Cooking Without Recipes: a Case Study for an Open-Ended Laboratory Experience in Semiconductor Processing

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Introduction

The need for graduate engineers with the ability to think critically about a design problem, work with teammates from different disciplines, communicate ideas effectively in both written and oral format, and to comprehend “the big picture” has been well-documented[1,2]. We have proposed a new method of designing laboratory courses for the upper division which promotes the development of such skills as well as teaching experimental design. We are currently testing our hypothesis that traditional weaknesses in data analysis, communication of ideas, and self-motivated acquisition of knowledge can be overcome by providing students with a laboratory environment which encourages open-ended experimentation. To this end, we are developing a methodology for converting typical “cookbook” laboratory courses to multi-disciplinary, team-based open-ended design experiences.

Our work is done in the context of the development of an interdisciplinary curriculum on electronic materials and devices[3]. The curriculum consists of a three-course sequence, primarily for Electrical and Materials Engineering majors. In two of the courses (“Electronic, Optical and Magnetic Properties of Materials” and “Semiconductor Device Physics”) we develop fundamental skill areas such as written and oral presentation of engineering ideas; data interpretation and presentation; and cooperative learning. These skills are then applied in an elective course on integrated circuit fabrication (“Electronic Materials Processing”). The course is completely team-based and the classroom is treated as a start-up company, nicknamed Spartan Semiconductor Services, Inc. The teams are hand-assembled by the instructors and rotating jobs are assigned to encourage leadership and responsibility. During the semester course, the students fabricate and test semiconductor devices as well as perform experiments on various aspects of semiconductor processing. This paper will focus on the development of this course.

Academic Context

San Jose Sate University is a primarily undergraduate institution which draws its students from the surrounding Silicon Valley. It is primarily a commuter school, and a majority of the engineering students transfer from community colleges as juniors. Many students hold part-time or full-time jobs in local industry while studying part-time; the result is that on the whole students do not go through the engineering program as part of a cohesive unit. This makes team learning skills an important skill on which to focus.

The course was taught in this format for the first time in Spring Semester 1995, and in revised form is being taught during Spring Semester 1996. During the Winter Quarter (1996) the course will be taught for the first time at California Polytechnic University, San Luis Obispo. A description of the conversion from semester to quarter course is included below.

Course Description

MatE 120A/EE 129 ("Electronic Materials Processing") is an undergraduate elective course in semiconductor processing. The format is 2 hours lecture, 3 hours laboratory per week. The students are not assumed to have any previous background in the subject, although many have some work experience in local industry. Because the course is multi-disciplinary, entering students have different backgrounds and consequently different prerequisites are applied. Students majoring in EE are required to have a pre-requisite or co-requisite course in Semiconductor Device Physics (EE 128). Materials Engineering majors are required to have taken the prerequisite course Electronic, Optical and Magnetic Properties of Solids (MatE 153). Chemical, Mechanical, and other Engineering majors are required to have taken the lower division course Introduction to Materials (MatE 25) and to be in their last year of study. In this way entering students are assumed to have one of the following: familiarity with electronic devices OR familiarity with the structure and properties of electronic materials OR maturity in their own discipline. Students are expected to contribute to the course by being active team members, not merely passive receptacles for knowledge.

The lecture course covers the fundamentals of integrated circuit fabrication, including silicon oxidation, impurity diffusion, physical and chemical vapor deposition of thin films, surface cleaning and photolithography. During the 15-week laboratory, student teams process two batches of 10 wafers using a five-mask, metal gate PMOS process. The teams also design and implement experiments on process development.

Team Structure

In keeping with the “start-up company” culture, on the first day of class the students complete an Employee Information Survey, shown in Figure 1. The information in the profiles is used by the instructors to compose the individual teams. In the 1995 class of 24 students, we created four teams of six students each, meeting during two different lab times (three hours per week). Ideally, the teams should have a maximum of four students[4], however limitations in laboratory facilities required us to limit the number of teams. In the 1996 class, we limited class size to 20 students, comprising five-member teams. The smaller team size is definitely more tractable in the laboratory setting. The teams are assembled to be as heterogeneous as possible, from the point of view of diversity in knowledge and work experience.

Name, Academic Major		
Address, Phone Number		
Employed? F/T	P/T	How many hours?
Current job title/description		
Prior experience with electronics or processing		
When do you expect to graduate?		
Grades in the following courses (for MatE’s): MatE 25, MatE 115, MatE 153		
Grades in the following courses (for EE’s): MatE 25, EE 122, EE 128		
GPA in major		
Is silicon a) a metal b) an insulator or c) a semiconductor?		
What is the numerical value of the charge on an electron?		
What do the initials “MOS” stand for?		

Figure 1. Questions from Employee Information Survey used to assemble teams.

Examples of team composition are shown in Figure 2. The teams were intended to be heterogeneous on three counts: GPA ("low" or "high", dividing line 3.0/4.0); work experience (relevant or not); and by major.

Course Sequence

The semester is divided into a sequence of six 2-week periods. During each two-week period, the teams have a specific set of goals, shown in Figure 4. One Team acts as the Fabrication and Test Team (the FATs). Their objective is to take the wafers through the next step of the process, and then to communicate the status of the run at the end of the two weeks with an Oral Status Report. The FAT team job sequence was assigned in a traveler which gives the sequence of processing steps for the PMOS process. For example, during the first two-week period the FAT Team cleans and oxidizes the wafers, then prepares the source/drain definition lithography.

The other Team is involved in Process Development (the PROs). This Team is assigned to investigate one of the process steps and to either characterize it or try to improve it. Examples of PRO Team activities are shown in Figure 3. At the end of the two-week period, the PROs report their results by making a poster and presenting it to the other team. Each poster is then displayed in the foyer of the laboratory so that the entire class can evaluate it.

Major:	Experience:	GPA	Major:	Experience:	GPA
Team 1 (Wednesday Red):			Team 2 (Monday Red)		
MatE	IC Lab tech	high	MatE	none	high
ISE/OR	none	high (Grad)	MSE	semi. eqpmnt	high (Grad)
EE	optical res.	high	MatE	organic chem.	low
EE	none	low	EE	none	high
EE	Test engr.	low	MatE	matls char. lab	low
ME	Wafer test	high			
Team 3 (Wednesday Blue):			Team 4 (Monday Blue):		
ChE	none	high	EE	IC Lab	low
MatE	none	low	ChE	photolith. tech.	high
GE	IC Pkg	high	EE	PCB test	high
EE	ckt.degn/test	high	MatE	Prcs.Tech	low
MatE	thin flm res.	high	MatE	matls.char.	high
			MatE	none	low

Figure 2. Typical team distribution profiles from Fall 1995 course offering.

Week	Fabrication and Test Team (FATs)	Process Development Team (PROs)
1	Safety, Overview of PMOS process, gowning procedures, MSDS sheets, tracking sheets, lab notebook, assigning team duties. Video: Silicon Run	
2	Field oxidation (Red Team)	Silicon Oxidation (Blue Team)
3	Source/drain lithography (Red Team)	Silicon Oxidation (Blue Team)
4	Source/drain oxide etch (Blue Team)	Diffusion of dopants (Red Team)
5	Source/drain diffusion (Blue Team)	Diffusion of dopants (Red Team)
6	Gate oxide etch/growth (Red Team)	Plasma & Wet Etching (Blue Team)
7	Source/drain contact etch (Red)	Plasma & Wet Etching (Blue Team)
8	Metallization (Blue Team)	Physical Vapor Deposition (Red)
9	Metal etch (Blue Team)	Physical Vapor Deposition (Red)
10	Contact anneal (Both Teams)	
11	Testing	
12	Testing	
13	Testing	
14	Final Oral Reports	

Figure 3. FAT Team and PRO Team schedule of activities.

Reports

The switch from PRO Team to FAT Team and vice versa happens every two weeks and is marked by a half-hour status report (where the wafers are handed off to the next FAT Team) and poster presentation during the lab period. Group grades are assigned on the basis of the oral status reports and the posters. The objective of the reports is clear, concise and effective presentations from which the new team gets enough information to carry out the next step in the process.

The FAT Teams had 20 minutes to give their Oral Status Report. We required only that each student participate in the oral report at least twice each semester. This frequently led to a situation in which one or two poised and confident students gave all the reports, while the shy students did not improve their communication skills. In the future we will require that no more than three students be involved in each oral report, with every student participating twice. Our objective was for the students to work together, practicing and evaluating each other before the reports were given so that the Team could put forth a good effort, even with a weak or shy presenter. However this did not occur. It appears that students on the whole do not like to criticize each other or to ask for help from their colleagues. Putting more pressure on them by weighing their grade on the group's performance did not seem to help; nor did decoupling the individual grade from the group grade. In order to promote the importance of presentation skills, in the 1996 course we will be giving out awards, which will translate into grade points, in various categories such as most improved presenter; best communicator; best student teacher; biggest effort; etc. and these awards will be assigned based on student and instructor evaluations.

The PRO teams present posters rather than oral status reports. The objective is to create a poster that speaks for itself, by telling the viewer what the experiment was, how it was completed, and what the results were. It should also intrigue the viewer and stimulate him/her to ask questions of the Team. We allowed only a five minute introduction (or "advertisement") to the poster presenters, and then encouraged students to ask questions in the lab while viewing the poster. We also required that any member of the PRO Team be able to defend the poster. This had mixed results, and it was difficult to find time to interview the poster presenters while simultaneously carrying on with the laboratory assignment. This should be formalized so that the poster gets a good evaluation and viewing. In the 1996 offering, all students are required to fill out an evaluation form for each poster and each oral report.

Each student submits an individual final report which should thoroughly describe the processing sequence and correlate the testing results to the processing sequence. This report, along with homework and the final exam, comprise the individual portion of each student's grade. The group portion is determined by the Oral Status Reports and the Posters.

The Start-up Culture

An effort was made to create a class culture as exciting as a start-up company. Most class handouts are labeled "Spartan Semiconductor, Inc." along with our logo, rather than with the course name. Grade points are given for innovative ideas, through the Employee Incentive Program. Guest speakers are brought in to lecture once or twice each semester. For example, a process engineer from a local chip company discussed his job working as a process integration engineer, interfacing with a foundry. Issues of design and process limitations became more realistic to the students as a result.

Testing

The objective of the device testing part of the course was to characterize the transistors and correlate their function (or lack thereof) with the processing conditions. This proved to be rather challenging. Due to some processing problems, very few of the devices worked. Furthermore, the MatE students had not taken a prior device physics course, so they were learning about MOS transistors functions while trying to test the very devices. As a result, we have added an experiment on MOS transistors early in the course so that all students begin the processing sequence with a clear picture of the devices they are fabricating.

Cooperative Learning in the Classroom

In addition to the Team-based laboratory experience, there are 2 hours of lecture each week, during which the basics of IC fabrication are discussed. The textbook used is Introduction to Microelectronics Fabrication[5]. The lectures are geared towards practical application of knowledge. To maintain the "company" attitude in the classroom, cooperative problem-solving exercises are performed at least once a week[6]. For example, during the first class period, students are randomly arranged into 2 or 3-person teams and asked to determine how many 4" silicon wafers will fit into the classroom. This type of "back-of-the-envelope" calculation is frequently performed by engineers, but many students are not capable or confident enough to do them. We focus on identifying the assumptions, estimating important parameters, and calculating a result. Then each team's results are discussed. This allows students the opportunity to think on their feet, defend their assumptions, and have confidence in their own approach. This type of learning does take at least 15 minutes out of each 50-minute period but we feel more learning occurs in that 15 minutes then in the lecture it replaces. Different learning teams are randomly assigned by the instructor for each exercise.

Team Self-Evaluation

During the 1995 course offering, a Team Self-Survey Form was administered at mid-semester. Sample questions and some results are shown in Figure 4. The most interesting result of the Self-surveys was that on the whole, most students felt that they benefited from the team learning approach, both in the lab and in the classroom, but that their team-mates benefited less. One interpretation of these results is that students felt that others knew more than they did, or that they needed their teammates more than others did. We found that without specific jobs assigned, some jobs went undone, and in some teams one or two individuals did all the work. Responsibility tended to become diffuse when team members did not have specific assignments. As a result, in the Winter 1996 course offering at Cal Poly, team roles were assigned. Initial feedback indicates that team members functioned more effectively when assigned specific roles. Figure 5 lists the Team Roles assigned. Observations and analysis of team behavior are being published elsewhere[7].

1) How do you feel about the team aspect of the laboratory activities? (Subjective)

2) Do you think you are learning more, less, or about the same by working in teams, as compared to working on your own, in the laboratory?

More(68%) Less(10%) Same(21%)

3) Do you think your teammates are learning more, less, or about the same by working in teams, as compared to working on their own, in the laboratory?

More(59%) Less(6%) Same(35%)

4) Do you think you are learning more, less, or about the same by working in teams, as compared to working on your own, in the classroom?

More(74%) Less(16%) Same(10%)

5) Compared to your teammates, how do you rank your team participation:

Very active, a team leader	(21%)
Active, a strong contributor	(53%)
Moderately active, contribute when asked	(26%)
Inactive, not contributing very much	(0%)
Barely participating	(0%)

Figure 4. Mid-semester course evaluation: sample questions and results.
19 Surveys were collected from the class of 24 students.

FATs		PROs
Schedule Coordinator		Resource Manager
Coordinates lab activities for the week. Must know the entire process for the week.		Coordinates lab time, interfaces with FAT Coordinator to prevent equipment overlap.
Traveler Monitor		Traveler Manager
Insures that traveler is complete and accurate.		Writes a traveler for the experiment and monitors it for accuracy.
Chemical/Equipment monitor		Materials/Equipment Manager
Maintains lab chemical records and equipment logs.		Gets experimental materials, handles chemical monitoring.
Safety Inspector		Safety Inspector
Responsible for continuous monitoring of group activities relative to safety protocols.		Responsible for continuous monitoring of group activities relative to safety protocols.
Test Wafer Monitor		Quality Assurance Manager
Insures that test wafers are included properly in process.		Insures accurate poster, coordinates poster - is conclusion supported by data?
Clean Protocol Monitor		Clean Protocol Monitor
insures that team follows proper clean procedures at all times.		insures that team follows proper clean procedures at all times.

Figure 5. Team assignments during Winter Quarter 1996 course offering at Cal Poly, for 6-member teams.

Portability

As discussed in the introduction, we are developing a methodology for teaching laboratory materials that is applicable to any engineering or science subject area and any university. The first stage of our efforts have focused on developing the course material and instructional methodology to support open-ended experimentation in three particular classes in MatE and EE. As our effort continues, those methods which have worked will be formalized into a comprehensive scheme for developing open-ended experimentation in any laboratory course. One factor which will always play a role in curricular development is the creativity and energy of the instructors adopting the techniques.

The portability of the semiconductor processing course has been proven by its adoption at another university. At the time of this printing, we (LSV) will have completed the first offering of this course at California Polytechnic State University in San Luis Obispo, California (Cal Poly) in the Materials Engineering Department. The course was presented in almost identical format to preserve the start-up company/team approach. Cal Poly is similar to SJSU in that it is a primarily undergraduate institution. However, Cal Poly is on a quarter system, allowing only 10 weeks for this 15-week course. We changed the process schedule slightly to fit the 10 weeks. Because of differences in equipment and students' background, device testing training (Weeks 7 and 8) was substituted for Process Development on etching. In contrast to the students in the SJSU course, Cal Poly students had completed a 3-unit course on microelectronics processing *before* taking the lab. However, the Cal Poly students in general had less industrial processing experience compared to the SJSU students. To teach a similar course in semiconductor processing requires a minimum set of facilities, discussed in several publications[8,9].

Summary

We describe a course in which the traditional "cookbook" approach to laboratory assignments is abandoned in favor of an attempt to experiment "without recipes". In fact, we do use a "recipe" to fabricate electronic devices (PMOS transistors), but simultaneously, experiments in processing science are designed, implemented, and reported on by students. By creating a "start-up company" atmosphere, one where the "employees" (students) are responsible for their own "profits" (learning), a more cooperative environment has been created, one where students learn more and strengthen many of the skills needed for industry in addition to gaining the knowledge content of semiconductor processing.

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