

Introduction to Semiconductors and the p-n Junction Diode

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Abstract

In this experiment the I-V characteristic of the p-n junction diode is determined and the application of the diode as a rectifier is investigated.

1 Theory

1.1 p-n Junction

A p-n junction diode consists of a p-type block of silicon placed in contact with an n-type block. Free electrons from the n-type region and holes in the p-type material will combine to form a narrow region where mobile charge has been depleted, called the depletion layer.

If the diode is connected in forward bias the applied voltage forces electrons into the n-type region and holes into the p-type region thus narrowing the depletion layer. A potential difference exists across the depletion layer due to the initial separation of charges. When the applied voltage reaches this potential difference current can flow freely through the diode.

If the diode is connected in reverse bias holes are extracted from the p-type region and free electrons from the n-type region and so the depletion layer widens. The mobile carriers are further inhibited from crossing the junction. A small current does flow due to the thermal generation of holes and electrons near the junction.

It can be shown that if a voltage V is applied in forward bias the current is given by

$$I = I_0 (\exp(eV/kT) - 1) \quad (1)$$

where I_0 is independent of the voltage V .

If we assume that $\exp(eV/kT) \gg 1$ we can then say

$$\log(I) = \log(I_0) + eV/kT$$

and so $\log(I)$ vs. V is linear with slope e/kT for large V .

1.2 Rectifiers

For a rectifier with a capacitor connected across the resistor, the capacitor discharges through R for approximately $1/f$ s per cycle. If we assume a small ripple voltage, i.e. $RC \gg 1/f$ then we can take the current through R as constant and so

$$I = C \frac{dV}{dt} = \frac{V_0}{R}$$

$$C \frac{\Delta V}{\Delta t} = \frac{V_0}{R}$$

$$\frac{\Delta V}{V_0} = \frac{\Delta t}{RC}$$

and so for half-wave rectification we have

$$\frac{\Delta V}{V_0} = \frac{1}{fRC} = \frac{1}{50RC}$$

for full-wave rectification we have

$$\frac{\Delta V}{V_0} = \frac{1}{2fRC}$$

2 I-V Characteristic

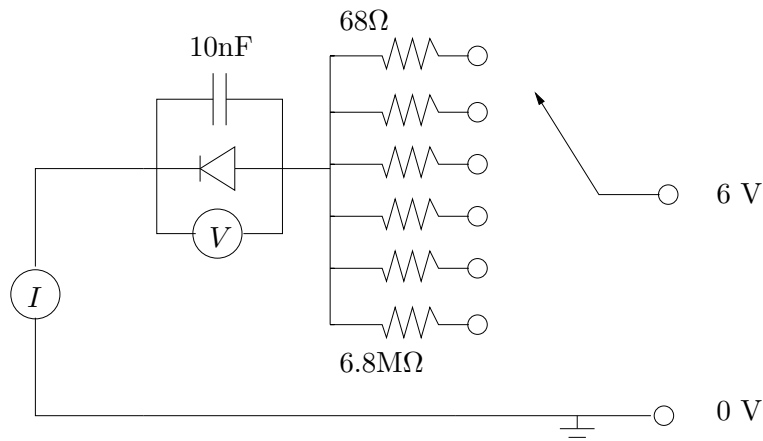


Figure 1: Circuit used to find the I-V characteristic for the diode.

The circuit shown in Figure 1 was set up, with the resistors varying by a factor of 10 between 68Ω and $6.8M\Omega$. This allows the voltage across the diode to be varied. The current and voltage across the diode were measured

with digital multimeters. For the room temperature measurements the current and voltage were measured quickly as possible before the steady state values were reached.

Figure 2 shows the room temperature I-V characteristic of the diode. The reverse current is very small when compared to the forward current.

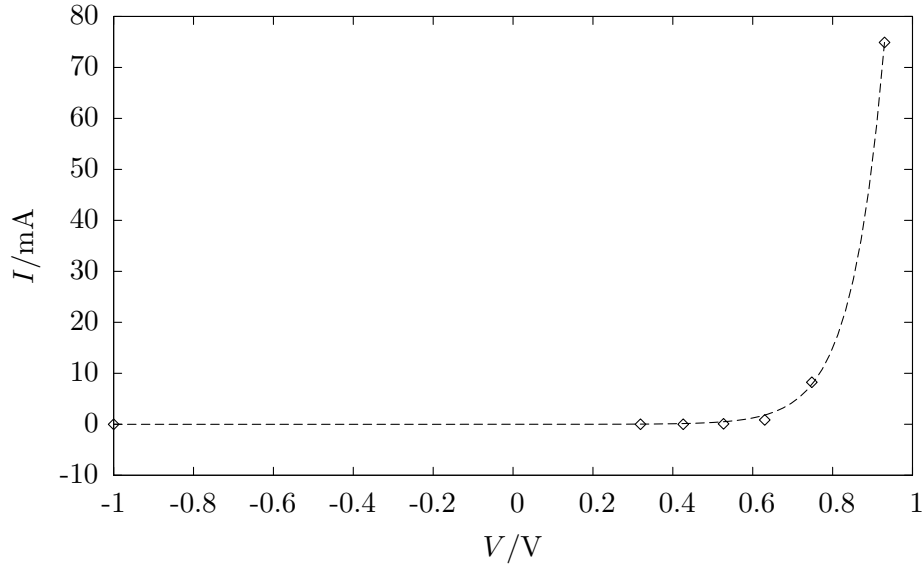


Figure 2: Diode I-V characteristic fitted to $I = a(\exp(bV) - 1)$

To find a value for e/kT we plot $\log(I)$ vs. V as shown in Figure 3. The line fitted to the plot has a slope of 19 ± 1 . This gives us

$$\frac{e}{kT} = 19 \pm 1$$

The expected value is

$$\frac{e}{kT} = \frac{1.6022 \times 10^{-19}}{1.3807 \times 10^{-23} \times 296} = 39.6$$

This differs by approximately a factor of 2 to the determined value of 19 ± 1 . This is due to the fact that for silicon (1) should be given as

$$I = I_0 (\exp(eV/\nu kT) - 1) \quad \text{where } \nu \approx 2$$

For $I = 74.9\text{mA}$ the voltage across the diode was measured to be
 Room Temperature .930V
 Steady State .922

Given that the temperature coefficient of voltage at constant current is $-2.3\text{mV}/^\circ\text{C}$ we can estimate the temperature rise of the junction above room temperature to be

$$\Delta T = \frac{0.922 - 0.930}{-0.0023} = 3.5^\circ\text{C}$$

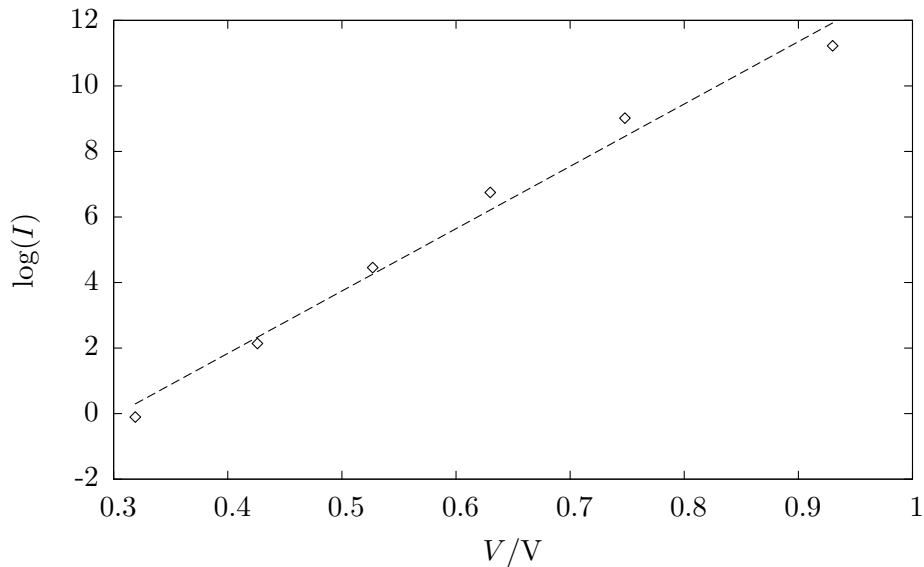


Figure 3: $\log(I)$ vs. V . The slope of the line is 19 ± 1 giving a value for e/kT .

3 Rectifiers

3.1 Half-Wave Rectifier

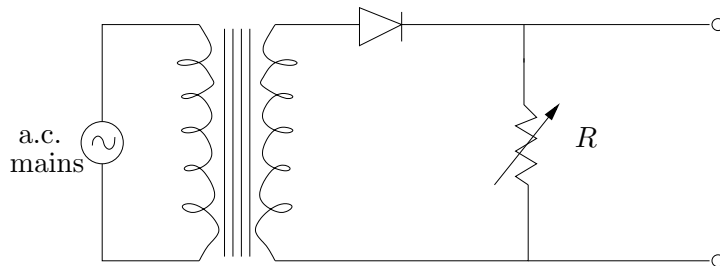


Figure 4: Half-wave rectifier circuit.

The circuit shown in Figure 4 was set-up with $R = 10000\Omega$. The peak voltage across R , V_0 and the R.M.S. voltage across the a.c. supply were measured to be $7.12 \pm .04\text{V}$ and $5.19 \pm .01\text{V}$ respectively. So ignoring the voltage across the diode 7.12 is approximately $\sqrt{2}$ times 5.19 .

Then a $4.7\mu\text{F}$ capacitor was connected across R . The fractional peak-to-peak variation of voltage $\Delta V/V_0$ was measured for different values of R . Figure 5 shows the data with the line fitted to the values of $\Delta V/V_0 < 0.1$ because we wish to find the slope for small ΔV . The slope of this line is

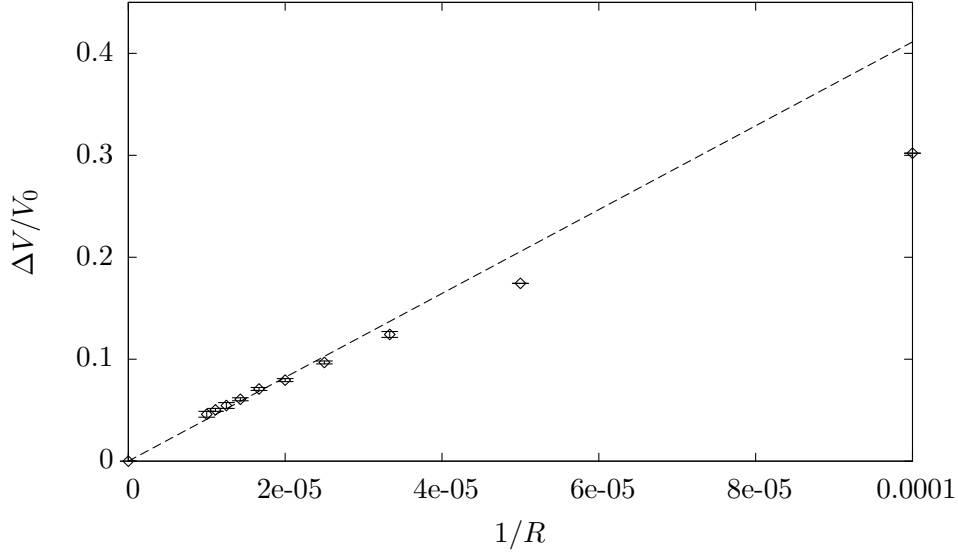


Figure 5: The fractional ripple voltage $\Delta V/V_0$ vs. $1/R$ is linear for ΔV small.

4100 ± 80 . This gives a value for C of

$$C = \frac{1}{50 \times 4100 \pm 80} = 4.9 \pm .1 \mu\text{F}$$

This is close to the actual value of $4.7 \mu\text{F}$ and as $\Delta V/V_0$ gets smaller, looking at the graph, we would expect the slope to get larger and so expect $1/(50 \times \text{slope})$ to tend even more to $4.7 \mu\text{F}$.

The current through the diode was found by putting a resistor $r = 10 \Omega$ between $R = 10 \text{k}\Omega$ and the transformer. The peak current was measured to be $i_p = 7.04 \pm .08 \text{mA}$ and it flowed for $3.6 \pm .1 \text{ms}$ of a 20ms cycle. The charge flowing through the diode per cycle was therefore

$$Q_D = (.0036 \pm .00001) \times (.00704 \pm .00008) = 25 \pm 1 \mu\text{C}$$

the charge flowing through the resistor per cycle was

$$Q_R = .02 \times .000696 = 14 \mu\text{C}$$

The maximum reverse voltage across the diode was measured to be $-13.8 \pm .2 \text{V}$.

3.2 Full-Wave Rectifier

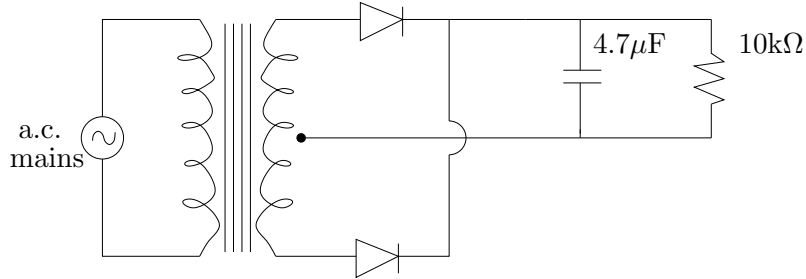


Figure 6: Full-wave rectifier circuit.

The full-wave rectifier circuit in Figure 6 was set up with the centre-tap connected as shown.

Figure 7 shows the waveforms measured across R from the half-wave and full-wave rectifier circuits with the capacitor disconnected. It is obvious from comparing the two waveforms that the full-wave has an amplitude of half that of the half-wave. This is due to the use of the centre-tap in the full-wave rectification circuit.

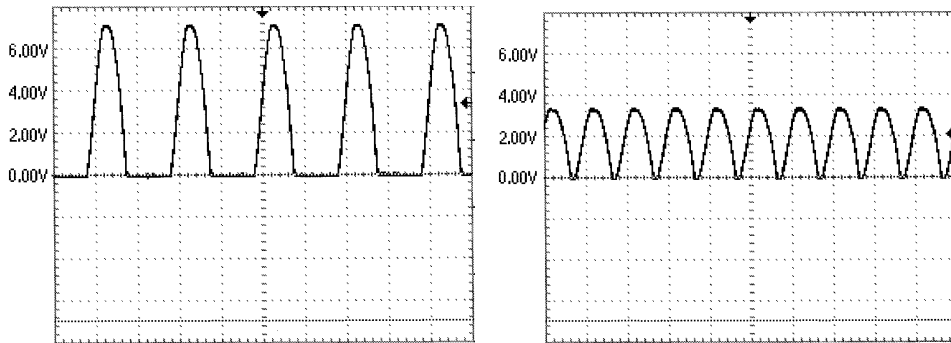


Figure 7: The waveforms from the half-wave and full-wave rectifiers respectively for $R = 10\text{k}\Omega$.

The fractional ripple voltage with $C = 4.7\mu\text{F}$ and $R = 10\text{k}\Omega$ was measured to be

$$\Delta V/V_0 = \frac{.54 \pm .02}{3.28 \pm .2} = .16 \pm .02$$

This is approximately double the value for the half-wave rectifier

$$\Delta V/V_0 = .30$$

for the same value of R . This is because the transformer is now centre-tapped and so the amplitude of the voltage has been halved.

The maximum reverse voltage on each rectifier was measured to be $-7.20 \pm .08\text{V}$. This is approximately half the value from the half-wave rectifier, $-13.8 \pm .2\text{V}$ and this is for the same reason as before, because the transformer is centre-tapped.

4 Conclusions

The I-V characteristic of the diode matched with theory very well. The temperature rise of the p-n junction above room temperature was estimated to be 3.5°C .

By measuring the ripple voltage for difference resistances the value of the capacitor was estimated to be $4.9 \pm .1\mu\text{F}$, this compares well with the true value of $4.7\mu\text{F}$. I say estimate because I had to judge myself below which value of $\Delta V/V_0$ the value of the slope should be taken.

References

- [1] Paul Horowitz and Winfield Hill. *The Art of Electronics*. Cambridge University Press.