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DEVELOPING A TEST FOR ASSESSING UNDERGRADUATE ENGINEERING STUDENTS' KNOWLEDGE AND UNDERSTANDING OF NANOELECTRONICS CONCEPTS

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ABSTRACT

This article reports the development of the Test of Knowledge and Understanding of Nanoelectronics Concepts (TKUNC). The instrument has three equivalent forms, with each form consisting of 31 multiple choice question items. Data were collected from two groups of students taking a nanoelectronics course. Rasch modeling was used to develop the tests. Results showed that the instrument was valid and reliable. The instrument can be useful in a variety of applications when measurement and comparisons of students' knowledge and understanding of nanoelectronics concepts are needed.

INTRODUCTION

Nanotechnology is an area of strategic importance for future industry. As a result, many countries have invested not only in research and development, but also in nanotechnology education. In the US, the National Nanotechnology Initiative (NNI) *(http://www.nano.gov/html/res/nni2.pdf)* was created in 2001 to develop 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[1-4]. Although an undergraduate degree program in nanotechnology is not commonly available in American universities at present, some research universities with extensive nanotechnology research activities have started offering various forms of nanotechnology undergraduate education[5-6]. Goodhew[7] summarized three formats for nanotechnology education, noting them types A, B, and C. Type A programs offer specialized "short modules" to graduate and undergraduate students. Type B offers specific Master's degrees for graduates with adequate background in large-scale science. Type C constructs new undergraduate programs, in which nanoscale concepts play a central role from the outset. As an example of a Type A program, the University at Buffalo has developed and offered one lecture-based course

EE340 “Nanotechnology, Engineering and Science” and a lab course EE342 “Nanoscience Lab”. In 2004, the National Science Foundation funded the National Center for Learning and Teaching (NCLT) in Nanotechnology at Northwestern University to advance nanotechnology education at the secondary and college levels by serving as a clearinghouse for resources related to nanotechnology education (*http://www.nclt.us*).

In addition, many universities are also creating courses and programs on nanotechnology for the general audience[8]. Such courses include not only an examination of the science behind nanotechnology, but also address issues of management, science policy, and ethics. Other efforts include the creation of two-year programs that prepare students for careers in nanotechnology by focusing on the transition to four-year universities or directly into employment with industry and pharmaceutical firms [8].

While specific topics included in a nanotechnology course may vary depending on the education level (e.g. undergraduate, graduate, or high school) and the emphasis (e.g. sciences or engineering), developing students’ knowledge and conceptual understanding of key nanotechnology concepts is an essential part of any nanotechnology course. Examples of such key concepts are size and scale, size-dependent properties, surface-dominated behavior, surface-to-volume ratio, quantum mechanics, to name just a few (for a detailed discussion of “big ideas” in nanotechnology education, please refer to *http://assessment-ws.wikispaces.com/file/view/Big_Ideas_of_Nanoscience-20feb07.pdf*).

Measurement instruments for assessing students’ knowledge and understanding of key nanotechnology concepts are needed in order to evaluate the effectiveness of various efforts of nanotechnology education. The present paper reports the development of an instrument for assessing students’ knowledge and understanding of nanoelectronics concepts.

METHODS

The Nanotechnology Course

Beginning Spring 2005, the State University of New York at Buffalo has been offering an undergraduate course titled “Nanotechnology, Engineering and Science” (EE340) to second-year engineering students. This one-semester course introduces fundamental concepts and techniques related to nanotechnology, particularly nanoelectronics. The course follows the textbook[9] co-authored by V. Mitin. There are eight chapters in the textbook, covering the following major topics:

- Chapter 1 Introduction;
- Chapter 2 Particles and waves: classical particles, classical waves, and wave-particle duality;
- Chapter 3 Wave mechanics: Schrödinger’s wave equation, wave mechanics of particles, atoms and atomic orbitals;
- Chapter 4 Materials for nanoelectronics: semiconductors, crystal lattices – bonding in crystals, electron energy bands, semiconductor heterostructures, lattice-matched and pseudomorphic heterostructures, lattice-matched and lattice-mismatched materials, inorganic-organic heterostructures, and carbon nanomaterials-nanotubes and fullerenes;
- Chapter 5 Growth, fabrication, and measurement techniques for nanostructures: bulk crystal and heterostructure growth, nanolithography, etching, and other means for fabrication of nanostructures and nanodevices, techniques for characterization of nanostructures, spontaneous function and ordering of nanostructure, clusters and nanocrystals, methods of nanotube growth, chemical and biological methods for nanoscale fabrication, and fabrication of nano-electromechanical systems;
- Chapter 6 Electron transport in semiconductors and nanostructures: time and length scales of the electrons in solids,

statistics of the electrons in solids and nanostructures, density of states of electrons in nanostructures, and electron transport in nanostructures;

- Chapter 7 Electrons in traditional low-dimensional structures: Electrons in quantum wells, electrons in quantum wires, and electrons in quantum dots;
- Chapter 8 Nanostructure devices: Resonant-tunneling diodes, field-effect transistors, single-electron-transfer devices, light-emitting diodes and lasers including organic light-emitting diodes, quantum-dot cellular automata, and nano-electromechanical systems.

The format of the course is primarily lecture, with the supplement of a set of required virtual labs for students to complete. A separate new lab course was developed and began in the fall 2007 semester titled EE342 "Nanoscience Lab" to offer students a hands-on learning approach to nanoelectronics. The lab course is offered annually since then.

The Knowledge and Understanding Test

The Test of Knowledge and Understanding of Nanoelectronics Concepts (TKUNC) uses a multiple-choice question format. The multiple-choice question format is the most popular format for assessing knowledge and conceptual understanding because of its ability to cover a large area of content at multiple cognitive levels of Bloom's taxonomy, i.e. remembering, understanding, applying, analyzing, etc. Multiple-choice questions are also efficient to administer (it usually takes 30 seconds – 1 minute for students to answer a question) and objective to score.

The creation of TKUNC followed a multi-stage process. First, we created three pilot sub-tests for each of the chapters 6 through 8 during the spring 2006 semester. Each sub-test included 12 multiple-choice question items and was given to students at both the beginning and the end of each chapter. Statistical analysis, i.e. item difficulty, discrimination and item response pattern, was conducted for each item and each sub-test as a whole. Discussions among researchers took place focusing on qualities of individual items and how they could be improved to ensure appropriate difficulty, good discrimination, and appropriate item response patterns.

Second, during the spring 2007 semester, a pre-test, consisting of 3 items from each of the chapters 2 through 8, was created and given to students (23 students) at the beginning of the course. At the end of each chapter (2-8), a post-test consisting of 13 to 16 items (chapter 2 included 16 items, chapters 3, 4, and 7 included 14 items, chapter 5 included 16 items, chapter 6 included 15 items, and chapter 8 included 13 items) was created and given to the same students after they completed each chapter. The post-test for each chapter included the 3 items in the pre-test given at the beginning of the course.

Therefore, there were 101 items altogether. We intended for the test to: (a) assess both knowledge and understanding of important nanoelectronics concepts, (b) be used as both pre-test and post-test, (c) have multiple equivalent versions or forms in terms of difficulty and content coverage so that students would not see the same questions again when they are assessed more than once (e.g. on pre-course test and on post-course test), and (d) be administered efficiently (about 30 minutes). In order to achieve the above objectives, at the third stage, we used a novel measurement approach called Rasch modeling to create three equivalent forms of the same test. We now describe the Rasch modeling approach.

Rasch modeling

Rasch modeling is an approach to developing measurement instruments that are both valid and reliable [10]. According to Rasch[11], for any item i with a difficulty D_i that can be scored as right (X=1) or wrong (X=0), the probability (P) of a person n with an ability B_n to answer the item correctly can be expressed as

$$P\,(X=1|B_n, D_i) = \frac{e^{(Bn-Di)}}{1+e^{(Bn-Di)}}$$

In the above model, a student's probability of answering a question correctly is solely determined by the difference between the student's latent ability (i.e. conceptual understanding) and the difficulty of the item. In a testing situation, Xs are a student's responses to test questions that are scored right or wrong. Based on the student's response pattern to a set of test questions, the process of Rasch modeling is to derive a most likely estimate of the student's ability (B_n) that has produced the response pattern. This modeling process is conducted by specialized computer programs using appropriate estimation algorithms such as the maximum likelihood estimation algorithm. In the present study, we used Winsteps[12] computer software to perform Rasch modeling. B_n is in a natural logarithmic unit ranging from $-\infty$ to $+\infty$. One important characteristic of B_n is that it does not vary from test to test. That is, students answering different test questions, such as different forms of a same test as in the situation of this study, will still have the same abilities. On the other hand, the conventional test scores based on the number of questions answered correctly are dependent on the test, i.e. students answering different test questions will have different test scores, and different test scores are incomparable.

Any measurement instrument must be both valid and reliable. The validity of a measurement instrument refers to the accuracy of scores from the instrument to represent what the instrument is intended to measure, i.e. knowledge and conceptual understanding of nanoelectronics concepts in the present study. The reliability refers to the consistency or reproducibility of the same score from a same measurement instrument, which is related to the number of errors in scores of students' knowledge and conceptual understanding in the present study. The conventional practice of developing a measurement instrument, i.e. writing a set of questions as a test and then giving it to students to answer, does not necessarily produce valid and reliable scores. This is because the questions on a test do not necessarily correlate with each other to measure the same construct (e.g. knowledge and conceptual understanding of nanoelectronics concepts). If different questions on the same test measure different constructs, then we can not add scores from different questions as a total score. Similarly, if a question is ambiguous, then the same student answering the question at different times may give different answers, which means the score produced by the instrument is not reliable. Rasch modeling is an empirical approach to making sure that questions on a measurement instrument measure the same construct and produce reliable scores. It achieves the above by fitting student responses to test question items into the Rasch model. Because there is one important requirement for the Rasch model, i.e. unidimensionality, which states that all items measure the same construct (e.g. knowledge and conceptual understanding of nanoelectronics concepts). If items fit the Rasch model, then the items measure the same construct, and the instrument has construct validity.

Next, we will present the three equivalent forms of the TKUNC, empirical evidence for its validity and reliability, and suggest ways to use the three forms in nanotechnology education.

RESULTS

Three Equivalent Forms of TKUNC

After submitting the scored students' responses to all 101 items to the Rasch model using the Winsteps[12] computer program, the fit between students' responses and the Rasch model was examined. Eight items did not fit the Rasch model well. After removing those eight items from the data set and submitting students' response to the remaining items to the Rasch model again, all items fit the Rasch model well.

Figure 1 presents the distribution of student abilities and item difficulties along a common Rasch scale.

```
PERSONS MAP OF ITEMS
         <more>|<difficult>
    3          +  5_Q7
               |  8_Q9
            X  |T
               |
               |  7_Q4
               |
               |
               |  2_Q13  3_Q8   7_Q6
    2       X T+  8_Q4   8_Q6
               |  6_Q8
               |  7_Q2   7_Q3
               |  7_Q1
            X  |  6_Q9   7_Q10  7_Q8
            X  |S 3_Q6   3_Q7   5_Q13  6_Q13
               |  7_Q13  7_Q14
               |  6_Q7   8_Q8
    1      XX  +  7_Q5   7_Q7   8_Q13  8_Q5   8_Q7
            X S|  6_Q5   8_Q3
           XX  |  4_Q10  4_Q14
               |  4_Q9
           XX  |  3_Q2   6_Q1   6_Q2   6_Q6   8_Q10
               |  2_Q16  3_Q3   4_Q7   8_Q2
         XXXX  |
           XX  |
    0      XX  +M 2_Q12  3_Q12  3_Q13  3_Q5   5_Q8   7_Q11  8_Q11
            X  |  4_Q1   7_Q9
      XXXXXXX M|  2_Q15  2_Q7   3_Q9   5_Q12  5_Q15
           XX  |  4_Q6   4_Q8   6_Q10
          XXX  |  2_Q3   3_Q1   5_Q6   6_Q14
          XXX  |
               |  3_Q11  3_Q4   5_Q11
            X  |  5_Q2
   -1      XX  +  2_Q8   5_Q10  5_Q9   6_Q11  6_Q3
               |
            X S|  2_Q11  2_Q14  2_Q9   4_Q11
            X  |S 4_Q2
               |  4_Q3   4_Q5   8_Q12
          XXX  |  2_Q5   3_Q10
               |  2_Q1
               |  2_Q2
   -2      XX  +  3_Q14  4_Q12  5_Q5
               |
               |
              T|
               |
               |
               |T 2_Q10  2_Q4   2_Q6   4_Q4   5_Q4
               |
   -3          +
               |
               |
            X  |
               |
               |
               |
               |
   -4          +  4_Q13
         <less>|<easy>
```

Figure 1. Person-Item Map

In Figure 1, the numbers on the left-most column are Rasch scale scores in a natural logarithmic unit (log-odds or logits specifically). Both test item difficulties and students' abilities are represented on this same Rasch scale. Students are represented by the symbol x (each x is one student) in the second column, and are arranged from the lowest ability at the bottom to the highest ability on the top. Similarly, test items are represented in the third column on the right and are arranged from the easiest (4_Q13) at the bottom to the most difficult (5_Q7) on the top. The dashed vertical line separating students and test items corresponds to the Rasch scale scores calibrated in logits on the left-most. "M" refers to the mean of students' abilities in the person column and the mean of item difficulties in the item column; "S" refers to one standard deviation from the mean, and T refers to two standard deviations from the mean.

As can be seen from Figure 1, the overall distribution of test item difficulties matches the overall distribution of students' abilities, suggesting good construct validity. We see that more students are located around the average Rasch scale score (0), and fewer students are located on the upper and lower ends of the Rasch scale. Similarly, more difficult items are situated toward the top and less difficult items toward the bottom. The first number of the item label indicates chapter, and second number indicates the question. For example, 5_Q7 indicates chapter 5 question 7. We see that the 93 items vary in terms of difficulty; the most difficult item is 5_Q7 with a difficulty index of about +3, while the easiest item is question 4_Q13 with a difficulty index of about -4.

Reliability in Rasch modeling is measured by a separation index and Cronbach's alpha. The person separation index is 1.72, which is equivalent to a Cronbach's alpha of 0.75, meaning that 25% (1-0.75) of the variance in Rasch scale scores of students' knowledge and conceptual understanding are due to measurement errors; the item separation index is 2.24, which is equivalent to a Cronbach's alpha of 0.83, i.e. 17% (1 - 0.83) of the variance in Rasch item difficulties of test items are due to errors. Typically, a separation index greater than 2.0 and a Cronbach's alpha greater than 0.8 are considered good. In the present study, the person separation index and its Cronbach's alpha are slightly below the expectation, while the item separation index and its Cronbach's alpha are good. Given that our test is not for high-stakes uses, we consider that the test is overall reliable.

Figure 1 also shows that multiple items are at similar difficulty levels, suggesting redundancy. We could create shorter tests using fewer items

Table 1. Distribution of Items Among Three Equivalent Forms

Form 1	Form 2	Form 3
2-1	2-4	2-2
2-3	2-5	2-6
2-10	2-7	2-8
2-11	2-14	2-9
2-12	3-2	2-13
2-15	3-4	2-16
3-1	3-5	3-3
3-6	3-7	3-9
3-11	3-8	3-10
4-1	3-12	3-13
4-4	3-14	4-3
4-5	4-2	4-7
4-8	4-6	4-9
4-11	4-13	4-10
4-12	5-4	5-5
4-14	5-6	5-8
5-2	5-9	5-11
5-7	5-15	5-13
5-10	6-1	6-3
5-12	6-5	6-8
6-2	6-9	6-10
6-6	6-11	6-14
6-7	7-3	7-1
6-13	7-10	7-4
7-2	7-11	7-5
7-6	7-13	7-9
7-7	8-8	7-14
7-8	8-9	8-3
8-2	8-10	8-6
8-4	8-12	8-5
8-7	8-13	8-11

to produce the same student ability estimates. Based on the above item-person map, we divided the 93 items into 3 sets of 31 items with approximately equal distribution of items difficulties and similar content coverage across the chapters. Table 1 presents the composition of the three TKUNC forms.

After creating the above three equivalent forms of the test, we submit the three forms to the Rasch modeling again. In order to avoid negative values of students' ability estimates due to logarithmic transformation and to have more intuitive interpretation of Rasch scale scores, Rasch difficulties were specifically set to have a mean of about 50 and standard deviation of about 9 using the Winsteps commands of UMEAN=50.796, and USCALE=9.147. This re-scaling would result in Rasch scale scores of persons' abilities to be roughly within the range from 0 to 100 [10]. In order to check the equivalence of the three forms, a repeated-measures analysis of variance was conducted to test if means of student Rasch scale scores on the three forms were statistically significantly different. The result showed that there was no statistically significant difference among the means of student scores on the three forms.

The Appendix includes the three equivalent forms of TKUNC.

Raw Score to Rasch Scale Score Conversion

When using the tests to measure students' knowledge and conceptual understanding of nanoelectronics concepts, users should not be expected to conduct Rasch modeling to obtain Rasch scale scores. A conversion table was thus created by Winsteps to help convert raw scores (i.e. total number of correctly answered questions on each TKUNC form, out of a maximum of 31) into Rasch scale scores. Table 2 presents the raw score – Rasch scale score conversion. For example, a raw score of 12 is equivalent to a Rasch score of 45.9 on Form 1, 45.8 on Form 2, and 45.2 on Form 3. Please note there are no scores of 0 and 31 in Table 2. This is because Rasch scale scores can not be computed when a student has answered no questions correctly or all questions correctly, due to the division by zero error.

Table 2. Raw Score – Rasch Scale Score Conversion Table

Raw score	Form 1	Form 2	Form 3
1	11.8	12.3	11.8
2	19.2	19.6	19.2
3	24.0	24.4	23.9
4	27.7	28.0	27.5
5	30.8	31.0	30.5
6	33.5	33.6	33.1
7	35.9	36.0	35.5
8	38.1	38.2	37.6
9	40.2	40.2	39.6
10	42.2	42.2	41.6
11	44.1	44.0	43.4
12	45.9	45.8	45.2
13	47.7	47.6	46.9
14	49.4	49.3	48.3
15	51.1	51.0	50.2
16	52.9	52.7	51.9
17	54.6	54.4	53.5
18	56.3	56.1	55.2
19	58.1	57.9	56.9
20	60.0	59.7	58.6
21	61.8	61.6	60.4
22	63.8	63.6	62.2
23	65.9	65.7	64.2
24	68.1	67.9	66.2
25	70.6	70.5	68.5
26	73.5	73.4	71.0
27	76.9	76.9	73.9
28	81.4	81.5	77.3
29	88.5	88.7	81.8
30	100.0	100.4	88.9

CHANGE IN STUDENTS' KNOWLEDGE AND CONCEPTUAL UNDERSTANDING AFTER TAKING NANOTECHNOLOGY COURSE

In order to provide a baseline for future comparison, we calculated students' gain in conceptual understanding after taking the discussed nanotechnology course. The mean pre-test Rasch scale score (with standard deviations in parentheses) at the beginning of the course was 43.6 (or 11 out of 31 correct); the class' post-test mean at the end of the course was 55.8 (or 18 out of 31 correct). Independent sample t-test showed that the difference between the pre-test and post-test means was statistically significant.

CONCLUSION

This paper reports the development of the Test of Knowledge and Understanding of Nanoelectronics Concepts (TKUNC). The instrument has three equivalent forms, with each form consisting of 31 multiple choice question items. The instrument is valid because the test items fit the unidimensional Rasch model, thus all items measure the same construct – knowledge and conceptual understanding of nanoelectronics concepts. Students also gain statistically significant more knowledge and conceptual understanding after taking a nanotechnology course. The instrument is also reliable in terms of various reliability indices.

The instrument can be used in many ways. One application is to use the instrument to assess the increase in students' knowledge and conceptual understanding during a nanoelectronics course. In order to do this, one form can be administered to students at the beginning of the course, and another form can be administered to students at the end of the course. Students' raw scores on the two forms are then converted into Rasch scale scores according to the above score conversion table, and the difference between the two sets of scale scores is used as the measure of increase in student conceptual understanding. Paired t-test may also be used to test the statistical significance in the change of Rasch scale scores. Another possible application is to use the instrument to assess the effect of an instructional innovation (i.e. incorporating virtual labs). In order to do this, students need to be grouped into a comparison group (i.e. without receiving the instruction innovation) and an intervention group (i.e. receiving instructional innovation). Both groups of students are then administered one form of the instrument at the beginning of the course, and then another form of the instrument at the end of the course. Again, students' raw scores are then converted into Rasch scale scores, and the difference in means of students' Rasch scale scores between the two groups can then be compared by using inferential statistics such as independent t-test or analysis of covariance. Other applications are also possible, as long as measurement of students' knowledge and conceptual understanding of nanoelectronics concepts is needed.

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REFERENCES

1. E.T. Foley, and M.C. Hersam, "Assessing the Need for Nanotechnology Education Reform in the United States," *Nanotechnology Law & Business*, **3**(4), 467-484 (2006).

2. M.C. Roco, "From vision to the implementation of the U.S. National Nanotechnology Initiative". *Journal of Nanoparticle Research*, **3**, 5-11 (2001).

3. M.C. Roco, "Nanotechnology—A Frontier for Engineering Education," *International Journal of Engineering Education*, **18**(5), 488–497 (2002).

4. M.C. Roco, "Converging Science and Technology at the Nanoscale: Opportunities for Education and Training", **21** Nature Biotechnology, 1247 (2003).

5. M.C. Hersam, M. Luna, and G. Light, "Implementation of Interdisciplinary Group Learning and Peer Assessment in a

Nanotechnology Engineering Course," *Journal of Engineering Education*, January, 2004, pp. 49-57.

6. M. Meyyappan, "Nanotechnology Education and Training," *Journal of Materials Education*, **26**(3-4), 311-320, (2004).
7. P. Goodhew, "Education Moves into a New Scale," *NanoToday*, **1**(2), 40-43 (2006).
8. C. Wu, "Sweating the Small Stuff," *American Society for Engineering Education Prism,* **14**(2), 22-27 (2004).
9. V. Mitin, V. Kochelap, and M. Stroscio, *Introduction to Nanoelectronics: Nanotechnology, Engineering, Science, and Applications*, Cambridge University Press, 2007, p. 329 .
10. T.G. Bond, and C.M. Fox, *Applying the Rasch model: Fundamental measurement in the human sciences* (second edition), Lawrence Erlbaum Associates Publishers.
11. G. Rasch, *Probabilistic models for some intelligence and attainment tests*, Danmarks Paedogogiske Institut/University of Chicago Press, 1960/1980.
12. J.M. Linacre, *Winsteps* (version 3.4); Winsteps, Inc., Chicago, 2003.

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APPENDIX

TEST OF KNOWLEDGE AND UNDERSTANDING OF NANOELECTRONICS CONCEPTS (TKUNC), FORMS 1-3

<u>Test of Understanding of Nanoscience Concepts (TUNC), Form 1</u>

2-1. What is an electron volt (eV)?
a. the energy an electron gains passing through a 1 volt electrostatic potential difference
b. e/$\hbar$, where e is the charge of an electron, and $\hbar$ is the reduced Planck's constant
c. e·V, where e is the charge of an electron and V is the potential difference
d. the energy an electron gains in a magnetic field of 1 T.

2-3. Knowing the frequency of a wave, what is needed to find the wave's wavelength?
a. the energy flux of the wave
b. the mass of the wave
c. the speed of light in the medium the wave is traveling in
d. the period of the wave

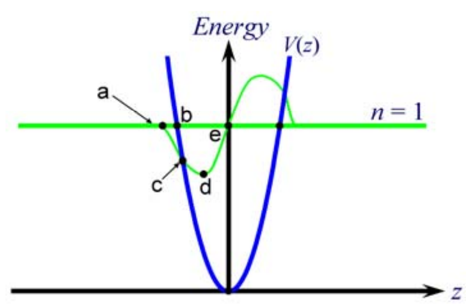
2-10. If we shoot particles through a double slit at a screen, one particle at a time, and if they are arranged in a diffraction pattern, what does this demonstrate?
a. particle nature of a particle
b. wave nature of a particle
c. position of previous electron determine the position of the next electron
d. electron spin determines location

2-11. Sort these particles from largest to smallest mass
a. neutron, electron, proton, photon
b. photon, neutron, proton, electron
c. neutron, proton, electron, photon
d. photon, electron, proton, neutron
e. none of the above

2-12. If we consider $\hbar = 0$, then which of the following statement is true?
a. the number of photons will decrease
b. the wave equation will become well defined
c. uncertainty between position and momentum must be observed
d. classical regime analysis is valid

2-15. If two waves with the same amplitude but different frequencies are combined, with an arbitrary phase shift, which of the following will occur?
a. the amplitude of the resultant wave will half
b. the amplitude of the resultant wave will double
c. no interference will occur
d. the frequency and phase difference will cancel the two waves

3-1. When a particle is restricted in all three dimensions, what type of quantum system is it in?
a. quantum well
b. quantum box
c. quantum wire
d. quantum tube

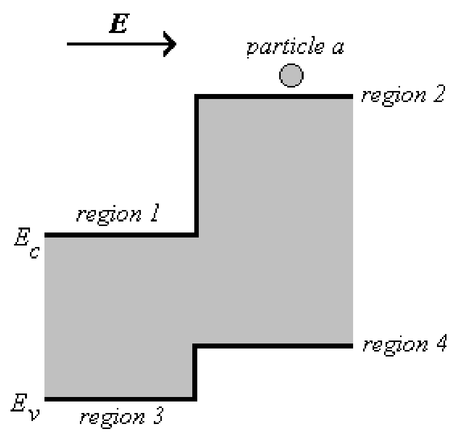


3-6. In the above figure where is the classical turning point in the parabolic quantum well?
a. position a
b. position b
c. position c
d. position b and c
e. position e

3-11. For the angular momentum quantum number, l = 0, 1, and 2, they are s, p, and d shells respectively. Which one is spherically symmetrical?
a. s
b. p
c. d
d. p and d

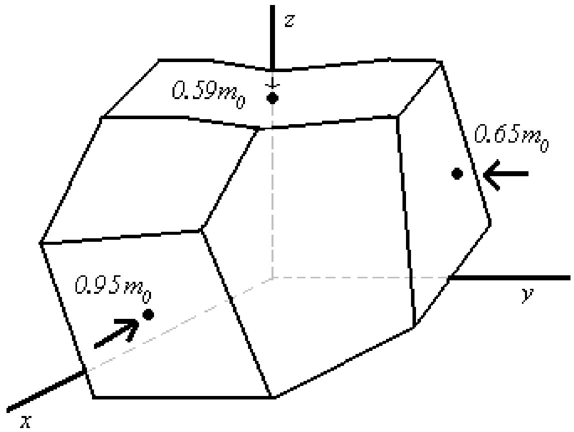
4-1. Which of the following is not a type of carbon nanotube?
a. chiral
b. armchair
c. hexagonal
d. zigzag
4-4. What type of the lattice has an additional atom at the center of the unit cell?
a. The simple cubic lattice
b. The body-centered cubic lattice
c. the face-centered cubic lattice
d. The diamond lattice

4-5. The energy difference between the conduction band and the valence band is referred to as?
a. electron affinity
b. energy gap
c. Fermi energy
d. work function



4-8. What type of a heterostructure is depicted in the above figure?
a. type I
b. type II
c. broken-gap line-up
d. none of the above

4-11. Which of the following represents a heterojunction?
a. GaAs
b. $Al_xGa_{1-x}As$
c. $GaAs/Al_xGa_{1-x}As$
d. Ge



4-12. In which direction will an electron with effective mass shown in the above diagram travel the fastest in this crystal?
a. along the *x*-axis
b. along the *y*-axis
c. along the *z*-axis
d. the electron will travel the same speed regardless of direction

4-14. What type of carbon nanotube is formed when $n = m$, using $\mathbf{C} = na_1 + ma_2$?
a. chiral
b. armchair
c. hexagonal
d. zigzag

5-2. What is the main limitation of optical lithography?
a. the quality of the masks
b. the diffraction limit of light
c. development process
d. the intensity of the light used

5-7. What type of semiconductor would make a good photodetector of visible light?
a. a semiconductor with direct bandgap greater than 1.5 eV
b. an indirect bandgap semiconductor
c. a semiconductor with direct bandgap smaller than 1.5 eV
d. a semiconductor with indirect bandgap smaller than 1.5 eV

5-10. Which of the following must be true for a perfect semiconductor (intrinsic material)?
a. the valence and the conduction bands are completely filled with electrons
b. the valence band is completely filled with electrons, while the conduction band is totally empty
c. the valence band is totally empty, while the conduction band is completely filled with electrons
d. the valence and the conduction bands are totally empty

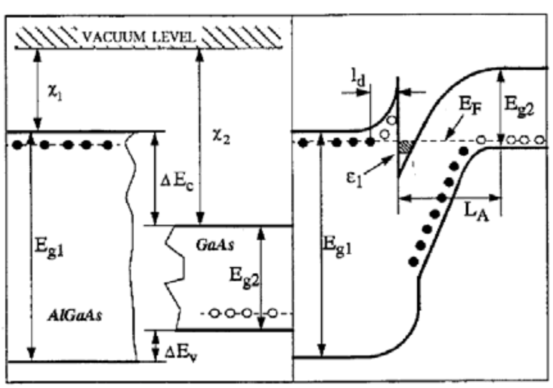
5-12. How is the force measured in AFM tapping mode?
a. the force is measured by measuring the change in the resonance frequency due to the force
b. the force is measured by the bending of a cantilever on which the tip is mounted
c. the force is measured by measuring the tunneling electric current due to the force
d. the force is measured by measuring the electron transmission due to the force

6-2. When can we consider a device as a one-dimensional (quantum wire) device? Here λ is the wavelength of an electron and L_x, L_y, and L_z are the dimensions of the device:
a. $\lambda << L_x, L_y, L_z$
b. $\lambda \approx L_z << L_y, L_x$
c. $\lambda \approx L_z, L_y << L_x$
d. $\lambda \approx L_x, L_y, L_z$
e. $\lambda \approx$ lattice constant

6-6. Which of the following device parameters can affect the quantized energy level spacing in a nanowire?
a. length of the nanowire
b. cross section of the nanowire
c. temperature of the nanowire
d. current flowing through the nanowire
e. a and b

6-7. The Fermi distribution function for a given temperature determines the probability of finding an electron at a particular energy. What is the probability of finding an electron with energy equal to the Fermi energy at 300K?
a. 0
b. ¼
c. ½
d. ¾
e. 1

6-13. Which criterion is important when observing single-electron transport effects in a single-electron device?
a. when the conductance of the device is much smaller than the quantum of conductance
b. when the Coulomb energy of charging is larger than the thermal energy
c. when the current associated with single-electron transport is less than fluctuations in the leakage current
d. when the electron temperature becomes higher than that of the lattice temperature
e. b and c



7-2. Using the band diagram in the above figure what types of dopants were added to GaAs?
a. no dopants were added
b. acceptors to make it p-type
c. donors to make it n-type
d. cannot be determined from the figure

7-6. What role do the gates play in the split-gate technique?
a. to form a conducting channel under the gates
b. to form an inversion channel
c. to deplete electrons under the gates
d. to turn on and off the device when properly biased
e. all of the above

7-7. What type of confining potential profile do the gates form in the split-gate technique?
a. triangular potential profile
b. rectangular potential profile
c. linear potential profile
d. circular potential profile
e. parabolic potential profile
f. none of the above

7-8. In a resonant-tunneling diode when does the resonant-tunneling process occur?
a. when the quasi-bound level is below the conduction band energy E_c, and above the Fermi energy, E_F
b. when the quasi-bound level is above the conduction band energy and Fermi energy, E_F
c. when the quasi-bound level in the quantum well is below the Fermi energy, E_F, but above the conduction band energy E_c
d. when the voltage bias applied exceeds the threshold voltage of the device

8-2. One of the unique features of resonant tunneling diodes is that they possess a region of negative differential resistance in their current voltage characteristic. What exactly is this negative differential resistance?
a. negative differential resistance occurs when voltage increases, yet current decreases
b. negative differential resistance occurs when voltage increases, and current continues to increase
c. negative differential resistance occurs when negative voltage is applied across the resonant tunneling diode and positive current is measured
d. negative differential resistance occurs when negative current is applied across the resonant tunneling diode and positive current it measured

8-4. What kind of junction is formed between the gate and the semiconductor in a metal-semiconductor field-effect transistor (MESFET)?
a. ohmic contact
b. Schottky contact
c. p-type contact
d. n-type contact
e. metal-insulator contact

8-7. In a metal-oxide semiconductor field-effect transistor what is the purpose of the silicon oxide material under the gate?
a. to insulate the gate from the conducting channel
b. to insulate the source from the drain
c. used as a buffer layer to account for the lattice mismatch between the poly-silicon material that makes up the gate and the Si substrate
d. to improve the conductance between the gate and the conducting channel

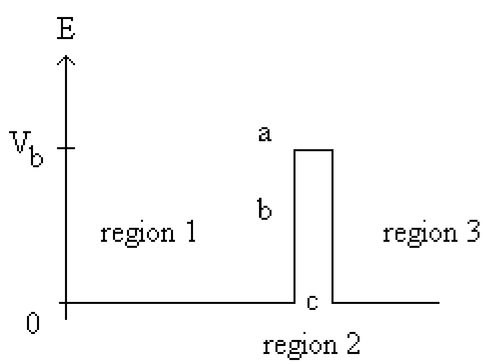
Test of Understanding of Nanoscience Concepts (TUNC), Form 2

2-4. If two waves with the same amplitude and frequency are combined, and the phase difference between the two waves is zero, which of the following is a property of the resulting wave?
a. amplitude of the wave is doubled
b. amplitude of the wave is half
c. frequency of the wave is doubled
d. amplitude of the wave is half

2-5. Which of the following represents a traveling wave?
a. $A\cos(\omega t - \mathbf{kz})$
b. $A\cos(\omega t + \pi)$
c. $A\sin(\omega t + \pi)$
d. $A\cos(\omega t)$

2-7. Knowing the particle's wave function $\psi(z)$, what is the probability density for finding a particle in a particular point of space?
a. $\psi^*(z)$
b. $\psi(z)\ \psi(z)$
c. $\psi(z)\ \psi^*(z)$
d. $\psi^*(z)\ \psi^*(z)$

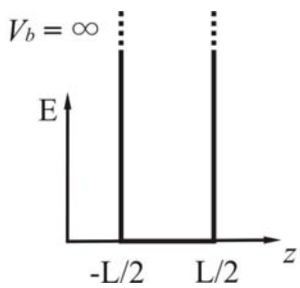
2-14. For a traveling wave, what is the density of the energy flux referred to?
a. phase velocity
b. wave density
c. wave surface
d. wave intensity



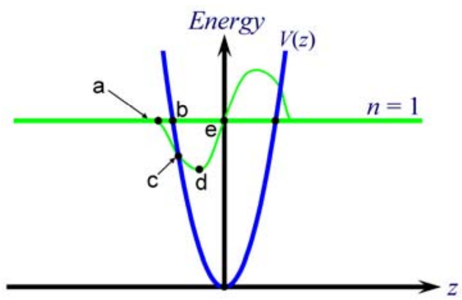
3-2. In the above figure which particle can travel (tunnel) from region 1 to region 3?
a. particle a that has an energy $E > V_b$
b. particle b that has an energy $0 < E < V_b$
c. particle c that has an energy $E = 0$ eV
d. both a and b
e. particles a, b, and c

3-4. The energy spectrum is discrete in a quantum system due to?
a. the size of the system is substantially larger then the de Broglie wavelength of the particle
b. probability being constant through the whole system
c. electron has continuous motion in all three directions
d. the size of the system is less or of the order of the de Broglie wavelength of the particle

3-5. The electron's lowest energy level in the potential well of width L and height V_b=∞ is



a. 0
b. $\hbar^2\pi^2/(2mL^2)$
c. $2\hbar^2\pi^2/(mL^2)$
d. V_b



3-7. Where is the highest probability density of finding a particle in the quantum system depicted above?
a. position a
b. position b and e
c. position c
d. position d
e. position e
f. all position within this diagram have equal probability

3-8. Where is the lowest probability density of finding a particle in the quantum system depicted above?
a. position b
b. position c
c. position d
d. position e
e. all positions within this quantum system have equal probability

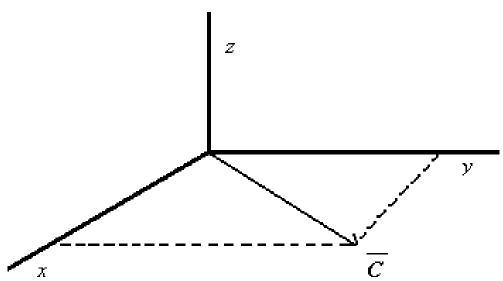
3-12. For a stationary wave function, which statement is true?
a. the wave function is time independent
b. the wave function depends on time only
c. the wave function depends on coordinate only
d. both a and c are true

3-14. Which quantum number of the electron can be associated with the value of $\pm 1/2$?
a. orbital quantum number
b. principal quantum number
c. the projection of the spin
d. magnetic quantum number

4-2. What is a "hole" when referring to semiconductors?
a. a location where a proton is missing in the energy gap
b. a location where a proton is missing in the overlapped energy bands
c. a location where an electron is missing in the conduction band
d. a location where an electron is missing in the valence band

4-6. A crystal without any periodicity is called?
a. crystalline
b. amorphous
c. polycrystalline
d. nanocrystalline

4-13. In the diagram below, what are the Miller indices of the vector **C**?



a. [100]
b. [110]
c. [111]
d. [101]

5-4. What is epitaxial growth?
a. growth of a crystal layer upon a compatible crystal substrate
b. growth of a crystal in a magnetic field
c. growth of a crystal in an electric field
d. growth of a crystal in the form of an ingot

5-6. What do donor impurities add to the semiconductor?
a. electrons
b. holes
c. phonons
d. none of the above

5-9. Why is chemical vapor deposition (CVD) more ideal for industrial use than molecular beam epitaxy (MBE)?
a. because in the chemical reactor the temperature of chemicals of CVD method are much higher than the temperature in molecular beams of MBE method
b. because in the chemical reactor the concentration of chemicals of CVD method is much higher than that of MBE
c. because the rate of crystal growth realized in CVD method is higher than that of MBE
d. because the CVD method is the dominant technique for the fabrication of perfect multilayered crystals of nanoscale thicknesses than that of MBE

5-15. What is it called in a heteroepitaxial system when only islands are formed?
a. shallow etching
b. long-range-ordered island structures
c. epitaxial growth
d. Stranski-Krastanow islands

6-1. In which of the following situations will the wavelength of an electron be the longest?
a. when the electron is in a vacuum at 300 K
b. when the electron is in GaN (m^* = 0.172) at 300 K
c. when the electron is in GaAs (m^* = 0.067) at 300 K
d. when the electron is in GaN (m^* = 0.172) at 77 K
e. when the electron is in GaAs (m^* = 0.067) at 77 K

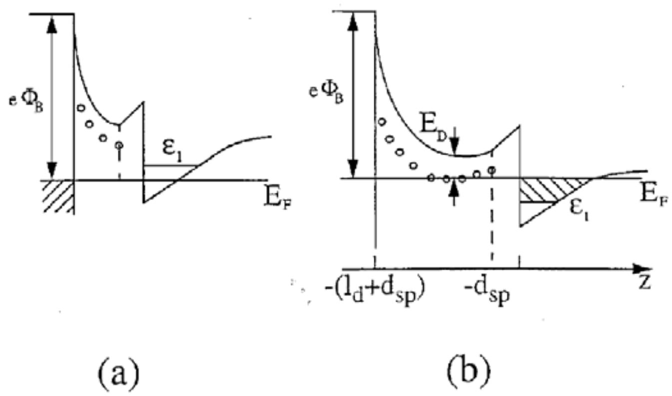
6-5. When the length of the sample is much greater than the mean free path, this is an example of which transport regime?
a. quantum ballistic transport
b. classical transport
c. classical ballistic transport
d. quasi ballistic transport

6-9. What is the highest energy of an electron in a metal at equilibrium in an ensemble of electrons at absolute zero temperature (0 K)?
a. an energy equal to zero joules
b. the energy of the lowest quantized energy level
c. an energy equal to the Fermi energy
d. an energy equal to the thermal energy

6-11. A voltage is applied to a nanowire. In which direction do the electrons and holes travel?
a. electrons travel in the same direction as the electric field vector, holes in the opposite direction to the electric field vector
b. electrons travel in the opposite direction to the electric field vector, holes travel in the same direction as the electric field vector
c. electrons and holes travel in the same direction as the electric field vector
d. electrons and holes travel in opposite directions to the electric field vector

7-3. Why do the bands bend when AlGaAs and GaAs form a junction?
a. band bending is a result of majority carriers moving from the wide-bandgap semiconductor to the narrow-bandgap semiconductor
b. band bending is a result of the valence and conduction band-offsets ΔE_c and ΔE_v
c. all of the above
d. none of the above

7-10. In a metal-oxide semiconductor field-effect transistor what is the purpose of the silicon oxide material under the gate?
a. to insulate the gate from the conducting channel
b. to insulate the source from the drain
c. used as a buffer layer to account for the lattice mismatch between the poly-silicon material that makes up the gate and the Si substrate
d. all of the above
e. none of the above



7-11. In the above figure which device is normally-on?
a. (a)
b. (b)
c. neither one
d. both

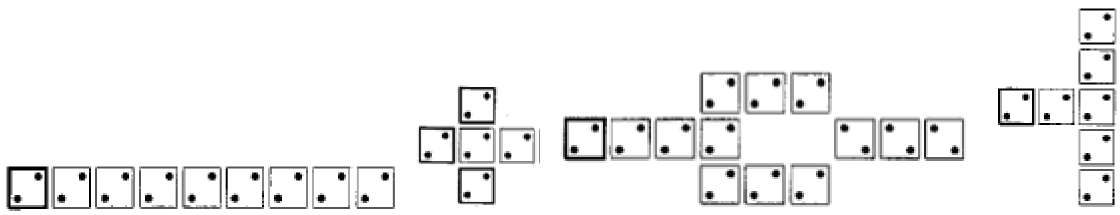
7-13. Conductivity of the device depicted above is determined by the concentration of free electrons inside the potential well. What would need to be done to increase the conductivity of the device?
a. decrease the thickness of the AlGaAs
b. apply a positive bias to the metal
c. a and b
d. none of the above

8-8. What type of confinement of electrons exists in a MOSFET?
a. confinement in 1-dimension
b. confinement in 2-dimensions
c. confinement in 3-dimensions
d. no confinement, a transistor is a classical device thus the length scales of its dimensions are not comparable to the electron's wavelength

8-9. In a velocity-modulation transistor (VMT) what exactly does the gate control?
a. the gate voltage controls the number of conducting electrons in the channel
b. the gate voltage controls the number of holes in the channel
c. the gate voltage redistributes a fixed number of electrons in the channel
d. the gate voltage alters positions of traps caused by impurities in the channel

8-10. Which of the following effects most greatly contributes to the conductance of a single electron at a time in a single-electron transistor composed of a metal quantum dot with a radius of 10nm, and with tunnel barriers coupling the source, drain, and gate to the dot? Assume negligible thermal energy contribution.
a. effects related to the Pauli Exclusion Principle
b. the Coulomb Blockade effect
c. interference effects between the wave function of the electron and the wave function of the metal quantum dot
d. interference effects in the wave functions of electrons tunneling onto the dot and electrons being reflected by the tunneling barriers

8-12. Which of the following quantum dot cellular automata devices can function as an inverter?



a. b. c. d.

8-13. The field of Nano-Electro-Mechanical Systems (NEMS) is known to produce devices that can resonate with high frequencies unattainable by conventional electronics. What is the reason why such NEMS based resonators can achieve such high frequencies?
a. Since the dimensions of a NEMS device is in the nanoscale range, the natural fundamental frequencies of features of the device at that scale is high
b. In conventional electronics where a resistance component, inductive component and capacitive component are needed to create a resonator, the power dissipation is greater than the power needed to operate a single mechanical NEMS resonator
c. NEMS resonators possess a higher Q-factor than their electrical resonator counterparts
d. Since the dimensions of the components of the NEMS devices are in the nanoscale, these components will have wave-like properties. Thus when multiple components having different phases in their wavefunctions interfere, the resulting wave function from the device can have a high frequency.

Test of Understanding of Nanoscience Concepts (TUNC), Form 3

2-2. Which particle has no mass?
a. electron
b. proton
c. photon
d. neutron

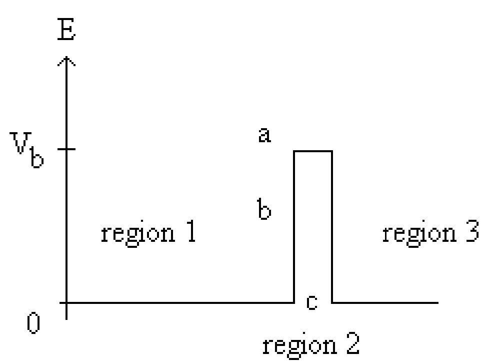
2-6. If an electromagnetic wave is traveling in the **z** direction and the electric field is polarized in the **x** direction, in which direction is the magnetic field polarized?
a. **x**
b. **y**
c. **z**
d. can not be determined from information given

2-8. What does the optical double slit experiment demonstrate?
a. Pauli exclusion principle
b. wave particle duality
c. Heisenberg exclusion principle
d. principle of interference

2-9. If you know the exact position of a particle in quantum mechanics ($\Delta x = 0$), what is the uncertainty in momentum (Δp)?
a. ∞
b. 0
c. 1
d. $\hbar$

2-13. Using a plane wave description of a free particle, what is the probability of finding a particle in any point of space?
a. 0
b. 1
c. constant
d. varies depending on location being analyzed

2-16. What is effective mass (m^*)?
a. the mass of a particle going through a double slit
b. the mass of a particle going through a crystalline
c. the mass of a particle going through a potential field
d. all of the above



3-3. Using the above figure which particle(s) can be reflected from the barrier?
a. particle a that has an energy $E > V_b$
b. particle b that has an energy $0 < E < V_b$
c. particle c that has an energy $E = 0$ eV
d. particle a and b

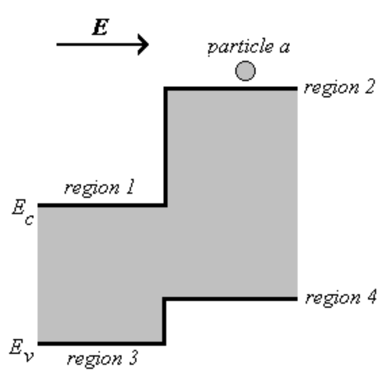
3-9. As the thickness of a quantum well increases, which of the following should increase with the width?
a. number of bounded states
b. potential barrier height
c. number of photons
d. distance between quantum levels in the well

3-10. When no two identical electrons may occupy the same quantum state simultaneously, it is referred to as?
a. Hund's rule
b. Principle of uncertainty
c. Wave particle duality
d. Pauli exclusion principle

3-13. The harmonic oscillator's lowest energy level in a potential with quadratic coordinate dependence is
a. 0
b. $\hbar\omega/2$
c. $\hbar\omega$
d. ∞

4-3. In a typical indirect-bandgap semiconductor what is generally needed for an electron and a hole to recombine?
a. a change in its momentum
b. a change in its energy and momentum
c. a change in its energy
d. a change in its spin

4-7. The energy distance between the conduction band bottom and the vacuum level is referred to as?
a. electron affinity
b. energy gap
c. Fermi energy
d. work function



4-9. If particle a is an electron placed in region 2 in the above figure, where do you expect it to travel?
a. from region 2 to region 1
b. stay at region 2
c. from region 2 to region 3
d. from region 2 to region 4

4-10. In which case can an electron participate in the conduction processes?
a. filled valence band and empty conduction band
b. filled valence band and partially filled conduction band
c. empty conduction band and holes present in valence band
d. all of the above

5-5. What types of photoresist are used in nanolithography?
a. negative photoresist
b. homogeneous photoresist
c. heterogeneous photoresist
d. positive photoresist
e. a and d

5-8. Which is the best microscope for imaging a single atoms?
a. optical microscope
b. scanning tunneling microscope
c. atomic force microscope
d. magnetic force microscope

5-11. Which of the following must be true for a scanning tunneling microscope (STM)?
a. tunneling electric current gives information on the area of the insulator film surface
b. tunneling electric current gives information on the area of the metal film surface
c. the force between the sample surface and a tip gives an image of the surface relief
d. electron transmission through the sample gives information on the area of the metal film surface

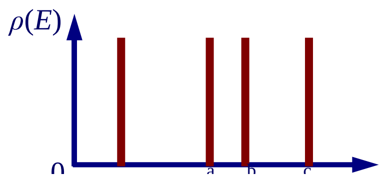
5-13. How is the image generated in scanning electron microscope (SEM)?
a. by detecting the tunneling electric current passed through the surface
b. by detecting the force between the sample surface and a tip
c. by detecting the electron transmission through the sample
a. by detecting the secondary electrons or X-rays emitted from the surface

6-3. An elastic scattering event alters which of the following properties of the electron?
a. the momentum of the electron
b. the mass of the electron in free space
c. the energy of the electron
d. the Fermi energy of the electron

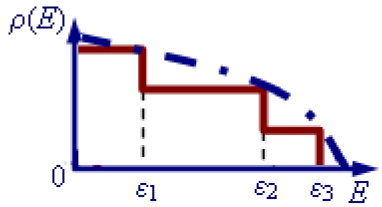
6-8. The Fermi distribution function for a given temperature determines the probability of finding an electron at a particular energy. What is the probability of finding an electron with energy equal to the Fermi energy at 77K?
a. 0
b. ¼
c. ½
d. ¾
e. 1

6-10. Which of the following graphs represents the density of states of a quantum wire?

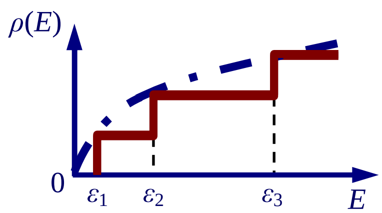
a.



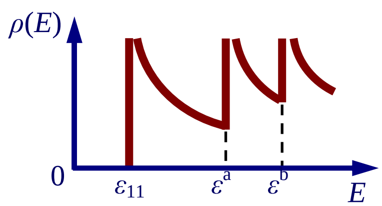
b.



c.



d.



6-14. Suppose that a sample has three types of scattering mechanisms affecting the transport of electrons across the device (phonon scattering, impurity scattering, and electron-electron scattering). Each scattering mechanism is of the same order of magnitude. When determining the total mobility how should we handle all these scattering events?
a. consider the effects of the most pronounced scattering mechanism and neglect the others when determining mobility across the device
b. inversely add the nobilities associated with each scattering event and arrive at a total mobility across the device
c. subtract the effects of scattering from the Heisenberg mobility and arrive at a corrected total mobility across the device
d. use the Heisenberg uncertainty principle when considering the chaotic motion of the electron through the device and determine the total mobility across the device

7-1. What can be done to a semiconductor to cause its work function to be equal to the energy difference between the valence band top and the vacuum level?
a. dope the semiconductor with donors
b. dope the semiconductor with acceptors
c. nothing can be done; the work function is used only to classify material as a metal, insulator, or semiconductor
d. change the x composition of the semiconductor

7-4. What factors change the Fermi energy, E_F?
a. temperature
b. impurities in the semiconductor
c. density of states
d. all of the above
e. b and c

7-5. What role does the heterostructure play in the split-gate technique?
a. used to prevent diffusion of impurities from the gates
b. used to form a 2-dimensional electron gas
c. used as a diode to prevent latch-up between the gates and GND
d. none of the above

7-9. One of the unique features of resonant tunneling diodes is that they possess a region of negative differential resistance. What exactly is this negative differential resistance?
a. negative differential resistance occurs when voltage increases, yet current decreases
b. negative differential resistance occurs when voltage increases, and current continues to increase
c. none of the above
d. a and b

7-14. What is the maximum number of electrons that can reside on the energy level denoted by ?1?
a. 0
b. 1
c. 2
d. 3
e. large number of electrons

8-3. Which of the following devices would not be considered a nanostructure device?
a. QD Cellular automata
b. Resonant tunneling diodes
c. Superconducting quantum interference device (SQUID)
d. Schottky diodes
e. Hot-electron transistors

8-6. When voltage is applied to the gate and drain in a MESFET the drain begins to affect the depletion region to the point where the current flowing through the device begins to saturate. When does this occur?
a. when the conducting channel is in the breakdown regime
b. when the conducting channel is in the triode regime
c. when the conducting channel is in the pinch-off regime
d. when the conducting channel is in the linear region
e. when the conducting channel is in the nonlinear regime

8-5. In an n-type MESFET what needs to occur before current can flow through the device?
a. fix a negative voltage on the gate and apply a voltage across the source and drain
b. ground the gate and apply a voltage across the source and drain
c. ground the source and drain and apply a positive voltage to the gate
d. a and b

8-11. In a p-n junction what types of dopants would be introduced into the p and n regions?
a. Acceptors in the p-type region and donors in the n-type regions
b. Acceptors in the n-type region and donors in the p-type region
c. Acceptors in the p-type region and acceptors in the n-type region
d. Donors in the n-type region and donors in the p-type region