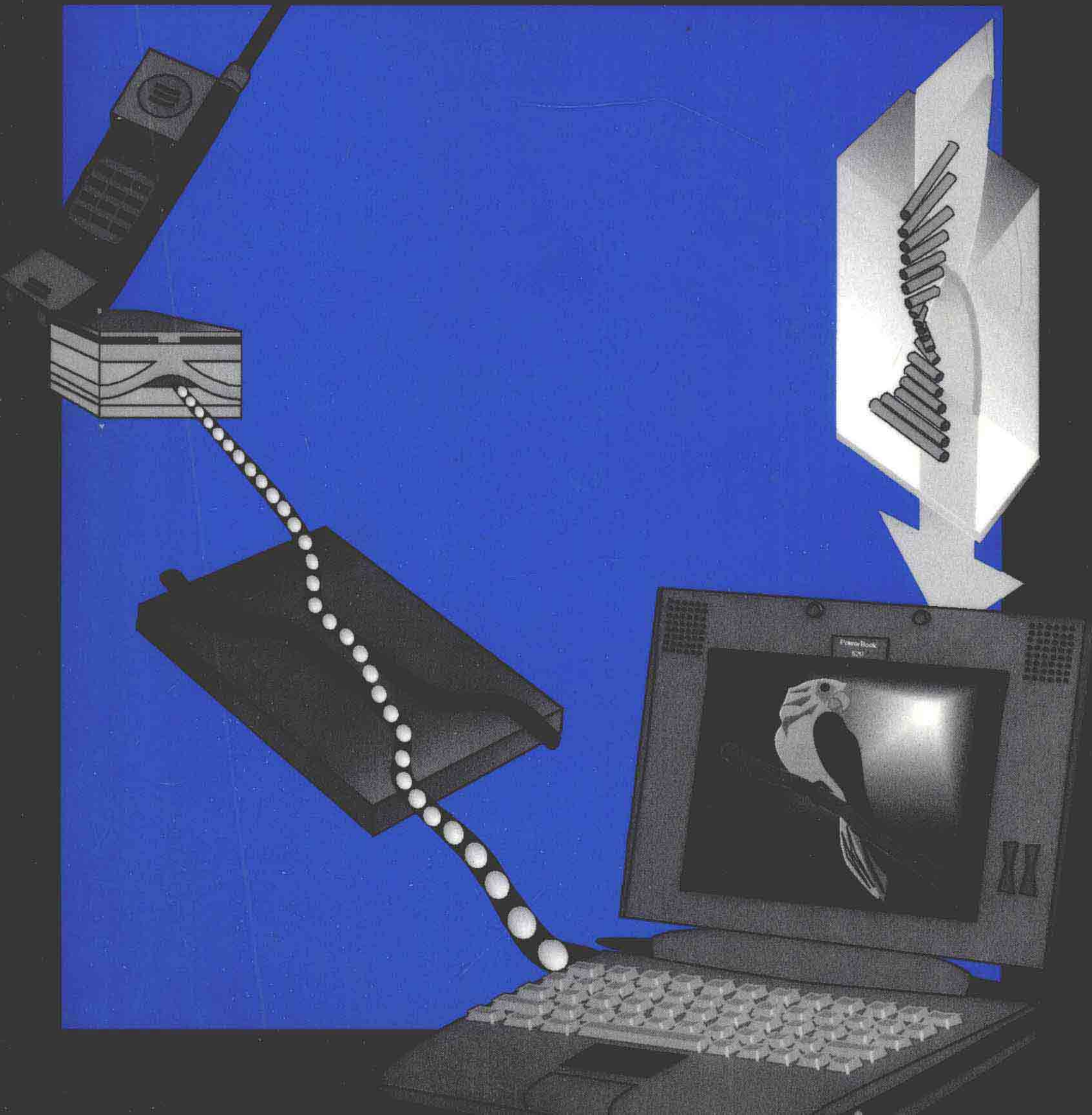
Jasprit Singh

Optoelectronics

An Introduction to Materials and Devices



OPTOELECTRONICS

An Introduction to Materials and Devices

Jasprit Singh
University of Michigan

The McGraw-Hill Companies, Inc.
New York St. Louis San Francisco Auckland Bogotá Caracas
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San Juan Singapore Sydney Tokyo Toronto

The editor was Lynn Cox;
the production supervisor was Louise Karam.
The book design and all illustrations were done by Teresa Singh;
the jacket was designed by Teresa Singh.
R. R. Donnelley & Sons Company was printer and binder.

OPTOELECTRONICS
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This book is printed on acid-free paper.

2 3 4 5 6 7 8 9 0 DOC DOC 9 0 9 8 7 6

ISBN 0-07-057650-5

Library of Congress Catalog Card Number: 95-78648

OPTOELECTRONICS

An Introduction to Materials and Devices

McGraw-Hill Series in Electrical and Computer Engineering

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About the Author

Jasprit Singh received his Ph.D. in solid state physics from the University of Chicago. He has carried out research in solid state electronics at the University of Southern California, Wright Patterson Air Force Laboratories, and the University of Michigan, Ann Arbor, where he is currently a Professor in the Department of Electrical Engineering and Computer Science. His research interests cover the area of semiconductor materials and their devices for information processing. He is also the author of *Physics of Semiconductors and Their Heterostructures*, McGraw-Hill (1993), *Semiconductor Devices: An Introduction*, McGraw-Hill (1994) and *Semiconductor Optoelectronics: Physics and Technology*, (1995).

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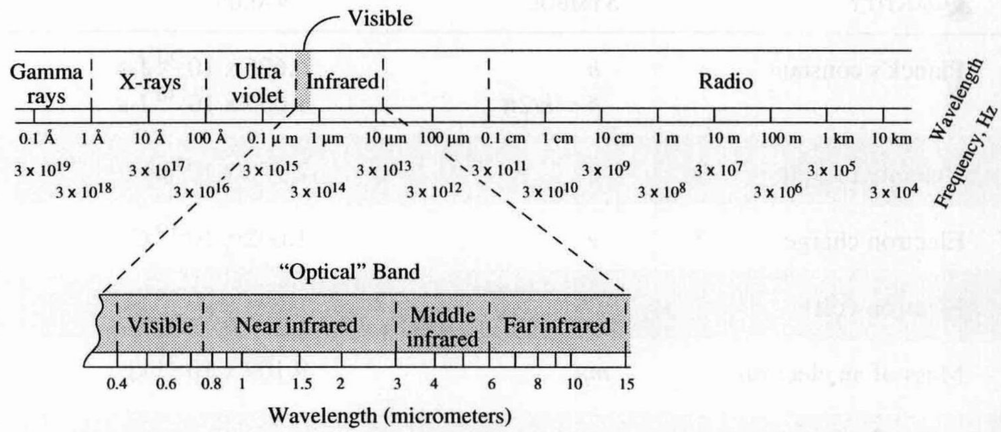
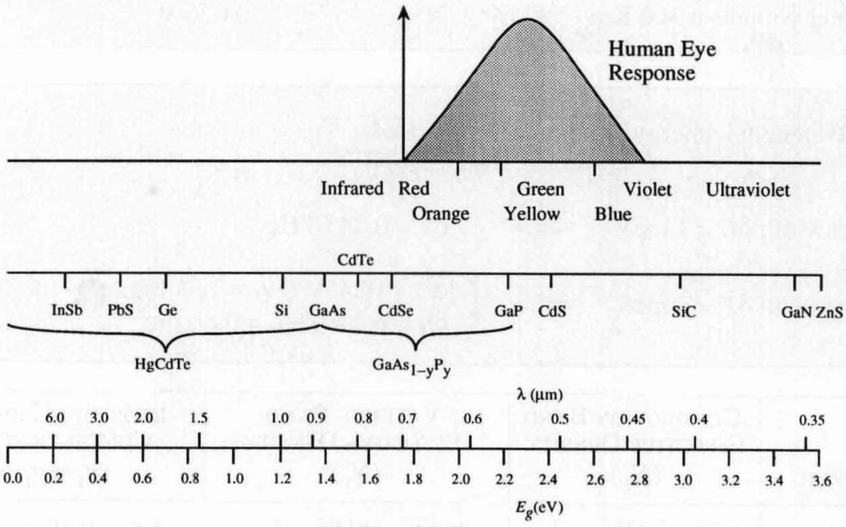
ELECTROMAGNETIC SPECTRUM



BANDGAPS AND CUTOFF WAVELENGTHS FOR SOME OPTICAL MATERIALS



FREQUENTLY USED QUANTITIES

QUANTITY	SYMBOL	VALUE
Planck's constant	h $\hbar = h/2\pi$	6.626×10^{-34} J-s 1.055×10^{-34} J-s
Velocity of light	c	2.998×10^{8} m/s
Electron charge	e	1.602×10^{-19} C
Electron volt	eV	1.602×10^{-19} J
Mass of an electron	m_0	9.109×10^{-31} kg
Permittivity of vacuum	$\varepsilon_0 = \frac{10^7}{4\pi c^2}$	8.85×10^{-14} F cm^{-1} $= 8.85 \times 10^{-12}$ F m^{-1}
Boltzmann constant	k_B	8.617×10^{-5} eVK^{-1}
Thermal voltage at 300 K	k_BT/e	0.026 V

Wavelength – energy relation: $\lambda(\mu m) = \frac{1.24}{E(eV)}$

Linewidth $\delta E = 1$ meV $\Longrightarrow$ $\delta\nu = 0.243$ THz

Linewidth $\delta E = 1$ meV $\Longrightarrow$ $\begin{cases} \delta\lambda = 19.4 \text{ Å} @ \lambda = 1.55\ \mu m \\ \delta\lambda = 6.2 \text{ Å} @ \lambda = 0.88\ \mu m \end{cases}$

MATERIAL	CONDUCTION BAND EFFECTIVE DENSITY (N_c)	VALENCE BAND EFFECTIVE DENSITY (N_v)	INTRINSIC CARRIER CONCENTRATION ($n_i = p_i$)
Si (300 K)	2.78×10^{19} cm^{-3}	9.84×10^{18} cm^{-3}	1.5×10^{10} cm^{-3}
Ge (300 K)	1.04×10^{19} cm^{-3}	6.0×10^{18} cm^{-3}	2.33×10^{13} cm^{-3}
GaAs (300 K)	4.45×10^{17} cm^{-3}	7.72×10^{18} cm^{-3}	1.84×10^{6} cm^{-3}

PREFACE

The last decade of the twentieth century is seeing unprecedented changes in human experience. These changes are occuring in the area of technology, politics, international trade, environmental conciousness and even a reevaluation of the meaning of the quality of life. As a result powerful new market forces are being unleashed spawning new industries. As the world becomes one big market place, the importance of information—fast, accurate and in a comprehensible form—has become paramount. Serving this global market are the information processing systems built upon computer networks and communication. It is indeed difficult to imagine any modern industry without access to computers and communication to be a key player in the changing market. The computer and communication systems are themselves evolving rapidly, thanks to a number of key "enabling technologies." These enabling technologies are loosely classified under the categories of semiconductor electronic devices, optoelectronics, and new developments in software. This book deals with the general area of optoelectronics.

Optoelectronics—the technology dealing with information processing with light—has been around for a long time. However, over the last fifteen years or so it has acquired a new potency, providing us products that could not have been possible without optoelectronics. Examples of these products are the compact disc players, optical communication systems, laptop portable computers, personal video cameras, laser printers, and so on. In all of these products, the optoelectronic component—whether it be a semiconductor laser, optical fiber, charge coupled device, or a liquid crystal display—has played a key role in bringing the product to the market place. It is widely expected that due to the increasing importance of information processing, optoelectronics-based products will have a global market share in 2010 which is comparable to the integrated- circuit-based market share. This would mean a twenty-fold increase in the market from the value of about ten billion dollars in 1995. It is quite clear that given the importance of optoelectronics, the electrical engineering curricula should cater to this area. Due to the historic status of semiconductor devices, in most electrical engineering schools, while transistors, diodes etc., are discussed at the undergraduate level, the discussion of optoelectronic devices is mostly avoided. This has been changing recently, although most schools still offer optoelectronic courses only to advanced graduate students.

My intention in writing this introductory textbook on optoelectronics is two-fold. Firstly, I wanted to develop a text that could be used for seniors and beginning graduate students who have had a course in semiconductor devices and one in electromagnetics or optics. Such a course, say, with a title like "An Introduction to Optoelectronics," could be offered in a setting where beginning graduate students and qualified seniors could take it together. One may argue that some texts in the market could already satisfy the needs for such a course. This brings me to the second reason for this text. I wanted to develop a text that addresses the technical areas that are responsible for present and future products. Most texts on introductory optoelectronics address the topics of semiconductor devices such as light emitting diodes, lasers, and detectors and focus on the technology that has led to the optical communication systems. Topics such as amorphous silicon thin film transistors, charge coupled devices, liquid crystal cells etc., are either skipped over completely or barely mentioned. Given that the optical communication systems, while of great importance, only account for about ten percent of the optoelectronic market, it is only fair that an introductory course on optoelectronics should discuss the other devices mentioned above in detail comparable to the traditional devices. I have tried to present such a treatment in this book.

Having discussed the motivations for this book, let me also express some concerns that may be faced by students (especially seniors who wish to learn about optoelectronics) and instructors. I have encountered these concerns in my classroom teaching and in discussions with colleagues. These concerns arise mainly from the notion that the level of quantum mechanics needed for appreciating optoelectronics is much higher than that needed for semiconductor electronic devices. This is not entirely true, since the concepts of semiconductor bandstructure, effective mass, mobility, etc., are all based on very advanced quantum mechanics. However, historically these concepts have been given to the undergraduate students without full justification—an approach that is extremely valuable. The exciting area of electronic devices is brought within the grasp of an undergraduate student by making him or her take a leap of faith by accepting the concepts of bandgaps, conduction band, valence band, mobility, etc., in semiconductors. I have used a similar approach in this text. Concepts of optical emission and absorption are introduced using intuitive arguments, rather than detailed quantum mechanical derivations. Once the student accepts these concepts, he or she can then learn about detectors, LEDs, lasers, display devices, etc. Given the fact that most electrical engineers will not take the two or three advanced quantum mechanics courses needed to fully understand electron-phonon or electron-photon interactions, this approach is entirely justified. This approach then allows the student to appreciate the excitement of optoelectronic devices.

This manuscript was typed by Ms. Izena Goulding, to whom I am extremely grateful. The figures, cover design, and the formatting of this book were done by Teresa Singh, my wife. She also provided the support without which this book would not be possible. I am also indebted to my colleagues and the administration at the University of Michigan for providing the atmosphere and the physical resources to make book writing possible in these times of fast paced research.

Finally, I want to thank Ms. Lynn Cox and Mr. George Hoffman, my editors at McGraw-Hill, for providing me with encouragement and support for this project. I am particularly grateful to the excellent team of referees who provided critical comments on this book. Their feedback was of great benefit to me. I gratefully acknowledge Professors Thomas A. DeMassa (Arizona State University), Joe C. Campbell (University of Texas), R. P. Kenan (Georgia Institute of Technology), David Brady ((University of Illinois), A. Safaai-Jazi (Virginia Polytechnic Institute and State University), James Coleman (University of Illinois), Marek Osinski (University of New Mexico), Karl Hess (University of Illinois), and Dr. Daniel Renner (Ortel Corp.).

A solution manual is available to the instructors wishing to use this textbook. Please write on your department stationary to McGraw-Hill to get a copy.

Jasprit Singh

INTRODUCTION

I.1 THE INFORMATION AGE

As we move into an intensely competitive and global economy, timely and accurate information is becoming of paramount importance. Of course, information has always been of great importance. Imagine the value of the knowledge of an oncoming hurricane or an advancing enemy. Such knowledge has been of importance for thousands of years. However, because of the enormous improvements in the computer and communication technologies, information affects every aspect of our lives. It is hard to imagine a world without computers, satellites, undersea fiber networks, televisions, fax machines, laser printers, and a myriad of other information processing tools. Whether we like it or not, most of the livelihoods of workers in industrially developed countries are intimately tied to the ability to access and process information.

The survival of today's industries depends not only on how good the products their workers make are, but how well the companies can respond to today's global market. For example, what good is a product without a customer? And very often these days the customer may be thousands of miles away. Information about market demands from thousands of miles away are as critical as the product itself. Thus, information access, information manipulation, and information communication are becoming increasingly important. As a result, the scientists and engineers who design and build information processing devices carry an enormous burden on their shoulders. Regardless of what the information is, we want to process it faster, with fewer inaccuracies, at a lower cost, with a system which consumes less space, etc. This text will address the information processing devices that fall under the category of *optoelectronics*. In principle, a vast range of devices can be classified under optoelectronics. These may include the neon light displays, the electric bulb and the television screen. However, we will focus only on those devices that have emerged over the past twenty years or so as enabling technologies in the information age. We will discuss this aspect further in a later section.

The modern age of information processing has been ushered in by the electronic devices, particularly the mass-produced high-density semiconductor devices. These devices process information at blinding speeds, crunching numbers at speeds of millions of instructions per second. Electronic devices are deeply entrenched in any information processing system, and for good reason. Can optoelectronic devices, which exploit light and electrons, make inroads into the domain of electronic devices? Over the last decade, optoelectronic devices have started to make an impact on the information processing scene. This impact has been felt most in the area of information communication, information storage (and retrieval) and information display. To understand the challenges facing optoelectronics and the potential payoffs, we examine the demands placed upon devices that are to be successful in information processing.

I.2 DEMANDS OF THE INFORMATION AGE

As noted in the previous section, we live in an age where acquiring, manipulating, and transmitting information are of utmost importance. In Fig. I.1 we show some of the important functions that need to be carried out in order to survive in the information age. Let us briefly examine these functions and see what sort of requirements they put on devices.

Information Reception/Detection
This is, of course, one of the most important functions in an information system. For example, in our own case we receive information about the world we live in by our eyes, nose, skin, ears, and tongue. Our five senses allow us to obtain important information about our surroundings, and this information is conveyed to our main processing unit—our brain. Devices which hope to serve as sensors/detectors must have a well-defined response to an external input. They must convert the input information into a form which can be used for further processing.

Information Enhancement/Amplification
Very often the information that is received is of either very poor quality, or is too "weak" to be directly useful. In such cases, the information must be amplified or enhanced. We often ask people to repeat themselves more loudly, since we cannot hear them well. Many hearing impaired people need hearing aids which can amplify the sound coming in. Thus, amplifiers are an essential part of an information processing system. To be able to amplify information, the device must have the very important characteristic of *gain*, i.e., a small change in input should result in a large change in output.

Information Manipulation
This is, of course, the most important and "intelligent" aspect of information processing. When some information comes in, much of it may be redundant or in a form

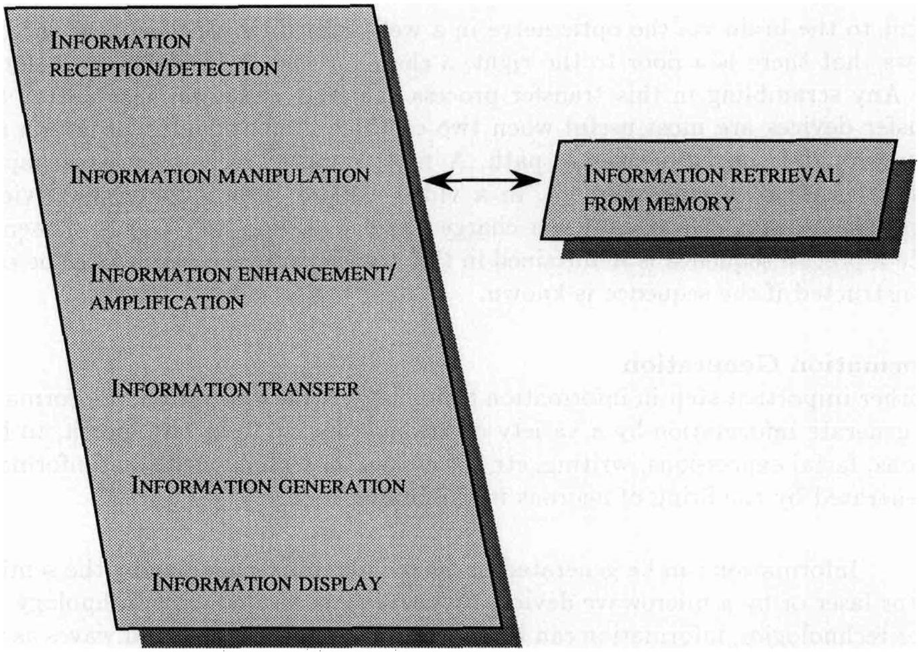


Figure I.1: Necessary functions to survive in the "information age."

that is not appropriate. Invariably, it has to be manipulated, which may mean carrying out processes like addition, subtraction, division, multiplication, comparison with previous information, extracting a "signature" of the information, etc.

Memory

Memory is obviously essential in an information processing system. The process of learning, comparing, selecting, and reusing information all require memory. The memory device should be able to store information by, perhaps, changing the state of the device, and then one should be able to retrieve the information (i.e., be able to WRITE/READ). This page that you are reading is a form of a memory—perhaps the most influential kind of memory in the history of humankind.

Memory is an area where a number of important technologies are used. Optical memories based on a plastic disc (the compact disc), magnetic tape memories, magnetic bubble memories, semiconductor memories, etc., all form important spokes of the memory technology.

Information Transfer

An important function in an information processing system is to be able to transfer the information or the results obtained after manipulating the information into a storage or memory. For example, when an image is seen by our eye, the information is sent to the brain via the optic nerve in a well-defined sequence so that the brain knows that there is a door to the right, a chair in front, a blackboard to the left, etc. Any scrambling in this transfer process can lead to serious disabilities. Such transfer devices are most useful when two or three dimensional information must pass through a one dimensional path. A most popular case where this happens is in the case of a video camera. In a video camera, a two dimensional view is recorded and sent sequentially via charge coupled devices (CCDs) to a memory. Since a precise sequence is maintained in this transfer, the scene can later be easily reconstructed if the sequence is known.

Information Generation

Another important step in information technology is the generation of information. We generate information by a variety of means, ranging from our speech, to hand actions, facial expressions, writing, etc. Of course, in each case the real information is generated by the firing of neurons in the brain.

Information can be generated in semiconductor technology by the semiconductor laser or by a microwave device. By coupling semiconductor technology with other technologies, information can be generated in the form of sound waves as well.

Information Display

The saying, "A picture is worth a thousand words," seems to be more and more valid as the amount of available information becomes greater and greater. Often in our daily life, a single facial expression conveys more information than any speech or writing could. Displaying information is extremely important and has great impact on human experience. Consider the enormous sum of money spent by companies on advertisements. Displays need not just be pictures—they can be words conveying information as well. Display technology is one of the fastest growing technologies in recent years. Nations and companies vie fiercely to obtain an edge in display technology. New display technologies, such as high density television (HDTV), flat panel displays, programmable transparencies, etc., hold keys to the economic success of many companies. Graphic workstations have already transformed the lives of designers of houses, automobiles, and microelectronic chips. Semiconductor technology has coupled extremely well with liquid crystal technology to produce displays. Also, for active displays and light sources, semiconductor devices such as LEDs and laser diodes serve an important need.