Semiconductor Diode Lasers

A semiconductor diode laser is a laser that uses semiconductor material in the fashion of a pn junction and is pumped with current[1]. A basic diagram is seen below.

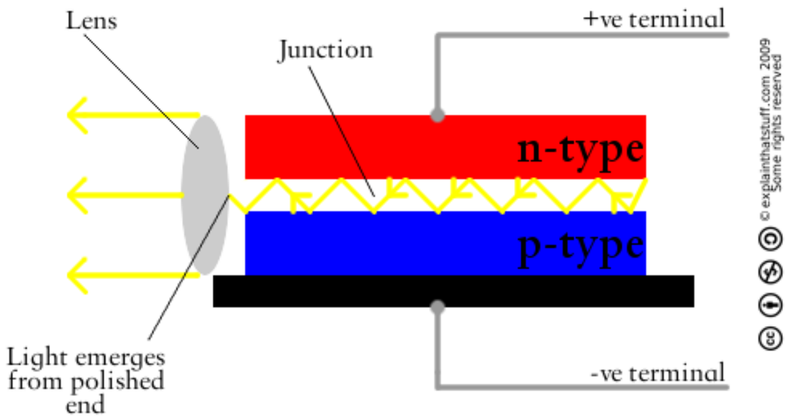

Figure 1 Basic semiconductor diode laser[2]

The material and basic structure is likened to that of an led, so what is the difference? Special considerations are made in ensuring that laser light is emitted rather than incoherent light, which will be discussed later.

Semiconductor diode lasers have an interesting history. The first demonstration of one used GaAs back in 1962 and was created by R. Hall. The first visible later came later in 1962 and was invented by Nick Holonyak. The fabrication of semiconductor diode lasers in the 1960s was primarily liquid phase epitaxy (LPE). The quality was improved in the 1970s, when techniques like molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) were developed. The better methods of growth improved the material quality significantly for lower thresholds and higher efficiencies. The challenges that were to be overcome next were room temperature and continuous wattage. Room temperature operation was achievable early on, but reducing the threshold current density below 100,000 A/C^2. The 1st continuous wave operation was achieved in 1970 by Zhroes Alferov.

The basis of operation for a semiconductor diode laser is the recombination of electrons and holes. Different methods of this can happen. In a traditional silicon pn junction, a depletion region is formed from the chemical potential differences of p doped region of silicon and an n doped region. When forward biased (positive terminal is hooked up to the n doped region and negative terminal is hooked up to the p doped region), more carriers are added to the system for electron-hole recombination. The recombination process generates a photon. The forward bias is the source of pumping that causes population inversion possible for the laser to work. The stimulated emission comes from the injection region. Because in this system, carriers are injected in through an electrical bias, semiconductor diode lasers are also known as “injection lasers.”

Talking about a traditional silicon pn junction is instructive, but not practical. Silicon is a semiconductor with an indirect bandgap, meaning that a lot of the electron recombination processes do not involve photon emission, but phonon in many cases. To make a practical semiconductor diode laser, direct bandgap semiconductors are required. There are many candidates such as gallium arsenide (GaAs), indium phosphide (InP), gallium antimonide (GaSb), and gallium nitride (GaN). Direct bandgap semiconductors are much more efficient. The wavelength that each material generates is related to the energy of the bandgap. Semiconductor diode lasers can have wavelengths in the visible, 405 nm for InGaN (blue laser), 650 nm for DVD drives and laser pointers and 780 nm for CD drives. Given these applications, semiconductor diode lasers can be made in very small sizes.

Figure 2 The scale of some semiconductor diode lasers.

We have discussed the material or the gain medium for these lasers, now lets move on to the resonator and other design considerations. Just having direct band gap semiconductor material is not enough to make an efficient laser. Creating heterostructures that enable electron-hole confinement are essential. Bulk semiconductor material is not a good choice, you want to create a layered heterostructure that confines the electrons and holes to a small region.

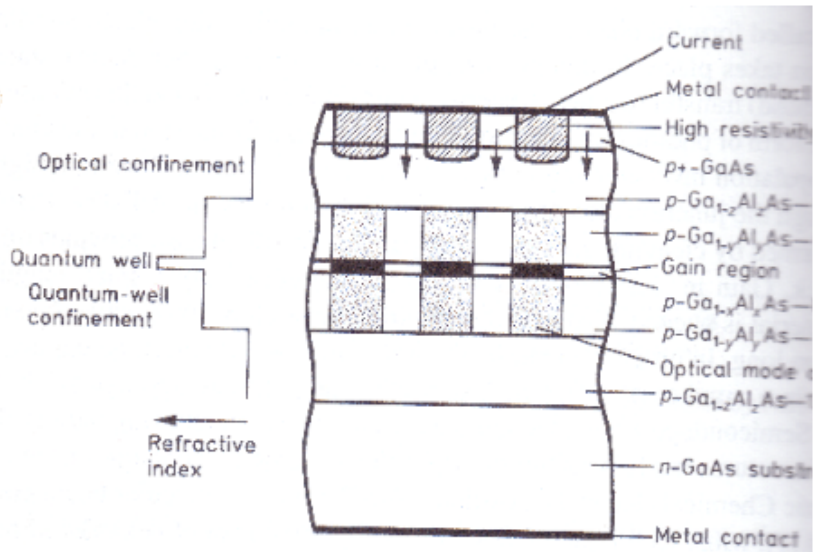

Figure 3 Layered Heterostructure for semiconductor diode laser[3].

As seen in Figure 3, GaAs/AlGaAs heterostructures are common and in the middle the confinement is called a quantum well and this is the gain region. All of the electrons and holes recombine in this region and allow for a very efficient gain medium. The efficiency can be as great as 35-50%. Adding multiple quantum wells can add even more benefit. Further confinement could possibly enhance efficiency even more. One particular type of multiple quantum well laser is called a quantum cascade laser, which operates off of the difference between energy levels in neighboring quantum wells. In addition to high efficiency because of confinement, the threshold is also lowered, making in much more feasible for a broad range of commercial applications.

Beyond confining the electrons and increasing the efficiency, we have not solved all of the operational issues. Once the coherent light is created, how do we focus it in one direction? With just a quantum well formed from a heterostructure, the light can spread out in all directions, creating power and direction problems. One way to handle this problem is outside the active region adding layers of higher refractive index, confining the light and allowing only an exit at one of the ends of the gain medium. A type of confinement includes having graded layers called a Graded-Index and separate carrier and optical Confinemet Hetrostrucuter (GRINSCH). The ends in a semiconductor diode laser are created by cleaving along a crystalline plane, allowing for multiple passes and buildup to occur just like a Fabry-Perot interferometer. Often the cleaving takes place on the [110] plane for example in GaAs. This plane is specular reflecting. The reason it is reflecting comes from the surface states along this cleaved edge that differs from the quantum well's band gap. However, these mirrors at this end are not without problems. Thermal buildup is a big problem from the absorption, which can lead to catastrophic optical damage (COD). A couple of ways to handle this is coating the ends with an appropriate dielectric like aluminum oxide or making non-absorbing mirrors. The mirror separation distance is often on the order of 500 μm. The reason that such a small cavity length is feasible is because of the effiency and gain possible in this material.

Now, lets examine the operational modes and kinds of semiconductor diode lasers can be made. Emitting apertures of 100-500 μm can produce output powers of 5W. Single 1 cm bars can have continuos wave operation up to 40 W. Stacked 1 cm bars, forming 2D arrays are possible with conductive cooling with a common heat sink. An alternative is the liquid colling for each bar in the array. In addition to the continuous wave, quasi-CW is possible which equates to a long pulse on the order much greater than 1 μs and can produce 60 to 100 W of power at peak though with a reduced lifetime. These various modes allow semiconductor diode lasers to be used as a pump laser to other systems. One reason is that the bandgap can be matched to the need of the laser it is pumping. Lasers like Nd:YAG, Nd:YLF, Nd:YVO4, Tm:YAG, Yb:YAG, Er: glass and Cr:LiSAF are all pumped by semiconductor diode lasers. Because of special development of thin, highly strained InGaAsP, Cr:LiCaAlF6 and Cr:LiSrAlF6 lasers were able to be pumped as well. So, we see that the widely varying operational modes allow semiconductor diodes to be a versatile laser.

Other aspects of the semiconductor diode laser are interesting as well. The output beam is shaped of like an oval light cone. The very thin emitting gain region has high anisotropy that contributes to this. To collimate such a beam, a numerical aperture requires NA = 0.5 or higher. The vertical direction is called the fast axis and has divergences around 40 degrees, while the slow axis is parallel to the thin gain region and has divergences on the order of 10 degrees. The lifetime of the diode laser is very sensitive to electrostatic dischare and high voltages. If pushed too hard, the high currents coupled with insufficient cooling often leads to structural defects that can lead to a predictable decrease in ouput over time. With the use of GaAs, oxidation and aluminum migration can be common problems that degrade the laser's performance. Other problems include facet damage from environmental factors like radiation and diffusion of solder into lattice. Even with tese defects, semiconductor diode lasers can operate for 10,000 hours in continuous wave mode. The ouptup spectra of a semiconductor diode is interesting. The wavelengths have been mentioned. For varying percentages of AlGaAs, you can vary the wavelength from 750-850 nm. The lindewidth is typically 4-5 nm but the state of the art can achieve 2.2 nm. Finally, the output is a linear relationship with the current once reaching threshold.

Semiconductor diode lasers are an extremely efficient laser based of pn junctions and quantum wells. They have very low power requirements compared to arc lamps and their size makes them versatile for many applications.

References

1 Available at http://en.wikipedia.org/wiki/Laser_diode.

2 Semiconductor Diode Lasers, Available at http://www.explainthatstuff.com/laserdiode.png, (2009).

3 Koechner, W., *Solid state lasers : a graduate text*. (Springer, New York :, 2003).