AC 2008-1736: DEVELOPING A LAB COURSE IN NANOTECHNOLOGY FOR UNDERGRADUATE ENGINEERING STUDENTS

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Developing a Lab Course in Nanotechnology for Undergraduate Engineering Students

Abstract

Nanotechnology is an area of strategic importance for future industry. Department of Electrical Engineering in collaboration with the Department of Physics has developed a new Interdisciplinary Nanoelectronics Laboratory for the Engineering/Science Undergraduate Curriculum at the University at Buffalo (UB). This is one of the very first and unique teaching laboratories in the area of nanoelectronics in the country for second and third year undergraduate students. Nine laboratory experiments as well as the manuals for these laboratory experiments have been developed. The list of the laboratory experiments includes: Propagation of Errors; Introduction to Scanning Tunneling Microscopy (STM); Study of the Highly Oriented Pyrolytic Graphite (HOPG) Surface Using STM; Introduction to Atomic Force Microscopy (AFM); Study of the Morpho Butterfly Wing Structure Using AFM; Diffraction of Electrons from Graphite; Diffraction of Light by a Double Slit - One Photon at a Time; Optical Absorption by CdSe Nanocrystals; Photoluminescence from InP Quantum Dots (QDs). This unique Laboratory was already used by local high school students who visited it during special events organized by the University. During the Summer 2007 semester, the laboratory has been used to train Science teachers from local schools. Nineteen undergraduate students were enrolled in lab course in the Fall 2007 semester. This paper reports a study on the effectiveness of the above newly developed nanotechnology laboratory course.

Introduction

Nanotechnology is a rapidly developing area and is strategically important for future industry. As a result, many countries have invested not only in nanotechnology research and development, but also in nanotechnology education. In the US, the 2001 National Nanotechnology Initiative (NNI) (http://www.nano.gov/html/res/nni2.pdf) calls for developing educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology. The need for nanotechnology education in the US has also been raised in the literature[1]. However, an undergraduate degree program in nanotechnology is currently still not commonly available in US universities, although some research universities with extensive research expertise have started offering various forms of nanotechnology undergraduate curricula[2,3]. Goodhew[4] summarized three possible formats for nanotechnology education, classifying them as types A, B, and C. Type A programs offer specialized "short modules" to graduate or undergraduate students. Type B programs offer specific Master degrees to graduate students with adequate background in large-scale science, and type C programs construct new undergraduate curricula, in which nano-concepts play a central role from the start. As an example of type C programs, the University at Buffalo (UB) has developed and offered a nanotechnology lecture-based course EE 240 for undergraduates each Spring semester beginning from 2005. The hands-on lab course EE342/PHY342 "Nanoscience Laboratory", which is based on the lecture EE 240 course, has been developed and offered for the first time in the Fall 2007 semester. These two courses precede the four existing nanotechnology courses that are offered to the UB senior undergraduate students as electives. The current paper reports the evaluation results of the EE342/PHY342 lab course.

Description of the EE342/PHY342 lab course

Nine laboratory experiments including experiments with Scanning Tunneling Microscope (STM) and Atomic Force Microscope (AFM), as well as the manuals for these laboratory experiments, were developed and the lab manuals were published by the Great Lakes Graphics & Printing center. The lab manuals have been prepared with the direct involvement of graduate and undergraduate students from the Electrical Engineering and Physics Departments of UB and Science teachers from New York State. Therefore, these manuals were adjusted to undergraduate students' level.

The following describes the nine labs developed:
1. *Propagation of Errors*
First, the students carried out an introductory experiment on uncertainty in measurements and the propagation of errors. The concepts introduced in this lab were used to analyze the data from all the subsequent experiments.

2. *Introduction to Scanning Tunneling Microscopy (STM)*
The students learned: 1) basic principles of operation of the STM and 2) user-oriented STM software. Using this knowledge the students obtained images of (111) Au film surfaces.

3. *Study of the Highly Oriented Pyrolytic Graphite (HOPG) Surface Using STM*
The students learned in more detail the operation of STM. This experiment required extensive use of the acquired skills to study at the nanoscale level the surface of HOPG sample. Students obtained with the help of STM the images of the atomic hexagonal structure for the graphite surface layer and estimated the lattice constant.

4. *Introduction to Atomic Force Microscopy (AFM)*
The students learned basic principles of operation of the AFM. Using this knowledge the students studied the surface of a silicon oxide microstructure and obtained the images of a periodic structure of the holes in the silicon oxide layer, including three-dimensional image of the silicon oxide layer.

5. *Study of the Morpho Butterfly Wing Structure Using AFM*
In this experiment students were introduced with the help of AFM to the fascinating world of tropical Morpho butterflies. The students studied the fine structure of the butterfly wings at the nanoscale level. Using these data the students were able to explain the origin of the brilliant iridescent color of the Morpho butterfly wings.

6. *Diffraction of Electrons from Graphite*
The students recorded the pattern generated by the diffraction of monoenergetic electrons by a polycrystalline graphite sample in a cathode tube for several values of the anode-cathode voltage. Analysis of the diffraction data yielded the lattice constant for graphite.

7. *Diffraction of Light by a Double-Slit – One Photon at a Time*
The students used a specially designed two-slit diffraction experiment to study the resulting interference in the regime, under which, on the average, only one photon passed through the slits at any given time. The students compared their results with the theoretical calculation of the diffraction pattern.

8. *Optical Absorption by CdSe Nanocrystals*
The students measured the absorption edge of four different low-pass filters using a broadband source and a spectrometer. From the cut-off wavelength the effective average band gap of the nanocrystals was determined. Using a simple particle-in-a box expression the students were able to calculate the average radius of the CdSe nanocrystals for each filter.

9. *Photoluminescence from InP Quantum Dots (QDs)*
The students excited the photoluminescence (PL) spectra from four different solutions of InP nanocrystals using a GaN diode. The PL spectra were recorded using a spectrometer. From the emission spectra the students determined the average InP nanocrystal radius. From the linewidth of the emission peak the students calculated the corresponding spread in the nanocrystal dimensions.

Results of evaluation of the EE342/PHY342 lab course

The following instruments were used in the evaluation of the EE342/PHY342 lab course:
1) Conceptual Test of Nanotechnology Concepts and Skills,
2) Survey of Attitude toward Nanotechnology and Nanotechnology Laboratory, and
3) Formative Assessment of Nanotechnology Labs.
The results of the application of the above instruments are as follows:

1) Conceptual Tests
Nineteen students completed *Conceptual Test of Nanotechnology Concepts and Skills* pre-test at the beginning of the lab course, and a post-test at the end of the course. The pre- and post-tests were identical, with 16 multiple-choice questions assessing the students' knowledge and understanding of nanotechnology concepts and skills involved in the labs. The results of assessment are as follows:

Conceptual Tests	Number of Students	Mean	Standard Deviation
Pre-test	19	7.84	2.267
Post-test	18	9.61	1.883

A *t*-test on the significance of the difference between the means of pre-test and post-test shows that the difference is statistically significant ($p = 0.014$, $df = 35$, $t = 2.574$), i.e. the students performed significantly better on the post-test than on the pre-test.

2) Survey of Attitude toward Nanotechnology and Nanotechnology Laboratory

Nineteen students completed a survey of *Attitude toward Nanotechnology and Nanotechnology Laboratory (see Appendix 1)*. Overall, students were very positive about the hands-on nanotechnology labs. On a scale from 1 to 5 with 5 to be most positive, the students' overall attitude was at 3.96.

3) Formative Assessment of Nanotechnology Labs

The *Formative Assessment of Nanotechnology Labs (FANL)* form was used to evaluate the effectiveness of the above-mentioned nine labs. The FANL form contains seventeen statements, followed by seven choices: Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree, Not Applicable, and Don't Know. The statements from the FANL form are as follows:

Content

1. The objectives of the experiment are clearly stated.
2. The experiment makes explicit connections to the theories of the EE 240 course.
3. The experimental tasks are appropriately challenging.
4. The underlying rationale for the techniques used is well explained.

Content Validity

5. The scientific information in the manual is accurate.
6. The charts and / or graphs in the manual aid in reaching the stated objectives for the experiment.
7. The manual information is free of grammatical, spelling, and typographic errors.

Student Engagement

8. The experimental procedures and instructions are clearly described.
9. The working space is well organized and prepared.
10. Individual attention is available when needed.
11. The instructor and/or TA are sufficiently familiar with the experiment and equipment.
12. The instructor and/or TA show concerns about equipment failures or other technical difficulties.
13. There are enough opportunities to interact with other students in a team.
14. There is enough time allocated for the experiment.

Grading and Feedback

15. The grading criteria are clear.
16. Adequate time is provided for writing the lab report.
17. Helpful feedback on reports is available.

Fifteen students out of nineteen taking the EE342/PHY342 lab course in the Fall 2007 semester completed the FANL form at the end of each of the labs. Although the students' evaluation varied from lab to lab and from aspect to aspect within a lab, overall, the students rated all the labs to be very effective. This is based on the fact that majority of the students either "Agreed" or "Strongly Agreed" with all the above seventeen statements for all the labs. Students' evaluation also pointed out a few areas for each lab that needed further improvement. For example, the students, who carried out the lab experiments No. 6 "Diffraction of Electrons from Graphite" and No. 3 "Study of the Highly Oriented Pyrolitic Graphite (HOPG) Surface Using STM", had to define the structure of graphite by two different methods – in the No. 6 experiment by detecting the diffraction of electrons from graphite crystal and in the 3rd one by using Scanning Tunneling Microscope to visualize the surface of graphite layer. Comparing the data obtained from the evaluation of these two labs students indicated that the manual for 6th lab has to be made free of grammatical, spelling, and typographic errors (statement 8 from the FANL form). Students' answers on statement 12 from the FANL form show that the TA conducting the 3rd lab has to be better trained to assist the students carrying out the experiment. The rest of answers on the statements from FANL form for these two labs are close to each other. The detailed descriptive statistics of these two labs are available in the Appendix 2. Note, that analyzing this data one must be take into account that the same student marked for all labs "Strongly Disagree" and "Disagree". All other students marked mostly "Agree" and "Strongly Agree" for all labs.

Conclusion

The results of evaluation of the EE342/PHY342 "Nanoscience Laboratory" course demonstrate that the developed lab course is popular among the undergraduate students and Science teachers from local schools and the small changes are needed in order to improve it. Feedback from students, who took the EE342/PHY342 course and demonstrations of AFM and STM experiments at local high school and two-year College show that the students are genuinely interested not only in the characterization of structures on nanoscale but also in nanofabrication of such structures. Taking all the above into account the main efforts will be applied to expand the spectrum of experiments and, in particular, to include nanolithography.

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APPENDIX 1

Survey of Attitudes toward Hands-on Nanotechnology and Nanotechnology Laboratory (SANL)

Instructions: For each of the following statements related to nanotechnology, please state your opinion by selecting (√) Strongly Agree (SA), Agree (A), Undecided (U), Disagree (D), or Strongly Disagree (SD).

Questions	SA (5)	A (4)	U (3)	D (2)	SD (1)
1. Hands-on Nanotechnology courses are fun					
2. Hands-on Nanotechnology courses increase my curiosity in nanotechnology					
3. Hands-on Nanotechnology courses provide me with the skills that will help me find employment					
4. Hands-on Nanotechnology courses should be offered earlier in my educational development					
5. More funding should be allocated to Universities to create and further develop Hands-on Nanotechnology courses					
6. Usage of Scanning Tunneling Microscopy in the Nanotechnology Laboratory is crucial for future developments in the field of nanotechnology					
7. Usage of Atomic Force Microscopy in the Nanotechnology Laboratory is crucial for future developments in the field of nanotechnology					
8. In the Nanotechnology Laboratory I will learn how to apply nanotechnology concepts learned in previous courses					
9. Skills acquired in my previous lab courses help me to effectively analyze a problem, perform experimental analysis, and properly document my results in the Nanotechnology Laboratory					
10. I feel that I have the necessary background on nanotechnology concepts to solve the problems in the Nanotechnology Laboratory					
11. My knowledge of wave-particle duality helps me to solve problems in the Nanotechnology Laboratory					
12. Nanotechnology Laboratory teaches me to measure parameters and determine parameter error in nanostructures					
13. The Nanotechnology Laboratory will help me appreciate the multidisciplinary nature of nanotechnology					
14. Would you recommend this Nanotechnology Laboratory to other students					

APPENDIX 2
Descriptive Statistics of Formative Evaluation of Lab Experiments

Abbreviations of Lab Experiments:
3 – *Study of the Highly Oriented Pyrolytic Graphite (HOPG) Surface Using STM*
6 – *Diffraction of Electrons from Graphite*

Lab	Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Don't Know
6	1			2 (13.3%)	4 (26.7%)	9 (60.0%)	
	2				7 (46.7%)	6 (40.0%)	2 (13.3%)
	3				7 (46.7%)	8 (53.3%)	
	4				8 (53.3%)	7 (46.7%)	
	5		1 (6.7%)		5 (33.3%)	8 (53.3%)	1 (6.7%)
	6		1 (6.7%)		10 (66.7%)	4 (26.7%)	
	7	1 (6.7%)	2 (13.3%)	4 (26.7%)	2 (13.3%)	6 (40.0%)	
	8		1 (6.7%)	2 (13.3%)	5 (33.3%)	7 (46.7%)	
	9				5 (33.3%)	10(66.7%)	
	10				3 (20.0%)	12 (80.0%)	
	11				2 (13.3%)	13 (86.7%)	
	12			1 (6.7%)	2 (13.3%)	12 (80.0%)	
	13		1 (6.7%)	2 (13.3%)	4 (26.7%)	8 (53.3%)	
	14			2 (13.3%)	3 (20.0%	10 (66.7%)	
	15	1 (6.7%)			7 (46.7%)	7 (46.7%)	
	16			2 (13.3%)	5 (33.3%)	8 (53.3%)	
	17		1 (6.7%)	1 (6.7%)	5 (33.3%)	8 (53.3%)	
3	1			3 (20.0%)	3 (20.0%)	9 (60.0%)	
	2				5 (33.3%)	8 (53.3%)	2 (13.3%)
	3		1 (6.7%)	1 (6.7%)	3 (20.0%	10 (66.7%)	
	4				7 (46.7%)	7 (46.7%)	1 (6.7%)
	5		1 (6.7%)		7 (46.7%)	6 (40.0%)	1 (6.7%)
	6		1 (6.7%)		8 (53.3%)	6 (40.0%)	
	7	1 (6.7%)		3 (20.0%)	5 (33.3%)	5 (33.3%)	1 (6.7%)
	8		1 (6.7%)	3 (20.0%)	3 (20.0%)	8 (53.3%)	
	9				4 (26.7%)	10 (66.7%)	1 (6.7%)
	10				4 (26.7%)	10 (66.7%)	1 (6.7%)
	11			1 (6.7%)	4 (26.7%)	10 (66.7%)	
	12			1 (6.7%)	4 (26.7%)	10 (66.7%)	
	13				7 (46.7%)	7 (46.7%)	1 (6.7%)
	14		1 (6.7%)		4 (26.7%)	9 (60.0%)	1 (6.7%)
	15	1 (6.7%)		2 (13.3%)	4(26.7%)	8 (53.3%)	
	16	1 (6.7%)	1 (6.7%)	1 (6.7%)	3 (20.0%)	9 (60.0%)	
	17				8 (53.3%)	7 (46.7%)	