Intrinsic Semiconductor

mistake

$$\boxed{{n_i}^2 = np = N_C N_V exp(-E_G/kT)}$$

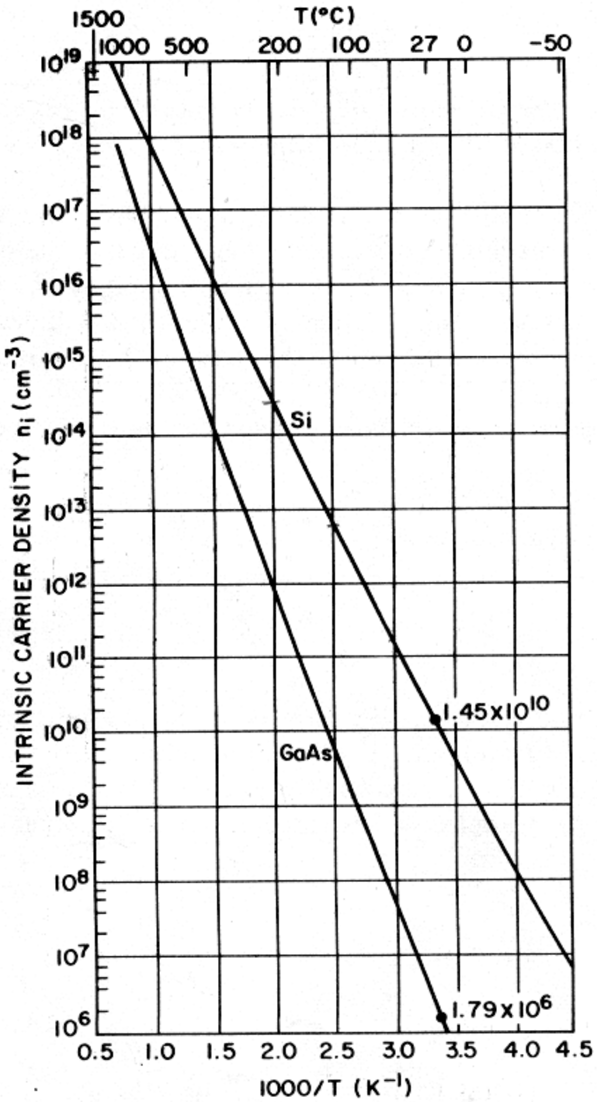
$$\frac{N_C}{N_V} = \frac{e^{2(E_C-E_F)/kT}}{e^{E_G/kT}}$$

$$n_i = \underbrace{N_C}_{\propto T^{3/2}} e^{-(E_c-E_F)/kT} = \boxed{N_C \left(\frac{m_h^*}{m_e^*}\right)^{3/4} e^{-E_G/2kT}}$$

a plot of $\ln(n_i T^{-3/2})$ $vs. 1/T$
$\rightarrow$ straight line with slope of $-E_G/2k$

$$\boxed{\sigma_{\mathrm{i}} = N_C q(\frac{m_h^*}{m_e^*})^{3/4}(\mu_n + \mu_p)e^{-E_G/2kT}}$$

Note: T-dependence of N_c is ignored.



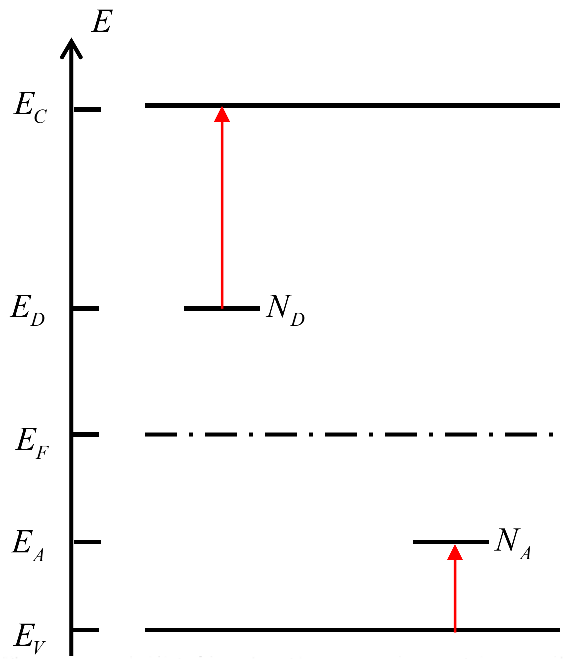
Donor and acceptor imperfections (Extrinsic Semiconductor)

- The electrical conductivity of semiconductor is controlled by thermal excitations across the band gap of the material and thermal excitation from localized imperfections.

- Substitution of atoms with different valence into a host crystal leads to shallow energy level close to either the conduction band or valence band.
  - Impurity atom with +1 valence compared to the host atom: donate electron (donor), creating an electron
  - Impurity atom with –1 valence compared to the host atom: accept electron (acceptor), creating a hole

- The wave function corresponding to an electron or a hole bound to a shallow donor or acceptor extends over many atomic dimensions so that the indeterminacy of Δx is large and the indeterminacy of Δk is small.

Donor and acceptor imperfections (Extrinsic Semiconductor)



- Ionization of a donor

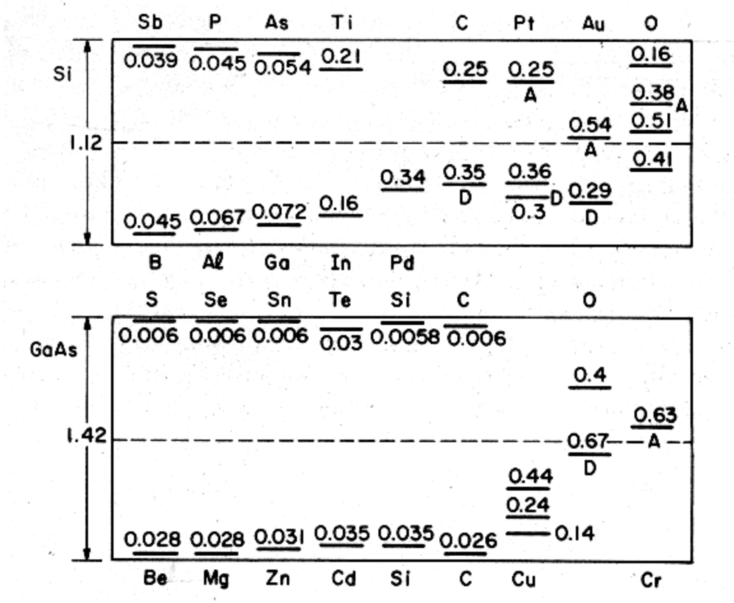
$$D^0 \rightarrow D^+ + e^-$$

Ionization energy $= (E_C - E_D)$

- Ionization of an acceptor

$$A^0 \rightarrow A^- + h^+$$

Ionization energy $= (E_A - E_V)$



Examples:

- donor: Si on a Ga site in GaAs, P on a Si site in Si,
- Acceptor: Si on a As site in GaAs, Ga on a Si site in Si

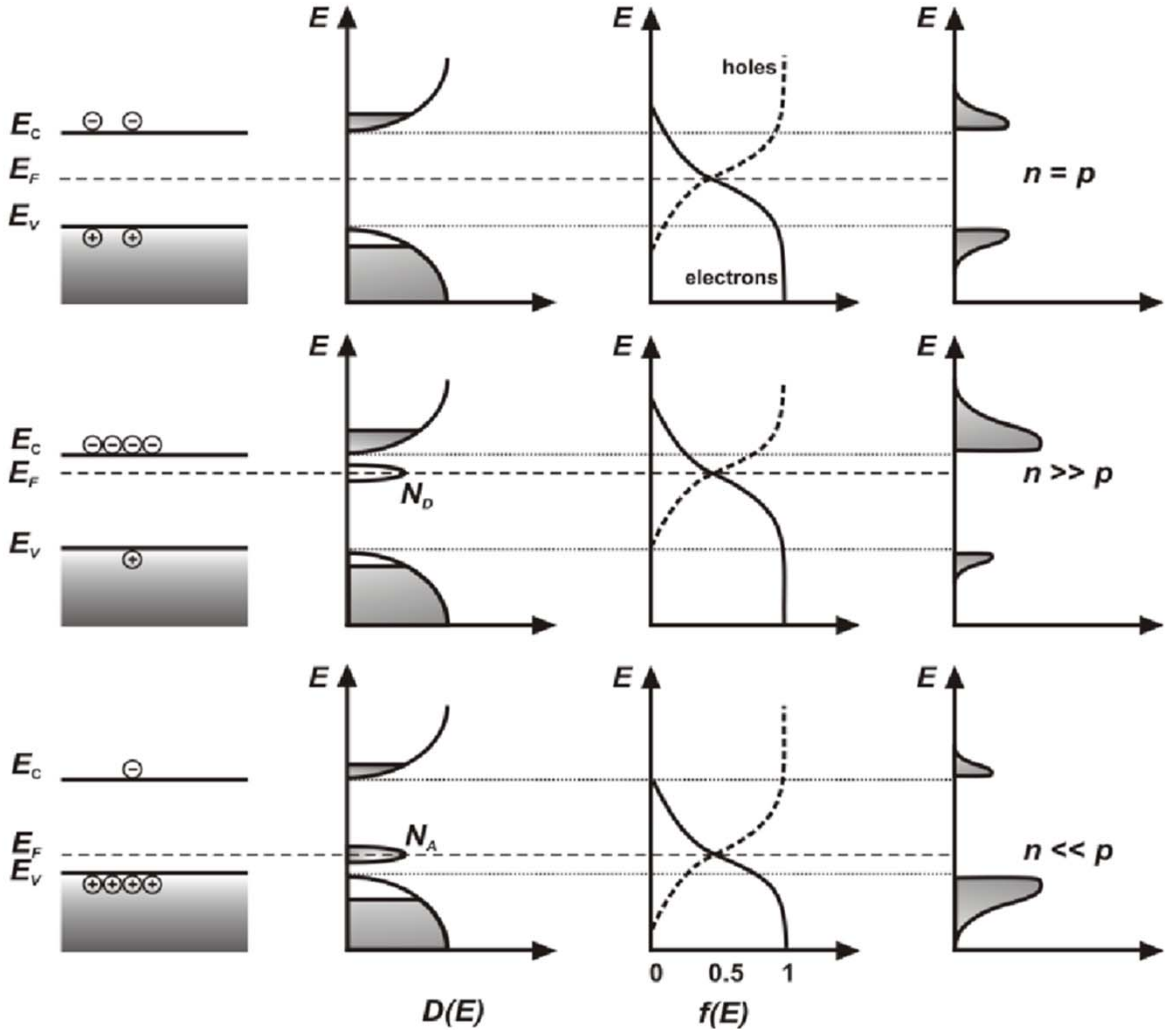
Donor and acceptor imperfections (Extrinsic Semiconductor)

Complete ionization

$$n = N_D$$

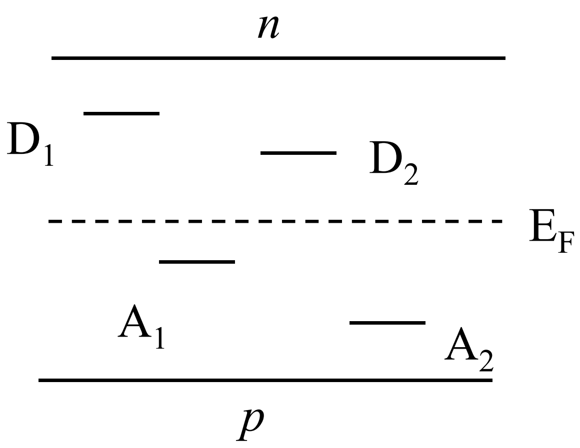
$$E_C - E_F = kT \ln\left(\frac{N_C}{N_D}\right)$$

The higher donor concentration, the smaller energy difference → Fermi level moves toward the bottom of the conduction band



Electrical Conductivity in Extrinsic Semiconductor

- Various donors and acceptors in extrinsic semiconductor



N_D: the total density of donor impurity

n_D: the density of electron-occupied donor (non-ionized donor)

N_D+: the density of the ionized donor

N_A: the total density of acceptor impurity

n_A: the density of electron-occupied acceptor (ionized acceptor)

N_A^-: the density of the ionized acceptor

- From T-dependence of E_F, T-dependence of free carrier density (n(T)) can be obtained.
- From charge neutrality condition

$$\sum_i (negative\ charge)_i = \sum_i (positive\ charge)_i$$

$$n + \sum_i (\text{electron occupied acceptors}) = p + \sum_i (\text{electron unoccupied donors})$$

$$\boxed{n + n_A = (N_D - n_D) + p}$$

Electrical Conductivity in Extrinsic Semiconductor

(1) $$n_D = N_D \left\{ \left(\frac{1}{g}\right) \exp\left[\frac{(E_D - E_F)}{kT}\right] + 1 \right\}^{-1}$$ (g: degeneracy factor)

ex) $g = 1$ for electrons in conduction and holes in valence
$g = 2$ for donor and acceptor due to two spin orientations

: when E_F decreases from donor level, n_D approaches zero.
when E_F increases toward donor level, n_D approaches N_D.

(2) $$\underbrace{(N_A - n_A)}_{\text{Hole-occupied acceptors}} = N_A \left\{ \left(\frac{1}{g}\right) \exp\left[\frac{(E_F - E_A)}{kT}\right] + 1 \right\}^{-1}$$ (g: degeneracy factor)

: when E_F increases from acceptor level, $(N_A - n_A)$ approaches zero.
when E_F decreases toward acceptor level, $(N_A - n_A)$ approaches N_A.

Positively charged donors: $$N_D{}^+ = (N_D - n_D) = N_D \left\{ 2 \exp\left[\frac{(E_F - E_D)}{kT}\right] + 1 \right\}^{-1}$$

Negatively charged acceptors: $$N_A^- = n_A = N_A \left\{ 2 \exp\left[\frac{(E_A - E_F)}{kT}\right] + 1 \right\}^{-1}$$

Electrical Conductivity in Extrinsic Semiconductor

From $n + n_A = (N_D - n_D) + p$

- For intrinsic material, $n_A = N_D - n_D = 0$

  $n = p$

- For donor only, $n_A = 0,\ p \ll n$

  $n = N_D - n_D$: At high T, all of donors are ionized, $n \rightarrow N_D$

- For acceptor only, $N_D - n_D = 0,\ n \ll p$

  $n_A = p$: At high T, all of acceptors are ionized, $p \rightarrow N_A$

- For donors and acceptors,

  (1) $N_D \gg N_A,\ p \ll n$ (assumption: all acceptors are ionized, $n_A \approx N_A$)

  $\rightarrow n + n_A = (N_D - n_D)$

  $\rightarrow$ As T increases, all donors are ionized, $n \rightarrow (N_D - N_A)$

  (2) $N_D \ll N_A,\ n \ll p$ (assumption: all donors are ionized, $(N_D - n_D) \approx N_D$)

  $\rightarrow n_A = N_D + p$

  $\rightarrow$ As T increases, all acceptors are ionized, $p \rightarrow (N_A - N_D)$

  (3) $N_D \approx N_A,\ p \approx n \approx 0$ ($\because$ At low T, donor and acceptor are dominant)

  $\rightarrow n_A = (N_D - n_D)$

Electrical Conductivity in Extrinsic Semiconductor

Temperature dependence of Fermi level for donor only,

$$n_A = 0, \quad p \ll n$$

$$n = N_D - n_D \;\rightarrow\; N_C \exp\left[-\frac{(E_C - E_F)}{kT}\right] = N_D \left\{2\exp\left[\frac{(E_F - E_D)}{kT}\right] + 1\right\}^{-1}$$

At high T extrinsic range, complete ionization of donors

$$\left(\frac{N_D g}{N_C}\right) \exp\left[\frac{(E_C - E_D)}{kT}\right] \ll 1$$

$$(E_C - E_F) = kT \ln\left(\frac{N_C}{N_D}\right) \quad \boxed{(n = N_D)}$$

$$\boxed{\sigma = N_D q \mu_n}$$

At low T extrinsic range, most donors un-ionized

$$\left(\frac{N_D g}{N_C}\right) \exp\left[\frac{(E_C - E_D)}{kT}\right] \gg 1$$

$$(E_C - E_F) = \frac{E_C - E_D}{2} + \left(\frac{kT}{2}\right) \ln\left(\frac{N_C g}{N_D}\right) \quad (n \ll N_D)$$

$$\boxed{n = \left(\frac{N_C N_D}{g}\right)^{1/2} \exp\left[-\frac{(E_C - E_D)}{2kT}\right]}$$

$$\boxed{\sigma = \left(\frac{N_C N_D}{g}\right)^{1/2} q\mu_n \exp\left[-\frac{(E_C - E_D)}{2kT}\right]}$$

Electrical Conductivity in Extrinsic Semiconductor

For intrinsic semiconductor

$$n_i = N_C \left(\frac{m_h^*}{m_e^*}\right)^{3/4} \exp\left[-\frac{E_G}{2kT}\right] \text{ and } \sigma_i = N_C q \left(\frac{m_h^*}{m_e^*}\right)^{3/4} (\mu_n + \mu_p) \exp\left[-\frac{E_G}{2kT}\right]$$

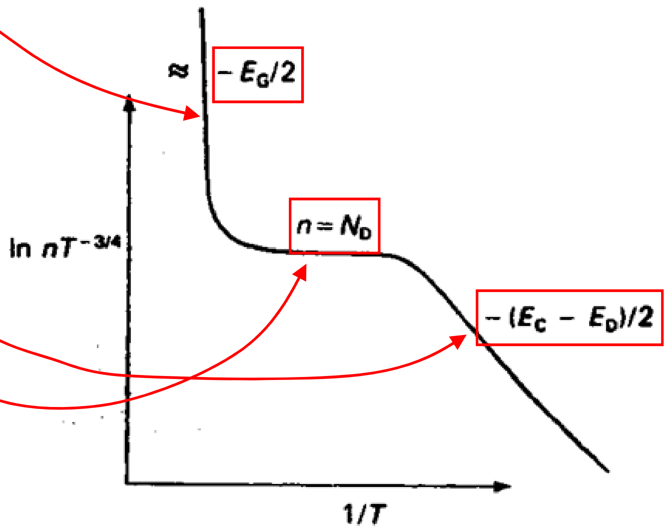
For extrinsic semiconductor with donors only,

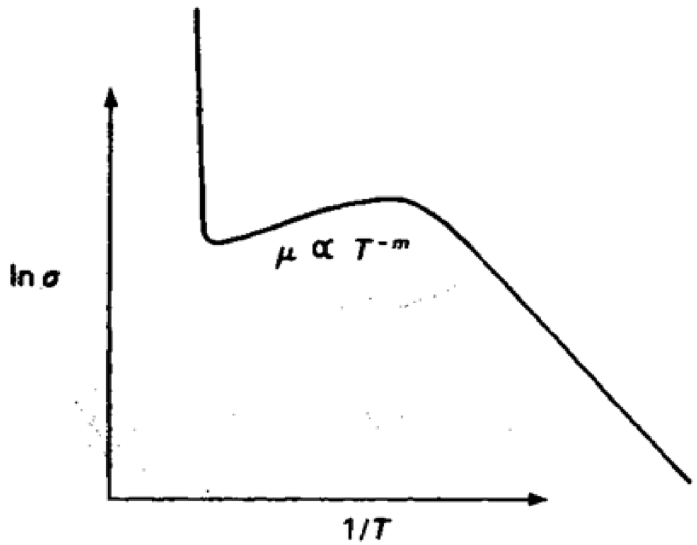
At high T extrinsic range,

$$n = N_D \text{ and } \sigma = N_D q \mu_n$$

At low T extrinsic range,

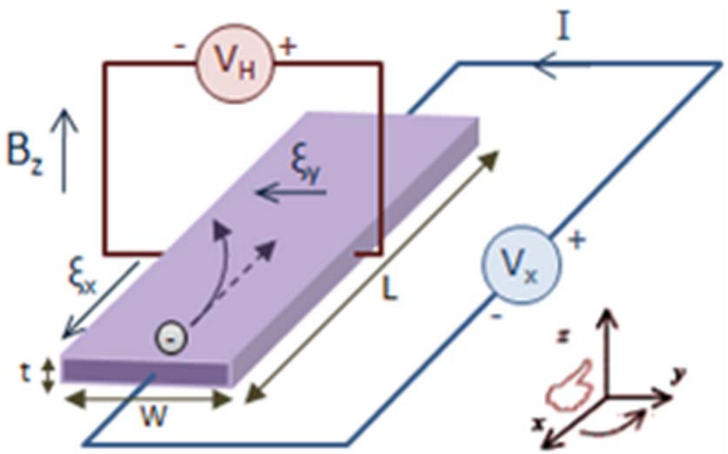
$$n = \left(\frac{N_C N_D}{g}\right)^{1/2} \exp\left[-\frac{(E_C - E_D)}{2kT}\right] \text{ and } \sigma = \left(\frac{N_C N_D}{g}\right)^{1/2} q\mu_n \exp\left[-\frac{(E_C - E_D)}{2kT}\right]$$





Hall Effect

The Hall effect is one of the most commonly used of the technique to distinguish the effects of carrier density and carrier mobility on conductivity.



By measuring V_H

$$V_H = \frac{I_x B_z}{nte}$$

$$n = \frac{I_x B_z}{V_H te}$$

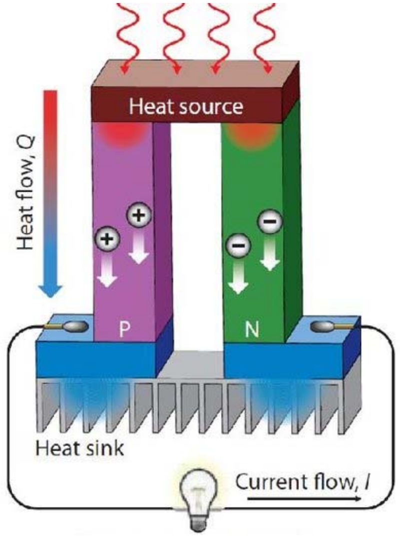
Hall coefficient $(R_H) = \frac{1}{ne}$

$$\mu_{Hall} = \frac{R_H}{\rho}$$

Other galvanomagnetothermoelectric effect

- Magnetoresistance

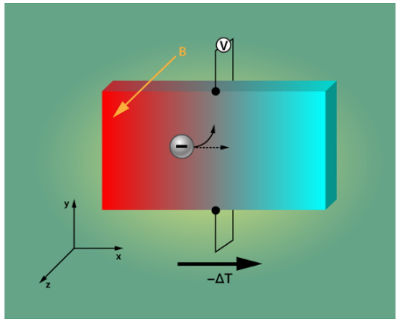
: change in electrical conductivity associated with an applied electric fields when magnetic field is applied.



- Seebeck effect

: When two ends of a conductor are at different temps, diffusion associated with this concentration gradient is counteracted by the buildup of an electric field.

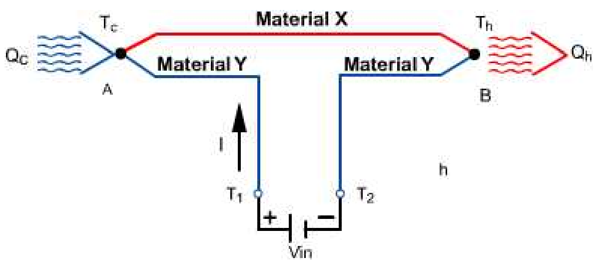
- Nernst effect



: When a material is exposed to temp gradient and magnetic field, mobile charges move from the warm to the cold side and this motion induces a force coming from magnetic field, resulting in an electric field.

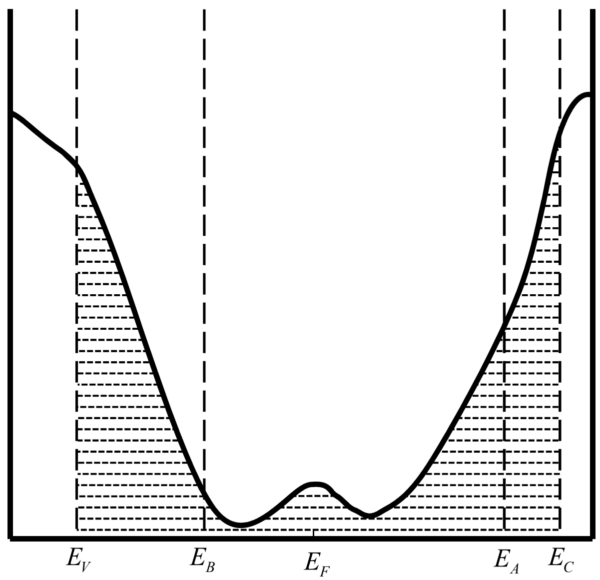
- Peltier effect

: If a voltage is applied to two terminals, electrical current will flow in the circuit. A slight cooling effect occurs at thermocouple junction *A* where heat is absorbed and a heating effect occurs at junction *B* where heat is expelled.

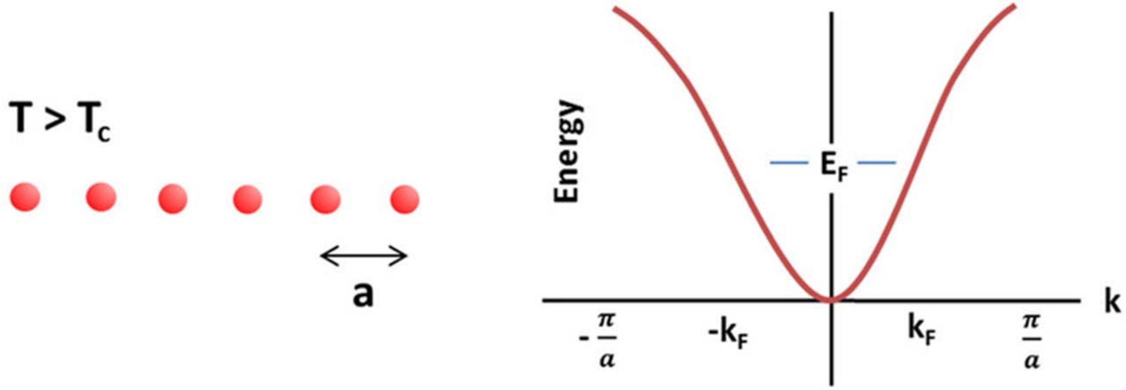


Amorphous semiconductors

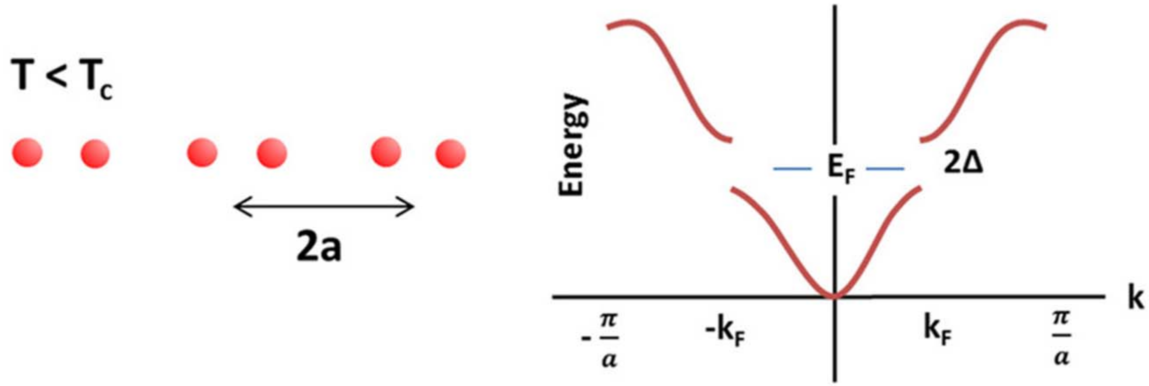
- Do not show long range order
- Larger potential for thin film transistors, large area uniform devices, solar cells,



Charge density waves

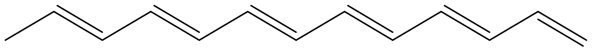


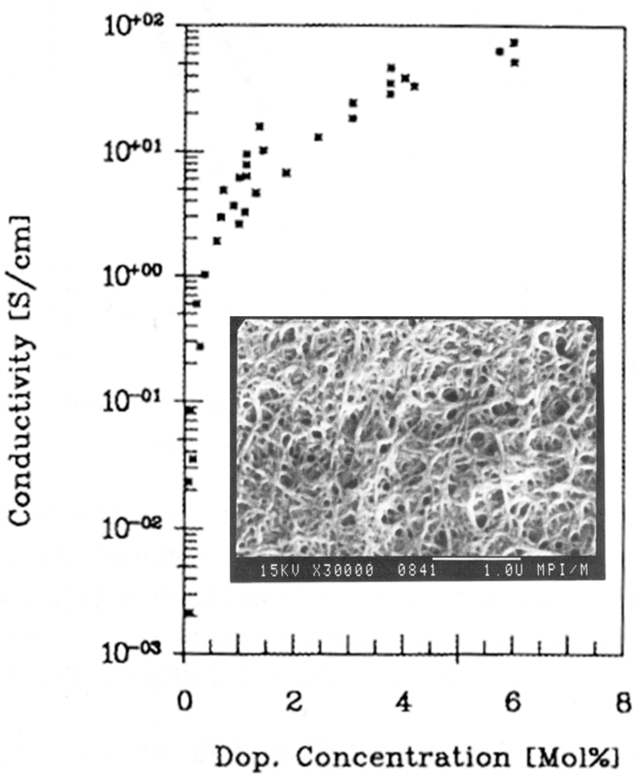
In a metal, the electron density is highly uniform. The equilibrium positions of the ions form a perfectly periodic lattice.



In quasi-one- and two-dimensional metals, however, static modulations of the density are stable under certain conditions. The electron gas and the ion lattice spontaneously develop a periodic modulation when the temperature decreases below a critical transition temperature T_p ('p' for Peierls). The modulation of the electron density is called a charge density wave (CDW).

Conducting polymers





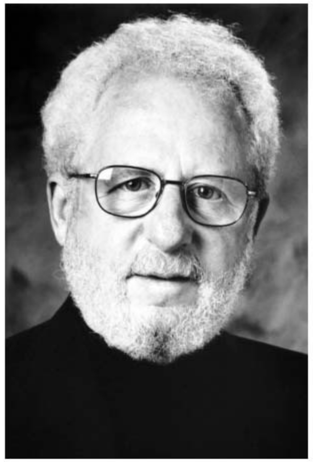


Photo from the Nobel Foundation archive.

Alan J. Heeger

Photo from the Nobel Foundation archive.

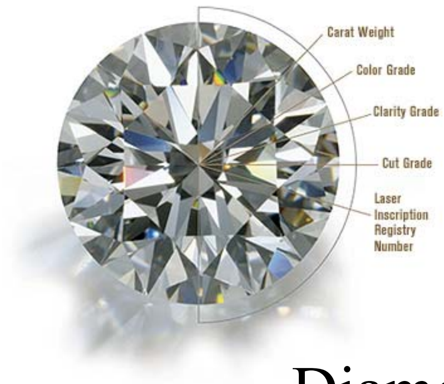
Alan G. MacDiarmid

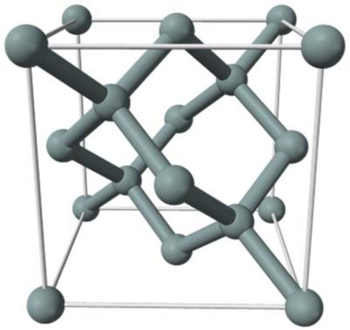
Photo from the Nobel Foundation archive.

Hideki Shirakawa

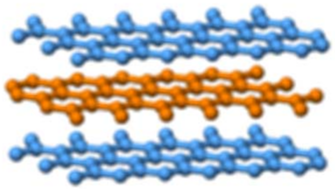
The Nobel Prize in Chemistry 2000 was awarded for the discovery and development of conductive polymers.

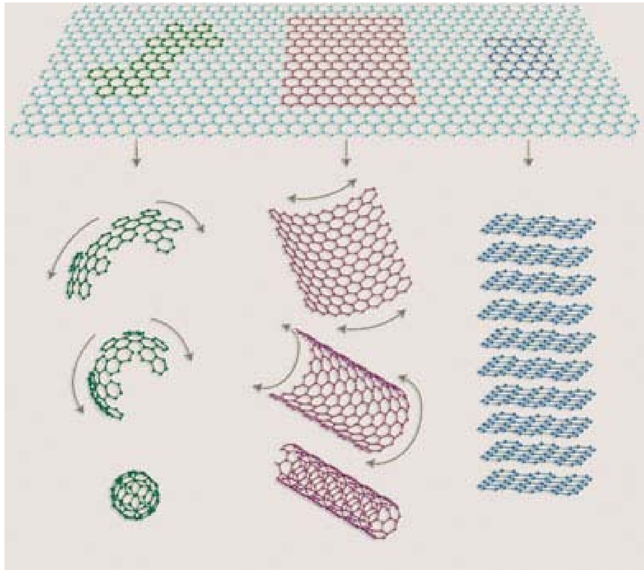
Carbon-based Materials

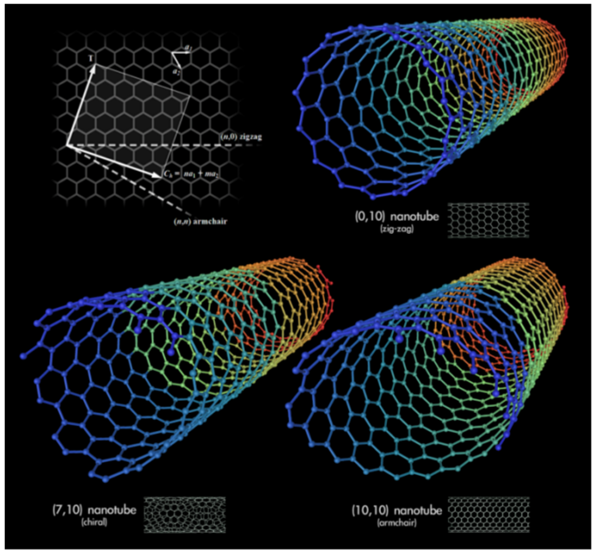




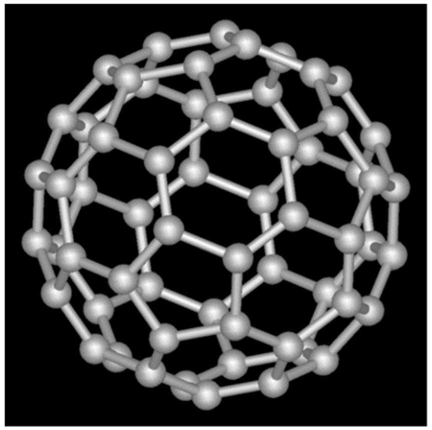
Diamond



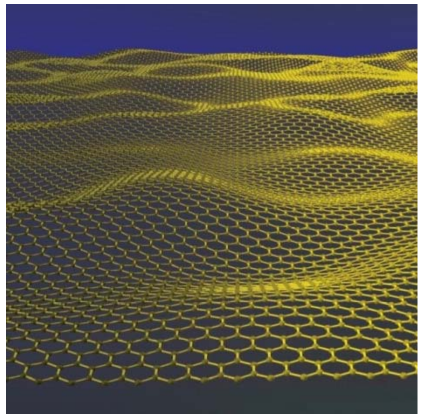




CNT



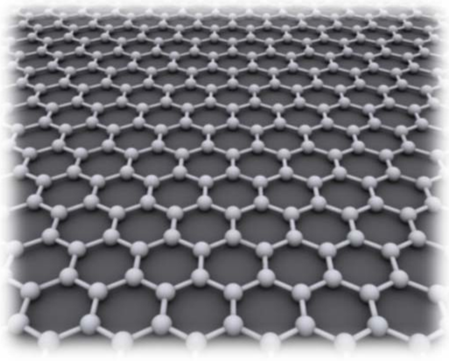
C_{60}



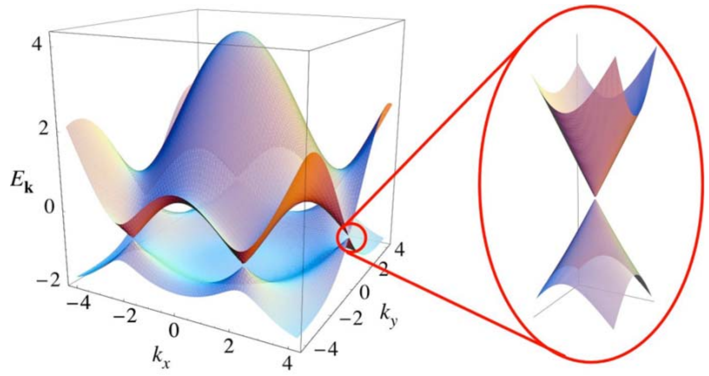
Graphene

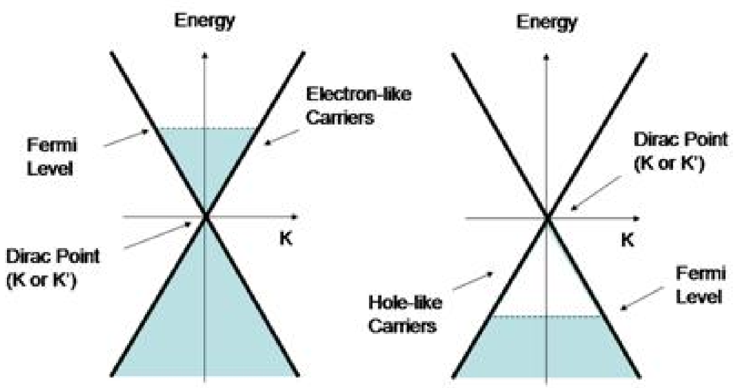
Carbon-based Materials: Graphene

Crystal structure of graphene

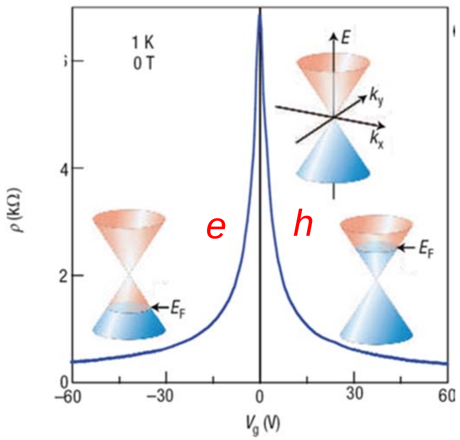


Band structure of graphene





Linear dispersion



Ambipolar conductance