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Microelectronic Engineering Education For Emerging Frontiers

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Abstract - With the support provided by the National Science Foundation and RIT Provost's vision for providing flexible curricula, the department of Microelectronic Engineering has instituted new and enhanced program initiatives – (1) offering a semiconductor processing minor for other science and engineering programs promoting access to state-of-the art semiconductor fabrication facilities to students from other programs; (2) crafting a five course elective sequence within the existing curriculum by eliminating legacy material and course consolidation; (3) developing a concentration program in nanotechnology and MEMS; (4) outreach programs for targeting larger and diverse participation in preparing workforce for the nation's future high tech industry; (5) enhance student learning through co-op and service. The mission is to generate multi faceted work force for the future semiconductor technologies and emerging frontiers spinning off from microelectronics, while simultaneously promoting enrollment particularly from women and minority students.

Index Terms – Microelectronics curriculum, Nanotechnology and MEMs education, Semiconductor processing minor.

I. INTRODUCTION

The invention of the transistor in 1947 at AT&T Bell Labs and the debut of the integrated circuit (IC) in the early 1960s mark the onset of the promising and soon to be a formidable semiconductor industry. From a beginning in which ICs were used in only in a limited number of specialized applications, has grown a technology that is pervasive in today's world. The introduction of IBM's personal computer (PC) in 1980 made semiconductor systems ubiquitous in homes and businesses. This large-scale integration has continued over three decades largely due to innovations, process advancements in manufacturing, and rapid implementation of new applications. Strong demand from a very broad spectrum of end markets propelled worldwide sales of semiconductors to a record \$235 billion in 2005; a year-on-year increase of 20 percent from the

\$166 billion recorded in 2003 according to a recent press release by the Semiconductor Industry Association (SIA) [1]. The industry's growth over the past three years is even more remarkable when viewed in the broader perspective that worldwide sales of semiconductors fell to \$139 billion in 2001 following the collapse of the dot-com boom, the 9/11 terrorist attacks, and a mild economic downturn.

The semiconductor industry consists of many groups of companies and institutions, all of which contribute to its vitality. At its center are the chip-manufacturers; but they are supported by a large number of outside organizations including manufacturers of chip processing and metrology tools, suppliers of materials and chemicals, analytical laboratories, industry associations that provide manufacturing standards and organize co-operative research efforts, and colleges and universities that provide technically trained workers. The semiconductor sector is currently dominated by silicon electronics of which eighty percent is complementary metal oxide semiconductor (CMOS) technology.

1.1 The Future of Microelectronics

Given the rate of technology innovation that the semiconductor industry has exhibited, it would come as no surprise if device manufacturers continued on a pace of rapid technology developments in design, manufacturing technology and new packaging implementation. Moore's Law of smaller, faster, cheaper devices will continue pushing faster clock speeds on microprocessors and increasing storage capability in memory devices. Manufacturing innovations have demonstrated readiness to implement 90nm and 65nm nodes on 300mm wafers. New process technologies (nanolithography, atomic layer deposition, plasma doping, laser rapid thermal annealing, chemical mechanical planarization, electrochemical deposition etc), substrate engineering (strained silicon, silicon on insulator (SOI), and SiGeOI, new materials (high and low k dielectrics, silicides, ferroelectric and magnetic), novel packaging (flip chip, wafer

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level redistribution layer) and software developments have exceeded predictions. On the device side, sub 25nm prototype MOSFETS have already been demonstrated. On the system side, current trends include increasing levels of integration; analog/mixed-signal design; high-speed communications chips; systems-on-a-chip (SoCs); and custom chips.

The semiconductor industry is rapidly reaching a point in its evolution where it will encounter serious challenges in the form of quantum effects and atomic level statistical fluctuations. As current lithographic methods reach their limit, the tools used in the development, manufacture, and testing of CMOS must be based on nanotechnology. Direct-write e-beam technology is an example of a nano-enabled tool that is already used for production. However, the true benefits of nanotechnology lie in leveraging the nanoscale properties of new materials to build new products. The biggest impact that nanotech will have on the semiconductor industry will fall outside the CMOS paradigm [2]. The impact is already being felt in:

Nonvolatile Memory: Non-volatile memory is a key enabler for mobile computing. Current Flash technology has limited capacity and speed, while commercially available nanoengineered solutions such as FRAM and MRAM offer considerable performance improvements. “Nanomemory” is getting considerable backing from industry giants such as Freescale, IBM, Infineon and Intel.

Plastic Electronics: Xerox, Sony and others indicate they are ready to bring thin-film electronics products to market. Unlike CMOS, plastic electronics keep unit costs low for small-volume production, while also offering superior thermal properties. This enables novel products to be created. By 2006, large roll-up screens for mobile computing will be available and plastic electronics will lower the cost of RFID tags making them usable for disposable items.

Nanosensors: Nanosensors offer a much lower detection threshold than rival technologies and are attracting strong interest for use in biotoxin detection for homeland security and in healthcare where they can provide early warning of cancer.

Nanostructures and nanodevices, which typically perform some electronic functions, and are perhaps the most critical subset of nanotechnology, essentially involve the manipulation of materials at the atomic level. Figure 1 highlights the explosive growth of nanoelectronics, from NEMS and optoelectronics to sensors used in biological applications. These fields will grow between now and 2030, and new types of nanosystems are likely to be developed as well [3].

The opportunities in nanoelectronics are considerable. It is predicted that CMOS will be supplemented by novel nano-enabled solutions, such as those described above. Prudent semiconductor manufacturers must plan for nanotech’s impact on their businesses today and prudent educators must plan for educating a high tech work engineering workforce [4, 5].

1.2 Employments in Semiconductor Industry

Microelectronics fabrication today probably employs the most highly trained engineering workforce of any manufacturing
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industry. As the density of integrated circuits rises (and therefore device feature size decreases) and as industry shifts to large wafer sizes, the complexity of microelectronic fabrication processes creates a demand for an ever more highly educated and trained workforce. The pool of skilled labor available to the U.S. semiconductor industry already appears to be shrinking. The number of bachelor's degrees in engineering granted annually by U.S. universities has been essentially static over the past decade and comes to only one-sixth of the combined total granted in China, India, Japan, South Korea, and Taiwan each year. Many foreign-born engineers are benefiting from first-class education at U.S. schools. As attracting skilled labor becomes an integral part of international industrial competition, these engineers are being offered significant inducements to return home, as are knowledge-rich engineers who now work in U.S. industry.

II. MICROELECTRONIC ENGINEERING AT RIT

The Bachelor of Science program in Microelectronic Engineering at RIT started in 1982 with basic PMOS process on 2” wafers. Today the program supports a complete 4 and 6 inch CMOS line equipped with diffusion, ion implantation, plasma PVD and CVD processes, electro-deposition, chemical mechanical planarization, I-line and deep UV wafer steppers, Perkin Elmer MEBES III electron beam mask writer, and device design, modeling and test laboratories. The program remains the only ABET (Accreditation Board for Engineering and Technology) accredited Bachelor of Science program granting a degree in Microelectronic Engineering. The program, which includes 5 quarters of required co-op, currently has over 130 undergraduate students. The Co-op is a program commences after the second year, and students alternate school with paid employment in the semiconductor industry. The laboratories at RIT include the largest university clean room for IC fabrication and are partially supported by our industrial affiliates, who provide curriculum input and support through donations of equipment.

Graduating students from this program are also very successful in M.S. or Ph.D. graduate programs in electrical engineering, materials science or related engineering or science fields. Several graduates have achieved leadership roles in the semiconductor industry. Currently, RIT has been awarded one of the New York State Office of Science and Technology (NYSTAR) Centers and the facility has expanding to incorporate MEMs, microsystems and photonics research areas.

III. CURRICULUM INNOVATIONS

We have recently received a support from the NSF to lead our program to the next level by introducing state-of-the-art educational material into the curriculum and new methodologies for learning through experiential co-op employment and multi-disciplinary design projects that incorporate service learning. We have initiated steps to enhance faculty expertise and laboratories by reformulating our programs to incorporate microelectronics, MEMS and nanotechnology in a reduced number of required courses NSF

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support at this critical time has enabled the department of microelectronic engineering at RIT to maximize the Provost's flexible curriculum initiative and complement the NYSTAR facilities improvement while reforming our curriculum to meet the needs of industry in the arena of nanotechnology. Specific programs are described as follows.

3.1 Minor in Semiconductor Processing for Non- μ E Students

We have developed a five course minor in microelectronics for non- μ E science and engineering students who desire exposure and experience to the exciting world of nanotechnology. We believe that this minor may do more to increase the number of women students with engineering experience at RIT by utilizing the large number already enrolled in the College of Science programs, as opposed to separate recruitment strategies geared solely toward engineering. This program is designed to provide basic knowledge to students from other engineering and science disciplines interested in a career in the semiconductor industry that include design, manufacture, equipment, chemicals, and software sectors. The minor consists of five courses: three core and two electives as given in Table I.

TABLE I
SEMICONDUCTOR PROCESSING MINOR CURRICULUM

Level	Courses
Freshmen Level	Intro to Microlithography
Sophomore Level	IC Technology
Senior Level	Thin Film Processes
Two Electives	Process Integration CMOS Processing Lab Microlithography Materials & Processes Microlithographic Systems Process and Device Modeling Nanoscale CMOS Microelectronics Manufacturing Microelectromechanical Systems

The prerequisites for each of these courses are basic university level math, physics and one course in chemistry. The courses are multidisciplinary in content so there is an enormous knowledge value for students of every science/engineering program.

These five courses will equip students from other disciplines to work in the semiconductor industry or go to graduate programs in emerging fields of MEMS, nanotechnology. For instance- electrical engineering students with fabrication and processing knowledge will be better circuit designers, understand the tools and relationships between electrical data and process conditions. Computer engineers will be better chip designers. Mechanical engineers, largely employed by the equipment industry and packaging industry will be at an advantage by knowing the processes involved. Similarly, chemistry students will find better job opportunities with chemical industries that support semiconductor fabs. The industrial engineers will be exposed to the fab layout, wafer flow, lot tracking and other manufacturing issues. Physics/materials science majors will be

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the top choice for operating and interpreting electron microscopy, surface analysis, Raman and other spectroscopic techniques.

3.2 Concentration in Integrated Nanotechnology

A long-term perspective suggests a tighter linkage between electronics technology and molecular biology. Indeed, it could be argued that the second half of the 20th century forged not one but two digital revolutions, fueled by two fundamental breakthroughs: transistorized digital computers and the cracking of the genetic code. Technological innovations of integrating DNA molecules directly onto microchips are under way for applications such as rapid diagnostics, drug delivery systems, and bio-identifications.

Our focus is on integration of nanotechnology with electronics - the 'beaker to chip' approach. We aim at preparing students who can integrate chemical, biological and other types of materials with on-chip circuitry.

Following the planning grant and other initiatives going on at RIT on Nanotechnology and Microsystems Engineering, following new courses have been envisioned.

- Nanoscale Phenomena: Materials and Devices
- Nanofabrication
- Nanocharacterization

These courses are multidisciplinary and taught by faculty from different disciplines. In addition to these 'core' courses, we will consolidate nanotechnology related courses currently being taught either as 'special topics' or as 'pilot' programs. Inclusion of nano courses from biology, electrical engineering, mechanical engineering, physics and chemistry will also be available as electives. This way, students could customize their nanotechnology concentration.

3.3 Reformulation of the BS μ E Program

Following the planning grant, we received in the year 2003, we have carried out an extensive restructuring of our curriculum. The previous program had only two professional electives. This did not allow students to take 'minor' programs outside the discipline. Students could not benefit from access to a large wealth of courses available in other programs such as biology, management, psychology, information technology, electrical and mechanical engineering critical for the new emerging fields. The new curriculum has 196 quarter credits that include 12 credits of free electives, 8 credits of professional electives, 92 credits of general education and five quarters of co-op experience. The combination of 3 free and 2 professional electives allows students to take a five-course minor.

3.4 Modernization

Implementation of this program requires updating some courses/laboratories and elimination of legacy material and course consolidation. The enhancements being implemented are:

Nanoscope Capability: Scanning probe microscopes (SPMs) are a class of tools that enable the nanoscale world to be imaged, measured, and manipulated. We have set up a new

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atomic force microscope laboratory that will perform all major SPM techniques including electric force microscopy, scanning tunneling microscopy, scanning thermal microscopy, and scanning capacitance microscopy.

Microlithography: RIT has been the leader in microlithography education and research. In the present course sequence, mask technology and fabrication techniques are covered in *Introduction to Microlithography* and advanced reticle enhancement techniques are taught in *Microlithography Systems*. New areas such as immersion lithography have been introduced. The inclusion of more advanced mask design, fabrication, and inspection methods and how they improve microlithography system performance are included. Adding topics such as SLM-based maskless lithography will further enhance the understanding of manufacturing techniques and alternatives. Alternative techniques- nanoprinting and soft lithography will also be introduced in the lithography sequence. In the new proposed nanofabrication course, bottom up approaches using self assembly will be included.

Processing: We have developed a robust student run one-micron CMOS process for sophomore to junior level lab courses and submicron processes for the senior level processing courses. We have implemented an advanced process with shallow trench isolation, sub 10nm nitrided gate oxide, high-k (3nm EOT), and nickel silicide processes. In doing so, we have strengthened the lecture courses-emphasizing new processes such as high density plasma depositions, etching, end point detection, CMP, ALD, while condensing well established processes such as oxidation, LOCOS, diffusion, and PVD. Currently, we have one course on thin film processes and with the recent advances made in thin film deposition and etch techniques, there is a need for another course and faculty expertise in advanced processes such as ALD, epitaxy, and self assembly.

Quantum, Solid State, Semiconductor Physics, Electromagnetic Fields: A new course on quantum solid state has been developed. Emphasis is placed on quantum mechanical tunneling, strain induced effects on carrier transport and effective mass in 2D and 1D structures. In the 3rd year semiconductor devices course important discussions on short channel effects are enhanced and section on JFETs is shortened. Contemporary and emerging MOS structures (with real aspect ratio) are discussed for analysis. Electromagnetic (EM) field fundamentals are extremely important in microelectronic engineering education. We have reconfigured EM Fields I course to include essential fundamentals of static and time varying fields and minimized overlap between university physics and engineering mathematics (vector calculus). A take home tutorial (managed on course e-site) has been made available for students.

Microelectromechanical Systems: This course provides an opportunity for graduate and senior level students to become familiar with the technology and applications of microelectromechanical systems (MEMS)--one of the fastest growing areas in the semiconductor business. MEMS represent the integration of microelectronic chips with microsensors, probes, lasers, and actuators. Topics covered in

this course include basic principles of MEMS and fabrication methodologies. An intensive laboratory accompanies this course that encompasses design, fabrication and testing of MEMS structures/devices using microfabrication techniques.

3.5 Co-operative Employment

All students of the BS program in Microelectronic Engineering are required to complete five quarters (10 week/quarter) of paid co-operative employment before graduation. Microelectronic engineering co-op students work for most of the major manufacturers of integrated circuits across the United States. Upon graduation students are well prepared to enter the industry immediately or to go on to advanced work in graduate school

Co-op opportunities have been expanded to include nanotechnology related jobs for engineering students. A local start up company, Integrated Nanotechnologies hired a large number of co-op students in recent years with microfabrication experience from RIT. Companies involved in biotechnology and sensors have been contacted for co-op opportunities where our students learn through real field experience the emerging applications of microelectronics and microfabrication.

GRADUATE PROGRAMS

The success of the BS program led to the development of graduate programs in microelectronic engineering. A unique Master of Engineering program in Microelectronic Manufacturing Engineering is offered through distance learning to allow engineers with traditional engineering and science BS degrees working in the semiconductor industry [6]. The Master of Science program emphasizes on research for preparing students for doctoral studies and for workforce development critically needed as addressed in the Semiconductor Industry Association's (SIA) International Technology Roadmap for Semiconductors (ITRS) [7].

RIT has developed a new combined five-year BS-MS program consisting of Bachelor of Science degree in Microelectronic Engineering and Masters of Science degree in Materials Science and Engineering. It is cross-disciplinary program designed to prepare students to meet the challenges requiring novel materials in modern integrated devices and circuits, MEMs and sensors. This program will foster education and research in nanoscale materials and devices. The proposed concentration curriculum will supplement this program very well.

A unique educational and research program that leads to a Ph.D. in Microsystems Engineering was instituted in 2002. This multi-disciplinary program builds on the strengths in microelectronic fabrications, photonic, imaging and micro-power research programs at the institute. Students are involved in cutting edge research and have access to modern facility, the largest of its kind in any academic institution. The program has graduated six students in the last four years.

Table II lists various curricula developed by the department.

TABLE II
CURRICULUM INNOVATIONS LED BY THE
MICROELECTRONIC ENGINEERING DEPARTMENT AT RIT

Programs	Requirements (quarter credits)	Year of Introduction
BS (Microelectronic Engineering)	196 credits + 15 months of Co-op	1982
ME (Microelectronics Manufacturing Engineering (also offered Online))	45 credits include 5 credits for Internship	1987
MS (Microelectronic Engineering)	45 credits include 9 credits of thesis	1995
BS–MS (Microelectronic and Materials Science and Engineering)	225 credits with 9 credits of thesis	2003
Minor Semiconductor Processing	20 credits of semiconductor processing courses	2005
PhD Microsystems Engineering	92 credits of graduate course work, 24 credits in dissertation research.	2002

SUMMARY

The curricula in microelectronic engineering at Rochester Institute of Technology have been evolving with new initiatives focused on the educational and research needs of the semiconductor industry that had made transition into the nanotechnology regime. These programs accompany the state of the art Semiconductor and Microsystems Fabrication Laboratory, the best undergraduate teaching “cleanroom” laboratory in the nation. Our commitment to high standard education in microelectronic engineering is focused for being

a significant part of semiconductor technology’s success and advances towards new frontiers.

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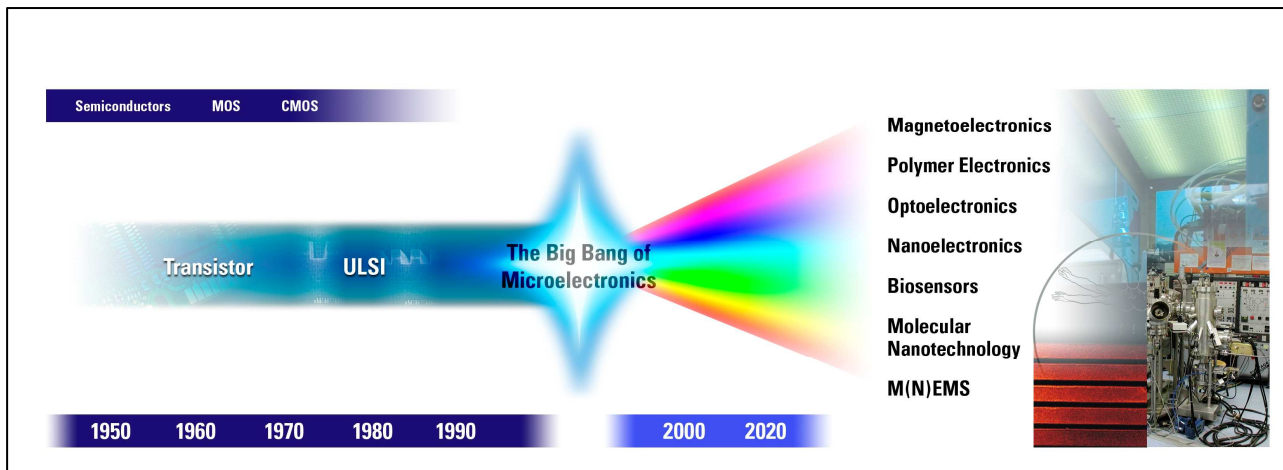


FIGURE 1

A STEADILY EVOLVING SEMICONDUCTOR INDUSTRY THAT HAS SUDDENLY EXPLODED IN A BIG BANG OF DEVICE TYPES AROUND THE TURN OF THE 21ST CENTURY (DESIGNED 2006 BY ETC DESIGN SERVICES, ROCHESTER INSTITUTE OF TECHNOLOGY BASED ON REFERENCE [3]).