A Program in

SEMICONDUCTOR PROCESSING

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CHEMICAL ENGINEERING includes the science of reactor design and optimization. As any production environment becomes process limited, the role of chemical engineering increases in importance. Semiconductor manufacturing is an ideal example of a maturing process ready for reactor optimization and design. As we break into the technology of Very Large Scale Integration (VLSI) and Ultra High Speed Integrated Circuits (UHSIC), yields in the fabrication facility become very important. High-throughput, high-yield processes must be developed so that our industries will be viable in a marketplace filled with overwhelming foreign competition. Such processes can only be developed after the fundamental physics and chemistry of the chemical reactions are well understood.

At Colorado State University (CSU), the departments of chemical engineering, electrical engineering, physics, and chemistry have responded to industry's need by creating a graduate program in integrated circuit (IC) process engineering. A student trained in most classical BSEE programs lacks the background in fluid mechanics, heat transfer, reaction kinetics and chemistry which is essential to integrated circuit manufacturing. While students with BSChE degrees have the best education for processing integrated circuits, they lack an understanding of circuit design, device physics, and EE language. The graduate programs in integrated circuit processing at CSU give students an opportunity to broaden their background while pursuing research on a state-of-the-art level.

C. M. McConica received her PhD (1982) in chemical engineering from Stanford University. She spent three years with Hewlett Packard (1979-1982) developing state-of-the-art deposition/etching processes for their 128Kb RAM and 640Kb ROM, all fabricated with 1 micron NMOS double-layer metal technology. The chips utilizing this technology are now sold in the HP 9000.

TABLE 1

National Average Monthly Salary Offers (BSChE)**

	1984*	1983	1982	1981
Total Offers	827	2023	6952	11695
ELECTRONICS				
% of Offers	11.5	15.8	4.4	2.9
Salary	$2173	$2109	$2112	$1915
PETROLEUM				
% of Offers	13.0	16.6	36.7	41.5
Salary	$2358	$2329	$2329	$2068
CHEMICALS				
% of Offers	47	34.5	39	36
Salary	$2304	$2260	$2241	$2016

*1984 data through June only
**CPC Salary Survey, The College Placement Council

EMPLOYMENT OF CHEs BY ELECTRONICS INDUSTRIES

The electronics industries have recently begun to recognize the value of hiring chemical engineers to fulfill their processing needs. Table 1 lists current salary offers and the percentage of the total number of offers made by the electronics, petroleum, and chemical industries to BSChE graduates. The statistics were compiled annually from the College Placement Council (CPC) Salary Survey between 1980 and 1984. The actual number of offers made by both the electronics and petroleum industries declined, but more so for

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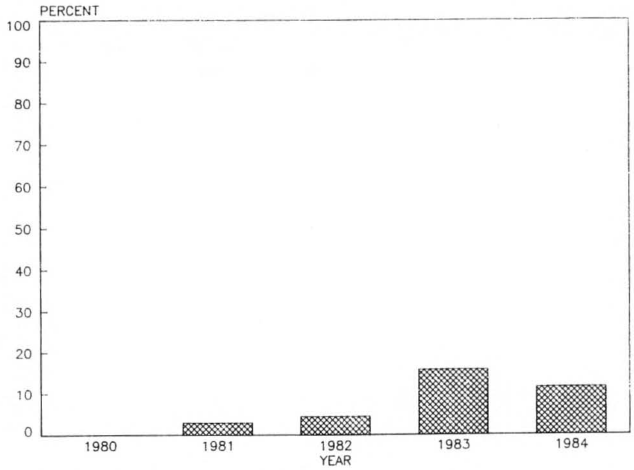

FIGURE 1. Percent of BSChE offers from microelectronics industries in the USA.

the latter. The table clearly shows the growing importance of the electronics industry for chemical engineers. In 1981, only 3% of all offers to BSChE graduates came from electronics, while 40% came from the petroleum industry. By 1983, however, 13% of all offers were coming from electronics firms and only 17% from petroleum industries. The chemical industries have consistently made 30% to 50% of all job offers to graduating chemical engineers. Fig. 1 presents the hiring trend by the electronics industry in bar-graph form.

At CSU the hiring rate by electronics firms has increased much more rapidly than the national rate (Fig. 2). This is a reflection of the proximity of microelectronics companies to CSU. Many companies have western headquarters and locate their research and fabrication facilities in appealing locations. While there is little petroleum refining or chemical production in Colorado, microelectronics is pervasive and growing. This is also true for Arizona, New Mexico, Idaho, Utah, Oregon, Washington, Minnesota and, most obviously, California. Other states with active microelectronics industries also have active petrochemical or traditional chemical industries. These industries are still hiring the majority of chemical engineers in those states.

The salaries offered to BSChE graduates by electronics companies since 1981 are an average of $196/month less than offers given by petroleum companies, and $127/month less than those offered by chemical companies. This is simply the result of hiring into an EE-dominated discipline where salaries have traditionally been lower. Many high tech companies believe that their remote locations, informal dress requirements, flexible work hours and stock option-profit sharing plans compensate for this salary differential. Female engineers in microelectronics firms enjoy the support of a relatively young professional work force and a primarily female fabrication work force.

The employment statistics listed are for BSChE graduates and clearly reflect the high demand for chemical engineers in electronics. We believe this demand would extend to the MS and PhD level if graduate students could be given the opportunity to pursue research relevant to microelectronics. The following sections describe the coursework and the research topics and facilities currently available to graduate students interested in integrated circuit fabrication.

INTEGRATED CIRCUIT PROCESSING PROGRAM

The presumed prerequisites for MSChE candidates are given in Table 2. Students without an engineering background may enter the program and complete these undergraduate courses at CSU. The MS program for a student with a BS

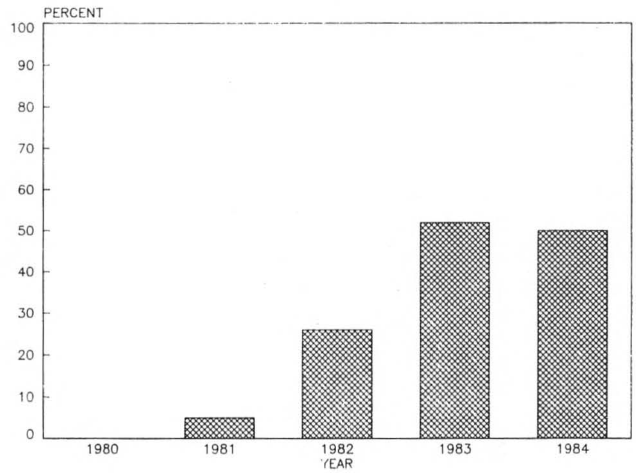

FIGURE 2. Percent of CSU chemical engineering graduates working in the field of microelectronics.

TABLE 2

Prerequisites for M.S. ChE

Organic Chemistry
Physical Chemistry
Fluid Mechanics
Unit Operations
Thermodynamics
Electrical Circuits
Reactor Design
Chemical Engineering Design

in chemical engineering normally contains 26 hours of coursework. An additional 4-6 credits are earned for the thesis. Chemical engineers in the IC processing program are required to take four core chemical engineering courses, and then are allowed to choose the remainder of their credits from courses offered by EE and other departments. A typical two-year MS course schedule is given in Table 3. The PhD program is an extension of the MS program, requiring more credits of coursework and successful defense of a dissertation based on original research. Many of the electrical engineering courses emphasize material properties, fabrication technologies, and solid state physics. No special prerequisites are required of the BSChE student. Chemical engineers do quite well in these courses because of their solid background in thermodynamics and transport phenomena. Students have the option to pursue courses which emphasize device design and device physics. These are not required of chemical engineers due to their more classical EE prerequisites.

INTEGRATED CIRCUIT PROCESSING RESEARCH

At Colorado State University there is an active solid state research group in the departments of chemical engineering, electrical engineering, and physics. Work is sponsored by the Department of Defense, the Department of Energy, the National Science Foundation, and the Colorado Microelectronics Industry. The focal point of the research work is a clean semiconductor fabrication laboratory. Current research activities include selective chemical vapor deposition of refractory metals (C. M. McConica), oxides and interfaces of silicon and compound semiconductors (C. W. Wilmsen), photovoltaic devices (J. Sites), transition metal silicides (J. E. Mahan), and polycrystalline silicon devices (J. E. Mahan).

The major research facilities supporting the research are

- **Solid state device fabrication facility (class 100 clean room, metallization, diffusion, oxidation, photolithography, wet chemistry, plasma etching, ion beam sputtering).**
- **Electron microscopy (ISI Super-II, ISI 100B and Hitachi HHS-2R scanning electron microscopes, Hitachi HU-200F transmission electron microscope).**
- **X-ray diffraction (GE diffractometer, Laue camera).**
- **Transport properties measurements (galvanomagnetic effects, thermoelectric power, temperature-controlled cryostat).**
- **Surface analysis facility (Auger electron spectroscopy, ESCA, UPS, SIMS analysis).**

The current semiconducter research effort in chemical engineering emphasizes an understanding of the kinetics of low pressure chemical vapor deposition. Metallic films are deposited on single wafers in a high vacuum system which can be used as a differential flow reactor. Classical methods of kinetics and catalysis are utilized to determine the kinetic parameters which govern

TABLE 3

M.S. ChE Course Schedule

FALL	
Mathematical Modeling	3 credits
Thermodynamics	3 credits
Semiconductor Devices I	3 credits
Seminar	1 credit
Thin Film Phenomena	3 credits
	13 credits
SPRING	
Advanced Reactor Design	3 credits
Solid-Gas Kinetics	3 credits
Seminar	1 credit
Principles of Semiconductors	3 credits
	10 Credits

Remaining courses in second year (3-9 credits) to be chosen from:

Introduction to Electron Microscopy
Organometallic Chemistry
Technique in Inorganic Chemistry
Surface Chemistry
Advanced Process Control
Advanced Mass Transfer
Semiconductor Devices II
VLSI Plasma Processing
Microelectronics
Semiconductor Materials
Optical Materials and Devices
VLSI Processing
Topics in Plasma Dynamics
Solid State Physics I
Solid State Physics II

THESIS—4-6 credits

the deposition reactions. The deposited films are then analyzed for electrical and physical properties. Through cooperation with local industries the students fabricate devices using the latest thin film technology. Other students are using CSU's kinetic results to model the behavior of industrial reactors. Again, local industries cooperate by allowing the comparison between our models' predictions and their deposition results.

The Department of Chemistry actively participates along with the previously mentioned departments in Colorado State University's Condensed Matter Sciences Laboratory. Current research activities include the study of molecular condensed phases (E. R. Bernstein), electrode surface modification (C. M. Elliott), techniques of elemental analysis and the chemical characterization of surfaces (D. E. Leydon), and NMR studies of solids (G. E. Maciel).

CONCLUSIONS

Chemical engineers are currently contributing to the electronics industry in growing numbers. Colorado State University has responded to industry demand for chemical engineers by offering a graduate program emphasizing integrated circuit processing. The program utilizes courses from several departments while allowing the student to apply chemical engineering techniques to an integrated circuit fabrication research topic. Graduates are receiving multiple offers from top quality semiconductor companies throughout the United States. □

ChE book reviews

COMPUTATIONAL METHODS FOR TURBULENT, TRANSONIC, AND VISCOUS FLOWS

Edited by J. A. Essers
Hemisphere Publishing Corp., 1983; 360 pages, $49.95

Reviewed by G. K. Patterson
University of Arizona

This book consists of six contributions in the general field of numerical simulation of turbulent flows. Each article is a strong contribution on the topic covered. Those topics are: "Numerical Methods for Coordinate Generation Based on a Mapping Technique," by R. T. Davis; "Introduction to Multigrid Methods for the Numerical Solution of Boundary Value Problems," by W. Hackbusch; "Higher-Level Simulations of Turbulent Flows," by J. H. Ferziger; "Numerical Methods for Two- and Three-Dimensional Recirculating Flows," by R. I. Issa; "The Computation of Transonic Potential Flow," by T. J. Baker; and "The Calculation of Steady Transonic Flow by Euler Equations with Relaxation Methods," by E. Dick.

To the novice attempting to learn the basics of numerical turbulence simulation, the organization of the book is not optimum. Although it is logical thematically to present grid generation, multigrid solution methods, and higher-level simulation in the first half of the book to lay a theoretical basis for the more practical topics to follow, the novice would feel more comfortable reading first about general methods for Reynolds-averaged modeling as presented for recirculating flows and transonic flows in the fourth through sixth chapters.

The book offers much to those who already have some knowledge of numerical simulation of turbulent flows. The treatment is not general and comprehensive for the entire turbulent and transonic flow modeling field. Each chapter presents a rather narrow topic from the author's particular viewpoint. Even though the collection represents the notes for a course presented at the von Karman Institute, no effort was made to link the presentations. Indeed, only one chapter was supplied with a nomenclature list, and each chapter has a different set of symbols.

The book would be valuable to those with some familiarity with numerical simulation of flow but without expertise in numerical modeling of turbulent, transonic flow. They should probably read the chapters in the order: 4, 5, 6, 2, 1, 3. That order corresponds to problem complexity and so is easier for non-experts. The book probably does not present much in each topic that an expert on that topic does not already know, so it should not be expected to provide much that is new if only that chapter is read. Its value is in its possible introduction of experts in one field, say coordinate generation and mapping, to another field where that expertise can be used, say external, transonic, turbulent flows. Having known little about transonic flows but much about incompressible turbulent flow modeling, I learned much from the last two chapters. □