Teaching MEMS Curriculum
in Electrical Engineering Graduate Program

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Abstract:

Microelectromechanical Systems (MEMS) refer to devices and systems in the size range of 1 micron (1 micron=10^{-6}m) to 1000 microns. Due to their small size, MEMS technology has the advantages of low weight, low cost, low power consumption and high resolution. MEMS have found broad applications in automobile, inertial navigation, light display, optical and RF communications, biomedicine, etc. World's MEMS market is growing rapidly each year. To meet the strong market demands on MEMS engineers and researchers, we developed MEMS curriculum in our master program in School of Engineering since Fall 2005. In this paper, we shared our experience in teaching the MEMS curriculum in master program of Electrical Engineering department. Three core courses have been developed for MEMS curriculum. The course description, goals, prerequisites, as well as the topics covered in these courses are discussed. Multimedia technology is used in the teaching to enhance the teaching results. Several MEMS course projects using ANSYS simulation are designed to help student accumulate experience in MEMS device design and simulation. Students are fascinated by the MEMS field and continue their master project/thesis research in MEMS. The MEMS curriculum attracted tremendous interest among students, and the students' feedback on the course have been excellent. This is part of our efforts to prepare students for the future need of economy revival.

1. Introduction

MEMS (Microelectromechanical Systems) refer to devices and systems in the size range of 1µm~1000µm, which combine both electrical and mechanical components, and are fabricated with semiconductor fabrication technology [1]-[4]. MEMS enable the integration of multiple functions into a single chip, such as sensing, actuation, computation, control, communication, power, etc. Due to their extremely small size, MEMS have the advantages of low cost, low weight, low energy consumption, high resolution, and easy integration in System-on-Chip (SoC) design. In 1959, Richard Feynman predicted the exciting potentials of future device miniaturization in his famous presentation [5]. The presentation led to a brand new research direction, and many scientists and engineers have devoted themselves into this field. During recent decades, many MEMS devices [6] have been successfully developed, including MEMS pressure sensors, accelerometers, microgyroscopes, micromirrors, resonators, micropumps, microvalves, MEMS gears, micromotors, optical switches, microneedles, MEMS inkjet printer nozzle, RF variable capacitors, lab-on-a-chip, DNA chips, etc. MEMS also merged with nanotechnology and created a new field of NEMS (Nanoelectromechanical Systems). Worlds' MEMS market keeps growing rapidly each year. MEMS technology has been successfully commercialized and found broad applications in various fields, such as automobile industry, optical display and communication, medical health care, aerospace, RF wireless communications, toys, consumer products. As an example, the SEM photo of a MEMS DMD (digitl micromirror device) [7] by Texas Instruments Inc.

is shown in Figure 1 [8]. Fabricated with aluminum surface-micromachining technique, the size of each mirror pixel is just 15µm×15µm. Each DMD chip contains hundreds of thousands mirror pixels for light projection. The DMD technology has been successfully used in high resolution projectors and projection TVs.
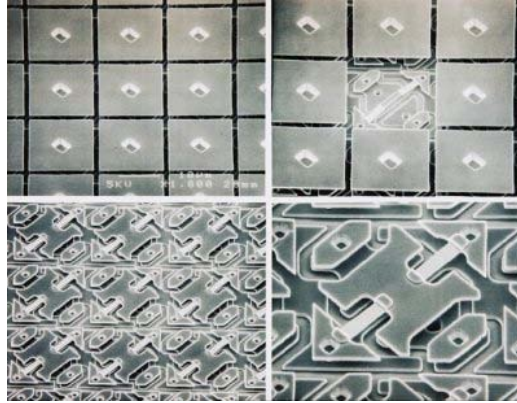

Figure 1. MEMS Digital Micromirror Device (DMD) by Texas Instruments Inc. [8]

MEMS have been successfully commercialized and widely used in many applications. MEMS industry maintained strong need for qualified MEMS engineers each year. However, as MEMS technology is a newly developed interdisciplinary field, most students did not have a chance to know MEMS in their undergraduate study. In order to meet the industry's need for a strong MEMS workforce, we developed MEMS curriculum in Electrical Engineering department at University of Bridgeport, CT. In this paper, we share the experience of the curriculum development, course teaching and student research advising in MEMS field. It has triggered tremendous interests among students and attracted many students into the MEMS field. Students are also doing their master project/thesis research in MEMS, and have published numerous student posters/papers in academic conferences. Efforts are also being made to further extend the MEMS education to nearby high school students, so that even more students will have a chance to get familiar with this amazing field in their early age. This will prepare them for the future career as MEMS engineers to meet the growing need of the industry.

2. MEMS Curriculum in Electrical Engineering department

In University of Bridgeport, we developed MEMS curriculum in Electrical Engineering department to introduce to students about this great field. The MEMS related curriculum includes 3 core courses in MEMS field: CPEG/EE 446 Introduction to MEMS, BME/EE 547: BioMEMS, and EE 448: Microelectronic Fabrication. The curriculum aims at offering students a comprehensive introduction about the basic concepts, working principle analysis and applications of MEMS, as well as the design, simulation, fabrication, packaging and testing of various MEMS devices. Students will accumulate experience in MEMS EDA tools such as ANSYS. The curriculum helps students prepare for their future career as MEMS engineers or for their higher-level education and research in MEMS field. The MEMS related core courses are discussed as below.

1). CpE/EE 446: Introduction to MEMS

This is a graduate level course (3.0 credit hours) cross-linked for both Electrical and Computer Engineering departments. This course covers the fundamentals of MEMS,

including MEMS introduction, basic microfabrication techniques, MEMS materials and their properties, MEMS device design and simulation, working principle analysis, MEMS device fabrication, MEMS packaging and assembly, signal testing, as well as MEMS device case study. The course introduces to students about the fundamental knowledge and skills of state-of-the-art MEMS technology. Basic concepts in MEMS design, working principle analysis, simulation, fabrication and testing are introduced. The course projects offer students experience in MEMS device design and simulation. Upon finishing the course, students will have a fundamental understanding about MEMS design, simulation, fabrication and testing.

2). BME/EE 547X: BioMEMS (BioMicroelectromechanical Systems)

This is an advanced level MEMS course aiming at the application of MEMS for biomedical applications. BioMEMS is the application of MEMS (Microelectromechanical Systems) technology in the fields of biomedical and health sciences. Due to their small size (1μm~1mm), BioMEMS have the advantages of low weight, low cost, quick response, high throughput, high efficiency, requiring much less sample/reagent, and easy system integration. BioMEMS has found broad applications in disease diagnosis, prevention and treatment. Various bio-MEMS products have been developed, such as microfluidic devices, neural interface devices, μTAS (micro total analysis systems), lab-on-a-chip, DNA chips, micro drug delivery system, microsurgical tools, bio-sensors.

This course introduces to students about the fundamentals of bio-MEMS technology, typical bioMEMS devices and their applications. The working principle analysis, design, simulation and testing of various bioMEMS devices (e.g. microfluidic devices, biosensors, lab-on-a-chip, DNA chip) are discussed. Upon completing this course, students will have a good understanding about the fundamentals of bioMEMS, and accumulate hands-on experience in the design and simulation of various bioMEMS devices.

3). EE 448: Microelectronic fabrication

A good MEMS designer must also have comprehensive knowledge and skills in MEMS fabrication. Many challenges in MEMS research actually lie in the fabrication instead of the design. Many defects introduced during device fabrication may degrade the device reliability and lead to device failure. If a MEMS engineer does not know these fabrication challenges, he/she may design a MEMS device which can never be fabricated with current available micromachining techniques. As a result, fabrication is also an important issue in MEMS. We developed EE 448: Microelectronic fabrication as part of the MEMS curriculum.

This course covers basic microelectronic fabrication processes for semiconductor and VLSI fabrication, including photolithography, plasma and reactive ion etching, ion implantation, diffusion, oxidation, evaporation, vapor phase epitaxial growth, sputtering, and CVD. Advanced processing topics such as next generation lithography, MBE, and metal organic CVD are also introduced. The physics and chemistry of each process are introduced along with descriptions of the equipment used for the manufacture of integrated circuits. The integration of microfabrication process into CMOS and bipolar

technology are discussed. In addition, MEMS micromachining and nanofabrication processes are also discussed in details.

The purpose of this course is to provide students with technical background and knowledge in silicon microelectronic fabrication process. Fabrication processes on Microelectromechanical System (MEMS) and nanotechnology are also introduced. Upon finishing this course, students will be familiar with the basic VLSI, MEMS and nanotechnology fabrication processes. They will be able to explain the physical and chemical mechanism for the fabrication process, and understand the basic procedures of the process.

3. Results and Discussion

MEMS curriculum has been developed in Electrical Engineering department at University of Bridgeport since Fall 2005. The program has been very successful and triggered tremendous interests among students. The classes were full and closed in the very early stage of course registration. The department had to open extra sections to accommodate the students who still want to join the courses. The students' feedback in the course evaluations has been excellent. They are very happy to have an opportunity to enter this amazing field of MEMS. Many students chose MEMS as their interested career and continue to do a master project/thesis research in this field. In the past few years, students have done their master project/thesis research in the design and simulation of various MEMS devices, such as MEMS accelerometers, comb resonators, piston/torsional/bi-functional micromirrors, variable capacitors, microgyroscopes, etc. Based on the research results, students had published various posters/papers in academic conferences. Some students are also pursuing their Ph.D study in the MEMS field after they complete their master degrees. A proper pipeline has been formed in our MEMS program. Each year some new students are joining this program, and some existing students graduate and find their job in MEMS industry or continue their Ph.D study in the MEMS field.

During the teaching of MEMS courses, course projects can help students accumulate experience in device design and simulation. We chose ANSYS [9] FEM software as the EDA tool for our MEMS courses. ANSYS offers multi-physics module for MEMS simulations. Its coupled-field analysis is very suitable for MEMS because MEMS devices generally involve multiple fields (e.g. gravity field, thermal field, electromagnetic field) in their operation. We prepared detailed ANSYS tutorials for each ANSYS project we assigned, so that students can quickly get familiar with the ANSYS tool even if they never used it before. ANSYS can work in GUI (graphical user interface) mode or command lines input mode. GUI interface is easy to learn, but takes longer time in building the device model. Command line input mode is quick in execution, but more difficult to learn. In the course projects, we used ANSYS GUI mode. But in student master project/thesis research, we encouraged students to use ANSYS command lines because it is more convenient for device design optimization. If we need to change the dimension of the design, we just directly change the corresponding lines in ANSYS command line codes. After executing the codes, the final simulation results can be easily obtained. In CpE/EE 446: Introduction to MEMS course, we designed 3 course projects for students. In the first project, students are asked to design a bulk-micromachined MEMS accelerometer with cantilever-mass structure, as shown in Figure 2. Students are asked to design the device model in ANSYS, and perform a modal analysis to find the

first 5 vibration modes and the corresponding resonant frequencies. The students are also asked to animate the five vibration modes of the accelerometer, and identify which vibration mode is the working mode of the accelerometer. This project helps students get familiar with ANSYS modal simulation.
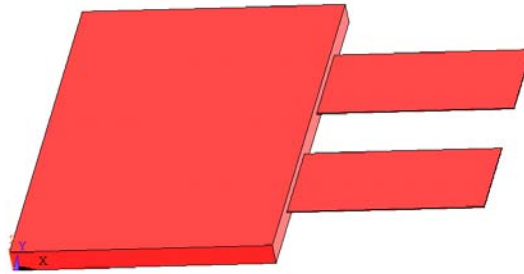

Figure 2. Bulk-micromachined MEMS accelerometer for ANSYS modal analysis

In the second project, students are asked to design and simulate a poly-silicon surface-micromachined MEMS comb accelerometer in ANSYS, as shown in Figure 3. The comb accelerometer contains 32 finger groups. Among them, 24 finger groups act as the sensing capacitance, and other 8 finger groups act as built-in self-test capacitance. The built-in self-test feature allows the device to be self-tested during in-field usage using electrostatic force. The students are asked to design the device model, simulate its displacement and capacitance change in response to 1g acceleration input as well as 10V self-test driving voltage. Students will also compare their simulation results with hand-calculation to see whether they are in agreement with each other. Students are also asked to design a differential-capacitance sensing circuitry to sense the differential capacitance change of the MEMS accelerometer in response to the acceleration input.
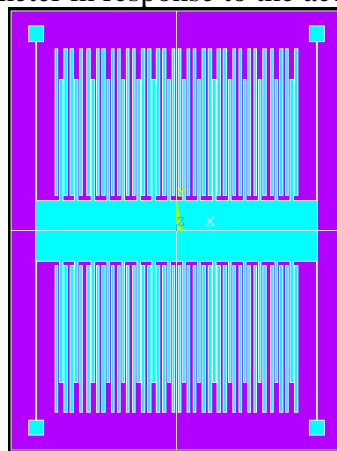

Figure 3. ANSYS model of surface-micromachined MEMS comb accelerometer

In project 3, students are asked to perform a fault simulation for point-stiction defects injected into different locations of a MEMS comb resonator, as shown in Figure 4. The purpose of this project is to help students get familiar with MEMS testing and fault simulation. MEMS devices are vulnerable to various defect sources during the fabrication and in-field application. All these may degrade the yield and reliability of MEMS, and lead to the failure of the MEMS devices. Point-stiction is a popular defect for MEMS, in which the movable part of MEMS device is stuck to the substrate at a certain point location. This may be due to the particle contamination, incomplete release etching, or a spot in photolithography mask, etc. In this project, students will inject point stiction defects to different locations (e.g. beams, anchors, shuttle mass, movable fingers, etc.) of the comb resonator, and see how the injected point-stiction defect affects the device

behavior. Thorough the fault simulation, students will see that depending on the location, a point-stiction defect may lead to catastrophic, parametric, or no effect on the device behavior. Furthermore, students will also perform multiple point-stiction defects simulation, and see how multiple point-stiction defects interact with each other: sometimes the faulty effects can enhance each other, while in other cases they may cancel each other.
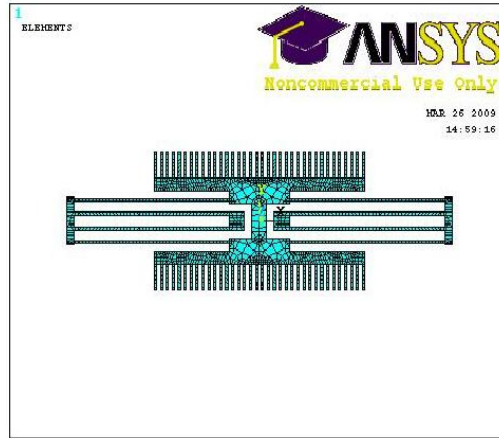

Figure 4. ANSYS point-stiction fault simulation of a MEMS comb resonator

During the teaching of MEMS courses, we also put emphasis on utilizing various multimedia technologies to enhance the teaching result. All the lecture notes are in powerpoint slides. When we are discussing a specific MEMS device example, we always show the vivid images and SEM photos of the real MEMS devices. In this way, students can have a better understanding about the device structure. Furthermore, when we are discussing the working principle of a MEMS device, we play some video clips showing the movement of the device. Students found these video clips very interesting and this help them understand the working principle of the MEMS devices. For example, the video clips showing the vibration of a MEMS comb resonator helps students to understand how a MEMS comb resonator is activated. They can also compare their ANSYS animation results with the video clips and this makes them very "excited" in doing the ANSYS simulation. In EE 448: Microelectronic Fabrication class, we also played the video, "Making of a Microchip" (by Texas Instruments Inc.) to students in class. This video illustrates various microelectronic fabrication processes (such as oxidation, photolithography, etching, etc.) in the real VLSI industry. It explains the working principle of each process, the facilities used for the process, and step-by-step demonstration of the process. Students found it much easier for them to understand the concepts of microelectronic fabrication processes after watching the video.

During the teaching, we found another way which is very helpful for students to understand the 3D structure and the fabrication flow of MEMS devices. We arranged a course project asking students to do a powerpoint presentation about the fabrication flow of a MEMS device (e.g. accelerometer, micromirror, resonator, etc.) using the 3D view of the device. In order to do this, students need to have a very clear understanding about the device structure, and the structure after each intermediate fabrication flow.

After completing the MEMS curriculum, many students are fascinated in it, and continue with a master project/thesis research in the MEMS field. We have advised students in their master project/thesis research in the design and simulation of various MEMS devices, such as MEMS accelerometers, microgyroscopes, micromirrors, microresonators,

MEMS variable capacitors, etc. Some students are also doing research in MEMS testing and fault simulation. Based on the research results, they have published student posters/papers in various academic conferences. After graduation, some students chose to continue their Ph.D study in MEMS field, while some other students find jobs as MEMS engineers in industry.

In addition to the MEMS curriculum in the EE graduate program, we are also making efforts to extend the MEMS education to the high school students in nearby communities. We plan to arrange some presentations to the high school students, and invite some high school students to do some student research in the MEMS field. This will help trigger the interests among high school students toward science and technology, especially in MEMS field. Some of the students may be attracted into the field and choose MEMS as their area of concentration in their future college study.

4. Conclusions

In this paper, we shared our experience in developing MEMS curriculum in Electrical Engineering graduate program at University of Bridgeport. The curriculum mainly includes three core courses: CpE/EE 446: Introduction to MEMS, BME/EE 547: BioMEMS, EE 448: Microelectronic Fabrication. The course description, goals, prerequisites, as well as the topics covered in these courses are discussed. The students showed strong interests and enthusiasm in these courses. Some MEMS course projects using ANSYS simulation have been proposed. Multimedia technologies (such as images, SEM photos, video clips) have been used to enhance the teaching outcomes. Student presentations using 3D view to show the MEMS device structure and fabrication flow are also used to help students understand the structure of the devices. Upon completion of the MEMS curriculum, many students chose MEMS as their research topic in their master project/thesis research. Based on the research results, various student posters/papers have been published in academic conferences. After graduation, some students continue their Ph.D study in MEMS field, while some other students find jobs as MEMS engineers in industry. We are also actively making efforts to further extend the MEMS education into high school students in nearby communities. This will help to introduce MEMS field to even more students in their early years, so that they may enter the MEMS field in their future college study. This will help prepare more qualified MEMS engineers for the future MEMS teaching and research needs.

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9. URL: http://www.ansys.com

Appendix

1. *Topics of CpE/EE 446: Introduction to MEMS*
   - Introduction to MEMS
   - MEMS materials and properties
   - MEMS structure analysis
   - MEMS sensing and actuation techniques
   - Micromachining processes for MEMS fabrication
   - MEMS CAD design and simulation (ANSYS FEM simulation)
   - MEMS for inertial measurement unit applications
   - MEMS for optical applications: MOEMS (microoptoelectromechanical Systems)
   - MEMS for RF communication applications: RF-MEMS
   - MEMS for biomedical applications: BioMEMS
   - MEMS packaging and reliability considerations.
   - MEMS testing, MEMS fault model and fault simulation.
   - Nanoelectromechanical Systems (NEMS).

2. *Topics of BME/EE 547X: BioMEMS (BioMicroelectromechanical Systems):*
   - Introduction to bio-MEMS.
   - Materials for bio-MEMS.
   - BioMEMS fabrication: bulk/surface micromachining, LIGA.
   - Soft fabrication and polymers
   - Microfluidic principles.
   - Microfluidic devices
   - MEMS biosensors
   - Microactuators and micro drug delivery system.
   - Micro total analysis system (µTAS), lab-on-a-chip.
   - Microarrays: polymerase chain reactor (PCR), DNA chip, functional genomics, bioinformatics.
   - BioMEMS for tissue engineering.
   - Packaging, power, data and RF safety of bioMEMS.

3. *Topics of EE 448: Microelectronic fabrication.*
   - Silicon wafer preparation
   - Lithography
   - Etching: Wet etching, dry etching.
   - Thermal oxidation of silicon
   - Diffusion
   - Ion implantation
   - Rapid thermal processing (RTP)
   - Vacuum science and plasma
   - Thin film deposition
   - Device isolation, contacts, and metallization
   - Packaging and yield
   - CMOS VLSI process integration
   - Bipolar process integration
   - MEMS fabrication: Micromachining processes
   - Nanofabrication processes: Nanolithography, bottom-up self-assembly.