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Review

Microsystem technology as a road from macro to nanoworld

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Abstract

Tremendous progress of microelectronic technology observed within last 40 years is closely related to even more remarkable progress of technological tools. It is important to note however, that these new tools may be used for fabrication of diverse multifunctional structures as well. Such devices, called MEMS (Micro-Electro-Mechanical-System) and MOEMS (Micro-Electro-Opto-Mechanical-System) integrate microelectronic and micromechanical structures in one system enabling interdisciplinary application, with most interesting and prospective being bio-medical investigations. Development of these applications requires however cooperation of multidisciplinary team of specialists, covering broad range of physics, (bio) chemistry and electronics, not mentioning medical doctors and other medical specialists. Thus, dissemination of knowledge about existing processing capabilities is of key importance. In this paper, examples of various applications of microelectronic technology for fabrication of Microsystems which may be used for medicine and chemistry, will be presented. Besides, information concerning a design and technology potential available in Poland and new, emerging opportunities will be given.
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Keywords: Microsystem technology; Surface characterization

1. Introduction

The progress in MEMS devices that has been observed for over the past decade [1,2] has provided a number of exciting new techniques facilitating a progress in characterization of biomedical and chemical interfaces. In this paper, several examples are presented to illustrate that MEMS technique is promising and powerful tool for surface investigation including bio-molecules, cell membranes, polymers and even living cells. The ability to add an extra dimension of chemical composition information to high-resolution microscopy, or microscopic information to spectroscopy, plays an increasingly useful part in applied research. The extreme sensitivity of micromechanical devices coupled with nanoscale science techniques extends their use well beyond imaging surface properties. Thermal, mass, magnetic, electrical, chemical, stress—among others—can be detected [3,4] at ultimate limits by transduction into micromechanical motion (Fig. 1). The invention of the scanning force microscope (SFM) [5,6] linked the use of micromechanics and microscopy at the atomic scale. Fields where MEMS technology offers its capabilities to bio-chemistry community are briefly described below.

2. Devices for thermal analysis in nano- and microscale

Scanning thermal microscopy (SThM) is a near field technique, which allows mapping of spatial variations of thermal properties of a sample, such as temperature, thermal conductivity, and diffusivity with submicrometer resolution [7,8,10]. This type of microscopy in combination with microthermal analysis (MTA) is now being used to visualize the spatial distribution of phases, components, contaminants in polymers, pharmaceuticals, foods, biological materials, locally induced phase transformations, and spatially resolved photothermal Fourier transform infrared spectroscopy. A large number of probes with different heat sensitive elements, including thermocouple,

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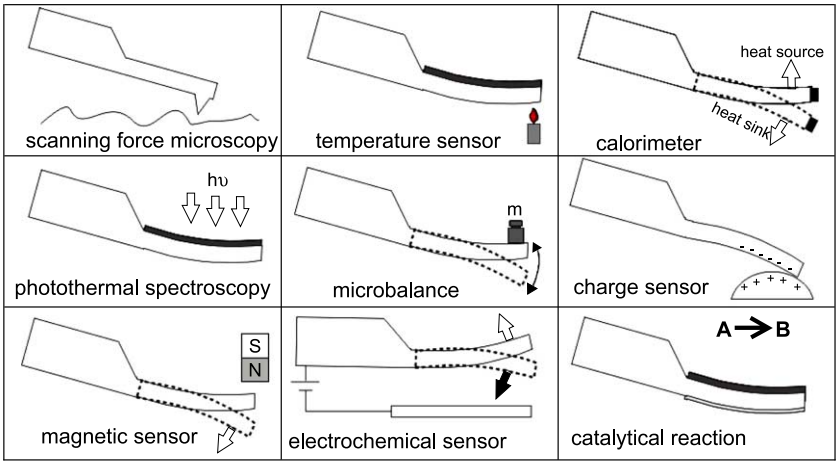

Fig. 1. Physical and chemical functions of cantilevers.

contact potential, Joule expansion, Schottky diode, and resistance based transducers have been developed over the past 10 years [8,9]. A resistive probe consists of a thin wire, making a point contact to the sample, scanned across the sample surface [11]. In the passive mode, the temperature of the sample is measured by monitoring the change in the resistivity of the wire. In the active mode, the sample is locally heated by applying an alternating electric current to the wire, thus allowing measurement of thermal conductivity and diffusivity of the sample or inducing local changes such as phase transformations or chemical reactions (Fig. 2).

In most known solution the thermal sensitive wire has a micrometer range dimensions (e.g. 75 μm OD coat with 5 μm platinum core) which results in a limited spatial resolution of such devices [10,11]. To improve the resolution a novel thermal probe presented here is based on the changes of the electrical resistivity of a nanometer-sized filament with temperature [12,13]. The filament is integrated into an atomic force scanning probe based on a piezoresistive type

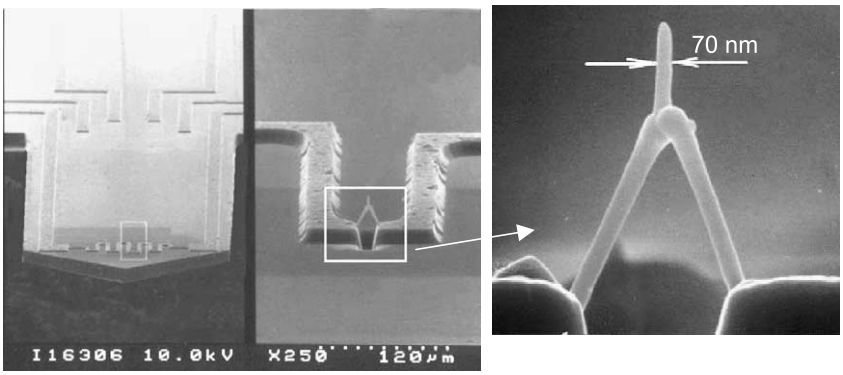

Fig. 2. SEM images of Thermal Nano Probe beam and the nano-tip [12,13].

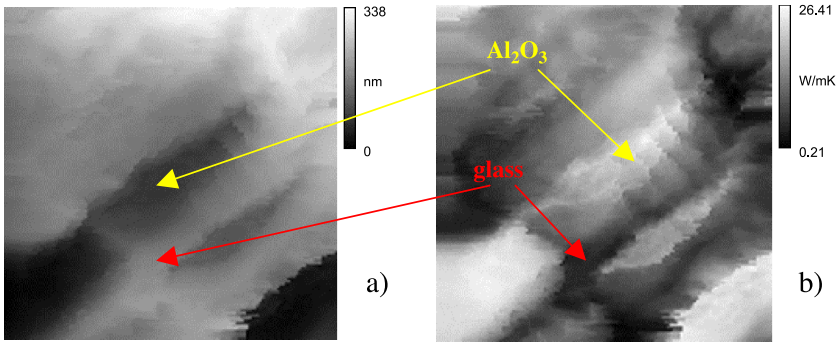

Fig. 3. Topography (a) and thermal conductivity distribution (b) on multiphase structure glass-Al_2O_3 ceramic obtained with Scanning Thermal Microscopy [14]. Scan area 5×5 μm.

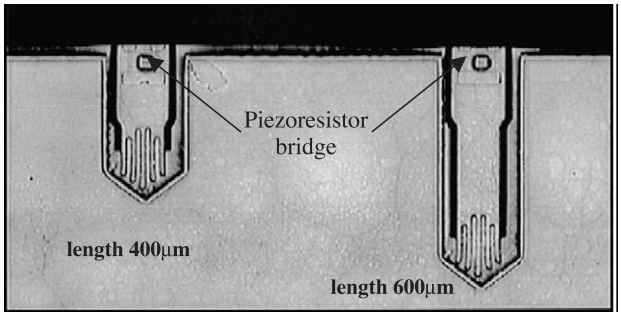

Fig. 4. Two versions of the thermoresistor probes.

cantilever. Using a focused ion beam technique, the front end of the Al meander is cut through, forming an approximately 1-μm wide gap. Employing an electron beam assisted deposition technique a sub-100 nm diameter Pt filament is deposited across the gap. The filament consists of an approximately 2 μm high loop with an additional spike deposited at the apex of the loop to improve spatial resolution. This probe is an example on how a combination of CMOS technology, bulk and surface micromachining, focused ion beam technology and e-beam induced deposition can be used to fabricate innovative nanoprobes, opening new research opportunities.

Fig. 3 shows topography and thermal conductivity distribution on glass-Al_2O_3 multiphase surface respectively. Achieved spatial resolution is of the order of less then 80 nm and a thermal resolution of 10^{-3} K.

Nanometer scale spatial resolution achieved by the described nanoprobe is not always required in biomedical research. In application where the temperature of a single bio-cell (e.g. plant or bacteria) has to be measured a flat measurement platform with dimensions in the range of 10–100 μm is needed. In addition, a precise touch-down detection is required to protect the sample

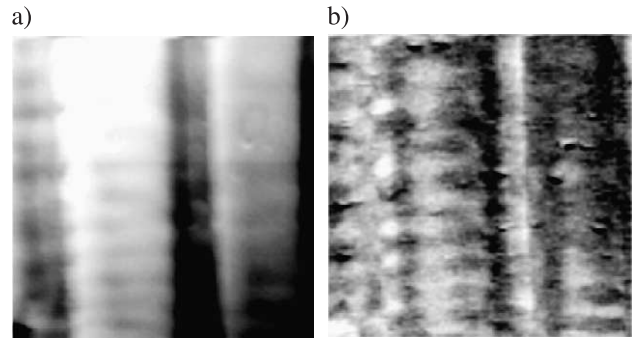

Fig. 6. AFM/SNOM characterisation of polycarbonate polymer film: (a) AFM topography image, (b) optical sample characterization.

against damage. A microprobe has been developed for contact temperature measurements of plant tissue sample. It consists of a silicon cantilever with a Ni thermoresistor deposited at the unfixed end (Fig. 4) [15]. Full piezoresistive bridge allows for measurements of a force acting on the microbeam and detect touch of a delicate tissue. Thermal resolution of presented probe is of the order of 5×10^{-2} K.

3. Devices for optical investigations in nanoscale

In scanning near field optical microscope (SNOM), an optical probe with aperture diameter well below the optical wavelength is moved over the sample to extend resolution of the optical microscopy over the limits imposed by interference phenomena. Precise sample-probe distance control is one of the key problems in SNOM. In typical solution a tapered, metal coated optical fiber is used as a shear force tip to estimate a distance to the surface and to perform the SNOM measurements [16]. A possibly solution is combination of

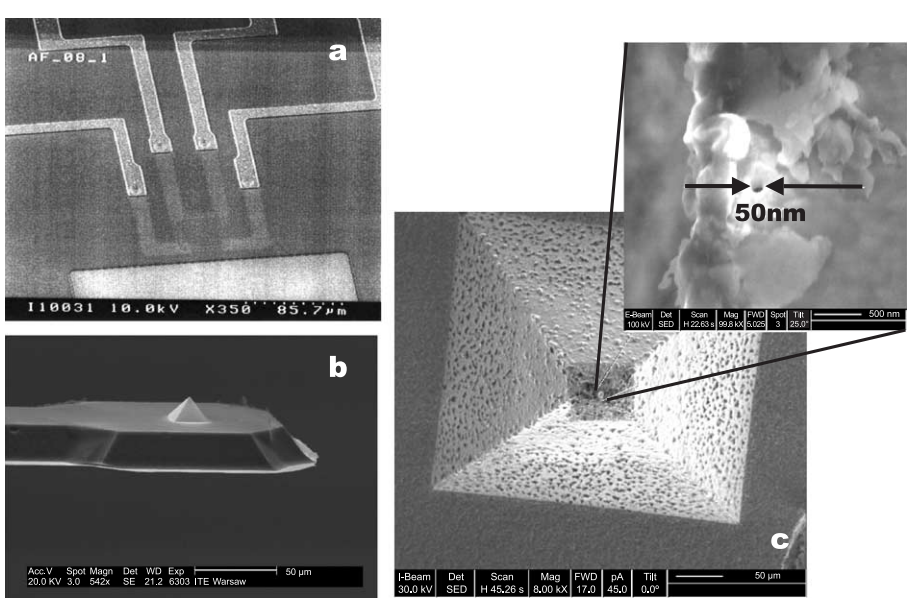

Fig. 5. SEM images of the piezoresistor set (a), the beam end (b), and the pyramid tip (c) with aperture (insert) [18,19].

SNOM and piezoresistive atomic force microscopy (AFM) probe [17] however a technology imposed geometrical arrangement of the device and precision of the aperture formation remains still an important issue. In the presented solution a highly reproductive batch processing allows for integration of both, cantilever playing role of an AFM detector and nanoaperture detector [18,19]. Moreover, illumination of the aperture is easier because of a wide input opening and its big cone angle. The angle of the apex cone is close to 50°, which renders it possible to obtain a high aperture transmission coefficient. Apertures in hollow pyramids have been formed by direct ion beam drilling with a focused beam of 30 keV Ga^+ions. Direct focused ion beam (FIB) drilling is a reproducible process for hole formation at the 30–100 nm diameter range. Formation of smaller apertures is possible if a special FIB drilling/deposition procedure is applied. Fig. 5 shows SEM image of the pyramidal tip at the end of the cantilever and the aperture of 50 nm.

In our experiments we investigated topographical and optical parameters of polycarbonate material, utilized for magneto-optical memory discs fabrication. In Fig. 6 images of the investigated sample are presented.

One may note that the optical characterization shown in Fig. 6b reveals significant non-uniformities which are not visible on topographic (AFM) image (Fig. 6a). In our opinion, the observed differences are connected with non-homogenities of the polymer material. It is worthwhile to note also, that presented microprobe may be considered as a tool for interesting investigation on interaction of matter (e.g. supramolecular films) with light in nanoscale.

4. Silicon nanobalance

The piezoresistive cantilever beam fabricated using combination of silicon micromachining with elements of CMOS IC's technology may be used as a highly sensitive nanobalance [20,21]. Such device, equipped with a porous silicon element to intensify adsorption processes has been fabricated (Fig. 7). Measurements of a shift of the cantilever resonance frequency allow for estimation of adsorbed substance weight e.g., gas, steam with single nanogram resolution. Applications of such a device include humidity and gas detection.

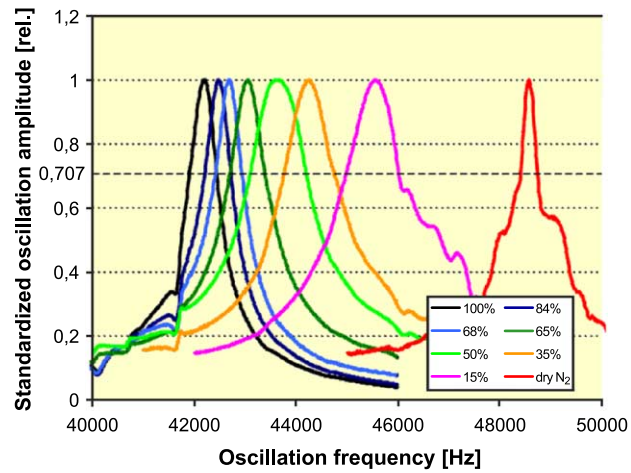

Fig. 8. Resonance curves of a T-shaped cantilever with a porous silicon element as exposed on various humidity levels [22].

Resonance curves of the cantilever have been measured by sweeping the excitation frequency of the piezo-actuator and monitoring the resulting beam deflection. The deflection has been measured using a piezoresistive circuit located at the support of the cantilever and additionally by monitoring of a laser beam reflected from the device.

The resonance curves for longitudinal mode are shown in Fig. 8. It may be noted that the quality factor of the beam which is inversely proportional to the width of the resonance curve first decreases with humidity then increases after reaching minimum. This effect may be related to mechanical behavior of water inside pores. For medium humidity relatively large water droplets can move inside pores dissipating mechanical energy. For low humidity the energy dissipation is smaller due to a small amount of water.

5. Micromachined hot-plate

To investigate phenomena in micro- and nanoscale researchers need many new microtools enabling operation

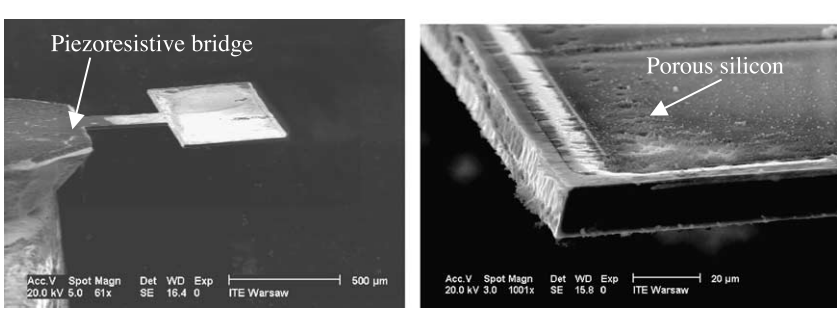

Fig. 7. SEM view of a T-shaped piezoresistive cantilever with a porous silicon element.

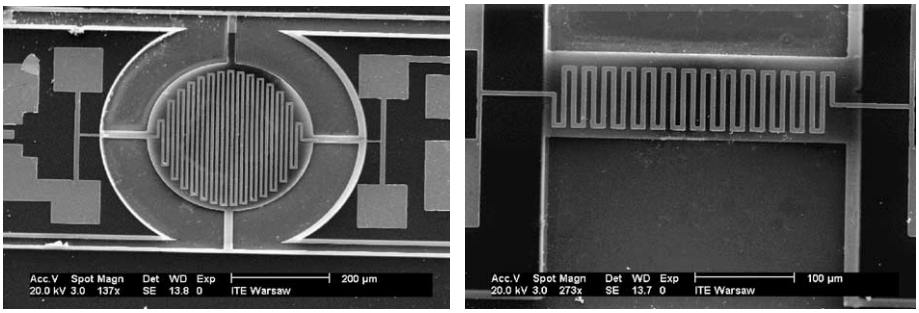

Fig. 9. SEM images of micromachined micro hot-plates.

even with nanogram samples. An example of such innovative tool developed using silicon micromachining is a micro-hot-plate. The basic idea was to realize a simple device on common silicon substrates using conventional photolithography, sputtering and evaporation techniques. The maximum power consumption amounts to 150 mW for an operation at 300 °C and the thermal response time is expected to be faster than 800 ms. Fast thermal time constant will allow the operation of device in temperature pulse mode. First examples of micro hot-plates are presented in this publication (Fig. 9).

6. Chemical sensors

In numerous research a field Effect Transistors were used as an effective ion sensitive transducers [23–26]. Current flow along channel of such a device is controlled by charge gathered on the transistor gate which is sensitive to the ions concentration in analyzed environment.

The technical solution and technologies used for fabrication of ISFET sensors differs depending on specific application. Two examples of such implementations are given here. In the first, basic version source and drain (S/D) contacts are placed at the front side of the chip. Such a configuration is called Front Side Contacted ISFET (FSC ISFET) (Fig. 10a). The bonding pads and the wires should be carefully protected against contact with analyzed solution. In the second version of the device called Back Side Contacted ISFET (BSC ISFET) (see Fig. 10b) the S/D contacts are placed on the passive (back) side of the chip that it is completely separated from the front side facilitating their protection. Fabrication of a BSC ISFETs consists of combination of CMOS and MEMS (Micro-Electro-Mechanical Systems) technology.

The measurement results show, that V_{GS}-pH dependence is highly linear in a wide range of pH (2–12) for the operating point U_{DS}=0.5 V, at constant current configuration I_D=0.1 mA. The experimental results indicate that all developed and investigated ISFET structures may be directly used for pH measurement in the wide pH range. Both types of sensors are used for chemical and biochemical investigations in laboratories in Europe and US.

7. Summary

Presented devices show that silicon microengineering provide powerful tools for diverse investigations of surface chemistry in micro- and nanoscale. Particularly, development of specialized arrays of devices for biochemical characterization seems to be very advantageous. Thus, silicon microengineering allows for fabrication of microtools filling the gap between our macro-world and the nanoworld, as pointed out by Richard Feynman, still full of new opportunities. However, to reach there, to design and fabricate of such devices close collaboration of multidisciplinary team of specialists, covering broad range of physics, biochemistry and electronics is required. The key problem seems to be to provide the researchers an easy access to the advanced and thus, expensive microengineering technology. Successful attempts to solve this problem were undertaken in leading countries. In Europe a pool of experts in the broad field of microsystem technology and access to technology is provided by EU supported EUROPRACTICE initiative [27], where a full range of assistance required in all

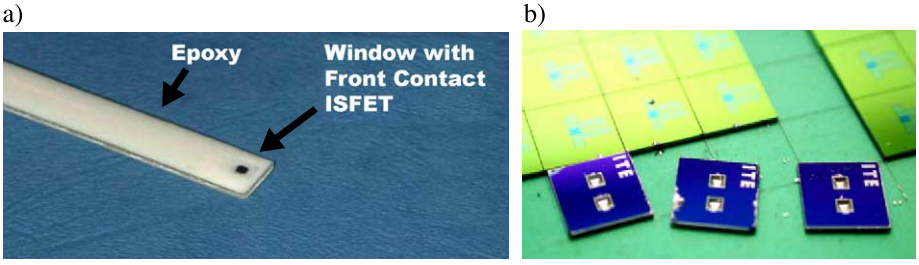

Fig. 10. (a) ISFET sensor assembled in a dipstick. (b) Back side contact ISFET sensor.

steps of product development is offered. Basing on this experiences and in the frame of EUROPRACTICE such opportunities emerge now in Poland as a result of creation of a National Centre of Silicon Micro- and Nanotechnology. The Centre is based on the existing technological potential of the Institute of Electron Technology, including a 4 in. silicon CMOS/MEMS technology R&D and pilot production line facility installed in 1200 m^2. Clean Rooms with cleanliness class ranging from 10 up to 1000. This cooperation is conceived as a bridge between university or research institutes laboratories, where fascinating new ideas emerge and industry, where the new inventions may be used to create new products, giving a chance young entrepreneurs to shape their professional future.

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