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Collaborative Classroom Tools for Nanotechnology Process Education

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Collaborative Classroom Tools for Nanotechnology Process Education

Abstract –The cost of equipment acquisition, operation and maintenance often places severe limitations on an institution's ability to introduce laboratory modules in nanotechnology courses. This is exacerbated by the larger class sizes and shorter class times at the undergraduate level (compared to graduate level). This is the main reason why nanotechnology is not taught at most undergraduate engineering curricula. The goal of this project was to develop innovative and cost-effective methods to bring meaningful and sustainable nanotechnology laboratory experience to the undergraduate classroom. Two major tools were developed to overcome the challenges – a computer-based nanofabrication trainer, and a remote interactive video system to link the laboratory to the classroom in real time. These tools are being integrated into junior and senior level engineering courses, two community college courses and workshops for high school science teachers.

Introduction

Low enrollment and poor student performance in academic programs in engineering, science and mathematics support the somber conclusions recently published by The National Academies in Rising Above The Gathering Storm, Revisited: Rapidly Approaching Category 5, an update to its seminal 2005 publication of similar title [1]. The report raises the specter of an impending talent gap which could severely jeopardize U.S. industrial competitiveness. This is highlighted by the comparison of the following trends in China and the U.S. In China, 37% of all undergraduate students major in engineering. Engineering enrollment grew from over 1.0 million in 1998 to over 7.0 million in 2007 [2]. The opposite trend is noted in the U.S. where only 7% of undergraduates are engineering majors and enrollment declined to 409,300 in 2005 [3]. Nevertheless, U.S. engineering degrees are still in demand worldwide due to the greater emphasis that is placed here on industrial relevance, modern laboratories, and hands on training.

At the same time, nanomaterials, components, and devices are making a major impact on the lives of U.S. citizens, with over 1,300 consumer products or product lines containing some nanotechnology component [4]. The inventory of products has grown by over 500% in the last five years. Nearly 50% of these consumer products originate in the United States [5]. In spite of this, the majority of Americans express low levels of knowledge about nanotechnology [6]. This is mainly due to the fact that nanotechnology is not yet widely recognized as an engineering discipline. Today's nanotechnology engineers were educated in other related fields – such as electrical, chemical or mechanical engineering – and acquired their nanotechnology expertise through on-the-job training. That may have been adequate to sustain an industry at its infancy, but as nanotechnology migrates more and more from the laboratory to the marketplace, the task of creating a skilled work force requires a more focused effort rather than relying on on-the-job training [7].

Although the importance of nanotechnology is well accepted by educators, it has not penetrated the mainstream engineering education curricula. This is primarily due to its resource-intensive nature, which brings unique challenges to undergraduate classrooms. A lecture-based approach circumvents most of these challenges, but is much less valuable to students and their employers and also undermines the competitive edge of U.S. engineering degrees. Furthermore, laboratory experience is an essential component in any field of engineering education, not just in nanotechnology. Typically laboratory classes are most commonly accomplished by having multiple stations with students working in small groups. Herein lies the challenge. In nanotechnology this model is unworkable because almost any experiment will involve equipment that are typically too expensive, unsafe or require extensive training to operate. Unlike in a circuits lab, or a structural mechanics lab, a single operator error can result in significant downtime and expense.

One approach that has been tried by many others is to supplement the lecture sessions with online tools and videos. However, pedagogical research has shown that passive approaches alone produce lower student engagement and learning outcomes. The challenge then is, how do we introduce meaningful laboratories into a nanotechnology curriculum that is not passive, and yet without requiring huge and continuing infrastructure investments? Another aspect to consider is sustainability. The laboratory modules need to be capable of running beyond their incubation grant period without requiring a continuous infusion of funds.

We have developed a two-pronged approach to meet these challenges. The first is a computer-based nanofab trainer. This should be distinguished from a simulator, in the sense that its purpose is to bring familiarity with real life processes and tools rather than to accurately predict physical phenomena. It is built as an empirical tool based on years of laboratory experience working with nanofab tools and processes. The second is a system to bring live interactive demonstrations from the laboratory (or cleanroom) to the classroom. Our assumption is that the institution already has the nanotechnology laboratories and trained staff through ongoing funded research. The video system allows the institution to leverage those existing infrastructure in their nanotechnology education without investing in laboratory expansion or new construction. With the two-way video and audio capability the students in the classroom can see the actions close-up, and in fact better than one could from inside the laboratory. The system has the flexibility to be located and set up easily at a remote location and interactivity is extended to individual student computers.

Live Collaborative Video System

The system is built around the Lifesize® Team 220 video conferencing system [8]. It contains a high-end hardware codec that can encode and decode (codec) multiple video channels in high-definition format. Since this was originally designed and sold for traditional video conferencing, it had to be modified to link a laboratory with a classroom. Furthermore, the system must be easily portable from one laboratory to another, because the intent was to leverage existing research laboratories on campus, which may be located in different buildings. The codec and the main hardware were built inside a mobile cart with cleanroom compatible material to ensure low particle emission. The laboratory codec communicates with the classroom codec through the internet or campus intranet. The cart also has a large LCD monitor to allow the operator in the laboratory to see and interact with the classroom. Two high-definition cameras plug into the codec, and can be positioned anywhere using light weight tripods. The cameras can be moved and zoomed by the laboratory operator and also by the instructor at the classroom end. In addition, the codec can also accept a VGA input, which can be a shared screen from equipment such as a microscope or a laptop computer. Hence, three video channels and one audio channel are sent from the laboratory to the classroom, and one video channel and one audio channel are sent from the classroom back to the laboratory. The video and audio are two-way, with multiple wireless microphones at the student desks, allowing the students to interact with the laboratory instructor and the laboratory instructor to see the students in real time.

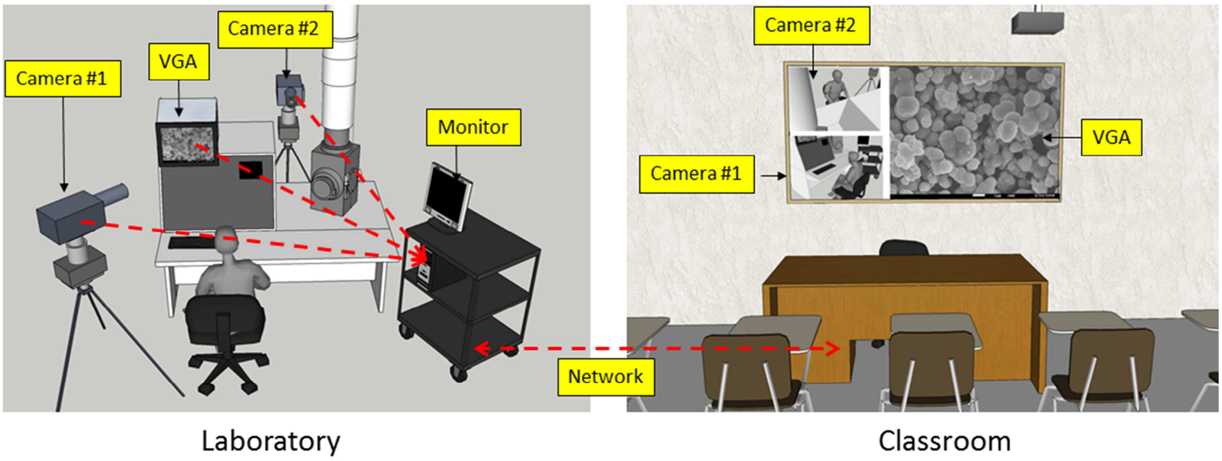

Figure 1: This is the concept diagram as proposed in the NSF-NUE proposal, linking the laboratory to the classroom.

For example, we demonstrated a scanning electron microscope (SEM) to a junior year "Introduction to Nanotechnology" course. The instructor, working from a laboratory, was able to discuss and point out the different parts of the equipment, and then take images from several samples of interest, all within the typical class time of 75 minutes. The students in the classroom saw the same SEM images as the operator, with a real time view of the sample preparation table and the laboratory environment. At all times they could converse with the laboratory instructor and ask questions.

Figure 2: This is the actual implementation of the system. Photo was taken during an actual classroom teaching.

Since it is a mobile system, it can be easily moved into any other laboratory, such as for demonstrating an Atomic Force Microscope (AFM) or Transmission Electron Microscope (TEM). We have also used it for conducting virtual tours of a cleanroom nanofabrication laboratory, where the laboratory instructor was able to demonstrate thin film deposition, photolithography and etch processes, all within the time frame of a single lecture.

This system has been successfully used in a week long summer workshop that was offered for high school STEM teachers. In the near future this video system will be linked with a community college, who is a partner in this NSF effort, so that classes there can be enhanced by the research labs at the other location. The system can also broadcast, teach and engage students in remote sites, such as elementary, secondary, high schools and community college.

Virtual Nanofab Trainer

This concept of remotely interacting with a laboratory instructor is supplemented with virtual tools for developing and understanding nanofabrication process sequences. We developed a LabVIEW-based nanofab process trainer to capture the main steps in a fabrication process. This software can be installed in the students' own computers, and allows them to sequence and visualize the step-by-step deposition, patterning and etch steps of typical device fabrication processes. The students can change process parameters and put a wafer through different steps to get a final functional device.

For example, the image below shows the result of a first-time user's attempt to fabricate an n-channel MOSFET using the trainer. Most of the display is devoted to a two-dimensional cross-sectional diagram of the sort typically seen in undergraduate textbooks, with dimensions marked in micrometers. (Note differing scales on the horizontal and vertical axes.) Starting from a blank silicon wafer, the student performed twenty-six discrete steps to arrive at this end-product by doping the wafer, depositing, patterning and etching layers. As shown in the legend to the right of the main diagram, different colors and shades represent different materials—in this case, aluminum, silicon dioxide, and silicon of different doping levels. Also to the right are three not-yet-implemented indicators that will track the time and expense required to implement the student's steps, as well as a measure of the end-product's quality. These measures will help students to learn about inevitable trade-offs in device fabrication. For example, in a process step that requires the student to establish a vacuum, a lower-pressure vacuum will result in a higher-quality result but will also require more time and cost. The time, expense and quality factors will be empirically included in the software so that the instructor can change and modify these criteria to mimic specific industry scenarios. For instance, the tradeoffs will be different for an electronic chip manufacturer from that of a discrete device manufacturer or a thin film coating service provider.

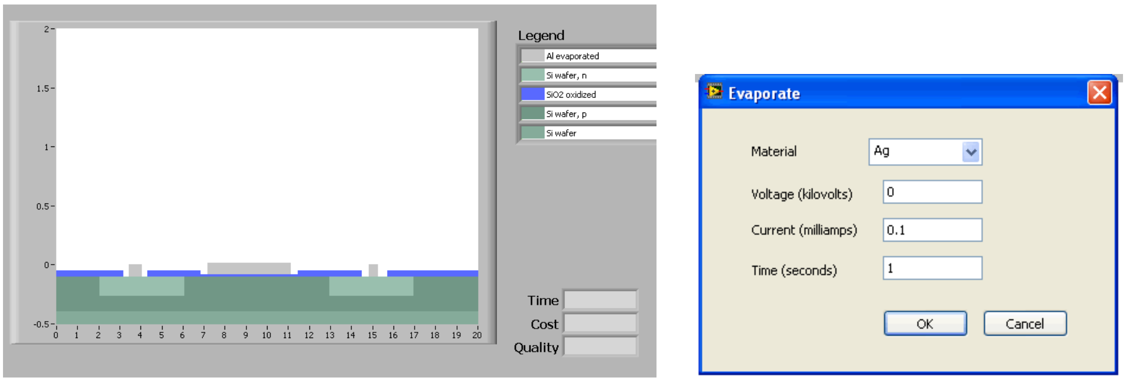

Figure 3: Virtual Nanofab trainer's main screen showing a MOS transistor fabrication process.

Each simulated step requires the student to make informed decisions about how to proceed. For example, to deposit a layer using evaporative deposition, the student specifies material and process parameters via the dialog box shown above on the right. The trainer then computes the thickness of the resulting layer and adds a layer of this thickness to the main diagram. To figure out which values to specify for these parameters, the student can consult built-in tables and charts that summarize empirical data concerning deposition rates, etch rates, and so on.

Other features of the trainer include the ability to save work to a file, which can then be opened later for revision or submitted to the instructor for evaluation; a history screen showing all of the steps taken so far, along with the ability to revert to any of these earlier steps; and tutorial screens that provide educational text, photographs, and short video clips of each processes in the lab.

Nanotechnology Curriculum

Using the innovative tools described earlier, we are developing four new nanotechnology courses between the two partner institutions of this project – a research university and a leading community college. All of these courses will contain lab modules which will be offered through the live collaborative video system and the nanofab trainer. The University and the Community College are being linked with a high bandwidth data connection to enhance this capability.

1. Introduction to Nanotechnology (Course I – Community College) will include the history of nanotechnology, study of the nanoscale world, applications, and an introduction to laboratory tools used in fabrication and characterization.
2. Nanotechnology Applications and Fabrication Techniques (Course II – Community College) will cover applications of nanotechnology in various fields with an emphasis on the fabrication tools, procedures, and measurement equipment.
3. Fundamental Principles of Nanotechnology (Course I – University) will introduce the fundamental scientific principles behind all things nano. Concepts explaining how forces, charges, energies and fields scale with shrinking dimensions will be introduced. Nano-fabrication techniques and the principles of metrology tools will be discussed. This will be followed by a study of the current application of nanotechnology in a few select areas such as electronics, photonics, sensors and advanced materials.
4. Applied Nanotechnology (Course II – University) will focus on four areas where nanotechnology has had a significant impact: Information Technology, Renewable Energy Sources, Nanomaterials and Biomedicine including the effects and ethics of nano-toxicology.

The first University course titled "Fundamental Principles of Nanotechnology" was already offered and the other ones have been developed and will begin starting Fall 2013.

Reaching Beyond the Boundaries of Higher Education

The project has extended well past the University – Community College partnership to include outreach to secondary school educators. The focus of these activities is on increasing the awareness of careers and opportunities in nanotechnology.

In 2012, we ran a week-long "Summer Nanotechnology Institute" for high school educators, with over 24 contact hours. Ten teachers had enrolled for this workshop, with six instructors from both partner institutions and a number of engineering graduate students helping. This was also an opportunity to test the collaborative video system and the nanofab trainer. The participants were awarded one graduate credit-hour for no charge and were given the option to purchase a second credit hour for a small fee. The workshop also included laboratory visits to a carbon nanotube synthesis lab and a nanofab cleanroom. Guest lecturers were invited from government labs and private industry to share their perspectives. The workshop was independently evaluated on the last day by an education specialist outside of this project team. In his report, he summarized the following conclusions:

"Effectiveness of live video system: *For a variety of reasons, the participants thought the live video was a very effective communication tool. They felt the minor technical problems could be addressed.*
Strengths to be continued: *The participants were unanimous about the substantive/content strengths of the workshop. One comment seemed to capture their views: "Please continue this program. It was very enlightening and encouraging."*
Weakness to be addressed: *Most of the comments about weaknesses revolved around some technical problems. Three minor issues were raised about the presentations, but no major weaknesses were identified about the substance/content of the sessions.*
General comments: *Most of the comments were positive "thank you" kind of statements. When viewed as a whole, the total set of comments was overwhelmingly positive; the few suggested improvements were clearly constructive comments. "*

This workshop will be run again in 2013 and in future years.

Concluding Remarks

Public awareness and access to laboratory infrastructure continue to be the main challenges in nanotechnology education at the undergraduate level. We have attempted to overcome both of these challenges by creating virtual trainers and live video links to laboratories. This ensure that the approach is not entirely passive approach which may disengage the students, while at the same time leveraging existing research laboratories without burdening them with large student traffic and teaching activities. Early results seem to indicate that this is working as intended, but more data from future year classes is needed before conclusions can be made. Educating high school teachers and creating lasting relationships is important in creating a pipeline of trained workforce at all skill levels in nanotechnology. We have been successful in reaching out to science teachers in the local area through intensive week-long workshops. It is expected that this will lead to formal partnerships with high schools where we can link the nanotechnology laboratories at the University with high schools.

Acknowledgement

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