ELECTRICAL PROPERTIES

OBSERVATION OHM'S LAW $V=RI$

$$\boxed{V=IR}$$

$R = \Omega$

$V = \text{Volt}$

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

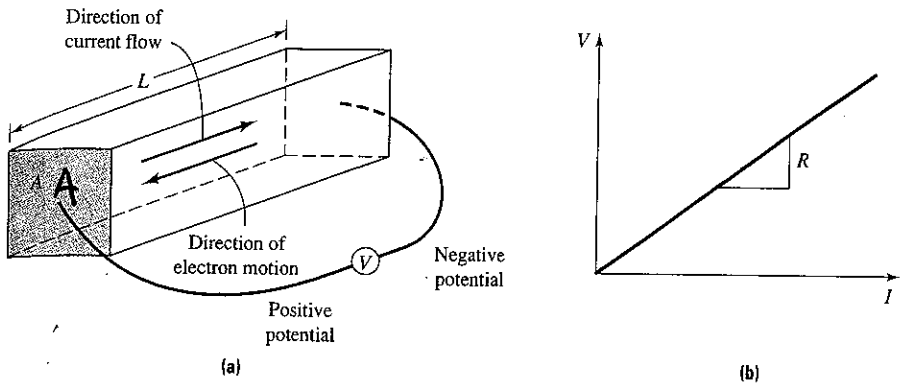
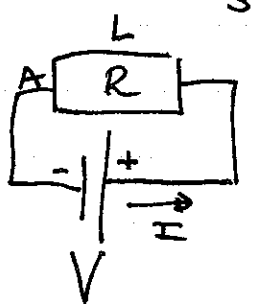


FIGURE 10.2–1 A simple electrical conduction experiment. **(a)** A bar of material of length L and cross-sectional area A is subjected to a voltage V. **(b)** The response of the system, current flow I, is a linear function of the magnitude of the driving force, voltage V. The constant of proportionality,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

SIMBOLS



CONVENTION

CURRENT FROM ⊕ → ⊖

(ONLY CONVENTION DEPENDS ON CARRIER)

$R(L, A)$ experimental

$L \to 2L \Rightarrow R \to 2R$

$R \propto L$

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

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

$R \propto \frac{L}{A}$ ρ = RESISTIVITY

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

$R\,[\Omega]$

$L\,[m]$ $A\,[m^2]$

$R = \rho \frac{m}{m^2}$

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

σ = CONDUCTIVITY

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

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

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

$\hookrightarrow \boxed{J = \sigma E}$

$\frac{I}{A} = J$ DENSITY

$V = E \cdot L$ Volt & electric FIELD

E1

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

Class of materials	σ [$(\Omega\text{-cm})^{-1}$]
Polymer	
Nylon	10^{-12}–10^{-16}
Polycarbonate	5×10^{-17}
Polyethylene	$< 10^{-15}$
Polypropylene	$< 10^{-15}$
Polystyrene	$< 10^{-16}$
Polytetrafluoroethylene	10^{-18}
Polyvinylchloride	10^{-12}–10^{-16}
Phenolformaldehyde	10^{-13}
Polyesters	10^{-17}
Silicones	$< 10^{-12}$
Acetal	10^{-15}
Metals and alloys	
Al	3.8×10^5
Ag	6.3×10^5
Au	4.3×10^5
Co	1.6×10^5
Cr	7.8×10^4
Cu	6.0×10^5
Fe	1.0×10^5
Mg	2.2×10^5
Ni	1.5×10^5
Pd	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	1.7×10^5
Zr	2.5×10^4
Plain carbon steel (1020)	1.0×10^5
Stainless steel (304)	1.4×10^4
Gray cast iron	1.5×10^4
Ceramics	
ReO_3	5.0×10^5
CrO_2	3.3×10^5
SiC	1.0×10^{-1}
Fe_3O_4	1.0×10^2
SiO_2	$< 10^{-14}$
Al_2O_3	$< 10^{-14}$
Si_3N_4	$< 10^{-14}$
MgO	$< 10^{-14}$
Si	1.0×10^{-4}
Ge	2.3×10^{-2}

OHM'S $V = RI \iff J = \sigma E$ (RESULT ← FORCE, MOVEMENT)

GOOD CONDUCTORS

σ BIG = shows 23 ORDERS OF MAGNITUDE

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

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 $N \left(\frac{m^{-3}}{cm^{-3}}\right)$

2) CHARGE OF CARRIER COULOMB C

3) MOBILITY μ $\left(\frac{m^2}{V \cdot s}\right)$

↓ RATIO SPEED / ELECTRIC-FIELD

~~VOLT SPEED~~

1 LION → v = ~~10~~ 10 mph

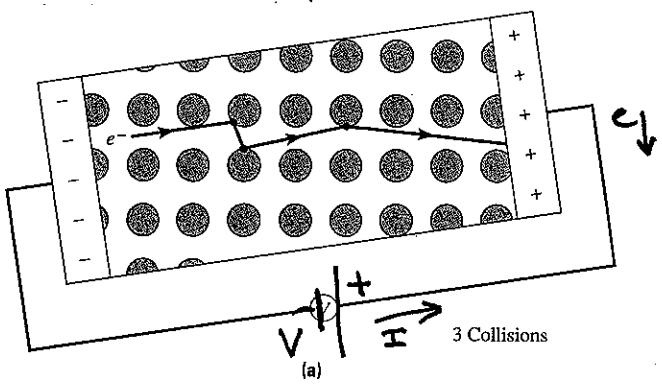
3 LIONS → v = 30 mph

RATIO SPEED / # OF LIONS

⇒ MOBILITY OF THE TEACHER

E2

MOBILITY ⇒ BUILD σ



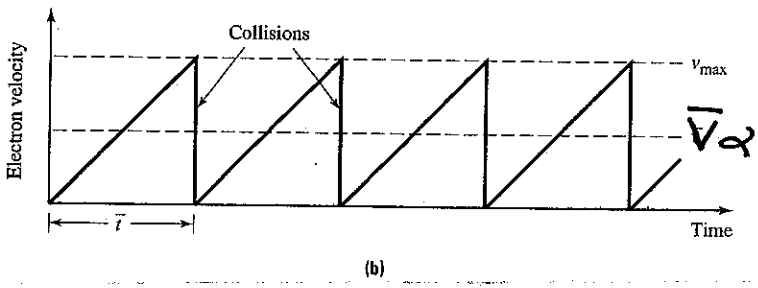


FIGURE 10.2–2
Particle model of an electron, e^-, moving through a crystal lattice. **(a)** Under an applied electric field, the mobile electrons are accelerated toward the positive potential and occasionally suffer collisions with the surrounding ion cores. **(b)** A plot of electron velocity versus 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).

$\bar{V} \propto$ Electric FIELD

COLLISIONS :- START FROM $V=0$
- ACCELERATION TO V_{max}
- COLLISION & RESTART

} ~~Voltage~~

COLLISION every τ relaxation time !

$v = at \Rightarrow$ $(F=ma)$ $am = Ee \Rightarrow$ $v_{max} = a\tau$

$a \propto E$ $\quad v_{AVG} \propto v_{max}$

$\propto E$ FIELD

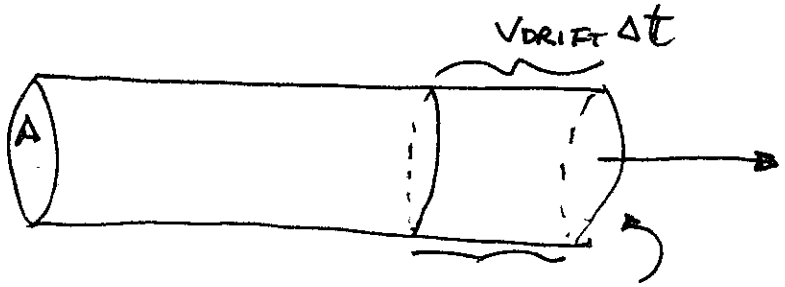
v_{AVG} = DRIFT VELOCITY !! ~ cm/s mm/s SMALL

$$v_{DRIFT} \equiv \mu E$$

MOBILITY

E3

CONDUCTOR



HOW MUCH "CHARGE" EXITS SURFACE IN TIME Δt ?
All the ~~CHARGE STORED~~ CLOSER THAN $v_{DRIFT}\,\Delta t$ from SURFACE !!

$$\Delta Q = \underbrace{(v_{DRIFT}\,\Delta t)\,A}_{\text{VOLUME}} \cdot \underbrace{*\,n}_{\text{DENSITY}} \underbrace{*\,q}_{\substack{\text{CHARGE}\\ \text{EACH PARTICLE}}}$$

PARTICLES.

$$\Rightarrow \frac{\Delta Q}{\Delta t} = A\, v_{DRIFT} * n * q \qquad J = \sigma E$$

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

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

($v_{DRIFT} = \mu E$)

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

EXAMPLE Li_2O ~~Li_2O~~

$Li^+ + Li^+ + O^{--}$

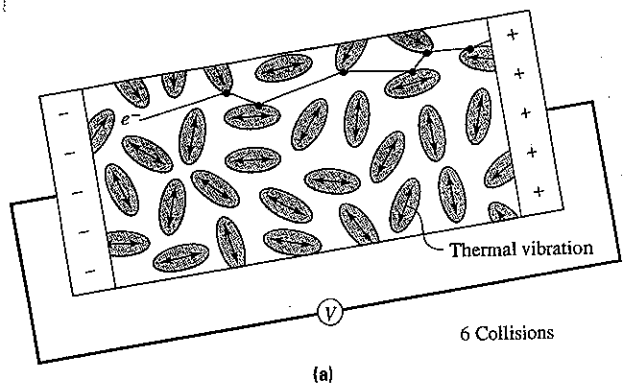
$q_{Li} = e \quad n_{Li}$

$q_O = -2e \quad n_O$

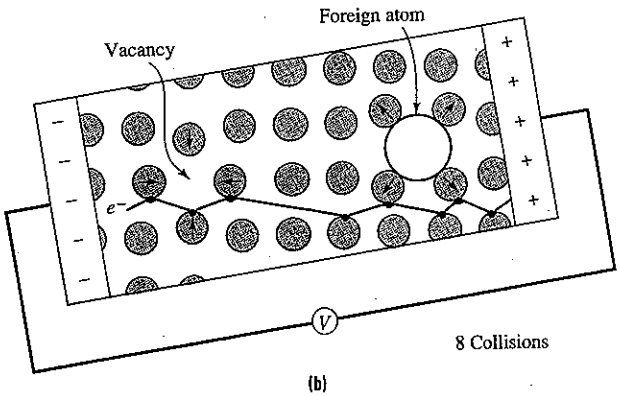
BUT $\mu_O < 0$ & $\mu_{Li} > 0$

(BECAUSE $O^{--} < 0$) $\Rightarrow$ CONVENTION q POSITIVE !! μ POSITIVE !!

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



(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

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

(MORE COLLISIONS, MORE TIGHT SPACES)

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

HOWEVER $\sigma = nq\mu$

$\downarrow \partial\mu/\partial T < 0$

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

BUT TEMPERATURE OR IMPURITIES CAN BOOST n!!

$\frac{\partial n}{\partial T}$ ← HUGE, LIKE SEMICONDUCTORS

$\frac{\partial n}{\partial N_D} > 0$

$\frac{\partial n}{\partial T} = 0$ METALS

CRYSTALLINE STRUCTURE ⇒ MANY LEVELS

FROM QMECHANICS : TAKE MY COURSE IF YOU WANT TO KNOW

1 atom (ISOLATED) ⇒ • LEVELS 1s · 2s 2p · 3s 3p 3d . . . DISCRETE

• ISOLATED

• OUTER ELECTRONS = VALENCE (LOCALIZED)

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

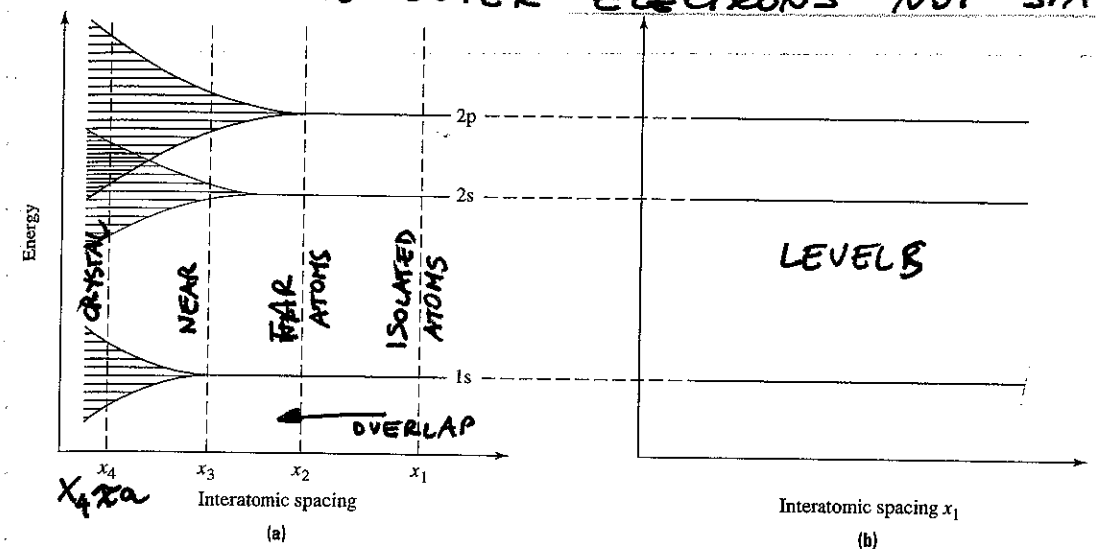
CRYSTAL ⇒ a • DISCRETE & ISOLATED

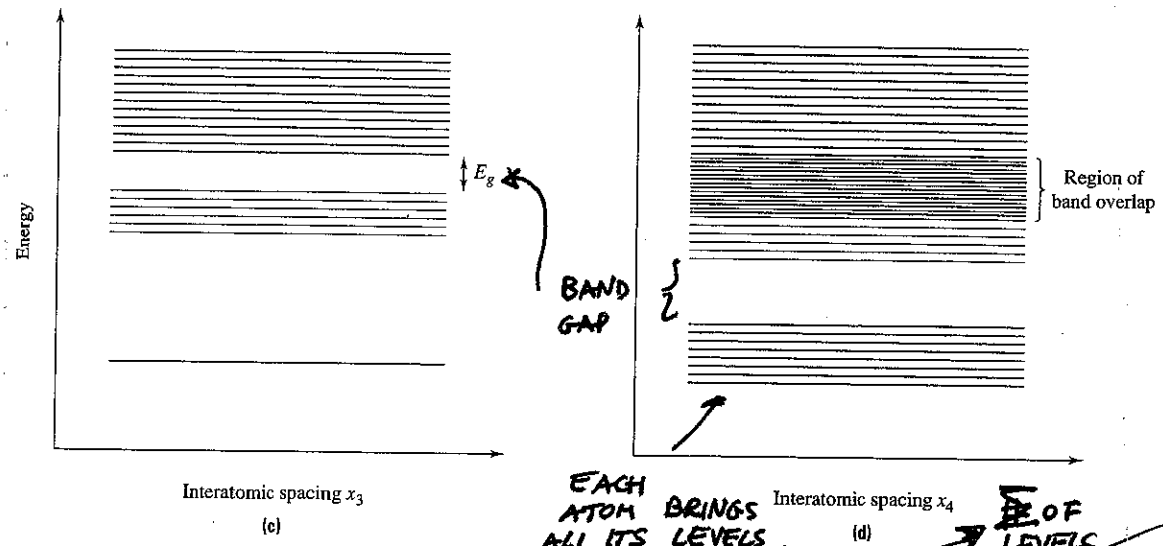
SPREAD INTO ENERGY BANDS

• OUTER ELECTRONS NOT SPATIALLY LOCALIZED ANYMORE

WIDER

NARROWER



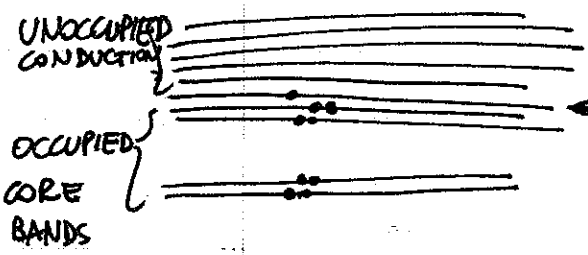


EACH ATOM BRINGS ALL ITS LEVELS ⇒ # OF LEVELS IS CONST.

E6

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.

ELECTRONS FILL FROM LOWEST ENERGY!



HIGHEST ENERGY BAND AT LEAST PARTIALLY OCCUPIED

VALENCE BAND

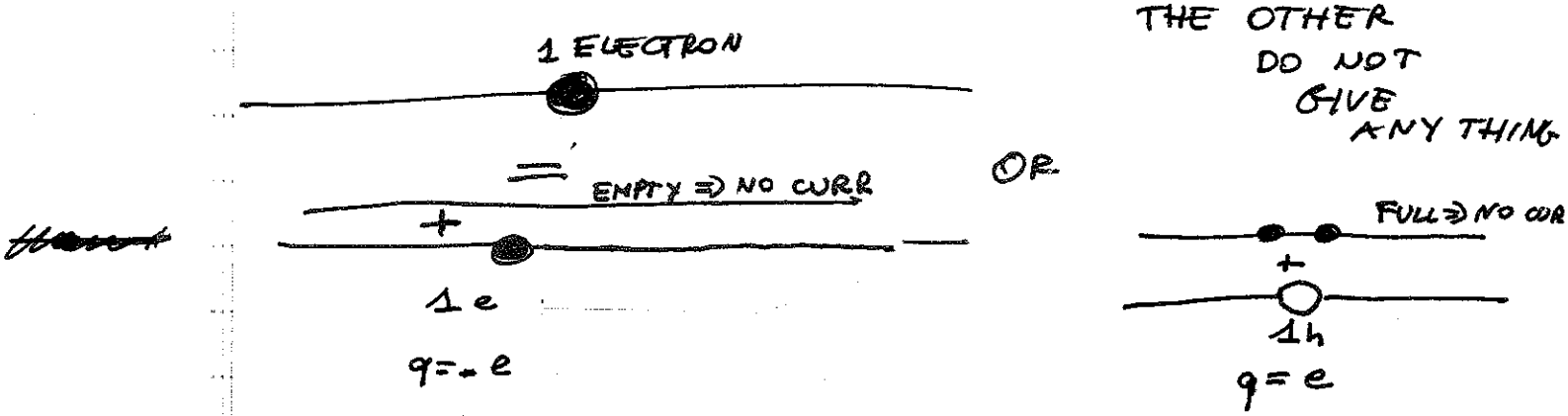
PROPERTY : COMPLETELY FILLED & COMPLETELY EMPTY BANDS ARE NOT CAPABLE OF TRANSPORTING ELECTRIC CHARGE THROUGH THE SOLD

COMES FROM LIOUVILLE THEOREM

ASK!!

ONLY PARTIALLY OCCUPIED LEVELS GIVE CONDUCTIVITY!!

⇒ GIVE CURRENT, THE OTHER DO NOT GIVE ANY THING



$m_e > 0$

μ_e

$m_h < 0$

μ_h

generically

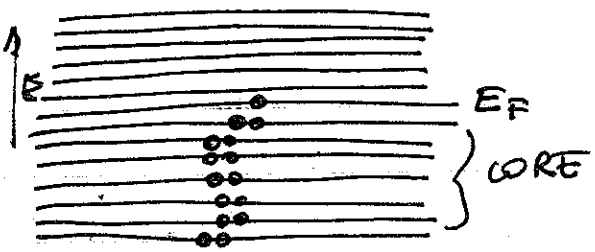
$\mu_h < \mu_e$

E7

TEMPERATURE EFFECT

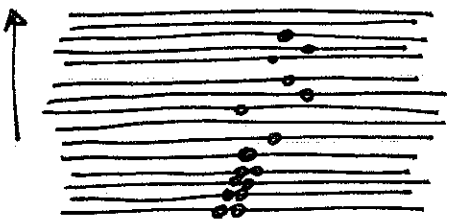
FERMI DIRAC DISTRIBUTION

T=0



E_F = ~~ENERGY~~ FERMI ENERGY

T>0



SOME ELECTRONS ~~ARE~~ EXCITED & POP UP FROM CORE BECAUSE TEMPERATURE

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

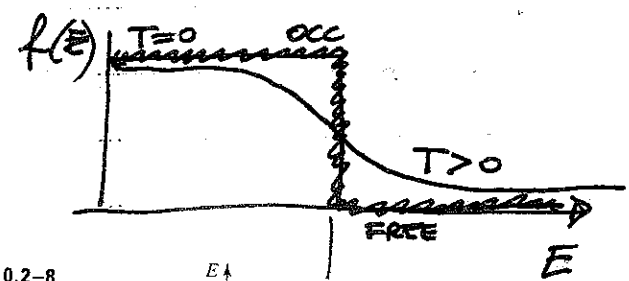
$k_F = \sqrt[3]{3\pi^2 n}$ FERMI MOMENTUM

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

PROBABILITY DISTRIBUTION OF OCCUPATION

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

FERMI — DIRAC DISTRIBUTION



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

$f(E>E_F) = 0$

⇒ T>0 $f(E \ll E_F) \to 1$ NO COND

$f(E \gg E_F) \to 0$

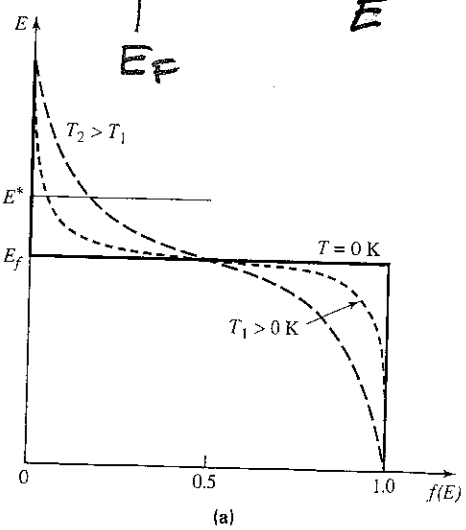
$f(E \approx E_F) \sim$ in (KT) NOT 0 OR 1 } COND

NO COND

~~RELEVANCE~~

$K_B T_{ROOM} \approx 25$ meV

$K_B \sim 8.6\ 10^{-5}$ eV/K



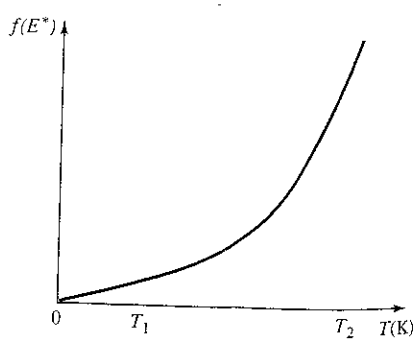
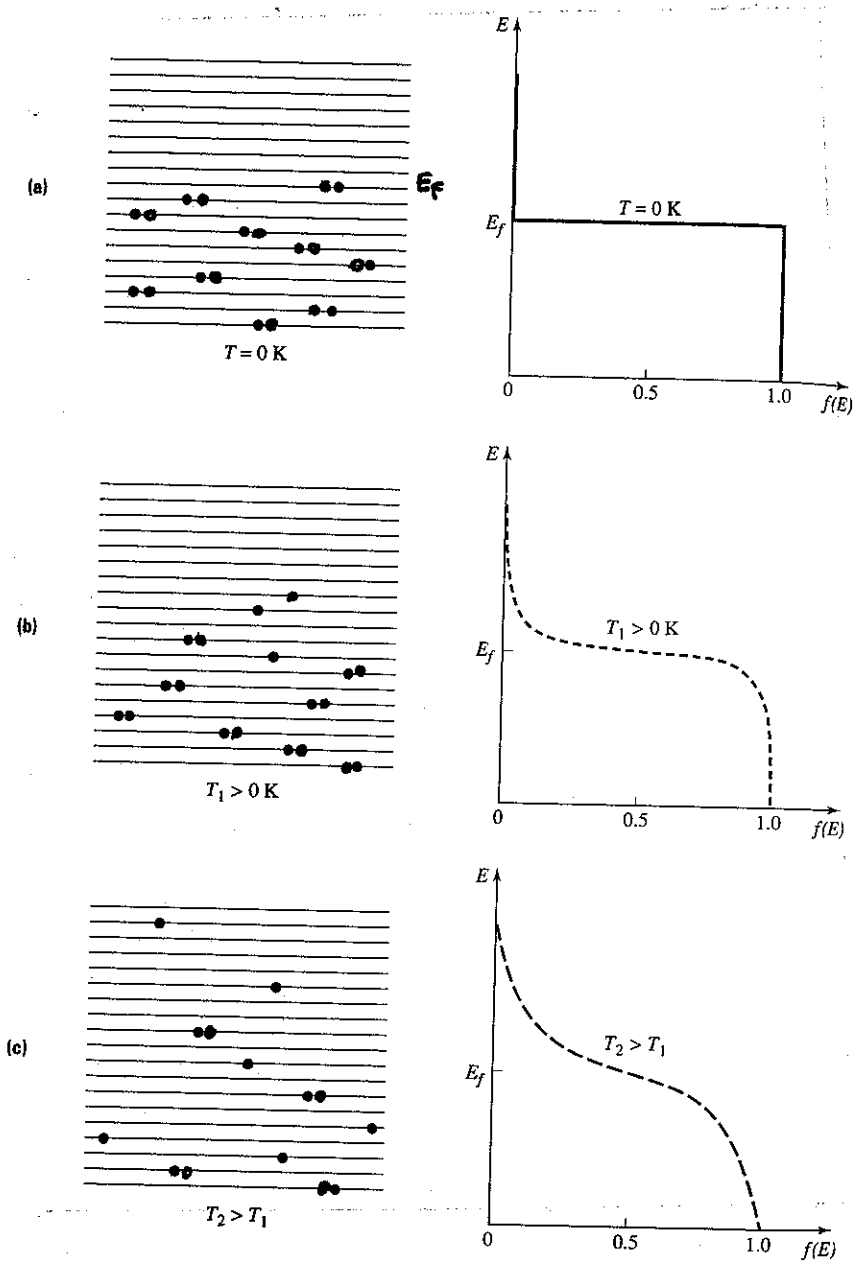


FIGURE 10.2–8
(a) The change in the probability of occupation, as described by the Fermi-Dirac distribution function $f(E)$, as a function of temperature; and **(b)** the probability that energy level E^* in part a is occupied, given by $f(E^*)$, as a function of temperature.

E8

FIGURE 19.2–9
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 $T_2 > T_1$.



T ↑ OCCUPATION IS SPREADING ALONG BANDS

STUDY CHAP 10

E9