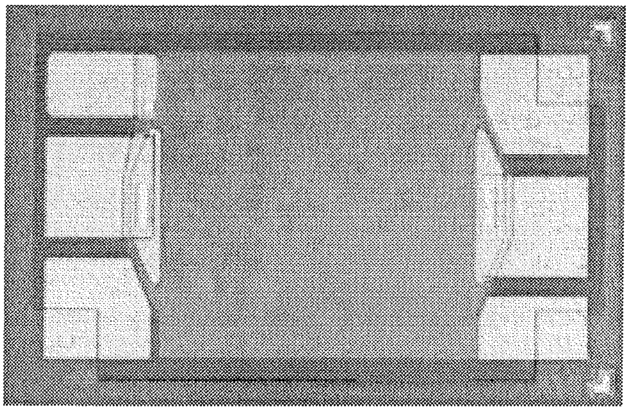


Figure 19: Silicon phototransistor (size 0.9 x 0.6mm^2).

Silicon radiation sensor: microstrip detector

In LMS designed and realized detectors /7/ with on-edge irradiation approach have high sensitivity and high space resolution, appropriate for tissue examination in the mammography and similar (Fig. 20).

Smart pressure sensor

LMS designed in cooperation with HIPOT-HYB a smart pressure sensor with digital temperature compensation and in - system calibration (Fig. 21).

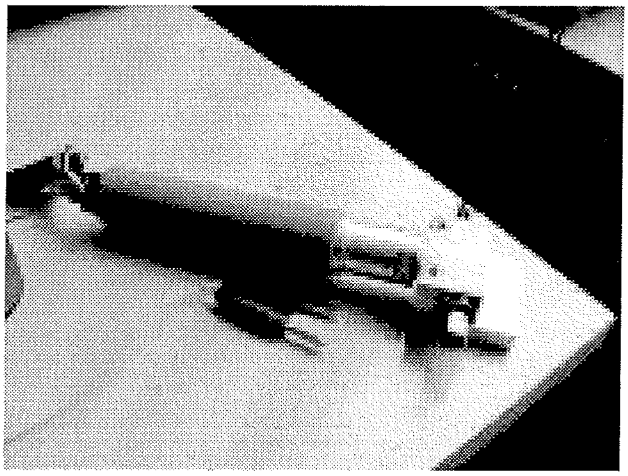


Figure 21: Smart pressure sensor prototype.

SMART SENSORS IN LMS

Smart sensors represent today's peak in sensor applications. In this section we present the essential properties of smart sensors in LMS /8/ and their characteristics during operation and calibration. Using a modern design microcontroller it is possible to implement a smart sensor in a single chip design, however modular smart sensor designs are preferable, since their implementations are more adaptable to end user. Operation of a smart sensor is similar to the operation of a normal sensor. The essence of its intelligence is due to the fact that it incorporates all necessary information in digital description for further use by a remote sensor controller. Smart sensor can be adapted on-site for end user application specific features and can be calibrated on site.

Smart sensor comprises several measurement channels: smart pressure sensor, which was implemented in LMS,

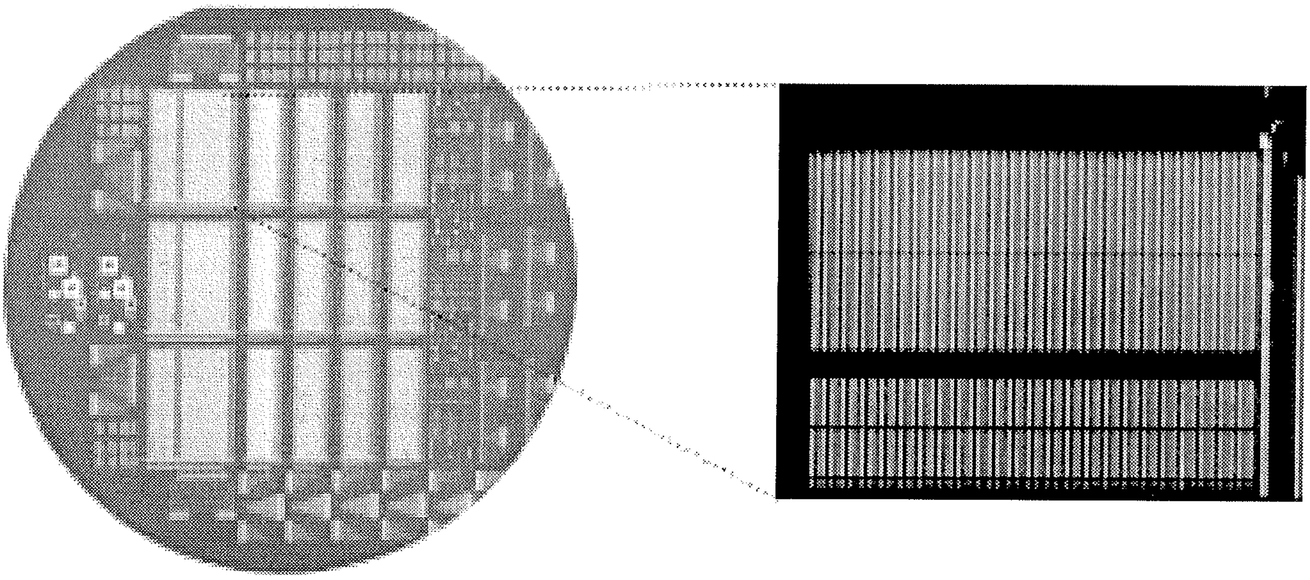


Figure 20: Microstrip detectors on a silicon wafer with a detail (right).

features pressure, temperature and two auxiliary actuator measurement channels. Each measurement channel as well as the smart sensor itself have a dedicated digital description of measurement properties - the TEDS (Transducer Electronic Data Sheet). The TEDS is available to be read and partially written by sensor controller. Smart sensors also feature virtual measurement channels, which gather information from several physical channels.

Additional preference of smart sensors is a standardized algorithm for calculating the raw sampled A/D data into measured pressure value. The scope of value calculation algorithm is very wide. Its conversion methods range from a simple look-up table to multivariate polynomial spline approximation, which can combine results from several measurement channels, resulting in multidimensional sensor compensation. Measured value of a smart sensor is presented strictly in SI units, which can be arbitrarily defined during calibration. Each measurement channel features a combined standard uncertainty. The control and status of a smart sensor can be achieved by a set of dedicated registers, organized hierarchically from individual measurement channel to general control and status. Error reporting is achieved by a unique system of interrupts, which can also be masked to prevent interrupts of known conditions. The smart pressure sensor, which was implemented by LMS and HIPOT-HYB, in excess of standard features, uses a special calibration algorithm, which minimizes the offset voltage impact and compensates temperature dependencies. The starting point of calibration is a raw pressure sensor without any offset or temperature compensation! The calibration procedure also eliminates sensor nonlinearity. Full-scale pressure is totally adaptable to the user needs.

Smart sensors will definitely change the relevance of standard sensor properties, described in section V. Nonlinearity, accuracy, sensitivity variation and selectivity will slowly recede into the background, while noise, resolution, hysteresis and repeatability will rapidly gain on significance.

CONCLUSION

A brief introduction to the elementary characteristics of a vast sensor domain has been given. Sensor terms and definitions were presented and described. An up-to-date sensor classification has been summarized. An overview of some sensor and micromachining technologies, which are implemented by LMS, has been presented. At the end a brief introduction to smart sensors has been given.

REFERENCES:

/1/ Jacob Fraden: *Handbook of modern sensors: physics, designs and applications*, 2nd ed. ISBN: 1-56396-538-0, AIP Press, 1997.

/2/ Kasap, Safa O.: *Principles of electrical engineering materials and devices*, Boston: Irwin : McGraw-Hill, cop. 1997, ISBN: 0-256-16173-9

/3/ Elwenspoek Miko, Jansen, Henri V.: *Silicon micromachining*, Cambridge, New York, Melbourne: Cambridge 1998, ISBN: 0-521-59054-X

/4/ Philip Wild: *Practical design techniques for sensor signal conditioning*, Prentice - Hall 1994, ISBN 0-916550-20-6

/5/ RESNIK, Drago, ALJANČIČ, Uroš, VRTAČNIK, Danilo, AMON, Slavko. *Bossed diaphragm with compensated convex corner mask*, 24th International Conference on Microelectronics and 32nd Symposium on Devices and Materials, September 25.-27. 1996, Nova Gorica. Proceedings. Ljubljana: MIDEM, 1996, pp. 331-326.

/6/ ALJANČIČ, Uroš, RESNIK, Drago, VRTAČNIK, Danilo, MOŽEK, Matej, TOPIČ, Marko, SMOLE, Franc, AMON, Slavko. *Silicon piezoresistive low-pressure sensors*, 36th International Conference on Microelectronics, Devices and Materials and the Workshop on Analytical Methods in Microelectronics and Electronic Materials, October 18. - 20. 2000, Postojna, Slovenia. Proceedings. Ljubljana: MIDEM - Society for Microelectronics, Electronic Components and Materials, 2000, pp. 145-149

/7/ VRTAČNIK, Danilo, KRIŽAJ, Dejan, RESNIK, Drago, ALJANČIČ, Uroš, AMON, Slavko. *Fabrication and characterization of FOXFET biased microstrip detector*, 35th International Conference on Microelectronics, Devices and Materials and Workshop on Microsystems, Ljubljana, Slovenia. Proceedings. Ljubljana: MIDEM - Society for Microelectronics, Electronic Components and Materials, 1999, pp. 245-250.

/8/ MOŽEK, Matej *Smart pressure sensor*: magistrsko delo, Ljubljana 2002

Prof. Dr. Slavko Amon
D. Vrtačnik, D. Resnik, U. Aljančič, M. Možek
Laboratory of Microsensor Structures
Faculty of electrical engineering,
University of Ljubljana
1000 Ljubljana, SLOVENIA
Tel. +386 (1) 4768 352
E-mail: slavko.amon@fe.uni-lj.si

Prispelo (Arrived): 06.06.2002 *Sprejeto (Accepted): 20.11.2002*