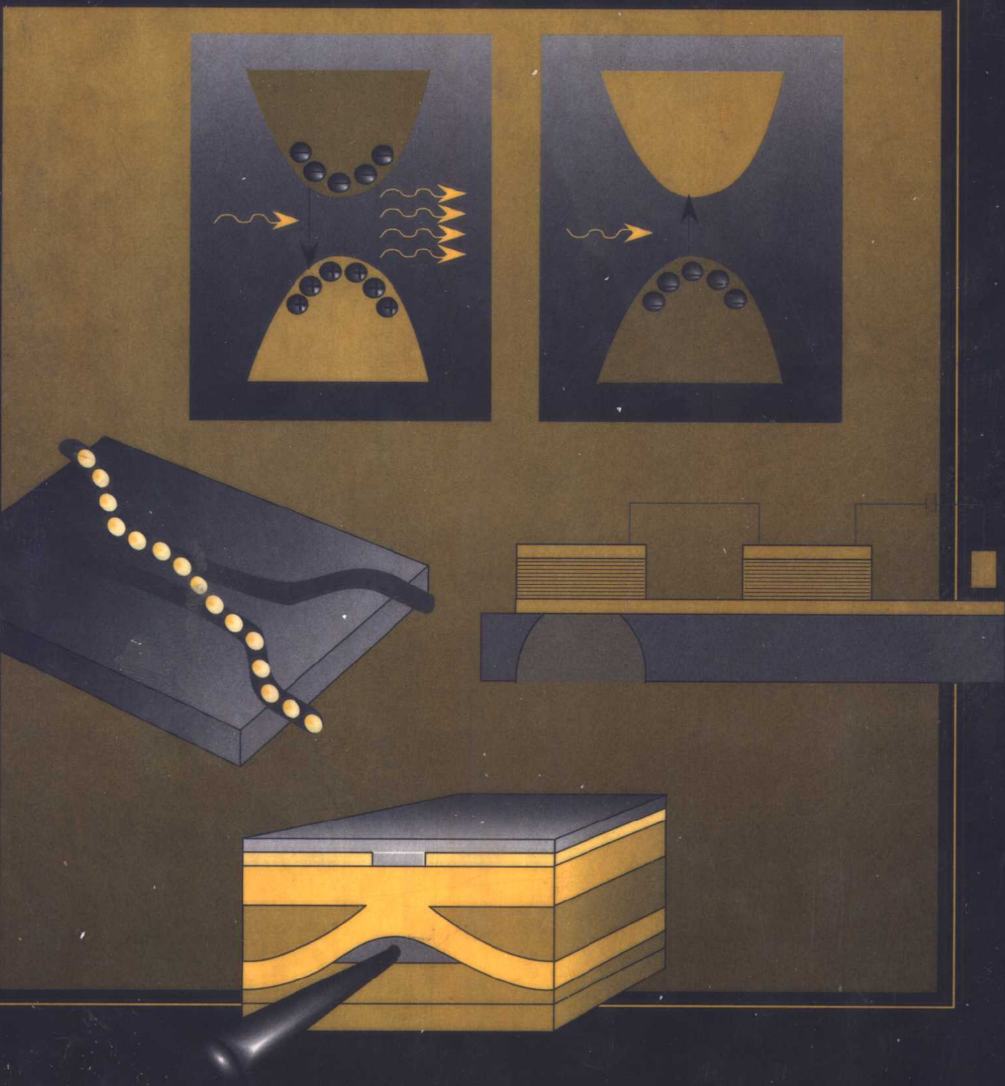
Jasprit Singh

Semiconductor Optoelectronics

Physics and Technology



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SEMICONDUCTOR OPTOELECTRONICS
Physics and Technology

Jasprit Singh
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SEMICONDUCTOR OPTOELECTRONICS
Physics and Technology

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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 Base, 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); and "Semiconductor Devices, An Introduction," McGraw-Hill (1994).

Preface

In 1988 the trans-Atlantic undersea cable TAT-8 was placed between North America and Europe using semiconductor optoelectronic components in a most demanding and harsh environment. The unsuccessful lawsuit of the satellite communication companies to block TAT-8 signified that the powerful electronic devices had met their match in communication applications. Today optoelectronic networks promise 500 TV stations (to the utter disgust of some and utter delight of others) where you can interactively demand movies, boxing matches, and order a variety of goodies. Indeed, when Wall street takeover/merger specialists use the words "optical networks" as freely as "aggressive growth mutual funds," the message is clear—optoelectronics is here!

With the maturing of semiconductor optoelectronic technology, the number of Universities offering optoelectronic courses and the breadth and depth of these courses is rapidly increasing. However, in this transient mode, it is not yet established what sort of knowledge base is necessary to train students of this field. A typical electrical engineer takes about 20 courses directly related to his or her field to get a Bachelors and about 10 more to get a Masters. Optoelectronics has not yet reached the stature where Universities can devote a similar effort for optoelectronics students. Of course, some of the traditional electronics courses are important for the student of optoelectronics as well. To develop a thorough understanding of optoelectronic devices, a user must have the following understanding:

Semiconductor Technology: It is important for the student to understand the state of technology and how devices are fabricated. It is also important to appreciate the challanges faced by the difficult technologies of optoelectronic integrated circuits (OEICs) or quantum wire lasers.

Physics of Semiconductors: The physics behind concepts such as effective mass, mobility, absorption coefficient, bandstructure, etc., should be understood. Also, the importance of semiconductor alloys and heterostructures should be appreciated. The interactions of photons and electrons, and concepts such as spontaneous and stimulated emission, excitonic and electro-optic effects are to be understood.

Semiconductor Optoelectronic Devices: The physical interactions between photons and semiconductors have to be exploited to design and optimize a variety of information processing devices.

System Needs and New Device Challanges: Since optoelectronic devices are not very mature at this stage (compared to electronic devices), it is important for the student to know what improvements can be made and the resulting payoffs. For this it is important to understand system needs.

It is admittedly difficult for any textbook to address all the needs outlined above in any real depth. As a result, textbooks tend to focus on one or two areas without providing the student a global picture. In this textbook, I have touched upon all the needs while providing an in depth coverage of two key topics—device physics and device design. The reader will find that the areas of technology and systems is covered in enough detail to provide a much needed appreciation of the challenges faced here. The areas of semiconductor physics, electron-photon interactions, and optoelectronic devices are covered in great depth.

This book is written primarily as a textbook for one or more optoelectronic courses. However, where appropriate, I have provided discussions on the state of the art issues. By offering a balanced discussion and about 150 worked examples, I hope that this textbook will not only serve the coursework needs for students, but would also be a long term resource for their future careers.

This manuscript was typed by Ms. Izena Goulding, to whom I am extremely grateful. The figures, cover design, and the typesetting 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 students, past and present: Dr. John Hinckley, Prof. Songcheol Hong, Dr. Mark Jaffe, Dr. John Loehr, Prof. Yeeloy Lam, and Mr. Igor Vurgaftman. I am extremely grateful to George Hoffman, my editor, for providing me valuable input from an outstanding group of referees. The referees were generous in providing positive criticism which I believe greatly benefited the book. I would like to thank Professor Joe Campbell of the University of Texas at Austin, Professor James Coleman of the University of Illinois at Urbana-Champaign, Professor Karl Hess of the University of Illinois at Urbana-Champaign, Professor Marek Osinski of the University of New Mexico, and Dr. Daniel Renner of the Ortel Corporation. I am also grateful to Professor Pallab Bhattacharya of the University of Michigan for valuable discussions.

This book shares some sections with the other two books, "Physics of Semiconductors and Their Heterostructures" (1993) and "Semiconductor Devices: An Introduction" (1994) which I have written, published by McGraw-Hill.

An Instructor's Manual is available to professors wishing to use this text. This manual has solutions to the end of chapter problems. In addition, a computer disc is available to address the following class of problems: i) electron and hole levels in quantum wells (4 band k.p model for holes); ii) optical confinement factor for a waveguide; iii) laser gain in quantum well lasers; iv) effect of strain on quantum well bandstructure and laser performance.

Please write, on your department stationary, to McGraw-Hill for a copy of this manual.

Jasprit Singh

INTRODUCTION

I.1 THE INFORMATION AGE

"Knowledge is power," says an ad campaign for a new business which exploits computer hookups and the latest in medical technologies to provide a health care package. Information and its distilled form—knowledge—has become a survival tool for all of us. 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. And, of course, just a few decades ago none of these gadgets were available. What has made us so dependent on information and its rapid processing? 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—preferably before our competition does it!

Regardless of what the information is, we want to process it faster, with less inaccuracies, at a lower cost, with a system which consumes less space, etc.. In fact, the driving forces for new technologies can range from the need to diagnose tumors in the brain to the diagnosis of a poisonous gas in a factory. It is estimated that at present (mid-nineties), over ten trillion bits of information are generated each day! Most of these bits can be attributed to the television industry, which should not be surprising to the reader.

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 and information storage and retrieval. However, so far the impact has been less in the area of "intelligent" information processing. To understand the challenges facing optoelectronics and the potential payoffs, we examine the demands placed upon devices that are

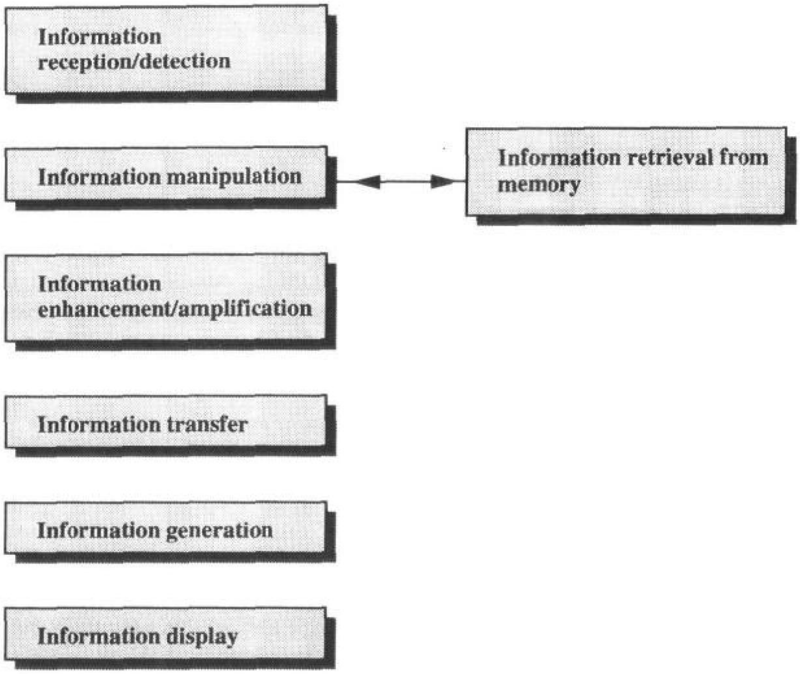

Figure I.1: Necessary functions to survive in the "information age."

Information Manipulation

This is, of course, the most important aspect of information processing. When some information comes in, much of it may be redundant or in a form 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. We are all frustrated when, at some crucial moment, our memory fails us. 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 mankind. The walls of the caves in which our ancestors lived thousands of years ago were a kind of memory.

Memory is an area where semiconductors have been most challenged. Even in high technology applications, semiconductor memories are not the only game in town. Optical memories based on a plastic disc (the compact disc), magnetic tape memories,

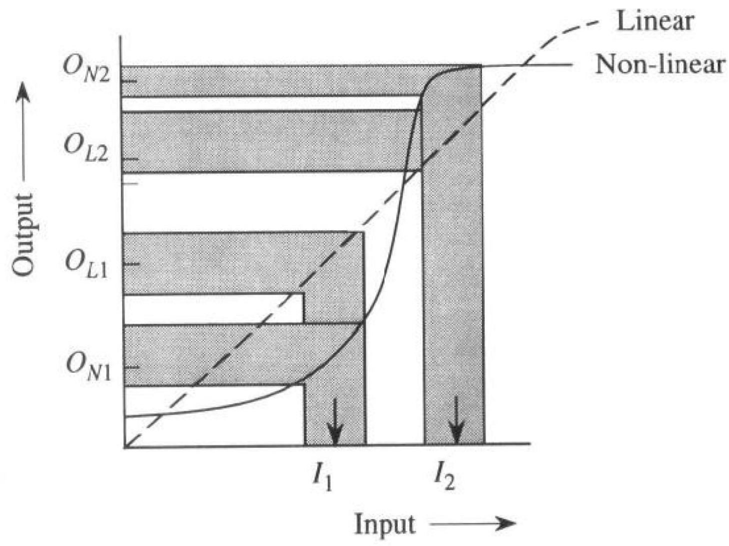

Figure I.2: The advantages of a non-linear input-output response in distinguishing closely-spaced inputs. A linear response system cannot separate the input signals I_1 and I_2 (with response O_{L1} and O_{L2}) as well as the non-linear response (with response O_{N1} and O_{N2}. Also, the non-linear device has a better noise immunity, as shown by the shaded areas.

magnetic bubble memories, etc., all form important spokes of the memory technology, along with semiconductor memories.

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 coming more and more valid as the amount of 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.

I.3 DEMANDS ON ACTIVE DEVICES

Based on our previous discussions of the information processing needs, the demands on active devices are summarized in Fig. I.3. In order for a device to succeed, it must display a physical phenomenon that leads to one or more of the properties mentioned in Fig I.3. Let us briefly discuss all of these requirements, along with other requirements coming from fabrication and market forces, in this section.

Non-Linear Response

Whether the task to be accomplished by a device is image enhancement or simple addition of two numbers, the key property a device must possess is the ability to distinguish between two "closely spaced" pieces of information. We have already discussed, in the previous section via Fig. I.2, the advantage of a non-linear response over a linear response.

Another consequence of a nonlinear response is manifested when two inputs are simultaneously inputted into the device. Consider the two inputs to have a form

$$I_{in} = I_1 \cos \omega_1 t + I_2 \cos \omega_2 t$$

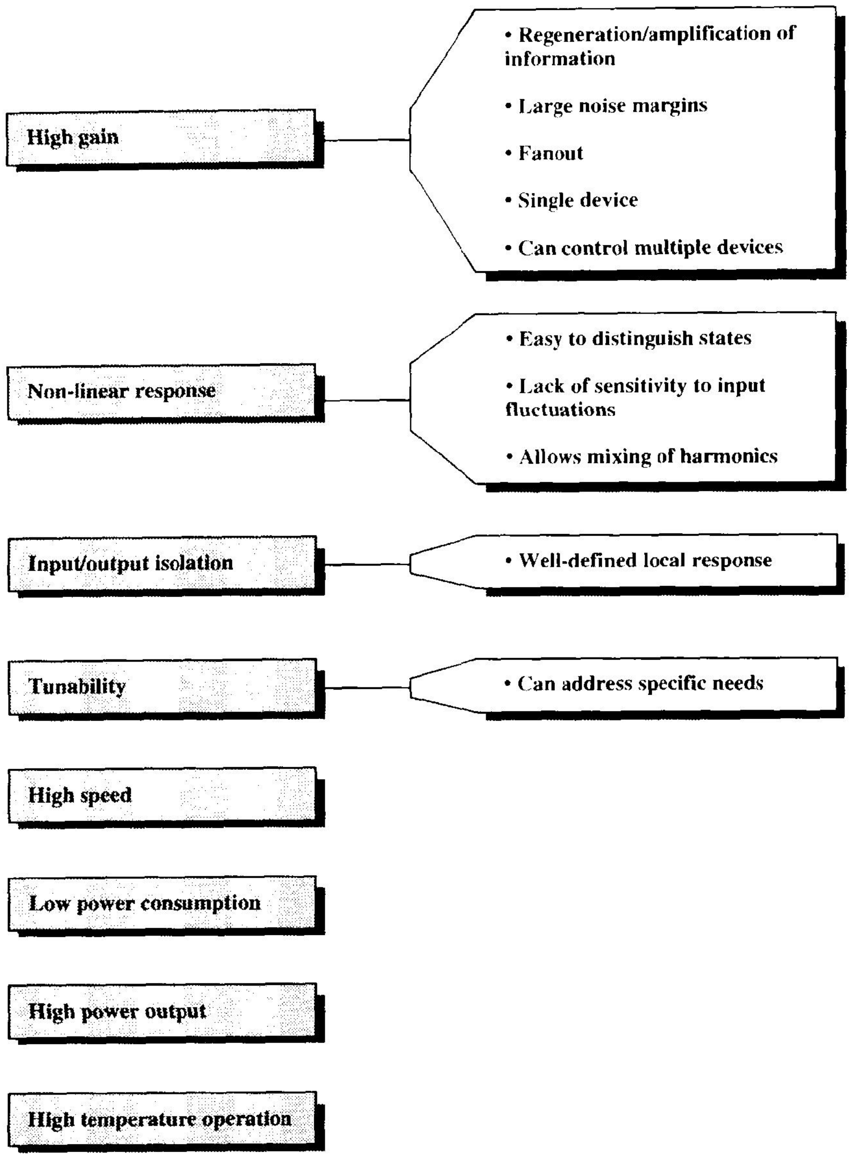

Figure I.3: Requirements of a useful device.

and let us assume a simple physical response of the form

$$I_o = \alpha I + \beta I^2$$

where α is the linear response coefficient and β represents a non-linear coefficient. Of course, the real output function may be more complicated. The output of the device to the input is now

$$I_o = \alpha \left[I_1 \cos \omega_1 t + I_2 \cos \omega_2 t \right] + \beta \left[I_1^2 \cos^2 \omega_1 t + I_2^2 \cos^2 \omega_2 t + 2 I_1 I_2 \cos \omega_1 t \cos \omega_2 t \right]$$

Noting that

$$\cos(a)\cos(b) = \frac{1}{2}\left[\cos(a+b) + \cos(a-b)\right]$$

we have

$$\begin{aligned} I_o &= \alpha \left[I_1 \cos \omega_1 t + I_2 \cos \omega_2 t \right] + \beta \left[\frac{I_1^2}{2}(1 + \cos 2\omega_1 t) \right. \\ &+ \left. \frac{I_2^2}{2}(1 + 2\cos(\omega_2 t) + I_1 I_2 \left\{ \cos(\omega_1 + \omega_2) + \cos(\omega_1 - \omega_2)t \right\} \right] \end{aligned}$$

The output now has signals of frequencies not only ω_1 and ω_2, but also $2\omega_1$, $2\omega_2$ as well as most importantly $(\omega_1 + \omega_2)$ and $(\omega_1 - \omega_2)$. Thus the non linearity is able to "mix" the two input signals and provide sum and difference signals. This is extremely useful for communication where a signal to be transmitted (say at audio frequencies) can be "carried" on a high frequency and then decoded.

Gain in the Device

If a physical phenomenon is to lead to a viable device, an important requirement is the presence of gain in the output-input relation. Thus, a small change in the input should produce a large change in the output. In most applications of devices, a "regeneration" of information is required, i.e., the output of previous step is used to generate another output in successive steps. The ability to introduce gain is one of the most powerful ingredients of most electronic devices, as we shall briefly discuss. Lack of gain has also been one of the pitfalls of many promising exotic device ideas.

The ability to provide gain (or amplify the incoming signal) is not only important for signal regeneration, it is also very useful, along with nonlinear effects, in providing large noise tolerances, especially in digital technologies. One of the great strengths of digital technologies comes from this "noise immunity" of the processed signal at each step of the processing. Thus, in most processing systems, an analog signal is converted to a digital signal (by A/D converters) in spite of the fact that a slight loss of accuracy