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DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY
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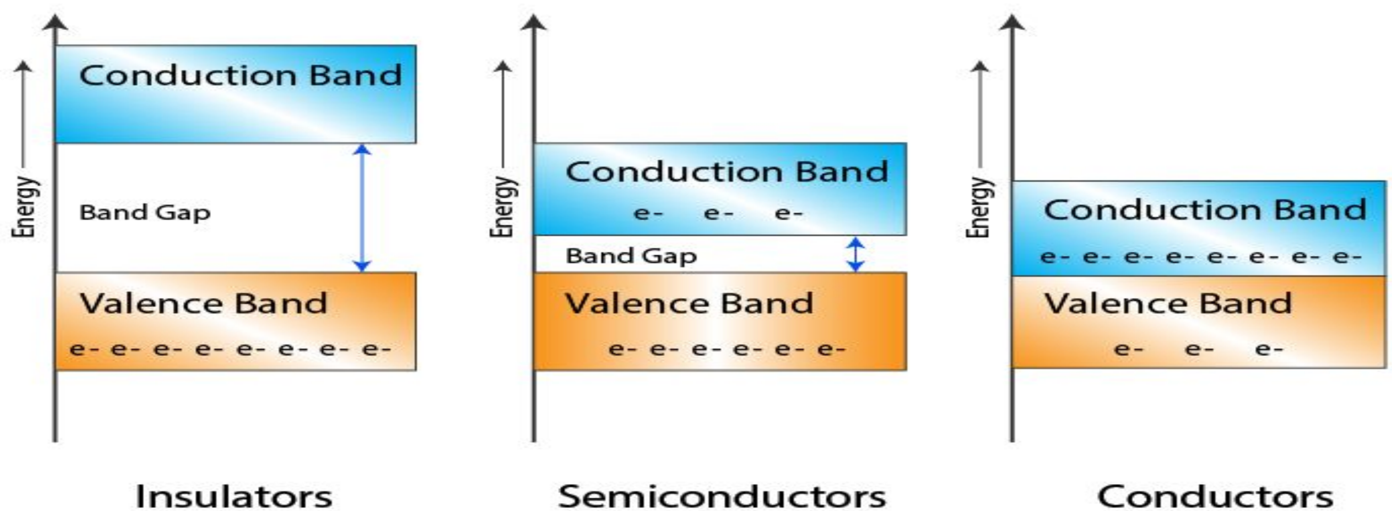
18PYB103J –Semiconductor Physics

Intrinsic semiconductors: *In semiconductors and insulators, when an external electric field is applied the conduction is not possible as there is a forbidden gap, which is absent in metals (good conductors).*

The field that needs to move electron to conduction band is extremely large. Take the example of silicon, where the forbidden gap is about 1 eV. This is approximately the energy difference between a location close to an ion core and another location away from the ion core. The distance between these two locations is about 1 Å (10^{-10} m).



$$\frac{1}{1+\{exp[E-E_F)/k_BT]\}}$$

Therefore, a field gradient of approximately 1V/ (10^{-10} m) = 10^{10} Vm^{-1} is necessary to move an electron from the top of the valence band to the bottom of the conduction band. Such a high field gradient is not realizable in practice.

A pure crystal of silicon or germanium is an intrinsic semiconductor. The electrons that are excited from the top of the valence band to the bottom of the conduction band by thermal energy are responsible for conduction. The number of electrons excited across the gap can be calculated from the Fermi-Dirac probability distribution at temperature:

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

The probability that a particle will have energy E

$$f(E)_{\text{Fermi-Dirac}} = \frac{1}{e^{(E - E_F)/kT} + 1}$$

See the Maxwell-Boltzmann distribution for a general discussion of the exponential term.

For low temperatures, those energy states below the Fermi energy E_F have a probability of essentially 1, and those above the Fermi energy essentially zero.

The quantum difference which arises from the fact that the particles are indistinguishable.

We can then write the conductivity σ of an intrinsic semiconductor as:

$$\sigma_i = n_e e \mu_e + n_h e \mu_h \qquad (4)$$

where e is the electronic charge, n_e and n_h are concentrations of electrons and holes per unit volume.

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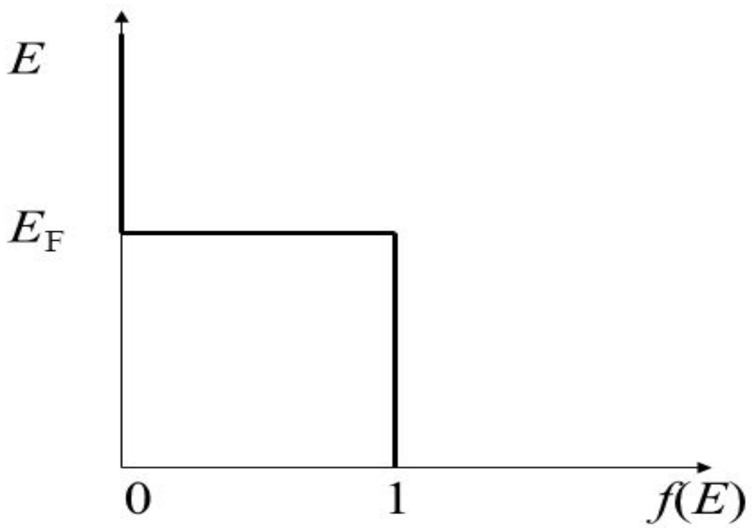
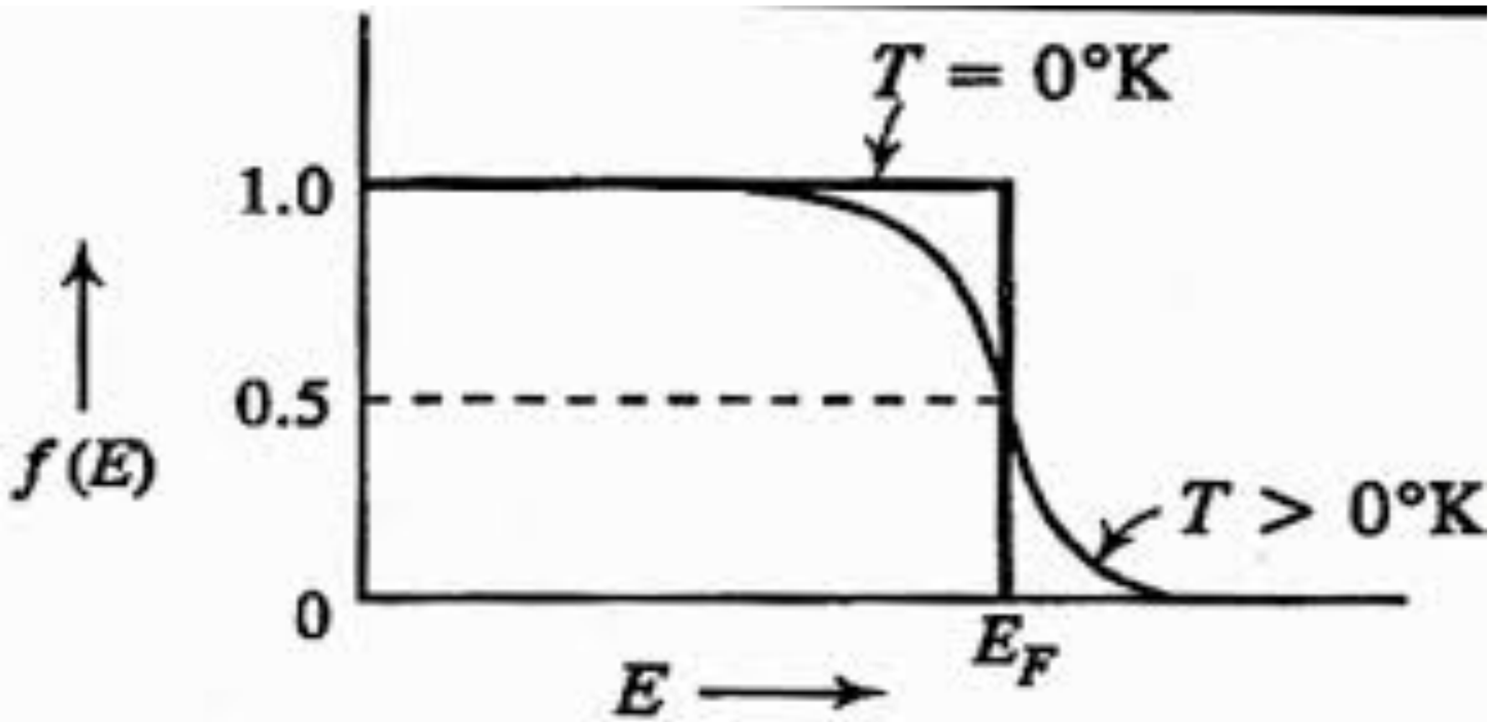
Fermi-Dirac distribution: Consider $T \to 0$ K

For $E > E_F$: $$f(E > E_F) = \frac{1}{1 + \exp(+\infty)} = 0$$

For $E < E_F$: $$f(E < E_F) = \frac{1}{1 + \exp(-\infty)} = 1$$



•*At absolute zero, all levels below E_F are completely filled and all levels above E_F are completely empty. This level, which divides the filled and vacant states, is known as the Fermi energy level.*



VARIATION OF f(E) WITH E

Definition of the Fermi Energy (E_F)

Fermi Energy (E_F): The Energy of the Top-most Filled Level in the Ground State of a System with *N* Electrons

In a Real System, the Energy of Electrons Will Increase with Increasing Temperature.

As Such, the Uppermost Energy Level Containing an Electron Will Shift with Temperature

The Fermi-Dirac Distribution [*f(E)*] Gives the Probability That an Orbital at Energy (*E*) Will Be Occupied in an Ideal Electron Gas at Thermal Equilibrium

$$f(E) = \frac{1}{\exp\left[\frac{(E-\mu)}{kT}\right]+1}$$

Here, μ is the chemical potential, k is Boltzmann's constant, and T is the absolute temperature

$$f(E) = \frac{1}{\exp\left[\frac{(E-E_F)}{kT}\right]+1}$$

At T = 0 K, the Fermi energy is equal to the chemical potential, and this assumption is a relatively good approximation in our finite temperature range

The fraction of electrons at energy E is equal to the probability $f(E)$. We can then write for the number n of electrons promoted across the gap:

$$n = N \exp(-E_g/2k_BT). \qquad (3)$$

where N is the number of electrons available for excitation from the top of the valence band. The promotion of some of the electrons across the gap leaves some vacant electron sites in the valence band. These are called *holes*. As each excited electron leaves back one hole, *an intrinsic semiconductor contains an equal number of holes in the valence band and electrons in the conduction band*, that is $n_e = n_h$. The number of each of these species is given by Equation(3). We can then write the conductivity σ of an intrinsic semiconductor as:

$$\sigma_i = n_e\, e\, \mu_e + n_h\, e\, \mu_h \qquad (4)$$

where e is the electronic charge, n_e and n_h are concentrations of electrons and holes per unit volume.

<u>Fermi level of Intrinsic semiconductor calculation:-</u>

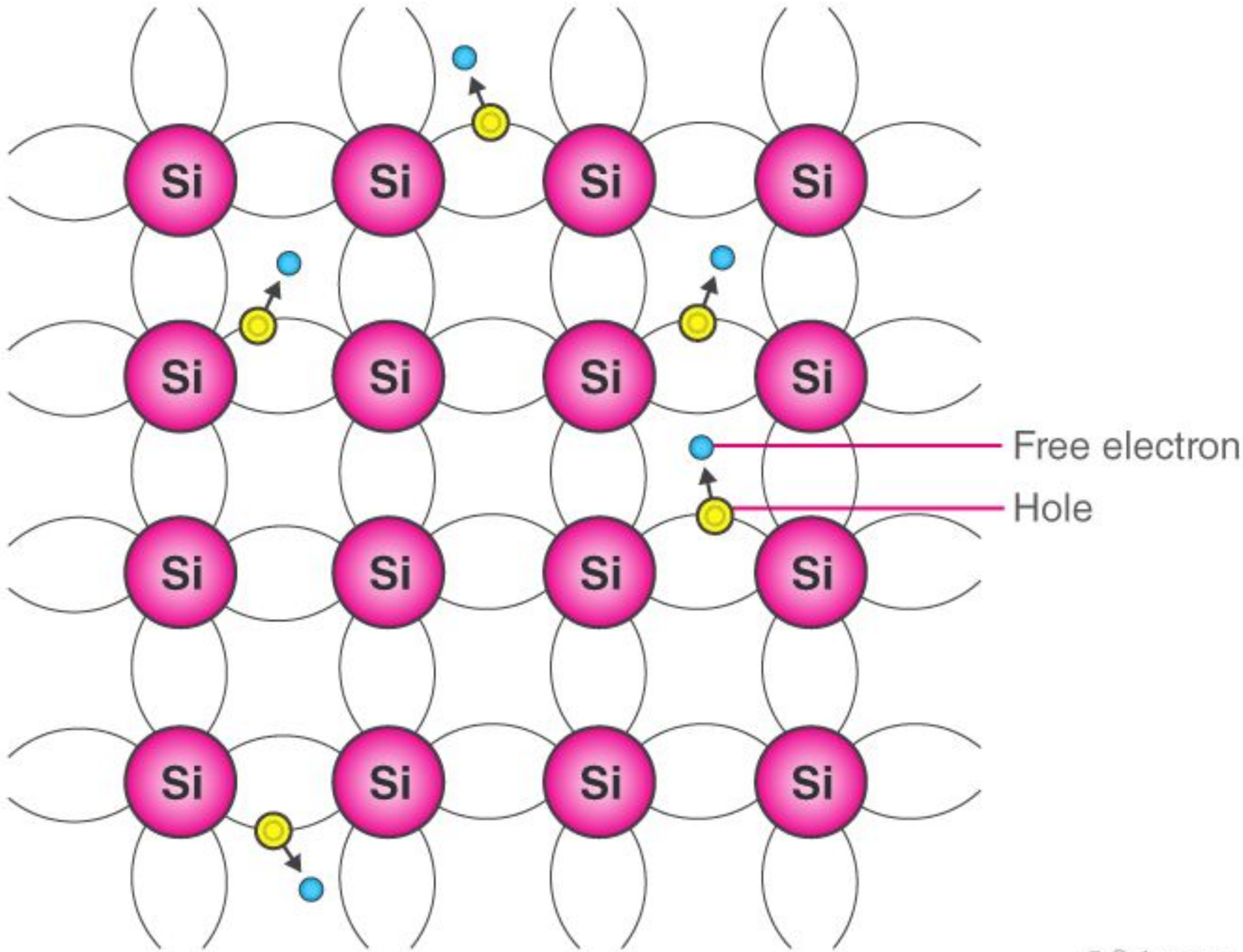
The number of free electrons per unit volume in an intrinsic semiconductor is n in conduction band and The number of holes per unit volume in an intrinsic semiconductor is p in valence band .

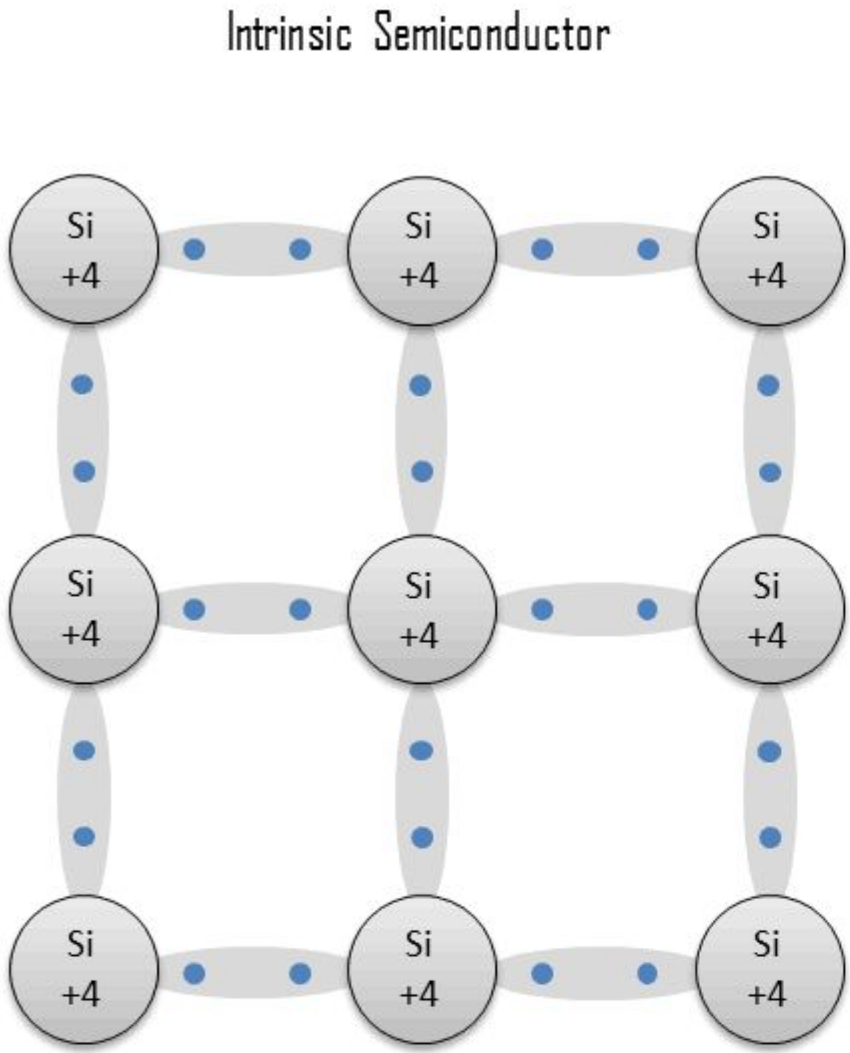
Since n = p in intrinsic semiconductors.

If we assume that, m^*_e(mass of electron)=m^*_p(mass of hole)

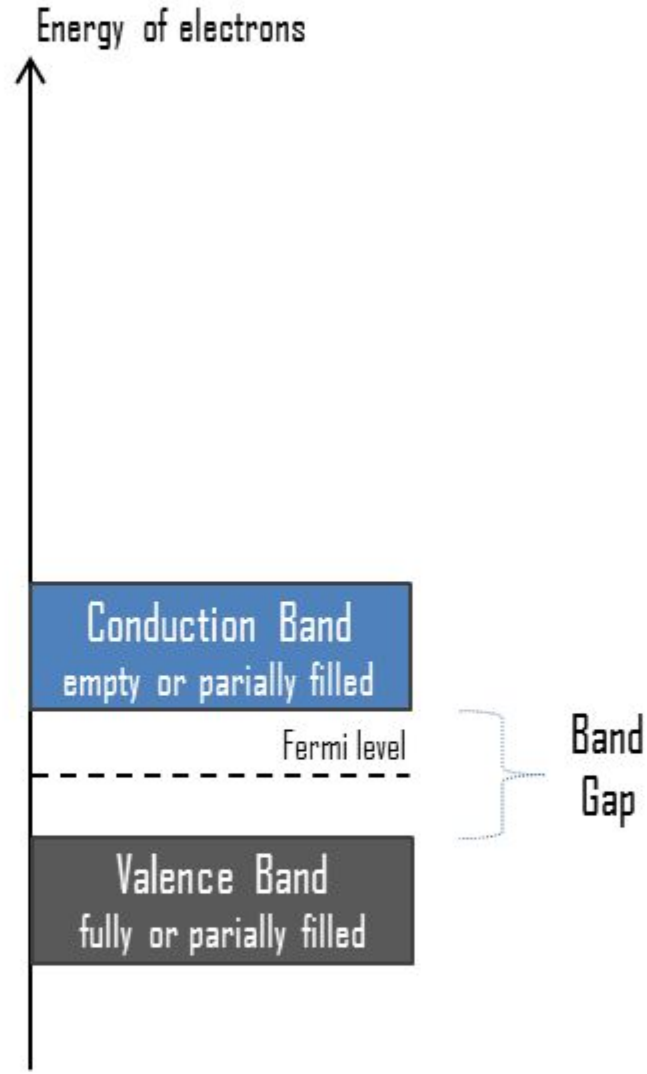
INTRINSIC SEMICONDUCTORS

BYJU'S
The Learning App





Intrinsic Semiconductor
Si
+4



Energy of electrons
Conduction Band
empty or parially filled
Fermi level
Band
Gap
Valence Band
fully or parially filled

$$n = 2\left(\frac{2\pi m_e^* kT}{\mathrm{h}^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{kT}\right)$$

$electron - density$

$$p = 2\left[\frac{2m_h^*\pi kT}{h^2}\right]^{3/2} .\exp\left(\frac{E_V - E_F}{KT}\right)$$

$$hole - density$$

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\exp\left(\frac{E_F - E_c}{kT}\right) = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}\exp\left(\frac{Ev - E_F}{kT}\right)$$

$$\mathrm{int}\, rinsic\_condition : -n = p$$

$$\left(m_e^*\right)^{3/2} exp\frac{\left(E_F - E_C\right)}{kT} = \left(m_h^{*\,3/2}\right)\exp\left[\frac{Ev - E_F}{KT}\right]$$

$$e^{2E_F/kT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}\exp\left(\frac{E_v + E_c}{kT}\right)$$

$$\frac{2E_F}{kT} = \frac{3}{2}log_e\left(\frac{m_h^*}{m_e^*}\right) + log_e\left[exp\left(\frac{E_v + E_c}{kT}\right)\right]$$

$$\frac{2E_F}{kT} = \frac{3}{2}\log_e\left(\frac{m_h^*}{m_e^*}\right) + \left(\frac{E_v + E_c}{kT}\right)$$

$$E_F = \frac{3kT}{4}\log_e\left(\frac{m_h^*}{m_e^*}\right) + \left(\frac{E_v + E_c}{2}\right)$$

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If we assume that, $m_e^* = m_h^*$

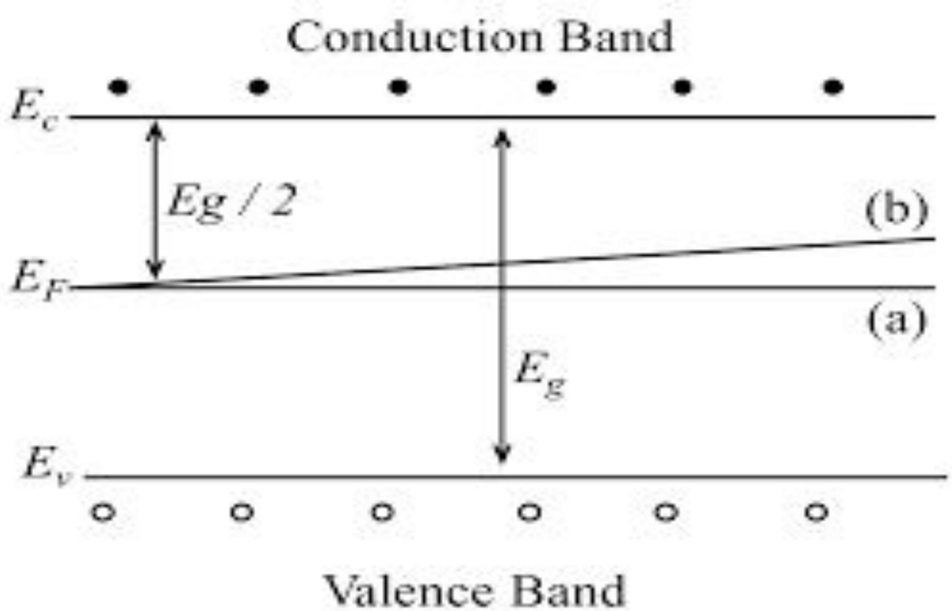
[since $\log_e 1 = 0$]

Thus, the Fermi level is located half way between the valence and conduction band and its position is independent of temperature. Since m_h^* is greater than m_e^*, E_F is just above the middle, and rises slightly with increase in temperature as shown in Fig. 1.4.

$$E_F = \left(\frac{E_v + E_c}{2} \right)$$

$$E_F = \frac{E_C + E_V}{2} + \frac{kT}{2} \ln \left\{ \frac{2\left\{ \frac{2\pi m_h^* kT}{h^2} \right\}^{\frac{3}{2}}}{2\left\{ \frac{2\pi m_e^* kT}{h^2} \right\}^{\frac{3}{2}}} \equiv \left[\frac{VB}{CB} \right] \right\}$$

Fig.1.4. Position of Fermi level in an intrinsic semiconductor at various temperatures (a) at T = 0 K, the Fermi level in the middle of the forbidden gap (b) as temperature increases, E_F shifts upwards



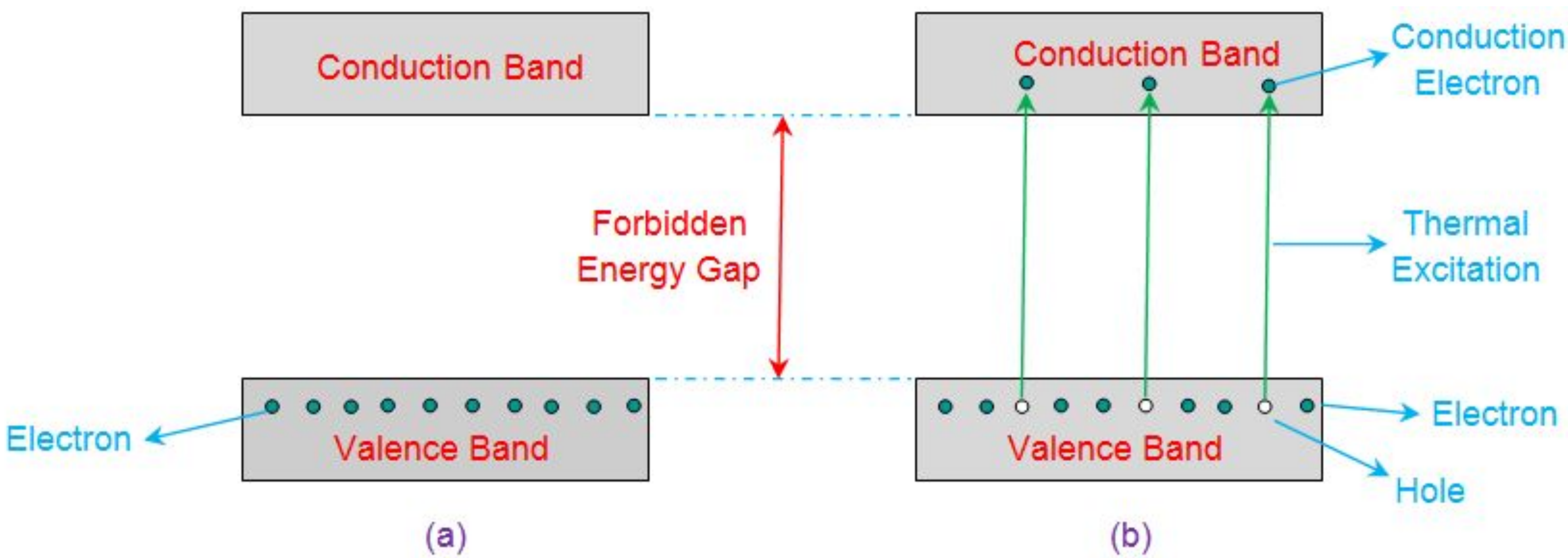
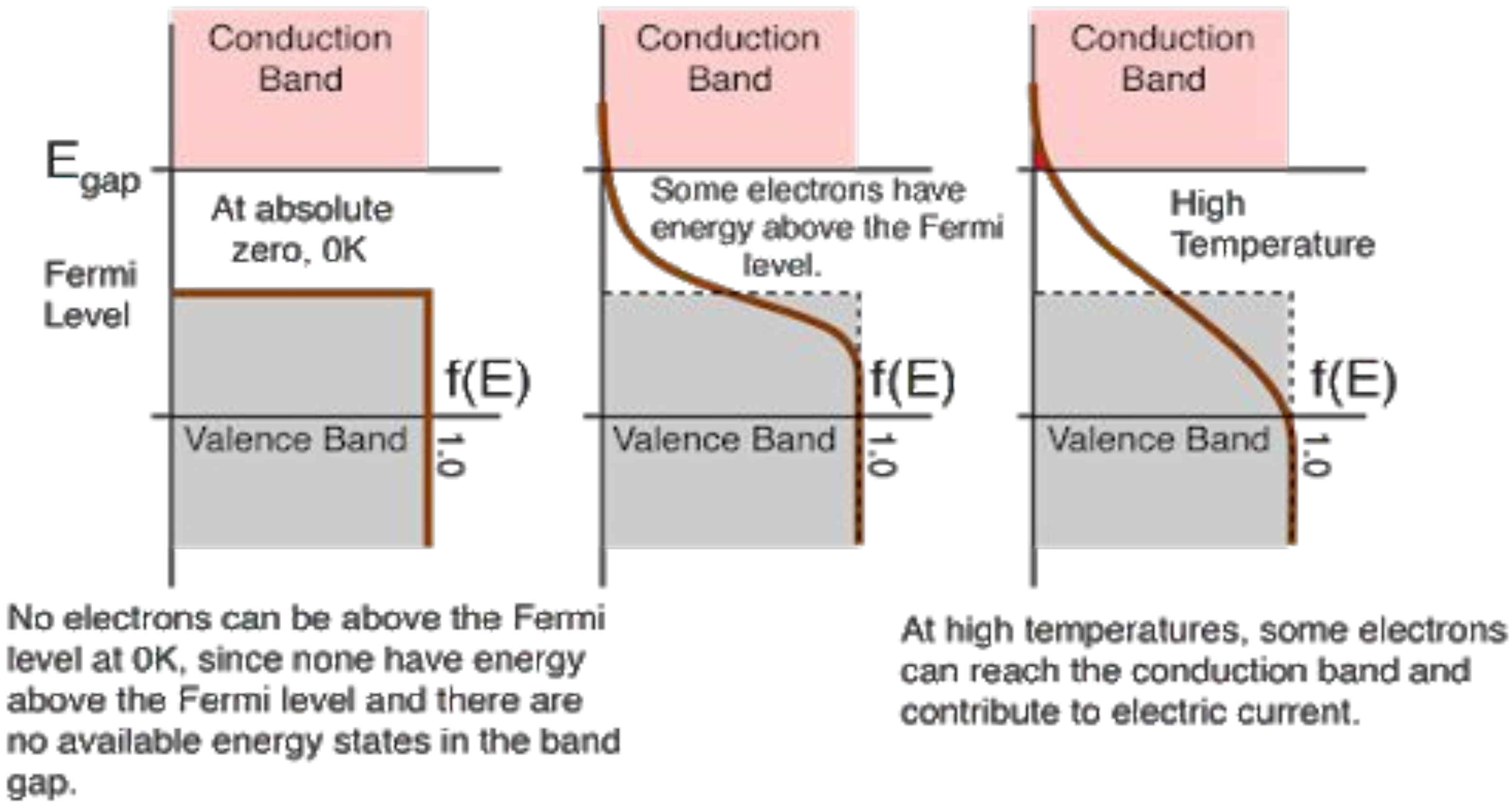


Figure 2 Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K


Conduction Band
Conduction Band
Conduction Band
E_{gap}
At absolute zero, 0K
Some electrons have energy above the Fermi level.
High Temperature
Fermi Level
f(E)
f(E)
f(E)
Valence Band
Valence Band
Valence Band
1.0
1.0
1.0
No electrons can be above the Fermi level at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.
At high temperatures, some electrons can reach the conduction band and contribute to electric current.