

Preface

The cover of this book shows the beautiful interaction of two streams of cosmic dust – this serves as a philosophical allegory to the contents of this book. We start with atoms fixed in a crystalline lattice. When these atoms are of the right type, and organized correctly, they profoundly influence the behavior of electrons, similar to the cosmic dust on the cover. Arranging many atoms together creates an artificial structure within the crystal, whose electrical and optical properties are entirely within our control. By understanding the art and science of atomic engineering we can create a wide array of sophisticated semiconductor devices.

This book is dedicated to the student who is specializing in solid state engineering especially in the areas of nanotechnology, photonics, and hybrid devices. He is expected to have a basic knowledge, at undergraduate level, of the fundamentals of semiconductor physics. The present book was developed with a view to nanotechnology, which we believe is the subject of today, tomorrow being perhaps dedicated to the interface between solid state and soft solids and biology. The reader is expected to have an elementary knowledge of quantum mechanics. For example he should understand what is meant by quantum confinement and realize its novelty and importance. He is expected to have come across such concepts as “the semiconductor superlattice,” “the quantum dot,” “the heterojunction,” and have learned why it is interesting to study these systems. In this book he is going to learn how to make devices which use the new quantum physics which results from the reduced dimensionality. (You would do well to refer to *Fundamentals of Solid State Engineering* as the ideal place to freshen up on these topics.)

To begin with, Chapter 1 of this book discusses modern single crystal semiconductor growth technology with a focus on recent development and technological improvements critical to modern semiconductor devices. In Chapter 2, we are going to learn the first steps on how to actually fabricate a bulk semiconductor device, how to prepare the material the substrate and achieve the doping. Then in Chapter 3, we consider the fabrication of an actual device structure. This involves patterning the semiconductor, and then wire bonding it to arrive at the desired circuit configuration. Patterning involves photolithography and electron beam lithographies. This is a

specialized topic of great importance also for the new emerging fields of organic and hybrid electronics. So more recently, scientists and engineers have also invented the so called nano-imprint lithography in which man-sized stamps are used to impress an image onto a surface. One can now also use atomic force microscope tip to move atoms around on surfaces. “Nano-membranes” can now be fabricated by etching away the substrate and producing ultra thin free standing semiconductor films which can also be “glued” onto another surface. These new developments have given device fabrication another very powerful degree of spatial resolution and flexibility. In addition, one has to imagine the AFM (atomic force microscope) tip moving around on surfaces, and placing magnetic atoms, magnetic clusters and fluorescent molecules and nanoparticles exactly into the location where they are needed on the surface. This technology will allow us to eventually make nanomachines, tools, and even surgical instruments. It is already routine now to implant nanosized metallic particles or fluorescent molecules of engineered sizes and shapes into cancer tumors, and then to irradiate them. With metallic particle at their resonance “plasmon” absorption frequencies for example, the particles get hot and destroy the tumor with minimal damage to the rest of the tissue. The key discovery here, was that one can tune the plasmon resonance (collective oscillation frequency of the charges on the surface of the metal particle) by changing the shape and size of particles. This requires “nanoengineering” and “nanotechnology.”

Making physically contactable electrical circuits on a micron scale constitutes what is the well-established chip technology. In Chapter 4 we review the operation of the p - n junction which constitutes one of the fundamental building blocks of many modern electronic and opto-electronic devices. In Chapter 5 we introduce the student to the technology of the transistor. The concept of switching and amplification is explained. The various types of transistor architectures are introduced. The focus is here not so much on absolute miniaturization, as to understanding present day transistor technology. The absolute miniaturization down to single electron devices is still very much a research field. We feel that this fascinating topic should be the subject of a specialized textbook because the present book is a book for engineers. However small, the devices described in this volume are ones which have current engineering applications. In Chapter 6, we consider the principles, design and fabrication of the semiconductor laser. Later in Chapter 7 the reader will learn how one makes and operates a Quantum Cascade Laser (QCL), a work of art in the application of quantum mechanics. But first, he has to learn the principles of light amplification and light confinement, i.e. waveguiding, and how one can make lasers using semiconductors. Semiconductors lasers are ideal for the mid-infrared wavelength regime. Mid-infrared wavelengths (3–12 μm) have a remarkable amount of versatility for many new types of applications. Perhaps the most

important aspect of this wavelength range is that all molecules are optically active in this regime, and quantitative infrared spectroscopy has been an industrial tool for many years. Most of the time these tools were however thermal sources, and they were limited in sensitivity and range. Mid-infrared lasers, use an excitation/illumination source, and have demonstrated very sensitive real-time and remote sensing capabilities. Besides simple spectroscopy, the direct absorption of light in the right range by specific molecules also lends itself to some potentially very useful medical technologies. Breath analysis, for example, has already been used to monitor health by checking for abnormal cell metabolism byproducts. In the future, it may also be possible to target or cauterize specific types of cells by their chemical or protein content for selective surgery. In addition, mid-infrared lasers, in some ranges, have very good atmospheric transmission, which potentially allows for improved, secure, free-space communication, which is less sensitive to weather conditions than existing near-infrared systems. The uniqueness of the QCL described in detail in Chapter 7, is that the laser transition takes place between two quantum “intersubband states”, whose energy difference can be engineered to produce lasers with different wavelengths using the same material system.

In Chapter 8 we turn our attention to measuring light intensities, not creating light. Each wavelength regime has its own characteristics uses and its own applications: seeing and recording visible daylight (500–700 nm) to seeing hotter objects in the dark (2–20 μm) and or behind walls, to seeing through paper for example (THz spectroscopy). Then there is a multitude of current and potential applications for sensitive detectors in the area of specific single and multicolor detection, in the field of communication, sensing security, robotics, artificial intelligence and medical diagnostics. A sensitive photodetector is a very powerful tool, and research and development in this field is worldwide. In Chapter 8 we learn about photoconduction and how to quantify photodetector noise and define figures of merits. Then in Chapter 9, we review the most important classes of photodetectors. We explain the special role that semiconductor physics plays and how these are fabricated using single atom deposition techniques. In the current detector technologies, three examples take advantage of the low dimensional properties that are predicted by quantum mechanics. They include: the Type II InAs/GaSb superlattice photodetectors, the quantum well intersubband photodetectors QWIP and the quantum dot infrared photodetector QDIP. From the point of view of dimensionality, strictly speaking, one has to point out that the Type II superlattice is actually a three-dimensional system, the same as a bulk semiconductor, while the other two systems are respectively two and zero dimensional systems. In Chapter 10, we begin our discussion of photodetectors with Type II materials.

The concept of the Type II InAs/GaSb superlattice was first proposed by Sai-Halasaz and Esaki in the 1970s. The superlattice is fabricated by alternating InAs and GaSb layers over several periods, creating a one-dimensional periodic structure, in analogy to the periodic atomic chain in naturally occurring crystals. The special feature of the Type II system is the bringing together of two materials for which the energy gaps are not aligned in energy space. The broken gap alignment as in the case InAs/GaSb leads to the situation in which electrons from the GaSb valence band can wander into the adjacent conduction band of InAs. The degree of this transfer can however be controlled by using thin InAs sandwiched layers for which the conduction band confinement can make the lowest levels again rise up above the GaSb valence band. The consequences for physics and technology are understandingly exciting. It took however a decade for this technology to reach the degree of maturity needed for the realization of the new predicted applications. Now the material systems we grow are good enough to give us the detector performance that is comparable to the state-of-the-art Mercury Cadmium Telluride (MCT) technology.

Chapter 11 is devoted to the important and beautiful area of Quantum Well (QW) and Quantum Dot (QD) physics and technology. There are several ways of fabricating small nano-size particles of semiconducting materials, but the ones we focus on in this chapter are grown using the “Stranski Krastanov” method. It was discovered by these researchers that lattice mismatch at semiconducting interfaces, could, beyond a certain point of strain, give rise to the spontaneous formation of dot like structures. The fascinating side is that these dots are fairly regularly spaced, and furthermore, they can be made to grow on top of each other. The chapter begins by introducing the basic operating principles of the intersubband detector, which are shared by the Quantum well intersubband detectors QWIPs and the Quantum Dot intersubband detectors called QDIPs. We describe how the QDIP operation deviates from the simple principles of bulk semiconductor operation when we discuss the theoretical advantages of QDIPs. Next we look at the growth technology for making the QDs that go into the QDs. The capabilities and limitations of the growth technology directly relate to whether or not the predicted theoretical advantages of QDIPs can be achieved. Finally, we finish by reviewing some of the major accomplishments in QDIP technology to date.

Whereas QDIPs and QWIPs are designed to cover the 2–15 μm range, at the other extreme, we have the UV photodetectors which operate in the <250 nm range. The high energy of the photon to be detected makes life easier, because here, we can use wide band gap materials such as the GaN, AlN and multilayers thereof materials. Large band gaps means that thermal excitation of carriers is very difficult even at room temperature, and thus the noise level is low. The growth of the GaN-AlN is however not

unproblematic and the details of this exciting subject area is covered by a specialized text book devoted to these materials by the present author

{*III-Nitrides Optoelectronic Devices* by M Razeghi and M Henini, published by Elsevier 2004}.

There is another area where GaN is being usefully developed and which is causing great deal of excitement and that is the detection of single photons. This has attracted the attention of scientists now for many years. Applications include Raman spectroscopy, fluorescence spectroscopy, and importantly now also quantum computing with photons. Photons emitted by lasers can keep their coherence over long (km) distances but the detection of the combined quantum states require the use of devices with very high level of sensitivity. Initially because of their high internal gain, photomultiplier tubes were used to demonstrate single-photon counting. However, their high volume and required voltages made these devices not so practical. Nowadays, material progress has led to the development of improved avalanche photodiodes with single-photon detection capabilities in traditional semiconductors, such as Si or InGaAs, as well as in novel wide-bandgap technologies. Integrated photon counting systems based on Si single-photon avalanche diodes (SPADs) are today commercially available for a wide spectral range from 350 nm to 900 nm; commercial InGaAs/InP avalanche photodiodes have been successfully tested as single-photon detectors at telecommunication wavelengths; and in the ultraviolet range, SiC and GaN avalanche photodiodes have demonstrated single-photon detection capabilities.

In Chapter 12, we review the basic properties of avalanche photodiodes. In the second part, we focus on the main characteristics and issues of Geiger mode operation (operating the device just above breakdown) for photon counting purposes. Towards the end of the chapter, we provide some examples of the state-of-the-art of single-photon avalanche diodes in Si, InGaAs, and GaN.

Finally in Chapter 13 we discuss the interesting developing new area of terahertz technology. In this chapter we describe recent developments in the technology of terahertz (THz) emitters. We begin, by presenting a short description of what can be done in the THz range, and later, some applications are described in detail. An overview of the different broadband sources available is presented. Further considerations are restricted to modern semiconductor THz emitters. Next, the current state of the art of the semiconductor THz emitter is presented. The Quantum Cascade Laser, which is one of the most efficient semiconductor emitters in the mid-infrared range, has now also been developed for the THz range. In this wavelength range, the device is usually fabricated using multiquantum well structures of GaAs/AlGaAs. Unfortunately these structures do not operate at room temperature under continuous wave working conditions. We conclude by discussing a new generation of THz emitters which are fabricated using

the wide band-gap semiconductors GaN/AlGaIn, and have the potential to allow for the realization of higher operating temperature THz QCLs.

The text is to a large extent based on original research carried out in my research group, the Center for Quantum Devices (CQD), at Northwestern University, Evanston. From the references, the reader will be able to identify the original work and he is encouraged to consult the original papers to deepen his understanding. I am grateful to my students, colleagues, and staff for their assistance during the preparation of this volume: Siamak Abdollahi-Pour, Yanbo Bai, Can Bayram, Binh-Minh Nguyen, Stanley Tsao, Dr. Shaban Darvish, Dr. Ryan McClintock, Dr. Bijan Movaghar, Dr. Jose L. Pau, Dr. Nicolas P  r  -Laperne, Dr. Steven Slivken, Dr. F  r  chteh H. Teherani, George Mach, and Laura Bennett. I would also like to thank Dr. Matthew Grayson for his careful reading of the manuscript and many helpful comments.

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