ECE 6204: Semiconductor Heterostructures for Energy Efficient Nanoelectronics
(Advanced Topics in Electronics)

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1. Instructor: Dr. Mantu Hudait, Associate Professor, Dept. of ECE, 626 Whittemore Hall
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2. Office Hours: Tuesday 1:30-2:30pm + any time (you can get hold of me in my office (626 Whittemore Hall)

3. Course Description:

With looming energy crisis around the globe, environmental issues, and climate changes due to potential global warming effects, we need not only energy efficient ULSI systems for computation and information storage to reduce electricity consumption, but also alternate sources of renewable energy to power future electronic systems. This course will provide a graduate level understanding of the application of semiconductor heterostructures into three major research areas:

(1) Low-power and high-performance energy computing;
(2) Energy conversion (photovoltaics and thermophotovoltaics); and
(3) Solid state lighting.

The heterogeneous integration of low power transistors, solar cells and energy efficient lighting in semiconductor industry has gained increasing importance. This course will provide students with an introduction and importance of semiconductor heterostructure for the designing of (i) low-power transistors; (ii) multijunction high efficiency solar cells and (iii) solid state lightening for display devices based on compound semiconductors. Students will learn to design tailor-made device architecture by bandgap and strain engineering without changing the lattice constant of semiconductors.

4. Learning Objectives

The lecture sessions provides learning opportunities that should enable students to do the following upon completion of this course:

A. Develop a basic understanding on the following key concepts in quantum and statistical mechanics relevant to physical and electrical properties of electronic materials and their applications to energy efficient computing, energy conversion and solid state lightening:

i. Quantum mechanics:

Crystal structure of solids; space lattices; wave particle duality; Schrodinger's wave equation; particle in a box; particle tunneling through a barrier; allowed and forbidden energy bands; propagating electron wave in a periodic lattice.

ii. Electronic structure of semiconductor heterostructures:

Energy bands, effective mass theory; density of states in 3D, 2D, and 1D; non-degenerate and degenerate semiconductors; heavy doping effect.

iii. Heterojunction band alignment:

Theories of the band alignment; measurement of the band alignment; physical interpretation of the band alignment.

iv. Quantum wells:

Carrier distribution and screening; transport properties; drift-diffusion equation; generation-recombination; abrupt structures and thermionic emission; quantum-mechanical reflection.

v. P-n junction:

Energy band diagram; hetero p-n junction; heterojunction diode current.

vi. Heterostructure quantum well field effect transistors:

Carrier transport in the quantum well field effect transistors (QWFETs); band alignment and high electron mobility; strain effect; charge-control model; materials consideration: GaAs and InP-based conventional and pseudomorphic QWFET; heterogeneous integration onto Si substrates; understand the physical structure and detailed operation of metal-oxide semiconductor field-effect transistors (MOSFETs); metal-oxide semiconductor high electron mobility transistors (MOS-HEMT); understand the terminal I-V characteristics of MOS-HEMTs and their associated non-idealities due to scaling.

vii. Photovoltaics and thermophotovoltaics:

Carrier recombination and lifetime; carrier transport of p-n junction under illumination; solar cell parameters and device design; III-V heterojunctions single and multijunction solar cells; tailor-made bandgaps for matching solar spectrum; quantum well and quantum dots-based solar cells.

viii. Solid state lighting:

Light emitting diodes; injection in a j-n junction LEDs; materials choices for high brightness LEDs; light extraction; white solid state lamps and applications.

B. Become proficient with the fundamental and applied device physics and its applications.

C. Learn to analyze device characteristics in detail and brainstorm ways towards improving them or adapting them to new applications.

5a. Text Books: You should have a useful 4214 level text as a reference. Different book chapters and journal articles will be used as the major source of information and it will be posted in Scholar.

Useful books for ECE 4214 course:

- D.A. Neamen, *Semiconductor Physics & Devices*, 2nd ed., Boston, MA: Irwin McGraw-Hill, 1997
- S.M. Sze, *Physics of Semiconductor Devices*, 3rd ed., New York, NY: Wiley, 2007
- Umesh Mishra and Jasprit Singh, *Semiconductor Device Physics and Design*, Springer, 2008 (e-book available through www.lib.vt.edu)

5b: Scholar based lecture notes, reprints of classic papers. Here are few good books for your reference:

- http://ecee.colorado.edu/~bart/book/
- http://cleanroom.byu.edu/EW_orientation.phtml
- http://www.ioffe.rssi.ru/SVA/NSM/Semicond/index.html
- J. Singh, *Physics of semiconductors and their heterostructures*, McGraw-Hill, 2001.
- Ayers, *Heteroepitaxy of Semiconductors: Theory, Growth and Characterization*, CRC
- Manasreh, *Semiconductor Heterojunctions and Nanostructures*, McGraw Hill
- P. Harrison, *Quantum Wells, Wires and Dots*, 3rd Edition, Wiley

FET:

- Taur and Ning, *Fundamentals of Modern VLSI Devices*, 2nd Edition, Cambridge
- S. Wolf, *Silicon Processing for the VLSI Era*, Vol. 3 (The Submicron MOSFET), Lattice Press
- Tsividis, *Operation and Modeling of the MOS transistor*, 2nd /3rd Edition, Oxford
- W. Liu, *Fundamentals of III-V Devices: HBTs, MESFETs and HFETs/HEMTs*, Wiley

Photovoltaics:

- Nelson, *The Physics of Solar Cells*, Imperial College Press
- Luque and Hegedus (Editor), *Handbook of Photovoltaic Science and Engineering*, Wiley
- Fraas and Partain, *Solar cells and their applications*, 2nd Edition, Wiley

LEDs:

- E. F. Schubert, *Light-Emitting Diodes*, 2nd Edition, Cambridge
- E. F. Schubert, Lecture notes

6. Pre-requisite: ECE 4214 or ECE 5200 or ECE 5205 or Equivalent

7. Syllabus

I.	Introduction to course	5%
II.	Quantum mechanics a. Crystal structures b. Particle in a box c. Bandgap	5%
III.	Electronic structure of semiconductor heterostructures a. Density-of-states: 3D, 2D, 1D b. Effective mass c. Heavy doping effect	10%
IV.	Heterojunction band alignment a. Theory of band alignment b. Measurement and interpretation of band alignment	5%
V.	Quantum wells a. Drift-diffusion b. Transport properties	10%
VI.	P-n junctions a. Hetero p-n junctions b. Heterojunction diode current	10%
VII.	Heterostructure field effect transistors a. Design, band alignment, and carrier transport b. Charge control model c. MOS-HEMT	20%
VIII.	Photovoltaics and thermophotovoltaics a. Carrier recombination and lifetime b. Carrier transport under illumination c. Heterojunction III-V single and multijunctions cells --solar cell --thermophotovoltaics d. Design of a multijunction solar cell e. QW and QD based cells	20%
IX.	Solid state lighting a. Injection in a p-n junction LEDs b. Materials choices for high brightness LEDs c. Light extraction d. White solid-state lamps and applications	15%

8. Grading Policy

Homework	25%
Midterm	30%
Final Exam	40%
Class participation	5%
	100%

<u>Home Work:</u>

Homework problems will be typically be assigned throughout the semester and will be due at the end of class one week following its assignment. Late homework will be accepted only in extraordinary circumstances AND by specific arrangement with the instructor. It is your responsibility to present your work in a clear and logical fashion. No assignments will be accepted beyond one day late, except in the case of unforeseen, officially documented absences. *Each* problem solution should be neatly worked out. You may consult with other students and with your instructor while you are working on assigned problems but your goal in consulting should be limited to exploring options and approaches rather than avoiding work. Experience tells us if you do not work on the homework yourself, you will pay for it later during exams. The ability to solve problems develops through disciplined effort and the exams will require you to be able to solve problems. To obtain full credit for a homework assignment you must submit it to your instructor in class on the due date. Experience tells us if you do not work on the homework yourself, you will pay for it later during exams.

<u>Computer problems</u>: Some of the homework may involve computer problems. It is expected students are familiar with one or more basic programming languages to solve numerical problems (C, Basic, FORTRAN, MATLAB, Mathematica etc.) Students may need to familiarize themselves with device simulators like SenTaurus, BandProf, NextNano etc

<u>In-Class Activities:</u>

Students have the ultimate responsibility for their learning and must decide for themselves on how to maximize progress and efficiency. Class attendance, participation in classroom discussions, reading the text in advance of class lectures, homework effort and the use of office hours may all be collectively viewed by the instructor as indications of student's interest and effort in learning the course material in addition to exams.

<u>Exams</u>:

There will be **<u>one mid-term exam and a final exam</u>**. One sheet of course notes may be used during the exam and other materials including textbook is not allowed.

<u>Academic Integrity</u>:

The Virginia Tech Honor Code establishes the standard for **ACADEMIC INTEGRITY** in this course, and will be strictly enforced. *Discussion* of class material with your classmates or the instructor is encouraged; however, ALL submitted work, must represent your own efforts, and you must pledge to this effect on all work. For more details on the relevant honor codes, consult the websites listed below:

- Graduate Honor System, http://filebox.vt.edu/studentinfo/gradhonor/

<u>Announcements</u>:

I will use Scholar to post lecture notes, homework assignments, homework solutions, and other information pertaining to the course materials. You should check your email and the Scholar on a regular basis.

<u>Attendance</u>:

Attendance all lecture classes is expected and critical to your successfully completing the requirements of this course. Though it is not a policy, come to the class and have fun! Since it is an advanced level class, it will greatly help you while you are present in class. In the event that you miss a lecture, it is your responsibility to obtain the missed notes from one of your classmates or from Scholar. If you have a conflict with a scheduled exam or with the submission of any in-class assignments, you must make arrangements with your instructor well in advance so that alternate times can be scheduled.