

“Light Emitting Diodes and Solid-State Lighting”

Instructor information:

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Course materials:

Course materials will be made available as hard copy. **In addition, students can buy a copy of the book Light Emitting Diodes from Kathy Hocker (Email hockek@rpi.edu Telephone 518-276-8072) for \$ 36.**

Lecture time and location: As scheduled

Office hours: To be announced

Description:

Light emitting diodes (LEDs) are devices that are used in a myriad of

applications, such as indicator lights in instruments, signage, illumination, and communication. This course covers all aspects of the technology and physics of infrared, visible-spectrum, and white-light-emitting diodes (LEDs) made from III-V semiconductors. It reviews elementary properties of LEDs such as the electrical and optical characteristics, as well as advanced device physics including high-efficiency device designs, light extraction, radiative and non-radiative recombination dynamics, spontaneous recombination in resonant-cavity structures, and packaging. It introduces related areas such as human vision, photometry, colorimetry, and color rendering. Application of infrared and visible-spectrum LEDs in silica fiber, plastic fiber, and free-space communication is discussed. Extensive semiconductor material data, device design data, and analytic formulas governing LED operation are provided. Exercises and illustrative examples are included and an introductory chapter reviews the historical developments and milestones of LED research and development. This course will be of interest to scientists and engineers working on LEDs, and to graduate students in electrical engineering, applied physics and materials science.

Level:

The course is intended for graduate students

Pre-requisite:

“Semiconductor Devices and Models 1” or equivalent

“Microelectronics Technology” or equivalent

Basic knowledge of electrical engineering, physics, and chemistry

Course content:**1 History of light-emitting diodes**

1.1 History of SiC LEDs

1.2 History of GaAs and AlGaAs infrared and red LEDs

1.3 History of GaAsP LEDs

1.4 History of GaP and GaAsP LEDs doped with optically active impurities

1.5 History of GaN metal-semiconductor emitters

1.6 History of blue, green, and white LEDs based on GaInN p-n junctions

1.7 History of AlGaInP visible-spectrum LEDs

1.8 LEDs entering new fields of applications
References

2 Radiative and non-radiative recombination

2.1 Radiative electron–hole recombination

2.2 Radiative recombination for low-level excitation

2.3 Radiative recombination for high-level excitation

2.4 Bimolecular rate equations for quantum well structures

2.5 Luminescence decay

2.6 Non-radiative recombination in the bulk

2.7 Non-radiative recombination at surfaces

2.8 Competition between radiative and non-radiative recombination
References

3 Theory of radiative recombination

3.1 Quantum mechanical model of recombination

3.2 The van Roosbroeck–Shockley model

3.3 Temperature and doping dependence of recombination

3.4 The Einstein model

References

- 4 LED basics: Electrical properties**
- 4.1 Diode current–voltage characteristic
- 4.2 Deviations from ideal I – V characteristic
- 4.3 Evaluation of diode parasitic resistances
- 4.4 Emission energy
- 4.5 Carrier distribution in p-n homojunctions
- 4.6 Carrier distribution in p-n heterojunctions
- 4.7 The effect of heterojunctions on device resistance
- 4.8 Carrier loss in double heterostructures
- 4.9 Carrier overflow in double heterostructures
- 4.10 Electron blocking layers
- 4.11 Diode voltage
- References

- 5 LED basics: Optical properties**
- 5.1 Internal, extraction, external, and power efficiency
- 5.2 Emission Spectrum
- 5.3 The light escape cone
- 5.4 Radiation pattern

- 5.5 The lambertian emission pattern
- 5.6 Epoxy encapsulants
- 5.6 Temperature dependence of the emission intensity
- References

6 Junction and carrier temperature

- 6.1 Carrier temperature and high-energy slope of spectrum
- 6.2 Junction temperature and peak emission wavelength
- 6.3 Temperature dependence of diode forward voltage
- 6.4 Junction temperature and diode forward voltage
- 6.5 Constant-current and constant voltage DC drive circuits
- References

7 High internal efficiency LED designs

- 7.1 Double heterostructures
- 7.2 Doping of active region
- 7.3 P-N junction displacement
- 7.4 Doping of the confinement regions
- 7.5 Non-radiative recombination
- 7.6 Lattice matching

References

8 Design of current flow

8.1 Current-spreading layer

8.2 Theory of current spreading

8.3 Current crowding in LEDs on insulating substrates

8.4 Lateral injection schemes

8.5 Current-blocking layers

References

9 High extraction efficiency structures

9.1 Absorption of below-bandgap light in semiconductors

9.2 Double heterostructures

9.3 Shaping of LED dies

9.4 Textured semiconductor surfaces

9.5 Cross-shaped contacts and other contact geometries

9.6 Transparent substrate technology

9.7 Anti-reflection optical coatings

9.8 Flip-chip packaging

References

10 Reflectors

- 10.1 Metallic reflectors
- 10.2 Total internal reflectors
- 10.3 Distributed Bragg Reflectors
- 10.6 Omnidirectional reflectors
- 10.6 Specular and diffuse reflectors
- References

11 Packaging

- 11.1 Low-power and high-power packages
- 11.2 Protection against electrostatic discharge
- 11.3 Thermal resistivity of packages
- 11.3 Chemistry of encapsulants
- 11.4 Advanced encapsulant structures
- References

12 Visible-spectrum LEDs

- 12.1 The GaAsP, GaP, GaAsP:N, and GaP:N material systems
- 12.2 The AlGaAs/GaAs material system

- 12.3 The AlGaInP/GaAs material system
- 12.4 The GaInN materials system
- 12.5 General characteristics of high-brightness LEDs
- 12.6 Optical characteristics of high-brightness LEDs
- 12.7 Electrical characteristics of high-brightness LEDs
- References

13 Ultraviolet LEDs

- 13.1 General material issues of AlGaInN-based UV emitters
- 13.2 UV devices emitting at wavelengths longer than 360 nm
- 13.3 UV devices emitting at wavelengths shorter than 360 nm
- References

14 Spontaneous emission from resonant cavities

- 14.1 Modification of spontaneous emission
- 14.2 Fabry–Perot resonators
- 14.3 Optical mode density in a one-dimensional resonator
- 14.4 Spectral emission enhancement
- 14.5 Integrated emission enhancement
- 14.6 Experimental emission enhancement and angular dependence

References

15 Resonant cavity light-emitting diodes

- 15.1 Introduction and history
 - 15.2 RCLED design rules
 - 15.3 GaInAs/GaAs RCLEDs emitting at 930 nm
 - 15.4 AlGaInP/GaAs RCLEDs emitting at 650 nm
 - 15.5 Large-area photon recycling LEDs
 - 15.6 Thresholdless lasers
 - 15.7 Other RCLED devices
 - 15.8 Other novel confined photonic emitters
- References

16 Human eye sensitivity and photometric qualities

- 16.1 Light receptors of the human eye
- 16.2 Basic radiometric and photometric units
- 16.3 Eye sensitivity function
- 16.4 Colors of near-monochromatic emitters
- 16.5 Luminous efficacy and luminous efficiency
- 16.6 Brightness and linearity of human vision

16.7 Circadian rhythm and circadian sensitivity
References

17 Colorimetry

17.1 Color matching functions and chromaticity diagram

17.2 Color purity

17.3 LEDs in the chromaticity diagram

17.4 Relationship between color and chromaticity

References

18 Planckian sources and color temperature

18.1 The solar spectrum

18.2 The planckian spectrum

18.3 Color temperature and correlated color temperature

References

19 Color mixing and rendering

19.1 Additive color mixing

19.2 Color-rendering

19.3 Color-rendering index for planckian-locus illumination sources

19.4 Color-rendering index for non-planckian-locus illumination sources
References

20 White-light sources based on LEDs

20.1 Generation of white light with LEDs

20.2 Generation of white light by dichromatic sources

20.3 Generation of white light by trichromatic sources

20.4 Temperature-dependence of trichromatic LED-based white light source

20.5 Generation of white light by tetra-chromatic sources
References

21 White-light sources based on wavelength converters

21.1 Efficiency of wavelength converter materials

21.2 Wavelength converter materials

21.3 Phosphors

21.4 White LEDs based on phosphor converters

21.5 UV-pumped phosphor-based white LEDs

21.6 White LEDs based on semiconductor converters (PRS-LED)

- 21.7 Calculation of the power ratio of PRS-LED
 - 21.8 Calculation of the luminous efficiency of PRS-LED
 - 21.9 Spectrum of PRS-LED
 - 21.10 White LEDs based on dye converters
- References

22 Optical communication

- 22.1 Types of optical fibers
 - 22.2 Attenuation in silica and plastic optical fibers
 - 22.3 Modal dispersion in fibers
 - 22.4 Material dispersion in fibers
 - 22.5 The numerical aperture of fibers
 - 22.6 Coupling with lenses
 - 22.7 Free-space optical communication
- References

23 Communication LEDs

- 23.1 LEDs for free-space communication
- 23.2 LEDs for fiber-optic communication
- 23.3 Surface-emitting Burrus-type communication LEDs emitting at

870 nm

23.4 Surface-emitting communication LEDs emitting at 1300 nm

23.5 Communication LEDs emitting at 650 nm

23.6 Edge-emitting superluminescent diodes (SLDs)

References

24 LED modulation characteristics

24.1 Rise and fall times, 3 dB frequency, and bandwidth in linear circuit theory

24.2 Rise and fall time in the limit of large diode capacitance

24.3 Rise and fall time in the limit of small diode capacitance

24.4 Voltage dependence of the rise and fall times

24.5 Carrier sweep-out of the active region

24.6 Current shaping

24.7 3 dB frequency

24.8 Eye diagram

24.9 Carrier lifetime and 3 dB frequency

References

Grading:

The final grade is composed of the following contributions: Midterm exam 40 %; Final exam 40 %; Homework 10 %; Project 10 %. The completion of your homework will be verified before the midterm exam and before the final exam.

Mandatory statement on academic dishonesty:

- Cheating on exams (such as copying from your neighbor) constitutes academic dishonesty.
- Turning in homework/reports/term papers as one's own, when they are not, constitutes academic dishonesty.
- A compilation of someone else's production/idea/work in a written or oral report must be attributed to the original source.
- The source of text passages stated in either paraphrased or *ad verbatim* form must be cited.
- Plagiarism is the use of someone else's production/idea/work without crediting the source. Plagiarism constitutes academic dishonesty.
- *Note:* Teamwork during class exercises and homework is allowed. The

use of calculators is also allowed.

- *Note:* If something is well known (common knowledge), the original reference does not need to be cited. Example: We can use Newton's second law ($F = ma$) without citing Sir Isaac Newton. We can discuss transistors without crediting William Shockley with the invention of the transistor.

The instructor's penalty for any academic dishonesty in this course is receiving no credit for any disputed work. In addition, a student who commits an act of academic dishonesty may be subject to disciplinary action by Rensselaer Polytechnic Institute.