Properties of Optoelectronic Devices

ISAAC WOODARD

Abstract: The basic properties of a 1N4004 diode, FDS100 photodiode, and a blue LED were characterized. A driver circuit using an LM317 voltage regulator was then constructed and tested on a blue, a green, and a red LED. The optical power of the blue LED was found as a function of driving current. The spectra of each LED was also found and used to predict the semiconductor material of the blue and green LEDs as InGaN and the red LED as AlGaAs. The experiment culminated in the measurement of the threshold current and slope efficiency of a Thorlabs L650P007 laser diode as well as the comparison of the pre and post lasing spectra. The laser diode was found to have a threshold current of 3.6 mA and a post-lasing slope efficiency of 1.16×10^{-3} mW/mA.

1. Introduction

General Properties of Diodes

A diode is a semiconductor device created by the junction of a p-doped and n-doped semiconductor material. The doping process creates holes, effectively positive charge carries, in the p-doped material and excess electrons in the n-doped material. The combination of the two materials creates a device which resists current flow in one direction but passes it easily in the other direction [1, 2].

Fig. 1 shows a diode in both forward and reverse bias orientation. When a forward bias is applied, holes and excess electrons are pushed into the middle of the junction and combine. If instead a reverse bias is applied, the holes and excess electrons are pushed to the outer edges of the diode and current flow is vastly reduced [1–3]. A certain threshold voltage is required for the diode to pass current easily in the forward direction. A threshold voltage of 0.6 V or 0.7 V is typcial for silicon diodes [2, 4]. The I-V curve of a diode rises exponentially near the threshold voltage [2].

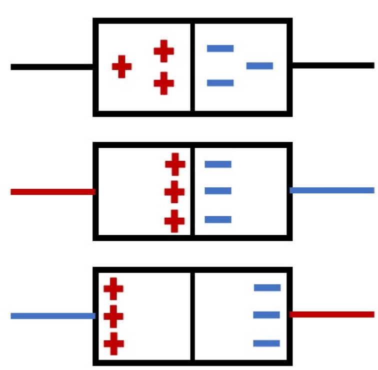

Fig. 1. A p-n junction diode with no applied bias (Top), forward bias (Middle), and reverse bias (Bottom). Holes are represented with plus signs and excess electrons are respresented with minus signs.

The voltage drop across a diode is most easily measured by placing it in series with a load resistor. The voltage drop across the diode V_D can then be measured by first measuring the voltage drop across the resistor. This can be done with a voltmeter or with an ammeter connected in series and Ohm's law. Applying the Kirchhoff Loop Rule then gives an expression for the diode voltage,

$$V_D = V - IR, \tag{1}$$

where V is the voltage of the power supply, I is the ammeter current reading, and R is the resistance of the resistor [2].

The junction of the two semiconductor materials in a diode gives it capacitive properties. These properties can be measured by applying an AC signal through the diode in series with a load resistor. We can then use the AC voltage divider equation to find the impedance Z_C of the diode due to its capacitance,

$$V_{out} = V_{in}\frac{Z_C}{Z_R + Z_C} \rightarrow Z_C = \frac{Z_R}{\frac{V_{in}}{V_{out}} - 1}, \tag{2}$$

where V_{out} is the amplitude of the AC signal across the diode, V_{in} is the amplitude of the AC signal from the function generator, and Z_R is the impedance of the resistor [2]. A DC offset should also be applied to maintain the direction of the diode bias.

With the impedance of the diode we can then calculate the capacitance C,

$$Z_C = \frac{-i}{\omega C} \rightarrow C = \frac{-i}{\omega Z_C}, \tag{3}$$

where ω is the angular frequency of the function generator [2]. The factor of i can be neglected if the phase is unimportant.

Photodiodes & LEDs

The band gap between the two junctions of a diode is particularly important for optoelectronic devices such as photodiodes and LEDs (Light Emitting Diode). For a photodiode, the band gap determines the wavelengths of light which can be efficiently absorbed, and for an LED the band gap determines the peak wavelength of light emitted. The band gap energy E_g can then be equated to the photon energy E,

$$E_g = E = h\nu, \tag{4}$$

where h is Plank's constant and ν is the frequency of the photon [1].

Photodiodes can be used as a photovoltaic and as a photodetector. If the photodiode is connected to a circuit and exposed to light, the absorption of the light will combine charger carriers across the diode junction and induce current flow [1]. This effect can be used to create a voltage if the photodiode is connected in series with a load resistor. Otherwise current will flow freely from the dide anode to the cathode. We will refer to the former case as "photovoltaic mode" and to the latter case as "short-circuit mode".

The photodiode can also be used as a photodetector if it is placed in a circuit with a load resistance. A reverse bias should also be applied to increase the sensitivity of the photodiode for detecting incoming light [3]. If the responsivity r of the photodetector is known as well as the voltage drop V_O across the detector and the load resistance R_L, the power P of the incoming radiation can be calculated [5],

$$V_O = PrR_L \rightarrow P = \frac{V_O}{rR_L}. \tag{5}$$

A plethora of semiconductor compounds can be used to create LEDs which emmit light across the visible spectrum and into the infrared and ultraviolet. Ternary III-V compounds can be used to create LEDs which emit at any wavelength on the visible spectrum. The aluminum and gallium composition of AlGaAs compounds can be tuned to give wavelengths from the infrared into the orange region of the visible spectrum, while the gallium and indium composition of InGaN compounds can be tuned to give wavelengths across the visible spectrum [1]. Nitride based semiconductor compounds are particularly notable for their ability to emit light in the blue to ultraviolet range [6].

Laser Diodes

A laser diode is another optoelectronic device designed to emit light. It differs from an LED, though, in that it is designed to emit light with greater directionality and with less spread in wavelength. The key characteristics of a laser diode can be found from a graph of optical power vs. drive current, also known as an L-I curve. From the L-I curve the threshold current and slope efficiency of the laser diode can be found [7]. The L-I curve of a laser diode typically contains two distinct regions: one for pre-lasing and one for post-lasing. Lasing is the process by which the laser diode amplifies light of a certain wavelength, giving it reduced spectra width compared to an LED. Before the threshold current of the laser diode is reached, the laser diode doesn't have enough current to lase and emits much like an LED. Lasing begins once the threshold current is reached. As the L-I curve changes from the pre-lasing region to the post-lasing region, the slope changes sharply [6]. The slope of the L-I curve gives the slope efficiency, generally indicated by η and given in units of mW/mA [5].

Laser diodes tend to be more sensitive to drive currents than LEDs and are easier to damage. For this reason a voltage regulator should be used to control current flow to the laser diode. An LM317 is a voltage regulator device which can be used for this purpose. The LM317 has three pins, Vin, Vout and Vadjust. A source voltage is applied to the Vin, while the regulated voltage comes from Vout. The Vadjust pin can be used to adjust the output voltage from 1.25 V to 37 V [8]. A convenient way to make this adjustment is to connect a potentiometer and a load resistor from Vout to Vadjust so that the voltage at the Vadjust pin can be controlled by the potentiometer.

2. Experiment

The experiment was divided into three parts. In Part 1, several exercises were performed to measure basic properties of a 1N4004 diode, a blue LED, and an FDS100 photodiode. For Parts 2 & 3, a driving circuit was created utilizing a voltage regulator. The circuit was used to power an LED in Part 2 and a laser diode in Part 3 to obtain L-I characteristic curves and spectra data.

Part 1A: I-V Curve of a 1N4004 Diode

The current through a 1N4004 diode was measured for applied voltages ranging from -2 V to 2 V in 0.1 V increments. A Rigol DP1308A power supply was used to supply the voltage. The diode was placed in series with a resistor R = 501.8 Ω and Fluke 179 multimeter as shown in Fig. 2. Measurements of the voltage drop across the diode V_D were made using the current reading from the multimeter and Eq. 1.

Part 1B: Capacitance of a 1N4004 Diode

The capacitance of the same diode from Part 1A was measured by applying a sinusoidal signal with a DC offset. A Rigol DG4162 function generator was used to apply the signal. The multimeter was connected in parallel across the diode to be used as an AC voltmeter as shown in Fig. 3. The same resistor was used with R = 501.8 Ω. The frequency of the signal f was 2000 Hz and the amplitude V_{in} was 10 mV. Values for the DC offset ranged from 100 mV to 1000 mV in 100 mV increments. The AC component of the signal allowed the capacitive impedance of the diode to be measured while the DC offset applied a forward bias to the diode to control the capacitance [3].

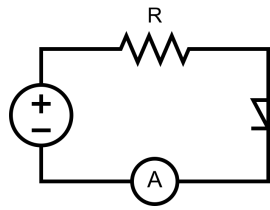

Fig. 2. A 1N4004 diode connected in series with a power supply, resistor and multimeter. R = 501.8 Ω. Schematics were made using Circuit Diagram's online editor [9].

The RMS voltage across the diode was converted to amplitude. From this the impedance of the diode was found using Eq. 2. With the diode impedance the diode capacitance was calculated using Eq. 3.

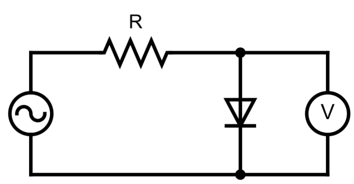

Fig. 3. A 1N4004 diode is connected in series with a function generator and resistor. A multimeter is connected across the diode as a AC voltmeter. R = 501.8 Ω.

Part 1C: I-V Curve of an FDS100 Photodiode

An FDS100 photodiode was used in place of the 1N4004 diode. The photodiode was connected in series with the same resistor R = 501.8 Ω and a DC power supply as shown in Fig. 4. The multimeter was connected in series as an ammeter. A dry erase marker cap was placed on the photodiode to prevent light induced current. Current measurements were made for supply voltages of -4.5 V to 2 V. Half volt increments were used for reverse bias and 0.1 V increments were used for forward bias. The resistor was used as in Part 1A to find the voltage drop across the diode.

Part 1D: L-I Curve of a Blue LED

The circuit from Part 1C was modified by putting a blue LED in place of the photodiode and connecting a resistor R = 501.8 Ω after the LED as shown in the left circuit in Fig. 5. The right side of Fig. 5 shows the photodiode connected in series with a load resistor and the second output of the DC power supply. A reverse bias of 2 V was applied to the photodiode to operate it as a photodetector [3]. The second multimeter was used to measure the voltage at Vout. Measurements of Vout were taken for LED currents from 0.01 mA to 5.33 mA. The supply voltage to the LED circuit was increased from 0 V to 6 V with 0.1 V increments from 2.3 V to 3 V to give special attention to the linear region of the L-I curve.

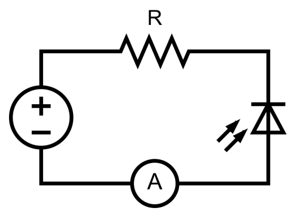

Fig. 4. An FDS100 photodiode is connected in series with a DC power supply, resistor and ammeter. R = 501.8 Ω.

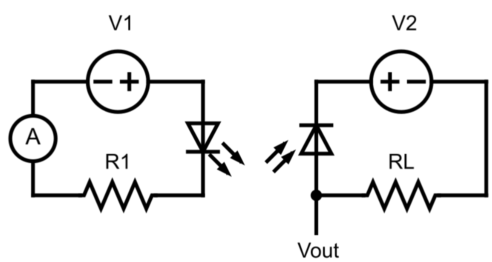

Fig. 5. (Left) A blue LED is connected in series with a DC power supply, resistor, and multimeter as an ammeter. R1 = 501.8 Ω. (Right) An FDS100 photodiode is connected in reverse bias to the second output of the DC power supply in series with a load resistor. A second multimeter was used to measure the voltage at Vout. RL = 50580 Ω.

Part 1E: Photovoltaic & Short-Circuit Modes of FDS100

The same LED circuit from Part 1D was used as shown on the left in Fig. 6. As in Part 1D the photodiode and LED were separated by 1 mm. Another circuit, shown on the right, was created with the photodiode connected directly to a second multimeter. The photodiode surface was positioned 1 mm from the LED and the ceiling lighting was switched off. The voltage and current of the photodiode was measured directly for LED currents ranging from 0.04 mA to 0.55 mA. The current through the diode was adjusted by changing the voltage from the power supply.

Part 1F: Rise Time of FDS100 Photodiode

The LED circuit from Part 1E was modified to use the function generator instead of the DC power supply as shown in Fig. 7. The function generator was set to output a square wave. The same circuit for the photodiode used in Part 1E was used with a 1 mm separation between the LED and photodiode. The voltage from the DC power supply ranged from 0 V to 1 V in 0.1 V increments up to 0.4 V. An oscilloscope was connected across the photodiode to show the rise time of the photodiode. The rise time was defined as the time taken for the photodiode voltage drop to increase from 10% of its maximum value to 90% of its maximum value. The maximum value was found by measuring the peak-to-peak voltage on the oscilloscope, and then vertical cursors were placed at the 10% and 90% voltage points to measure the rise time. The horizontal axis scale was adjusted to show the rise time section in as much detail as possible.

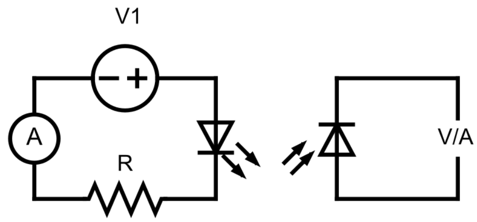

Fig. 6. (Left) A blue LED is connected in series with a DC power supply, resistor, and multimeter as an ammeter. R = 501.8 Ω. (Right) An FDS100 photodiode is connected directly to a multimeter used as either a voltmeter or ammeter.

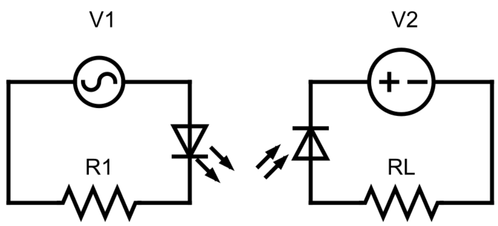

Fig. 7. (Left) A blue LED is connected in series with a function generator, resistor, and multimeter as an ammeter. The function generator is set to a square wave output and R1 = 501.8 Ω. (Right) An FDS100 photodiode is connected in reverse bias to the second output of the DC power supply in series with a load resistor. An oscilloscope was connected across the photodiode. RL = 50580 Ω.

Part 2: LED Optical Power and Spectra

A driver circuit was built using an LM317 voltage regulator as shown in Fig. 8. The circuit includeded a 10 kΩ potentiometer used to adjust the current flow to an LED. A 33 Ω resistor was used to connect the potentiometer to terminal 1 on the LM317. Also connected to terminal 1 was a 10.1 μF polarized capacitor and a 1N4004 diode in reverse-bias orientation. The driver circuit was used to power a blue LED while measuring the light output with the photodiode circuit shown in Fig. 6. Once again the LED to photodiode separation was 1 mm and the ceiling lights were turned off, but this time a reverse-bias of 3 V was applied to the photodiode and the load resistor had a value of 31000 Ω. A multimeter in ammeter mode was connected in series with the LED to measure the input current while a Rigol DM3058 multimeter was used to measure Vout in the photodiode circuit. The Rigol multimeter was used to acquire more sensitive voltage readings. The current values ranged from 1.52 mA to 37.2 mA.

After collecting photodiode voltage data for the blue LED at different current inputs, the spectra of a red LED, a green LED, and the blue LED were measured using a Thorlabs CCS175 spectrometer. The LEDs were supplied with enough current to turn on the blue LED and the spectra were measured by positioning the spectrometer's fiber optic input close to the LED surface so that a peak became visible on the spectrometer software. Careful positioning was required to couple the light from the LED into the fiber.

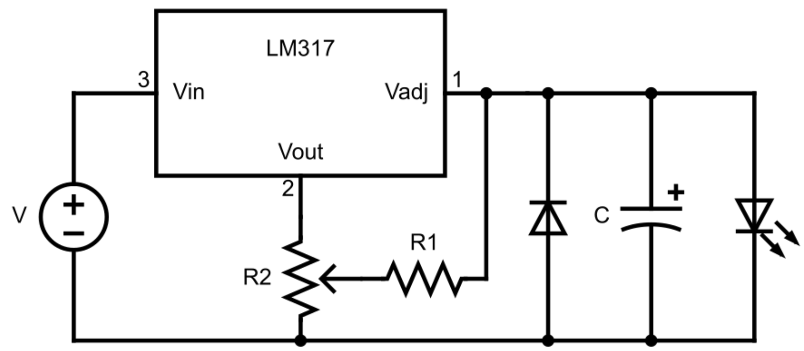

Fig. 8. A DC power supply is connected to the input of an LM317 regulator. A potentiometer is connected at the LM317's output to adjust the current flow to an LED. V = 7 V, R1 = 33 Ω, R2 = 10 kΩ, C = 10.1 µF

Part 3: Laser Diode Optical Power and Spectra

A Thorlabs L650P007 laser diode was used in place of an LED in the driver circuit from Part 2 shown in Fig. 8. The laser diode was placed with pin 2 oriented upstream and pin 3 oriented downstream [10]. The current into the laser diode was adjusted using the potentiometer and the light output was measured with the photodiode circuit using the same setup as in Part 2. Photodiode voltage readings were collected for input currents of 1.49 mA to 24.7 mA.

After collecting photodiode voltages as a function of input current, the spectrometer was used to measure the laser diode spectrum for input currents below and above the threshold current. Ten spectra were measured for inputs from 1.49 mA to 24.7 mA. The input current was increased slowly at first but jumped rapidly after reaching about 3 mA.

3. Results & Analysis

Part 1A: I-V Curve of a 1N4004 Diode

The current flow through the 1N4004 diode as a function of the diode bias can be seen in Fig. 9. From -2 V to 0.3 V no current was measured with the multimeter. After 0.5 V the current flow increased exponentially. The exponential region is near the typical 0.6 V threshold voltage of silicon diodes [2]. The orange data point falls outside of the general trend and was excluded from the exponential fit. A data sheet for Vishay Intertechnology's 1N400 series of diodes shows the exponential rise of the I-V curve for a forward-biased diode beginning at slightly above 0.6 V for a temperature of 25° [11]. The curve on the data sheet plots current on a log scale, so the linear region indicates the same exponential behavior seen in the tested 1N4004 diode.

Part 1B: Capacitance of a 1N4004 Diode

The capacitance of the 1N4004 diode as a function of the diode bias is shown in Fig. 10. The capacitance was calculated using the frequency and amplitude of the function generator, the measured voltage across the diode, and Eqs. 2 & 3.

The capacitance is unchanged for bias values well below the threshold voltage, but begins to trend upward at 0.4 V. This trend appears to be exponential rather than linear, though the R^2

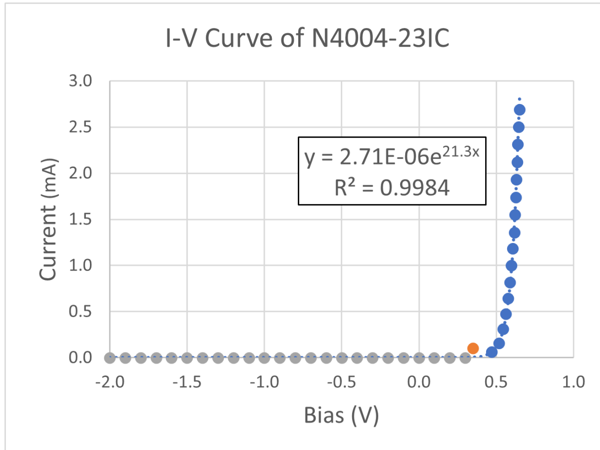

Fig. 9. Forward bias of a 1N4004 diode plotted against current. Current flow is negligible below 0.3 V. The blue points are fitted with an exponential trendline. The orange point was excluded from the fit.

value of the fit is less than satisfactory. While the exact nature of the trend needs more data to

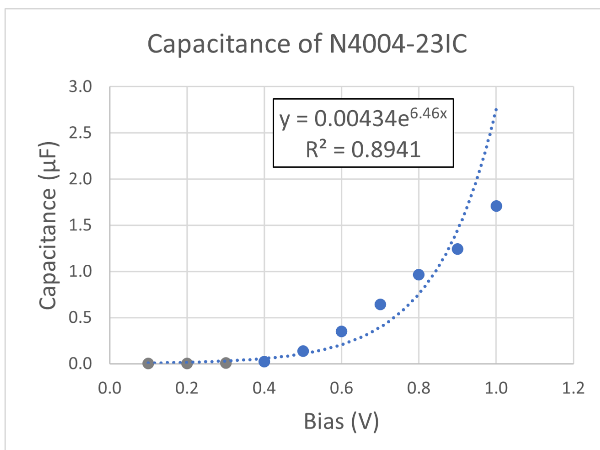

Fig. 10. Forward bias of a 1N4004 diode plotted against the capacitance of the diode. Capacitance appears unchanged up to 0.3 V. The blue points are fitted with an exponential trendline.

clarify, it is clear the capacitance of the diode increases with increasing forward bias. The Vishay data sheet does not give a typical junction capacitance for the frequency used. Additional data collection would benefit from using the frequency of 1 MHz used in the data sheet for comparison purposes [11].

Part 1C: I-V Curve of an FDS100 Photodiode

The current flow through the FDS100 photodiode as a function of the diode bias can be seen in Fig. 11. No current was measured from -4.5 V to 0.3 V. Starting at 0.4 V the current increased exponentially. The threshold voltage appears to be the same as the 1N4004 diode. The similar characteristics of the two I-V curves is likely due to the photodiode material being silicon [5].

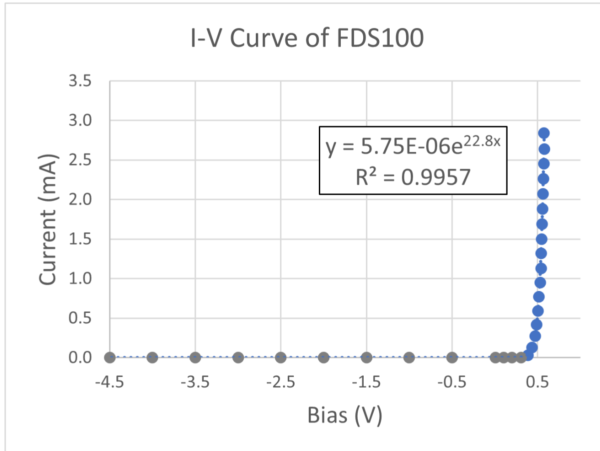

Fig. 11. Forward bias of an FDS100 photodiode plotted against current. Current flow is negligible below 0.3 V. The blue points are fitted with an exponential trendline.

Part 1D: L-I Curve of a Blue LED

The optical power of the blue LED was found as a function of current as shown in Fig. 12. The plot includes just the data which displayed a linear relation between the current and power. The optical power represents the light received by the photodetector. It was calculated using

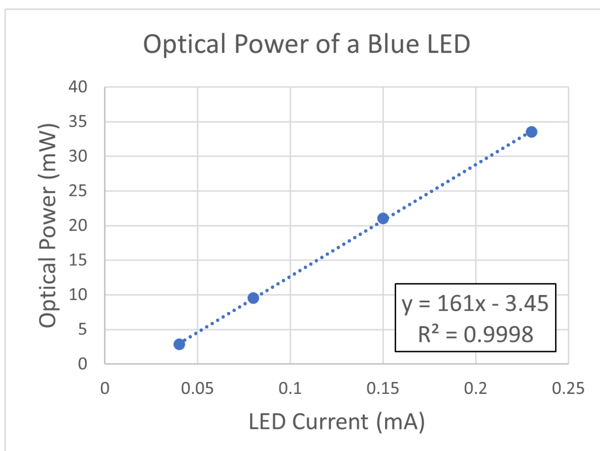

Fig. 12. Plot of the linear region of a blue LED's optical power as a function of input current.

Eq. 5, the measured photodiode voltage values, the resistor resistance, and the responsivity of the photodiode at the LED wavelength. The blue LED was found to have a wavelength of approximately 500 nm, giving a responsivity of 0.16 A/W for the photodiode [5].

Data was also collected outside the linear region of the LED. Being outside the linear region, that data wasn't useful for the analysis in Part 1E. While the four data points found in the linear region show a clear linear relationship, several more data points within that region should be taken to verify the linear characteristic.

Part 1E: Photovoltaic & Short-Circuit Modes of FDS100

The induced voltage and current of the FDS100 photodiode were measured as a function of the LED optical power of the same blue LED used in Part 1D. The relations can be seen in Fig. 13. Both induced voltage and current were found to increase linearly with increasing LED power.

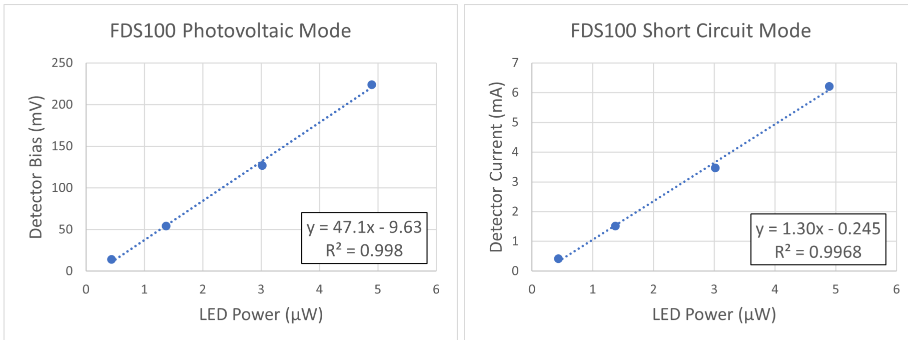

Fig. 13. (Left) Bias of an FDS100 photodiode as a function of a blue LED's incident optical power while operated in photovoltaic mode. (Right) Current flow through an FDS100 photodiode as a function of a blue LED's incident optical power while operated in short-circuit mode. (Both) The LED power was found by processing measured current values with the linear fit from Part 1D.

The induced current was found to be on the order of the maximum rated reverse current value of 5 mA from the photodiode's specification sheet [5]. Clearly the maximum value was exceeded, however, so further research may be needed to find an appropriate reference value.

The data was taken before identifying the linear region of the LED in Part 1D. This lead to some data being taken outside the LEDs linear region, so the trend found in Part 1D could not be used to determine the LED optical power from the measured LED currents. As in Part 1D, several more data points for photodiode voltage and current within the LED's linear region are needed to verify the linear relationships of the photodiode.

Part 1F: Rise Time of FDS100 Photodiode

The rise time of the FDS100 photodiode was measured as a function of the photodiode reverse bias as shown in Fig. 14. The rise time was defined as the time taken for the photodiode voltage to increase from 10% to 90% of its maximum value. At 0 V bias the rise time was at its maximum value, but decreased with increasing reverse bias.

The decay appears to be exponential, but a good fit could not be obtained in Microsoft Excel. Additional data points should also be taken to better characterize the trend. The fourth data point at 0.4 V is particularly problematic as it shows no change in rise time from a reverse bias of 0.2 V. Rise time data was taken using the oscilloscope viewing screen, but exporting the data to other software may improve the measurement of the rise time.

The photodiode specification sheet provides a rise time value for a load resistance of 50 Ω, LED wavelength of 632 nm, and applied voltage of 20 V [5]. If additional data wer taken those parameters could be used to provide a reference value for the rise time.

Part 2: LED Optical Power and Spectra

Using the circuit shown in Fig. 8 to drive the blue LED, the optical power of the LED was found as a function of drive current. This relation is plotted in Fig. 15. The optical power was found using the FDS100 photodiode as a detector and applying Eq. 5. The LED optical power showed

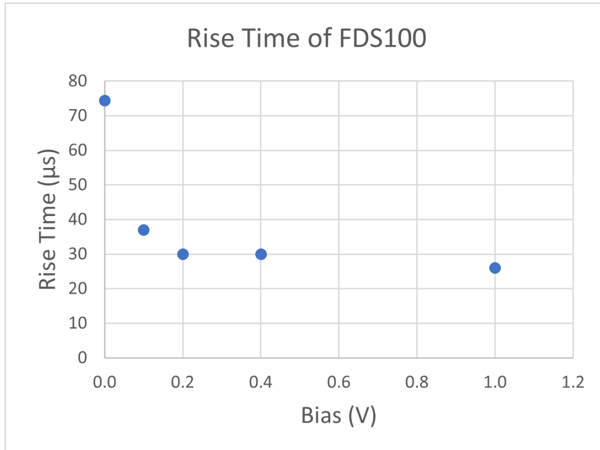

Fig. 14. Rise time of the FDS100 photodiode as a function of diode reverse bias. The photodiode signal was induced by a blue LED operated with a square wave signal. The rise time was defined as the time taken for the photodiode voltage to increase from 10% to 90% of its maximum value.

a linear increase with increasing drive current over a wide range of current values in contrast to the results in Part 1D.

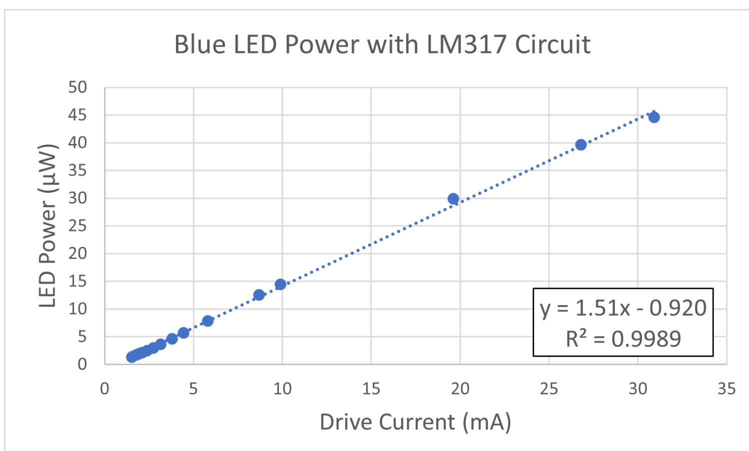

Fig. 15. Optical power of a blue LED as a function of drive current. The LED was powered with an LM317 driver circuit. Optical power measurements used an FDS100 photodiode at a distance of 1 mm as a detector and were calculated using Eq. 5.

The peak spectra of the blue, green, and red LEDs are shown in Fig. 16. The spectrometer had a lower measurement limit of 500 nm, so only a portion of the peak for the blue LED was visible. The intensity of the red LED was much greater than the blue and green LEDs, reducing visibility of the noise and giving a clearly defined peak. The FWHM of the peaks for the green and red LEDs was found by inspecting the plots in Microsoft Excel.

The peak wavelengths for the green and red LEDs were determined from the wavelength of the maximum intensity measurement on their respective plots. The peak wavelength of the blue LED was taken to be 500 nm, since only the front tail of the peak was visible. These results are

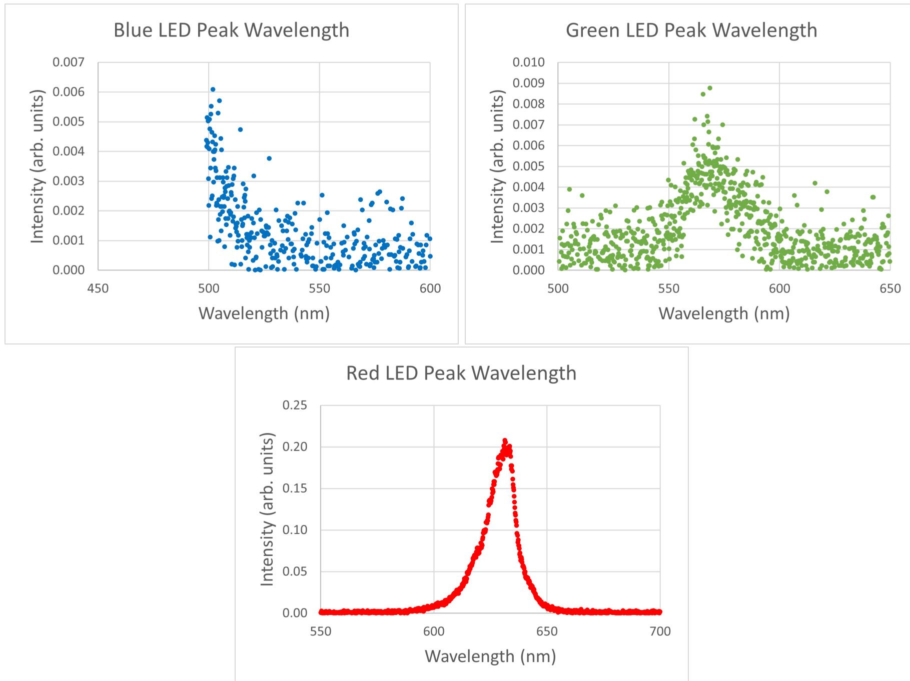

Fig. 16. Peak spectra of a blue (Left), green (Right), and red (Bottom) LED. Only a portion of the peak for the blue LED was visible to the spectrometer. The FWHM of the green LED peak was 23 nm and the FWHM for the red LED peak was 15 nm. The intensity of the red LED was much greater than the blue and green LEDs.

summarized in Table 1.

LED Color	Peak Wavelength (nm)	Photon Energy (eV)	Candidate Material
Blue	500	2.48	InGaN
Green	569	2.18	InGaN
Red	632	1.96	AlGaAs

Table 1. Peak wavelengths for the blue, green, and red LEDs. The energy of a photon at the peak wavelength was calculated using Eq. 4. Likely semiconductor materials used in each LED are given in column 4.

The photon energy at the peak wavelength for each LED was then calculated using Eq. 4. The photon energies were used to aid in identifying likely candidates for the semiconductor material used to make each LED. Coldren et al cites InAlGaAsP based compounds as commonly used for red LEDs, while GaN-based compounds are commonly used for blue LEDs [6]. This is consistent with the information given by Saleh and Teich in *Fundamental of Photonics*. They describe AlGaAs compounds as capable of ranging from 1.42 eV to 2.16 eV, and describe how InGaN compounds can be tuned to emit both green and blue light [1].

Part 3: Laser Diode Optical Power and Spectra

The optical power of the L650P007 laser diode was measured as a function of drive current. The circuit driving the laser diode was the same circuit shown in Fig. 8, with the optical power again measured using the FDS100 photodiode as a detector. Fig. 17 shows the optical power as a function of current both before and after lasing.

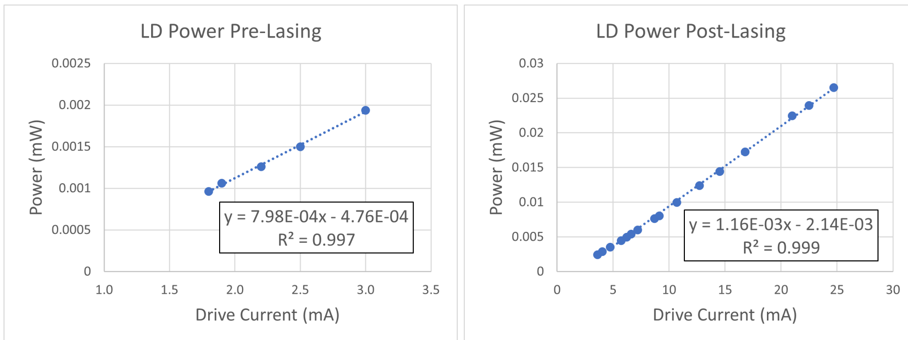

Fig. 17. Pre-lasing (Left) and post-lasing (right) curves for the optical power of a L650P007 laser diode measured as a function of drive current. Optical power measurements used an FDS100 photodiode at a distance of 3 mm as a detector and were calculated using Eq. 5.

Two of the pre-lasing data points with current values of 1.49 mA and 1.6 mA were ommited. The two points didn't follow the linear trend and drive currents in that region did not show any laser light when inspected with the spectrometer. The first data point on the post-lasing curve had a value of 3.6 mA, giving a practical indication of the threshold current. The slope efficiency for pre-lasing was 7.98×10^{-4} mW/mA and for post-lasing it was 1.16×10^{-3} mW/mA.

The specification sheet for the laser diode cites values of 20 mA for the typical threshold current and 1 mW/mA for the typical slope efficiency [10]. These values differ significantly from the measured threshold current and slope efficiencies. The cited value for threshold current is nearly the maximum current value on the post-lasing curve in Fig. 17. The discrepancy in slope efficiency could be partly explained by the photodiode receiving only a portion of the light emitted by the laser diode, but the difference of several orders of magnitude is problematic. Both the threshold current and slope efficiency require further investigation.

The linewidth of the laser diode was also measured for spectra below and above the observed threshold current. Shown in Fig. 18 are the peak spectra taken using the spectrometer for drive currents of 2.04 mA and 24.92 mA.

Peak spectra were also found for a number of other drive currents as summarized in Table 2. As mentioned earlier, the spectra for drive currents at 1.49 mA and 1.62 mA were anamolous. The peak identified at roughly 980 nm was also found in the spectra for the blue LED. A possible explanation is that it was due to ambient infrared radiation and was picked up by the spectrometer due to a lack of significant emmission at other wavelengths.

There is a noticeable shift in the ratio of the FWHM to the peak intensity from the pre-lasing drive current of 2.04 mA to the other drive currents. This indicates amplification is focused on the central wavelength in the laser diode as desired for laser output in the post-lasing regime [3].

4. Discussion

The results and analysis show some additional opportunities for improvement of the experiment beyond those already mentioned.

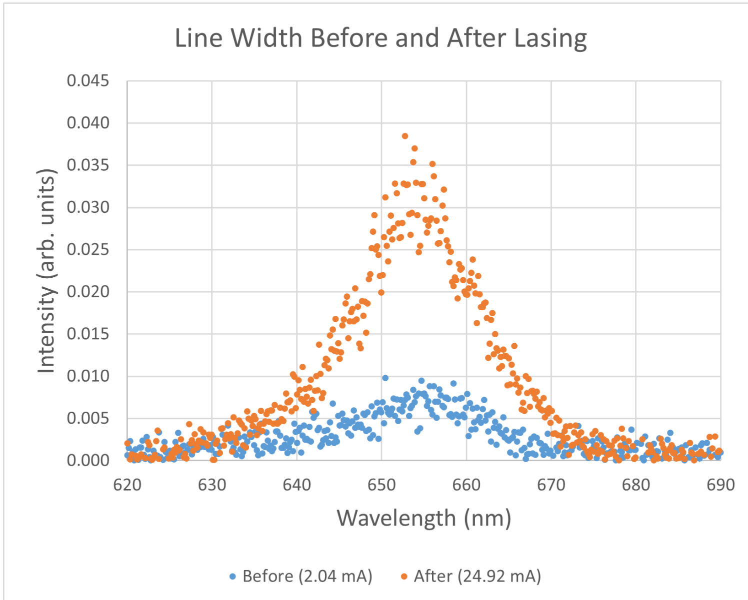

Fig. 18. Peak spectra for a L650P007 laser diode before lasing and after lasing. The ratio between the width and peak intensity is reduced for the post-lasing peak.

I (mA)	Peak λ (nm)	FWHM (nm)	Peak Intensity (AU)	FWHM to Intensity Ratio
1.49	973	130	0.00980	13300
1.62	983	130	0.0235	5530
2.04	654	17	0.0149	1140
2.56	658	14	0.0249	562
2.90	657	12	0.0214	561
6.26	657	12	0.0241	498
10.7	656	15	0.0298	503
15.4	656	15	0.0820	183
24.9	654	13	0.037	351

Table 2. Wavelengths of peak values on spectra curves for several drive currents are given in column 2. FWHM values determined by inspection in Microsoft Excel are given in column 3. The FWHM and peak intensities in column 4 are used to find the ratio of FWHM to peak intensity in column 5.

A reoccuring issue was obtaining enough data in the region of interest, most notably in Parts 1D-1F as well as the spectrum analysis for pre-lasing in Part 3. This issue could have been prevented by performing two iterations of data collection for each part of the experiment. The first iteration would use broad increments in measurements to identify the region of interest, and the second would use smaller increments within the identified region.

The selection of a blue LED for the majority of the experiment proved to be a poor choice due to the measurement limitations of the CCS175 spectrometer. Since the peak wavelength of the LED was needed to specify the responsivity of the photodiode, a green or red LED would have been a better choice. In addition, the responsivity of the photodiode peaks at 980 nm, making a red LED the best choice of the three [5].

The measured spectra for the blue and green LEDs also suffered from significant noise compared to the red LED. Operating the blue and green LEDs at greater drive currents could improve the process of identifying the peak wavelength and FWHM from their spectra.

The analysis of the results could be improved by investigating the fraction of optical power received by the photodetector from the emitting device. Understanding this fraction would allow determination of the absolute power emitted by the LEDs and laser diode. The determination of the peak wavelengths of the LEDs and laser diode could also be improved by using peak fitting software such as Mathematica. This would also aid in determining the FWHM values of the peaks.

Finally, a general note which has not yet been addressed is that the voltage output from the DC power supply was not the same as the voltage the power supply was set to output. The difference was generally a thousandth of the desired value so was assumed to be small enough not to affect the results.

5. Conclusion

The general properties of a 1N4004 diode, FDS100 photodiode, and blue LED were characterized in Part 1 of the experiment. In Part 1A the 1N4004 diode was found to have a threshold voltage near the typical value of silicon diodes with the expected exponential rise in current near the threshold voltage. In Part 1B the 1N4004 diode showed a rise in capacitance with increasing forward bias, though the capacitance could not be compared to a reference value. In Part 1C the FDS100 photodiode gave an I-V curve very similar to the 1N4004 diode. In Part 1D the blue LED displayed a linear relationship between optical power and driving current over the range of 0.04 mA to 0.23 mA. In Part 1E the photodiode displayed linear relationships of induced bias in photovoltaic mode and induced current in short-circuit mode with LED optical power. In Part 1F the rise time of the photodiode decreased with increasing reverse bias, though the data were insufficient to determine a trend.

In Part 2 of the experiment the blue LED was driven with an LM317 circuit to determine the optical power as a function of driving current. This relation was linear over a range of 1.42 mA to 37.2 mA with a slope of 1.51 μW/mA. The spectra of a green, a red, and the blue LED were also measured. The respective peak wavelengths were 569 nm, 632 nm, and 500 nm. The likely semiconductor material for the blue and green LEDs was InGaN and the likely material for the red LED was AlGaAs. Unfortunately, the center of the peak for the blue LED spectra fell outside the range of the spectrometer and this impacted the accuracy of the responsivity value of the photodiode.

In Part 3 of the experiment the laser diode was driven with the same LM317 circuit to again determine the optical power as a function of driving current. This relation was linear with two distinct slopes separated at the threshold current of 3.6 mA. The slope efficiency of the pre-lasing region was 7.98×10^{-4} mW/mA and the slope of the post-lasing region was 1.16×10^{-3} mW/mA. Both the threshold current and slope efficiencies differed significantly from the values given in the specification sheet.

While the results matched the expected findings qualitatively, there are some quantitative issues which demand further experimentation using the improvements covered in the Results & Analysis and Discussion. In particular, the lasing region of the L-I curve for the laser diode may have been incorrectly identified. The slope efficiencies also need further analysis of the fraction of optical power incident on the photodiode to determine agreement or disagreement with the value from the specification sheet.

Acknowledgements

Thanks to the author's lab partner, Max Canella, for his persistent enthusiam in carrying out the experiment, to Motoaki Honda for his repeated help troubleshooting the equipment and understanding the theory, to April Bell and Riley Monsrund for their counsel in composing this report, and to all the author's other labmates which provided their support. Also thanks to Nima Dinyari and Motaki Honda for providing the equipment used for the experiment.

References

1. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics 2nd Edition* (John Wiley & Sons, 2007).
2. P. Scherz and S. Monk, *Practical Electronics for Inventors, 4th Edition* (McGraw-Hill, 2016).
3. M. Honda, "Class discussion," (28 July 2021, 30 July 2021).
4. "Diode," Wikipedia (Accessed 20 August 2021), https://en.wikipedia.org/wiki/Diode.
5. Thorlabs, *Specification Sheet: Si Photodiode FDS100* (6 September 2017).
6. L. A. Coldren, S. W. Corzine, and M. I. Masanovic, *Diode Lasers and Photonics Integrated Circuits 2nd Edition* (John Wiley & Sons, 2021).
7. T. Hertsens, "Measuring diode laser characteristics: Diode lasers approach ubiquity, but they still can be frustrating to work with," Lasers & Optron. **8** (February 1989).
8. T. Instruments, *LM317 3-Terminal Adjustable Regulator Datasheet* (April 2020).
9. Circuit Diagram, (Accessed 7 August 2021), https://www.circuit-diagram.org/.
10. Thorlabs, *Product Specification Sheet: Laser Diode L650P007* (1 April 2010).
11. V. G. Semiconductor, *General Purpose Plastic Rectifier* (29 April 2020).