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Teaching MEMS at Undergraduate Level

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ABSTRACT

This paper presents author's experience in teaching a course on "Design and manufacture of microsystems" to undergraduate mechanical and electrical engineering students in the past ten years. Courses in MEMS are usually offered at graduate level and by electrical engineering departments in American universities. However, more mechanical engineering majors have enrolled in this course in responding to the need of industry for engineers who have knowledge and experience in the design of device structures at micrometer levels. Course topics included the scaling laws, working principles of microsensors and actuators, silicon-based and polymeric materials for MEMS, physical-chemical processes for microfabrication, MEMS systems design, and assembly-packaging-testing techniques. Introduction of nanoscale engineering is also included in the end of the course.

1. Introduction

The technological advances of microsystems engineering in the past 20 years have been truly impressive in both paces of development and new applications. Microsystems engineering involves the design, manufacture, and assembly, packaging and testing (APT) of microelectromechanical systems (MEMS), and the peripherals. The broad applications of microsystems in aerospace, automotive, biotechnology, consumer products, defense, environmental protection and public safety, healthcare, pharmaceutical and telecommunications industries have resulted in staggering billions of dollars in annual revenue for the microsystems and related industries.

The strong demand for MEMS and microsystems products by a rapidly growing market has generated strong interest, as well as need for engineering educators to offer courses on this subject in their respective institutions [1-5]. There has been significant number of engineering schools in the country have MEMS and Microsystems technologies in their curricula at undergraduate level. This paper will offer author's experience in teaching MEMS technology to his undergraduate mechanical and electrical engineering students. It appears that these students are more amenable to this inherent multidisciplinary technology then other engineering disciplines. The author is also of the opinion that MEMS which was once viewed to be too advanced for undergraduate classes is also suitable for students in the undergraduate level if it is taught properly with adequate textbooks.

2. A MEMS Course for Undergraduate ME and EE Majors

The author began teaching a MEMS course to senior year ME and EE majors for the first time in 2000. This course has been offered since as an elective course for Senior year mechanical and electrical engineering students. It is offered in the Fall semester every year with three-hour/week for 15 weeks. The average enrollment for the classes is 25 students.

Pre-requisites for the MEMS course:

Students enrolled in this class are expected to satisfy prerequisite courses of: Introduction to Materials (a required course for all engineering majors), Fundamental to Mechantronics Engineering (a co-listed courses for both ME and EE majors) and Mechanical Engineering Design for ME majors. Students from EE majors would have satisfied the first two of the three prerequisite courses. They are expected to learn the MEMS structure design on their own with personal mentoring by the author.

Course contents:

The course covers the overview of design, manufacture and packaging of microdevices, and the emerging nanotechnology. Major subjects covered in the course include: engineering physics and mechanics, scaling laws for miniaturization, microfabrication techniques, material selection, microsystems design, microsystems packaging design and introduction of nanotechnology and engineering.

Course goals:

1. To learn about electromechanical design and packaging of microdevices and systems.
2. To learn of the basic design principles for MEMS and Microsystems.
3. To learn the basic principles of microfabrication techniques for microdevices and microsystems, as well as integrated circuits.
4. To learn the basic principles involved in microsystems packaging and testing.
5. To learn the basic principle of nanotechnology, and nanoscale engineering analysis.

Student learning objectives:

1. To be able to explain what MEMS and microsystems are.
2. To explain the working principles of many MEMS and microsystems in the marketplace.
3. To understand the relevant engineering science topics relating to MEMS and microsystems.
4. To be able to distinguish the design, manufacture and packaging techniques applicable to microsystems from those for integrated circuits.
5. To become familiar with the materials, in particular, silicon and its compounds for MEMS.
6. To be able to explain the basic and relevant design principles of MEMS and microsystems.
7. To learn the scaling laws for miniaturization.
8. To be able to identify the optimal microfabrication and packaging techniques for microdevices and systems.
9. To be able to handle mechanical systems engineering design of microscale devices.
10. To learn the fundamentals of nanotechnology.

Grading scheme:

Student's overall marks consist of the following components: 25% on a mid-term quiz, 25% on course projects, and 50% on the final examination.

Textbook for the course:

The textbook adopted for author's class satisfies the need to reach the aforementioned course goal and student learning objectives. A thorough search for suitable textbooks in the marketplace, resulted his adopting his own book published by McGraw-Hill in 2004 [15] till 2008 when the book was sold out by the publisher in 2006. He continued use the second edition of the same book published by John-Wiley and Sons in 2008 [6] since then. Content of the current adopted textbook for the course is available in Appendix 1.

3. Major Challenges in Teaching MEMS to Undergraduate Classes

Many American universities offer MEMS course at graduate level. There are many universities offer the same course at undergraduate level in many countries in the world in recent years. There are few challenging issues in teaching the MEMS technology at undergraduate level as will be outlined below.

Challenge No. 1: Cross engineering-science of MEMS:

MEMS is an engineering topic that relates closest to science than any other sub-disciplines of mechanical and electrical engineering. Teaching MEMS to engineering students require the inclusion of advanced science topics such as quantum physics and the theories and principles of electrochemical-physical processes, which are not covered in both Lower and Upper Divisions engineering curricula. Students often find difficulty in relating these advanced scientific topics with their learning of MEMS.

Challenge No. 2: The multidisciplinary nature of MEMS:

Engineering curricula in American universities are customarily designed with single disciplines in aerospace, civil, chemical, electrical, and mechanical engineering. Students enrolled in any of these discipline majors are not accustomed to course subjects that cross their own disciplines. MEMS technology, by virtue of its name, is multidisciplinary; it involves virtually all other major disciplines in engineering and science as illustrated in Figure 1.

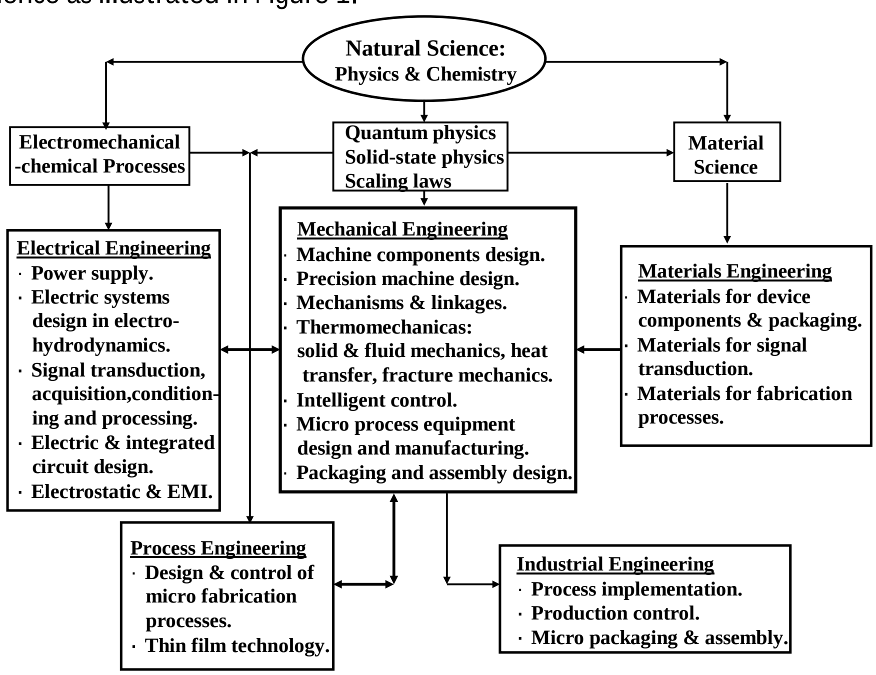

Figure 1 The Multidisciplinary Nature of MEMS Technology [6]

Undergraduate students enrolled in the MEMS classes are required to learn course subjects that are not in their majors often by special self-study assignments by the instructor.

Challenge No. 3: To think "small:"

"Size effect" is not normally a major concern in teaching undergraduate engineering classes. This effect, however, is a critical factor in almost all aspects of micro- and nano-scale engineering; ranging from rigid-body dynamics, fluid mechanics to machine design in MEMS and microsystems. Intermolecular forces, for example are conveniently ignored in all other engineering subjects by the so called "law of average", but it becomes a significant factor in dealing with substances at micro-scale level. Students also have hard time to envisage how small microdevice components at micrometer scale can be fabricated and have these devices function properly as expected. Scaling law, which has been foreign to them in the past has now become the critical principle to follow in dealing with the design of MEMS and microsystems.

Challenge No. 4: Gaining hands-on experience:

Students in the MEMS class were taught how components in micrometer scale are fabricated by physical-chemical processes such as etching and depositions. Experimenting these processes require clean room facility, which is beyond the reach of financial resources of many institutions. Consequently, instructors of MEMS classes need to find ways to expose students to gain hands-on experience by some innovative means. There is a follow-up course on "Microelectromechanical systems fabrication and design" developed and offered at author's department to facilitate student's acquiring limited but necessary hands-on experience in design, fabrication, and testing of microelectromechanical systems (MEMS). Processes including photolithography, etching, and metal deposition applied to MEMS. This course also teaches students with design problems for MEMS transducer components focused on experiments of fabricating and testing simple MEMS devices using relatively simple physical-chemical processes without the need for high class clean room chamber and sophisticated facility to produce these devices [7, 8].

Challenge No. 5: Suitable textbooks:

As described in the aforementioned Section 3 of the paper MEMS is a technology that encompasses virtually all engineering disciplines and natural science in physics and chemistry. There have been excellent books published on MEMS for research, such as in References [9-11]. However, there appears lack of suitable textbooks available in the marketplace; an early textbook published by Maluf [12] offered overview of MEMS but appeared too brief for student's learning of the subject. There have been another two textbooks published on MEMS intended to be textbooks for engineering classes at undergraduate level [13, 14]. Both appear to be imbalanced between the design and microfabrication of microdevices, and the science such as doping and molecular interactions. The author is of opinion that such balance is important to allow student's real appreciation in the "engineering principles" of the MEMS technology.

4. Textbook for Teaching MEMS at Undergraduate Level

As presented in Section 2 of the paper, the textbook that the author has been using for his course on "Microsystems Design and Manufacture" was first published in 2002 [15], and its second edition published in 2008 with expanded coverage of microassembly, packaging and testing and a new chapter on introduction to nanoscale engineering [6]. These books were written for instruction in one-semester undergraduate Upper Division and entry-level graduate classes. They were time-tested for satisfying the course goal and student learning objectives as outlined in Section 2. The layout and the organization of the related topics, and the many design examples presented in these books, are expected to usher practicing engineers too in learning the MEMS and microsystems technologies.

Both editions of this book are intended for class instruction that covers a 15-week semester at both the undergraduate and graduate levels. Students are expected to have acquired the prerequisite knowledge in college mathematics, physics, and chemistry, as well as in engineering subjects such as fundamental material science, electronics and machine design.

The latter edition of the book consists of twelve chapters covering the course subjects as presented in Appendix 1. It is not possible to cover all these course subjects in the depth that many instructors would like in their teaching the class. However, it is impo0rtant to strike a proper balance between breadth and depth in covering each of these course subjects. It is author's opinion that breath is more important than depth for engineering students at undergraduate level. The broader scope of the course subjects that they learn in the class would provide them with the necessary knowledge and skills to communicate with their counterparts from other disciplines at workplaces after their graduation.

5. Fundamentals in MEMS Education to Undergraduate Engineering Students

A fact that is shared by many experts in the field of MEMs and Microsystems is that this technology was evolved from the rapid advance of semiconductor technology in the 1980s. Indeed, one would identify many senior personnel in the MEMS and Microsystems industry has such background and many were graduates with advanced academic degrees in physics or electrical engineering. The dominance of personnel with science and EE experience in the early stage of the MEMS industry soon revealed a significant difference between the parent microelectronics technology and the offspring microsystems technology as outlined in the author's textbooks [6, 15]. Knowledge and experience in semiconductor and microelectronics as by many of these veterans did not result in many successful MEMS and Microsystems products in the marketplace. What the industry really needs is engineering staff with members equipped with the knowledge and experience from many other engineering disciplines as illustrated in Figure 1.

Following are a few unique features of microsystems technology that are significantly different from traditional technical disciplines that engineering students need to learn.

5.1 The radically different fabrication technologies

Many engineering schools in the country offer courses on manufacturing involving the use of machine tools in such fabrication processes as drilling, stamping, machining and millings, etc. microsystem components cannot be produced by any of these traditional processes. They can only be produced by chemical-physical processes requiring special clean room facility with workers wearing specially design suits, as shown in Figure 2. The concept of involving “process” in place of “machine tools” is an important fact in the minds of microsystems engineers.

Figure 2 A Radically Different Manufacturing Facility for Producing MEMS Products

5.2 The very different ways in the design of microsystem products

Microsystem products are often in micrometer or sub-micrometer scales. Design of machine components of such minute sizes is radically different from that for machine components of macro or meso-scales. Major differences can be outline as follows:

1) Design for manufacturability: It requires special ways to build the required 3-dimensional geometry of the components. The design of parts joints with same or dissimilar materials in the micrometer scale such as hinges for pivoting movements, etc., and the process on how these parts can be produced present major challenge to engineers

2) Design for minute available space: Much innovative ideas are required in the design of machine components that fit in extremely small available space but remain functional. For instance, minute beams are used in place of “bulky” coil springs in the design of microaccelerometers and microgyroscopes.

3) Unusual applied loads: Unlike conventional structure design, parts of microsystems are often subjected to forces that are not well-known to engineers. Examples like: electrostatic and piezoelectric forces, molecular (or van der Waals) forces, electrohydrodynamic forces and surface tensions in microfluidics, etc. There are also forces arisen from many microfabrication processes due to thermal and molecular mismatching to be considered in the design analyses.

4) Size effects on material characterization: Engineering students are accustomed to treat materials with constant properties in their design. This treatment, however, breaks down in the case of designing microstructure components at sub-micrometer and nano-scales. Material properties not only vary with temperature, they also vary with the size of the components. This strong size-effect on material characterization of microsystem components makes it necessary to develop new

constitutive laws, as well as new phenomenological equations, such as heat conduction equation for the design of micro and nanoscale components as presented in the course.

5.3 The very different product design:

Successful design of microsystems requires the integration of: electromechanical design, the design of fabrication processes, and the assembly and packaging of the micro-scale components to the product and the system for reliability and in-service testing of the product. Coupling of all these major efforts in the design stage of the product is necessary because all steps in these design tasks are mutually affected by the consequences of these subsets. For instance, a microsystem cannot be expected to perform the expected function without proper design of microelectronics for the optimal power supply and microcircuits for signal transduction and motion control. These microelectronic circuits need to be packaged with the MEMS devices in the product. The requirement in integrated approach in design, fabrication and packaging is a major deviation from the design of conventional products, and it presents major challenges to engineers, managers and executives of the MEMS and microsystems business and industry.

6. Summary and Conclusion

The continuous growth of MEMS and microsystems technology can be sustained only by adequate supply of human resource of engineers equipped with the necessary basic unique knowledge and experience in the MEMS and microsystems technologies. Teaching MEMS and microsystems at undergraduate level in engineering schools is both feasible and practical if it is done properly with adequate textbooks. These engineering graduates will provide the MEMS industry and business with much needed skill in producing successful micro-scale products. The MEMS education at undergraduate level will also prepare many students for their advanced studies, e.g., in nanotechnology at graduate schools after their graduation.

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Appendix:

Contents of a Textbook Used for Teaching MEMS at Undergraduate Level

Appendix

Contents of a Textbook Used for Teaching MEMS at Undergraduate Level

Chapter	Chapter Title	Content
1	Overview of MEMS and Microsystems	MEMS and microsystems; Typical MEMS and microsystems products; Evolution of microfabrication; Microsystems and microelectronics; Multidisciplinary nature of MEMS; Application of MEMs in: automotive industry, healthcare, aerospace, industrial products, consumer products and telecommunication
2	working Principles of Microsystems	The six different types of microsensors; four different types of microactuators; MEMS and microactuators; Microactuators with inertia: microaccelerometers and microgyroscopes; Microfluidics
3	Engineering Science	Atomic structure of matter; Ion and ionization; Molecular theory of matter and intermolecular forces; Doping of semiconductors; Diffusion processes; Plasma physics; Electrochemistry
4	Engineering Mechanics for Microsystems Design	Bending of plates; Mechanical vibration; Thermomechanic; Fractures mechanics Thin-film mechanics; Overview of finite element stress analysis
5	Thermofluid Engineering and Microsystems Design	Fluid mechanics at macro- and meso-scale; Equation in continuum fluid dynamics; Laminar flow in circular conduits; Computational fluid dynamics; Incompressible fluid flow in microconduits; Overview of heat conduction in solids; Heat conduction in multi-layered thin films; Heat conduction in sub-micrometer scale
6	Scale Laws in Miniaturiza-tion	Introduction to scaling; Scaling in solid geometry, rigid body dynamics; electro-static and electromagnetic forces, electricity, fluid mechanics and heat transfer
7	Materials for MEMS and Microsystems	Substrates and wafers; Silicon as substrate material; Silicon compounds; Silicon piezoresistors; Gallium arsenide; Quartz; Piezoelectric crystals; Polymers; Packaging materials
8	Microfabrication Fabrication Processes	Photolithography; Ion implantation; Diffusion; Oxidation; Chemical vapor deposition; Physical vapor deposition; Deposition by epitaxy; Etching
9	Overview of Micromanufac-turing	Bulk micromanufacturing; Surface micromachining; LIGA process; Summary of micromanufacturing
10	Microsystems Design	Design considerations; Process design; Mechanical design; Mechanical design using finite element method; Design of silicon die of a micropressure sensor; Design of microfluidic network systems; Computer-aided design
11	Assembly, Packaging and Testing of Microsystems	Overview of microassembly; High cost of microassembly; Microassemly processes; Major technical problems in microassembly; Microassembly work cells; Challenging issues in microassembly; Overview of microsystems packaging; General considerations in packaging design; The three-level of microsystems packaging; Interfaces in microsystems packaging; Essential packaging technoloogies; Die preparation; Surface bonding; Wire bonding; Sealing and encapsulation; Three-dimensional packaging; Selection of packaging materials; Signal mapping and transduction; Design case on pressure sensor packaging; Reliability in MEMS packaging; Testing for reliability
12	Introduction to Nanoscale Engineering	Micro and nanoscale technologies; General principle of nanofabrication; Nanoproducts; Application of nanoproducts; Quantum physics; Molecular dynamics; Fluid flow in submicrometer and nanoscales; Heat conduction at nanoscale; Measurement of thermal conductivity of solids at nanoscale; Challenges in nanoscale engineering; Social impacts of nanoscale engineering