A HANDS-ON LABORATORY IN THE FUNDAMENTALS OF SEMICONDUCTOR MANUFACTURING

The Capstone Course of a New Undergraduate Option

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The semiconductor industry has grown to be the largest manufacturing sector in the United States since the invention of the first solid-state transistor by Bardeen, Brattain, and Shockley at Bell Labs in 1947. With sales of novel communication solutions for data networking, broadband, wireless, and optoelectronics, together with the continued strong demand for advanced personal computers, the global semiconductor industry is expected to grow to $1 trillion in the next decade.[1] To maintain the speed at which innovations and inventions are generated, there is an unprecedented demand for highly educated and trained engineers in semiconductor manufacturing industry in the United States and throughout the world.

This demand for experienced engineers is at **all** degree levels and has intensified with the development of revolutionary new products for the internet, computers, and communication technologies. However, the traditional engineering education training is often inadequate in preparing students for the challenges presented by this industry's dynamic environment and insufficient to meet employer's criteria in hiring new engineers. Since engineering education is a career-oriented education,[2,3] curriculum reform is needed to meet the dynamic changes in employment, starting at the undergraduate degree level.

Chemical engineers have an important role to play in semiconductor manufacturing. They are needed to design, operate, and control the sophisticated chemical processes that fabricate the chips, and to research and develop new processes capable of making the next generation of ever-denser integrated circuits. They require knowledge of chemistry, engineering, mathematics, and physics to process electronic materials at dimensions between 10 and 1000 angstroms. Naturally, well-trained chemical engineers are highly sought after by the semiconductor industry, which offers challenging job opportunities and high salaries.

To better prepare chemical engineering students for the challenges in the field of semiconductor manufacturing, specialty laboratory courses on microelectronics fabrication have been gradually introduced into the chemical engineering curriculum. Some examples are: the Department of Chemical Engineering at the University of Illinois at Chicago used the world-wide web to instruct a course on microelectronics processing[4,5] and to provide students with flexible working hours and schedules; the Department of Chemical and Material Engineering at San Jose State University set up a new concentration in microelectronics process engineering[6] that requires chemical engineering students to take one prerequisite course before they can take the laboratory course focusing on cooperative learning; and the Department of Chemical Engineering at Colorado School of Mines has a similar course on interdisciplinary microelectronics processing laboratory[7] where students are required to take one prerequisite course before they can take the laboratory course.

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This paper presents a new chemical engineering laboratory course that focuses on a multidisciplinary training program for chemical engineering students in semiconductor manufacturing, which is the focus of a new undergraduate option at UCLA.

SEMICONDUCTOR MANUFACTURING OPTION

The curriculum at UCLA is on the quarter system. The semiconductor manufacturing option is composed of 47 courses, totaling 199 course units, and is similar to the core curriculum, as outlined in Table 1. The major differences from the core chemical engineering curriculum include

- *Reducing the advanced chemistry elective courses from three to two*
- *Adding a Science of Engineering Materials course to replace one chemistry elective course*
- *Adding a Physics of Materials course to replace the Introduction to Mechanics of Deformable Solids course*
- *Adding a Physical Principles of Semiconductor Devices course*
- *Replacing one undergraduate unit operation laboratory course with the newly established semiconductor manufacturing laboratory course*
- *Requiring two elective courses in semiconductor manufacturing, with at least one of them in the chemical engineering department*

The knowledge and skills are provided through a series of six courses that emphasize the application of fundamental chemical engineering disciplines in solid-state physics, materials science of semiconductors, and chemical process engineering. The Science of Engineering Materials course introduces students to various materials used in engineering design and the Physics of Materials course teaches the electronic, optical, and magnetic properties of solid materials. Moreover, Physical Principles of Semiconductor Devices focuses on the fundamentals of semiconductor materials and basic semiconductor-based electronic devices.

These prerequisite courses prepare students for the capstone laboratory course on semiconductor manufacturing (detailed in the next section). In addition to the core courses, two elective courses in the semiconductor manufacturing area are required from over ten courses in the chemical engineering, electrical engineering, and material science departments.

The need to establish a new laboratory course stems from the fact that specialty laboratory courses on microelectronics

TABLE 1
Semiconductor Manufacturing Option
(Numbers in () represent credit units; courses in ***Italic bold*** are courses specific to this semiconductor manufacturing option)

	FALL	WINTER	SPRING
1st Year	(4) Chemical Structures (4) Calculus and Analytical Geometry (5) English Composition	(4) Chem Energetics and Change (4) Calculus and Analytical Geometry (5) Physics for Scientists and Engineers (4) General Elective	(2) General Chemistry Lab (4) Introduction to Organic Chemistry (4) Calculus/Several Variables (7) Physics for Scientists and Engineers and Lab
2nd Year	(4) Introduction to Chemical Engineering (3) General Chemistry Lab (4) Calculus/Several Variables (7) Physics for Scientists and Engineers & Lab	(4) Introduction to Eng. Thermodynamics (6) Organic Chemistry (4) Linear Algebra and Applications (4) Introduction to Computing	(4) Intermediate Inorganic Chemistry (4) Infinite Series **(4) *Science of Engineering Materials*** (4) General Elective
3rd Year	(4) Momentum Transfer (4) Math in Chemical Engineering (4) Physical Chemistry (4) Electrical and Electronic Circuits	(4) Heat Transfer (4) Chemical Engineering Thermodynamics **(4) *Physics of Materials*** (4) General Elective	(4) Mass Transfer (4) Separation Processes (6) Chemical Engineering Lab I (4) General Elective
4th Year	**(4) *Physical Principles of Semiconductor Devices*** (4) Chemical Reaction Engineering (4) Chemical Elective (4) General Elective	**(6) *Semiconductor Manufacturing Lab*** (4) Process Dynamics and Control (4) Process Economics and Analysis **(4) *Semiconductor Manufacturing Elective***	(4) Chem Proc Computer-Aided Design and Analysis **(4) *Semiconductor Manufacturing Elective*** (4) Chemical Elective (4) General Elective

fabrication have traditionally been offered in the electrical engineering departments throughout the country. In these laboratory courses, the number of students enrolled has to be regulated due to the stringent cleanroom safety requirement, and priorities in enrollment are often given to students in the electrical engineering department. Therefore, chemical engineers can only occasionally receive training in this area through co-listed courses[8] or through specialty non-laboratory courses such as thin film processing.[9,10] This situation limits chemical engineering students from gaining systematic training in the area of semiconductor manufacturing and motivated the establishment of this hands-on laboratory course in the Chemical Engineering Department at UCLA.

SEMICONDUCTOR MANUFACTURING LABORATORY

This new course is a six-credit-unit course that comprises four hours of lectures and four laboratory hours each week to provide both knowledge and training in semiconductor manufacturing. The lectures are organized into modules and are instructed in parallel with the laboratory work, as shown in Table 2.

In the first seven weeks of the quarter, the course focuses on theories and models for various chemical processes, and in the last three weeks it focuses on electronic device characterization and design of experiments. It is worth noting that chemical engineering students form teams with electrical engineers and material scientists in the laboratory to carry out the entire process flow in making solid state devices, including capacitors, p-n junctions, and complementary metal-oxide-semiconductor (CMOS) transistors. This special team assignment simulates a real work environment in microelectronics-related industries, where engineers are required to apply knowledge from various disciplines to engineer novel semiconductor manufacturing processes.

The focus of the course, especially in the lectures, is to combine the chemical engineering principles (transport, kinetics, and thermodynamics) with the fundamentals in microelectronics-related semiconductor manufacturing. This is very different from, and complements, the focus of a similar course offered in the electrical engineering department. Through collaboration of the faculty in both departments, the weekly laboratory sessions are offered jointly and students from the various departments are teamed up to combine expertise from their own discipline in solving the problems in fabricating microelectronics.

Priorities are given to chemical engineering students who have taken all the prerequisite courses in the Semiconductor Manufacturing Option, but students with proper prerequisites from all science and engineering departments are welcomed to the course.

Sample of Course Lecture

Each course module focuses on either a unit operation of the chemical processes, theory of electronic devices, or device testing. Due to the lack of an up-to-date and comprehensive textbook, the author developed course materials[11] and used several reference books[12-14] in the classroom. The course module on ion implantation and a sample of students' homework are briefly described here.

Ion implantation is one important process step in microelectronics fabrication. Ion implantation is an alternative to diffusion for introducing known concentrations of dopants into specific locations in silicon wafers. During the ion implantation process, energetic ions penetrate a solid target, lose their energy due to collisions with atomic nuclei and electrons in the target solid, and eventually stop to rest. The course module covers the theory of ion stopping, the mathematical formulation of the concentration distribution of the implanted ions, the channeling effect, the implantation damage, the dopant activation annealing, and finally a Monte Carlo simulation of the implanted profile.

Sample of Student's Homework

Students are trained to use a Monte Carlo based software,[15] which allows them to learn the dynamics during the ion implantation process. Using Monte Carlo simulation, ion im-

TABLE 2
Course Outline for the Semiconductor Manufacturing Laboratory Course

Week	Lecture	Laboratory
1	Introduction to Device Fabrication Introduction to Chemical Processing	Define N-well for PMOS devices Define active area for CMOS devices
2	Optical Lithography Crystal Growth	Gate oxide growth Polysilicon Deposition
3	Silicon Oxidation Wafer Cleaning	Define polysilicon gate Etch gate oxide
4	Diffusion Ion Implantation	Ion implantation to form source and drain of MOSFET devices
5	Simulation Lab (TRIM) Midterm	Deposition of interlayer dielectric (SiO_2)
6	Film Deposition (I): Semiconductors Film Deposition (II): Dielectrics/Metals	Define contact areas to gate, source, and drain
7	PN Junction MOS Capacitors	Aluminum deposition and etching
8	MOSFET Devices Electrical Characterization	Device testing (diodes, capacitors)
9	Film Patterning (Etching) Metallization and Interconnection	Device testing (MOSFETs)
10	Design of Experiments	Poster presentation

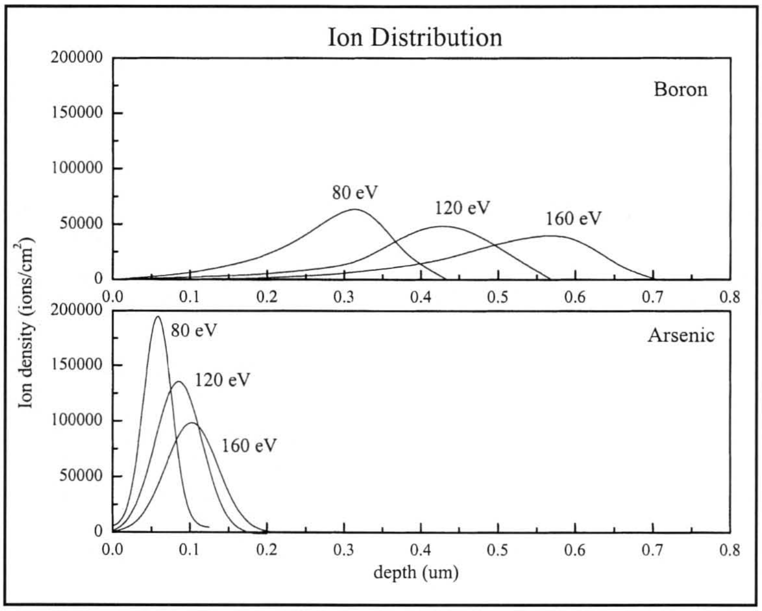

Figure 1. *Ion implantation simulation.*

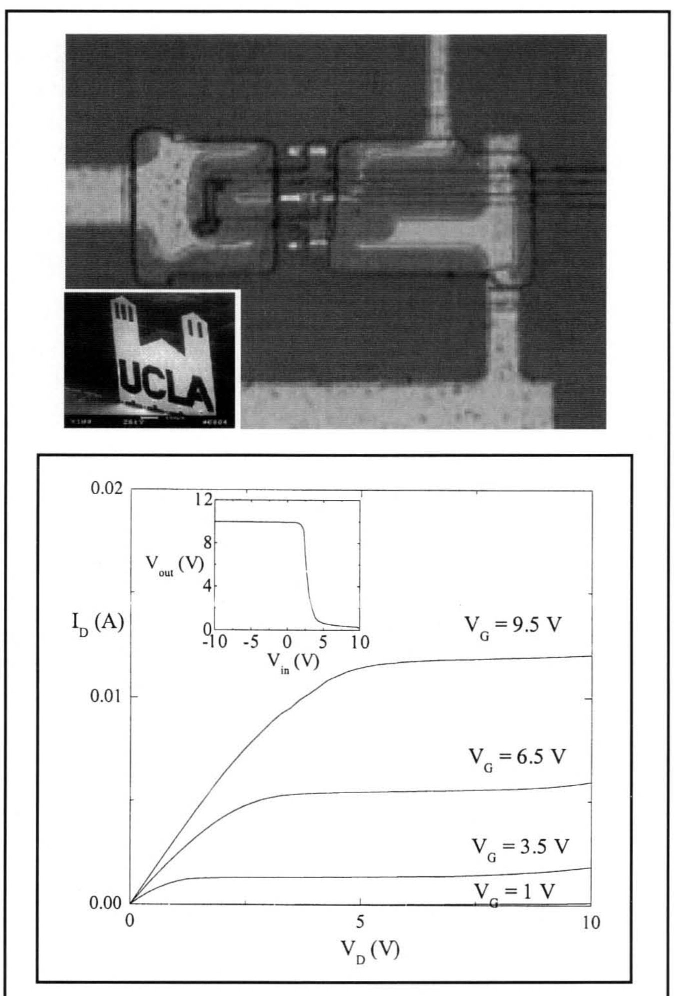

Figure 2. *CMOS (MEMS) device fabricated at UCLA and the measured NMOS and CMOS performance.*

plantation is simulated by tracking the history of an ion through successive collisions with target atoms using the binary collision assumption. The trajectory of each ion as a function of its energy, position, and direction is determined. A large number of ion trajectories are calculated to yield statistically meaningful results. This topic ties very nicely to the mass-transfer problems in dopant diffusion that the students also learned in the class. An example of students' homework simulation results on ion distribution is shown in Figure 1.

Statistical Design of Experiments

It is critically important that students learn statistical analysis in the laboratory course. This course module discusses the normal and Student t-distributions, the null hypothesis, randomization and blocking of experiments, and factorial design. Students learn how to assess the effects and interactions of important process parameters and systematically improve their experiments. Due to time constraints, the fractional factorial design and response surface analysis are not covered in the course, but students can easily learn these concepts based on their acquired knowledge in this course.

New Photolithographic Masks for Fabricating Micro- and Nano-Electronics

A new seven-mask set that contains micrometer- to nanometer-scaled CMOS devices, bipolar junction devices, diodes, capacitors, and alignment markers designed to minimize the translational and orientational misalignment is designed for this laboratory course. Students learn how to complete CMOS processing, starting from patterning isolation field silicon dioxide to finishing the device structure by patterning aluminum metal lines, using a total of seven photolithographic steps. In the process of making these miniature electronic devices, students learn how to carry out unit operations in photolithography, oxidation, chemical and physical vapor deposition, ion implantation, and wet and dry etching. As precision and thoroughness are required to ensure the reproducibility of the patterned thin-film materials and the performance of the semiconductor electronic devices that students built, students learn to cooperate and be responsible for the performance of the team. Through the laboratory experience, the fundamental principles of materials processing taught in the lectures are better realized by the students.

Teamwork, Report, and Presentation

As this is an experimentally oriented laboratory, students need to be trained to use delicate vacuum equipment, sophisticated thin-film processing systems, specialized metrology and spectroscopic techniques, and electrical testing devices. To ensure effective training, each laboratory session is assigned one teaching assistant to work with one full-time staff in the laboratory. These teaching assistants are graduate students who have previously taken the same course. All of the above mentioned activities take place in a dedicated student microfabrication laboratory, approximately 700 ft^2, located inside the Nanoelectronics Research Facility[16] at UCLA. It is a Class 1000 HEPA filtered clean room where students conduct photolithography, wet cleaning, wet etching, and all metrology measurements. The advanced material processing steps are carried out in the nanoelectronic research lab.

[Chemical Engineers] are needed to design, operate, and control the sophisticated chemical processes that fabricate the chips, and to research and develop new processes capable of making the next generation of ever-denser integrated circuits.

A SEM image of devices fabricated by the students is shown in Figure 2 along with the device results tested by the students. Each team has to turn in a comprehensive team report at the end of the quarter summarizing the processing details and electrical characterization.

The laboratory report is an integral component of the students' overall performance in the class. Starting with an executive summary, students include an introduction, a concise summary, and discussion of their fabrication process and experimental results, including process measurements and device measurements.

With the theory of the fabrication processes from the lectures, students predict process parameters such as field oxide thickness and color, gate oxide thickness, junction depths and doping levels, sheet resistances, polysilicon thickness, aluminum thickness and sheet resistance, and make comparisons with actual measurements when possible.

The device parameters include measurements from diode (saturation current, forward turn-on voltage, reverse breakdown voltage, and the ideality factor), MOSFET (threshold voltage, transconductance, channel mobility), and other devices such as bipolar junction transistor and ring oscillator.

The most important part of the report is the discussions. Students are asked to provide a thorough evaluation of the experimental results and an explanation for any discrepancies between the measurements and calculations, and to suggest modifications to the processes to improve the device performance when applicable. They are graded on the insight shown in correlating device characterization to process sequences, as it is the most critical part of their training.

In addition to technical writing, students are also trained in their technical presentations. At the end of the course, each team presents a poster that covers one important process used in manufacturing integrated circuits. Example topics include: chemical vapor deposition of dielectrics, semiconductors, and metals; plasma etching; surface passivation and modification; surface tribology of chemical-mechanical polishing; and chemistry-based micro-electromechanical systems. The presentation includes a description of the chemistry and physics of the material processing, the state-of-the-art technology used in that particular field, an estimate of the market size of the technology, and the current research and development. Students present the poster to the entire class, handle the discussion and questions, and are given grades based on the technical and presentation merit of their work.

ASSESSMENT

In its first two offerings in the Spring quarter of 2000 and the Winter quarter of 2001, the semiconductor manufacturing laboratory course attracted the maximum number of students (15) that the facility could safely accommodate. The students appraised the course and the instructor with an excellent overall rating of 8.42/9.00. The students were very positive about their learning experience; some of their comments were:

- *That the material covered a broad range of topics related to the objective of the course*
- *That the instructor was masterful in objectives*
- *That the lecture notes were very helpful and well organized*
- *That they wish to do more practical work in the lab sessions.*

As the ultimate measure of the success of this option is the placement of students after they graduate, we are pleased to see that students who completed this option successfully entered the workforce in the semiconductor industry. Some of them have given us their assessment of the value of the course *after* they started working. *e.g.*:

- *The course that you put together allowed me to pick up the manufacturing process at TRW within weeks. Even though I am working with GaAs and InP HBT, the basic processing is still the same as 104C. I [am] responsible for mostly making sure the Ultra Tech Steppers are running smoothly; if something goes wrong I have to run experiments to figure out what's wrong.*
(Message from a student now working at TRW)
- *Our group is focusing on tungsten CVD, so the main tool is for tungsten deposition. Although the*

tool is more advanced than what I learned in class, the concept of the whole process is similar. I would say the lectures are very useful, because the lectures really assist me in quick and better understanding of the process methodology. In addition, it's wonderful that you showed us the Integra One in class and explained about the loadlock system. In the labs, I saw loadlock systems everywhere, and they remind me of your last lecture in the nanolab. (Message from a student now working at Novellus)

Because of students' positive feedback and the large number of them who are interested in this option, the laboratory has been fully renovated with support from the School of Engineering at UCLA and various industrial sponsors. The capacity of the bottlenecking process step, photolithography, has been doubled. Two parallel lithographical systems enable the training of more students in each laboratory session. To accomodate the large number of students and with the additional resources allocated (one full-time staff), we can now offer the course twice a year, each with four laboratory sessions per quarter, to train up to forty chemical engineering students and sixty electrical engineering students in a year's time.

The laboratory course and the new semiconductor manufacturing option have been accredited by the Accreditation Board for Engineering Technology (ABET) in 2000 as an integral component of the chemical engineering curriculum. This laboratory course was also recently featured in an article titled "Learn to Make Your Own Semiconductor Device" in the NSF Engineering On-Line News:[17]

In its first offering by Chang, the course attracted the maximum number of students that the facility could safely accommodate. Renovations over the summer made it possible to increase the number to 20 students per quarter (40 per year) . . . the lab lets students fabricate their own integrated circuits in the school's cleanroom facility . . . This experience is invaluable, and ensures them great career opportunities.

SUMMARY

The curriculum innovation and integration in semiconductor manufacturing and engineering enable training of students for the greater challenges in the 21st century. This hands-on undergraduate laboratory course aims to train students in semiconductor manufacturing through a series of lectures, laboratory experiments, a laboratory report, and a technical presentation. Up to forty undergraduate students can be trained each year through this program. Students who have successfully completed this option are highly sought after by industrial recruiters and academic graduate programs nationwide.

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