E14e Semiconductor Diodes

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1 Introduction

In the following experiment the characteristics of three diodes, Si, Zener and the LED, will be analysed and measured. For the first set up of the experiment, the Si, Zener and the LED will be set up in a forward bias configuration. Where for the Si diode, the emission coefficient will be found. As for the Zener diode, where an additional reverse bias configuration is measured, the breakdown voltage, the direct resistance and the differential resistance is measured. And for LED, the threshold and the average emitted wavelength is found. For the second part of the experiment, a different Si diode in a metal encasement is measured under reverse bias configuration to find the change in capacitance with an increasing absolute applied voltage, and as such the change in the depletion zone with it.

2 Theoretical Exploration

The equations are taken from E14e Semiconductor Diodes

Power P-N Junction Diodes have a capacitance analogous depletion layer which behave similar to a dielectric or an insulating material. Similar to how capacitance function, where trapped charge carriers in the electrode exert electric field between the plates and store the said electric charge, the p-n junction of a diode creates an insulating depletion region between the n,p doped regions. The amount of voltage being applied, and the configuration of if it is forward or reversed affects the capacitance of the set up. A forward bias would indicate that the power supply's positive terminal is aligned with the p-junction, similar between negative and the n junction. A reversed bias configuration has the negative terminal in line with the p-junction, and the positive terminal in line with the n-junction. In the following explorations, the Si, Zener and the LED diodes would be measured under forward bias configuration (Task I/II). With additionally the Zener (Task II) and the Si (Task III) in a reverse bias configuration.

2.1 Task II

In the second task, the emission coefficient n of a silicon (Si) diode is determined through analysis of its current-voltage (I-U) characteristic using the Shockley diode equation. The Shockley equation describes the behavior of a diode under forward bias and is given by:

$$I = I_s \left(e^{\frac{U}{nU_T}} - 1 \right) \implies \frac{I}{I_s} = e^{\frac{U}{nU_T}-1} \tag{1}$$

where I is the diode current [A], U is the applied voltage across the diode [V], I_s is the forward bias current [A], n is the emission coefficient (dimensionless).

$U_T = \frac{kT}{e}$ is the thermal voltage [V], $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant, T is the absolute temperature [K], for room temperature($T \approx 300K$),$e = 1.602 \times 10^{-19}$ C is the elementary electric charge.

For the Zener Diode, the breakdown voltage, V_R, can be found by finding the point after which the reverse bias configuration stops behaving in linearly. Which will be found through extrapolation. The Direct Current Resistance, R, and the differential Resistance, r, at the breakdown voltage would be calculated through the following equations;

$$R = \frac{U}{I} \quad r = \frac{dU}{dI} \tag{2}$$

For light-emitting diode (LED), it is assumed that the energy gained by the charge carriers when crossing the threshold voltage U_S is released in the form of photons. The energy of the emitted photon is approximately equal to the energy provided by the threshold voltage, given by

$$E = eU_S = \frac{hc}{\lambda} \tag{3}$$

where E is the photon energy in joules, $e = 1.602 \times 10^{-19}$ C is the elementary charge, U_S is the threshold voltage of the LED in volts, $h = 6.626 \times 10^{-34}$ Js is Planck's constant and $c = 3.00 \times 10^8$ m/s is the speed of light in vacuum.

The wavelength of the emitted light can be calculated as:

$$\lambda = \frac{hc}{eU_S} \tag{4}$$

The spectral width of the emitted light is due to the thermal energy distribution of the charge carriers. At room temperature ($T \approx 300$ K), the thermal energy is approximately $kT \approx 26$ meV, where $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant. This corresponds to a typical spectral half-width of approximately 30 to 40 nm, depending on the central wavelength. This broadening reflects the variation in photon energies due to the temperature-dependent energy distribution in the semiconductor.

2.2 Task III: Junction Capacitance of a power diode in a reverse bias voltage configuration

This circuit is set up under reverse bias voltage, which would mean that with an increasing voltage, the stronger attraction between the negative terminal and the p junction (similar for the n junction and the negative terminal) leads to an increasing width of the depletion zone. In the depletion zone, the ions do not move from one side to the other but exert electric field. As such, allowing charge to be stored in the said region. An increasing depletion zone would mean a decreasing capacitance.

The thickens of the depletion layer can be shown to dependent on the applied voltage through;

$$d_s = (\frac{2\epsilon_r\epsilon_0(n_A + n_D)(V_D - V)}{en_An_D})^{1/2} \tag{5}$$

where, utilising $C_s = \frac{dQ}{dU}$, the above equation yields,

$$C_S V = A\sqrt{\frac{2\epsilon_r\epsilon_0 n_A n_D}{2(n_A + n_D)(V_D - V)}} = \frac{\epsilon_r\epsilon_0 A}{d_s} \tag{6}$$

Where C_s is the capacitance of the diode. C_s can be defined as

$$C_s(V) = C_0 \cdot \sqrt{\frac{V_D}{V_D - V}} \tag{7}$$

With defining the capacitance for vanishing applied voltage (V=0) as C_0.

The total capacitance of the whole circuit, C_{tot} would be the sum of the C_s, depletion layer capacitance and "a voltage-independent capacitance C_g parallel to the depletion-layer capacitance " (E14e Semiconductor Diodes), $C_{tot} = C_s + C_G$. In the same manner, as the circuit is set up as a RLC circuit, the total capacitance can alternatively be considered as $C_{tot} = \frac{1}{L\cdot(2\pi f)^2)}$, where L is the inductance of a connected coil and f the frequency at resonance for a set input voltage. Utilising both expressions one can get,

$$C_s + C_G = C_0 \cdot \sqrt{\frac{V_D}{V_D - V}} + C_G = \frac{1}{L\cdot(2\pi f)^2)} \tag{8}$$

Where a plotting and curve fit of C_{tot} from the relation in terms of frequency and one of in terms of diode capacitance, one can find the value for C_G. And as such, get the depletion zone equation as, from equation 6 and $C_s = C_{tot} - C_g$

$$\frac{\epsilon_r\epsilon_0 A}{C_{tot} - C_G} = d_s \tag{9}$$

Where equation 9 would be the equation used to graph the depletion zone against voltage. And both capacitance equations, $C_{tot} = C_s + C_G$ and $C_{tot} = \frac{1}{L\cdot(2\pi f)^2)}$, as the curve fit and measured capacitance respectively.

3 Task I&II: Current-Voltage Characteristics of Diodes

3.1 Experimental Exploration

3.1.1 Materials

- DC Power Supply (Tektronix PWS4323)
- Multimeters (Agilent 24405A)
- Semiconductor diodes: Si diode, Zener diode and LED (blue)
- Resistor, $R_V = 1000\Omega$
- Voltage Generator (Arbitrary Function Generator, GW INTEK AFG-2005)

3.1.2 Methadology and Set up

The current-voltage (I-U) characteristics were measured following the convention that the current I is the dependent variable and the voltage U is the independent variable, i.e., the characteristic is expressed as $I(U)$. This convention also applies to all diagram labels, where the first-named variable represents the dependent quantity.

The specified electrical limits of the components didn't exceed during measurements. The maximum forward current for the Si diode (1N4151) and the LEDs (red and blue) is $I_{max} = 20mA$, while the maximum power dissipation for the Zener diodes (SZX21/6.2 and SZX21/6.8) is $P_{max} = 200mW$. These limits were respected throughout the experiment to ensure the safe operation of the components and the reliability of the recorded data.

For the measurements, the circuits shown in Diagram 1 were used. In the case of the silicon diode(a), the $I(U)$ characteristic was recorded under forward bias conditions only. For the Zener diodes(b), measurements were carried out for both forward and reverse bias to observe the breakdown behavior. In the case of the light-emitting diodes (LEDs)(c), the current-voltage characteristic was recorded only for forward bias operation. A total of 20 measurements were taken for each configuration, as it corresponded to the current minimum and maximum range of $0 \leq I \leq 20$, as limited by the electronic components.

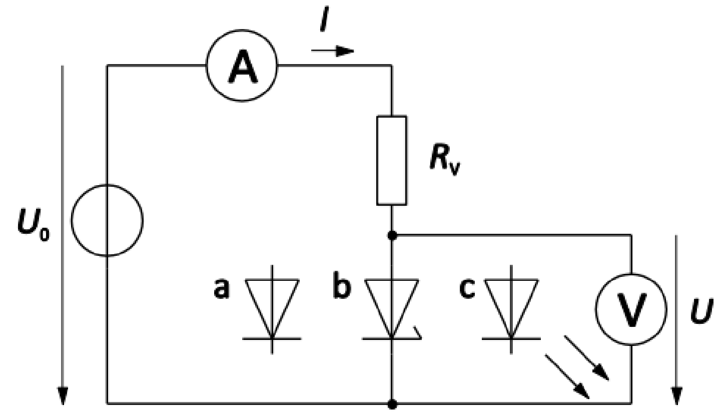

Diagram 1 Circuit for the measurement of current-voltage characteristics of diodes (E14e Semiconductor Diodes)

3.2 Analysis

3.2.1 Data and Results

Note: The Zener Diode Data is not ours but is provided by Professor Michael Ziese

The following figure, Figure 1, presents the Current against Voltage characteristics for the forward bias configuration of the diodes. The reverse bias set up of the Zener Diode had been omitted due its large range (which shrank other graphs to the extend such that they could not properly be seen). Individual graphs of each diode will be further analysed below.

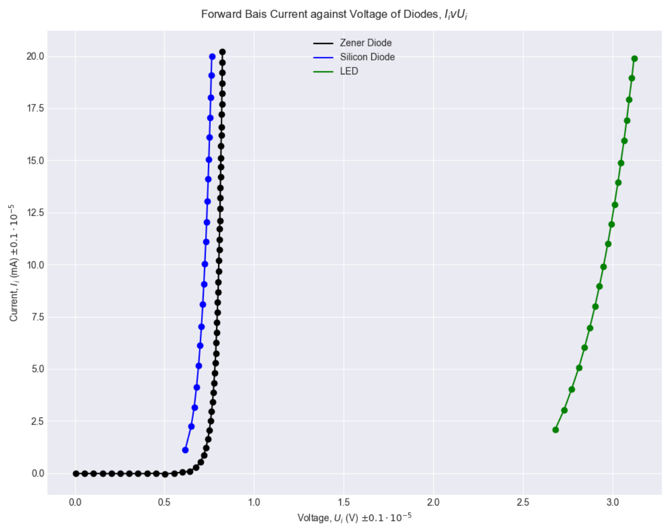

Figure 1: Current-voltage characteristics diagram of the diodes

As seen in the figure above, all the diodes, under the forward bias configuration, presents an overall increasing trend from an increasing voltage. The characteristics of each is further explored below. The data for the forward bias Zener diode had been further shrank for the above figure (up to its 15th data point), as to be able to properly present it within the 20 mA range. The full range of the data can be found below in its individual analysis.

As part of the second task, the analysis of the Silicon diode was performed through a curve fit on the log(I)-U characteristic to best fit the data and accurately extract the values of n and U_T. Using Eq. 1, the equation for non-linear regression was: $log(I) \approx log(I_s) + \frac{U}{n \cdot U_T}$. The below figure, Figure 2, presents the original data and its respective logarithmic plotting.

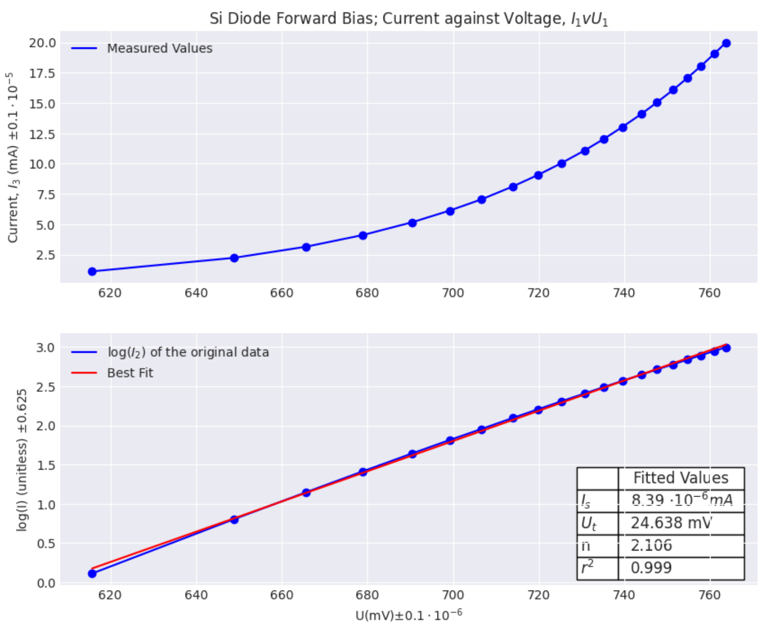

Figure 2: (a) The Original Data; Current against Voltage (b) The log(I)-U characteristic to best fit the data

The above fitting, 2 (b), shows agreement with the logarithm of the original data at a $R^2 = 0.999$, with a $R^2 = 1$ being a perfect fit. Due to this precision of the data, the needed parameters for the exploration can be extracted from the fit. As such, from the fit, the parameters obtained are $I_S = 8.39nA$, $U_T = 24.638mV$ and $n = 2.106$. More details in the Discussion.

As part of the second task, the analysis of the Zener Diode was performed through analysing the behaviour of the Reverse Bias configuration. The below figure presents (a) The Original Data of the Forward Bias, Current against Voltage, and (b) The Original Data of the Reversed Bias, Current against Voltage, with the point of the breakdown voltage identified.

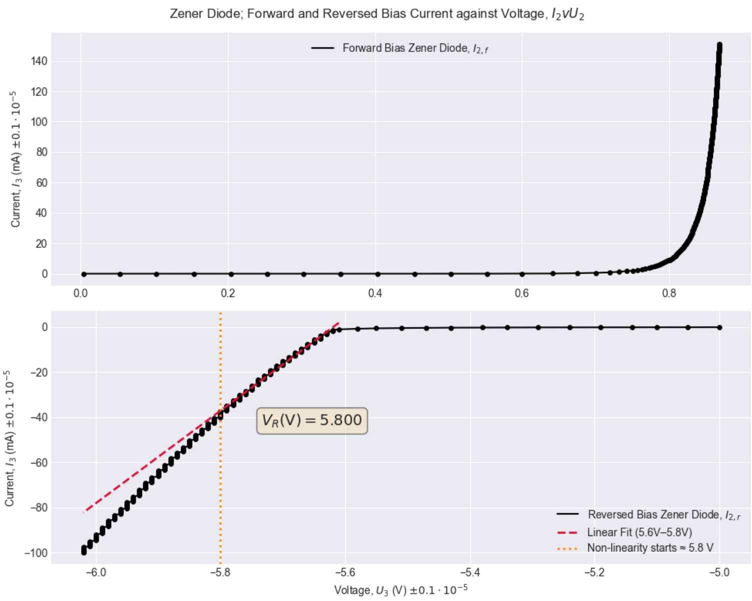

Figure 3: (a) Forward Bias Original Data; Current against Voltage (b) Reverse Bias Original Data: Current against Voltage

In the above figure, the provided data set of the current and voltage had been multiplied with a -1 as to present a more accurate result in correspondence to the real values. Both Figure 3 (a) and (b) present expected results. With a change in voltage corresponds to a change in current as per its sign in change in voltage. The Breakdown Voltage, V_R has been identified as to be **5.804600** $\approx 5.8V$. Where the linear part of the current characteristic was found by utilising the condition that a set number of points has to have a linear relation under an order of $R^2 = 0.999$ or better. The last point before the the said condition fails was taken as V_R. The approximately linear part of the initial part, |0-5.6| V has been ignored as it does not correlate to the breakdown region of the reverse bias configuration but is the area of Reverse Saturation Current, a region of high resistance and low current pass. Following equations from 2, the following parameters at the point of V_R has been identified:

Parameter	Value Ω
R_{V_R}	$154.666 \approx 154$
r_{V_R}	$19.999 \approx 20.0$

Table 1: Found values for task II; R_{V_R}, r_{V_R}

For the LED, the threshold voltage U_S was determined by fitting a straight line to the linear region of the forward-biased current-voltage characteristic. The intersection of this linear fit with the measured curve was taken as the point where significant current conduction and photon emission begin. This threshold voltage was then used in subsequent calculations of the emitted photon energy and wavelength, corresponding to the region.

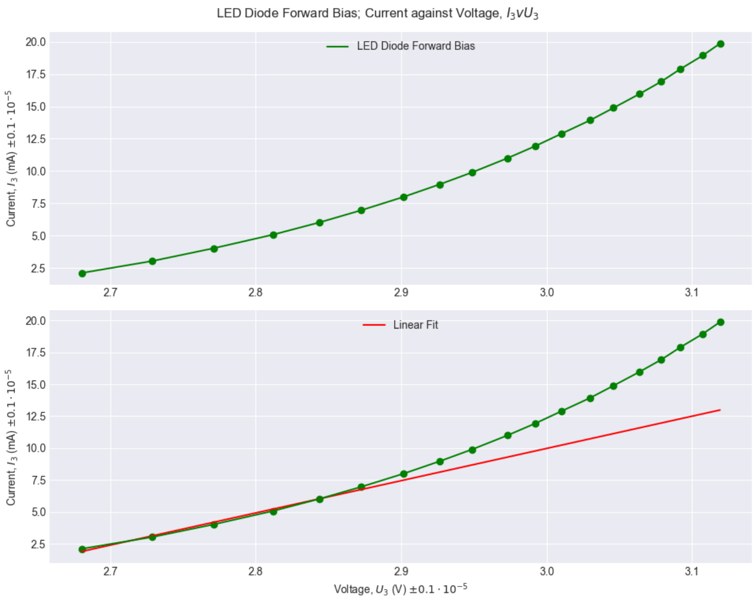

Figure 4: (a) The Original Data of the LED Diode; Current against Voltage
(b) The Linear Fit to find the threshold voltage

The threshold voltage is defined to be the point at which the data cannot be approximated by a linear regression. The linear regression was not done through a curve fit, as a curve fit would try to find a linear regression taking into account all points, including the exponential parts. Instead, a function (found in the appendix if needed) which takes some number of data points (starting with 2) and compares if they all together behave linearly. The comparison is done by the condition that a linear regression of those limited number of points has an R^2 value of 0.999 or higher. Same approach as from the Zener Reverse Bias Configuration. From this, it led to the above figure, and yielding a threshold voltage of $U_S = 2.9017V$, and the corresponding wavelength, calculated using Equation 4, was $\lambda_{intersection} = 426.83nm$.

3.2.2 Discussion

In the first task, due to the significantly higher absolute range of the voltage of the reversed bias regime of the Zener Diode, it was more practical to only present the forward bias configuration. The forward configuration presents expected results, where an increasing voltage results in an increasing current. With a nearly asymptotic *jump* close to some voltage limit. Such a limit for the Silicon Diode is approximated to ≈ 0.70 V, for the LED diode as ≈ 3.17 V, and for the forward Zener as ≈ 0.75 V. Furthermore, due to the limited range of the current, the full extent of the *jump* is not presented. As LEDs typically require higher threshold voltages than standard silicon or Zener diodes because they must overcome the bandgap energy associated with photon emission, a limited range of up to only 20mA, the LED's current-voltage characteristic appears almost linear. The full extend of the data set might not have had been properly captured. Which explains the forward voltage threshold of LED as above 2V compared to the 0.6-0.8V range typical for Silicon and Zener diodes.

For the second task, a non-linear regression was performed on the log(I)-U characteristic. The extracted parameters are close to the expected values for a silicon diode, where the n factor is typically of $n \approx 2$ order (Nanda, K. K. "Current Dependence of Ideality Factor of Silicon Diodes.") and the thermal voltage at room temperature ($T \approx 300K$) is $U_T \approx 25mV$ (directly from the formula $\frac{kT}{e}$). In our case, we obtained $n = 2.106$ and $U_T = 24.63mV$, which are in very good agreement with theory. While small deviations can be attributed to temperature fluctuations or uncertainties in the fitting procedure, the results overall confirm the quality of the data.

The average wavelength of the LED, obtained through estimating the linear part of Figure 4 giving $\lambda_{intersection} = 426.83nm$, falls within the range of blue-violet wavelength range, $\lambda \in [400, 450]nm$. This is in line with what was seen in doing the experiment, where a blueish hue was seen. The spectral half-width of the emitted light is approximately $kT \approx 26meV$ at room temperature, which corresponds to a wavelength spread of about $30, 40nm$.

The Zener diode presents a behaviour, where the region of high resistance (the parts where the current is close to zero) is much longer in the reverse bias set up compared to the forward bias configuration. This is mainly due to how for forward, the nearly exponential jump is from the in built potential barrier due to PN junction electric field being overwhelmed and breaking at some point of a voltage. As such, increasing voltage is about being able to overwhelm the potential barrier in place from the electric field. While for reversed, increasing voltage yields to having enough energy to knock electrons off atoms, which in place create a chain reaction of knocking of more atoms - creating a nearly exponential jump. As such, energy required to reach enough energy to knock of electrons is much higher then the just breaking a potential barrier. The value of the breakdown voltage is of within the range for a Zener diode, where it is of range of [2.4 200] V (âWhat Is a Zener Diode? | TTI, Inc.â), where 5.8V falls within. Further making the found value conrete.

3.3 Error Analysis

The uncertainties for the measurements of the Voltage and Current are taken as the smallest decimal in the given measured values. The uncertainty in log of Figure 3 was taken as the average between the log of the maximum and minimum of the logarithm of the current. The uncertainty in found parameters were either taken from multiplying the found intersection voltage with the constants (as such for the wavelength in LED) or through the Mean Square Root for found parameters from linear regression (as for I_S, U_T and n). The Mean Square Root provides an approximation of how accurate are the found parameters in terms of the theoretical data (from the Shockley Equation) and the Measured Data. The smaller is the value, the more accurate is the parameter. The uncertainty in V_R is taken same as for Voltage, as it is derived from its respective voltage data set.

Parameter	Uncertainty	Mean Squared Error
$\Delta\lambda_{average}$	$7.31270.. \cdot 10^{-31} \approx 7.31 \cdot 10^{-31}$ m	-
ΔV_R	$\pm$ 0.1 $\cdot 10^{-5}$ V	-
ΔI_S	-	≈ 1.0001
ΔU_T	-	≈ 0.0486
Δn	-	≈ 0.0042

Table 2: Uncertainty and Mean Squared Error

4 Task III: Junction Capacitance of a power diode in a reverse bias voltage configuration

4.1 Experimental Exploration

4.1.1 Materials

- Silicon Power Diode, with the following characteristics
  - Cross Sectional Area, A = 25 mm^2
  - Relative Permittivity, $\epsilon_r = 11.8$
- Resistor, $R_V = 1000\Omega$
- Resistor, $R_M = 100\Omega$
- Capacitor, $C = 2\mu F$
- Inductor, $L = 220mH$
- TDS2000C Digital Storage Oscilloscope
- Voltage Generator (Arbitrary Function Generator, GW INTEK AFG-2005), accompanied with a Multimeter (Agilent 24405A).
- DC Power Supply (Tektronix PWS4323)
- Residual Items; Wires, Breadboard, Laptop, etc...

4.1.2 Methodology and Set Up

The circuit is set up following the below diagram, Diagram **2** (E14e Semiconductor Diodes). To ensure reverse bias configuration, the negative terminal of the DC Power Supply is set connected in line with the p-doped region (which corresponds to region of positive charges). While the Multimeter is connected in parallel with the DC Power Supply - measuring negative voltage due to the reverse bias set up. The measurements is taken for voltage range of $-30V \leq U \leq -0.5V$, with a measurement increment of -0.5 V, totalling 19 values. For each value of the input voltage, adjust the Oscilloscope to find the frequency which corresponds to a Lissajous Figure of $\frac{\pi}{2}$ against the horizontal / vertical line in the first quadrant. The found frequency corresponds to the resonance frequency for the set input voltage. Utilizing the theory from Section **2.2**, there has to be an increasing frequency value pattern. If not, reattach the diode in the opposite manner.

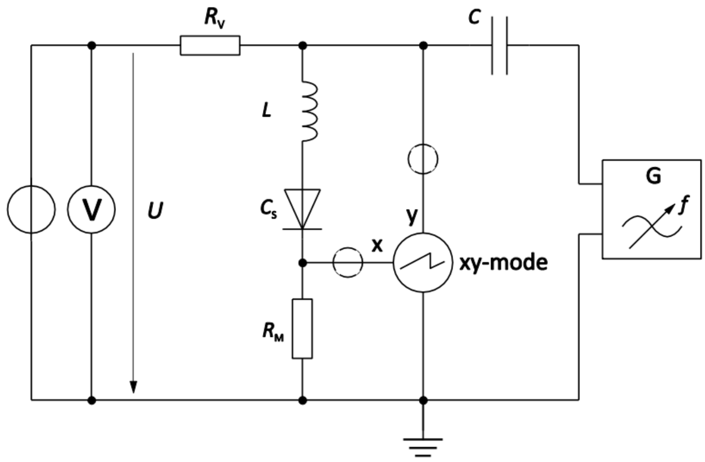

Diagram 2 Set up for the Junction Capacitance under Reverse Bias Configuration.

4.2 Analysis

4.2.1 Data and Results

From the measured data, the following data (with uncertainties on the graph) presents the total capacitance, C_{tot} (in Faraday and an order of magnitude of 10^{-9} - nF), against the *increasing* voltage applied to the circuit. The Measured $C_{tot,M}$ has been calculated through equation 8, in terms of frequency, and the Fit Curve $C_{tot,F}$ through equation 8, in terms of C_s and C_G

Figure 5 presents the expected result of, increasing absolute voltage results in a decreasing total capacitance of the circuit. This is as expected, as an increasing voltage creates higher attraction between the diodes p,n doped regions and their respectively negative and positive terminals aligned from the power supply creates a higher delation zone - which reduces the effectiveness of the charge storing. The Curve Fit and the Measured Data came out to an R^2 value of $0.9996178189940529 \approx$ **0.9996**, which correlates to a nearly perfect match between both data sets. With a mean average percentage difference between the sets as ≈ 0.6941 %, a max difference of $\approx 6.846 \cdot 10^{-13} F$ and a mean absolute error of $\approx 2.168 \cdot 10^{-21} F$, it can be said that the two data sets, in correlation to each other, are ***accurate and precise***. This would mean the found values from the fit, C_G, the extrapolation of the depletion zone, d_s from C_s and the depletion-layer capacitance d_0 of the unbiased junction, would be within their respective real values.

Below Figure 6 presents the Depletion Zone, d_s, (in meters and an order of magnitude of 10^{-6} - μm), against an *increasing* voltage. d_s has been calculated through equation 9. he provided data set of the current and voltage had been multiplied with a -1 as to present a more accurate result in correspondence to the real values

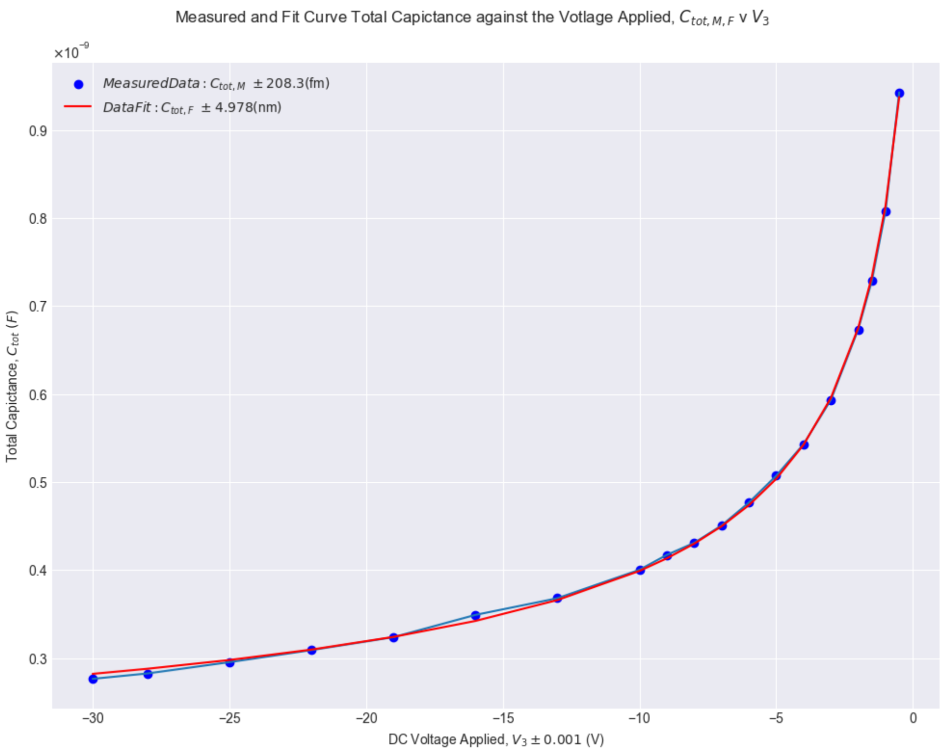

Figure 5: Measured and Fit Curve Total Capacitance against the Voltage Applied, $C_{tot,M,F}$ v V_3

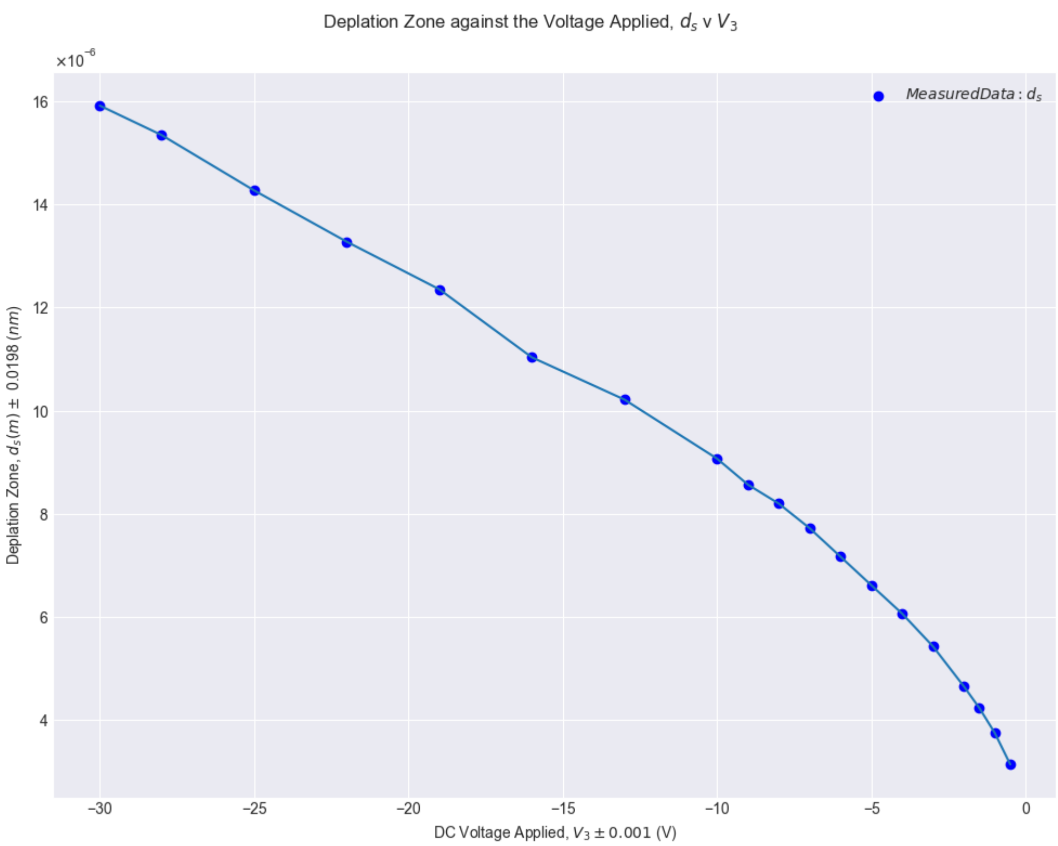

Figure 6: Depletion Zone against the Voltage Applied, d_s v V_3

Figure 6 presents a behaviour in correlation to the total capacitance graph, above Figure 5. Where as explored in the Theoretical Section, a decreasing capacitance from an increasing absolute voltage would result in an increasing depletion zone. The form of the graph seems to be of pattern $\sqrt{x}$, as the graphs follows a half-parabola shape turned on its side. Compared to other similar graphs, such as of e^x, figure 6 has a more gradual curve to a plateau and in its simplest form starts at the origin (where as e^x starts at the point (0,1) rather than (0,0) and has a more sudden jump to a plateau). Utilising both Figure 5 and 6, the following parameters values where extrapolated;

Parameter	Value
C_G	$1.123130256..\cdot 10^{-10} \approx 0.1123\ (nF)$
d_o	$2.486810204..\cdot 10^{-6} \approx 2.487\ (\mu m)$
C_0	$1.050335647.\cdot 10^{-9} \approx 1.050\ (nF)$

Table 3: Found values for task III; C_G, C_0, d_0

4.2.2 Discussion

Both figures present a results which are in line with the theoretical expectations, and the found values are within a reasonable magnitude. As C_0 corresponds to the capacitance for vanishing applied voltage ($V_3 = 0$), the found value of 1.050 nF would correspond to approximately the correct position on Figure 5. As the graph is approaching a value close to 1 nF at positions closer to $V_3 = 0$. In the same manner, d_0 is the depletion zone width in an unbiased junction, it would correspond to the width of the diode in its relaxed state, i.e without any voltage being applied in none of the configuration (forward or reversed). This would mean the value has to be smaller than the smallest value in the d_s set. And as the smallest value in the d_s set is $\approx 3\mu m$ (corresponding to 0.5 V), the value of 2.4687 μm is of reasonable degree of accuracy. The value of C_G has no real comparison to evaluate the accuracy of the data. However, it is of order of the total capacitance C_{tot}, of $\cdot 10^{-9}$ order, making it more viable to say it is of reasonable approximation. The errors and validity of the data is within the range of the expected errors, from such as energy lose, non idealised set up, etc....

4.3 Error Analysis

The uncertainties in measured values, the voltage and the frequency, correspond to the smallest measurable value from the electronic device. While other values are propagated through standard uncertainty formula, where the square root of the partial derivative of any parameter with an uncertainty would be the uncertainty in the function. As such, the following equations were found

Uncertainty in Total Capacitance; given $C = \frac{1}{L(2\pi f)^2}$

$$\Delta C = \left|\frac{\mathrm{d}C}{\mathrm{d}f}\right| \Delta f = \left|-\frac{2}{L(2\pi)^2 f^3}\right| \Delta f \tag{10}$$

Uncertainty in C_g, given $C(U) = C_g + C_0\sqrt{\frac{U_D}{U_D - V}}$

$$\Delta C = \sqrt{\left(\frac{\partial C}{\partial C_g}\Delta C_g\right)^2 + \left(\frac{\partial C}{\partial C_0}\Delta C_0\right)^2 + \left(\frac{\partial C}{\partial U_D}\Delta U_D\right)^2 + \left(\frac{\partial C}{\partial V}\Delta V\right)^2} \tag{11}$$

Uncertainty in Depletion Zone Width, $d_s = \frac{\varepsilon_r \varepsilon_0 A}{C(U) - C_g}$

$$\Delta d_s = \sqrt{\left(\frac{\partial d_s}{\partial C}\Delta C\right)^2 + \left(\frac{\partial d_s}{\partial C_g}\Delta C_g\right)^2 + \left(\frac{\partial d_s}{\partial V}\Delta V\right)^2} \tag{12}$$

Uncertainty in Depletion Zone Width at Zero Voltage, $d_0 = \frac{\varepsilon_r \varepsilon_0 A}{C_0}$

$$\Delta d_0 = \left|\frac{\mathrm{d}d_0}{\mathrm{d}C_0}\right| \Delta C_0 = \frac{\varepsilon_r \varepsilon_0 A}{C_0^2}\Delta C_0 \tag{13}$$

Where it all yields to;

Parameter	Value
Δf	0.0001 (Hz)
ΔV	0.001 (V)
$\Delta C_{tot,M}$	2.082726796...$\cdot 10^{-17} \approx$ 208.3 (fm)
$\Delta C_{tot,F}$	4.978233666...$\cdot 10^{-12} \approx$ 4.978 (nm)
Δd_s	1.980922620...$\cdot 10^{-7} \approx$ 0.0198 (nm)
Δ	2.117435244...$\cdot 10^{-8} \approx$ 21 (nm)

Table 4: Mean Propagation Error and Uncertainty

5 Conclusion

With the externally provided data for the Zener Diode, the lab report was able to find the required parameters for all circuit configurations. With an accuracy of reasonable range, and no one measurement being off from the theoretically expected values by a large margin, and low uncertainty, the report was able to explore the required theory and application of diodes in the context of forward and reversed bias configurations. The existing errors and deviations are expected, as they are in the range of what would have been expected for a non ideal systems. Further research in the topic would be; Analysing how reverse bias affects the LED diode, and looking at the behaviour at ranges above the limits presented here.

6 Citation

Unknown Author. *E14e Semiconductor Diodes.* Course General Physics Laboratory 2, 2025.

Unknown Author. *Guide to Experiment E14e: Semiconductor Diodes.* Course General Physics Laboratory 2, 2025.

Nanda, K. K. "Current Dependence of Ideality Factor of Silicon Diodes." Current Science, vol. 74, no. 3, 1998, pp. 234â37. JSTOR, http://www.jstor.org/stable/24100871. Accessed 6 May 2025.

Detrick, David. âWhat Is a Zener Diode? | TTI, Inc.â Www.tti.com, 4 Apr. 2022, www.tti.com/content/ttiinc/en/resources/blog/what-is-a-zener-diode.html.

7 Appendix

```
def find_linear_region(x, y, max_window=30, r2_threshold=0.99):
    for end in range(3, max_window):
        x_window = x[:end]
        y_window = y[:end]
        slope, intercept, r_value, p_value, std_err = linregress(x_window,
        ↪  y_window)
        if r_value**2 < r2_threshold:
            return end - 1  # go back one step if RÂ2justdropped
    return max_window

cutoff = find_linear_region(U3, I3, max_window=30, r2_threshold=0.99)
```