Shockley-Haynes Experiment

Clea Dronne
10475323
Third Year Lab Report
University of Manchester
(This experiment was performed in collaboration with Sacha Barre.)
(Dated: May 20, 2022)

This experiment aimed to reproduce the results obtained in the Shockley-Haynes experiment from the 1950s [1]. The mobility, diffusion constant and lifetime of two different N-type semiconductor samples were measured. The values $\mu = 1150 \pm 30$ cm^{2}s^{-1}V^{-1}, $D = 90 \pm 10$ cm^{2}s^{-1} and $\tau = 12 \pm 4$ cm^{2}s^{-1}V^{-1} were obtained (1st sample). The mobility quoted was significantly lower than values cited in literature [2], which could be explained by the different sample properties and methods used in this experiment.

I. INTRODUCTION

The study of semiconductors and the behavior of minority carriers is crucial to be able to exploit semiconductor materials in electronic devices. A semiconductor is a material that has conductivity properties between a conductor and an insulator. Its band gap (between conduction and valence bands) is of about 1eV, low enough for charge carriers to be able to jump from one to the other [3].

An intrinsic semiconductor (like Germanium - group IV), can be doped to modify its electrical properties. They can be doped with electrons or holes, respectively N-type or P-type semiconductors [4].

The Shockley-Haynes experiment was first performed in the 1950s [1]. This new experimental technique allowed for the measurements of semiconductors properties such as mobility and lifetime directly, instead of using indirect methods such as the Hall effect.

In this experiment, three properties of semiconductors were studied. The mobility measures how quickly minority carriers move through a material under an electric field. The diffusion constant describes the random motion of minority carriers in the material. The lifetime is the average time it takes a minority carriers to recombine with the majority carriers in the material.

II. THEORY

The experiment studied the motion of minority carriers in semiconductors. Their movement is modelled by the diffusion equation,

$$D\frac{\partial^2 n}{\partial x^2} - \mu E\frac{\partial n}{\partial x} - \frac{n}{\tau} = \frac{\partial n}{\partial t}, \tag{1}$$

where n is the minority carrier density, μ is the mobility, D the diffusion constant, τ the lifetime and E the sweeping electric field applied unto the semiconductor [5]. A solution to this equation, if we assume that at $t = 0$, the minority carrier distribution is a delta function $y(x, 0) = A\delta(x)$, is

$$n(x,t) = \frac{A}{\sqrt{4\pi Dt}} \exp\Big(- \frac{(x-\mu Et)^2}{4Dt} - \frac{t}{\tau}\Big). \tag{2}$$

The signal is detected at $x = d$ (distance from injection point), and reaches a maximum at t_0. By taking the first derivative, the equation

$$\mu E = \Big[\frac{d^2}{t_0^2} - \frac{2D}{t_0}\Big(1 + \frac{2t_0}{\tau}\Big)\Big]^{\frac{1}{2}} \approx \frac{d}{t_0} \tag{3}$$

is obtained, where the approximation is valid in the high field region $E \gg D/\mu d$.

Mobility and diffusion values can be checked with the Einstein relation [6]

$$D = \frac{\mu k_B T}{e}, \tag{4}$$

where k_B is the Boltzmann constant and T the temperature.

III. EXPERIMENTAL METHOD

A. Apparatus

The experimental setup for this experiment was very similar to the original Shockley-Haynes experiment [1]. A sweeping electric field $E = V_s/d$ was created along a semiconductor bar of size d, between points A and B. The semiconductor was Germanium (Ge).

A short pulse of minority charge carriers was injected at point E. In this experiment, this was done with a laser pulse (different from original experiment). The minority charge carriers were collected at point C.

The resistance and diode behaviour of the Ge semiconductor were measured. The current I against voltage V graphs obtained are mirrored version of what were the expected behaviours of resistors and diodes [3]. This confirmed that the minority carriers (and not majority carriers) were detected at point C, and that the samples analyzed were N-type semiconductors.

The distance d between the fibre injection point and collector point was calibrated. d was measured using a

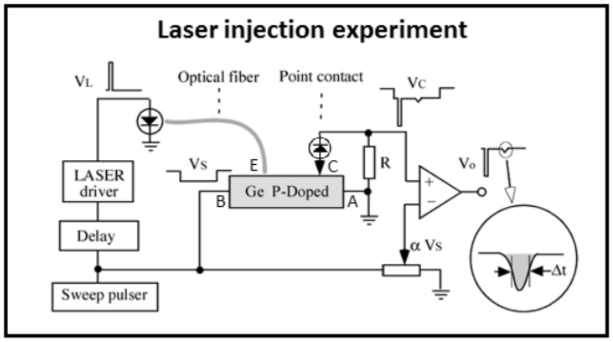

FIG. 1. Diagram of the equipment (edited from lab script)

caliper. Similarly l, the size of the semiconductor sample, was measured.

For this experiment, two different samples were studied (both N-type). For each sample, the sweeping voltage V_s and the distance d were varied (separately). V_s was varied between 17V and 50V, and d between 3.0mm and 5.5mm or 5.0mm depending on the sample. Data was collected in 1V or 0.1mm steps.

For all data sets obtained, the signal was bell shaped, with a background of varying steepness. This background was subtracted, with an exponential function of the form $y = \exp(-bx + c) + d$.

Equation 2 can be approximated to a Gaussian function, by assuming that $t_0 \leq \tau$ and $(Dt_0)^{1/2} \ll d$. A Gaussian model $y = a \exp -(x-b)^2/(2c^2) + d$ was therefore fitted to the data sets. The parameters of the Gaussian were used in the following steps to calculate the mobility, the diffusion constant and the lifetime of the samples.

B. Mobility

Using the high field approximation in Equation 3, the mobility was deduced. When varying the sweeping field V_s, d/t_0 was plotted against $E = V_s/l$. When d was varied, l/t_0 was plotted against V_s/d. In both case, a linear function of the form $y = mx$ was fitted to the data, and the mobility μ was the slope m of the curve.

In Equation 2, it was assumed that at $t = 0$, the charge carriers are injected in the sample as a delta function $y(x, 0) = A\delta(x)$. However, this is not physically possible, and charge carriers are in reality injected in a time interval dt. This leads to a superposition of solutions of the form of Equation 2. Therefore, the mobility is dependent on the sweeping voltage V_s that is applied, and a correction can be modelled [5]

$$\mu = \mu_0 \Big[(1 + x^2)^{\frac{1}{2}} - x\Big] \tag{5}$$

where

$$x = \frac{2kT}{eE_0 d}\Big(\frac{t_0}{\tau} + \frac{1}{2}\Big). \tag{6}$$

where k is the Boltzmann constant and T the temperature.

This correction was applied onto the mobility values obtained when varying the sweeping voltage V_s. This systematic bias is larger at lower V_s values, where the peaks are broader. This is explained by the stronger effect of the diffusion and recombination of the excess minority charge carriers on the surface of the sample.

C. Diffusion Constant and Lifetime

When approximating the signal to the Gaussian, the diffusion constant D was related to the standard deviation ω of the Gaussian, following the equation

$$D = \frac{(t_p d)^2}{(16 \ln 2) t_0^3} \tag{7}$$

where $t_p = 2\sqrt{2 \ln 2}\sigma$ is the full width half maximum of the peak.

$(t_p d)^2$ was plotted against t_0^3 and a linear function of the form $y = mx$ was fitted to the data. The diffusion constant D was inferred from the slope of the curve.

For the lifetime, using Equation 2 and assuming the peak of the pulse occurs at $d = \mu E t_0$, the height n_0 of the pulse is given by

$$n_0 = \frac{A}{\sqrt{4\pi D t_0}} \exp\Big(-\frac{t_0}{\tau}\Big), \tag{8}$$

where n_0 is the height of the curve and given by the Gaussian model. n_0 was therefore plotted against t_0, and the above equation was fitted to the data, from which the lifetime τ was calculated.

IV. RESULTS

In this section, the plots shown were obtained from the 1st sample analysed. Results from the 2nd sample are quoted.

A. Mobility

The results obtained when varying V_s are shown in Figure 2. The dependence of the mobility on the sweeping voltage was highlighted, as the mobility value decreased as V_s increased. The correction was applied and reduced this dependence. The mean and standard deviation were taken on the range of mobility values, which gave $\mu = 1130 \pm 90$ cm^{2}s^{-1}V^{-1}. When varying d, the value for mobility was found to be $\mu = 1177 \pm 4$ cm^{2}s^{-1}V^{-1}, the final value for 1st sample was therefore $\mu = 1150 \pm 30$ cm^{2}s^{-1}V^{-1}. For the 2nd sample, the value $\mu = 1020 \pm 20$ cm^{2}s^{-1}V^{-1} was obtained.

B. Diffusion Constant and Lifetime

The graph obtained for the diffusion constant of the 1st sample, when varying both V_s and d is displayed in Figure 3.

This gave diffusion values $D = 80 \pm 10$ cm^{2}s^{-1} for the 1st sample, and $D = 70 \pm 4$ cm^{2}s^{-1} for the 2nd sample.

For the lifetime, the values obtained were $\tau = 12 \pm 4$ μs for the 1st sample and $\tau = 9 \pm 10$ μs for the 2nd sample.

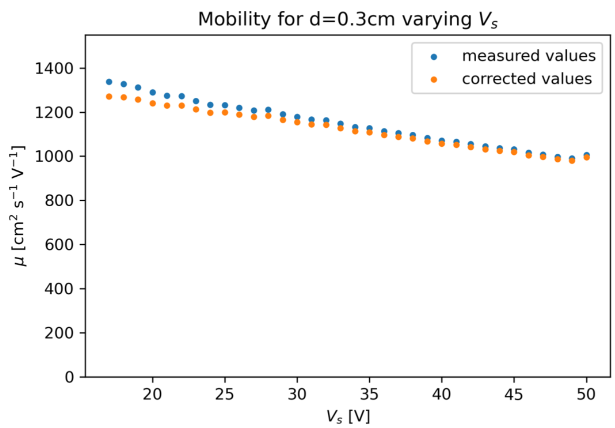

FIG. 2. Plot for the Mobility values, and highlighting their dependence and V_s. The values obtained after the correction are also displayed, and $\mu = 1130 \pm 90$ cm^{2}s^{-1}V^{-1} was inferred.

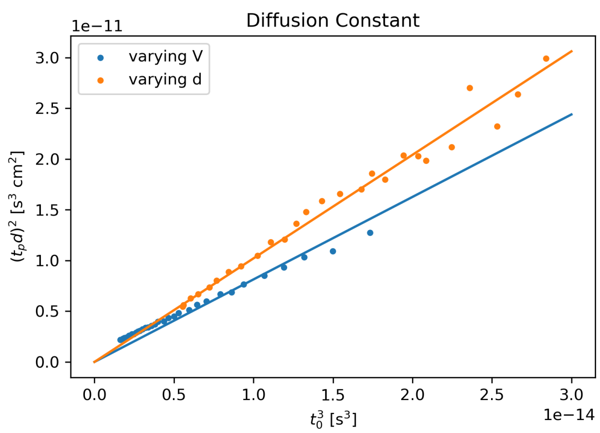

FIG. 3. Plot for the Diffusion Constant, displaying two different data sets: varying V_s and varying d (1st sample). The diffusion constant D was deduced from the slope of the line. $D = 73 \pm 3$ cm^{2}s^{-1} when varying V_s and $D = 92 \pm 1$ cm^{2}s^{-1} when varying d.

C. Sources of Uncertainties

The main source of uncertainty on the results arose from the use of the Gaussian fits, which led to statistical uncertainties on the parameters t_0, t_p and n_0.

Random uncertainties were inferred from the measurements of $l = 2.0 \pm 0.1$ cm and $d = 0.30 \pm 0.01$ cm.

Some additional physical factors were not considered in the analysis. For example, the temperature of the room was not monitored during the experiment, which could have induced a bias on the data taken on certain days. Additionally, the temperature increase of the sample at higher voltages due to Joule heating, could not be completely controlled.

Another factor is the degree of impurity of the sample, which was unknown in this experiment. This additional contribution to the mobility of the minority carriers

$$\frac{1}{\mu_{\text{measured}}} = \frac{1}{\mu_I} + \frac{1}{\mu_L} \tag{9}$$

where μ_I is the mobility contribution from the impurities in the sample and μ_L from the lattice, was neglected in the measurements.

Results could also have been optimized by spending more time preparing the sample. Data taken, especially for the 2nd sample was extremely noisy and unstable, and did not lead to any conclusive results for the lifetime ($\tau = 9 \pm 10$ μs).

V. CONCLUSION

	1st Sample	2nd Sample
Mobility cm^{2}s^{-1}V^{-1}	1150 ± 30	1020 ± 20
Diffusion cm^{2}s^{-1}	80 ± 10	70 ± 4
Lifetime μs	12 ± 4	9 ± 10

TABLE I: Summary of results

The results obtained are summarized in Table I. These are not consistent with the values available in literature for N-type semiconductors $\mu = 1900 \pm 50$ cm^{2}s^{-1}V^{-1} [2]. The lifetime cannot be compared to literature, since it is very dependent on the sample used.

Using the Einstein relation [6], it can be deduced that from the mobility value obtained in this experiment (1st sample), the corresponding diffusion value should have been $D = 30$ cm^{2}s^{-1}. This highlighted a systematic bias in the results of this experiment. The statistical and random uncertainties, identified as the major sources of errors, are not sufficient to explain such a deviation. Possible explanations included temperature and impurities.

[1] J. R. Haynes and W. Shockley. The mobility and life of injected holes and electrons in germanium. *Phys. Rev.*, 81: 835–843, Mar 1951.
[2] M. B. Prince. Drift mobilities in semiconductors. i. germanium. *Phys. Rev.*, 92:681–687, Nov 1953.
[3] John Singleton. *Band theory and electronic properties of solids*. Oxford University Press, Oxford, 2012.
[4] Simon M Sze and Kwok K Ng. *Physics of Semiconductor Devices*. John Wiley Sons, Incorporated, New York, 2006.
[5] J. P. McKelvey. Diffusion effects in drift mobility measurements in semiconductors. *Journal of Applied Physics*, 27(4):341–343, 1956.
[6] P T Landsberg. Einstein and statistical thermodynamics. III. the diffusion-mobility relation in semiconductors. *European Journal of Physics*, 2(4):213–219, oct 1981.