ENTERPRISE PORTFOLIO

Hybrid MEMS

By Darko Belavič

Research & Development for Industry

Micro-electro-mechanical systems (MEMS) can be fabricated with a variety of technologies and from a range of materials. MEMS are normally made by micro-machining silicon, but for certain applications ceramic materials are a very useful alternative that can be used for ceramic micro-electro-mechanical systems (C-MEMS) or in combination with silicon MEMS. This hybrid structure is called a hybrid micro-electro-mechanical system (H-MEMS). The development flexibility is an opportunity for small and medium-sized enterprises in this fast-growing market.

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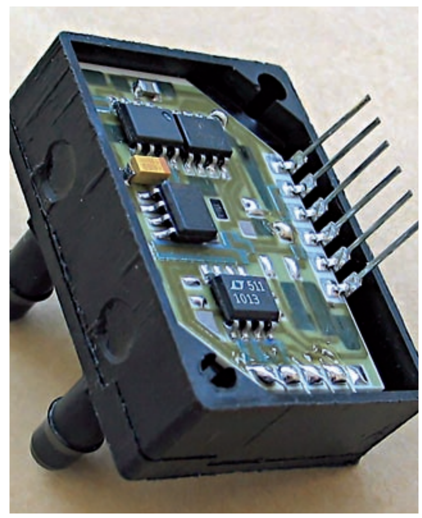
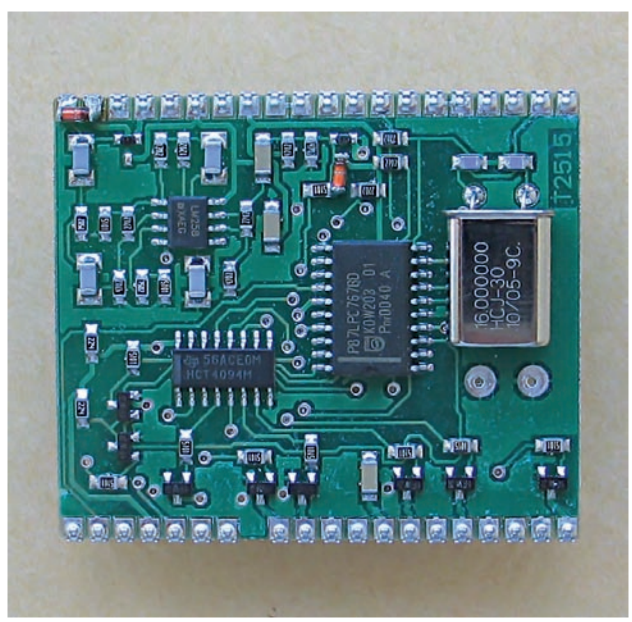
Introduction

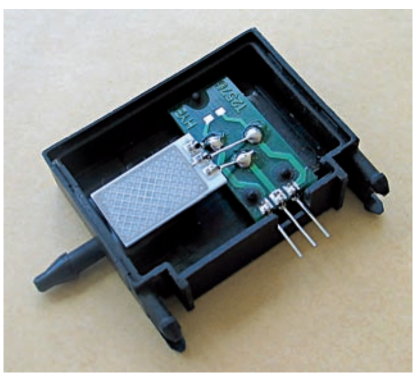
The acronym MEMS stands for micro-electro-mechanical systems, and was used for the first time in the United States in the late 1980s. Around the same time, Europeans were using the designation “microsystems technology” (MST). MEMS are miniature devices that convert physical quantities to or from electrical signals and which depend on mechanical structures, materials and other parameters. MEMS refers to devices that have a characteristic length of less than 1mm but more than 1µm, and that combine electrical and mechanical components. A microsystem might comprise one or more sensors and/or actuators, and an electronic circuit that conditions the sensor signal and/or generates an electrical signal for the actuator. MEMS can be fabricated with a variety of technologies and from a range of materials. Most MEMS are made by micro-machining silicon, but in some applications ceramic materials are a very useful alternative. These ceramic micro-electro-mechanical systems (C-MEMS) are typically larger (meso-size) and mostly used in harsh environments. The laminated 3D structures made by LTCC (low-temperature cofired ceramic) technology are especially suitable for C-MEMS [1-8]. Both the sensors for mechanical quantities and the actuators are fundamental parts of MEMS. The most important technology for manufacturing sensors and actuators in C-MEMS is thick-film technology. A thick-film resistor can be used to sense, and piezoelectric materials can be





used to actuate, the mechanical deformations in MEMS structures. Thick-film technology can be used in C-MEMS not only to produce the sensor and actuator elements themselves but also the electronic circuits for signal processing [3-6].

Packaging is an essential technology in the construction of MEMS devices. In most cases the device's development and design process is faced with strict requirements: device size is decreasing, while functions and performance are expanding, and at the same time the cost of the sensor has precise limitations. In this respect, developments in sensor technology are proceeding in two directions. The first direction is towards high-volume production, integrating all, or most, of the electronic and MEMS device functions into a single chip. The second direction is towards small- and medium-volume production with a high flexibility of applications, using one or more interconnection technologies to integrate the MEMS device(s), the integrated circuit(s) and the pas-



An introduction to Hyb d.o.o.

By Dušan Plut

Dušan Plut, General Director

Hyb has a long tradition in the field of thick-film hybrid circuit technology. The plant in Šentjernej was established in 1972, when the first hybrid circuit was produced. In the 1980s Hyb initiated production of invasive blood pressure sensors and in the late '80s of industrial pressure sensors and transducers. In 2001 the company was bought by Novoline Holding. The owner has made significant investments in technology, facilities, development and marketing.

Today Hyb is a modern, future-oriented company. Its business philosophy is based on marketing, development and production of thick-film hybrid circuits, pressure sensors and transducers. The majority of Hyb's products are custom designed. Close cooperation with our customers throughout the development phase is crucial for the ultimate success of the end product on the market. Besides custom-designed products, Hyb also develops a proprietary brand, Hybysens.

Hyb's product line encompasses medical sensors, industrial sensors and transducers, automotive sensors, telecommunications and consumer electronics.

In the area of medical sensors, Hyb develops and produces invasive blood pressure sensors for critical care that constitute approximately 5% of the world market. The IUP sensor was designed primarily for the American market. A new generation of sensors and a complementary medical program are currently in the development phase.

Hyb's industrial sensors, transducers and switchers cover the niche of low pressure range sensors. Hyb's competitive strengths are in its flexibility and orientation to designing, producing and calibrating products for the customer.

The automotive industry is the third market sector where Hyb is present, where basic automotive products (hybrid circuit boards) are upgraded to pressure sensors and switchers. Last year Hyb started marketing its own MAP sensor, and several new products are being developed.

Since the very beginning Hyb has been cooperating with the Jožef Stefan Institute, especially with its Electronic Ceramics Department. Important R&D partners are also the Faculty of Electrical Engineering at the University of Ljubljana and the Hipot-RR company in Šentjernej.

A balanced combination of investments in basic and applied research is key in the long-term competitiveness of the company in turbulent markets, where product lifecycles are shorter and shorter, and where even the markets themselves appear and disappear. No one can afford to rest on their laurels or on current successes. At Hyb we invest in our people in all fields and encourage the creativity and innovativeness of the entire organization. Hyb constantly endeavours to gain the trust of its business partners with the best possible products and services. The same attention paid to the development of new products and the improvement of previously launched products is also devoted to the development and improvement of the process of providing high-quality service to our business partners.

sive components in a MEMS module. Thick-film interconnection technology on a ceramic substrate is essential to meet these demands. The electronic circuits for signal processing in sensor applications range from a simple amplifier to a "smart" sensor. In addition, many different electronic circuits may lead to the same function or operation. The common electronic conditioning circuit for sensor applications needs an excitation voltage or current, an instrumentation amplifier, a voltage reference and an output stage.

The market for sensors and MEMS

The global market for silicon-based MEMS devices is very difficult to analyse because of the definition of the market(s). Therefore, the results of different market analyses (iNEMI, NEXUS and Yole Development) [11-13] yield different absolute numbers, but the annual growth of the market is in all cases similar and relatively very high (about 17% CAGR). The growing MEMS market also has an influence on the markets for materials and equipment for MEMS, which are shown in Table 1. The silicon-based MEMS device market was $3.85 billion in 2004 and is forecast to reach $6.0 billion at the end of 2006 and $8.1 billion in 2008, thus resulting in a 16% CAGR.

The biggest share of the MEMS market (especially in Europe) belongs to automotive applications, which was, and still is, the major area of application and the driving force for silicon-based MEMS products. In 2004 alone, the worldwide automotive market used more than half (65%) of all the MEMS sensors produced, followed by industrial applications (about 20%), consumer-type applications (6%), and only 5% in the area of communications and computers.

Today, small and medium-sized enterprises are the driving force behind the technological development of MEMS, since these companies are able to adapt new technologies in a flexible way with short turn-around times. Most of them buy the silicon MEMS devices on the open market and use them in their innovative products.

MEMS packaging and integration

Packaging issues are very important and challenging for the applicability of MEMS because they are usually sensitive to mechanical or thermo-mechanical stresses. Due to special requirements and in particular to specific mechanical and thermo-mechanical properties, a ceramic is probably the most common substrate material for assembling silicon MEMS devices. The reason lies in its physical properties, which include: high compressive strength and hardness, thermal expansion similar to silicon, and dimensional stability. LTCC technology also has many benefits for the packaging of silicon-based MEMS. Firstly, it is possible to make cavities in the sub-

Table 1: World MEMS market ($ billion)

	2004	2006	2008	CAGR
MEMS Systems	29.50	41.00	57.00	18%
MEMS Devices	3.85	6.00	8.10	16%
Materials for MEMS	1.48	1.90	2.50	14%
MEMS Equipment	0.51	0.67	0.85	15%

strate in which the silicon-based MEMS can be bonded and hermetically sealed. Secondly, the match between the linear thermal expansion coefficient (TEC) of ceramics and silicon is fairly good (2.6×10^{-6}/K vs. $5\text{-}7\times10^{-6}$/K for LTCC), which is very important for sensitive MEMS devices in wider-temperature-range applications [1,3]. The combination of silicon- and ceramic-based MEMS formed in a hybrid structure is called a hybrid micro-electro-mechanical system (H-MEMS).

Microelectronics and MEMS technology have completely different system-integration requirements. The microelectronics of the future will integrate increasingly complex subsystems onto a single planar chip, enlarging its size to several cm2, as it currently stands. In contrast, microsystems usually require smaller areas, which can only be produced through 3D integration. Protection against harsh environments and the special interfaces between the sensor and measurement environment are other important factors in the system integration of MEMS devices.

In most of the industrial pressure sensors produced by HYB, the sensors are built in two parts, functionally divided into a pressure-sensor front-end (Fig. 1) and an electronic conditioning circuit combined with thick-film technology. The sensor element is a silicon MEMS device (gauge silicon piezoresistive pressure sensor), which is a silicon die with a thin diaphragm in the middle. The diaphragm is formed by etching into the silicon die. Into this diaphragm four piezoresistive resistors are diffused, which are electrically connected to form a Wheatstone bridge. One of the key technologies for the successful production of pressure sensors is bonding the silicon die to the (ceramic) substrate (Fig. 2). Depending on the sensor application, different polymer adhesives are chosen to satisfy the demands of various users.

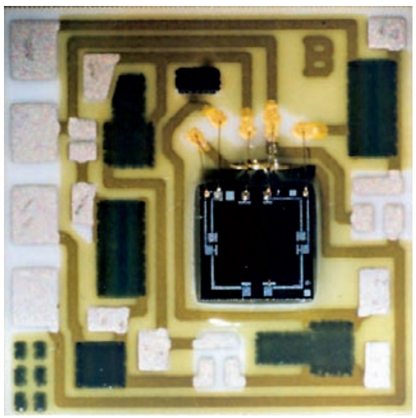


Fig. 1: Typical passive pressure-sensor front-end

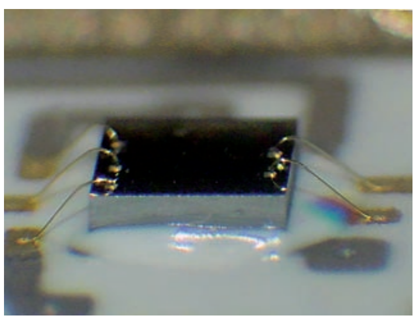


Fig. 2: The silicon die (piezoresistive pressure sensor) is bonded to the ceramic substrate

Miniaturization is a consistent theme in the development of new MEMS and pressure sensors. An example is the miniaturization of a pressure switch, as shown in Fig. 3. The miniaturisation of the pressure switch was possible by using high-density interconnections and a naked chip semi-custom ASIC.

C-MEMS made with thick-film technology on a ceramic substrate are widely used in harsh environments. In comparison with semiconductor sensors they are more robust, have a wider operating temperature range, have good long-term stability and have no organic compounds. In general, the sensitivity of such thick-film pressure sensors is lower than with silicon sensors, but the operating ranges are wider. Fig. 4 shows piezoresistive thick-film ceramic pressure sensors based on an alumina ceramic cell with bonded electronic conditioning circuits.

Fig. 3: A comparison of three generations of pressure switch (HYB d.o.o.)

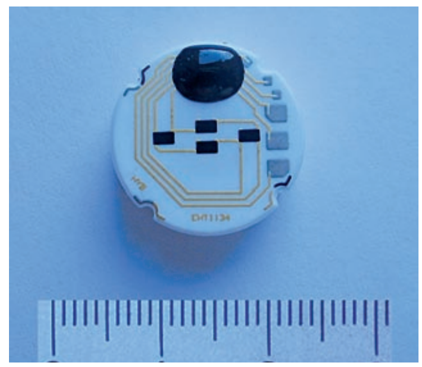


Fig. 4: Ceramic pressure sensor with ASIC for signal conditioning (HYB d.o.o.)

Low-temperature cofired ceramics

Advanced ceramic technologies, like low-temperature cofired ceramics (LTCC), are a rapidly growing part of the hybrid electronic-module market in Europe. More than 25% of this market in the year 2004 belonged to LTCC technology. LTCC technology is a three-dimensional ceramic technology utilizing the third dimension (z) for the interconnect layers, the electronic components and different 3D structures such as cantilevers, bridges, diaphragms, channels and cavities. It is a mixture of thick-film and ceramic technologies. Thick-film technology contributes the lateral and vertical electrical interconnections, and the embedded and surface passive electronic components (resistors, thermistors, inductors, capacitors). Ceramic technology contributes the electrical, mechanical and dielectric properties as well as different 3D structures [7-8].

HIPOT-R&D d.o.o., Šentjernej, Slovenia

The HIPOT-R&D Research and Development in Technologies and Systems Company was established in 1996 to act as a research organisation for local electronic components companies. Current research and development activities are organised at HIPOT-R&D through the research and development group. This group is responsible for research, development and technology transfer in the fields of thick-film hybrid microelectronics, sensors (primarily pressure sensors), electronics, electronics technologies, and electromechanical devices and systems. In the field of research and development, as well as in system upgrading, the company works closely with scientific institutions and technical associations, both in Slovenia and worldwide. The cooperation with its research partner, the Jožef Stefan Institute in Ljubljana, is traditional and goes back to the 1970s. One division of HIPOT-R&D is actually located in Ljubljana at the Jožef Stefan Institute, while the other is in Šentjernej, at the same location as its industrial partner HYB d.o.o. This distribution facilitates excellent cooperation between partners.

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LTCC materials in the green state (called green tapes, before sintering) are soft, flexible, and easily handled and mechanically shaped. A large number of layers can be laminated to form high-density interconnections and three-dimensional structures. The fabrication process includes several steps, which are termed LTCC technology (Fig. 5). The separate layers are formed by the mechanical shaping of meso-size features (0.1-15 mm), and then the thick-film layers are screen-printed. All the layers are then stacked and laminated together with hot pressing. This laminate is sintered in a one-step process (cofiring) at low temperatures

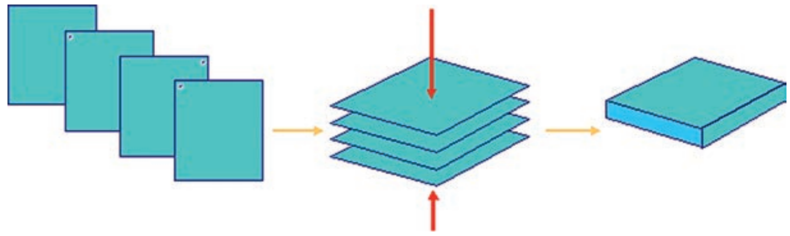


Fig. 5: LTCC technology.

(850–900°C) to form a rigid monolithic ceramic multilayer circuit (module). Some thick-film materials need to be post-fired; this means the paste needs to be screen-printed on the pre-fired laminate and then fired again. The whole LTCC process saves time, money and reduces the circuit's dimensions compared with conventional hybrid thick-film technology. The important advantage for MEMS applications is the lower Young's modulus (about 100 GPa) of LTCC materials in comparison with alumina (about 340 GPa). The disadvantages of LTCC technology are a lower thermal conductivity (about 2.5 to 4 W/mK) in comparison with alumina and the shrinkage (about 10 to 15% in the x/y-axes and about 10 to 45% in the z-axis) of the tape during sintering. An example of a MEMS application, a thick-film piezoresistive pressure sensor on an LTCC substrate, is shown in Fig. 6.

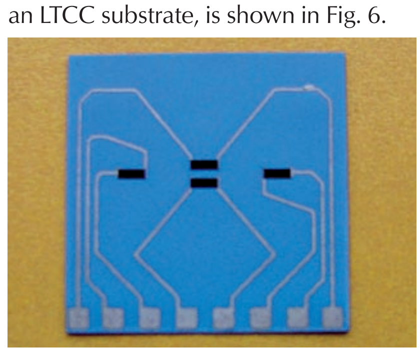


Fig. 6: Thick-film piezoresistive pressure sensor on an LTCC substrate

Research priorities

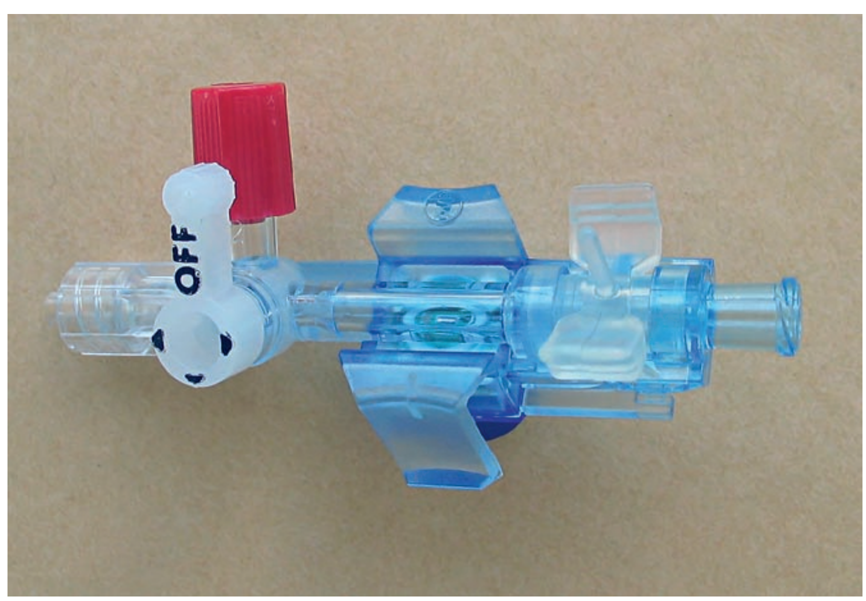
The research priorities for the next 5 to 10 years on MEMS and sensors are very important for the successful development and production of new products in the future [11]. Some of the research priorities are general, but some are specific to MEMS and sensors. Six topics with research priorities are the following:

1. Manufacturing Processes

- Manufacturing processes that support rapid miniaturization
- Significant cost reduction in manufacturing processes
- Development of new testing technologies to improve yield and reduce test costs
- In-system electrical and optical test technologies that can be incorporated into the build process
- Improved packaging manufacturing processes
- Development and deployment of surface micromachining technologies for sensors

2. System Integration

- IT infrastructure research is needed to ensure the fast and secure transfer of increasingly large amounts of data across the supply chain
- Research is needed to develop tools for meeting environmental compliance regulations cost effec-



tively and securely
- PLIM (Product Lifecycle Information Management) security research is needed to guarantee that only the data that is needed is supplied to the appropriate supply-chain nodes
- Improved planning/PLIM methodologies that deal with ever-changing market needs over the lifecycle of a product and optimize the resources of the entire system

3. Technology Integration

- Smart sensor
- Wireless communication
- Robust and low-cost out-of-plane optical coupling, e.g. surface-mounted device to embedded waveguide
- Development of Low Voltage MEMS: Innovative MEMS structure designs, monolithic integration with ICs
- Low-cost, high-reliability, dirt-tolerant, optical interconnects

4. Energy and the Environment

- Development of a flexible, miniaturized energy supply for integration in self-contained sensors
- Development of good scientific methodologies to assess the environmental impact of materials and the potential trade-offs of alternatives
- Development of cost-effective, energy-efficient power sources
- Development of a common, meaningful, straightforward definition of sustainability

5. Materials and Reliability

- Reliable materials systems for the first level of interconnect between new device technology and new substrates, including laminate materials with higher density, competitive cost, improved dimensional stability, planarity, low moisture absorption and low warping
- New interconnect and packaging technologies deploying nanomaterials supporting decreased pitch and increased frequencies
- Polymers will be used for MEMS devices
- Low-cost, higher thermal conductivity packaging materials, such as adhesives, thermal pastes and thermal spreaders, need to be developed for use in products ranging from high-performance computers to automotive applications
- Improved materials for energy sources and energy-storage systems
- Next generation of lower-cost solder alloys
- Realization of the potential for embedded sensors will require the development of miniaturized sensor elements, integrated control systems, and micro-actuators that can all be interconnected in a single package with a small form factor
- Biocompatible materials for the packaging of biosensors backed by long-term reliability and safety data
- Miniaturization is especially critical for implantable devices, and one of the keys to achieving this is the availability of ultra-small, standalone power sources with a long life. Although continued research into miniaturized fuel cells is required, this area may benefit from breakthrough developments in nanotechnology for energy-storage devices.

6. Design

- Co-design of mechanical, thermal and electrical performance of the entire chip, package and associated heat-removal structures
- Mechanical and reliability modelling
- Thermal and thermo-fluid simulation
- Thermo-mechanical models for nanoscale-level technology, such as experimental tools capable of measuring electrical, thermal and mechanical phenomena/material properties at smaller scales, for which scale-dependent algorithms will be needed that have the ability to shift scales
- Simulations (thermal and mechanical) for optimizing hybrid lamination schemes for electrical and optical needs
- Improved and integrated design tools for emerging technologies like embedded passives, nanotechnology, and opto-electronic PCBs, including low-cost, fine-line substrate and PCB routing technologies enabling denser package I/O and multi-physics simulations (e.g. Joule heating in sub-50-nm interconnects, electro-chemical phenomena in bio-MEMS devices)
- Integrated mechanical, electrical and thermal package/product design
- Integrated design and simulation tools needed for RF modules and devices
- Modelling and simulation of spin as electrons move through different materials; spin relaxation modelling

HYB d.o.o., Šentjernej, Slovenia

The HYB Hybrid Circuits and Sensors Company (which is in the SME category) has had experience in the production of custom thick-film hybrid circuits since 1972 and experience in the production of pressure sensors for medical applications since 1986, and for industrial applications since 1994.

A thick-film hybrid circuit can be described as a small, self-contained electronic circuit (module) made up of a ceramic substrate with applied thick-film technology and a variety of different component types mounted on it using various assembly techniques. The markets for these products are mainly where reliability, space and weight are at a premium. Moreover, in most cases the customer provides these and other special performance requirements. This is known as a custom-designed hybrid circuit. HYB has the technical staff to handle all aspects of the design and manufacturing process.

HYB is a renowned European designer and producer of pressure sensors for medical and industrial applications. The company is able to design, develop and manufacture pressure sensors with silicon or ceramic sensor elements and the required signal conditioning electronic circuitry.

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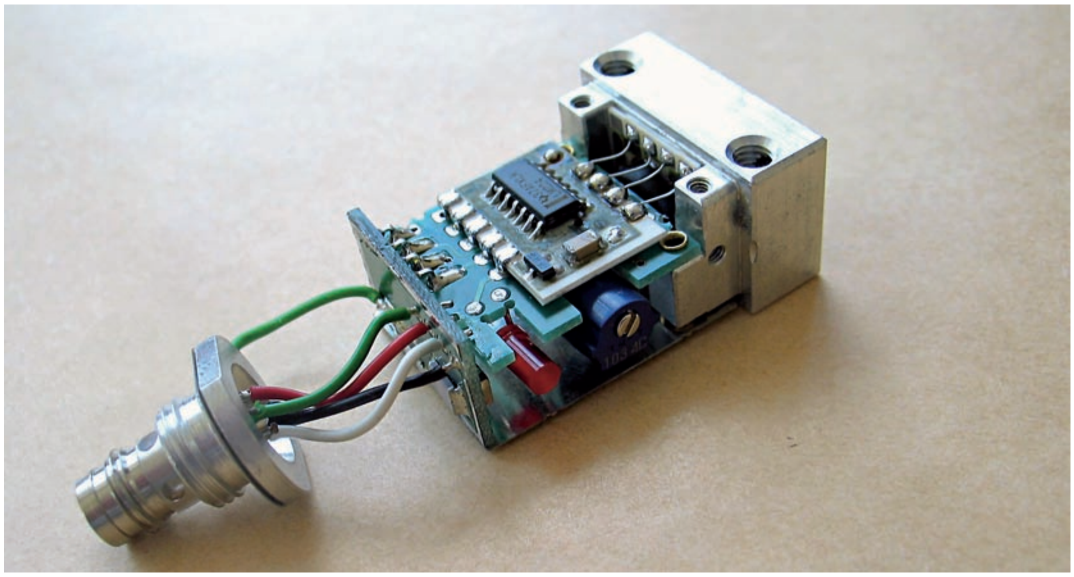
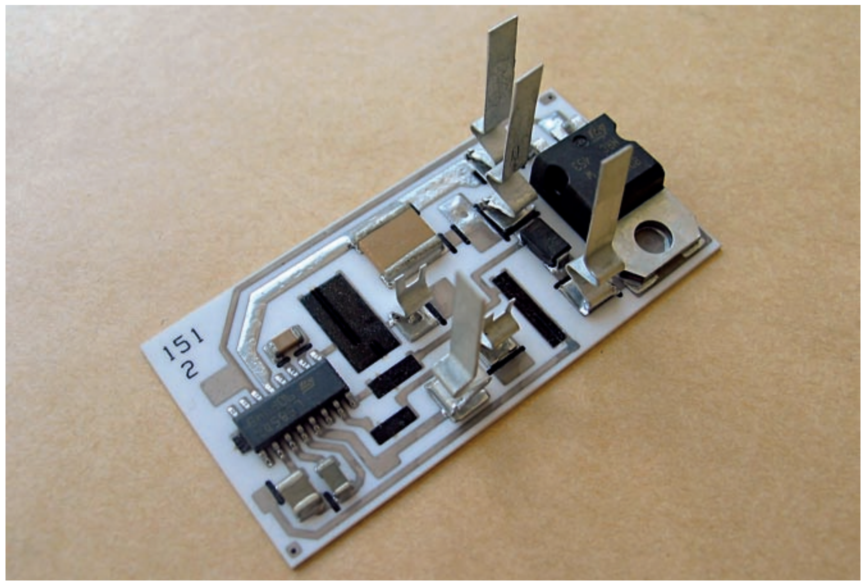
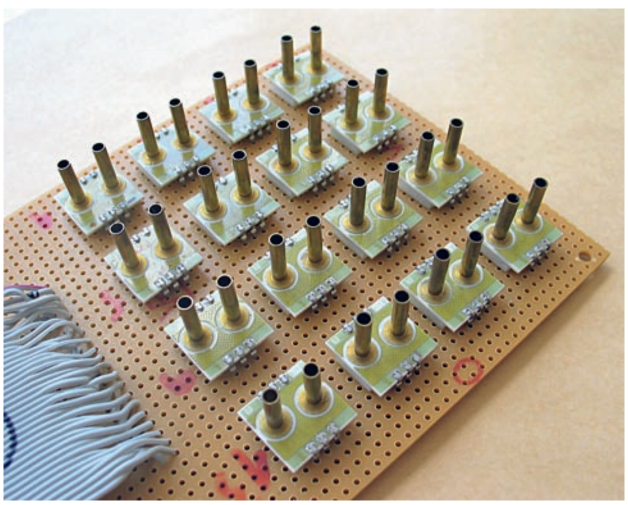
Technology needs in the next ten years

Realization of the potential for embedded sensors will require the development of miniaturized sensor elements, integrated control systems and micro-actuators, which can all be interconnected in a single package with a small form factor.

Packaging technology must evolve towards higher levels of integration using system-in-package solutions, sometimes as an intermediate step towards eventual system-on-chip implementation.
The iNEMI (International Electronics Manufacturing Initiative) recommends [12] more aggressive development and deployment of surface micromachining technologies for sensor components, as well as lithography, electroforming and moulding processes for the high-volume production of integrated sensor/actuator systems. This is a process involving forming structures in a polymer mould photo-lithographically, and then electroplating into these cavities.
Advances in microelectronic fabrication technologies combined with system-on-chip design will lead to the rapid development of the control systems needed for smart embedded sensors [12]. These needs especially affect the automotive industry, which currently utilizes a multi-package module for many sensor applications that require the integration of sensors, microprocessors, signal conditioning, communications, power source and memory functions.







Among the main non-technical barriers to sensor-technology development are the lack of adequate cross-disciplinary collaboration, qualified human resources and the lack of widely established and accepted standardization – especially with respect to communication protocols [12]. Ultimately, these non-technical barriers can be best addressed through closer cooperation between industry and academia in order to cultivate a technical workforce capable of developing and communicating innovative ideas that cross traditional disciplinary boundaries.

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Ceramic materials in MEMS applications

By Marija Kosec

Development trends in the field of electronic components, sensors and packaging technologies are tending towards miniaturisation and integration of various functions. The research community consists more and more of scientists and engineers from different disciplines; particularly obvious is the collaboration of materials scientists with electronic engineers. Materials in this industry continue to have significant influence on meeting the major manufacturing requirements of integration for smaller size, higher reliability, greater functionality, higher bandwidth, environmental friendliness, lower cost through increased modularity, etc. This also holds for electro-mechanical systems (MEMS), but in addition to the electronic performance of materials systems, there are also product-specific materials requirements: mechanical, electro-mechanical, chemical and, in some cases, optical performance. Common MEMS are made by micro-machining silicon, but there is a place for ceramic materials as well. Ceramic materials and technologies in MEMS production can be used on three levels. The first level is the fabrication of sensors and actuators as an integral part of the MEMS. Typical examples are piezoelectric materials for actuators and/or sensors and thick-film resistor materials for sensors. The second level is ceramic-based MEMS, which can be made as a 3D structure using advanced ceramic technologies. These ceramic MEMS are typically larger and are mostly used in harsh environments. The third level is the package for MEMS, which are the most widely used ceramic materials in MEMS manufacturing. Ceramic materials are suitable for packaging because of their mechanical, chemical, electrical and thermo-mechanical properties.

Prof Dr Marija Kosec, Head, Electronic Ceramics Department Jožef Stefan Institute.

Mitja Jerlah by the high precision screen-printer.

Dr Marko Hrovat, coordinator of several research projects.

Dr Marina Santo Zarnik, co-ordinator of several research projects.

To fulfil the demanding requirements of MEMS technology, intensive research on new materials and their applications is required.

The Electronic Ceramics Department at the Jožef Stefan Institute is involved in research, education and development of materials that are closely related to application in electronics, mainly complex multifunctional materials and structures. Materials of interest include ceramic piezoelectrics, ferroelectrics, relaxors, “conductive” oxides and materials for solid oxide fuel cells (SOFCs). The emphasis is on the creation of properties through synthesis and structure on the nano-, micro- and macro- level. The Institute’s research staff have experience with various technologies such as tape casting, spin coating, screen printing, electrophoresis deposition as well as thorough structural and functional characterization.

In the field of MEMS technology the department traditionally works with strategic research partner HIPOT-R&D and industrial partner HYB. The department is also involved in many research projects or other forms of cooperation in Europe and worldwide.