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Undergraduate Research Opportunities in Microelectronics at Boise State University

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Abstract--Several opportunities exist for undergraduates in the Microelectronics area at Boise State University. This paper will describe the Research Experience for Undergraduates (REU) program funded by the National Science Foundation and other opportunities that have resulted for undergraduates due to external support. BSU became a NSF REU site for Microelectronics research in 1999. Each year 10 students are recruited nation-wide from various engineering and science disciplines to come to BSU for 8 weeks. The students work intensively with various faculty advisors and graduate student mentors. Another unique feature of our program is the tie to local industry. In 1999-2001, three students have and will benefit from an interaction with a local company, SCP Global Technologies, and this will be described.

1. INTRODUCTION

In 1996, Boise State University initiated the development of undergraduate programs in a new College of Engineering. BS degree programs in Civil, Electrical, and Mechanical Engineering were established. Since its beginning, these programs have grown rapidly in terms of enrollment and external funding support for research. In July 2001, the Computer Science department will move from the College of Arts & Sciences to the College of Engineering to enable closer collaborations with engineering. Local industry support along with external funding has helped to provide excellent laboratory facilities, new office and classroom space, used and new equipment, as well as internship and collaborative research opportunities.

The Idaho Microfabrication Lab, a small Class 1000 cleanroom was completed in 1998 [1]. An adjoining room is now used to house processing equipment due to space constraints in the cleanroom. Device characterization and VLSI CAD labs have been developed for educational and research purposes [2]. The newest development is a materials characterization laboratory initiated by two new Materials Science faculty members in the Electrical and Mechanical Engineering departments [3, 4]. Undergraduate research opportunities in these laboratories, as well as established laboratories in Chemistry, will be described with an emphasis on the NSF REU program. A local company, SCP Global Technologies, has allowed a participating REU student into their facilities each summer to collaborate on a research project. To aid in the task of mentoring undergraduates, a recent graduate program in engineering (fall semester 2000) has approximately 25-30 full and part-time students enrolled.

2. RESEARCH OPPORTUNITIES

Several research grant proposals have been submitted and awarded in the past four years for the Departments involved in this paper. External funding from government agencies such as NSF, DARPA, NASA, DOE, SRC, the Inland Northwest Research Alliance (INRA), and private funding from Wireless Systems, Inc. has resulted. These grants have allowed faculty members to obtain varying levels of research support by hiring postdoctoral fellows, laboratory managers, technical writers, graduate and undergraduate students. A $200,000 NSF REU grant was awarded to BSU to provide summer research support in the Microelectronics area for thirty undergraduate students from across the country during the period 1999-2001.

Many of the research projects are of interest to local Microelectronics companies and enjoy their support. Currently, senior design projects for Electrical Engineering majors are sponsored by the following companies: Micron Technology, Micron Electronics, Hewlett-Packard, Jabil, American Microsystems Inc., Amkor, SCP Global Technologies, Extended Systems, In-System Design, and Zilog. The generous support of these companies for the programs at Boise State is evident in several areas: support from the Industrial Advisory Board, mentoring programs, sponsoring senior design projects, providing adjunct faculty, giving plant tours, providing internships, placing graduates,

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donating lab equipment, and helping to install and maintain that equipment.

3. MICROELECTRONICS RESEARCH

Many research projects at BSU involve undergraduates working as research assistants. The following projects will be described in more detail: CO_2 wafer cleaning, magnetic thin films, fabrication of 3-D microstructures, quantum-dot computing, degradation of ultra-thin oxide films, electrochemical corrosion, SOI CMOS device modeling, and low power RF-CMOS IC's for wireless applications.

A. CO_2 Wafer Cleaning

This research project involves the use of a special nozzle to create a jet stream of high purity carbon dioxide for possible use in microelectronic cleaning applications. One focus area is to evaluate the effectiveness of the CO_2 cleaning technique by characterization of the electrical properties of oxides grown on silicon surfaces and compare to properties obtained on surfaces cleaned by various conventional chemical techniques. The other area is related to studying the environmental aspects of adopting a cleaning technique that could replace the amount of conventional chemical cleaning and water rinsing currently used in integrated circuit manufacturing. The objective of this research project is to gain a fundamental understanding of the effectiveness of an alternate cleaning technique for silicon wafers. Oxide integrity was investigated with standard electrical measurements on metal-oxide-semiconductor (MOS) capacitors. Capacitance and current measurements as a function of applied voltage were used for electrical characterization with a mercury probe to form a temporary metal contact.

Oleg Gurinovich (REU student 2000) acquired C-V and I-V data from a semiconductor parameter analyzer (HP 4155) and an LCR meter (HP 4284) to evaluate thermally grown oxides on silicon. Samples had been cleaned by CO_2 techniques and were compared to samples cleaned by conventional RCA techniques. Evaluation of semiconductor parameters such as threshold voltages, leakage currents, and oxide breakdown characteristics was performed and oxides cleaned by CO_2 compared favorably to oxides cleaned by conventional techniques. Oleg also spent time at a local company, SCP Global Technologies, evaluating particle removal effectiveness for CO_2 cleaned wafers and this is the subject of a summer 2001 research project.

B. Magnetic Thin Films

This project is funded by a NSF CAREER grant. Due to the lack of characterization facilities in 1999, Terry Gafron, a former Electrical Engineering student at BSU, spent the summer at NIST Laboratories in Boulder, Colorado. Terry Gafron collaborated with research scientist, Dr. Stephen Russek, on the fabrication of spin-valves that are used as "read heads" in the data storage industry. Small spin-valve devices are susceptible to damage from high current densities during prolonged operation and electrostatic discharge (ESD) events. Irreversible changes are the result of device heating and electromigration. In this research project, we examined the stability of spin-valve devices when the substrates are kept at low temperature (77K). The low substrate temperature allows one to apply large current densities with less device heating and hence to directly determine if device failure is correlated with the applied current density or the device temperature. Despite the low substrate temperature, the devices could be heated more than 500°C above the substrate temperature by the applied current. We found only small irreversible changes in device resistance and magnetoresistance for all current densities for which the device temperature was less than 200°C. The device failure point was the point at which thermal runaway occurred.

C. Fabrication of 3-D Microstructures

This project began June 1, 2000 and involves a collaboration between BSU and the Microelectronics Center of North Carolina (MCNC). Two postdoctoral fellows, two graduate, and two undergraduate students are involved from BSU working with two research scientists at MCNC. The objectives of the project are to optimize and study the advanced processing techniques necessary for the formation of through-wafer interconnects. BSU personnel are responsible for the etching of silicon and the chemical mechanical planarization (CMP) of Cu. MCNC will fill the etched vias with liner materials and electroplated Cu. The undergraduates involved in this project have been primarily responsible for technical support due to the large amount of facility work in acquiring the etch system and CMP tool. The focus will change in additional years due to the fact that equipment will be in place to study the processing techniques of interest to this program.

D. *Computing with Quantum Dots*

Quantum-dot cellular automata (QCA) are a method of computing with small numbers of electrons. The static shape of a particular automaton corresponds to a problem to be solved, while the time-dependent evolution of the distribution of electrons within the automaton corresponds to a computation to solve the problem. In a well-formed automaton, the lowest possible energy distribution represents a solution. Previously proposed automata show very little energy difference between the lowest energy and the next higher states. As a consequence, such devices will function correctly only at very low operating temperatures. REU students have been studying ways to manipulate the architecture of the QCA so that they may function at much higher temperatures than originally envisioned. Students Davis Moore, Lawrence Spear, and Daniel Kelly have investigated computing with quantum dashes, quantum rings, and layered QCA, respectively. This year Lucille Sylvester and Ethan Schuchman will investigate non-cellular versions of QCA.

E. *Electrochemical Corrosion*

Two related projects used electroanalytical methods to study corrosion processes on materials used in microchip fabrication. REU student Jill Sprague worked on a project coordinated with SCP Global Technologies to determine rate and amount of corrosion occurring in back-end-of-line (BEOL) processes in the fabrication of integrated circuits (IC's). Several materials were subjected to voltammetric analysis in commercially available etch solvents. The effects of aqueous solutions of the etch solvents were also examined, to simulate conditions in wafer cleaning processes. Tafel plots yielded information on corrosion current under these various conditions, and permitted computation of corrosion rates. Results of these tests were used to determine the best etch solvents and the optimum conditions for cleaning wafer surfaces with minimum loss of the semiconductor or metal circuit components. E_{corr} vs. time plots were generated, and showed that the open circuit potential changed rapidly with time on exposure of the wafer surface to the etching solutions. Jill had the opportunity to present these findings to the company in a formal setting that included the vice-president of corporate research and several group managers.

A second project investigated possible anti-corrosion strategies on conductive and semiconducting substrates, based on self-assembled monolayers. REU student Ryan Meyer identified several corrosion resistant coatings for protection of reactive metal components during microchip fabrication processes. Alkyl selenides were synthesised and used to prepare self-assembled monolayers on several surfaces including copper, aluminum, gold, titanium nitride and tungsten. Electrochemical corrosion analysis methods including cyclic voltammetry and Tafel plots were used to quantify corrosion rates during exposure to etching solutions used in microcircuit fabrication, and also during exposure to distilled water, simulating rinse processes. The monolayers were evaluated for contact angle with water, cyclic voltammetric behavior, corrosion current and corrosion potential. For the copper surface, a 12-carbon straight chain alkyl selenide exhibited three orders of magnitude lower corrosion current than self-assembled monolayers prepared from the analogous sulfide. This indicates superior corrosion protection, as predicted by the formation constants for the solution phase coordination complexes. The contact angle was found to be a function of the delay time between coating the surface and making the measurement. This is interpreted as a reorganization of the SAM over time, with better moisture protection (greater contact angle) corresponding to longer times. Effective methods for removing anti-corrosion self-assembled monolayers continue to be investigated. One method under investigation is removal exposure to dissolved ozone in the final rinse. The student is presently preparing a manuscript describing this work.

A third student, Annette Ma, prepared coated electrodes by electropolymerization, having selective binding sites for Hg^{2+} ion. The semiconducting polymer was composed of thiophene monomers, co-polymerized with functionalized thipohene in various ratios of these two monomers. The selective binding site is a heterocycle having three oxygen and two nitrogen heteroatoms, 1, 4, 10-trioxa-7, 13-diazacyclo-pentadecane. This heterocycle was chosen for its high selectivity for mercury over other mono- and divalent heavy metal ions. Electrodes having several different ratios of the monomers were prepared and operated in both voltammetric and amperometric modes. Response of the electrode was determined both in terms of mercury detection and in terms of selectivity for mercury in the presence of cadmium, dissolved oxygen, and other possible interferences. The detection limit for aqueous solutions was found to be sub-part-per-billion, which compares favorably with the atomic absorption cold vapor method for mercury. Selectivity of mercury is over 1000:1 relative to cadmium in mixed solutions, meaning that cadmium is not a serious interference until its concentration is several orders of magnitude greater than that of mercury. The student presented this work in a poster session at Boise State University and also contributed to a presentation made in a symposium on field portable instrumentation for environmental analysis, at the American Chemical Society National Meeting in San Francisco, March 2000. A presentation on this mercury probe will be made at the Materials Research Society conference in San Francisco, April 2001 and a patent application for this probe has been filed with the United States Patent office.

F. Ultrathin Oxide Films

Theodora Caldwell is performing research under the SRC undergraduate education alliance grant. She is undertaking a study of degradation mechanisms in ultrathin (< 5 nm) gate dielectrics. Microelectronics education is performed within the context of the project and focuses on several aspects. The first is learning of and in a specific field. The second is learning to work independently and underscores problem solving. The third is dissemination of information by writing a final report or giving a presentation. The learning phase occurs with direct interaction with the faculty member and with encouraged reading of selected papers and excerpt from texts. The faculty member discusses bonding and band diagrams in general and as applied to metal-oxide-semiconductor capacitors (MOSCAPs) and field effect transistors (MOSFETs). The latter is discussed so that understanding of MOS device physics and quantum mechanical mechanisms such as carrier tunneling are conceptually understood. The student is then taught procedures for test and measurement equipment (e.g., wafer level probe station, HP4145, HP4155) to characterize MOSCAPs and MOSFETs. Characterization results are then discussed using the concepts acquired in previous discussions of device physics to understand the results. Results are explained using band theory and device physics concepts. "What-if" scenarios are discussed to promote problem solving. Although not heavily emphasized, the student is guided through the use of software for data analysis and modeling.

At this point, the student is encouraged to work independently and focus on problem solving. This may additionally involve setting up and or purchasing new equipment. The faculty member and student meet periodically to discuss results and plan the next phase of experiments. Band theory, device physics and quantum mechanical phenomena are utilized throughout the discussion. The results and discussion will most likely lead to dissimilar testing methods and analysis. If useful, the PI will suggest the student read material directly related to the results, conclusions or problems encountered.

The student is then encouraged to begin writing a final report or presentation. Initially, it may include only background information and results. Yet, this motivates the student to better understand the concepts of the study and to examine problems from various directions.

Specifically, the project focuses on the study of degradation mechanisms in ultrathin gate oxides. The student will use the latest in IC measurement equipment to develop test methods to measure degradation in ultrathin gate oxides. These methods will then be used to study degradation mechanisms in gate oxides that have been grown using several different growth methods in an array of thicknesses. The data will be analyzed to determine if a correlation exists between the type of degradation mechanisms observed as a function of growth methods and thickness variations.

G. RF SOI

Dr. Stephen Parke's research on design and modeling of silicon-on-insulator, ultra-low-power MOSFETs at radio and microwave frequencies began in Fall 1999, funded by a $500,000 NSF EPSCoR grant. This work was expanded in Fall 2000 to include sub-volt SOI-RFCMOS transceiver circuit design, fabrication, and test through a $2 million, 3-year private research grant from Wireless Systems, Inc. Ten undergraduate students have been funded so far in this project. They all have offices in one large research lab where they are able to both work and study together, along with a few post-doctoral researchers and graduate student researchers. In most cases, they have tailored their capstone Senior Design project around some aspect of the larger RF-SOI research project. Some students have assisted in setting up sophisticated microwave test equipment and developing characterization/modeling methodologies. Others are helping to establish a four-mask MOSFET "research" process flow for the Idaho Microfabrication Lab. Five of these undergraduate researchers have or will stay at BSU to complete their Master's degree. Thus retention of these students for graduate-level research is excellent.

4. FUTURE PLANS

The NSF REU program has allowed 30 undergraduate students to perform high quality research at Boise State (1999-2001). Other research grants have also allowed several opportunities for undergraduates and have paved the way for pursuit of their graduate degree in some cases. BSU's long-term vision is to become a national center for microelectronics education and research. This will be enhanced with addition of a doctoral program that is included in the five-year plan for the College of Engineering. Finally, research collaboration with faculty members in other BSU departments such as Chemistry, Physics, and Geophysics, and with non-profit organizations and industry, while already strong, will be expanded through further joint proposals for undergraduate research.

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