NANO- AND MICROSYSTEMS ENGINEERING

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Contents

Summary

Nano- and microsystems engineering is an actively developing direction that creates functionally finalized nano- and microdimensional devices and systems, whose characteristics essentially differ from the parameters of systems and devices of analogous designation created by the traditional technologies.

Construction of microelectromechanical systems includes an experience of constructive, engineering and production experience of different technological fields, among them technologies of integral circuits, mechanical engineering, material science, electrical engineering, chemistry and chemical engineering, hydraulic engineering, optics and control and measuring equipment.

Modern MEMS are used in cars as accelerometers for sensors controlling air-bag expanding, heads of ink-jet printers, reading and recording heads of disk drives of computers, microcircuits of projection displays, blood pressure meters, optical switching devices, microvalves, biosensors and many other devices that are produced and delivered in large industrial amounts.

Microelectromechanical systems are one of the most advanced technologies of 21st century; they made revolution in production of both industrial articles and consumer goods as a result of joining of microelectronic silicon-based technologies and technologies of micromachining. MEMS technologies and MEMS devices may have deep influence on our mode of life.

1. Structure and Properties of Nanophases

As a scientific and technical direction, the microsystems engineering was formed at the beginning of the 1990's as a result of joining of two directions: Microsystems Technology (MST) and Microelectromechanical Systems (MEMS). The integration of electronic, mechanical, liquid, optical and other components for creating the devices from several microns to a few millimeters in size is the basic task of the new direction.

Naturally, the devices with electronic circuits governing actuating mechanisms although not of millimeter size were made in the decades before the era of microsystems technology. So, what was the reason for the events, which occurred in the 1990's? It is however strange, the invention in 1958 of the model of the integrated circuit, which combined electronic components in a single semiconductor crystal, was the reason. Passage to the planar technique with the production of integrated circuits gave a possibility to make the huge amount of identical elements simultaneously in a single technological process, which substantially reduced their cost. An additional advantage of the planar technique is the possibility of an increase in the integration degree, i.e., an increase in the quantity of elements per unit of area due to the decrease of sizes of elements. An increase in the integration degree clearly demonstrates the decrease of sizes of semiconductors from the initial 20-30 mkm in 1958 to 45 nm at present, and the use of different semiconductor materials and types of the logic (MOP, CMOS, TTLS - complementary metal oxide semiconductor, etc.) allowed increasing the speed and reducing the energy consumption of electronic devices.

Thus, with the passage to the new production technology, electronic components have advantages due to an increase in the productivity, efficiency and best mass and dimensions parameters in comparison with the sensors and the actuating mechanisms made by the traditional technologies. The incorporation of electronic controller into the housing of actuating mechanism is the unique solution of the problem of integration in this case. It is easy to verify this independently by means of taking a more or less complex electromechanical device to pieces. When implementing this approach, it is necessary to solve a number of problems, beginning from the fact that the electronic and executive mechanical components are made separately, by means of different technologies, with the use of a wide spectrum of the materials being often incompatible with each other, and so forth, ending with the final assembling. As a result: low reliability, significant mass and overall sizes, energy consumption, and high prime cost. The resulting situation can be described by the technological dead end, where a different ideology of construction might be a solution, what permits to miniaturize optical, mechanical, electronic, liquid components, to combine in one small volume the large number of devices with different physical operating principles.

The result of the search for this ideology was the formation and explosion of microsystems engineering. The devices created by the new technology have several advantages over usual analogs. First, like the integrated circuits, it is possible to produce them by large series, what considerably reduces their prime cost. Second, they can be directly incorporated into integrated circuits (to be arranged on one semiconductor crystal), which makes it possible to create complex and simultaneously compact systems.

2. Principles of Functioning and Feature of Designing

Before detailed study of microelectromechanical systems, let us examine the basic principles of their functioning. As it follows from the name, the operating principle of such systems consists in the conversion of electrical energy into the mechanical one for the actuating mechanisms, and mechanical action for changing the recordable electrical parameters (conductivity, capacitance, and inductance) for the sensors.

Let's list main principles of functioning of micromechanical systems:

- Electrostatic: the displacement of the elements of construction charged by the similar or opposite charges;
- Electromagnetic: displacement due to interaction of the moving elements of the construction with the magnetic field;
- Electrostrictive and magnetostrictive: they are based on the effect of a change in the linear dimensions of substance during the application of the electrical or magnetic field to it;
- Piezoelectric: it is based on the direct and reverse piezoelectric effect in some dielectrics. In the case of direct effect, under the action of mechanical stresses, the polarization of dielectric appears, and in the case of inverse effect, the dielectric is deformed under the action of the electric field;
- Thermal expansion: displacement due to deformation of the material of the construction as a result of heating or cooling.

On the first stages of the development of microsystems engineering, many people had an illusion that the design of micromechanical devices is free of any special difficulties; what may be easier than to take a known macroobject, and to prepare its functional microcopy? As a rule, similar attempts to transfer the classical principles of the construction of macroobjects into the microcosm failed. The functioning of mechanical, hydraulic and other systems in the microcosm depends on many phenomena: the influences of intermolecular forces and forces of surface tension, roughness of surface, viscosity of liquids and gases, temperature gradient, diffusion, influence of electromagnetic pour on, electrostatic forces, etc. It is possible to illustrate this argument by the example of the construction of micro-liquid devices. It is known that it is possible to blend liquids by means of turbulence, i.e., active mixing, or by diffusion, the latter being slower. In the micro-liquid devices, the flows are laminar due to low flow velocity; therefore, mixing liquids is possible only by diffusion, or using the artificially organized turbulent flows in the special ultrasonic cameras that, undoubtedly, complicate the construction. The adhesion caused by the action of intermolecular forces is capable of having a significant effect on the work of the mechanical systems containing moving elements contacting with each other due to occurrence of friction.

The non-optimal selection of materials will lead to the fact that the substantial part of the energy consumed by device will be spent for overcoming frictional forces, and the increase of mechanical loads will lead to the premature wear and the breakdown.

Finally, in contrast to the traditional macrosystems of systems, the repair of microsystems is impossible. Therefore, the central objective of the development is to obtain the completely functioning system in the first realization.

3. The MEMS Materials

In 1982, Kurt Petersen, an employee of the company IBM, published the article, in which he proposed to use silicon as the construction material for preparing different moving mechanical elements (gears, lath, the membranes, bridges, consoles, springs and so on) of three-dimensional mechanical structures. The technology of bulk wet etching of silicon developed earlier and the basic technological processes of the production of integrated circuits made it possible to realize this challenging idea after combining electronic and mechanical structure on one semiconductor substrate, as a result. At present, silicon heads the list of construction materials as before, and it is a part of more than 60% of MEMS devices.

Contemporary microsystems are the complex compositions, which consist of the large number of different materials, including polymers, metals, and ceramics along with semiconductors. The construction materials of microsystems technology conditionally are divided into two groups. The first group comprises: single-crystal, polycrystalline, porous silicon, dioxide and nitride of silicon (SiO_2, Si_3N_4), polymers, tungsten, nickel, copper, gold, silver, diamond-like films, which are used for the forming of frameworks, electrical conductors, antifriction coatings. The second group comprises so-called active materials, which perform function of displacement sources and sensors due to the shape memory effect, as well as the memory effect for electrostatic, piezoelectric, magnetic, and other properties. They include: quartz, piezoceramics, permalloy, the alloy of titanium and nickel, the materials of group A_3B_5.

In the course of development of hybrid micromechanical systems consisting of the different materials, it is necessary to consider the following criteria:

- Crystallochemical compatibility including the types and parameters of crystal lattices of semiconductor materials in the multilayered structures;
- The admissible thermal load accounting for Debye temperature, Curie point, and, for semiconductors, also the transition temperature for the state when the concentration of its own charge carriers is close to the extrinsic one;
- Mechanical strength;
- Electrochemical compatibility.

In the MEMS, the construction materials are used mainly in the form of films. For example, for passivation, formation of dielectric layers, metallization, masking. The thickness of such layers varies in the range from several nanometers to several hundred micrometers.

It is possible to obtain thin films by several methods: physical precipitation or condensation from the gaseous phase (the thermovacuum or cathode sputtering); chemical precipitation from the gaseous phase (pyrolysis, reactive cathode sputtering); the electrolytic deposition from the solutions of salts of metals (application of electrolytic platings, the chemical copper plating); the anodic or the thermal oxidation of the surface, ionic dispersion.

3.1. Thermal Oxidation

Thermal oxidation is used frequently in silicon technology, particularly for the generation of insulating and dielectric layers, or masks for the subsequent etching a surface of a substrate. Silicon dioxide (SiO_2) possesses outstanding electrical (insulation), mechanical (hardness) and optical (transparency).

For the oxide layer formation, silicon wafers can be treated in an oven simultaneously at a typical process temperature up to 850-1200 °C.

Oxidation in the absence of water vapor is referred to as "dry" oxidation. Layers formed by this method have very good dielectric properties and are free from defects; however, the layer growth is quite low. For a silicon dioxide layer thickness of 100 nm, the process duration is approximately 10 hours at a temperature of 900 °C. If oxidation is carried out in an atmosphere of wet oxygen by enriching with water vapor, such oxidation is referred to as "wet" oxidation, which achieves a much higher growth rate (approx. 100 nm per hour), however, the layers are of inferior quality.

Thermal oxidation of silicon in oxygen or water vapor may be described by following chemical reactions:

$$\mathrm{Si}\ (\mathrm{solid}) + \mathrm{O_2}(\mathrm{gas}) \xrightarrow{850\text{–}1200^\circ\mathrm{C}} \mathrm{SiO_2}(\mathrm{solid})$$

$$\mathrm{Si}\ (\mathrm{solid}) + 2\mathrm{H_2O}\ (\mathrm{gas}) \xrightarrow{850\text{–}1200^\circ\mathrm{C}} \mathrm{SiO_2}(\mathrm{solid}) + 2\mathrm{H_2}(\mathrm{gas})$$

As the thickness increases, the rate of formation of oxide film decreases, since oxygen must diffuse through the growing film before to enter into the reaction with silicon on the plate surface. For thin layers (< 50 nm), the rate of film growth is nearly constant, and the dependence of the film thickness on time is almost linear. For the thick films (> 200 nm), the diffusion coefficient decreases, which leads to the deviation of the growth rate from the linear dependence; in the case of very thick film, it assumes dependence as square root on the duration of oxidation process.

Due to the difference in thermal expansion coefficients between silicon oxide $0.4\cdot10^{-6}$/K and silicon $5.3\cdot10^{-6}$/K, mechanical stress is induced in the wafer cooling from the process temperature. This leads to compressive stress in the oxide layer and tensile stress in the silicon layer. The stress can be partially relieved by annealing.

Most often, thickness of oxide layer is few deciles of micron, and the upper thickness limit in practice is 1-2 microns for usual thermal oxidation.

3.2. Chemical Vapor Deposition

The process is defined as the deposition from a gaseous phase where the material to be deposited is created by a chemical reaction on or in proximity to the substrate. Source of a material deposited on a substrate is its gasiform compound. For reaction to progress and thus for deposition, energy must be supplied, for instance in the form of heat (pyrolysis), with the help of a plasma (PECVD: Plasma enhanced CVD) or by laser light (LECVD: Laser enhanced CVD).

Examples of some reactions are:

$$SiCl_4 + 2H_2 \xrightarrow{1150°C} Si + 4HCl$$

$$WF_6 \xrightarrow{400°C} W + 3F_2$$

$$2TiCl_5 + 5H_2 \xrightarrow{700°C} 2Ti + 10HCl$$

The deposition rate is 1-10 µm/hour and depends on the process conditions. Generally, CVD gives good surface quality and sufficient purity of layers combined. There exists an abundance of CVD reaction schemes and processes, which include almost all metals, most oxides, nitrides and carbides.

SiO_2 films can be obtained by several methods. They can be obtained as a result the reaction between silane and oxygen that takes place at a temperature 300… 500 °C, in the reactor for the chemical deposition at the low pressure:

$$SiH_4 + O_2 \xrightarrow{500°C} SiO_2 + 2H_2$$

The alternative method of obtaining the dioxide of silicon is by the following chemical reaction of dichlorosilane with the clean water vapor:

$$SiCl_2H_2 + 2H_2O \xrightarrow{900°C} SiO_2 + 2H_2 + 2HCl$$

Si_3N_4 films may be obtained in a similar way at mean temperatures and low pressures in the chemical precipitation device and at low temperatures by plasma precipitation. Most frequently, silicon nitride films are obtained in the first type device by the following reaction:

$$3SiCl_2 + H_2 + 4NH_3 \xrightarrow{800°C} Si_3N_4 + 6H_2 + 6HCl$$

To deposit the polysilicon films, it is possible to use the silane pyrolysis reaction, which takes place at a temperature of 600… 650 °C and at a low pressure.

$$SiH_4 \xrightarrow{600°C} Si + 2H_2$$

3.3. Physical Vapor Deposition

During PVD (physical vapor deposition) of metallic coatings, the material passes from the solid state to the gaseous one, with subsequent precipitation of the material to the substrate. Material can pass to the gas phase as a result of evaporation (under the action of thermal energy) or as a result of cathode sputtering (under the action of the bombarding ions).

3.3.1. Thermal Evaporation

Thermal evaporation and deposition is the most frequently used method of obtaining metallic films. In high vacuum evaporation, the metallic substance is heated up by resistance heating in a crucible to a temperature at which the metal evaporates. To obtain especially pure films, resistance heating is substituted by electron beam bombarding, what promote evaporation. The resulting atomic or molecular flow propagates in the vacuum chamber rectilinearly and reaches the substrate surface. The vapor condenses, and the film is formed on the substrate surface. The deposition rate is usually between 1 and 100 nm/s.

The merits of thermovacuum deposition include relative simplicity of process and weak thermal load experienced by the substrate during the condensation of vapors on its surface

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Biographical Sketch

Kirill Potlovskiy was born in Moscow in 1975. In 2001, he graduated from the Moscow State Institute of Electronics and Mathematics. Candidate of Technical Sciences, docent. Basic fields of research: microsystems engineering, LIGA technology.

Dr. Potlovskiy works at the Bauman Moscow State Technical University. He is the author of more than twenty scientific articles and inventions.