Micro- and Nanoelectromechanical Sensors

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Abstract. The development of micromachining technologies enabled the production of different miniature sensors of physical, chemical and biological quantities. They belong either to micromachanical (MEMS) or nanoelectromechanical systems (NEMS). Some of these sensors already found mass market application (pressure sensors, accelerometers, thermal infrared sensors). The tendency of a decrease of their dimensions resulted in the appearance of sensors mostly connected with nanotechnologies. Actually, the very utilization of these sensors enables the further development of nanoscience. In this work we present our practical results connected with different MEMS sensors, as well as some theoretical results on determination of ultimate performance of MEMS and NEMS sensors.

INTRODUCTION

The development of the integrated circuits (IC) technology, started by the invention of the bipolar transistor in 1947, and the requirement for an ever increasing amount of information has been increased the number of transistors in chip over the years (Moore's law) so that in complex ICs this number will reach a billion. On the other hand, cost-efficiency dictated only a small increase of the overall dimensions of chips, which required a reduction of the dimensions of the elementary electron devices, so that today the minimum achieved dimensions are on the level of 100 nm, with a trend of further decrease.

The fact that throughout a long period sensors had been produced by techniques of precision mechanics had become a problem in further miniaturization of complete systems. This was the reason for the appearance of so-called microsystem (MS) or microelectromechanical (MEMS) technologies [1,2]. MS technologies use primarily the fundamental processes of the IC technologies, i.e. film deposition, doping and lithography. Besides these processes the MS also use special procedures of etching and bonding enabling sculpting of three-dimensional structures.

Today MS technologies continually introduce the advantages of miniaturization into number of diverse fields, e.g. automotive electronics, telecommunications, biomedical systems, chemical reactors, pharmacy and many others. This global technology uses natural resources efficiently and this preserves the ecosphere. MS technologies increase the efficiency owing to a decrease of dimensions and weight (i.e. the consumption of smaller amounts of materials for fabrication), lower energy
consumption, lower production cost, longer lifetime, the use of readily available materials.

Of course, the microworld differs from the macroworld. The most important in the microworld are surface forces, like surface tension and friction forces. For instance, the forces of surface tension in liquids in which MEMS structures are formed by chemical etching may break these structures during extraction from the solution. On the other hand, inertial forces are only important in accelerometers and resonant sensors.

Naturally, the trend of the reduction of the MS dimensions continues. This was especially boosted by the invention of microscopes with scanning probe (scanning tunneling microscope and atomic force microscope [3]). Thus the nanoelectromechanical systems (NEMS) appeared [4,5]. Here again, the nanoworld, in the narrow sense, differs from the macroworld and microworld. Besides surface tension, atomic forces are of special importance in the nanoworld and, clearly, quantum effects become marked. In certain circumstances NEMS are influenced by the forces due to fluctuations of vacuum (Casimir effect) [6,7].

As a consequence of the fact that miniature micocantilevers are used in the AFM for the detection of atomic forces to the level down to $10^{-18}$ N, a new generation of ultra-sensitive microcantilever-based sensors recently appeared [8,9]. These sensors can be used to measure different physical and chemical values which basically characterize the nanoworld and the knowledge of which is necessary to have a better insight into the nanoworld. Besides this, these cantilevers are the basic tool to be used for fabrication of nanodevices.

In the following text we will show our research results on the example of a MEMS piezoresistive pressure sensor, as well as some result of research on determination of ultimate performance of microcantilever-based resonant sensors.

**SILICON PIEZORESISTIVE PRESSURE SENSORS**

Our research in the field of influence of pressure to semiconductor has lasted, with breaks, from 1967. In the beginning the piezojunction effect in bipolar semiconductor devices has been researched [10,11], and later, after 1980, our research has been directed toward the effect of the change of resistivity due to mechanical deformation. The both effects have the same cause – the change of energy band structure due to deformations of semiconductor crystal lattice. One of the most important characteristics of the both effects is a marked anisotropy.

The very concept of the silicon piezoresistive pressure sensors was introduced by Tufte et al [12,13], but it was only the emergence of the MS technologies [1] which enabled miniaturization and mass production peculiar for the IC technologies.

As an illustration, in Fig. 1 we show one of the basic procedures of the fabrication of diaphragm of a Si pressure sensor using bulk micromachining. Bulk micromachining makes use of the fact that in some solutions (most often potassium hydroxide, KOH, or tetramethyl-amonium hydroxide, TMAH) single crystalline silicon is etched with different rates in different crystallographic directions [2]. For example, Si is etched in KOH 100 times faster in the <100> crystallographic direction than in <111>
direction. This technology also uses the fact that some dielectrics (SiO₂, Si₃N₄) and highly-doped p-type silicon are very slowly etched (The so-called etch stop).

![Diagram of diaphragm fabrication](image)

**FIGURE 1.** Basic procedures of the fabrication of diaphragm of a Si pressure sensor using bulk micromachining.

Another technology of great importance is the electrostatic bonding of silicon with glass whose thermal expansion coefficient at the bonding temperature is approximately equal to that of Si. This technique, together with some novel ones (SOI - silicon on insulator) enabled fabrication of completely new and much more reliable sensor structures, and, even more important, significantly expanded the field of their applicability.

Fig. 2 shows our modern sensor chip fabricated by bulk micromachining. The sensor has built-in protection against overpressures and is able to withstand excess pressures and pressure shocks of several hundreds of bars (while at the same time its operating range is a few bar).

![Modern sensor chip](image)

**FIGURE 2.** IHTM-CMTM pressure sensor fabricated by bulk micromachining, including insert for pressure overload protection. a) top view; b) sensor structure; photo of a sensor under pressure.

For the design of MEMS it is of great importance to know mechanical and electronic parameters of silicon. For instance, its elastic properties can be described by a fourth-rank elastic constant tensor, while the piezoresistive effect is described by the fourth-rank piezoresistive tensor. Luckily, due to cubic symmetry of Si crystal (diamond lattice), both of these tensors have only three components each (S₁₁, S₁₂, S₄₄, i.e. π₁₁, π₁₂, π₄₄). While calculating deformations (e.g. diaphragm or microcantilever
deflection) under applied mechanical stress (its direction defined by the cosines between its vector and the crystallographic axes \((n_1, n_2, n_3)\)) it is necessary to know Young's elasticity module. It can be obtained using the components of the elasticity tensor as

\[
1IE = S_{11} - 2S(n_1^2n_2^2 + n_2^2n_3^2 + n_3^2n_1^2); \quad S = S_{11} - S_{12} - S_{44}/2
\]  

(1)

In the case of piezoresistive effect two coefficients connected with the current flow are defined, the longitudinal piezoresistive coefficient \(\pi_l\) (current in the direction of the applied deformation, defined by the vector \((n_1, n_2, n_3)\)) and the transversal \(\pi_t\) (current is in the direction perpendicular to applied deformation, defined by the vector \((l_1, l_2, l_3)\)). In this way the resistance change due to piezoresistive effect is given by

\[
\Delta R / R = \pi_l \sigma_l + \pi_t \sigma_t
\]

\[
\pi_l = \pi_{11} - 2\pi_4(n_1^2n_2^2 + n_2^2n_3^2 + n_3^2n_1^2); \quad \pi_t = \pi_{12} + \pi_4(n_1^2l_2^2 + n_2^2l_3^2 + n_3^2l_1^2)
\]

\[
\pi_4 = \pi_{11} - \pi_{12} - \pi_{44}
\]

(2)

Besides the tendency to obtain the maximum output voltage for a given external pressure, which requires to place the resistors on the diaphragm in the position of the largest mechanical stress and crystallographically in the direction of the maximum piezoresistive coefficient, there are two additional problems which must be taken into account. These regard the problems of temperature dependence and of nonlinearity of sensitivity. The solution of the problem of temperature dependence is in finding a profile of diffused dopants in the piezoresistor for which the temperature coefficients of resistivity and of piezoresistivity are equal, but with opposite signs [14]. For the solution of the other problem one must perform numerical calculations of mechanical stresses in the diaphragm and find the places where nonlinearities due to nonlinear piezoresistive coefficient and due to nonlinearity of mechanical stresses cancel [15]. This optimization was followed by experiments [16,17], enabling us to implement sensor chips with top characteristics. When the chips are accurately fabricated, the basic measurement error of our SP-6 and SP-9 chips which includes linearity, repeatability and hysteresis equals several hundredths of a percent full scale. This value is near to the limit of what single crystal silicon can furnish as the basic material of the sensor. The temperature error of these chips can be reduced an order of magnitude by passive compensation (external resistors).

**CANTILEVER- BASED SENSOR**

We mentioned in Introduction that miniature cantilevers and very thin diaphragms are basic NEMS components. The cantilevers were first used for the AFM, to measure very small forces, and today they are the elements of numerous miniature sensors measuring different physical and chemical parameters [8,9]. They are also used as oscillating (vibrating) elements in autonomous oscillators, replacing the quartz ones, enabling the integration of the oscillators with silicon IC and thus significantly
reducing the dimensions of contemporary wireless devices [18]. The most interesting applications of cantilevers are yet to come – for instance, for NMR (Nuclear Magnetic Resonance) microscopes with mechanical detection with a sensitivity on the level of single protons [4,19]. It is expected that microcantilevers, although simple, will be one of the basic components of NEMS quantum circuits [6], and they should make possible the study of fundamental aspects of nanomechanics [7,20].

MEMS and NEMS sensors attract large attention due to a number of their advantageous properties: high sensitivity, fast response, miniature dimensions, low production cost, possibility of real-time, in-situ monitoring. They enable the measurement of various physical and chemical parameters, e.g. force, mass, surface stress, specific gas concentration, temperature, pressure, flow, moisture, infrared and ultraviolet radiation and many others. They can operate in the air, vacuum or liquids. The latter makes them convenient for the investigation of biological structures (cell components and DNA) and biochemical and biophysical processes in physiological conditions [21].

The operation of microcantilever sensors is based on the measurement of the cantilever deflection resonant frequency changes caused by the measurand.

With a decrease of the dimensions of micromechanical devices some phenomena become marked. They are negligible in the macroworld, and crucially influence the limiting performance of MEMS/NEMS devices. The field of our interest was phase noise, which limits the sensitivity and the minimum detectible signal of resonant sensors, as well as the accuracy of frequency in MEMS/NEMS oscillators [22,23,24]. As an illustration of the importance of these investigations let us mention that the level of the phase noise is the main factor determining the possibility of the application of the oscillators in telecommunications. On the other hand, the knowledge of the dependence of the minimal detectable signal on geometric and physical parameters of the sensor enables the optimization of its design and working parameters.

Phase noise has different components which are consequences of different physical processes in MEMS and NEMS resonators. These are thermo-mechanical noise, noise due to temperature fluctuations and adsorption-desorption noise. The spectral density of total phase noise is equal to the sum of spectral densities of these particular components.

We will explain the determination of minimum detectable signal on the example of a microcantilever sensor for gas concentration measurement according to the mass of the absorbed particle on the surface of the cantilever (Fig. 3) [25,26]. The processes of adsorption and desorption of the surrounding gas proceed on the surface of each solid body. The dimensions of microcantilevers are so small that the mass od adsorbed particles does not represent a negligible addition to their total mass. Thus the resonant frequency of the cantilever is changed, and by measuring this frequency the mass of the adsorbed particles can be determined (and then the concentration of the gas).

Since adsorption and desorption are random processes, the number of the adsorbed particles fluctuates, and so does the resonant frequency of the microcantilever. These fluctuations represent the adsorption-desorption (AD) noise. For the case of single-layer adsorption, for which we assume that it can be represented by the Langmuir's isotherm, we derived the expression for the mean square deviation of the resonant
For this derivation we used an analogy between the AD and generation-recombination processes in semiconductors.

![Diagram of sensor with microcantilever for measurement of gas concentration](image)

**FIGURE 3.** Sensor with microcantilever for measurement of gas concentration

By analyzing other noise sources we found out that under certain ambiental condition in a certain spectral range AD noise may dominate in very small cantilevers. The minimum detectable mass is determined by total noise in the measurement range.

We also derived the expression for AD noise density and minimum detectable mass for the presence of two gases around the cantilever [27], and currently we analyze multilayer adsorption and the influence of fluctuations in this process on the minimum detectable mass.

Another problem, with a great importance for the operation of contactless AFM [28] and of resonant microcantilever sensors, regards the determination of frequency noise in MEMS/NEMS self-oscillating systems. This is necessary for the determination of minimum inertial mass that can be determined by microcantilever sensors [4,29]. Generally, the determination of the frequency and phase noise such oscillators is quite complex because oscillators are actually nonlinear systems. To determine the spectral density of phase noise in the case of simple dissipative processes in the oscillator, it is necessary to solve Fokker-Planck's equation or the corresponding Langevin equation. For the mean square value of the frequency thermo-mechanical noise in a bandwidth \( B \) we obtained the expression

\[
\langle \Delta \omega \rangle^2 = c \cdot (x - \arctan y), \quad c = 2D \theta / \pi, \quad x = \pi B / D \theta, \quad D \theta = \frac{1}{A_0^2} \frac{k_B T}{K_{\text{eff}}} \frac{\omega_0}{Q_l}, \quad \omega_0 = \frac{K_{\text{eff}}}{m_{\text{eff}}}.
\]

while the minimum detectable mass is given by

\[
\delta m = \sqrt{\langle \Delta m \rangle^2} = \frac{2K_{\text{eff}}}{\omega_0^3} \sqrt{\langle \Delta \omega \rangle^2}.
\]

\( \Delta \omega \) is diffusion constant, \( A_0 \) is the amplitude of cantilever oscillations, \( K_{\text{eff}} \) is stiffness constant of cantilever, \( m_{\text{eff}} \) effective mass of microcantilever, \( \omega_0 \) its resonant frequency, \( Q_l \) is Q-factor of the oscillator, \( T \) is the absolute temperature.

Our calculations of the minimum detectable mass show that using resonant sensors masses of the order of \( 10^{-21} \) g can be detected, which is two orders of magnitude smaller than the mass of a single protein molecule or approximately equal to the mass of a DNA base pair (Fig. 4).
FIGURE 4. Minimum detectable mass versus bandwidth for microcantilever sensors

In this moment a team from the Cornell University, USA, led by H. Craighead [29], is already able to measure mass with a precision of an atogram (10^{-18} g). Let us finish by a quote from Conclusion in ref. [29]: 'The next milestone in nanoelectromechanical mass detection is achieving zeptogram (10^{-21} g) sensitivity, which will prove whether nanomechanical mass spectroscopy is feasible. We anticipate this prize will attract even more researchers to join the mass-sensitive NEMS community in next few years'.

CONCLUSION

The paper presents some of the results of the research in the IHTM-CMTM, Belgrade in the field of MEMS and NEMS technologies. It has been stressed that the investigations of MEMS piezoresistive pressure sensors resulted in high-quality sensor chips. They served as the basis for a whole range of industrial pressure transmitters already largely applied in our industry (power production and distribution, oil industry, gas, heating plants, waterworks, breweries, sugar refineries, etc.) Many different investigations on a number of different MS sensors are currently underway (IR detector with bimaterial effect, flow sensors with thermopile, etc.)

In the field of NEMS, besides the above mentioned theoretical investigations, currently underway is the fabrication of microcantilevers with piezoresistive measurement of deflection or resonant frequency. This will be the basis for the fabrication of a number of new generation physical, chemical and biological sensors.

It is expected from theoretical investigations that the study of noise in small systems will enable new applications of contactless AFM microscopes and help in the
design and implementation of novel MEMS/NEMS oscillators for the application in wireless communications.

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