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Semiconductor Lasers: a Comparative Study

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1 Introduction

The goal of this experiment is a comparative study of in-plane semiconductor laser diodes and Vertical-cavity surface-emitting lasers diodes, short VCSEL. The studied characteristics are the threshold current as well as the spectrum and their temperature dependence and the slope efficiency. Furthermore, advantages of these characteristics are discussed for real life applications.

2 Theory

2.1 Basic laser principles

The term laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The basic and main properties of beams of light produced by lasers are that they are monochromatic, coherent and highly collimated.

Basic quantum mechanics tells us that under the right circumstances an electron can go from its ground state (lowest-energy orbit) to a higher (excited) state, or it can decay from a higher state to a lower state. These energy states are quantified. For an electron to jump to a higher energy state, the atom must receive energy from the outside world. This can happen for example by absorbing energy in the form of electro- magnetic radiation, i.e. absorbing a photon, whose energy is given by $E = \hbar\omega = \frac{hc}{\lambda}$. When an electron drops from a higher state to a lower state, the atom must give off energy, either as kinetic activity (non-radiative transitions) or as electro-magnetic radiation (radiative transitions). In the latter case, it emits a photon whose wavelength is given by the difference between the two energy states, i.e. $\lambda_{\text{photon}} = \frac{hc}{\Delta E}$.

The basic mechanism of a laser is determined by three different processes.

The process of an electron decaying from an excited energy state to a lower energy level, thereby emitting a photon is "spontaneous emission". The photon is emitted in a random direction and with a random phase.

The second process is called "stimulated emission". Let us suppose we have an electron in an energy state E_2, which will most probably decay to a lower energy level E_1. If a photon with an energy $E_{\text{ph}} = E_2 - E_1$ is absorbed, there is a non-negligible probability that the decaying of the electron will produce an additional photon which is emitted at exactly the same wavelength, in exactly the same direction, and with exactly the same phase as the passing photon.

The last process is called "absorption", whereby an atom absorbs an photon, which excites an electron to a higher energy state. These three processes are illustrated in figure (1).

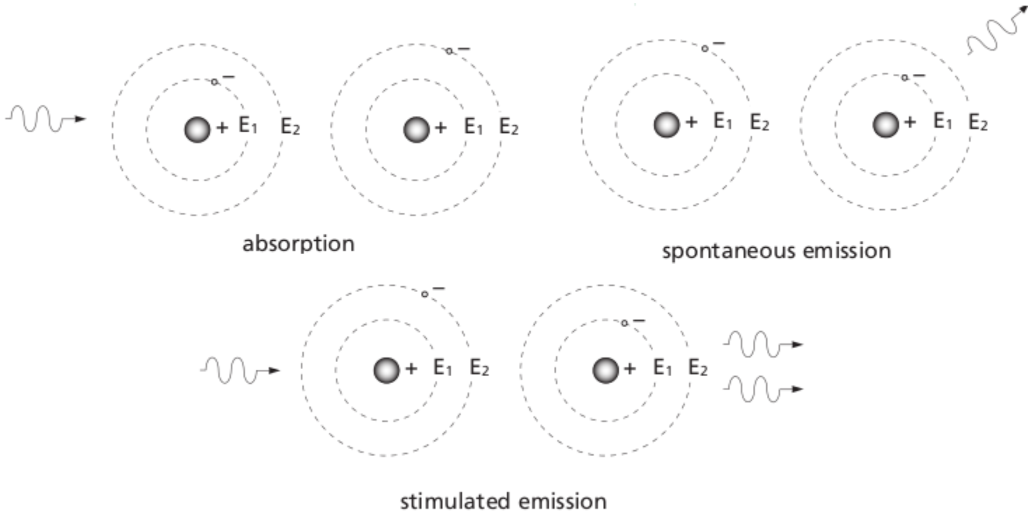


Figure 1: Illustration of spontaneous and stimulated emission, as well as absorption. [1]

The most simple model of a laser works as follows: Let us consider a group of atoms, all in exactly the same excited state. An incoming photon interacts with the first atom, causing stimulated emission of a coherent photon; these two photons then interact with the next two atoms in line. This causes a "chain reaction", illustrated in figure (2), which produces a large amount of coherent photons, all with identical phases and all traveling in the same direction, thereby "amplifying" the initial photon. The energy to put these atoms in excited states is provided an external energy source.

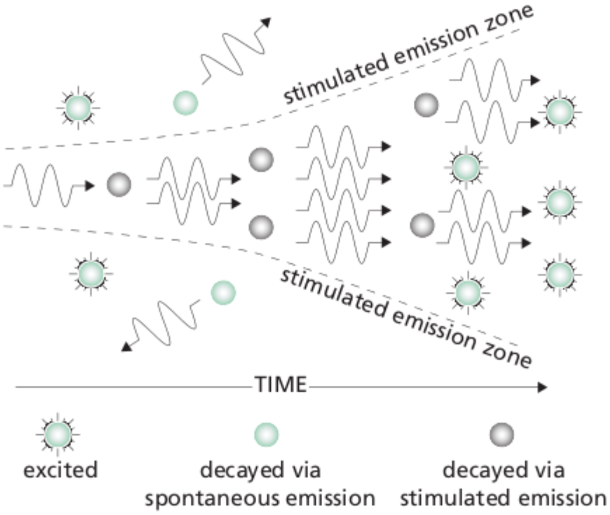


Figure 2: Amplification by stimulated emission. [1]

In a general case, there are always more atoms that have a lower energy level rather than higher one. If we assume that the probability for an individual atom to absorb a photon is higher than the probability for an excited atom to emit a photon through stimulated emission, a collection of atoms will rather absorb than emit, therefore inhibiting amplification. It is therefore necessary to increase the population of excited atoms. This process is generally called "population inversion".

As mentioned above, most of the excited atoms in the population emit spontaneously and therefore do not contribute to the overall output. To gain the significant amplification needed for a laser, a "positive feedback mechanism", i.e. a mechanism that ensures that most of the atoms present in the lasing medium contribute to the amplification, is essential. This system is called the resonator, which basically consists of two mirrors (one totally reflecting and one partially reflecting), which reflects the photons back into the excited population for further amplification.

2.2 Laser diodes

2.2.1 In-plane semiconductor lasers vs. VCSEL

VCSEL stands for vertical-cavity surface-emitting laser. It is a type of semiconductor laser diode which emits a laser beam perpendicularly to its surface, as opposed to the conventional in-plane laser diodes, which emit by layers, i.e. parallel to the surface. Figure (3) illustrates the two different types of laser diodes.

VCSEL diodes have a number of advantages, particularly during fabrication: VCSEL can be controlled during the process of fabrication and because VCSELs emit perpendicularly to their surface, it is possible to create matrices of several thousands of VCSELs on a single material layer.

2.2.2 Laser diode characteristics

A laser diode is a laser whose active medium is a semiconductor similar to that found in a light-emitting diode. The output optical power varies as a function of the current passing through the diode. If the current passing through the diode is below a threshold current I_{th}, the output power is quasi null. As the current increases over the threshold I_{th}, the output optical power increases significantly at a sharp slope.

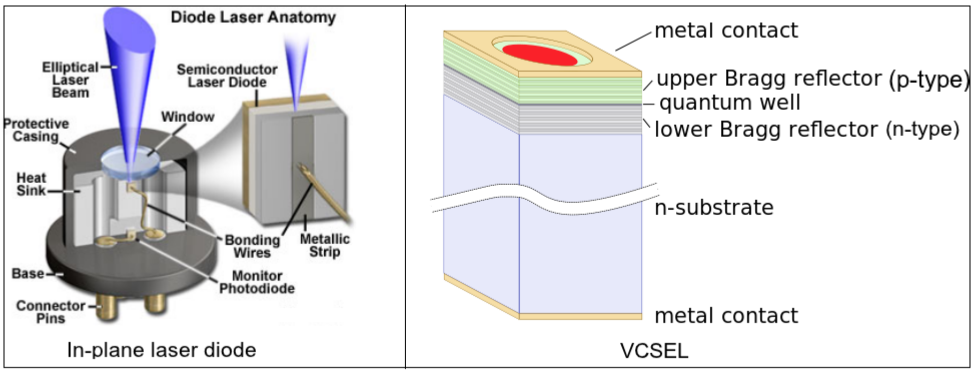


Figure 3: Scheme of an in-plane laser diode and a VCSEL. [1]

The main characteristics of a laser diode are:

- Temperature dependence of the threshold current: The threshold current of laser diodes can have a strong dependence on temperature. For normal laser diodes, there exists an empirical relationship between the threshold current and the temperature:

$$I_{\text{th}} = I_0 e^{\frac{T}{T_0}} \tag{1}$$

  where T_0 is the characteristic temperature of the diode. This phenomenon can be attributed to the fact that as temperature increases, the non-radiative processes in the device would increase and compete with the system for photons (see [2]).

- Slope efficiency: given by the slope of the curve, when the current is superior to the threshold current.

- Temperature dependence of the spectrum: The spectrum of a laser is generally a narrow peak at a single wavelength. The position of the peak as well as the width of the spectrum can vary with temperature.

3 Experiment Procedure

The experiments were conducted as described in the original lab notices [3] and [4]. Furthermore, as to document our personal experiences and help future experimenters, we wrote a complement to the notices [5].

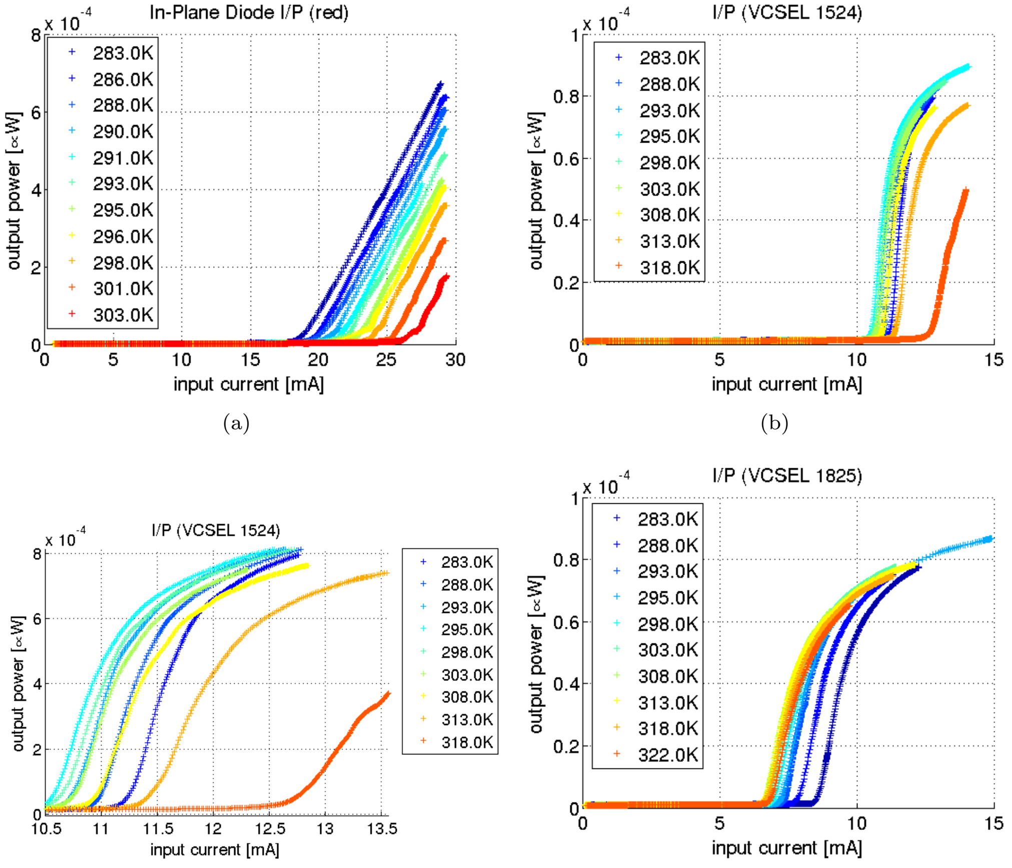
4 Results

This section presents our results obtained for studying the diodes' different characteristics.

4.1 Output Power - Input Current Curves

Figure 4 shows the I/P curves obtained for in-plane diodes and VCSELs. It should be noted that the power scale is proportional to Watts (notice the "$\propto$" symbol). This is because the photo diodes used to measure the output powers were not located directly adjacent the lasers (due to physical constraints arising from the way the lasers were mounted). Furthermore, stray light may have influenced the power readings. However, as all experiments were conducted in the same environment, the error on the measurements should be the same for all experiments, hence the proportionality.

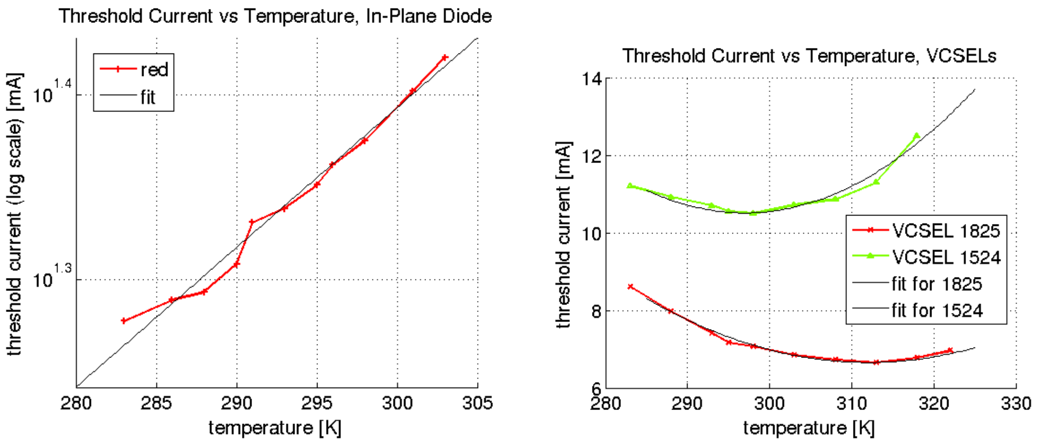
The threshold currents of the obtained curves clearly depend on temperature. Therefore, a good way to determine the behaviour of that current, is to plot it as a function of temperature.



(a) (b)

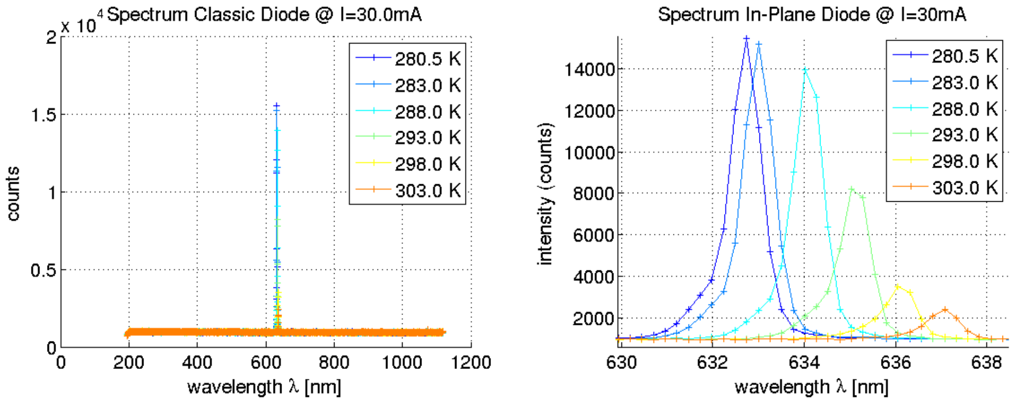
(c) Zoom of (b) (d)

Figure 4: Output power vs input current of in-plane laser diode and two different VCSELs (the numbers given for the VCSELs are their respective coordinates on the matrix, i.e. 1524 is the diode located at row 15 and column 24).



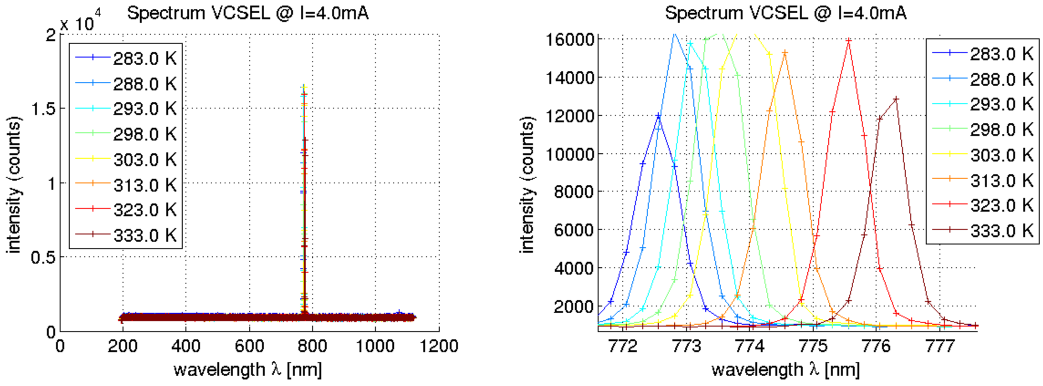
(a) (b)

Figure 5: Threshold current as a function of temperature, including fits. *Note the logarithmic y-scale on figure (a)*



(a)

(b) zoom



(c)

(d) zoom

Figure 6: Temperature dependency of the spectra of in-plane diodes ands VCSELs. Figures (b) and (d) show zooms of the spectra.

This is done in figure 5. Furthermore, fits are computed to determine the nature of the behaviour (refer to section 5 for a discussion on the current relation to temperature).
The results obtained in this section will also be used to study the slope efficiency.

4.2 Spectra

The spectra obtained for an in-plane diode as well as for a VCSEL are shown in figure 6. The spectra were obtained under a varying temperature and constant current.

5 Discussion

5.1 Threshold current

Considering the obtained results, it is clear that the current at which the diodes start emitting laser (i.e. the threshold current), depends on temperature. This dependency is different for in-plane diodes and VCSELs.

First of all, the threshold current of an in-plane diode varies about 7mA for a temperature variation of 20K, whereas the VCSELs only vary a maximum of 3mA for about 40K. This means that a VCSELs threshold current is about 4 times less temperature sensitive than its in-plane counter-part.

Second, the variation, as shown in figure 5 depends differently on temperature. Computing an exponential fit such as the one described in theory

$$I_{th} = I_0 e^{T/T_0} \tag{2}$$

yields the values of $I_0 = 15.45$mA and $T_0 = 57.4$K, with an r^2 value of 0.98. On the other hand, the best fits for the VCSELs' threshold currents are given by

$$I_{th} = \alpha + \beta(T - T_{min})^2 \tag{3}$$

with the parameters given respectively: $\alpha = 6.656$mA, $\beta = 0.00226$mA/K^2, $T_{min} = 312$K, $r^2 = 0.99$ in the first case, and $\alpha = 10.51$mA, $\beta = 0.00407$mA/K^2, $T_{min} = 297$K, $r^2 = 0.95$ in the second case. This follows the empirical law given in [6], and reinforces the observation that the threshold current of VCSELs varies less with temperature than in-plane diodes.

Finally, an interesting point to notice is that the two tested VCSELs show different threshold currents even though they were on the same matrix. This shows that even though fabricated in bulk, VCSELs need to be tested individually to confirm compliance with a required threshold current.

5.2 Slope efficiency

Another important characteristic that can be derived from the I/P figure, is the slope efficiency of the diodes. This characteristic indicates how "fast" the power increases with current once the diode starts emitting laser. In the cases of both in-plane diodes and VCSELs, the slope of power to current is linear above but near the threshold current for any temperature. However, only in the case of VCSELs, as the current increases the slope seems to converge and the power attains a maximum. This flattening was unobservable for the in-plane diode since the maximum current was limited due to the experiment setup, however it may still exist (further experiments would have to be conducted). Nevertheless, it can still be observed that the VCSELs have a higher slope efficiency but attain a lower maximum power.

Also, the obtained results show that the slope efficiency does not depend on temperature (i.e. the slopes are the same for a given diode for all temperatures). However, a wider range of temperatures would have to be measured to confirm this observation.

5.3 Spectrum temperature dependence

The last tested characteristic is the temperature dependence of the diodes' spectra. In both cases, it can be seen that the spectrum is very narrow (for any temperature) which conforms to the properties of lasers. The width of the spectrum also stays constant with respect to temperature. However, it shifts to longer wavelengths with increasing temperature. This shift is present in both diodes, however it is more acute in the case of the in-plane diode. The mean spectrum shift per temperature ($\frac{\Delta\lambda}{\Delta T}$) is of 2nm/K in the case of the in-plane diode and of only 0.07nm/K in the case of the VCSEL.

6 Conclusion

This report studied the temperature dependence of three important characteristics of lasers for two different types of diodes. It can be concluded that vertical-cavity surface-emitting laser diodes are generally less sensitive to temperature than classic, in-plane diodes.

As heating, hence temperature variation, occurs whenever a laser is operated, VCSELs gain advantage over in-plane diodes in applications that require high precision lasers, since less or no active cooling is required to maintain a given characteristic. As an example, consider a laser interferometer or a DVD/Bluray reader. These devices require a precise knowledge of the lasers wavelength as to insure an accurate distance measure, or in the case of a reader, to enable a high data density. However, as the laser heats up its spectrum shifts and interferes with operation. As VCSELs have a lower spectrum shift than in-plane diodes, these types of diodes may enable better operation with no need of active cooling.

However, in applications where high power lasers are required, the results in this report show that VCSELs are not the preferred solution since they saturate faster at a lower power than in-plane diodes. Nevertheless, our results aren't conclusive (as we did not measure the maximum power of both diodes) and further experiments would have to be conducted.

References

[1] "Basic Laser Principles." `www.bgu.ac.il/~glevi/website/Guides/Lasers.pdf`, 2012.

[2] "What is a diode?." `http://www.askkia.com/articles/what-is-a-diode.html`, October 2012.

[3] R. Hannema and A. Kuonen, "Notice TPA: VCSEL," September 2012.

[4] R. Hannema and A. Kuonen, "Notice TPA: Comparaison de lasers a semi-conducteurs classique et VCSEL," August 2012.

[5] J. Odersky and S. Loewe, "Semiconductor Lasers: Experiment Notice Complement," October 2012.

[6] C. Chen, P. O. Leisher, A. A. Allerman, K. M. Geib, and K. D. Choquette, "Temperature Analysis of Threshold Current in Infrared Vertical-Cavity Surface-Emitting Lasers," *IEEE JOURNAL OF QUANTUM ELECTRONICS*, vol. 42, p. 1079, October 2006.

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