Simulation Approaches for Microelectronics and Nanofabrication Advanced Technology Education

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Abstract: The role of computer simulations on student learning and education in the fields of nanotechnology and microelectronics is studied in this work. Exercises based on selected nanoHUB simulations (offered by the Network for Computational Nanotechnology (NCN), Purdue University) were assigned to over 25 undergraduate students from community colleges and universities. Each exercise was assigned every 1-2 weeks over 12 weeks of the Nanofabrication Manufacturing Technology program of 18 credits offered by the Center for Nanotechnology Education and Utilization at Pennsylvania State University. These exercises included setting technical parameters and inputs for concepts such as oxidation, nano-optics, photovoltaics, semiconductor doping, etc., and analyzing the simulation results/outputs. Feedback on the simulations and simulation-driven learning was regularly received from students and analyzed. This feedback is discussed in this article. Students appreciated additional learning through simulations that complemented lectures and hands-on laboratories. Simulations were most effective when students had a background in the technical topics covered in the simulation exercises. Students strongly preferred simulations that were convenient and simple to use and that allowed simulation parameters to be tuned easily. This work can help toward improving STEM education and receive insights into strategies that could enable effective student learning.

Keywords: STEM education, simulations, nanotechnology, microelectronics, community colleges, universities

Introduction

Nanotechnology, nanoscience, and microelectronics are among the fastest-growing areas and have received significant attention in a spectrum of organizations, including education, industries, national labs, and workforce development [1-6]. There has been an increasing effort to disseminate nanotechnology education across community colleges and universities, focusing on undergraduate and graduate students. The Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act supports collaborations between academia, industries, and government organizations and emerging needs for workforce and talent in the areas of semiconductors, microelectronics, packaging, and nanotechnology [7-10]. Skilled talent is necessary to meet the increasing need in semiconductor manufacturing and nanotechnology workforce. A need to infuse nanotechnology and microelectronics in curricula across colleges and pre-college schools through course developments, focused educational programs, and workforce development initiatives has been realized [11,12]. Teaching fundamental concepts of nanotechnology and semiconductor manufacturing to students enrolled in schools ranging from elementary schools to undergraduate and graduate schools will assist in developing this required workforce. Teaching nanotechnology usually consists of lectures, projects, and experimental labs, and newer pedagogical techniques are continuously being developed and identified [13-16]. Simulations go hand in hand with theory and experimental education as new technologies and educational materials are being developed [17]. Simulations are a more economical alternative to expensive equipment and labs typically required in nanotechnology and microelectronics education [18]. Additions of simulations to the traditional methods of instruction has resulted in mixed observations in the literature, with the simulations enriching the students' experience in some cases while not effecting the experience at all in other cases [19].

In this work, the influence of adding simulations from the nanoHUB database on student-learning in nanotechnology courses is studied. Feedback from 25 students on how adding simulations to the curriculum impacted their educational experience is reported.

Methods

Six Penn State nanotechnology classes infused simulations from the nanoHUB platform as assignments or exercises as part of the 18-credit Summer Nanofabrication Manufacturing Technology (NMT) program of the Center for Nanotechnology Education and Utilization (CNEU), Penn State. The NMT program includes education on the following topics through lectures, hands-on labs, homework assignments, exams, and projects.

1. Safety
2. Cleanrooms
3. Vacuum
4. Materials in nanofabrication and microelectronics (Semiconductors, doping, metals, dielectrics, polymers, etc.)
5. Materials growth and deposition (including oxidation, physical/chemical vapor deposition, solution-based synthesis, Czochralski's method, atomic layer deposition, and so on)
6. Lithography
7. Etching
8. Bottom-up synthesis
9. Quantum dots and other nanostructures
10. Nanobiotechnology
11. Microfluidics
12. Characterization (covering >10 characterization techniques)

Simulation tools from the nanoHUB database were selected based on their suitability within the course curricula and their difficulty levels. The infused simulation tools were selected to match the typical difficulty levels of exercises that community college and four-year college students typically take. These simulations were in addition to the lectures, hands-on labs, homework, online labs, and projects that students completed. Following is the list of the eight selected nanoHUB simulation tools distributed and assigned over the 12 weeks.

1. Ohm's law
2. Effect of doping on semiconductors
3. Carrier concentration
4. Basic bulk silicon transport data
5. PN junction
6. Process lab – Oxidation
7. Nanosphere optics lab
8. Organic photovoltaics lab

Assignment handouts corresponding to each of these simulation tools were prepared. The handouts included basic science and engineering theory of the simulation topic, a demonstration of how to use the simulation tool and questions based on the simulation results. Feedback from students was obtained after each assignment on the nanoHUB simulation tool and the role of the tool in their learning process.

Results and Discussion

Throughout the 12 weeks of the CNEU-NMT program, students completed multiple surveys. They were given points for completing the surveys, but not for what they wrote in them. Twenty-five students provided feedback on the nanoHUB simulation tools-based exercises.

Students appreciated the value of the simulations in addition to experiments and theory in the learning. They appreciated the different number of cases that could be simulated, which would typically take an unrealistically long time to be tested by experiments. The students enjoyed changing and understanding how different parameters affected the results and outputs. Simulations aided the students in learning technical topics better, and they would prefer to use the simulation tools in the future, as appropriate. Topics were selected for the simulations that matched with the students' interests and with the flow of the courses. Students preferred simulation tools that were convenient to use and fast enough to give results quickly. Students provided feedback on improving the graphical user interface and making the nanoHUB simulation tools easier and more convenient to use. Students also suggested preparing video tutorials on using the simulation tools and providing brief instructions on using the simulation tools in the lectures. Table 1 shows feedback from 25 students on a series of questions gauging the interests of students in the nanoHUB simulation tools and the usefulness of the tools in the learning process.

Students' favorite and least favorite nanoHUB simulation activities were identified through systematic feedback surveys, Figure 1. Students selected Ohm's law, oxidation, and carrier concentration as their top three favorite simulation tools on average. Students had prior background on Ohm's law and using the corresponding tool was straightforward. Oxidation was covered in depth in the lectures and hands-on labs by the instructor and teaching assistants; the corresponding nanoHUB simulation tool strengthened students' understanding of oxidation. Students found the nanoHUB simultation tools most valuable when the simulation exercises were assigned at times when the topics were covered in lectures and hands-on labs. Students also enjoyed the tools the most when they had a prior background in the technical topic being simulated. PN junction, nanosphere optics, and organic photovoltaics were students' least favorite nanoHUB simulation activities.

Table 1. Student feedback on nanoHUB simulations incorporated in nanotechnology courses

	Survey questions asked / Options provided for responses	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1	It was valuable to learn about simulations in the Nanofabrication Manufacturing Technology (NMT) Certificate Program	28%	48%	20%	4%	0%
2	When learning a technical topic in the future, I would like to learn the simulations (if it is a possibility) along with experiments and theories	32%	40%	12%	4%	12%
3	I understand the role and value of simulations in the nanotechnology field better because of the simulations done in the NMT program	12%	56%	12%	8%	12%
4	Topics for the simulations were appropriately selected and were within my areas of learning interest	12%	28%	32%	20%	8%
5	The nanoHUB simulation tools were easy and friendly to use	4%	20%	28%	20%	28%
6	The nanoHUB exercises procedures were convenient to follow	4%	8%	48%	12%	28%
7	The nanoHUB simulations exercises helped me to understand the technical topics better	8%	20%	16%	16%	40%

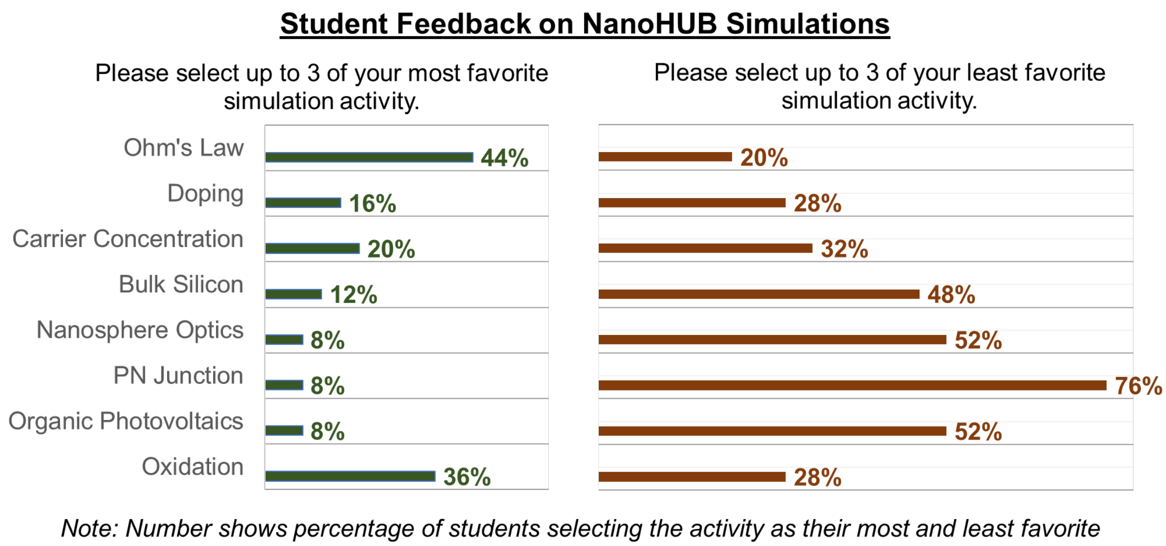

Fig. 1. Students' feedback on their three most favorite and least favorite nanoHUB simulation tools. Students identified Ohm's law, oxidation, and carrier concentration as their most favorite nanoHUB simulation tools. PN junction, organic photovoltaics, and nanosphere optics were chosen as their least favorite nanoHUB simulation tools.

Additionally, intensive feedback on each of the nanoHUB simulation tools used in the courses was obtained. Figures 2-7 show first-hand feedback obtained from students directly on selected nanoHUB simulation tools.

Ohm's Law Simulation Tool: Student Feedback

- *"I learned how resistance, voltage, and current interact with each other. I found the line graph self plotting points was helpful."*
- *"I learned more about the relationship between power, voltage, and current. This tool was helpful because it displayed a graph to see what was happening"*
- *"I learned the inverse relationship between current and resistance. I wish the simulation was more user-friendly. A tool that can trace the graph would be more ideal than customizing increments of x and y values"*
- *"The software lacked some basic functions, such as scrolling/zooming with the scroll wheel or being able to quickly click between text boxes"*
- *"It felt a little confusing to use I learned about constant current and resistance"*

Fig. 2. Feedback of students on the nanoHUB Ohm's law simulation tool. The Figure includes feedback obtained directly from the students.

Effect of Doping on Semiconductors: Student Feedback

- *"This simulation helped me to understand the energy levels of electrons in semiconductors and whether n- or p-type doping is most appropriate"*
- *"I learned how varying doping levels and temperature significantly impact the conductivity and carrier concentration in semiconductors"*
- *"I found the visualization of the data very helpful to interpret what is happening. I would recommend to have a video tutorial compared to just screen shots in order to better convey how to use the software"*
- *"I think the simulation having a graph and numerical charts is helpful. However, feel like the charts can be straightened up to make things easier to read"*
- *"This software was difficult to understand, but that might just be because the content is very unfamiliar"*

Fig. 3. Students' feedback on the nanoHUB Effect of Doping on Semiconductors simulation tool. The Figure includes feedback obtained directly from the students.

Nanosphere Optics Simulation Activity: Student Feedback

- *"It was my favorite nanohub so far. The direction were clear and the inputs were not misleading. The graph was my favorite part and easy to understand"*
- *"The graphs were easy to use and good at showing the different plots"*
- *"I learned how the optical properties of gold nanoparticles change depending on the particle diameter. The simulation could benefit from a more user-friendly interface and better-detailed tutorials.*
- *"The simulation needs a proper tutorial, but it is useful for simulating the light interactions of nanoparticles"*
- *"I learned about red shifts and blue shifts still think the nanohub program is outdated and clunky to use"*

Fig. 4. Students' feedback on the nanoHUB Nanosphere Optics simulation tool. The Figure includes feedback obtained directly from the students.

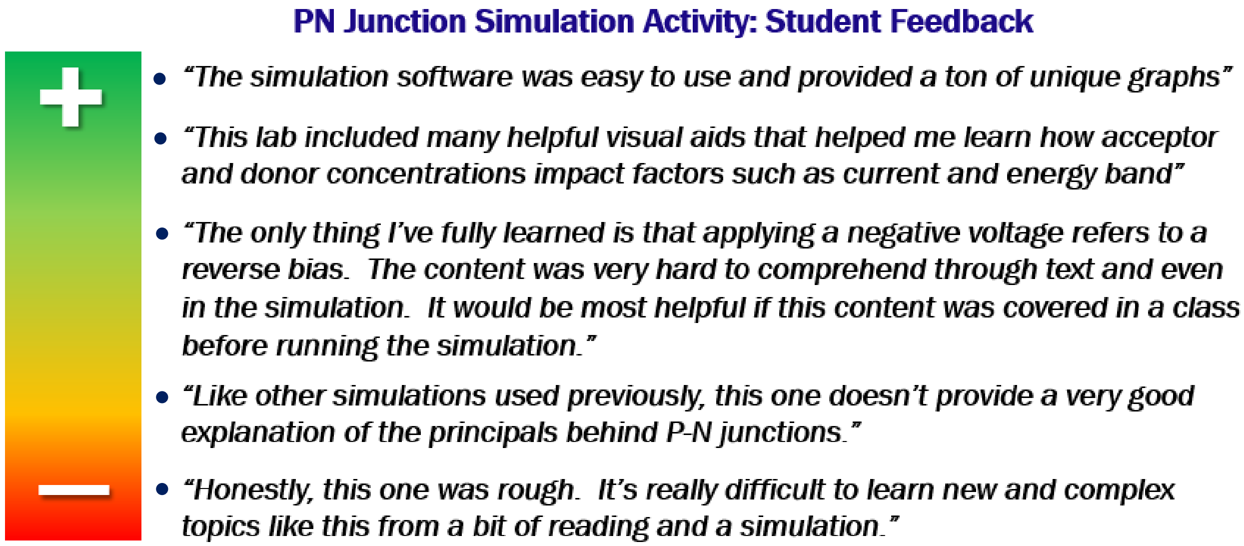

Fig. 5. Feedback of students on the nanoHUB PN Junction simulation tool. The Figure includes feedback obtained directly from the students.

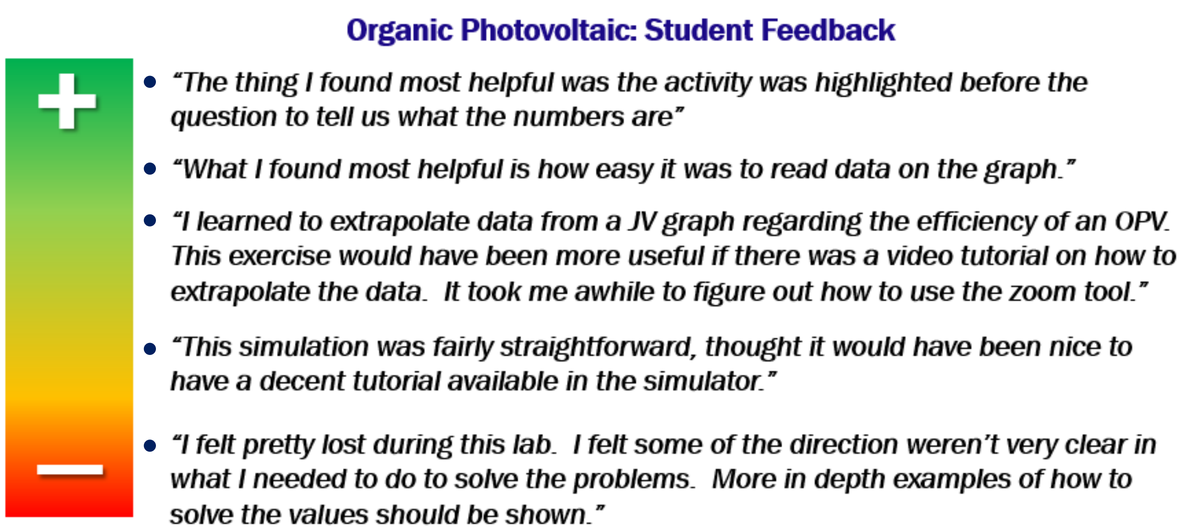

Fig. 6. Feedback of students on the nanoHUB Organic Photovoltaic simulation tool. The Figure includes feedback obtained directly from the students.

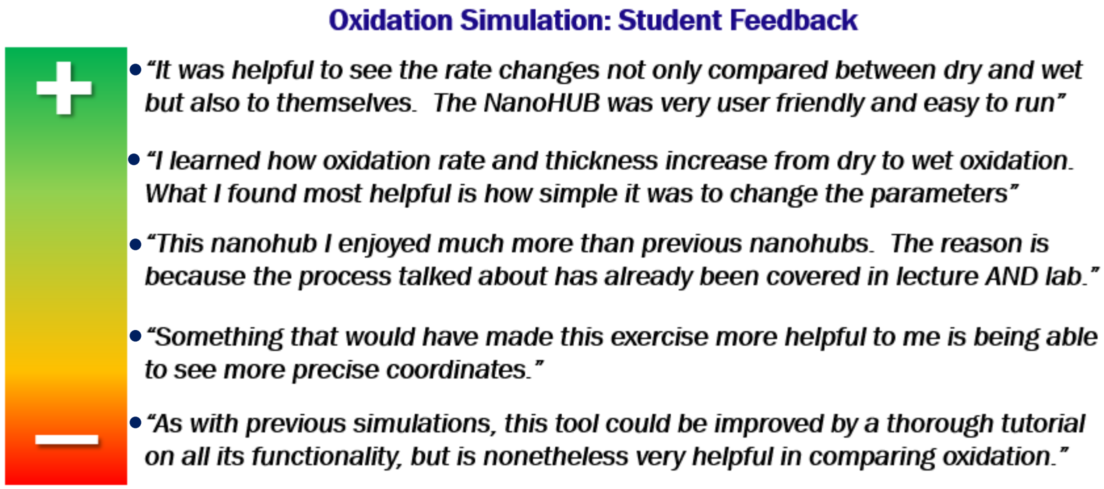

Fig. 7. Students' feedback on the nanoHUB Oxidation simulation tool. The Figure includes feedback obtained directly from the students.

Conclusion

This study has aided in understanding the impact of the addition of simulation tools in the nanotechnology education process. Simulations could add value to learning by providing alternative ways of teaching technical topics. It adds a way of working and learning for students who may not enjoy theory and experimental labs but would enjoy working on computers through simulations. Simulations also help students to emulate various experimental conditions. In order to infuse simulations in nanotechnology education effectively, it is essential for the tools to be very convenient to use and have an engaging graphical user interface. It is also important to provide very clear instructions to students on using the simulation tools through various modes, including handouts, video demos, and training from instructors and teaching assistants.

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