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, 203 Transportation Building

**Course Webpage:** [http://oasis.mechse.illinois.edu/me498.html](http://oasis.mechse.illinois.edu/me498.html)

**Course Instructor:** Prof. Elif Ertekin

**Office:** 225 MEB

**Office Hours:** TBD

**e-mail:** ertekin@illinois.edu

**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. 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.

Other activities will be incorporated into the semester, including a tour of a solar decathlon home and guest lectures from specialists in PV-related areas and industry.

**Course Evaluation:** Graduate students: Homework: 40%, In-class quizzes: 40%, Class Project: 20%. Undergraduate students: Homework: 60%, In-class quizzes: 40%. Scores will be curved (separately for graduates and undergraduates), and final grades will then be distributed according to: 97–100 A+, 94–96 A, 90–93 A-, 87–89 B+, 84–86 B, 80–83 B-, 77–79 C+, 74–76 C, 70–73 C-, 67–69 D+, 64–66 D, 60–63 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).


**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 design your own as long as you obtain instructor approval for your idea. A short proposal will be due Fri Oct 21, so you should start thinking about your project as soon as possible. The end result of your work will be a 4-page APL-style paper and a 20 minute presentation during the scheduled final exam period. Be prepared to defend your conclusions to your audience – your classmates and a panel of local PV experts!

**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 third week of the class. There will be 5-6 homework assignments throughout the semester – be aware that they are long.

- The two in-class quizzes will be on Friday Oct 7th and Friday December 2nd.
### 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 due to scheduling of makeup classes, availability of guest instructors, etc.

<table>
<thead>
<tr>
<th>Week</th>
<th>Topic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>Historical perspective, overview of world energy challenges and competing energy technologies. Fossil fuels - resources and availability. Options for capturing solar energy: photovoltaics, solar thermal, photosynthesis, photocatalysis.</td>
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<tr>
<td>2</td>
<td>Thermodynamics</td>
<td>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.</td>
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<tr>
<td>3 and 4</td>
<td>Semiconductors Materials for PV</td>
<td>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.</td>
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<tr>
<td>5 and 6</td>
<td>Transport in Semiconductors</td>
<td>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.</td>
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<tr>
<td>7</td>
<td>IV Characterization</td>
<td>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.</td>
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<tr>
<td>8</td>
<td>Contacts</td>
<td>Contacts: work function, ohmic and Schottky barrier, transparent conducting oxides.</td>
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<td>9</td>
<td>Commercial Technologies – Crystalline Silicon</td>
<td>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.</td>
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<tr>
<td>12–13</td>
<td>Developing Technologies</td>
<td>Earth-abundant solar cell materials: CZTS, iron pyrite, Graetzel cells, hybrid perovskites, multiband cells, hot carrier cells, multiple exciton generation, nanoscale PV.</td>
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<tr>
<td>14</td>
<td>Defects and Defect Magic</td>
<td>Why are some solar cells tolerant of defects, and not others? What will it take to discover the next best solar cell material?</td>
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<tr>
<td>15</td>
<td>Wrap-Up</td>
<td>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.</td>
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