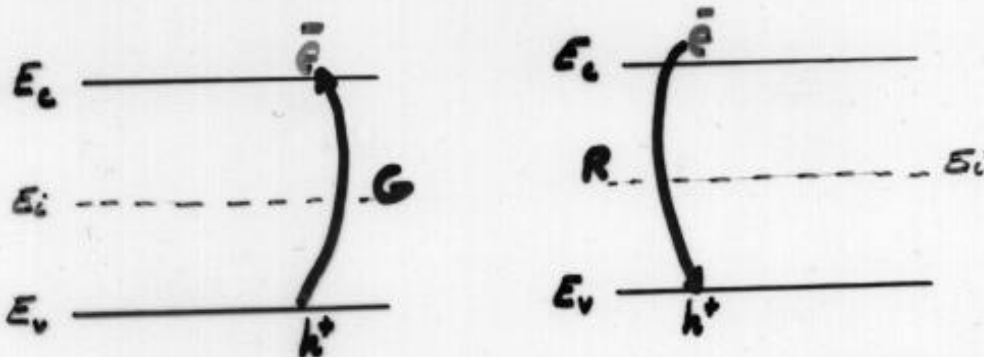


THERMAL EQUILIBRIUM STATISTICS

THERMAL EQUILIBRIUM

NO NET ENERGY TRANSFER BETWEEN ELECTRONS, HOLES AND LATTICE



EQUILIBRIUM: $R = G$ (RATE: ELECTRON-HOLE
 { GENERATION } PER UNIT TIME
 { RECOMBINATION }

MASS-ACTION LAW (EQUILIBRIUM)

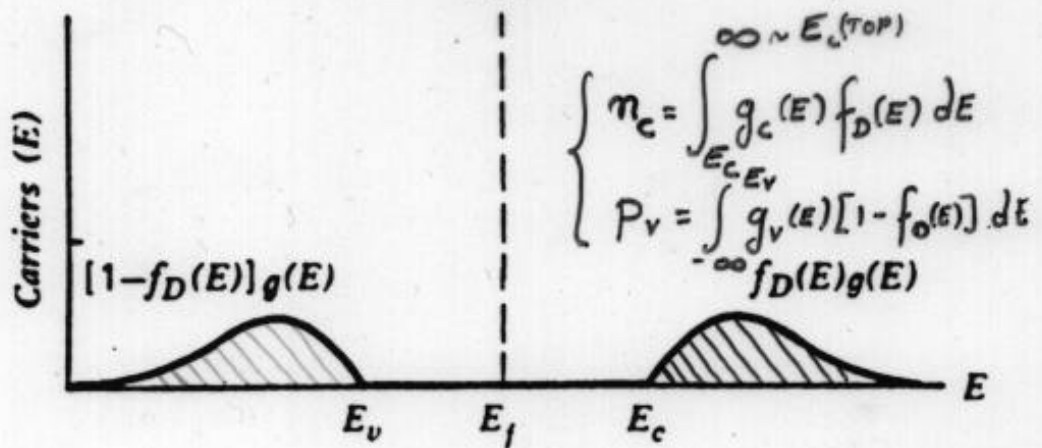
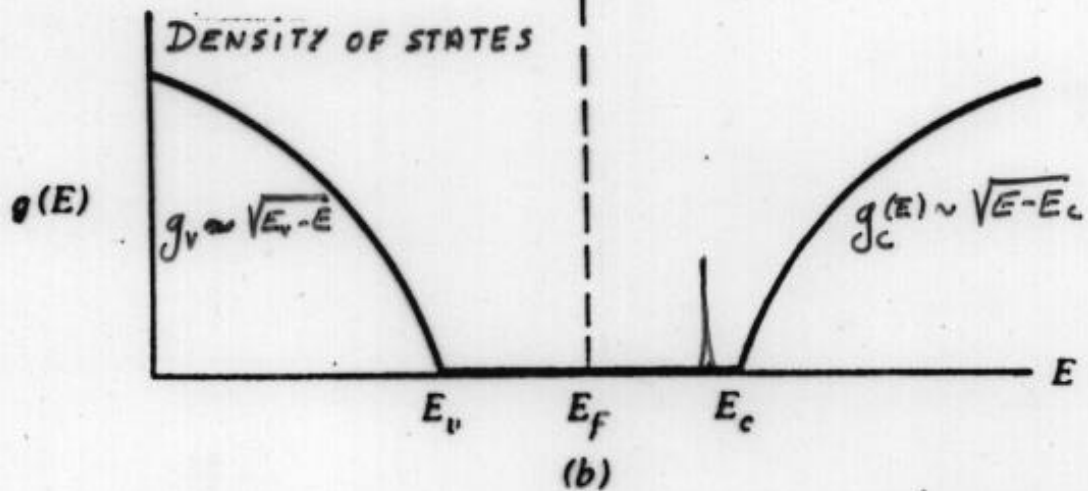
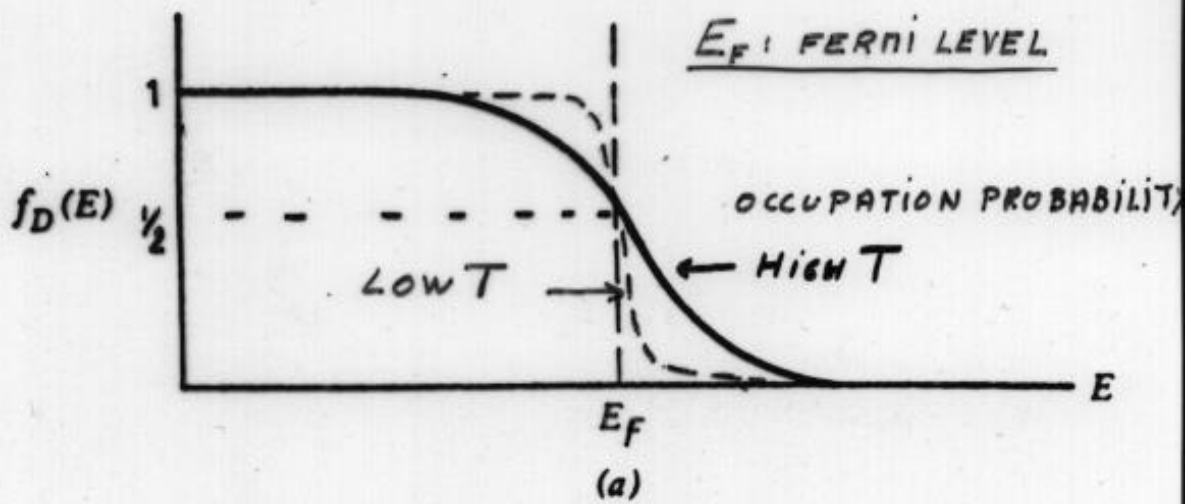
$$pn = n_i^2(T)$$

NEUTRALITY

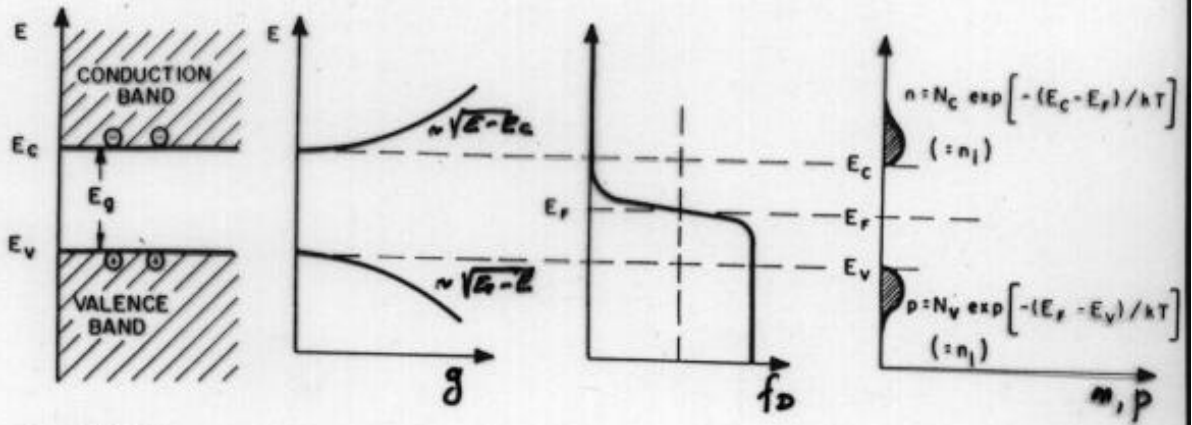
$$\underbrace{N_d^+ + p}_{\text{POSITIVE CHARGE}} = \underbrace{N_a^- + n}_{\text{NEGATIVE CHARGE}}$$

$$\left\{ \begin{aligned} N_d^+ + \frac{n_i^2}{n} &= N_a^- + n \\ n^2 + n(N_d^+ - N_a^-) - n_i^2 &= 0 \\ n &= \frac{N_d^+ - N_a^-}{2} + \left[\left(\frac{N_d^+ - N_a^-}{2} \right)^2 + n_i^2 \right]^{1/2} \\ p &= \frac{n_i^2}{n} \end{aligned} \right.$$

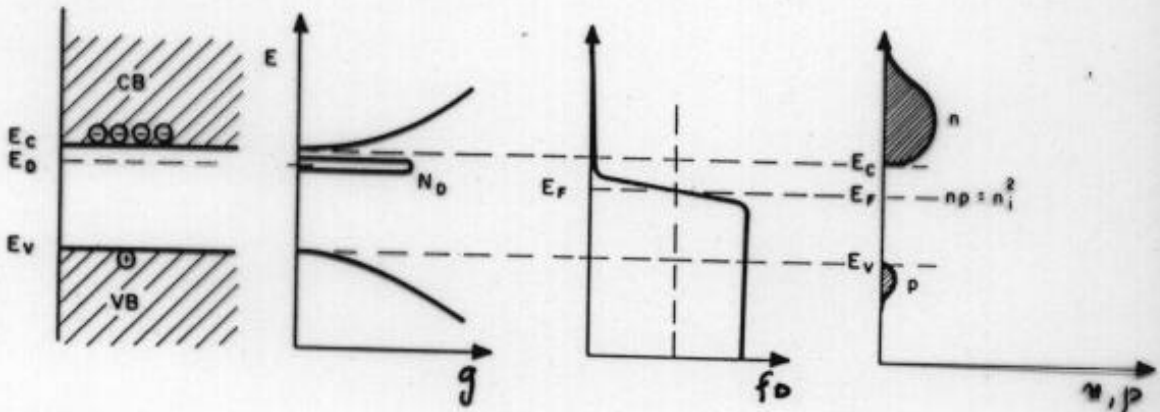
FERMI LEVEL : $f_D(E) = \frac{1}{1 + \exp[(E - E_F)/kT]}$



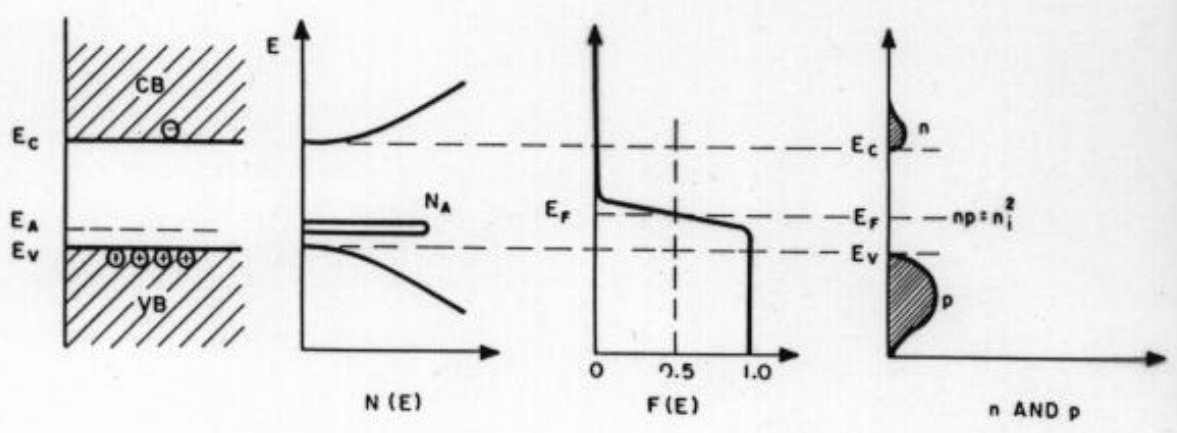
I N T R I N S I C



n - T Y P E



P - T Y P E



FERMI LEVEL

$$f_D(E) = \frac{1}{1 + \exp[(E - E_F)/kT]}$$

E_F : FERMI ENERGY LEVEL

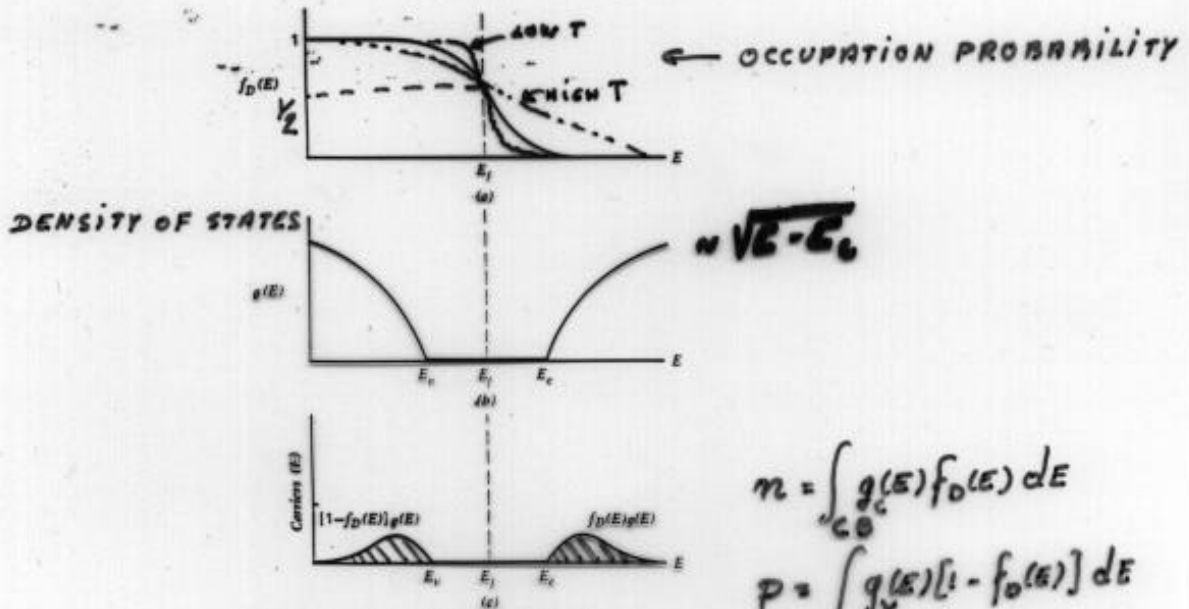


Figure 1.10 (a) Fermi-Dirac distribution function describing the probability that an allowed state at energy E is occupied by an electron. (b) The density of allowed states for a semiconductor as a function of energy; note that $g(E)$ is zero in the forbidden gap between E_v and E_c . (c) The product of the distribution function and the density-of-states function.

FOR $E_c - E_F \gg kT$
 $E_F - E_v \gg kT$ } $f_D(E) \approx f_n(E) = \exp\left(-\frac{E - E_F}{kT}\right)$ NON DEGENERATE

$$n = N_c \exp\left(\frac{E_c - E_F}{kT}\right)$$

$$p = N_v \exp\left(-\frac{E_F - E_v}{kT}\right)$$

$$N_c = 2 \left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

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

$$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

$$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

IMPURITY STATISTICS

- DONORS

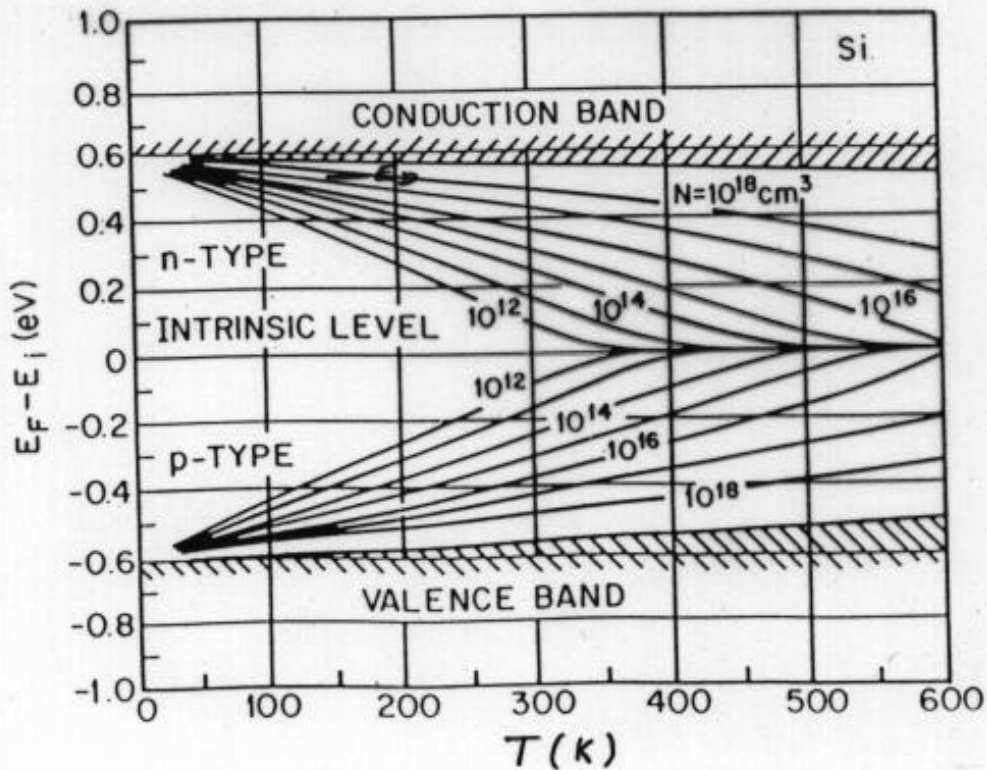
$$N_D^+ = N_D \left[1 - \frac{1}{1 + g_D \exp\left(\frac{E_D - E_F}{k_B T}\right)} \right]$$

g_D : DONOR LEVEL DEGENERACY
(= 2 IN Si)

- ACCEPTORS

$$N_A^- = \frac{N_A}{1 + g_A \exp\left(\frac{E_A - E_F}{k_B T}\right)}$$

g_A : ACCEPTOR LEVEL DEGENERACY
(= 4 IN Si)



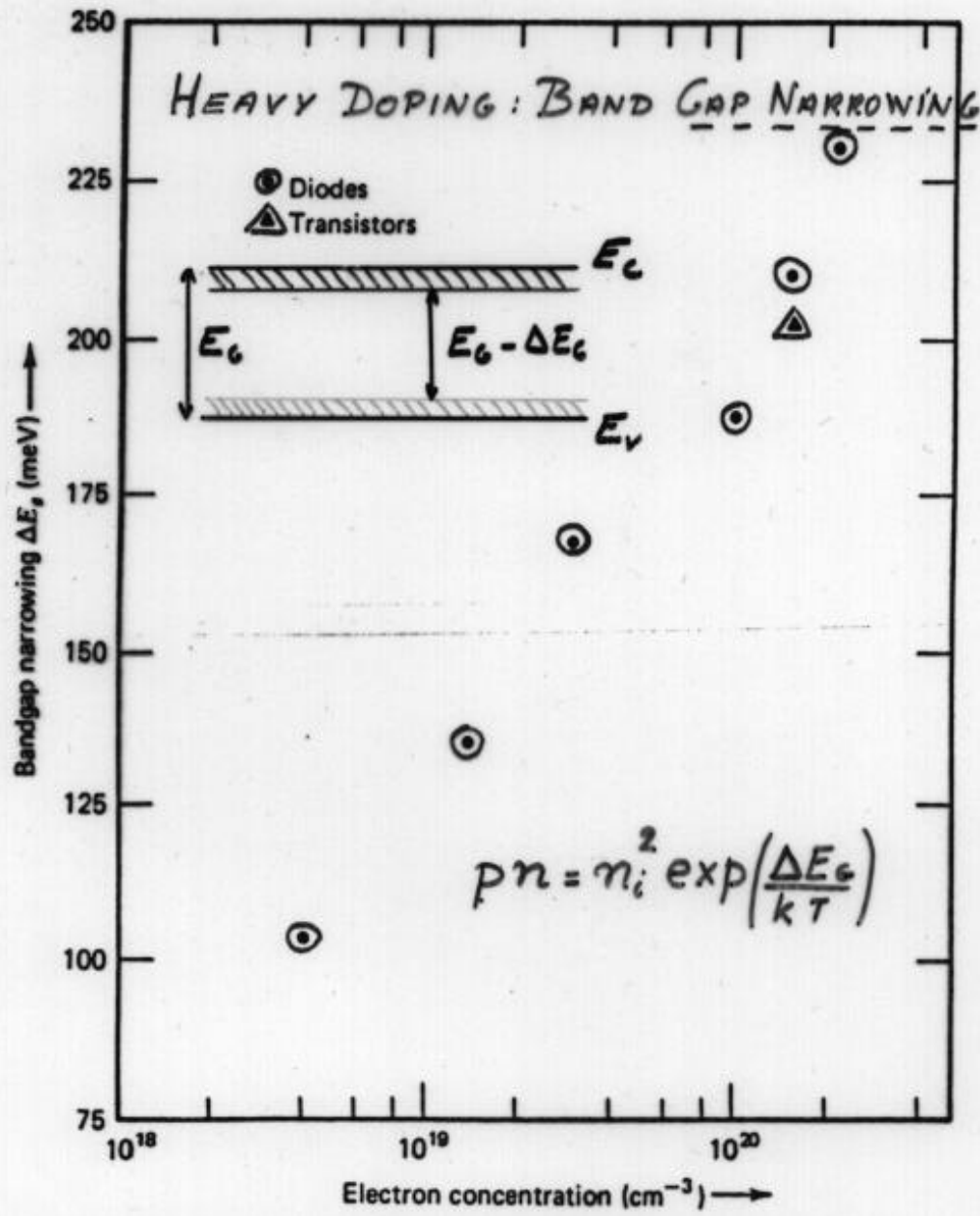


Figure 1.12 Energy-gap narrowing ΔE_g as a function of electron concentration. [A. Neugroschel, S. C. Pao, and F. A. Lindholm, IEEE Trans. Electr. Devices, ED-29, 894 (May 1982)].

QUASI FERRI LEVELS (NON-EQUILIBRIUM)

$$n = n_i \exp\left(\frac{E_{Fn} - E_i}{kT}\right)$$

$$E_{Fn} = E_i + kT \ln\left(\frac{n}{n_i}\right)$$

$$p = n_i \exp\left(\frac{E_i - E_{Fp}}{kT}\right)$$

$$E_{Fp} = E_i - kT \ln\left(\frac{p}{n_i}\right)$$

↓

$$pn = n_i^2 \exp\left(\frac{E_{Fn} - E_{Fp}}{kT}\right)$$

AT EQUILIBRIUM $E_{Fn} = E_{Fp} = E_F \rightarrow pn = n_i^2$

QUASI FERRI POTENTIALS

$$\phi_{Fn} = -\frac{E_{Fn}}{q}$$

$$\phi_{Fp} = -\frac{E_{Fp}}{q}$$

} CONVENIENT PARAMETERS FOR DEVICE MODELING.