Physics of Solar Energy

APPH E4130, Fall 2009

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Tuesdays and Thursdays

9:10 – 10:25 am, 337 Mudd

The Fall 2009 E4130 course is designed for graduate students and seniors of physics-related majors, such as applied physics, electrical engineering, physics and chemistry. Contents include the nature of solar radiation, wave-particle duality, positional astronomy, interaction of sunlight with matter, advanced quantum mechanics including time-dependent perturbation theory and derivation of the Golden Rule, semiconductor theory with an analysis of the *pn*-junctions, theory of solar cells including the Shockley-Queisser limit and various types of solar cells, solar photochemistry including the physics of photosynthesis and dye-sensitized solar cells. Energy storage and concentration solar energy are briefly covered. Prerequisites include partial differential equations, elementary quantum mechanics, thermodynamics, and electromagnetism.

Basic research in solar energy utilization is a necessary component of the new energy economy. A comprehensive summary of the current research directions in solar energy utilization can be found in a recent report, *Basic Research Needs for Solar Energy Utilization*, Office of Science, US DOE, 2005 (available online at http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf). A distilled version, entitled *Solar Energy Conversion*, is published on *Physics Today*, March 2007. The current course is intended to provide a solid scientific basis for that field of research.

The course is organized in 12 chapters, 24 lectures. The number following the chapter title indicates the number of lectures for that chapter.

Chapter 1: Introduction (2)

Lecture 1. September 8. Outline of the course. Units of energy and power. Basic scientific facts of solar energy. History of solar energy utilization: from ancient to current.

Lecture 2. September 10. Comparison of various renewable energy resources: hydropower, wind, geothermal, tidal, and biomass. Various approaches of utilizing solar energy.

Chapter 2: Nature of solar radiation (3)

Lecture 3. September 15. Maxwell's equations. Vector potential. Light as electromagnetic wave. Polarization. Absorption. Fresnel's equations. Hamiltonian format of interactions of electromagnetic fields with atomic systems. Standing electromagnetic waves in a cavity.

Lecture 4. September 17. Blackbody radiation. Equilibrium of radiation in a cavity. Relation between radiation field energy density and radiation spectrum. Planck's formula in energy unit. Maximum spectral density. Planck's formula in wavelength unit. Wien displacement law. Stefan-Boltzmann law.

Lecture 5. September 22. Photoelectric effect. Einstein's theory of photons. Einstein's derivation of the black-body formula. Wave-particle duality.

Chapter 3: Origin of solar energy (1)

Lecture 6. September 24. Basic parameters of the Sun. Measurement of the solar constant. The structure of the Sun. The origin of solar energy: Lord Kelvin's theory and Hans Bethe's theory.

Chapter 4: Tracking sunlight (3)

Lecture 7. September 29. Rotation and orbital motion of the Earth around the Sun. A spherical trigonometry primer.

Lecture 8. October 1. Terrestrial sphere, longitude and latitude. Celestial sphere and coordinate systems: the horizon system, the equatorial system, and the ecliptic system. Coordinate transform.

Lecture 9. October 6. The definition of time: solar time, sidereal time, universal standard time, local standard time. Equation of time, the analemma. Intensity of sunlight on an arbitrary surface at any time.

Chapter 5: Interaction of sunlight with matters (2)

Lecture 10. October 8. Interaction with the atmosphere. Kirchhoff's law. Lambert's law. Bouguer-Lambert-Beer law. Absorption of the molecules. Air mass. Standard testing spectrum. Rayleigh scattering. Direct and scattered sunlight. Definitions of insolation.

Lecture 11. October 13. Interaction of sunlight with Earth. A thermodynamics primer. Heat pump and refrigeration.

Chapter 6: Thermodynamics of solar energy (1)

Lecture 12. October 15. Theoretical efficiency limit of any devices to convert solar energy into work, or electrical energy and chemical energy.

Midterm Exam, October 22

Chapter 7: Quantum excitation (3)

Lecture 13. October 27. The Dirac notation, bra and ket. Equation of motion. Stationary states. The hydrogen atom. Ritz combination rule. Hydrogen molecular ion. The covalent bond.

Lecture 14. October 29. Many-electron systems. Density functional approximation. Molecules: HOMO and LUMO. Semiconductors: valance band and conduction band.

Lecture 15. November 5. Time-dependent perturbation by a periodic disturbance. The Golden Rule. Excitation cross section. Radiationless transition. Radiative transition. Detailed balance.

Chapter 8: *pn*-junction (2)

Lecture 16. November 10. Formation of a *pn*-junction. Space charge and internal field. Quasi-Fermi levels.

Lecture 17. November 12. Effect of bias voltage. Lifetime of excess minority carriers. Diffusion length. The Shockley diode equation.

Chapter 9: Semiconductor solar cells (3)

Lecture 18. November 17. Structure of a solar cell. Separation of charge. The solar cell equation. Fill factor and maximum power.

Lecture 19. November 19. Effect of band gap. Detailed balance of radiative recombination. The Shockley-Queisser limit. Various electron-hole-pair recombination mechanisms.

Lecture 20. November 24. Crystalline silicon solar cells. Thin film solar cells: CIGS, CdTe and a-silicon. Tandem solar cells.

Chapter 10: Solar photochemistry (2)

Lecture 21. December 1. Physics of photosynthesis. Research in artificial photosynthesis.

Lecture 22. December 3. Dye-sensitized solar cells. Organic solar cells.

Chapter 11: Concentration solar energy (1)

Lecture 23. December 8. Three types of imaging optics: trough or linear collectors, central receiver with heliostats, and parabolic dish concentrator with on-axis tracking. Solar thermal electricity using Stirling engine or Ranking engine. Solar photovoltaics with concentration. Non-imaging optics.

Chapter 12: Energy storage (1)

Lecture 24. December 10. Necessity of storage for solar energy. Chemical energy storage. Thermal energy storage. Flywheels. Compressed air. Rechargeable batteries.

Final Exam, December 17

References:

Physics of Solar Energy, book manuscript.

In addition, several books are listed here. (1) through (3) are reserved in Engineering Library:

(1) J. Nelson, *The Physics of Solar Cells*. Imperial College Press, 2003. (TK2960 .N45 2003g)

(2) P. Würfer, *Physics of Solar Cells*, *From Principles to New Concepts*. Wiley-VCH, 2005. (Ordered)

(3) A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, Third Edition, John Wiley and Sons, 2006. (TJ810 .D82 2006)

(4) M. Stix, *The Sun, An Introduction*, Second Edition, Springer 2002 .

(5) J. Meeus, *Astronomical Algorithms*, Second English Edition, Willmann-Bell 1998.

(6) W. M. Smart, *Text-Book on Spherical Astronomy*, Fifth Edition, Cambridge University Press 1962.

(7) J. P. Peixoto and A. H. Oort, *Physics of Climate*, American Institute of Physics, 1992.

(8) L. D. Landau and E. M. Lifshitz, *Quantum Mechanics (Non-Relativistic Theory)*, Third Edition, Butterworth Heinemann, 1977.

(9) S. M. Sze, *Principles of Semiconductor Devices*, John Wiley & Sons, 1969.

(10) B.G. Streetman and S. Banerjee, *Solid State Electronic Devices*, Sixth Edition, Prentice Hall, 2006.

(11) J. I. Pankove, *Optical Processes in Semiconductors*, Prentice-Hill, 1971.

(12) R. E. Blankenship, *Molecular Mechanisms of Photosynthesis*, Blackwell Science, 2002.

(13) D. Voet and J. G. Voet, *Biochemistry*, Third Edition, John Wiley & Sons, 2004.

Grading policy:

Homework, 12 sets, 2.5% for each set. Total: 30%.

Midterm exam, 20%.

Final exam: 40%.

Term paper: 10%.

Both exams are close-book. A calculator is allowed and required.