An Inquiry
on
The Working Principles of a Laser Diode

Submitted by:
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To:
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Abstract

To gain a better understanding of where we are headed; it is advantageous to know where we have been. Optical semiconductor devices are a major workhorse of today’s technology, but every new discovery presents us with new, greater, challenge. Preparation to meet this challenge compels us to be familiar with the basic foundations that offer themselves to us as building blocks.

Introduction

Optical semiconductor devices have been integrated into almost every aspect of our lives. The road leading to the prevalence of these devices in today’s technology began in a letter to Electrical World reported in the February 9, 1907 edition:

To the Editors of Electrical World:

Sirs:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 19 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 120 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current, but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermo-electric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

New York, N. Y. 

H. J. Round.

At the time the properties of the materials was poorly controlled, the SiC (carborundrum) that Round used for this experiment was a crystal found near Niagara Falls, and the process of emission was not well understood as well.

We now know that the SiC crystal that Round used was a natural n-type semiconductor and that in connecting a metal conductor to the crystal he unknowingly created what we now refer to as a Schottky diode, but the question remains: why was light produced?

The answer lies in understanding the behavior of the electrons within the system.

Content

We have learned through the study of solid state physics that elementary semiconductors such as silicon and germanium tend crystallize in an ordered atomic configuration and bonding arrangement where the electrons are shared between atoms.
If a Silicon crystal is doped with another atom such as Antimony, the extra electron of the Antimony can no longer remain at its lowest energy state. Since the electron is at a higher energy it has greater possible mobility across the crystal. In Round’s case, by connecting the n-type semiconductor to the metal lead, a number of electrons at a higher energy level can lower their energy level by traversing the semiconductor-metal junction. As we have studied before, as the electrons transition from a higher level to the lower level the energy can be released as photons according to the equation: \[ \lambda = \frac{hc}{E} \]. The Band Theory of solids can model this effect.

In the Band Theory of Solids, the density of electrons and the density of holes form respectively the conduction band and the valence band, which are related to the probability of an electron existing at a given energy level and are given by:

\[
\rho_c(E) = \frac{4\pi}{h^3} \left(\sqrt{m_{dc}}\right)^3 \sqrt{E - E_c}
\]

\[
\rho_v(E) = \frac{4\pi}{h^3} \left(\sqrt{m_{dh}}\right)^3 \sqrt{E_v - E}
\]

The difference between the edges of the bands mark the ‘band gap’ and represent the difference of energy for an electron to leave the conduction band and fill a hole in the valence band.
In metals however, the valence band and the conduction band overlap, this is why electrons can move freely across a wire. Thus, when the n-type semiconductor is in contact with a metal, similar to what Round produced with his carborundum crystal, electrons near the junction diffuse into the metal until an equilibrium is reached near the junction.

This causes the conduction and valence bands of the crystal near the junction to be forced to higher density levels (3a). Then, in order for electrons to move across the junction, the density of electrons in the rest of crystal must be raised (3b). If the density of electrons in the crystal is increased far enough, ‘holes’ from the metal can traverse the junction and when the electrons undergo a direct transition from the conduction band to the valence band the energy can be released as a photon with a wavelength close to \( \lambda = \frac{hc}{E_c - E_v} \).

![Figure 3: Band diagram of a Schottky diode under (a) equilibrium conditions, (b) forward bias, and (c) strong forward bias](image)

Development in materials fabrication in the 1950s brought about the ability to create class III-V compounds which do not occur naturally. The novelty of these compounds fostered greater experimentation and development in LED’s and sequences of specially designed layers to facilitate a direct transition of energy levels to produce a photon with the desired wavelength.

LED construction is primarily divided into two groups: surface emitting (4a) and edge emitting (4b). In both of these types, photons are created in the recombination process of the holes and electrons at the p-n junction in a homojunction diode.

There are a few complications to creating an efficiently focused LED. One early reason was due to defects in the crystal lattice structure. These defects cause additional levels within the band gap that can trap electrons. Another problem is that since the excited electrons move randomly from the conduction band to the valence band the phase of the light is completely

![Figure 4: Basic LED types](image)
incoherent. This is further complicated by the possibility of the electrons and holes to occupy additional states at the acceptor and donor levels (5) giving the spontaneous emission of photons a broad spectrum. All of these obstacles were destined to be overcome however, due to the lure of the incredible internal quantum efficiencies of the diode in producing photons.

The advent of the laser in 1960 and the accomplishment of stimulated emission of visible photons reinforced the aspiration of creating a semiconductor laser. The search for a method to provide coherent, monochromatic light coupled with the efficiency and size benefits of a LED began with the goal of producing stimulated emission.

In order to observe stimulated emission in semiconductor device the rate of electron transition from the conduction band to the valence band must be greater than the rate of transition from the valence band to the conduction band. Due to this necessity lasing of a homojunction device required large amounts of current, this however resulted in a increase in temperature since electrons and holes will also drift through the junction without going through recombination. At first, this was counteracted by operating the diode at low temperatures and under pulsed conditions.

Another improvement introduced was the introduction of a cavity resonator to the semiconductor junction. By making use of the natural planes in the structure of crystal lattice the diode can be cleaved on both ends forming
mirrored surfaces which, when separated by the distance that satisfies the condition for cavity resonance: \( m\lambda = 2d \), filters out the spontaneous emission not related to the lasing mode. This also has a side effect, the crystal structure at these edges is not uniform with the rest of the crystal lattice and has available energy levels within the band gap. Thus, the energy of some photons when traversing the junction from the semiconductor to free-space is absorbed by that surface and produces more heat.

Additionally, the presence of heat within a semiconductor has an effect on the energy levels within the semiconductor and thus the band gap. This narrowing of the band gap gives rise to increased mobility of electrons transitioning states and energy absorption in the form of heat causing an avalanche effect.

One method to reduce the heat of a diode was the introduction of heterostructures. The objective of the heterojunction is to reduce the drifting of electrons and holes through the n-p junction without undergoing the desired recombination to produce a photon. By pairing a p-type semiconductor with a relatively small band gap to a n-type semiconductor desirable discontinuities of the energy bands can be observed. Here, even under forward bias conditions, a considerable potential barrier of available states prevents holes from drifting across the junction. This increases the likelihood of electrons recombining with holes and releasing energy in the form of a photon.

![Energy Band Diagram for a pn-heterojunction](image)

The discovery that finally allowed the laser diode to operate continuously at room temperature and subsequently brought the diode laser into widespread commercial development was the double heterostructure.
By sandwiching a semiconductor layer with a relatively small band gap between a standard pn-junction, thermal equilibrium conditions distribute the holes and electrons raising the band densities across the junction. Then, by introducing a suitable forward bias, the injected electron density in the n-type semiconductor increases to a level higher than the electron density in the layer with the relatively small band gap. This creates region where the potential barriers trap both electrons and holes essentially forcing them to undergo the recombination process releasing their energy in the form of a photon.

Figure 8: Energy Band Diagram for a double heterojunction

Conclusion

Today, nearly all commercially sold laser diodes are constructed upon the principle of the double heterojunction structure. However, the next great idea that will transform the way we think is always just around the corner. The reason that I wanted to study this topic was two-fold. First, after studying the basics of semiconductor devices in Electronics I, I believed I had an adequate understanding of how semiconductor junctions work. However, unlike my basic understanding of the workings of an incandescent light, I could not quite grasp how a semiconductor could produce light. Now, through the process of studying the behavior of electrons and photons at a pn-junction I have gained valuable insights into the basic quantum energy model as well as the relationship between electrons, photons, and phonons. I think what excites me the most however is where I studied that was not in the scope of this project. I stumbled across and had my interests piqued by photodiodes, new discoveries in plastic laser diodes and much more.
(1) http://hyperphysics.phy-astr.gsu.edu/Hbase/solids/