An Interdisciplinary Curriculum for Microelectronics

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Abstract

A group of ten faculty members from four departments and two colleges are developing an interdisciplinary undergraduate and graduate curriculum in the area of microelectronics, optoelectronics, and nanotechnology. Our goal is to introduce the concepts of microchip fabrication in the sophomore year and then develop an option or minor in microelectronics engineering, open to students from various branches of engineering and the sciences, that may be completed as part of the curriculum in each participating department. We have developed an introductory microchip fabrication laboratory in which students process 4-inch wafers to create working nMOSFETs and other devices. It is anticipated that this course will be required of all students in Computer Engineering, Electrical Engineering, Materials Science and Engineering, and Physics, and has only freshman chemistry as its prerequisite. Interested students who then select the microelectronics option then take a sequence of core courses in solid state physics and semiconductor processing technologies, and select electives from a menu including range of electronics materials processing courses, semiconductor devices, semiconductor manufacturing processes, optoelectronic devices, photonic and optical materials, and nanotechnology.

We have designed our curriculum to take advantage of Virginia Tech's five-year bachelors/masters program for honors-level students and have revised our entire entry-level graduate program offerings to mesh with our undergraduate program. The advanced courses are designed such that students in the five-year option, as well as entering graduate students, can pursue courses in all areas of electronic materials and semiconductor manufacturing.

We are working with several semiconductor manufacturing firms to develop a co-op program that will allow students to work in state-of-the-art production facilities in partial fulfillment of the requirements of the option.

I. Introduction

This paper describes a comprehensive revision to the curriculums of several disciplines at Virginia Tech to develop an innovative combined curriculum and research experience for the design of microelectronics devices, processes and manufacturing operations which integrates current research from various areas of microelectronics manufacturing. The participating faculty members are able to draw on research expertise in the fields of solid state physics, semiconductor processing, electronic ceramics, optoelectronics materials, power semiconductor devices and power ICs, electronics packaging, VLSI design, nanofabrication technology, and operational control of semiconductor manufacturing processes. A three-course core is being developed to level the background of entering students from various disciplines. In addition, several tracks of advanced study are proposed in the areas of processing, devices, nanofabrication, and manufacturing/operations planning. All the students get hands-on experience in the newly developed undergraduate and graduate cleanrooms; and, in addition, will work on senior research project in a chosen area of interest in microelectronics manufacturing.

In our integrated program, students may elect concentrations in microelectronic materials, processes, and systems that:

- is comprehensive in that it includes an introduction to semiconductor manufacturing for up to 500 undergraduates per year and is required of all students in computer engineering, electrical engineering, materials science and engineering, and physics;
- integrates the Transfer Program of the Virginia Community College System (VCCS) to provide a "2 + 3" program for exceptional entry-level students;
- provides a university option for a concentration in microelectronic materials for those students who elect to continue their education in the field;
- is diverse and includes semiconductor manufacturing processes and operations, operational control of semiconductor facilities, photonic, ceramic, magnetic and organic materials, nanotechnology and self-assembling materials, power and high-frequency/high-speed devices, and the packaging of each of these;
- emphasizes the role of research in education and integrates increasingly sophisticated modeling and experimental and processing "hands-on" experience within a comprehensive curriculum;
- capitalizes on the strengths of our institution in multimedia methodologies and educational technologies (including distance learning) for the development of a pedagogically excellent curriculum; and
- attracts exceptional undergraduates to graduate research through our 5-year BS/MS program for Honors Students in which undergraduate research leads directly to, and is incorporated within, our advanced degree programs.

This combined education/research program is built on the foundation of a multimillion dollar (almost $8 million) investment by Virginia Tech in new teaching and research infrastructure and is the cornerstone of our strategic plan to place our institution among the top ten Research I Universities in the field within a decade.

The curriculum described in this paper is a coherent, advanced undergraduate pedagogical pathway by which motivated students can obtain an in-depth education in microelectronics (in the broadest sense of the word). We describe a unique and innovative curriculum that solves a number of difficult problems. It:

- develops a process to expose large numbers of students to the excitement of microelectronics as a career very early in their undergraduate education;
- provides a clear educational pathway for students who start their education in the Virginia Community College System (VCCS);
- provides and opportunity for those so inclined to obtain a superior education in the field through a university option in microelectronics;
- improves on the standard course-based undergraduate education by providing team-based research projects; and
- encourages the best of our students to continue their graduate education through an exciting new 5-year bachelors/maser program.

Students with appropriately high qualifications may choose to pursue candidacy for their degree "in Honors." At this time, a student's work focuses on major interests and part of the work is in independent study. An honors research thesis is one requirement of this degree designation. Students may seek the "in honors" degree in every major offered by the university.

Undergraduate students with a QCA (GPA) of 3.5 or above may apply for admission to the Graduate School upon the completion of 75 hours of undergraduate study. During the two semesters following admission to graduate school, the student may complete up to 12 hours of graduate work, jointly enrolled in the Graduate School and the undergraduate department. Successful completion of 12 hours of graduate work with no less than a "B" average will be considered completion of the last 12 hours of the undergraduate degree. This allows students to complete both the requirements for an undergraduate degree and a master's degree in five years.

The program we describe in the following section is carefully designed to allow all interested students in good standing in the university to receive an education in microelectronics, but it also encourages our best and brightest to participate in honors thesis research and the five year bachelors/masters program.

II. Curriculum

The wide diversity of the interests and expertise of our faculty, and the large number of departments in which they find their homes, makes it rather difficult to develop a curriculum that will allow students from multiple fields of science and engineering to receive a comprehensive education in microelectronics and participate in significant undergraduate research, and yet complete everything within the constraints of the various degree requirements of their chosen field of study. Furthermore, in order to have a sufficiently large student body to justify the very significant expenses associated with developing and staffing the cleanrooms and associated processing tools, we must find ways to attract undergraduates unfamiliar/ unacquainted with microelectronics to study in this exciting field.

We believe that we have indeed found a creative and innovative solution to this multifaceted problem. In the following paragraphs we describe a program of study involving seven new courses. These include: a core course/laboratory experience to be offered to all students in each of our various programs of study that will be taken by over 500 sophomores/juniors per year as a part of their normal education. We anticipate a yield of 5% or about 25 students per year who will enter a new University Concentration/Option in microelectronics. This option will comprise three required courses, one elective specialization course, and a senior or honors thesis research project. The required courses include solid state theory, semiconductor device fabrication technology, and semiconductor materials characterization. The specialization, or "track," courses include semiconductor device design, semiconductor processes, manufacturing operations, and "special topics" including nanofabrication/technology and photonic and optical materials,. These courses have been carefully developed along non-traditional paths because the required courses must provide all the prerequisite materials for the four tracks and each track must support all of the current and anticipated new areas of research excellence of our faculty. Early in our considerations of the structure of this program it became clear that to meet minimum administration enrollment requirements, we could offer no more than four tracks or options, regardless the number of areas of research excellence. However, we also determined that each of the track courses should be introductory rather than comprehensive because advanced undergraduate students and inexperienced graduate students entering the field at the graduate level would be able to extend their education through various of the over a dozen advanced courses already offered at Virginia Tech. Since these latter courses are part of our normal graduate education, we do not describe them here other than to note that our proposed undergraduate curriculum, for the first time, provides a uniform path for students from all areas of science and engineering to enter the exciting field of microelectronics rather than the normal hodge-podge of widely divergent courses and prerequisites previously offered by independently acting departments.

III. Curriculum Development

We have developed, or are developing the following courses. The status of each course is discussed following each course description.

MSE 2214: Elementary Semiconductor Processing (2 hours)

This course is an introduction to the semiconductor manufacturing process. Topics include: semiconductor devices and integrated circuit types; semiconductor materials and process chemicals; crystal growth and wafer preparation; contamination control; oxidation; photolithography; doping; deposition; metallization; wafer test and evaluation; packaging; and manufacturing technology. It is specifically designed for non-majors who are interested in understanding the exciting technology behind many of the devices that affect our lives. Suitable for engineering, science, and liberal arts majors. The only prerequisite is freshman chemistry.

This course is offered at the sophomore level and thus allows transfer credit for a similar course offered by the VCCS for qualified students from the community colleges who wish to continue their education at the university level.

This course has been submitted to the University Governance system for formal approval. It will be taught as University Honors 3004 to 11 of our top science and engineering students during the Spring 2001 semester.

ECE 2224 (MSE 2224): Introduction to Semiconductor Processing Laboratory (1 hour)

In this laboratory course, a 4-inch silicon wafer is processed using oxidation, dopant diffusion, photolithography, chemical etching, and physical vapor deposition to create simple operating semiconductor devices such as resistors, capacitors, PN junction diodes, and transistors. The devices are then characterized for electrical performance. The concepts of process yield and reliability are introduced. The prerequisites are freshman chemistry and sophomore physics. The course is taught in a newly completed Class 10000 cleanroom using the Modu-Lab series of teaching tools.[1,2]

The course is offered at the sophomore level and thus allows transfer credit for a similar course offered by the VCCS for qualified students from the community colleges who wish to continue their education at the university level.

This course has been submitted to the University governance system for approval. It was taught for the first time in Fall 2000 to 28 undergraduate students from ECE, ChemE, and MSE. It will be taught again in Spring 2001 and every semester thereafter.

MSE 3255-56/Physics 3455-56: Foundations of Quantum and Solid State Physics (4 hours each with lab)

This two-semester course includes topics in quantum and solid state physics with applications to engineering materials and devices. 3455: wave-particle duality, Schrödinger wave equation; atoms and molecules; crystal structures; x-ray and neutron diffraction; energy band theory, electrical and thermal transport properties of metals, insulators, and semiconductors. 3456: electrical properties of semiconductors and nanostructured materials; semiconductor-metal junctions; optical properties of semiconductors and semiconductor heterojunctions; semiconductor LEDs and LASERS; properties and applications of magnetic materials. Laboratory experiments include the photoelectric effect, electrical conductivity of metals and semiconductors, and I–V curves of PN junctions and BJT's. Prerequisites include freshman chemistry, sophojmore physics, and sophomore calculus including differential equations.

The course has been formally approved by the University governance and has been taught each semester since Fall 1999. 3455 is a required course of all Physics majors and both courses are required of all MSE majors.

ECE 4214: Semiconductor Devices (3 hours)

The intent of this module is to provide students with the ability to design and lay out introductory digital CMOS circuits. In addition, this course allows students to see how to implement physically some of the designs or design techniques they have learned in prior segments. The ability to design digital integrated circuits or to at least be able to analyze designs is becoming a necessity for many electrical and computer engineering students entering the work force or pursuing an advanced degree. Students will utilize contemporary design tools for circuit modeling, performance analysis, and physical design.

In the current curriculum, CMOS VLSI is taught with the intent of exposing students to all of the major processes necessary to manufacture a digital CMOS integrated circuit. Currently, much of the process is taught abstractly with hands-on exposure limited to a small subset of the steps. By integrating ISE, MSE, and ECE involvement, the new module remedies this without overwhelming the students. We have developed a possible integration strategy. In this design flow, a student is given the task of designing a ring oscillator to function at a particular frequency (for example). Here, the students design a circuit based upon the statistical process parameters obtained from the ISE module. The MSE and ISE-driven design rules govern mask generation, which is then followed by device fabrication. The outcome of fabrication is utilized by all parties to refine statistical models and design parameters.

In an associated laboratory component, students will design an appropriate MOS circuit, prepare the necessary mask set, and fabricate and test the circuit in the new microelectronic fabrication laboratory. Using techniques learned in the characterization module and theories developed in this module, students will be expected to compare theoretical with results with experimental reality and explain any observed differences. At this time, we anticipate that the laboratory will be offered as a separate course with significantly increased academic credit.

The lecture portion of this course is a significant revision of an existing course that is taught each spring. We are performing the necessary revisions each semester. The new laboratory part of the course will be developed during the 2001/2002 AY.

ECE 4234/MSE 4234: Semiconductor Processing (3 hours)

This course introduces microelectronic device production and characterization to advanced undergraduates and first year graduate students. By its own nature, this is a highly interdisciplinary subject that encompass physics, chemistry, statistics, chemical engineering, electrical engineering, materials science and engineering and mechanical engineering. As with most technological fields, it also has ramifications into green engineering and human behavior to mention a few.

The course will provide quantitative descriptions of unit operations in silicon processing used for logic and memory chip manufacturing. Processes to be addressed include: plasma-based techniques (deposition, etching, surface modification), ion implantation, chemical vapor deposition (CVD), wet processing (electroless plating, electo-plating and electro-etching), microlithography, chemical mechanical polishing (CMP), and wafer cleaning. The course includes a succinct treatment on packaging of semiconductor devices in which the student gains a basic theoretical and practical knowledge. The student is introduced to packaging architecture and functions, electrical/mechanical design, thermal management, materials selection and system's testing.

This course is a revision and synthesis of three existing courses in ECE and MSE. The first version of the combined course was taught during the fall 2000 semester. Significant additional revisions to the course are required.

ECE/MSE 4235-36: Introduction to electronic packaging (3 hours each)

This two-course sequence covers principles and analyses for design and manufacture of electronic packages. 4235: design issues such as electrical, electromagnetic, thermal, mechanical, and thermo-mechanical, are covered at the lower levels of packaging hierarchy. Materials and process selection guidelines are discussed for the manufacturing and reliability of chip carriers, multi-chip and hybrid modules. 4236: system-level package design issues for meeting application requirements and modeling tools for analyzing electronic packages are introduced. Materials and process selection guidelines are discussed for the manufacturing and reliability of packaged electronic products.

This course sequence was taught for the first time in Fall/Spring 1999-2000.

ECE 4274/MSE 4274: Introduction to Microelectronics Packaging Laboratory (1 hour)

In this advanced interdisciplinary laboratory course , students work in teams of three, ideally mixing one EE, one ME, and one MSE student, who solve an integrated packaging problem that involves device physics, thermal transport, and materials selection.

The course was taught for the first time in Spring 2000.

ECE/MSE/Physics 4984: Nanofabrication/Technology (3 hours)

Current feature sizes in large scale integrated (LSI) microelectronics circuits are already as small as a few hundred nanometers. If the rate of miniaturization continues, feature sizes will reach ten nanometers within the next two decades. At this length scale, quantum effects begin to dominate the fundamental properties and processes in the devices, and microelectronics has become "nanoelectronics." Conductance quantization and quantum fluctuations will need to be dealt with in device designs. At the same time, opportunities for new effects and devices, such as the single-electron transistor arise. This course will develop the fundamental ideas of how quantum confinement affects the behavior of materials and provide a practical background in the fabrication and characterization of nanostructures for electronic, magnetic, optoelectronics, electromechanical, and biological applications.

Methods of nanoscale fabrication will be discussed ranging from molecular beam epitaxy to electron beam lithography to self-assembed monolayers to fullerene nanotubes. The effects of electron confinement on the electrical, magnetic, and optical properties of nanostructures will be presented in terms of quantum wells, wires, and dots. Practical implementations of such structures include GaAs/InGaAs superlattices, fullerene nanowires, and CdSe nanoparticles. Finally, students will learn of the quantum modifications to and limitations of traditional device performance as well as novel device architectures that attempt to take advantage of quantum and nanoscale phenomena.

This course has been developed and submitted to the University Governance System for approval. It will be taught in the Spring 2001 semester for the first time.

ECE 4984/MSE 4984: Semiconductor Characterization (4 hours with lab)

This course will introduce the student to the wide range of structural and electrical characterization tools required to monitor the design and manufacture of microelectronic devices. The experimental procedures for, and the underlying theory of, I–V, C–V characterization, film thickness measurements by ellipsometry will be studied. Foundational understanding and research techniques appropriate for discovering and developing ways to assess the quality, monitoring the processing, and guide the development of processing for microelectronic devices will be presented. Strategies involving statistical sampling and the Deming Inspection Criteria will be considered. Measurement methods involving various forms of microscopy (acoustic, electron, atomic force, and infrared) infrared thermal imaging, and X-ray radiography, will be studied. Engineering issues related to how to select or identify appropriate NDE methods will be explored.

This course will be developed during the 2001/2002 AY.

ISE 4984 Operational Control of Microelectronics Manufacturing Facilities (3 hours)

The objective of this course is to provide substantial knowledge of issues, principles, and methodologies for addressing the special challenges brought about by the need to better control operations of a microelectronics production facility. Techniques and methods of manufacturing systems engineering and operations research are applied to issues in facility design and layout, material handling and flow control, inventory control, production planning and scheduling, equipment selection, maintenance and clean room integrity, as well as improvement of facility and fabrication line efficiency, and production lead times. Human factors and ergonomics principles are applied in an overview fashion to issues of safety, workstation design, and inspection. Statistical techniques are introduced to monitor and improve quality, assurance and reliability of the production process as well as the product. A systems integration perspective is adopted in the course, from which students will learn to integrate engineering, business, management and other functions of microelectronics manufacturing companies.

This course is being developed during the 2000/2001 AY and is expected to be taught during the 2001/2002 AY.

Senior/Honors Project (4 - 6 hours) (all microelectronics faculty)

Students participating in the microelectronics option will be assigned either individual or team projects based on their choice of track and the current ongoing research of the faculty. Such projects have been undertaken very successfully in a less structured manner for many years and we envision little change to our current methodology. Thus, we have not included research project design/development in this proposal. The senior projects/ honors theses are the critical component of our proposal in that they are the mechanism by which research and curriculum are combined to provide the desired educational experience for our students.

This course will be developed during the 2001/2002 AY.

IV. Conclusions

The team of faculty developing the microelectronics program at Virginia Tech has been working on this curriculum for almost two years. In that time, we have introduced six new courses and significantly revised five existing courses. In addition, we have completed a new 1,800 ft^2 Class 10000 cleanroom dedicated to undergraduate teaching[1] and have successfully developed a process that allows sophomores to build (and understand the fundamentals of!) basic semiconductor devices such as p-n junctions and nMOSFETs.[2] This is approximately 50% of the anticipated effort that will be required to create our envisioned option in microelectronics.

Surprisingly, we have found that the creation of a common introduction for students from all disciplines to the necessary solid state physics foundation for our program has been the most difficult course to design. This is because of the large amount of material that must be covered, the wide diversity of introductory courses in the sponsoring departments, and the limitations of time in our already compressed undergraduate curriculum. Although progress has been made in this direction, and a new course is being taught, we anticipate that significant renovation of this foundation course is still required Apart from this issue, our program is developing rapidly in the desired directions. Early student response to, and industrial endorsement of, our program has been excellent.

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Bibliograhy

1. R. W. Hendricks, *An Undergraduate Microchip Fabrication Facility*, (this symposium).
2. C. T. Timmons, D. T. Gray, and R. W. Hendricks, *Process Development for An Undergraduate Microchip Fabrication Facility,* (this symposium)

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