Diodes

Purpose
In this experiment, you will investigate the current-voltage characteristic of semiconductor diodes and determine the parameters of non-ideal diodes.

Equipment
- Two DMMs
- Adjustable DC power supply
- Oscilloscope
- 120 VAC and transformer board (lab equipment) for rectifier circuits
- Ten turn 1 kΩ potentiometer with attached resistor network (lab equipment)
- 1 kΩ resistor
- Capacitors
  - 22µF
  - 220 µF
- Diodes
  - 1N914 (Si, switching)
  - 1N34 (Ge)
  - 1N4733 (Si, regulator)
  - 1N4007 (Si, rectifier)
  - A red light-emitting diode

Background
A simplified model for the I-V characteristics of an ideal semiconductor diode relates the current and voltage by

\[ I = I_o \left( e^{\frac{qV_A}{k_B T}} - 1 \right) \]  

(1)

\( I_o \) is the reverse saturation current, \( V_A \) is the applied voltage across the diode and is positive for the forward bias condition, \( T \) is the temperature, \( k_B \) is Boltzmann’s constant, and \( q = 1.602 \times 10^{-19} \text{C} \). (Usually the magnitude of the electronic charge is represented by a lower case “\( e \)” but I have written it as “\( q \)” in order to prevent confusion in the above equation)

Figure 1. The current characteristics of an ideal diode.
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Figure 1 shows the characteristics of an ideal diode under both forward and reverse bias. In forward bias the current increases exponentially, or nearly so, and in reverse bias the current is relatively constant and is equal to \( I_0 \).

Equation 1 can be approximated since the argument in the exponential of Equation 1, at 300 K or room temperature, is large enough such that the effect of subtracting “1” from the exponential term is negligible at sufficiently high forward bias voltages. At 300 K the argument is

\[
\frac{q}{k_B T} = \frac{q}{0.0258 \text{ eV}} = 38.76 \text{ V}^{-1}
\]

(2)

Consequently, for positive applied voltages, forward bias, Equation 1 can be approximated by

\[
I \approx I_0 e^{qV_A/k_B T} \quad \text{in forward bias } V_A >> 0
\]

(3)

How large \( V_A \) must be in order to use this approximation can be garnered from Table 1 where the term in braces in Equation 1 and the exponential term in Equation 2 are compared. A value of \( V_A = +0.1 \) V results in 2% difference between the expressions, with the percent difference decreasing at even larger positive values of \( V_A \).

<table>
<thead>
<tr>
<th>( V_A )</th>
<th>( e^{qV_A/k_B T} - 1 )</th>
<th>( e^{qV_A/k_B T} )</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>5.94474</td>
<td>6.94474</td>
<td>-16.8216</td>
</tr>
<tr>
<td>0.1</td>
<td>47.22941</td>
<td>48.22941</td>
<td>-2.11732</td>
</tr>
<tr>
<td>0.2</td>
<td>2325.076</td>
<td>2326.076</td>
<td>-0.04301</td>
</tr>
<tr>
<td>0.3</td>
<td>112184.3</td>
<td>112185.3</td>
<td>-0.00089</td>
</tr>
<tr>
<td>0.4</td>
<td>5410628</td>
<td>5410629</td>
<td>-1.8E-05</td>
</tr>
<tr>
<td>0.5</td>
<td>2.61E+08</td>
<td>2.61E+08</td>
<td>-3.8E-07</td>
</tr>
</tbody>
</table>

In reverse bias (\( V_A < 0 \)) the current is negative and, at room temperature or ~300 K, modest values of \( V_A \) result in the exponential term being much smaller than one. For \( V_A = -0.1 \) V the exponential term has the value \( 1/48 \) at room temperature and the current is within 2% of \( -I_0 \) for the ideal diode. Consequently Equation 2 becomes, in reverse bias,

\[
I = -I_0 \quad \text{reverse bias } V_A << 0
\]

(4)

At larger negative values of \( V_A \), the approximation of equation 4 is even better. Hence, under reverse bias conditions the current does not change under sufficient applied voltage; it is said to “saturate” and hence \( I_0 \) is termed the reverse saturation current.

With Equation (3) in mind the characteristics of an ideal diode are straightforward in forward bias. Taking the common log of equation 3 gives

\[
\log I = \frac{q}{2.303k_B T} V_A + \log I_0
\]

(5)

Figure 2 shows a semi-log plot of the current versus voltage for an ideal diode in forward bias. For sufficient applied voltage the curve is linear with an intercept equal to \( \log (I_0) \). Hence, this is an additional and perhaps a better method to determine \( I_0 \).
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Figure 2. Plot of \( \log I \) versus \( V_A \) (forward bias) for an ideal diode.

**Less than ideal diodes**

For real diodes, not ideal, the current versus applied voltage curves deviates from the ideal case. This deviation is dependent on the applied voltage. To quantify the behavior of real diodes, the ideal diode equation (Equation 1) is modified to include an “ideality” factor in the exponential. For a real diode,

\[
I = I_0 \left( e^{qV_A/(nk_BT)} - 1 \right),
\]

where \( n \) is the “ideality” factor and is equal to one for an ideal diode. Again, under sufficient forward bias, this expression can be written

\[
I \approx I_0 e^{qV_A/(nk_BT)} \quad \text{in forward bias } V_A >> 0.
\]  

Taking the common log of this expression as before yields,

\[
\log I = \frac{q}{2.303 n k_B T} V_A + \log I_0.
\]  

Equation 8 shows that under sufficient forward bias a semi-log plot of current versus applied voltage for real diodes is a straight line. The ideality factor \( n \) is not constant for all forward bias voltages but changes depending on the forward bias voltage and the characteristics of real diodes. For many diodes, at low forward currents \( n \) approaches 2 and at intermediate currents \( n \approx 1 \), and at high currents \( n \approx 2 \). Also apparent in many diodes is a region at high currents where the resistance of the bulk diode material decreases the current from the ideal to such a degree that a specific value for \( n \) cannot be determined. Figures 3 and 4 show semi-log I-V plots for real diodes with the values of \( n \) listed in the plots were obtained from least squares fitting.
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Figure 3. Plot of \( \ln I \) as a function of \( V_A \) in forward bias for a real diode.

Figure 4. Plot of \( \ln I \) as a function of \( V_A \) in forward bias for a real diode.
Exercise 1: I-V curves of diodes

- Measure the exact resistance of the 1 kΩ resistor.

For each diode:

- Construct the circuit shown in Figure 1 using the 1 kΩ resistor and the DC power supply. Attach one multimeter so that it measures the voltage drop across the diode and attach the other multimeter so that the current through the diode can be monitored. As it is, the bipolar power supply will work only when the diode is biased a certain way. Why? Note: You may have to construct a different circuit to obtain all the necessary data for this experiment.

- Measure the voltage across the diode and the current through the diode in both the forward and reverse bias conditions. As you vary the power supply voltage, monitor the power dissipated in the resistor \( P = \frac{V^2}{R} \). Do not let the power dissipated in the resistor exceed its power rating.

- Repeat the above measurements using each diode.

For each diode, on separate graphs,

- On linear scales plot the current (y-axis) versus the bias voltage.
- On semi-log scales plot the current versus the forward bias voltage.
- For each diode determine \( I_0, V_0 \), and the ideality factor.

Figure 1. Circuit network for measuring the forward and reverse bias current in a diode.

Questions:
Discuss and compare the I-V curves for the different diodes.
Exercise 2: The half-wave rectifier

Construct a half-wave rectifier using a 1N4007 diode as shown in Figure 2 with $R=470\ \Omega$. The transformer and 120 VAC input are lab equipment and come as a single unit. In this circuit the oscilloscope monitors the output of the diode. **Double-check your circuit before applying power—if the circuit is incorrect, you will likely blow a fuse!**

Sketch the output waveform using the oscilloscope with

1) no capacitor,
2) a 22 $\mu$F capacitor, and
3) a 220 $\mu$F capacitor in the circuit.

![Figure 2. The half-wave rectifier circuit.](image)

Exercise 3: The Full Wave Rectifier

Now convert the circuit into a full-wave rectifier by adding a second 1N4007 diode, as shown in Figure 3. **Double-check your circuit before applying power—if the circuit is incorrect, you will likely blow a fuse!**

Sketch the output waveform with the oscilloscope with

1) no capacitor,
2) a 22 $\mu$F capacitor, and
3) a 220 $\mu$F capacitor in the circuit.

![Figure 3. The full wave rectifier circuit.](image)

Questions

Explain the shapes of the output waveforms in the half-wave and full-wave rectifier circuits.