Introduction to Semiconductor Devices

References
2. Background notes (Appendix A)
3. Specification sheet for Diode 1N4001 (Appendix B)

Introduction

Simple conductors, such as many metals, obey Ohm’s law, that is the current \( I \) through the material is strictly proportional to the potential difference applied \( V \)

\[
V = IR \tag{1}
\]

for a wide range of values of \( I \) and \( V \), where the constant of proportionality is the resistance \( R \). That is, in an ohmic material, \( R \) is independent of the potential difference applied.

The behavior of semiconductors differs from that of simple metals in several ways: Eq. 1 is true only over limited ranges of \( V \) and the resistivity of semiconductors decreases, instead of increases, with temperature. In this lab, you will investigate the \( IV \) and temperature characteristics of a diode made out of silicon, one of the elements that exhibits these properties, in order to understand the fundamental reasons for these differences.

Prelab Questions

1. What is the resistance of a reverse-biased diode?
2. What determines the maximum forward voltage which may be applied to a junction diode?
3. Why do semiconductor diodes become less effective at high temperatures?
4. This looks like an easy experiment, but it is not. In Part I, you will need to give serious thought to how you are going to determine the current through the diode and the voltage across it at the same time. Keep in mind that the resistance of the voltmeter is not infinite, so that there will be a small current flowing through it when there is a voltage applied to it. The current may be larger than the reverse current of the diode. You will need to think carefully to find a solution to this problem.
5. Design a circuit to measure the \( IV \) characteristic using an oscilloscope. You will need to ensure that you have only one point on your circuit connected to ground. Note that each input to the oscilloscope has two connections and that one of these two wires is grounded. The output of the function generator that you are provided with has two connections and neither of these is grounded.
Apparatus

- diodes
- various resistors
- digital multimeters
- DC power supply
- oscilloscope (optional)
- function generator (optional)

Caution

Please ensure that your circuit protects the diode from currents larger than the Maximum Rectified Current specified in the specification sheet (Appendix B).

Experiment

Part 1 - Diode Characteristics

Measure the current-voltage ($IV$) characteristic for the diode provided for both directions of current through the diode. Some thought will be required to do this, especially for current in the reverse direction. Compare your results with the rectifier equation (Eq. A1). How well does the rectifier equation describe your data? What is the best value of Boltzmann's constant that you can determine from your measurements? How well does this agree with the accepted value? Comment on the statement taken from a well-known electronics text (Brophy) "It turns out that this experimental current-voltage characteristics of practical junction diodes are in good agreement with the rectifier equation."

Part 2 - Temperature Dependence

Repeat your measurements and analysis for the diode cooled in liquid nitrogen. You should concentrate on the forward-bias characteristics here. The reverse-bias characteristics are extremely difficult to measure at these temperatures. Please comment on why this is true.

Part 3 (Optional) - Using an oscilloscope to view IV characteristics

Use the oscilloscope and the function generator to examine the IV characteristic of the diode. Apply an AC voltage to the diode and monitor the current through the diode as well as the applied voltage. The characteristic may then be viewed by means of the X-Y option on the oscilloscope. Record and discuss your observations.

View the rectifying properties of a diode. Monitor the time-dependence of the applied voltage and the voltage across the diode simultaneously. Record and discuss your observations. Why might this behaviour be useful?
Appendix A - Background Notes
(Adapted from Berkeley Physics Laboratory, 2d Edition)

SEMICONDUCTOR BASICS

Semiconductors are a class of materials whose electrical properties are intermediate between good metallic conductors and good insulators. They are of enormous practical interest, forming the basis for a wide variety of devices used in electronic circuitry, including diodes, transistors, photocells, particle detectors, and integrated circuits.

The simplest semiconductors are the elements silicon and germanium. The electrical conductivity of these materials is much less than that of most metals, but it increases very rapidly with temperature, unlike the metals, in which the conductivity nearly always decreases with increasing temperature. Furthermore, the presence of certain kinds of impurities in silicon or germanium, even in extremely small concentrations, can increase the conductivity enormously.

The conductivity of any material depends on the existence of electrons which are more or less free to move within the material. In metals there are many mobile electrons, even at low temperatures. Germanium and silicon at low temperatures have no free electrons, because of their crystal structure. Each atom has four valence electrons and in the crystal lattice each atom has four nearest-neighbor atoms situated at the corners of a regular tetrahedron. Each valence electron participates in a covalent (shared-electron) bond with one of the nearest neighbors; thus all valence electrons are bound to individual atoms and none are free to move. But only a small amount of energy is needed to break one of these bonds, 1.1 eV for silicon, and only 0.7 eV for germanium. This energy can be supplied by thermal motion; hence as the temperature increases, more and more bonds are broken and electrons become free to participate in conduction. The positively charged vacancies or holes can also move by successive replacement of adjacent electrons, so these also contribute to conductivity. Thus, we see why the conductivity increases rapidly with temperature. This type of conductivity is called intrinsic conductivity to distinguish it from impurity or extrinsic conductivity, to be discussed next.

If some atoms of an element having five valence electrons, such as arsenic, are added, four are involved in the covalent bonds, but the fifth is very loosely bound (binding energy of the order of 0.01 eV), and even at low temperatures can break away and move freely through the lattice. Such an impurity is called a donor impurity or an n-type impurity, since the atoms donate negatively charged current carriers. Conductivity of an n-type semiconductor at ordinary temperatures is chiefly due to the electrons from n-type impurities.

Correspondingly, an impurity with only three valence electrons, such as gallium, can take an electron from an adjacent germanium atom to complete its four bonds. This leaves a hole at the adjacent atom and this hole can migrate through the lattice, contributing to the conductivity. Such an impurity is called an acceptor impurity and the resulting material is called a p-type semiconductor.

JUNCTIONS

A remarkable aspect of semiconductor technology is that a material can be produced which has different impurities in different regions, changing smoothly from n-type at one end to p-type at the other. In this case we have a surplus of electrons at one end and of holes at the other. Each tends to diffuse across the boundary or junction into the opposite region, in which it becomes a minority carrier. However, as Fig. 1 shows, the electric fields resulting from this redistribution of charge limit the extent of this diffusion.
We represent (above) a matrix of impurity atoms, which are distributed through the semiconductor.

Electrons and holes in the vicinity of a p-n junction will diffuse across the junction and recombine.

As a result, an electric field is established, which prevents further recombination.

If we apply an electric field in the forward direction, we get a large recombination current.

If we apply the field in the reverse direction, we get only a small current from those carriers thermally generated in the junction.

Thus, the $I-V$ graph of a p-n junction is strongly asymmetric.

**Figure 1**: Schematic diagram of carriers at a semiconductor junction.
Now suppose an electric field is imposed across the junction. If the direction of the field is from the p to the n region, the resulting forces tend to drive the holes across the boundary into the n region, the electrons in the opposite direction into the p region, resulting in a considerable current flow across the junction. But if the $E$ field has the opposite direction, then both electrons and holes are pushed away from the junction, resulting in a negligible current flow. Another way to say the same thing is that an electric field from p to n region helps the diffusion process in pushing carriers across the junction, while the opposite direction of $E$ opposes this diffusion. Thus a p-n junction is strongly directional in its electrical properties, acting as a rectifier. It is a good conductor from p to n, but poor from n to p. The terms forward bias and reverse bias are often used in describing semiconductor device behavior. Forward bias refers to a voltage in the direction of easy current flow across a junction, from p to n region: reverse bias refers to the opposite situation.

**DIODES**

The simplest semiconductor diode is just a p-n junction. It is possible to derive an analytical expression for the voltage-current relationship for this device. The derivation makes use of the fact that a given potential difference across the junction corresponds to a certain electron energy, and the number of electrons having this much energy is determined by the Maxwell-Boltzmann distribution. Thus, it should not be surprising that the expression contains the factor $\exp(eV/KT)$, where $e$ is the electron charge, $V$ the potential difference, $K$ Boltzmann’s constant, and $T$ the absolute temperature. The result of this analysis, which will not be given in detail here, is that the current $I$ is given by:

$$I = I_0 (e^{eV/KT} - 1)$$  \[A1\]

where $I_0$ is the maximum reverse current for large negative $V$. $I_0$ is a characteristic of each particular diode that does not depend on voltage but has some temperature dependence.
Appendix B - Specification Sheet

**SILICON RECTIFIERS**

OPERATING/STORAGE TEMPERATURE RANGE: -65°C to +175°C

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<th>TYPE</th>
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<th>Maximum Average Rectified Current @ Half-Wave Resisive Load 60Hz</th>
<th>Maximum Forward Peak Surge Current @ 8.3ms Superimposed</th>
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