Fundamentals of Modern Photovoltaics

Engineering the Conversion of Light to Electricity

Credits:	3/4 (undergraduates/graduates)
Course Time and Location:	MWF 11:00-11:50am, Delivered Online
	[link for online lectures will be provided via email prior to the first class]
Course Webpage:	http://oasis.mechse.illinois.edu/me432.html
Course Instructor:	Prof. Elif Ertekin
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Prerequisite: For undergraduates: fourth year standing or talk to instructor.

Course Description: Recent observations confirm that, based on the rates of observed emissions, the worst-case IPCC scenario trajectories (or worse) are being realized. Greenhouse gas concentration trajectories must be reduced below even the Intergovernmental Panel on Climate Change "stringent mitigation" climate futures scenario (Representative Concentration Pathway 2.6) [1] to hold the global average temperature to well below 2°C above pre-industrial levels, the target set by the Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) [2]. Rapid, sustained, and effective mitigation is critical to avoid dangerous climate change, and wide-scale deployment of low-carbon sources of energy are critical to capping atmospheric CO_2 concentrations. Photoelectric conversion – especially the direct conversion of photons from the sun to electricity – represents the largest single untapped source of low-carbon energy for the planet.

In this course, we will develop a fundamental understanding of how solar cells convert light to electricity, how solar cells are made, how solar cell performance is evaluated, and the photovoltaic technologies that are currently on the market and/or under development. Using thermodynamics, materials physics, and engineering analysis we will assess and critique the potential and drawbacks of modern photovoltaic technologies, including single– and multi– crystalline silicon, tandem cells, CdTe, CIGS, PVT, bulk heterojunctions (organic), Graetzel cells, nanostructure–based, hybrid perovskite, and third generation PV.

We'll start with an analysis of the potential of and fundamental limits to photovoltaic energy conversion on earth, which will be considered in the context of competing technologies such as other renewables and fossil fuels. We will then explore the processes that take place during solar cell operation: light absorption, carrier thermalization, charge separation, charge transport, and charge extraction. Each process will be considered for a variety of existing and emerging solar cell technologies. Graduate students will apply this knowledge towards a solar energy project of their choosing.

Anti-Racism and Inclusivity Statement: See the statement from the Grainger College of Engineering Task Force on Anti-Racism and Inclusivity. The effectiveness of this course is dependent upon each of us to create a safe and encouraging learning environment that allows for the open exchange of ideas while also ensuring equitable opportunities and respect for all of us. Everyone is expected to help establish and maintain an environment where students, staff, and faculty can contribute without fear of personal ridicule, or intolerant or offensive language. If you witness or experience racism, discrimination, micro-aggressions, or other offensive behavior, you are encouraged to bring this to the attention of the course director if you feel comfortable. You can also report these behaviors to the Bias Assessment and Response Team (BART). Based on your report, BART members will follow up and reach out to students to make sure they have the support they need to be healthy and safe. If the reported behavior also violates university policy, staff in the Office for Student Conflict Resolution may respond as well and will take appropriate action.

Online Format: Due to COVID, this class will take place entirely online this semester. Lectures will be given live during the scheduled class time. I will not post the link to attend the lectures publicly, but on the day before the first lecture I will email it to everyone registered for the class.

Since some of you may be in very different time zones, attendance during the live lectures is not mandatory. For those for whom timezones are not an issue, I encourage you to participate in the live sessions. I will try to make them engaging and interactive, and you may even occasionally get to see my cats. The live lectures will be recorded and posted to the ME432-Fall2020 Channel on Mediaspace. Please watch these if you can't attend during the scheduled time.

If anyone is facing extra challenges with the online format (poor internet connection, difficult time zone, etc.), I will work with you to address those challenges. Don't hesitate to get in touch if you need special accommodations.

Websites that we will use this semester:

- Recorded lectures on ME 432 Channel on Mediaspace
- Online discussion forum on Piazza - we will use this instead of office hours
- Gradescope - Homework assignments and quizzes will be made available here. Please submit your assignments as a single pdf file here. You cannot access it yet but I'll provide you with an access code to sign up code during the first week of class.

Course Communication: If you need to contact the instructor or the TA for this class, the preferred method of communication is Piazza (rather than email). This helps the instructors keep all course related content together in one space and makes it less likely that your email will get lost in my inbox. For general questions about course logistics, concepts, homework, etc please post publicly since others may have the same question as you. For sensitive issues, you can post privately to the Instructor.

Course Evaluation: Graduate students: Homework: 40%, In–class quizzes: 40%, Class Project (checkpoints during semester and presentation during regularly scheduled final exam) : 20%. Undergraduate students: Homework: 55%, In–class quizzes: 40%, Final Exam : 5%.

Note that there is no formal final exam for this class. We will use the scheduled final exam time for graduate student class project presentations. Undergraduate students are expected to attend in order to provide feedback (a template will be provided) on each presentation.

Final grades will then rounded to the nearest integer and distributed according to: 97 – 100 A+, 93 – 96 A, 90 – 92 A-, 87 – 89 B+, 83 – 86 B, 80 – 82 B-, 77 – 79 C+, 73 – 76 C, 70 – 72 C-, 67 – 69 D+, 63 – 66 D, 60 – 62 D-, 0 – 59 F.

Required Textbooks: There are no required textbooks; however, some useful reading materials are listed below. I will periodically post reading assignments online (not graded, but to your benefit to keep up).

- C. Honsberg and S. Bowden, *Photovoltaics: Devices, Systems and Applications CDROM.* Online at: http://www.pveducation.org/pvcdrom
- A. Luque and S. Hegedus. *Handbook of Photovoltaic Science and Engineering.* John Wiley & Sons, 2011. ISBN: 9780470721698. (online access through UIUC)
- M.A. Green, *Solar Cells: Operating Principles, Technology and System Applications.* ISBN 0138222703.
- R. H. Bube. *Photovoltaic Materials.* World Scientific, 1998. ISBN: 978-1860940651.
- J. Poortmans and V. Arkhipov. *Thin Film Solar Cells: Fabrication, Characterization, and Applications.* John Wiley & Sons, 2006. ISBN: 9780470091265. (on reserve at grainger)
- S. R. Wenham, M. A. Green, M. E. Watt, and R. Corkish. *Applied Photovoltaics.* 2nd ed. Earthscan Publications, 2007. ISBN 9781844074013.
- S.–S. Sun and N. S. Sariciftci. *Organic Photovoltaics: Mechanisms, Materials, and Devices.* CRC Press, 2005. ISBN: 9780824759636.
- S. M. Sze and K. K. Ng. *Physics of Semiconductor Devices.* 3rd ed. Wiley–Interscience, 2006. ISBN: 9780471143239. (on reserve at grainger)
- P. Wurfel. *Physics of Solar Cells: From Basic Principles to Advanced Concepts.* Wiley–VCH, 2009. ISBN: 9783527408573.
- J. Nelson. *Physics of Solar Cells (Properties of Semiconductor Materials).* Imperial College Press, 2003. ISBN: 9781860943492. (on reserve at grainger)
- M. A. Green. *Third Generation Photovoltaics: Advanced Solar Energy Conversion.* Springer, 2005. ISBN: 9783540265627. (online access through UIUC)

Class project: The class project is required for graduate students only. This year, I will give students a choice in the topic for the final class project. I will provide a list of possible topics, or you are welcome to roll your own as long as you obtain instructor approval for your idea. The end result of your work will be a 10 page report/paper and a 10 minute presentation, both due during the formal final exam for the class. You will work in teams of two. Be prepared to defend your conclusions to your audience! For students in difficult time zones, we can make arrangements for you to pre-record your presentation that we will all watch during the regularly scheduled presentation time (Fear not – I will forward questions to you for you to respond to).

Undergraduate students are expected to attend and provide feedback on the presentations.

Project Checkpoints for Graduate Students:

- A short proposal will be due Fri Oct 2, so you should start thinking about your project as soon as possible (3% of total semester grade).
- During the week of Nov 2-6th, we will schedule 10 minute progress update meetings for each team with the instructor (6% of total semester grade).
- Final presentations: during the scheduled final exam period (11% of total semester grade).

Academic Integrity: See the university's Student Code, Article 1, Part 4. Infractions will not be tolerated.

Important Dates:

- Homework will be assigned and due on roughly a two week basis, with the first assignment due in the second week of the class. There will be 6 homework assignments throughout the semester – be aware that they are long.
- The two take-home quizzes will be released during class time on Monday Oct 12th and Wednesday December 2nd. You will receive the quiz via Gradescope and have 48 hours to complete it.
- Grad students: a project proposal (1-2 paragraphs) is due on Friday Oct 2nd.
- Grad students: project progress update meetings will take place during the week of Nov 2-6th. You will sign up for 10 minute meeting slots.
- Grad students: final project presentations will take place during the scheduled final exam time for the class. Reports are also due at this time.
- This class has no formal final exam apart from project presentations.

References

[1] IPCC, 2014: Climate change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[2] Paris Agreement, Decision 1/CP.21, 2015. UNFCCC secretariat. Online; accessed 26-May-2017.

Tentative Course Syllabus: Please note that this plan reflects the general flow of the course and topics to be covered, but the dates listed are approximate.

Week 1	Introduction	Historical perspective, overview of world energy challenges and competing energy technologies. Options for capturing solar energy: photovoltaics, solar thermal, photosynthesis, photocatalysis. Climate – what we know and how we know it.
Week 2	Thermodynamics	The sun, blackbody radiation, atmospheric absorption, solar spectra (AM0, AM1, AM1.5), insolation, estimating solar array outputs. Solar cell operation as a thermodynamic cycle. Carnot limit, blackbody limit, Landsberg limit, practical efficiencies in real devices.
Weeks 3 and 4	Semiconductor Materials for PV	Electronic structure of materials: insulators, metals, and semiconductors. Semiconductors: crystal structure, light absorption, spectrum overlap, direct vs. indirect, phonons, and phonon scattering, carrier thermalization, charge separation and recombination.
Weeks 5 and 6	Transport in Semiconductors	Intrinsic and doped semiconductors, electrons and holes, Fermi Energy, drift and diffusion current, carrier effective masses, mobilities, diffusion coefficients, Einstein relations, PN junctions, built-in electric field, IV curves, minority carrier mobilities, lifetimes, and diffusion length
Week 7	IV Characterization	Short circuit current, open circuit voltage, ideal vs. non-ideal behavior, fill factor, series and shunt resistances, maximum power point, characteristic load, internal and external quantum efficiencies. Radiative recombination, Shockley–Quiesser limit, non–radiative recombination: Shockley-Read-Hall, surface recombination, Auger recombination, grain boundaries.
Week 8	Contacts	Contacts: work function, ohmic and Schottky barrier, transparent conducting oxides
Week 9	Commerical Technologies – Crystalline Silicon	Silicon abundance, refining, and crystal growth. History, state–of–the–art, PERL cells, HIT, back contacts, other design considerations. Wafer to module processing, encapsulants, module testing and IEC standards, systems integration, inverters and micro inverters, connecting to the grid, BIPV.
Weeks 10–11	Commerical Technologies – Thin Films	Amorphous silicon, Cadmium Telluride, CIGS, Multijunction solar cells and concentrations, organic solar cells
Weeks 12–13	Developing Technologies	Earth–abundant solar cell materials: CZTS, iron pyrite. Graetzel cells, hybrid perovskites, multiband cells, hot carrier cells, multiple exciton generation, nanoscale PV.
Week 14	Defects and Defect Magic	Why are some solar cells tolerant of defects, and not others? What will it take to discover the next best solar cell material?
Week 15	Wrap–Up	Economic breakdown of technology: materials, manufacturing, installation. Life cycle analysis, energy pay back time, growth of PV market, future projections, role of policy, the energy storage challenge.