AC 2011-366: DEVELOPMENT OF A NEW LECTURE/LAB COURSE ON QUANTUM MECHANICS FOR ENGINEERING STUDENTS

Vladimir Mitin, University at Buffalo, SUNY

Vladimir Mitin, SUNY Distinguished Professor at the Department of Electrical Engineering at the University at Buffalo, The State University of New York. He was the Chair of that Department for two terms: 2003-2006 and 2006-2009. During 1993-2003 he was a Professor in the Department of Electrical and Computer Engineering at Wayne State University in Detroit, Michigan. His fields of specialization are nanoelectronic, microelectronic and optoelectronic devices and materials. Currently he is working in the following areas: design and simulation of devices; heat dissipation in nano-structure and nanodevices; light absorption and emission in inhomogeneous materials, heterostructures, and nanostructures. Special emphasis in his research now is in simulation and modelling of nanosensors, and quantum dot infrared photodetectors. He has more than 500 publications including ten patents, four monographs and five textbooks. He obtained his Doctor of Science degree in 1987 from the Institute of Semiconductors of Ukrainian Academy of Sciences in Kiev, Ukraine.

Nizami Z Vagidov, University at Buffalo, The State University of New York

Dr. Nizami Vagidov is a Research Assistant Professor of Electrical Engineering at University at Buffalo. He is an author and co-author of more than 90 publications mostly in the field of electronics and nanoelectronics. He taught undergraduate and graduate courses at Wayne State University, Detroit, MI. In 2010 he with two co-authors has published an introductory to quantum mechanics textbook for undergraduate students ”Quantum Mechanics for Nanostructures”.

Prof. Athos Chariton Petrou
Xiufeng Liu, University at Buffalo, SUNY

Development of a New Lecture/Lab Course on Quantum Mechanics for Engineering Students

Introduction

A new introductory quantum mechanics course for juniors/seniors was developed by the authors of the current paper. They believe that a quantum mechanics course must be the *first course in nanoelectronics* and must precede any nanoelectronics or nanoscience courses since quantum mechanics embraces all aspects of nanoscale science from the conceptual modeling via the fabrication and processing of nanomaterials to applications of nanodevices and nanosystems. Usually science and engineering undergraduate students take nanoscience and engineering courses without preliminary knowledge of quantum mechanics. The difficulties that they encounter in understanding the new counterintuitive concepts of quantum mechanics and the frustrations they feel prevent them from making any real progress and thus discourage them to pursue careers in the nanoelectronics field.

The main idea on how to teach introductory course on quantum mechanics is in the development of a new combined lecture/lab course where students learn the fundamental laws and principles of quantum mechanics by using the study of nanostructures as a vehicle. The new notions that students acquire in lecture rooms can be applied when they carry out lab experiments and virtual labs using educational Java applets. Such combination of learning tools helps students with very different educational backgrounds to comprehend the novel quantum-mechanical concepts[1] and apply them for the solution of problems in nanoelectronics. The developed lab manual complements the textbook[2] written specifically for this course. The combined lecture/lab introductory to quantum mechanics course was pilot-tested and offered at University at Buffalo (UB) in the Fall 2010 semester and the corresponding evaluation and assessment of the taught course were carried out.

Description of the combined lecture/lab course

Here we reiterate that the *first course in nanoelectronics must be introductory quantum mechanics course.* Since the operating principles of nanodevices that students study in nanoscience or nanoelectronics courses are wholly defined by quantum-mechanical principles, students have difficulties[3] in understanding how these devices operate. This leads to frustration and many students after this experience do not take any higher level nanoscience courses and do not pursue a career in this field. For this reason the first course that undergraduate students must take, before taking any nanoelectronics or nanoscience courses, should be an *introductory quantum mechanics course.* Such course was developed and offered for the first time at UB in Fall 2010 semester. Preliminary results describing the course lecture materials, applets, a lab manual, and assessment tools were presented at the “Symposium on Advances in Higher Education in Nanoscale Science and Engineering”, August 5-8, 2009, University at Albany, SUNY[4].

Specifically developed for this course is the textbook “Quantum Mechanics for Nanostructures”[2] based on the learning quantum mechanics via nanostructures. The electronic states of simplest nanostructure – zero-dimensional nano-object – quantum dot (QD) are calculated and compared with the ones for the smallest object at atomic scale - hydrogen atom, H. Additionally, the electronic states of both objects are studied in the lab room (lab experiments: “Atomic spectra; hydrogen Balmer lines; sodium D-doublet “ and “Photoluminescence from InP quantum dots”) and through carrying out virtual labs (educational Java applets “Quantum Dot” and “Hydrogen Atom”[5]). Then, a more complex nano-object – a QD molecule, which consists of two coupled QDs is compared with a hydrogen molecule, H_2. The main advantage of the coupled QD system is in the fact that the distance between the constituent dots as well as the height of the potential barriers are variable parameters, while in two-atom molecules they are fixed. After studying these simplest nano-objects, a linear chain of QDs, which constitute a quantum wire or a one-dimensional object, is discussed. Here, students recognize the importance of tunneling phenomena for electron transport in nanostructures. The final chapter of the textbook contains a short review of modern fabrication techniques of nanostructures using bottom-up and top-down approaches. The textbook consists of eight chapters and three appendices. Each chapter contains plenty of worked out examples, short summaries, and homework problems.

In the Fall 2010 semester in the lecture part of the combined lecture/lab quantum mechanics course, taught at UB, the following topics from the textbook have been covered:

1. Short review of classical motion of particles
2. Short review of milestones in nanoscience and nanotechnology. Nanostructures and quantum physics
3. Wave-particle duality and its manifestation in radiation and particle behavior
4. Layered nanostructures as the simplest systems to study electron behavior in a one-dimensional potential
5. Quantum harmonic oscillators
6. Approximate methods of finding quantum states
7. Quantum states in atoms and molecules
8. Crystals as atomic lattices
9. Quantization in nanostructures
10. Nanostructures and their applications.

The textbook is accompanied by a lab manual with eight developed experiments: 1). Quantum yard stick – measurement of Planck’s constant; 2). Photoelectric effect: waves behaving as particles; 3). Diffraction of light by a double-slit – one photon at a time; 4). Photoluminescence from InP quantum dots; 5). Introduction to Atomic Force Microscopy (AFM); 6). Study of InAs quantum dots using AFM; 7). Atomic spectra; hydrogen Balmer lines; sodium D-doublet; and 8). Transitions between confined subbands in the conduction and valence bands in GaAs/AlGaAs heterostructure quantum wells (inter- and intra-band transitions).

In the **first lab** “Quantum yard stick – measurement of Planck’s constant” students learn how to distinguish whether a physical system is macroscopic or microscopic. The first step is to measure the appropriate yard stick, Planck’s constant, h. Rather than using the photoelectric effect, the students use a series of light-emitting diodes (LEDs), which emit in the visible range. The students record the $I-V$ characteristics of these LEDs, and from these characteristics determine the threshold voltage, V_0, at which each LED starts emitting light. The threshold voltage V_0 is related to the bandgap E_g of a semiconductor material of the LED as:

$$eV_0 = E_g . \tag{1}$$

The students use a grating spectrometer to measure the average wavelength λ at which the LED emits. This is related to the bandgap as:

$$E_g = \frac{hc}{\lambda}. \tag{2}$$

If we combine these two equations we get:

$$\frac{1}{\lambda} = \frac{e}{hc} V_0 \ . \tag{3}$$

A plot of $1/\lambda$ versus V_0 yields a straight line and allows students to determine Planck's constant, *h*. In the lab report students are asked to use Planck's constant as a yard stick to classify systems as microscopic or macroscopic.

In the **second lab** "Diffraction of light by a double-slit – one photon at a time" students study double nature of light particle - photon. The specially designed two-slit diffraction experiment allows students to study interference of photons in the regime, under which, on the average, only one photon passes through the slits. Students are able to observe the process of building up the interference pattern. This experiment is analogous to Tonomura's experiment[6]. The difference is that instead of studying wave-particle duality of an electron, students study the wave nature of the light particle (photon) in real time.

In the **third lab** "Photoelectric effect: waves behaving as particles" students repeat the famous experiment carried out by Heinrich Hertz and interpreted by Albert Einstein in 1905. The most striking aspect of this experiment is that photons (particles of light) with energy less than the work function of the cathode metal cannot extract electrons from it.

In the **fourth lab** "Photoluminescence from InP quantum dots" students study photoluminescence spectra from four different solutions of InP quantum dots photoexcited by a GaN diode. From the emission spectra students determine the average InP quantum dot radius. From the linewidth of the emission peak students calculate the corresponding spread in the quantum dot dimensions.

The **fifth and sixth labs** "Introduction to atomic-force microscopy (AFM)" and "Study of InP quantum dots using AFM" students are introduced to the operational principles of AFM, specifically Nanosurf EasyScan 2 AFM, and characterize the sizes and shapes of InP quantum dots on GaAs wafer using AFM.

In the **seventh lab** "Atomic spectra; hydrogen Balmer lines; sodium D-doublet" students use a grating spectrometer to measure the wavelengths of two sources. a) Hydrogen lamp: the students record the wavelengths of the Balmer lines of hydrogen. The measured values are compared to the calculated wavelengths using the Bohr's model of hydrogen atom. b) Sodium lamp: the students record the yellow D-line from sodium and resolve its two components which are associated with the 3p electron state, which is split into the $P_{3/2}$ and $P_{1/2}$ states due to the spin-orbital coupling. The students measure the energy separation of the two components of the D-line and compare it with the value in the literature.

In the last and the **eighth lab** "Transitions between confined subbands in the conduction and valence bands in GaAs/AlGaAs heterostructure quantum wells (inter- and intra-band transitions)" students study properties of the objects with dimensionality higher than quantum dots – quantum wells (two-dimensional objects). In this experiment the students create a quasi-monochromatic light beam using the combination of a broadband source (tungsten-halogen lamp) and a grating spectrometer. The beam is reflected from the surface of a GaAs/AlGaAs quantum well and the intensity of the reflected light is measured as a function of the incident photon energy. The samples are placed in an exchange gas cryostat operating at liquid nitrogen temperature. Optical fibers are used to couple the incident light and collect the reflected beam. The intensity of the reflected light is measured using a photodiode in conjunction with a lock-in amplifier. The students record the reflectivity spectra from several QW structures that have different well widths. From the reflectance spectra they determine the transition energies between the conduction and valence subbands. At these photon energies the reflectance exhibits sharp variations, which are easily detected. Students also use a computer program to calculate the energies of the inter- and intra-band transitions. On the basis of these calculations they identify the various transitions in the reflectance spectra and determine the well width.

Assessment tools

To assess student learning of quantum-mechanical principles, two conceptual tests were developed. The pre-test includes 15 questions to assess their general understanding of quantum-mechanical principles learned while in high-school and at the university. The post-test consists of 45 questions and includes the 15 pre-test questions. The pre-test was given in the beginning of the semester and the post-test was given at the end of the semester. Two surveys were also administered: "Survey of Student's Interest toward Quantum Mechanics (SSIQM)" (Appendix 1) and "Evaluation of Effectiveness of Quantum Mechanics Course Materials". The first survey was given to students and the second survey was given to the instructor and teaching assistant at the end of the course. Also two evaluation forms were developed before the course was offered in 2010: 1) Formative Laboratory Experiment Evaluation Form and 2) Formative Evaluation of Java Applets (Appendices 2 and 3). These were given to students during the course for formative feedback. These instruments will be given every time the course is offered to validate them.

Six weeks before the end of the semester, students were given two comprehensive problems (design projects) to assess their ability to apply quantum-mechanical laws to a specific problem. Thus, we could assess the conceptual understanding of the material and the ability of students to solve the problem using the hands-on experience they acquired while carrying out laboratory experiments. We had four student groups with two members and one group with three members for a total of eleven students. The students were given two comprehensive design projects: "Ultra-violet cut-off filter based on quantum dots" and "Quantum-well infrared photodetector (QWIP) for the 10 μm spectral range". In the first project, students had to choose a suitable material for the quantum dots and their dimensions. The cut-off wavelength of this filter had to be 380 nm and not absorb more than 20% of the incident radiation. Students also had to design the experimental setup to test their filter. In the second project the students had to design a far-infrared quantum-well infrared photo-detector (QWIP) operating in 10 μm spectral range. They had to choose the materials for the growth of quantum wells, their dimensions, and design the experimental setup to test their QWIP. To assess these design projects, a form "Evaluation of Students' Design Project" was developed (Appendix 4).

These design projects gave additional insight into students' understanding of quantum phenomena. Students were given a design project to help evaluate their level of knowledge and understanding. They were given clear goals and constraints in order to achieve proper understanding. While working on these design projects, students constantly refreshed and analyzed on a deeper level some of the quantum-mechanical concepts they felt they did not completely understand. Thus, solving practical design problems helped them to improve their knowledge of quantum mechanics. Since the outcome of the design project was a practical device whose operation was based on quantum-mechanical principles, students had to take into account the complexity of the problem and justify each step of the solution. The essential parts of the design project were the choice of the device material, theoretical justification of the solution, and the use of an experimental setup to test the device operation. Analysis of the submitted project reports revealed some of the hurdles that students had to overcome while other assessment methods such as quizzes, exams, and lab reports could not do this.

Results of assessment and evaluation

1. Assessment of conceptual understanding of quantum-mechanical principles and laws
We assessed students' conceptual understanding of key concepts of quantum mechanics using a pre- and post-test design. Fifteen common questions were included in the test given at the beginning of the course and in the test at the end of the course. Students' average scores were 9.1 out of 15 (or 60.7%) on the pre-test and 11.6 out of 15 (or 77.3%) on the post-test. Paired-t-test showed that the increase in students' conceptual understanding of quantum mechanics concepts was statistically significant ($p < 0.01$).

2. Formative evaluation of lab experiments
We also used an 18-question instrument to assess students' perceptions of the quality of eight lab experiments. The questions related to content presentation, content validity, audience engagement, grading, and feedback. On a scale from 1 (Strongly Disagree) to 5 (Strongly Agree), students consistently responded positively to the questions as shown in Table 1 where the overall averages of students' ratings of the eight labs are presented.

Table1. Overall students' ratings of the eight labs

Lab	Lowest rating	Highest rating	Overall rating
#1	3.5	4.8	4.3
#2	3.4	5.0	4.4
#3	3.3	5.0	4.3
#4	3.0	5.0	4.4
#5	3.0	5.0	4.3
#6	3.0	5.0	4.4
#7	3.0	5.0	4.3
#8	3.5	5.0	4.4

3. Formative evaluation of Java virtual labs
We used a 16-question instrument to assess students' perceptions of the quality of Java virtual labs. The questions related to content presentation, content validity, and audience engagement. On a scale from 1 (Strongly Disagree) to 5 (Strongly Agree), students' scores on the questions

ranged from 3.9 to 4.8 with an overall average of 4.3 indicating high quality of the Java virtual labs.

4. Students' interest in quantum mechanics

We assessed students' interest in quantum mechanics at the end of the course using a measurement instrument consisting of 14 questions. On a scale from 1 (Not at all) to 5 (All the time), students' scores on the questions ranged from 2.3 to 4.6 with an overall average of 3.1 indicating students' moderate interest in quantum mechanics.

Conclusion

A new combined lecture/lab course was developed and offered for the first time in Fall 2010 at UB. A textbook and lab manual that complements this textbook were published. For the evaluation of students' understanding of quantum-mechanical concepts, two multiple-choice paper-pencil tests, one as pre-test and another as post-test, have been developed. In addition two design projects were given to students in the second half of the semester. Overall, the preliminary findings of formative and summative evaluations support the claim that the newly developed course was effective in helping students develop conceptual understanding and interest in quantum mechanics. We have also identified areas for further improvement of hands-on and virtual lab experiments. The course materials as well as evaluation instruments form a solid foundation for further development and expanded offering in other institutions of this course for engineering students.

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6 http://www.hitachi.com/rd/research/em/doubleslit.html

APPENDIX 1

Survey of Students' Interest toward Quantum Mechanics (SSIQM)

Instructions: For each of the following statements related to quantum mechanics, please state your opinion by selecting (√) All the time (AT), Most times (MT), Sometimes (ST), Occasionally (O), or Not at all (N).

Questions	AT (5)	MT (4)	ST (3)	O (2)	N (1)
1. I ask the instructor questions related to quantum mechanics (QM) after class					
2. I take detailed notes during class					
3. I listen to lectures attentively					
4. I discuss QM topics with classmates and friends					
5. I make thoughtful responses to instructor's questions					
6. I continue doing the lab after class					
7. I search for additional literature on QM topics					
8. I attend every lecture and lab					
9. I think about other experiments that I may carry out with the equipment I have learned to use					
10. I want to do my own project on QM topics					
11. I think about advanced studies in QM topics					
12. I spend enough time on my assignments					
13. I ask instructor questions related to QM in class					
14. I look on the Internet for news on QM applications					

APPENDIX 2

Formative Laboratory Experiment Evaluation Form (Lab No)		**Date:**						
Please, use the 7-point scale to indicate your agreement or disagreement with each statement. **Content**		**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Not Applicable**	**Don't Know**
1	The objectives of the experiment are clearly stated.	1	2	3	4	5	n/a	dk
2	The experiment makes explicit connections to the theories of the course.	1	2	3	4	5	n/a	dk
3	The experimental tasks are appropriately challenging.	1	2	3	4	5	n/a	dk
4	The underlying rationale for the techniques used is well explained.	1	2	3	4	5	n/a	dk
	Content Validity							
5	The scientific information in the manual is accurate.	1	2	3	4	5	n/a	dk
6	The charts and / or graphs in the manual aid in reaching the stated objectives for the experiment.	1	2	3	4	5	n/a	dk
7	The manual information is free of grammatical, spelling, and typographic errors.	1	2	3	4	5	n/a	dk
	Audience Engagement							
8	The experimental procedures and instructions are clearly described.	1	2	3	4	5	n/a	dk
9	The working space is well organized and prepared.	1	2	3	4	5	n/a	dk
10	Individual attention is available when needed.	1	2	3	4	5	n/a	dk
11	The instructor and/or TA is sufficiently familiar with the experiment and equipment.	1	2	3	4	5	n/a	dk
12	The instructor and/or TA shows concerns about equipment failures or other technical difficulties.	1	2	3	4	5	n/a	dk
13	There are enough opportunities to interact with other students in a team.	1	2	3	4	5	n/a	dk
14	There is enough time allocated for the experiment.	1	2	3	4	5	n/a	dk
	Grading and Feedback							
15	The grading criteria are clear.	1	2	3	4	5	n/a	dk
16	Adequate time is provided for writing the lab report.	1	2	3	4	5	n/a	df
17	Helpful feedback on reports is available.	1	2	3	4	5	n/a	dk
18	Please, provide written comments, questions, or suggestions:							

APPENDIX 3

Formative Evaluation of Java Virtual Labs		Date:						
Please, use the 7-point scale to indicate your agreement or disagreement with each statement. **Content**		**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Not Applicable**	**Don't Know**
1	All sections are clearly identified.	1	2	3	4	5	n/a	dk
2	The objectives of the Java Applets are clearly stated.	1	2	3	4	5	n/a	dk
3	The content of linked sites is worthwhile and appropriate.	1	2	3	4	5	n/a	dk
4	A contact person or address is identified for each Java Applet.	1	2	3	4	5	n/a	dk
5	All resources that are cited give credit to the author.	1	2	3	4	5	n/a	dk
6	The materials provide the reader with avenues for further research.	1	2	3	4	5	n/a	dk
7	The information within the Java Applet is consistent with the stated objectives of the Java Applet.	1	2	3	4	5	n/a	dk
8	The information is organized such that it will be easily understood by	1	2	3	4	5	n/a	dk
Content Validity								
9	The scientific information for the course is accurate.	1	2	3	4	5	n/a	dk
10	The charts and / or graphs aid in reaching the stated objectives for the	1	2	3	4	5	n/a	dk
11	The information is free of grammatical, spelling, and other typographical errors.	1	2	3	4	5	n/a	dk
Audience Engagement								
12	The Java Applet content promotes inquiry learning.	1	2	3	4	5	n/a	dk
13	Students are encouraged to think and reflect.	1	2	3	4	5	n/a	dk
14	Students are encouraged to continue exploration and research with additional hypertext links on the web site.	1	2	3	4	5	n/a	dk
15	When appropriate to the Java Applet, data sharing with other students is encouraged.	1	2	3	4	5	n/a	dk
16	Please, provide written comments, questions, or suggestions:							

APPENDIX 4

Evaluation of Students' Design Project			**Date:**	
Aspects	**2**	**1**	**0**	**Score**
1. The solutions of the problem are reasonable				
2. Correctly chosen theoretical justification of the device operation				
3. Correctly chosen materials for the device implementation				
4. The procedures chosen for experimental setup are appropriate				
5. Documentation is complete with details				
			Total	

Analytic Scoring Scheme for Students' Design Project:

Satisfactory = 2

Partial Satisfactory = 1

Unsatisfactory = 0