Optoelectronics

Brian Reicher
Lab partner – Will Kovarik
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Abstract:
In this experiment, we explore optoelectronic circuits, namely with silicon photodiodes and light emitters (LEDs). We first analyze the electrical and optical properties of red and blue LEDs and noted the onset voltages for the respective colors at 1.6 and 3.0 V due to the energy required to produce different wavelengths of light. Then, we dive into the properties of silicon photodiodes, namely by manipulating a photodiode with ND filters to map output voltage, finding V_{PD}^{MAX} to read 0.331V, and the average percent transmission of one filter to be 77%. We finally investigated photodiode frequency response, and were able to see the steep drop-off in PD gain as we increase the frequency of a sawtooth wave passed into a red LED within reasonable distance from the PD. We also calculated the effective capacitance of the PD to be 1.13nF.

I. INTRODUCTION

Here, we delve into the world of optoelectronics, the study and application of electrical systems detecting/emitting/controlling light. They offer several massive benefits in the worlds of electrical engineering & IT, namely immunity to EM interference given that photons (particle-like quantization of light) have no charge. Additional properties follow as multichannel capability, high speed pulses, and eased coupling. Numerous optoelectronic applications exist in today's technical world, ranging from fiber-optic communication pathways to simplistic TV remotes. The core components in all optoelectronic devices include silicon light detectors (photodiodes), LEDs (different compounds for different colors), and lasers/detectors for communication. These LEDs (light emitting diodes) are simplistic semiconductor devices that emit light when current flows through them. The blue LED used in this experiment won the Nobel Prize in Physics in 2014, as the laureates had created such emitters from groundbreaking energy-efficient and environmentally sustainable sources. Silicon photodiodes are devices made form pn-junctions that produce current directly proportional to a supplied light power. They are held by a limit to their max voltage, with non-linear trends at higher voltages when V_{PD} becomes a significant value (contributing fraction to the Silicon-band gap).

II. APPARATUS

The apparatus consisted of the following.

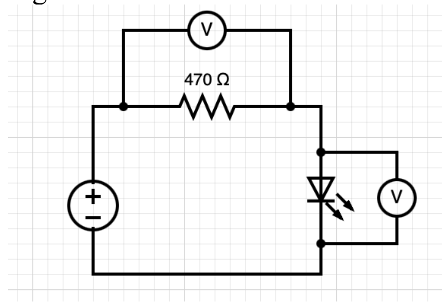
- 2 GW Digital Multimeters GDM-8145
- GW Instek GDM-8145
- Oscilloscope, Tektronix TBS1052B-EDU
- Resistors (470Ω, 470kΩ), capacitor (0.1 μF)
- Si photodiode (PD), VTB8441BH
- LED, red output
- LED, blue output TLHB4200
- Neutral-density (ND) optical filters, Roscolux #397
- PP ProjectBoard K2400 with +5 V, +/- 15 V power supplies, grounding supply
- GW Instek Function Generator GFG-8216A
- Various wires, clips, and connectors

III. PROCEDURES AND RESULTS

A. <u>LED Properties</u>

In this section of our experiment, we analyzed the electric and optical properties of LEDs. We connected the red LED (afterwards using the same setup using the blue LED) and 470 Ω resistor in series to a variable DC voltage supply as shown in Fig. 1. We began to vary the voltage up to a given LED V_{max}=~9.4V/13V while measuring the voltage drop over the resistor and LED using our two DMMs. Here, we use the equation:

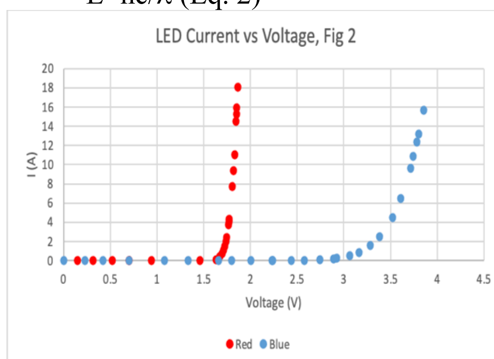
Fig. 1 Red/blue LED circuit



$I_{LED}=V_R/R$ (Eq. 1)

To plot I_{LED} as a function of V_{LED}, shown in Fig. 2 for both LED colors. We can see the diode properties of the LEDs, as they act as current limiters (infinite resistance) until a threshold voltage which then causes the resistance to drop exponentially and current to skyrocket with increased voltage. The two curves do vary, however, as the onset voltages for the two colors exist quite separately, with V_{onset}^{Red}=1.6V and V_{onset}^{Blue}=3V. They are inherently different because higher frequency/lower wavelength photons require more energy to create. We can observe the equation:

$E=hc/\lambda$ (Eq. 2)



Where λ represents wavelength, h Planck's constant (6.626E-34 m^2kg/s), and c the speed of light (3E8 m/s). From Eq. 2, knowing that blue light has a shorter frequency than red light leads us to understand that blue light is more energetic than red light, and would then require more voltage to turn on, given that:

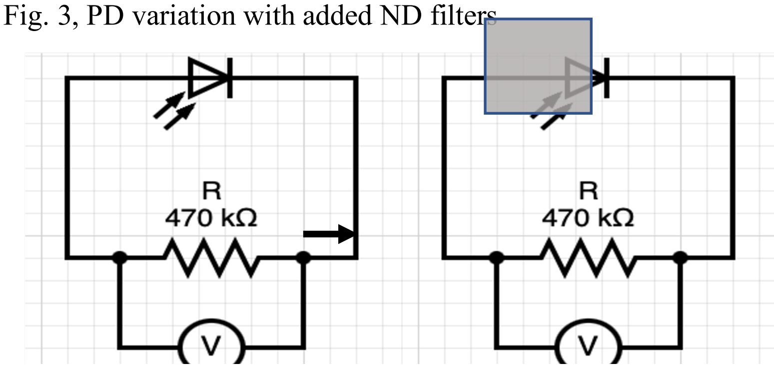
$VI=P=\text{Energy/time}$ (Eq. 3)

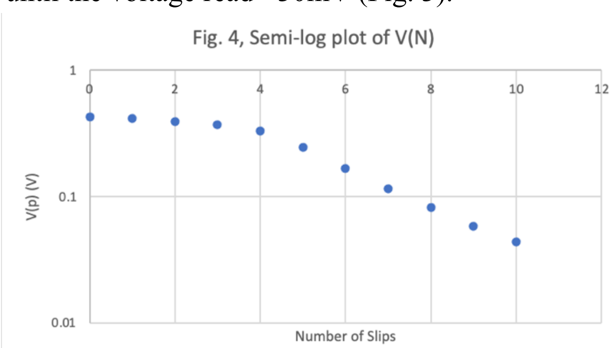
Where P is the power over the diode, V the voltage drop, and I the current, showing that the energy of the light is directly proportional to the voltage needed.

B. <u>Silicon Photodiode properties</u>

In the following section of the experiment, we investigated photodiodes (PD), namely how they react in the presence of neutral density optical filters (ND). We aimed to determine the linear response region of a silicon PD with room light illumination. We first connected a 470 kΩ resistor in parallel with the photodiode, with the PD facing upwards to collect light from the room. We used a DDM to measure the voltage over the resistor and kept measuring as we added more ND filters on top of the PD until the voltage read <30mV (Fig. 3).

Fig. 3, PD variation with added ND filters





As we record voltage values for increasing ND filters, we can create a semi-log plot of V_{PN} versus N, the number of ND filters (Fig. 4). From this plot, we can clearly see the disparity in a non-linear region, N=(1,3), and a linear from N=(4, 10). We can note this value as V_{PD}^{max}=0.331 V, the measured value where N=4 turns linear. Now through analyzing the linear regime of the log plot, we can say that the percent transmission of one ND filter in the linear region would stand to be:

V_{N+1}/V_N (Eq. 4)

This reads as the percentage of the initial voltage that remains in the configuration with an additional filter. Consequently, we can say that in the linear region the average percent transmission from N=(4,10) is the average of all ratios of respective voltages in the given range, which gives PT=76.74%.

C. Photodiode Frequency Response

In the final experiment, we looked to investigate the frequency response of a photodiode. We did this by modulating LED output brightness as via a function generator with a sawtooth wave. By bending a red LED over a PD, we connected the function generator to a 470 Ω current limiting resistor in series. We measured V_{FG} and V_{PD} by connecting two oscilloscope channels (DC coupling) to the PD and FG (Fig. 5). Adjusting the function generator to a sawtooth wave with maximum amplitude, we placed a piece of paper over our experiment to dim all light on the PD, ensuring V_{PD} reads below V_{PD}^{max}=0.331 V. Following this, we increased the function generator frequency from 10 Hz to 1MHz, recording voltage values at chosen points and saturating extra data around the inflection point (Fig. 6). We can see that this graph remains at a constant ~100 mV until an approximate 100Hz threshold where V_{PD} rapidly decreases and saturate at ~28 mV for high frequencies. The PD voltage in this case does not go positive and negative like the input sawtooth wave because the PD driver is the red LED. This causes current to only flow in one direction through the LED, due to basic properties of all diodes (in this case flowing in the positive direction), and the LED cannot supply any sort of inverting light source. Consequently, the PD only is receiving bursts of one-directional LED input, generating spikes of positive voltage. After analyzing V_{PD}, we quickly look to plot gain:

Fig. 5 PD frequency response circuit diagram

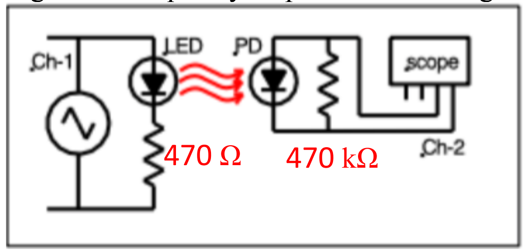
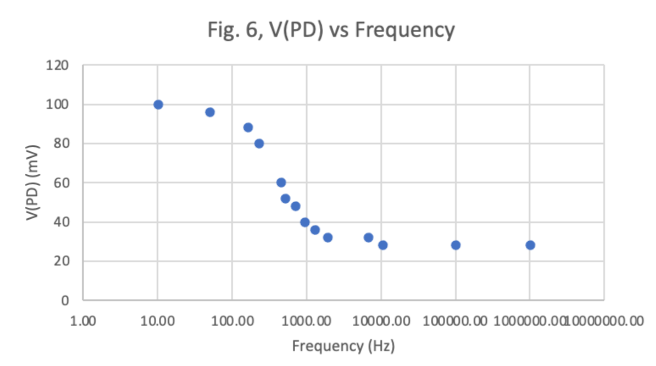


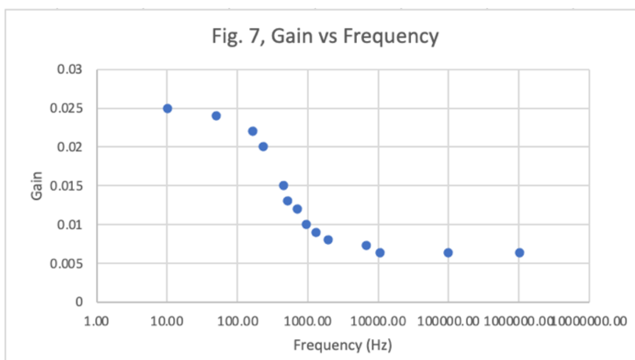
Fig. 6, V(PD) vs Frequency



$$G = V_{PD}/V_{FG} \text{ (Eq. 5)}$$

Which is a function of f (Hz) on a log-scale, show in Fig. 7. This plot looks very similar to Fig. 6, which makes sense given that V_{FG} was in theory the same constant maximum value for all frequencies, so Fig. 7 is just a scaled version of Fig. 6. From this plot, however, we look to calculate the frequency f_o to compute the effective capacitance of the PD and circuit. We start by representing the output power ratio in decibels:

Fig. 7, Gain vs Frequency



$$\beta = 10\mathrm{LOG}(P_f/P_i) \text{ (Eq. 6)}$$

And rewriting in terms of circuit voltage/resistance to say (using simplified Eq. 1, 3):

$$\beta = 10\mathrm{LOG}(V_f^2/R_f/V_i^2/R_i) \text{ (Eq. 7)}$$

And in terms of gain, pulling the voltage-square factor out of the log and eliminating R to say:

$$\beta = 20\mathrm{LOG}(G_f/G_i) \text{ (Eq. 8)}$$

And since $G_i = G_{max}$:

$$\beta = 20\mathrm{LOG}(G_{time}/G_{max}) \text{ (Eq. 9)}$$

In this scenario, we want to use Eq. 9 to solve for f_o, the frequency where G has decrease to the 3-dB point. We can then substitute these values into our equation to find that:

$$-3=20LOG(G_{3dB}/G_{max}) \text{ (Eq. 10)}$$

Rearranging for G_{3dB}, we find that:

$$G_{3dB}=10^{-0.15}G_{max}=0.707G_{max} \text{ (Eq. 11)}$$

Looking at Fig. 7, we can estimate G_{max} to be 0.025. From this value we can extrapolate:

$$G_{3dB}=0.707*0.025=0.0176 \text{ (Eq. 12)}$$

This leads us to say that f_o would be the frequency in Fig. 7 where G=0.0176. From this value we can estimate the critical frequency f_o=500 Hz. Using this value, we can now compute PD/circuit capacitance. From:

$$\tau=RC \text{ (Eq. 13)}$$

$$\omega_o\tau=1 \text{ (Eq. 14)}$$

$$\omega_o=2\pi f_0 \text{ (Eq. 15)}$$

We can write that:

$$C= 1/(2\pi f_0 R) \text{ (Eq. 16)}$$

Substituting our circuit's values for f_0=500 Hz, R=470 kΩ, we find that C=1.13 nF. This compares with high accuracy to the junction capacitance from the PD specification datasheet of 1 nF (113%). In this scenario, V_{PD} is sacrificed when maximum frequency is increased by dropping R to R/100. This is because current is directly proportional to resistance given the simplified form of Eq. 1:

$$V=IR \text{ (Eq. 17)}$$

IV. SUMMARY

In conclusion, we explored a multitude of optoelectrical devices/properties in this set of experiments. Specifically utilizing silicon photodiodes and light emitters (LEDs), we analyzed the electrical and optical properties of red and blue LEDs and noted disparity in onset voltages for the respective colors at 1.6 and 3.0 V (blue frequencies require higher onset voltages because of greater needed energy). By manipulating a photodiode with ND filters to map output voltage, we estimated V_{PD}^{MAX} to read 0.331V. Through operating on the linear region of our V_{PD} plot, we were able to estimate the percent transmission of one filter to be 77%. Lastly, when analyzing photodiode frequency response, and were able to see the positive-only attribute of V_{PD}, as well as the steep drop-off in PD gain as we increase the frequency of a sawtooth wave passed into a red LED for higher frequencies. By analyzing the critical frequency, f_o=500 Hz, we were able to find the configuration capacitance of 1.13nF, which is 113% of the specified value. All findings are summarized in Table 1.

Table 1:

Optoelectronic Element	Onset voltage (V)	V^{max} (V)	Percent Transmission (%)	f_o (Hz)	Calculated Capacitance (nF)	Measured Capacitance (nF)
Red LED	1.6					
Blue LED	3.0					
Photodiode		0.331		500 Hz	1.13	1
ND Filter			77%			