

ECE4904 Lecture 2

Lec 1 Review: Energy Band Development

Electron energy levels quantized; energy exchange

Bonding Model

Mobile electron; Hole

Dopant atoms: Substitute for Si atom in lattice from column III, V

Energy Band Model

Energy level quantization

Dopant atoms in energy band model

Fermi level E_F : Energy at which $P\{\text{occupied}\} = 50\%$

Intrinsic Fermi level E_i : E_F for pure (intrinsic) semiconductor

Midway between E_C , E_V

Effect of Doping

Donor doping N_D moves E_F toward conduction band E_C

Acceptor doping N_A moves E_F toward valence band E_V

Carrier Concentration: n electrons ; p holes

Intrinsic material: $n = p = n_i = 1E+10 / \text{cm}^3$ at $T=300K$

Strongly temperature dependent!

E_F relative to E_i tells you if semiconductor is n-type or p-type

np product relationship: $np = n_i^2$ (nondegenerate semiconductor in equilibrium)

Most cases: Majority carrier concentrations determined by doping

Handouts:

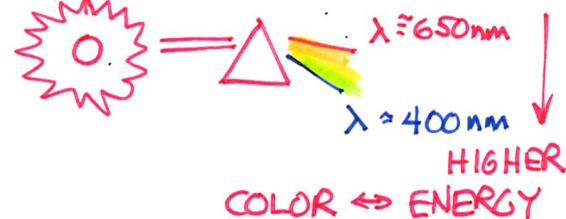
Textbook figures / Bonding model slides / Energy band model "tour"

Bonding model 1-minute quiz

Doping cases approximations

ENERGY LEVELS (QUANTUM STUFF)

SUNLIGHT



ENERGY IN PHOTON
DEPENDS ON WAVELENGTH
 $E = h\nu$ } FREQ
ENERGY PLANCK'S
6.63 E-34 joule · sec

DEFINE
Ø ENERGY:
∞ FAR AWAY

$$\lambda = \frac{c}{\nu} \Rightarrow E = \frac{hc}{\lambda}$$

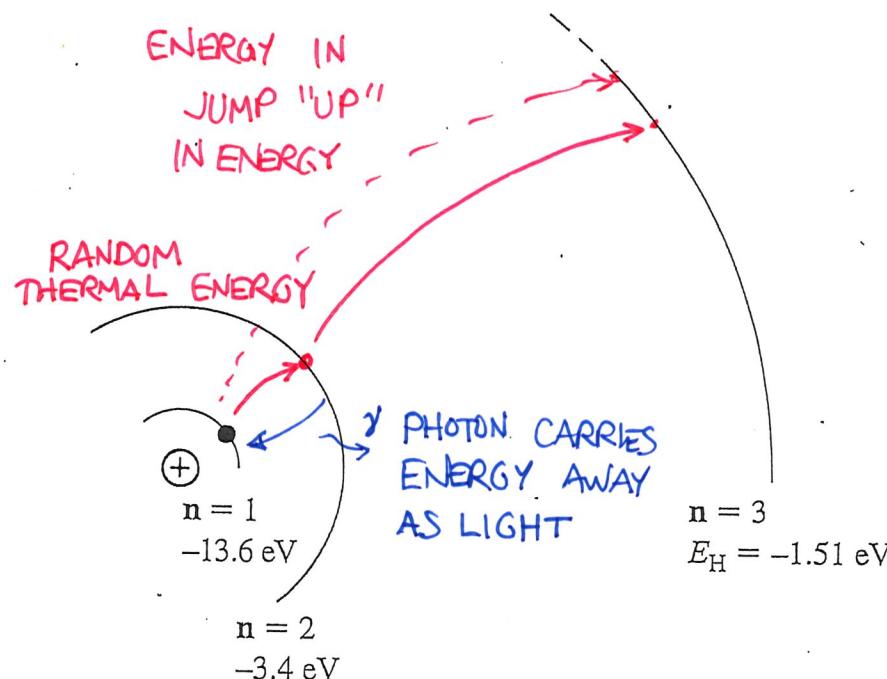
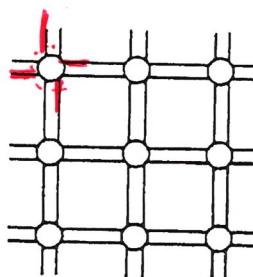


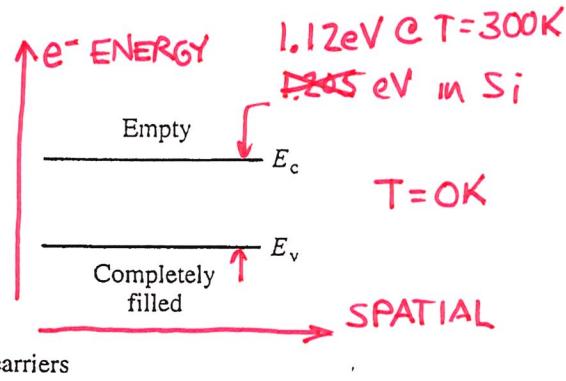
Figure 2.1 The hydrogen atom—idealized representation showing the first three allowed electron orbits and the associated energy quantization.

e^- SHARED
IN BOND

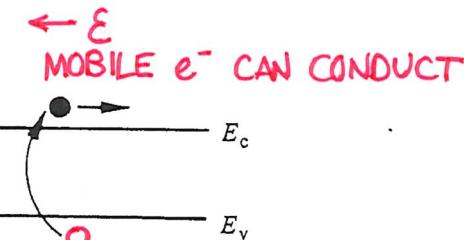
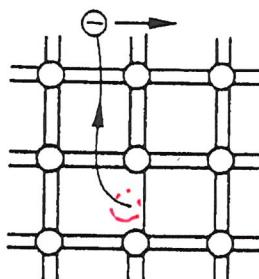
BONDING MODEL



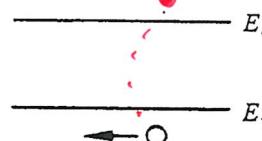
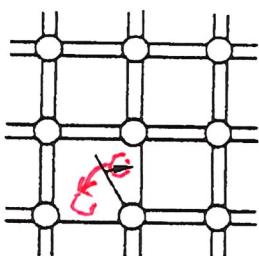
ENERGY BAND MODEL



e^- BREAKS FREE
OF COVALENT
BOND

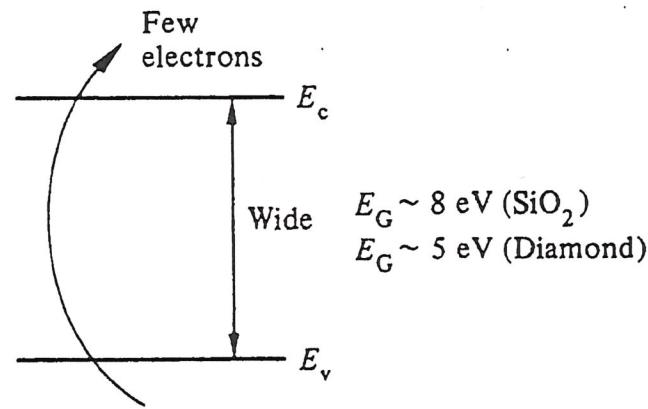


MOBILE "HOLE"
BEHAVES LIKE
MOBILE +
CHARGE

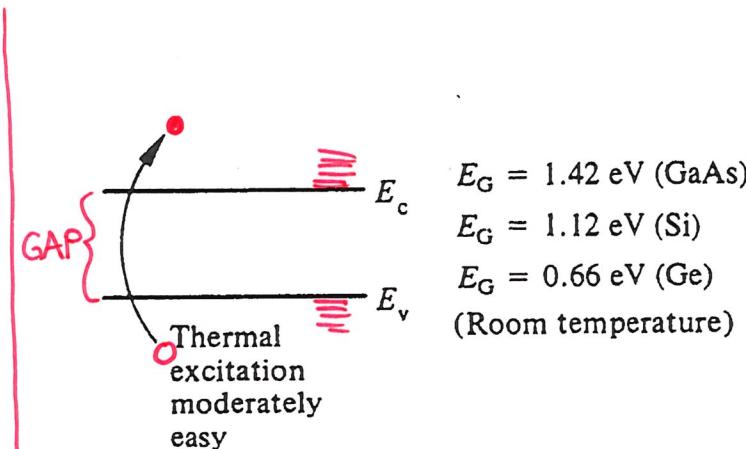


(c) The hole

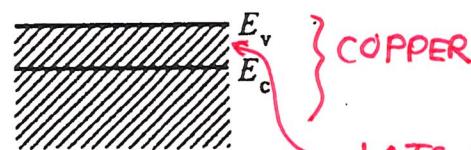
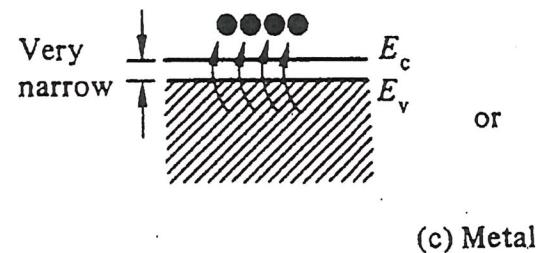
Figure 2.7 Visualization of carriers using the bonding model (left) and the energy band model (right). (a) No-carrier situation; (b) visualization of an electron; (c) visualization of a hole.



(a) Insulator



(b) Semiconductor



LOTS OF e^- WITH ENERGY $> E_c$
AVAILABLE TO CONDUCT

Figure 2.8 Explanation of the distinction between (a) insulators, (b) semiconductors, and (c) metals using the energy band model.

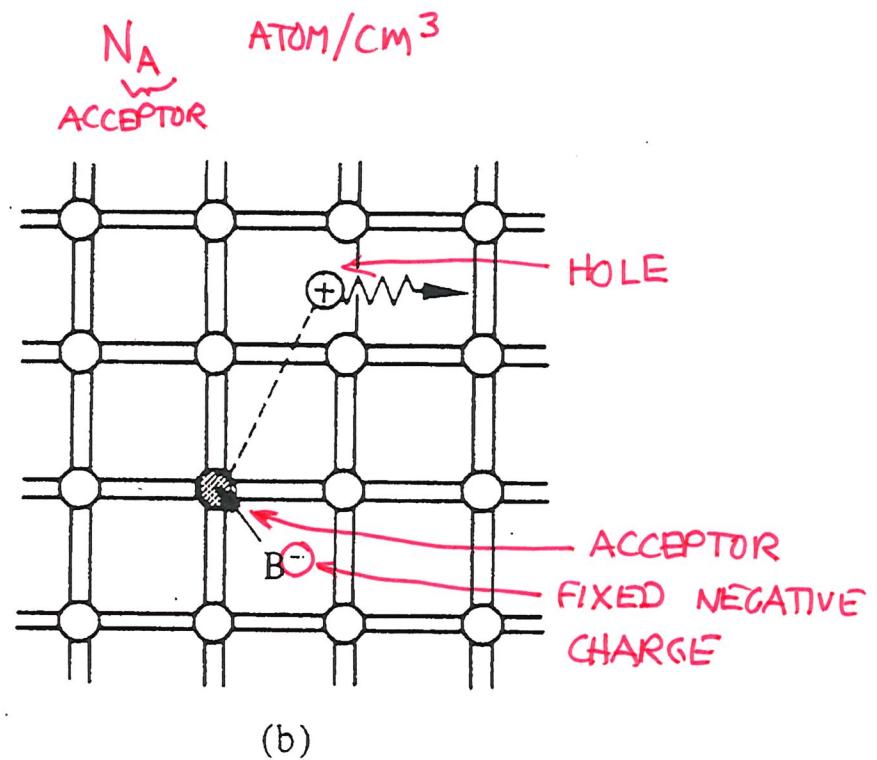
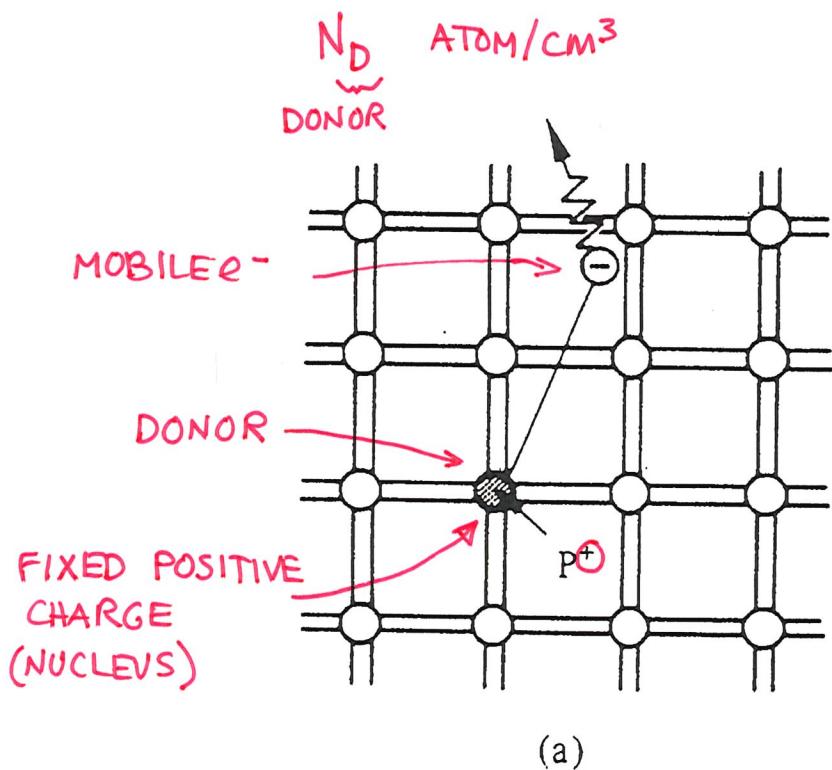
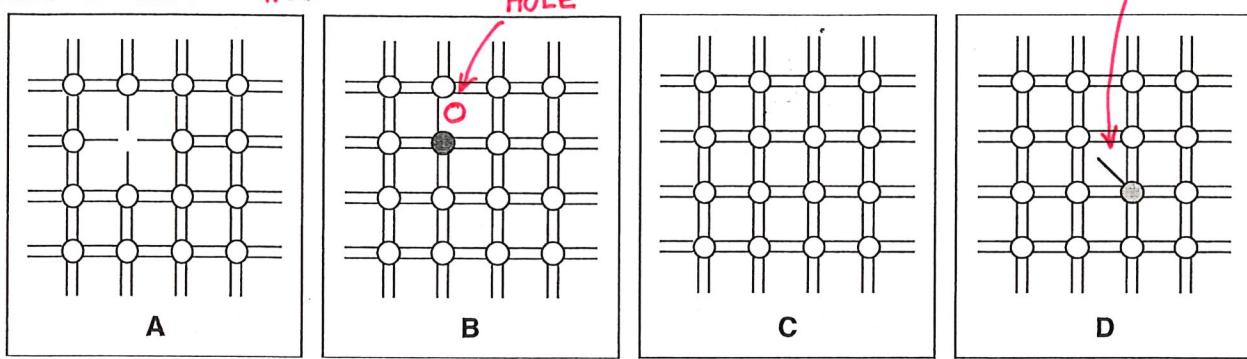


Figure 2.10 Visualization of (a) donor and (b) acceptor action using the bonding model. In (a) the Column V element P is substituted for a Si atom; in (b) the Column III element B is substituted for a Si atom.

ECE4904 One Minute Quiz: Bonding Model

Four bonding model diagrams, labeled A – D, are shown below:
 "POINT DEFECT" "TRAP"



For each of the five types of semiconductor situations described below, indicate the letter of the corresponding bonding diagram AND explain your choice (no more than one or two simple but convincing sentences necessary)!

Note: A diagram may be used once, more than once, or not at all.

- i) D A semiconductor doped with a donor impurity.

DONATE EXTRA e^-
EXTRA LINE IN BONDING MODEL

- ii) B A P-type semiconductor.

positive mobile charges
HOLES MISSING e^- MISSING LINES IN BONDING MODEL

- iii) D An N-type semiconductor.

negative mobile charges dominate

- iv) C An intrinsic semiconductor at temperature T=0K.

PURE MATERIAL (NO DOPANTS) ALL e^- USED IN BONDING

- v) B A semiconductor doped with an acceptor impurity.

MISSING e^- CAN ACCEPT e^- FROM NEARBY ATOM

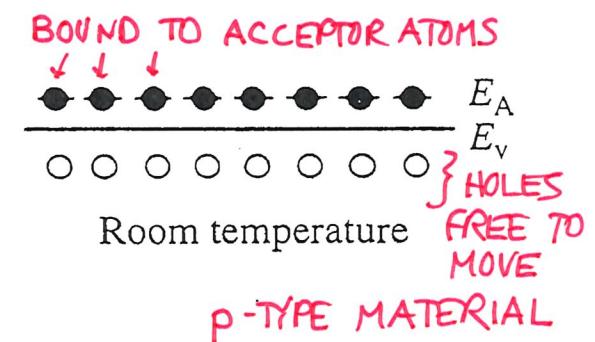
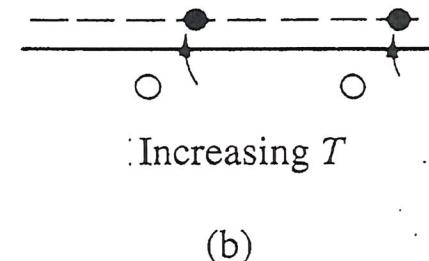
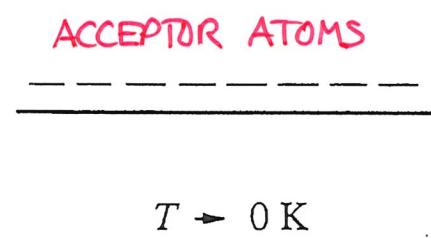
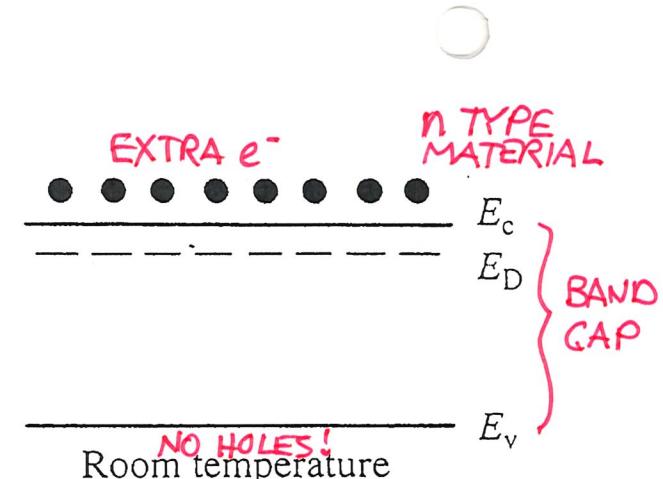
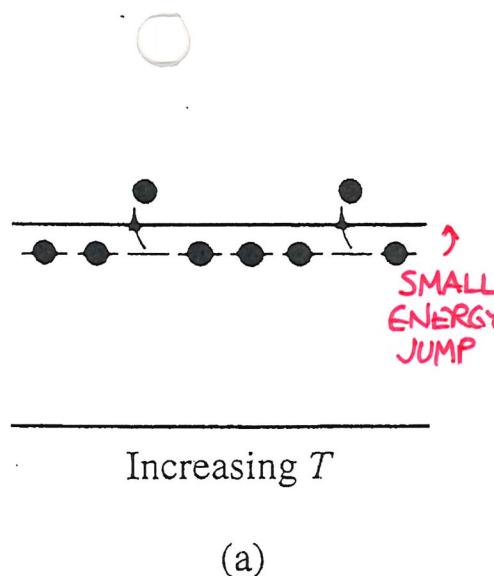
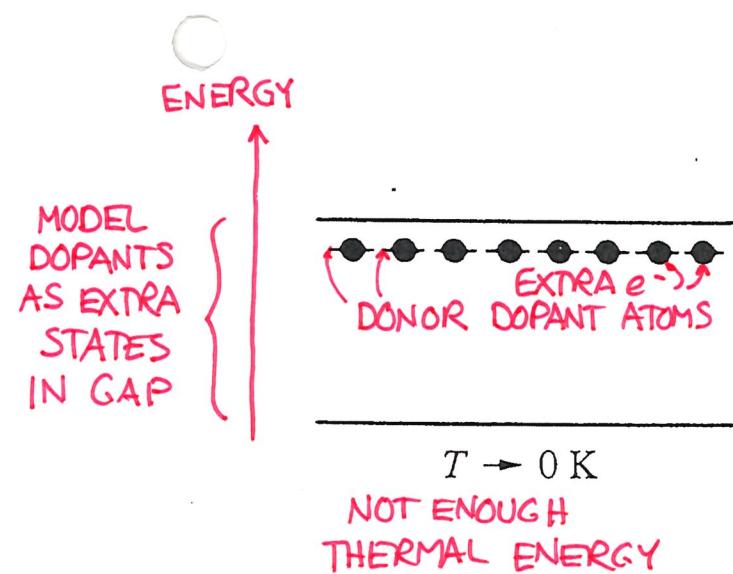


Figure 2.13 Visualization of (a) donor and (b) acceptor action using the energy band model.

MOBILE CHARGE

$$n = n_i; e^{(E_F - E_i)/kT}$$

$$p = n_i; e^{(E_i - E_F)/kT}$$

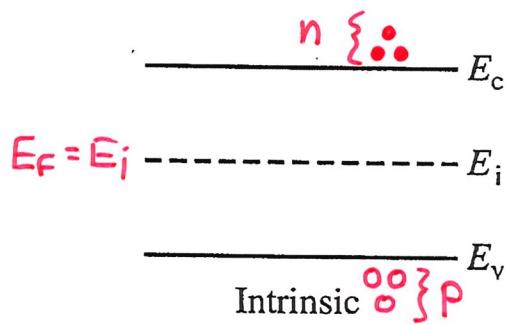
ALSO CHARGE NEUTRALITY
(CONSIDER FIXED CHARGES)

$$q_e(p - n + \underbrace{N_D - N_A}_{\text{FIXED FROM DOPANT ATOMS}}) = 0 \quad \left. \begin{array}{l} \text{COMBINE WITH} \\ np = n_i^2 \end{array} \right\}$$

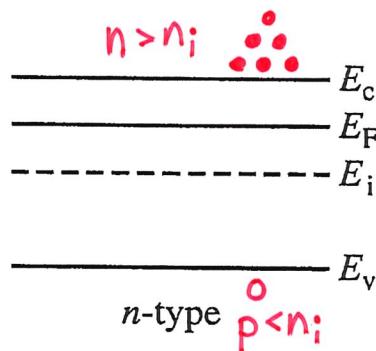
\Rightarrow HOW DOES DOPING AFFECT n, p ?

INTRINSIC CARRIER CONCENTRATION

$$n = p = \tilde{n}_i$$



$E_F > E_i$: n-TYPE



$E_F < E_i$: p-TYPE
CARRIER MODELING

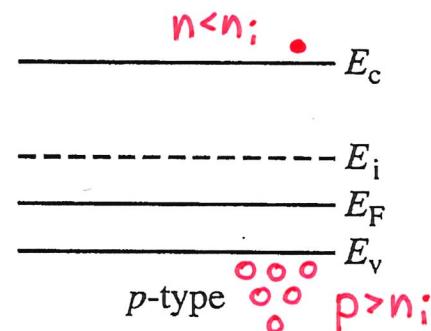


Figure 2.18 “At a glance” representation of intrinsic (left), n-type (middle), and p-type (right) semiconductor materials using the energy band diagram.

E_F FERMI ENERGY: 50% PROBABILITY THAT STATE IS OCCUPIED

FERMI FUNCTION ~~NOT~~ PROBABILITY THAT A STATE AT A GIVEN ENERGY IS OCCUPIED

DOESN'T MEAN THAT THERE IS A STATE AT THAT ENERGY!

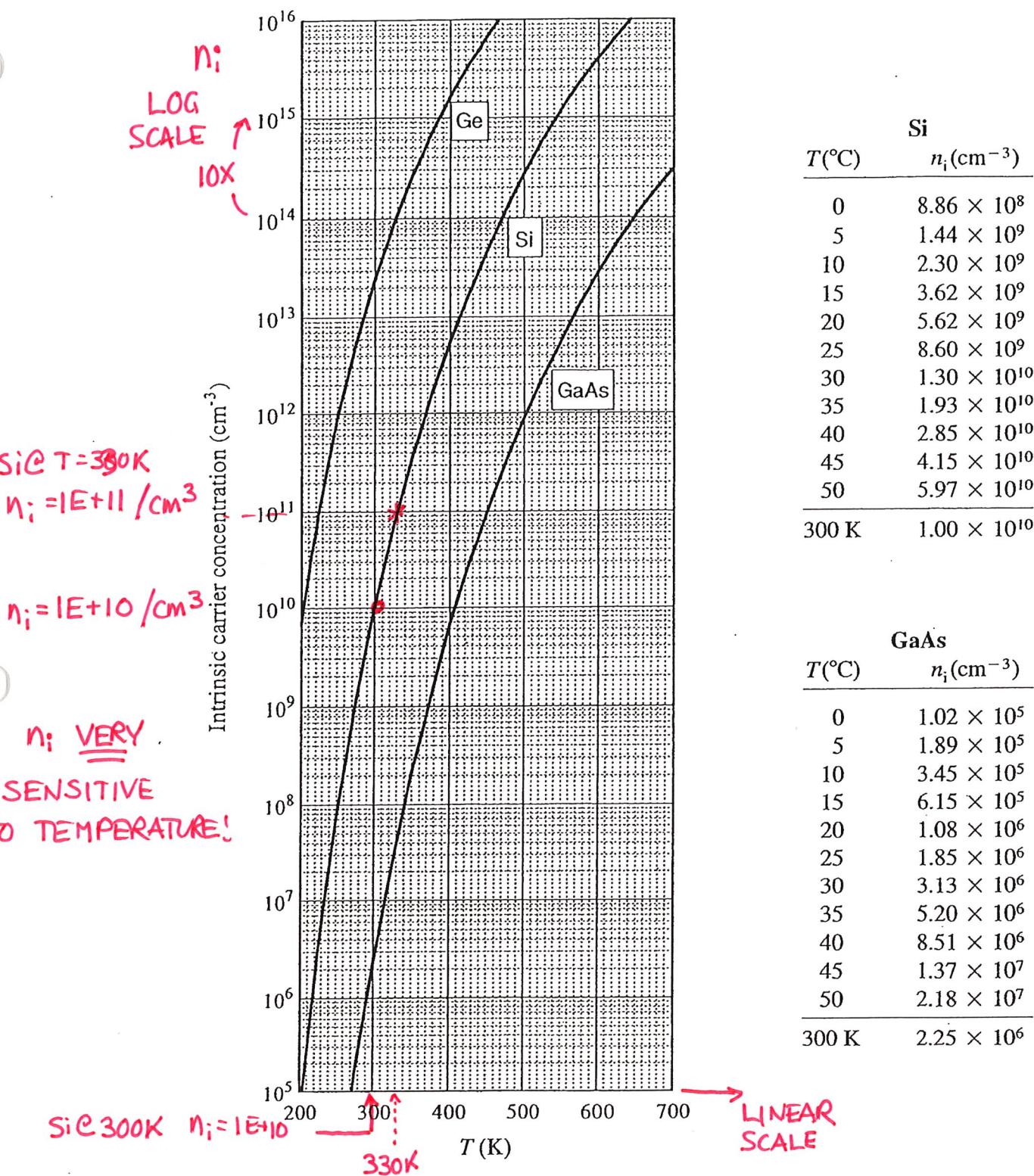
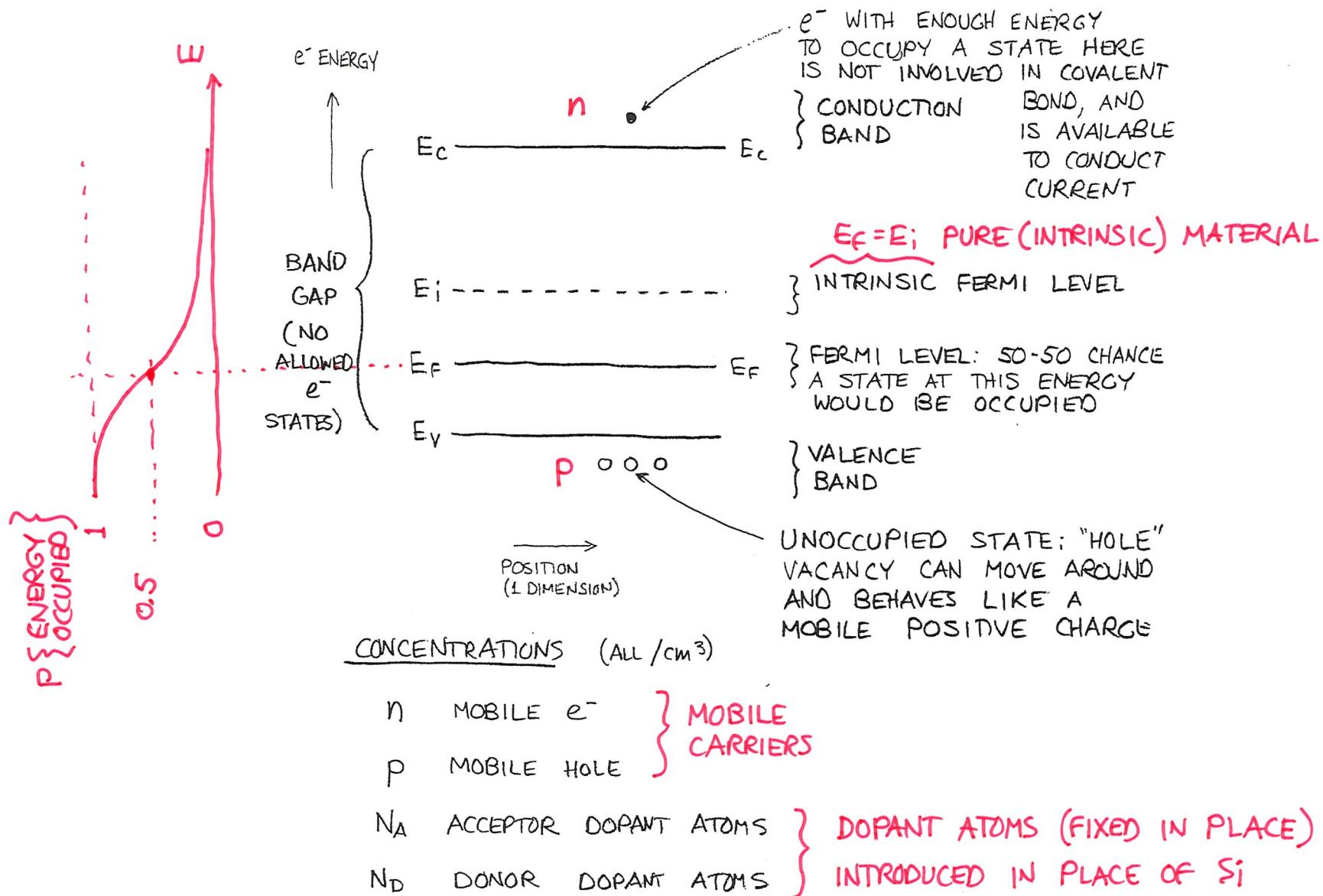


Figure 2.20 Intrinsic carrier concentrations in Ge, Si, and GaAs as a function of temperature.

n_i NOT CONSTANT! SENSITIVE TO TEMPERATURE
DON'T WANT PERFORMANCE TO DEPEND ON n_i (USUALLY)

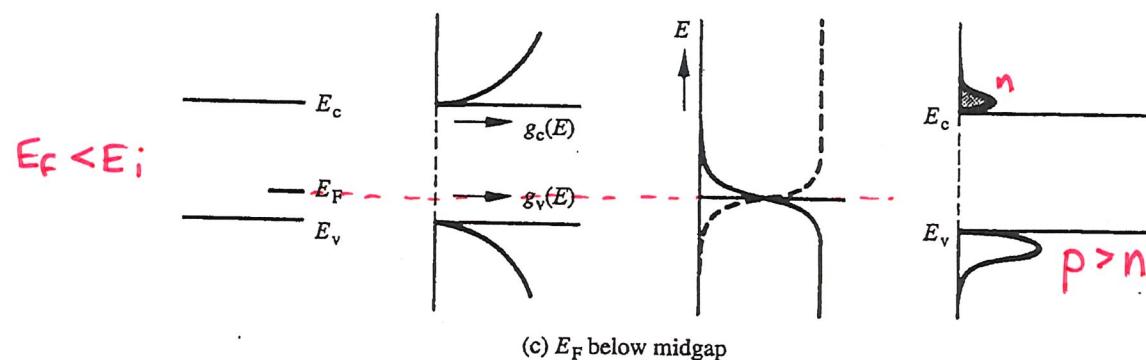
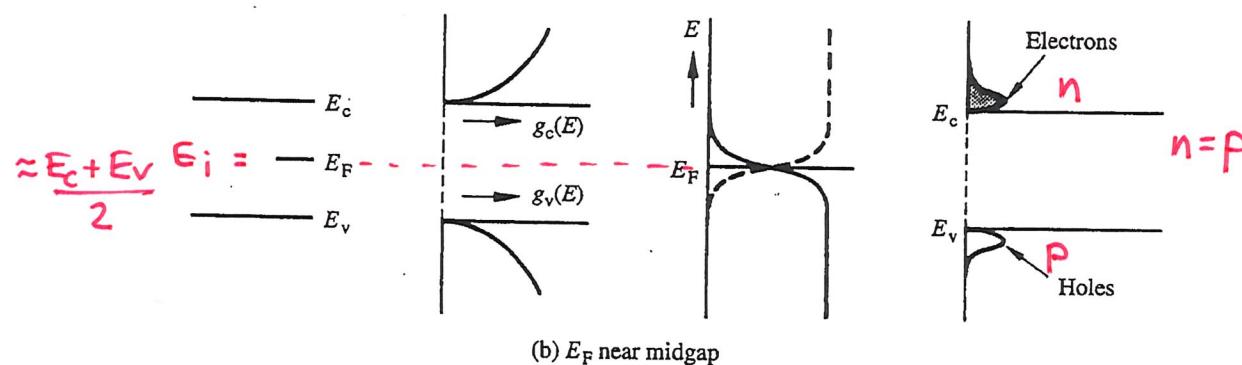
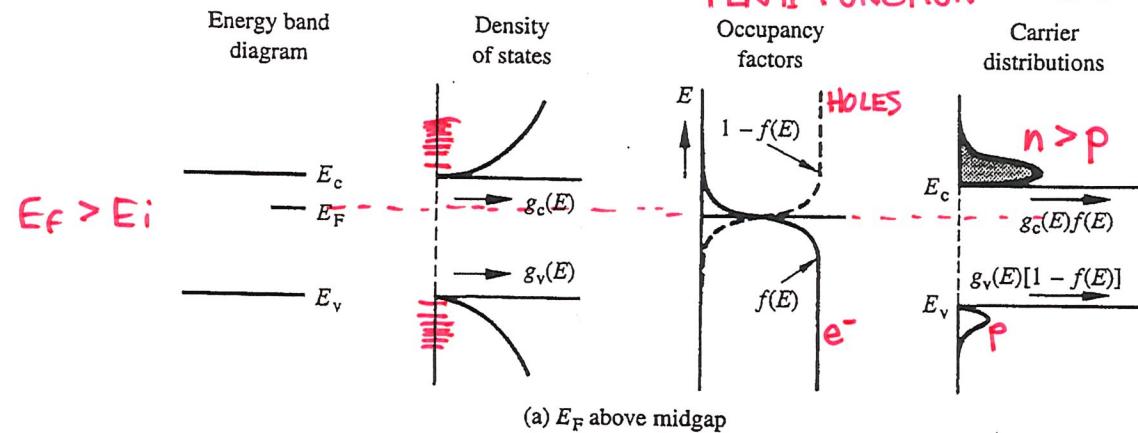
ECE4904 Energy Band Diagram "Tour"



FERMI FUNCTION

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

.026 eV @ T=300K



E_F RELATIVE
TO
 E_c
 E_i
 E_v

TELLS YOU
P-TYPE
N-TYPE

Figure 2.16 Carrier distributions (not drawn to scale) in the respective bands when the Fermi level is positioned (a) above midgap, (b) near midgap, and (c) below midgap. Also shown in each case are coordinated sketches of the energy band diagram, density of states, and the occupancy factors (the Fermi function and one minus the Fermi function).

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

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

$$np = n_i^2$$

"np PRODUCT RELATIONSHIP"

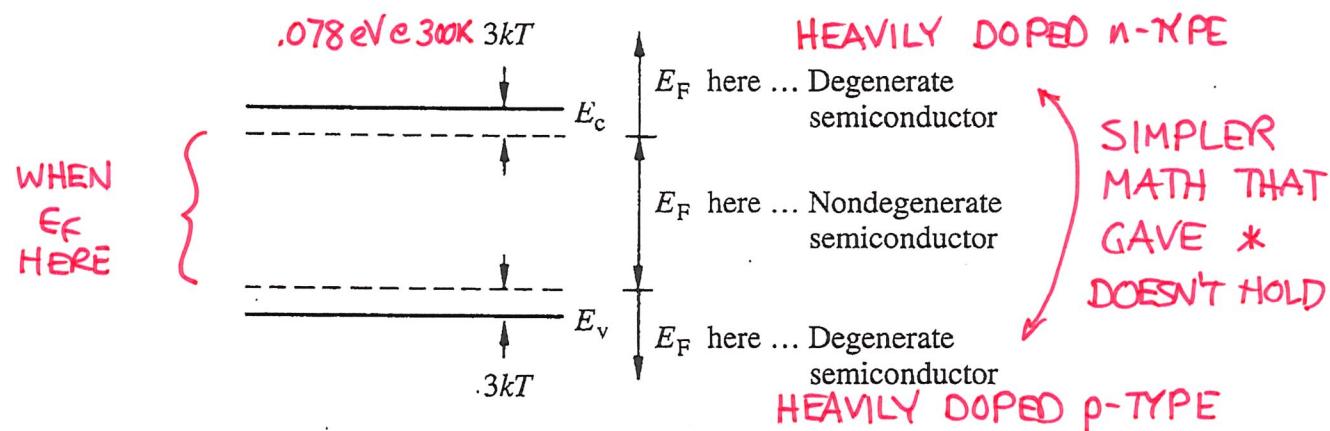


Figure 2.19 Definition of degenerate/nondegenerate semiconductors.

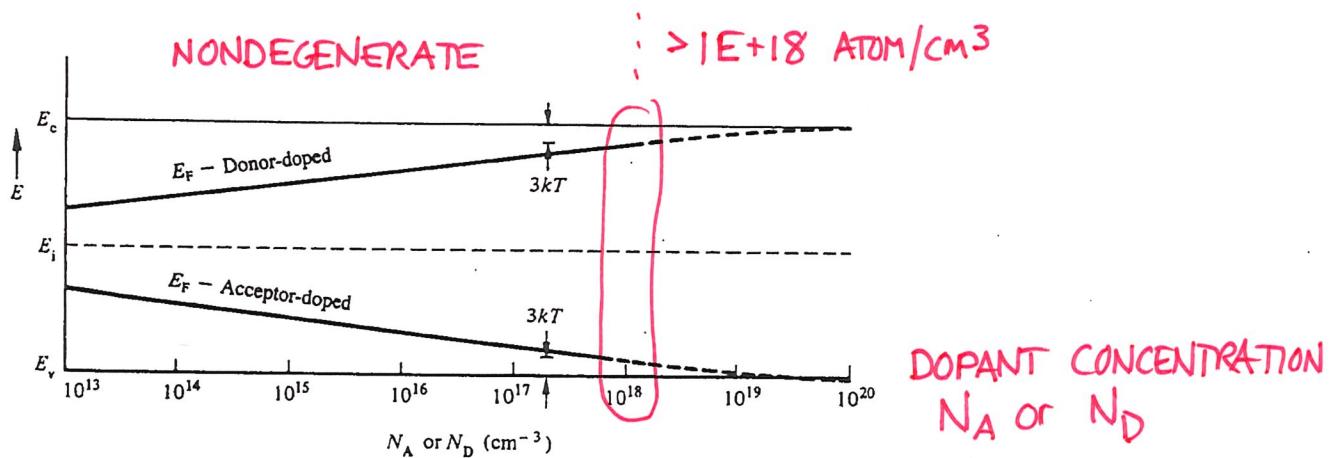


Figure 2.21 Fermi level positioning in Si at 300 K as a function of the doping concentration. The solid E_F lines were established using Eq. (2.38a) for donor-doped material and Eq. (2.38b) for acceptor-doped material ($kT = 0.0259 \text{ eV}$, and $n_i = 10^{10}/\text{cm}^3$).

Case 1: Intrinsic Semiconductor ($N_A=0, N_D=0$)

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2} \Rightarrow n = n_i$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2} \Rightarrow p = n_i$$

Case 2a: Semiconductor Doping dominated by Donors ($\underline{N_D \gg N_A}$, $\underline{N_D \gg n_i}$)

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2} \Rightarrow n = N_D$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

$$np = n_i^2 \Rightarrow p = \frac{n_i^2}{N_D} < n_i$$

$$p = \frac{(1E+10)^2}{1E+15} = 1E+5$$

Case 2b: Semiconductor Doping dominated by Acceptors ($\underline{N_A \gg N_D}$, $\underline{N_A \gg n_i}$)

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$n = \frac{n_i^2}{N_A}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2} \Rightarrow p = N_A$$

MAJORITY CARRIER CONCENTRATION:
FROM DOPING

NICE! NOT TEMP DEPENDENT!

Case 3: Doped Semiconductor at High Temperature ($n_i \gg |N_D - N_A|$)

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2} \quad n = n_i$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2} \quad p = n_i$$

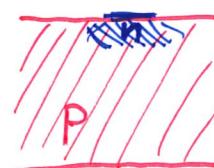
ALL SEMICONDUCTORS
EVENTUALLY "LOOK"
INTRINSIC AT HIGH
ENOUGH TEMPERATURE

Case 4: Compensated Semiconductor (N_A, N_D comparable)

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

NEED FULL EXPRESSION



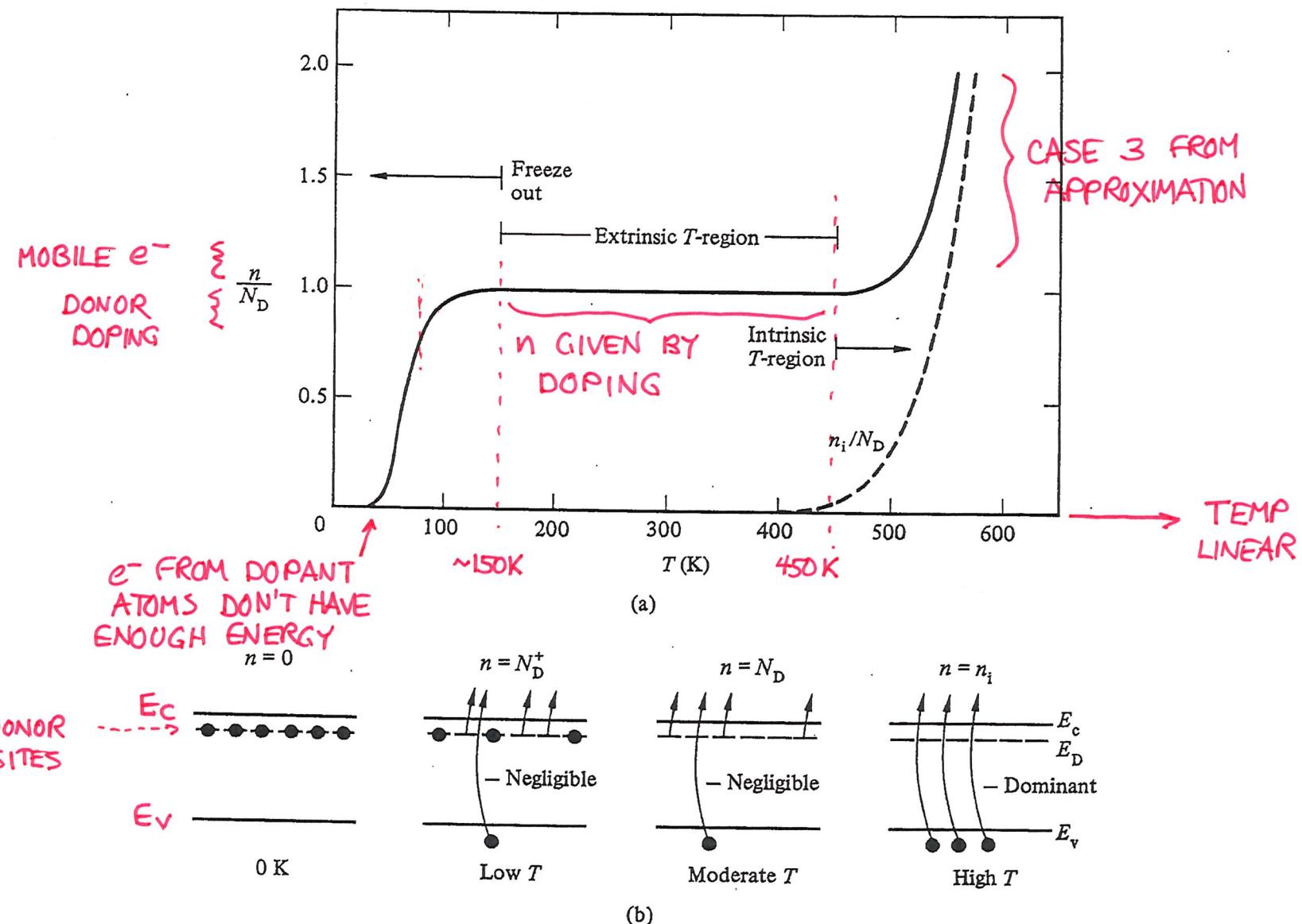


Figure 2.22 (a) Typical temperature dependence of the majority-carrier concentration in a doped semiconductor. The plot was constructed assuming a phosphorus-doped $N_D = 10^{15}/\text{cm}^3$ Si sample. n_i/N_D versus T (dashed line) has been included for comparison purposes. (b) Qualitative explanation of the concentration-versus-temperature dependence displayed in part (a).