Modern diodes and transistors are made from semiconductive materials (i.e., materials with conductivity in the range of \(10^3\) to \(10^{-8}\) S per cm). Typical semiconductive materials used in electronic devices are silicon, germanium, gallium arsenide, and silicon carbide.

Silicon, Si, atomic number 14, is the eighth most common element in the universe by mass.

**Table of Elements**

| Group # | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Period  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 1       | H  | He | Li | Be | B  | C  | N  | O  | F  | Ne | Na | Mg | Al | Si | P  | S  | Cl | Ar |
| 2       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 3       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 4       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 5       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 6       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 7       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

* Lanthanoids
  - La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

** Actinoids
  - Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr
Silicon has the following atomic configuration:

Silicon rarely appears in its pure crystalline form in nature. To use silicon in semiconductor devices, it needs to be grown in crystals of very high purity. Then it is cut into wafers which are then doped to alter their conductive states.

Doping is a process where impurities are added in a controlled manner to change the electrical conductivity of selected portions of a silicon wafer. Pure silicon has no free electrons and applying a voltage has little effect on producing an electron flow.

Silicon wafers

All electrons are locked up into covalent bonds between neighboring atoms.
By adding atoms with 5 valence electrons to the silicon wafer, n-type silicon is created. Which has "extra" electrons that can be moved around quite easily.

Phosphorus

Atomic Configuration

n-type silicon

Phosphorus atom
added to Si wafer
→ provides unbound electron

P-type silicon is obtained by adding atoms with 3 valence electrons. Has "extra" holes that can be moved around easily.

Boron

Atomic Configuration

P-type silicon

Missing electron (hole) acts like positive charge that can be easily moved.
Diode symbol:  

Forward biasing:
- anode more positive than cathode
- positive charge flows from anode to cathode

Reverse biasing:
- cathode more positive than anode
- no current can flow through diode

\[ i_D \rightarrow v_D \]

\[ i-v \text{ characteristics of ideal diode} \]

- \[ v_D \]

**pn Junction Diodes** are formed by sandwiching together n-type and p-type Silicon

\[ \text{pn junction diode} \]

To make one-way gate tricky is to make charge carriers (unbound electrons and holes) in n and p regions interact in such a way that current flows in only one direction.

Forward biased:

Electrons from n side and holes from p side are forced toward pn junction by electrical field supplied by battery.

Electrons and holes combine and current can flow.
Reverse biased:

Holes are attracted to - of battery and electrons are attracted to + of battery. This creates zone at pn junction free of charge carriers called depletion region.

$i$-$v$ characteristic of $pn$ junction diode

Shockley equation (after William Bradford Shockley, one of the inventors of the transistor)

Where

- $i_0$: reverse saturation current, $\approx 10^{-5} - 10^{-15}$ A
- $n$: diode ideality factor, $n \approx 1.7$
- $V_T$: thermal voltage, $V_T = kT/q = 25.7$ mV at $25^\circ C$
- $k$: Boltzmann constant, $k = 1.38 \times 10^{-23}$ J/K
- $T$: absolute temperature in K, $25^\circ C = 298.15^\circ K$
- $q$: electron charge, $q = 1.6 \times 10^{-19}$ C
For silicon diodes the main region of interest is when \( V_D > 0.4 \text{V} \). In this case \( \frac{V_D}{n_{VT}} = \frac{0.4}{0.026} = 15.38 \) and \( e^{15.38} \gg 1 \) so that the Shockley equation can be approximated by

\[ i_D = i_0 e^{V_D / (n_{VT})} \rightarrow \ln i_D = \frac{1}{n_{VT}} V_D + \ln i_0 \]

If \( \frac{V_D}{n_{VT}} > 10 \)

corresponding to \( V_D > 0.5 \text{V} \) @ 25°C (and \( n \geq 2 \))

Thus, plotting \( \ln i_D \) versus \( V_D \) yields \( \ln i_0 \) and \( \frac{1}{n_{VT}} \) from the slope of the \( \ln i_D \) line.

Real p-n junction diodes also have a series resistance \( R_S \):

- **Series resistance**
- **Ideal p-n junction diode**

\[ \text{Voltage at real diode terminals} \]

In this case \( V = V_D + V_R = V_D + R_S i_D \rightarrow V_D = V - R_S i_D \)

\[ \ln i_D = \frac{1}{n_{VT}} (V - R_S i_D) + \ln i_0 \]

\[ \ln i_D + \frac{R_S}{n_{VT}} i_D = \frac{1}{n_{VT}} V + \ln i_0 \]

\[ \ln (i_D e^{R_S i_D / (n_{VT})}) = \ln i_0 \text{ if } i_D \ll \frac{n_{VT}}{R_S} \]

Example: If \( i_D = 100 \mu\text{A} \), \( n_{VT} = 50 \text{mV} \), and \( R_S = 10 \Omega \)

\[ e^{R_S i_D / (n_{VT})} = 1.01 \text{, if } i_D = 500 \mu\text{A} \rightarrow e^{R_S i_D / (n_{VT})} = 1.105 \]

Thus, the series resistance \( R_S \) affects the \( \ln i_0 \) vs. \( V_D \) line only significantly for \( i_D \leq 1 \text{ mA} \).
Example: A 1N914 small signal silicon diode was measured and the following values were obtained for \( i_0 \) versus \( v = v_T + v_0 \)

<table>
<thead>
<tr>
<th>( i_0 [\text{mA}] )</th>
<th>( v [\text{V}] )</th>
<th>( i_0 [\text{mA}] )</th>
<th>( v [\text{V}] )</th>
<th>( i_0 [\text{mA}] )</th>
<th>( v [\text{V}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>0.48</td>
<td>1.20</td>
<td>0.61</td>
<td>37.0</td>
<td>0.82</td>
</tr>
<tr>
<td>0.19</td>
<td>0.51</td>
<td>2.42</td>
<td>0.64</td>
<td>64.9</td>
<td>0.88</td>
</tr>
<tr>
<td>0.31</td>
<td>0.52</td>
<td>5.43</td>
<td>0.69</td>
<td>102.5</td>
<td>0.94</td>
</tr>
<tr>
<td>0.49</td>
<td>0.56</td>
<td>9.05</td>
<td>0.72</td>
<td>144.8</td>
<td>1.00</td>
</tr>
<tr>
<td>0.66</td>
<td>0.57</td>
<td>12.5</td>
<td>0.74</td>
<td>196.4</td>
<td>1.07</td>
</tr>
<tr>
<td>0.81</td>
<td>0.59</td>
<td>19.8</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A plot of \( \ln(i_0) \) versus \( v \) (dotted black line with red points at which measurements were made) and \( \ln(i_0) \) versus \( v_0 \) (straight blue approximation from measurements with \( i_0 \leq 1 \text{mA} \)) is shown below.

The slope of the dashed blue line is \( \frac{1}{nV_T} \) and the offset is \( \ln(i_0) \). In this figure \( \frac{1}{nV_T} = 18.655 \Rightarrow n = 2.086 \) at 25°C \( (V_T = 25.7 \text{mV}) \) and \( \ln(i_0) = -18.0446 \Rightarrow 457 \times 10^{-8} \text{A} \).
Once \( n \) and \( i_0 \) are determined, \( V_D \) can be computed for the measured \( i_D \) values using

\[
i_D = i_0 \left( e^{\frac{V_D}{nV_T}} - 1 \right) \Rightarrow \frac{i_D + i_0}{i_0} = e^{\frac{V_D}{nV_T}}
\]

\[\Rightarrow V_D = nV_T \cdot \ln\left(\frac{i_D + i_0}{i_0}\right)\]

Then \( V-V_D = R_s i_D \Rightarrow R_s = \frac{V-V_D}{i_D} \)

In practice \( R_s \) is computed as the average over all \( R_s \) values for sufficiently large \( i_D \) (e.g. \( \geq 50\text{mA} \)) measurements.

The graph below shows the measured \( i_D, V \) pairs (red dots), the computed \( i_0, V_D \) pairs (using the Shockley equation with the estimated \( n, i_0 \) (dashed blue line) and the computed \( i_0, V \) pairs (dashed green line) from the estimates of \( n, i_0 \) and \( R_s \). The red circled measurement values were used to estimate \( n, i_0 \) and the red triangle measurement values were used to estimate \( R_s \).

The Matlab program that was used to compute \( n, i_0 \) and \( R_s \) and produce the graphs is shown on the next page.
Semiconductor Diode: i-v Characteristic for 1N914 Silicon Diode

% Plot i versus v to verify n, i0 and Rs parameter estimation

% 10-20-10, 1-25-09, P. Mathys

% v is voltage in V across diode including series Rs, as measured on
% diode leads
% i is current through diode in mA
v = [0.48 0.51 0.53 0.56 0.57 0.59 0.61 0.64 0.69 0.72 0.74];
i = [0.11 0.19 0.31 0.49 0.66 0.81 1.20 2.42 5.43 9.05 12.5];
v = [v 0.77 0.82 0.88 0.94 1.00 1.07];
i = [i 19.8 37.0 64.9 102.5 144.8 196.4];
i = i*1e-3;  % i in amperes

ixDlin = find(i>=0.0001&i<=0.001);  %Range of i where ln(i) ~ linear in v
ixR = find(i>=0.050);  %Range of i where (v-vD) ~ Rs*i

vlin = v(ixDlin);  %Range of v where ln(i) ~ linear in v
lni_lin = log(i(ixDlin));  %ln(i) for range where ln(i) ~ linear in v
polyDlin = polyfit(vlin,lni_lin,1);  %First degree (straight line) polynomial fit
pl = polyDlin(1);  %p1 = 1/(n*vT)
p0 = polyDlin(2);  %p0 = ln(i0)
lni_line = pl*v+p0;  %Straight line approximation to ln(i)

figure(1)
subplot(1,3,1)
plot(v,log(i),':k',v,log(i),'.r',v(ixDlin),log(i(ixDlin)),'or',v,lni_line,'--b')
grid  %Add straight line approx to plot
ylim([-10 0])  %Limit y-axis display to -10...0
xlabel('v [V]'), ylabel('ln(i), i in A')
str1 = '1N914 Silicon Diode'
str1 = [str1 ', ln(i) \approx approx ' num2str(pl) ' ** v - ' num2str(-p0)];
title(str1)

vD = linspace(0.001,1.0,100);  %Array with vD=0.001 ... 1.0 V, 100 values
vT= 25.7e-3;  %Thermal voltage at 25 degC
n = 1/(pl*vT);  %Diode ideality factor
i0 = exp(p0);  %Reverse saturation current
iD = i0*(exp(vD/(n*vT))-1);  %ID from Shockley equation
vDm = n*vT*log(i10+1);  %Compute vD from iD for measured i values
vR = v-vDm;
RMs = vR(ixR)/i(ixR);
Rs = mean(RMs);
vcomp = vD+Rs*iD;

clear

figure(2)
subplot(1,3,1)
plot(v,i,:k,v,i,.r',vD,iD,--b',vcomp,iD,--g',...v(ixDlin),i(ixDlin),'or',v(ixR),i(ixR),'^r')
grid  %Plot (v,i) and (vD,iD) pairs
xlim([0.3 1.1])  %Limit x-axis display to 0.3 ... 1.1 V
ylim([0 0.2])  %Limit y-axis display to 0 ... 0.2 A
xlabel('v,v_D [V]'), ylabel('i,i_D [A]')
str2 = '1N914 Silicon Diode';
str2 = [str2 ', n = ' num2str(n) ', i_0 = ' num2str(i0) ' A'];
str2 = [str2 ', R_s = ' num2str(Rs) ' \Omega'];
title(str2)
legend('measured (v,i)','measured points','computed (v_D,i_D)','...'
computed (v,i)','used for i_0,n','used for R_s',2)
A simulation in Eispice of the 1N914 model that is provided has the following schematic (using a voltage source and a resistor in series to limit the current, as would be done for an actual measurement in the lab).

![Eispice schematic](image)

\[ I_s=2.52e-9 \quad R_s=0.568 \quad N=1.752 \]

The parameters of the 1N914 model that comes with Eispice are a little different than the ones computed on the previous pages. The i-v characteristic looks as follows:

![i-v characteristic](image)

As for this model is smaller and thus the forward voltage drop of the diode is smaller.
The diode model that is used in LTspice can be modified using the .model directive. This is shown in the schematic below.

\[ I_s = 1.4566e-8 \quad R_s = 0.93696 \quad N = 2.0858 \]

Now the parameters that were computed previously in Matlab are used instead of the values provided by LTspice. \( R_s \) is defined as a parameter so that the ideal diode characteristic (for \( R_s = 0 \)) can also be seen in the i-v plot below.
Applications for Diodes:

Half-wave rectifier

Full-wave rectifier

Simple Model for pn-junction diode in forward-biased mode:

Forward voltage drop