ECE/MSE/PY 489/589 Course Syllabus

Solid-State Solar and Thermal Energy Conversion

Course Description

This course studies the fundamental and recent advances of energy harvesting from two of the most abundant sources, namely solar and thermal energy. The first part of the course focuses on photovoltaic science and technology. The characteristics and design of common types of solar cells are discussed, and the known approaches to increasing solar cell efficiency will be introduced. After the review of the physics of solar cells, we will discuss advanced topics and recent progress in solar cell technology. The second part of the course is focused on the thermoelectric effect. The basic physical properties, Seebeck coefficient, electrical and thermal conductivities are discussed and analyzed through the Boltzmann transport formalism. Advanced subjects such as carrier scattering time approximations in relation to dimensionality and the density of states are studied. Different approaches for further increasing efficiencies are discussed, including energy filtering, quantum confinement, size effects, band structure engineering, and phonon confinement.

Course Objectives/Goals

The course offers the expertise students need in both areas of photovoltaic and thermoelectrics and prepares them for graduate research or to work in solar cell manufacturing or thermoelectric industry. The goal is to prepare the students with the fundamentals and advanced topics of solid-state energy conversion. In the first part of the course, the science and engineering of various types of solar cells are introduced. The students will learn how the efficiency of solar cells are improved from fundamental points of view. Concepts such as tandem, multi-barrier, intermediate band, quantum dot intermediate band, hot carriers, Plasmonics, and the effect of temperature will be discussed. In the second part, concepts in thermoelectrics, such as coefficient of performance, multi-stage devices, Seebeck coefficient, effect of temperature and density of states, Thomson effect, specific heat, Dulong-petit limit, Debye and Einstein models, phonon scattering mechanisms, and thermal conductivity are conveyed through physical equations and pictorial descriptions.

Learning Outcomes

By the end of this course, undergraduate and graduate students will be able to:

- Explain the operation of various solar cells, including multijunction, multiple excitation generation, multibarrier, quantum dot, hot carrier, intermediate band, plasmonic, heterogenous, dye-sensitized, and perovskite solar cells.
- Outline the parameters affecting the behavior of various solar cells and thermoelectrics
- Interpret the experimental data of various solar cells and thermoelectrics
- Distinguish the underlying physics of electron and phonon transport in semiconductors
- Identify the promising density of states, lattice structure, and phonon dispersion for efficient solar cell and thermoelectric energy conversion
- Explain the microscopic origin of the Peltier effect, Seebeck voltage, and Thomson effect
- Evaluate the effectiveness of strategies for making good thermoelectric materials

In addition, the graduate students, after completion of the course project, will be able to:

- Calculate quasi-Fermi levels, dark current, current-voltage characteristics, and efficiency of solar cells versus wavelength, temperature, and geometrical factors.
- Formulate the temperature and doping concentration-dependent photovoltaic efficiency
- Critically review the advanced topics in photovoltaic and thermoelectrics published in scientific journals

Course Structure

The course is equally divided into two parts, solar cells, and thermoelectrics. It starts with a review of semiconductor physics and continues with the section of the solar cell. The mid-term exam will be taken at the end of the first section and covers the solar cell lectures. The second part of the course focuses on thermoelectrics and continues to the end of the course. The final exam covers the thermoelectrics lectures only. A computational project will be

assigned as part of 489, which will be divided into multiple sections and will be given as we make progress through the course. The project requires programming in MATLAB. Students must spend additional time learning MATLAB if they do not have the necessary experience. The project is optional for ECE 489. Undergraduate students who do the project will receive up to 15% credit towards their course grades.

Course Policies

Class participation:

Participation in class discussions is an essential part of the learning process in this course. Although not explicitly graded, your contributions and insights will be evaluated and assessed to manage borderline grades (e.g., change B+ to A-, B- to B, etc.). While your participation grade is subjective, it will not be random or arbitrary. Your comments demonstrate some reflective thinking, and frequent quality comments are highly encouraged.

Computers and Communications Devices during class:

You will affect everyone's learning if your cell phone, laptop, etc. makes noise or is visually distracting during class. For this reason, you are asked to turn off your mobile devices and close your laptops during class unless you are taking notes on your laptop. You must turn the sound off so that you do not disrupt other students' learning.

Recording of the class:

The lectures may be recorded by students for personal use, but may not be further copied or distributed in any form without the written consent of the instructor.

Quiz Policy:

The course has weekly quizzes. There is no make-up quiz if you miss one unless for medical reasons. The lowest graded quiz is dropped for all students. Schedule conflicts like job interviews, attending conferences, other exams, etc., are not accepted to waive a quiz. The quiz is waived only for medical reasons if you provide a letter from the clinic confirming that you were sick on the day of the class. No other evidence is accepted for illness.

There are additional provisions for the covid cases. If someone is tested positive, thinks exposed, or is unsure if infected, they stay at home and take the online quiz. They should upload the covid test result with their quiz. In cases that someone is too sick from covid to take the online quiz, that will also qualify for the waiver. If someone has to be quarantined, they can take the online quizzes until the quarantine period is ended.

Instructors

Daryoosh Vashaee (dvashae) - *Instructor*
Email: dvashae@ncsu.edu
Phone: 9195159599
Office Location: 451 MRC or Online with an appointment
Office Hours: Tu 11:30am-12:30pm
Office hours are subject to change. I will make every effort to give advance notice, but unavoidable appointments may force last-minute changes. My office hours are for your convenience. Please feel free to take advantage of them.

Course Meetings

Lecture
Days: TuTh
Time: 8:30AM - 9:45AM
Campus: Centennial
Location: EB3 02207
This meeting is required.

Final Exam

Day: 4/25/2024
Time: 8:30 AM – 11:00 AM

Campus: Centennial
Location: EB3 02207

Course Materials

Lecture Notes:

Lecture slides will be provided to the students.

Textbooks:

a) **Semiconductor Devices, Physics and Technology** - *S. M. Sze and M. K. Lee*
Edition: 3 (any other edition is also helpful)
ISBN: 978-0470537947
Web Link: http://www.wiley.com/WileyCDA/WileyTitle/productCd-EHEP001825.html
e-book: Available through NCSU library for free.
This textbook is required.

b) **The physics of solar cells** - *Jenny Nelson*
Edition: 1
ISBN: 1860943403, 9781860943409
Web Link: http://www.worldscientific.com/worldscibooks/10.1142/p276
Cost: ~$100 (hard copy), ~$60 (soft copy)
eBook: 1st edition https://fuelrfuture.com/energy/physicsOfSolarCellsNelson.pdf
This textbook is optional.

c) **Introduction to Thermoelectricity** - *H. Julian Goldsmid*
Edition: 2
ISBN: 3662492563, 9783662492567
Web Link: http://www.springer.com/la/book/9783662492550
This textbook is optional.

d) **Materials, Preparation, and Characterization in Thermoelectrics** - *David Michael Rowe*
Edition: 1
ISBN: 1439874700, 9781439874707
Web Link: https://www.crcpress.com/Materials-Preparation-and-Characterization-in-Thermoelectrics/Rowe/p/book/9781439874707
This textbook is optional.

e) **PV Education – A good introduction on the basics of the photovoltaic**
Web Link: https://www.pveducation.org/pvcdrom/welcome-to-pvcdrom

Requisites and Restrictions

Students must be familiar with the basics of semiconductors to the level that they can understand the physics of the PN junction diode (energy bands, doping, electric field, potential, drift current, diffusion current).

Prerequisites

NCSU Students: E304 (Intro to Nanoscience and Technology), or ECE302 (Microelectronics), or MSE355 (Electrical, Magnetic and Optical Properties of Materials), or PY407 (Introduction to Modern Physics).
Other students: Equivalent to one of the above courses.

Co-requisites

None.

Restrictions

None.

General Education Program (GEP) Information

GEP Category

This course does not fulfill a General Education Program category.

GEP Co-requisites

This course does not fulfill a General Education Program co-requisite.

Transportation

This course will not require students to provide their own transportation. Non-scheduled class time for field trips or out-of-class activities is NOT required for this class.

Safety & Risk Assumptions

None.

Grading

Component	Weight	Details
Quiz	**30**	Online quizzes are given every week. All quizzes are closed book and notes, and no formula sheet is allowed. Calculators are permitted - no laptop, ipad. One lowest grade quiz will be forgiven for each student.
Midterm exam	**30 (489)** **15 (589)**	Mid-term exam covers semiconductor fundamentals and solar cells. The exam is closed book and notes and no formula sheet is allowed. No Graphing Calculators are allowed on tests or exams. You may bring in a simple NON-graphing calculator if you would like one to aid in calculations.
Project	**15**	There is a course project which is divided into sections and distributed as we make progress in the course. Course project is not required for 489. However, undergraduate students who do the project will receive up to 15% bonus credit.
Final exam	**40**	Final exam covers thermoelectrics section only. It is closed book and notes, and no formula sheet is allowed. No Graphing Calculators are allowed on tests or exams. You may bring in a simple NON-graphing calculator if you would like one to aid in calculations.

Letter Grades

This course uses Standard NCSU Letter Grading:

97	≤	A+	≤	100	73	≤	C	< 77
93	≤	A	<	97	70	≤	C-	< 73
90	≤	A-	<	93	67	≤	D+	< 70
87	≤	B+	<	90	63	≤	D	< 67
83	≤	B	<	87	60	≤	D-	< 63
80	≤	B-	<	83	0	≤	F	< 60
77	≤	C+	<	80				

Requirements for Auditors (AU)

Information about and requirements for auditing a course can be found at http://policies.ncsu.edu/regulation/reg-02-20-04.

Policies on Incomplete Grades

If an extended deadline is not authorized by the Graduate School, an unfinished, incomplete grade will automatically change to an F after either (a) the end of the next regular semester in which the student is enrolled (not including summer sessions), or (b) by the end of 12 months if the student is not enrolled, whichever is shorter. Incompletes that change to F will count as an attempted course on transcripts. The burden of fulfilling an incomplete grade is the responsibility of the student. The university policy on incomplete grades is located at http://policies.ncsu.edu/regulation/reg-02-50-03. Additional information relative to incomplete grades for graduate

students can be found in the Graduate Administrative Handbook in Section 3.18.F at http://www.fis.ncsu.edu/grad_publicns/handbook/

Academic Integrity

Students are required to comply with the university policy on academic integrity found in the Code of Student Conduct found at http://policies.ncsu.edu/policy/pol-11-35-01

All assignments will be screened for plagiarism and academic integrity. Copying another student's assignment or computer program, turning in an assignment that is identical or very similar to others' work, or receiving help on assignments without permission of the instructor is a violation of academic integrity and will be treated strictly by NCSU Policy and Procedures. Violations will result in your being sanctioned, including receiving a failing grade, receiving a notation of a violation of academic integrity on your transcript (F!), and being suspended from the University.

Honor Pledge

Your signature on any test or assignment indicates, "I have neither given nor received unauthorized aid on this test or assignment."

Late Assignments

Late assignments are NOT acceptable.

Electronically-Hosted Course Components

There are no electronically-hosted components for this course.

Accommodations for Disabilities

Reasonable accommodations will be made for students with verifiable disabilities. In order to take advantage of available accommodations, students must register with the Disability Services Office at Suite 2221, Student Health Center, Campus Box 7509, 919-515-7653. For more information on NC State's policy on working with students with disabilities, please see the Academic Accommodations for Students with Disabilities Regulation (REG 02.20.01).

NC. State University Policies, Regulations, and Rules (PRR)

Students are responsible for reviewing the PRRs, which pertain to their course rights and responsibilities. These include: http://policies.ncsu.edu/policy/pol-04-25-05 (Equal Opportunity and Non-Discrimination Policy Statement), http://oied.ncsu.edu/oied/policies.php (Office for Institutional Equity and Diversity), http://policies.ncsu.edu/policy/pol-11-35-01 (Code of Student Conduct), and http://policies.ncsu.edu/regulation/reg-02-50-03 (Grades and Grade Point Average)

NC State University provides equality of opportunity in education and employment for all students and employees. Accordingly, NC State affirms its commitment to maintaining a work environment for all employees and an academic environment for all students that is free from all forms of discrimination. Discrimination based on race, color, religion, creed, sex, national origin, age, disability, veteran status, or sexual orientation is a violation of state and federal law and/or NC State University policy and will not be tolerated. Harassment of any person (either in the form of quid pro quo or creation of a hostile environment) based on race, color, religion, creed, sex, national origin, age, disability, veteran status, or sexual orientation also is a violation of state and federal law and/or NC State University policy and will not be tolerated. Retaliation against any person who complains about discrimination is also prohibited. Any person who feels that he or she has been the subject of prohibited discrimination, harassment, or retaliation should contact the Office for Equal Opportunity (OEO) at 919-515-3148.

Course Lectures

NOTE: Each lecture may take more or less than one session. The course lectures are subject to change.

Week 1:

Lecture 01 Introduction to Photovoltaics and Thermoelectrics

Lecture 02 Solar insolation and light interaction with matter

Week 2:

Lecture 03 Basic concepts, Bandgap, Density of states, Fermi energy, Temperature effect

Week 3:

Lecture 04 Drift diffusion, Carrier mobility, Quasi fermi levels

Lecture 05 Basics of PN junction

Week 4:

Lecture 06 Interface, Schottky contact, Photodiode

Week 5:

Lecture 07 PN junction solar cells

Lecture 08 Advanced PVs, Tandem, Multi-barrier, Intermediate band, Quantum dot intermediate band solar cells

Week 6:

Lecture 09 Hot carriers in photovoltaics

Lecture 10 Plasmonic, Inorganic, Quantum dot photovoltaics

Week 7:

Lecture 11 Perovskite solar cells, Temperature effects

Week 8:

Lecture 12 Thermoelectric Introduction

Lecture 13 Coefficient of performance, Optimum geometries

Week 9:

Lecture 14 Multi-stage thermoelectrics

Lecture 15 Deriving relaxation time approximation equations

Week 10:

Lecture 16 Pictorial representation of Seebeck voltage

Lecture 17 Effect of temperature and density of states on Seebeck coefficient

Week 11:

Lecture 18 Microscopic origin of Seebeck voltage and Peltier cooling, Low dimension

Week 12:

Lecture 19 Microscopic origin of Thomson Effect

Lecture 20 How does Nano help?

Week 13:

Lecture 21 Specific heat, Dulong-petit limit, Debye and Einstein models, Phonon-Phonon scattering, Normal and Umklap processes

Week 14:

Lecture 22 Phonon density of states, Heat capacity, van Hove singularities, Thermal conductivity

Week 15:

Lecture 23 Boson peak, Clathrates, Half-Heuslers, Skutterudites