"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
Textured semiconductor surfaces
9.7 Cross-shaped contacts and other contact geometries
9.8 Transparent substrate technology
9.9 Anti-reflection optical coatings
9.10 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.