Lab Report

The Shockley Haynes Experiment

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September 24, 2021

1 Introduction

The Shockley Haynes experiment is predicated on the knowledge that photons incident on a semiconductor such as germanium (Ge) will create electron-hole pairs. Using an optical fibre cable we can create electron-hole pairs by exciting a piece of germanium with infrared radiation. Placing an electric field flowing through the germanium sample allows us to cause the electrons and holes to move in opposite directions due to their opposite charges. Changing these parameters such as the Sweep Voltage (V_s), The strength of the infrared radiation (V_L) and the distance between the germanium sample and the optical fibre cable (d_d) we can use an oscilloscope to observe the changes in voltage detected by a gold detector, record these changes and do calculations to find things such as the carrier mobility (μ), carrier lifetime of the holes (τ) and diffusion coefficient of holes (D_h) of the sample.

As semiconductors such as germanium typically already have a high concentration of electrons flowing through them, it is difficult to observe any changes in mobility, lifetime or diffusion. If we excite the germanium and producing a far higher concentration of holes than was there prior, we can easily observe a visible voltage increase and monitor changes as we change the parameters of the experiment.

2 Background and Theory

In modern electronics, carrier mobility plays an extremely vital role in things such as Bipolar junction transistors. The speed that an electron or hole travels inside a semiconductor when being dragged by an electric field is described by the carrier mobility function:

$$v = \mu E \tag{1}$$

Where v is the drift velocity, μ is the carrier mobility and E is the electric field being applied to the semiconductor.

In our experiment we used a piece of equipment specifically designed to simulate the Haynes Shockley experiment and an oscilloscope to measure the voltage change and transit time of the holes inside the germanium. In order for the above equation to be useful we have to break it down into variables we can either control or measure throughout the experiment. The equation is broken down as follows:

$$\mu = \frac{d_d}{t_d}\frac{L}{V_s} \tag{2}$$

$$\text{where; } v = \frac{d_d}{t_d} \text{ and } E = \frac{L}{V_s}$$

Where d_d is the distance of the optical fibre cable from the semiconductor, t_d is the transit time, L is the length of the semiconductor and V_s is the sweep voltage applied to the semiconductor.

The second characteristic of a semiconductor we can measure using this experiment is the carrier lifetime of the holes. As the newly excited electron hole pairs move in opposite direction overtime they will connect with each other and recombine meaning there is a reduction in the number of free carriers, this is sometimes known as the recombination rate. We can change all of the variables mentioned previously however it is extremely important that the excitation power V_L remains constant as this will directly affect how many holes are created in the semiconductor. The equation to calculate recombination rate is as follows:

$$S = n_0 \cdot e^{-\frac{t_d}{\tau_h}} \tag{3}$$

Where S is the area under the curve created by the increase in voltage, n_0 is the number of holes before the excitation, t_d is the transit time and τ_h is the characteristic decay time

We can simplify this equation by removing the exponential using logarithms as follows:

$$\ln(S) = \ln(n_0 - \frac{t_d}{\tau_h}) \tag{4}$$

This form of the equation allows us to graph ln(S) vs t_d and get a linear graph we can use to find the carrier lifetime τ.

Finally we want to measure the diffusion constant of the hole carriers in Ge. When the infrared radiation excites the germanium sample a large concentration of holes are created that weren't there previously, as the holes move towards the electric field they also spread out away from each other in order to move from an area of high concentration to an area of low concentration. The equation to calculate the diffusion constant is as follows:

$$D_h = \frac{(d_d W)^2}{(16ln(2))t_d^3} \tag{5}$$

Where D_h is the diffusion constant, d_d is the distance from the optical fibre cable to the semiconductor, W is the full width half maximum (FWHM) of the voltage increase and t_d is the transit time.

When measuring the FWHM as part of this experiment, the actual width measured may be affected by the duration of the infrared radiation exciting the germanium. We attempt to simulate an infinitely short excitation within our calculations by subtracting the duration of the light pulse ($\approx 5\mu$s) from the width measured using the following equation:

$$W_m = \sqrt{W_{in}^2 + W^2} \quad \text{or} \quad W^2 = W_m^2 - W_{in}^2 \tag{6}$$

Where W_m is the FWHM we measured, W_{in} is the duration of the light pulse from the optical fibre cable and W is the ideal FWHM.

Finally, once we have determined values for both our carrier mobility (μ) and diffusion constant (D_h) we can compare the ratio of them with known physics constants and determine our level of accuracy. This comparison is known as 'The Einstein relation for diffusion' and the relationship is as follows:

$$\frac{D_h}{\mu} = \frac{k_b T}{q} \tag{7}$$

Where D_h is the diffusion constant we calculate, μ is the carrier mobility we calculate, k_b is Boltzmann's constant, q is the charge of the carrier (electrons and holes have opposite charges but the magnitude of both is equal) and T is the temperature of the room in kelvin ($\approx$ 300K)

3 Results

3.1 Excitation power

Table 1: List of results for variable excitation power V_L

V_L (V)	V_s (V)	d_d (cm)	t_d (μs)
26.2±0.05	15.3±0.05	0.4±0.05	32.0±0.05
20.1±0.05	15.3±0.05	0.4±0.05	31.6±0.05
13.0±0.05	15.3±0.05	0.4±0.05	30.4±0.05
15.8±0.05	15.3±0.05	0.4±0.05	31.0±0.05
18.6±0.05	15.3±0.05	0.4±0.05	31.2±0.05

All errors are determined using one half of the measuring unit.

Carrier mobility calculations using Eq. 2

$$(V_L = 26.2) \qquad \mu = \frac{0.4}{32.0 \times 10^{-6}} \frac{2}{15.3} = 1634.0 \pm 195.3 \text{ cm}^2/\text{V} \cdot \text{s}$$

$$(V_L = 20.1) \qquad \mu = \frac{0.4}{31.6 \times 10^{-6}} \frac{2}{15.3} = 1654.7 \pm 197.8 \text{ cm}^2/\text{V} \cdot \text{s}$$

$$(V_L = 18.6) \qquad \mu = \frac{0.4}{31.2 \times 10^{-6}} \frac{2}{15.3} = 1675.9 \pm 200.3 \text{ cm}^2/\text{V} \cdot \text{s}$$

$$(V_L = 15.8) \qquad \mu = \frac{0.4}{31.0 \times 10^{-6}} \frac{2}{15.3} = 1686.7 \pm 201.6 \text{ cm}^2/\text{V} \cdot \text{s}$$

$$(V_L = 13.0) \qquad \mu = \frac{0.4}{30.4 \times 10^{-6}} \frac{2}{15.3} = 1720.0 \pm 205.6 \text{ cm}^2/\text{V} \cdot \text{s}$$

Error Analysis:

$$\sqrt{(\frac{0.05}{0.4})^2(\frac{0.05}{32 \times 10^{-6}})^2} + \sqrt{(\frac{0}{2})^2(\frac{0.05}{15.3})^2} = \pm 195.3$$

$$\sqrt{(\frac{0.05}{0.4})^2(\frac{0.05}{31.6 \times 10^{-6}})^2} + \sqrt{(\frac{0}{2})^2(\frac{0.05}{15.3})^2} = \pm 197.8$$

$$\sqrt{(\frac{0.05}{0.4})^2(\frac{0.05}{31.2 \times 10^{-6}})^2} + \sqrt{(\frac{0}{2})^2(\frac{0.05}{15.3})^2} = \pm 200.3$$

$$\sqrt{(\frac{0.05}{0.4})^2(\frac{0.05}{31.0 \times 10^{-6}})^2} + \sqrt{(\frac{0}{2})^2(\frac{0.05}{15.3})^2} = \pm 201.6$$

$$\sqrt{(\frac{0.05}{0.4})^2(\frac{0.05}{30.4 \times 10^{-6}})^2} + \sqrt{(\frac{0}{2})^2(\frac{0.05}{15.3})^2} = \pm 205.6$$

By graphing the excitation power vs transit time and subbing $V_L = 0\text{V}$ into the equation of the line $1.18 \times 10^{-7}(x) + 2.9 \times 10^{-5}$ we get a true travel time of 29×10^{-6} seconds or 29 μs.

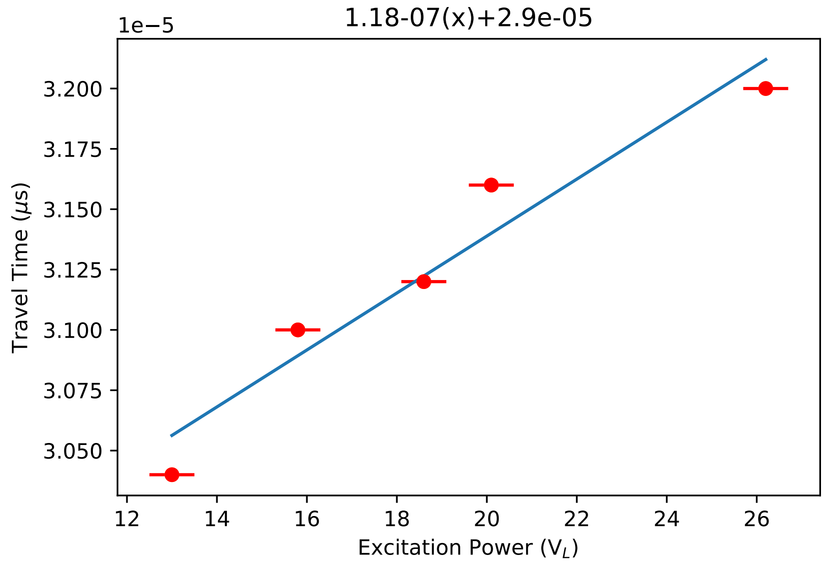

Figure 1: Graph of Excitation Power (V_L) vs Travel Time (μs)

3.2 Transient time versus distance

Table 2: List of results for variable fibre cable distance d_d

V_L (V)	V_s (V)	d_d (cm)	t_d (μs)	S (Vs)	W (μs)
17.2±0.05	30.8±0.05	0.4±0.05	22.2±0.05	$2.62 \times 10^{-}5$	6.87
17.2±0.05	30.8±0.05	0.45±0.05	22.6±0.05	$1.12 \times 10^{-}5$	7.0
17.2±0.05	30.8±0.05	0.5±0.05	23.6±0.05	$1.87 \times 10^{-}5$	7.2
17.2±0.05	30.8±0.05	0.55±0.05	26.6±0.05	$2.48 \times 10^{-}5$	8.2
17.2±0.05	30.8±0.05	0.6±0.05	28.0±0.05	$2.47 \times 10^{-}5$	7.5
17.2±0.05	30.8±0.05	0.65±0.05	28.6±0.05	$9.11 \times 10^{-}8$	8.2
17.2±0.05	30.8±0.05	0.7±0.05	29.8±0.05	$8.73 \times 10^{-}6$	8.5
17.2±0.05	30.8±0.05	0.75±0.05	30.4±0.05	$8.00 \times 10^{-}6$	9.8
17.2±0.05	30.8±0.05	0.8±0.05	31.4±0.05	$3.79 \times 10^{-}6$	9.8
17.2±0.05	30.8±0.05	0.85±0.05	33.4±0.05	$4.91 \times 10^{-}6$	7.8
17.2±0.05	30.8±0.05	0.9±0.05	35.8±0.05	$5.00 \times 10^{-}6$	8.5
17.2±0.05	30.8±0.05	0.95±0.05	36.6±0.05	$5.03 \times 10^{-}6$	6.37
17.2±0.05	30.8±0.05	1±0.05	37.0±0.05	$5.00 \times 10^{-}6$	5.32
17.2±0.05	30.8±0.05	1.05±0.05	38.6±0.05	$5.23 \times 10^{-}6$	7.1
17.2±0.05	30.8±0.05	1.1±0.05	39.6±0.05	$5.03 \times 10^{-}6$	8.4
17.2±0.05	30.8±0.05	1.15±0.05	41.0±0.05	$4.83 \times 10^{-}6$	8.7
17.2±0.05	30.8±0.05	1.2±0.05	42.6±0.05	$4.56 \times 10^{-}6$	7.7

All errors are determined using one half of the measuring unit.

By graphing d_d vs t_d we can calculate the carrier mobility from the slope by rearranging Eq. 2 as follows $d_d = \frac{\mu V_s}{L} t_d$. This graph gives us a slope of 38721, by subbing this into our equation we get:

$$38721 = \frac{\mu(30.8)}{2}$$

solving for μ we get:

$$\mu = \frac{38721(2)}{30.8} = 2514.35 \text{ cm}^2/V \cdot s$$

Error Analysis:

$$W = \sqrt{(8.5 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 6.9 \times 10^{-6}$$

$$W = \sqrt{(8.6 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 7.0 \times 10^{-6}$$

$$W = \sqrt{(8.8 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 7.2 \times 10^{-6}$$

$$W = \sqrt{(9.6 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 8.2 \times 10^{-6}$$

$$W = \sqrt{(9 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 7.5 \times 10^{-6}$$

$$W = \sqrt{(9.6 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 8.2 \times 10^{-6}$$

$$W = \sqrt{(9.9 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 8.5 \times 10^{-6}$$

$$W = \sqrt{(11 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 9.8 \times 10^{-6}$$
$$W = \sqrt{(11 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 9.8 \times 10^{-6}$$
$$W = \sqrt{(9.3 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 7.8 \times 10^{-6}$$
$$W = \sqrt{(9.9 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 8.5 \times 10^{-6}$$
$$W = \sqrt{(8.1 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 6.4 \times 10^{-6}$$
$$W = \sqrt{(7.3 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 5.3 \times 10^{-6}$$
$$W = \sqrt{(8.7 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 7.1 \times 10^{-6}$$
$$W = \sqrt{(9.8 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 8.4 \times 10^{-6}$$
$$W = \sqrt{(10 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 8.7 \times 10^{-6}$$
$$W = \sqrt{(9.2 \times 10^{-6})^2 - (5 \times 10^{-6})^2} = 7.7 \times 10^{-6}$$

We also see from the y-intercept that when the travel time is 0, the distance d_d is -0.448 cm, this would imply that our d_d in the earlier calculation is off by as much as 0.448 cm. If we redo the previous calculations with a d_d value of 0.848 cm we get a carrier mobility μ value closer to 3500 cm^2/V s rather than 1600 cm^2 / V s which is a difference of 32.78% compared to the previous difference of 44.45%.

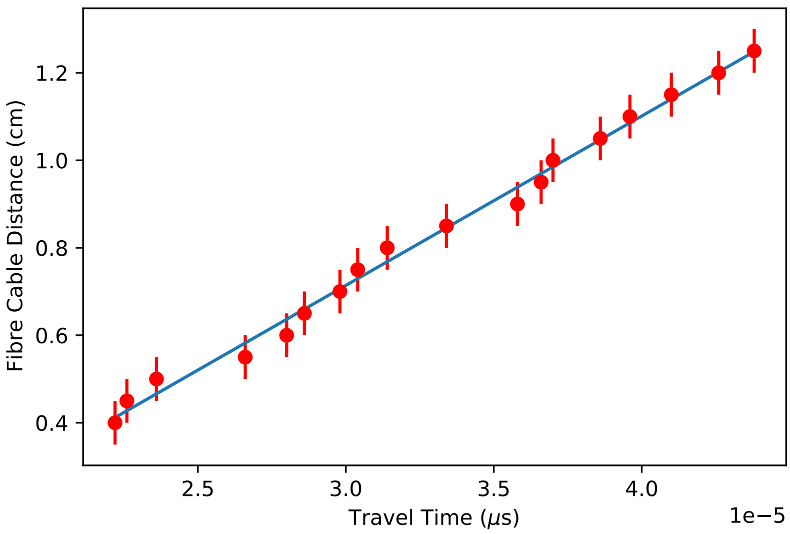

Figure 2: Graph of Travel Time (μs) vs Fibre cable length (cm)

3.3 Transient time versus sweep voltage

Table 3: List of results for variable sweep voltage V_s, for multiple distances d_d

V_L (V)	V_s (V)	d_d (cm)	t_d (μs)
26.2±0.05	29.1±0.05	1.25±0.05	38.6±0.05
26.2±0.05	35.8±0.05	1.25±0.05	35.6±0.05
26.2±0.05	43.5±0.05	1.25±0.05	35.4±0.05
26.2±0.05	47.3±0.05	1.25±0.05	37.4±0.05
26.2±0.05	30.4±0.05	1.25±0.05	43.0±0.05
26.2±0.05	25.8±0.05	1.25±0.05	43.2±0.05
26.2±0.05	25.8±0.05	0.4±0.05	22.8±0.05
26.2±0.05	29.7±0.05	0.4±0.05	21.0±0.05
26.2±0.05	41.1±0.05	0.4±0.05	18.0±0.05
26.2±0.05	50.0±0.05	0.4±0.05	18.8±0.05
26.2±0.05	29.0±0.05	0.4±0.05	23.0±0.05
26.2±0.05	19.3±0.05	0.4±0.05	28.6±0.05
26.2±0.05	13.1±0.05	0.4±0.05	34.8±0.05
26.2±0.05	13.1±0.05	0.5±0.05	38.4±0.05
26.2±0.05	27.0±0.05	0.5±0.05	23.8±0.05
26.2±0.05	36.8±0.05	0.5±0.05	21.2±0.05
26.2±0.05	43.7±0.05	0.5±0.05	20.4±0.05
26.2±0.05	25.0±0.05	0.65±0.05	30.8±0.05
26.2±0.05	36.0±0.05	0.65±0.05	24.0±0.05
26.2±0.05	48.3±0.05	0.65±0.05	22.2±0.05
26.2±0.05	50.0±0.05	0.65±0.05	26.4±0.05
26.2±0.05	50.0±0.05	0.9±0.05	27.6±0.05
26.2±0.05	40.0±0.05	0.9±0.05	32.6±0.05
26.2±0.05	31.7±0.05	0.9±0.05	34.0±0.05
26.2±0.05	20.4±0.05	0.9±0.05	41.8±0.05

All errors are determined using one half of the measuring unit.

By plotting the graph of t_d vs V_s for varing sweep voltages and distances using the re-arranged Eq.2 as follows: $\frac{d_d L}{t_d} = \mu V_s$. We get 5 separate graphs, each with their own slope value for carrier mobility μ. These graphs and the value of their slope is shown below:

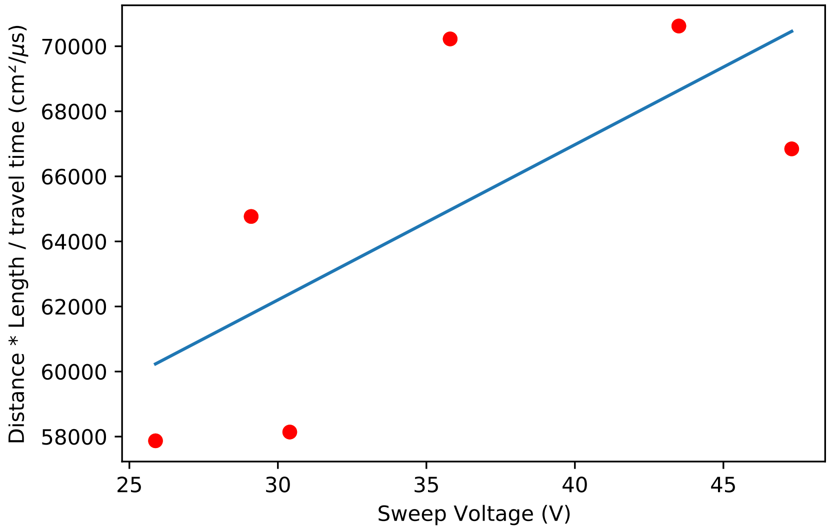

Figure 3: Graph of Sweep Voltage (V_s) vs $\frac{d_d L}{t_d}$ for $d_d = 1.25$cm

$\mu = 477$

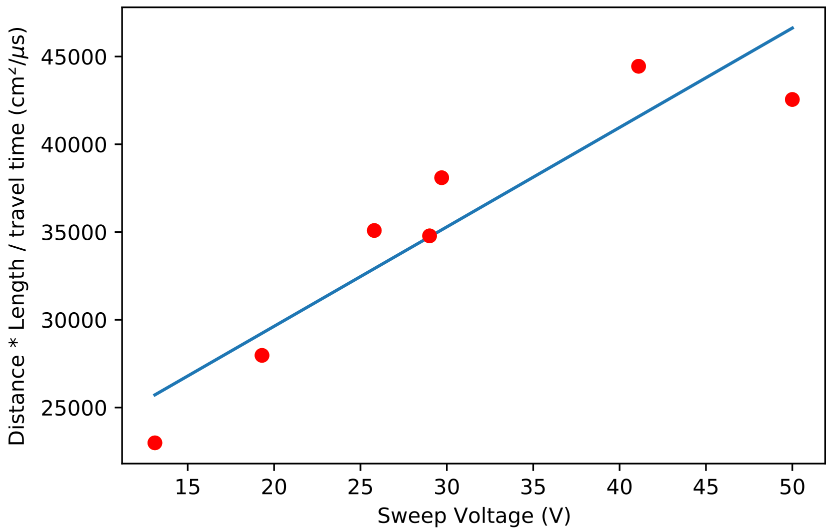

Figure 4: Graph of Sweep Voltage (V_s) vs $\frac{d_d L}{t_d}$ for $d_d = 0.4$cm

$\mu = 566$

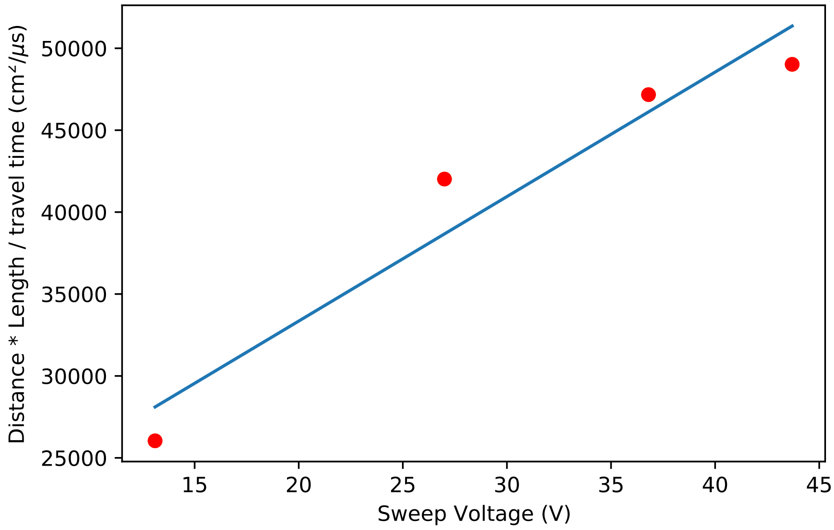

Figure 5: Graph of Sweep Voltage (V_s) vs $\frac{d_d L}{t_d}$ for $d_d = 0.5$cm

$\mu = 760$

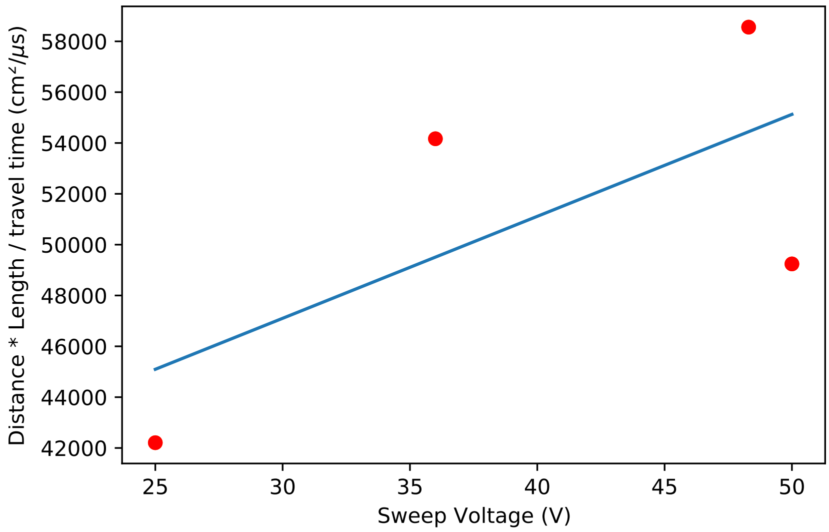

Figure 6: Graph of Sweep Voltage (V_s) vs $\frac{d_d L}{t_d}$ for $d_d = 0.65$cm

$\mu = 401$

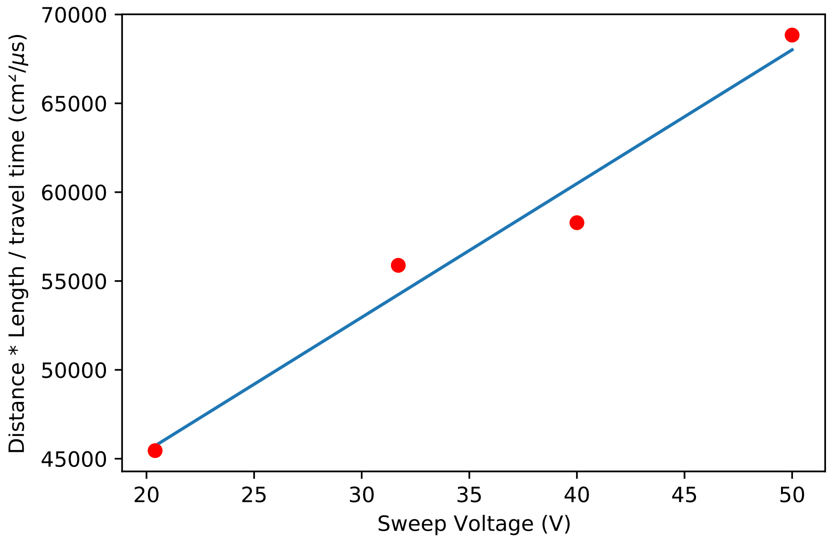

Figure 7: Graph of Sweep Voltage (V_s) vs $\frac{d_d L}{t_d}$ for $d_d = 0.9$cm

$\mu = 753$

3.4 Lifetime analysis

By plotting ln S vs t_d we get a carrier lifetime value of 3.51×10^{-6} or 3.51 μs

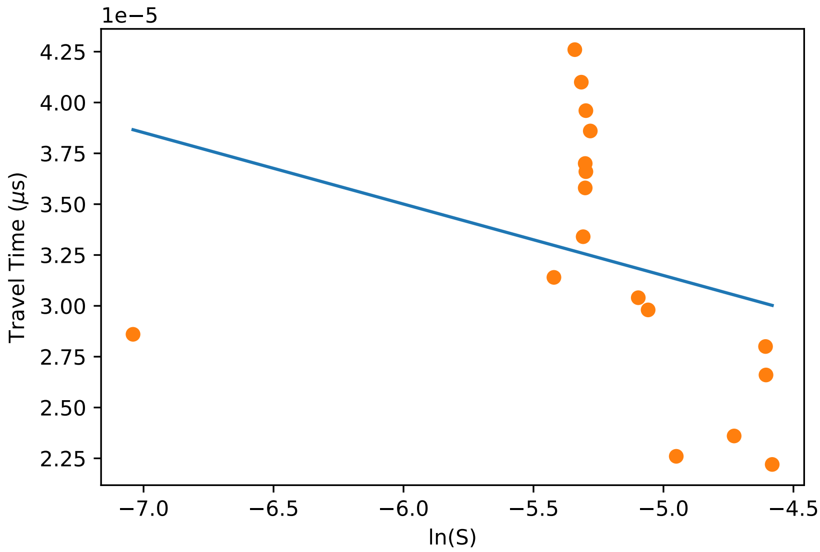

Figure 8: Graph of ln(S) vs Travel time (μs)

3.5 Diffusion constant

By plotting t_d^3 vs $\frac{(d_dW)^2}{16ln(2)}$ we achieved a slope value of 4.77×10^{-6}. Meaning our Diffusion constant is 4.77×10^{-6} cm^2 / s

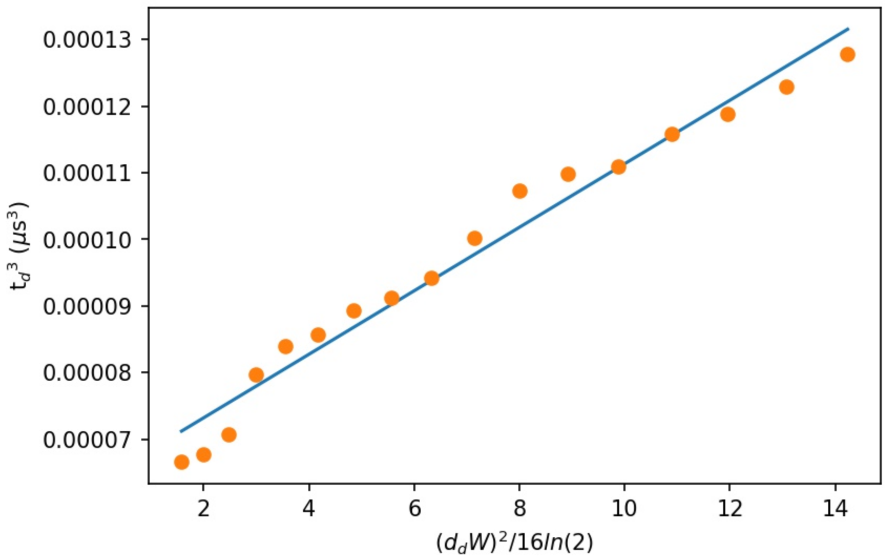

Figure 9: Graph of $\frac{(d_dW)^2}{16ln(2)}$ vs Travel time (μs^3)

The Einstein relationship for diffusion: Using Eq. 7 we can check our calculated values for carrier mobility and diffusion constant versus known constants. The calculation is as follows:

$$\frac{4.77\times10^{-6}}{2514.35} = \frac{1.38\times10^{-23}(300)}{1.6\times10^{-19}}$$

$$1.9\times10^{-9} = 0.026$$

We can see that the equation does not balance and there is a percentage difference of 200%

4 Conclusion

We have calculated the following values for the mobility coefficient: $1634.0 \pm 195.3, 1654.7 \pm 197.8, 1675.9 \pm 200.3, 1686.7 \pm 201.6, 1720.0 \pm 205.6, 2514.35, 477, 566, 760, 401$ and 753 cm^2/V$\cdot$s. A carrier lifetime of 3.51×10^{-6}s or 3.51μs, and a diffusion constant of 4.77×10^{-6} cm^2 / s. We attempted to verify our mobility coefficient and diffusion constant values using the The Einstein Relationship for Diffusion and calculated a ratio way outside the accepted range.