

ECE 443 LEDs and Solar Cells, Spring 2023

Recording this course, including lectures, discussions, or other activities, is forbidden. Sharing or posting any course content material online is also forbidden. Any violation of these policies will be forwarded to the Office of Student Conflict Resolution for disciplinary action.

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Lectures: MWF 2:00-2:50 pm – ECEB 3017 (lectures) **or** EH 406B8 (computer labs)

Nano Labs: MTR 12-1:50 pm WF 9-10:50 am WF 11-12:50 pm

Meet w/ Instr.: Right after lecture classes.

Meet w/ HW TAs: **TBD**

Meet w/ Lab TAs: Right after lab classes.

Meet w/ Project TAs: Right after lab classes.

Catalog Description: This course explores the energy conversion devices from fundamentals to system-level issues. The course starts with a review of the electronic structure of atoms and semiconductors, quantum physics, and compound semiconductors. Then semiconductor heterostructures and low dimensional quantum structures, forming the basis of modern devices such as light emitting diodes and solar cells are introduced. Topics covered include energy transfer between photons and electron-hole pairs, light emission and capture, emission and absorption engineering via device simulation/design, radiative and non-radiative processes in devices, electrical and optical characteristics, carrier diffusion and mobility, and light extraction and trapping for high efficiency devices. Computer labs and clean-room labs reinforce modern device design and analysis such as light emitting diodes and solar cells.

Pre-requisites: ECE 340 Semiconductor Devices * *Familiarity with semiconductor physics, materials, and junctions are required.*

Purpose: This is an advanced course in energy conversion physics, devices, and design technology. The course covers fundamentals as well as modern research topics and will accommodate a broad range of backgrounds and interests from Electrical Engineering, Engineering Physics, and Material Science and Engineering. If you are unsure of your individual preparation for this class, please check with the instructor. A solid knowledge on quantum mechanics, solid-state physics, semiconductors, and familiarity with a numerical computing software (e.g. Matlab, Python) are recommended.

Approach to ECE 443: In this course, we cover important and timely developments. Starting with the first lecture, reading materials will be assigned. To keep up with the class lectures and discussions, it is suggested that students read the handouts in advance of the lecture. The class is student-driven: The more questions the class asks, the better the in-class student learning experience.

Timeline: There are 62 hrs. lectures composed of: 20 hrs. classroom & 5 hrs. project presentation lectures, 15 hrs. hands-on computer lab lectures., and 22 hrs. hands-on experimental labs, spread over 14 weeks.

Lecture Electronics Policy: During the classroom lectures, computer lectures, and nano labs, cell phones or similar non-class use of electronics are prohibited. If, due to unforeseen circumstances, the student needs access to her/his cell phone, she/he shall inform the instructor in the beginning of the lecture and should sit in a way (typically furthest from the others) not to allow further student distraction.

Grading: 5 × Homework Assignments (15%). 3 × 40-min Computer Lab Assessments (15%). 6 × Nano Lab Assessments (15%). Term Project (15%). 3 × 50 minute-long in-class Assessments (40%).

Historical Grading: Historical grades are below. This data does not imply future grading trends. The course content is revised annually. Student body and student performance vary annually.

S16: {8 Graduates; 9 Seniors; 1 Junior}	2 A+ 9 A	3 B+ 2 B 2 B-	2 C+
S17: {7 Graduates; 3 Seniors}	2 A+ 7 A	1 B+	
S18: {4 Graduates; 11 Seniors; 1 Junior}	4 A 5 A-	1 B+ 1 B 2 B-	2 C+ 1 C
S19: {3 Graduates; 13 Seniors; 2 Juniors}	1 A+ 7 A 2 A-	3 B+ 1 B 2 B-	1 C 1 D+
S20: {1 Graduate; 3 Seniors}* <i>*COVID-19 pandemic has impacted the S20 final enrollment severely.</i>	1 A	1 B+ 1 B	1 C+
S21: {4 Graduates; 6 Seniors}	1 A+ 1 A 3 A-	3 B+ 1 B	1 C-
S22: {4 Graduates; 14 Seniors}	2 A+ 2 A 4 A-	5 B+ 2 B	3 C+
S23: {3 Graduates; 9 Seniors; 1 Junior}	5 A	3 B+ 4 B	1 C+

Classroom Lectures (20 hrs.): The classroom lecture topics evolve annually. The classroom lectures involve ppt presentations, black board notes, example problems, and in-class discussion.

GENERAL TOPICS	Hrs.
I. Solid State Materials & Semiconductor Physics & Modern Epitaxy	8
II. Light Emitting Diodes	8
a) Spectral Engineering	
b) Radiative and Non-radiative Recombination Mechanisms	
c) Opto-Electro-Thermal Properties	
d) Trade offs in Materials, Physics, and Engineering towards Eliminating Efficiency Droop	
III. Solar Cells	8
a) Photovoltaic Effect, Photocurrent, and Quantum Efficiency	
b) Origins of Dark Current and Open Circuit Voltage	
c) Light Management (i.e. confinement, recycling, concentration) and Thermal Effects	
d) General Strategies for High Efficiency (>50%) Solar Cells	
Total:	24

Homework: The course calendar lists the HW assignment and due dates. HWs are always due pre-class. Due approximately every week, and some will contain open-ended “research” problems. That is, not all necessary information will be provided up front, you may have to look up constants, material properties, and make reasonable approximations. Some homework will involve computational work with Matlab, Origin, or freeware software (BandEng, wxAMPs) available on campus, including numerical integrals, straightforward finite difference problems, and simple device simulation. You may work in groups on the homework, although separate write-ups must be submitted. In the **Spring 24**, there will be **5 homework sets**, weighing a total of **15%**.

Computer Lectures: Industrial finite element modelling Crosslight software is used during the hands-on computer labs for the design and simulation of quantum structures, light emitting diodes, and solar cells. For each lab set, there will be one in-class quiz to assess the student learning. The computer lab alternates for lectures as to be posted on a weekly basis (dependent upon the classroom lecture progress). The quiz is open book and open source. Each quiz will be for 40 minutes only, and the students will be asked to provide their own software simulation code results in-class, at the end of the quiz time. The quiz starts sharp at 2:05 pm and will end sharp at 2:45 pm. The students will email their quiz solutions and source code to the TA in charge. If post-marked later than 2:45 pm, 10% deduction per minute is implemented. No solutions will be accepted after 2:50 pm. Students are encouraged to complete their quiz questions as early as possible and submit them early. Students cannot ask fellow students or

the TAs/instructors for help during the quiz and students are expected to solve their own assessment problem with all open book and open sources (including handouts, books, and online/web resources). **Three** 40-min Simulation Assessments weigh a total of **15%**. The select topics of computer lab are:

- (1) Quantum well simulation (*instruction & assessment*)
- (2) AlGaAs-based LED simulation (*instruction & assessment*)
 - InGaN-based micro-LED simulation (*instruction*)
 - InGaN-based cubic LED simulation (*instruction*)
- (3) Si-based solar cell simulation (*instruction & assessment*)
 - Multi-Junction III-V solar cell simulation (*instruction*)

Term Project: The class involves a term project. This will be an open-ended research project of your choice. The report is written following the National Science Foundation (NSF)-style. The details on timeline, rubric, and guidelines are available on the course webpage [<https://443.ece.illinois.edu/course-information/>]. You are encouraged to work in pairs/teams, and to think of topics as the course progresses. However, each student will submit an individual project.

Nanofabrication Laboratory: Nanofabrication Lab is conducted in the ECEB instructional cleanroom. Cleanroom activities include the electrical, optical, and thermal characterization of light emitting diodes and solar cells. There are a total of six labs. Each lab (except for the Safety Training) is for two weeks where the first week is training and second week is student experimentation. There is a formal nanofabrication lab report submission after each nanofabrication lab set.

- # 1, Safety Training, (Pass or Fail).
- # 2, Scanning Electron Microscope Inspection of LEDs and solar cells.
- # 3, Leakage paths and loss mechanisms in LEDs.
- # 4, Temperature effects on LEDs.
- # 5, Leakage paths and loss mechanisms in solar cells.
- # 6, Temperature & Series/Parallel connection & Concentration effects on solar cells.

Assessments: **3** × 50 minutes-long in-class Assessments (40%).

- Feb. 12 (Monday), in-class
- Mar. 22 (Friday), in-class
- April 12 (Friday), in-class

In assessments, students are responsible for all subjects covered in the class including blackboard lectures, printed lecture notes, homework reading assignments, and all homework. Each will be during **class time in ECEB 3017**. This is a closed book and closed notes assessment. You can bring ONE standard index card (3 by 5 inches) with hand-written notes - you can write on both sides. The instructor will be validating your index cards before the assessment begins. Students are encouraged to write all the fundamental constants (h, pi, electron mass, and so on) into your index card. It is the students' responsibility to have all the constants and equations ready in your index card. Calculators and rules are allowed. Unless stated otherwise, students should do their work on the page of the problem and if necessary, on the preceding blank page. Students should explicitly show the units in their works, as well as in the answers. Students should circle the answer. Students should be neat and write clearly. If the instructor cannot read or follow your work, students get zero credit and welcome to appeal one-on-one. For each problem, students must show complete work and indicate their reasoning. Students should not expect any credit if they do not show the complete work and describe their procedures, even if the answer is correct.

Grade Appeal: Grade appeals or corrections are to be requested within one week after the posting.

Reading: No single textbook covers all topics. We will rely on recent news items, journal papers, lecture handouts, lecture notes/slides, and reading sections from several books including “Light Emitting Diodes” by E. Fred Schubert (Cambridge, 2003) (Lectures III-V) [<http://www.amazon.com/Light-Emitting-Diodes-E-Fred-Schubert/dp/0521865387>], and “The Physics of Solar Cells” by J. Nelson (Imperial College Press, 2003) (Lectures VI-VIII) [<http://www.amazon.com/Physics-Solar-Properties-Semiconductor-Materials/dp/1860943497>]. Multiple hard copies of these books are available in the reserve section of the Grainger Library. Please also see the other resources at the course webpage [<https://443.ece.illinois.edu/resources/>].

Attendance Policy: Attendance at all lectures is mandatory. Students are advised to contact both the TAs and the instructor via email (before the lecture) if they are to miss any lecture and note the unforeseen circumstances. Instructor and TAs reserve the right to take class attendance to use in future decision-making regarding course attendance policies. Class attendance includes in-class participation.

Course Policy on Absence: In the event of illness, you must receive an Excused Absence Form from the Undergraduate College Office, Room 207 Engineering Hall, indicating what work you have missed and the reason for the absence. This form must be signed by a physician or medical official for a medical excuse, or by the Office of the Dean of Students (Emergency Dean) for a personal excuse due to personal illness, family emergencies, or other uncontrollable circumstances. The office may be reached at 333-0050. Note that Excused Absence Forms in the case of illness are now only given out by the office for the case of serious illness lasting more than 3 days. For missed classes or hourly exams, present the completed form in person to the course director Prof. Bayram as possible after you return.

INSTRUCTIONAL OBJECTIVES

A. By 1st assessment, students know the following:

1. List common applications of LEDs and Solar Cells ⁽⁷⁾
2. List methods of semiconductor deposition technologies and identify their relative (dis)advantages. ⁽¹⁾⁽²⁾⁽⁷⁾
3. Understand electrical, structural, and optical effects of impurities on semiconductors. ⁽¹⁾
4. Calculate lattice constants and bandgap energies of III-V ternary and quaternary compound semiconductors using Vegard's law. ⁽¹⁾
5. Identify available substrates and lattice-matched alloys atop for common photonic applications. ⁽¹⁾⁽²⁾⁽⁷⁾
6. Calculate energy band discontinuities at the heterojunctions by back-of-the-envelope calculation, free-ware BandEng simulator, and industrial Crosslight Software and identify limitations in each approach. ⁽¹⁾
7. Find the allowed energy levels and the density of states in quantum well structures by back-of-the-envelope calculation and Crosslight Software. ⁽¹⁾

B. By 2nd assessment, students should know the items listed under A and the following:

8. Establish the physical understanding of light reflection, light absorption, and spontaneous emission rates by using Einstein relations. ⁽¹⁾
9. Explain the operating principles of LEDs and explain threshold voltage, quantum efficiency, power efficiency, luminous efficiency, color rendering, and other figures of merit and their temperature behavior. ⁽¹⁾
10. Understand the equivalent circuit model of an LED. ⁽¹⁾
11. Measure and assess light extraction, internal, and external efficiencies of LEDs and their temperature-dependent behavior. ⁽¹⁾
12. Explain the fundamentals of solid-state lighting (SSL) and identify SSL's current challenges. ⁽⁴⁾
13. Identify present and future areas of applications for LEDs. ⁽³⁾⁽⁴⁾
14. Simulate heterojunction LEDs by optimizing semiconductor material parameters and establish the physical understanding of various design parameters in LEDs. ⁽¹⁾⁽⁷⁾
15. Experimentally measure I-V and spectrum of a LED and extract data concerning the internal loss, external quantum efficiency, internal quantum efficiency, output power, and threshold current. ⁽¹⁾⁽⁶⁾⁽⁷⁾
16. Satisfactorily test and characterize the LEDs on wafer. ⁽¹⁾⁽⁶⁾

C. By 3rd assessment, students should know the items listed under A & B plus the following:

17. Understand the differences between photoconductivity and photoelectricity. ⁽¹⁾
18. Understand the differences between a battery and a solar cell. ⁽¹⁾
19. Explain the operating principles of solar cells and explain fill factor, short circuit current, open circuit voltage, internal quantum efficiency, external quantum efficiency, and other figures of merit and their temperature behavior. ⁽¹⁾
20. Understand the equivalent circuit model of a solar cell. ⁽¹⁾
21. Measure and assess light absorption, internal, and external efficiencies of solar cells and their temperature-dependent behavior. ⁽¹⁾⁽⁶⁾
22. Develop the ability to design single and multi-junction solar cells by optimizing semiconductor material parameters and heterojunction engineering using free-ware wxAMPs simulator and Crosslight Software and identify limitations in each approach. ⁽¹⁾⁽²⁾
23. Explain the fundamentals of photovoltaics (PV) and identify PV's current challenges. ⁽⁴⁾
24. Identify present and future areas of applications for PVs. ⁽⁴⁾
25. Simulate heterojunction solar cells by optimizing semiconductor material parameters and establish the physical understanding of various design parameters in solar cells. ⁽¹⁾
26. Experimentally measure I-V and IQE of a solar cell and extract data concerning the internal loss, external quantum efficiency, internal quantum efficiency, output power, short circuit current, and open circuit voltage. ⁽¹⁾⁽⁶⁾⁽⁷⁾
27. Satisfactorily test and characterize commercial solar cells. ⁽¹⁾⁽⁶⁾
28. Address a need in society through a new design of a LED or a Solar Cell using Crosslight Software, analyze and write a professional report on the design choices and outcomes, and present the final design and findings to the class. ⁽³⁾⁽⁴⁾⁽⁶⁾⁽⁷⁾