PN Junction

With silicon, you can create n-type material and p-type material by doping the silicon crystal. When you place a p-type material adjacent to n-type material, you get a pn junction - also known as a diode.

Diodes allow current to flow in only one direction. For example, assume the doping in the n and p region is $10^{16}$ atoms per cc. In the p-type region,

$$p_p \approx 10^{16}$$

$$n_p = \left( \frac{n_i^2}{p_i} \right) = 2.25 \cdot 10^4$$

In n-type silicon, the doping is Phosphorus, resulting in

$$n_n \approx 10^{16}$$

$$p_n = 2.25 \cdot 10^4$$

At the pn junction, some electrons and holes are created through thermal electrons. This is a small number, however, so assume it's zero. If electrons and holes are not created, current can only flow by electrons and holes flowing towards the pn junction (where they combine and disappear).

Assume the current is flowing from the p-side to the n-side (the left figure below.) In this case, you are using majority carriers, so there are approximately $10^{16}$ charge carriers.

Now, assume the current is flowing from the n-side to the p-side. In this case, you are using minority carriers, resulting in only $2.25 \cdot 10^4$ charge carriers. If the diode has a resistance of 1 when using majority carriers (current p to n), it has a resistance of $444\Omega$ when using minority carriers (!).

**A diode only allows current to flow from p to n**

![Current Flow Diagram](image)

majority carriers: # charge carriers = $10^{16}$  
minority carriers: # charge carriers = $10^4$

The net result is a diode has low resistance in one direction (p to n) but high resistance in the other direction (n to p). The difference in resistance is huge: $10^{12} : 1$ in this case. As a result, a good approximation for a diode is to say

- A diode is a short (zero ohms) when current flows p to n
- A diode is an open circuit (infinite ohms) when current tries to flow n to p

January 3, 2011
This is reflected in the symbol for a diode: an arrow reminding you which direction current can flow in a diode:

In addition, you get diffusion current. Above 0K, all electrons are in motion. At the pn junction, there are lots of holes on the p-side, and almost none on the n-side. Due to random motion of the holes, holes will drift from the p-side to the n-side, with almost no holes drifting back. The same occurs for electrons in the n-type region. The net result is current flow across the pn junction, termed drift current.

Eventually, the holes accumulate in the n-side and the electrons accumulate on the p-side:

This has several effects:

(a) A region with no charge carriers is created near the pn junction, termed the depletion region. Since there are no charge carriers, there is no current flow.

(b) A capacitor is created: you have charge across an insulator. The capacitance is small, but it's non-zero. If you have a high-speed switching circuit, you need to take this capacitance into account when calculating the rise times for signals.

(c) A voltage is created between the n-side and the p-side. If you try to get current to flow from p-to-n, you have a voltage drop across the diode equal to

\[ V_d = V_T \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

For Silicon at 273C, this works out to
\[ V_d = (0.026 V) \ln \left( \frac{10^{16} \cdot 10^{16}}{(1.5 \cdot 10^{10})^2} \right) = 0.697 V \approx 0.7 V \]

Silicon diodes have about a 0.7V drop across them when current flows.

(d) The voltage varies with different types of materials. These are approximately as follows:
   - Silicon: 0.7V
   - Germanium: 0.3V
   - Red LED: 1.9V (varies)
   - Blue LED: 3.3V (varies)

(e) The voltage varies with temperature. Since the intrinsic carrier concentration is:
   \[ n_i^2 = A_o T^3 e^{-E_c/kT} \]
as T varies, Vd varies. Plotting this in SciLab:

```matlab
-->C = [-30:30]';
-->T = C+273;
-->Ao = 2.36e33;
-->ni = (Ao*(T.^3).*exp(-1.1/k ./ T) ).^0.5;
-->Vd = 0.026*log(1e32 ./ (ni .^ 2));
-->plot(C,Vd);
-->xlabel('Celcius');
-->ylabel('Vd');
```

You can use the voltage drop across a diode to measure temperature. The change in voltage isn't large, but it's there. It's also almost a linear relationship.
You can also use a diode to measure temperature and radiation by trying to push current backwards through the diode. If you try to send current through a diode from the n-side to the p-side, there are actually two sources of current flow:

- Drift current: current flow due to the resistance of the device. This is almost zero due to the large resistance of a diode to reverse current flow (444 GΩ).
- Thermal Current: Above 0K, there will be a few electrons and holes created in the depletion zone due to random motion of electrons. Once an electron is created, it flows into the n-region and the hole flows into the p-region. This is actually the main contributor to current flow in a reverse biased diode.

Similarly, if you expose a diode to radiation, the radiation can kick an electron out of its covalent bond, creating an electron-hole pair. By measuring the current flow, you also have a radiation sensor. You can verify this by applying light to a reverse-biased LED as follows:

![Diode schematic](diode_schematic.png)

In a dark room, there should be no current flow through the diode. If you shine a light on it, however, current is created by the light kicking electrons out of their covalent bond at the pn junction. This current is converted to a voltage by the 1M resistor as

\[ V = IR \]