FYSC23

Semiconductor lab

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Abstract

The purpose of the experiment was to investigate properties of solid state materials, particularly light emitting diodes (LEDs). LEDs exploit the bandgap of semiconductor materials to emit light when voltage is applied, functioning like a reverse solar cell diode. During the experiment the threshold voltage was investigated for a white LED, in this case a blue LED with a phosphor coating. The temperature dependency and freeze-out effect was also investigated with a yellow LED, cooling it in liquid nitrogen. Furthermore, red, green, and blue LEDs where used to check if they could excite each other and produce electricity like a solar cell diode.

The result of the experiment gave the threshold voltage of the white LED to be 2.7 V, and then a linearly increasing intensity afterwards. The yellow LED showed a decrease in current and increase in intensity as well as a shift in wavelength indicating a change in bandgap due to freeze-out. Finally, the red, green, and blue LEDs showed that the bandgap of the emitting LED must be higher than the LED that is to be excited to produce any voltage.

Contents

1 Introduction

Semiconductors are becoming more and more important for our society. One important application of semiconductors is light emitting diodes (LEDs) [1] which are used in e.g. displays and lighting, but also have application in medicine. LEDs also show a much better efficiency than earlier lightbulbs, thus decreasing the global energy consumption [1], something which is becoming increasingly more important. The basic part of the LED, the pn-junction, is also used in solar cells and can be used to produce energy from light [1].

2 Theory

The bands in solid materials are energy continuums that arises in solid state materials due to the number of atoms being close to each other [1]. In semiconductors and insulators the valance band is the highest band under the Fermi energy and where the electrons are bound to the atoms. The conduction band is the lowest band above the Fermi energy, and where electrons can move freely [1]. The bandgap is the energy difference between the valance band and the conduction band and can be used to describe different materials. For conductors the bandgap is zero and electrons are free to move, for insulators the bandgap is large and a lot of energy is needed to excite an electron from the valance band to the conduction band, and for semiconductors the bandgap exist but is smaller than for insulators [1]. The definition of the size of the bandgap for insulators and semiconductors is a bit arbitrary, but is usually said to be around 3 eV [1].

Semiconductors, as stated in the previous section, have a bandgap under 3 eV but above 0 eV. This bandgap can easily be excited and opens up for many applications [1]. One example is exciting the bandgap using light absorption from the sun to produce a voltage and thus energy. Applying a bias to a semiconductor can be used to excite the bandgap. Depending on the direction of the direction of the bias, the band can be increased or lowered. If an electron is excited from the valance band to the conduction band, a hole is left in the valence band which behave as a positive particle [1]. If an excited electron receives more energy then the band gap, it will thermalize in the conduction band and lose energy to phonons and then eventually recombine with a hole in the valance band, resulting in a photon of the energy corresponding to the band gap [1].

Doping is a process where impurities are added to a semiconductor to change its properties. Usually the impurity atom either have one more electron than the semiconductor atom, or one less electron [1]. If the impurity has one more electron it is called a donor and if it has one less it is called and acceptor. If it is a donor that is added the doping is called n-type, and for an acceptor it is called a p-type. The effect on the semiconductor is mainly that the bandgap will change, by adding either a donor state just below the conduction band or an acceptor state just above the valance band [1]. The binding energy of the extra electron or hole is on the order of the thermal energy at room temperature. Thus, donor or acceptor atoms can be easily ionized. However, at low temperatures, this ionization does not occur. If a semiconductor is cooled sufficiently, it will experience freeze-out, where the effects of doping disappear, effectively restoring the intrinsic bandgap [1].

A pn-junction arises when connecting a p-type and an n-type semiconductor. The electrons in the donor states in the n-type will combine with the holes in the acceptor states in the p-type, creating a depletion zone. This zone will be negative on the p-side and positive on the n-side creating an electric field, stopping further diffusion of electrons and holes [1]. The electric field will create a drift current from the p-side to the n-side, while the abundance of electrons on the n-side will create a diffusion current from the n-side to the p-side. In equilibrium these currents will be equal. If a forward bias is applied the n-side electrons will have a lower potential barrier to overcome and the diffusion current will increase [1]. For a reverse bias, the potential barrier will increase and the diffusion current decreases.

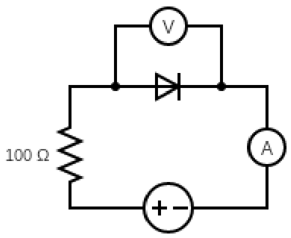
An LED is a pn-junction where the recombination of electrons and holes emit light. This light is directly proportional to the bandgap energy [1]. Thus, by using specific semiconductors and doping the bandgap energy can be controlled and thus the light that is emitted. Thus, an LED and a solar cell diode are very similar, and an LED will produce a current when light is shone on it [1], if the light is energetic enough.

3 Experiment

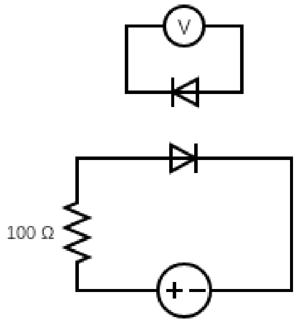
During the first part of the lab, we measured the intensity of a white diode at different voltages. The white diode was a violet diode, covered in a phosphorus layer that emitted a white spectrum. The voltage was controlled through a DC source, as shown in Figure 1a. Twelve measurements were taken of the voltage from the DC source, the voltage across the diode, the current through the circuit, and the intensity. The measurements were taken evenly between 1 to 9 V. The intensity of the diode was evaluated through an glass fibre cable placed directly above the diode. The intensity was displayed in a computer program called AvaSoft, where counts for different wavelengths were shown. The intensity was determined by evaluating the intensity at the largest peak. The integration time used was 70 ms, which involved averaging every 10th measurement.

In the second part, the same circuit was used; however, this time a yellow diode was employed instead. The fibre optic cable was taped directly onto the diode. One measurement was taken of the voltage from the DC source, the voltage across the diode, the current through the circuit, and the intensity. A screenshot was also captured of the spectrum in the AvaSoft program. Keeping the same voltage from the DC source, the diode was placed in liquid nitrogen, and a similar measurement was taken.

In the last part, another circuit was used, as seen in Figure 1b. This time, neither an ammeter nor a voltmeter was used in the main circuit. Instead, a separate circuit was implemented with a diode and a voltmeter connected in parallel. The integration time was changed to 2 ms. The DC source was turned on until the diode in the main circuit shone brightly. The other circuit was then placed close to the main circuit to check if the diode in the smaller circuit registered any voltage. This procedure was repeated for all combinations of red, green, and blue diodes.



(a) This sktch shows the circuit for part 1 and part 2.



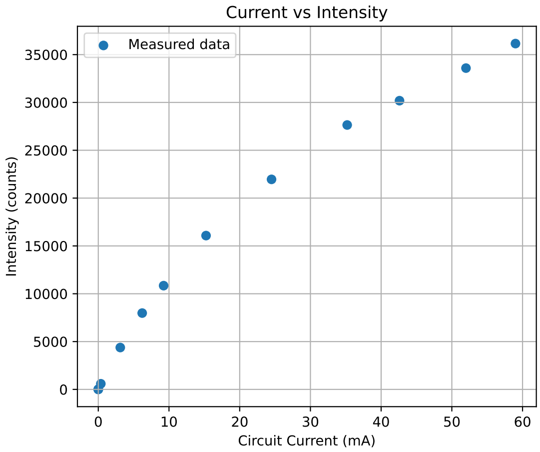
(b) This sktch shows the circuit for part 3, with the two different diodes.

Figure 1: Above one can see the circuits used in this lab. Both circuits used an resistor with 100 .

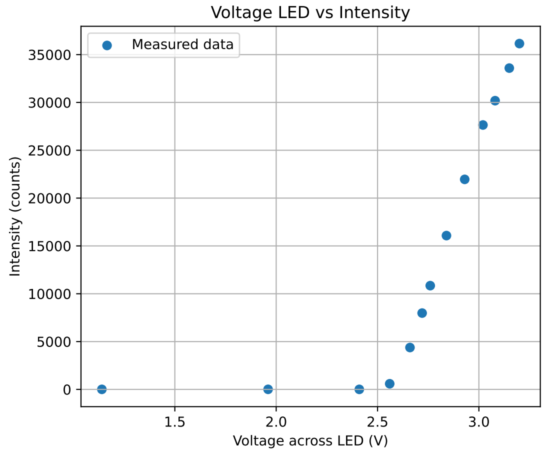
4 Result

4.1 Part 1

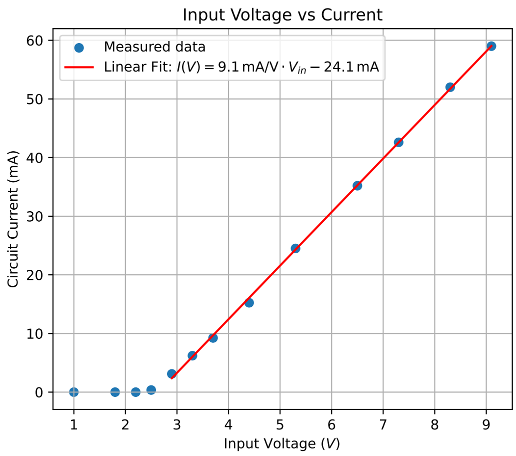
In the first part the peak which was measured from the white diode was located at 454.17 nm. Using the data obtained from the measurements Figure 2 was obtained. From the linear fit in Figure 2a one can see that that the linear fit intersects the x-axis at $V_{\text{in}} = 2.7\,\text{V}$. This means that a voltage under this value would yield no current output, which can be seen in the figure. Thus, one can conclude that the forward bias is $V_{\text{in}} = 2.7\,\text{V}$.



(a) This plot displays the itensity of the LED over the current in the circuit.



(b) This plot displays the itensity of the LED over the voltage across the LED in the circuit.



(c) This plot displays the current in the circuit over the voltage from DC-source. A linear fit was used for the non-zero measurements, since this fit would be used to calculate the forward bias.

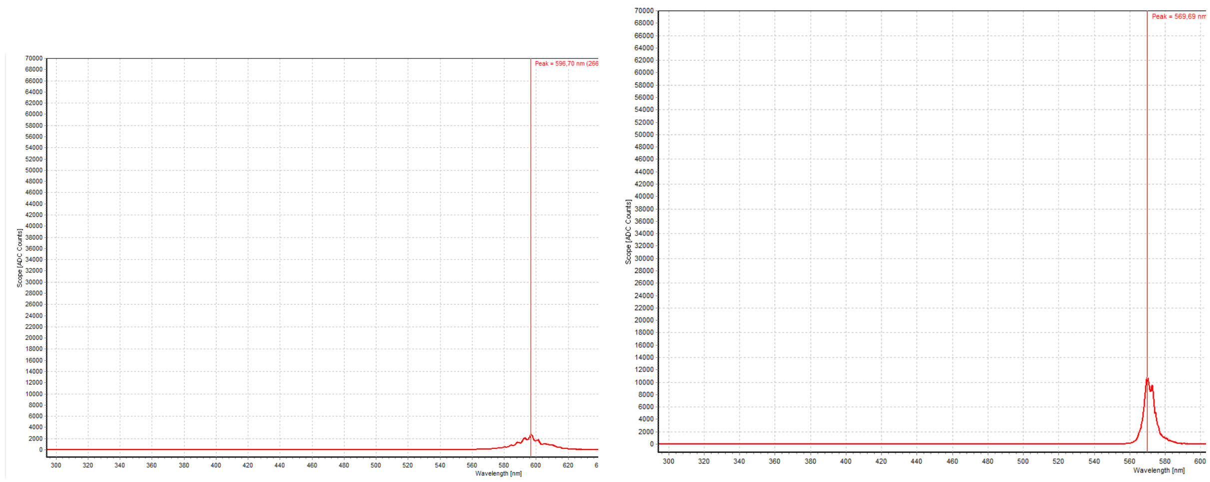
Figure 2: Plots of the measurements.

4.2 Part 2

The measurements from the circuit before was combined with the measurements from the program, as seen in Figure 3, in Table 1. Notably the wavelength of the peak shifted, and the intensity increased when the diode was submerged in liquid nitrogen.

Table 1: This table shows the measurements.

Measurement	V_{in} (V)	V_{LED} (V)	$I_{circuit}$ (mA)	λ_{peak} (nm)	Intensity (counts)
Room temperature	5.0	2.06	30.8	596.70	2663.70
Liquid nitrogen	5.0	4.44	7.7	569.69	10757.70



(a) This was the output from the program at room temperature.

(b) This was the output from the program when submerged in liquid nitrogen.

Figure 3: This figure display the output from AvaSoft at the different measurements.

4.3 Part 3

The result from the different diode constellations as detectors and emitters can be seen in Table 2. The table shows that shorter wavelength diodes can excite longer wavelength diodes, but not the other way around.

Table 2: This table displays which combinations of detectors and emitters yielded an voltage output from the diode in the smaller circuit.

Emitter | Detector:	Red	Green	Blue
Red	Output	No output	No output
Green	Output	Output	No output
Blue	Output	Output	Output

5 Discussion

5.1 Part 1

The emitted light has two main peaks. One peak was in the blue part of the spectrum while the other, broader peak was at the yellow part of the spectrum. This combination appears white to our eyes. The reason for the yellow peak is that the inside of the LED is coated with phosphor which is excited by the LED and then re-emit light in the yellow part of the spectrum.

After the threshold voltage is reached the current increases linearly with the voltage. The reason is that the amount of electron-hole pairs created is proportional to the energy deposited by the voltage. The voltage need to be applied in the forward direction to shin because there is no diffusion current in the reverse direction, and it is this current that recombines to emit light.

The intensity of the light increases with increasing current and voltage, which is expected since this increases the amount of electron and thus the rate of recombination. More recombination means more light Different coloured LEDs have different bandgaps and the threshold voltage will therefore be different. For white LEDs a blue or preferably violet is preferred since this excited the phosphor and the resulting light is white.

5.2 Part 2

The current drops when the sample was dropped into liquid nitrogen, which is due to the fact that the resistance is correlated with the temperature. Thus a much lower temperature gave a lower resistance, and thus a lower current. The light emission intensity increased when submerged. This is due to low temperature results in fewer phonons and thus less phonon scattering. Thus a low temperature means more electron- hole recombination, and thus more light emission.

The change in wavelength of the LED corresponds to the low temperature implying a freeze out of the LED. This means that the donors/ acceptors does not have enough energy to get ionized and no doping occurs. Thus the band gap is increased, implying a lower wavelength of the emitted photons. This freeze out phenomenon should effect all doped materials.

5.3 Part 3

For a diode used as a solar cell the bandgap should be small enough to absorb as much light as possible from the sun's spectrum, but large enough to extract energy. Too small of a bandgap will be easily excited but after thermalization of the election most of the energy is gone and turned to heat and cannot be used for electricity generation, while too large of a bandgap will not be excited enough by the light. For the LED's tested in the lab, the best one would be the red LED since it will be excited by the largest points of the sun's spectrum, and is still sufficiently great to extract energy from the excited electron. The other colours would absorb too small of a fraction of the sunlight to be efficient.

6 Conclusion

To conclude, this lab, we investigated the properties of LEDs through various measurements. By examining the relationship between voltage, current, and emitted intensity we were able to find the forward bias of the LED. Furthermore, we saw how a temperature decrease affected the LED through a freeze out. This freeze out demonstrated that the removal of the doping resulted in a wider bandgap and a shorter wavelength. The absorption of semiconductors was also discussed where the mechanism of solar power was discussed. Thus the different characteristics of LEDs was examined.

References

[1] Philip Hofmann. *Solid State Physics: An Introduction.* Wiley-VCH, 2nd edition, 2015.