NANOELECTROMECHANICAL SYSTEMS

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Summary

The description of construction and functioning of nanoelectromechanical systems (NEMS) as a further development of microelectromechanical systems (MEMS), is the most intensively evolving field of modern microelectronics. The emergence of NEMS domain is also a result of general progress of nanotechnologies and the design of nanotechnology elements. This domain is on the forefront of nanotechnology programs for the 2010s in the Western countries under a name of nanoelectromechanics.

Currently NEMS are in the research stage. There are a great number of scientific publications, which are dedicated to this area, but there is no information about its commercial applications.

The state of the art of this domain and a wider specter of its practical applications and its prospects are considered in this chapter.

1. Introduction

Micro-electro-mechanical systems (MEMS) are devices that represent the most intense development in modern microelectronics. The main challenge of microelectromechanics is the design of unique micromechanical structures for various purposes. This research direction is based on achievements of advanced microelectronic technologies and inherits the basic advantages of electronic microchips: high reliability and reproducibility of characteristics, low cost, and large scales of applications.

The essence of micromechanics implies that advanced microelectronic technologies, for instance, deep etching of silicon [or silicon-on-insulator (SOI) structures make it possible to create integrated circuits (IC) simultaneously with micromechanical structures possessing unique parameters (determined by their microscopic or nanoscopic sizes, the transported mass being 10^{-4} to 10^{-18} g) controlled by electronic circuits.

The most important feature of MEMS is the precision (earlier inaccessible in mechanics) fabrication of moving elements of mechanical structures and their unification in one technological cycle with controlling and processing electronic elements created on the basis of the complementary metal–oxide–semiconductor (CMOS) technology.

The basic element of micro-electro-mechanical systems (MEMS) is the electromechanical converter of energy. Such converters can be based on various physical principles: electromagnetic, electro thermal, piezoelectric, or electrostatic. The preference is given to electrostatic converters, which display the best technological efficiency. Capacitive electromechanical converters of energy have undisputable advantages over inductive converters from the viewpoint of structural simplicity and processability: there is no need to use magnetic circuits, windings, etc

The history of the development of MEMS technology can be divided into several stages starting from mid 1950-s to the beginning of 1960-s, when such huge corporations as Bell Laboratories and some academic organizations conducted first researches aimed to establish the basis of the future technology.

When the tremendous prospects of the new technology were understood, by the beginning of 1970-s the academic science has begun to receive funds that came mainly from the industry for the solution of such tasks as cost reduction and extension of applications of MEMS devices. This stage lasted more than a decade. Then the decade of micro-machine construction came. It is called micro-mechanical epoch, which still continues.

As applied to large-scale problems of practical importance, the current stage of MEMS evolution can be assumed to start in 2000, when the U.S. President announced a new governmental research program entitled National Nanotechnology Initiative (NNI) with a half-billion budget. The program was successfully developed, and the guaranteed annual investment in research and development activities now reached one billion. Research in this field is also supported by other states, for instance, by Japan where a national project aimed at developing MEMS industry up to 2016 was announced.

At the moment, the range of MEMS applications is extremely wide, and the number of various articles reaches hundreds of millions. We can also speak not only about significant improvement of parameters of available devices, but also about the development of principally new MEMS-based devices.

MEMS research became the most significant and rapidly developing area of electronic industry. This fact is evidenced by numerous international conferences: IEEE International Conference on Solid-State Sensors, Actuators, and Microsystems, IEEE Annual International Conference on Microelectromechanical Systems (the MEMS conference), Eurosensors conference, IEEE Workshop on Solid-State Sensors, Actuators, and Systems, and also conferences dealing with more particular issues of

MEMS applications (optical MEMS, microactuators, and Bio-MEMS), problems of MEMS commercialization, etc.

There appeared many new academic journals published for MEMS developers: IEEE/ASME Journal of Microelectromechanical Systems, Sensors and Actuators, Journal of Micromechanics and Microengineering, Lab on a Chip, Nanomicrosystem Engineering (Russia), Nanotechnology, Nature Nanotechnology, and Smart Materials and Structures. In addition, some journals, such as Science, Nature, Applied Physics Letters, Journal of Applied Physics, New Journal of Physics, Proceedings of the National Academy of Science, Nano Letters, Analytical Chemistry, Langmuir, etc., often publish papers on MEMS physics, methods of MEMS fabrication, and MEMS applications. There are some recent electronic journals dealing with the MEMS topic only, for instance, Memsjournal.com, MEMS Investor Journal, etc.

The development of MEMS is carried by hundreds of research laboratories in different countries. In China alone there are more than a hundred of such centers and universities. Big international scientific conferences are constantly organized. One of them named "Nanotechnology and MEMS/MCT/micromachines: Global perspectives of the technology, its application and commercialization" took place in Chicago in 2007. A big international conference and exhibition "The integration and commercialization of micro- and nanosystems" took place in Hainan, China with participation of more than 500 developers. It had the following sections: micro-nano electrical mechanical systems, micro- and nanomechanics, micro and nanosystems, micro and nano "fluids", etc.

One can point out such applications of MEMS as:

- Microoptoelectromechanics (displays, adaptive optics, optical microcommutators, fast-response scanners for cornea inspection, diffraction gratings with an electrically tunable step, controlled two- and three dimensional arrays of micromirrors, etc.);
- RF devices (RF commutators, tunable filters and antennas, phased antenna arrays, etc.);
- Displacement meters (gyroscopes, highly sensitive two- and three-axis accelerometers with high resolution, which offer principally new possibilities for a large class of electronic devices);
- Sensors of vibrations, pressures, velocities, and mechanical stresses; microphones (there are millions of them in cellular phones). Back in 2004, Intel started to deliver RF front-end assemblies fabricated by the MEMS technology for cellular phones. They integrate approximately 40 passive elements, which allow the producer to save up to two thirds of space in the phone casing;
- Wide range of devices for working with microvolumes of fluids and for applications in biology, biochips, biosensors, chemical testing, creation of a new class of chemical sensors, etc.
- Microactuators and nanopositioners; microgenerators of energy

Many experts think that the telecommunications market is one of the promising areas of MEMS implementation. A private company MEMX (www.memx.com) separated in 2000 from the Sandia National Laboratory governed by the U.S. Department of Energy. This company is successful in commercialization of MEMS technologies related to optical commutators for fiber-optical telecommunications systems

The current status of MEMS allows us to argue that an industrial technology of principally novel microelectronic devices with a wide range of applications has been created. It should be noted that the MEMS technology did not appear from scratch: it evolved in parallel to the technology of semiconductor microchips, and the relation between electrical and mechanical forces, as applied to various devices, has been studied for a long time.

It is seen that the area of MEMS applications is extremely wide, and the prospects of using new generations of MEMS devices capable of qualitative transformations in almost all fields of engineering are even more glorious. It becomes obvious that none of the fields of modern electronic engineering, including domestic electronic equipment, will avoid the touch of the new industrial revolution.

The YOLE Développement market-research company (www.yole.fr) says that the MEMS market has increased by more than a factor of 40 for the last four years, and the sales volume reached 5.1 billion dollars in 2005; the sales volume is expected to exceed 13 billion dollars in 2010, judging by its annual growth rates of 15–18% (MEMS Investor Journal, http://www.memsjournal.com, Semiconductor International Weekly, Special Report: MEMS, January 19, 2007). Though the growth in the MEMS field for the last five years has been much faster than the growth in the overall semiconductor industry and has been considered as the most important event in commercial electronics, YOLE Développement predicts that the boost of new developments and MEMS applications is still to be expected. This trend was confirmed at the meeting of the basic MEMS producers with the Globalpress group (San Francisco, March 30–April 2, 2009), where the prospects of further development of this direction in microelectronics was discussed. In view of the rapidly growing sales, the majority of the basic MEMS producers (more than 20 companies) makes significant investments (despite the deceleration of consumer expenditures in 2009) into new production lines with a transition from 6-inch to 8-inch substrates (mainly, SOI with two or three layers of polysilicon up to 3–4 μm thick).

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Biographical sketch

Eduard Gennadievich Kostsov has graduated from the Physical faculty of the Saratov State University, department of theoretical physics.

In 1968 he has received PhD degree for his thesis «The research of influence of micro relief of electrode surface on the processes of current conduction and the phenomena of breakdown in thin film metal-dielectric-metal system». The theme of his doctorate thesis is «Transient processes in films of linear dielectrics and ferroelectrics».

E. G. Kostsov is a specialist in physical electronics, physics of dielectrics, ferroelectrics and the element base of microelectronics, micro- and nanoelectromechanics. He is author and co-author of more than 250 scientific papers, two monograph, 30 patents. His main research interests include the development of new microelectronic elements, theoretical and experimental study of transient physical processes in dielectric and ferroelectric films, study of charge transfer in thin film structures.

He has established a new direction in the microelectronics, which is related to the introduction of ferroelectric materials into the structure of integrated circuits. This direction might lead toward massive using of ferroelectrics in memory chips (dynamic, read-only, electrically reprogrammable), uncooled thermal imaging devices and in the recent years in microelectromechanical systems, etc.

He has developed physical and technical principles of optical high performance digital computing devices and created universal optical logical elements and 3D integral schemes with optical links on their basis.