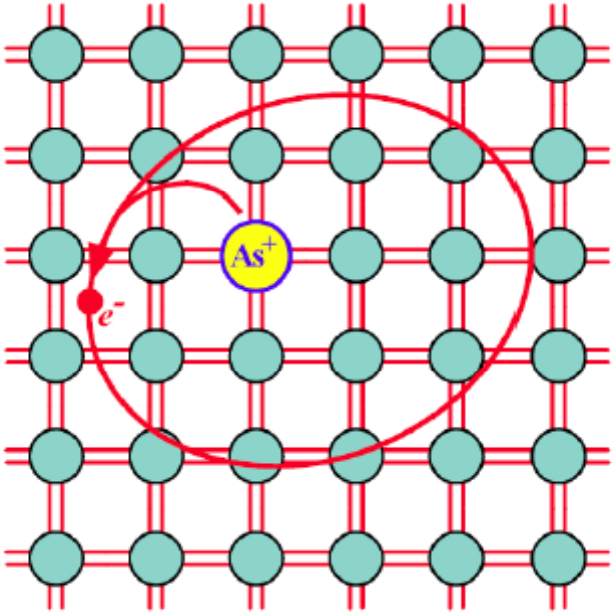
Extrinsic Semiconductors

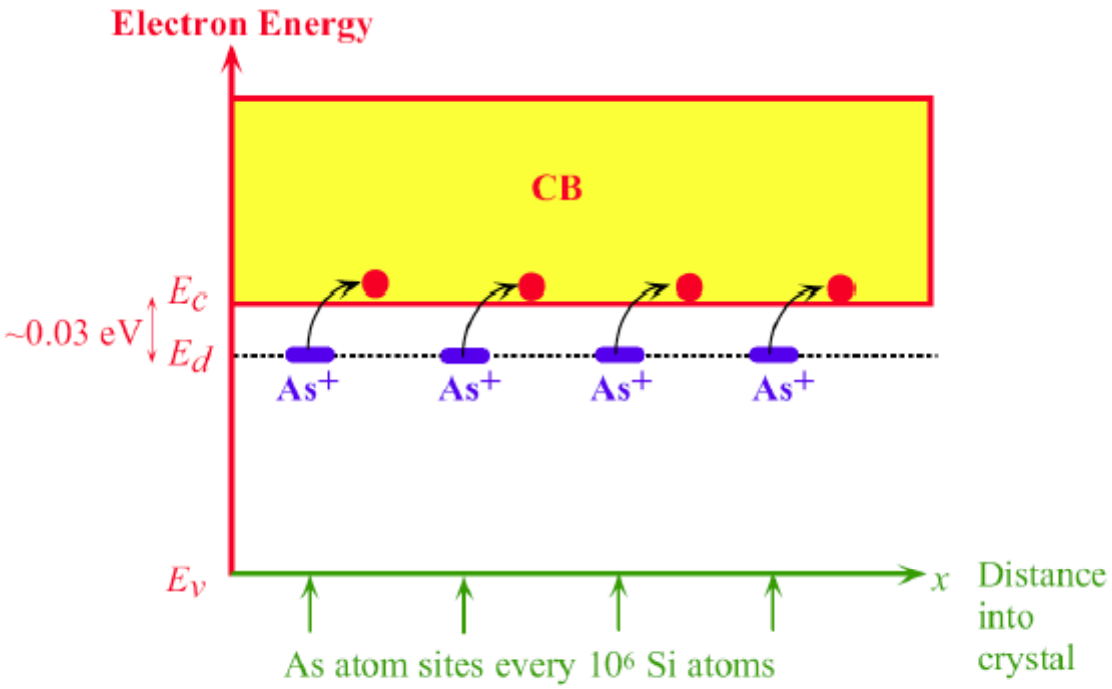
n-type SC



Arsenic-doped Si crystal.
The four valence electrons of As allow it to bond just like Si, but the fifth electron is left orbiting the As site. The energy required to release the free fifth electron into the CB is very small.

Fig 5.9

Extrinsic Semiconductors



Energy band diagram for an n-type Si doped with 1 ppm As. There are donor energy levels just below E_c around As^+ sites. Fig 5.10

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Extrinsic Semiconductors

N-type Conductivity

$$\sigma = eN_d\mu_e + e\left(\frac{n_i^2}{N_d}\right)\mu_h \approx eN_d\mu_e \qquad 5.16$$

$$\boxed{\sigma = eN_d\mu_e \qquad 5.16}$$

e = electronic charge

N_d = donor atom concentration in the crystal

μ_e = electron drift mobility,

n_i = intrinsic concentration,

μ_h = hole drift mobility

Extrinsic Semiconductors

Occupation Probability at a Donor

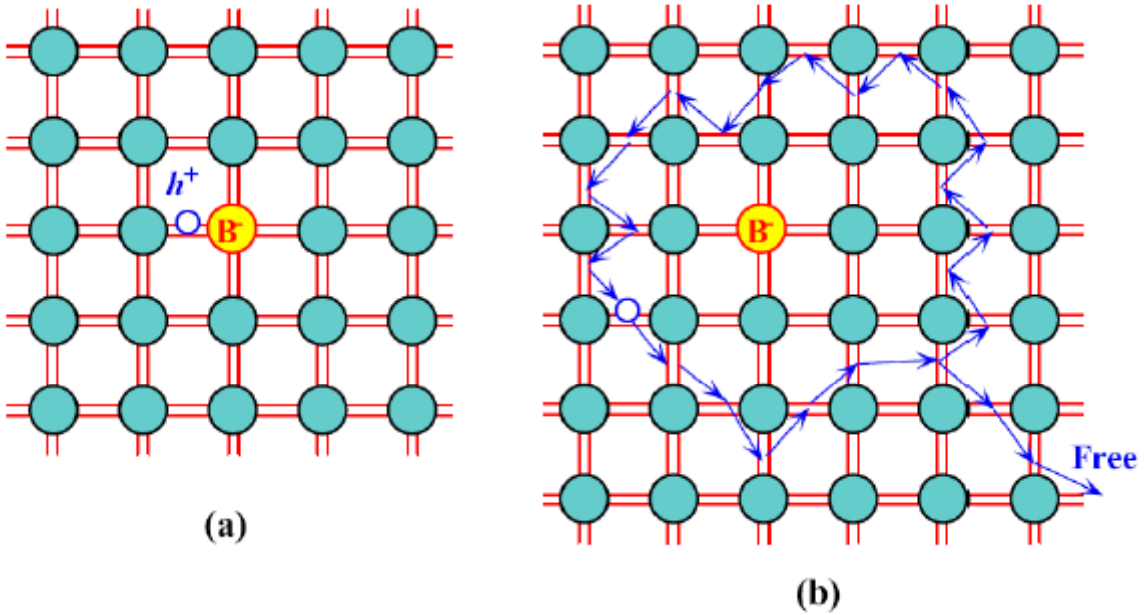
$$f_d(E_d) = \frac{1}{1 + \frac{1}{2}\exp\left[\frac{(E_d - E_F)}{kT}\right]} \qquad 5.17$$

$f_d(E_d)$ = probability of finding an electron in a state with energy E_d at a donor

E_d = energy level of donor

½ comes from the fact that donor can only take one electron

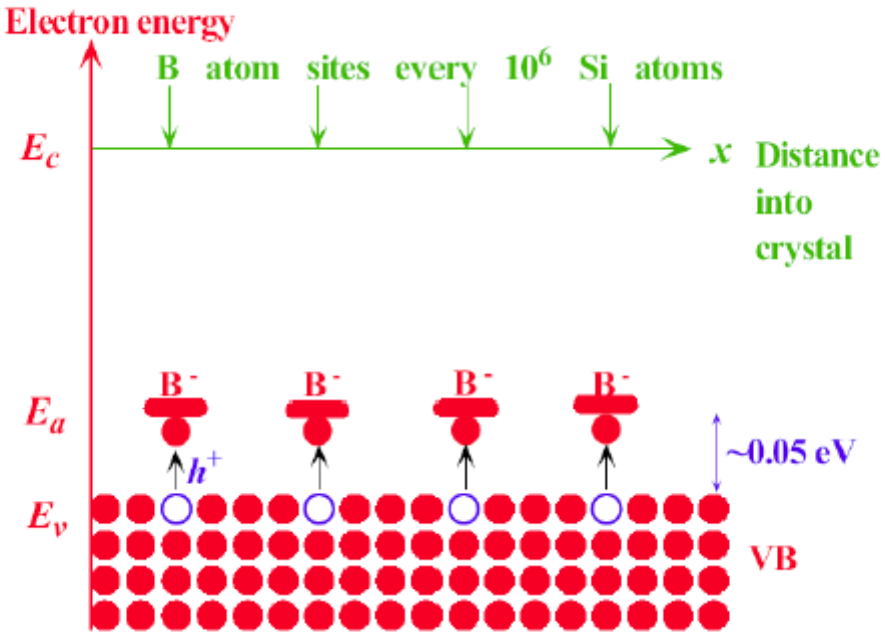
Extrinsic Semiconductors



Boron-doped Si crystal.
B has only three valence electrons. When it substitutes for a Si atom, one of its bonds has an electron missing and therefore a hole, as shown in (a). The hole orbits around the B^- site by the tunneling of electrons from neighboring bonds, as shown in (b). Eventually, thermally vibrating Si atoms provide enough energy to free the hole from the B^- site into the VB, as shown.

Fig 5.11

Extrinsic Semiconductors



Energy band diagram for a *p*-type Si doped with 1 ppm B. There are acceptor energy levels E_a just above E_v around B^- sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB. Fig 5.12

Extrinsic Semiconductors

P-type Conductivity

$$\sigma = eN_a\mu_h + e\left(\frac{n_i^2}{N_a}\right)\mu_e \approx eN_a\mu_h$$

$$\boxed{\sigma = eN_a\mu_h}$$

e = electronic charge
N_a = acceptor atom concentration in the crystal
μ_h = hole drift mobility,
n_i = intrinsic concentration,
μ_e = electron drift mobility

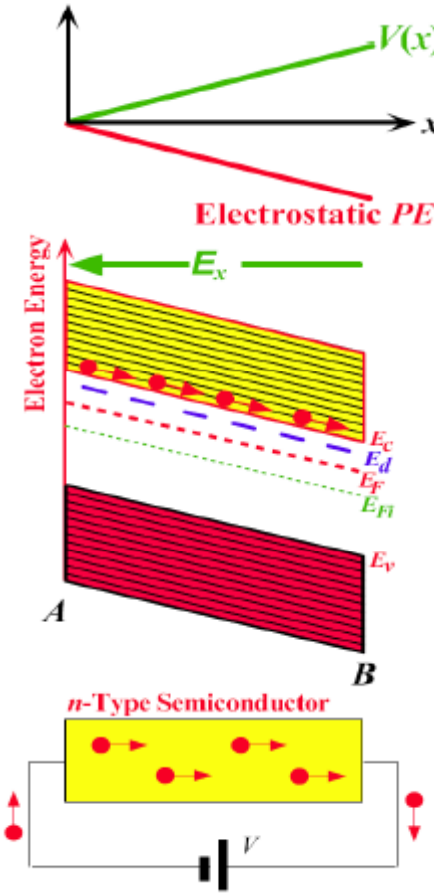
Extrinsic Semiconductors

Table 5.2 Examples of donor and acceptor ionization energies (eV) in Si

Donors			Acceptors		
P	**As**	**Sb**	**B**	**Al**	**Ga**
0.045	0.054	0.039	0.045	0.057	0.072

For donors it is energy below CB
For acceptors it is energy above VB

Extrinsic Semiconductors



Band Bending

Energy band of n-type SC connected to a voltage

Energy band diagram of an *n*-type semiconductor connected to a voltage supply of *V* volts.

The whole energy diagram tilts because the electron now also has an electrostatic potential energy.

Fig 5.13

Extrinsic Semiconductors

Compensation Doping

More donors than acceptors $N_d - N_a >> n_i$

$$n = N_d - N_a \qquad p = \frac{n_i^2}{n} = \frac{n_i^2}{N_d - N_a}$$

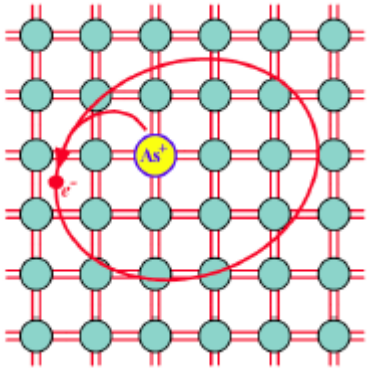
More acceptors than donors $N_a - N_d >> n_i$

$$p = N_a - N_d \qquad n = \frac{n_i^2}{p} = \frac{n_i^2}{N_a - N_d}$$

Extrinsic Semiconductors

Binding energy of electron in H-atom

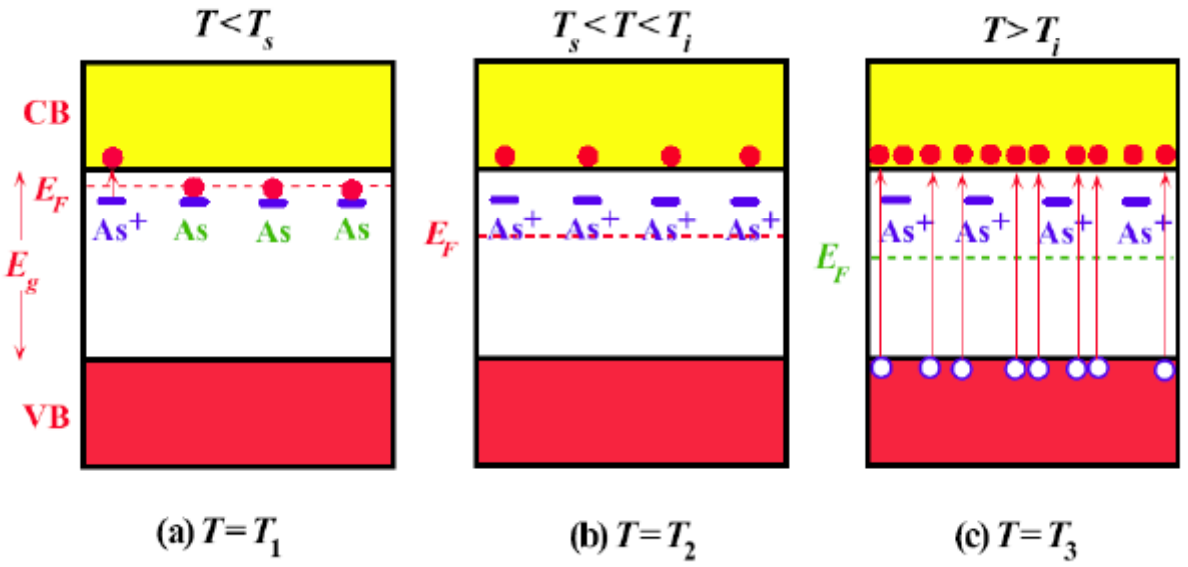
$$E_b = -E_1 = \frac{m_e^* e^4}{8\varepsilon_o^2 h^2} = 13.6 \text{ eV}$$



$$E_b^{Si} = \frac{m_e^* e^4}{8\varepsilon_o^2 \varepsilon_r^2 h^2} = 13.6 \text{ eV}\left(\frac{m_e^*}{m_e}\right)\left(\frac{1}{\varepsilon_r^2}\right) \qquad 5.15$$

For Si $\varepsilon_r = 11.9$ and $\frac{m_e^*}{m_e} = \frac{1}{3}$ so $E_b^{Si} \approx 0.032eV$

Temperature Dependence of Conductivity



(a) Below T_s, the e^{-1} conc. is controlled by the ionization of the donors.
(b) Between T_s and T_i, the e^{-1} conc. = concentration of donors since they would all have ionized.
(c) At high T, thermally generated electrons from the VB exceed the # # of e^{-1} from ionized donors and the SC behaves as if intrinsic.

Fig 5.14

Temperature Dependence of Conductivity

5.3.1 Carrier Concentration

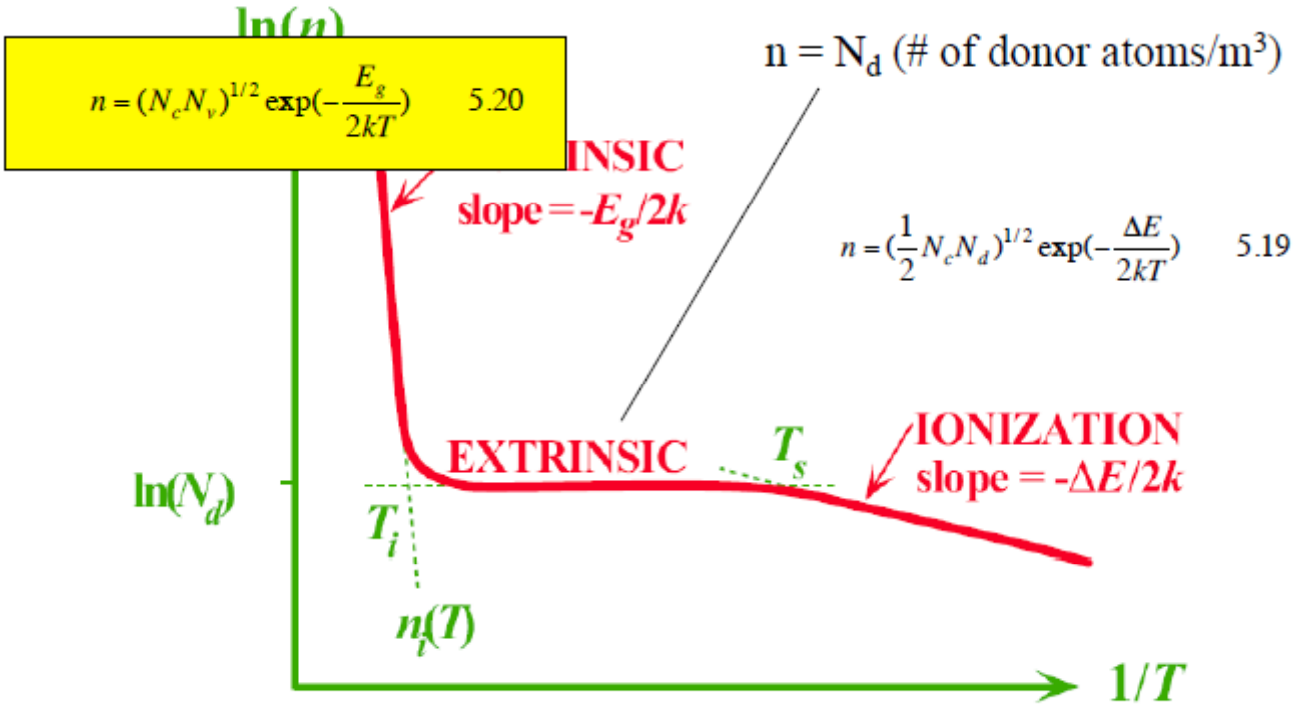
Low Temperature Regime:

$$n = \left(\frac{1}{2} N_c N_d\right)^{1/2} \exp\left(-\frac{\Delta E}{2kT}\right) \qquad 5.19$$

Compare to intrinsic case:

$$n = \left(N_c N_v\right)^{1/2} \exp\left(-\frac{E_g}{2kT}\right) \qquad 5.20$$

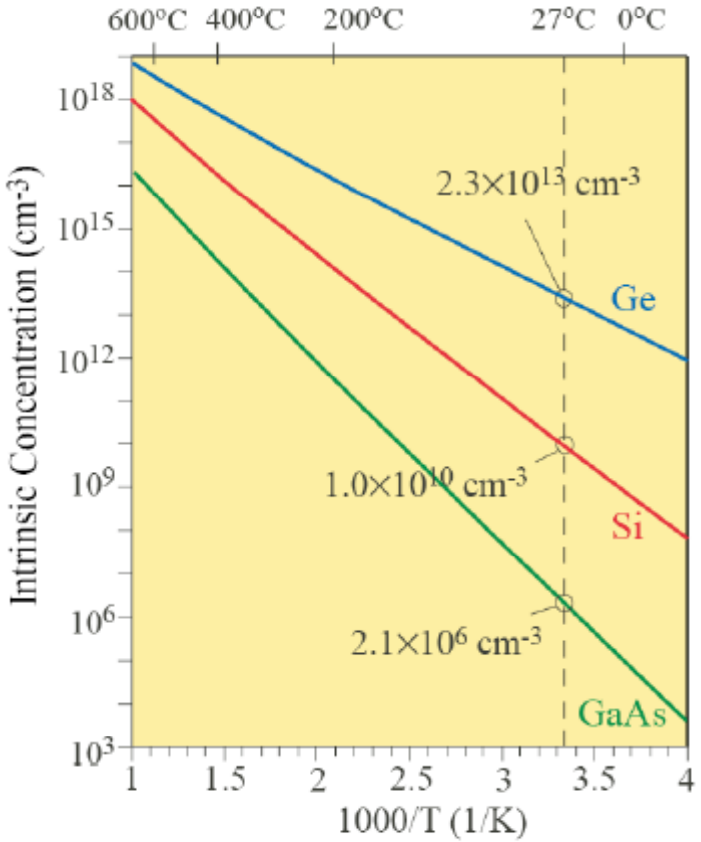
Temperature Dependence of Conductivity



The temperature dependence of the electron concentration in an *n*-type semiconductor.

Fig 5.15

Temperature Dependence of Conductivity



The temperature dependence of the intrinsic concentration

Fig 5.16

Temperature Dependence of Conductivity

5.3.2 Drift Mobility and Impurity Dependence

$$\mu = \frac{e\tau}{m_e^*} \qquad 5.21$$

$$\tau = \frac{1}{S v_{th} N_S} \qquad 5.22$$

S is the cross-section area of the scatters, v_{th} = mean speed of electrons, aka as thermal velocity
N_s is number of scatters per unit volume.

$$S = \pi a^2$$

$$\frac{1}{2} m_e^* v_{th}^2 = \frac{3}{2} \mathrm{kT}$$

Temperature Dependence of Conductivity

Lattice Vibration Scattering Limited Mobility

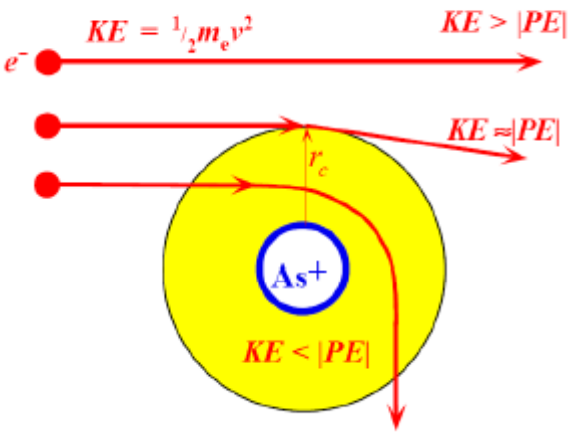
$$\tau_L = \frac{1}{(\pi a^2) v_{th} N_S} \quad \alpha \quad \frac{1}{(T)(T^{1/2})} \quad \alpha \quad T^{-3/2}$$

$$\tau_L \ \alpha \ T^{-3/2} \qquad 5.23$$

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Temperature Dependence of Conductivity

Scattering of electrons by an ionized impurity.



$$|PE| = \left(\frac{e^2}{4\pi\varepsilon_o\varepsilon_r r}\right)$$

It is only when KE ≈ PE that electron will get scattered. So

$$3/2kT = |PE(r_c)| = \left(\frac{e^2}{4\pi\varepsilon_o\varepsilon_r r_c}\right)$$

$$r_c = \frac{e^2}{6\pi\varepsilon_o\varepsilon_r kT} \qquad S = \pi r_c^2 = \frac{\pi e^4}{(6\pi\varepsilon_o\varepsilon_r kT)^2} \;\alpha\; T^{-2}$$

Temperature Dependence of Conductivity

Ionized Impurity Scattering Limited Mobility

$$\tau_L = \frac{1}{S v_{th} N_I} \quad \alpha \quad \frac{1}{(T^{-2})(T^{1/2}) N_I} \quad \alpha \quad \frac{T^{3/2}}{N_I}$$

$$\mu_I \propto \frac{T^{3/2}}{N_I} \qquad 5.24$$

μ_I = ionized impurity scattering limited mobility

Temperature Dependence of Conductivity

Effective or Overall Mobility

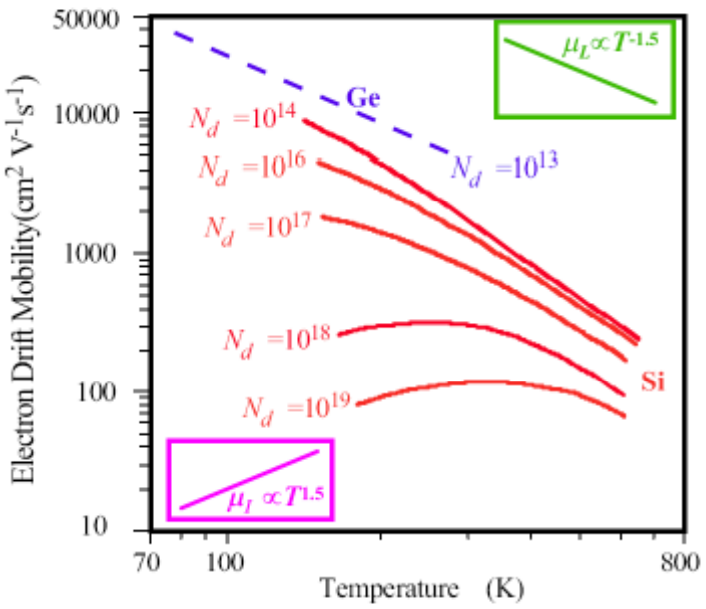
$$\frac{1}{\mu_e} = \frac{1}{\mu_I} + \frac{1}{\mu_L} \qquad 5.25$$

μ_e = effective drift mobility

μ_I = ionized impurity scattering limited mobility

μ_L = lattice vibration scattering limited mobility

Temperature Dependence of Conductivity



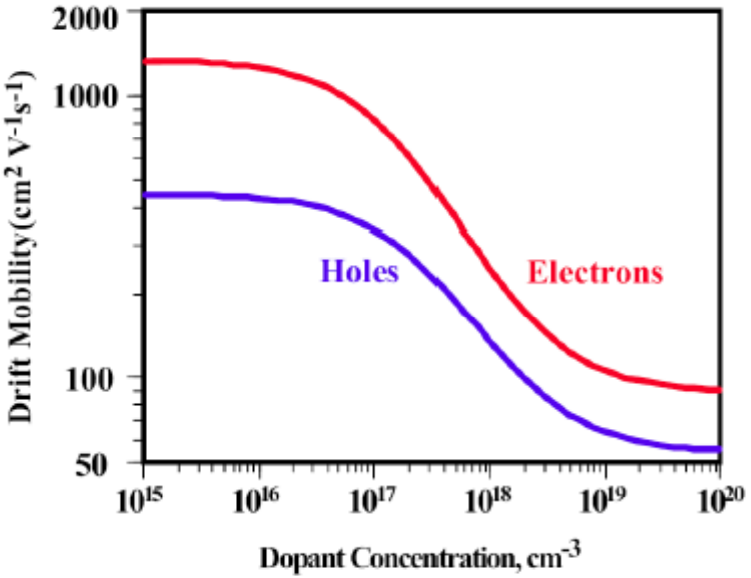
Lets look at experimental results. Note LOG-LOG

In English: At the lowest T, increasing the T increases the v_{th} of electrons so as to not be affected by impurities.

BUT , further increases in T causes the atoms to vibrate more and scatter more. So mobility decreases again.

Log-log plot of drift mobility versus temperature for *n*-type Ge and *n*-type Si samples. Various donor concentrations for Si are shown. N_d are in cm^{-3}. The upper right inset is the simple theory for lattice limited mobility, whereas the lower left inset is the simple theory for impurity scattering limited mobility.

Temperature Dependence of Conductivity



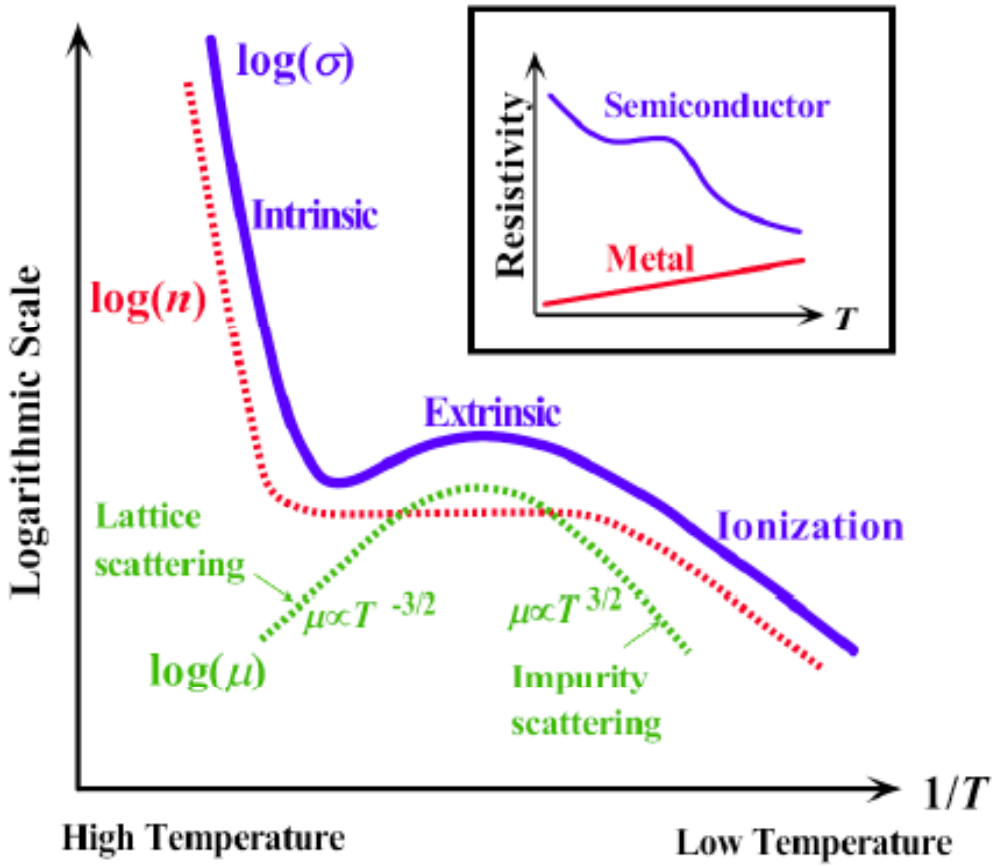
More LOG-LOG experimental results

Increasing the dopant concentration is NOT good for mobility!

The variation of the drift mobility with dopant concentration in Si for electrons and holes at 300 K.

Fig 5.19

Temperature Dependence of Conductivity



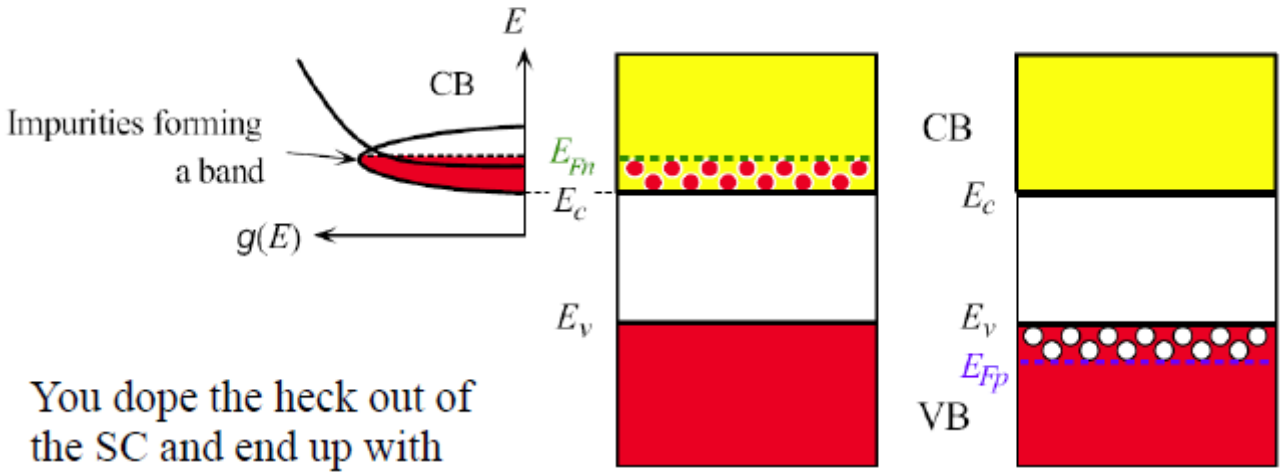
Temperature Dependence of Conductivity

For n-type extrinsic SC

- At very low temperatures the conductivity is quite low because there are few electrons in the CB. Impurity atoms are holding on to their electrons.
- At intermediate temperatures, all the dopant atoms donate their electrons to CB and conductivity saturates.
- At very high temperatures, the conductivity is very high because Si-Si bonds are being broken.
- Mobilities depend on dopant concentration. For low dopant concentrations mobility is only affected by phonons.
- When dopant concentrations are high they can trap electrons at lower temperatures. The trapping probability, however, deceases with increasing T.
- All these conclusions apply to p-type SC as well.

Temperature Dependence of Conductivity

Degenerate Semiconductors



You dope the heck out of the SC and end up with an impurity band. Then Boltzmann statistics no longer valid. SC acts as a metal, with $\rho \alpha T$.

(a) Degenerate *n*-type SC. Large number of donors form a band that overlaps the CB.
(b) Degenerate *p*-type semiconductor.

Fig 5.21