EE236: Experiment 1

Estimation of band gap of different semiconductor materials through diode I/V characterization

Param Rathour, 190070049
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1 Overview of the experiment

This report contains my approach to the experiment, the circuit's design with the relevant simulation code and output plots.

1.1 Aim of the experiment

To understand the relation between Band Gap (E_g) and I/V characteristic of different diode materials.

1.2 Methods

There are 2 ways to calculate E_g,

- Using Emission intensity vs wavelength plot to find peak emission wavelength (λ)
- Using forward I/V and $\log I/V$ characteristics determined using Ngspice, we also get ideality factor (η) and Saturation Current (I_S)

Finally, V_D vs E_g was plotted and their relation was observed.
My goal was to simulate these circuits correctly and verify all values.

2 Design

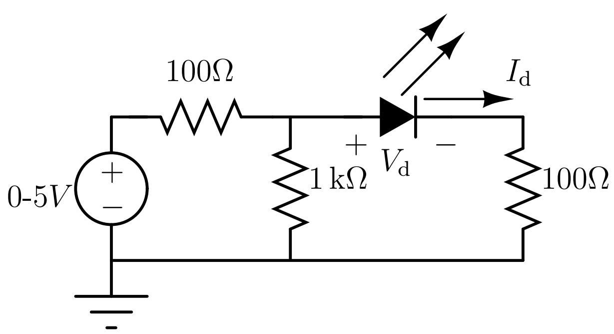


Figure 1: Diode Characteristics Circuit

Simulation model was as shown in Figure 1.
RED, BLUE, GREEN, WHITE and 1N914 Diode were used in this experiment.
Light Emitting Diodes (LEDs) are used as they all have different Band Gaps (E_g).
First, measure peak emission wavelength (λ) using the spectrum given in Lab Handout and calculate E_g of LEDs by using below equation

$$E_g = \frac{hc}{\lambda} = \frac{hc}{\lambda\ (\mathrm{nm})}\ \mathrm{eV} \tag{1}$$

E_g for diode 1N914 is 1.1V. [2] I plotted I/V Characteristics of these diodes by exporting spice

Diode	Peak Emission Wavelength (λ in nm)	Band Gap (E_g in eV)
RED	625	1.984
BLUE	460	2.69565
GREEN	520	2.3846
WHITE[1]	450	2.75556
1N914	-	1.1

Table 1: Band Gap for different diodes using Peak Emission Wavelength

simulation vectors to python.
Analytically,

$$I_D = I_S\left(e^{\frac{q\cdot V_D}{kT}} - 1\right) \quad \text{where} \quad I_S = I_{00}\cdot e^{-\frac{E_g}{kT}} \tag{2}$$

By taking natural logarithm of I_D and neglecting -1 term, we get log I/V Characteristics as below

$$\ln\left(\frac{I_D}{I_S}\right) = \frac{q\cdot V_D}{kT} \quad \rightarrow \quad \ln(I_D) = \underbrace{\frac{q}{kT}}_{slope}\cdot V_D + \underbrace{\ln(I_S)}_{y-intercept} \tag{3}$$

This graph is a straight line in some range of I, V. We can calculate its slope to get η and y-intercept by interpolating that straight line to get I_S

$$\text{slope} = \frac{\ln I_{D_2} - \ln I_{D_1}}{V_{D_2} - V_{D_1}} = \frac{1}{\eta V_T} \rightarrow \eta = \frac{1}{V_T}\left(\frac{V_{D_2} - V_{D_1}}{\ln I_{D_2} - \ln I_{D_1}}\right) \tag{4}$$

$$I_S = \exp\left(\text{y-intercept}\right) \tag{5}$$

Also, using $I_S = I_{00}\cdot e^{-\frac{E_g}{kT}}$ in Equation 2

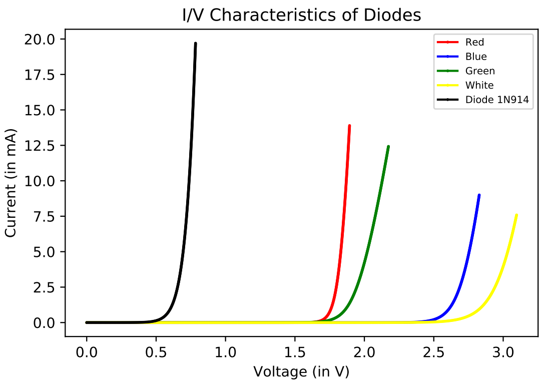
$$\ln\left(\frac{I_D}{I_{00}}\right) + \frac{E_g}{kT} = \frac{q\cdot V_D}{kT} \tag{6}$$

So $V_D\ \alpha\ E_g$ for constant $\frac{I_D}{I_{00}}$

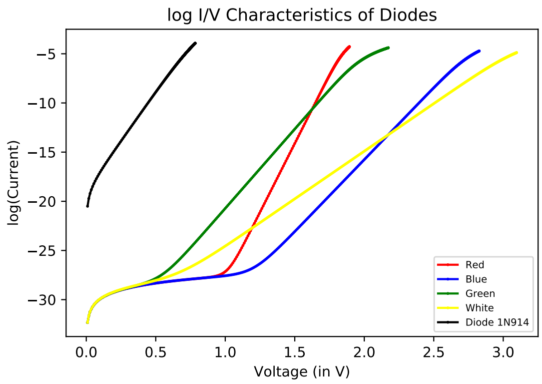
[2]Blue + Yellow light (emitted from Phosphorus), but Blue ($\sim$ 450nm) has higher emission intensity

3 Simulation results

3.1 Plots



(a) I/V Characteristics



(b) $\log I/V$ Characteristics

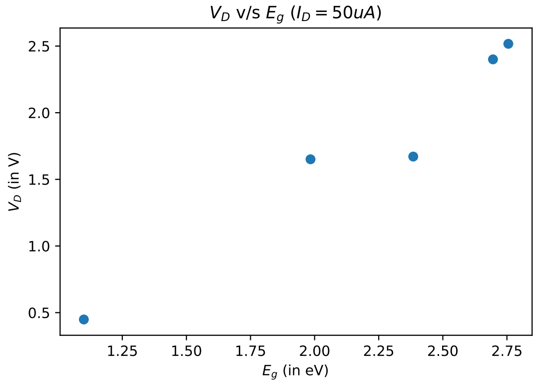
Figure 2: Characteristics for different diodes

The threshold voltage is greatest for White LED and lowest for 1N914, just like band gap is most for White and least for 1N914. This is consistent with correlation between V_D & E_g.
Using the $\log I/V$ characteristics, the calculated η and I_S are as follows

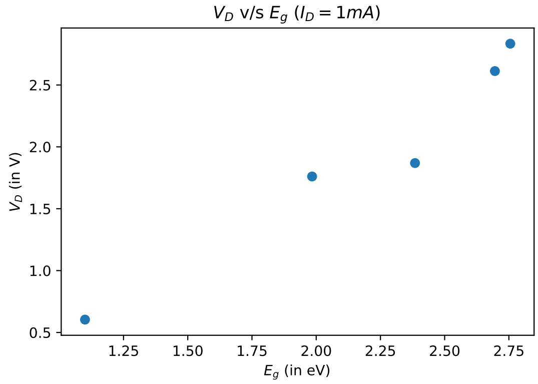
Diode	Slope	y-intercept	Linearity Factor (η)	(I_S in A)
RED	27.97786	-56.08417	1.37471	$4.39493 \cdot 10^{25}$
BLUE	14.44299	-44.73580	2.66298	$3.72810 \cdot 10^{20}$
GREEN	16.12014	-36.83358	2.38592	$1.00780 \cdot 10^{16}$
WHITE	9.68498	-34.27989	3.97125	$1.29547 \cdot 10^{15}$
1N914	16.95640	-17.07630	2.26826	$3.83580 \cdot 10^{08}$

Table 2: η and I_S for different diodes

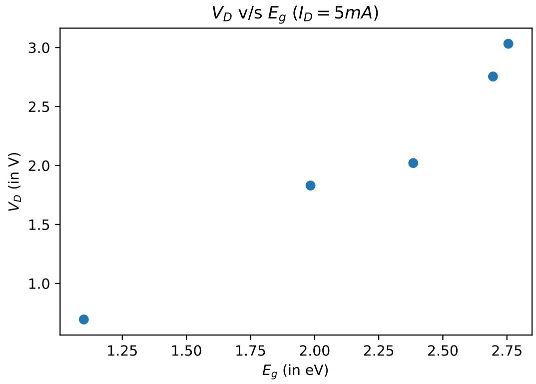
The above values are pretty reasonable.
The equation 2 is Shockley equation which works for ideal diodes, whereas equation 3 is only satisfied when $(qV_D >> kT)$



(a) $I_D = 50\mu$A



(b) $I_D = 1m$A



(c) $I_D = 5m$A

Figure 3: V_D vs E_g

Expected correlation was linear but we get non-linear plot for each I_D. Also, there isn't much difference between the three cases. $I_D = 5m$A gave plot closest to line.

3.2 Code Snippets

3.2.1 I/V Characteristics

3.2.1.1 Ngspice

3.2.1.1.1 RED LED

```
Param Rathour (190070049), I/V characteristics of RED LED

.include red_5mm.txt                        ; Includes Diode Model
R1 in mid1 100                              ; Resistor
R2 mid1 gnd 1k                              ; Resistor
R3 mid3 gnd 100                             ; Resistor
DR mid1 midR RED                            ; Diode
VdR midR mid3 0                             ; Dummy Voltage to measure I_d
Vin in gnd dc 0                             ; DC source Vin
.dc Vin 0 5 0.01                            ; DC Analysis
```

```
.control
run
plot I(VdR) vs {V(mid1) - V(mid3)}
let I1 = 50u
let I2 = 1m
let I3 = 5m
meas dc Vm1I1 FIND V(mid1)  WHEN I(VdR) = I1
meas dc Vm3I1 FIND V(mid3)  WHEN I(VdR) = I1
print Vm1I1-Vm3I1                       ; V_D when I_D = I_1 = 50uA
meas dc Vm1I2 FIND V(mid1)  WHEN I(VdR) = I2
meas dc Vm3I2 FIND V(mid3)  WHEN I(VdR) = I2
print Vm1I2-Vm3I2
meas dc Vm1I3 FIND V(mid1)  WHEN I(VdR) = I3
meas dc Vm3I3 FIND V(mid3)  WHEN I(VdR) = I3
print Vm1I3-Vm3I3

wrdata R.txt I(VdR) {V(mid1) - V(mid3)} ; Exporting Vectors
.endc
.end
```

3.2.1.1.2 BLUE LED

```
Param Rathour (190070049), I/V characteristics of BLUE LED

.include blue_5mm.txt                   ; Includes Diode Model
R1 in mid1 100                          ; Resistor
R2 mid1 gnd 1k                          ; Resistor
R3 mid3 gnd 100                         ; Resistor
DB mid1 midB BLUE                       ; Diode
VdB midB mid3 0                         ; Dummy Voltage to measure I_d
Vin in gnd dc 0                         ; DC source Vin
.dc Vin 0 5 0.01                        ; DC Analysis
.control
run
plot I(VdB) vs {V(mid1) - V(mid3)}
let I1 = 50u
let I2 = 1m
let I3 = 5m
meas dc Vm1I1 FIND V(mid1)  WHEN I(VdB) = I1
meas dc Vm3I1 FIND V(mid3)  WHEN I(VdB) = I1
print Vm1I1-Vm3I1
meas dc Vm1I2 FIND V(mid1)  WHEN I(VdB) = I2
meas dc Vm3I2 FIND V(mid3)  WHEN I(VdB) = I2
print Vm1I2-Vm3I2
meas dc Vm1I3 FIND V(mid1)  WHEN I(VdB) = I3
meas dc Vm3I3 FIND V(mid3)  WHEN I(VdB) = I3
```

```
print Vm1I3-Vm3I3

wrdata B.txt I(VdB) {V(mid1) - V(mid3)}
.endc
.end
```

3.2.1.1.3 GREEN LED

```
Param Rathour (190070049), I/V characteristics of GREEN LED

.include green_5mm.txt                  ; Includes Diode Model
R1 in mid1 100                          ; Resistor
R2 mid1 gnd 1k                          ; Resistor
R3 mid3 gnd 100                         ; Resistor
DG mid1 midG GREEN                      ; Diode
VdG midG mid3 0                         ; Dummy Voltage to measure I_d
Vin in gnd dc 0                         ; DC source Vin
.dc Vin 0 5 0.01                        ; DC Analysis
.control
run
plot I(VdG) vs {V(mid1) - V(mid3)}
let I1 = 50u
let I2 = 1m
let I3 = 5m
meas dc Vm1I1 FIND V(mid1)  WHEN I(VdG) = I1
meas dc Vm3I1 FIND V(mid3)  WHEN I(VdG) = I1
print Vm1I1-Vm3I1
meas dc Vm1I2 FIND V(mid1)  WHEN I(VdG) = I2
meas dc Vm3I2 FIND V(mid3)  WHEN I(VdG) = I2
print Vm1I2-Vm3I2
meas dc Vm1I3 FIND V(mid1)  WHEN I(VdG) = I3
meas dc Vm3I3 FIND V(mid3)  WHEN I(VdG) = I3
print Vm1I3-Vm3I3

wrdata G.txt I(VdG) {V(mid1) - V(mid3)}
.endc
.end
```

3.2.1.1.4 WHITE LED

```
Param Rathour (190070049), I/V characteristics of WHITE LED

.include white_5mm.txt                  ; Includes Diode Model
R1 in mid1 100                          ; Resistor
R2 mid1 gnd 1k                          ; Resistor
```

```
R3 mid3 gnd 100                        ; Resistor
DW mid1 midW WHITE                     ; Diode
VdW midW mid3 0                        ; Dummy Voltage to measure I_d
Vin in gnd dc 0                        ; DC source Vin
.dc Vin 0 5 0.01                       ; DC Analysis
.control
run
plot I(VdW) vs {V(mid1) - V(mid3)}
let I1 = 50u
let I2 = 1m
let I3 = 5m
meas dc Vm1I1 FIND V(mid1)  WHEN I(VdW) = I1
meas dc Vm3I1 FIND V(mid3)  WHEN I(VdW) = I1
print Vm1I1-Vm3I1
meas dc Vm1I2 FIND V(mid1)  WHEN I(VdW) = I2
meas dc Vm3I2 FIND V(mid3)  WHEN I(VdW) = I2
print Vm1I2-Vm3I2
meas dc Vm1I3 FIND V(mid1)  WHEN I(VdW) = I3
meas dc Vm3I3 FIND V(mid3)  WHEN I(VdW) = I3
print Vm1I3-Vm3I3

wrdata W.txt I(VdW) {V(mid1) - V(mid3)}
.endc
.end
```

3.2.1.1.5 Diode 1N914

```
Param Rathour (190070049), I/V characteristics of Diode 1N914

.include Diode_1N914.txt               ; Includes Diode Model
R1 in mid1 100                         ; Resistor
R2 mid1 gnd 1k                         ; Resistor
R3 mid3 gnd 100                        ; Resistor
Dd mid1 midD 1N914                     ; Diode
VdD midD mid3 0                        ; Dummy Voltage to measure I_d
Vin in gnd dc 0                        ; DC source Vin
.dc Vin 0 5 0.01                       ; DC Analysis
.control
run
plot I(VdD) vs {V(mid1) - V(mid3)}
let I1 = 50u
let I2 = 1m
let I3 = 5m
meas dc Vm1I1 FIND V(mid1)  WHEN I(VdD) = I1
meas dc Vm3I1 FIND V(mid3)  WHEN I(VdD) = I1
print Vm1I1-Vm3I1
```

```
meas dc Vm1I2 FIND V(mid1)  WHEN I(VdD) = I2
meas dc Vm3I2 FIND V(mid3)  WHEN I(VdD) = I2
print Vm1I2-Vm3I2
meas dc Vm1I3 FIND V(mid1)  WHEN I(VdD) = I3
meas dc Vm3I3 FIND V(mid3)  WHEN I(VdD) = I3
print Vm1I3-Vm3I3

wrdata D.txt I(VdD) {V(mid1) - V(mid3)}
.endc
.end
```

3.2.1.2 Python for Plotting

```python
name = ['R', 'B', 'G', 'W', 'D']
full_name = ['Red', 'Blue', 'Green', 'White', 'Diode 1N914']
colour = ['Red', 'Blue', 'Green', 'Yellow', 'Black']

fig, ax = plt.subplots()
ax.set_xlabel('Voltage (in V)')
ax.set_ylabel('Current (in mA)')
ax.set_title('I/V Characteristics of Diodes')
for j in range(5):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab1\\' +  name[j]
        + '.txt', header=None, skipinitialspace=True, delim_whitespace=True)
    data.columns = ["sweep", "I", "sweep", "V"]
    ax.plot(data["V"], 1000*data["I"], '-o', color = colour[j], markersize=1)
ax.legend(full_name, fontsize = 'x-small')
fig.set_dpi(150)
plt.savefig('1.pdf')
```

3.2.2 $\log I/V$ Characteristics

3.2.2.1 Ngspice

3.2.2.1.1 RED LED

```
Param Rathour (190070049), log I/V characteristics of RED LED

.include red_5mm.txt                    ; Includes Diode Model
R1 in mid1 100                          ; Resistor
R2 mid1 gnd 1k                          ; Resistor
R3 mid3 gnd 100                         ; Resistor
DR mid1 midR RED                        ; Diode
VdR midR mid3 0                         ; Dummy Voltage to measure I_d
Vin in gnd dc 0                         ; DC source Vin
.dc Vin 0 5 0.01                        ; DC Analysis
```

```
.control
run
let Vout = V(mid1) - V(mid3)
let VD1 = 1.4
let VD2 = 1.8
meas dc ID1 FIND I(VdR) WHEN Vout = VD1
meas dc ID2 FIND I(VdR) WHEN Vout = VD2
let lnID1 = log(ID1)
let lnID2 = log(ID2)
let eta = (VD2 - VD1) / ((26/1000) * (lnID2 - lnID1))
print lnID2 - lnID1
print eta
plot log(abs(I(VdR))) vs Vout
.endc
.end
```

3.2.2.1.2 BLUE LED

```
Param Rathour (190070049), log I/V characteristics of BLUE LED

.include blue_5mm.txt                   ; Includes Diode Model
R1 in mid1 100                          ; Resistor
R2 mid1 gnd 1k                          ; Resistor
R3 mid3 gnd 100                         ; Resistor
DB mid1 midB BLUE                       ; Diode
VdB midB mid3 0                         ; Dummy Voltage to measure I_d
Vin in gnd dc 0                         ; DC source Vin
.dc Vin 0 5 0.01                        ; DC Analysis
.control
run
let Vout = V(mid1) - V(mid3)
let VD1 = 2
let VD2 = 2.5
meas dc ID1 FIND I(VdB) WHEN Vout = VD1
meas dc ID2 FIND I(VdB) WHEN Vout = VD2
let lnID1 = log(ID1)
let lnID2 = log(ID2)
let eta = (VD2 - VD1) / ((26/1000) * (lnID2 - lnID1))
print lnID2 - lnID1
print eta
plot log(abs(I(VdB))) vs Vout
.endc
.end
```

3.2.2.1.3 GREEN LED

```
Param Rathour (190070049), log I/V characteristics of GREEN LED

.include green_5mm.txt                   ; Includes Diode Model
R1 in mid1 100                           ; Resistor
R2 mid1 gnd 1k                           ; Resistor
R3 mid3 gnd 100                          ; Resistor
DG mid1 midG GREEN                       ; Diode
VdG midG mid3 0                          ; Dummy Voltage to measure I_d
Vin in gnd dc 0                          ; DC source Vin
.dc Vin 0 5 0.01                         ; DC Analysis
.control
run
let Vout = V(mid1) - V(mid3)
let VD1 = 1.4
let VD2 = 1.8
meas dc ID1 FIND I(VdG) WHEN Vout = VD1
meas dc ID2 FIND I(VdG) WHEN Vout = VD2
let lnID1 = log(ID1)
let lnID2 = log(ID2)
let eta = (VD2 - VD1) / ((26/1000) * (lnID2 - lnID1))
print lnID2 - lnID1
print eta
plot log(abs(I(VdG))) vs Vout
.endc
.end
```

3.2.2.1.4 WHITE LED

```
Param Rathour (190070049), log I/V characteristics of WHITE LED

.include white_5mm.txt                   ; Includes Diode Model
R1 in mid1 100                           ; Resistor
R2 mid1 gnd 1k                           ; Resistor
R3 mid3 gnd 100                          ; Resistor
DW mid1 midW WHITE                       ; Diode
VdW midW mid3 0                          ; Dummy Voltage to measure I_d
Vin in gnd dc 0                          ; DC source Vin
.dc Vin 0 5 0.01                         ; DC Analysis
.control
run
let Vout = V(mid1) - V(mid3)
let VD1 = 2
let VD2 = 2.5
meas dc ID1 FIND I(VdW) WHEN Vout = VD1
```

```
meas dc ID2 FIND I(VdW) WHEN Vout = VD2
let lnID1 = log(ID1)
let lnID2 = log(ID2)
let eta = (VD2 - VD1) / ((26/1000) * (lnID2 - lnID1))
print lnID2 - lnID1
print eta
plot log(abs(I(VdW))) vs Vout
.endc
.end
```

3.2.2.1.5 Diode 1N914

```
Param Rathour (190070049), log I/V characteristics of Diode 1N914

.include Diode_1N914.txt                ; Includes Diode Model
R1 in mid1 100                          ; Resistor
R2 mid1 gnd 1k                          ; Resistor
R3 mid3 gnd 100                         ; Resistor
Dd mid1 midD 1N914                      ; Diode
VdD midD mid3 0                         ; Dummy Voltage to measure I_d
Vin in gnd dc 0                         ; DC source Vin
.dc Vin 0 5 0.01                        ; DC Analysis
.control
run
let Vout = V(mid1) - V(mid3)
let VD1 = 300m
let VD2 = 500m
meas dc ID1 FIND I(VdD) WHEN Vout = VD1
meas dc ID2 FIND I(VdD) WHEN Vout = VD2
let lnID1 = log(ID1)
let lnID2 = log(ID2)
let eta = (VD2 - VD1) / ((26/1000) * (lnID2 - lnID1))
print lnID2 - lnID1
print eta
plot log(abs(I(VdD))) vs Vout
.endc
.end
```

3.2.2.2 Python for Plotting

```
name = ['R', 'B', 'G', 'W', 'D']
full_name = ['Red', 'Blue', 'Green', 'White', 'Diode 1N914']
colour = ['Red', 'Blue', 'Green', 'Yellow', 'Black']

fig, ax = plt.subplots()
```

```
ax.set_xlabel('Voltage (in V)')
ax.set_ylabel('log(Current)')
ax.set_title('log I/V Characteristics of Diodes')
for j in range(5):
    data = pd.read_csv('E:\Program_Files\Spice64\EE236\Lab1\\' +  name[j]
        + '.txt', header=None, skipinitialspace=True, delim_whitespace=True)
    data.columns = ["sweep", "I", "sweep", "V"]
    x = data["V"]
    y = np.log(abs(data["I"]))
    s = int(len(x)/3)
    ax.plot(x[1:], y[1:], '-o', color = colour[j], markersize=1)
    slope, intercept, r_value, p_value, std_err =
        stats.linregress(x[s-10:s+10],y[s-10:s+10])
    print("Slope =",slope,"Y-intercept =", intercept,
        "eta =",1/(slope*26/1000), "I_S =", np.exp(intercept))
ax.legend(full_name, fontsize = 'x-small')
fig.set_dpi(150)
plt.savefig('2.pdf')
```

3.2.3 V_d vs E_g

3.2.3.1 $I_D = 50\mu$A

```
V_D = [1.650567, 2.400236, 1.670948, 2.516862, 0.4486670]
E_g = [1.984, 2.6956, 2.3846, 2.7555, 1.1]
plt.scatter(E_g, V_D)
plt.title("$V_D$ v/s $E_g$ ($I_D = 50uA$)")
plt.xlabel('$E_g$ (in eV)')
plt.ylabel('$V_D$ (in V)')
plt.savefig('3.1.pdf')
```

3.2.3.2 $I_D = 1m$A

```
V_D = [1.760637, 2.612411, 1.868984, 2.833760, 0.6039569]
E_g = [1.984, 2.6956, 2.3846, 2.7555, 1.1]
plt.scatter(E_g, V_D)
plt.title("$V_D$ v/s $E_g$ ($I_D = 1mA$)")
plt.xlabel('$E_g$ (in eV)')
plt.ylabel('$V_D$ (in V)')
plt.savefig('3.2.pdf')
```

3.2.3.3 $I_D = 5m$A

```
V_D = [1.830159, 2.754815, 2.020659, 3.032356, 0.6946520]
E_g = [1.984, 2.6956, 2.3846, 2.7555, 1.1]
```

```
plt.scatter(E_g, V_D)
plt.title("$V_D$ v/s $E_g$ ($I_D = 5mA$)")
plt.xlabel('$E_g$ (in eV)')
plt.ylabel('$V_D$ (in V)')
plt.savefig('3.3.pdf')
```

4 Experiment completion status

I was able to complete all sections in lab.

5 Questions for reflection

- White light is composed of Blue + Yellow light (emitted from Phosphorus), but Blue ($\sim$ 450nm) has higher emission intensity. So that $E_g = 2.75$eV should is used.
- The equation 2 is Shockley equation which works for ideal diodes, whereas equation 3 is only satisfied when ($qV_D >> kT$)
- $I_D = 5m$A gave plot closest to straight line.

Overall, the lab was good. Although reports took the most of my time.
Thanks!