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MICROELECTRONICS PROCESS ENGINEERING: A NON-TRADITIONAL APPROACH TO MS&E

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ABSTRACT

Materials Science and Engineering straddles the fence between engineering and science. In order to produce more work-ready undergraduates, we offer a new interdisciplinary program to educate materials engineers with a particular emphasis on microelectronics-related manufacturing. The bachelor's level curriculum in *Microelectronics Process Engineering (μProE)* is interdisciplinary, drawing from materials, chemical, electrical and industrial engineering programs and tied together with courses, internships and projects which integrate thin film processing with manufacturing control methods. Our graduates are prepared for entry level engineering jobs that require knowledge and experience in microelectronics-type fabrication and statistics applications in manufacturing engineering. They also go on to graduate programs in materials science and engineering. The program objectives were defined using extensive input from industry and alumni. We market our program as part of workforce development for Silicon Valley and have won significant support from local industry as well as federal sources. We plan to offer a vertical slice of workforce development, from lower division engineering and community college activities to industry short courses. We also encourage all engineering majors to take electives in our program. All our course and program development efforts rely on clearly defined learning objectives.

Keywords: *microelectronics process engineering*

INTRODUCTION

The program in Microelectronics Process Engineering (μProE) at San Jose State University began with a directive from the college Dean to explore how the Materials Engineering (MatE) department could better serve the needs of Silicon Valley. It seems obvious that electronic materials should be a strong emphasis for a department located in the heart of Silicon Valley, but prior to 1992 there were no required courses in electronic materials in the MatE program. There were lecture-only elective courses on semiconductor processing offered independently in both the Materials Engineering and the Electrical Engineering departments. However, most graduates of both ChE and MatE were going to work at semiconductor, data storage and equipment manufacturing companies.

The simultaneous appointment of MatE, EE and ChE faculty with backgrounds in semiconductor processing and experience working in interdisciplinary engineering environments provided the impetus for the three departments to start working together. First, a new required course in Electronic Properties of Materials (MatE 153) was established for both MatE and EE students[1]. Next, the three departments offered a joint laboratory course in semiconductor processing, "Basic Integrated Circuit Processing and Design" (MatE/EE 129). This course continues to be offered as a team-taught, team-based course utilizing a fictional company, Spartan Semiconductor Services, as a pedagogical environment[2,3]. Students work in parallel teams to produce and test NMOS circuits as well as to design and implement process characterization and development projects. These two courses, developed with the aid of an NSF ILI grant[4], now serve as the introductory core for the new Microelectronics Process Engineering program.

Two additional courses have since been developed, with the assistance of an NSF CCLI grant[5]. "Advanced Thin Film Processes" (MatE/ChE 166) and "Microelectronics Manufacturing Methods" (MatE/EE 167) are required in the μProE program and are available as electives for all other engineering majors. The former course (166) examines individual unit processes and characterization techniques used in microelectronics fabrication, while introducing statistical design of experiments (DOE). In the latter course (167) student teams run a CMOS factory, perform ISO audits, explore effects on product yield, and learn to apply statistical process control (SPC) methods such as control charts to their factory. Both courses utilize the pedagogical environment of Spartan Semiconductor Services, Inc. (S3i), to provide a realistic context for the learning activities and to motivate students to master their learning objectives. The courses will be discussed further below.

The μProE program in its entirety is comprised of (i) a set of academic programs, (ii) a laboratory and its associated technologies, (iii) an industry partnership program, (iv) faculty and student research efforts, (v) a short course program, and (vi) linkages to high schools and community colleges. Our objective is to provide a vertical slice of workforce development in areas related to microelectronics-type manufacturing. At this point, the first four components of the program are in place and in various stages of growth. The latter two components are in earlier stages of development. There is a high degree of linkage between these six components of the program, as will be shown. This paper will focus on the academic programs with some discussion of the laboratory technologies as they relate to those programs. Course structure, development of learning objectives, and marketing of the program will be discussed below.

THE ACADEMIC PROGRAMS

The academic programs (degree-granting) offered either through the μProE program or in association with it are shown in Table I. The BS Concentration and the Minor rely strongly on the four μProE courses mentioned above (129, 153, 166 and 167), and these courses are also available for engineering electives. The lower division modules are one-time lab activities which can be integrated into a number of lower division courses, such as Freshman Engineering (E10), Introduction to Materials (MatE 25) or General Chemistry (Chem 1A/1B). These activities allow lower division students to get a "taste" of microelectronics processing and devices while they still have the option of changing their major or choosing a minor or concentration area. The MSE degree is popular with local engineers seeking an advanced degree in the interdisciplinary area of electronic materials and devices. The CME department offers many graduate electives in semiconductor processing, many of them taught by industry experts, but they generally do not have lab sections. These graduate students may enroll in up to 9 units of undergraduate courses,

Table I. μProE academic programs.

Program/Opportunity	Target Customer
BS General Engineering, Concentration in Microelectronics Process Engineering (μProE)	BS Engineering students
Electronic Materials Processing Minor	Any science or engineering major
Elective Sequence	Any science or engineering major
Lower Division Modules	Undecided freshmen engineering students; chemistry students
Master of Science in Engineering, Concentration in Electronic Materials and Devices	Graduate students with any BS Engineering degree

Table II. Examples of μProE Program Objectives.

ABET Outcome	μProE Program Objective: *A graduate of the μProE program should be able to...*
1. Ability to apply knowledge of mathematics, science and engineering	1.1 Make all required calculations for predicting and designing process step (e.g. diffusion, ion implant, etc.). 1.2 Make effective estimations and assumptions where necessary and document reasoning. 1.3 Compare analytical calculations with simulated results and tabulated data.
2. Ability to design and conduct experiments and analyze and interpret data	2.1 Use statistical design of experiments and response surface methodology to characterize and optimize a process. 2.2 Design a metrology procedure to characterize a process or device. 2.3 Select appropriate measurement techniques to characterize a process. 2.4 Capture limitations and error ranges of measurement tools.
4. Ability to function on multidisciplinary teams	4.1 Designate team roles and assign and monitor specific tasks of team members. 4.2 Resolve conflict within team. 4.3 Self-assess performance of assigned roles within team

which may provide significant laboratory experiences for them. Currently a number of MSE students are performing technology development for the program as the subject of their Masters thesis research[6]. Each of these programs will be discussed below in some detail, with the exception of the graduate program.

BS Program in Microelectronics Process Engineering

The BS Program has been initiated as a Concentration within the General Engineering program. The GE program exists to serve as an "incubation site" for new programs in the College of Engineering and provides the freedom to try new interdisciplinary curricula. Once the program is fully enrolled and successful, the option exists within the University to pursue degree standing for the program and apply for ABET accreditation. The program is being developed using ABET outcomes, program objectives and an assessment structure which will ensure that it is well-positioned for accreditation when the time comes. All new course design begins with a detailed list of specific learning objectives.

μProE Program Objectives

Thirty-five program objectives were developed for the new μProE program, which are correlated to the ABET outcomes. Several of these objectives are shown in Table II as examples. Assessment of the program is continuous. We check to see if graduates of the program have met the program objectives; we constantly check whether our courses and other activities are deigned in such a way that provide opportunities for mastery of the objectives and each course in the program must be clearly linked to various program objectives. The course learning objectives (discussed below) allow us to assess whether student have mastered coursework, and also allow us to assess whether we have designed the course properly to fit the program objectives. The first graduate of the program (May 2001) has gone on to graduate school, well aware that he will be the seed of an extensive alumni database for reviewing long-term program outcomes!

Microelectronics Process Engineering Core Courses

Figure 1 shows most of the courses required for the interdisciplinary μProE degree as a flow diagram. Not all of the required and elective courses are shown here, but the contribution of each of the four disciplines is shown along with the core μProE courses. With this interdisciplinary aspect, we were able to initiate a new program with only three new courses.

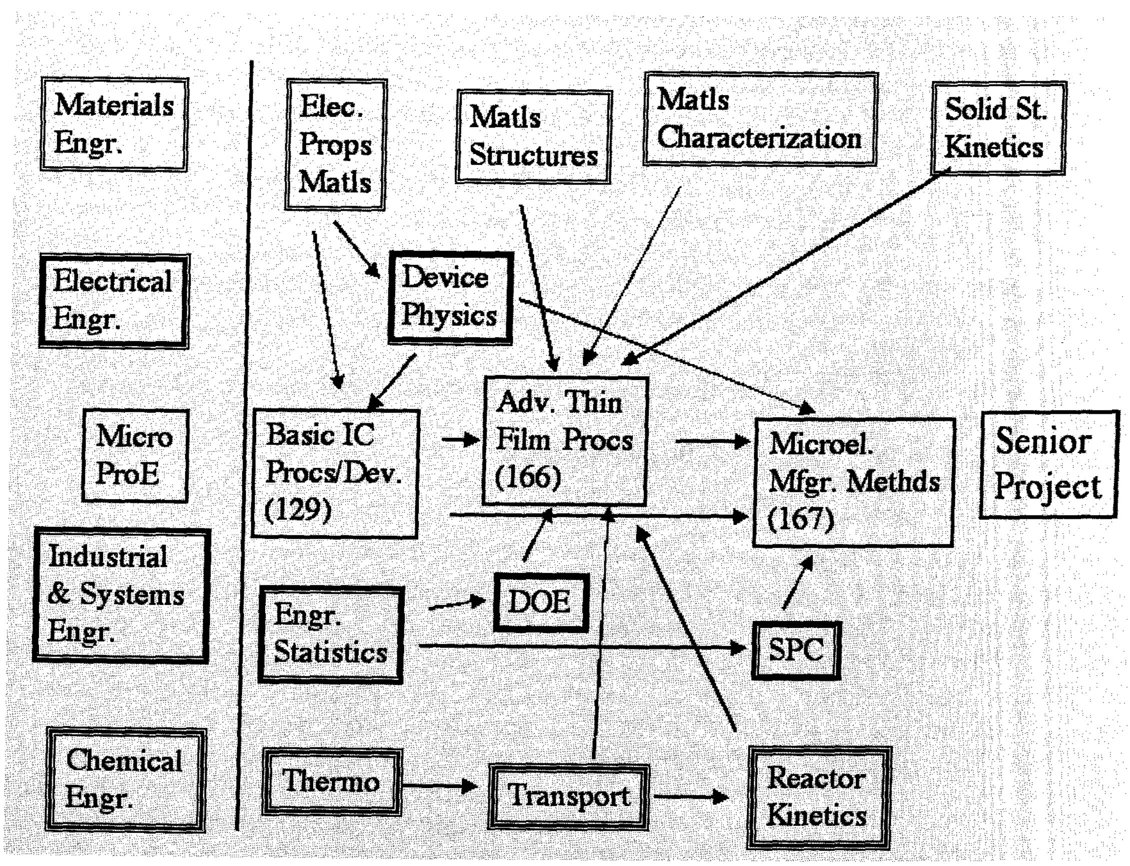

Figure 1. Flow diagram of interdisciplinary course work leading to μProE degree.

Table III. Examples of Course Learning Objectives from MatE/EE 167.

MatE/EE 167, Microelectronics Manufacturing Methods
After successfully completing the course assignments, lab assignments, reviewing lecture notes, participating in class discussions, homework assignments and examinations, a student should be able to...
Model wet and dry oxidation using SUPREM
Discuss methods of reducing/controlling fixed oxide charge
Use SPICE level 1 models to simulate t_{PHL};
Extract threshold voltage, gate oxide thickness, and body doping of PMOS and NMOS transistors using CV plot data.
Identify sources of variation
Describe tools and actions which can minimize special cause and common cause variation
Calculate central line, upper and lower control limits for x-bar chart
Determine when a process is not in statistical control

Table IV. Examples of Learning Objectives and Course Activities for "Advanced Thin Film Processes".

Learning Objectives for MatE/ChE 166	
Learning Objective	*Course Activity to Achieve LO*
Explain different ways to measure dielectric and metal thickness.	Written Homework, Team experiment design
Discuss different ways of measuring the chemical composition and impurity level and identify the best measurement technique for different situations.	Research Paper
Identify process steps that may result in variation during photolithography	Experiment/Poster
Design an experiment to optimize the reactive ion etch process for thermal oxide films.	Experiment/Oral presentation

Table V. Examples of learning objectives for solar cell test module.

Solar Cell Test Module Learning Objectives
After completing the preparatory exercise and homework assignment, attending the lecture and performing the lab activity, an Engineering10 student should know how to...
Identify when and where photovoltaic cells were invented.
List some solar cell applications.
Build a test circuit using digital millimeters, solar cell & resistors.
Measure current and voltage using a digital multimeter.
Record the data accurately and legibly.
Plot the data appropriately in an Excel spreadsheet.
Distinguish between current (I) and current density (J).
Describe how illumination level controls power output.
Design and implement a cell layout to power a battery charger.

Each of these three courses (129,166,167) integrates more than one discipline within the course structure. For example, MatE/EE 167 combines CMOS processing with SPC, and is typically taught by an EE professor paired with an ISE professor. MatE/ChE 166 combines DOE with thin film processing and characterization and is typically taught by a pair of ChE and MatE professors. MatE/EE 129, the basic processing course, is usually taught by a team from ChE, MatE and EE. This course in particular has been taught by ten different faculty members, including part-time instructors from industry, and still retains its robust team-centered structure. A new NMOS process was developed this year to replace the original PMOS technology.

Course Learning Objectives

In order to ensure that courses contribute to a set of program objectives, the first step in course design is defining the specific course learning objectives (LOs). A typical 3-unit course will have 50 to 100 learning objectives. Learning (in the cognitive domain) refers to the acquisition of knowledge, and Bloom's taxonomy classifies this acquisition into six levels of mastery, from the novice (Level One) to the expert (Level Six)[7]. Within a discipline, acquisition of knowledge can be assessed in terms of the student's ability to perform certain activities associated with the level of mastery. For example, a novice in a scientific discipline might be expected to merely *list* some fundamental concepts, while an expert could be expected to *design* a system based on the same concepts.

Table III shows some examples of learning objectives for MatE/EE 167. In practice, the first set of LOs is often produced concurrently with the first course offering. By the time of the second offering, the course has been tailored to an appropriate size and shape, and further tinkering with the course LOs is fairly minor. However, courses based on LOs remain flexible and can always be changed to meet future program needs. The beauty of basing a curriculum on well-defined course objectives is that courses lose their identification with a single individual. Not only are most of our courses developed in teams of faculty, but when new faculty teach a course for the first time, remaining faithful to the course objectives is the only requirement. The *course activities* are intimately related to the *course learning objectives*, but the faculty are only accountable for meeting the latter. Designing new activities and new ways to meet course objectives provides plenty of room for innovation by faculty.

In the μProE program, the technical course learning objectives are written around fundamental concepts, rather than state-of-the-art equipment. For example, Table IV shows a few learning objectives from the Advanced Thin Film Processes course (MatE/ChE 166). These objectives can in principle be met in many different types of laboratories on different types of equipment. Specific course activities are carried out on whatever equipment is available; when equipment upgrades occur the activity can be changed, but the course objective remains the same.

Electronic Materials Processing Minor and Electives

Any engineering or science major at SJSU may enroll in the μProE courses, subject to a prerequisite check. Usually an upper division student in any technical major is allowed to enroll in MatE/EE 129, the basic processing course. Student teams are deliberately made interdisciplinary in this course with a mixture of academic background and experience. Any student can continue on to 166 or 167 after completing 129. Most of our enrollment is μProE, MatE, ChE and EE students, but we have had occasional ISE, ME, CmpE, Physics, Math, and Chemistry majors. We have also had business majors or MBA students request a spot, but in general they do not have the technical background needed for the academic rigor. A student who completes 12 units of work in this field (outside the requirements of their major) may apply for a Minor degree, which appears on the diploma. Many students take the courses as technical electives in their major so as to avoid taking extra units.

Lower Division Modules

The lower division modules are one-time educational experiences in the μProE lab, intended to interest lower division students in majoring in μProE or taking courses in this area. Courses which contain 3-hour lab sessions and which can spare one or two weeks of the semester can include in their curriculum a processing or testing component. For example, we are currently developing a two-week solar cell module for freshman engineering courses. The first week, students make silicon solar cells in the lab; the second week they test their cells and perform a design activity. Other courses which contain modules include Introduction to Materials (sophomore class) and Electronic Properties of Materials (junior class). We plan to offer a module to chemistry and physics classes. Community college instructors occasionally bring in their students to perform modules as well.

Modules also require learning objectives, especially because they aid in designing a concentrated experience that is oriented towards specific learning activities which go beyond "getting familiar with the lab". Since the purpose of the modules is to recruit students into our μProE courses, they take place during other courses taught by other departments and instructors. Identifying learning objectives which serve the goals of the "parent" course makes them attractive to the other departments. For example, the solar cell testing module makes use of Excel spreadsheets, plotting routines, and curve fitting. These are some of the goals of Engineering10 (Freshman Engineering), assuring that this module will become an integral part of the course. Table V shows a partial list of the learning objectives for the solar cell testing module. This module was successfully tested in three E10 sections this semester and student feedback was very positive. The current energy situation in California may have motivated students' interest in solar cells, but the attention to detail which was used in the module design was a result of the requirement of being faithful to the learning objectives.

PROGRAM MARKETING AND ENROLLMENT

The original motive for development of the μProE program was as a method of increasing the enrollment in the MatE program itself. That program has suffered from low enrollment for many years and frequently comes under fire for its low number of majors and small course sizes. It was thought that by providing more course and lab activities in the area of electronic materials, new students would be attracted to the Materials Engineering field. Although the enrollment in the μProE courses has increased significantly (30 students in the first joint MatE/EE offering of 129 in 1995 has increased to offering the course twice a year with full enrollment of 45 students). There are now 10 μProE majors and many ChE and EE students taking μProE courses. However the MatE program still suffers from low visibility, and since the μProE majors do not take some of the MatE core courses, those class sizes remain small. Therefore other means of marketing and publicizing the MatE program must be undertaken. Since the merger of ChE and MatE into one department (CME), all marketing for ChE, MatE and μProE will soon be integrated into a single effort aimed at enhancing our visibility in high schools and community colleges. Some of our activities are discussed below.

Prospective students learn about the μProE program through our website, through their high school or community college teachers, through Engineering Open House and Discovery Camp, or through SJSU's on-line application form. Although many students have never heard about materials engineering, the words "Microelectronics" tends to catch their attention. The program began accepting students Fall 99, and we will graduate our first student this June. We currently have 10 majors, 20 new admitted students for Fall 2001 , and about 65 students have taken a μProE elective course this academic year (2000-01). Although these are small numbers by enrollment standards, they are a significant increase to the CME Department statistics. We are relying on this program to provide enough majors and elective students to allow the traditional MatE program to continue as a small program.

The μProE program has received significant funding from local industry to support the lab activities, with over $450,000 to date. Some of these funds have been used for program promotion and recruiting. The present economic climate presents a new challenge. Significant resources must be channeled into recruiting and retention to keep the program healthy and promote its growth. For example, this semester we have initiated the Discover Engineering Camp, a one day hands-on exploration of all the programs in our department for high school students. We are highlighting the Materials, Chemical, Biochemical, Environmental Health and Safety and Microelectronics Process Engineering programs. We administer a brief survey to all incoming freshmen and transfer students at their first advising session to determine what influenced their decision to enter the CME department, where they heard about the major, etc., as an ongoing aid to understanding where to direct our outreach efforts. Results from the survey indicate that about 75% if our students are transfers and learn about their major from community college faculty and counselors. Very few if any learned about materials science during high school or from a high school teacher. We are trying to change that by establishing stronger links with local high school teachers, especially those who teach in the local high school Engineering programs (16 local high schools offer this program).

SUMMARY

A unique B.S. curriculum in Microelectronic Process Engineering is offered at SJSU. Students from materials, chemical, and electrical engineering also populate the course sequence in semiconductor processing. Courses focus on manufacturing methods such as design of experiments and statistical process control in addition to fabrication methods. An NMOS process is functioning and a CMOS process is under development. Laboratory processes available include oxidation, spin-on dopant diffusion, reactive ion etching, sputter metallization and contact lithography; other processes such as implant and CVD are performed by local vendors.

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