LECTURE #25

EXTRINSIC SEMICONDUCTORS: INTENTIONALLY ADD IMPURITIES (i.e., "DOPE" THE SEMICONDUCTOR)

(1) n-type: NEGATIVE CHARGE CARRIERS
(e.g., ADD ATOMS WITH 5 VALENCE ELECTRONS TO A GROUP IV SEMICONDUCTOR)

↳ COLUMN V ELEMENTS: P, As, Sb → ELECTRON "DONORS"

* THE EXTRA ELECTRON IS THERMALLY PROMOTED TO THE CONDUCTION BAND, LEAVING BEHIND A POSITIVELY IONIZED IMPURITY

WHAT IS THE ENERGY OF THE DONOR LEVEL?

APPROXIMATE THE BINDING ENERGY ($E_c - E_D$) AS A HYDROGEN ATOM WITH THE DIELECTRIC CONSTANT OF THE SEMICONDUCTOR AND THE ELECTRON EFFECTIVE MASS:

$$E_c - E_D \simeq \left(\frac{e^2}{4\pi\varepsilon}\right)^2 \frac{m^*}{2\hbar^2}$$

FOR Si, $\varepsilon \sim 12\varepsilon_0$, $m^* = 0.05m$ ← FREE ELECTRON MASS

$$\Rightarrow E_c - E_D \simeq 0.05\,eV$$

SINCE DONOR LEVELS ARE SO CLOSE TO THE CONDUCTION BAND EDGE, NEARLY ALL DOPANTS ARE IONIZED AT ROOM TEMPERATURE.

$\Rightarrow \quad n \simeq N_d^+ \simeq N_d$ AT ROOM TEMPERATURE
(ASSUMING THAT $N_d \gg n_i$)

N_d = CONCENTRATION OF DONOR IMPURITIES
N_d^+ = CONCENTRATION OF IONIZED DONOR IMPURITIES

NOTE. THE PREVIOUS DERIVATION FOR n STILL HOLDS FOR EXTRINSIC SEMICONDUCTORS (ASSUMING THAT THE SYSTEM IS IN THERMAL EQUILIBRIUM)

$$\therefore \quad n = N_c e^{-(E_c - E_F)/k_B T} \simeq N_d \gg n_i$$
(ASSUMING NONDEGENERATE DOPING)

$$\Downarrow$$

$E_F > E_i$ FOR n-type

NOTE: USING OUR PREVIOUS DERIVATION OF E_i, WE CAN EXPRESS n AND p AS:

$$n = n_i e^{(E_F - E_i)/k_B T}$$

$$p = n_i e^{(E_i - E_F)/k_B T}$$

THESE EQUATIONS IMPLY THAT n-type DOPING INCREASE n AT THE EXPENSE OF p

↳ SEE FIG. 3-16

FURTHERMORE, $\boxed{np = n_i^2}$ LAW OF MASS ACTION

(2) p-type: POSITIVE CHARGE CARRIERS
(e.g., ADD ATOMS WITH 3 VALENCE ELECTRONS TO A GROUP IV SEMICONDUCTOR)

→ COLUMN III ELEMENTS: B, Al, Ga → ELECTRON "ACCEPTORS"

* ACCEPTOR LEVELS ARE NEAR THE VALENCE BAND EDGE
  ⇒ $p \simeq N_a^- \simeq N_a$ AT ROOM TEMPERATURE
  (ASSUMING THAT $N_a \gg n_i$)

  ⇒ $E_F < E_i$ FOR p-type

  ⇒ p-type DOPING INCREASES p AT THE EXPENSE OF DECREASING n

  → SEE FIG. 3-16

NOTE: AT HIGH TEMPERATURES, THERMALLY ACTIVATED CARRIERS ACROSS THE BAND GAP WILL EXCEED THE DOPANT CONCENTRATION

⇓

INTRINSIC REGIME

AT LOW TEMPERATURES, NOT ALL OF THE DOPANTS WILL BE IONIZED ⇒ IONIZATION REGIME

→ SEE FIG. 3-18

QUANTITATIVELY, THE CARRIER CONCENTRATIONS CAN BE CALCULATED WITH THE FOLLOWING RELATIONSHIPS:

(1) $N_a^- = N_a f(E_a) = N_a \frac{1}{1+e^{(E_a-E_F)/K_BT}}$

(2) $N_d^+ = N_d(1-f(E_d)) = N_d \frac{1}{1+e^{(E_F-E_d)/K_BT}}$

(3) SPACE CHARGE NEUTRALITY: $p + N_d^+ = n + N_a^-$

(4) LAW OF MASS ACTION: $np = n_i^2$

FOR EXAMPLE, CONSIDER A SEMICONDUCTOR DOPED WITH ACCEPTORS AND DONORS:

AT ROOM TEMPERATURE, $N_d^+ \simeq N_d$, $N_a^- \simeq N_a$

$\therefore p + N_d = n + N_a$, $np = n_i^2 \Rightarrow p = \frac{n_i^2}{n}$

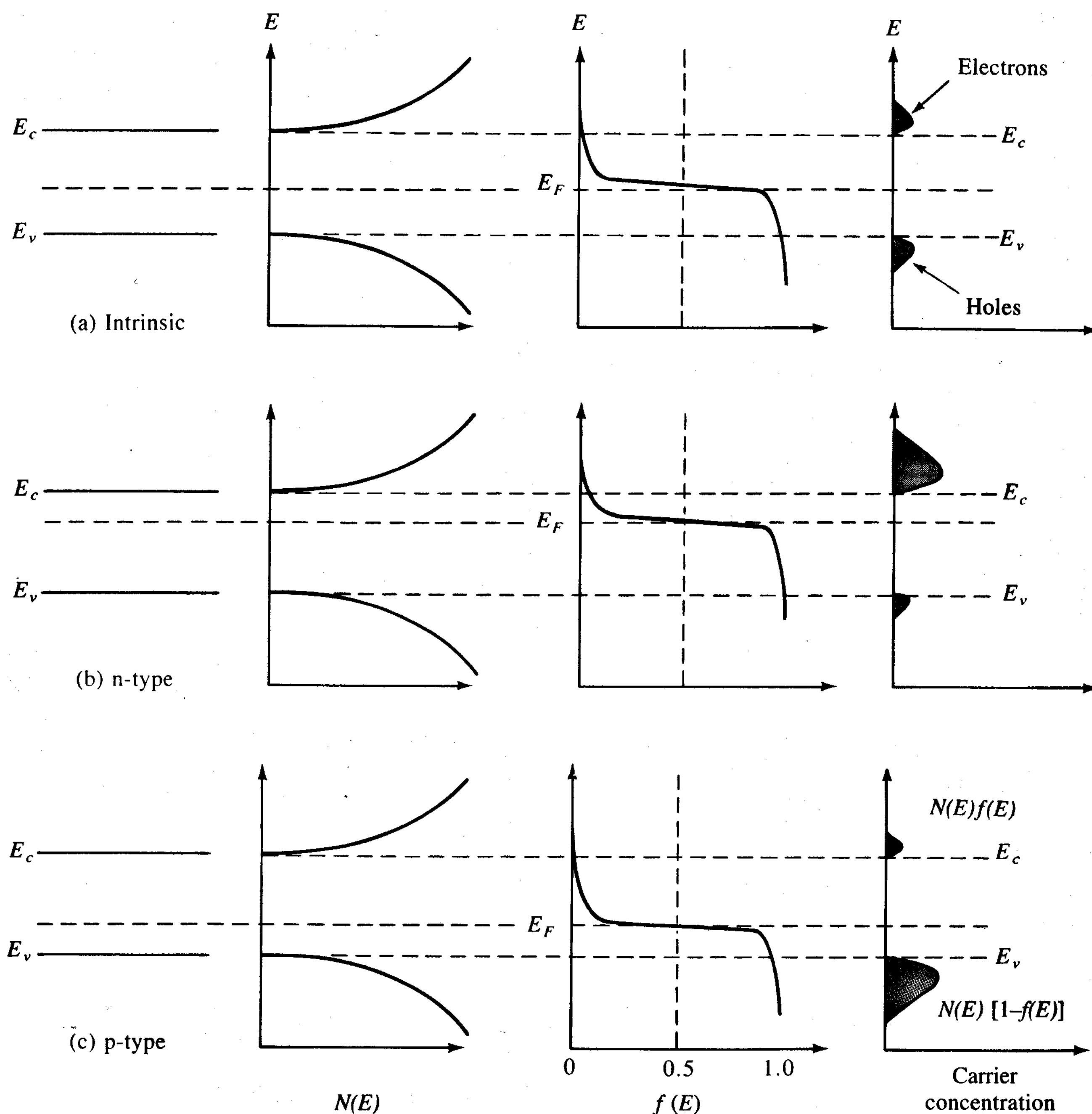
$\therefore \frac{n_i^2}{n} + (N_d - N_a) - n = 0$

$n^2 - (N_d - N_a)n - n_i^2 = 0$

$\therefore n = \frac{(N_d - N_a) + \sqrt{(N_d-N_a)^2 + 4n_i^2}}{2}$

IF $(N_d - N_a) \gg n_i$, $n \simeq N_d - N_a \Rightarrow$ COMPENSATION

i.e., THE NET ELECTRON CONCENTRATION IS APPROXIMATELY THE DIFFERENCE BETWEEN DONOR AND ACCEPTOR CONCENTRATIONS



Schematic band diagram, density of states, Fermi–Dirac distribution, and the carrier concentrations for (a) intrinsic, (b) n-type, and (c) p-type semiconductors at thermal equilibrium.

Figure 3-16

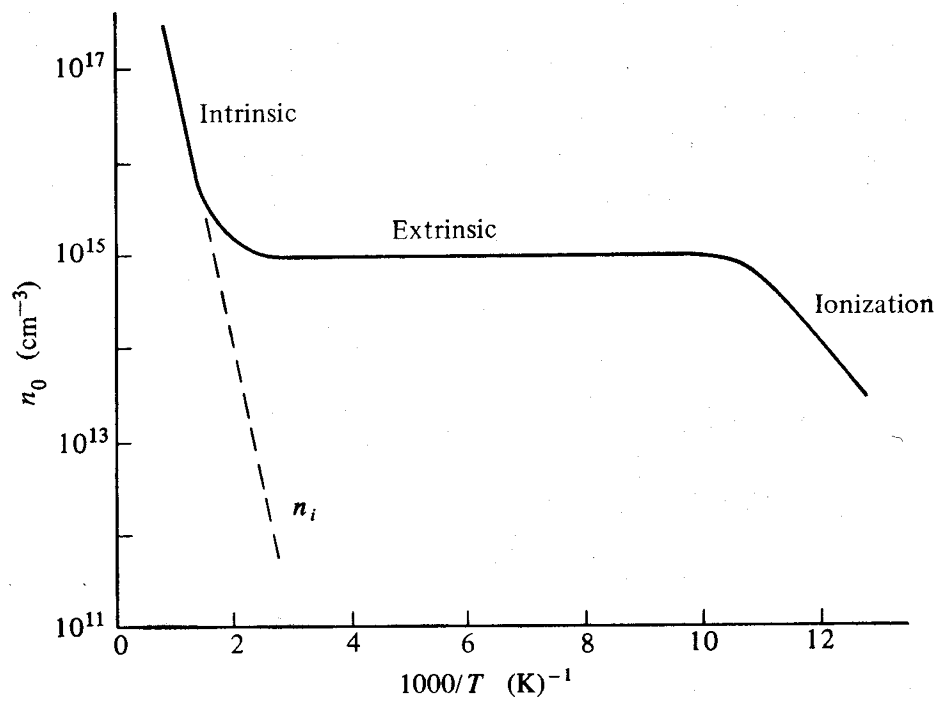


Figure 3-18 Carrier concentration vs. inverse temperature for Si doped with 10^{15} donors/cm^3.