Title
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Quantum Wells and Optical Cavities in Lasers

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***Abstract*—The pertinence of lasers in society is often overlooked. Lasers can be used to depict the structural integrity of light, which is incredibly beneficial to the realm of education as it can sculpt the intangible through applications of holographic display. Specifically, the medical field has found use in holograms to identify and depict any tissue damage (Haleem, 2020). Additionally, certain cancers can be killed with lasers.**

I. INTRODUCTION

Two ways in which lasers are created is through the use of quantum wells and optical cavities. A quantum well requires using a series of semiconductors to which the middle semiconductor has a smaller bandgap than its neighboring two semiconductors. Since quantum wells are only one dimensional, these will trap the electrons in the plane of the semiconductor. On the other hand, a Fabry-Perot (FP) cavity is used to trap a fraction of photons, while emitting the other fraction. The two different mechanisms allow for the maintenance of population inversion to which we can classify the devices under laser diodes and solid-state lasers. Examples of the apparatuses are pictured below as figure 1 and 2 respectively. The topic came about upon review of the paper ”Integrated structured light architectures” by Lemons, R., Liu, W., Frisch, J.C. and et al.

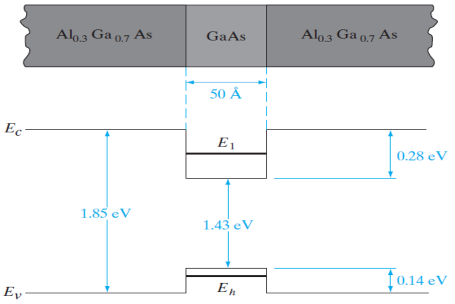

Fig. 1. (Streetman, 2014)

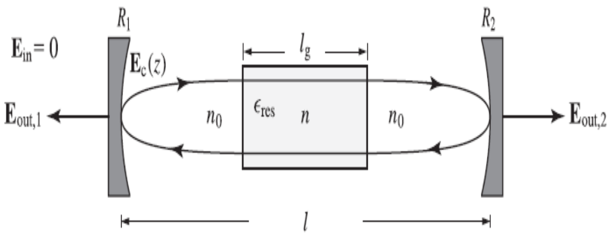

Fig. 2. (Liu, 2017)

II. METHODS

A. Varying Doping and Temperature

Doping can be used in both apparatuses, but is only a necessity in the solid-state laser. Electricity is the driving force behind exciting the electrons in the quantum well, while light is used to excite the dopant atoms in the doped semiconductor found in the solid-state laser. Lasers are desired to have a large number of successful radiative recombinations in order to emit light and maximize efficiency.

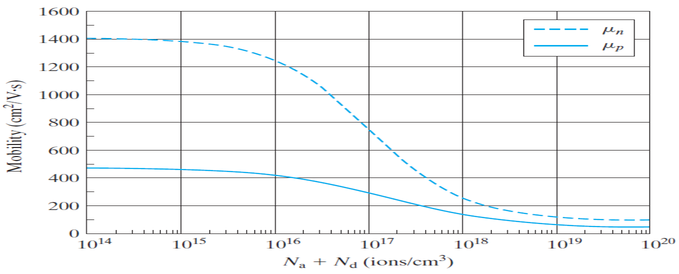

Fig. 3. (Hu, C., 2017)

Figure 3 describes the relationship between mobility and doping that can be applied to diode lasers. Increasing the doping decreases the mobility of the charge carriers in the laser diode. The relation between the mobility and the carrier lifetime τ is expressed through equation 1:

$$\mu = \frac{e\tau}{m*} \tag{1}$$

Thus, the carrier lifetime decreases when the doping increases. Using Einstein’s relation (equation 2)

$$L_D = \sqrt{D\tau} \tag{2}$$

we see that the diffusion length of the carrier is directly proportional to the square root of the carrier lifetime. When the carrier lifetime is high, there is greater probability and chance for radiative recombination of electrons. Note that a high doping profile does not translate to the emission of fewer photons as doping introduces a greater number of charge carriers that can recombine. Though if the diode contains an unwanted dopant that hinders the efficiency of the laser, we can increase the temperature of the semiconductor to recover its intrinsic behavior lost from doping (particularly the mobility). This can be seen through equation 3 which determines the intrinsic concentration of a particular semiconductor.

$$n_i = \sqrt{N_c N_v e^{(\frac{-E_g}{2kT})}} \tag{3}$$

The density of states in the conducting band and valence band are determined by equations 4 and 5 respectively.

$$N_c = 2(\frac{2\pi m_n^* kT}{h^2})^{3/2} \tag{4}$$

$$N_v = 2(\frac{2\pi m_p^* kT}{h^2})^{3/2} \tag{5}$$

Taking the limit as T$\rightarrow \infty$, the result is $n_i \rightarrow \infty$. Thus, n_i will always be larger than whatever dopant was initially found in the semiconductor. A similar property can be found with a solid-state laser.

In the solid-state laser utilizing a Fabry Perot Cavity, the round trip gain is defined as equation 6

$$G_c^2 = e^{\frac{-T}{\tau_c}} \tag{6}$$

Having a round trip gain of $G_c = 1$ implies perfect efficiency. To achieve this, equation 7 is used

$$e^{\frac{-T}{\tau_c}} = 1 \tag{7}$$

Taking the limit as $\tau_c \rightarrow \infty$ while holding temperature constant we get that $G_c = 1$. On the other hand, when we hold τ_c constant and vary the temperature, we find that when $T \rightarrow \infty$, $G_c = 0$. This agrees with the observations made by Dr. George F. Smith where it was said that most solid-state lasers require cryogenic temperatures in order to operate in the continuous wave regime if a Kerr cell is not present in its operation (Byoir, 1965). Therefore, at absolute 0, $T = 0K$, $G_c = 1$. That isn't to say that that noncryogenic temperatures do not benefit the solid-state laser since increasing the temperature of the devices results in the domination of homogeneous broadening. This brings every atom closer to exhibiting similar properties to one another (almost like how intrinsic semiconductors can dominate impurities). A broader transition line results in a larger range of wavelengths that can be used for recombination. Inhomogeneous (usually Doppler broadening) broadening also broadens the range of acceptable wavelengths from the source. The problem with inhomogeneous broadening is that the photons that exit the device are not guaranteed to be in phase with each other since atoms can have distinct properties in the plasma with this type of broadening. This becomes a problem for the application of lasers using solid semiconductors since they are made to exhibit the monochromaticity property.

III. Results and Discussion

A. Doping and Temperature Dependence

Increasing the dopant in either laser type will increase the amount of carriers that can recombine to emit a photon, but will decrease the diffusion length. This results in less time for a carrier to recombine.

On the other hand, increasing temperature in a diode laser can bring the semiconductor closer to its intrinsic form. At some high temperature, the doping concentration can be overwhelmed by the intrinsic concentration resulting in a restored diffusion length, but reverts the benefits introduced by doping. As for solid-state lasers, increasing temperatures can result in homogeneous broadening. Under homogeneous broadening, atoms contain very similar properties which help keep light in phase to satisfy the monochromatic property of lasers.

IV. Conclusion

Depending on the mode of operation, high temperatures may be favored over low temperatures (and vice verse). A balance between doping and temperature should be applied in order to maximize efficiency in the laser design.

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