

AC 2009-113: INTRODUCING THE SMALL WORLD: DEVELOPING THE MEMS/NANOTECHNOLOGY CURRICULUM

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Introducing the Small World – Developing MEMS/Nanotechnology Curriculum

Abstract

MEMS (Microelectromechanical Systems) and nanotechnology are believed to be the exciting drive to trigger the next wave of technology revolution. *MEMS* refer to systems in micro scale (1 micron to 1 millimeter) that integrates mechanical components, sensors, actuators, and electronics on a common silicon substrate through micromachining technology. Due to its low cost, small size, light weight and high resolution, MEMS has been widely used in automobiles, medical health care, aerospace, consumer products and RF communications. *Nanotechnology* refers to a field of applied science and technology about materials and devices in the atomic and molecular scale, normally 1 to 100 nanometers. It can offer better built, longer lasting, cleanser, safer and smarter products for home, communications, medicine, transportation, agriculture and many other fields. MEMS and nanotechnology can be combined to create a new exciting field of NEMS (Nanoelectromechanical system).

In order to introduce engineering students into this amazing micro and nanotechnology field, we developed three corresponding graduate-level courses: Introduction to MEMS (EE446) and Introduction to Nanotechnology (EE451), and Microelectronic Fabrication (EE448). In addition, we have other related courses to support this program, such as EE 447: Semiconductor, EE 404: CMOS VLSI, EE 410: Bio-sensors, etc. This paper will discuss the course structure, syllabuses, course modules, student feedbacks, as well as future plans for this program. This curriculum offer students comprehensive knowledge and experience in MEMS and nanotechnology. Students use various CAD tools such as ANSYS FEM to design and simulate various MEMS/NEMS devices in the course projects. Multimedia technology is also used during the classroom teaching. We played vivid photos/videos to show the operation of MEMS/NEMS devices and state-of-the-art micro/nano fabrication processes in industry. Students demonstrated tremendous interest in this micro/nanotechnology program. The enrollment to these courses has been overwhelming and we have to create extra sessions to accommodate students with strong interest in this program. Our graduated students are well prepared for the industry in micro/nanotechnology fields. This program can also be helpful for the effort of the Connecticut Nanotechnology Curriculum Committee.

1. Introduction

Nowadays, the technology advancement has the trend of making things smaller and smaller. Taking VLSI technology as an example, the feature size of a CMOS transistor is shrunk to deep submicron or nanometer domain. A state-of-the-art Intel CPU chip may contain millions or even billions of transistors. As the VLSI technology continue to become smaller and smaller, people are also considering shrinking the size of mechanical components (mirrors, gears, pumps, etc.) to microns and integrating them with VLSI circuits into a system. MEMS and nanotechnology are exactly the enabling technologies for this dream. MEMS mainly deal with things in the scale of $1\mu\text{m}\sim 1000\mu\text{m}$, and nanotechnology deals with things in the scale of $1\text{nm}\sim 1\mu\text{m}$. Some interesting examples about the scale of both natural and manmade things are illustrated in Figure 1 [1].

The Scale of Things – Nanometers and More

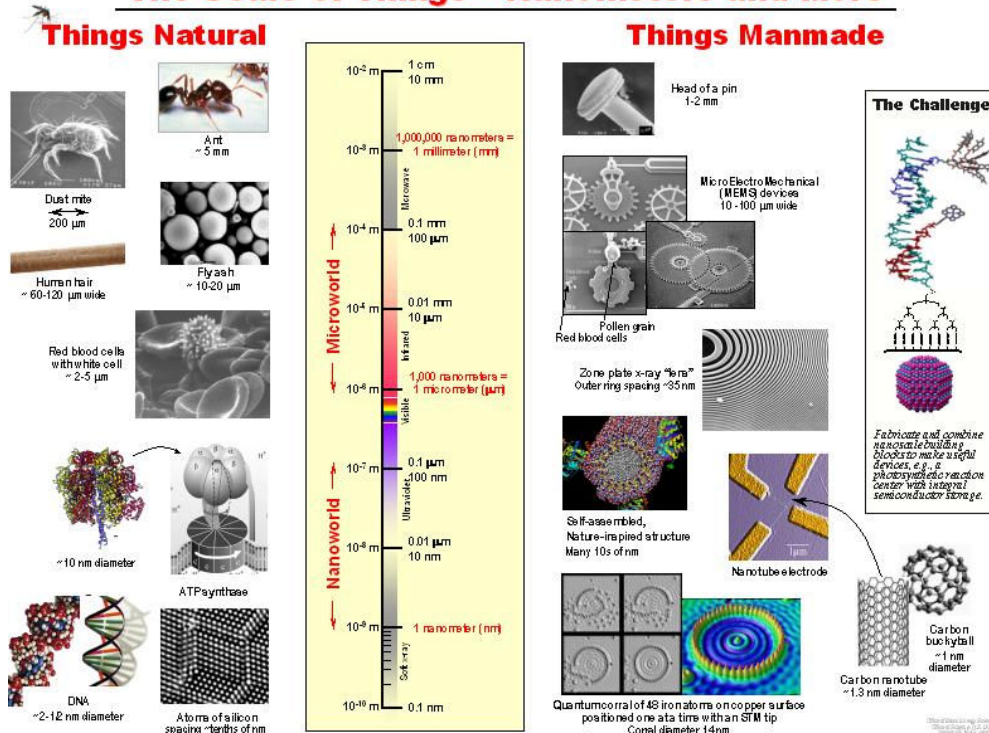


Figure 1. The scale of things – nanometers and more [1]

MEMS are the acronym of “Microelectromechanical Systems”. The typical size of MEMS components is in the range from $1\mu\text{m}$ to 1 mm . MEMS is actually a relatively "young" technology with history of only several decades. In 1959, R. Feynman predicted a future prosperity of science and technology about the "small" world [2]. Since then, scientists and engineers made tremendous effort to explore this amazing "small" world. In 1962, world's first silicon integrated piezoelectric actuator was developed [3]. In 1982, K. Peterson discussed the properties of silicon as a mechanical material [4]. This was the milestone for silicon to become an important structural material for MEMS. Various MEMS devices have been developed in recent decades. In 1994, world's first commercial surface-micromachined accelerometer [5] was developed by Analog Devices, Inc. Nowadays, MEMS technology has been commercialized by industry and used for many applications. MEMS technology integrates functions of sensing, actuation, computation, control, communication and power into a single chip. Typical MEMS devices include MEMS pressure sensor, accelerometer, micro-gyroscope, micro-motor, resonator, valve, gear, micro-mirror, optical switch, micro-needle, RF capacitor, lab-on-chip, etc. MEMS have the advantages of low cost, small size, low weight, high resolution, low energy consumption and high efficiency etc. MEMS have been successfully used in automobile industry, medical health care, aerospace, consumer products and RF telecommunications. The world's MEMS market is increasing rapidly each year. It is expected to be more than 60 billion USD in 2010 [6]. The rapid growth of MEMS market is a strong impulse for the research and development of MEMS. Some commercial MEMS products are shown in Figure 2. The SEM photo of a surface-micromachined MEMS comb accelerometer by Analog Devices is shown in Figure 3 [7].

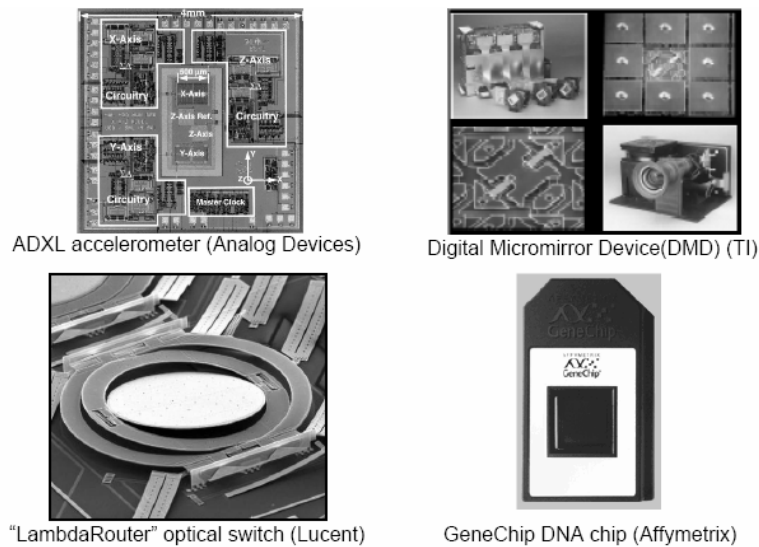


Figure 2. Examples of some commercial MEMS products

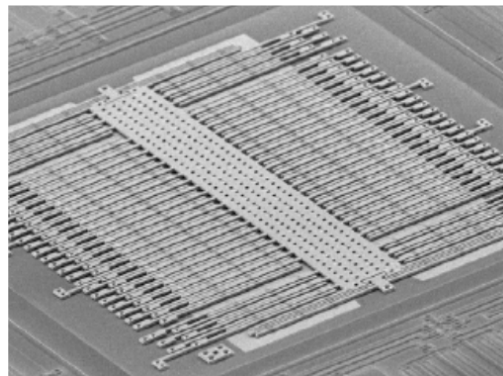


Figure 3. SEM photo of a comb accelerometer by Analog Devices Inc. [7]

As we further shrink the feature size into nanometer ($1\text{nm}=10^{-9}\text{m}$), we enter the domain of a newly-developed exciting field – Nanotechnology. Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 1000 nanometers, where unique phenomena enable novel applications. By scaling products down to nanometer, we can make them smaller, cheaper, faster and better. Nanotechnology can be used for many applications, such as electronics, catalysts, water purification, solar cells, coatings, and life-science. Nanotechnology also introduces totally new physical phenomena for science and technology. For example, quantum behavior and other effects become dominant in such small size range. Previous equations and laws for macro world may not be applicable for nanotechnology devices. Hence all the previous theories may need to be reconsidered. As an interdisciplinary field, nanotechnology involves many different research areas, such as physics, chemistry, biology, material science, polymer science, electrical, computer engineering, chemical engineering, mechanical engineering, medicines, and many others. It has been widely used in various applications, such as electronics, materials, health/biotech, chemical, environmental, energy, aerospace, automobile, security, and many others. The structure model of a single-walled carbon nanotube is shown in Figure 4 [8]. Nanotechnology is believed to be the drive to further maintain the Moore's Law for VLSI industry in the next decades. MEMS and nanotechnology also jointly created a brand-new field of NEMS (nanoelectromechanical system), which has attracted the interest of many scientists and engineers.

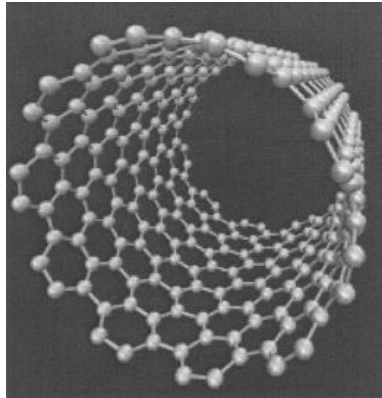


Figure 4. A single walled carbon nanotube [8]

Both MEMS and nanotechnology greatly rely on the progress of their fabrication techniques. Traditional microelectronic fabrication techniques have been well-developed in VLSI industry. MEMS can directly “borrow” these mature microfabrication processes from VLSI technology, such as oxidation, photolithography, thin-film deposition, dry/wet etching, etc. In addition to these, MEMS also developed its own specific fabrication processes, such as silicon-glass anodic bonding, silicon-silicon direct bonding (SDB), laser micromachining, laser micromachining. MEMS fabrication processes can be divided into several categories including surface-micromachining, bulk-micromachining, LIGA, and other non-standard fabrication processes. For nanotechnology, nanofabrication processes with feature size of nanometer range are required. Nanofabrication can use two different approaches: top-down approach and bottom-up approach [9]. In the traditional top-down approach, the fabrication starts with a rough, large-scale material and carves it till finally the nano-devices are shaped. The nanolithography techniques, such as extreme UV lithography (EUV), X-ray lithography, E-beam projection lithography (EPL), ion projection lithography, microcontact printing, nanoimprinting, and SPM (scanning probe microscope) based techniques are used in top-down approach. In bottom-up approach, it creates a construct by assembling simple building blocks (atoms, molecules, etc.) according to pre-designed scheme. It relies on the self-assembly and self-organization of the molecules, which is totally different from the top-down approach used in VLSI fabrication in the past decades. In conclusion, micro and nano fabrication techniques are important knowledge backgrounds to understand the MEMS and nanotechnology.

2. MEMS and Nanotechnology Curriculum

As newly-developed exiting high-technologies, MEMS and nanotechnology has achieved tremendous progress in the past decades. Many MEMS and nanotechnology products have been developed and commercially available in the market. They have greatly changed many aspects of our life style. They are also believed to trigger the next wave of technology revolution. In University of Bridgeport, we developed MEMS and nanotechnology curriculum to introduce this exciting “small” world to students. There are three core courses for this MEMS/Nanotechnology major: CpE/EE 446: MEMS, EE 451: Introduction to Nanotechnology, and EE448: Microelectronic Fabrication. In addition, students are recommended to take some elective courses, such as EE 447: Semiconductor, EE 404: CMOS VLSI, EE 410: Bio-sensors, etc. These courses are open to all undergraduate/graduate students in School of Engineering, including department of

Electrical Engineering, Computer Engineering, Computer Science, Mechanical Engineering, as well as Technology Management. Upon completion of this MEMS/nanotechnology curriculum, students will have a good understanding about the basic concepts and knowledge in MEMS and nanotechnology. They will also accumulate some hands-on experience on the design, simulation and testing of various MEMS/nanotechnology devices. They will also have a clear understanding about the various fabrication processes for MEMS and nanotechnology devices/systems.

1). CpE/EE 446: Introduction to MEMS

This is a three-credit-hour graduate level course cross-linked for both Electrical and Computer Engineering departments.

Course description: MEMS (Microelectromechanical Systems) refers to devices and system with very small size (in the range of microns). It is one of the most important high technologies developed in 20th century. This course covers the fundamentals of MEMS. It includes the introduction to MEMS, basic microfabrication techniques, MEMS materials and their properties, MEMS device design and simulation, working principle analysis, MEMS device fabrication sequence, MEMS packaging and assembly, signal testing, MEMS device case study.

Goals of the course: This course is designed to introduce 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 will be introduced. MEMS industrial applications in various areas will be discussed. The course project will give students hands-on experience in MEMS device design and simulation. Upon finishing the course, students will have a fundamental understanding about MEMS design, simulation, fabrication and testing.

Prerequisites: Undergraduate and graduate students with engineering or physics background. Basic knowledge in undergraduate mechanics and mathematics are required.

Topics: The following topics are covered in this MEMS course.

- Introduction to MEMS
- MEMS materials and properties
- Basic microfabrication techniques
- MEMS for industrial and automotive applications
- MEMS CAD design and simulation
- MEMS for photonic applications
- MEMS for life sciences applications
- MEMS for RF applications
- MEMS packaging and reliability considerations
- MEMS fault testing

Lab Projects: MEMS projects can help students to accumulate valuable experience in MEMS device design and testing. In this course, three lab projects on MEMS devices design and simulation are assigned. The goal of the projects is to help student accumulate skills and experience in MEMS CAD design and simulation. Students use ANSYS CAD tool to build the device model, and simulate its response to input stimulus. Through these

projects, students will get familiar with MEMS device design and performance analysis. These projects were well-designed and proven to be very popular among students. According to the feedback from the students, they enjoyed the challenges in the projects, and felt that they learned some really useful skills in MEMS device design and simulation. In project #1, students are asked to design a three-dimensional ANSYS model for a bulk-micromachined beam-mass-structured MEMS accelerometer device and simulate its first five vibration modes using ANSYS modal analysis. Based on this, they will identify the resonant frequency of the device in its working mode. In project #2, students designed a surface-micromachined comb accelerometer and simulate its differential capacitance change due to input acceleration using ANSYS structure-electrical coupled-field analysis. In project #3, students are asked to perform ANSYS fault simulation for point-stiction defects on various locations of a MEMS comb accelerometer device. Point-stiction defect is a popular MEMS defect in which the movable part of the device is stuck to substrate at a certain point. A screen shot of the ANSYS model for the movable part of a surface-micromachined comb accelerometer with a point-stiction defect at one beam is shown in Figure 5. MEMS fault simulation is directly related to MEMS yield and reliability. Based on this project, some students did their master projects or thesis on MEMS yield and reliability analysis. Some other students did their research on the design optimization of various MEMS devices including piston/torsional micro-mirrors, comb resonator, micro-gyroscope, etc. The ANSYS projects in this course help students get well-prepared for their further research in the MEMS field.

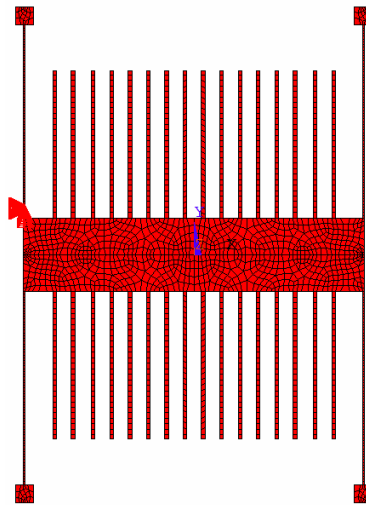


Figure 5. ANSYS model of a MEMS comb accelerometer with point-stiction defect

2). EE 451: Introduction to Nanotechnology

This is a graduate level course with 3 credit hours. It covers the basic concepts and theories in the newly-emerging nanotechnology.

Course Description: Nanotechnology is the science and engineering involved in the design, synthesis, characterization and application of materials and devices with the size in nanometer (10^{-9} m) scale. As a newly emerged exciting high-technology, it has attracted intensive interest and heavy investments around the world. Nanotechnology is a general-purpose technology which will have significant impact on almost all industries and all areas of society. It can offer better built, longer lasting, cleanser, safer and smarter

products for home, communications, medicine, transportation, agriculture and many other fields. This course will cover basic concepts in nanoscience and nanotechnology.

Goals of the Course: The goal of this course is to introduce to students the general concepts/terminology in nanoscience and nanotechnology, as well as their wide applications. Upon finishing this class, student will have a clear understanding about basic concepts in this field, such as carbon nanotube, nanowire, bottom-up self-assembly, molecular electronics, molecule manipulation, etc.

Prerequisites: Undergraduate and graduate students with engineering or physics background.

Topics: i). Nanoscale fabrication and characterization.

- Nanolithography
- Self-assembly and self-organization
- Scanning probe microscopes

ii). Nanomaterials and nanostructures.

- The geometry of nanoscale carbon
- Carbon Nanotubes, quantum dots, nanocomposites

iii). Nanoscale and molecular electronics.

- Advances in microelectronics - from microscale to nanoscale devices
- Molecular electronics, single electron transistors

iv). Nanotechnology in magnetic systems.

- Semiconductor nanostructures for quantum computation
- Nanotechnology in magnetic storage

v). Nanotechnology in integrative systems.

- Nanoelectromechanical systems (NEMS)
- Micromechanical systems (MEMS)

vi). Nanoscale optoelectronics.

- Quantum-confined optoelectronic systems
- Organic optoelectronic nanostructures

vii). Nanobiotechnology.

- Biomimetic nanostructures
- Biomolecular motors, nanofluidics.

In this course, we played some vivid short videos about nanotechnology before each class. These videos generally last from several seconds to several minutes. They greatly promoted students' interest in the field of nanotechnology. Students concentrated on the lecture from the first to the last minute in the class. Multimedia teaching has been proved to be a very effective teaching method in this course.

3). EE 448: Microelectronic fabrication

This is also a graduate-level course with 3.0 credit hours. In this course, we introduce typical microelectronic fabrication processes such as single-crystal silicon growth, oxidation, photolithography, etching, thin-film deposition, diffusion and implantation, metallization. In addition, we also covered MEMS micromachining fabrication processes, such as surface-micromachining, bulk-micromachining, LIGA and other micromachining processes. We also discussed various nanofabrication processes, such as nanolithography,

self-assembly and self-organization. We used some typical MEMS and nano device as example to show the fabrication sequence step by step. We also bought an education video, “Making of a Microchip”, from Texas Instruments and played it in class. This video illustrates various fabrication processes used in real industry. Students can see from the video many state-of-the-art fabrication facilities used in the industry, such as photolithography machine, oxidation oven, RIE etching machine, PVD/CVD chambers, etc. This is very helpful for students to understand the basic concepts in microelectronic fabrication.

Course Description: 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.

Goals of the course: 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.

Prerequisites: Undergraduate and graduate students with engineering or physics background.

Topics:

- An overview of microelectronic fabrication
- Lithography
- Thermal oxidation of silicon
- Diffusion
- Ion implantation
- Film deposition
- Interconnections and contacts
- Packaging and yield
- CMOS VLSI process integration
- Bipolar process integration
- MEMS micromachining processes
- Nanotechnology fabrication processes

3. Results and Discussion

The MEMS/Nanotechnology curriculum has been developed in University of Bridgeport since Fall 2005 semester. Students demonstrated tremendous interest in these courses. The enrollment rate of the courses was very high. The courses were often closed in the

first few days of the course registration. Even each section of the courses had 30 seats available, there were still many students in the waitlist. As a result, the department had to open extra sessions to accommodate the students in the long waitlist. Students enjoy the interesting topics in these courses. In the homework we also asked students to search and read research papers in MEMS and nanotechnology fields via university library, and present their findings of the research work in those papers. In this way, students have a better understanding about the most up-to-date research frontiers in MEMS and nanotechnology. In the course evaluation, students rated these MEMS and nanotechnology courses as most interesting and useful. Students rated the courses as “wonderful”, “fantastic”, and “one of the best courses they have ever taken”. Thanks to the curriculum, they have “discovered a most exciting field they never heard about before”. After the courses, students also showed significant interest in doing master project/thesis research on MEMS and nanotechnology fields. Some students did very successful research work on various MEMS and nanotechnology issues, such as micro-mirror design optimization, MEMS accelerometer fault simulation, MEMS reliability analysis, nanodevice fabrication process design, etc. More and more students have been attracted into our MEMS/nanotechnology curriculum. We are very excited about introducing this MEMS and nanotechnology curriculum so that students can have an opportunity to look into this amazing “small” world. Although currently these courses are available for students to satisfy their graduation requirements, in the future we are going to develop a true MEMS/nanotechnology track with its own core courses and research project requirements. As more and more students graduate with this field of concentration and find their jobs in MEMS and nanotechnology, we will be able to collect feedbacks from industry companies regarding the performance of these students and their suggestions in further improving this program.

One faculty in this curriculum is also a member of Connecticut Nanotechnology Curriculum committee. He collaborated with other colleagues in the committee to develop curriculums for nanotechnology programs in Connecticut state, and to build a "clearinghouse" where courses open to students from throughout public and independent colleges and universities can be delivered. The MEMS/nanotechnology curriculum in University of Bridgeport can be a good support for this state-wide endeavor of nanotechnology curriculum. In addition to the graduate-level MEMS and nanotechnology curriculum, we are also planning to introduce the curriculum to junior or senior undergraduate students through Senior Design/Special Topics for one to two credit hours. Students with related engineering backgrounds (e.g. electrical engineering, mechanical engineering, chemistry, computer engineering) will be able to join this program. Furthermore, we are also trying to extending this effort to K-12 education. We are preparing some presentations or courses for introducing MEMS and nanotechnology to students in elementary schools, middle schools and high schools in the state. We wish to trigger the interests of more kids so that they may become the scientists and engineers in the MEMS and nanotechnology fields in the future.

4. Conclusions

In this paper, we discussed the MEMS and nanotechnology curriculum developed in University of Bridgeport. The curriculum includes three core courses: CpE/EE 446: MEMS, EE 451: Introduction to Nanotechnology, and EE448: Microelectronic Fabrication. In addition, some other related supportive courses are also available. The course description, goals, prerequisites, as well as covered topics of these core courses

are proposed. The students' feedbacks on this curriculum are very enthusiastic. The MEMS/Nanotechnology curriculum has been proved to be very helpful to introduce to students about this amazing "small" world. More new courses are expected to be developed in the future to further strengthen these MEMS/nanotechnology curriculum.

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