A Combined Research/Educational Curriculum in Smart Sensors and Integrated Devices

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Abstract: *We are developing a new curriculum which integrates ongoing research efforts in our new Center for Smart Sensors and Integrated Devices into a cooperative educational and traineeship program. A forerunner to this program was initiated with funding by a National Science Foundation Combined Research and Curriculum Development (CRCD) program grant. This program developed a central course sequence where multi-disciplinary-industrial collaborative work was combined with current device materials and structures research to form a comprehensive two semester hands-on course on sensor development and VLSI Technology. Students study the physics and technology of sensors and related devices, the associated electronics needed to drive the device and process information, and the techniques used for device fabrication. Students design , fabricate, and characterize sensor devices in a teaching laboratory and design associated VLSI circuitry for hybridization with the device.*

The new program builds upon existing sensor-related projects and the NSF CRCD sponsored course sequence to develop a concerted program in the area of sensor integration with VLSI circuitry, a growing research strength at Wayne State University. Active programs in wide-bandgap semiconductor materials, graded pyroelectrics, photonic systems, thin-film magnetic devices, organic film devices, and integrated (intelligent) technology form the core research that will be the cornerstone of a new interdisciplinary curriculum. The curriculum will consist of a series of hands-on (lecture and laboratory) courses on sensors and integrated devices developed by university and industrial participants. Undergraduate and graduate training is based on teaming where students work individually on different components of a major interdisciplinary project. Projects developing specialized integrated devices in the following strategically important areas are being developed: (i) automotive, (ii) spacecraft, (iii) aircraft, (iv) enabling technology, (v) biomedical, and (vi) energy systems. This research-educational initiative has the active support of industry, particularly Ford and General Motors, who have provided substantial resources to initiate this program and who will participate in lectures, research training, and oversight/assessment of the project. An outline of the combined research/educational curriculum in smart sensors and integrated device will be reported.

II. Background

The development of electronic and photonic materials, devices, and associated interactive electronics is a strategically important research and educational area for the US economical and technological bases as we enter the 21st century. Over the past two decades significant advances have been attained in sensor research, both in terms of the science, the materials, and the device development.[1] The devices range from automotive exhaust sensors to blood glucose sensors with each of these technological achievements adding to the efficiency, health, and quality of life of people throughout the nation. The next natural extension of this research is to incorporate integrated technology into the sensor technology.[2] In fact, the most significant impact in this area will be the integration of electronic processing with sensors or devices into so-called "smart sensors and devices" which will not only be able to acquire data but also to analyze, control, and feedback signals on a single integrated chip. Just as sensor research requires a multi-disciplinary effort, the "smart sensor" area will have to draw upon scientists and engineers to study a multitude of topics from materials synthesis and characterization to VLSI circuitry simulations in a coordinated fashion in order to develop application-specific devices. Although a number of universities have research programs in sensor technology - specifically in silicon-based and micro-machining technology, there is a profound shortfall in research and educational training efforts which combine sensor and electronic processing into a single concentrated effort for the hybrid integration of sensor technology with VLSI circuitry. As an initial step to fulfill this need, in 1994 we initiated a new research and educational program in smart sensor and integrated devices with the aid of a National Science Foundation Combined Research-Curriculum Development grant and an ongoing research project with Brookhaven National Laboratories for the development of a smart sensor interface for the drift detectors in the STAR project at RHIC.[3] Utilizing the existing research expertise, a two-course lecture/laboratory sequence on smart sensors and integrated devices was created.[4] Matching student demand is the pressure arising from industry for trained researchers with this expertise. From this initial effort, a more concerted research effort into the area of smart sensors has culminated with the formation of a Center for Smart Sensors and Integrated Devices (SSID) which has strong backing from Wayne State University, the State of Michigan, and industry.

The educational need in this area is to provide a more effective integration of very large scale integration (VLSI) circuitry with sensors. We have developed a combined research-curriculum initiative, funded by the National Science Foundation, which uses existing materials development research for microelectronics devices in combination with integrated electronic circuitry to make "smart devices". The devices covered in this course include standard state-of-art sensor devices as well as pioneering prototype sensors from wide band gap semiconductors, pyroelectric materials and magnetic multilayers. The course materials are developed from our current research projects as outlined in Table 1.[5]

	Wide Bandgap Semiconductors	*Organic Thin Films*	*Graded Pyroelectric Films*	*Magnetic Materials*
Automotive	Auto Exhaust sensors, Engine pressure sensors; High power-high temperature electronics; and Micro and Nonosensor arrays	Toxic chemical sensors	Intelligent IR collision avoidance sensors	Giant magneto-resistance sensors
Spacecraft	High temperature electronics, UV exo-atmospheric solar blind detector, and smart drift radiation detectors		Thermal Imaging Sensors	GMR Positioning Sensors
Aircraft	High temperature-high power electronics and environmental and diagnostic sensors			GMR Positioning Sensors
Enabling Technology	Smart UV welding sensor systems Enabling sensor arrays		Intelligent IR imaging in automatic welting	Integrated giant magneto-resistance data storage devices
Biomedical	x-ray imaging sensor arrays Integrated SAW chemical and biological sensors	Bio/Chemical, Toxic chemical, Immuno, protein, photo, and drug screening sensors	IR imaging	Integrated giant magneto-resistance data storage devices
Energy	High temperature/ power electronics for intelligent power control		Inexpensive IR heat imaging systems	

Integrated Technology

Table 1. Strategic application areas with materials and corresponding integrated sensors and devices.

The course includes a hands-on lecture/laboratory sequence using existing experimental methods to design and fabricate prototype smart devices. A VLSI/Device Simulation Laboratory has been developed for the course sequence to allow students to design and simulate the devices before fabrication. Sensor device design and construction is followed by VLSI circuitry developed to integrate with the working device. An emphasis is placed on design aspects and teamwork in completing the projects. This type of integrated technology where students are trained in device design, fabrication and integrated circuitry is what industries need to be competitive. For this reason, a close collaboration with local industries has been established to enhance the course curriculum and aid in the course design. Industrial participants include Ford Motor Company in the area of special automotive sensors such as high temperature exhaust sensors and General Motors in the area of collision avoidance sensor systems. The goals and objectives, educational methodology, curriculum design, details of industrial interactions and accomplishments are outlined in this paper.

III. Curriculum Development

Overview

A key element to this initiative is the development of a comprehensive education and training program which uses a synergistic coupling of research in smart sensors and integrated devices with the development of a new interdisciplinary Masters/Ph.D. degree program. The multi-disciplinary research of this technology requires courses and training beyond that found in traditional graduate training programs and curriculums. In addition, there is a need to integrate state-of-the-art research on smart sensors into the curriculum both in terms of formal lecture presentations and laboratory experiences. Correspondingly, we are developing both educational and training initiatives that are strongly coupled to the SSID center and participating departments and colleges. The curriculum is patterned after the previously successful initiative associated with our previous NSF-CRCD grant as several new hands-on, lecture/laboratory courses will be developed jointly by both participating SSID faculty and industrial collaborators and will utilize the SSID center's extensive facilities. We are developing undergraduate and graduate-level courses on sensor materials, material and device characterization, and VLSI (both analog and digital) technology with an overall emphasis on their relationship to smart sensor research. (See Figure 12 for a schematic outline of the curriculum.)

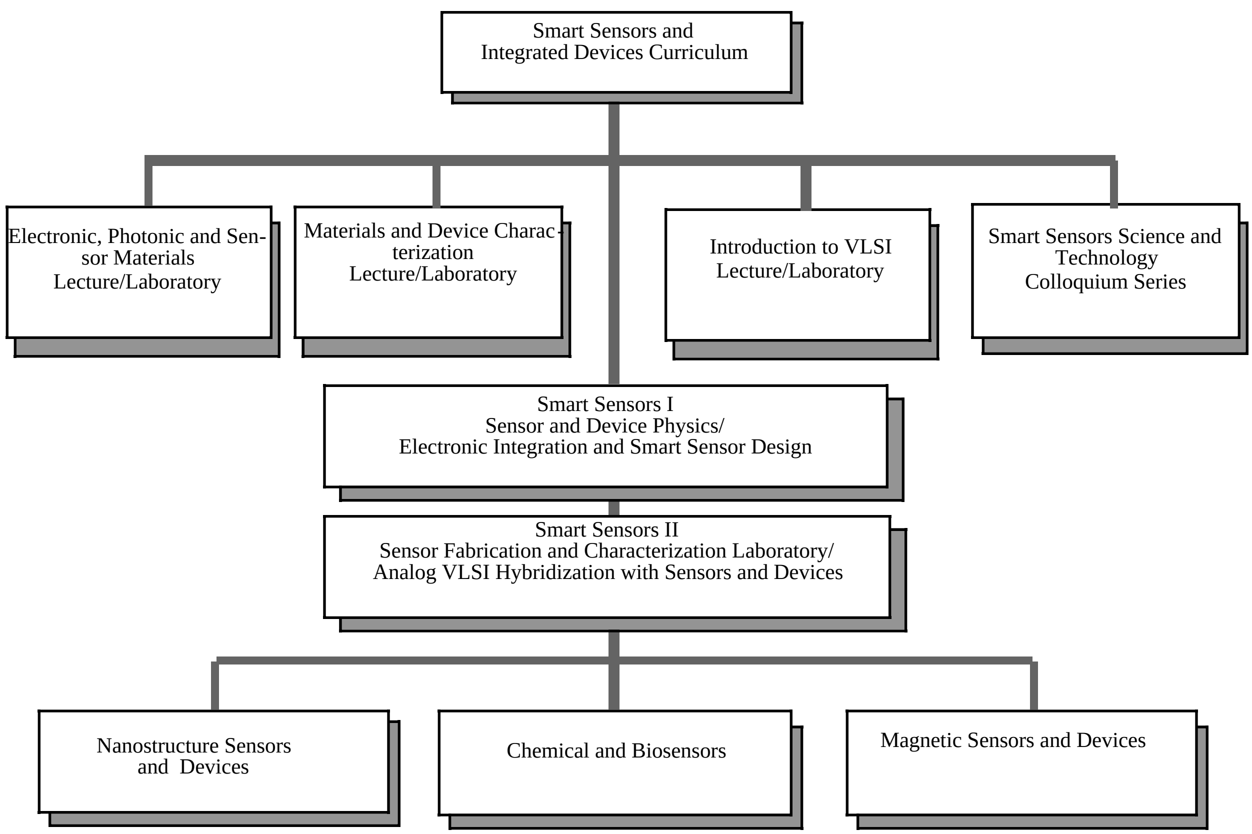

Figure 1- Outline of core curriculum for the new undergraduate and Masters/Ph.D. program.

After learning the basics in these courses, students would proceed to a two-course sequence on smart sensors in which they would be active participants/researchers in the development of actual smart sensors. A final tier of courses at a more advanced level covering specific sensors and devices would be taken by the senior doctoral students. These courses would form the basic core curriculum for students pursuing graduate degrees in this area with the actual degrees being associated with the departments, e.g., Electrical and Computer Engineering, Physics & Astronomy, or Chemistry. The facilities for this traineeship program are either presently available or will be during the next twelve months as the formation of the new SSID center has greatly expanded the central laboratory space and major equipment for coupling the research and educational effort in smart sensors and integrated devices at Wayne State University. In addition to numerous material characterization equipment located in the Colleges of Engineering and Science, seven major laboratories consisting of the Electronic Materials and Integrated Technology (EMIT) cleanroom/device fabrication, sensor characterization, and VLSI design laboratories in the Department of Electrical and Computer Engineering; MBE deposition and magnetic/electrical property characterization laboratories in the Department of Physics & Astronomy; and the nanofabrication and bio/chemical sensors laboratories in the Department of Chemistry will form the remainder of the Center's core facilities.

Formal Course Contents

A principal coordinator is responsible for the integrity and thoroughness of each course and will coordinate team teaching and industrial participation. We have established a practice of integrating leading industrial scientists and engineers into our course lectures and have had frequent guest lectures on special topics within many of our existing courses. This exchange is very stimulating both for the students and for the industrial participants.

In what follows, we outline the contents of current and proposed courses which form the core curriculum for the undergraduate and Masters/Ph.D. program in smart sensors and integrated devices research traineeship. In addition to these core courses, the students will also take required standard courses from the traditional program in respective departments to satisfy their degree requirements. The smart sensors and integrated devices curriculum combined with the normal core Masters/Ph.D. curriculum does not cause a net increase in the total number of courses required- rather the elective courses will be replaced with the extensive hands-on educational experience outlined below. Thus, students will gain both breadth and depth in general education as will as depth in smart sensors and integrated devices background combined with an extensive research traineeship background. The teaming effort in research thrust areas will be extended into the educational initiative, particularly in the hands-on laboratory experience. Substantial progress has been made already in combining research and education under the combined research and curriculum program initiated over the past three years.

Electronic, photonic, and sensor materials (Lecture/Lab)

The technology of electronic and photonic materials and computational techniques for semiconductor device simulation is of vital importance to most of the leading manufacturing industries and government laboratories in the United States. In fact, direct feedback from local industries indicates a pressing need for students with a strong background in new advanced electronic and photonic materials synthesis, processing technology, and computational techniques. In response to this need, the Department of Electrical and Computer Engineering has developed two new courses in the solid state sequence. The courses are ECE 550 (Electronic and Photonic Materials) and ECE 551 (Electronic and Photonic Materials Laboratory).

ECE 550 and 551 are a unique two sequence laboratory/lecture course on electronic and photonic materials synthesis, processing, simulation and characterization. This new course sequence is designed to fulfill the demand of high-technology industries and research laboratories for students with a strong background and hands-on experience in advanced electronic and photonic materials synthesis, processing, and computer simulation techniques.

I. Semiconducting Materials

1. Semiconductor elements, compounds, and alloys
2. Amorphous semiconductors
3. Wide bandgap semiconductors
4. Low-dimensional semiconductors

II. Other Materials

1. Organic thin films
2. Conducting polymers
3. High Tc-superconductors
4. Magnetic material

III. Growth of Single Crystals of Semiconducting Material

1. Bulk crystal growth
2. Liquid phase epitaxy
3. Vapor phase growth
4. Chemical vapor deposition and plasma enhanced CVD
5. Molecular beam epitaxy and plasma assisted MBE
6. Energetic condensation (plasma and laser)
7. Computer simulation of materials synthesis

IV. Materials Processing Techniques

1. Key electronic and photonic device structure
2. Metal semiconductor contacts/Thin films
3. Etching (plasma and laser)
4. Diffusion
5. Ion implantation
6. Simulation of materials synthesis

Material and device characterization (Lecture/Lab)

I. Diffraction methods

1. X-ray diffraction
2. Reflection high energy electron diffraction
3. Low energy electron diffraction

II. Electron Spectroscopies

1. Auger electron spectroscopy
2. Photo electron spectroscopy
3. Electron energy loss spectroscopy

III. Microscopy methods

1. Scanning electron microscopy
2. Transmission electron microscopy
3. Atomic force microscopy and scanning tunneling microscopy

IV. Electrical property measurements

1. Current-Voltage characteristics
2. Capacitance-Voltage characteristics
3. Electrical transport measurements

V. Optical measurements

1. Ellipsometry measurements
2. UV-Visible absorption
3. Infrared and Raman scattering

VI. Magnetic Characterizations

1. Magnetization (SQUID, vibration sample magnetometer)
2. Magnetoresistance
3. Ferromagnetic resonance

Introduction to VLSI (Lecture/Lab)

1. Create standard cell for NMOS & PMOS transistors with any given W/L ratio.
2. Design of current source/sink, current mirror, and voltage reference.
3. Design, simulation, and properties of common source amplifier.
4. Design, simulation, and properties of CMOS inverter amplifier.
5. Design, simulation, and properties of ring and RC oscillators using cascaded CMOS inverters.
6. Design, simulation, and properties of Schmitt trigger circuit using CMOS inverter.
7. Design, simulation, and properties of common gate and cascade amplifiers.
8. Design, simulation, and properties of common drain (current) amplifier or source follower.
9. Design, simulation, and properties of differential amplifier.
10. Design, simulation, and properties of CMOS comparator.
11. Design, simulation, and properties of CMOS Op Amps.
12. Design, simulation, and properties of CMOS folded cascade Op Amps.
13. Design, simulation of various analog circuits: MOS Multipliers, Linear Voltage-Current Converters, DA, AD etc.
14. Project submission process to MOSIS.

Smart Sensor Science and Technology Seminar

A series of seminars will be arranged related to sensor materials science and technology. This series will provide an opportunity for participating groups to disseminate their research in a formal way to other research groups and industrial participants. In addition, internal funding has been budgeted for invited presentations from national experts in sensor and integrated device related topics. These seminars will also be coordinated with the Michigan Chapter of the American Vacuum Society in order to facilitate a broader interaction with local industries and other universities.

Smart Sensor and Integrated Devices I and II

We have developed a course sequence which details the solid state device (and physics) aspects of sensors and related devices and analog VLSI design as a building block for sensor integration. Students begin by learning about the basic types of sensors and related devices currently used and under investigation. Sensor device design strategies are discussed in the context of current applications and future needs- a mixture of generic sensor devices, specific state-of-the-art sensors, novel new possibilities in smart sensors and integrated devices. The specific physical measurands are correlated to particular devices and the fabrication techniques employed in device fabrication are discussed. This initial introduction to sensor technology is followed by a team project where students design a sensor to meet a particular application. Device fabrication methods are planned and a block diagram of the integrated electronics associated with the device is designed. Following their design projects, the students will work on a sequence of VLSI design experiments to learn the basic tools necessary for a final comprehensive project combining the fabrication and characterization of a sensor, the development of associated VLSI circuitry, hybridization of the sensor and VLSI circuit, packaging, and finally testing the devices. The sensor physics and technology course sequence topics are outlined below.

Measurands

1. Biological (biomass, identities, concentrations)
2. Chemical (identities, concentrations, states)
3. Electric (charge, current, potential, electric field)
4. Magnetic (amplitude, phase, polarization, flux)
5. Mechanical (position, velocity, accel, force, stress, pressure, strain, mass)
6. Optical (amplitude, phase, polarization, spectrum)
7. Radiation (type, energy, intensity)
8. Thermal (temp, flux, Specific heat, conductivity)
9. Acoustic (wave amplitude, phase, polarization, velocity)

Acoustic Sensors

1. Acoustic waves
2. Piezoelectric Materials
3. Acoustic Sensing
4. SAW Sensors
5. Emerging Acoustic Sensor Technology
6. Sensor Integration Strategies
7. Design and Fabrication Methods
8. Applications

Magnetic Sensors

1. Materials and Effects
2. Hall Sensors
3. Magnetoresistive Sensors
4. Magnetostrictive Sensors
5. Magnetotransistors
6. Emerging Magnetic Sensors and Devices
7. Design and Fabrication Methods
8. Applications

Mechanical Sensors

1. Piezoresistivity Materials and Effect
2. Piezoresistivity Sensors
3. Capacitive Sensors
4. Displacement Sensors
5. Emerging Mechanical Sensor Technology
6. Sensor Integration Strategies
7. Design and Fabrication Methods Applications

Radiation Sensors

1. Materials and Effects (Physics)
2. IR Sensors
3. Visible-Light Sensors
4. High Energy Sensors
5. Emerging Devices (UV and Rm Temp IR)
6. Integration Strategies
7. Design and Fabrication Method
8. Applications

Thermal Sensors

1. Heat Transfer and Thermal Effects
2. Thermal Structures
3. Sensing Elements
4. Thermal and temperature Sensors
5. Emerging Thermal Sensor Technology
6. Integration Strategies
7. Design and Fabrication Methods
8. Applications

Chemical Sensors

1. Interaction of Gaseous and Aqueous Species
2. Acceleration of Chemical Reactions
3. Thin Film, FET and Ion Sensors
4. Thick Film and Bulk Sensors
5. Emerging Chemical Sensors
6. Integration Strategies
7. Design and Fabrication Methods
8. Applications

Biosensors

1. Immobilization of Biological Elements
2. Mass Transport in Biosensors
3. Transaction Principles
4. Packaging Biosensors
5. Emerging Biosensor Technology
6. Integration Strategies
7. Design and Fabrication Methods
8. Applications

Hands-on Laboratory Projects

1. Design and fabrication of prototype sensors
2. Device characterization and testing
3. VLSI design for prototype sensor
4. Submission of VLSI design through MOSIS system
5. Hybrid integration of sensor and circuitry

6. Final testing of hybrid deviceSpecific Sensors and Devices

The last component of the formal core curriculum consists of a set of advanced courses in nanostructure sensors and devices, chemical and biosensors, and magnetic sensors and devices. These three courses will be developed for senior doctoral students in order to provide greater knowledge and insight into each of these areas, especially with respect to the requirements that sensors and devices have to the automotive industry, space and aircraft systems, etc. Details of the actual course content will be formulated during the second year of the program as faculty and industrial participants attain a better perspective of the research direction of the SSID and the advancement of the students.

Thesis/Dissertation Research

In addition to the core curriculum, students will work on original research projects as part of their thesis or dissertation. However, unlike typical science and engineering thesis/dissertation projects, this training program will provide students with an opportunity to be part of a larger research team similar to how scientists and engineers work and interact in industry or in major government research facilities. These graduate students will work individually on different components of a major project that is far more sophisticated than an individual doctoral level project typically permits. While gaining focused skills in particular research areas, students will interact and team through regular group meetings and seminars on their particular major project. This will allow students to have a broader depth of training and education in particular aspects of a research project while simultaneously gaining breadth in a very comprehensive initiative. Ultimately, it will also allow a more advanced research project to be completed and better trained researchers to compete in tomorrow's job market.

IV. Summary and Conclusions

We are developing a new curriculum which integrates ongoing research efforts in our new Center for Smart Sensors and Integrated Devices into a cooperative educational and traineeship program. The new program builds upon existing sensor-related projects and the NSF CRCD sponsored course sequence to develop a concerted program in the area of sensor integration with VLSI circuitry, a growing research strength at Wayne State University. Active programs in wide-bandgap semiconductor materials, graded pyroelectrics, photonic systems, thin-film magnetic devices, organic film devices, and integrated (intelligent) technology form the core research that will be the cornerstone of a new interdisciplinary curriculum. The curriculum will consist of a series of hands-on (lecture and laboratory) courses on sensors and integrated devices developed by university and industrial participants. Undergraduate and graduate training is based on teaming where students work individually on different components of a major interdisciplinary project. Projects developing specialized integrated devices in the following strategically important areas are being developed: (i) automotive, (ii) spacecraft, (iii) aircraft, (iv) enabling technology, (v) biomedical, and (vi) energy systems. This research-educational initiative has the active support of industry, particularly Ford and General Motors, who have provided substantial resources to initiate this program and who will participate in lectures, research training, and oversight/assessment of the project.

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