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The University of Sheffield
Electrical and Electronic Engineering

Light Emitting Diode – Lab Report

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2 Introduction

The Light Emitting Diode (LED) Laboratory aims to give students the opportunity to gain the basic practical skills used whilst working in a clean room. The primary objective is to understand and consider the health and safety factors of working in clean room (hazardous chemicals, high temperature equipment); this understanding should be exercised whilst completing the fabrication of an LED using the Indium Dot process to form a top metal contact on the device. The current-voltage (I-V) characteristics of the fabricated device will be measured to provide experience using a probe station and source measurement unit (SMU). The electrical and optical characteristics of commercial LEDs will be measured using an SMU, Spectrometer and Optical Power Meter. These experimental results will be related to the theoretical material from the devices section of module EEE118 to reinforce key theoretical concepts with practical experience.

3 Background

LEDs are widely used in a multitude of technologies, such as communications and motion detection. In recent years they have been increasingly used in commercial products such as car headlights/indicators and smartphone camera flashes. They are replacing other available light sources (Compact Fluorescent Bulb, Incandescent Bulb) due to their higher power efficiency (a high percentage of the input power is converted to output light as opposed to being dissipated as heat), wide available package sizes (SMD to cabinet mount) and high reliability [1, pp. 62, 76]. These characteristics make them easier to integrate into small or low power systems and reduce maintenance costs due to increased component lifetimes.

4 Theory

The theory section aims to explain in basic terms how an LED operates, the current-voltage characteristics of an LED, conversion efficiency and semiconductor wafer growth. Sufficient detail to understand the conclusions of this report will be given.

4.1 LED Operation

LEDs are formed by producing PN (P-type to N-type) or PIN (P-type to Intrinsic to N-type) junctions from specific compound semiconductors from group III-V such as Gallium Nitride (GaN) and Gallium Phosphide (GaP) [1, p. 76]. When a forward bias voltage is applied to the LED the potential barrier is reduced, allowing electrons and holes to flow through the depletion region and recombine with the majority carriers in the p-type and n-type regions respectively [2, p. 211]. This recombination releases excess energy. Direct bandgap semiconductors are used to ensure that this excess energy is released as a photon of visible light. This photon release mechanism is shown using the electron energy states in **Figure 4.1**.

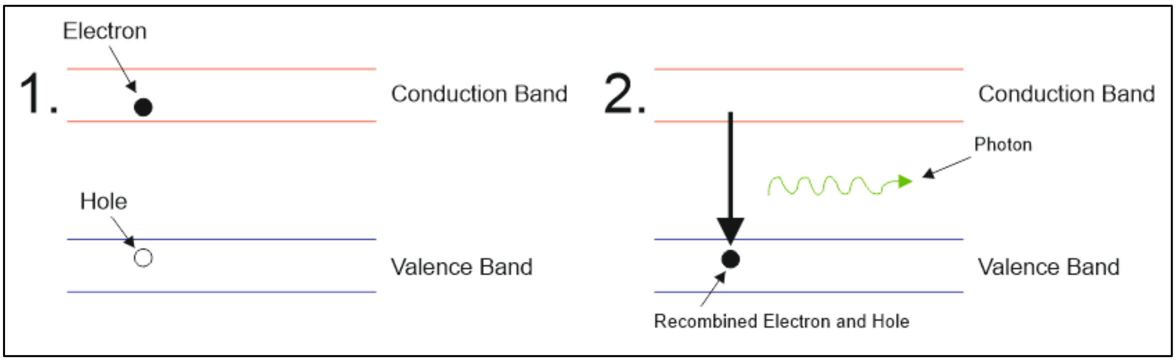

Figure 4.1: Electron Energy Diagram

4.2 LED Current-Voltage (I-V) Characteristics

The current-voltage (I-V) characteristics of the LED stem from the Shockley Diode Equation; this equation is an algebraic representation of the current flow in a Diode. The Shockley Diode equation is as follows [2, p. 206]:

$$I = I_0 \left(e^{\frac{eV_f}{k_B T}} - 1 \right) \tag{1}$$

Where I_0 is the Reverse Bias Saturation Current, V_f is the Forward Bias Voltage and T is the Temperature in Kelvin. This equation shows us that at a constant temperature, the current flowing through a diode increases exponentially with voltage. In practice an LED also has a resistance value, as a result real world experimental data will have a linear component of current increase with voltage.

4.3 Conversion Efficiency

The conversion efficiency refers to the percentage of input power that is converted to visible light. The conversion efficiency can be calculated using the following equation:

$$Conversion\ Efficiency = \frac{P_o}{V_f I_f} \times 100 \tag{2}$$

Where P_o is the optical power of the LED, V_f is the Forward Bias Voltage and I_f is the Forward Bias Current. The conversion efficiency allows us to compare the operation of LEDs to other sources of light such as incandescent bulbs and compact fluorescent bulbs.

4.4 Semiconductor Wafer Growth

Although the exact process of fabricating semiconductor wafers is outside the scope of this report it is important to note the processes that can be used to produce these wafers. One of two growth methods can be used: metalo-organic vapour phase epitaxy (MOVPE) or molecular beam epitaxy (MBE).

The pre-prepared wafer used to fabricate the LED in this experiment was comprised of an n-type Gallium Arsenide (GaAs) substrate, n-type Aluminium Gallium Indium Phosphide (AlGaInP) bottom layers, central intrinsic layers and p-type Aluminium Gallium Indium Phosphide (AlGaInP)/Gallium Indium Phosphide top layers. This forms a PIN junction. The intrinsic semiconductor is used to form a potential well that the charge carriers fall into, increasing the rate of recombination and thus the amount of light emitted.

5 Method and Results

This section discusses the process of fabricating the LED, recording the fabricated LED I-V curve, electrically testing commercial LEDs and optically testing commercial LEDs. The results for each experiment will be given following each method, discussion of these results can be found in the discussion section.

5.1 LED Fabrication Process

Firstly, the p-type (top) surface of the pre-prepared semiconductor wafer section was found by looking for the dark grey surface that did not have a gold coating. A small sample of Indium was cut with a scalpel using a piece of glass as a cutting board; ideally the cut Indium should be no more than $1mm^2$ in area. Indium is used as it is soft, allowing it to be more easily cut and bonded to the semiconductor wafer. The sample of Indium was placed in the centre of the p-type side of semiconductor wafer section as identified previously and pressed down with tweezers to ensure good contact. Finally, the wafer is placed on a hot plate set to 230°C with the p-type side up for approximately 1 second; this melts the Indium, improving the electrical connection between the Indium and the p-type side of the semiconductor wafer.

5.2 Fabricated LED I-V Curve

The fabricated LED was placed in a probe station using a pair of tweezers. It is important to ensure the wafer is positioned so that the bottom contact (n-type) forms a good electrical connection with the base of the probe station. Using the camera or optical microscope the probes were positioned over the top of the Indium contact, the Z Axis movement dial was then used to lower the probe and form an electrical connection with the Indium contact.

The source measurement unit (SMU) was set to a compliance of 50mA and a maximum voltage of ±2V.Voltages in the range of ±2V where then applied to the LED in steps of 0.2V; the circuit current was recorded at each step. Voltages up to 3V may be required before the LED starts to emit light. If necessary increase the current compliance to 100mA. The results were then used to produce the I-V curve for the fabricated LED, as shown in **Figure 5.1**.

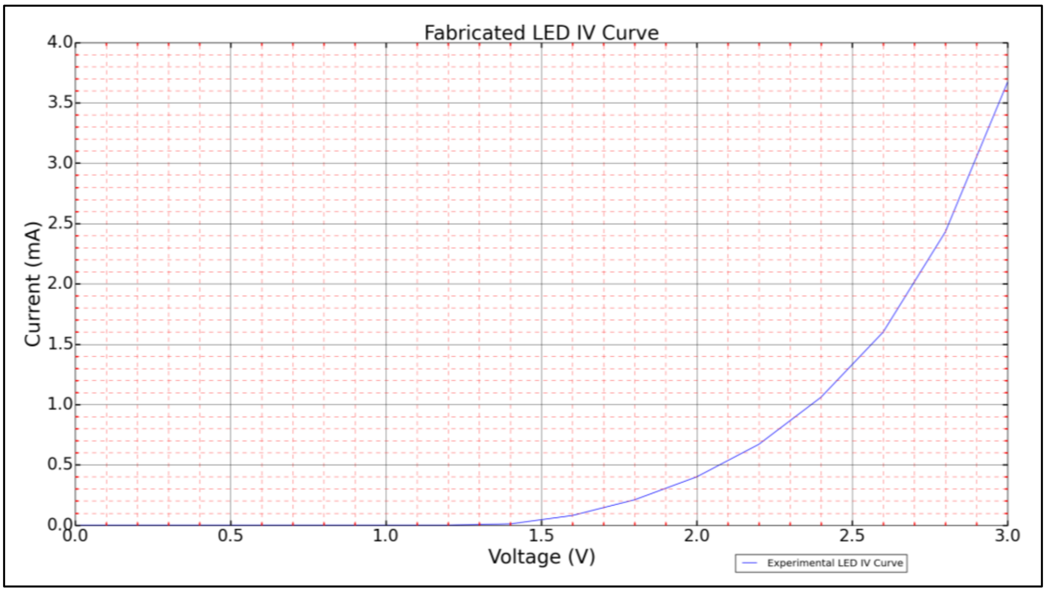

Figure 5.1: Fabricated LED I-V Curve produced using Python XY [4]

5.3 Commercial LED Electrical Tests

An SMU was set to a current compliance of 100mA; crocodile clip leads were used to supply each LED with a forward bias voltage so that the Turn on Voltage, Forward Voltage and perceived colour of each LED could be recorded. The Turn on Voltage is the voltage at which the LED first starts to emit light. The Forward Voltage is the voltage at which the LED has 50mA of current flowing through it. The results from these experiments are shown in **Figure 5.2**.

Commercial LED Testing Results				
Perceived Colour	Red	Yellow	Green	White
Turn On Voltage (V)	1.47	1.65	1.78	2.4
Forward Voltage (at 50mA) (V)	1.96	2.33	2.73	3.2
Peak Wavelength (nm)	662	582	571	458
Line Width (FWHH) (nm)	21	34.68	27.1	27.5
Optical Power (at 50mA) (mW)	0.88	0.017	0.07	1.77
Conversion Efficiency (W/W) (%)	0.009	0.00015	0.0005	0.011

Figure 5.2: Commercial LED Testing Results

5.4 Commercial LED Optical Tests

The voltage output of the SMU was set so that the current flow through each LED was 10mA; a spectrometer and its associate computer software were then used to measure the emission spectrum of the LED. It is important to ensure the input of the spectrometer does not saturate, saturation is indicated by a flat line at the top of the emission spectrum peak amplitude. The peak wavelength and line width were recorded using the data from the spectrometer, the line width was calculated using the Full Width Half Height method (FWHH).

The optical power meter was used to record the optical power of each LED in mW. During this test the voltage output of the SMU was set so that each LED had a 50mA current flowing through it. The conversion efficiency was then calculated using the formula in **Equation 2**. The results from these experiments can be seen in **Figure 5.2**.

6 Discussion

The I-V characteristics of the LED shown in **Figure 5.1** show that the LED complies with the Shockley Diode equation as outlined in **Equation 1** [2, p. 206]. The LED shows an exponential increase in forward current after the switch on voltage of approximately 1.4 – 1.5V. This switch on voltage complies with the red light the LED emitted and correlates with the 1.47V switch on voltage of the commercial red LED shown in **Figure 5.2**. As discussed in the theory section the current voltage characteristic of the LED becomes more linear between 2.6 and 3V due to the LEDs internal resistance.

The difference in turn on voltages exhibited in **Figure 5.2** is due to the different built in voltages of the PN junctions in each LED; this is due to the different semiconductor materials used to construct the PN junction in each LED. Lower band gap energy materials have a lower built in voltage [2, pp. 208, 209] and thus produce a higher wavelength of output light. Thus, the red has the lowest turn on voltage of 1.47V and the highest peak wavelength of 662nm whilst the white LED (which uses a blue LED and a phosphor to produce white light) has the highest turn on voltage of 3.2V and the lowest peak wavelength of 458nm.

The conversion efficiencies shown in **Figure 5.2** are remarkably low given that commercial LEDs can achieve upwards of 10% conversion efficiency. It is likely this is caused by a combination of the low-cost LEDs that were used and the high forward current that was used during this test generating a higher input power than necessary. The white and red LEDs were the most efficient of the tested devices with conversion efficiencies of 0.011 and 0.009% respectively. This is particularly useful for white LEDs which are widely used in lighting applications where efficiency is important (E.g. home and street lighting).

The red LED has the lowest emission line width at 21nm, whereas the yellow LED has the highest emission line width at 34.68nm. Thus, the yellow LED must have a wider range of potential energies in the conduction and valence band than the red LED; consequently, it produces a wider range of light wavelengths than the red LED.

The white LED emission spectrum shows a peak wavelength of 458nm, this falls within the blue section of the visible light spectrum. Further insight can be drawn from the example white LED emission spectrum shown in **Figure 6.1**. The white LED uses a blue LED in conjunction with a phosphor that acts as a black body radiator to produce light across the full visible light spectrum [3].

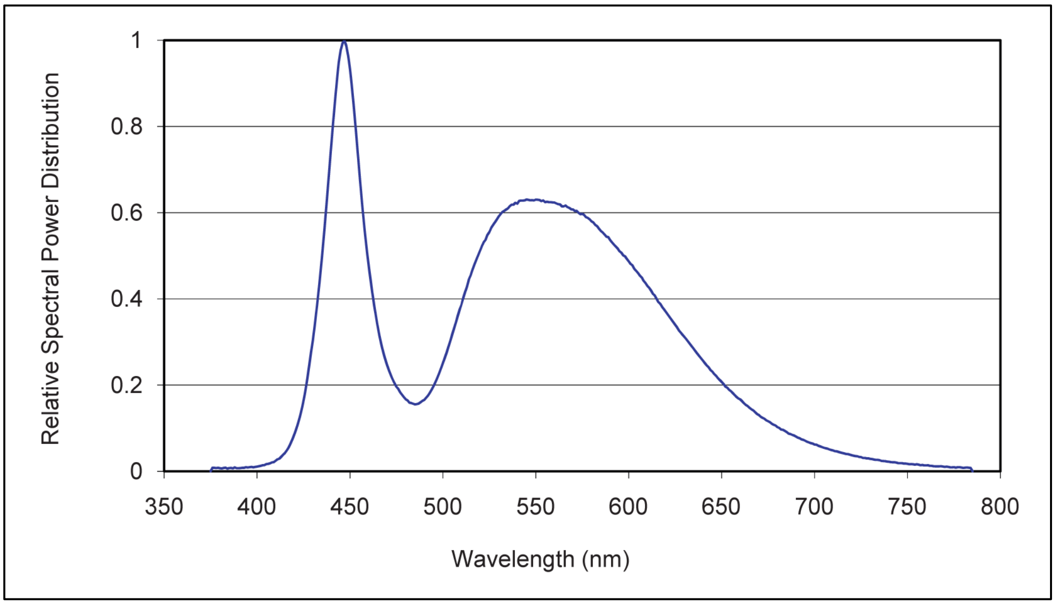

Figure 6.1: White LED emission spectrum from "nextgenlite.com" [5].

Examples of applications for each of these different LED colours are as follows: Red – Photo development room lighting, Yellow – Car Indicators, Green – Airport Runway Lights or Ship Navigation Lights, White – Car Headlights or Camera Flash.

For a manufacturer to have confidence in selling these LEDs they should perform tests to measure the LED heat power dissipation and the reverse breakdown voltage. The SMU can be used for the reverse breakdown voltage test; however, a temperature probe must be acquired for the heat power dissipation test.

During our experimentation we had two key errors. Initially the probe was not pushed down enough onto the Indium contact to form a good electrical connection, this made our original I-V characteristic curve incorrect. We also did not initially use an LED current of 50mA when measuring the commercial LED optical power, however this was rectified by changing the SMU settings.

7 Conclusion

In conclusion, the health and safety factors of working in a clean room were considered through a pre-lab activity and a conversation with the lab technician before we were given access to the clean room facility. This included outlining the clean room safety features (fire alarm, oxygen depletion alarm, gas cut-off switches) as well as the correct Personal Protection Equipment (PPE) and tools to use whilst in the lab (goggles, smock, gloves and tweezers).

Indium was successfully deposited on the pre-prepared wafer to form a top metal contact; this is shown through the measured LED I-V characteristics from **Figure 5.1** using results taken with the probe station and SMU. The I-V curve conforms to the Shockley diode equation with a switch on voltage of 1.4 – 1.5V which complies with the red light the LED emitted.

The electrical and optical characteristics of a set of commercial LEDs were measured using an SMU, Spectrometer and Optical Power Meter. The measurements were recorded in **Figure 5.2**. Several of these measured characteristics have been related to the theory discussed in the devices section of module EEE118 in **section 6**.

The measured conversion efficiency was much lower than the expected 10% or greater expected from a commercial LED with a measured range of 0.0009 to 0.011%; this is possibly due to the circuit used to drive the LEDs and the low cost of the devices being tested. The turn on voltages measured correlated with the measured peak wavelengths of the LEDs output light, showing that a lower band gap energy LED material produces a higher wavelength of light.

Finally, the white LED was shown to use a combination of a blue LED and a phosphor to produce white light [3]. This was confirmed by the emission spectra shown in **Figure 6.1**.

8 References

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