P7: Haynes-Shockley experiment

Aims

This experiment investigates the dynamics of minority carriers in a semiconductor. The detailed consideration of carrier motion in a semiconductor is complex but the main phenomena are:

a) The drift of carriers in an applied electric field,
b) The diffusion of carriers away from regions of high concentration, and
c) The recombination of holes and electrons in pairs, resulting in the annihilation of both types of carrier.

This experiment is a version of the well known Haynes-Shockley experiment first done in 1950. A photocopy of the original paper is available [1]. The idea is to observe the drift of holes down an applied field in silicon and study their mobility, diffusion and recombination with electrons.

Safety

There are no special safety considerations for the user in this experiment. Please take care to follow the instructions so as not to damage the semiconductor.

1. Background

At zero temperature (T = 0K) a semiconductor behaves as an insulator. With T >0, electrons may have enough energy to be excited from the valence to the conduction band as shown in Figure 1. For each electron in the conduction band, a hole is left in the valence band. This gives rise to a small conductivity σ contributed to by both holes and electrons. *(Further details are given in [2]. Please read it before the lab session).*

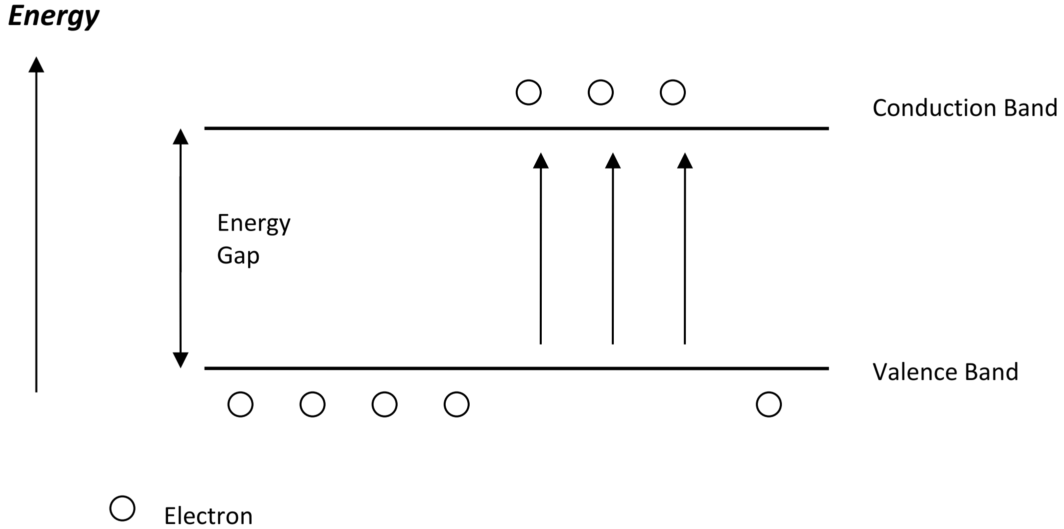

Figure 1. Energy band diagram for intrinsic conductivity in a semiconductor at T >0.

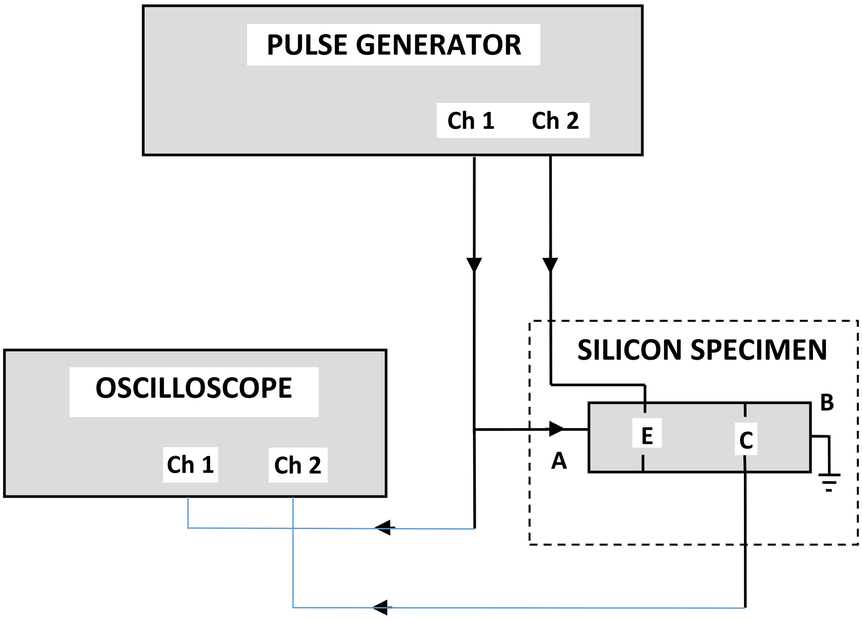

Figure 2. Schematic of the experimental set up.

2. Setting up the apparatus

The circuit will be as depicted in Figure 2. The pulse generator (Tektronix AFG1022) supplies two outputs which can be locked in time to each other. These can be adjusted in amplitude, duration (width) and delay.
The oscilloscope monitors the signal from the collector C (one of the contacts C_1-C_4 as shown in Figure 3) and the output from Ch 1 (applied field pulse) of the pulse generator.

In this experiment, holes are injected into the semiconductor by an electrical pulse rather than thermal excitation of electrons. The sample of silicon used is a bar of n-type silicon that has holes injected into it (to make it locally p-type) by the emitter pulse (from Ch 2) at point E. The whole specimen is encapsulated in a transistor type mount. Contacts A and B at the ends (950 μm apart) are ohmic (non-rectifying) and are used for creating the driving electric field in the specimen. Any of the four closely spaced contacts (C_1-C_4) can be connected to the oscilloscope to observe collector pulses.

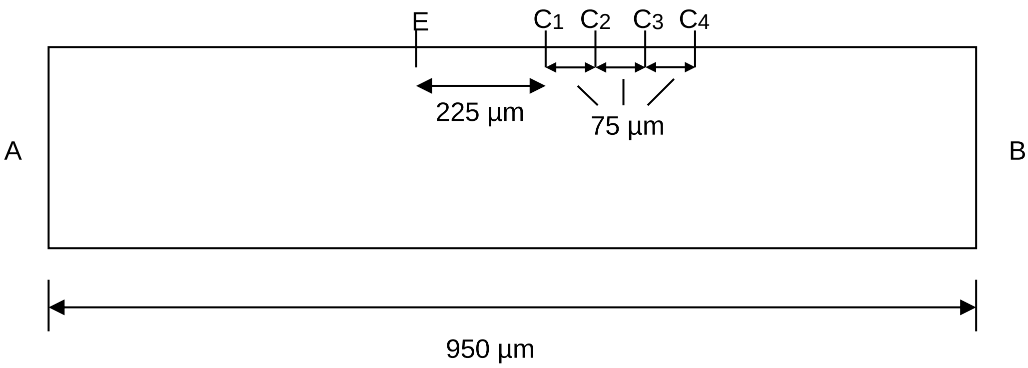

Figure 3. Simplified diagram of the silicon specimen.

Using the Tektronix AFG1022 dual channel function generator:
Use [CH1/2] to switch display between channel 1 / 2.
Channel 1 :

- Pulse waveform
- Frequency = 1kHz
- High = 8V
- Low = 0V
- Width = 6μs
- The amplitude can be varied using the soft keys.

Channel 2 : (to use preset waveform)

- Arbitrary waveform (editable)
- [Browse]; INTER; (Filename USER2); [Callout]
- [Back] x4

Channel 2 : (to set up waveform if preset is not available)

- Arbitrary waveform [editable], [new]
- Frequency = 1kHz
- High = 10V
- Low = 0V
- Points = 8000
- Interpolation = Off
- Point 1,2 = 0V ; Point 3 = 10V ; Point 4 = 0V
- [Write]; INTER; (Filename eg USER0); [Save].

These parameters may already be held in the function generator memory!

Before connecting up the semiconductor, check the signals on the oscilloscope.
Connect channel 1 and 2 outputs to channel 1 and 2 on the oscilloscope and set it to trigger on channel 1. With the timebase on 1μs/div and both channels on 5V/div you should see a broad field pulse with a narrow emitter pulse slightly delayed from the start of it.
Now connect channel 1 output to channel 1 on the oscilloscope and point A of the specimen, channel 2 output to the emitter contact of the specimen (point E), and set the scope to trigger on channel 1.
In operation, a field pulse of 4 V to 10 V and duration of about 6 μs is applied to the bar from channel 1 of the pulse generator at a frequency of 1 kHz.

DO NOT increase the pulse repetition frequency (PRF) above 1 kHz or the silicon chip may be damaged. (i.e. period should not be shorter than 1 ms).

Do not vary the pulse generator settings from those given. If you have any problems, ask the demonstrator.

A positive pulse from channel 2 of the pulse generator is applied at the emitter E, with a short delay (0.3 μs) from the beginning of the field pulse, width 0.1 μs and amplitude 10 V. The holes injected into the bar at E diffuse away to the left and right recombining with electrons as they do so. The processes are shown in Figure 4.

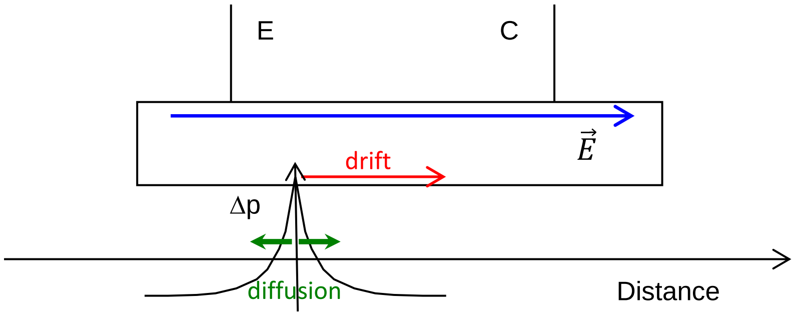

Figure 4. Emitter pulse, injected at the emitter point (contact E*) of the sample. The pulse drifts under the influence of the electric field,$\vec{E}$, present because of the voltage drop down the length of the bar.*

In addition, under the influence of the field between A and B, the hole pulse (from the emitter) drifts down towards C_4, the holes continuing to diffuse and recombine as they do so. At C_1, C_2, C_3 or C_4 a recognisable hole pulse can be picked up and displayed on Channel 2 of the scope (sensitivity at ~10-50 mV/div). Measurements of this pulse give values of the drift velocity, diffusion constant and hole lifetime.
There are four collectors provided and after some experimentation, you may find C_3 the best. It is useful that the emitter pulse "breaks through" on both channels 1 and 2 as it provides a mark for beginning the timing (see Figure 5). However, examine the other collectors C_1, C_2 and C_4.

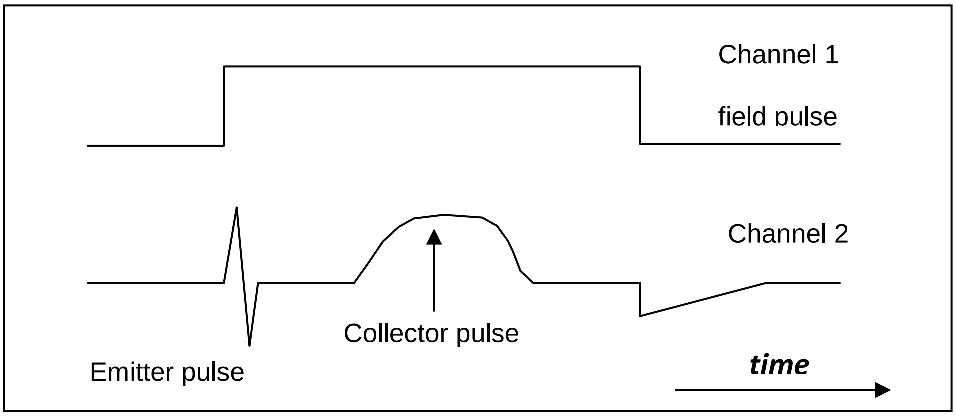

Figure 5. Shape of the pulses on the screen of oscilloscope.

It is also necessary to ensure that the field pulse at A produces a voltage at E less than the voltage of the pulse injected into E from Channel 2 of the pulse generator. However, too high a voltage at E from the emitter pulse will produce asymmetry in the collector pulse so a compromise has to be reached.

Data Collection

- To improve the quality of your measurements you may wish to use the averaging capability of the digital oscilloscope.
- If you read the details of experimental sections (a-d) carefully, you will understand what has to be measured from the oscilloscope for each part of the experiment.
- You can then collect from one contact in one data “run” all the information needed for the different calculations of sections (a-d). Thus, you can efficiently and carefully collect many data points during the session and then proceed to a full analysis, which will check the quality of the data.
- As an alternative to analysing the data on the oscilloscope, you can export the data as a csv file (via a thumb drive) to Excel.
- Analyse the data during the lab session. If you have made a mistake, you need to uncover this while you still have the ability to collect more data.

3. Experimental measurements and theory

(a) Drift Velocity and Mobility (μ)

The drift velocity of a hole in a field E is equal to μE. The distance between contact E (emitter) and, say, contact C_3, is 375 µm. If the voltage V is applied across the whole bar of length L and for all of the drift time, it can be reasonably assumed that the field is uniform during the time of the pulse at a value $E = V/L$. In this case the time of transit from E to C_3 is:

$$t = \frac{d_3 L}{\mu V}, \tag{1}$$

where d_3 is the distance between E and C_3, so for a given sample tV should be a constant. A more elaborate theory shows that the peak of the hole pulse will travel from E to C_3 in time t.

Observe t as a function of applied field pulse amplitude V. One partner should plot V against t^{-1}, the other t against V^{-1}. From the plotted results obtain a linear relation and deduce μ from the slope. Compare results in the laboratory. Observe the intercepts. Do they tell you anything? What is the uncertainty in your measurement of the gradient? Hence, find the uncertainty in the measurement of the mobility. (See Appendix 1.)

(b) Carrier Transport

If a small electric field, $\vec{E}$, is applied to a semiconductor, the carriers will experience a force given by $-q\vec{E}$. The carriers already have a thermal velocity, v_{Th}, due to the temperature of the material. We can find the thermal velocity by considering the kinetic energy of the carriers, i.e.

$$\frac{1}{2}mv_{Th}^2 = \frac{3kT}{2}.$$

The carriers will be accelerated along the direction of the field but experience collisions with the vibrating atoms of the semiconductor and impurity atoms in the crystal. These collisions stop the acceleration of the carriers and randomise the direction of their velocity during the collision. The overall effect of the field and the collisions is to give the carriers a net drift velocity, v_d, through the semiconductor in addition to their thermal velocity. The mobility of a carrier is related to the drift velocity it acquires from an applied field.

Using an idea from classical gas theory, we can assume that the carriers have an average distance between collisions called the mean free path and the time between collisions is the mean free time, τ_F. We can find an expression for the drift velocity by equating the momentum impulse gained by a carrier from the field during mean free time between collisions with the momentum it has due to the drift velocity. Hence,

$$dp = Fdt = -qE\tau_F = mv_d\ ,$$

$$v_d = -\left(\frac{q\tau_F}{m}\right)E \equiv -\mu E\ ,$$

$$\mu = \frac{q\tau_F}{m}\,.$$

For silicon, the "effective" mass of the carriers is 0.41 m_e for holes and 0.28 m_e for electrons where m_e is the mass of an electron. Using the details above and your results, find:

a) the thermal velocity of electrons and holes in silicon at room temperature,
b) the drift velocity of holes in silicon in this experiment, using your result, and
c) the mean free scattering time, τ_F, for holes in silicon.

(c) Carrier Diffusion

It will be observed that the hole pulse broadens as the time t is increased (i.e. as V is reduced). This is due to diffusion. If all the excess holes were generated as a pulse of initially zero width, then the spatial width of the hole pulse in the sample (measured at half peak amplitude) at time t is given by:

$$W = \sqrt{(16(ln2)D_h t)} \tag{2}$$

where, D_h is the diffusion constant for holes in n-type material.

As the hole pulse sweeps past the collector it will be seen as a pulse of duration t_p (measured at half amplitude, see Figure 6) where:

$$t_p = \frac{W}{\mu E} = \frac{WL}{\mu V}\,. \tag{3}$$

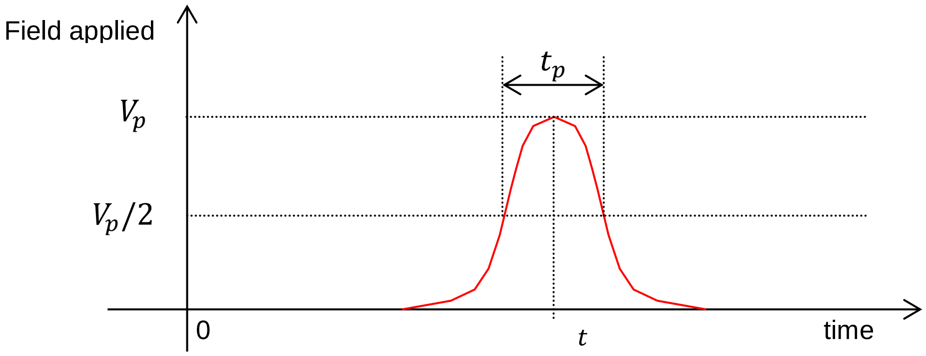

Figure 6. The hole pulse as a function of time.

By substituting μV from Equation 1 and W from Equation 2 into Equation 3, it is seen that there should be a linear relationship between $t_p{}^2$ and t^3. Observe t_p as a function of t. Attempt to deduce a value for D_h by making a suitable plot, and examining the best-fit gradient. Make certain the origin is shown on the graph, but do not force the line of best fit to go through it. It is best to plot t_p versus $t^{1.5}$. Use regression analysis to find the error on your gradient and hence on the diffusion constant.

(d) Recombination and Carrier Lifetime

If carrier recombination were negligible, the hole pulse would broaden as t increases and would fall in amplitude, but the area under the pulse (which represents the total number of holes) would be constant (i.e. the maximum hole concentration multiplied by W is a constant). Since the height of the observed pulse (V_p) is proportional to the maximum hole concentration, this amounts to $V_p W$ = constant. Now $W = \mu V t_p / L$ so the condition for zero recombination loss can be specified as:

$$V_p t_p V = \text{constant} \tag{4}$$

If, on the other hand, holes last for an average time τ_h before recombining with electrons, the number in the pulse will fall exponentially with the drift time t, according to $\exp(-t/\tau_h)$, where τ_h is called the lifetime of the minority carriers, and has a value of a few microseconds in the material used here. Thus the relationship to be investigated is:

$$V_p t_p V \propto \exp\left(-\frac{t}{\tau_h}\right). \tag{5}$$

A plot of $\log(V_p t_p V)$ against t should yield a value for τ_h. Make suitable measurements, plot this graph and so estimate τ_h and give your uncertainty in this value.

Discuss the assumptions made in the theory in the light of results obtained from the experiment.

References

[1] J. Haynes and W. Shockley. *Physical Review* **81**, 835-843 (1951). In Laboratory.
[2] D. Greig, *Electrons in Metals and Semiconductors,* (McGraw-Hill, 1969), pp. 85-93 and pp. 131-145.

Other recommended literature

S.R. Elliott, *The Physics & Chemistry of Solids*, (Wiley, 1998). Read about band theory pp. 509-360 and Semiconductors pp. 490-512.

B.I. Bleaney and B. Bleaney, *Electricity & Magnetism*, [OUP]
1st Ed. 1957, chap. 19.7, p. 536 In Laboratory, not too much information in book
2nd Ed. 1965, chap. 19.5, p. 554
3rd Ed. 1976, chap. 17.5, p. 546.

R.B. Adler, A.C. Smith and R.L. Longini, *Introduction to Semiconductor Physics*, (Wiley, New York 1964), pp. 171-181 and pp. 221-230.

Transistor Technology Evokes New Physics, Nobel Prize Lecture of William Shockley, 11th December 1956, pp. 344-374. Can be read on www.nobelprize.org website.

Appendix 1

The theory suggests that $t = (d_3\ L)/\mu V$, or $tV = (d_3\ L)/\mu\ = K$ (a constant for your sample).

It is likely that both t and V are subject to "zero" errors in which case the equation should read:

$$(t + t_0)(V + V_0) = K\ .$$

Expanding this and rearranging gives:

$$t_0 V + tV_0 + t_0 V_0 - K = -tV\ ,$$

which is of the form:

$$ax + by + c = z,$$

where x, y, z are known (by experiment: $x = V, y = t, z = -tV$) and a, b, c are unknown.

This cannot be solved analytically as there are too many unknowns, but as we have several pairs of data points it would be possible to use matrix techniques or iterative algorithms to arrive at a least squares solution for the zero errors V_0 and t_0.