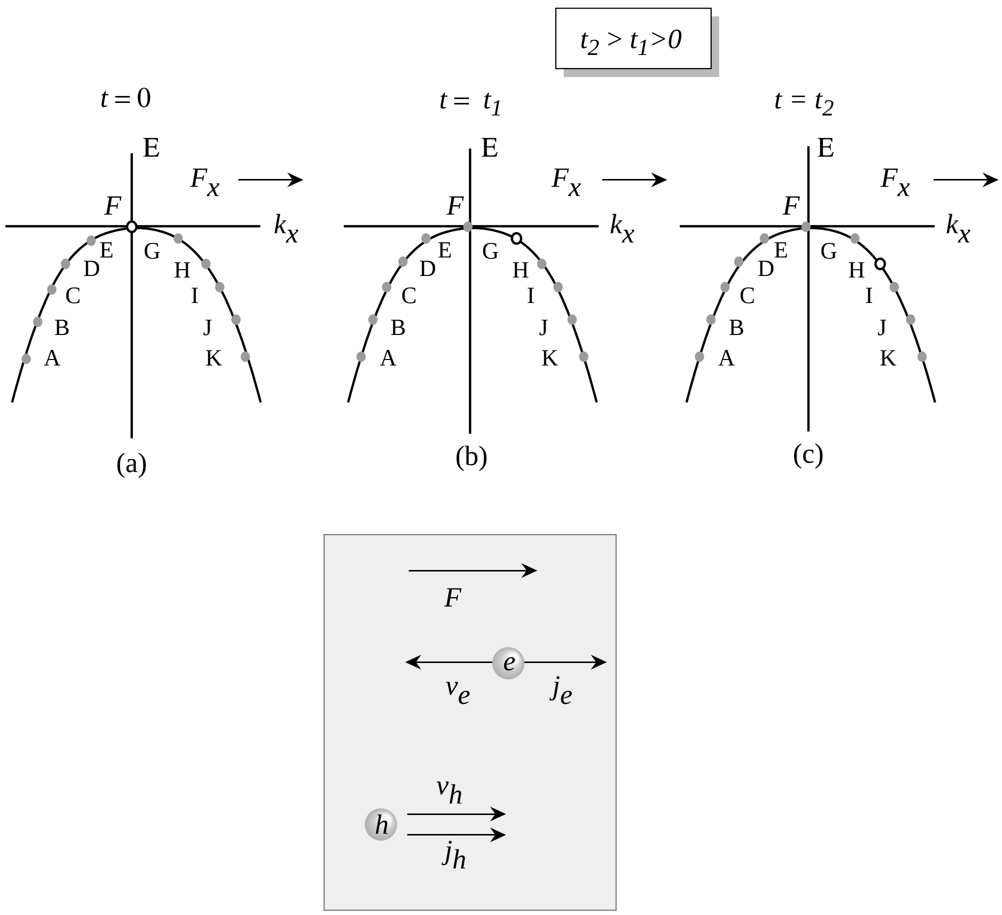
Chapter 2

SEMICONDUCTOR BANDSTRUCTURE

HOLES IN SEMICONDUCTORS: HOW DO HOLES MOVE?

Holes behave *as if* they carry a positive charge.

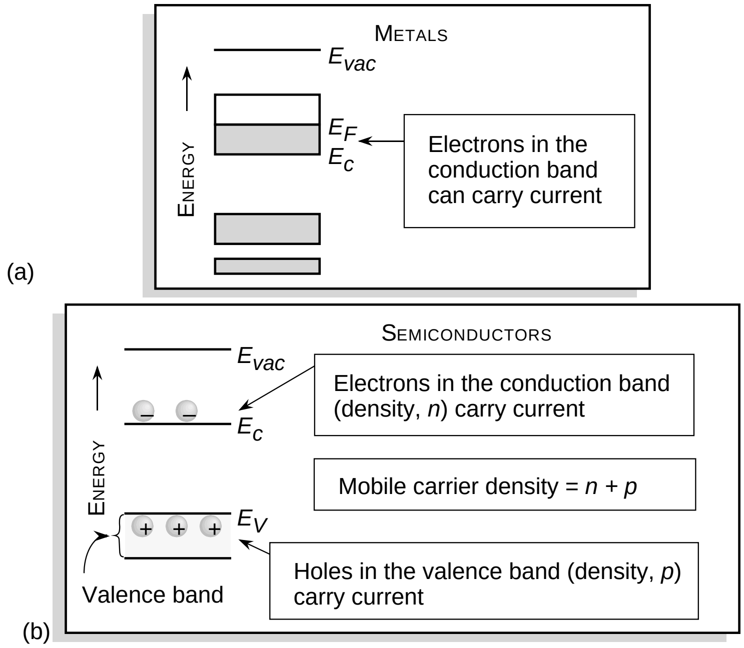


(d)

The movement of an empty electron state, i,e,. a hole under an electric field. The electrons move in the direction opposite to the electric field so that the hole moves in the direction of the electric field thus behaving as if it were positively charged, as shown in (a), (b), and (c). (d) The velocities and currents due to electrons and holes. The current flow is in the same direction, even though the electron and holes have opposite velocities. The electron effective mass in the valence band is negative, but the hole behaves as if it has a positive mass.

FREE CARRIERS IN SEMICONDUCTORS: INTRINSIC CARRIERS

In semiconductors, at finite temperatures, there are electrons in the conduction band and holes in the valence band.



(a) A schematic showing allowed energy bands in electrons in a metal. The electrons occupying the highest partially occupied band are capable of carrying current. (b) A schematic showing the valence band and conduction band in a typical semiconductor. In semiconductors only electrons in the conduction band holes in the valence band can carry current.

For small electron *(n)*, hole *(p)* densities we can use Boltzmann approximation:

$$n = N_c \exp\left[(E_F - E_c)/k_BT\right]$$

where

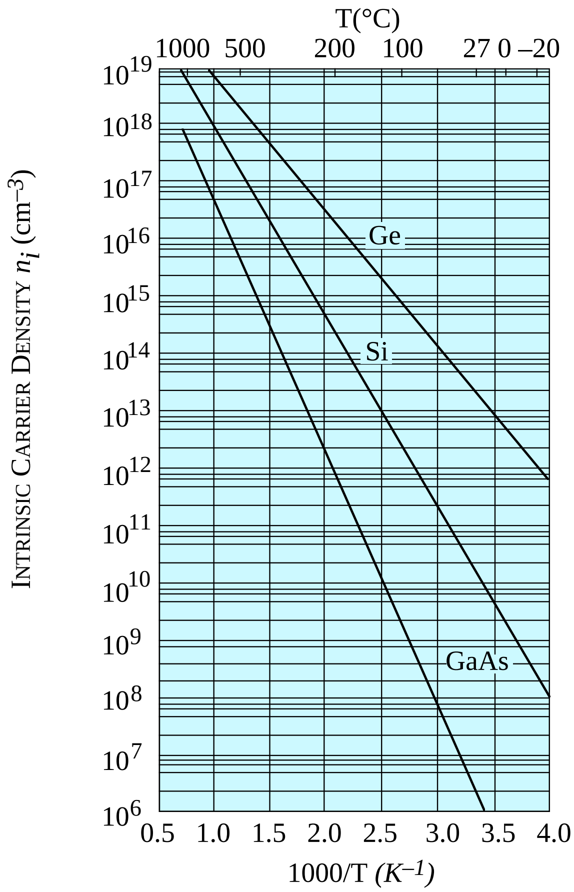
$$N_c = 2\left(\frac{m_e^* k_BT}{2\pi\hbar^2}\right)^{3/2}$$

$$p = 2\left(\frac{m_h^* k_BT}{2\pi\hbar^2}\right)^{3/2} \exp\left[(E_v - E_F)/k_BT\right]$$

$$= N_v \exp\left[(E_v - E_F)/k_BT\right]$$

Intrinsic case: $$n_i = p_i = 2\left(\frac{k_BT}{2\pi\hbar^2}\right)^{3/2}(m_e^* m_h^*)^{3/4} \exp(-E_g/2k_BT)$$

INTRINSIC CARRIER DENSITIES FOR SOME SEMICONDUCTORS



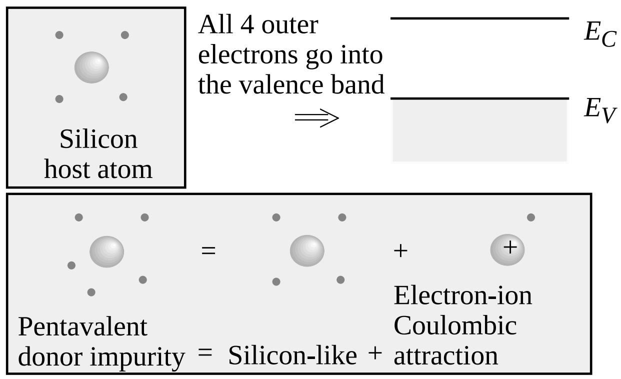
Temperature dependence of n_i, p_i in Si, Ge, GaAs

MATERIAL	CONDUCTION BAND EFFECTIVE DENSITY (N_C)	VALENCE BAND EFFECTIVE DENSITY (N_V)	INTRINSIC CARRIER CONCENTRATION ($n_i = p_i$)
Si (300 K)	2.78×10^{19} cm^{-3}	9.84×10^{18} cm^{-3}	1.5×10^{10} cm^{-3}
Ge (300 K)	1.04×10^{19} cm^{-3}	6.0×10^{18} cm^{-3}	2.33×10^{13} cm^{-3}
GaAs (300 K)	4.45×10^{17} cm^{-3}	7.72×10^{18} cm^{-3}	1.84×10^{6} cm^{-3}

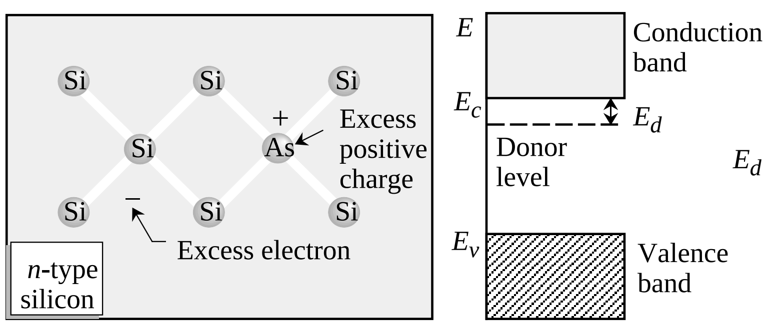
Effective densities and intrinsic carrier concentrations of Si, Ge and GaAs. The numbers for intrinsic carrier densities are the accepted values even though they are smaller than the values obtained by using the equations derived in the text.

DOPING OF SEMICONDUCTORS: DONORS AND ACCEPTORS

If an impurity atom replaces a host semiconductor atom in a crystal it could donate (donor) an extra electron to the conduction band or it could accept (acceptor) an electron from the valence band producing a hole.



A schematic showing the approach one takes to understand donors in semiconductors. The donor problem is treated as the host atom problem together with a Coulombic interaction term. The silicon atom has four "free" electrons per atom. All four electrons are contributed to the valence band at 0 K. The dopant has five electrons out of which four are contribted to the valence band, while the fifth one can be used for increasing electrons in the conducton band.



$$E_d = E_c - 13.6\left(\frac{m^*}{m_o}\right)\left(\frac{\varepsilon_o}{\varepsilon_s}\right)^2 \text{eV}$$

Arsenic (As) atom donates one electron to the conduction band to produce an *n*-type silicon

Charges associated with an arsenic impurity atom in silicon. Arsenic has five valence electrons, but silicon has only four valence electrons. Thus four electrons on arsenic form tetrahedral covalent bonds similar to silicon, and the fifth electron is available for conduction. The arsenic atom is called a donor because when ionized it donates an electron to the conduction band.

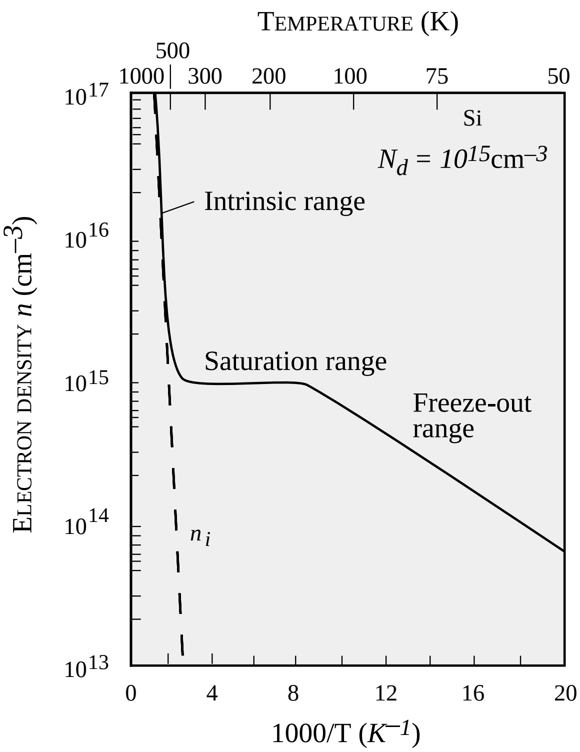
FREE CARRIERS IN DOPED SEMICONDUCTORS

If electron (hole) density is measured as a function of temperature in a doped semiconductor, one observes three regimes:

Freezeout: Temperature is too small to ionize the donors (acceptors), i.e., $k_BT < E_C - E_D$ ($k_BT < E_D - E_V$).

Saturation: Most of the donors (acceptors) are ionzed.

Intrinsic: Temperature is so high that n_i > doping density.



Electron density as a function of temperature for a Si sample with donor impurity concentration of 10^{15} cm^{-3}. It is preferable to operate devices in the saturation region where the free carrier density is approximately equal to the dopant density.

It is not possible to operate devices in the intrinsic regime, since the devices always have a high carrier density that cannot be controlled by electric fields.
$\longrightarrow$ every semiconductor has an upper temperature beyond which it cannot be used in devices. The larger the bangap, the higher the upper limit.