Report

on

LASER DIODE TECHNOLOGY AND APPLICATIONS

Submitted to

Dr. Andres La Rosa

Portland State University

Physics 464

March 8, 2005

by

Jason Hill

Abstract

This report presents an overview of the Diode Laser; its construction, function and application. Lasers in the form of laser diodes are in widespread use today. Diode lasers are used in a large number of industrial applications; the most prevalent use of the laser diode is probably in CD and DVD drives for computers and audio/video media systems. Diode lasers are also used in many other applications ranging from laser photocopy machines and printers to optical fiber communications, medicine, and some areas of IC manufacture.

Introduction

In this paper I will explain the basics of how a laser diode functions. I will describe the differences between a laser diode and a normal diode and a light emitting diode. I will also define the terms homojunction and heterojunction and how they relate to laser diodes. I will then explain the differences between edge emitting lasers and vertical cavity surface emitting lasers (VCSELs).

Due to their small size, low power consumption, and precision, laser diodes are used in a variety of applications. They are ideal for optical storage devices such as CD and DVD-ROMs. They are also well suited for medical purposes such as interferometry which is used in devices like the pulse oximeter. They are also much more efficient at pumping solid state lasers than the older flash-bulb mechanisms. And due to their inexpensive production, they are used in handheld laser pointers which are used to the benefit of many presenters and are also used to the frustration of many movie-goers.

Content

How a Laser Diode Works

When a diode is forward biased, holes from the p-region are injected into the n-region, and electrons from the n-region are injected into the p-region. If electrons and holes are present in the same region, they may radioactively recombine – that is the electron “falls into” the hole and emits a photon with the energy of the bandgap. This is called spontaneous emission, and is the main source of light in a light-emitting diode.

Under suitable conditions, the electron and the hole may coexist in the same area for quite some time (on the order of microseconds) before they recombine. If a photon of exactly the right frequency happens along within this time period, recombination may be stimulated by the photon. This causes another photon of the same frequency to be emitted, with exactly the same direction, polarization and phase as the first photon.

In a laser diode, the semiconductor crystal is fashioned into a shape that is somewhat like a piece of paper – very thin in one direction and rectangular in the other two. The top of the crystal is n-doped, and the bottom is p-doped, resulting in a large flat p-n junction. The two ends of the crystal are cleaved so as to form perfectly smooth, parallel edges; two reflective parallel edges are called a Fabry-Perot cavity. Photons emitted in precisely the right direction will be reflected several times from each end face before they are emitted. Each time they pass through the cavity, the light is amplified by stimulated emission. Hence, if there is more amplification than loss, the diode begins to lase.

This general description of laser diode is what is known as a homojunction laser diode. Unfortunately, they are extremely inefficient. They require so much power that they can only be operated in short "pulses"; otherwise the semiconductor would melt. Although historically important as will be shown later, they are simply not practical.

The double heterojunction laser makes use of a low bandgap material which is sandwiched between two high bandgap layers. One commonly-used pair of materials is GaAs with AlGaAs. Each of the junctions between different bandgap materials is called a heterojunction, hence the name double heterojunction (DH) laser. The advantage of a DH laser over a homojunction laser is that the region where free electrons and holes exist simultaneously is confined to the thin middle layer. This means that many more of the electron-hole pairs can contribute to amplification and not as many electron-hole pairs are left out in the poorly amplifying periphery. In addition, light is reflected from the surface of the heterojunction, so the light gets confined to the region where the amplification takes place, which improves the efficiency of the device. See Figure 1.

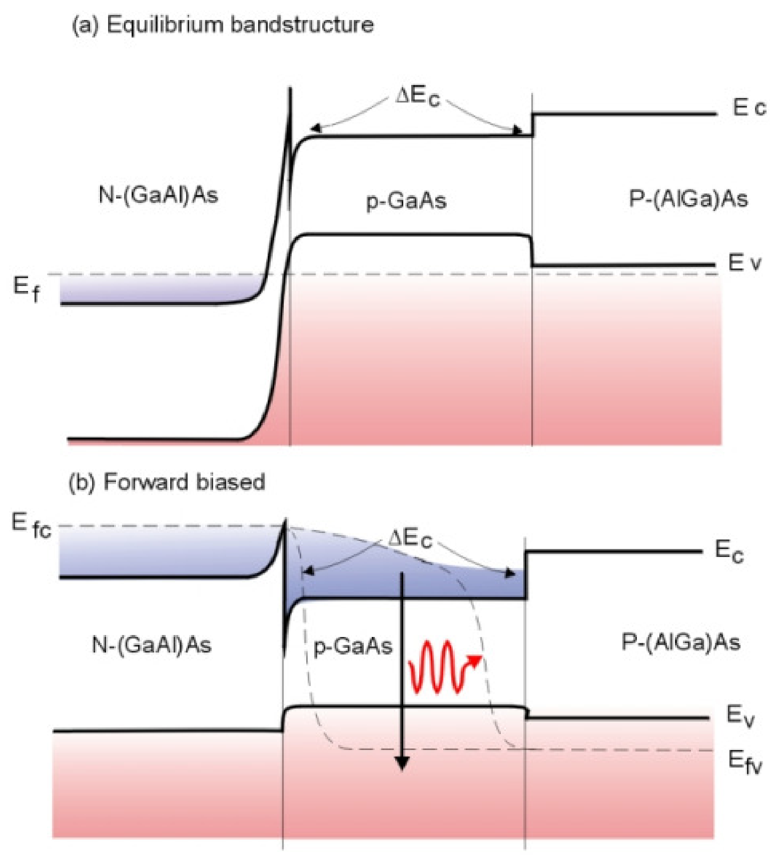

Figure 1: Bandgap diagram of an NpP AlGaAs/GaAs/AlGaAs heterojunction

The top pane of Figure 1 shows the band structure of a double heterojunction in equilibrium, meaning no voltage applied. The middle area shows ΔE_C which is the potential energy barrier needed to be overcome for recombination of electrons and holes to take place. The bottom pane shows the same double heterojunction in forward active mode. The energy level of the larger bandgap N-type GaAlAs has been raised so that it is now above the ΔE_C potential energy barrier. This allows the electrons to flow into the p-GaAs region where they are confined by the lower bandgap material. Similarly, holes flow in from the P-type AlGaAs to the p-GaAs valence band. The electrons and holes are confined where they can combine radioactively. This form of "population inversion" isn't enough by itself to produce lasing. For stimulated emission to take place, the light must remain in the cavity long enough to interact with other electrons. This is achieved by creating a Fabry-Perot cavity with mirrored ends, where the light can reflect back and forth many times before leaving the cavity. If the gain equals loss, lasing will occur.

The other type of laser I will discuss is the Vertical Cavity Surface Emitting Laser (VCSEL). The basic structure of the VCSEL is shown in Figure 2. The main difference between the edge emitting and surface emitting lasers is the orientation of the optical cavity. The layers of semiconductive material are orthogonal to the direction of emitted light. During recombination, photons can be emitted in many different directions, but the direction of emitted light will be controlled by the orientation of the reflective mirrors.

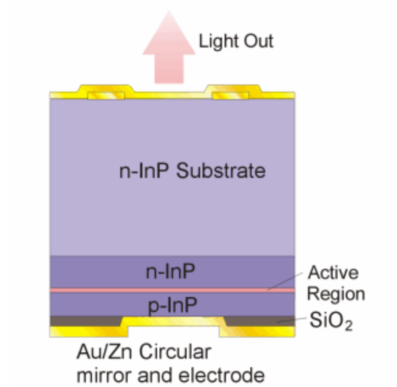

Figure 2: Metallic Reflector VCSEL

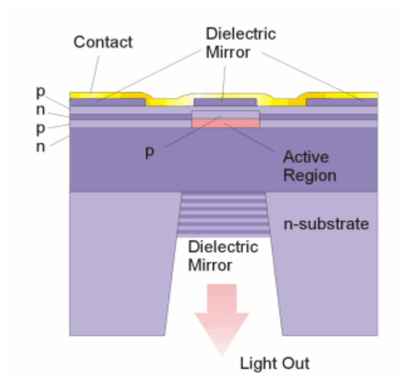

Figure 3: Etched Well VCSEL

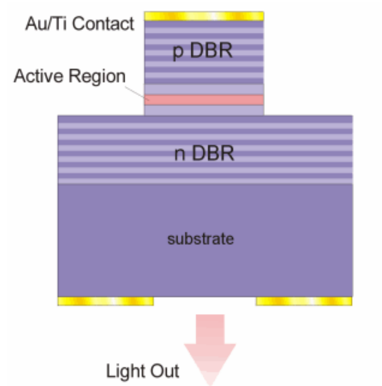

Figure 4: Air Post VCSEL

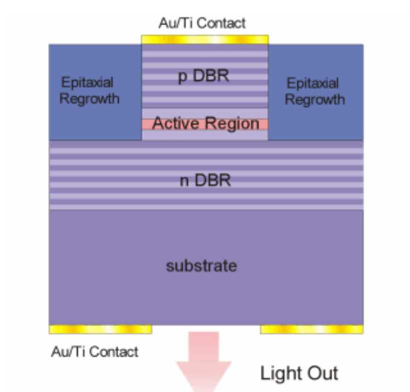

Figure 5: Buried Regrowth VCSEL

Due to the VCSELs' short optical cavity length, the photon has very little time to stimulate another electron to recombine, therefore better mirrors needed to be developed. Metallic mirrors were not reflective enough; they could only provide 30% reflection. The VCSELs needed 99.9% reflection. This was achieved through the use of layered dielectric materials called Distributed Bragg Reflectors (DBRs). Through the evolution of VCSELs, engineers came up with several different models which improved performance. The first improvement on the Metallic Reflector VCSEL came with the Etched Well VCSEL as seen in Figure 3. This model used layered dielectrics for its reflective mirrors. It also had an etched well to control the area of recombination. The next evolution came with the Air Post VCSEL as seen in Figure 4. This model used DBRs and created a post by etching the surrounding material away. This post also worked to control the area of recombination. Finally Figure 5 shows the Buried Regrowth VCSEL. This model took the Air Post VCSEL and through an epitaxial process, filled in the etched area with another material. This allowed for a more precise control over recombination.

Another way to control the properties of the laser diode was to introduce quantum wells into the laser device. This is quite common in modern VCSELs. If the middle layer is made thin enough, it starts acting like a quantum well. This means that in the vertical direction, electron energy is quantized. The difference between quantum well energy levels can be used for the laser action instead of the bandgap. This is very useful since the wavelength of light emitted can be tuned simply by altering the thickness of the layer. The efficiency of a quantum well laser is greater than that of a bulk laser due to a tailoring of the distribution of electrons and holes that are involved in the stimulated emission process.

The problem with quantum well devices is that the thin layer is simply too small to effectively confine the light. To compensate, another two layers are added on, outside the first three. These layers have a lower refractive index than the center layers, and therefore contain the light more effectively. This type of design is called a separate confinement heterojunction (SCH) laser diode. Almost all commercial laser diodes since the 1990's have been SCH quantum well diodes.

History of the Diode Laser

In 1952, while investigating group III-V compound semiconductors; Heinrich Welker of Siemens in West Germany identified GaAs as a member of the semiconductor family. However, the benefits of this compound were not immediately evident. It was thought to be not nearly as useful as silicon since gallium arsenide had no stable native oxide (like silicon had with SiO_2) and it was difficult to produce in a high-purity form. These reasons prevented researchers from exerting much effort to the study of GaAs diodes as late as 1958.

By the early 1960's new technologies in the growth of semiconductor crystals evolved, leading to the commercial availability of GaAs diodes. The search for a higher voltage tunnel diode led researchers to study GaAs diodes and they found that a GaAs *p-n* junction had extremely high internal quantum efficiencies, as high as 85 to 100 percent. These discoveries demonstrated that a semiconductor diode could be a very efficient generator of photons and could perhaps be the most efficient "converter" of electrical energy into optical energy ever demonstrated.

Applications of Laser Diodes I
Laser Pointers

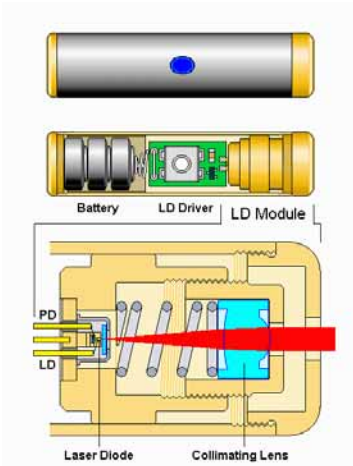

Figure 6: Typical Red Laser Pointer

The most visible applications of laser diodes are the ever more popular laser pointers. The basic laser pointer, which can be purchased for only a few dollars, is the standard red laser pointer. The red laser pointer emits a 670 – 635nm beam. The human eye perceives the 635nm beam to be about five times brighter than the 670nm beam. The red laser pointer is quite a simple device and is very inexpensive to manufacture. Figure 6 shows a diagram of a typical red laser pointer.

The green laser pointer is a much more complex device. Figure 7 shows a diagram of the green laser pointer. It is actually a Diode Pumped Solid State Laser (DPSS) that uses a laser diode to emit an 808nm beam that optically pumps an $Nd:YVO_4$ crystal, which in turn emits a 1064nm beam. This beam is then processed by a KTP crystal, which halves the wavelength to 532nm. This is very close to 555nm, the wavelength to which the human eye is most sensitive. This means that at the same power as the red laser (<5mW), the green laser will appear about 30 times brighter.

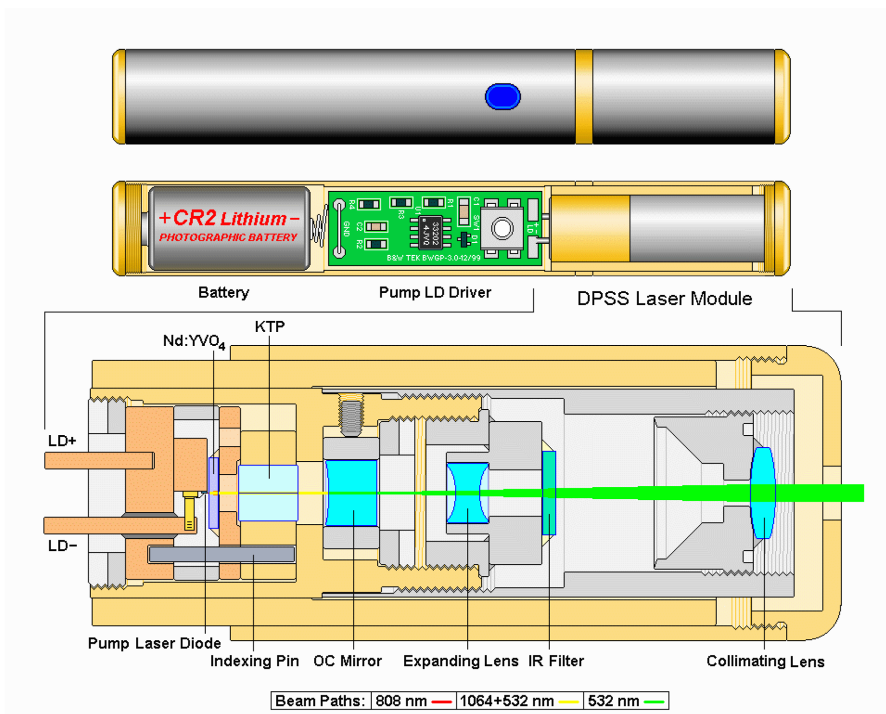

Figure 7: Green DPSS Laser Pointer

Applications of Laser Diodes II
Optical Storage Devices

CD-ROM drives operate at a wavelength of 780nm, which is near-infrared. DVD-ROMs operate at 650nm, which is within the red spectrum. The size of the beam which can be focused from a laser diode is dependent upon the wavelength of the light that is emitted. The smaller the wavelength, the tighter the beam; and a tighter beam means a smaller diffraction spot. Figure 8 shows the relative sizes of diffraction spots for different colored laser beams.

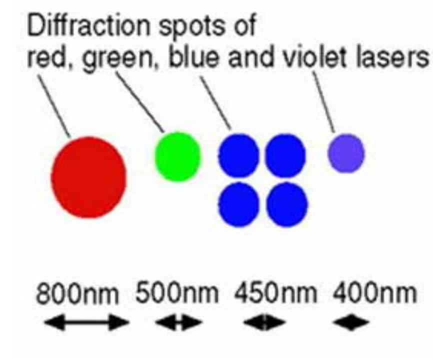

Figure 8: Relative diffraction spot size of different colored lasers

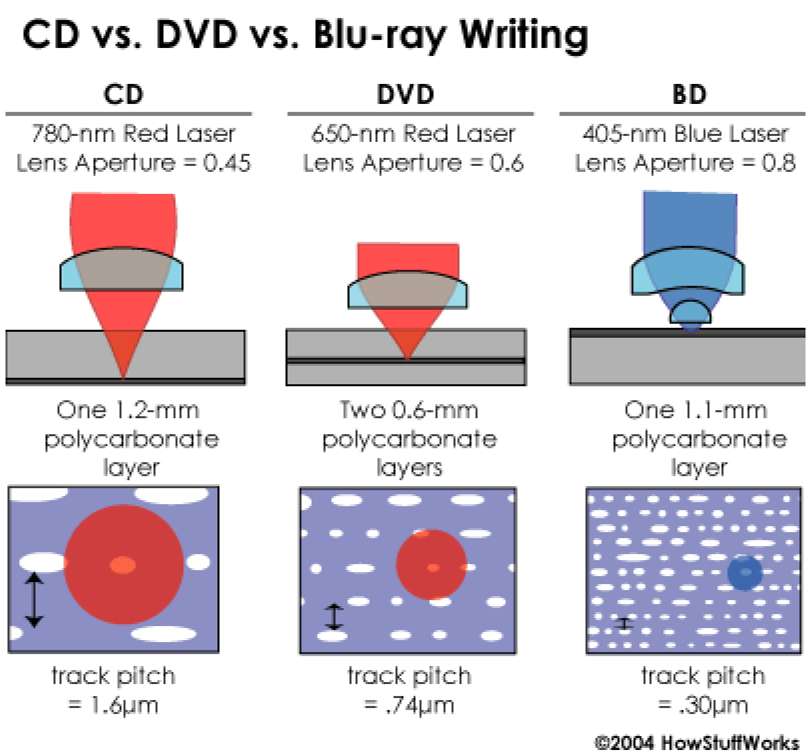

Figure 9: CD vs. DVD vs. BD

The amount of data that can be stored using an optical system is dependent upon the size of the diffraction spot. If you want to store more data, you need a higher wavelength laser. The optical storage industry has been moving towards higher wavelength lasers over the last few years. The most prevalent high-wavelength technology is Blu-Ray laser. Blu-Ray is a copyrighted technology developed in 1997 that is being used by Dell, HP Hitachi, Sharp, Sony, Disney and many others. The Blu-Ray is a 405nm blue-violet laser that can store almost six times as much data as a standard 650nm DVD. Figure 9 diagrams the differences in beam size and data resolution for CD-ROM, DVD-ROM, and BD (Blu-Ray Disc).

Conclusion

The laser diode is a spectacularly versatile device due to both its incredibly small size and the precision with which it can be manufactured. I began this investigation of the laser diode because I was intrigued with its history. The race to be the first to bring the supposition of a semiconductor diode to fruition was fascinating. The air of competition drove the researchers to new heights faster than I would have thought possible.

Throughout this paper I have discussed the basics of laser diodes in terms of materials and physical structure. Even though my explanations may have seemed simplistic, I hope that some of the elegance of this device has shown through. The prevalence of the laser diode in modern technology cannot be overstated. Advances in material engineering are currently taking laser diodes to unforeseen achievements. Quantum advances are making laser diodes more precise and efficient that ever before. Progress is also being made at an ever increasing rate at improving the power output of laser diodes.

In conclusion, the laser diode is an integral part of the laser family and is of great concern to modern physics and especially optical processes.

Works Cited

"Blue LEDs and Lasers." eurotechnology.com. 15 Sept. 2004. 26 Feb. 2005

Dupuis, Russell D. "The Diode Laser, The First 30 Days, 40 Years Ago." Optics & Photonics News Apr. 2004. 27 Jan. 2005 <http://www.osa-opn.org/abstract.cfm?URI=OPN-15-4-30>.

Goldwasser, Samuel M. "Diode Lasers." Sam's Laser FAQ. 19 Dec. 2004. 28 Jan. 2005 <http://repairfaq.ece.drexel.edu/sam/laserfaq.htm#faqtoc>.

"Laser Diode." Radio Electronics.com. 28 Jan. 2005. Adrio Communications Ltd. 28 Jan. 2005 <http://www.radio-electronics.com/info/data/semicond/laser_diode/laser_diode.php>.

Suematsu, Y. Semiconductor Lasers and Photonic Integrated Circuits. London: Chapman & Hall, 1994.