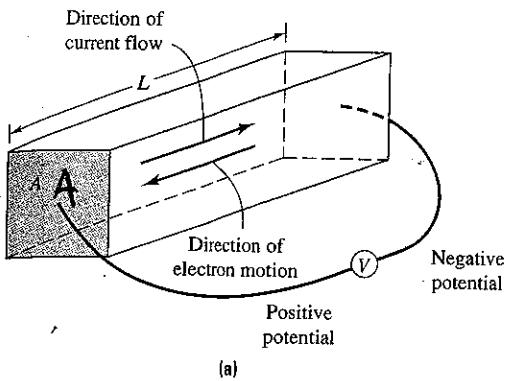


ELECTRICAL PROPERTIES

OBSERVATION

OHM'S LAW

$V=IR$



$$V = I R$$

Chapter 10 Electrical Properties

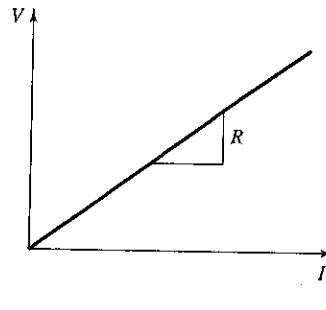


FIGURE 10.2-1 A simple electrical conduction experiment. (a) A bar of material of length L and cross-sectional area A is subjected to a voltage V . (b) The response of the system, current flow I , is a linear function of the magnitude of the driving force, voltage V . The constant of proportionality, or slope, is the resistance R .

$R(L, A)$ experimental

$$L \rightarrow 2L \Rightarrow R \rightarrow 2R$$

$$R \propto L$$

$$A \rightarrow 2A \Rightarrow R \rightarrow \frac{R}{2}$$

$$R \propto \frac{1}{A}$$

}

$$R \propto \frac{L}{A} \quad \rho = \text{RESISTIVITY}$$

$$\Rightarrow R = \rho \frac{L}{A} \Rightarrow \rho [\Omega m]$$

$$R [\Omega] \quad L [m] \quad A [m^2] \quad \rho = \rho \frac{m}{m^2}$$

$$\rho = \frac{1}{\sigma}$$

$\sigma = \text{CONDUCTIVITY}$
 $\hookrightarrow [\Omega m]^{-1}$ (OR SIEMENS??)
CHECK IT OUT

$$\rho = \sigma^{-1}$$

E_1

$$V = RI \Rightarrow V = \rho \frac{L}{A} I = \rho L J \Rightarrow \frac{V}{L} = \rho J \Rightarrow E = \rho J$$

$$\frac{I}{A} = J \quad \xrightarrow{\text{DENSITY}}$$

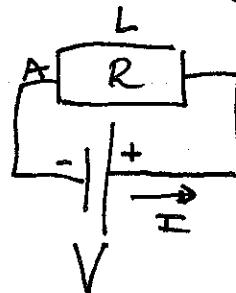
$$V = E \cdot L \quad \xrightarrow{\text{volt & electric field}} \quad \hookrightarrow J = \sigma E$$

$$R = \Omega$$

$$V = \text{Volt}$$

$$I = \text{Ampere} = \frac{C}{Sec}$$

SIMBOLES



CONVENTION

CURRENT FROM
 $\oplus \rightarrow \ominus$
(ONLY CONVENTION
DEPENDS ON CARRIER)

TABLE 10.2-1 Electrical conductivities for a variety of materials at room temperature.

Class of materials	σ [$(\Omega \cdot \text{cm})^{-1}$]
Polymer	
Nylon	$10^{-12} - 10^{-15}$
Polycarbonate	5×10^{-17}
Polyethylene	$< 10^{-16}$
Polypropylene	$< 10^{-15}$
Polybutyrene	$< 10^{-16}$
Polytetrafluoroethylene	10^{-18}
Polyvinylchloride	$10^{-12} - 10^{-15}$
Phenoformaldehyde	10^{-13}
Polyesters	10^{-10}
Silicones	$< 10^{-12}$
Acetal	10^{-15}
Metals and alloys	
Al	3.8×10^7
Ag	6.3×10^7
Au	4.3×10^7
Co	1.6×10^7
Cr	7.8×10^7
Cu	6.0×10^7
Fe	1.0×10^7
Mg	2.2×10^7
Ni	1.5×10^7
Pt	9.2×10^4
Pb	4.8×10^4
Pt	9.4×10^4
Sn	9.1×10^4
Ta	8.0×10^4
Zn	1.7×10^4
Zr	2.5×10^4
Plain carbon steel (1020)	1.0×10^4
Stainless steel (304)	1.4×10^4
Gray cast iron	1.5×10^4
Ceramics	
ReO ₃	5.0×10^3
ClO ₄	3.5×10^3
SiC	1.0×10^3
Fe ₂ O ₃	1.0×10^3
SiO ₂	10^{-14}
Al ₂ O ₃	10^{-14}
Si ₃ N ₄	10^{-14}
MgO	$< 10^{-14}$
Si	1.0×10^0
Ge	2.5×10^0

$$\text{OHM'S } V=RI \Leftrightarrow J=\sigma E$$

RESULT \leftarrow FORCE
MOVEMENT

GOOD CONDUCTORS

σ BIG shows 23 ORDERS OF MAGNITUDE

TOP SILVER $\sigma_{\text{Ag}} = 6.3 \times 10^5 (\Omega \cdot \text{cm})^{-1}$

TO POLYMERS $\sigma \sim 10^{-18} !!$
INSULATORS

Si & Ge are INSULATORS $\sigma \sim 10^{-4}, 10^{-2}$

CONDUCTIVITY DEPENDS ON FACTOR

1) DENSITY OF CARRIERS

PER UNIT VOLUME $N (\frac{\text{m}^{-3}}{\text{cm}^{-3}})$

2) CHARGE OF CARRIER

COLLOMB C

3) MOBILITY $\mu (\frac{\text{m}^2}{\text{V.s}})$

RATIO SPEED

ELECTRIC - FIELD

~~SPEED~~

1 LION $\rightarrow N = 10 \text{ mph}$

$\pi \pi^b \rightarrow -\pi^b$

RATIO SPEED
OF LIONS

3 LIONS

$\pi \pi^b \pi \pi^b \rightarrow -\pi^b$

$N = 30 \text{ mph}$

E2

\Rightarrow MOBILITY OF THE TEACHER

MOBILITY \Rightarrow BUILD σ

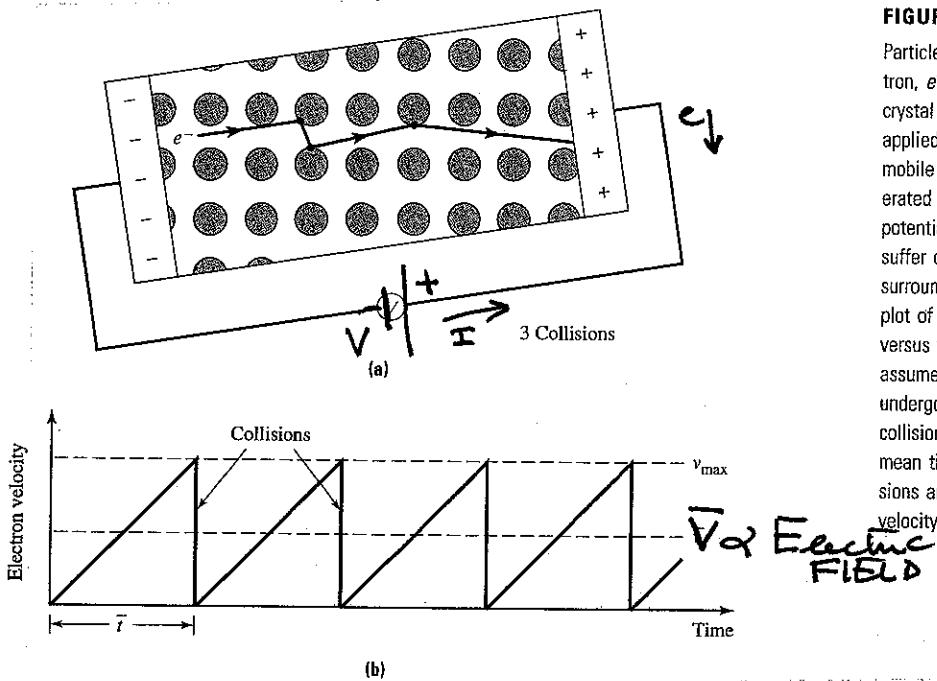


FIGURE 10.2-2

Particle model of an electron, e^- , moving through a crystal lattice. (a) Under an applied electric field, the mobile electrons are accelerated toward the positive potential and occasionally suffer collisions with the surrounding ion cores. (b) A plot of electron velocity versus time for an electron assumed to continuously undergo the acceleration-collision cycle (\bar{t} is the mean time between collisions and \bar{v} is the average velocity).

COLLISIONS :- START FROM $V=0$ }
 - ACCELERATION TO v_{max} }
 - COLLISION & RESTART } *Start again*

COLLISION every \bar{t} relaxation time !

$$V = at \Rightarrow$$

$$(F = ma)$$

$$\frac{a}{\text{acc}} m = \frac{F}{\text{Force}} e \Rightarrow v_{\text{max}} = a \bar{t}$$

$$a \propto E$$

$N_{\text{avg}} \propto N_{\text{max}}$

$$N_{\text{avg}} = N_{\text{max}} / \bar{t}$$

$\propto E_{\text{FIELD}}$

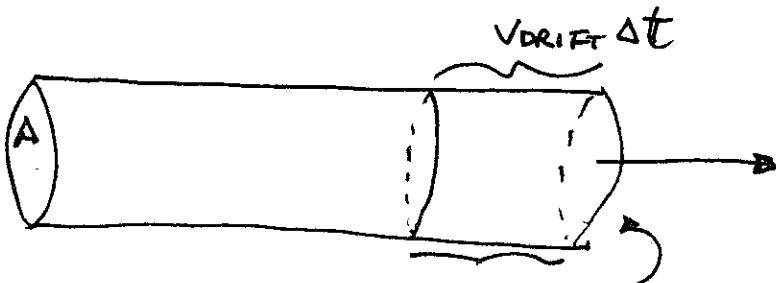
$N_{\text{avg}} = \text{DRIFT VELOCITY} !! \sim \text{cm/s mm/s SMALL}$

$$N_{\text{DRIFT}} = \mu E$$

MOBILITY

E3

CONDUCTOR



HOW MUCH "CHARGE" EXISTS SURFACE IN TIME Δt ?

All the ~~charge stored~~ CLOSER THAN $N_{DRIFT} \Delta t$
from SURFACE !!

$$\Delta Q = \underbrace{(N_{DRIFT} \Delta t) A}_{\text{PARTICLES}} \cdot \underbrace{\mu}_{\text{VOLUME}} * \underbrace{n}_{\text{DENSITY}} * q_{\text{CHARGE EACH PARTICLE}}$$

$$\Rightarrow \frac{\Delta Q}{\Delta t} = A N_{DRIFT} \cdot \mu * q \quad J = \sigma E$$

$$\Rightarrow I = \frac{\Delta Q}{\Delta t} \quad J = \frac{1}{A} \frac{\Delta Q}{\Delta t}$$

$$J = N_{DRIFT} n q = \underbrace{n q \mu}_{\sigma} E \quad \Rightarrow \quad \boxed{\sigma = n q \mu}$$

IF MORE THEN 1 SPECIE $\sigma = \sum_i n_i q_i \mu_i$

EXAMPLE Li_2O $q_{Li} = e \quad n_{Li}$

$Li^+ + Li^+ + O^{2-} \quad q_O = -2e \quad n_O$

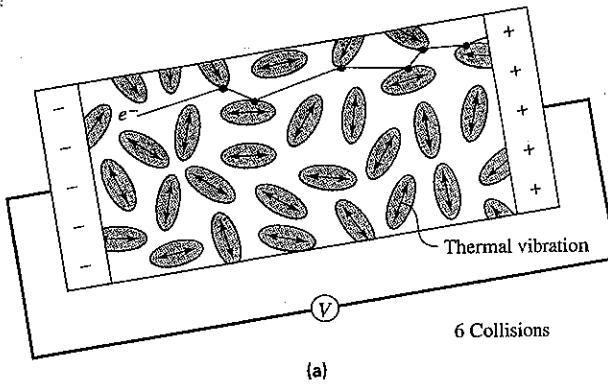
BUT $\mu_O < 0$ & $\mu_{Li} > 0$

(BECAUSE $O^{2-} < 0$) \Rightarrow CONVENTION

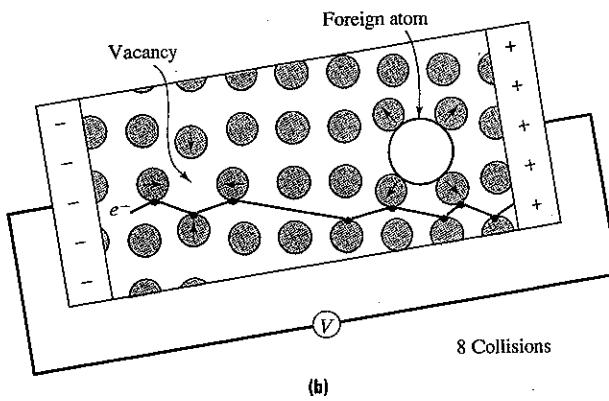
q POSITIVE ..
 μ POSITIVE ..

$$\sigma = n_{Li} q_{Li} \mu_{Li} + n_O q_O \mu_O + n_e e / \mu_e$$

E4



(a)



(b)

FIGURE 10.2-3 A schematic illustration of the effects of temperature and point defects on electron motion. (a) As temperature increases, the amplitude of the thermally induced atomic vibrations increases. This causes a decrease in the mean time between collisions and, therefore, a corresponding decrease in the electron mobility. (b) The mean time between collisions and, therefore, the electron mobility decrease with increasing defect concentration.

TEMPERATURE

$T \uparrow \mu \downarrow$ (electrons get slower, more collisions)

$$\frac{\partial \mu}{\partial T} < 0$$

IMPURITIES

$N_{\text{DEFECTS}} \uparrow \mu \downarrow$

(more collisions, more tight spaces)

$$\frac{\partial \mu}{\partial N_D} < 0$$

HOWEVER

$$\sigma = n q \mu$$

$$\downarrow \frac{\partial \mu}{\partial T} < 0$$

$$\text{OR } \frac{\partial \mu}{\partial N_D} < 0$$

BUT TEMPERATURE OR IMPURITIES
CAN BOOST n !!

$\frac{\partial \mu}{\partial T} \leftarrow \text{Huge, like semiconductors}$
 $\frac{\partial \mu}{\partial N_D} > 0 \rightarrow \frac{\partial \mu}{\partial T} \leftarrow \text{Metals}$

E5

CRYSTALLINE STRUCTURE \Rightarrow MANY LEVELS

FROM QMECHANICS: TAKE MY COURSE
IF YOU WANT TO KNOW

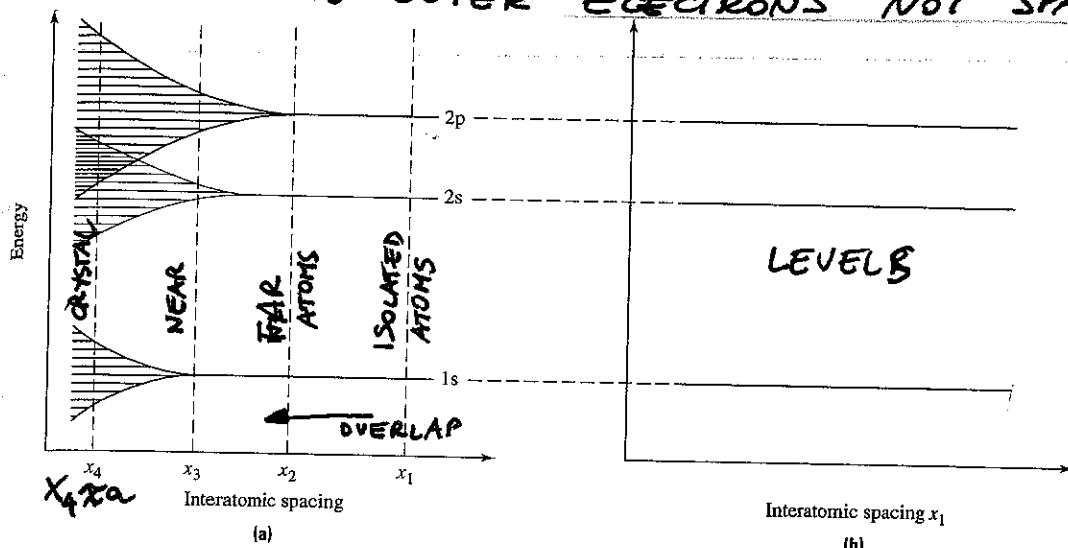
- 1 atom (isolated) \Rightarrow • LEVELS $1s \cdot 2s \cdot 2p \cdot 3s \cdot 3p \cdot 3d \dots$ DISCRETE
 - ISOLATED
 - OUTER ELECTRONS = VALENCE (LOCALIZED)

atoms CLOSE! \Rightarrow • LEVELS are FUNCTION OF SEPARATION (a)

CRYSTAL \Rightarrow a

- DISCRETE DISCRETE & ISOLATED SPREAD INTO ENERGY BANDS

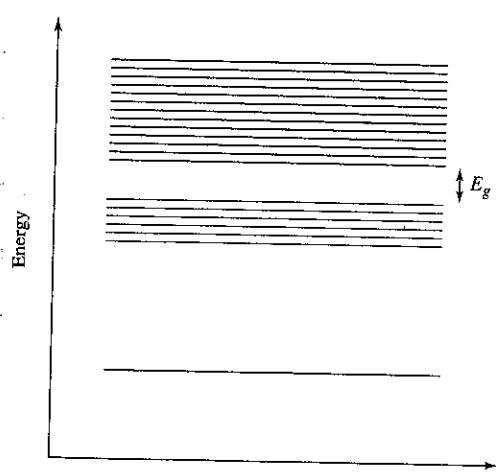
- OUTER ELECTRONS NOT SPATIALLY LOCALIZED ANYMORE



(a)

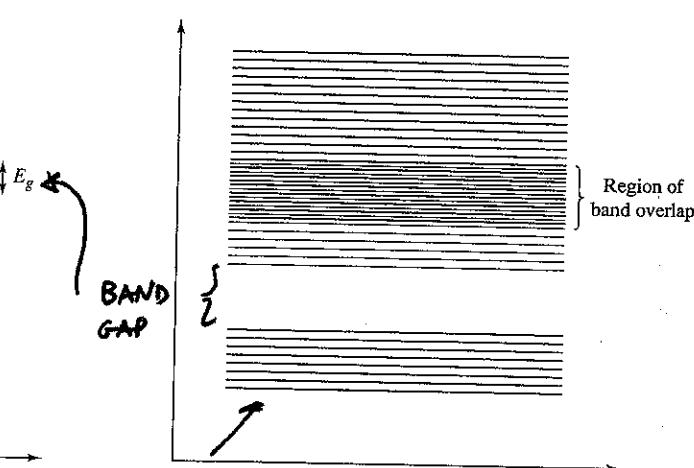
Interatomic spacing x_1

(b)



Interatomic spacing x_3

(c)



EACH ATOM BRINGS ALL ITS LEVELS

Interatomic spacing x_4

(d)

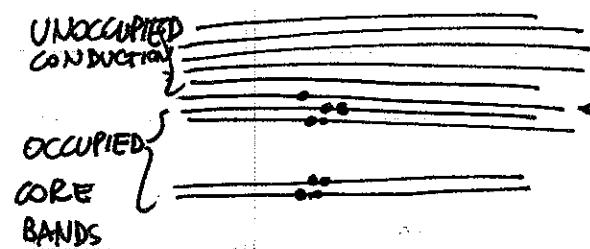
IS OF LEVELS

IS CONST.

FIGURE 10.2-4 Energy bands in solids. (a) The energy band structure as a function of interatomic separation distance. (b) For large separation distances, the electrons associated with any atom are independent of those of all other atoms. (c) For separation distance x_3 , the isolated energy levels in a single atom split into a band of discrete levels separated by small energy differences. (d) For separation distance x_4 , the 2s and 2p energy bands overlap to form an extended energy band.

E6

ELECTRONS FILL FROM
LOWEST ENERGY!



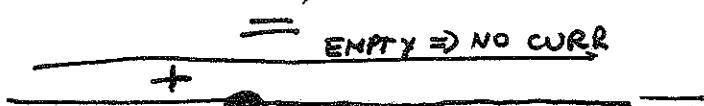
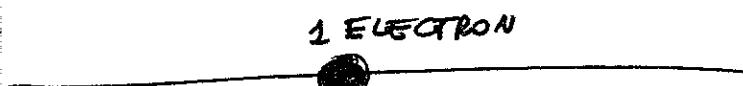
HIGHEST ENERGY BAND
AT LEAST PARTIALLY OCCUPIED
VALENCE BAND

PROPERTY : COMPLETELY & COMPLETELY BANDS ARE NOT
CAPABLE OF TRANSPORTING ELECTRIC CHARGE
THROUGH THE SOLID

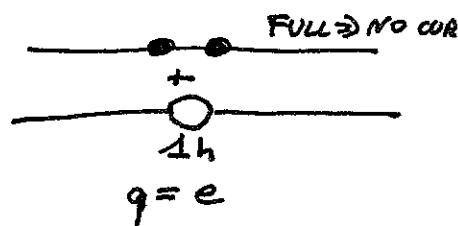
COMES FROM
LIOUVILLE THEORY
~~QUESTION~~ ASK!!

ONLY PARTIALLY OCCUPIED LEVELS GIVE CONDUCTIVITY!

⇒ GIVE CURRENT,
THE OTHER
DO NOT
GIVE
ANYTHING



OR



$$m_e > 0$$

$$\mu_e$$

$$m_h < 0$$

$$\mu_h$$

generically
 $\mu_h < \mu_e$

E7

EXAMPLE

NORFET? BIG or SMALL?

check

v_{DRIFT} for Al wire

$$R = 0.0283 \Omega$$

$$L = 1 \text{ m}$$

$$\mu_e = 1.22 \cdot 10^{-3} \frac{\text{m}^2}{\text{Vs}}$$

} with $3A = I$

with $3A$?

$$V = RI \Rightarrow \frac{V}{L} = E$$

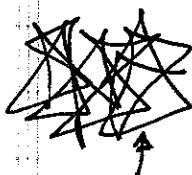
$$\Rightarrow E = \frac{RI}{L} \Rightarrow v_{\text{DRIFT}} = \mu_e E = \mu_e \frac{RI}{L}$$

$$= \frac{1.22 \cdot 10^{-3} \cdot 2.83 \cdot 10^{-2} \cdot 3}{1} \text{ m/s}$$

$$\sim 0.1 \frac{\text{mm}}{\text{s}} \quad \underline{\text{SLOW}}$$

mm & cm/sec NOR
speed of light

$$v_{\text{DRIFT}} \sim \text{mm/s}$$



$$\text{VIBRATION} \sim \frac{1}{2} m_e v_{\text{th}}^2 \approx \frac{3}{2} kT$$

Temp
Room

$$v_{\text{th}} \approx 1000 \text{ km/sec}$$

FAST!!

but what moves at c? (SPEED OF LIGHT)

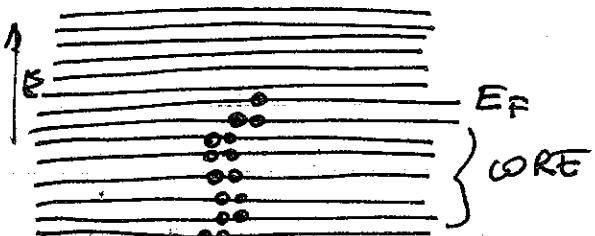
ASK!

E7b

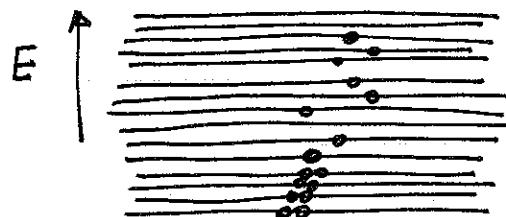
TEMPERATURE EFFECT

FERMI DIRAC DISTRIBUTION

$T=0$



$T > 0$



$$E_F = \text{fixed FERM ENERGY}$$

SOME ELECTRONS ARE EXCITED
& POP UP FROM
CORE BECAUSE TEMPERATURE

$$n = \frac{N}{V} \quad \text{density of electrons}$$

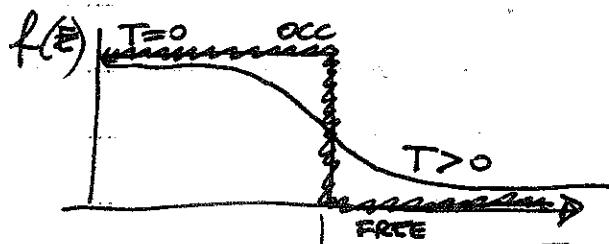
$$K_F = \sqrt[3]{3\pi^2 n} \quad \text{FERMI NUMBER TUM}$$

$$E_F = \frac{\hbar^2}{2m_e} K_F^2$$

PROBABILITY DISTRIBUTION OF OCCUPATION

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

FERMI -
DIRAC
DISTRIBUTION



$$T=0 \quad f(E < E_F) = 1$$

$$f(E > E_F) = 0$$

$$\Rightarrow T > 0 \quad f(E < E_F) \rightarrow 1$$

$$f(E > E_F) \rightarrow 0$$

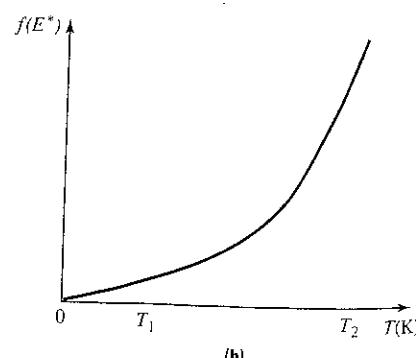
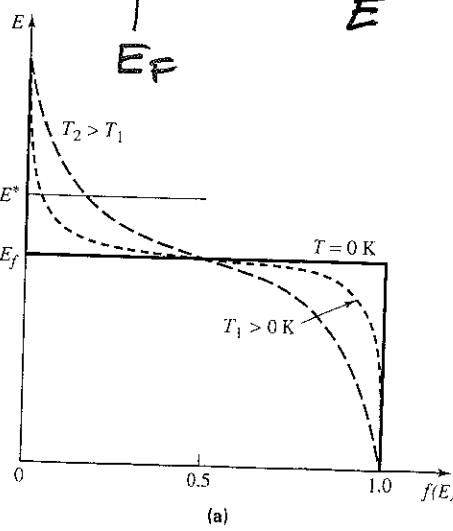
$$f(E \approx E_F) \sim \frac{1}{(kT)} \quad \text{NO COND}$$

$$\text{NOT } 0 \quad \text{OR } 1 \quad \text{COND}$$

FIGURE 10.2-8

(a) The change in the probability of occupation, as described by the Fermi-Dirac distribution function $f(E)$, as a function of temperature; and (b) the probability that energy level E^* in part a is occupied, given by $f(E^*)$, as a function of temperature.

E8

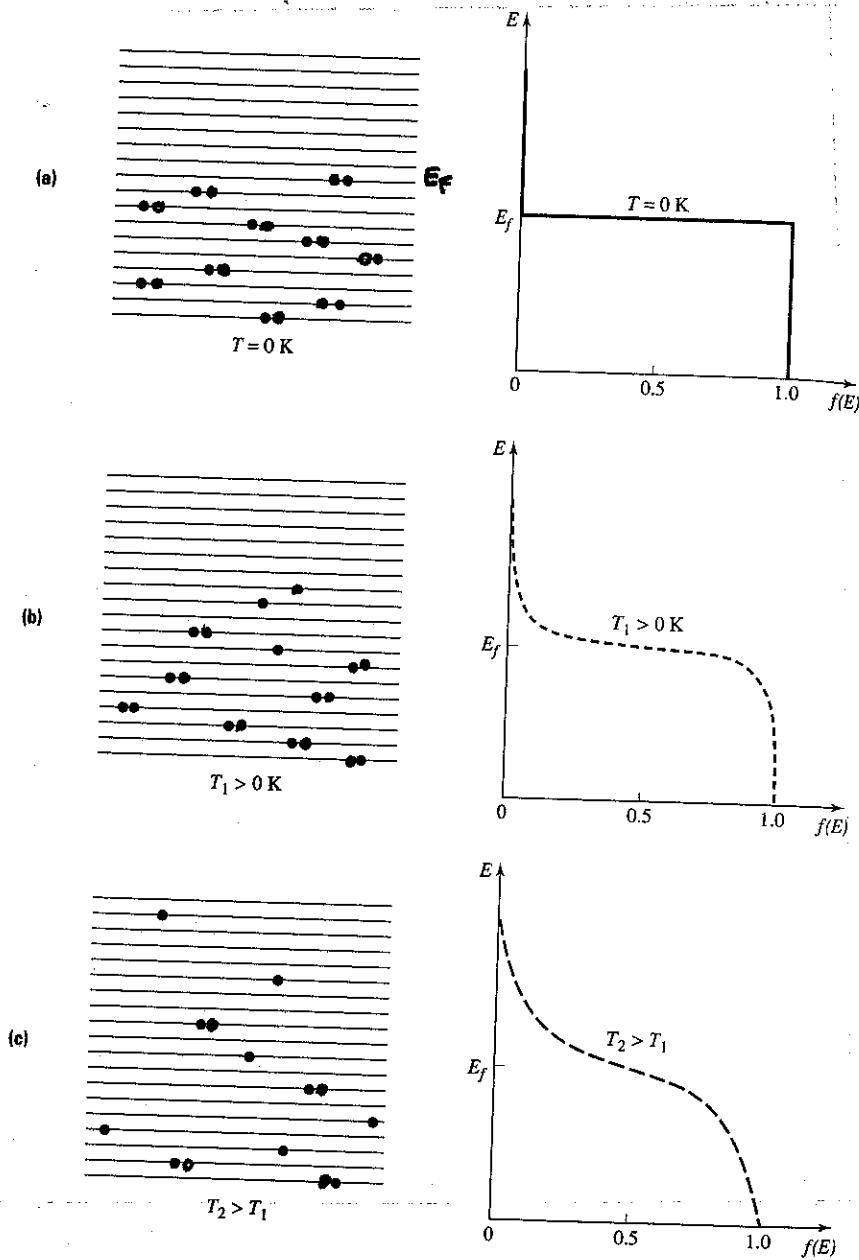


$$k_B \text{ ROOM } \approx 25 \text{ meV}$$

$$k_B \approx 8.6 \times 10^{-5} \text{ eV/K}$$

FIGURE 10.2-9

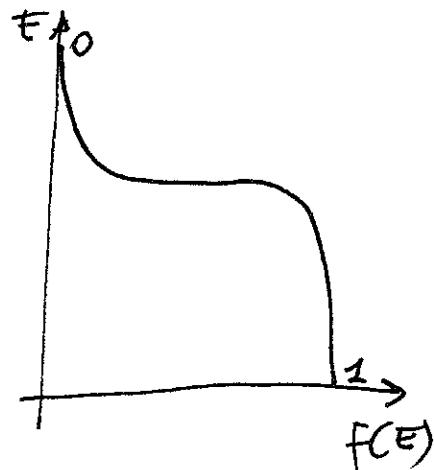
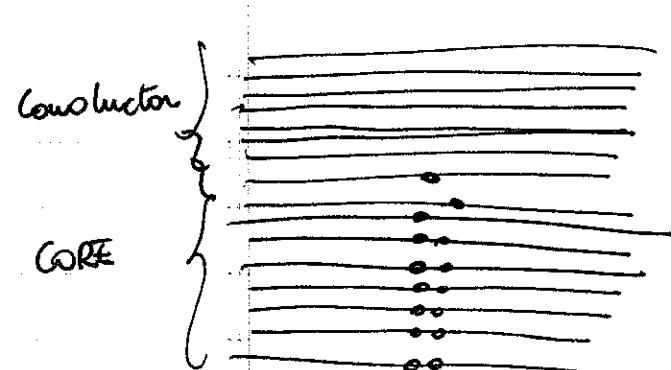
The relationship between the occupied energy levels and $f(E)$ as a function of temperature for solids with a partially filled energy band: (a) at 0 K, (b) at $T_1 > 0$ K, and (c) at $T_2 > T_1$.



$\uparrow T \uparrow$ OCCUPATION IS SPREADING ALONG BANDS

STUDY CHAP 10

E9



Pick 1 electron,

the probability that this electron is in the conduction band, is prop $E > E_c$

$$P[E > E_c] = \int_{E_c}^{\infty} f(E) dE = P(T)$$

↑
depends on Temperature

Number of electrons in CONDUCTION BAND is not the product of AVAILABLE ELECTRONS * PROB($E > E_c$)
But you must multiply (# AVAILABILITY OF LEVEL)

$$N_e = 2 \int_{E_c}^{\infty} f(E) g(E) dE = N_0 \exp\left(\frac{-E_g}{kT}\right)$$

SPIN

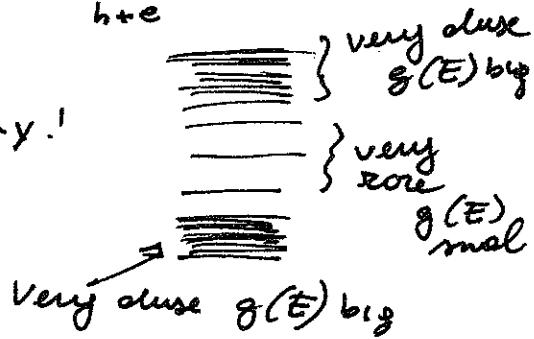
↑
density of states

MEASURE AVAILABILITY!

EXAMPLE

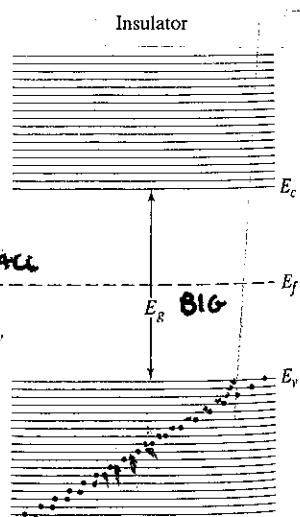
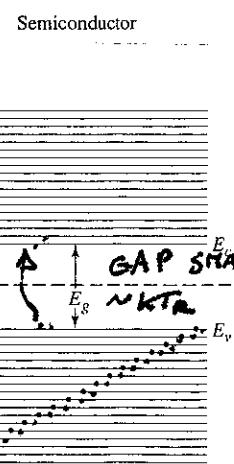
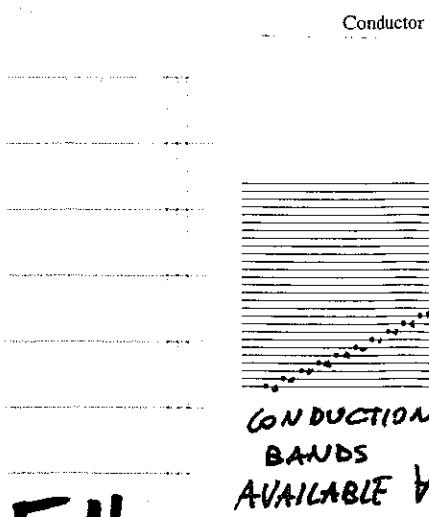
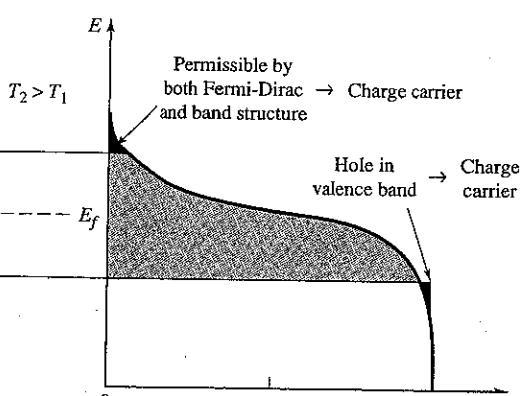
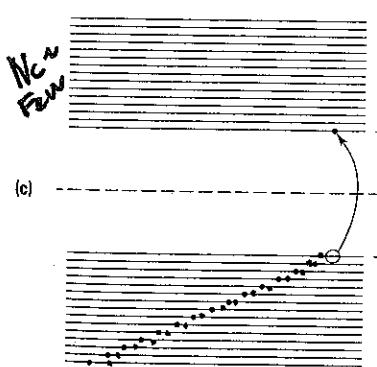
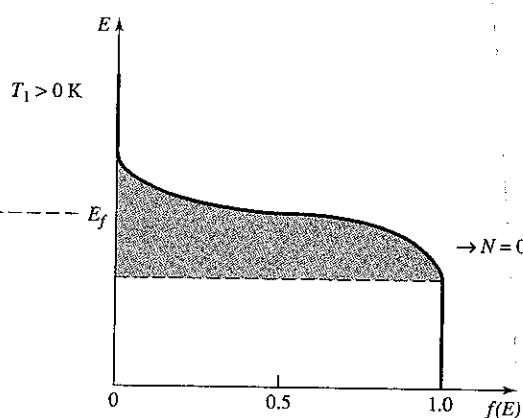
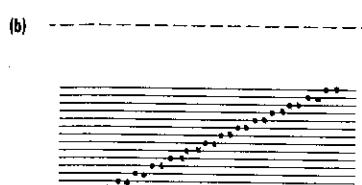
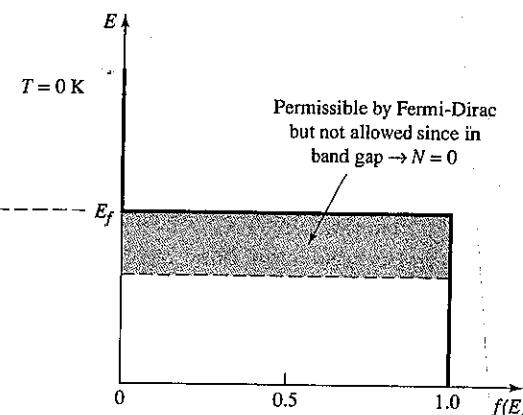
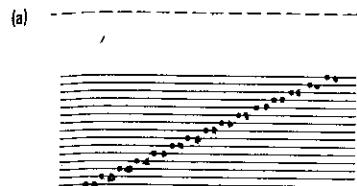
prob that

level, which exist with
density $g(E)$, is populated
(depends on T)



\Rightarrow
 $g(E)dE = \# \text{ of levels}$
between $[E, E+dE]$

E10



Remember
 E_F is the
 Max Energy
 electrons can HAVE
 @ $T = 0$, if
 a level exist @ $E = E_F$



CONDUCTORS

E_F happens in
 a region with
 bands \Rightarrow
 there are partially
 POPULATED BANDS $\forall T$!!

SEMICONDUCTOR

E_F happens inside
 a GAP $< 2.5 \text{ eV}$, there
 are partially
 occupied BANDS
 only at $T \sim \text{DECENT}$

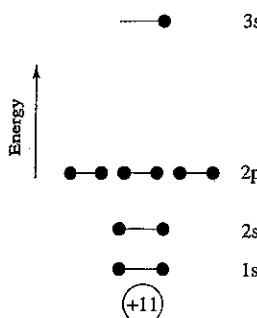
INSULATOR

GAP IS SO BIG
 you need $T > T_{\text{melt}}$
 $> 2.5 \text{ eV}$

EII

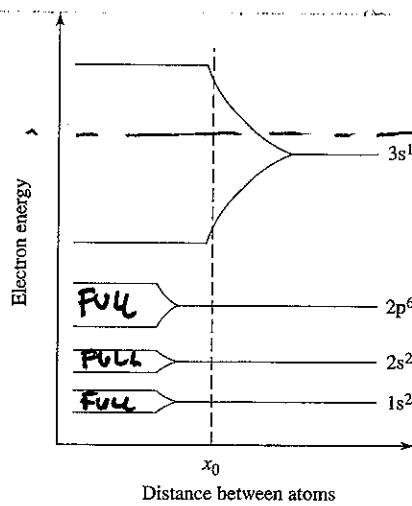
METALS CONDUCTORS Na & Mg!

EXAMPLE



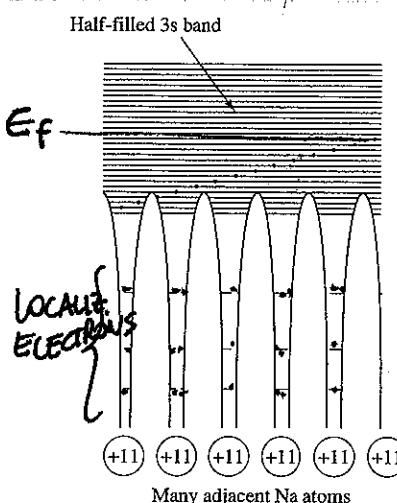
Single Na atom

(a)



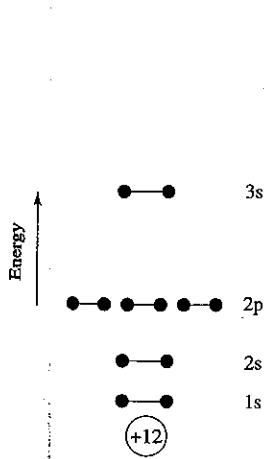
Distance between atoms

(b)



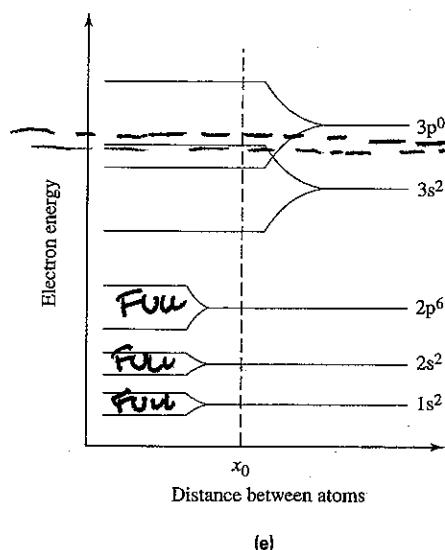
Many adjacent Na atoms

(c)



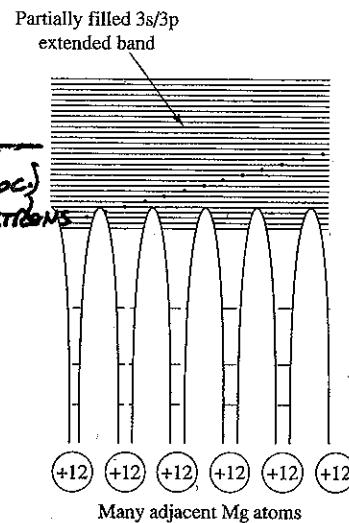
Single Mg atom

(d)



Distance between atoms

(e)

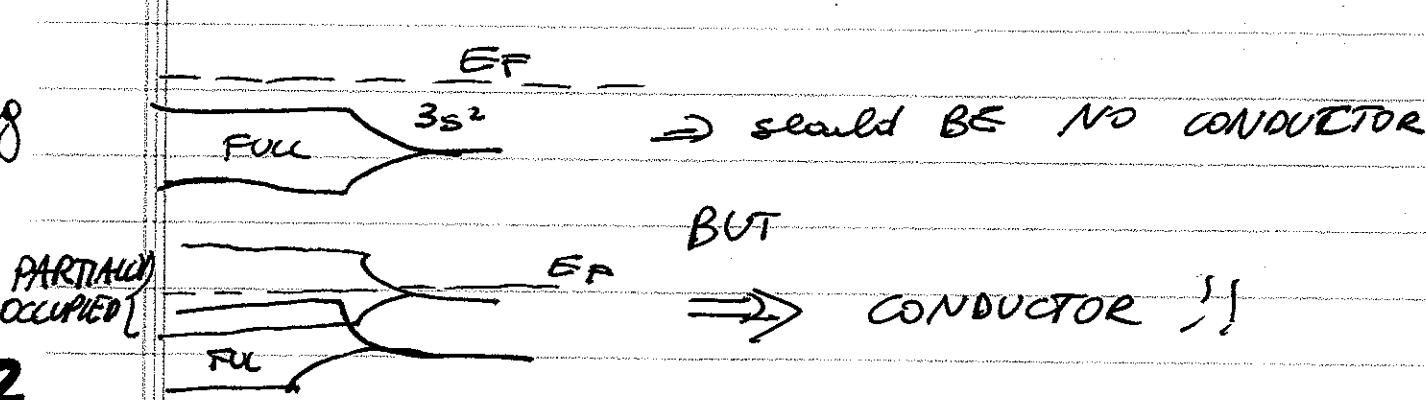


Many adjacent Mg atoms

(f)

FIGURE 10.2-12 Electron band structures for metallic Na and Mg: (a) electron energy levels for an isolated Na atom, (b) splitting of the energy levels as a function of distance between two Na atoms, (c) the energy band diagram for Na showing a half-filled 3s band, (d) electron energy levels for an isolated Mg atom, (e) splitting of the energy levels as a function of distance between two Mg atoms, and (f) the energy band diagram for metallic Mg showing a partially filled 3s/3p extended band.

Mg



E12

CONDUCTORS: SUMMARY \Rightarrow

$$\sigma = N_e q_e \mu_e$$

\uparrow

available electrons for conduction

$$N_e = N_{\text{cond}} = \text{CONST with } T$$

$$q_e = \text{charge} : e$$

$$\mu_e = \text{mobility} \quad T \uparrow \mu_e \downarrow \quad \frac{\partial \mu}{\partial T} < 0$$

$\Rightarrow \frac{1}{\rho}$ BECAUSE σ is PHYSICS $\Rightarrow \rho$ is ENGINEERING
Resistivity

$$\Rightarrow \rho = \rho_0(1 + \alpha_e T)$$

\downarrow coefficient
more precisely

FOR TABLE

$$\rho = \rho_0 [1 + \alpha_e (T - T_{ref})]$$

~~Temperature coefficient of resistivity of~~
~~Temperature coefficient of~~
 \uparrow Temperature
coefficient of resistivity

TABLE 10.2-2 Electrical resistivities ρ_0 and temperature coefficients of resistivity α_e for selected conductors.

Conductor	Reference temperature (°C)	$\rho_0 (\Omega \cdot \text{cm})$	$\alpha_e (\text{C}^{-1})$
Al	-20	2.65×10^{-8}	0.0043
Al	20	1.59×10^{-8}	0.0044
Au	0	2.35×10^{-8}	0.0040
Co	0	6.24×10^{-8}	0.0060
Cr	0	1.29×10^{-8}	0.0030
Cu	20	1.67×10^{-8}	0.0068
Fe	20	9.71×10^{-8}	0.0065
Mg	20	4.45×10^{-8}	0.0065
Ni	20	6.54×10^{-8}	0.0069
Pd	20	1.08×10^{-8}	0.0083
Pb	20	2.06×10^{-8}	0.0044
Pt	20	1.06×10^{-8}	0.0039
Sn	0	1.10×10^{-8}	0.0047
Ta	-25	1.25×10^{-8}	0.0038
Zn	20	3.92×10^{-8}	0.0043
Zn	20	4.00×10^{-8}	0.0044

Source: Adapted from *Handbook of Materials Science*, Vol. I. Copyright CRC Press, Boca Raton, FL.

SEMICONDUCTORS!



$$\sigma = N_h e \mu_h + N_e e \mu_e$$

$$\frac{\partial \mu_h}{\partial T} < 0 \quad \frac{\partial \mu_e}{\partial T} < 0$$

but $N_h, N_e \uparrow$ BOOST

$$\frac{\partial N_h}{\partial T} = \frac{\partial N_e}{\partial T}, \text{ HUGE EXPONENTIAL}$$

$$N_h = N_e = N_0 e^{-E_g/2kT}$$

FUNDAMENTAL

TABLE 10.2-3 Band gaps and charge-carrier mobilities for a variety of semiconductors.

Material	Band gap (eV)	μ_h (cm²/V-s)	μ_e (cm²/V-s)
C* DIAMOND	5.4	1800	1400
Si	1.107	1900	500
Ge	0.67	3800	1820
III-V compounds with the zinc blende crystal structure			
BN	~4	—	—
AlP	2.5	—	—
AlAs → FOR LED	2.16	1,200	400
AlSb	1.60	200–400	550
GaP → FOR LED	2.24	300	100
GaAs → HIGH SPEED EL.	1.35	8,800	400
GaSb	0.67	4,000	1400
InP → FOR LED	1.27	4,600	150
InAs	0.36	33,000	460
InSb	0.165	78,000	740
II-VI compounds with the zinc blende crystal structure			
ZnS	3.54	180	5
ZnSe	2.58	540	28
ZnTe	2.26	340	100
CdTe → QUANTUM DOTS	1.44	1200	50
Other crystalline semiconductors			
β -SiC	2.3	4000	—
α -SiC	2.9	4000	2000
ZnO	3.2	180	—
CdS	2.42	400	—
CdSe → QUANTUM DOTS	1.74	650	—
CuAlS ₂	2.5	—	—
CuFeSe ₂	0.16	—	—
AgInSe ₂	1.18	—	—
ZnSiAs ₂	1.7	—	50
PbS	0.37	600	500
CdO	2.5	100	—
BaTiO ₃	2.8	—	—
Polymers			
Polyacetylene	1.4	—	—
Poly(<i>p</i> -phenylene sulfide)	4.0	—	—
Polypyrrole	3.0	—	—

*Although carbon (diamond) is an insulator by our definition, it is included here for comparison.

Source: Adapted from *Handbook of Chemistry and Physics*, 61st ed. Copyright CRC Press, Boca Raton, FL.

IONICS : No free electrons (or holes)

BUT IONS MOVE? ATOMS Na^+ Cl^- move jumping left & right \Rightarrow by DIFFUSION

$$\Rightarrow \mu \sim \text{Diff.} \quad \mu_{\text{ion}} = \frac{q}{kT} \text{D}_{\text{ION}}(T, \text{Defect})$$

charge
↓
EINSTEIN RELATIONS
temp ↑ diff: ↓
 $\sim e^{-Q/kT}$

$$\Rightarrow \sigma = \underbrace{N_e \mu_e e + N_h \mu_h e}_{\text{IF SMALL}} + \sum_{\text{IONS}} N_{\text{ion}} q_{\text{ion}} \mu_{\text{ion}}$$

↓
No T
↓
 $\sim \frac{1}{T}$

$\uparrow \text{ext} \quad \uparrow \text{ext} \quad \uparrow \text{ext}$
 $\uparrow \text{small } T \quad \uparrow \text{small } T$

GAP \Rightarrow CONSIDERABLE CURRENT!
 $< 2.5 \text{ eV}$

TRANSFERENCE NUMBER = % of conductivity
of a species
of the species vs the total
of the IONIC



↓

$$\sigma_{K^+}/\sigma_{KCl} = 96\% \quad @ 435^\circ C$$

$$\sigma_{Cl^-}/\sigma_{KCl} = 4\%$$

$$\sigma_{K^+}/\sigma_{KCl} = 88\%$$

$$\sigma_{Cl^-}/\sigma_{KCl} = 12\%$$

$@ 600^\circ C$

↓
with
Temperature

EIS

DEFECTS & IMPURITIES

reduce σ in conductors, metals & ionics!

$$\frac{\partial \mu}{\partial N_D} < 0 !! \quad \text{BUT FOR}$$

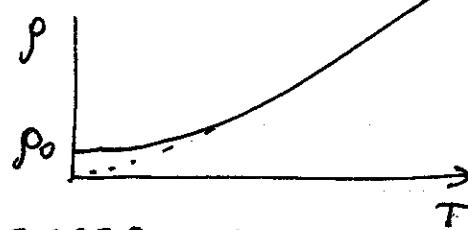
SEMICONDUCTORS \Rightarrow COMPLETELY DIFFERENT!

FOR METAL

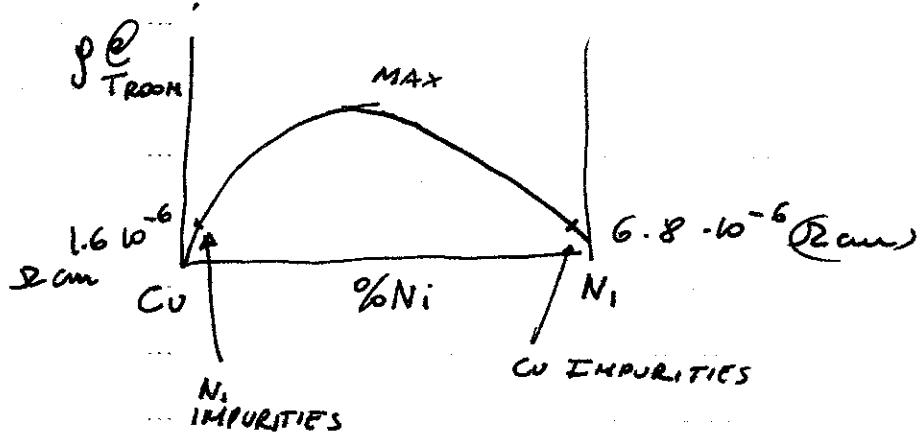
$$\textcircled{1} \quad T=0 \quad \rho = \rho_0 + \alpha T$$

removing one
DUE BY DEFECT

if $\rho_0 \sim 0$



SUPERCONDUCTOR



SEMICONDUCTORS : INTRINSIC

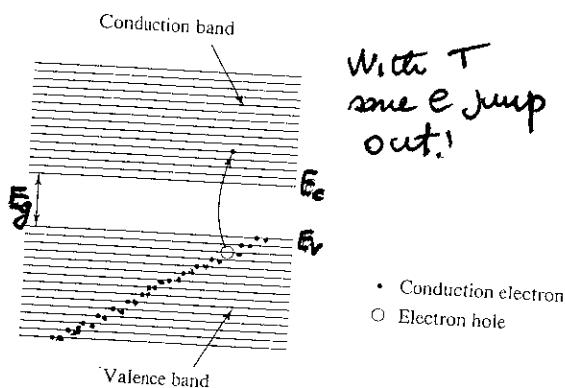
PURE ELEMENT HAS CHARGES (e & h) ~~ARE CREATED~~
ONLY BY TEMPERATURE

CALLED INTRINSIC SEMICONDUCTOR

NO IONIC DIFFUSION CONTRIBUTION

$$\sigma = n_e q e \mu_e + n_h q_h \mu_h = e (n_e \mu_e + n_h \mu_h)$$

$\downarrow \downarrow \quad \downarrow \downarrow$



E_c = conduction energy
= min of conduction BANDS

E_v = valence energy
= max of valence bands

E_g = energy gap

- 1) q is NOT function of T , it's just $\underline{e}!!$
- 2) $\frac{\partial n}{\partial T} \ll 0$ but small in range!
since $\rho = \rho_0 (1 + \alpha \Delta T) \Rightarrow \mu \sim \mu_0 - \beta T$
 $\Rightarrow \frac{\partial \mu}{\partial T}$ ~~is linearly~~ decrease linearly.
- 3) ~~$\frac{\partial n_e}{\partial T}$~~ $\frac{\partial n_e}{\partial T}$ & $\frac{\partial n_h}{\partial T}$ are HUGES!! exponentially more

FOR INTRINSIC, THERE IS NO EXTRA CHARGE

E17 $\Rightarrow n_h = n_e$ IF YOU PRODUCE 1 e YOU PRODUCE 1 h

$$\Rightarrow N_e = N_h = N_0 \exp\left(-\frac{E_g}{2kT}\right) \quad \text{from } \int f(\epsilon)g(\epsilon)d\epsilon$$

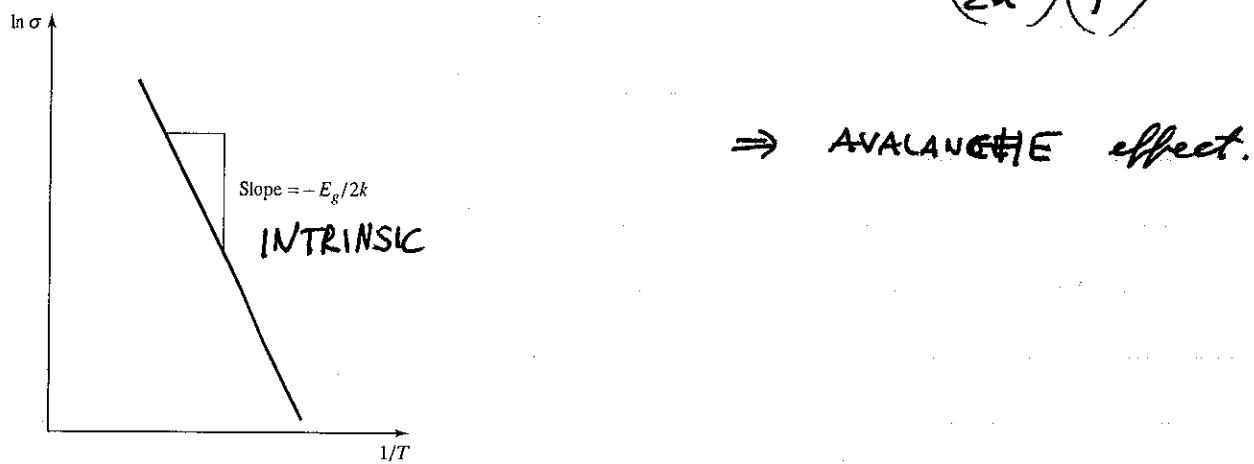
integrals!

$$\Rightarrow \sigma = \underbrace{N_0 e(\mu_e + \mu_h)}_{\text{small } T \text{ variation}} \exp\left(-\frac{E_g}{2kT}\right) - \underbrace{\text{Big } T \text{ variation}}$$

$$\approx \sigma_0 \text{ constant} = N_0 e(\mu_e + \mu_h)$$

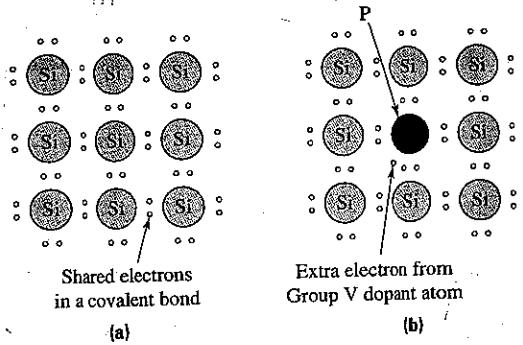
$$\Rightarrow \sigma = \sigma_0 \exp\left(-\frac{E_g}{2kT}\right)$$

$$\Rightarrow \text{plot } \log \sigma = \log \sigma_0 - \left(\frac{E_g}{2k}\right)\left(\frac{1}{T}\right)$$



SEMICONDUCTORS : EXTRINSIC !

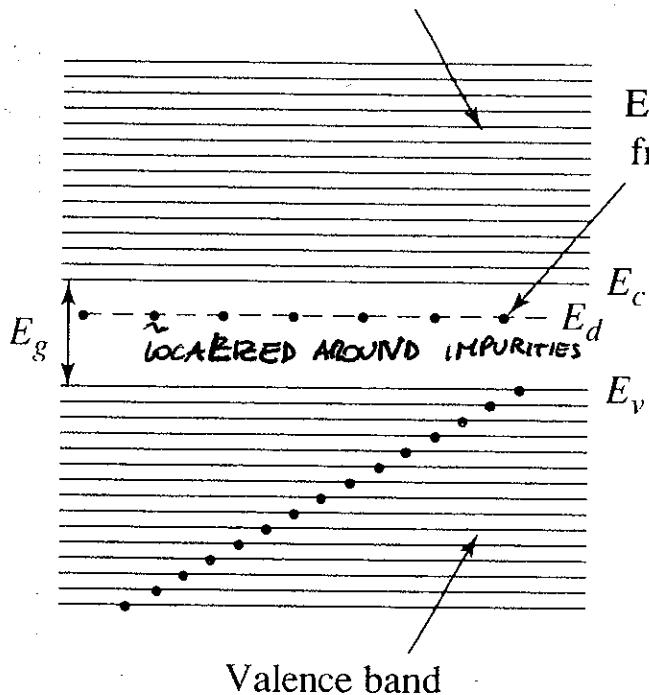
What happens if we add impurities?



Remove some Si & add P
⇒ extra electron

EACH IMPURITY CREATES
ONE EXTRA LEVEL
DONOR LEVEL WITH E_d

Conduction band



Extra electrons from Group V dopants

E_d is very close to E_c

$$\Rightarrow E_c - E_d \approx 40 \text{ meV}$$

at ROOM TEMP

$$kT_{\text{room}} \approx 25 \text{ meV}$$

$$\Rightarrow \exp\left(-\frac{E_c - E_d}{kT}\right) \approx 0.2$$

1 ≈ 2.25 $16^{1/2}$

\approx

at ROOM Temperature
all donor ~~like~~ electrons
have jumped out their
donor levels & are FREE
⇒ plenty of conductivity

$$\Rightarrow N_h = N_d \exp(-E_{\text{gap}}/2kT) \neq n_e$$

$n_e \approx \text{Concentration of donors}$
↓ all jumped out $\rightarrow N_d$

WORKING RANGE

$\ln \sigma$

$1/T$

HIGH TEMP JUMPS OUT

Slope = $-E_g/2k$ (intrinsic behavior)

Exhaustion region

LOW TEMP ONLY DONOR

Slope = $-(E_c - E_d)/k$ (extrinsic behavior)

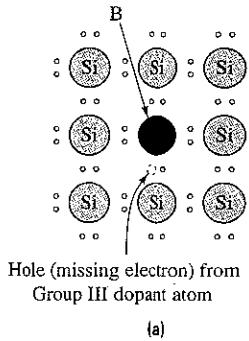
(b)

$$@ \text{LOW TEMP} \quad n_e = N_d \exp(-(E_c - E_d)/kT)$$

$$N_{\text{type}} \sigma = N_e e \mu_e \exp(-E_c - E_d)/kT$$

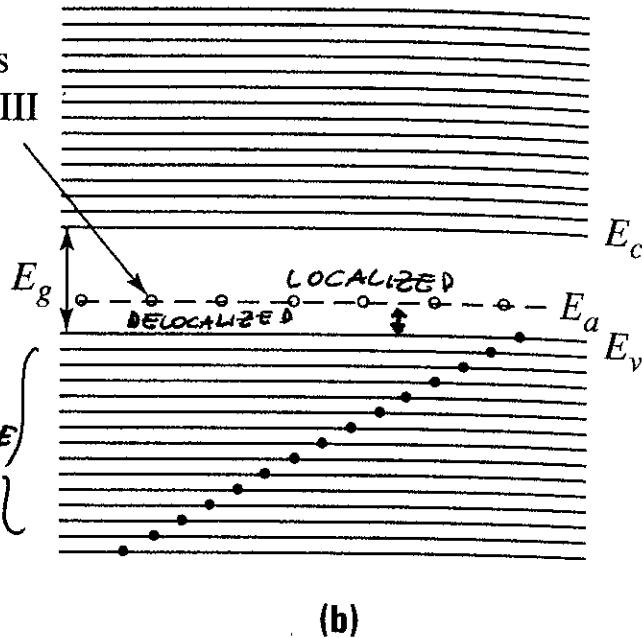
EXTRINSIC : P-TYPE (extra holes)

we add holes:



(a)

Extra holes
from Group III
dopants



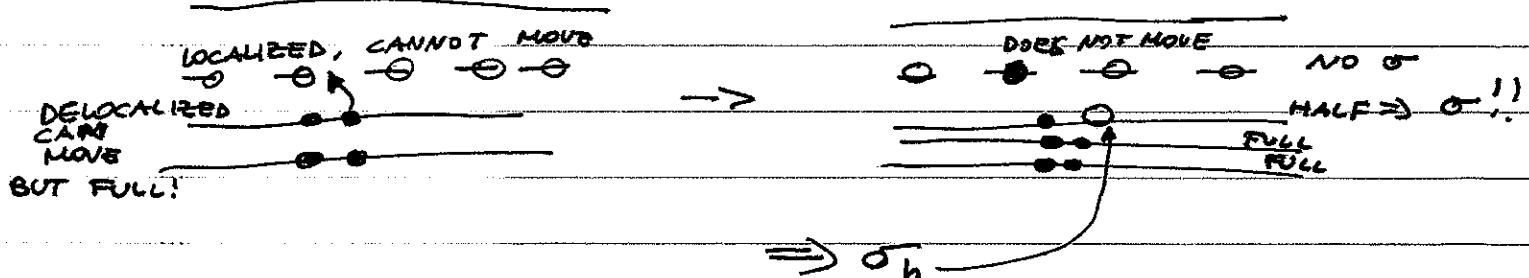
ACCEPTOR LEVELS

LOCALIZED LEVELS

WITH HOLES INSIDE!

In 1 electron

from VALENCE CORE TO THE ACCEPTOR LEVEL



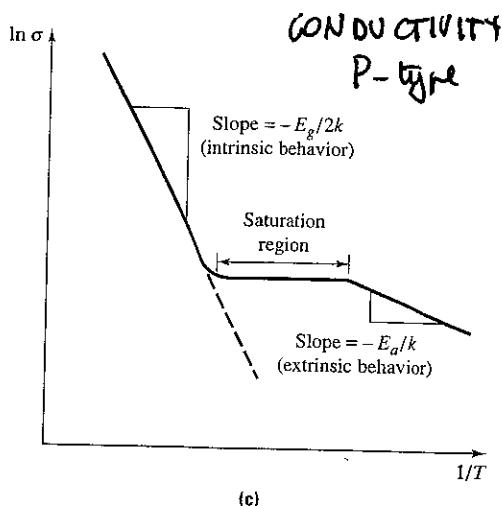
$\Rightarrow n_h \sim \text{ONLY INTRINSIC}$

~~But~~ $n_h \sim$ goes with $\exp(-\frac{E_a - E_v}{kT})$
↑ because only 1 "hole" is generated.

$\Rightarrow n_h \gg n_e \approx \text{CONCENTRATION OF IMPURITIES} \Rightarrow \sigma = \sigma_h = N_0 q n_h \exp(-\frac{E_a - E_v}{kT})$

E20

NOT E_a but $E_a - E_v$
in book



$$\sigma_h = N_0 q \mu_h \exp\left(-\frac{E_a - E_v}{kT}\right)$$

SUMMARY

INTRINSIC \Rightarrow ONLY Temperature generated carriers = SMALL
EXTRINSIC \Rightarrow INTRINSIC + CARRIERS OF IMPURITIES (DOPANTS)
small extra e or h (N & P-types)

TABLE 10.3-1 Impurity energy levels (E_a or E_d) in Si and Ge.

Host	Dopant	Energy level
Silicon	Sb	$E_a - E_v = 0.059 \text{ eV}$
	P	$E_a - E_v = 0.044 \text{ eV}$
	As	$E_a - E_v = 0.049 \text{ eV}$
	Bi	$E_a - E_v = 0.059 \text{ eV}$
	B	$E_a = 0.045 \text{ eV}$
	Al	$E_a = 0.057 \text{ eV}$
	Cu	$E_a = 0.065 \text{ eV}$
	In	$E_a = 0.160 \text{ eV}$
Germanium	H	$E_a = 0.260 \text{ eV}$
	P	$E_a - E_v = 0.012 \text{ eV}$
	As	$E_a - E_v = 0.013 \text{ eV}$
	B	$E_a = 0.010 \text{ eV}$
	Al	$E_a = 0.010 \text{ eV}$

$$E_a \rightarrow E_a - E_v$$

FREE

SEMI CONDUCTOR TYPE

σ_0

Act
Energy

INTRINSIC

$M_h = M_e$

$N_0 e(\mu_e + \mu_h)$

$\exp(-E_g/2kT)$

EXTRINSIC N-TYPE

$M_B \approx N_d \gg M_h$

$N_0 e \mu_e$

$\exp(-(E_c - E_d)/kT)$

EXTRINSIC P-TYPE

$M_h \approx N_A \gg M_e$

$N_0 e \mu_h$

$\exp(-E_a - E_v)/kT$

DEFECTS

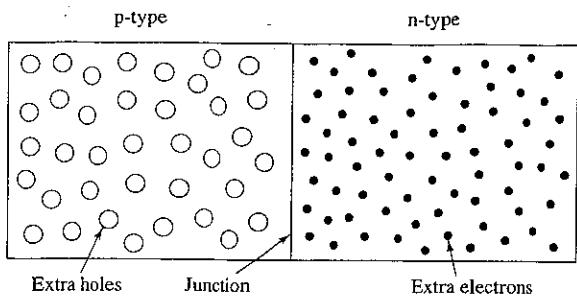
DEFECTS : SOURCES OF TROUBLES

- about charge mobilities but
- introduce extra localized electron levels that ~~messes~~ mess up mechanism
- act like a carrier - charge recombination sites!
(electron holes & meet its hole & vice versa!)
- FAST SEMICONDUCTORS
⇒ minimize defects,
need for big crystals (single crystals, no poly!)

SIMPLE DEVICES

- measure Temp : intrinsic $\log \sigma \sim \frac{E_g}{2k} \frac{1}{T}$
- light detector : light $\lambda \Rightarrow E = \frac{\hbar c}{\lambda}$ DE-BROGLIE
↳ \hbar : PLANCK CONSTANT
 $E > E_{gap} \Rightarrow$ generation
of extra charges
⇒ boost of conductivity

But, more important is
JUNCTIONS \Rightarrow PN, \Rightarrow TRANSISTORS!



N-TYPE @ ROOM
electrons promoted in

conducting bonds
⇒ holes
stuck in
DONOR

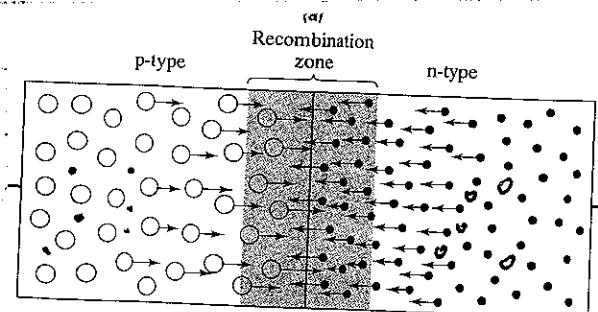
Free electrons FROZEN HOLES

P-TYPE @ ROOM TEMPERATURE

~ Free holes FROZEN electrons
 promoted to be free + electrons stuck

N -TYPE

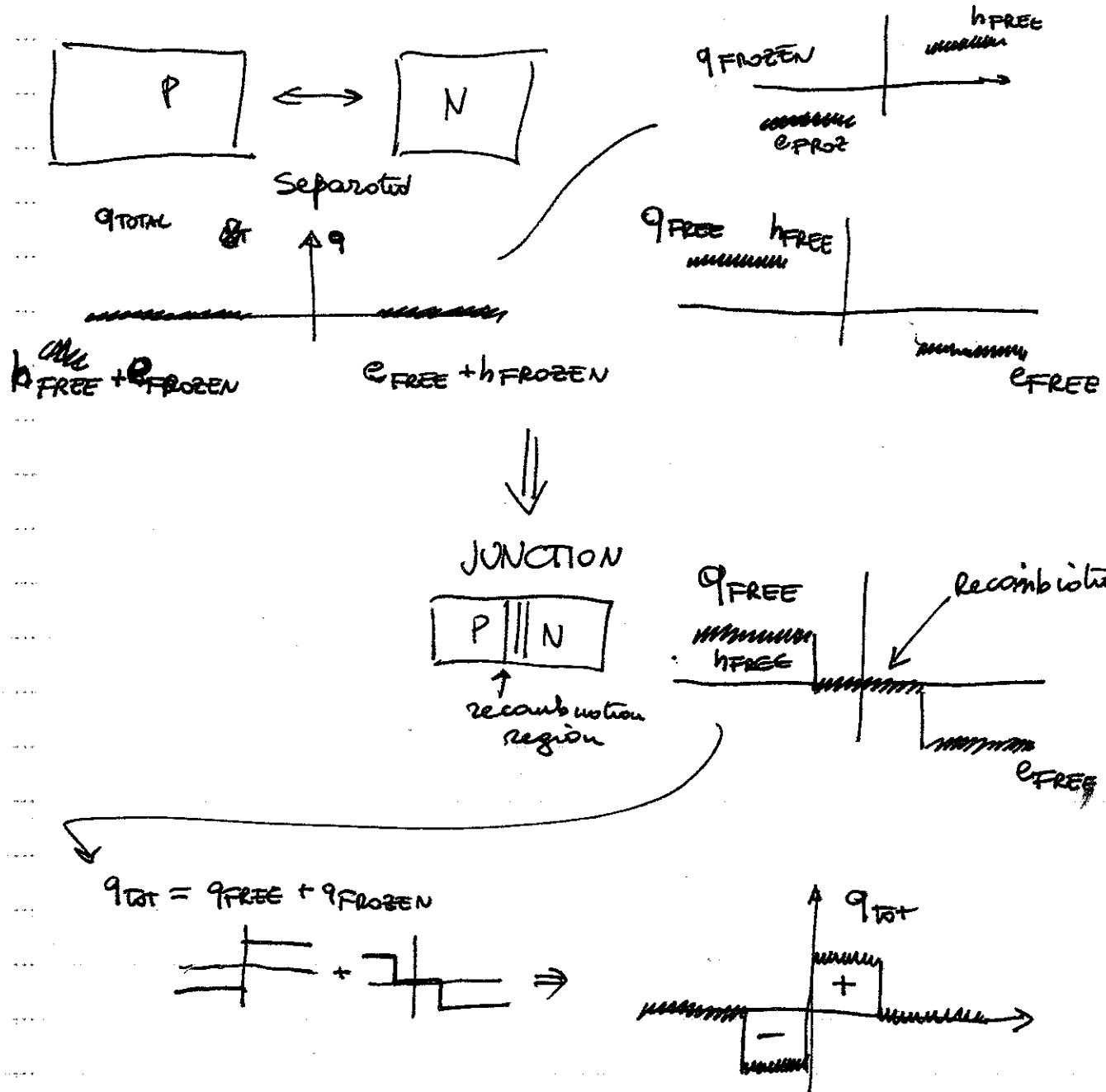
Free electrons in N region feel free holes in P.



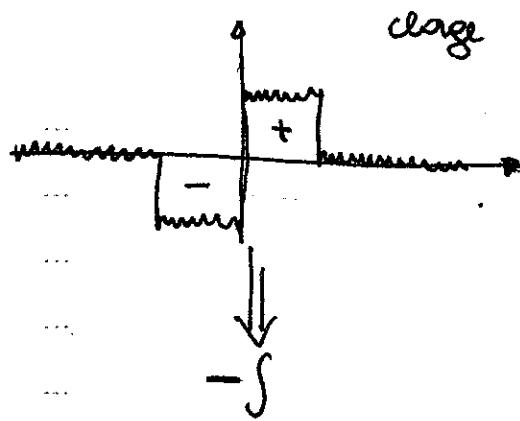
၅၃

BREAK

TOTAL CHARGE



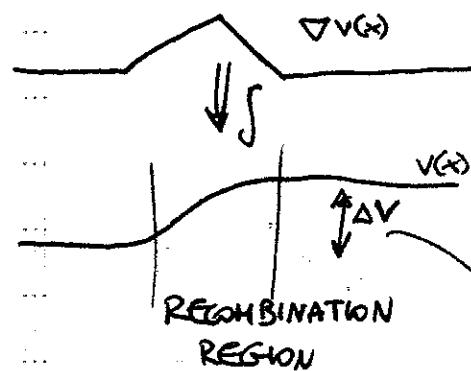
\Rightarrow NON BALANCE OF CHARGE By JUNCTION



⇒ FROM MAXWELL

$$\nabla^2 V(x) = -q(x)/\epsilon_0 \Rightarrow \text{forget the } \epsilon_0!$$

$$V(x) = \iint q(x) dx dy$$

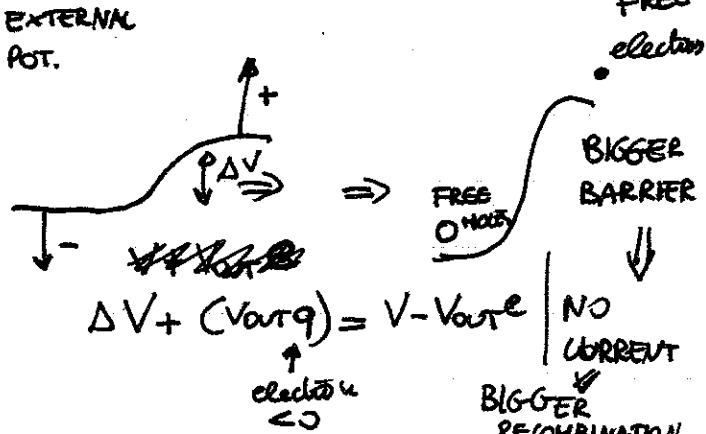
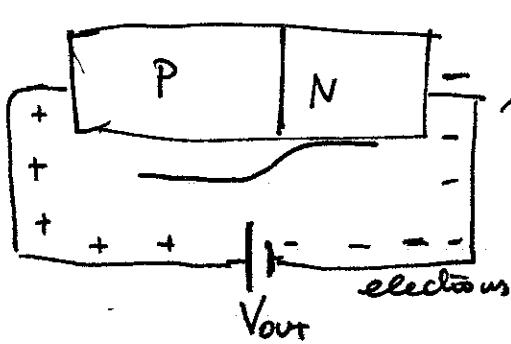


JUNCTION CAUSES A JUMP
ON THE INTERNAL POTENTIAL

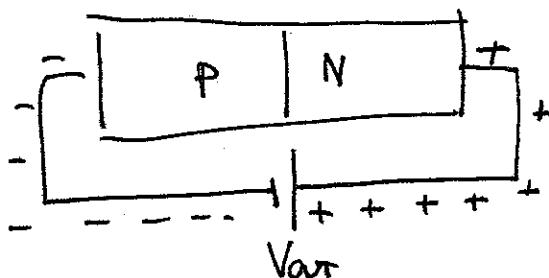
AFFECT ELECTRIC CURRENT!!

$$\Delta V \sim 0.7 \text{ eV for Si!}$$

REVERSE BIAS



FORWARD BIAS



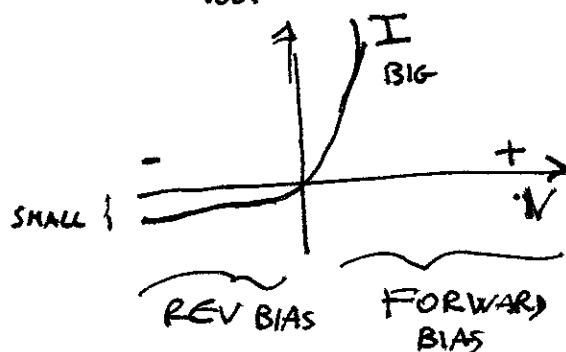
$$V = \Delta V + (V_{out}q) = \Delta V - V_{out}$$

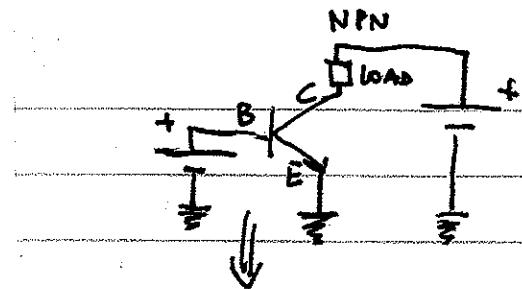
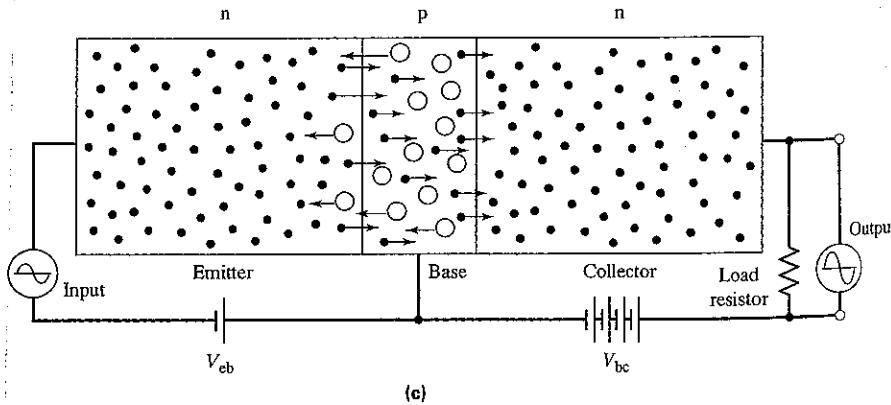
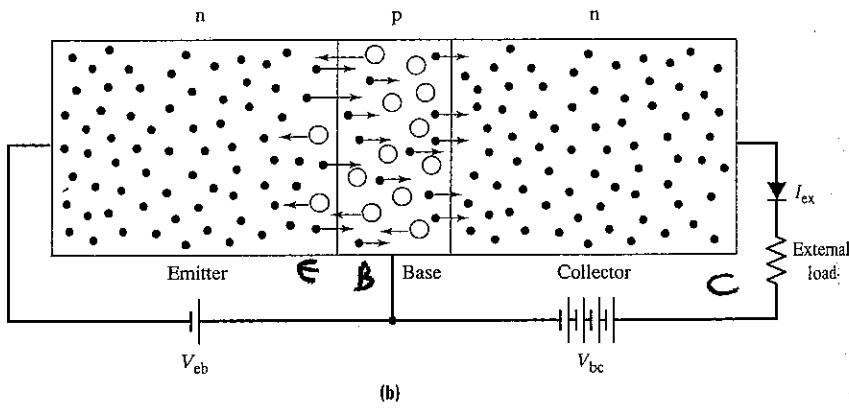
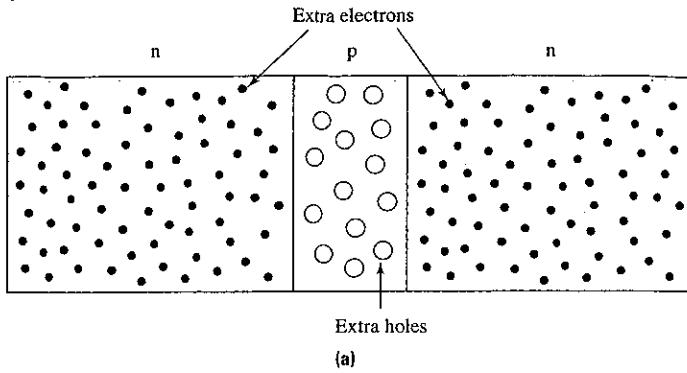
$$V = \Delta V - V_{out}$$

$$I = I_0 (e^{eV/kT} - 1)$$

SMALL BARRIER
NO BARRIER

PLENTY OF CURRENT
~ OPEN CIRCUIT (REV)
~ CLOSE CIRCUIT (FWD).
SMALL RECOMB REGION





BASE is THINNER
THAN RECOMBINATION
REGION

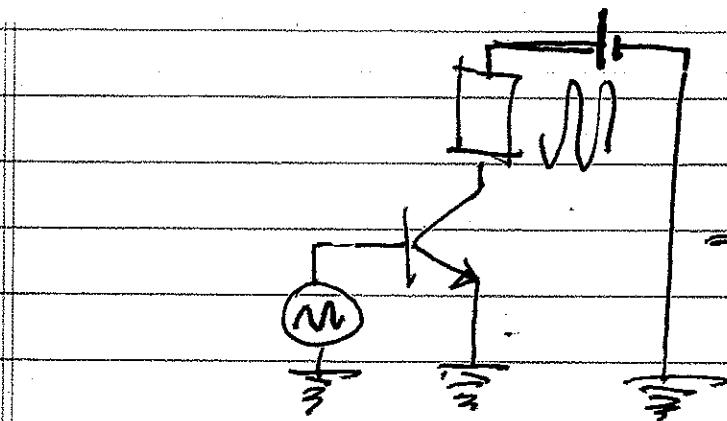
$\Rightarrow V_{be}$, accelerates
electrons from
E to B, but

B is thin \Rightarrow not
enough space for
recombination

\Rightarrow travel to C

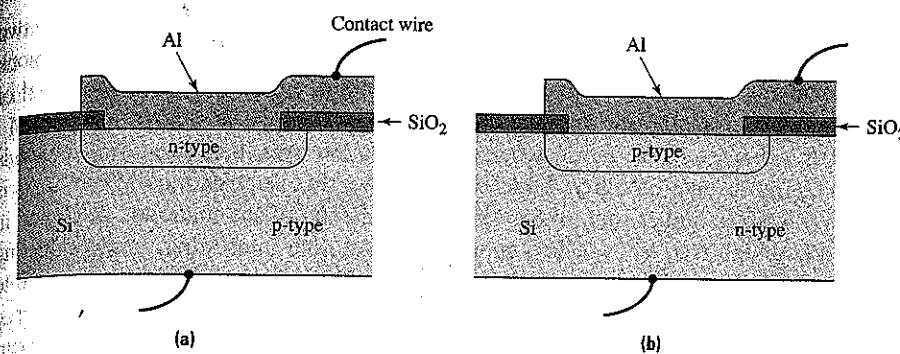
$\Rightarrow V_{bc}$ controls
conductivity
between
E & C

\Rightarrow amplification

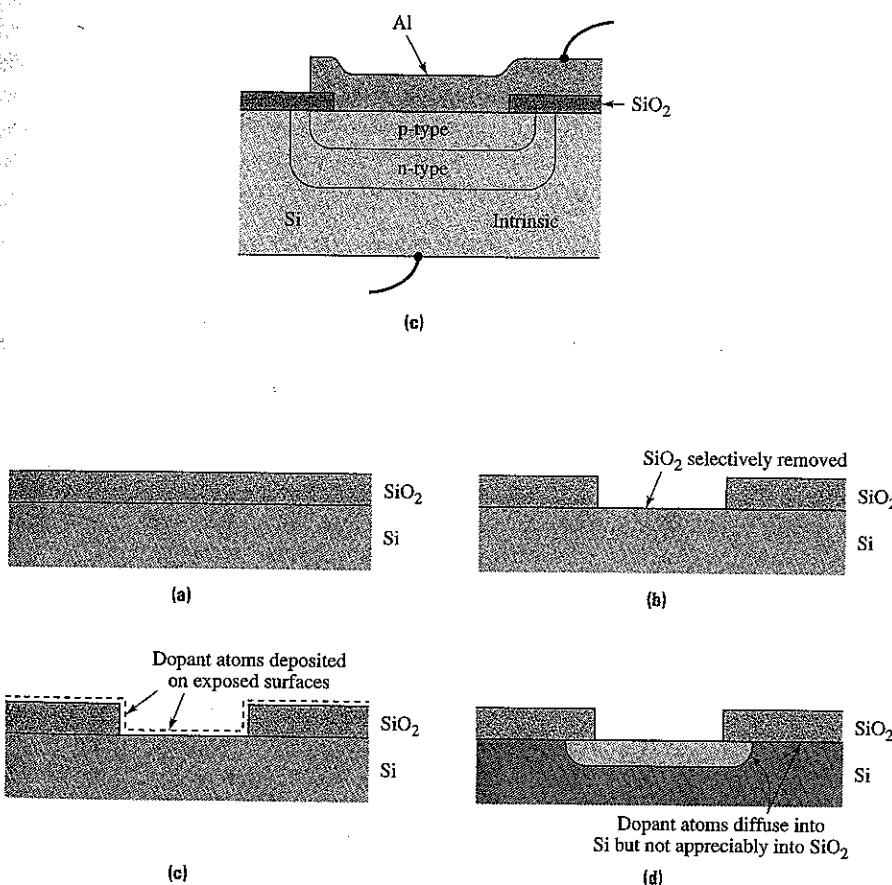


E26

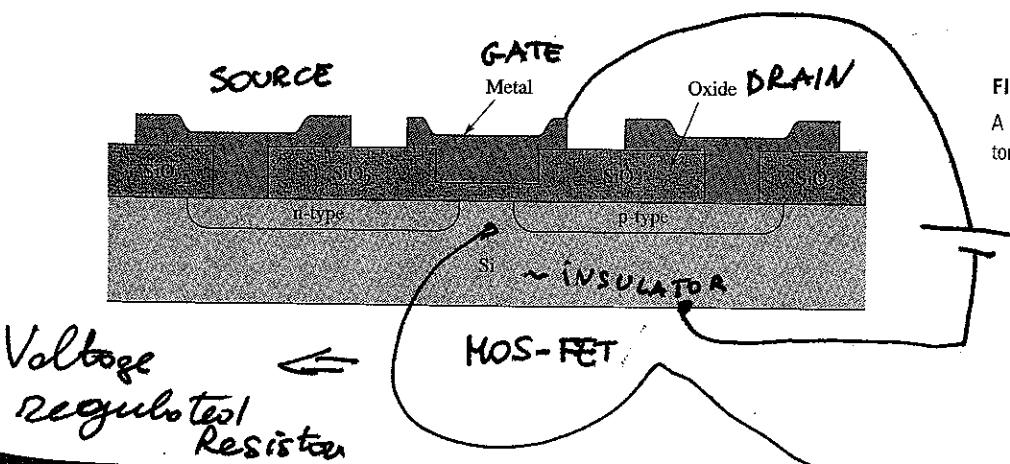
INTEGRATED CIRCUITS


FIGURE 10.3-9

Three methods for fabricating a pn junction diode:
(a) diffusion of an n-type dopant into a p-type substrate,
(b) diffusion of a p-type dopant into an n-type substrate, or
(c) sequential diffusion of n-type and p-type dopants into an intrinsic substrate.


FIGURE 10.3-10

The method for introducing a controlled amount of a dopant into a silicon substrate: **(a)** the oxidized wafer, **(b)** the SiO₂ surface oxide layer is removed from the region to be doped, **(c)** dopant atoms are introduced onto the surface, and **(d)** the dopant is thermally diffused into the underlying silicon.


FIGURE 10.3-11

A metal-oxide-semiconductor (MOS) capacitor.