A Research Experience for Teachers:
Connecting Graduate Level Research to the Science Classroom

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Introduction

The Research Experience for Teachers program provides an opportunity for teachers and university researchers to interact. These interactions result in benefits for the science teacher that can be used to assist their teaching practice. The benefits include hands on experience with modern research in a university setting, collaborating with university staff and students, learning advanced science processes, and opportunities to bring new knowledge and understanding into the science classroom.

Two science teachers, Xiao Zhang, a high school physics teacher and Michael Schaefer, a Lower School general science educator worked with several members of the UIC Department of Chemical Engineering. In the Advanced Materials Research Laboratory(AMReL), Professor Christos Takoudis guided several graduate students at their various levels of research in nanotechnology, photolithography and flexible plastic electronic applications. *This report will discuss background information, the type of research conducted in the AMReL, and relevant reflections and connections between the research and the teachers' practice in the classroom. The pedagogical principle of scientific inquiry from the National Science Education Standards will serve as a framework to make comparisons between actual research methods practiced in the laboratory and curriculum as experienced in the science classroom.*

What is nanotechnology?

The term 'nanotechnology' has gained more public recognition in recent years as it plays an increasingly significant role in the fields of electronics, chemistry and biology. Industry, governments and research institutions are all paying attention to this expanding field as it may provide solutions to problems in microelectronics, medicine and in materials design. Applications currently being researched include creating smaller and more powerful computers, detecting molecules of a substance in the air or in blood, producing 'smart' fabrics, and developing stronger, lighter structural materials.

Nanotechnology involves the analysis and manipulation of substances on a nanometer length scale and developing tools or devices with which to do so.[1] By some definitions, it means working with materials below one hundred nanometers in length. Basically, the process of nanotechnology requires the knowledge and tools to view, analyze, or manipulate individual atoms and molecules.[2] A nanometer equals one billionth of a meter, or one ten-thousandth the width of a human hair, or the length of three to five atoms across. Individual atoms can be viewed, analyzed and even moved through the use of specialized electron microscopes. Other specialized equipment can be utilized to manipulate multiple atoms to create nanostructures such as nanocrystals and nanotubes. The physical and chemical properties of nanometer-scale objects might differ from the properties of larger structures made from the same material.

Microelectronic Production Technology

Computers continue getting smaller and more powerful as a result of improved production techniques that allow for an increased number of circuits and transistors to fit in a given area. The first microprocessor, or fingernail size control center of a computer, developed in 1971 contained about 2,700 transistors. In 2000, a microprocessor chip could contain about 42 million transistors, and by 2003 that number had increased to 330 million. (**Figure 1)**[3]

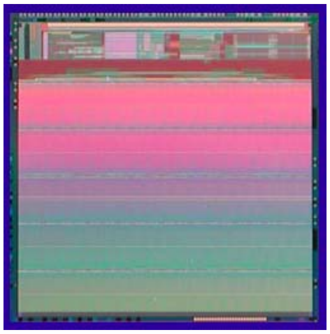


Figure 1. Microprocessor Chip containing 330 million transistors. (Intel, Mark Bohr, 2003)

Due to advances in photolithography, the copper wiring, or circuits, on a chip are now about 90 nm wide. One limitation for further increasing the number of circuits and transistors on a chip is the inability of the insulator between the circuits to function at a thinner scale. (**Figure 2)**[4] Below a certain thickness, about 15 nanometers, the silicon dioxide insulator cannot prevent electrons from ‘tunneling’ through, thus losing its ability to effectively insulate. Alternative materials are being examined for their insulative ability below a thickness of 15 nanometers. At this nanometer scale, highly specialized tools, including electron microscopes are necessary to view and analyze the exact thickness and material makeup of microprocessor components.

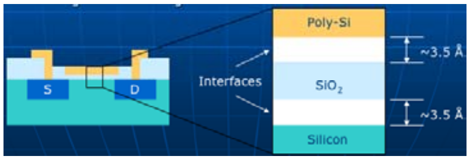


Figure 2. Diagram of cross section of silicon chip and Poly-Silicon transistor. The insulator is SiO_2, silicon dioxide. (Javier Rosado, 2003)

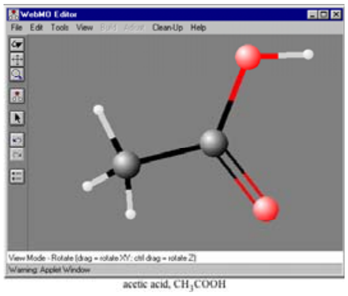
Research Projects in the AMReL

Among current engineering projects in the AMReL, the two teachers focused their primary efforts with the graduate students who were researching novel materials for semiconductor insulators and researching electroless plating methods to develop flexible plastic substrates for electronic devices. Other projects include research on nanotubes and molecular computer simulations.

One graduate student, Anand Deshpande, is researching new materials that might be used on microchips as an electrical insulator between a silicon semiconductor substrate and a metal conductor. He is concerned with the properties of the insulator as well as the properties of the nano-scale interface, or the place where the silicon atoms and the insulator atoms meet. Anand is experimenting with the elements hafnium and tantalum to create a new thinner insulator that has the insulative properties of the thicker silicon dioxide, yet the capacity to work effectively on a smaller scale.

Through the use of molecular simulation software and calculations to determine electrical properties, it was discovered that these two elements are theoretically capable of accomplishing that task. **(Figure 3)**

Because this would be a new insulator and there is no existing information on its effectiveness, new questions were raised. Is it possible to apply a pure layer of hafnium or tantalum to a silicon substrate? What molecules will make up the interface with the silicon substrate and how might that affect its insulative properties? How will this affect the performance of the semiconductor?



acetic acid, CH_3COOH

Figure 3. Simple molecule of acetic acid. (WebMo software)

Some of these questions can be partially answered through hypotheses based on current knowledge of hafnium, molecular chemistry, and electricity. To develop more complete answers, it is necessary to develop a plan that includes applying the hafnium to a silicone substrate and performing tests to determine the product's molecular structure.

Figure 4. Anand Deshpande operating his hafnium delivery system in the AMReL

Anand constructed a delivery system to apply a layer of hafnium on to a 2cm sq silicon wafer. The system included a high temperature electric reactor, a vacuum pump, valves, pressure gauges, thermometers, a controller, insulated tubes, cooling water, and an argon gas flush. Mathematical calculations were performed to determine the specific flow rate and duration of the hafnium application for desired thickness. Before application, safety issues related to the volatility of the hafnium medium were addressed, the system was tested and then it was flushed with argon gas. **(Figure 4)** Once the reactor, which contained the silicone wafer, reached a temperature of 400°C, the hafnium was released into the system for a span of five minutes.

After cooling, the sample wafer was analyzed to determine some of its physical properties. An elipsometer projects UV rays on the sample to determine the precise thickness of the hafnium. Then, using the infrared light waves of the Fourier Transformed Infrared Spectroscopy (FTIR), the molecular structure of the insulator and

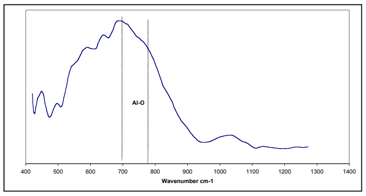


Figure 5. FTIR graph indicating the specific energy 'fingerprint' of aluminum oxide. (Anand Deshpande, 2004)

interface can be confirmed. The data from the test is displayed on a graph and analyzed. Since each type of molecule will produce its distinct graph or ‘fingerprint’ of energy in its electron bonds, (**Figure 5)** the desired presence of hafnium and hafnium oxide or undesired presence of other substances can be inferred. The FTIR results on Anand’s sample indicated the presence of a hafnium layer with an interface of hafnium oxide over the silicone while results from the elipsometer indicated its appropriate thickness.

The sample could now be prepared for further and final analysis under the Scanning Transmission Electron Microscope (STEM). To obtain maximum microscopy data, the STEM sample will have a cross section of two interface layers and measure 1 x3 x 0.01mm.

Producing samples at this reduced scale is a lengthy process that includes milling, gluing and grinding of the wafer. The two teachers were involved in this phase, employing the use of a diamond cutting wheel, binocular microscope, razor blades, tweezers, glue, wax, hot plate, oven, grinding wheel and diamond grinding paper, to produce a satisfactory sample. Machining and hands-on tasks required over twenty hours of work and curing in an oven required an additional time of twenty hours. Challenges included broken and lost sample pieces and the trial and error required for precise manipulation. **(Figures 6 to 10)**


Figure 6. Checking progress on diamond cutting wheel.


Figure 7. Xiao Zhang gluing sample together.


Figure 8. Using razor blade and tweezers to manipulate sample prior to grinding.


Figure 9. Sample on glass cylinder ready for further grinding.

The STEM is a highly specialized instrument that provides detailed images and data of individual molecules at the angstrom scale. An angstrom is 1/10 of a nanometer. The $2.2 million microscope stands approximately 1.5 meters above the table and has a 1,000,000x magnification power. Since the slightest movement, expansion or contraction of the metal STEM components could shift the view a few angstroms, the room is designed to minimize vibration, sound and temperature fluctuations. **(Figure 11)**


Figure 10. Grinding sample on diamond paper.

Working with the microscopy specialist, Anand will spend three to four days using the STEM to analyze two samples and to confirm the data received from the FTIR. He discovers that his sample consists of a layer of amorphous hafnium oxide on the crystalline silicon substrate.


Figure 11. Microscopy specialist, Alan Nicholls operating the Scanning Transmission Electron Microscope (STEM).


Figure 12. Jin describes some MAL equipment used for research and production.

Another project involves Dong-Un Jin, a graduate student who is investing his efforts to research the issues and production related to flexible plastic electronics. He is studying how to develop electronic circuitry on flexible plastic substrates. Applications of flexible plastic electronics include production of the radio frequency identification tag (RFID), 'smart' clothing, and LCD screens for computers and maps that can be rolled up.

Jin practiced his research and production in the AMReL and in the Microfabrication Applications Laboratory (MAL). His project involved applying electronic circuitry to a flexible plastic substrate, or a thin piece of laminating film. Ultraviolet light is used in the photolithography process to imprint the circuitry design on the substrate. Electroless plating is a multi-step chemical process that allows copper to adhere to the circuitry design.
(Figures 12 to 14)

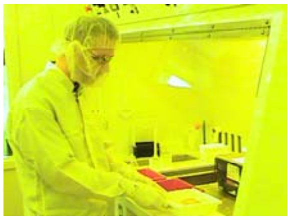


Figure 13. Mike Schaefer soaks a silicone wafer in a developing solution. Yellow lighting is used during the photolithography process.


Figure 14. Developed wafer in the MAL. Note the circuitry.

Reflections
During our tenure in this research setting, we were impressed by the scientific research and potential of its application and contributions to the technological community. Inspired to teach more creatively and to further inspire our students to investigate and explore, we continually reflected on the connections between the AMReL and our own teaching practice and classroom. We discussed possible curricula for our classroom that would parallel some of the processes conducted by the graduate students. Some processes in which we participated were adaptable for science lessons at all levels. Students could challenge themselves to design and build electric circuits of varying size and complexity

They could prepare samples of various items for view under the microscope and in chemistry classes, students could experiment with electroless plating. Ultimately, students should be given multi-step challenges that best simulate real problems that are solved over a period of time, rather than over one or two class sessions.

Effective implementation in the classroom must consider the limited class period, the degree of complexity of the process, and the developmental level of the students. A teacher can design curriculum that parallels specific chemical engineering processes, however, learning these individual processes is not as important as practicing basic science skills and solving complex problems that are meaningful and relevant. A teacher should focus on creating an environment in which meaningful investigations are commonplace and in which students prepare for the rigorous demands of higher level scientific exploration. The RET program allowed us to experience the actual applications of science skills that our students will need to be effective in their scientific endeavors.

Meaningful Investigations

"One challenge to teachers of science and to curriculum developers is making science investigation meaningful."[5] The National Science Education Standards suggests two sources for making science investigation meaningful, by choosing "scientific topics that have been highlighted by current events", and "actual science-and technology-related problems".[6]

The difficulty of making science investigations meaningful to high school students is in essence a question of choice. High school students usually have not yet developed a sustaining interest in scientific inquiry. They are, on the other hand, told that science is important, and are required to take multiple science courses. Students may become proficient in conducting science investigations without being personally invested in them. While not all students are going to become scientists and engineers, it is hoped that they will continue to engage in science investigations. If not, they would quickly loose their proficiency even if it had been attained in the first place. Students, however, do have a choice in believing whether science investigations are meaningful for them.

Professors and graduate students chose science investigation as their career. Experiencing the reasons why they made their choice give meaning to the suggestions from National Science Education Standards. One day, when we entered the lab, we knew something exciting had happened. One of the graduate students in the lab had successfully demonstrated to some colleagues in another lab that their applications could theoretically be mass-produced using current technology used by industry. This investigation happened upon request, not as a part of a graduate thesis. However, it is pursued with great interest because that the result of this investigation, whether positive or negative, is meaningful to further investigations by other scientists and engineers.

One of the keys to successfully implementing the suggestions from the National Science Education Standards is giving students the opportunity to choose the science investigation themselves. What is required is to have the flexibility to conduct science investigations in the course. There is certainly not a lack of interesting topics. But what if the student is “not interested in science”? Students need to be shown the interdisciplinary nature of science inquiry and the impact of scientific inquiry impact on non-science disciplines, evolution, sports, and special relativity being three conspicuous examples of the latter. When the student makes the connection, the investigation of choice will become meaningful to the student.

Scientific Inquiry

“Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work.” [7]

“For students to develop the abilities that characterize science as inquiry, they must actively participate in scientific investigations, and they must actually use the cognitive and manipulative skills associated with the formulation of scientific explanation.” [8]

The National Science Education Standards outline what students need to know to be scientifically literate and emphasizes that inquiry is central to science learning “When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge and communicate their ideas to others.” [9] An inquiry based education teaches students to think critically and logically, to identify assumptions and to consider alternative explanations. By combining action, thinking and reasoning skills, students develop an understanding of science and the ability to carry out scientific exploration.

Following is a list of a few of the many abilities that the standards specify a student should have in order to conduct scientific inquiry. These abilities will be discussed in the following section.

- **Ask and refine questions**
- **Design, and conduct investigation**
- **Employ appropriate tools, equipment and techniques to gather data, extend senses, analyze and interpret the data**
- **Communicate and defend a scientific argument**
- **Assess Prior Knowledge**

Ask and Refine Questions

Students should be able to ask a question about objects, organisms, events and refine questions. Graduate students spend up to a year deciding on a research topic. This includes reviewing previous research, examining current research projects, and defining what questions have and have not been addressed. Through this, graduate students define an area of interest and develop and refine new questions.

In the classroom, students are encouraged questions, and they often discover that these questions lead to more questions. In the first grade, children ask questions before, during, and after activities. Some questions are answered through further investigation into the activity while some are answered through discussion with the teacher. Inquiry at the beginning of a study often provides a baseline of students’ current knowledge and a path to initiate study of the topic. For example, in the beginning of an astronomy unit, children ask questions such as, “What is the big bang?” or “Can people live on Mars?” Some of these questions become the foundation of the unit and are explored as projects, models or with research in various branches of knowledge. As a final step in many experiments and activities, children must formulate related questions that would provide new information if answered. Through the year, students understand that questions are healthy and provide the framework for building knowledge. They learn methods for formulating and refining questions about their world.

Use Equipment & Tools

A typical science research institution has a variety of equipment and specialized tools available. The graduate students with whom we worked in the AMReL must learn the specific techniques for using sophisticated equipment such as the elipsometer, scanning transmission electron microscope (STEM) and the Fourier transformed infrared spectroscope (FTIR). They also spend time learning techniques to interpret and analyze the various types of data obtained, whether it is a set of numbers, a graph or a photograph. Some researchers in the AMReL employ their mechanical skills to build complex chemical delivery systems. (Figure 4) Anand received several hours of training to learn the techniques of preparing a viable sample for the STEM and then worked directly with the electron microscopy specialist to view the sample. Using chemicals requires understanding of their hazards and knowledge of safety procedures.

Similar to the graduate researchers, students in the science classroom need to learn how to safely and effectively use equipment and tools to perform experiments, to construct devices and to test hypotheses. In school, all grades practice using equipment and tools to observe, obtain, analyze and interpret data. Students use the microscope, collect data electronically and use software to create and interpret data tables and graphs. Students at all levels construct devices that vary in complexity from paper airplanes in earlier years to functional robots in high school.

An adequate education should expose children to a variety of scientific phenomena and to various methods of exploring scientific understanding. Through formulating questions and searching for answers and solutions, students gain knowledge, independence, and hopefully develop a lifelong curiosity. The items available in the classroom allow a student to collect information, answer questions, and to formulate new questions. The skills and techniques acquired through asking questions and through the use of equipment and tools in the classroom will transfer to endeavors in graduate research as well as in professional and personal life.

Design and Conduct Scientific Investigations

To successfully design and conduct scientific investigation requires meeting many criteria. The National Science Education Standards states, “regardless of the scientific investigation performed, students must use evidence, apply logic and construct an argument for their proposed explanations.”[10]

The most significant difference between high school and graduate school can be the relative importance of the designing phase of scientific investigations. For one thing, graduate students must obtain funds to conduct scientific investigations. They must "use evidence, apply logic and construct an argument for their proposed explanations" to demonstrate to the professor the soundness of their design first.

Scientific investigations are clearly more meaningful to the students if they are involved in the designing phase. How can the teacher get students involved in the designing phase? One of the keys is to teach students the tools used in scientific investigations. To do so, the teacher must design activities specifically for allowing the students to get acquainted, and explore how a specific piece of equipment is used, during the process of which, students must learn how to collect accurate enough measurements.

In two instances, RET program offered an opportunity to participate in the operations of state-of-art scientific equipment. As a part of an investigation to the interface of hafnium oxide on a silicon substrate down to the atomic level, we were invited to participate in imaging the interface with STEM. We were also invited to the Advance Materials Research Laboratory to learn about electroless plating and the photolithographic process. While far from becoming experts in operating the equipment, we learned to better appreciate the care that goes into maintaining the equipment and the degree of precision achieved.

Learning the knowledge in handling tools for scientific investigation might take place instead of some scientific content. In practice, students only have a limited amount of class time for science. Becoming more comfortable with using tools for scientific investigation will allow students to become more engaged in the process, rather than the result. The establishment of the prior knowledge base, in skills in particular, will allow students to conduct meaningful scientific investigations. After all, the process of scientific investigations should not be a mystery, or worse yet "magical" to the students.

Assess Prior Knowledge

"Thus in a full inquiry, instructional strategies such as small-group discussions, labeled drawings, writings, and concept mapping should be used by teachers of science to gain information of students' current explanation." [11] Assessment of prior knowledge is always necessary for successful instruction. Through the RET experience, however, the meaning of "current explanation" has become more important in designing instructional strategies.

In high school, the students' impression is often that there is a correct and final explanation of a phenomenon. This impression is partially true. The process of science inquiry enables students to arrive at an adequate explanation of a phenomenon, property, characteristic, etc. In one episode of Paul Hewitt's recorded lecture based on his textbook *Conceptual Physics*[12], he talks about the physics of a boxer's punch. Previous to learning about momentum, his explanation is relative speed, i.e. by moving the body towards the punch, the relative speed of the punch is reduced. This explanation is, he realizes, inadequate because the reduction in relative speed is miniscule in comparison to the reduction in impact. The proper explanation is the extension of the time component of impulse will reduce the force in inverse proportion. Indeed prior knowledge has given way to a "correct explanation".

In the graduate study environment, however, arriving at an adequate explanation is a process during which competing explanations are supported by different evidences, or interpretations of evidences. Scientific understanding is crouched in terms of current explanation not a final, correct explanation. In fact, one of the most common research topics is to test competing explanations. Successful conclusion of the research will discredit some explanations, or give more credibility to one explanation. The presentation of research results most often ends with suggestion for further research to clarify the current explanation.

Special relativity is an case of which students' "current explanation" of relative velocity and vector addition of velocities, often studied in the first semester, becomes later the prior knowledge inadequate in explaining phenomenon at the a speed comparable to a fraction of the speed of light. Students need to know that explanations evolve. To this end, it is often important to add an addendum to explanations in "ideal situations". For example, Ohm's law demonstrates the relationship between potential difference, current flow and resistance. Yet if the instructor says nothing about non-Ohmeric resistors, students will be lead to the wrong impression that Ohm's law adequately explains all resistors. A full inquiry should go beyond Ohm's law. Repeating the process of prior knowledge to current explanation shows the students the importance of asking questions such as "Are there any exceptions?" or "Does it always works and when does it not?".

Communicate and Defend a Scientific Argument

The National Science Education Standards states, "Students in school science programs should develop the abilities associated with accurate and effective communication".[13] While scientific accuracy is the basis for any scientific argument, effective communication requires more than just accuracy. In fact, most high school students and adults lack the skills to communicate effectively in science or any other area. To learn how to communicate and defend a scientific argument has ramification for the students in other ways as well.

Both professors in charge of the RET program emphasized the importance of effective communication. Graduate students are expected to attend and present weekly group meetings. Often, the speaker of the group meeting practices with the group their presentations they would have to deliver to an outside group. Everybody is expected to contribute, to ask questions and provide suggestions at the end of the presentation, not only on the content but also on the delivery of the presentation. Graduate students also received help in writing formal papers. The peer review process helps both the presenter and the audience in becoming a more effective communicator of scientific arguments.

Constructive peer review is essential for high school students to learn to communicate more effectively. High school students often lack the experience to communicate effectively. Observing presentations at graduate or professional level can become too difficult for the students to follow. The most practical method of learning presentation skills is to observe other students. However, most students fear giving a presentation because they are afraid that their efforts will be criticized. To establish an environment where students will be constructive in giving their opinions, and are comfortable enough to take constructive criticism is the key for learning effective communication. It is also important to practice delivery. Video taping the presentation can be a useful method of deconstructing what is effective and what is not.

Summary

The RET program provided a professionally valuable experience for the two science teachers. They gained first hand knowledge of the graduate level research environment, its researchers, and its processes and relationships. They participated in a number of activities that included hands-on process, discussion, and giving and attending formal presentations. Researchers at the UIC Department of Chemical Engineering continually utilize the science skills that are outlined in The National Science Education Standards and these same standards are practiced in the teachers' science classrooms. Understanding these skills and the connections between the two settings provides a framework for the teachers to build upon when designing and implementing curriculum that is meaningful to the students, effective for learning, and relevant to scientific application.

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