# MICROMECHANICS ON SILICON

**Jan Dziuban**

*The most spectacular works of Micromechanics Group of Semiconductor Laboratory of The Technical University of Wrocław are presented. Silicon simple micromechanical constructions - beams, vias-as well as more complicated micromachines and microsystems - pressure sensors, flow meters with rotating turbine - have been described.*

*The material presented here has been obtained during last six years of the research.*

## 1. Introduction

Micromachine technology relates to science and industry of designing, studying and fabricating of mechanical or electromechanical structures, devices, components and systems which posses dimensions in micrometers [1].

In the paper, some works which have been done in the Institute of Electronic Technology, Wrocław by Micromechanics Group in co-operation with former CEMI TEWA, and Institute of Electron Technology of Warsaw, are presented.

The paper summaries a state of an art in micromechanics on silicon.

Basic works were done during the discovery period of 70's [2,3,4].

Research works financed by CPBR's (12.2; 8.7) allowed to obtain in late 80's industrial potential [5,6], reorientation of Polish economy almost killed all the activity in micromechanics in 1990; the re-born of a research, basic and industry-oriented started in 1991 [8,9]. The discipline grows, and should be our national semiconductor speciality [7].

"Pure" mechanical devices followed by electromechanical sensors will be shortly described.

## 2. Mechanical micromachines

The most spectacular mechanical devices are micromachines. Very small turbines, gear-boxes , electric, pneumatic and steam engines are good examples here. The first Polish militurbine made from single-crystal silicon is presented in the Fig.1 [10].

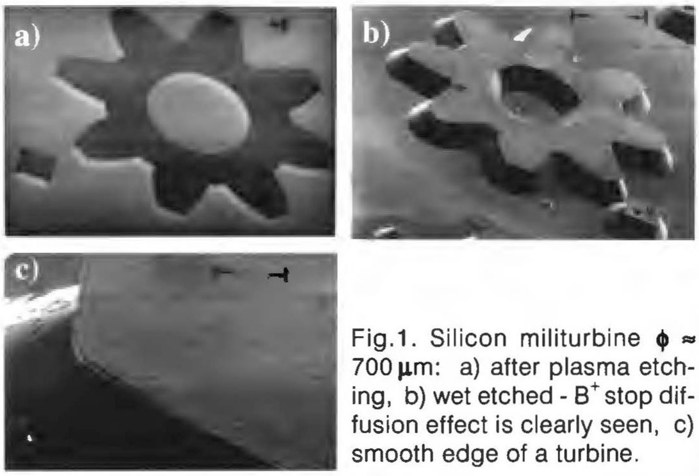


Fig.1. Silicon militurbine ϕ ≈ 700 μm: a) after plasma etching, b) wet etched - $B^+$ stop diffusion effect is clearly seen, c) smooth edge of a turbine.

**Institute of Electronic Technology of the Technical University of Wrocław, Janiszewskiego 11/17 str., 50-372 Wrocław, Poland**

The device is batch-produced. Silicon 3" wafer is thermally oxidised and photoprocessed to obtain $SiO_2$ mask for plasma reactive etching. Militurbine is plasma-etched, the substrate is then again oxidised, back side oxide is removed, and wet etching in KOH-$H_2$O-IZA mixture in 80°C separates turbines. Very smooth surfaces are obtained in modified process. Shape of turbines is produced in wet etching procedures described previously but boron stop diffusion is used.

Next generation of Si turbines is presented in the Fig.2 [11]. Ø100 μm turbines are probably the smallest ever produced in Poland. Metallic turbine made in CMOS compatible process is presented in the next picture (Fig.3)[12].

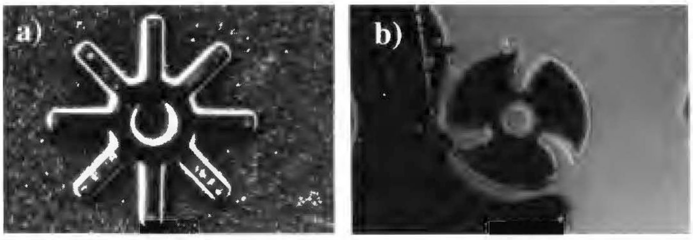


Fig. 2. Silicon micro turbine ϕ ≈ 100 μm.: a) turbine version I, b) turbine version II.

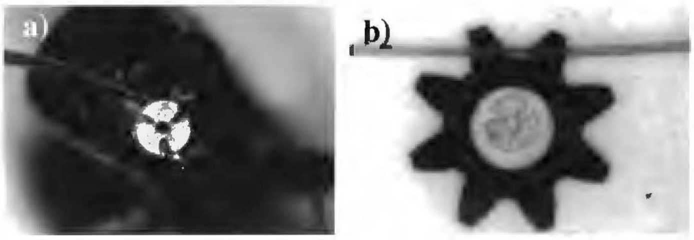


Fig. 3. Al - turbine: a) a device lays on an ant nose, b) mili and micro turbine, in comparison to human hair.

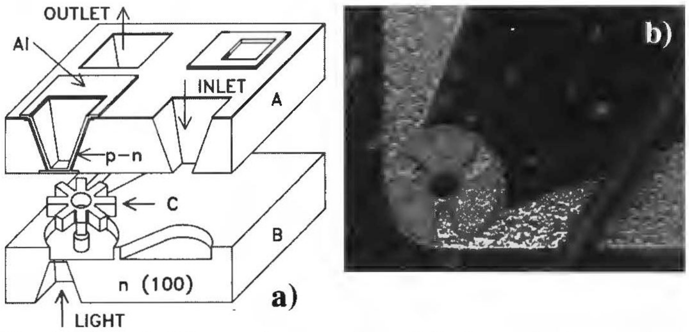


Fig. 4. Micro turbine works as a flow-detector: a) microsystem design, b) assembled device, note human hair.

The microsystem from the Fig.4 [13] is proposed for microflow measurements of bio-active fluids. Rotating microturbine shadows light passing from illuminating opening with 2 μm thick membrane to light sensitive p-n junction. Pulses of photo induced voltage are generated periodically, proportionally to the

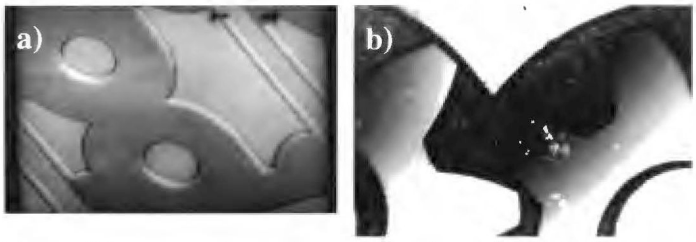


Fig. 5. Silicon gear box: a) a stator, b) assembled device.

speed of rotation of a turbine. Fabrication process of the device consists of 70 main technological steps.

Packaging of micromachines is difficult. Speciality techniques of silicon to glass bonding must be used [14]. A silicon gearbox with rotating under pneumatic actuation rotors is shown in the Fig.5. A glass cover is bonded after the assembling procedure of the device.

Potentially micromachines will find application in ophtalmology, micro reparation in micro robots [15]. In our reality, the devices should be treated more as smart modern toys rather, than serious tools. But who does know what is going on?

## 3. Simple mechanical silicon structures

More complicated Si micromachines consist of small simple details very well known from day-after-day live: openings, vias, grooves, bridges, membranes etc.

Following, simple three-dimensional Si construction will be presented. V-grooves are wet etched in KOH water solutions in (100) oriental single crystal silicon wafer, they are used as fibre-optics aligners and positioners [16] (Fig.6). Free standing beams are produced in multi-step technology with the application of $B^+$ stop diffusion effect. Silicon beams are used in many different types of vibrating sensors, the most interesting applications are light modulators and TV-projectors. An example of silicon beams with varying length, hundreds of micrometer long, 2 μm thick and over 100 μm width are presented in the Fig.7.

Technology of fabrication of openings and membranes (Fig.8) is in comparison to the production of other Si micromachines very simple. Detailed description of the fields of applications of such small devices will cross the limit of this work; diesel-engine jets, ink-jet printers, speed limiters of flows are the best known examples.

Membranes, some microns thick and with planar dimensions crossing thousands of microns, perfectly flat are the basis of pressure sensors, gas valves and restrictors etc. Following, some examples of membrane-type pressure sensors will be shown.

## 4. Membrane type pressure sensors

Many varying type of pressure sensors with silicon membrane have been designed, modelled and introduced to the mass production in the last 6 years.

Two by two mm pressure sensors with 1038 μm x 1038 μm square membrane thick 15 μm was designed by us in 1989. The structure obtained good metrological parameters [17] and has been introduced into production in former CEMI-TEWA company (type Z02). This simple sensor works as following: pressure of fluids pressing onto the surface of thin silicon membrane deflects the membrane and generates strong tensile stresses near edges of the membrane. Stresses are sensed by four piezoresistors which are situated near edge of the membrane. Theirs resistivity depends proportionally to the value of stress, than to the pressure. Changing its resistivity, piezoresistors in arms of Wheatstone's bridge generate output signal. Our next pressure sensors was bio-medicine version of described earlier Z02. Metal contacts are located from one side of the die. Going ahead, structure becomes more and more complicated.

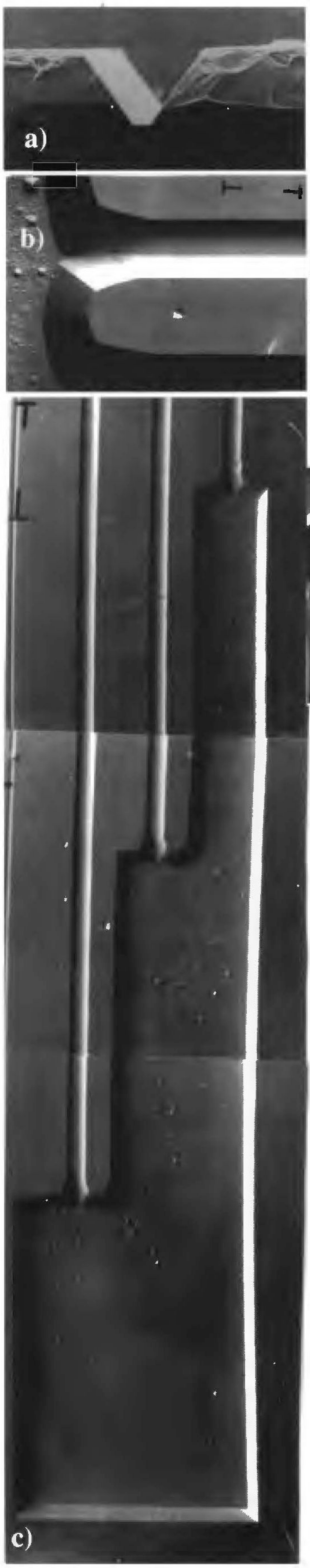


Fig. 6. V-grooves etched in Si wafer: a) cross-section, b) bird eye view, c) mechanical part of an accelerometer (see Fig.12)

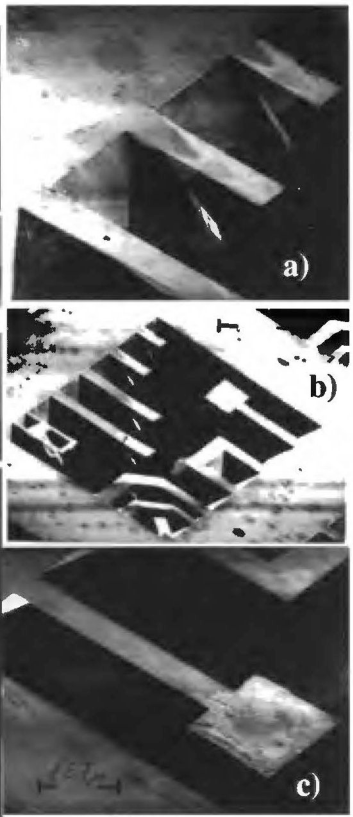


Fig. 7. Silicon beams: a) a long time wet etching, freedomize $B^+$ doped beams, b) a mirror at the end of a beam.

A new "cut resistors" were tested in 1991 [18,19], very innovative double-bridge self compensating structure has been designed in the period of 1990-1992 [20]. Next, in strong co-operation with Institute of Electronic Technology of Warsaw, a new design of pressure sensor for industrial application has been discovered [21]. Some examples of piezoresistive pressure sensors are presented in the Fig.9.

"Cut resistors" and "self-compensating" pressure sensors have been designed and published by us for the first time in the literature.

A silicon, membrane-type new ophto-pressure sensors is described below [22]. Bossed-type thin membrane has etched V-groove, in which fibre is attached by hard epoxy glue. The p-n junction was produced precisely 10 μm from upper edge of the membrane (Fig.10). Pressure deflects membrane, moves fibre changing illumination of p-n junction. Photovoltage on outputs connection of the device will change proportionally to the pressure. Such construction may be very useful

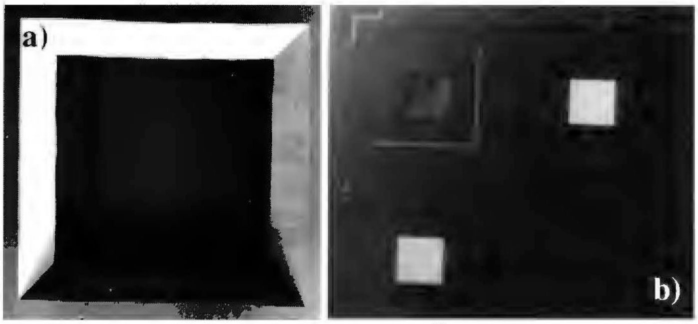
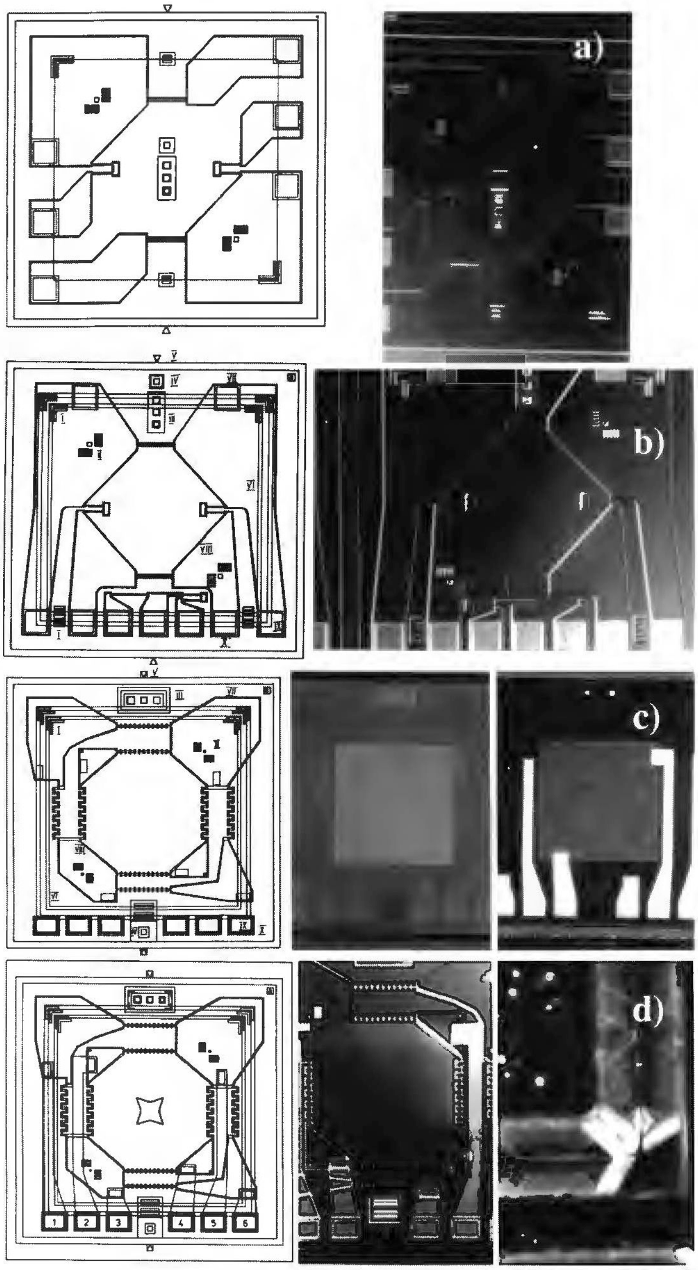


Fig. 8. Perfectly smooth 1038x1038 $\mu m^2$ flat membrane (a) and small 10x10 $\mu m^2$ vias (b), stop-diffused (d=1 $\mu$m.) very thin membrane covers the third opening.



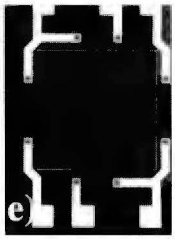
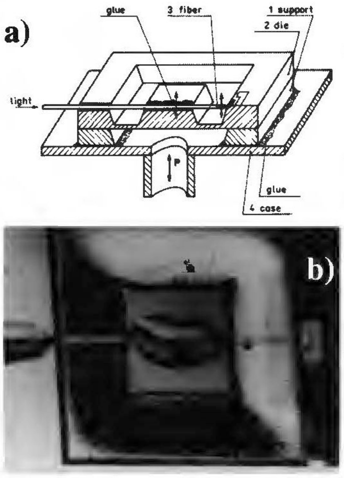


Fig. 9. Pressure sensors: some model from the period 1989 - 1995: a) Z02 from 1989 (ITETU - CEMI TEWA), b) "bio" from 1990 (ITETU - CEMI TEWA), c) "cut double bridge" from 1991 (ITETU - CEMI TEWA), d) "bossed cut double bridge" from 1991 (ITETU - CEMI TEWA), e) "industrial" ITE Warsaw (Fig.11).



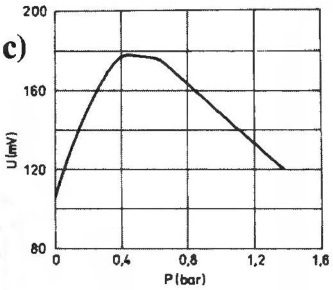


Fig. 10. Pressure sensor with a fibre: a) details of a design, b) photo picture of an assembled sensor, c) output signal versus pressure.

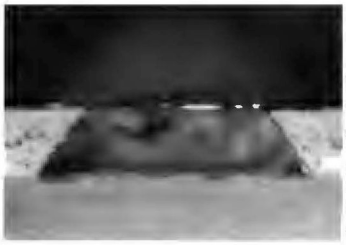


Fig. 11. Silicon piezoresistive pressure sensor die bonded to the glass substrate. The device was sawed through a membrane, etched cavity and intermediate glass silicon layer is shown.

in specific application (hazardous gases, atomic industry etc.) because it works without electrical supply generating electrical galvano separated output signal.

Works on pressure sensors are still under the progress. Our previous silicon sensors on thick glass (Fig.11) will be followed by next generation of packaged in SS316 body with SS316 separating membrane pressure transmitters equipped with microprocessorized electrical circuit [23].

## 5. Accelerometers

Simple micromachined silicon accelerometer was built and tested [24]. In the micromachined silicon structure with deep cavity and V-grooves, p-n junction located near edge of the

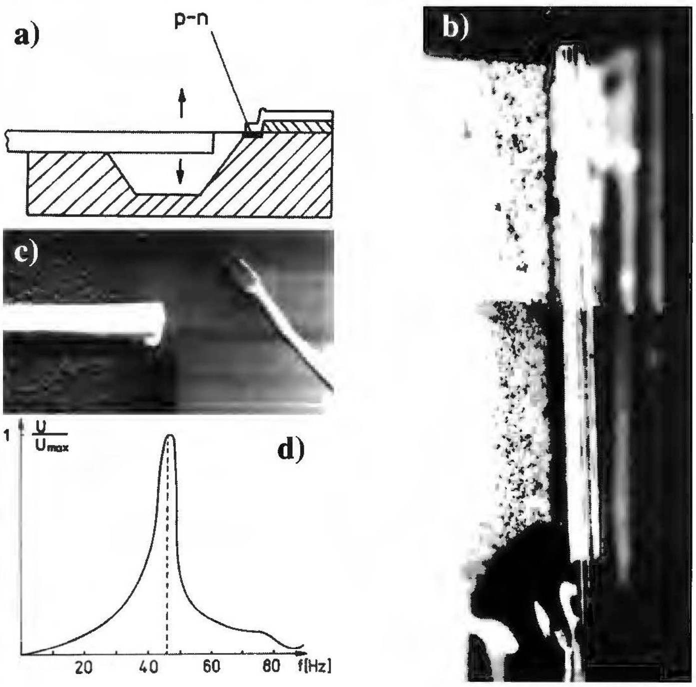


Fig. 12. Silicon accelerometer with a fibre: a) details of a design, b) view of the sensor, c) fibre looks at p.-n junction, d) output signals.

cavity works as a light detector with photo voltage output signal. Acceleration (shocks or vibration) moves up and down end of a fibre and changes p-n illumination (Fig.12).

Unique accelerometer micromachined in silicon with moving micro miniature mercury ball was presented in [25] and positively commented in technical papers [26]. Sand-glass like shape of etched cavity allows small (ϕ 20-50 μm) Hg ball moves through the channel (Fig.13). Manoeuvring channel width and length, Hg ball diameter a matrix of sensors in a set of many single units, detects shocks and impacts. The device is very simple, may be used like a post stamp to detect impacts during transport of fragile goods.

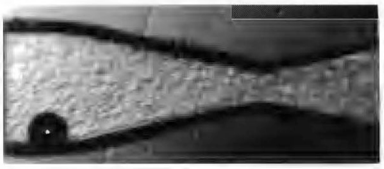


Fig. 13. Silicon shock detector with moving micro mercury ball.

## 6. Micro-total analyses systems

The most spectacular works in micromachining of silicon are connected with microsystems for total analysis of chemicals. μTAS will find applications everywhere in: anti pollution service, environment controlling, drug and anti drug service. Chromatography, micro electrophoresis, DNA-finger prints are expected potentially revolutionary application of μTAS.

Our work on micro gas chromatography started in 1994. Probably only 1-2 years of deletion in comparison to leading world laboratories may be observed here. Capillary columns (packed columns) of some microns width and of meters of length are made from silicon they are the key components of microchromatograph. Microcolumns etched in silicon, bonded to Corning glass are shown in the Fig.14 [27].

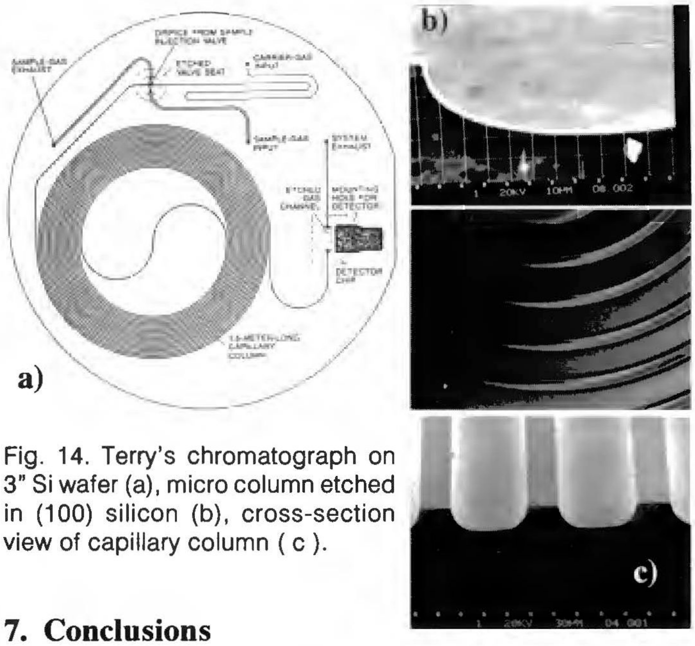


Fig. 14. Terry's chromatograph on 3" Si wafer (a), micro column etched in (100) silicon (b), cross-section view of capillary column ( c ).

## 7. Conclusions

Micromachine technology has been researched in our Institute for over ten years. Short formula of this article does not allow to present more detailed full scope of our works. We hope the future contact with MST-News Poland will precise our description and will spread up phenomenon of micromechanics.

Examples which have been presented in the article, clearly show that 3 μm, class 100, standard CMOS laboratory, equipped with double-side alignement mask aligner and simple units of wet isotropic and anisotropic selective etching of silicon is efficient to obtain good results in micromechanics. Let us be allowed to express some ideas here.

4 $mm^2$ of (100) silicon in the form of pressure sensor die with good parameters, costs approximately 6 to 8 USD, in mass volume, when bought from abroad. 16 $mm^2$ of silicon in the form of the die of 16 MB DRAM costs 10 USD. To produce micromachines 3 inches, 3 μm designed rule, class 100 laboratory, plus unique skill-oriented techniques of micromachining, bonding and packaging of sensors is needed. To produce 16 MB DRAM, a 1 billion USD investment is a need. What is more, annual grow-up factor (AGF) in sensor market is 20-24% a year and only 6 to 10% in VLSI devices.

Discussions on commercialisation of micromachines show clearly that high AGR trend will be stable till 2005 year. Especially μTAS-s and smart sensors will dictate as so called frontier technologic devices future trends in high-tech production.

Why schould not be Micromechanics on Silicon (micromachines technology, microelectromechanics system MEMS) our Polish speciality?

It fits to Polish specific because of:

a) industry resources
b) high potential of research and education
c) no delay observed
d) market oriented production.

Varying types of microsensors modelled in universities and research institutes should be processed in mass scale by Foundry equipped in CMOS and bipolar, 4" lines. Small enterprises co-operating with semiconductor producers will apply (package, give additional conditioning circuits etc.) the end - products. This programme needs good atmosphere of pro-innovative economical sources and promoting fiscal system.

## Short biography note

**Jan A. DZIUBAN** was born in 1951 in Sanok (Poland). His M. Sc. (1974) followed by Ph. D. (1977) concerned solid-state technology. He works as the senior leader in Silicon Micromechanics Program and assistant professor in the Institute of Electronic Technology of Wrocław TU. He is a member of the Board of Polish Society for Sensors Technology and Eurosensors Program Committee.

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# OXIMETRIC SENSORS

**Tadeusz Pałko**

*The paper presents most popular photoelectric and electrochemical methods of measurement of oxygen content in blood and other liquids and also in gases. Own construction oximetric sensors and their main features are also presented. The photoelectric transducers are usually used for measurement of blood oxygen saturation. The electrochemical transducers are used for measurement of oxygen pressure in blood and other liquids and in gases.*

## 1. Introduction

Measurements of oxygen contents in liquids and gases (oximetry) are very important in many areas, particularly in medicine and environmental protection. Blood and expiratory gas oximetry is very essential for diagnosis of cardiopulmonary diseases, particularly in assessment and management of high risk patients. Oximetric measurements of liquids and gases for environment examination enable evaluation of water and air quality and other substances.

There are many methods for measurement of oxygen content such as mass spectrometry, heat conductance, magnetic, magneto-electric, electrochemical. The latter three are usually used. Most popular are photoelectric and two electrochemical methods, namely: amperometric and fuel cell [1-6]. These methods were used in own construction oximetric sensors and will be described.

## 2. Photoelectric method

Photoelectric method is usually used for the assessment of blood oxygen saturation and is denoted as $sO_2$ or $SO_2$. The $sO_2$ is determined as a percentage ratio of oxyhemoglobin ($HbO_2$) in the total amount of hemoglobin ($Hb + HbO_2$) [2].

The blood oxygen saturation can be measured in both the *in vitro* and *in vivo* cases. Standard laboratory *in vitro* technique for determining blood oxygen saturation is usually based on transmission spectrophotometry to differentiate oxygenated blood (oxyhemoglobin) from deoxygenated blood (reduced hemoglobin). Light of selected wavelengths is transmitted through a cuvette containing a blood sample (Fig. 1). Wavelengths are chosen so that the absorption characteristics (Fig. 2) of oxyhemoglobin and reduced hemoglobin are different. The light transmission through the sample varies with wavelength, depending on the relative concentrations of oxyhemoglobin and hemoglobin.

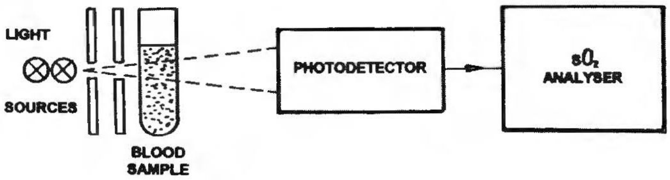

Fig. 1. Transmission spectrophotometry principle for *in vitro* measuring oxyhemoglobin saturation ($sO_2$) in blood samples.

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**Institute of Precision & Biomedical Engineering**
**Warsaw University of Technology**
**Chodkiewicza 8 str., 02-525 Warsaw, Poland**