OPTICAL PROPERTIES OF SEMICONDUCTORS
ECE 723 (NCSU)

Prerequisites: ECE 530 or some Quantum Mechanics and Solid State Physics at an undergraduate level

Dr. Robert M. Kolbas
434 EGRC
kolbas@ncsu.edu
919 515-5257 (office)
919 513-2709 (lab)
919 821-4676 (home)

Purpose: Develop an understanding of the interaction of light with semiconductor materials and devices. See course outline for details.

Text: No required text. Class notes are provided on web site.
Low cost paperback: Optical Properties of Semiconductors by Jacques I. Pankove
ISBN 0-486-60275-3 (Dover)

Class notes and power point slides will be provided on line. For on campus students check the Wolfware site for ECE 723. For off campus students the Engineering on Line office will provide the appropriate information to access the web site(s).

Texts previously used for course:
• Semiconductor Optoelectronic Devices by Pallab Bhattacharya
• Optical Properties of Semiconductors by J. Pankove. (Dover)
• Semiconductor Optoelectronics: Physics and Technology by Jasprit Singh

Other text: see attached list.

GRADING SYSTEM

Homework (best 10 out of 11, see below) 15%
In class exam I February 18, 2015 25%
In class exam II April 1, 2015 25%
Final Exam 35%
100%
Homework:
- If we are not assigned a TA then the homework rules (and possibly the weighting of the grading system) will be revised.
- Homework problems will be posted on the web site and are due approximately one week later in class unless other explicit instructions are given. See schedule at the end of this document.
- A solution set will be provided on the day the homework is due.
- The best 10 out of 11 (maybe 12) home work scores will used to calculate the home work grade.
- No late homework assignments will be accepted.
- The calendar at the end of the handout shows the date that the homework is due.

ADMINISTRATIVE
- I will use the +/- grading system.
- Please bring any administrative problems to my attention quickly (e.g. missing homework, etc.). Do not wait until the end of the semester.
- If you miss course work, homework or an exam without prior permission of the instructor then the official university policy as posted on the NCSU web site applies. If you know that you will be absent please contact the instructor prior to the absence so that arrangements can be made to make up the work.
- Students with disabilities should contact Disability Services for Students in order to afford themselves access to the appropriate resources. See http://www.ncsu.edu/provost/offices/affirm_action/
- The NC State policy of academic conduct applies to this course. See http://www.ncsu.edu/student_affairs/osc/
- To receive audit recognition you must present a mutually agreeable study plan to me and then fulfill the study plan requirements. Only attending class does not constitute an audit. You are welcome to sit in class and participate as long as your presence does not infringe on the students registered in the class.
- **Bring a calculator to the exams. Please do not bring computers or calculators that store text or equations or that can communicate with other devices. A simple scientific calculator will suffice. Exams will be closed book, closed notes, etc. unless notified otherwise.**
- You are welcome to work in groups on the homework assignments. However, you must hand in your own solutions. A zero score will be assigned to any homework or exam that reveals that blatant cheating is occurring.
- When the course is taught in a studio there are restrictions on eating and other activities that interfere with professional recording and preservation of the facility. The technical staff will provide details of these regulations. If class is not held in a studio, you are free to eat, sleep, dream, etc. in class as long as you do not disturb your neighbors or me, or violate university regulations. If someone is doing something that disturbs you during class bring it to my attention after class.
- Please, no audio or video recording of the class or help sessions.
COMMENTS ON TEACHING AND LEARNING

The purpose of a 700-level course is not to 'spoon feed' you exactly the material that you are to learn (as is done in undergraduate and some graduate courses) but rather to guide and direct you to what is most important to learn, and teach you how to think critically about the subject. Some students (and I) find it frustrating that all the information that is needed is not in one or two text books, but by definition this is the nature of a 700-level course. A list of other reference books is included to help you combat this problem. Two barriers you may encounter in taking ECE 723 are: 1) you need to remember the basics from several other courses (in addition to the prerequisite ECE 530) in order to absorb/appreciate the material in ECE 723, and; 2) you need to learn how to extend what you know in order to solve problems that you have never encountered (i.e. you need to learn how to think, not just repeat what you have absorbed). If you are a Ph.D. student and experience this frustration don't fight it, learn to deal with it constructively because it will be with you the remainder of your technical career. Here are some quotations that express the same message.

Education is the ability to listen to almost anything without losing your temper or your self-confidence.

Computers are useless. They only give you answers.

Only the curious will learn and only the resolute overcome the obstacles to learning. The quest quotient has always excited me more than the intelligence quotient.

Education is what survives when what has been learned has been forgotten.

Your education is a series of successively smaller lies.
Pankove’s book is dated but has the best information about absorption and emission processes in semiconductors. It has been reprinted by Dover and is relatively inexpensive. Class notes will be provided on the web. In past semesters we have used “Optical Properties of Semiconductors” by Pankove, “Semiconductor Optoelectronic Devices” by P. Bhattacharya or “Optoelectronics An Introduction to Materials and Devices” by Jasprit Singh. The following two tables outline of the subject material that we will cover and the corresponding sections of these optional textbooks. The absence of section numbers does not mean that the material is not in the text but rather that it may be distributed throughout the book. For some subjects we will cover more material than is in these textbooks. For other subjects we will cover less material than is presented these books.

<table>
<thead>
<tr>
<th>Subject Material</th>
<th>Bhattacharya Section Numbers</th>
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<tbody>
<tr>
<td><strong>1. Semiconductor Materials</strong></td>
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<tr>
<td>1. Overview and introduction</td>
<td>1.1</td>
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<tr>
<td>2. Evolution of semiconductor materials</td>
<td>1.4, 1.7</td>
</tr>
<tr>
<td>3. Physical properties and important parameters</td>
<td>1.6, 2.2</td>
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<tr>
<td>4. Atomic bonding and crystal structure</td>
<td>1.2, 1.3</td>
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<tr>
<td>5. Band structure (energy-momentum, density of states)</td>
<td>2.1, 2.2, 2.3, 2.5</td>
</tr>
<tr>
<td>6. Heterostructures and superlattices</td>
<td>1.5, 4.4</td>
</tr>
<tr>
<td><strong>2. Optical Constants in Solids</strong></td>
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<tr>
<td>1. Reflectivity</td>
<td>7.1</td>
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<tr>
<td>2. Index of refraction, absorption coefficient, etc.</td>
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<tr>
<td>3. Kramers-Kronig Relations</td>
<td>3.5</td>
</tr>
<tr>
<td>4. Waveguides and Fabry-Perot cavities</td>
<td>6.2, 6.10</td>
</tr>
<tr>
<td><strong>3. Absorption of Light in Semiconductors</strong></td>
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<tr>
<td>1. Photon-electron interaction</td>
<td>3.1</td>
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<tr>
<td>2. Direct transitions, indirect transitions</td>
<td>3.2</td>
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<tr>
<td>3. Excitons, free and bound</td>
<td>1.7.5, 3.2.3</td>
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<tr>
<td>4. Doping effects</td>
<td>3.2.4</td>
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<tr>
<td>5. Other absorption processes</td>
<td>3.2.5</td>
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<tr>
<td>6. Field effects</td>
<td>3.3, 3.4</td>
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<tr>
<td>7. Quantum well and superlattice absorption characteristics</td>
<td>3.4</td>
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<tr>
<td>8. Material characterization techniques</td>
<td>3.10</td>
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</tbody>
</table>
### 4. Recombination in Semiconductors

1. Radiative and nonradiative recombination  
2. Band to band recombination  
3. Excitons, free and bound  
4. Doping effects  
5. Other recombination processes  
6. Defects and traps  
7. Quantum wells and superlattice radiative recombination  
8. Material characterization techniques

### 5. Photodetectors

1. Review of junctions (pn, Schottky)  
2. Photoconductive detectors  
3. Photovoltaic detectors  
4. Other detectors  
5. Performance characteristics  
6. Design criteria

### 6. Semiconductor Light Emitting Diodes and Lasers

1. Light emission from pn junction devices  
2. LED design and performance  
3. Einstein A and B coefficients  
4. Stimulated emission and gain  
5. Optical and electrical pumping  
6. Semiconductor laser operation  
7. Laser design  
8. Semiconductor laser menagerie  
9. Quantum well lasers  
10. Surface emitting lasers
The following table is provided to guide you to the chapters corresponding to the lectures. It is not intended to be inclusive or exclusive of the material that you will need to learn.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Bhattacharya Chapter</th>
<th>Pankove Chapter</th>
<th>Singh Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Semiconductor Materials</td>
<td>1, 2</td>
<td>1</td>
<td>1, 2</td>
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<tr>
<td>2. Optical Constants in Solids</td>
<td>3</td>
<td>4</td>
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<tr>
<td>3. Absorption of Light in Semiconductors</td>
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<td>3, 5</td>
<td>4, 5</td>
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<tr>
<td>4. Recombination in Semiconductors</td>
<td>3, 6</td>
<td>6, 7</td>
<td>4, 5</td>
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<tr>
<td>5. Photodetectors</td>
<td>8</td>
<td></td>
<td>6, 7, 8</td>
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<tr>
<td>6. Semiconductor Light Emitting Diodes and Lasers</td>
<td>4, 5, 6, 7</td>
<td>8, 9, 10</td>
<td>9, 10, 11</td>
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</table>

You may also need to look at some of the books listed on the following pages to find complete coverage of the material presented in the lectures.

**REFERENCE BOOKS**

**Optoelectronics**

*Semiconductor Lasers and Heterojunction LED's*  
Kressel and Butler  
ISBN 0-12-426250-3  
Academic Press

*Heterostructure Lasers, Parts I and II*  
Casey and Panish  
ISBN 0-12-163101-X  
Academic Press

*Optical Processes in Semiconductors*  
Pankove  
J. Dover

*Semiconductor Optoelectronics*  
Moss, Burrell and Ellis  
Wiley and Sons

*Physics of Semiconductor Laser Devices*  
G. H. B. Thompson  
Pitman Press
<table>
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<tr>
<th>Title</th>
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<th>Publisher</th>
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<tr>
<td><em>Introduction to Optical Electronics</em></td>
<td>0-03-084694-3</td>
<td>Holt, Rinehart, Winston</td>
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<tr>
<td>A. Yariv</td>
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<tr>
<td><em>Introduction to Optical Electronics</em></td>
<td>0-06-043444-9</td>
<td>Harper and Row</td>
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<td>K. A. Jones</td>
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<td><em>Theory of Dielectric Optical Waveguides</em></td>
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<td>McGraw Hill</td>
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<tr>
<td>D. Marcuse</td>
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<tr>
<td><em>Optoelectronics: An Introduction</em></td>
<td>0-13-638461-7</td>
<td>Prentice Hall</td>
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<tr>
<td>J. Wilson and J. F. B. Hawkes</td>
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<td><em>Semiconductor Injection Lasers</em></td>
<td>0-87942-130-4</td>
<td>IEEE Press</td>
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<td>J. K. Butler, editor</td>
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<td><em>Optical Electronics</em></td>
<td>0-521-31408-9</td>
<td>Cambridge</td>
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<td>A. K. Ghatak and K. Thyagarajan</td>
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<td><em>Guided Wave Photonics</em></td>
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<td><em>Photoelectronic Properties of Semiconductors</em></td>
<td>0-521-40491-6</td>
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<td><em>Optical Electronics in Modern Communications</em></td>
<td>0-19-510626-1</td>
<td>Oxford University Press</td>
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<td><em>Frequency Control of Semiconductor Lasers</em></td>
<td>0-471-01341-2</td>
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<td>Motoichi Ohtsu, Editor</td>
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<td><em>Diode Lasers and Photonic Integrated Circuits</em></td>
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<td>Larry A. Coldren and Scott W. Corzine</td>
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<tr>
<td><em>Semiconductor Lasers, Past, Present, and Future</em></td>
<td>1-56396-211-X</td>
<td>American Institute of Physics</td>
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<td><em>Waves and Fields in Optoelectronics</em></td>
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<td>Hermann A. Haus</td>
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<td><em>Optoelectronics, An Introduction to Materials and Devices</em></td>
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Semiconductor Optoelectronics, Physics and Technology  
Jasprit Singh  
McGraw-Hill  
ISBN 0-07-057637-8

Elements of Optoelectronics and Fiber Optics  
Chin-Lin Chen  
Irwin  
ISBN 0-256-14182-7

Monolithic Diode-Laser Arrays  
Nils W. Carlson  
Springer-Verlag  
ISBN 3-540-57910-9

Principles of Quantum Electronics  
Dietrich Marcuse  
Academic Press  
ISBN 0-12-471050-6

Quantum Electronics  
Amnon Yariv  
Wiley and Sons  
ISBN 0-471-60997-8

Semiconductor Physics and Devices

Physics of Semiconductor Devices  
M. Shur  
Prentice Hall  

Semiconductors  
R. A. Smith  
Cambridge

Physics of Semiconductor Devices  
Sze  
Wiley

Semiconductor Devices and Integrated Electronics  
Milnes  
Van Nostrand Reinhold

Solid State Physical Electronics  
Van der Ziel  
Prentice Hall

Solid State Electronic Devices  
B. Streetman  
Prentice Hall

Semiconductor Physics  
Seeger  
Springer-Verlag

Physics and Technology of Semiconductor Devices  
A. S. Grove  
Wiley
Electrons and Holes in Semiconductors
Shockley

Physics of Semiconductors
J. Moll

Semiconductors and Semimetals (series)
Willardson and Beer, editors

Modular Series on Solid State Devices
Addison and Wesley

Physical Properties of Semiconductors
C. M. Wolfe, N. Holonyak, Jr., G. E. Stillman

Fundamentals of Semiconductor Devices
Yang

Physical Foundations of Solid State and Electron Devices
A. M. Ferendeci

Solid State Physics

Wavemechanics of Crystalline Solids
R. A. Smith

Introduction to Solid State Physics and its Applications
Elliott and Gibson

Solid State Physics
Blakemore

Elementary Solid State Physics
M. A. Omar

Principles of the Theory of Solids
J. M. Ziman

Solid State Physics
Ashcroft and Mermin

Introduction to Solid State Physics
Kittel

Solid State Physics
Ashcroft and Mermin

Introduction to Solid State Physics
Kittel
Solid State Theory
Harrison McGraw Hill

J. P. McKelvey Krieger

Electronic Properties of Crystalline Solids: An Introduction to Fundamentals

Electronic Structure and Transport Properties of Crystals

G. Burns Academic Press

SPECIAL NOTE for Fall 2014:
This on campus course will be captured and distributed via the Internet and/or electronic media as part of the Engineering Online (EOL) program for the distance students. These video recordings may contain an image of you entering the classroom, asking questions or being a part of the studio class. Please notify Dr. Linda Krute, Director of EOL, in writing at ldkrute@ncsu.edu if you DO NOT want your image to be included in the lecture presentation. If we do not hear from you after the first week of the class, we will assume that you are in agreement with this procedure.
ECE 723 Spring 2015 Scheduled as if MW 75 minute class at 2:20-3:30PM  
Instructor: Robert Kolbas kolbas@ncsu.edu

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<tr>
<td>2015</td>
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|  4    |   5   |   6   | 7 Class 1  
First Day of Classes |   8   |   9   |  10  |
| 11    | 12 Class 2 | 13    | 14 Class 3  
HW #1 due |   15  |  16   |  17  |
| 18    | 19 Holiday | 20    | 21 Class 4  
HW #2 due |   22  |  23   |  24  |
| 25    | 26 Class 5 | 27    | 28 Class 6  
HW #3 due |   29  |  30   |  31  |
| 1 FEB | 2 Class 7 | 3     | 4 Class 8  
HW #4 due |   5   |  6    |  7   |
|  8    | 9 Class 9 | 10    | 11 Class 10  
HW #5 due |   12  |  13   |  14  |
| 15    | 16 Class 11 | 17 Class 13 | 18 Class 12  
Exam 1 |   19  |  20   |  21  |
| 22    | 23 Class 13 | 24 Class 15 | 25 Class 14  
HW #6 due |   26  |  27   |  28  |
|  1   | 2 MAR  | 2 Class 15 | 3 Class 17  
4 Class 16  
HW #7 due |   5   |  6    |  7   |
|  8   | 9 Spring Break Week | 10  | 11 Spring Break Week |   12  |  13   |  14  |
| 15    | 16 Class 17 | 17 Class 19 | 18 Class 18  
HW #8 due |   19  |  20   |  21  |
| 22    | 23 Class 19 | 24 Class 21 | 25 Class 20  
HW #9 due |   26  |  27   |  28  |
|  29  | 30 Class 21 | 31 Class 23 | 1 Class 22APRIL  
Exam 2 | 2 Holiday | 3 Holiday |  4  |
|  5   | 6 Class 23 | 7 Class 25 | 8 Class 24  
HW #10 due |   9 Class 26  
10 11  |
| 12   | 13 Class 25 | 14 Class 27 | 15 Class 26  
HW #11 due |   16  |  17   |  18  |
| 19    | 20 Class 27 | 21    | 22 Class 28  
Homework #12? |   23  |  24 Last Day of Classes  
25  |
| 26    | 27 Reading Day | 28 Reading Day | 29 Finals Begin |  30  |  1 MAY  
FINAL EXAM  
1-4 PM |  2  |
|  3   | 4       | 5     | 6     | 7 Last day of finals |   8   |  9   |

Homework and exam dates are shown. Any changes will be announced in email. Homework grade determined from best N-1 of N assignments (typically best ten of eleven). See text of syllabus for details.