COMPREHENSIVE MEMS CURRICULUM AT UCLA

Jack W. Judy^{1,3}, Greg P. Carmen², Frank M.-C. Chang¹, Yong Chen², Harold H. Fetterman¹, Nasr N. Ghoniem², Warren S. Grudfest^{1,3}, Vijay Gupta², Chih-Ming Ho^{2,3}, Yongho S. Ju^{2,3}, William J. Kaiser¹, Pirouz Kavehbour^{2,3}, Chang-Jin Kim^{2,3}, Robert T. M'Closky², Carlo D. Montemagno^{2,3}, Laurent Pilon², Jacob J. Schmidt³, Eli Yablonovitch¹, and Xiaolin Zhong²

¹Electrical Engineering Department, ²Mechanical and Aerospace Engineering Department, ³Biomedical Engineering IDP, University of California, Los Angeles, Los Angeles, CA 90095 USA

ABSTRACT

UCLA has spent the last 15 years pioneering the thorough development of possibly the most comprehensive graduate-level MEMS curriculum in the world, which is jointly offered by the EE and MAE departments. Students from EE and MAE are admitted directly into a formal MEMS major field, complete a set of 4 core courses, take a MEMS preliminary exam, complete the rest of their course work by selecting from MEMS and non-MEMS electives, take a qualifying exam, and complete their theses (M.S. and/or Ph.D.). To date at least 9 specifically MEMS/nano-related graduate-level elective courses have been developed and are presently being offered. To date well over 100 graduate students have completed or are completing this unique program. Those that have graduated have gone on to be productive faculty at U.S. and international academic institutions, engineers at MEMS and non-MEMS companies, and have started a number of MEMS start-up companies.

I. INTRODUCTION AND BACKGROUND

As the field of microelectromechanical systems (MEMS) has grown and matured in research universities, companies, and national laboratories, the demand for well-prepared students and employees in the MEMS field has also grown [1]. To meet this demand, a variety of pedagogical structures have been developed with differing strategies for meeting different facets of this demand. Examples include graduate-level MEMS courses, graduate-level non-MEMS courses, MEMS short courses and tutorials, and most recently undergraduate-level MEMS courses that sometimes include hands-on laboratories.

In the early years of the field of MEMS, much of the education of future MEMS professionals came from training research in classes well developed to meet other specific needs (e.g., analog-circuit design, linear and non-linear elasticity, linear and non-linear dynamics, mechanics of thin-films, materials science, solid-state physics, etc.). Soon, institutions offering single graduate-level courses on MEMS, which primarily covered bulk micromachining, surface micromachining, transduction mechanisms for sensors, force-generation methods for actuators, basic mechanics, and relevant material science. However, given the enormous breadth of such single-course approaches, depth was limited and largely followed the particular individual interests of the students and instructors. Also, at this point no institution offered MEMS as a major field within any academic department (e.g., EE, MAE, etc.). Instead, students were admitted into the major field of their advisor (e.g., solid-state electronics, photonics, mechanical design, etc.) and the students focused their course work and took preliminary exams in these non-MEMS major-field areas. This situation has largely endured at most institutions in the U.S., with the exception being those that hired additional MEMS faculty (or had originally non-MEMS faculty that become active in the MEMS field), which made it possible to offer additional MEMS courses (e.g., MEMS design, BioMEMS, etc.).

II. UCLA MEMS CURRICULUM DEVELOPMENT

The UCLA MEMS curriculum-development process followed that described above, with a few key differences. In the early 1990's a few institutions, such as UCLA, pioneered having two graduate-level MEMS courses. A two-course format allowed the material covered in the original single course to be distributed over twice the amount of time, so that greater depth and breadth was possible. Frequently, the first course focused more on MEMS fabrication (EE M250A / MAE M280) and the second more on MEMS design (EE M250B / MAE M282). At UCLA we went a step further and offered additional courses: (1) a course focused on system-level issues that are important for realizing a complete instrument (EE 250C), (2) a course focused on microscale science, particularly microscale fluid dynamics and heat transfer (MAE 281), (3) a survey course focused on the most recent results presented at MEMS conferences and journals (MAE 287), and (4) an introductory course on basic MEMS fabrication offered at the *undergraduate* level that included a weekly 4-hour hands-on laboratory session (EE M150L / MAE M180L) [2]. As is hopefully made apparent by the course numbers, the MEMS curriculum at UCLA is one that is strongly collaborative between the EE and MAE departments, with the "M" preceding the course number indicating that the course is cross listed with another department.

This set of courses provided the academic critical mass to allow another major UCLA uniqueness / innovation to precede, namely the creation of MEMS as its own *major field* within both the MAE and EE departments. This means that at UCLA, prospective graduate students specifically apply to enter into the MEMS major fields of the EE department or MAE department. These students complete a set of the previously mentioned courses and then their mastery of the topics is tested through a preliminary exam held after the first year. Students who pass are allowed to pursue their PhD in the MEMS major field, often completing an M.S. thesis along the way. Those that cannot pass the MEMS preliminary exam, typically graduate with a M.S. degree in the MEMS major field by completing a thesis or eventually passing a MEMS comprehensive examination (non-thesis option). Although some may feel that MEMS is not appropriate as a major field (e.g., too new, not fundamental enough, what are the key MEMS equations, MEMS should only highlight an academic degree and not be the focus of one, etc.), and there was some resistance at UCLA as well, in the end the UCLA MEMS faculty argued persuasively that the field of MEMS had enough merit (i.e., depth and breadth) to stand on its own. Students working towards a MEMS degree have plenty of other course slots to fill with classes outside of MEMS, which are typically taken in the application area of their thesis research (e.g., biology, chemistry, physics, neuroscience, etc.) or are otherwise complimentary engineering courses (e.g., circuit design, mechanics, control theory, etc.).

Due to the rise of biology and medicine as application areas for MEMS and the corresponding demand for MEMS instruction for biomedical engineering (BME) students, the core MEMS classes are now cross listed with the BME interdepartmental

program (IDP) as well (e.g., EE M150L / MAE M180L / BME M150L, etc.) to facilitate and regulate student enrollment. Although some MEMS courses are cross listed with BME, there is no BME-based MEMS major field. Instead, MEMS is a required component of the bioinstrumentation major field within BME and the MEMS courses are frequently taken by BME students in other major fields (e.g., biomechanics, neuroengineering, etc.).

Another evolution to the MEMS curriculum was the way it has adapted to the rise of “nano”, which did much to distract attention away from the field of MEMS – despite nano being perceived by many in the MEMS as largely a logical extension / evolution of the MEMS field or what used to be called chemistry. Although this is quite true for top-down fabrication technologies, it is admittedly not the case for bottom-up fabrication and molecular engineering. Thus we have expanded the official name of the “MEMS” major field to become the “MEMS / Nanotechnology” major field. Additional courses focused on nano-specific and bottom-up approaches have been added to the program (MAE 287, MAE 287L, MAE 258A, BME C251, BME 257) and top-down nano-related content has also been added, when and where appropriate, to the existing core MEMS classes.

In the years leading up to 2006, many other MEMS and MEMS-related faculty have been hired and a many other MEMS courses and MEMS-related courses have been developed and are now offered at UCLA. In the following section, the present UCLA MEMS curriculum and its course offerings will be described. To our knowledge, it represents the most comprehensive MEMS-oriented curriculum in the world.

III. UCLA MEMS CURRICULUM

Although the UCLA MEMS curriculum for graduate students is customized / optimized for each collaborating academic unit (i.e., EE, MAE, and BME), at the heart is a *common core*, which is a set of classes that each academic unit requires its student to take. In addition, each department has its own *department-specific MEMS core*, which is an additional course that when added to the common core represents the subject matter for the preliminary exams. Lastly, there are a number of MEMS classes that students may take as electives to complement their core MEMS knowledge and the classes they take in non-MEMS fields (e.g., the field of the application of their MEMS research project, other engineering electives that support their research, etc.). The following sections describe the (1) common MEMS core, (2) department-specific MEMS core, (3) MEMS minor, (4) MEMS seminars, (5) joint MEMS preliminary exam, and (6) elective MEMS courses offered at UCLA. The rest of this section will describe the motivation, philosophy, and design of each component. A list of all UCLA MEMS courses and a brief description of their content is provided in the appendix.

A. Common MEMS Core

The common MEMS core is essentially MEMS fabrication, which includes the undergraduate MEMS-fabrication course and laboratory and the follow-on graduate-level MEMS-fabrication course. As graduate students matriculate in the fall, some entering MEMS graduate students do not have a sufficient background in micromachining (e.g., do not know the capabilities and limitations of different forms of lithography). Starting them off with a graduate-level MEMS fabrication class with peers that have much more MEMS experience, will either do an injustice to the beginning or advanced students. Our pedagogical strategy has been to require all MEMS graduate students to complete the introductory MEMS course offered at the undergraduate level (EE M150 / MAE M180 / BME M150) unless they can demonstrate an appropriate level of knowledge in that material. Perhaps more

importantly, the hands-on laboratory course (EE M150L / MAE M180L / BME M150L), gives students the practical clean-room experience that only the most exceptional MEMS applicant has after completing a B.S. degree in engineering at most universities. As a result, the undergraduate MEMS classes are populated mostly by graduate students (66%). The courses are listed at the undergraduate level for two reasons: (1) the level of material is rather basic, with the biggest challenge being the sheer amount of it, and is quite similar to undergraduate IC-fabrication classes; (2) undergraduate students with an interest in MEMS should have easy access to take a MEMS class (i.e., not have to take graduate-level courses) and to get the hands-on experience in the lab. Such laboratory skills and experience will help them should they either decide to enter the MEMS industry with a B.S. degree or apply for graduate school at a school with an active MEMS-research program. After the fall quarter, UCLA MEMS students are fully primed on the basics of MEMS fabrication and have considerable laboratory experience. This makes it possible for them not only to launch into the graduate-level MEMS curriculum, but also to become active in the lab for their research project. The graduate follow-on MEMS fabrication course (EE M250A / MAE M280 / BME M250A) builds upon the undergraduate course by covering more advanced and truly MEMS-specific processes. In addition, a significant emphasis is placed on process integration, with many examples taken from current MEMS literature. For a list of specific topics, please see the course description in the appendix.

B. Department-Specific MEMS Core

For students entering the MEMS graduate program in the UCLA EE department, the required core course is on MEMS design (EE M250B / MAE M282). It is felt that it is critical for EE-based MEMS students to understand the MEMS-design process for a variety of mechanical structures, transduction mechanisms, and actuation mechanisms. In contrast, students entering the MEMS graduate program in the UCLA MAE department are required to take the MEMS core course on micro-scale and nano-scale sciences (MAE 281). It is felt that unlike EE-based MEMS students, MAE-based MEMS students already have an understanding for the design of mechanical structures and motors due to their undergraduate training in these areas. The topic of transduction mechanisms is important, but it was felt that the mastery of microscale and nanoscale phenomena (e.g., micro-scale and nano-scale fluid mechanics, heat transfer, etc.) would be more vital as they are extensions of existing fields of knowledge for MAE students. An alternative way to make up this material is for MAE students to take MAE 284, since it also touches on these concepts.

C. MEMS Minor

As with other major fields in the school of engineering at UCLA, the field of MEMS has a minor. The MEMS minor is a year-sequence of MEMS courses that graduate students from other major fields can complete to satisfy a breadth requirement. The MEMS minor is simply the three courses that represent the common MEMS core and the department-specific MEMS core. Thus students can take the EE-flavored MEMS minor or the MAE-flavored MEMS minor. Of course, students with unique circumstances can petition for a different three-course sequence of MEMS classes for their minor.

D. MEMS Seminars

We do not have a regular dedicated MEMS seminar series at UCLA. Instead, the MEMS seminars are given on an ad-hoc basis in EE, MAE, and BME, and are well advertised to the UCLA MEMS community and beyond through our mailing lists.

E. Joint MEMS Preliminary Exams

After the EE and MAE MEMS graduate students complete their respective core courses in MEMS, they will take the MEMS preliminary exam. For efficiency, this exam is organized jointly between MAE and EE. The testing of the core MEMS-fabrication content is done equally by MAE and EE faculty. The testing of the MEMS-design content is largely done by EE faculty, but the MAE faculty also contribute in this area. The testing of the micro-scale and nano-scale science is done by the MAE and BME faculty instructors.

A variety of prelim-exam formats have been used, with the present version being a stable (hasn't changes in a few years) optimization of competing approaches and university regulations: a combination of a written exam and an oral examination. Oral exams are felt to be the most effective at delineating knowledge and ignorance, but written exams are more time efficient and can be instructive about the capabilities of some students.

F. Elective MEMS Courses

Due to the hiring of additional MEMS faculty within the engineering school at UCLA, other non-core MEMS-related courses have been developed and are offered as electives to graduate students from MEMS and other major fields. The topics they cover includes:

- MAE 284: Sensors, Actuators, and Signal Processing
- MAE 283: Experimental Mechanics for MEMS
- MAE 285: Interfacial Phenomena
- MAE 286: Molecular Dynamics Simulation
- MAE 287L: Nanoscale Fabrication, Characterization, and Biodection Laboratory
- MAE 288: Laser Microfabrication
- MAE 258A: Nanomechanics and Micromechanics
- BME C251: Nanofabrication of Biomedical Systems Using Nonconventional Materials
- BME 257: Engineering Mechanics of Motor Proteins and Cytoskeleton

A brief description for each core MEMS courses and the above listed elective MEMS courses is provided in the appendix.

IV. GRADUATES FROM THE PROGRAM

Since 1990, there have been over 100 students that have graduated from or are presently active in the MEMS program from UCLA in EE and MAE with an M.S. degree or M.S. / Ph.D. degrees. Many of these students have gone on to productive careers in academia (both in the U.S. and at international universities), the existing MEMS industry, as well as creating new MEMS start-up companies. The feedback received from our graduates has been quite positive. Instances of constructive criticism have lead to course-content modifications and other programmatic enhancements. In addition, an unknown number of graduate students have completed the MEMS minor, which has hopefully proved beneficial for their research project or has been at least be enlightening about a maturing field of engineering with many applications. Lastly, 173 *undergraduate* students have completed the undergraduate MEMS course. Although some of these undergraduate students were inspired enough by this class to pursue MEMS in graduate school, it is our hope that others found at least some aspect of the broad range of course material covered useful in their engineering careers.

V. CONCLUSIONS

Although the creation of MEMS as a major field at UCLA was initially somewhat controversial, we have found it to be a successful and valuable contribution to the academic system at

UCLA and beyond. Indeed, the program has now grown to over 14 courses across two departments (EE and MAE) and one interdepartmental program (BME). The MEMS courses have proven to be very popular with students from many other departments, not only within the engineering school, but from other schools as well (e.g., physical sciences, life sciences, medicine, and business). The MEMS focus of the academic core of the program and the preliminary exams insures depth and mastery of the essential MEMS knowledge. Fears that students will become overly specialized in MEMS are not realized due to the insistence that students take a strong set of electives in the application area of their research project and key related engineering fields. The opportunity for undergraduates to take an introductory MEMS-fabrication course with a hands-on laboratory, provides them with a unique experience upon which to base a graduate-school direction or their future involvement in the MEMS industry. Since we at UCLA are constantly striving to adapt our MEMS courses and MEMS curriculum to the ever-changing needs of our students and the MEMS and nanotechnology industries, we welcome comments and suggestions on how we could modify and improve our program.

VI. ACKNOWLEDGEMENTS

Some of the work presented in this paper was supported by an NSF Career Award (ECS 9876285).

VII. REFERENCES

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VIII. APPENDIX

The following is a list and brief summary of each course in the UCLA MEMS major field. The common core courses and core course unique to EE and MAE are identified.

A. Common Core Courses

Introduction to Micromachining and MEMS

EE M150 / MAE M180 / BME M150:

Begins by introducing the field of MEMS and provides examples to demonstrate its broad utility, stimulate interest, and promote a curiosity for how they are made. After the basic concept of micromachining is introduced, the following vital micromachining processes are described on a qualitative and quantitative basis: photolithography, wet etching (isotropic and anisotropic), dry etching (vapor, plasma, RIE, ion milling), vacuum systems, physical vapor deposition (evaporation and sputtering), chemical vapor deposition, thermal oxidation, diffusion, implantation, electroplating, and design of experiments (DOE).

Introduction to Micromachining and MEMS Laboratory

EE M150L / MAE 180L / BME M150L:

A companion hands-on laboratory to the main lecture course listed above. In the past the two courses were merged one. However, to ease enrollment limitations and to provide full credit to the students and instructors, the course was split. Students may take the main lecture course above without taking the lab, but enrollment in this lab requires co-enrollment in the main lecture course. In this lab the students complete a 6-mask micromachining

process that combines surface and bulk micromachining to realize microsensors (e.g., accelerometers, pressure sensors, magnetometers), microactuators (e.g., thermal actuators, magnetostatic, lorentzian), and a variety of test structures.

MEMS Fabrication

EE M250A / MAE 280 / BME M250A:

Treatment of advanced micromachining processes and their integration into complete processes to construct MEMS. Topics covered include: thick-film lithography (SU-8, LIGA), soft lithography, DRIE, wafer bonding, electroless plating, photo-electro-chemical etching, chemical-mechanical polishing, and batch-assembly techniques. In addition, materials issues such as mechanical properties and residual/intrinsic stress are also covered.

B. Department-Specific Core Courses

MEMS Design

EE M250B / MAE 282 / BME M250B:

Introduces key design concepts, methods, and examples, such as design rules, MEMS foundries, and MEMS CAD, and basic MEMS-relevant micromechanics. Covers a wide range of transduction mechanisms, gives examples of microsensors and microactuators mechanisms, and discusses their use in MEMS designs. Design project is a major component of this course.

Microsciences

MAE 281:

Covers fundamental science issues in micro-scale domain. Topics include micro fluid science, microscale heat transfer, mechanical behavior of microstructures, as well as dynamics and control of micro devices.

C. Electives MEMS Courses

Experimental Mechanics for MEMS

MAE 283:

Methods, techniques, and philosophies being used to characterize microelectromechanical systems for engineering applications. Material characterization, mechanical/material properties, mechanical characterization. Topics include fundamentals of crystallography, anisotropic material properties, and mechanical behavior (e.g., strength/ fracture/fatigue) as they relate to microscale. Considerable emphasis on emerging experimental approaches to assess design-relevant mechanical properties.

Sensors, Actuators, and Signal Processing

MAE 284:

Principles and performance of micro transducers. Applications of using unique properties of micro transducers for distributed and real-time control of engineering problems. Associated signal processing requirements for these applications.

Interfacial Phenomena

MAE 285:

Interfacial phenomena are becoming increasingly important as the size of engineering systems decreases, which leads to and increase in surface area and energy. The fundamental concepts of interfacial phenomena are introduced including: surface tension, surfactants, interfacial thermodynamics, interfacial forces, interfacial hydrodynamics, capillarity, dynamics of the triple line and electrowetting. Various applications are presented including MEMS systems, wetting phenomena, foams and emulsions, and biological systems.

Molecular Dynamics Simulation

MAE 286:

Introduction to the basic concepts and methodologies of used to perform molecular dynamics simulation. Advantages and disadvantages of this approach for various situations will also be explored and evaluated. An emphasis will be placed on systems of engineering interest, especially microscale fluid mechanics, heat transfer, and solid-mechanics problems.

Nanoscale Fabrication, Characterization, and Biodection Laboratory

MAE C287L:

A multidisciplinary course that introduces laboratory techniques of for specifically nanoscale fabrication, characterization, and biodection. Topics include basic physical, chemical, and biological principles that are related to these techniques, top-down and bottom-up (self-assembly) nanofabrication, nano-characterization (AEM, SEM, etc.), and optical and electrochemical biosensors. Students are encouraged to use their own creativity and interests to self-designed experiments.

Laser Microfabrication

MAE 288:

Science and engineering of laser microfabrication of advanced materials, including semiconductors, metals, and insulators. Topics include fundamentals of laser interactions with advanced materials, transport issues in laser microfabrication (e.g., thermal, mass, chemical, carrier, etc.), state-of-the-art optics and instrumentation for laser microfabrication, applications such as rapid prototyping, surface modification (i.e., both physical and chemical), micromachines for three-dimensional MEMS and data storage, and other up-to-date research activities. Student term projects.

Nanomechanics and Micromechanics

MAE 258A:

Recent advances in analytical and computational modeling frameworks to describe the mechanics of materials at scales ranging from the atomistic, through the microstructure or transitional, and up to the continuum are covered in this course. Topics include solving the quantum-mechanics equations of motion and applying them to the mechanics of nanosystems, atomic simulation methods and their applications at the nanoscale, and the leading continuum-mechanics-based framework used today to describe the non-linear deformation behavior of materials at the local (e.g. single phase or grain level) and macroscopic (e.g., polycrystal) scales.

Nanofabrication of Biomedical Systems Using Nonconventional Materials

BME C251:

Use of nontraditional substrates and materials in the bottom-up fabrication of biomedical nanosystems. Materials and fabrication issues, post-processing integration, compatibility with standard processes, and conventional top-down fabrication environments. Packaging concerns. Imaging and diagnostics techniques. Reliability issues.

Engineering Mechanics of Motor Proteins and Cytoskeleton

BME 257:

Introduction to the physics of motor proteins and the cytoskeleton. Topics include: mass, stiffness and damping of proteins, thermal forces and diffusion, chemical forces, polymer mechanics, mechanics of the cytoskeleton, structures of cytoskeletal filaments, polymerization of cytoskeletal filaments, force generation by cytoskeletal filaments, active polymerization, motor-protein structure and operation. Emphasis on and engineering rather than a biological perspective.