Semiconductor Fundamentals

Presented to
EE2187 class in Semester 1 2019/20

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Lecture 11

Course information

- Semiconductors Materials - Types of Solids, Space lattice, Atomic Bonding,
- Introduction to quantum theory, Schrodinger wave equation, Electron in free space, Infinite well, and step potentials, Allowed and forbidden bands
- Electrical conduction in solids, Density of states functions, Fermi-Dirac distribution in Equilibrium,
- Valence band and Energy band models of intrinsic and extrinsic Semiconductors. Degenerate and non degenerate doping
- Thermal equilibrium carrier concentration, charge neutrality
- Carrier transport – Mobility, drift, diffusion.

Reference

Text Book:

1. Physics of Semiconductor Devices, *S. M. Sze*, John Wiley & Sons (1981).
2. Solid State Electronics by *Ben G. Streetman and Sanjay Banerjee*, Prentice Hall International , Inc.
3. Semiconductor Physics and Devices, Donald A. Neamen, Tata Mcgraw-Hill Publishing company Limited.
4. Advanced Semiconductor Fundamentals by Pirret

Reference Book:

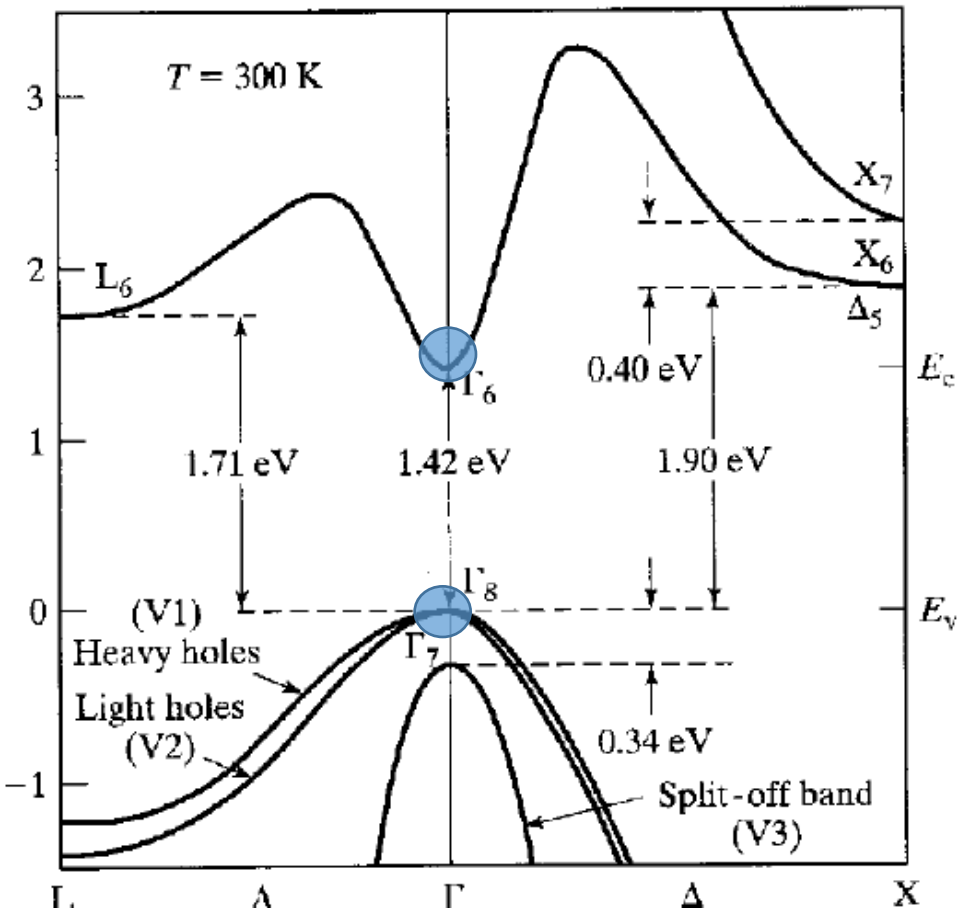
1. Fundamentals of Solid-State Electronic Devices, *C. T. Sah*, Allied Publisher and World Scientific, 1991.
2. Complete Guide to Semiconductor Devices, *K. K. Ng*, McGraw Hill, 1995.
3. Solid state physics, Ashcroft & Mermins.
4. Introduction to Solid State Electronics, *E. F. Y. Waug*, North Holland, 1980.

Recap

$$n_o = \int_0^{E_{top}} f(E)g(E)dE$$

$$DOS\ in\ 3DCrystal,\ \ g(E) = \frac{m*}{2\pi^2\hbar^3}\sqrt{2m*(E-Ec)}$$

DOS Si, Ge and GaAs



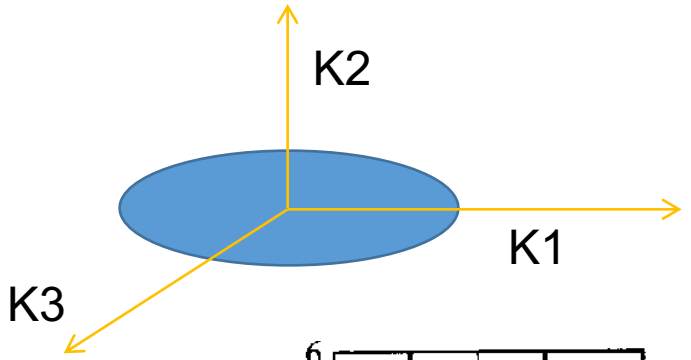
$$DOS = \frac{m*_n}{2\pi^2\hbar^3}\sqrt{2mn*(E-Ec)}$$

$$DOS = \frac{m*_n}{2\pi^2\hbar^3}\sqrt{2m*_{lh}(Ev-E)}$$

$$DOS = \frac{m*_n}{2\pi^2\hbar^3}\sqrt{2m*_{hh}(Ev-E)}$$

Effective mass in ellipsoidal band i.e Si, and Ge

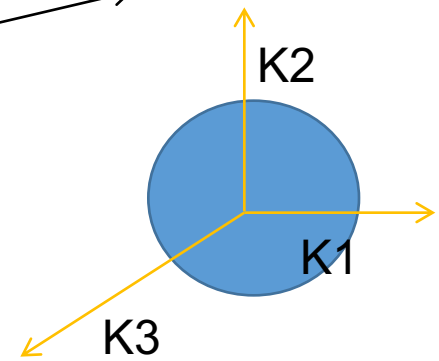
$$E - Ec = \frac{\hbar^2 k_1^2}{2m_l^*} + \frac{\hbar^2 k_2^2}{2m_t^*} + \frac{\hbar^2 k_3^2}{2m_t^*}$$



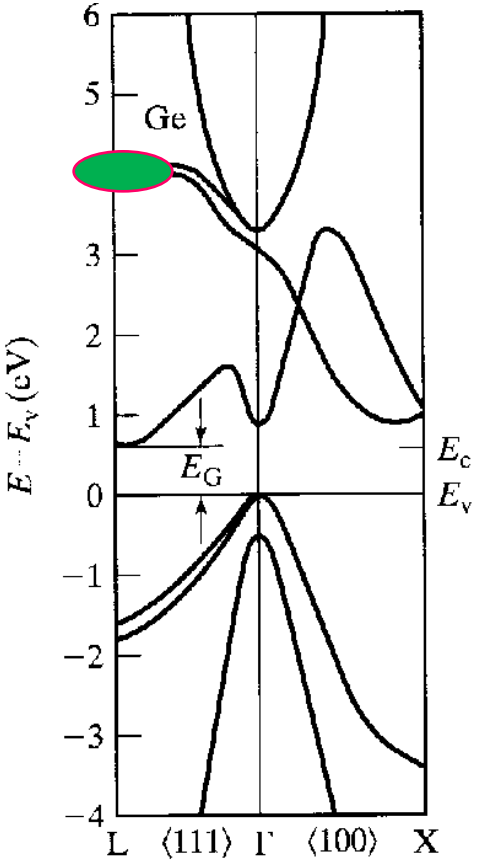
$$1 = \frac{k_1^2}{\frac{(E - Ec)2m_l^*}{\hbar^2}} + \frac{k_2^2}{\frac{(E - Ec)2m_t^*}{\hbar^2}} + \frac{k_3^2}{\frac{(E - Ec)2m_t^*}{\hbar^2}}$$

a^2 b^2

$$N_{el}\frac{4}{3}\pi a b^2 = \frac{4}{3}\pi k_{eff}^3$$

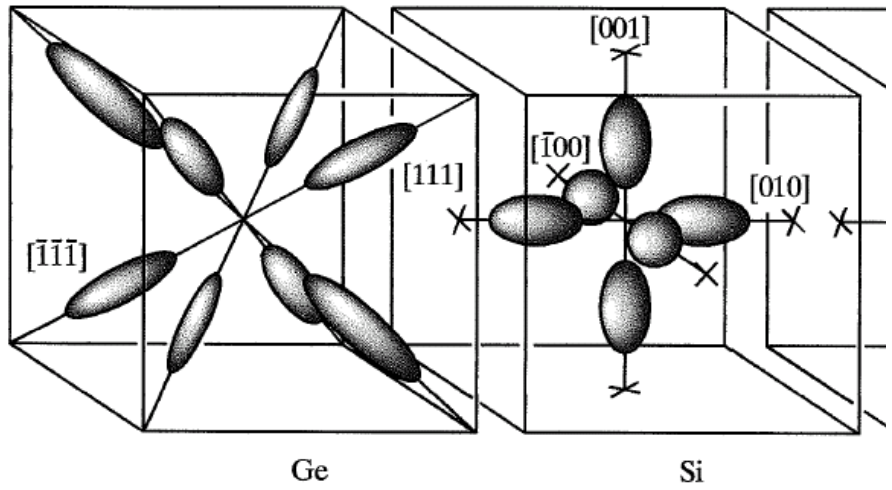


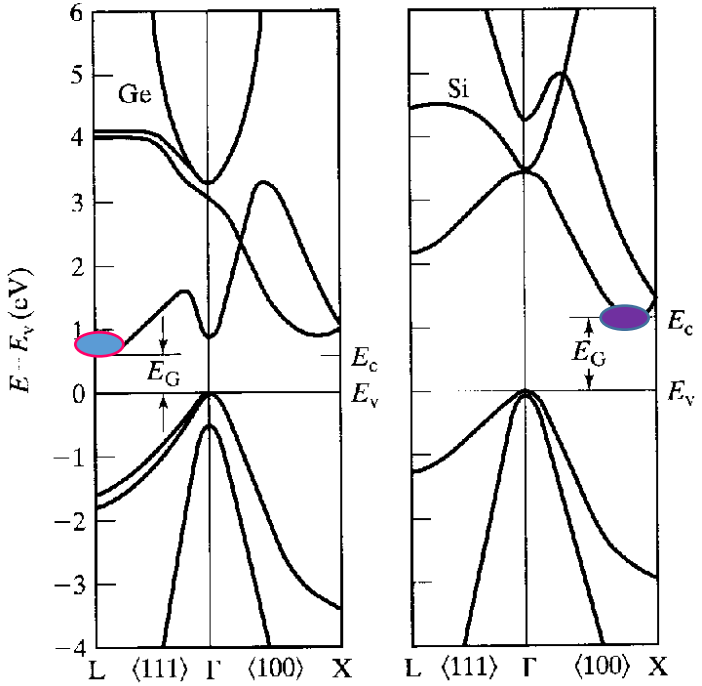
$$m_{eff}^* = N_{el}^{2/3}(m_l^* m_t^{*2})^{1/3}$$



Density of states for case of Ge/Si in conduction band

$$g_c(E) = \frac{m_n^{*3/2}}{\hbar^3}\sqrt{\frac{2(E - Ec)}{2}}$$





$$m_{eff}^{*} = 4^{2/3}(m_l^{*} m_t^{*2})^{1/3}\ for..Ge$$

$$m_{eff}^{*} = 6^{2/3}(m_l^{*} m_t^{*2})^{1/3}\ for..Si$$

Density of electron/holes in energy interval dE-

$$n_o = \int_0^{E_{top}} f(E)g(E)dE$$

f(E) can obey MB distribution if electron behave as classical particle.
i.e. ~$Ae^{-E/kT}$

But Electron don't obey MB distribution as it is quantum particle and fermions', hence it obey Fermi Dirac distributions.

Classical MB
Fermions FD
Boson BE

⇨ QM particle

Rule for filling the electron

Pauli Principle: Only one electron per state

Total number of electrons is conserved $N_T = \sum_i N_i$

Total energy of the system is conserved $E_T = \sum_i E_i N_i$

Fermi- Dirac distribution function

When T>0

At thermal equilibrium, the electrons do not simply fill the lowest energy states first.

Fermi-Dirac statistics which gives the distribution of probability of an electron to have an energy *E at temperature T*

$$f_e(E) = \frac{1}{\exp\left(\frac{E - E_F}{k_b T}\right) + 1}$$

E_F is the Fermi energy and k_b is the Boltzmann constant.

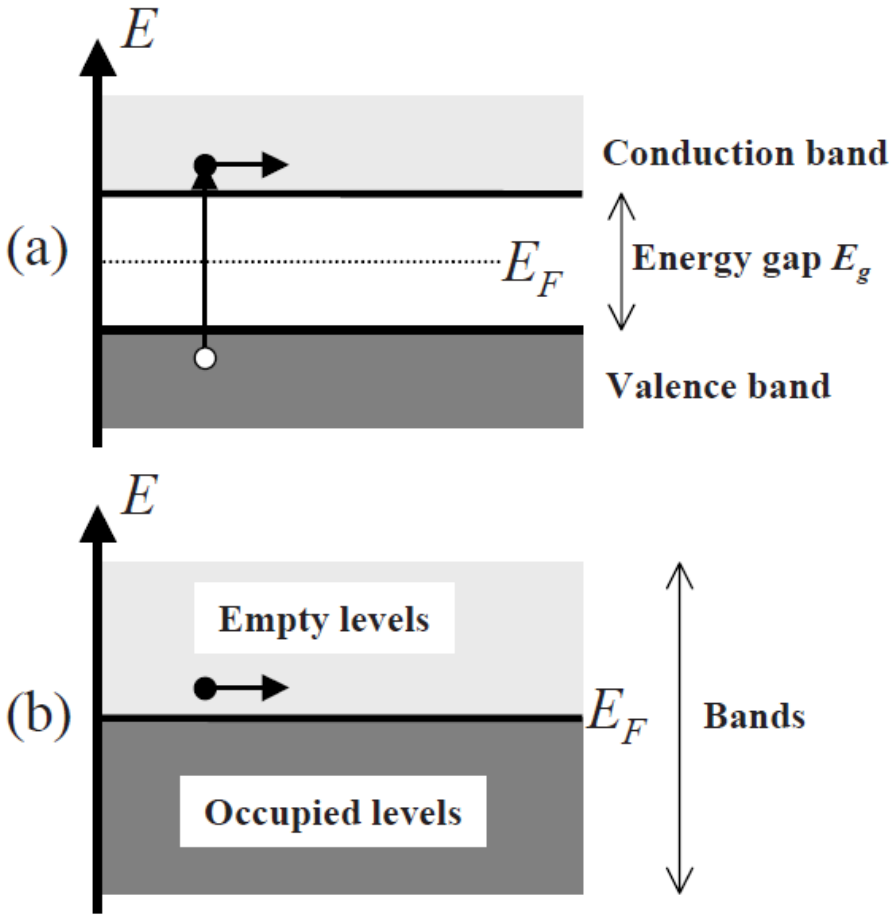
Fermi-Dirac statistics involves a chemical potential μ instead of the Fermi energy E_F. *This chemical* potential depends on the temperature and any applied electrical potential. But in most cases of semiconductors, the difference between μ and E_F *is* very small at the temperatures usually considered.

Fermi Level

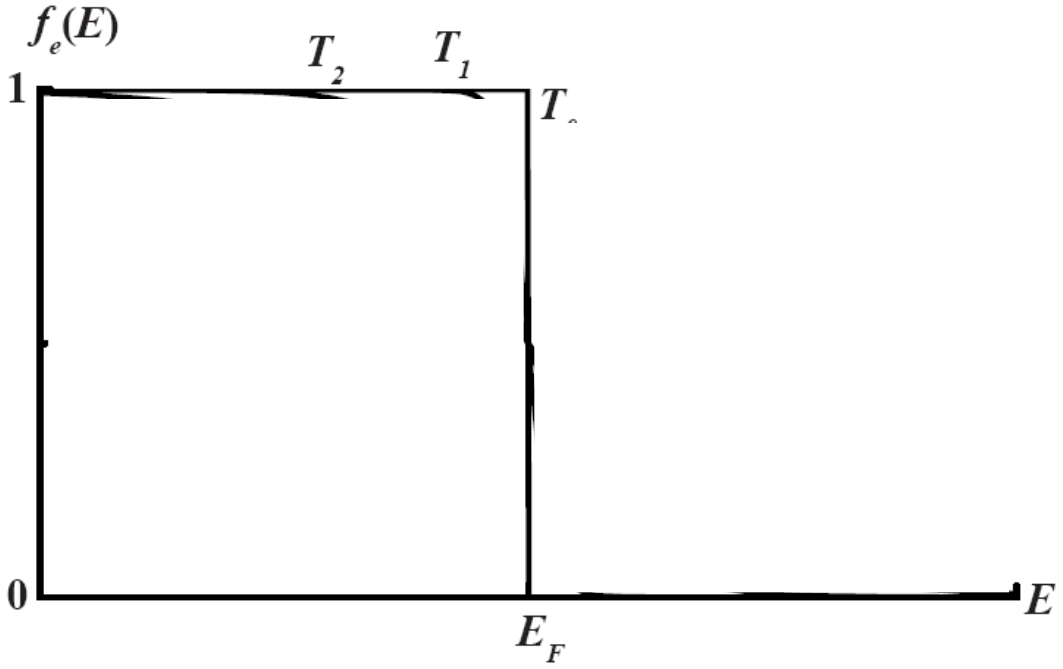
Assumption: solid where there are *m energy levels and n electrons, a*nd (*m > n)*

At equilibrium, when no electron is in an excited state (e.g. at the absolute zero temperature, 0 K), the lowest *n energy levels will be occupied* by electrons and the next remaining *m-n energy levels remain empty.*

If the highest occupied state is inside a band, the energy of this state is called the Fermi level and is denoted by E_F.



More Insight



(1) At $T = 0\ K$ and $E<E_F$

(a)Fermi-Dirac distribution is unity

At $T = 0\ K$ and $E>E_F$

(b)Fermi-Dirac distribution $[f_e(E]$ is Zero

(2) At $T > 0\ K$

(a) $E=E_F$, $f_e(E]=1/2$

(b)$E>E_F+3KT$,

$$\exp[(E-E_F)/kT]>1 \Rightarrow f_e(E)\approx \exp-[(E-E_F)/kT]$$

Most states with energy above 3KT from E_F will be empty.

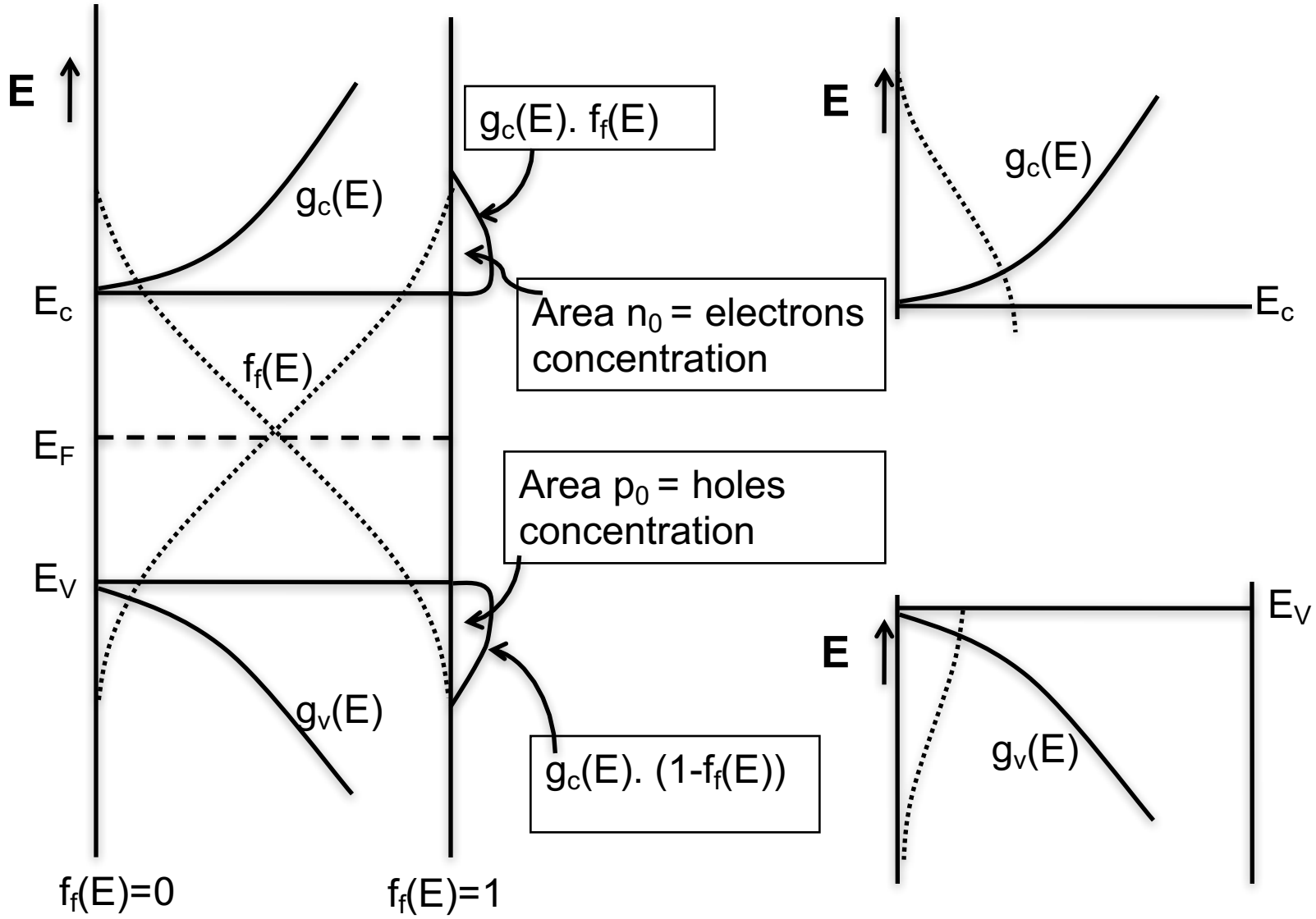
(c) $E<E_F-3KT$,

$$\exp[(E-E_F)/kT]<1 \Rightarrow f_e(E)\approx 1-\exp(E-E_F)/kT]$$

Most states with energy below 3KT from E_F will be filled.

(d) E>>3KT, beyond E_f then MB and FD merged as in the case of Si

Equilibrium Distribution of Electrons and Holes



Now again

$$n_o = \int_{E_c}^{E_{top}} f(E)g(E)dE$$

$$n_o = \int_{E_c}^{E_{top}} \frac{\frac{m_n^{*3/2}}{\hbar^3}\sqrt{(E-E_c}dE}{1+\exp(E-E_F)/kT}$$

May not be integrable

Apply MB distribution as Eg/2~16KT

$$n_o = \int_{E}^{\infty} \frac{\frac{m_n^{*3/2}}{\hbar^3}\sqrt{(E-E_c}dE}{\exp(E-E_F)/kT} = N_c e^{-(\frac{E_c-E_f}{kT})}$$

$$N_c = 2(\frac{m_n^* kT}{\pi\hbar^2})^{3/2} \approx 10^{19}$$

Effective density of states in CB

Heavily Doped Si

For heavily doped the semiconductor MB distribution does not hold so, need to solve Fermi integral for solution.

e.g let us take $n=10^{20}$

We get $E_F > E_c$ which is not possible

$$n_o = \int_E^{\infty} \frac{\frac{m_n^{*3/2}}{\hbar^3}\sqrt{(E-E_c}\,dE}{\exp(E-E_F)/kT} = N_c e^{-(\frac{E_c-E_f}{kT})}$$

So $$n_0 = \frac{2N_c}{\sqrt{\pi}} F_{1/2}\left(\frac{(E-E_C}{kT}\right)$$

Holes in Semiconductor

$$p_o = \int_{E_{bott}}^{Ev} \{(1 - f(E)\} g_v(E) dE$$

$$p_o = \int_{E}^{\infty} \frac{\frac{m_p^{*3/2}}{\hbar^3} \sqrt{(E_v - E} dE}{\exp(E - E_F)/kT} = N_v e^{-\frac{(E_F - E_v)}{kT}}$$

$$N_v = 2\left(\frac{m_v^* kT}{\pi\hbar^2}\right)^{3/2}$$

Since $m_n^* \neq m_p^*$

$N_c \neq N_c$

Fermi Level in Intrinsic Semiconductor at Equilibrium

$$m^*_{n_{dos}} \neq m^*_{p_{dos}}$$

$$N_c \neq N_c$$

But at Equilibrium $n_0 = p_0$

$$Nc^{-\frac{(E_c - E_F)}{kT}} = N_v^{-\frac{(E_F - E_v)}{kT}}$$

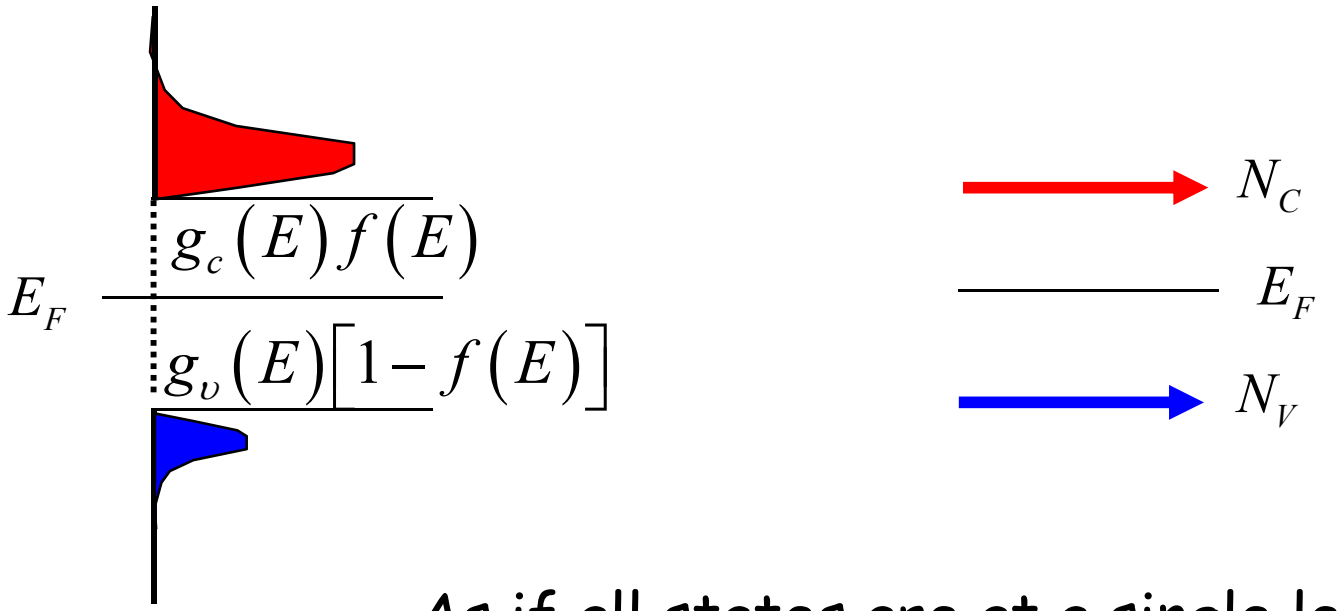
$$E_F = \frac{E_C + E_V}{2} + kT \ln \frac{m^*_{p_{dos}}}{m^*_{n_{dos}}}$$

$$if\ , m^*_{p_{dos}} = m^*_{n_{dos}}$$

E_F will be in middle of band gap

Effective Density of States

$$n = N_C \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_c) \rightarrow N_C e^{-\beta(E_c - E_F)} \quad if \quad \beta(E_c - E_F) > 3$$



As if all states are at a single level E_C

Intrinsic carrier concentration

Product of n_0 and p_0

$$p_o = N_v e^{-\frac{(E_F - E_v)}{kT}}$$

$$n_o = N_c e^{-\frac{(E_c - E_F)}{kT}}$$

$$n_o p_o = N_v e^{-\frac{(E_F - E_v)}{kT}} N_c e^{-\frac{(E_c - E_F)}{kT}}$$

$$n_o p_o = N_v N_c e^{-\frac{(E_c - E_v)}{kT}} = N_v N_c e^{-\frac{E_g}{kT}}$$

$$n_i^2 = N_v N_c e^{-\frac{E_g}{kT}} = n_o p_o$$

Where E_g is band gap,
At equilibrium $n_o = p_o = n_i$
n_i depends upon temperature and band gap

	N_c ($/cm^3$) (10^{18})	N_v ($/cm^3$) (10^{18})	$\frac{m_n^*}{m_o}$	$\frac{m_p^*}{m_o}$
Si	28	10.4	1.08	.56
Ge	10.9	6	.55	.37
GaAs	.47	7	.067	.48

	E_g (eV)	Concentration ($/cm^3$) 300K	Concentration ($/cm^3$) 400K
Si	1.12	$1.5 10^{10}$	$\sim 10^{13}$
Ge	.72	$2.4 X 10^{13}$	$\sim 10^{16}$
GaAs	1.42	$1.8 X 10^{6}$	-
SiC	3.5	10	100