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Project MECA: Training Course in Microsystems with Piezoresistive Feedback

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***Abstract* — Training course on practical aspects in design, technology and prototype fabrication of microsystems with piezoresistive feedback, exploiting the shared infrastructure is presented. The course content is considered in the scope of building a sustainable Knowledge Alliance between the partners in Erasmus+ Project# 562206-EPP-1-2015-1-BG-EPPKA2-KA - MECA**

***Keywords* — microsystems, self-sensing flexures, piezoresistors, transducer, full bridge.**

I. INTRODUCTION: PROJECT MECA

Project MECA [1] is aiming creation of cloud-based European infrastructure in organization of education in micro-/ nano-electronics. For the purpose, partners in the project share and jointly exploit various resources, incl. remote access to dedicated design and simulation software. More particularly, one main focus of the project are need analyses in shared ICT infrastructure, up-to-date learning materials and providing all necessary means for highly effective education.

Specific approach of all educational courses is based on challenges due to the multi-disciplinary nature of the learning material in micro-/nano-electronics and the need powerful CAD systems, servers, specific equipment and labs to be involved into education. Since, none of the partners can't afford and maintain solely complete set of educational infrastructure and means, thus access to the shared resources is a key motivation factor to participate the project.

Through the partnership between HEI and SME ideas, methodologies and experience are freely shared, aiming permanent up-date of the educational programs to keep them adequate to the quickly changing and emerging new technologies.

Eight (?) HEIs and eight (?) SMEs, having expertise in microelectronics and ICT, are project partners. Almost 30% of the courses (e.g., five of seventeen in total) are related to the education in microsystems [2].

This paper refers the content of the educational course titled: "Design, Prototyping and Advanced Applications of Silicon Microsystems with Piezoresistive Feedback", shortly „Piezoresistive Microsystems".

II. GENERAL DESCRIPTION OF THE COURSE "PIEZORESISTIVE MICROSYSTEMS"

The course comprises five parts: Introduction, Technologies for Prototyping of Piezoresistive Microsystems, Design of Microsystems with Embedded Flexures, Advanced Applications of Self-sensing Microsystems and Evaluation of the learners. Various, practically oriented issues of the development and implementation of functionally different microsystems are in depth considered. Knowledge and capacity of the learners in the area of microsystems are evaluated at the end of the course.

Fig.1. Logos of the partners in the Erasmus+ Project# 562206-EPP-1-2015-1-BG-EPPKA2-KA - MECA

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III. REVIEW OF THE APPLICABLE MICROTECHNOLOGIES

In the first part of the course, a general overview of the technologies, particularly the state of the art in electronics and microelectronics, is given. The driving forces of the progress started since invention of the first vacuum lamps until advanced 10nm node devices are highlighted in various aspects – technical, economical, quality of life, etc..

Working definitions of main categories, exploited in the course are formulated in the beginning. Also, answering the questions, like: “Why silicon is the material of microelectronics for more than sixty years?” and ”Why piezoresistive microsystems have so high potential to become very important sub-system in the future commercial products?”, multiple aspects of the extremely dynamic development of the technologies fabrication of microsystems are addressed. Various advantages and drawbacks of the piezoresistive microsystems are analyzed as well the options for future development of novel detecting and measuring devices are given. Specifically, the correlation between symmetry of the properties of the raw silicon material and anisotropy of the properties is explained and highlighted.

In the second chapter of the Introduction, principles of operation of different silicon microsystems, based on detection bending of flexures with self-sensing piezoresistor are explained and demonstrated. Examples of such microsystems are shown in fig. 1.

At the end of this part, the method for control and evaluation of the learning outcomes is explained. The specific contribution in the overall score is highlighted and recommendations about maximizing the impact of the course on practical implementation of microsystems are formulated.

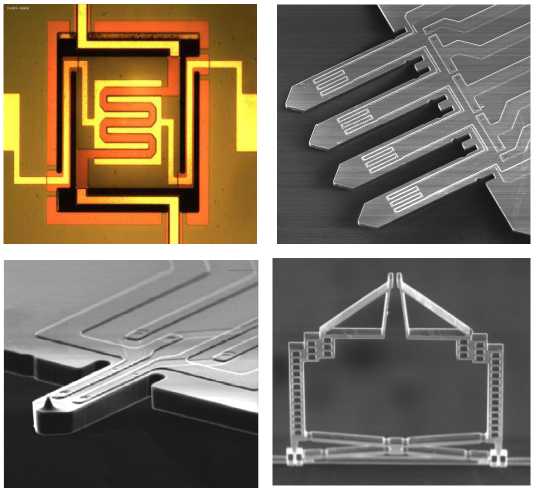

Fig. 2. Examples of microsystems, described in course titled “Piezoresistive Microsystems”

IV. TECHNOLOGIES FOR PROTOTYPING OF PIEZORESISTIVE MICROSYSTEMS

Second part of the course comprises following important topics, related to implementation of silicon microsystems:

- Review of the main properties of silicon and the reasons for being main material in electronics for more than sixty years are presented and explained. Various supplementary and process specific materials, needed for fabrication of silicon microsystems, like: photoresists, developers, wet etching mixtures, solid and d gaseous materials, as well as various quartz ware and processing cassettes, etc., are demonstrated;

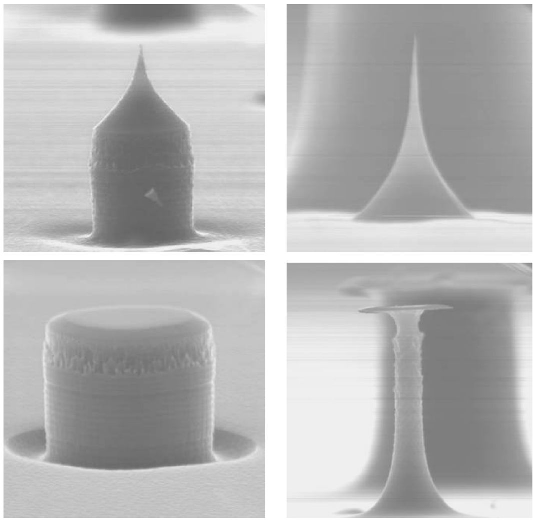

Fig. 3. Examples of 3D structures, obtained with one and the same circular mask for photolithography and surface micromachining with varying anisotropy and selectivity

- Review of the components of the eco-system for manufacturing of microsystems, providing the required working conditions and related infrastructure, like: definitions, meaning and impact of the clean room parameters, ultrapure deionized water (DIW) supply and other fluids, are presented. Special attention is paid on risk and safety issues and brief comments on real cases are given;

- Processes for thin film growth/deposition and patterning, which are applicable in micro technologies are reviewed in the next chapter of this part. Special attention is paid on processes, which are specific for microsystems: alignment in double side lithography and surface/bulk micromachining. The correlation between availability of certain processes and overall process chain implementation is analyzed on several examples.

- Process integration in the perspective of the required fabrication technology, taking into account characteristics, like: process/materials compatibility, selectivity, anisotropy, etc. is explained. As an example, options for implementation of 3D structures with one and same mask are illustrated in fig. 3. All examples in the course are real process-flows developed in prototyping facility, where practical issues can be demonstrated and trained. Incl., prototypes, newly developed in the course, can be also implemented.

- Economical aspects of the chosen technologies, such as: running costs vs. impact of the of the clean room class on microsystems quality, selection between wet/dry etching, single wafer/ batch processing, etc., are considered in the next chapter. Specifics of prototyping and mass fabrication process flows are considered and discussed.

- Integrated process flow - Example 1: Process integration for fabrication of integrated self-sensing cantilevers with planar piezoresistors for chemical detection and atomic force microscopy (AFM). Examples of devices prototyped with these technologies are illustrated in fig. 4.

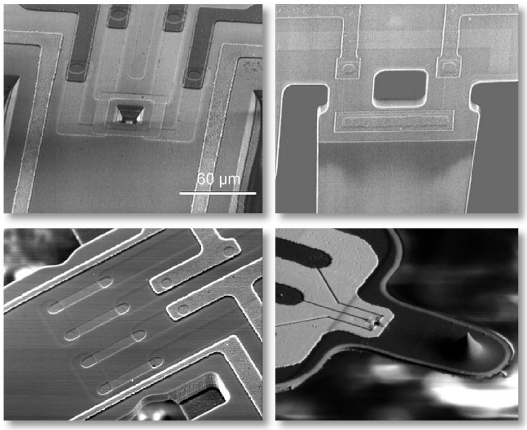

Fig. 4. SEM micrographs of cantilevers with strain sensing elements: planar piezoresistors and nanogranular tunneling resistors(bottom-right)

Besides to the planar piezorestors, this part of the course is related to the constrains of implementation the technologies: complex and multi-step processing with high thermal budget, long processing time, issues related to compatibility and selectivity of materials and the patterning methods. Constrains in implementation of low stiffness self-sensing cantilevers are presented, as well as the options for exploitation of alternative sensing elements like nanogranular tunneling resistors and discontinuous layer patterns are also considered.

- Integrated process flow - Example 2: Process integration for fabrication of microsystems with piezoresistors embedded into the sidewalls of the micro flexures is step-by-step demonstrated. By means of multiple examples the specific behavior of the elements during processing are explained. One example of specific problem related to the photoresist coating of high aspect ratio patterns is illustrated in fig. 5. The impact of non-uniform photoresist coatings on various patterning processes is illustrated and explained in details. Criteria for choosing the process sequence and corresponding economical aspects as key elements in successful technology implementation, are also considered.

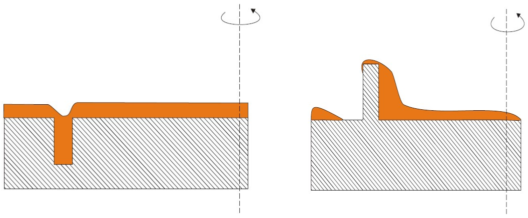

Fig. 5. Schematic representation of the problems in photoresist spin coating of high aspect ratio patterns, usually exploitable in fabrication of microsystems

V. DESIGN OF PIEZORESISTIVE SELF-SENSING MICROSYSTEMS

Following main topics are addressed in the third part of the course:

- Test procedures in microsystems' development. Examples of dedicated test structures used for in-/off-line control of parameters are shown in fig. 6. Parameters calculation and data interpretation, as well as functional measurement, are presented in this chapter.

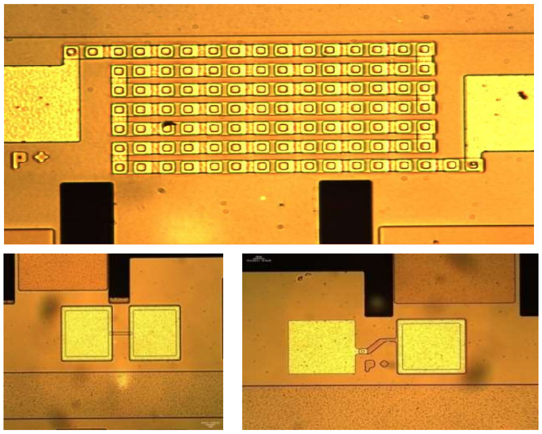

Fig. 6. Optical micrograph of dedicated test structures, used for in-line control of doping processes. Test structures are available in all dies on wafer level

- Design of microcantilevers with planar piezo-resistors: examples. Common design of microcantilever device with piezoresistive feedback is shown in fig. 7 (left). The breakdown in masks for photolithography patterning is illustrated in the right part of the figure. Correlation of the latest with the selected process-flow is set in center of this presentation. The specific design rules are explained in details, as well examples and exercises are used for better understanding of this critically important issue.

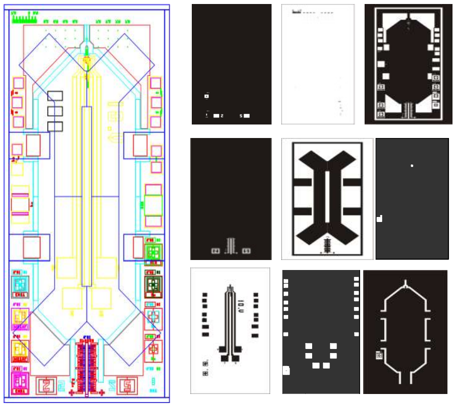

Fig. 7. Left: Design of self-sensing AFM cantilever and Right: Breackdown in masks for photolithography patterning

- Design of microsystems with flexures and sidewall piezoresistors is the subject of the next dedicated lecture.

Layout of one representative embodiment of such a device is displayed in fig, 8 – microgripper with an integrated monomorph actuator and feedback sensors for opening the arms.

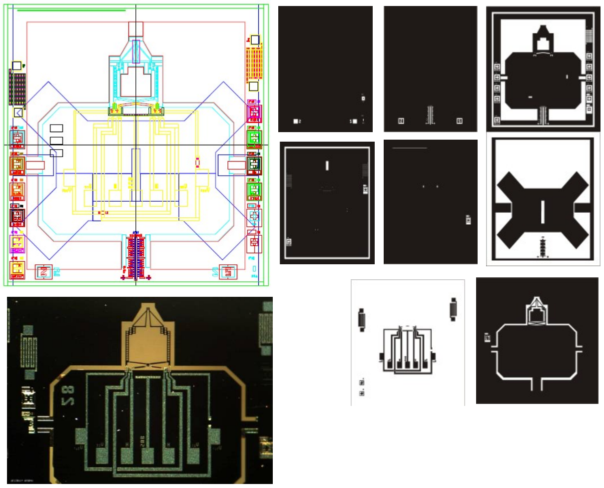

Fig. 8. (left): Design of self-sensing microgripper with sidewall piezoresistors AFM cantilever and (right): Breackdown in masks for photolithography patterning

Number of examples demonstrating the synergy between material properties, micromachining processes and application specific design of the microsystems, are presented. Due to the key importance of the flexures in the microsystems, various primitive elements are disclosed. Particularly, detail explanations of the specific advantages of the devices with sidewall piezoresistors are given. The impact of the voltage dividers as shown in fig. 9, on overall performance of the microsystems is highlighted. Also, the main advantages, like: very high sensitivity, uniformity of parameters in a voltage divider, differential rejection of the temperature dependence, etc. are explained. At the end of the lecture, a review of the available devices is given, highlighting the vast range functionalities that can be implemented simultaneously on a single substrate.

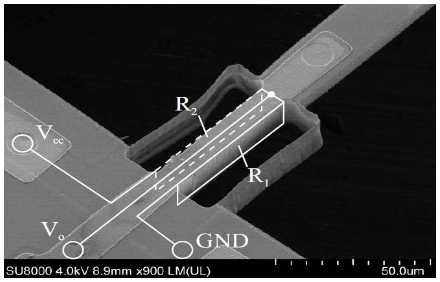

Fig. 9. SEM micrograph of the fixed base of a flexure with a pair of sidewall piezoresistors R_1 and R_2, connected in a voltage divider

VI. ADVANCED APPLICATIONS OF MICROSYSTEMS WITH PIEZORESISTIVE FEEDBACK

In this part of the course, following topics are presented:

- Advanced applications of microcantilevers with planar piezoresistors. Cantilevers with various layouts and additionally integrated elements, like bimorph actuators and conductive tips are demonstrated. Special attention is paid on exploitation of various full bridge configurations and, more particularly, on thermal behavior of the piezoresistors and sources of the drift are analyzed.

- Application of self-sensing cantilevers in atomic force microscopy (AFM). Historically, AFM cantilevers are between the earliest exploitable microsystems with embedded flexures. Principle of operation of AFM is explained and correlation between cantilevers parameters and the overall performance of the microscope is presented. Special attention is paid on comparison between self-sensing and optical detection of the cantilevers' bending, as well as the very different current applicability of both methods is illustrated and explained. Based on the possible scanning configurations: the sample and/or the cantilever sensor, the impact of self-sensing cantilevers on the emerging methods for combined microscopy is highlighted in details.

- Application of piezoresistive microsystems in chemical sensing. Examples of microsystems comprising planar or sidewall piezoresistors are presented. Different methods for dynamic and static sensing in gases and liquids are described and compared. In particular, the options for optimization of the sensors in the mentioned different applications are disclosed. Also, correlation between processing parameters, cantilevers' layout and overall performance of microsystems in gas sensing/recognition is demonstrated.
- Position sensors with sidewall piezoresistors: 1D and 2D cases. The concept for contact position measurement is illustrated in fig. 10. Single and permanent contact point is provided and up to six degrees of freedom of an object can be simultaneously detected. Advantages and drawbacks of this method are also presented and discussed.

Embodiment of position sensors having the above mentioned features requires sensors to comprise at least two separate rigid parts, movable relatively each other. The parts have to be monolithically connected with flexures, thus the movement is transduced with no loose move, shifting or buckling. Examples of various flat mechanisms that comply with the requirements, additionally providing travel range between 50μm and 2mm [3], are given and explained.

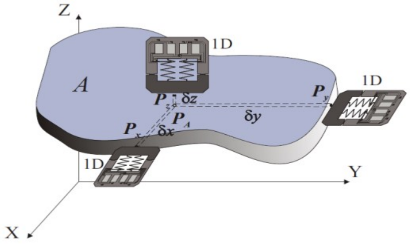

Fig. 10. Schematic representation of the exploitation of microsystems with sidewall flexures for position measurement: the number of independent sensors is equal to the DoFs if accurate monitoring is aimed

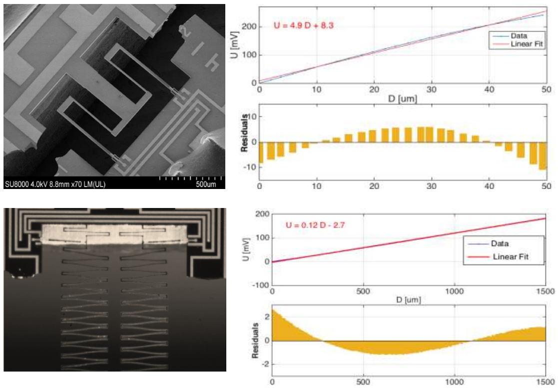

Fig. 11. Micrographs of of flexures with sidewall piezoresistors that provide a travel range of: (above) – up to 200µm and (bottom) – 1.5mm

The correlation between accuracy and resolution is discussed along with consideration of accurate measurement of vector values like displacement and forces. Respectively, examples of 1D sensor are demonstrated in fig. 11 and 2D position sensors are shown in fig. 12.

- Examples of exploitation of 1D and 2D contact position sensors. The aim of this lecture is to demonstrate advantages of exploitation of position sensors in AFM scan stages over the currently used alternatives. Specifically, the absence of creep and hysteresis in piezoresistive sensors is highlighted and in addition, the benefits due to the small spring constant sensors are discussed. Various results are demonstrated and comments are given.

- Force measurements with microsystems comprising embedded flexures with sidewall piezoresistors. Specific approaches to measure different in amplitude and nature forces are presented; as well the limits of direct applicability of the silicon microsensors are shown. Further, different mechanical transducers are introduced and examples are explained, showing vast area of applicability. Examples are used to illustrate the advantages in exploiting the position sensors instead of the standard strain gauges.

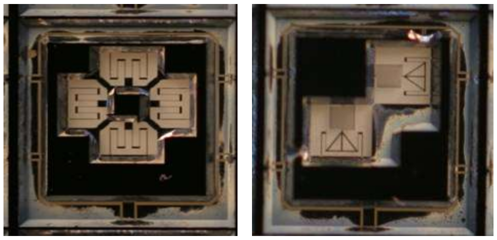

Fig. 12. Micrographs of two different microsystems for 2D position monitoring: (left) – travel range of 50µm and (right) – travel range of 600µm

Options for objects' traceability for various monitoring applications in M2M and IoT, are disclosed. Respectively, novel methods for exploitation of sensors posessing dynamic range of >100 000 scale intervals, based on accurate weighing and position monitoring, are considered.

The impact of specific parameters, like: very high uniformity of the force gauges and techniques to achieve it, linearity, precision, drift, etc on operation of such systems is explained. Main algorithms and formulas for calculation the weight and position of the objects are also presented and commented in details.

VII. EVALUATION OF THE LEARNING OUTCOMES

At the end of the course, the learners will be divided in groups, each group developing an application specific microsystem. In accordance with the specification, every learner solely proposes a conceptual design of the microsystem and prototyping technology. Incl. every learner will exploit CAD and computer simulations means available at his affiliation (това е споделената инфраструктура). After that, in a on-line discussion into the group, joint overall design of the microsystem, excl. flexure layouts, are created. Latest comprises all additional elements, like: shape and size of the die, die multiplication on the wafer, alignment marks, test patterns and test devices, lettering, verniers, etc. After that, every learner designs at least two masks for photolithography: one mask for embodiment of "its own" flexure in accordance with specific optimization results and one mask for patterning of other layers. Thus, the correlation between individual patterns and overall device performance is presented individually during examination. Learners are encouraged to communicate and exploit all available resources, incl. specific CAD and simulation tools in preparation the test device, demonstrating the similarities and differences of the different tools. Also, by encouraging the learners to create different layouts on one wafer, they are convinced in advantages of the fabrication technology for microsystems with sidewall piezoresistors.

Final evaluation and scoring will be performed by professional teachers from Technical University-Sofia, which is also the coordinator of MECA project.

VIII. COMMENTS AND CONCLUSIONS

Educational course in piezoresistive microsystem was created in the frame of project MECA. The course is based on practical experience in development of various microsystems and multiple aspects are concerned. The course is suitable for education of wide range of learners, focused on issued derived from practical implementation of microsystems. It is aimed to bridge the gap between microsystems developers and system integrators, providing them with novel enabling technologies.

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REFERENCES

[1] Tzanova, S., D. Demarchi, Knowledge Alliance in Microelectronics, 9th annual ICERI, 14-16 November, 2016, Seville, Spain

[2] Illyefalvi-Vitez, Z., O. Krammer, S. Tzanova, MicroElectronics Cloud Alliance(MECA)-Presentation of a New Erasmus+ Project, ISSE2016, Pilsen, Czech Republic

[3] V. Stavrov, G. Stavreva, A. Shulev, “Contact position microsensors with travel ranges between 50µm and 2mm”, Proc. of 30th Eurosensors Conference, EUROSENSORS2016, Budapest, September, 2016 (8153)