NTU H3 Semiconductor Physics and Devices - Lab 3 P-N Junction Devices Laboratory Report

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Apr 12th 2023

Constants

(NTU H3 Semiconductor) In[1]:=

```
kB=1.380649×10^-23 (*m^2 kg s^-2 K^-1*);
h=6.62607015×10^-34 (*m^2 kg s^-1*);
ℏ=h/(2π);
q=1.6×10^-19(*C*);
ϵ=8.8541878128×10^-14 (*F cm^-1*);
me=9.1093837×10^-31(*kg*);
```

Introduction

This Laboratory Report aims to explore the follows with a knowledge base of the NTU H3 Semiconductor Physics and Devices curriculum:

For a P-N junction (1N4001)

- The I-V characteristics of the P-N junction
- The temperature dependence of the I-V characteristics
- Diode parameter extraction with measurements and observations under reverse bias

For a Light Emitting Diode (LED)

- The light current characteristics of an LED
- The emission spectrum

P-N Junction: Characteristics, Diode Parameter Extraction and Temperature Dependence

Diode I-V Characteristics

Theory

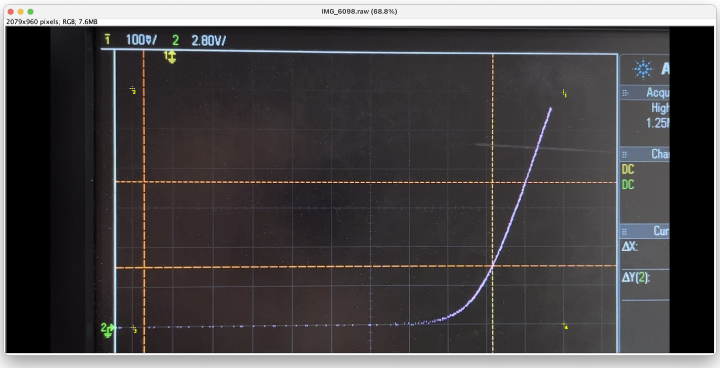
For an ideal diode, its current as a function of applied voltage, V, is given as

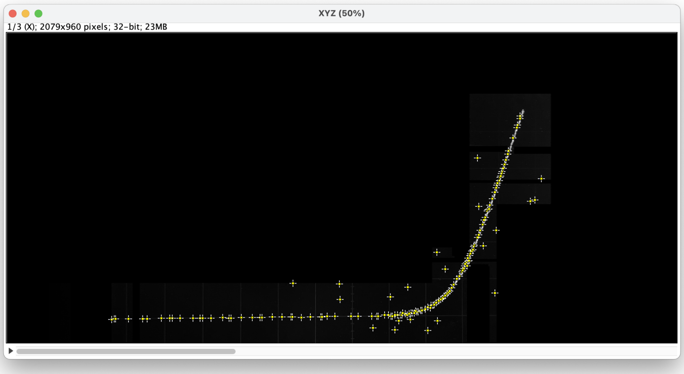
$$I = I_0 \left(e^{\frac{qV}{nkT}} - 1\right)$$

where I_0, the reverse saturation current, is given as

$$I_0 = qA\left(\frac{D_p}{L_p} p_{n0} + \frac{D_n}{L_n} n_{p0}\right)$$

Experiment





[Left: Anchor Points; Right: Unfiltered Data Points by Maxima Search]

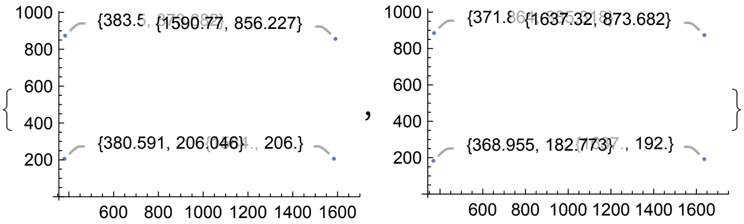
(NTU H3 Semiconductor) In[7]:=

```
lowTAnchors={{1637.3182`,873.6818`},{371.8636`,885.3182`},{368.9546`,182.7727`},{1637.
```

(NTU H3 Semiconductor) In[∘]:=

```
{ListPlot[Callout[#] & /@ highTAnchors], ListPlot[Callout[#] & /@ lowTAnchors]}
```

(NTU H3 Semiconductor) Out[∘]=



(NTU H3 Semiconductor) In[8]:=

```
lowTRep={x1→lowTAnchors⟦1,1⟧,y1→lowTAnchors⟦1,2⟧,x2→lowTAnchors⟦2,1⟧,y2→lowTAnchors⟦2
lowTMap[pt_]:={0.1×11(1-(0.000018916312653698914` (-830744.0913268594`-20.863700000000
highTMap[pt_]:={0.1×11(1-0.000023866378947413272` (-754118.00044628`-17.40899999999987
```

Diode under Room Temperature

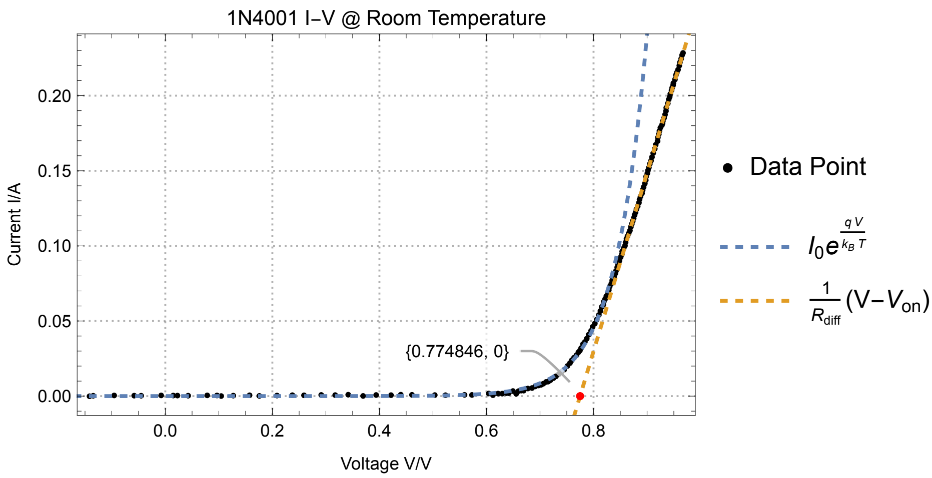
(NTU H3 Semiconductor) In[11]:=

```
lowTCurvePts=lowTMap/@lowTRaw//Sort;
lowTFitFunction=a E^(k v);
lowTLinearFitFunction=1/R(v-vOn);
lowTFit=FindFit[lowTCurvePts⟦;;80⟧,lowTFitFunction,{a,k},v];
lowTLinearFit=FindFit[lowTCurvePts⟦90;;⟧,lowTLinearFitFunction,{R,vOn},v];

Show[ListPlot[lowTCurvePts,PlotStyle→{Black},FrameLabel→{"Voltage V/V","Current I/A"},

StringForm["Turn-on voltage: `1` V, Differential Resistance: `2` Ω",DecimalForm[vOn/.l
```

(NTU H3 Semiconductor) Out[16]=



(NTU H3 Semiconductor) Out[17]=

Turn-on voltage: 0.77485 V, Differential Resistance: 0.8428 Ω

Temperature Dependence

Theory

In the Lab Manual, it is suggested that for a wide variety of diodes, the average value of the gradient of voltage *V* as a function of temperature *T* at constant current *I* is found to be

$$\frac{\partial V}{\partial T}\Big|_{I=\text{constant}} = -2.4\ \text{mV} / \text{K}$$

Taking the advantage of this conclusion, given the simplification of the V-T relation as linear, the change in temperature can be expressed as

$$\Delta T = \Delta V \left(\frac{\partial V}{\partial T}\Big|_{I=\text{constant}}\right)^{-1} = -2.4\ \text{mV} / \text{K}\ \Delta V$$

Experiment

Diode under High Temperature

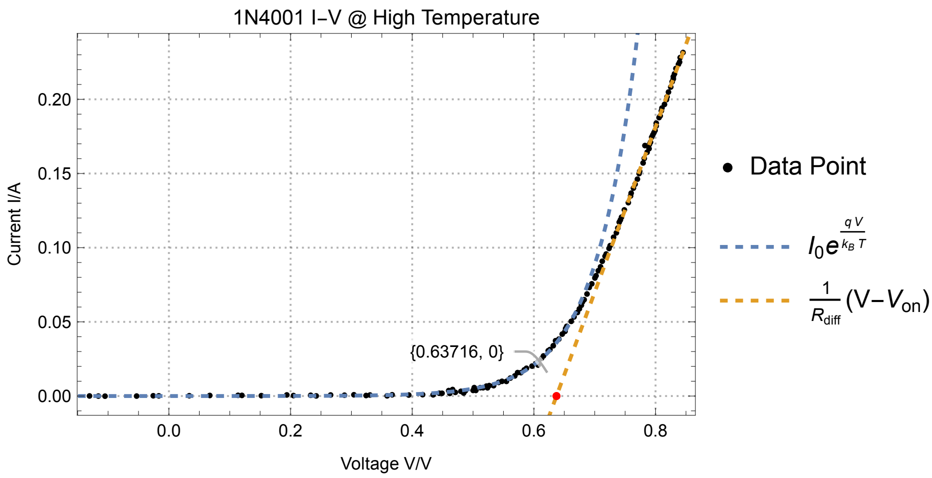
(NTU H3 Semiconductor) In[18]:=

```
highTCurvePts=highTMap/@highTRaw//Sort;
highTFitFunction=a E^(k v);
highTLinearFitFunction=1/R (v-vOn);
highTFit=FindFit[highTCurvePts[[;;70]],highTFitFunction,{a,k},v];
highTLinearFit=FindFit[highTCurvePts[[90;;]],highTLinearFitFunction,{R,vOn},v];

Show[ListPlot[highTCurvePts,PlotStyle→{Black},FrameLabel→{"Voltage V/V","Current I/A"}

StringForm["Turn-on voltage: `1` V, Differential Resistance: `2` Ω",DecimalForm[vOn/.h
```

(NTU H3 Semiconductor) Out[23]=



(NTU H3 Semiconductor) Out[24]=

Turn-on voltage: 0.63716 V, Differential Resistance: 0.89817 Ω

Explanation for the observed shift in the I-V characteristics

Changes in mobility: The mobility of charge carriers in the diode's p-type and n-type regions can change with temperature. This change can result in a change in the carrier diffusivities and thus alter the diffusion current through the P-N junction and thus its IV characteristics as well.
Changes in carrier generation and recombination: The rate of carrier generation and recombination in a diode can change with temperature. This change can affect the diode's forward and reverse bias currents.

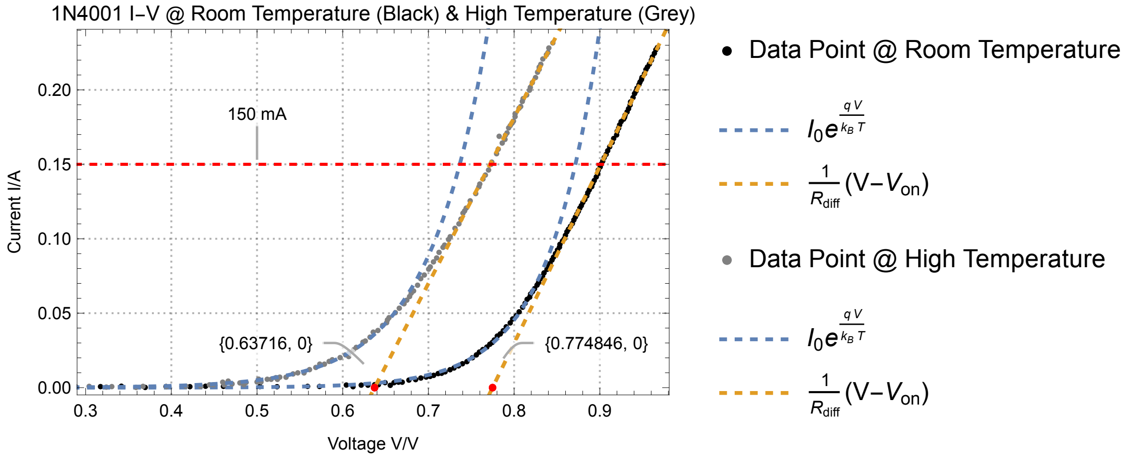
Voltage shift at constant 150mA current (mV)

(NTU H3 Semiconductor) In[25]:=

```
Show[ListPlot[lowTCurvePts⟦20;;⟧,PlotStyle→{Black},FrameLabel→{"Voltage V/V","Current

vShift=InverseFunction[(1/R (v-vOn)/.highTLinearFit/.v→#)&][0.150]-InverseFunction[(1/
StringForm["Voltage shift: `1` mV",DecimalForm[1000 vShift,5]]
```

(NTU H3 Semiconductor) Out[25]=



(NTU H3 Semiconductor) Out[27]=

```
Voltage shift: -129.38 mV
```

Deduced diode temperature change (K)

With the given average value of $\frac{\partial V}{\partial I}\ |_{I=\text{constant}} = -2.4\ \text{mV}/K$,

(NTU H3 Semiconductor) In[28]:=

```
pVpI=-2.4×10^-3;StringForm["Temperature change: `1` K",DecimalForm[vShift/pVpI,5]]
```

(NTU H3 Semiconductor) Out[28]=

```
Temperature change: 53.908 K
```

I-V Characteristics Under Reverse Bias

Theory

The Ideal Diode Equation is given as

$$I = I_0 \left(e^{\frac{qV}{nkT}} - 1\right)$$

It can be re-expressed by taking the natural logarithm on both sides of the equation

$$\ln I = \ln I_0 + \frac{q}{nkT} V$$

where the applied voltage *V* is linearly related to the current *I* with a gradient of $\frac{q}{nkT}$

With a known I-V characteristics by a plot of ln I against V, the gradient $\frac{q}{nkT}$ and y-intercept $\ln I_0$ can be easily obtained. Thereafter, the ideality factor *n* and the reverse saturation current I_0 can be calculated as such:

$$n = \frac{q}{kT} \frac{1}{\text{gradient}}$$

$$I_0 = e^{\text{y-intercept}}$$

Experiment

(NTU H3 Semiconductor) In[29]:=

```
dataIV={{0.3554`,9.9989`*^-6},{0.4495`,0.000099989`},{0.5528`,0.00099989`},{0.6674`,0.
dataIV~Prepend~{"Voltage V/V","Current I/A"}//TableForm
```

(NTU H3 Semiconductor) Out[30]//TableForm=

Voltage V/V	Current I/A
0.3554	9.9989×10^{-6}
0.4495	0.000099989
0.5528	0.00099989
0.6674	0.0099989

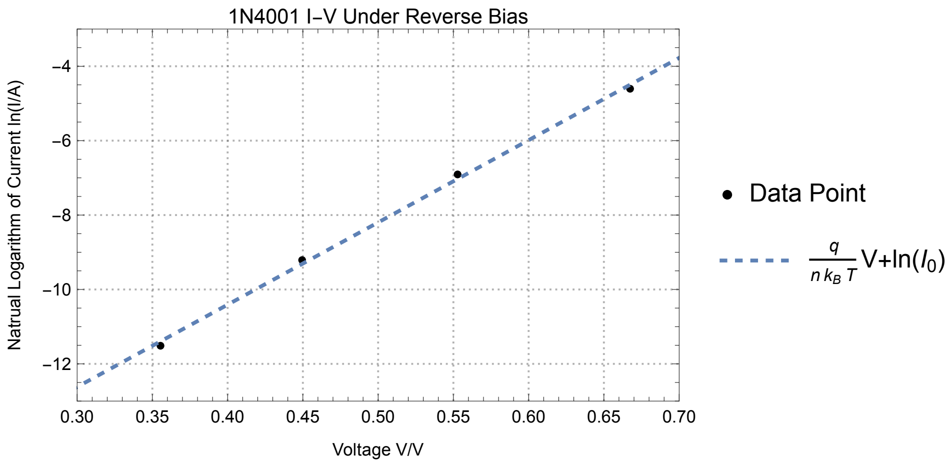
(NTU H3 Semiconductor) In[31]:=

```
dataIVSemiLog=Table[{dataIV[[i,1]],Log[dataIV[[i,2]]]},{i,1,Length[dataIV]}];
rbFitFunction=m v+b;
rbFit=FindFit[dataIVSemiLog,rbFitFunction,{m,b},v];

Show[ListPlot[dataIVSemiLog,PlotStyle→{Black},PlotRange→{{0.3,0.7},{-13,-3}},FrameLabe

StringForm["Ideality factor n: `1`, Reverse Saturation Current I0: `2` A",q/(kB (273.1
```

(NTU H3 Semiconductor) Out[34]=



(NTU H3 Semiconductor) Out[35]=

Ideality factor n: 1.7878, Reverse Saturation Current I_0: 4.34633×10^{-9} A

Explanation

Slope of the ln(I) versus V relationship can be found by plotting a linear fitting function. The gradient of the function $\frac{q}{n k T}$ give the slope.

Therefore, $n = \frac{q}{k T} \frac{1}{m}$, where m is the gradient of the linear fitting function.

Reverse saturation current can be obtained by evaluating $e^{y\text{-intercept}}$.

Light Emitting Diodes: Light Emission Properties

Light Current Characteristics of an LED

Theory

The total amount of charge passing through the LED can be expressed in terms of the diode current:

$$dQ = I\,dt$$

The number of carriers injected is given by

$$\frac{dQ}{q} = \frac{I\,dt}{q}$$

The number of electron injection per unit time is given by the product of total carrier injection and injection efficiency γ_n

$$N = \frac{I}{q}\gamma_n$$

Considering the 100% internal quantum efficiency and external quantum efficiency *F*, the total power output is approximately

$$P = \left(E_g + \Delta E\right)\frac{I}{q}\gamma_n F$$

where $\left(E_g + \Delta E\right)$ is the average energy emission upon recombination.

The power *P* per area can be thereafter converted to photometric measure of brightness via the standard luminosity curve.

Experiment

(NTU H3 Semiconductor) In[36]:=

```
dataLI={{0.,1.},{5.×10^-3,7.},{10×10^-3,17},{15×10^-3,27},{20×10^-3,37},{25×10^-3,45},{30×10^-3
dataLI~Prepend~{"Current I/A","Illuminance L/lx"}//TableForm
```

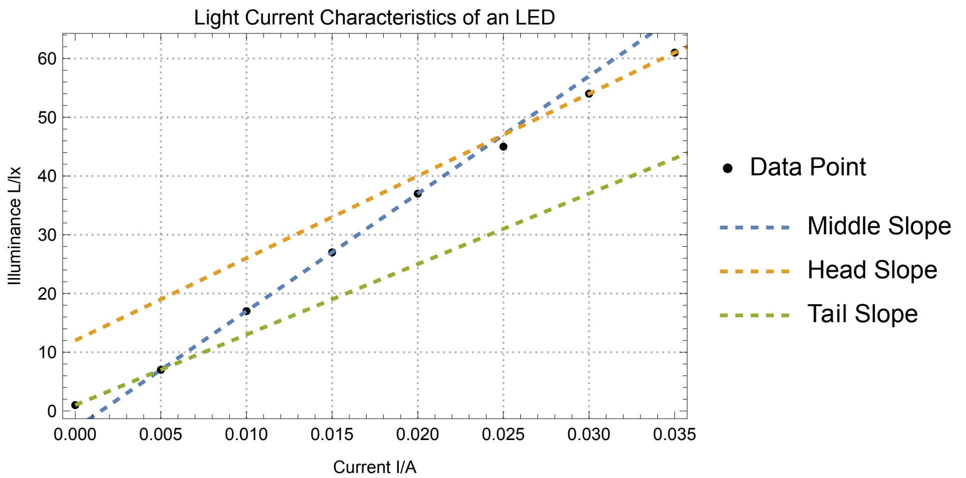
(NTU H3 Semiconductor) Out[37]//TableForm=

Current I/A	Illuminance L/lx
0.	1.
0.005	7.
0.01	17.
0.015	27.
0.02	37.
0.025	45.
0.03	54.
0.035	61.

(NTU H3 Semiconductor) In[54]:=

```
fitFuncLI=a i+b;
fitLI=FindFit[dataLI[[2;;5]],fitFuncLI,{a,b},i];
fitLIHead=FindFit[dataLI[[-2;;-1]],fitFuncLI,{a,b},i];
fitLITail=FindFit[dataLI[[1;;2]],fitFuncLI,{a,b},i];
Show[ListPlot[dataLI,PlotStyle→{Black},FrameLabel→{"Current I/A","Illuminance L/lx"},F
```

(NTU H3 Semiconductor) Out[58]=



Comments on results

- In general, the illuminance of an LED is proportional to the current passing through it within experimental errors.
- From $I = 0$ mA to $I = 5$ mA and from $I = 20$ mA to $I = 35$ mA, the rate of increase of illuminance with respect to current is observably lower than that from $I = 5$ mA to $I = 20$ mA,

Reason to carry out the experiment inside the black box

To minimise the impact of ambient light going into the luxmeter, resulting in an overestimation of the amount of light emitted from the diode.

Reason for non-zero reading of luxmeter when the current passing through the LED is 0 mA

There might still be a very small amount of leakage of ambient light into the box.

Emission Spectrum of an LED

Theory

The electron density with respect to energy can be expressed as

$g_c(E)\, f(E)$

where $g_c(E)$ is the density of states in the conduction band, and $f(E)$ is the Fermi-Dirac distribution that shows the probability of finding an electron at energy E.

Similarly, the hole density with respect to energy can be expressed as

$g_v(E)\,(1 - f(E))$

where $g_v(E)$ is the density of states in the valence band, and $(1 - f(E))$ shows the probability of finding a hole at energy E.

Assume the homogeneity of the likelihood of recombination occurring between any two arbitrary energy levels outside of the forbidden band.
Consider change in energy $\mathbf{\Delta E \geq E_g}$ associated with a particular recombination process.
All energy levels E in the valence band that makes this recombination possible give the set

$\{E \mid E \in [E_c - \Delta E, E_v]\}$

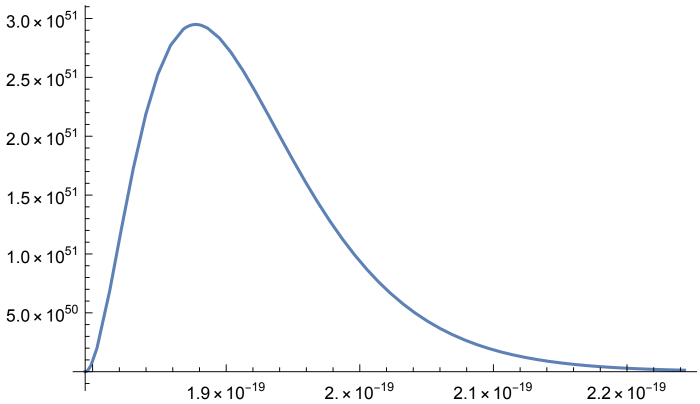
Consider a **small band of energy $(E, E + dE)$**, the probability density of the recombination that gives out energy ΔE to happen within this band is

$g_c(E)\, f(E)\, g_v(E)\,(1 - f(E))\, dE$

Integrate the expression across all possible E values to yield the total above stated probability density:

$$\int_{E_c - \Delta E}^{E_v} g_c(E)\, f(E)\, g_v(E)\,(1 - f(E))\, dE$$

This whole integral is the probability density function with respect to the change in energy ΔE given $g_c(E)$, $g_v(E)$, and $f(E)$. It has the shape as below



In the experiment, the grating spectrometer has an wavelength band of 1 nm. This translates to an energy band of

$$\left[\frac{1240}{\lambda+0.5}, \frac{1240}{\lambda-0.5}\right]$$

At a specific λ, the total number of possible transitions is given by the integral

$$\int_{\frac{1240}{\lambda+0.5}}^{\frac{1240}{\lambda-0.5}} \left(\int_{E_c-\Delta E}^{E_v} g_c(E)\, f(E)\, g_v(E)\, (1-f(E))\, dE\right) d\Delta E$$

With this, the peak wavelength could be found by finding the maxima of the function. Further conversions would help to find the exact power output at individual bands of wavelengths.

Experiment

(NTU H3 Semiconductor) In[43]:=

```
dataVvWL={{600,86.91×10^-3},{610,86.91×10^-3},{620,87.97×10^-3},{630,247.52×10^-3},{635,478.
dataVvWL~Prepend~{"Wavelength λ/nm","Illuminance L/lx"}//TableForm
```

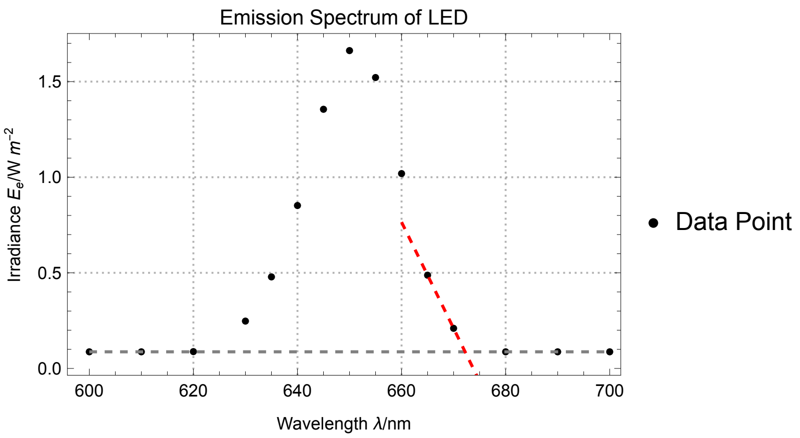
(NTU H3 Semiconductor) Out[44]//TableForm=

Wavelength λ/nm	Illuminance L/lx
600.	0.08691
610.	0.08691
620.	0.08797
630.	0.24752
635.	0.47872
640.	0.85195
645.	1.3553
650.	1.6622
655.	1.5214
660.	1.019
665.	0.4875
670.	0.20976
680.	0.086935
690.	0.086933
700.	0.086933

(NTU H3 Semiconductor) In[61]:=

```
Show[ListPlot[dataVvWL⟦(*2;;-2*)⟧,PlotStyle→Black,PlotLegends→{"Data Point"},PlotTheme
```

(NTU H3 Semiconductor) Out[61]=



Bandgap energy of LED

By linear extrapolation of data points at 665 nm and 670 nm, the approximate minimum energy in the emission spectrum is given by λ, in nm:

(NTU H3 Semiconductor) In[46]:=

```
lambdaSol=Solve[(209.76×10^-3-487.50×10^-3)/(670-665)(λ-670)+209.76×10^-3==86.933×10^-3,λ][[1]]
```

(NTU H3 Semiconductor) Out[46]=

```
{λ → 672.211}
```

As such, the band gap energy of the LED is:

(NTU H3 Semiconductor) In[47]:=

```
StringForm["E_g: `1` eV",DecimalForm[1240/λ/.lambdaSol,5]]
```

(NTU H3 Semiconductor) Out[47]=

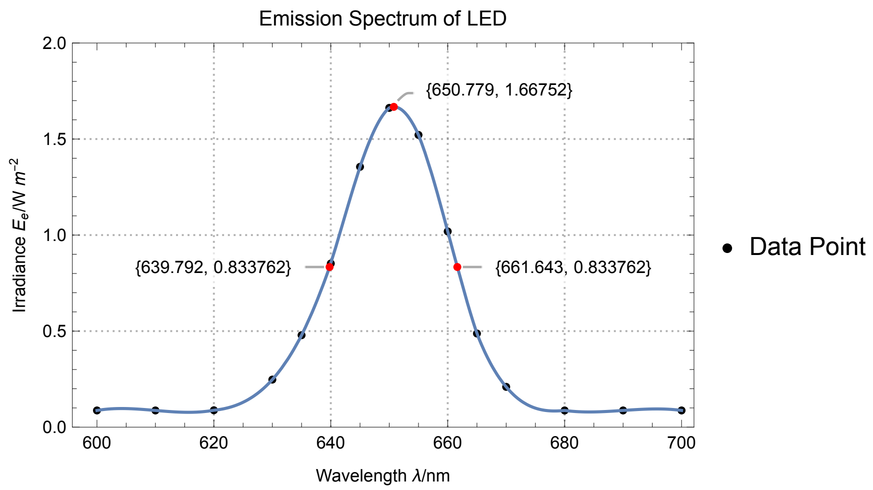
E_g: 1.8447 eV

Linewidth of LED

(NTU H3 Semiconductor) In[48]:=

```
specInterp=Interpolation[dataVvWL];
maxL=FindMaximum[specInterp[λ],{λ,620,680}];
leftHalfL=FindRoot[specInterp[λ]==maxL[[1]]/2,{λ,620,650}];
rightHalfL=FindRoot[specInterp[λ]==maxL[[1]]/2,{λ,650,680}];
Show[ListPlot[dataVvWL[[(*2;;-2*)]],PlotStyle→Black,PlotLegends→{"Data Point"},PlotTheme
StringForm["Linewidth: `1` nm",DecimalForm[(λ/.rightHalfL)-(λ/.leftHalfL),5]]
```

(NTU H3 Semiconductor) Out[52]=



(NTU H3 Semiconductor) Out[53]=

Linewidth: 21.851 nm

Discussion

i. What factors determine the turn-on voltage of a p-n junction diode? Explain its dependence on the factors that you mentioned.

The turn-on voltage is determined by the built-in voltage of a p-n junction which forms the potential barrier that inhibits the carrier from travelling across the metallurgical junction and forms current. The larger the built-in voltage, the larger the turn-on voltage for the p-n junction. The built-in voltage can be expressed as

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

This is with the assumption that the Fermi level of both p and n sides satisfies the conditions below to ensure that Maxwell-Boltzmann equations holds:

$$E_c - E_F > 3\,k\,T \;\; \& \; E_F - E_v > 3\,k\,T$$

As seen in the equation, the built-in voltage is dependent on the following factors:

- Temperature - Higher temperature will results in higher v_{bi}, raising the turn-on voltage, assuming the change in temperature is not in a range that significantly affects the intrinsic carrier concentration.
- Doping - Higher doping on p or n side will results in higher v_{bi}, raising the turn-on voltage.
- Intrinsic carrier concentration - Materials with higher intrinsic carrier concentration will have lower turn-on voltages, ceteris paribus.

ii. Explain why the gradient of the measured L-I curve in part 4.4 becomes smaller at large current.

As current increases, the electron injection increases. This will result in a high level Auger recombination occurring in the semiconductor. This means that more recombination of electron hole pairs is offering energy to other electron hole pairs to bring other electrons to higher energy levels in the conduction band and other holes to lower energy levels in the valence band. These other electron hole pairs would thermalise and lose their energy in the form of phonons to lattice vibration. Therefore, there is net energy lose and not all energy is converted to light. This results in LED under high current injection having lower efficiency and thus the gradient measured at higher I is lower.

iii. Explain the factors that influence the spectral line width of the emission spectrum that you measured in part 4.5.

Temperature and the energy band profile of the semiconductor.
The LED emission spectrum is highly related to the characteristics of the function of $g_c(E)\,f(E)$ and $g_v(E)\,(1 - f(E))$.
As they are in terms of E_c and E_v, the energy band profile will affect the distribution of electrons and holes at different energy levels in the conduction and valence band, resulting in changing spectral line width.

In addition, the increase in temperature will result in more stretched Fermi-Dirac distribution along the energy axis, thus widening the distribution of carriers at different energy levels in the conduction and valence band, resulting in an increased spectral line width.

Conclusion

The objectives mentioned in the Introduction section were investigated and discussed backed with theory and experimental data.