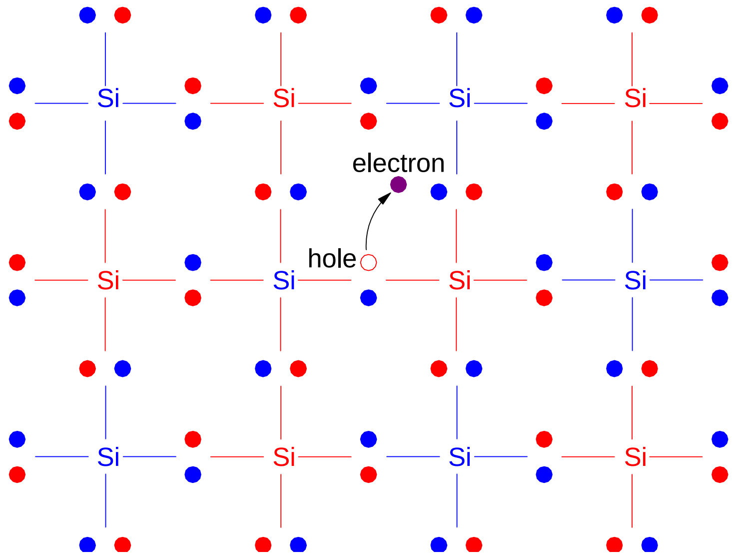
Semiconductors

Silicon is an element in column 4A of the periodic chart. This means that Silicon has 4 electrons in it's outer shell. Silicon crystals are diamond cubic - meaning each silicon atom has four neighbors:



Above 0K, some electrons can escape the covalent bond. This creates a free electron and a resulting missing electron in the crystal: termed a hole. In Silicon, the number of free electrons is a function of temperature:

$$n_i^2 = A_o T^3 e^{-E_G'/kT}$$

where EG is the energy gap at 0K, k is Boltzmann's constant, and Ao is a constant, For Silicon, EG varies with temperature:

$$E_G \approx 1.1 - 3.6 \cdot 10^{-4} T$$

or at 300K,

$$E_G = 1.1eV$$

$$k = 8.617343 \times 10^{-5} \frac{eV}{K}$$

$$np = n_i^2 \approx (1.5 \cdot 10^{10})^2$$

Silicon has two ways to carry charge: electrons and holes. Above 0K, some of the electrons in their covalent bonds will break free due to thermal energy. Once free, the electron is free to move about the crystal, carrying current with a negative charged carrier.

Once an electron breaks out of its covalent bond, a hole is left in the crystal. This hole can be filled with an adjacent electron - resulting in the apearance of the hole moving. Thus the hold behaves like a positively charged charrier.

The mobility of electrons and holes are different - with electrons being more free to move about (and likewise have a lower resistance:

$$\mu_n = 1300 \frac{cm^2}{Vs}$$

$$\mu_p = 500 \frac{cm^2}{Vs}$$

Problem: Find the resitivity of Silicon at 300K:

Solution: The conductivity is due to electrons and holes, which are both 1.5×10^{10} / cc

$$\sigma = n_i q(\mu_n + \mu_p) = (1.5x10^{10} cm^{-3})(1.6x10^{-19} C)(1300 + 500) \frac{cm^2}{Vs}$$

$$\sigma = 4.32x10^{-6} \frac{1}{\Omega cm}$$

$$\rho = \frac{1}{\sigma} = 231,481 \Omega \cdot cm$$

which makes pure silicon a poor conductor:

Example: Find the resistance of a piece of silicon at 293K with a length of 1mm and a cross sectional area of 0.5mm x 0.5mm (an 0402 resistor)

Solution:

$$R = \frac{\rho L}{A} = \frac{(231{,}481 \Omega \cdot cm)(0.1 cm)}{(0.05 cm)^2} = 9.26 M\Omega$$

You can change the resistance of silicon by doping. For silicon, the product np is constand:

$$np = n_i^2$$

In p-type silicon, you dope the silicon with Boron, with a typical doping of 10^{16} atoms per cc. In this case, most of the holes will be due to the doping:

$$p \approx 10^{16} /\text{cc}$$

with just a few due to thermal electrons:

$$n = \left(\frac{n_i^2}{p} \right) = 2.25 \cdot 10^5 /\text{cc}$$

The resistance of the same piece of sillcon doped with Boron is:

$$\sigma = q(n\mu_n + p\mu_p) = (1.6x10^{-19} C)(2.25x10^5 \cdot 1300 + 10^{16} \cdot 500) \frac{cm^2}{Vs}$$

$$\sigma \approx qp\mu_p = (1.6x10^{-19} C)(10^{16} \cdot 500) \frac{cm^2}{Vs}$$

$$\sigma = 0.8 \frac{1}{\Omega cm}$$

$$\rho = \frac{1}{\sigma} = 1.25 \Omega \cdot cm$$

The resistivity is 184,000 times smaller, resulting in the resistance of the silicon being 184,000 times lower:

$$R = \frac{\rho L}{A} = \frac{(1.25\Omega \cdot cm)(0.1cm)}{(0.05cm)^2} = 50\Omega$$

If you dope the silicon with phosphorus, (an element with 5 electrons in its outer shell), the crystal will have extra electrons. This creates n-type silicon:

$$n \approx 10^{16}/cc$$

$$p = \frac{n_i^2}{n} = 2.25 \cdot 10^5/cc$$

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

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

$$p_n = 2.25 \cdot 10^5$$

and the resistivity and resistance is:

$$\sigma = q(n\mu_n + p\mu_p) = (1.6x10^{-19}C)(10^{16} \cdot 1300 + 2.25x10^5 \cdot 500)\frac{cm^2}{Vs}$$

$$\sigma \approx qn\mu_n = (1.6x10^{-19}C)(10^{16} \cdot 1300)\frac{cm^2}{Vs}$$

$$\sigma = 2.08\frac{1}{\Omega cm}$$

$$\rho = \frac{1}{\sigma} = 0.481\Omega \cdot cm$$

$$R = \frac{\rho L}{A} = \frac{(0.481\Omega cm)(0.1cm)}{(0.05cm)^2} = 19.2\Omega$$

Observations:

- n-type silicon has slightly lower resistance than p-type silicon with the same doping. This doesn't matter that much since you can increase the doping concentration of p-type material to compensate for this.
- It's fairly easy to build resistors out of silicon: just vary the doping concentration.
- The intrinisic carrier concentration varies with temerature. At high temperatures, there are more charge carriers. This allows you to use silicon as a temperature sensor, where resistance drops with temperature. Such sensors are called thermistors (thermal resistors).

Semiconductor Resistors:

Problem: Design an 0402 resistor with a resistance of 1000 Ohms.

Why? Resistors are pretty useful devices. By varying the doping, you can vary the resistance of a piece of Silicon.

Solution: The resistivity you want is

$$R = \frac{\rho L}{A} = \frac{(\rho\ \Omega cm)(0.1cm)}{(0.05cm)^2} = 1000\Omega$$

$$\rho = 25\Omega \cdot cm$$

$$\sigma = 0.04\frac{1}{\Omega \cdot cm}$$

$$\sigma \approx qn\mu_n = (1.6x10^{-19}C)(n \cdot 1300)\frac{cm^2}{Vs} = 0.04\frac{1}{\Omega \cdot cm}$$

$$n = 1.9 \cdot 10^{14}/cm^3$$

Dope the Silicon with Phosphorus with a concentration of $1.9 \cdot 10^{14}$ Phosphorus atoms per cubic centimeter. The resulting resistor will have a resistance of 1k Ohm.

Problem: Design a 10k resistor.

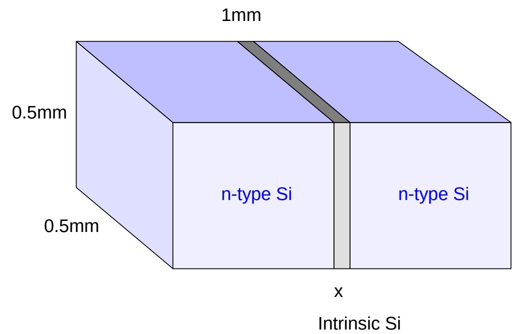
Solution: If the doping is 10 times lower, you'll have 10 times fewer charge carriers, and hence, 10 times the resistance.

$$n = 1.9 \cdot 10^{13}/cm^3$$

It's pretty easy designing resistors with Silicon.

Thermistors:

Problem: Design an 0402 resistor with Silicon doped at 1016/cc sandwiching a small section of intrinsic Si. Specify the width of the intrinsic Silicon so that the resistor has a resistance of 1k at 25C.



Assume a doping of $n=10^{16}$/cc for the n-type Silicon. This results in a resistance of 19 Ohms from the previous analysis. Ignoring this (since it's much less than 1k), the ressistance of the intrincic Silicon needs to be 1k.

At 273K,

$$\rho = \frac{1}{\sigma} = 231,481\Omega \cdot cm$$

$$R = 1000 = \frac{\rho L}{A}$$

$$1000 = \frac{(213,481\Omega \cdot cm)(x)}{(0.05cm)^2}$$

$$x = 11.7\mu m$$

Add a thin strip of intrinsic Silicon in the middle of the resistor and the resistance rises to 1k Ohm.

Note that the resulting resistor is sensitive to temperature:

$$n_i^2 = A_o T^3 e^{-E_G'/kT}$$

$$\sigma = q(n\mu_n + p\mu_p) = (1.6x10^{-19}C)(n_i)(1300+500)\frac{1}{\Omega\cdot cm}$$

$$A_0 = 2.36\cdot 10^{33}$$

$$E_G = 1.1eV$$

$$k = 8.617343\times 10^{-5}\ \frac{eV}{K}$$

In SciLab you can plot the resistance vs. temperature:

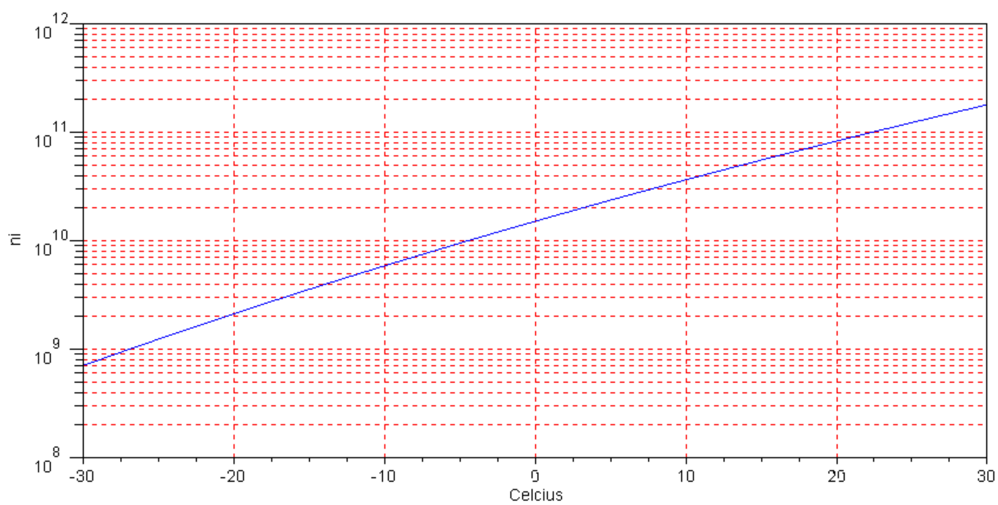
```
-->Ao = 2.36e33;
-->k = 8.61e-5;

-->C = [-30:30]';
-->T = C+273;

-->ni = (Ao*(T.^3).*exp(-1.1/k ./ T) ).^0.5;

-->plot(C,ni)
-->xlabel('Celcius')
-->ylabel('ni')
-->xgrid(5)
```

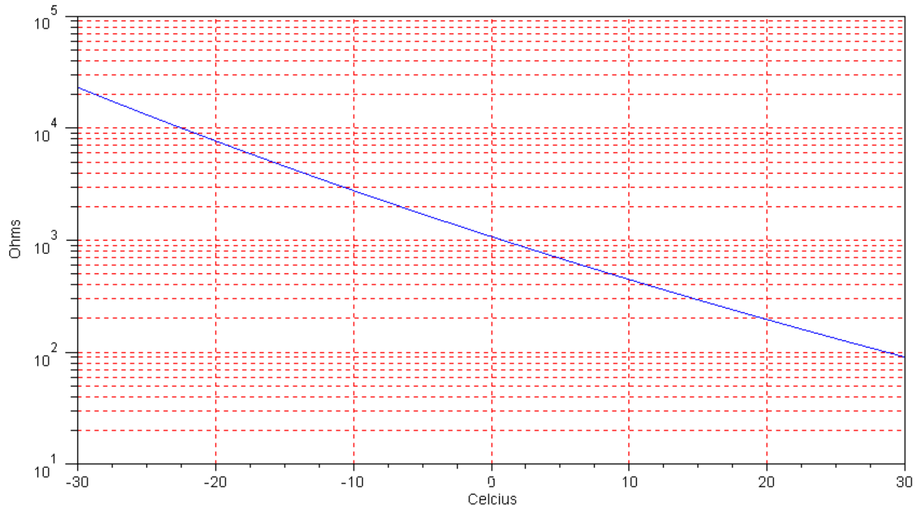
The intrinsic carrier concentration, ni, varies considerabl from -30C to +30C.



Likewise, the resistance across this 11.7um strip of Silicon varies with temperature:

```
-->sigma = (1.6e-19)*(ni)*(1800);
-->p = 1 ./ sigma;
-->R = p*(11.7e-6) / (0.05)^2;
```

```
-->plot(C,R)
-->xlabel('Celcius');
-->xgrid(5)
-->ylabel('Ohms');
```



This is a temperture-sensitive resistor, termed a thermistor. By measuring its resistance, you know the temperature.