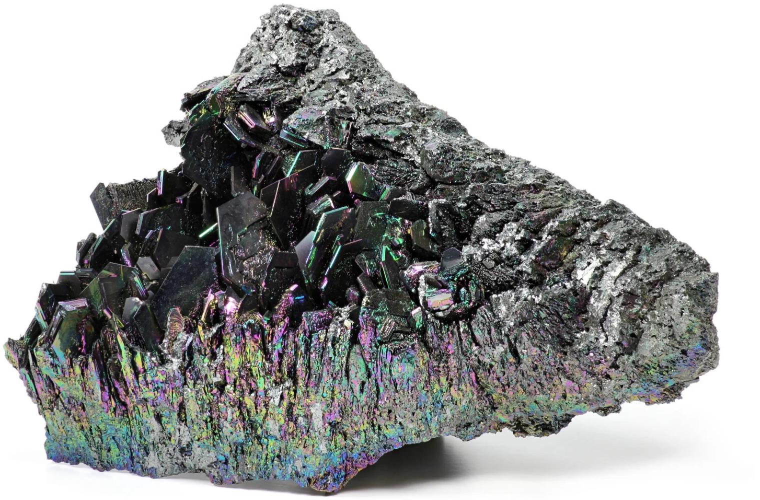
Semiconductors

ECE 320 Electronics I (Digital Electronics)

Jake Glower - Lecture #4

Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

Semiconductors



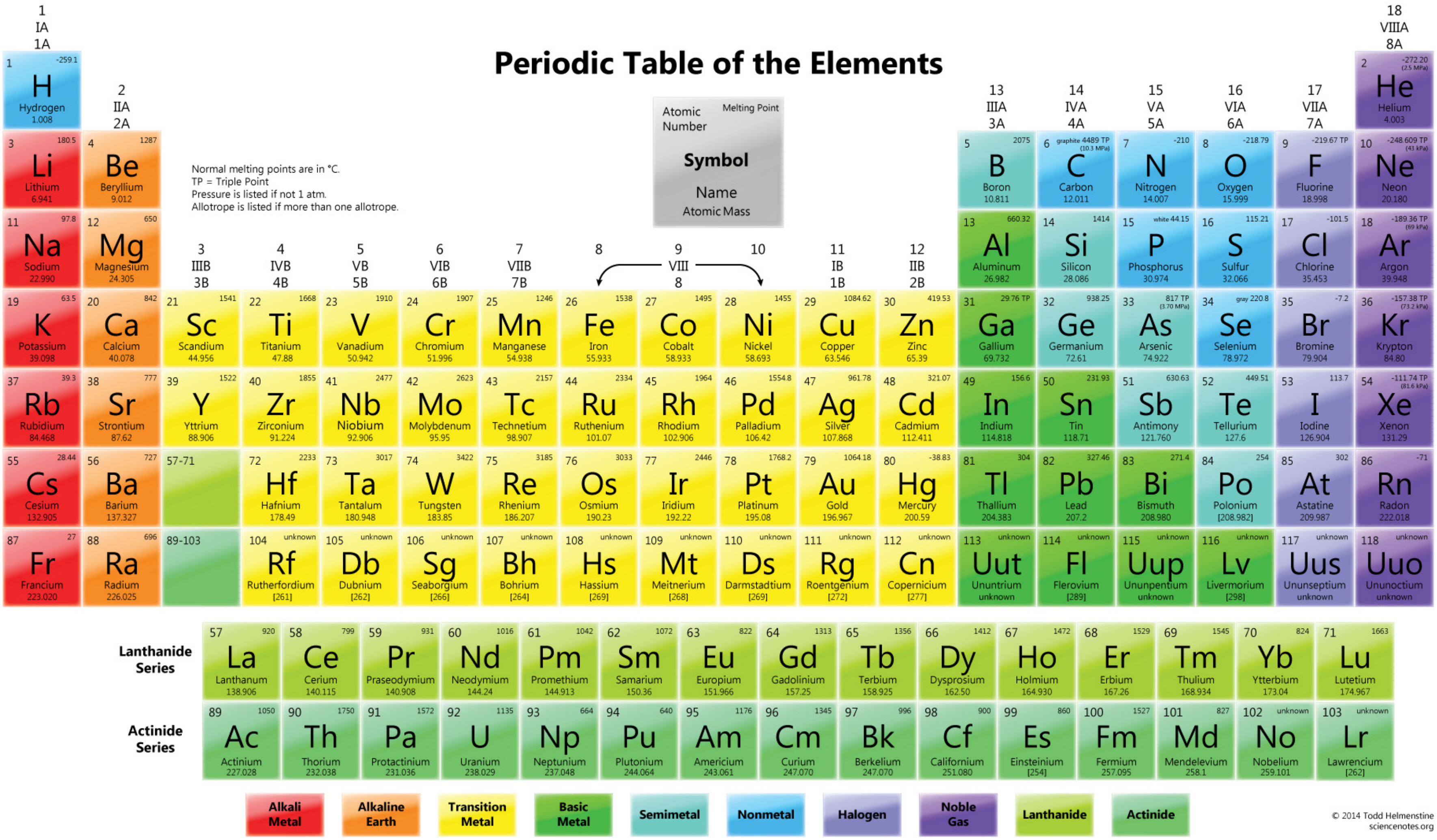
Silicon is a key element for many electronics devices

It has properties that are very different from other elements like metals

- Metals
  - Resistance goes up as temperature goes up
  - Only one type of charge carrier (electrons)
- Semiconductors (Silicon)
  - Resistance goes down as temperature goes up
  - Two types of charge carriers (holes and electrons)

Lecture Topics

- Why does silicon behave this way?
- What are electrons and holes?
- What can you do with silicon?



Periodic Table of the Elements

Normal melting points are in °C.
TP = Triple Point
Pressure is listed if not 1 atm.
Allotrope is listed if more than one allotrope.

Atomic Number
Melting Point
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 -259.1 H Hydrogen 1.008																	2 -272.20 (2.5 MPa) He Helium 4.003
3 180.5 Li Lithium 6.941	4 1287 Be Beryllium 9.012											5 2075 B Boron 10.811	6 graphite 4489 TP (10.3 MPa) C Carbon 12.011	7 -210 N Nitrogen 14.007	8 -218.79 O Oxygen 15.999	9 -219.67 TP F Fluorine 18.998	10 -248.609 TP (43 kPa) Ne Neon 20.180
11 97.8 Na Sodium 22.990	12 650 Mg Magnesium 24.305											13 660.32 Al Aluminum 26.982	14 1414 Si Silicon 28.086	15 white 44.15 P Phosphorus 30.974	16 115.21 S Sulfur 32.066	17 -101.5 Cl Chlorine 35.453	18 -189.36 TP (69 kPa) Ar Argon 39.948
19 63.5 K Potassium 39.098	20 842 Ca Calcium 40.078	21 1541 Sc Scandium 44.956	22 1668 Ti Titanium 47.88	23 1910 V Vanadium 50.942	24 1907 Cr Chromium 51.996	25 1246 Mn Manganese 54.938	26 1538 Fe Iron 55.933	27 1495 Co Cobalt 58.933	28 1455 Ni Nickel 58.693	29 1084.62 Cu Copper 63.546	30 419.53 Zn Zinc 65.39	31 29.76 TP Ga Gallium 69.732	32 938.25 Ge Germanium 72.61	33 817 TP (3.70 MPa) As Arsenic 74.922	34 gray 220.8 Se Selenium 78.972	35 -7.2 Br Bromine 79.904	36 -157.38 TP (73.2 kPa) Kr Krypton 84.80
37 39.3 Rb Rubidium 84.468	38 777 Sr Strontium 87.62	39 1522 Y Yttrium 88.906	40 1855 Zr Zirconium 91.224	41 2477 Nb Niobium 92.906	42 2623 Mo Molybdenum 95.95	43 2157 Tc Technetium 98.907	44 2334 Ru Ruthenium 101.07	45 1964 Rh Rhodium 102.906	46 1554.8 Pd Palladium 106.42	47 961.78 Ag Silver 107.868	48 321.07 Cd Cadmium 112.411	49 156.6 In Indium 114.818	50 231.93 Sn Tin 118.71	51 630.63 Sb Antimony 121.760	52 449.51 Te Tellurium 127.6	53 113.7 I Iodine 126.904	54 -111.74 TP (81.6 kPa) Xe Xenon 131.29
55 28.44 Cs Cesium 132.905	56 727 Ba Barium 137.327	57-71	72 2233 Hf Hafnium 178.49	73 3017 Ta Tantalum 180.948	74 3422 W Tungsten 183.85	75 3185 Re Rhenium 186.207	76 3033 Os Osmium 190.23	77 2446 Ir Iridium 192.22	78 1768.2 Pt Platinum 195.08	79 1064.18 Au Gold 196.967	80 -38.83 Hg Mercury 200.59	81 304 Tl Thallium 204.383	82 327.46 Pb Lead 207.2	83 271.4 Bi Bismuth 208.980	84 254 Po Polonium [208.982]	85 302 At Astatine 209.987	86 -71 Rn Radon 222.018
87 27 Fr Francium 223.020	88 696 Ra Radium 226.025	89-103	104 unknown Rf Rutherfordium [261]	105 unknown Db Dubnium [262]	106 unknown Sg Seaborgium [266]	107 unknown Bh Bohrium [264]	108 unknown Hs Hassium [269]	109 unknown Mt Meitnerium [268]	110 unknown Ds Darmstadtium [269]	111 unknown Rg Roentgenium [272]	112 unknown Cn Copernicium [277]	113 unknown Uut Ununtrium unknown	114 unknown Fl Flerovium [289]	115 unknown Uup Ununpentium unknown	116 unknown Lv Livermorium [298]	117 unknown Uus Ununseptium unknown	118 unknown Uuo Ununoctium unknown

Lanthanide Series	57 920 La Lanthanum 138.906	58 799 Ce Cerium 140.115	59 931 Pr Praseodymium 140.908	60 1016 Nd Neodymium 144.24	61 1042 Pm Promethium 144.913	62 1072 Sm Samarium 150.36	63 822 Eu Europium 151.966	64 1313 Gd Gadolinium 157.25	65 1356 Tb Terbium 158.925	66 1412 Dy Dysprosium 162.50	67 1472 Ho Holmium 164.930	68 1529 Er Erbium 167.26	69 1545 Tm Thulium 168.934	70 824 Yb Ytterbium 173.04	71 1663 Lu Lutetium 174.967
Actinide Series	89 1050 Ac Actinium 227.028	90 1750 Th Thorium 232.038	91 1572 Pa Protactinium 231.036	92 1135 U Uranium 238.029	93 664 Np Neptunium 237.048	94 640 Pu Plutonium 244.064	95 1176 Am Americium 243.061	96 1345 Cm Curium 247.070	97 996 Bk Berkelium 247.070	98 900 Cf Californium 251.080	99 860 Es Einsteinium [254]	100 1527 Fm Fermium 257.095	101 827 Md Mendelevium 258.1	102 unknown No Nobelium 259.101	103 unknown Lr Lawrencium [262]

Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetal
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide

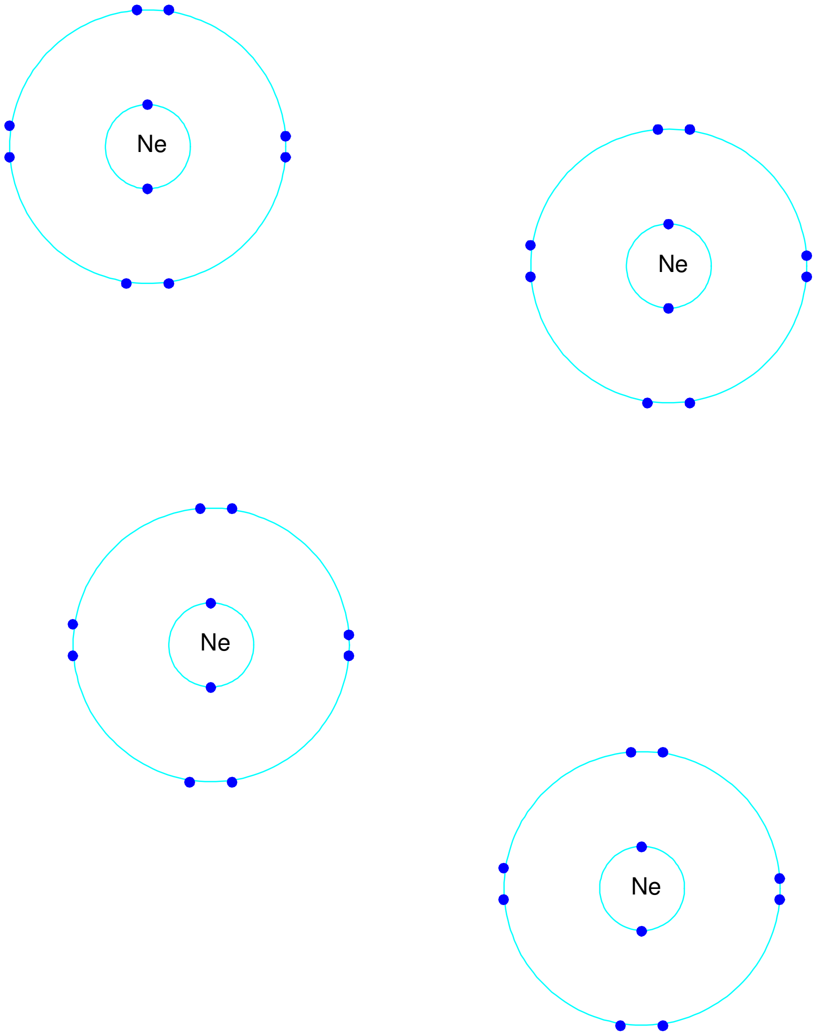
Noble Gasses: Column VIIIA

All electron shells filled

- No desire to give up an electron
- No desire to accept more electrons

These elements

- Do not interract with other atoms
- Do not conduct electricity
  - No free charge carriers



Halogens and Nonmetals

Column VIA and VIIA

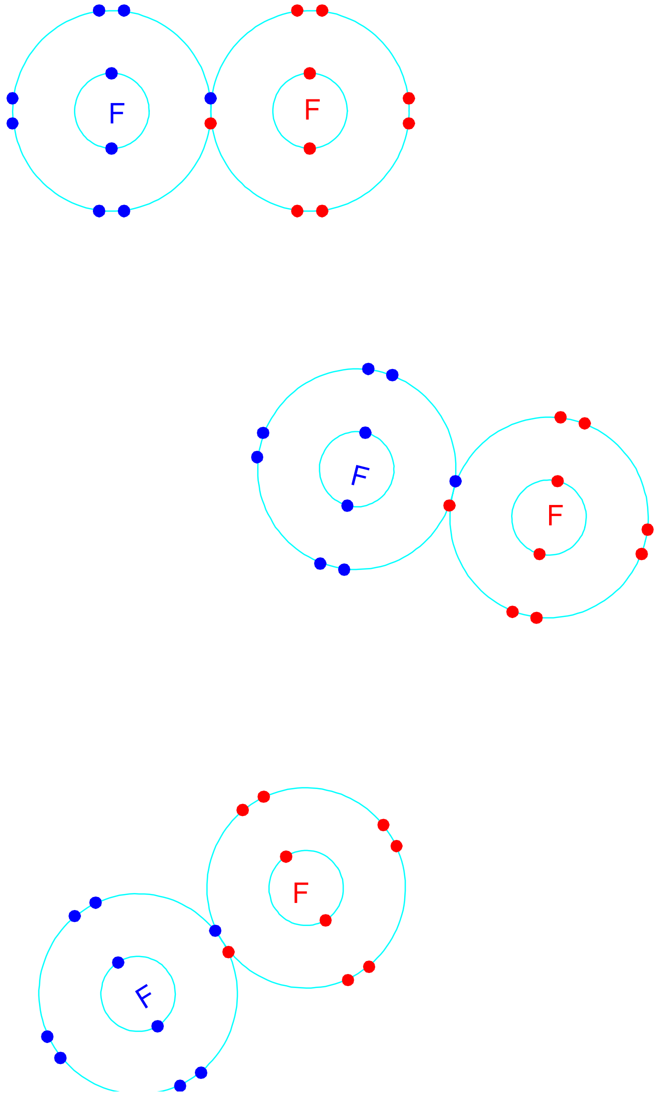
Example: F_2, O_2, N_2

One to three electrons short of filling all orbitals

- Forms a covalent bond with another atom

Resulting molecule is similar to a Noble gas

- Gas (low molecular weight)
- Does not conduct electricity
- (No free electrons)



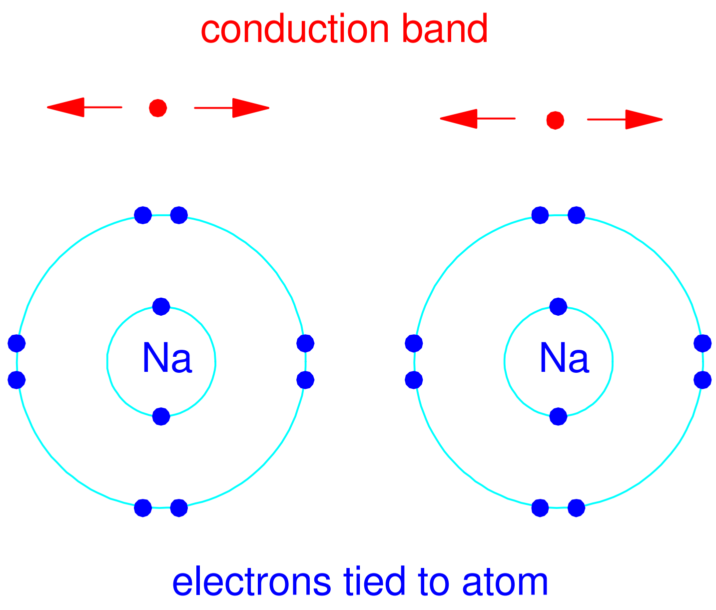
Metals

Column IA, IIA, IIIA

- Sodium, Magnesium, Aluminum

Core is a Noble gas (Neon)

- Has excess electrons
- These electrons are loosely tied to the atom
- They are free to move in the conduction bands



Properties of Metals

- One type of charge carrier
  - Electrons in the conduction band
- Resistance goes up as temperature goes up
  - Can be used to measure temperature
  - RTD (resitive thermal device)

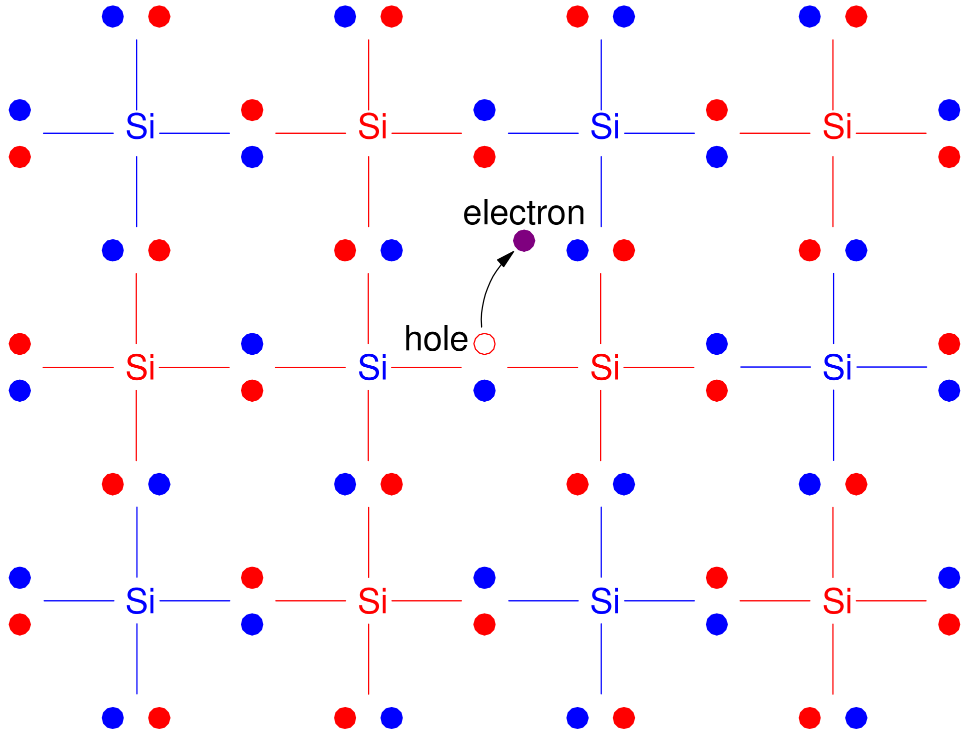
$$R = (1 + \alpha T) \cdot R_0$$

Be	a = 2.5%/C	most sensitive
Ni	a = 0.681%/C	
Fe	a = 0.651%/C	
Cu	a = 0.43%/C	
Al	a = 0.429%/C	
Pt	a = 0.385%/C	
Nd	a = 0.16%/C	least sensitive

Silicon

Column IVA of the periodic chart

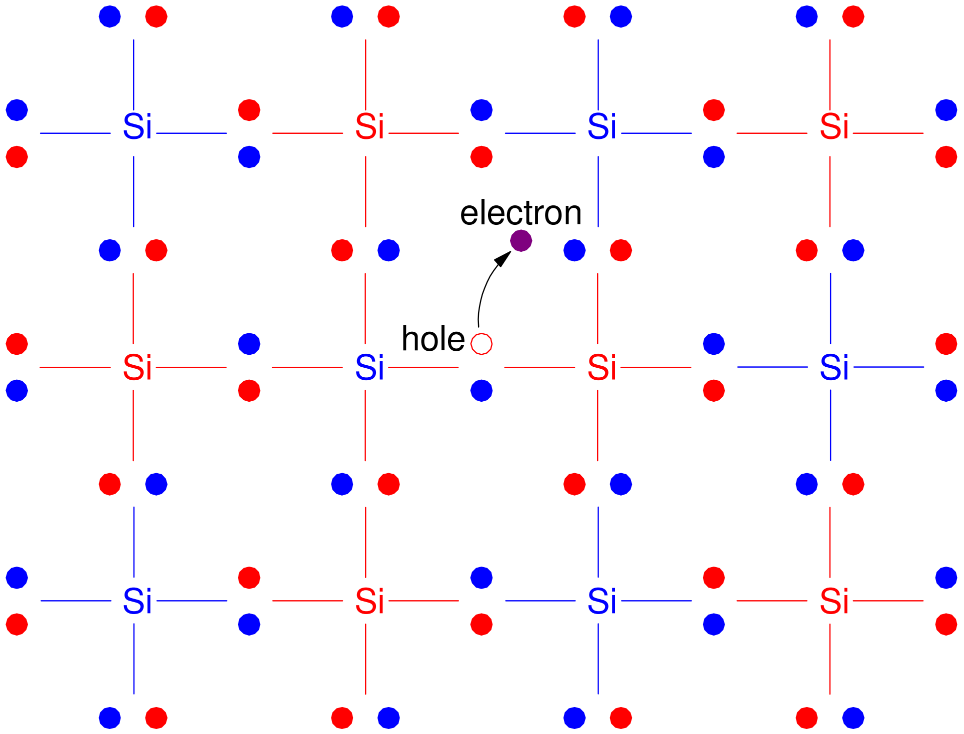
- 4 electrons in its outer shell
- Forms a covalent bond with 4 neighbors
- Resulting crystal has no free electrons
  - At 0K silicon is an insulator



Electrons and Holes

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.
- The covalent bond which is missing an electron acts like a positive charge carrier, termed a hole.



Mobility of Holes and Electrons

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

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

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

Meaning:

- n-type silicon has lower resistance than p-type silicon

or

- p-type silicon requires 2.6x heavier doping to get the same resistance

From a practical standpoint, it doesn't matter

- You can make resistors out of n-type or p-type silicon
- The doping concentration is so low that 2.6x isn't significant

Problem: Find the resitivity of Silicon at 300K:

Solution: The conductivity is due to electrons and holes, which are both $1.5x10^{10}$ / cc

$$\sigma = n_i q(\mu_n + \mu_p) = (1.66 \cdot 10^{11} cm^{-3})(1.6x10^{-19} C)(1300 + 500)\frac{cm^2}{Vs}$$

$$\sigma = 4.78x10^{-5} \frac{1}{\Omega cm}$$

$$\rho = \frac{1}{\sigma} = 20,917\Omega \cdot cm$$

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:

$$R = \frac{\rho L}{A} = \frac{(20{,}917\Omega \cdot cm)(0.1cm)}{(0.05cm)^2} = 836k\Omega$$

Thermal Properties of Silicon

Above 0K, some electrons can escape the covalent bond:

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

- EG is the energy gap at 0K
- k is Boltzmann's constant
- $A_0 = 2.36 \cdot 10^{33}$

For Silicon:

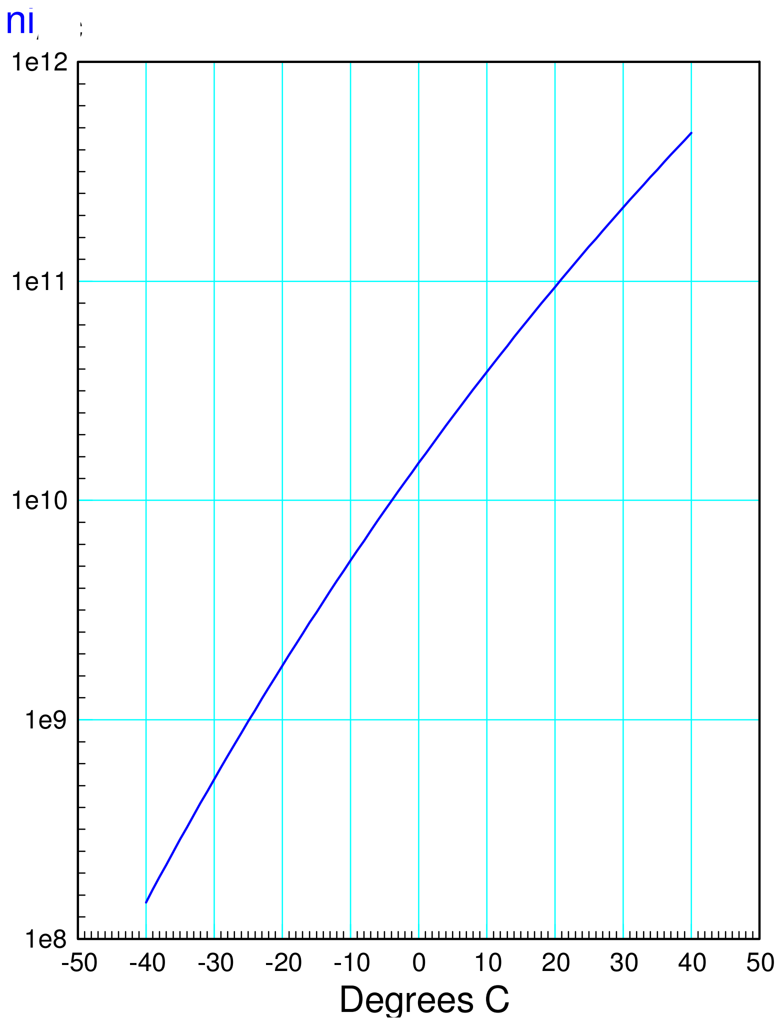
$$E_G \approx 1.2 - 0.00036T \quad \text{eV}$$

or at 300K,

$$E_G = 1.1eV$$

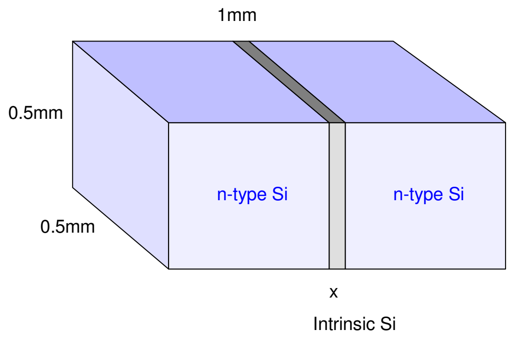
$$k = 8.617343 \times 10^{-5} \ \frac{eV}{K}$$

$$np = n_i^2 \approx (1.70 \cdot 10^{11})^2$$



Thermistors:

Problem: Design an 0402 resistor with Silicon doped at 10^{16}/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,

$$\rho = \frac{1}{\sigma} = 20,917\Omega \cdot cm$$

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

$$1000 = \frac{(20,917\Omega \cdot cm)(x)}{(0.05cm)^2}$$

$$x = 119\mu m$$

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:

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

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

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

$$E_G = 1.1eV$$

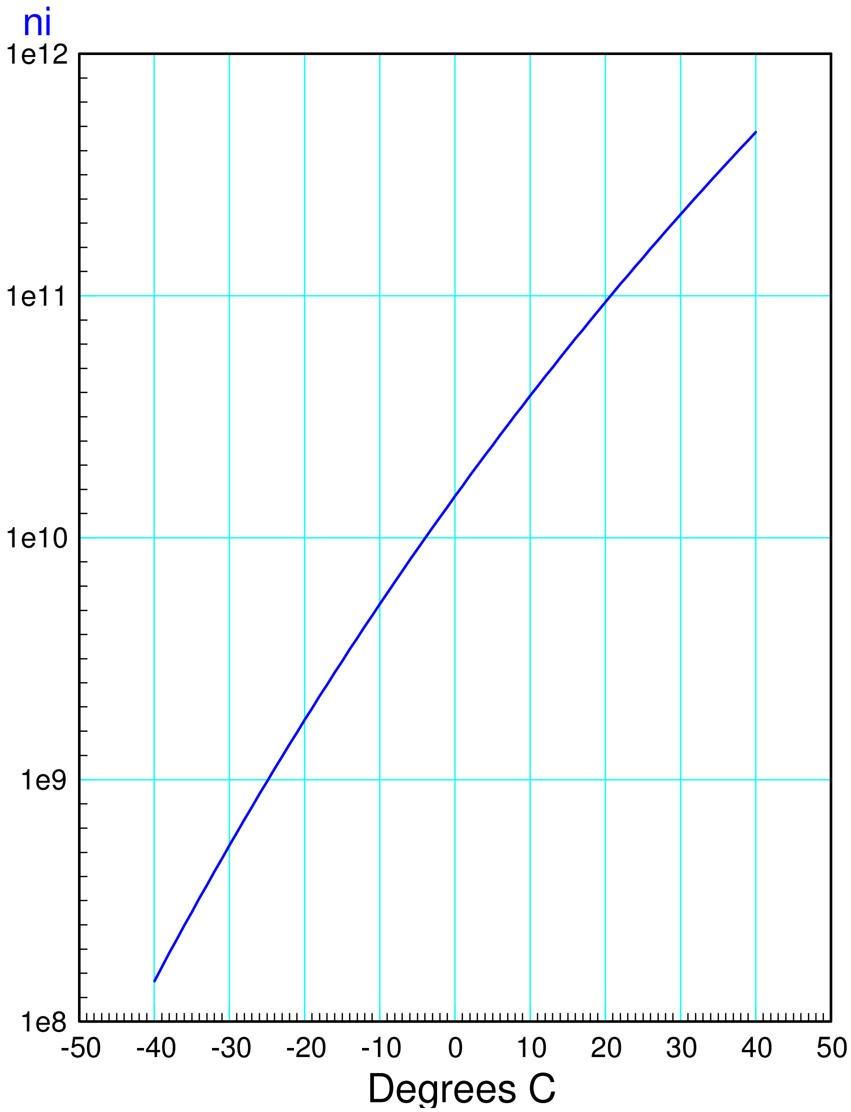
$$k = 8.617343 \times 10^{-5}\ \frac{eV}{K}$$

In Matlab you can plot the resistance vs. temperature:

- The intrinsic carrier concentration, ni, varies considerable from -40C to +40C.

```
C = [-40:40]';
T = C + 273;
Ao = 2.36e33;
Eg = 1.2 - 0.00036*T;
k = 8.617343e-5;
ni = sqrt( Ao*(T.^3).*exp(-Eg./(k*T)));

plot(C,ni)
xlabel('Celsius');
ylabel('ni')
```

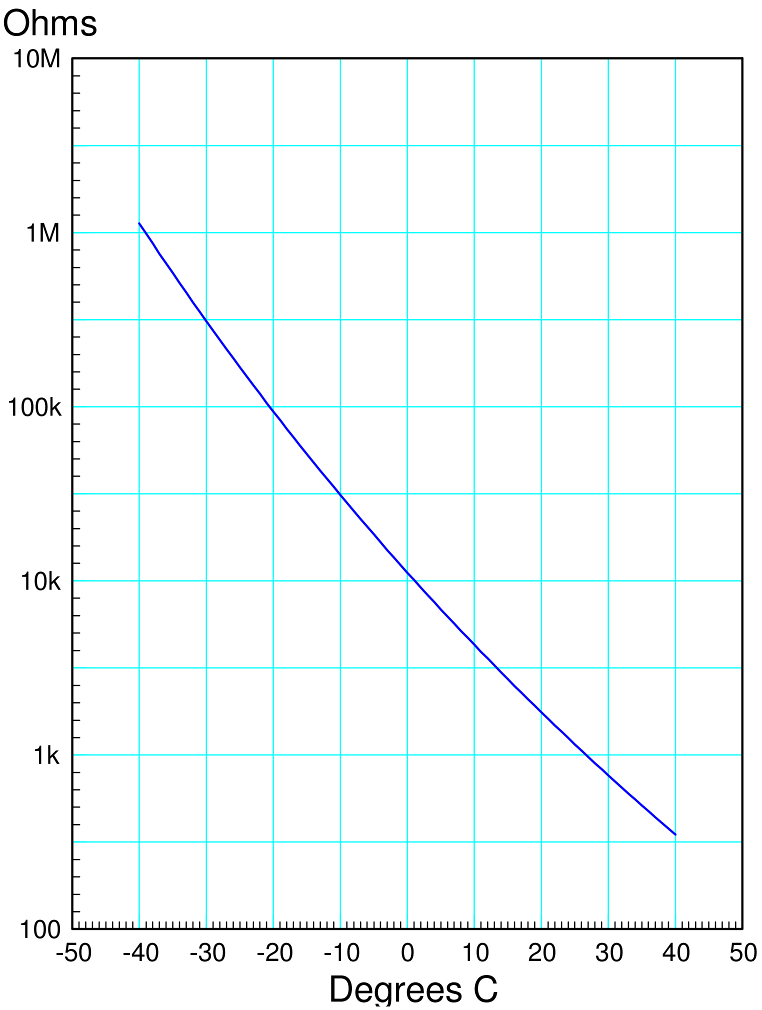


Likewise, the resistance across this 119um strip of Silicon varies with temperature:

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

```
sigma = (1.6e-19)*(ni)*(1800);
p = 1 ./ sigma;
R = p*(119e-6) / (0.05^2);

plot(C,R)
xlabel('Celsius');
xgrid(5)
ylabel('Ohms');
```



Doping

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

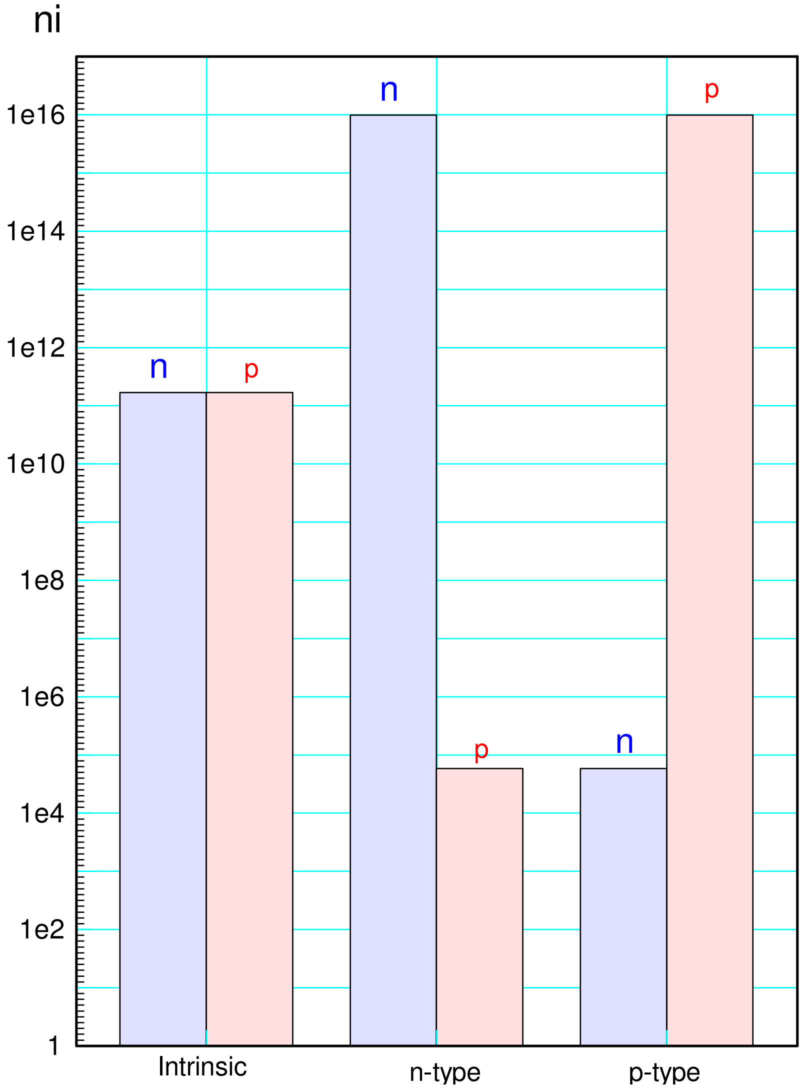
$$np = n_i^2$$

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:

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

with just a few due to thermal electrons:

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



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:

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

$$\sigma \approx qn\mu_n = (1.6x10^{-19}C)(10^{16} \cdot 1300)\frac{cm^2}{Vs} + 2.08\frac{1}{\Omega cm}$$

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

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

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 R = 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.

Summary

Semiconductors are different than metals

- Their resistance drops as temperature increases
  - Allows you to build thermistors
- They have two types of charge carriers
  - electrons
  - holes

With doping, you can

- Set the resistance of a piece of silicon
- Make it an n-type semiconductor
  - Almost all of the charge carriers are electrons
- Make it a p-type semiconductor
  - Almost all of the charge carriers are holes