The Haynes-Shockley experiment

Aims and Objectives

- Understand the behaviour of minority carriers in a semiconductor.
- Measure the lifetime, τ, the diffusion coefficient, D, and the mobility, μ of holes injected into n-type germanium.
- Test the Einstein relationship between diffusion and mobility.

Introduction

This is an adaptation of an experiment first described by Haynes and Shockley in 1946 (see Recommended Reading). In this experiment, the transport characteristics of the minority carriers in a semiconductor can be investigated. In this case, the minority carriers are holes in n-type germanium. The characteristics measured are the lifetime, τ, the diffusion coefficient, D, and the mobility, μ. With this information, Einstein's relationship $D/\mu = k_BT/e$ can be tested.

Background

If a pulse of holes is injected into a bar of n-type germanium to which a steady d.c. field is being applied, the holes will drift under the influence of the field. The centre of the bunch will have a velocity $v = \mu E$, where E is the field strength, and μ is the mobility of the holes. The bunch will also spread out due to diffusion. Diffusion theory shows that if a bunch starts at time $t = 0$ as a δ-function in space, it will spread out to give a Gaussian distribution with density proportional to

$$\frac{1}{2\sqrt{\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right) \tag{1}$$

where x is the distance from the centre of the bunch. In addition, the total number of holes in the bunch will decrease with time due to recombination with the majority carriers. The rate of recombination will be proportional to the number of holes - the number of available electrons is very much larger. Therefore, the number of holes will decay away exponentially as

$$\exp\left(-\frac{t}{\tau}\right) \tag{2}$$

where τ is the lifetime of the hole. Thus the motion of the bunch can be described as a distribution of charge changing with time and distance as

$$Q(x,t) = \frac{Q(0)}{2\sqrt{\pi D t}} \exp\Big(-\frac{(x-\mu E t)^2}{4Dt} - \frac{t}{\tau}\Big). \tag{3}$$

If a rectifying point contact is applied to the specimen at a position x_0, then as the charge Q passes, an extra potential proportional to Q will appear at the contact. This extra potential will have an approximately Gaussian shape with time, centred at $\mu E t_0 = x_0$.

The shape will be approximately Gaussian provided that $\mu^2 E^2 \tau \gg 4D$. Measurement of the position of the maximum, its height, and half-width as a function of E allows values for D, μ and τ to be obtained.

Why?

Experimental Method

A germanium sample is available with solder (Bi-doped Sn) applied to each end. This solder provides an ohmic contact between the semiconductor and the copper wiring. Without this buffer layer, a Schottky barrier would form at the metal-semiconductor interface and the field needed to evaluate μ would not be equal to the voltage drop across the sample divided by the length of the sample.

Why Bi?

With ohmic contacts at each end, the field can be calculated from the potential difference applied across the sample. The end contacts can be checked by measuring the resistance between them, using an ohmmeter at the end of the Drift field cable. It should be a few hundred ohms.

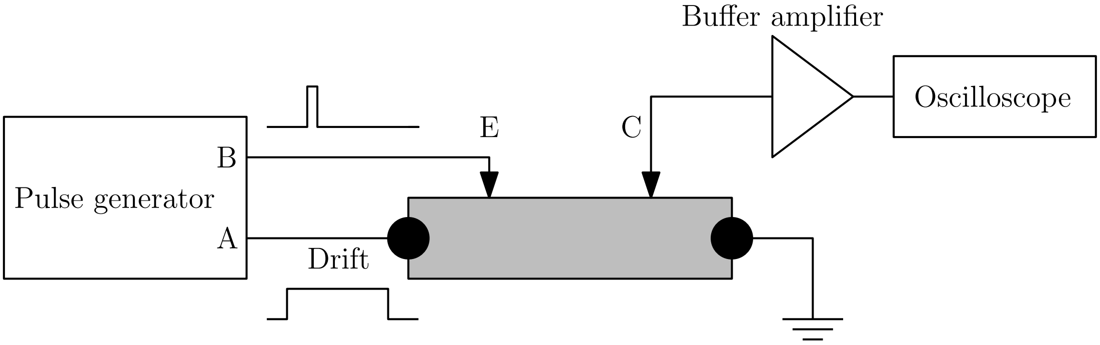
Two gold pins form the rectifying contacts. The rectifying nature of the emitter contact can be checked by measuring the forward and reverse conduction using the diode test range of a DVM. Is the direction of the Schottky diode at the contact consistent with the materials in use?

Holes are injected at the emitter contact and swept towards the collector by the drift field. The emitter contact remains at a fixed location on the sample, while the collector contact can be made and unmade using the lever, and its position adjusted using the micrometer drive. It is best not to scrape the contact along the sample. Surface impurities drastically reduce the minority carrier lifetime τ. It is therefore very important not to touch the surface of the sample with your fingers or anything else. The sample has been polished and etched (800 grit, then 40 minutes in hot hydrogen peroxide) to remove surface oxides and contamination. Nevertheless, making a "good" contact on the surface requires some patience, and eventually polishing will be needed again.

Why?

History: what is a "cat's whisker"?

In the measurements, the main "drift" field is applied to the length of the Ge bar as a pulse approximately 100 μs long; this is sufficient time for any injected carriers to move along the bar. Shortly after the start of the 100 μs drift pulse, holes are injected by a 1 μs positive-going pulse at the emitter contact. The holes are detected as they pass the collector contact. The sequence is repeated every few ms, and the collector signal is captured on an oscilloscope.



The output from the collector, after buffering by an op-amp (attached to the collector probe), should be connected to the oscilloscope. The scope is best triggered externally from the pre-pulse output of the pulse generator. One scope channel can then monitor one of the main pulses, and the other channel the collector output.

A transient is observed at the collector at the time of the emitter pulse, and this can be used to establish the initial ('zero') time point. Obviously the amplitude of the emitter pulse must be greater than the field voltage for any injection to occur. The amount of injected charge is proportional to the difference in voltage between the specimen and emitter. If the field voltage is changed then the height of the emitter pulse must be changed accordingly in order to keep the amount of charge injected the same.

Possible investigations

First of all, spend some time observing the workings of the pulse generator on the oscilloscope.

Start with a short distance, about 1 mm, between the emitter and collector pins. This should give a relatively strong signal which decays with distance. For a fixed distance between the two contacting pins, obtain a trace on the oscilloscope. Measure the time it takes for the hole pulse to travel from the emitter pin to the collector pin, the peak height of the pulse, and the half-width at half maximum. Adjust the repetition rate of the pulse generator and the length of the field pulse so that sample heating is negligible. Use signal averaging (Acquire | average) on the scope to help get clean data.

Now investigate how this changes as the distance between the two contact pins is changed. This should give you the drift velocity; you can then also see how this depends on the drift field. Calculate the electric field across the sample, by looking at the field pulse. Check by looking at the collector voltage in the absence of the emittrer pulse.

The shape of the hole pulse can be approximated as a Gaussian. Calculate the area under the peak. With this information, you can investigate how the total charge carriers change as a function of time, and hence obtain the lifetime of the charge carriers. The change of the half-width of the peak as a function of time is related to the diffusion constant.

What do you actually observe? Why?

Recommended Reading

J. R. Haynes and W. Shockley, *Investigation of Hole Injection in Transistor Action*, Physical Review **75**, 691 (1949).

J. R. Haynes and W. Shockley, *The Mobility and Life of Injected Holes and Electrons in Germanium*, Physical Review **81**, 835 (1951).

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