THIRD YEAR LABORATORY

MINORITY CARRIER DYNAMICS IN SEMICONDUCTORS

1 Aims

In this experiment, you will develop an understanding of the physics of minority carriers and their dynamics in semiconductors by carrying out the Shockley-Haynes experiment. You will use this your understanding to quantitatively measure the carrier mobility μ, diffusion constant D and lifetime τ of the minority carriers in a semiconductor.

2 Objectives

1. To use the equipment for the experimental investigation of the diffusion and drift of minority carriers in p and n-type germanium using a modified Shockley-Haynes technique.
2. To measure μ, D and τ of the minority carriers in a sample of Ge at room temperature.

Safety Notice

The optically-injected Shockley-Haynes equipment uses a high power infrared (905 nm) laser source. While this laser source is Class 3B, the light is attenuated such that the effective power output at the fibre end is $< 2.5\mu\mathrm{W}$ and is therefore Class 1. Do not attempt to open the equipment or move the fibre. The sweep voltages used can be set up to 50 V.

3 Introduction

In the early 1950s the study of the physics of semiconductors was very important as the hope was to exploit such materials in electronic devices such as transistors. It was known that by doping Ge with group III or group V impurities it was possible to produce materials where the conductivity was dominated by holes (p-type material) or electrons (n-type material) respectively. One type of electronic device (a light emitting diode) relies on the injection of electrons/holes into regions of the semiconductor where holes/electrons are in the majority, so called minority carrier injection. Understanding how and how far the minority carriers move, and how long they exist is vital to predict the device properties. In 1949 Haynes and Shockley described an experiment in which they were able to measure some of the dynamical properties of injected minority carriers[1, 2]. With the equipment supplied you will be able to carry out an updated version of their classic experiment and measure the minority carrier properties in Ge. Further useful reading on the subject can be found in References [4, 5, 6].

4 Experimental Details

A schematic diagram of the equipment is shown in Figure 1, and is similar to the original Shockley-Haynes set-up. In the original experiment, an electric "sweeping" field $E = V_s/\ell$ is created along a small bar of a doped semiconductor by applying an external voltage $V_s = V_{\mathrm{BA}}$ across the bar ends B and A separated by distance (sample length) $\ell = |\mathrm{BA}|$. A short pulse of excess minority charge carriers are injected into the sample by a probe at point E; the carriers are swept along the bar by the electric field. Through detection of this excess-charge pulse by a collector at point C (before reaching the bar end or carrier recombination), the drift velocity, diffusion constant and minority carrier lifetime can be calculated. The emitter-collector distance is $d = |\mathrm{EC}|$, and the distance between the collector and the zero-potential end A of the sample is $x_0 = |\mathrm{CA}|$.

Independent of the injected charge carriers, a much larger current of equilibrium carriers results in a constant component of the collector signal as well as in the Joule heating of the semiconductor bar. In order to simplify zooming into the small current due to the excess carriers only, a bias voltage αV_s, where $\alpha = x_0/\ell$, is applied at C; the sign of both sweeping voltage and bias is determined by the type of minority carrier we wish to collect. And to minimize the effect of Joule heating, the sweeping voltage is applied in the form of pulses with low duty-cycle.

In your modified experiment, the charge injection is performed using a laser pulse synchronised to the sweeping field. The injection pulse applied by the laser is much shorter than the sweeping pulse (~ 20 ns) and is designed to create an approximately delta-function shaped distribution of excess charge at the injection point E. This pulse of charge is then swept down the bar by the sweeping field to be detected at the point contact C. Both the sweeping pulse and the signal at the collector can be detected by the oscilloscope which can be used to measure properties of the pulse.

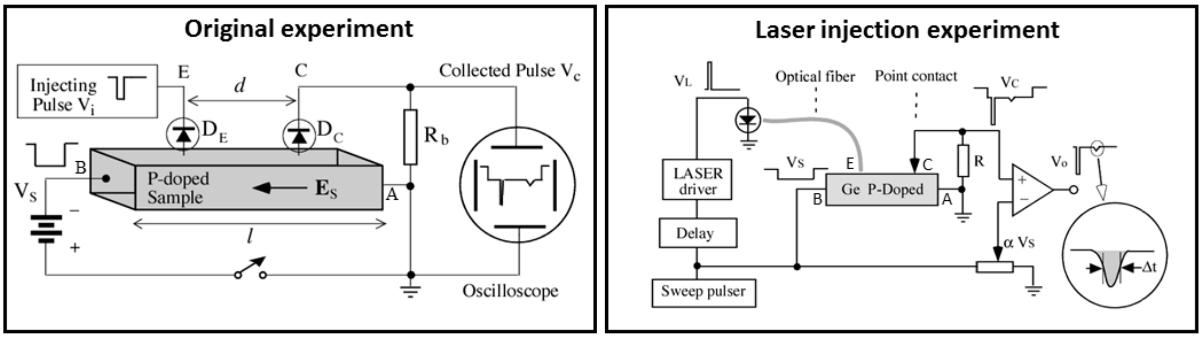

Figure 1: A block diagram of (Left) the original Shockley-Haynes experiment for p-doped germanium and (Right) the optical injection system that you will use.

Initially, you should measure the resistance and diode-behaviour of the Ge bar. On the back of the experimental equipment, a rotary switch is available to make contact to the bar via the x and y BNC ports. By selecting **D**, the voltage-current characteristics V_{BC} vs. I_{BC} of the probe-germanium contact can be measured. By selecting **R**, the behaviour of the ohmic end-contacts V_{BA} vs. I_{BA} is probed. You should measure and record these, and ensure that you can explain what you see.

Return the device to **H&S** mode for subsequent measurements. The experiment can be conducted varying different parameters – the laser-collector separation d, the laser power (via V_{D}), the sweep-laser delay t and the sweep voltage (V_{s}). The sweeping pulse duration, laser duration and repetition rate are fixed. If necessary, you might wish to check the alignment of the points E and C along the current direction from B to A.

To begin with, you should start with a sweep voltage of around V_s =10 V. Typical experimental results are shown in Figure 2.

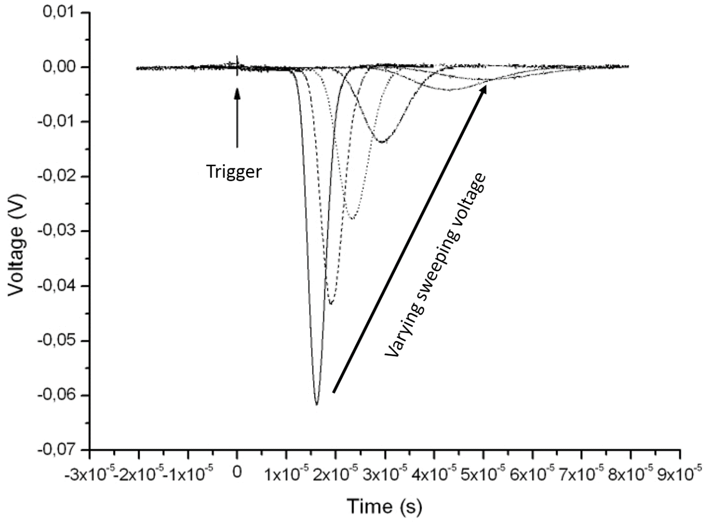

Figure 2: A typical signal from this experiment, showing a set of pulses collected at a constant fibre-collector separation d and varying sweep voltage V_s.

5 Theory

In the presence of an external force eE, charge carriers drift with the velocity $v = \mu E$, where μ is their mobility. They are also involved in random motion, independent of E, so in time t move away an average distance $r \sim (Dt)^{1/2}$ into an arbitrary direction, with D being the diffusion constant. In the kinetic theory, the transport coefficients μ and D are proportional to the mean free path of the particle under study; for Brownian motion of classical particles, they are linked by the Einstein relation [3]:

$$D = \frac{\mu k_\mathrm{B} T}{e}.$$

The excess (non-equilibrium) carriers only survive some average lifetime τ – before reaching either a crystal defect or surface where they can recombine (e. g. the time required to reach surface is $\tau \sim h^2/D$ where h is the bar's thickness).

The equation governing the dynamics of the excess minority carrier density $n(x,t)$ is:

$$D\frac{\partial^2 n}{\partial x^2} - \mu E \frac{\partial n}{dx} - \frac{n}{\tau} = \frac{\partial n}{dt},$$

where the distance down the bar is x and t is the time. A solution to this equation, assuming that the minority carrier distribution at $t = 0$ is a delta-function $y(x,0) = A\delta(x)$, is:

$$n(x,t) = \frac{A}{\sqrt{4\pi Dt}} \exp\left(-\frac{(x-\mu Et)^2}{4Dt} - \frac{t}{\tau}\right). \tag{1}$$

The signal received by the collector at $x = d$ will be proportional to $n(d,t)$ and will rise to a maximum at time t_0, which is naturally identified as the transit time, and then falls off again as shown in Figure 2. To obtain an algebraic expression for t_0, the maximum occurs when

$$\frac{\partial n(d,t)}{\partial t} = 0.$$

We thus obtain an equation relating E and t_0:

$$\mu E = \left[\frac{d^2}{t_0^2} - \frac{2D}{t_0}\left(1 + \frac{2t_0}{\tau}\right)\right]^{1/2},$$

which for the case of $\frac{2Dt_0}{d^2}\left(1+\frac{2t_0}{\tau}\right) \ll 1$ [e. g., when $t_0 \lesssim \tau$ and $(Dt_0)^{1/2} \ll d$; *could you comment on the meaning of these conditions?*] gives

$$E \approx \frac{d}{\mu t_0}\left[1 - \frac{Dt_0}{d^2}\left(1 + \frac{2t_0}{\tau}\right)\right].$$

We can see that even for $E = 0$ a finite transit time will be observed; this is the *diffusion* of carriers. In the limit where E is very large (either $E \gg \frac{D}{\mu d}$ if $E \gtrsim \frac{d}{\mu\tau}$ or $E \gg (\frac{D}{\mu^2\tau})^{1/2}$ if $E \lesssim \frac{d}{\mu\tau}$), the following relation holds:

$$t_0 = \frac{d}{\mu E}.$$

Typically this condition will be met when the applied voltage V_s exceeds ~ 10 V and $d > 1$ mm. You should check these figures yourself.

6 Measurements

Measure the mobility by working in the high field region and plotting $E = V_s/\ell$ against d/t_0. Check when the high field approximation breaks down.

To determine D really requires that you fit your data to Equation 1 but this is an optional exercise. A simpler approach is to assume that the shape of the detected pulse is Gaussian and measure its width t_p at half the maximum height. You should be able to show that

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

You can then use this equation to obtain a value of D. One approach would be to keep d fixed and vary t_0 by varying E. A plot of t_p^2 against t_0^3 should yield a straight line with gradient $16D\ln 2/d^2$. Please check whether your values of μ and D agree with the Einstein relation.

To obtain the minority carrier lifetime you should note that from Equation 1 (provided you are in the high-field region) the peak of the detected pulse should occur when $d = \mu E t_0$. Therefore, the height n_0 of the pulse is given by

$$n_0 = \frac{A\exp\left(-\frac{t_0}{\tau}\right)}{\sqrt{4\pi D t_0}}$$

Then, after measuring n_0 versus t_0 (which you can vary by either adjusting d, or E, or both), you may use

$$\ln\left(\sqrt{t_0}n_0\right) = \ln\left(\frac{A}{\sqrt{4\pi D}}\right) - \frac{t_0}{\tau}$$

to determine τ.

To compare you values of mobility, diffusion constant and lifetime you should consult previously published data. Whether your data is comparable will tell you to an extent about the physical processes that can determine these physical parameters.

7 Potential extensions

If you have completed and checked the measurements in the main manuscript, a number of potential extensions are available for this experiment.

- You may wish to attempt a non-linear fit to your data using Equation 1.
- Both n and p type samples are available for use. Discuss measuring both samples with your demonstrator.
- You may wish to consider various treatments for the sample, such as taking data at different temperatures.

References

[1] J. R. Haynes and W. Shockley. Investigation of hole injection in transistor action. *Phys. Rev.*, 75:691–691, 1949.

[2] J. R. Haynes and W. Shockley. The mobility and life of injected holes and electrons in germanium. *Phys. Rev.*, 81:835–843, 1951.

[3] P. T. Landsberg. Einstein and statistical thermodynamics. iii. the diffusion-mobility relation in semiconductors. *European Journal of Physics*, 2(4):213, 1981.

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[5] S. M. Sze and K. K. Ng. *Physics of Semiconductor Devices*. Wiley, 2006.

[6] S. Wang. *Fundamentals of semiconductor theory and device physics*. Prentice-Hall series in electrical and computer engineering. Prentice Hall, 1989.

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