The evolution of MEMS and modelling methodologies

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Abstract

Purpose – The purpose of this paper is to show the evolution of microsystems together with modeling methods in the space of dozen years as a result of finished research in the frame of several projects.

Design/methodology/approach – In this paper several approaches are presented. First, microsystems were built in multi project wafer technology. They were demonstrators like micromotor, micromirrors or micropumps modeled using dedicated design tool. A multi purpose chip was also designed using HDL description and FEM simulations. The next project concerned chemical sensors, where specialized models were developed and implemented in VHDL-AMS in order to perform multidomain behavioral simulations. Dedicated tools were also developed for medical applications.

Findings – The evolution of MEMS technology is strictly connected with simulation and modeling methods. The success and short time to market need fast and accurate simulation methods. This paper shows that the approach depends on application. Moreover, it is connected with the access to the technology.

Originality/value – This paper presents a brief overview on projects performed in DMCS-TUL department. It shows the evolution of modeling methods and technology used in developing and fabrication of microsystems for various applications.

Keywords Modelling, Simulation, Computer software, Actuators, Sensors, MEMS, Micromotor, Water monitoring, ChemFET, Thermal actuator, Pressure sensor

Paper type General review

1. Introduction

The main goal of this paper is a discussion of the methods of modelling methodology and computer aided design (CAD) of microsystems in the space of the last 20 years. The first modelling approach was developed during the ESPRIT-BARMINT project (Esteve *et al.*, 1997; Turowski and Napieralski, 1996), where first microsystems were built in multi project wafer (MPW) micromachining technology. Next approach was the "Application of the high level VHDL-AMS language to computer modelling, design and realization of integrated Microsystems" KBN Polish Grant No 8 T11F 010 12 (1997-1999). Then, specialised models were developed during the SEWING (System for European Water monitorING) project FP of EU SEWING (2001-2004). In order to show the specific problems of microsystem design to the students, the 5th EU Framework Program REASON (Research and Training Action for System on Chip Design) was undertaken 5FP of EU REASON (2002-2005) in collaboration with 22 partners from 18 countries. A special emphasis was put on sharing our experience with the partners from the Central and

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Eastern Europe. Not only the models, but also special "Educhips" and laboratories were prepared. As the follow up of the REASON, the new EduMEMS (Developing Multidomain MEMS Models for Educational Purposes) project 5FP of EU EduMEMS (2011-2015) started in July 2011 and we plan to present models, methodology and fabricated chips to students. The development of microsystems and their fabrication was possible as a result of a close cooperation with the LAAS-CNRS from Toulouse (France) Napieralski (2009) and CFDRC from Huntsville (USA) Napieralski (2009). The modelling technique is always a function of technology and application of sensors. A specific approach KBN Polish Grant 8 T11B 021 19 (2000-2003), will be thoroughly discussed in this paper.

2. The beginning of the microsystems – new projects

The first development in the domain of microsystem design started in 1994 with the first European project concerning Microsystem Integration: ESPRIT-BARMINT (Esteve *et al.*, 1997; Turowski and Napieralski, 1996). The first MPW chip was produced in the frames of Circuit Multi Project (CMP) by Europractice (www.europractice.com – Europractice Services). It was a real turning point in microsystem design because micromachining technology became available to all universities and design laboratories in the world. The main goal of the project was to design and integrate different functions (sensing, actuating, signal processing) using collective fabrication processes on silicon mono-substrates or using silicon multichip modules, so as to arrive at generic, low cost, efficient, complete microsystems. The additional goal was the design and fabrication in CNRS-LAAS clean room some devices produced for demonstration purposes. These included:

- silicon micromotor (Salman *et al.*, 1998);
- silicon micropump (Pacholik *et al.*, 1995); and
- silicon micromirror (Cichalewski *et al.*, 2003).

Furthermore, DMCS elaborated the first MPW microsystem designed and manufactured in micromachine technology.

As the first example, the design and fabrication of very small size rotary variable capacitance micromotors (VCM) will be discussed. The cross-section of the device is shown in Figure 1. It was necessary to create some numerical programs solving the

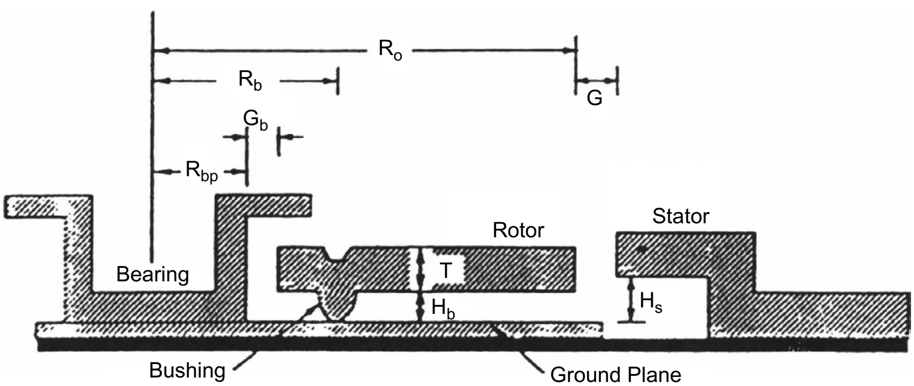


Figure 1. Cross-section of a silicon micromotor

initial problems with weak drive torque of the device and the problem with the movement initiation.

In order to find the optimal design of a VCM, the μTORQUE (Figure 2(a)) and MICROTOR PC based design tools devoted to the design and simulation of static and dynamic behaviour of various structures of integrated VCM were developed. This model takes into account the edge effect of both the rotor and stator poles for actual estimation of the total equivalent circuit capacitance in the rotor plane. The micromotor drive torque and electrically based rotor side pull force, including their angular dependence, are modelled here using the modified analytical parallel-plate capacitance model.

The μTORQUE program helps to investigate the variation of electrostatic drive torque acting on the rotor of an electrostatic VCM, as a function of a rotor position for different values of the geometric parameter, as well as supply voltage, as shown in Figure 2(a).

The optimal geometrical dimensions can be determined by means of successive sampling of the dimensional space describing the main geometrical design parameters in the stator-rotor plane. Figure 2(b) shows the simulated drive torque for the 12/8 pole configuration, as a function of the rotor position, for different rotor pole widths using MPPM, as displayed by the μTORQUE PC-design tool.

The last circuit designed in the frames of the BARMINT project was a chip containing infrared radiation sensors (IRS), an electro-thermal converter (ETC), gas flow sensors (GFS), which can act also as the ETC device, acceleration sensor (AS) and point light sources (PIX) (Janicki *et al.*, 2004b). Silicon wafers that have been manufactured through the standard CMOS MPW process steps are processed further to release the microstructure areas formed from the thin films available in this process. The microsensor structure, which is typically formed by the polysilicon layer on the silicon dioxide, is released by etching the underlying silicon area (Figure 3).

The ETC device (Figure 4) consists of 13 serially connected aluminium-polysilicon thermocouples and a polysilicon heating resistor at the end of a cantilever. The device is thermally isolated from the bulk. The heat flow depends strongly on the proper and exact releasing of the microstructure after the etching post processing step. For the design of such a device, the behavioural simulation is required and it takes into account the following phenomena:

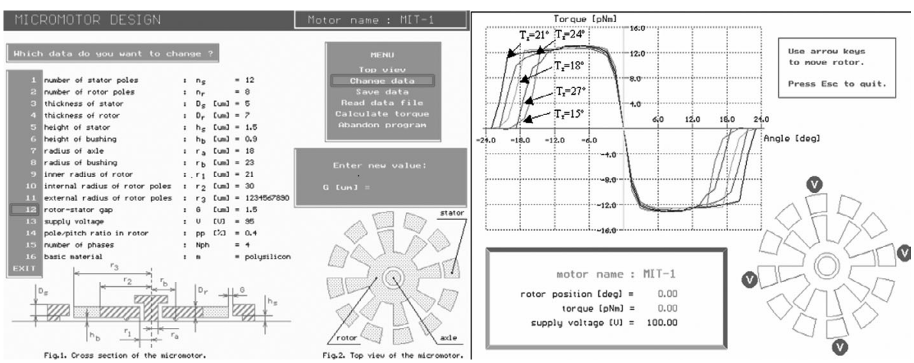


Figure 2.
(a) The μTORQUE program enables changing of the micromotor parameters, as well as the power supply voltage; (b) simulated drive-torque of a 12/8 micromotor as a function of rotor position for different rotor pole widths

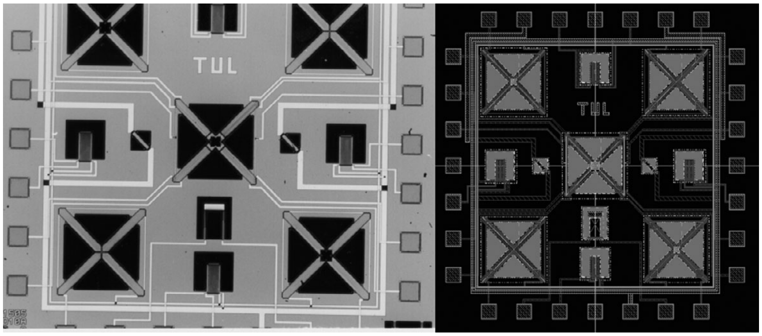
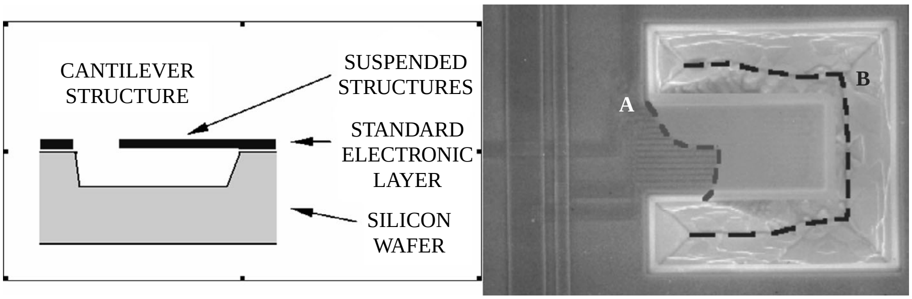


Figure 3. Microscopic view of a micromachined chip and its layout in Cadence



(a) **(b)**

Figure 4. (a) Simplified model of an ETC; (b) simplified cross-section of the suspended structure of an ETC

- heat generation in the heating resistor;
- heat transfer through the suspended structure causing the temperature difference;
- Seebeck phenomenon – thermopile voltage generation (without load);
- thermal changes of the heater and thermopile resistance; and
- heat flow to the ambient.

The analogue extension of the hardware description language (HDL-A) model includes the differential equation of the heat transfer in the suspended structure. The structure of the device enables the use of a one-dimensional equation. The structure was divided into ten elements and each of them was described by the difference equation, using the finite difference method (FDM). Additionally, the following second order effects were included in the developed model:

- thermal changes of the heater resistance;
- thermopile resistance and its thermal changes; and
- heat flow to the ambient.

The HDL-A model describes the behaviour of the ETC device. It includes also the differential equations of the heat transfer in the suspended structure.

3. Microsystems for European water monitoring

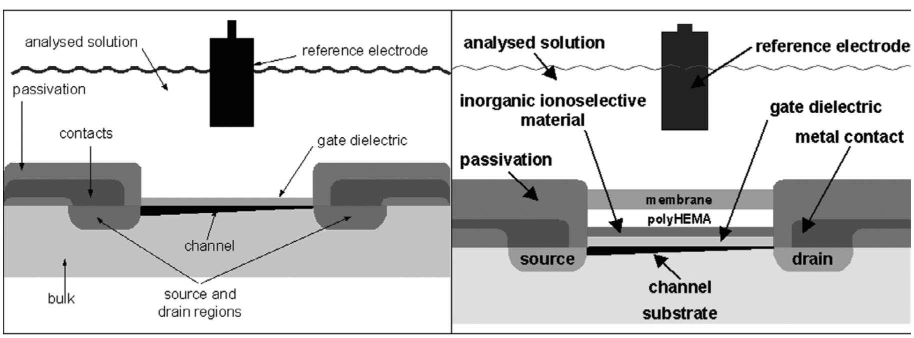
Research in the field of water pollution monitoring was performed under SEWING (System for European Water monitorING) project of 5FP of EU SEWING (2001-2004). The system consists of chemical sensors that measure pollution ions in water, electronic processing part that process data from sensors and transmission circuit that send data to an external computer. A few European institutions elaborated this complicated system. The Polish scientists were involved mainly in the development of chemical sensors.

The main part of the chemical part is an ISFET, which stands for Ion-Sensitive Field Effect Transistor. This device is a classical MOS, which is modified to react to hydrogen ion concentration in a measured solution. The modification relies on the removal of a standard metal-polysilicon-dielectric gate, which is replaced by a more complex structure sensitive to hydrogen ion concentration (Figure 5(a)). When the transistor gate is coated with an ion selective membrane, the ISFET can be used for the detection of various species in the surrounding electrolyte, other than the hydrogen ions. Such a device is known as the CHEmically Modified Field Effect Transistor (CHEMFET). The cross-section of it is shown in Figure 5(b). As it can be seen, the ISFET and CHEMFET differ over the channel area only. Frequently, the PolyHEMA layer is used between membrane and the dielectric layer, main function of which is stabilisation of the sensor operation.

ISFET model was implemented in the VHDL-AMS, which allows multidomain behavioural simulations of complex microsystems. The multidomain behavioural simulators have many advantages. First of all, both the analogue and the digital components of a system can be simulated in a single environment. Moreover, if required, some thermal, mechanical or chemical sensors might be incorporated in the simulations as well. More detailed presentation of the simulations together with the analysis of different realisations can be found in Janicki *et al.* (2004a, b), Daniel *et al.* (2004).

4. Educational projects

Project, which was conducted in parallel with SEWING, was the REASON (Research and Training Action for System on Chip Design) project also of 5FP of EU REASON (2002-2005). One of very interesting goals was the fabrication of the educational integrated circuits. They were made available together with the necessary lab hardware and manuals as commercial products.



(a) (b)

Figure 5.
(a) ISFET cross-section;
(b) CHEMFET cross-section

On the basis of the results obtained in REASON project, and after the realization of many projects related to MEMS, a similar action as for the VLSI started in MEMS design. The new EduMEMS (Developing Multidomain MEMS Models for Educational Purposes) project 5FP of EU EduMEMS (2011-2015) has started. Its main goal is the creation of a very advanced research team that can develop the most advanced models of each MEMS component in the shortest time. This interdisciplinary approach is now necessary to obtain adequate model of each component used in a MEMS system. As a demonstrator, three devices will be chosen, on which the new approach will be tested. At the beginning, the proper model of each device in a single domain will be obtained. In this way, it will be possible to develop, for example, a mechanical model, an electrical model, a thermal model, and so on. After that, the influence of one model on a second one will be taken into account. This leads to a development of multidomain models of each device. These models will be used during the design of the final chip, which can be manufactured in one of the micromachining technologies. The demonstrator will give an indication whether the model of each device is adequate for real sensor functions.

5. Cooperation with the CFDRC (USA)

The cooperation with the CFDRC started in 1997 and concerned mostly 3D simulation of many devices.

Design process for microsystems is very similar to the design process for integrated circuits – it ends with generation of the set of technology masks. However, there are differences in the design flow, which concern:

- simulation (multi-domain simulations);
- layout edition (special design rules); and
- extraction (special rules for additional devices extraction).

In the case of Microsystems, the visualization step is very important. A new 3D visualization tool for Multi-User MEMS Process (MUMPS) technology was developed by DMCS (Studzinski *et al.*, 2001), which offers an opportunity of data format conversion from the standard layout input description formats (CIF, RDIF) to the format accepted by the 3D simulation programs. In Figure 6, the top view of vibration sensor in 2D Virtuoso Layout Editor in CAD software is presented. Visualization can be used as a preliminary verification of the basic assumption of the design which may not be visible well enough in a simple 2D layout editor. Such a verification can be treated as additional test and performed together with typical testing procedures such as DRC, ERC and LVS.

6. Cooperation with LAAS-CNRS (FRANCE)

During 30 years of cooperation with the LAAS-CNRS many scientific projects have been performed. The main benefit of this cooperation is an access to the technology in place. LAAS laboratory offers a clean room with high-class equipment for micro and nanosystems prototyping.

Close cooperation was established during BARMINT and SEWING projects described earlier. Next, the work focused on a multi-dimensional model of an overheated actuator.

Although this device is relatively simple (Figure 7), it involves many coupled phenomena of different nature like electrical, thermal and mechanical. Thus, the actuator

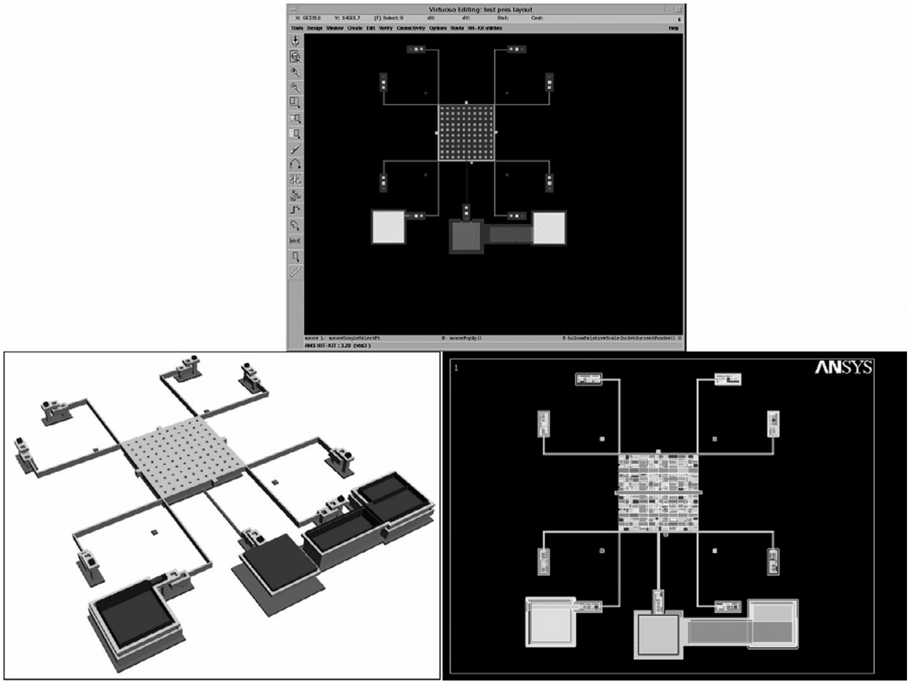


Figure 6.
Top view of vibration sensor in 2D Virtuoso Layout Editor in Cadence (top), visualization of the sensor in MUMPS3D (bottom-left), interface of ANSYS multidomain simulator after importing layout from MUMPS3D (bottom-right)

is an excellent example of an application of the multidomain simulation methodology. The mathematical description of the finite elements method (FEM) approach employed in the device and the gradual simplification of the description has been presented in Zubert *et al.* (2004). Furthermore, the real structures where fabricated in AIME laboratory (Atelier Interuniversitaire de Micro-électronique, Toulouse, France) and are still used in teaching activities for students.

LAAS laboratory specialized also in a variety of micromachined sensors. For many years they have performed research on membrane-based sensors. During the period of cooperation between LAAS and DMCS many students trained on those devices while writing their master theses. The main topics concerned piezoresistive pressure sensors

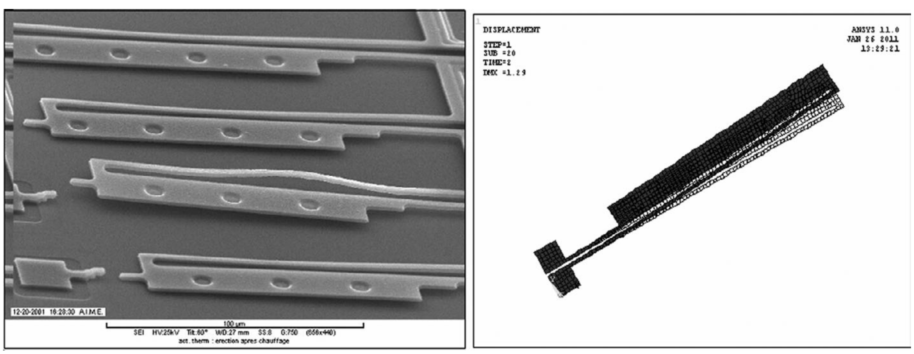


Figure 7.
Example of devices manufactured in the AIME laboratory and its model in FEM simulator

and membrane characterisation. The knowledge in this field is also used in commercialization of developed solution in many areas of science. One of the last works done in the LAAS laboratory within the framework of the CAPTAM project (CApteur de Pression Télémétrique Auto-etalonnable Miniature pour la mesure de fonctions physiologiques sur l'homme) concerned a medical application. The aim of this project was to develop a highly miniaturized pressure sensor usable for measurement of arterial and intracranial pressure in humans, which integrates the temperature pressure and has a feature of auto calibration (Figure 8).

The main part of the project was the development of the sensitive cell (Olszacki, 2009; Maj, 2009). The pressure sensor uses a thin membrane placed above the cavity with reference pressure formed by bonding of two wafers. A pressure difference between the external and the reference wafers causes the membrane deflection. This mechanical response (more precisely the stress induced within the membrane) is converted into the electrical signal by four implanted piezoresistors placed on the membrane (the exact position depends on the membrane shape) connected into the Wheatstone bridge. Although the principle of operation is widely known, the development was not a simple task due to specific requirements of the sensor. First, the dimensions of the cell were limited by desired sensibility. Second, the integrated electrostatic actuator introduced additional criterion into the optimization of the cell. The actuator was obtained by taking the silicon membrane and silicon substrate as electrodes. Such electrode placement enables the application of a known electrostatic pressure to the membrane (voltage between the electrodes) and to verify its mechanical response. Additionally, the device has an integrated temperature sensor to allow correct measurement in a human body. The photograph of the sensor cross-section and sensitive cell is shown in Figure 9(a) and (b), respectively.

Figure 8.
Typical implantable intracranial pressure sensor

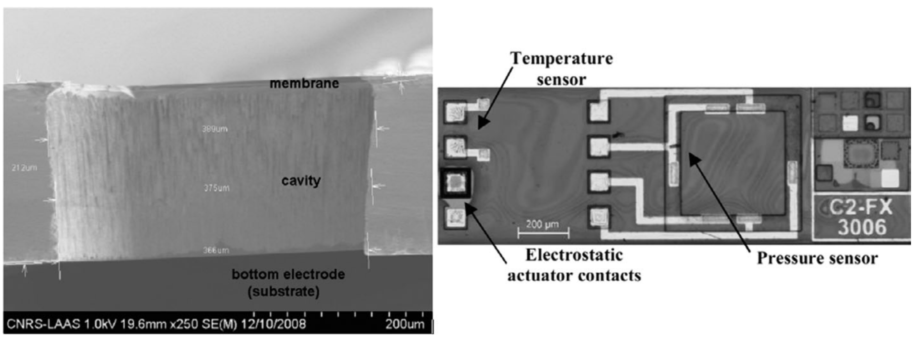
Due to the specific application, the device had to be packaged in a specific way to allow simple implantation of the sensor into the human head. Additionally, the components used in packaging had to be biocompatible (Figure 10(a)). As a novel solution, the sensor has a wireless communication with the receiver to allow the patient to move freely and make easier other medical inspections and data acquisition and storage. It was obtained by using a dedicated catheter with a mounting cover for wireless transceiver (Figure 10(b)).

The works in this project focused also on modelling methods. Because of the pressure sensor and the electrostatic actuator use the same mechanical element (membrane), the use of numerical models in prototyping phase was necessary. The main task was to find an optimal sensor and actuator sensitivity. In fact these two parameters depend inversely on the membrane dimensions. Therefore, the specific tools were developed to facilitate the optimization phase of the sensor design (Olszacki *et al.*, 2008; Maj *et al.*, 2011).

7. Conclusions

This paper presented a brief review of the developments carried out in the DMCS showing the path from microelectronics to nanotechnology with application to microsystems. It has been shown in the paper that:

- MEMS design requires the use of 3D and multi-domain simulators. For the fast design (at the system level) reduced models have to be used.



(a) (b)

Figure 9.
(a) Photograph of the sensor cross-section; (b) photograph of the sensitive cell

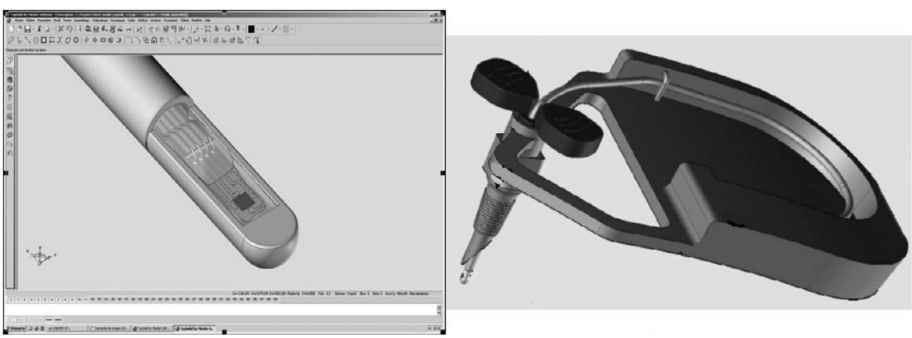


Figure 10.
(a) Concept of the pressure sensor with packaging; (b) the model of the complete pressure sensor with dedicated catheter

- MPW through the EUROPRACTICE and CMP gives an access to the newest VLSI and MEMS technology, but some World top processes (Sandia National Labs.) are still not available.

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Michal Szermer received the MSc and PhD degrees from Technical University of Lodz (Poland) in 1998 and 2004, respectively. His research focuses on the integrated circuits design with special consideration of mixed-signal circuits. He took part in many projects connected with ASICs design. Recently, he became scientific coordinator of the EduMEMS project in the frame of 7th FP of EU focused on development of new MEMS structures for educational purposes.

Cezary Maj received the MSc degree in Electronics from Technical University of Lodz in 2005 and a PhD degree in Microelectronics from both the Technical University of Lodz (Poland) and Institut National des Sciences Appliquées de Toulouse (France). He specializes in microelectronics and his research focuses on modelling, fabrication and characterization of microsystems. He has taken part in a few projects connected with development of sensors for various applications.