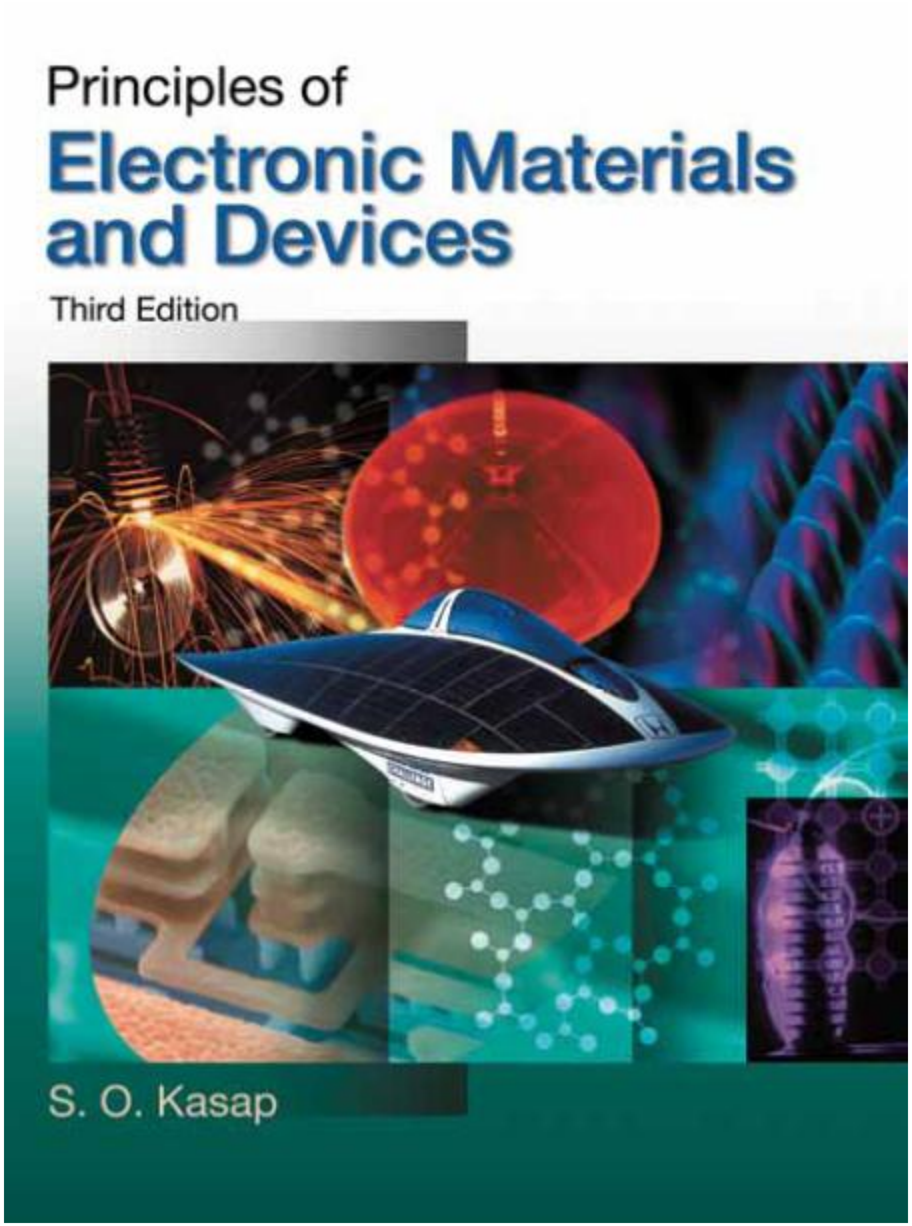
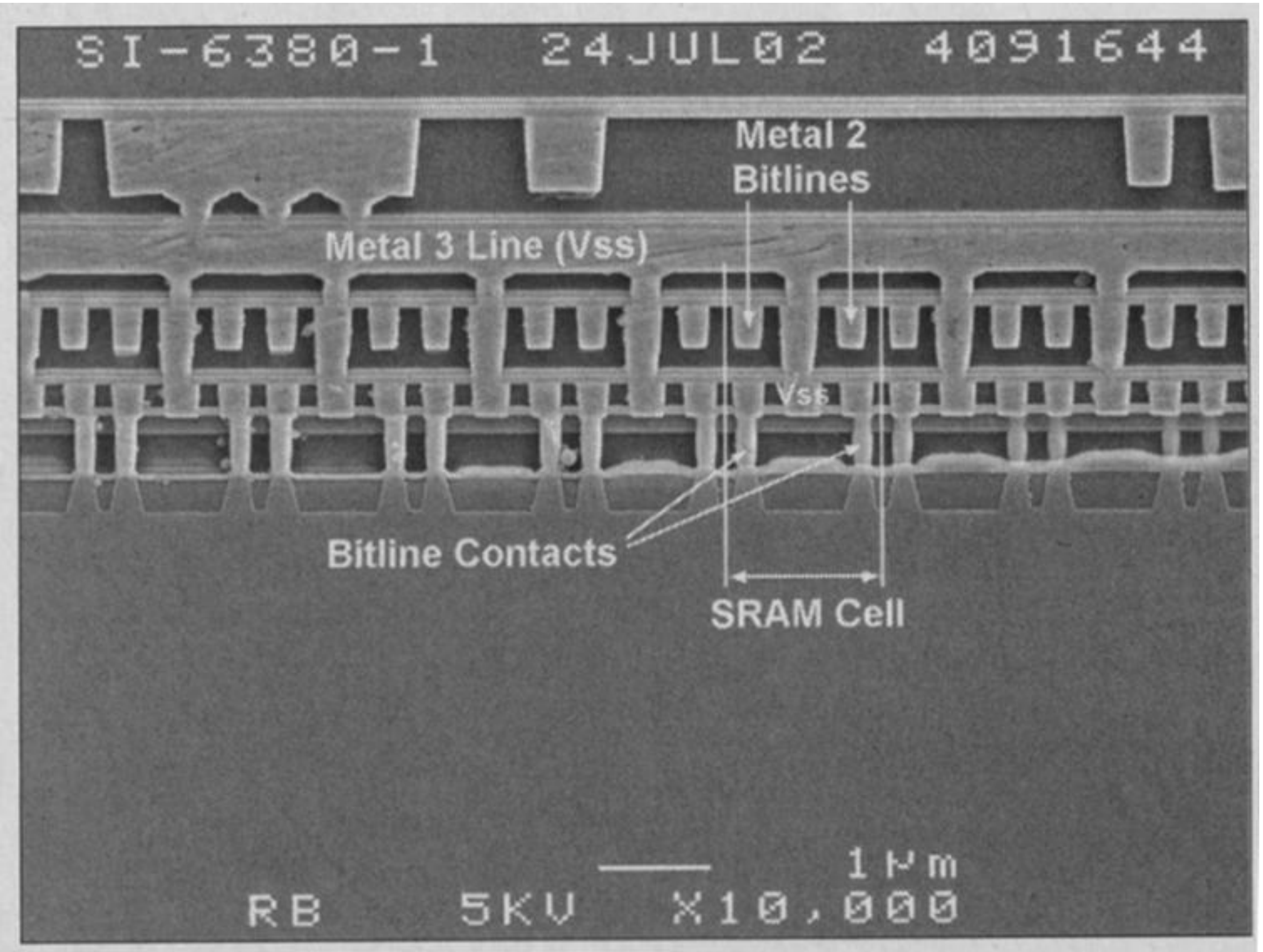

Principles of
Electronic Materials
and Devices
Third Edition
S. O. Kasap

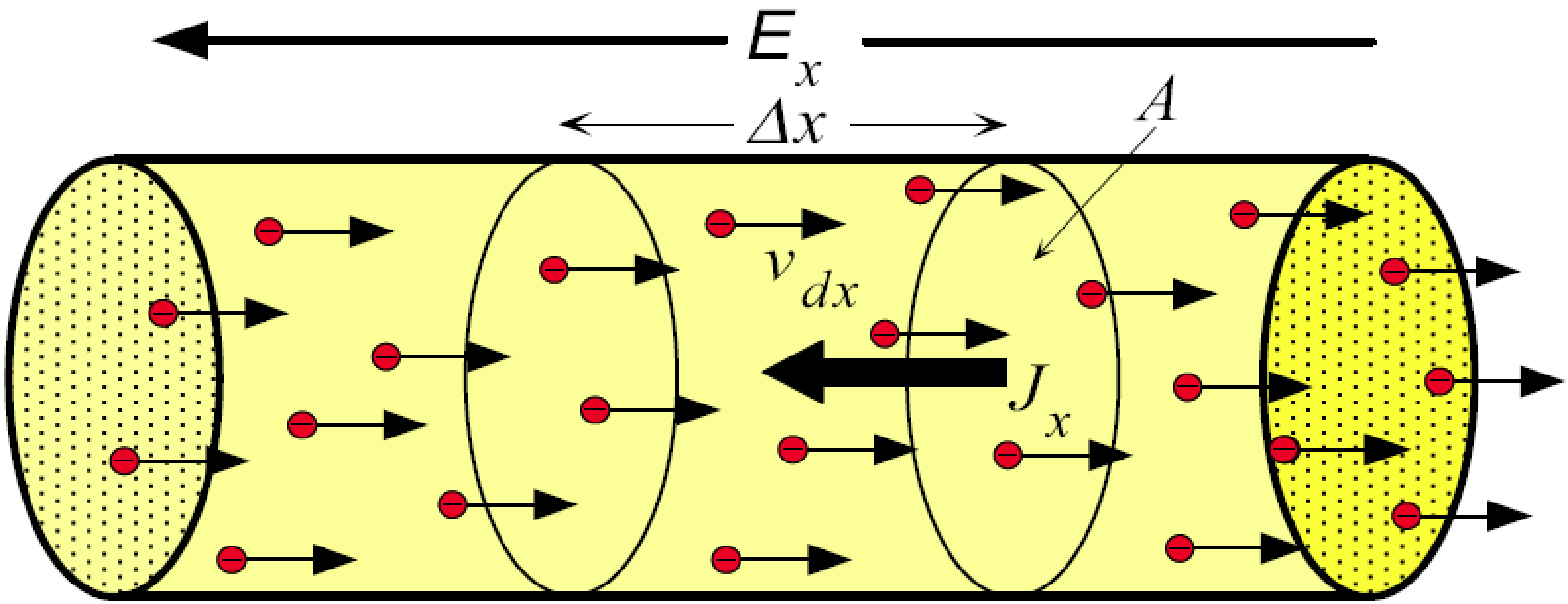
Mc Graw Hill

Metal interconnects are used in microelectronics to wire the devices within the chip, the intergraded circuit. Multilevel interconnects are used for implementing the necessary interconnections.



5. A SEM cross section of the interconnect in an SRAM cell.

|SOURCE: Dr. Don Scansen, Semiconductor Insights, Kanata, Ontario, Canada



Drift of electrons in a conductor in the presence of an applied electric field. Electrons drift with an average velocity v_{dx} in the x-direction. (E_x is the electric field.)

$$J_x = \frac{\Delta q}{A\,\Delta t} = \frac{enAv_{dx}\,\Delta t}{A\,\Delta t} = env_{dx}$$

Fig 2.1

Definition of Drift Velocity

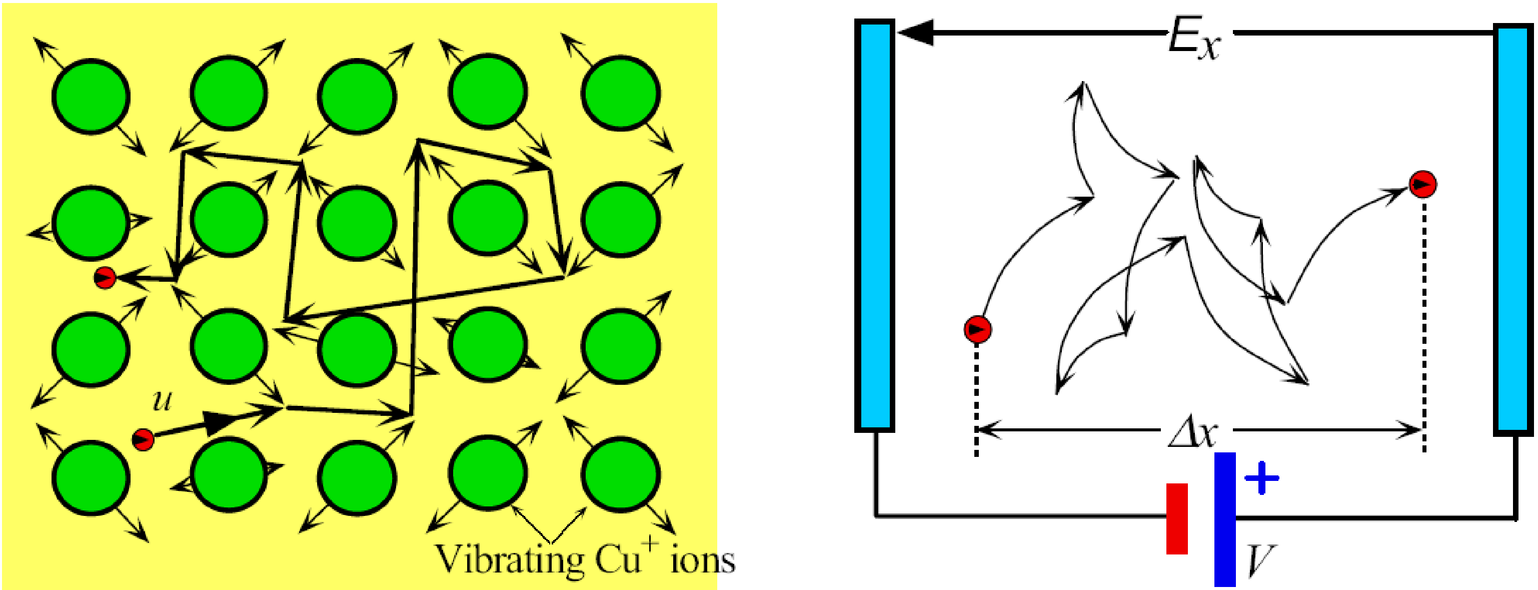
$$v_{dx} = \frac{1}{N}\left[v_{x1} + v_{x2} + v_{x3} + \cdots + v_{xN}\right]$$

v_{dx} = drift velocity in x direction, N = number of conduction electrons, v_{xi} = x direction velocity of ith electron

Current Density and Drift Velocity

$$J_x(t) = env_{dx}(t)$$

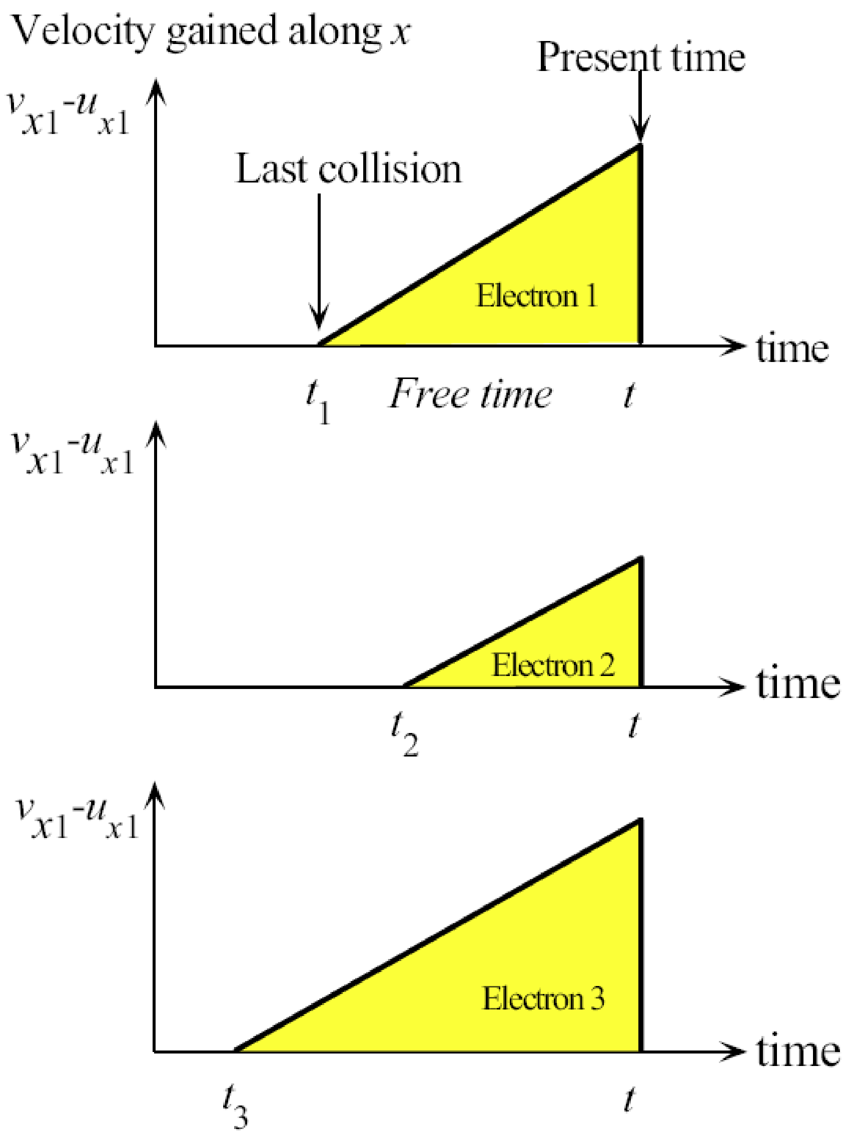
J_x = current density in the x direction, e = electronic charge, n = electron concentration, v_{dx} = drift velocity



(a) (b)

(a) A conduction electron in the electron gas moves about randomly in a metal (with a mean speed u) being frequently and randomly scattered by thermal vibrations of the atoms. In the absence of an applied field there is no net drift in any direction.
(b) In the presence of an applied field, E_x, there is a net drift along the x-direction. This net drift along the force of the field is superimposed on the random motion of the electron. After many scattering events the electron has been displaced by a net distance, Δx, from its initial position toward the positive terminal

Fig 2.2



$$v_{xi} = u_{xi} + \frac{e\mathcal{E}_x}{m_e}(t - t_i)$$

Velocity gained in the *x* direction at time t from the electric field (E_x) for three electrons. There will be *N* electrons to consider in the metal.

Fig 2.3

Definition of Drift Mobility

$$v_{dx} = \mu_d E_x$$

v_{dx} = drift velocity, μ_d = drift mobility, E_x = applied field

Drift Mobility and Mean Free Time

$$\mu_d = \frac{e\tau}{m_e}$$

μ_d = drift mobility, e = electronic charge, τ = mean scattering time (mean time between collisions) = relaxation time, m_e = mass of an electron in free space.

Unipolar Conductivity

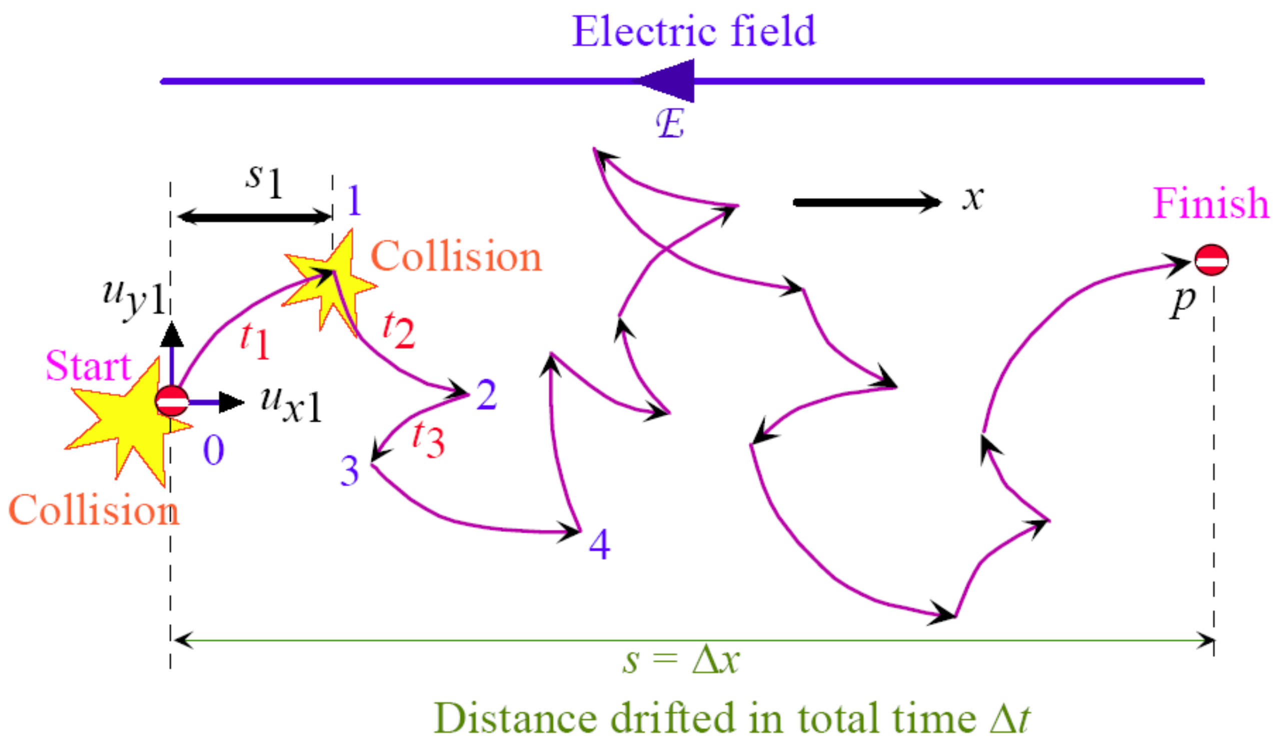
$$\sigma = en\mu_d = \frac{e^2 n\tau}{m_e}$$

σ = conductivity, e = electronic charge, n = number of electrons per unit volume, μ_d = drift velocity, τ = mean scattering (collision) time = relaxation time, m_e = mass of an electron in free space.

Drift Velocity

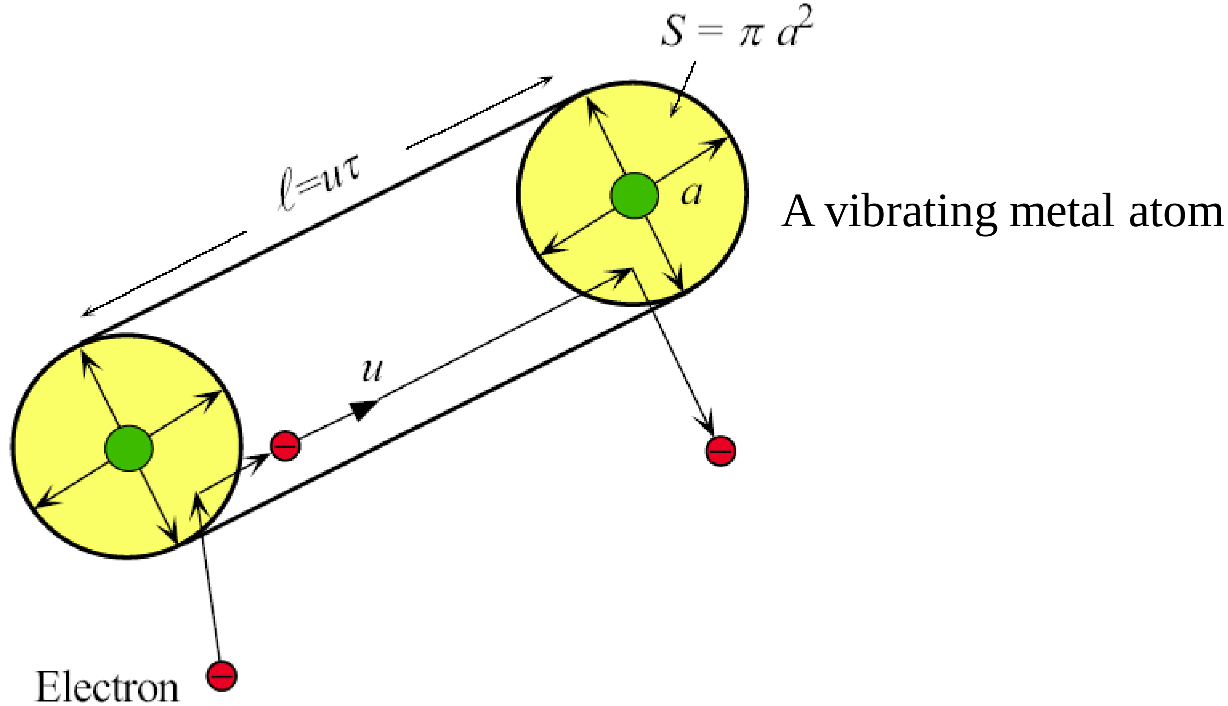
$$\frac{\Delta x}{\Delta t} = v_{dx}$$

Δx = net displacement parallel to the field, Δt = time interval, v_{dx} = drift velocity



The motion of a single electron in the presence of an electric field E. During a time Interval t_i, the electron traverses a distance s_i along x. After p collisions, it has drifted a Distance $s = \Delta x$.

Fig 2.4



Scattering of an electron from the thermal vibrations of the atoms. The electron travels a mean distance $\ell = u\tau$ between collisions. Since the scattering cross-sectional area is S, in the volume $s\ell$ there must be at least one scatterer, $N_s(Su\tau) = 1$.

Fig 2.5

Mean Free Time Between Collisions

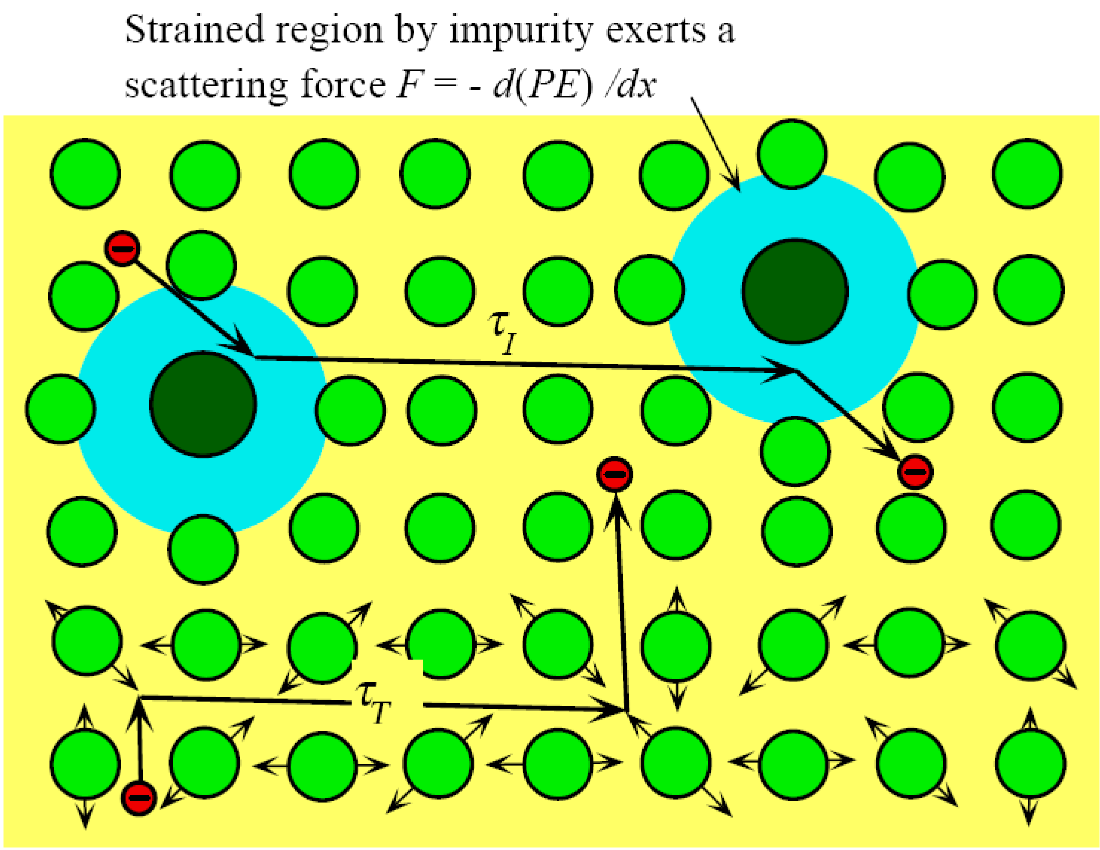
$$\tau = \frac{1}{SuN_s}$$

τ = mean free time, u = mean speed of the electron, N_s = concentration of scatterers, S = cross-sectional area of the scatterer

Resistivity Due to Thermal Vibrations of the Crystal

$$\rho_T = AT$$

ρ_T = resistivity of the metal, A = temperature independent constant, T = temperature



Two different types of scattering processes involving scattering from impurities alone and from thermal vibrations alone.

Fig 2.6

Table 2.1 Resistivity, thermal coefficient of resistivity α_0 at 273 K (0 °C) for various metals. The resistivity index n in $\rho \propto T^n$ for some of the metals is also shown.

Metal	ρ_0 (nΩ m)	$\alpha_0 \left(\frac{1}{K}\right)$	n	Comment
Aluminum, Al	25.0	$\frac{1}{233}$		
Antimony, Sb	38	$\frac{1}{196}$		
Copper, Cu	15.7	$\frac{1}{232}$	1.15	
Gold, Au	22.8	$\frac{1}{251}$		
Indium, In	78.0	$\frac{1}{196}$		
Platinum, Pt	98	$\frac{1}{255}$	0.94	
Silver, Ag	14.6	$\frac{1}{244}$	1.11	
Tantalum, Ta	117	$\frac{1}{294}$	0.93	
Tin, Sn	110	$\frac{1}{217}$	1.11	
Tungsten, W	50	$\frac{1}{202}$	1.20	
Iron, Fe	84.0	$\frac{1}{152}$	1.80	Magnetic metal; $273 < T < 1043$ K
Nickel, Ni	59.0	$\frac{1}{125}$	1.72	Magnetic metal; $273 < T < 627$ K

SOURCE: Data were extracted and combined from several sources.

Matthiessen's Rule

$$\rho = \rho_T + \rho_I$$

ρ = effective resistivity, ρ_T = resistivity due to scattering by thermal vibrations only, ρ_I = resistivity due to scattering of electrons from impurities only.

$$\rho = \rho_T + \rho_R$$

ρ = overall resistivity, ρ_T = resistivity due to scattering from thermal vibrations, ρ_R = residual resistivity

Definition of Temperature Coefficient of Resistivity

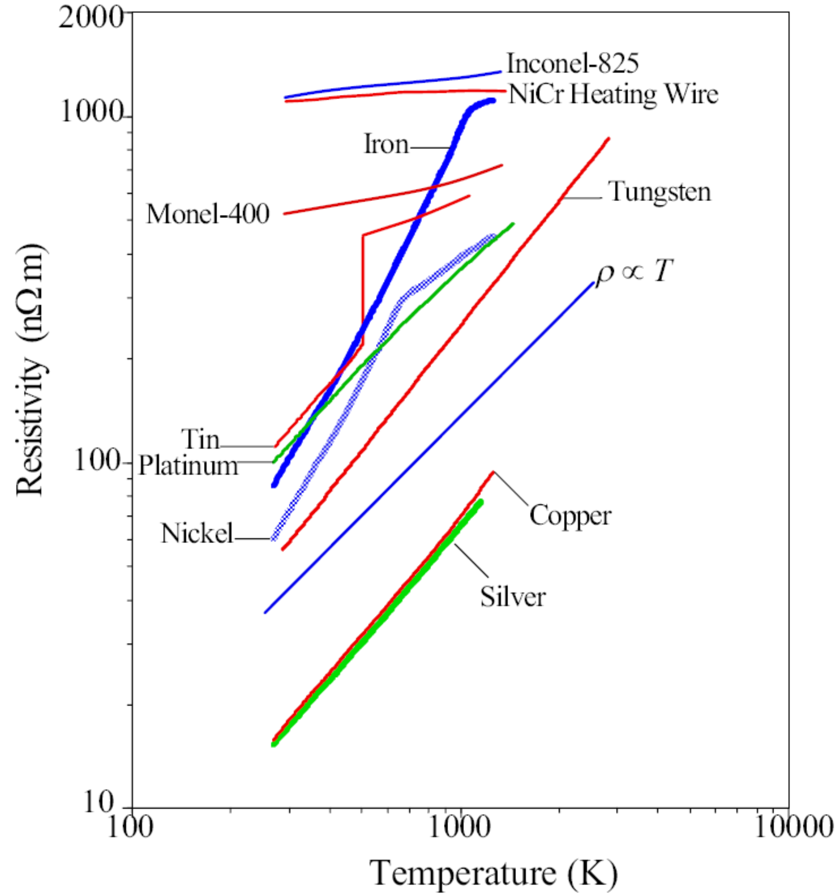
$$\alpha_o = \frac{1}{\rho_o}\left[\frac{\delta\rho}{\delta T}\right]_{T=T_o}$$

α_o = TCR (temperature coefficient of resistivity), $\delta\rho$ = change in the resistivity, ρ_o = resistivity at reference temperature T_o , δT = small increase in temperature, T_o = reference temperature

Temperature Dependence of Resistivity

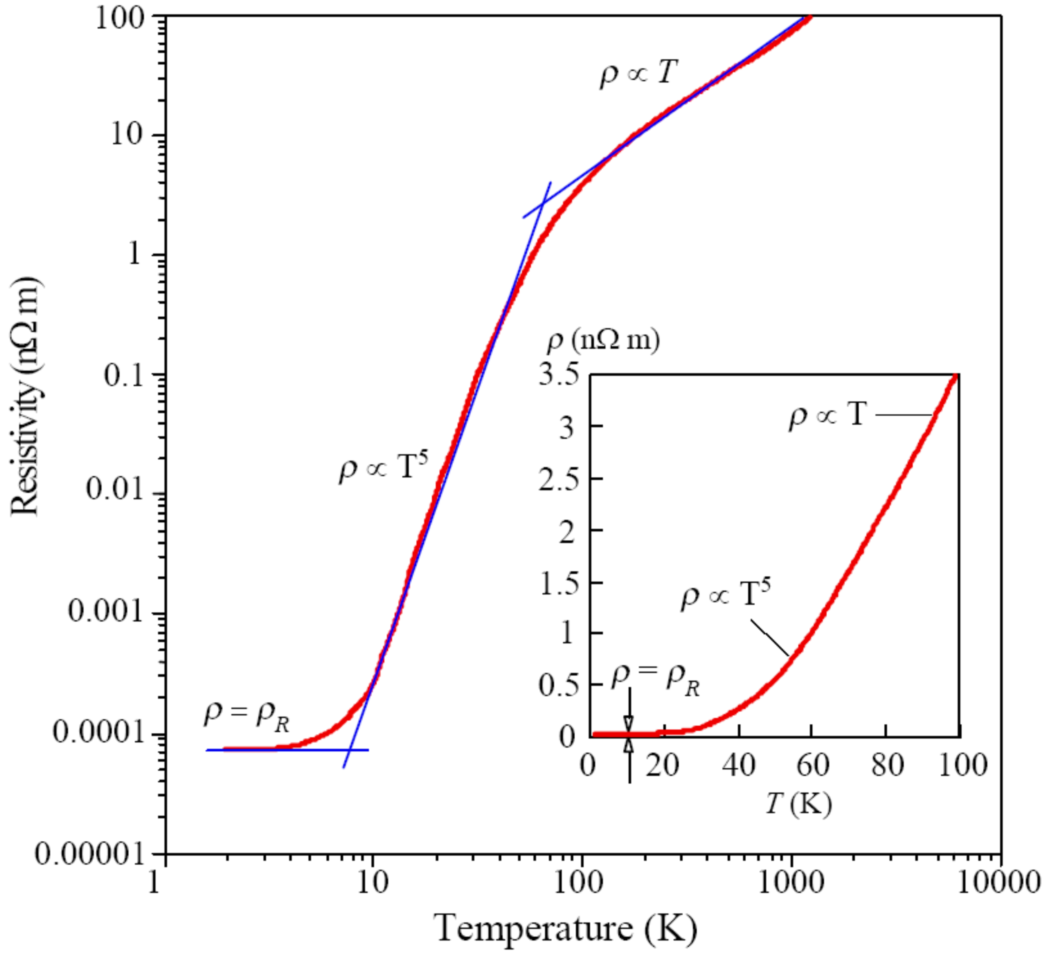
$$\rho = \rho_o\,[1 + \alpha_o(T - T_o)]$$

ρ = resistivity, ρ_o = resistivity at reference temperature, α_0 = TCR (temperature coefficient of resistivity), T = new temperature, T_0 = reference temperature



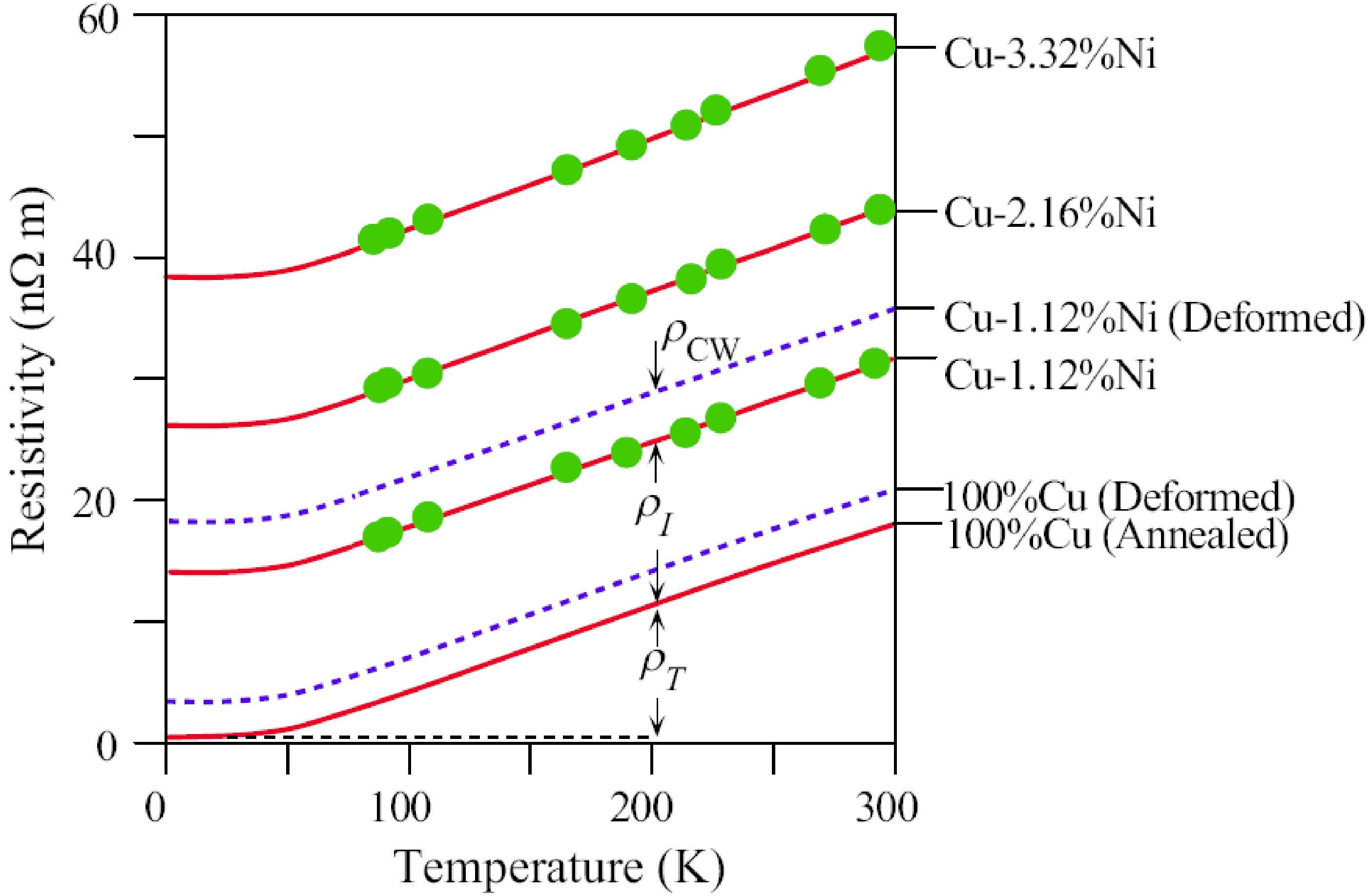
The resistivity of various metals as a function of temperature above 0 °C. Tin melts at 505 K whereas nickel and iron go through a magnetic to non-magnetic (Curie) transformations at about 627 K and 1043 K respectively. The theoretical behavior ($\rho \sim T$) is shown for reference.
[Data selectively extracted from various sources including sections in Metals Handbook, 10th Edition, Volumes 2 and 3 (ASM, Metals Park, Ohio, 1991)]

Fig 2.7



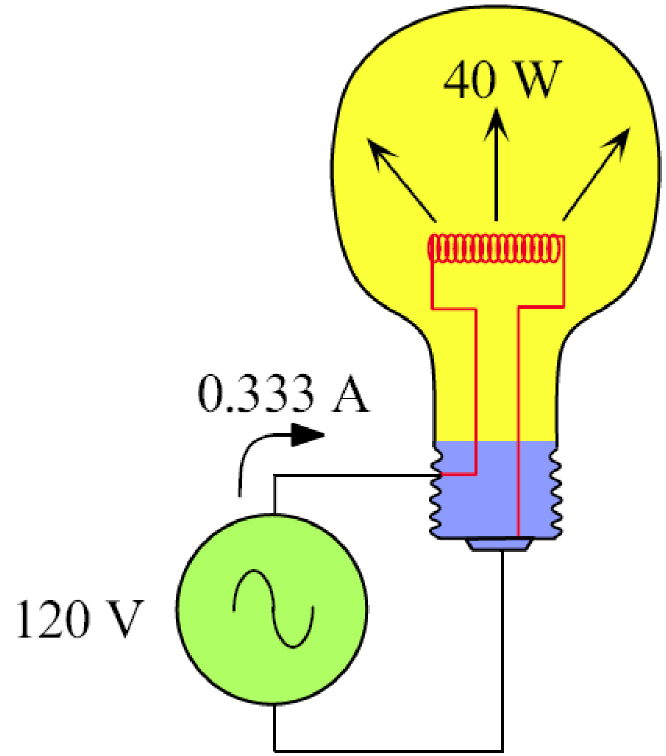
The resistivity of copper from lowest to highest temperatures (near melting temperature, 1358 K) on a log-log plot. Above about 100 K, $\rho \propto T$, whereas at low temperatures, $\rho \propto T^5$ and at the lowest temperatures ρ approaches the residual resistivity ρ_R. The inset shows the ρ vs. T behavior below 100 K on a linear plot (ρ_R is too small on this scale).

Fig 2.8



Typical temperature dependence of the resistivity of annealed and cold-worked (deformed) copper containing various amounts of Ni in atomic percentage.
SOURCE: Data adapted from J.O. Linde, *Ann Pkysik*, 5, 219 (Germany, 1932)

Fig 2.9

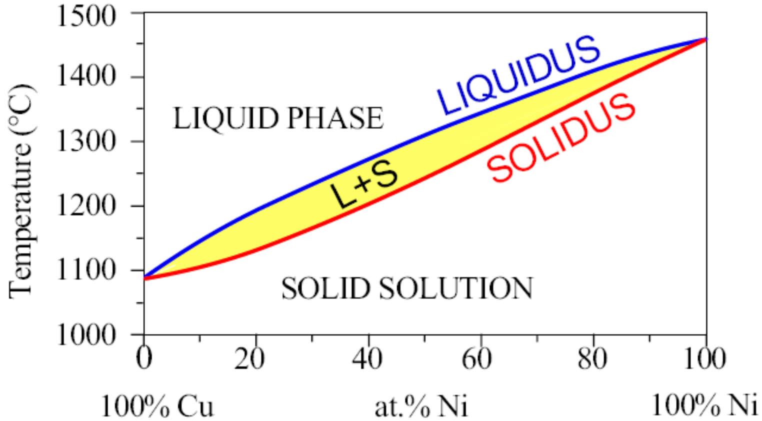


Power radiated from a light bulb is equal to the electrical power dissipated in the filament.

Fig 2.10

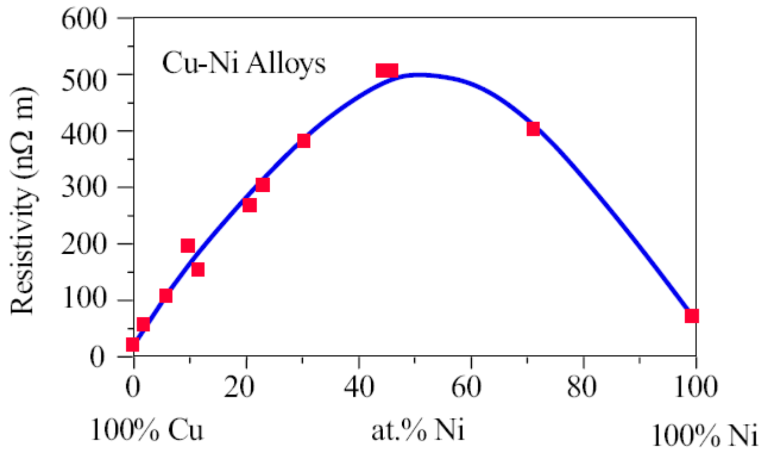
Table 2.2 The effect of alloying on the resistivity

Material	Resistivity at 20 °C (nΩ m)	α at 20 °C (1/K)
Nickel	69	0.006
Chrome	129	0.003
Nichrome	1120	0.0003



(a)

(a) Phase diagram of the Cu-Ni alloy system. Above the liquidus line only the liquid phase exists. In the *L* + *S* region, the liquid (*L*) and solid (*S*) phases coexist whereas below the solidus line, only the solid phase (a solid solution) exists.



(b)

(b) The resistivity of the Cu-Ni alloy as a Function of Ni content (at.%) at room temperature

The Cu-Ni alloy system.
SOURCE: Data extracted from *Metals Handbook*, 10^{th} ed., 2 and 3 Metals Park, Ohio: ASM, 1991, and M. Hansen and K. Anderko, *Constitution of Binary Alloys*, New York: McGraw-Hill, 1958.

Fig 2.11

Table 2.3 Nordheim coefficient C (at 20 °C) for dilute alloys obtained from $\rho_I = CX$ and $X < 1$ at.%*

Solute in Solvent (element in matrix)	C (nΩ m)	Maximum Solubility at 25 °C (at.%)
Au in Cu matrix	5500	100
Mn in Cu matrix	2900	24
Ni in Cu matrix	1200	100
Sn in Cu matrix	2900	0.6
Zn in Cu matrix	300	30
Cu in Au matrix	450	100
Mn in Au matrix	2410	25
Ni in Au matrix	790	100
Sn in Au matrix	3360	5
Zn in Au matrix	950	15

*NOTE: For many isomorphous alloys C may be different at higher concentrations; that is, it may depend on the composition of the alloy.

SOURCES: D.G. Fink and D. Christiansen, eds., *Electronics Engineers' Handbook*, 2nd ed., New York, McGraw-Hill, 1982. J. K. Stanley, *Electrical and Magnetic Properties of Metals*, Metals Park, OH, American Society for Metals, 1963. Solubility data from M. Hansen and K. Anderko, *Constitution of Binary Alloys*, 2nd ed., New York, McGraw-Hill, 1985.

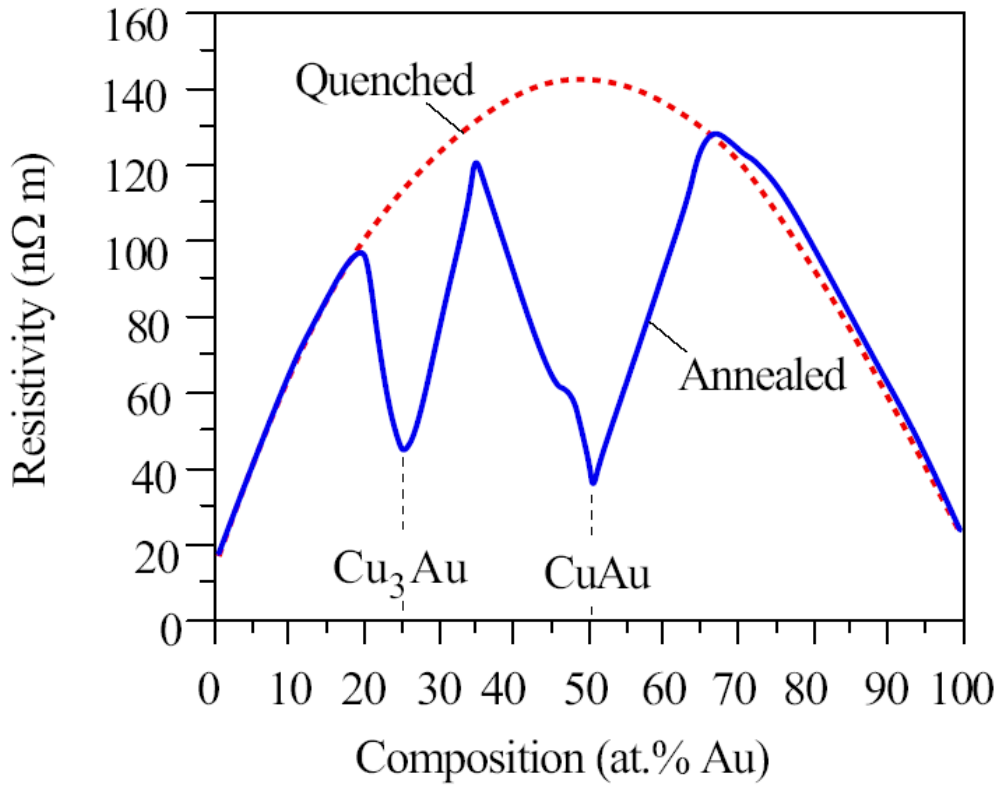
Nordheim's Rule for Solid Solutions

$$\rho_I = CX(1 - X)$$

ρ_I = resisitivity due to scattering of electrons from impurities

C = Nordheim coefficient

X = atomic fraction of solute atoms in a solid solution



Electrical resistivity vs. composition at room temperature in Cu-Au alloys.
The quenched sample (dashed curve) is obtained by quenching the liquid, and the Cu and Au atoms are randomly mixed. The resistivity obeys the Nordheim rule. When the quenched sample is annealed or the liquid is slowly cooled (solid curve), certain compositions (Cu_3Au and CuAu) result in an ordered crystalline structure in which the Cu and Au atoms are positioned in an ordered fashion in the crystal and the scattering effect is reduced.

Fig 2.12

Combined
Matthiessen and Nordheim Rules

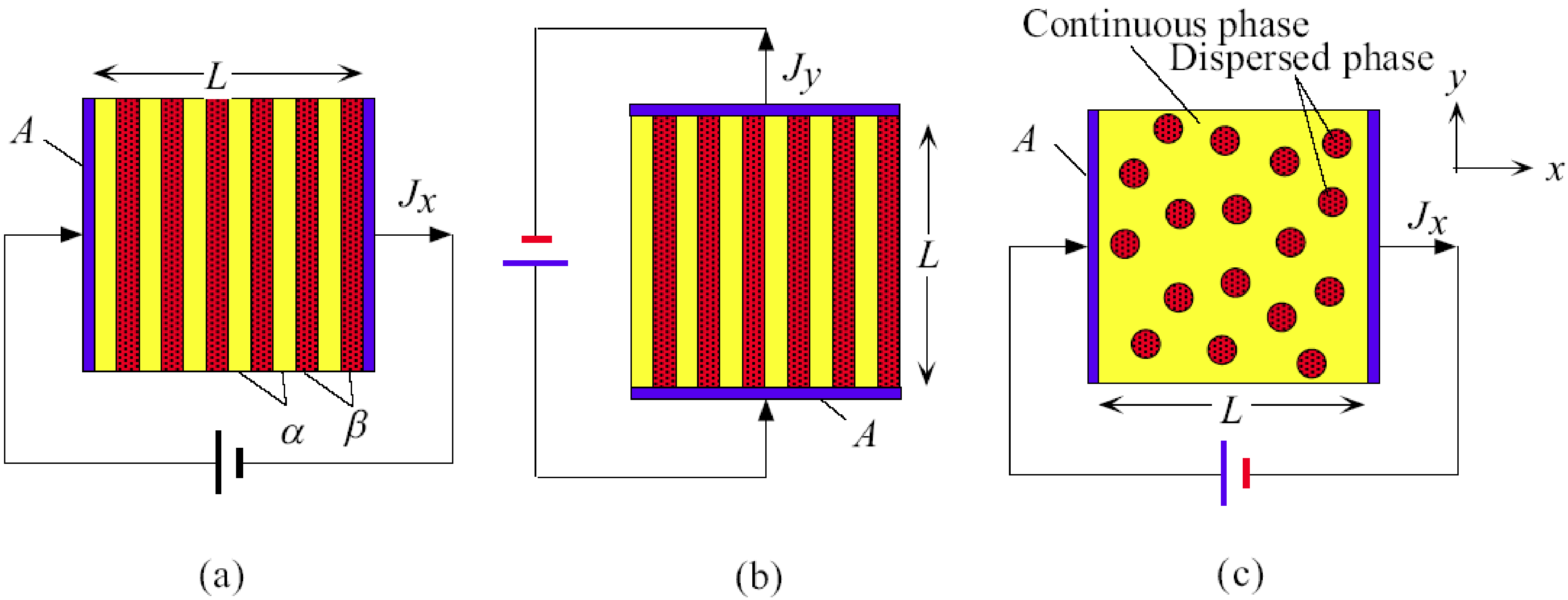
$$\rho = \rho_{\text{matrix}} + CX(1 - X)$$

ρ = resistivity of the alloy (solid solution)

ρ_{matrix} = resistivity of the matrix due to scattering from thermal vibrations and other defects

C = Nordheim coefficient

X = atomic fraction of solute atoms in a solid solution



The effective resistivity of a material with a layered structure.
(a) Along a direction perpendicular to the layers.
(b) Along a direction parallel to the plane of the layers.
(c) Materials with a dispersed phase in a continuous matrix.

Fig 2.13

Effective Resistance of Mixtures

$$R_{\text{eff}} = \frac{L_\alpha \rho_\alpha}{A} + \frac{L_\beta \rho_\beta}{A}$$

R_{eff} = effective resistance

L_α = total length (thickness) of the α-phase layers

ρ_α = resistivity of the α-phase layers

A = cross-sectional area

L_β = total length (thickness) of the β-phase layers

ρ_β = resistivity of the β-phase layers

Resistivity-Mixture Rule

$$\rho_{\text{eff}} = \chi_\alpha \rho_\alpha + \chi_\beta \rho_\beta$$

ρ_{eff} = effective resistivity of mixture, χ_α = volume fraction of the α-phase, ρ_α = resistivity of the α-phase, χ_β = volume fraction of the β-phase, ρ_β = resistivity of the β-phase

Conductivity-Mixture Rule

$$\sigma_{\text{eff}} = \chi_\alpha \sigma_\alpha + \chi_\beta \sigma_\beta$$

σ_{eff} = effective conductivity of mixture, χ_α = volume fraction of the α-phase, σ_α = conductivity of the α-phase, χ_β = volume fraction of the β-phase, σ_β = conductivity of the β-phase

Mixture Rule $(\rho_d > 10\rho_c)$

$$\rho_{\text{eff}} = \rho_c \frac{(1 + \frac{1}{2}\chi_d)}{(1 - \chi_d)}$$

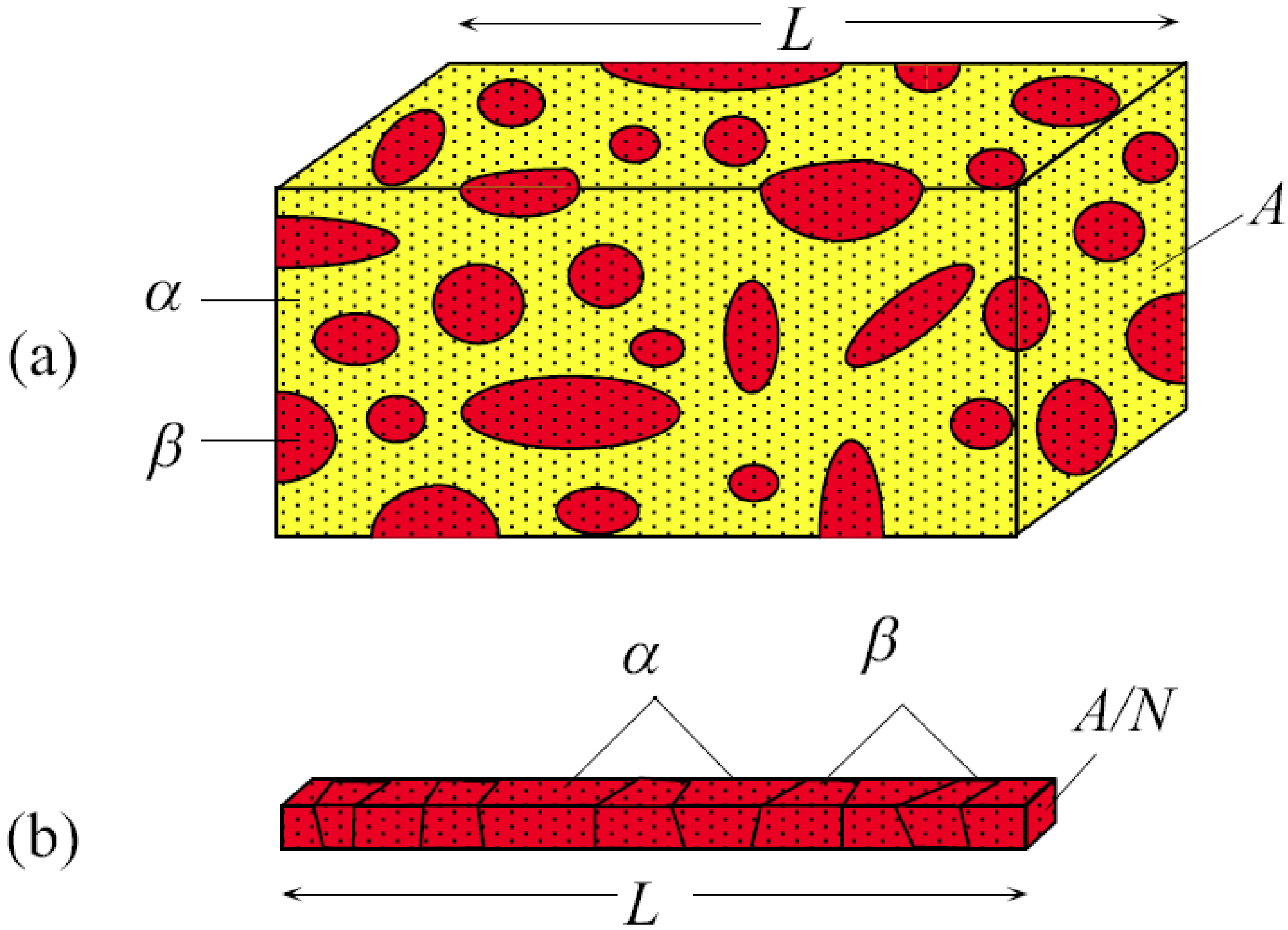
ρ_{eff} = effective resistivity, ρ_c = resistivity of continuous phase, χ_d = volume fraction of dispersed phase, ρ_d = resistivity of dispersed phase

Mixture Rule $(\rho_d < 0.1\rho_c)$

$$\rho_{\text{eff}} = \rho_c \frac{(1 - \chi_d)}{(1 + 2\chi_d)}$$

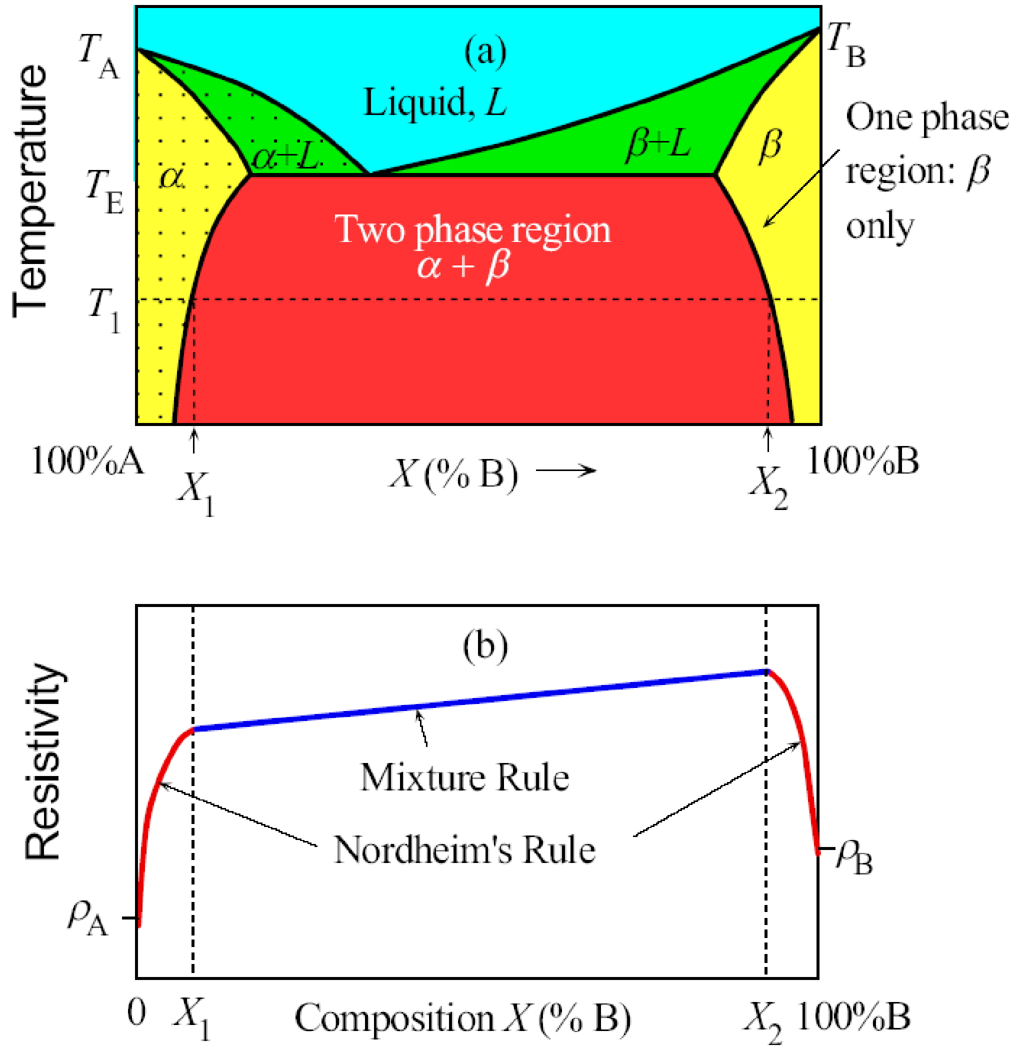
ρ_{eff} = effective resistivity, ρ_c = resistivity of the continuous phase, χ_d = volume fraction of the dispersed phase, ρ_d = resistivity of the dispersed phase

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)



(a) A two-phase solid.
(b) A thin fiber cut out from the solid.

Fig 2.14



Eutectic-forming alloys, e.g., Cu-Ag.

(a) The phase diagram for a binary, eutectic-forming alloy.

(b) The resistivity versus composition for the binary alloy.

Fig 2.15

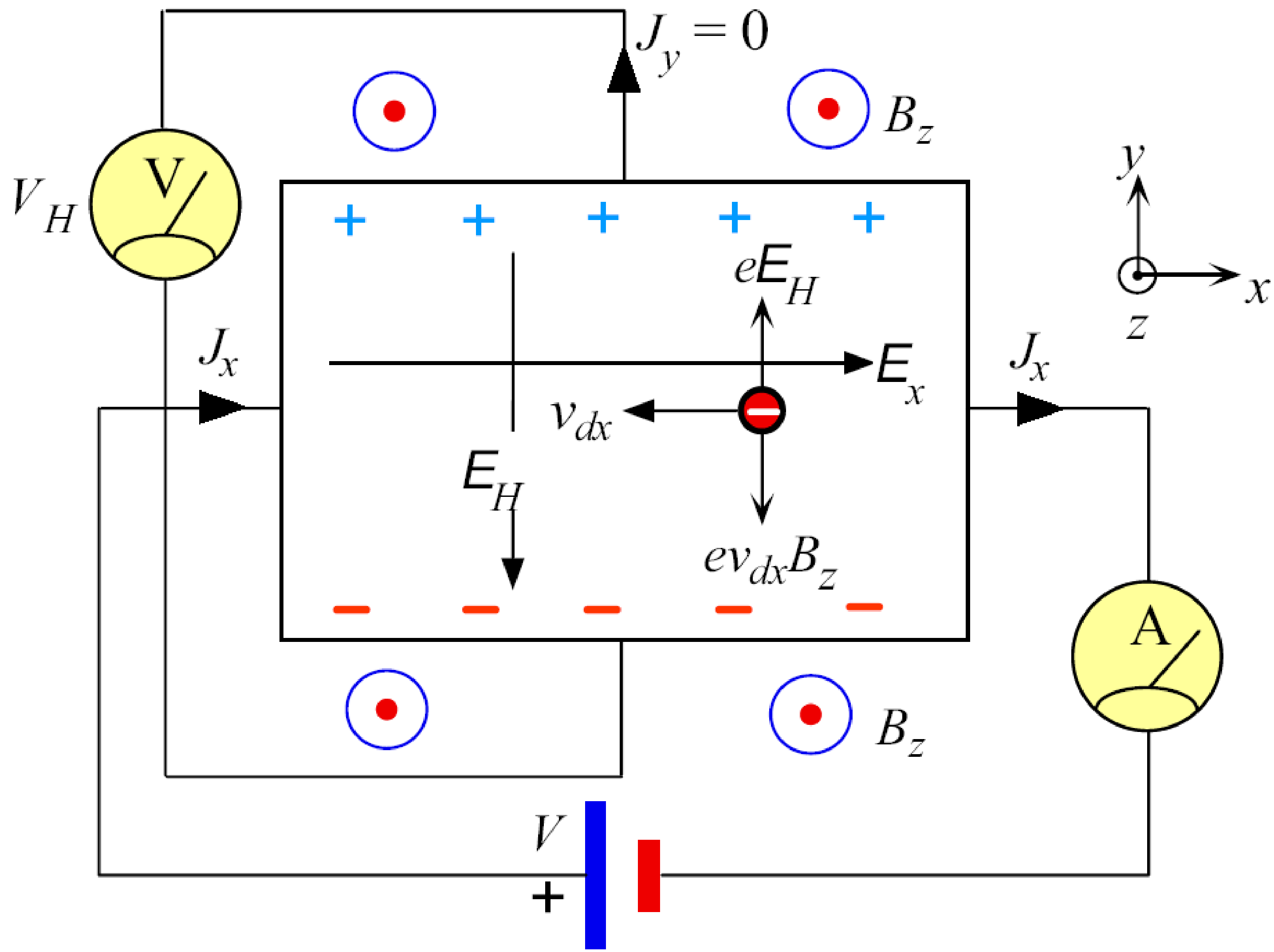
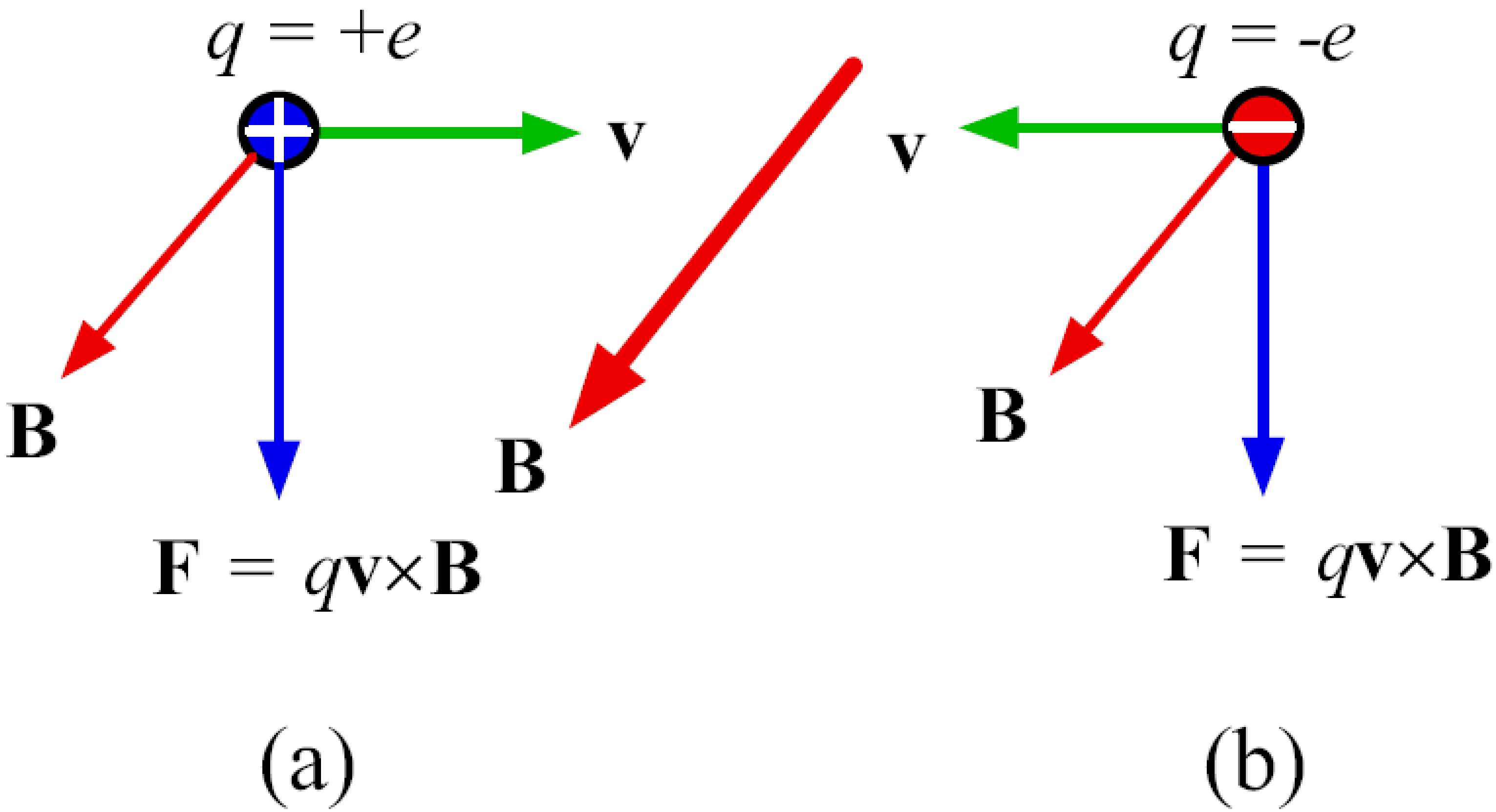


Illustration of the Hall effect.
The z direction is out of the plane of the paper. The externally applied magnetic field is along the z direction.

Fig 2.16



A moving charge experiences a Lorentz force in a magnetic field.

(a) A positive charge moving in the x direction experiences a force downwards.

(b) A negative charge moving in the -x direction also experiences a force downwards.

Fig 2.17

Lorentz Force

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

F = force, q = charge, **v** = velocity of charged particle, **B** = magnetic field

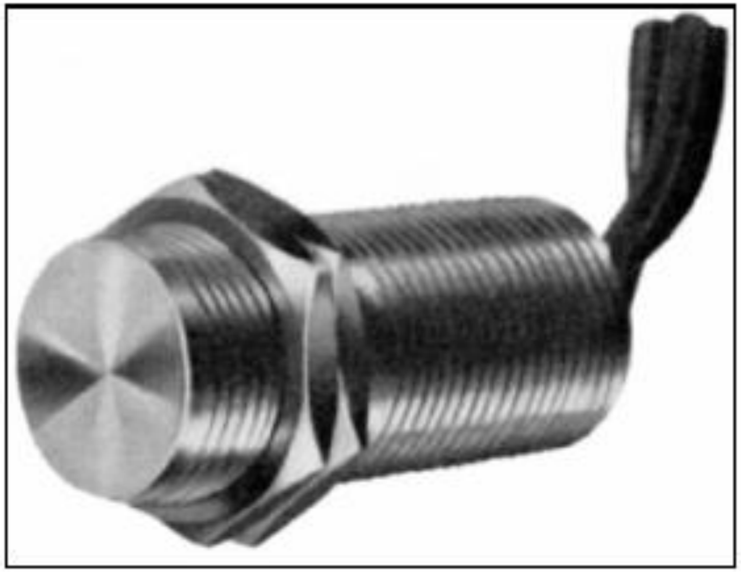
Definition of Hall Coefficient

$$R_H = \frac{E_y}{J_x B_z}$$

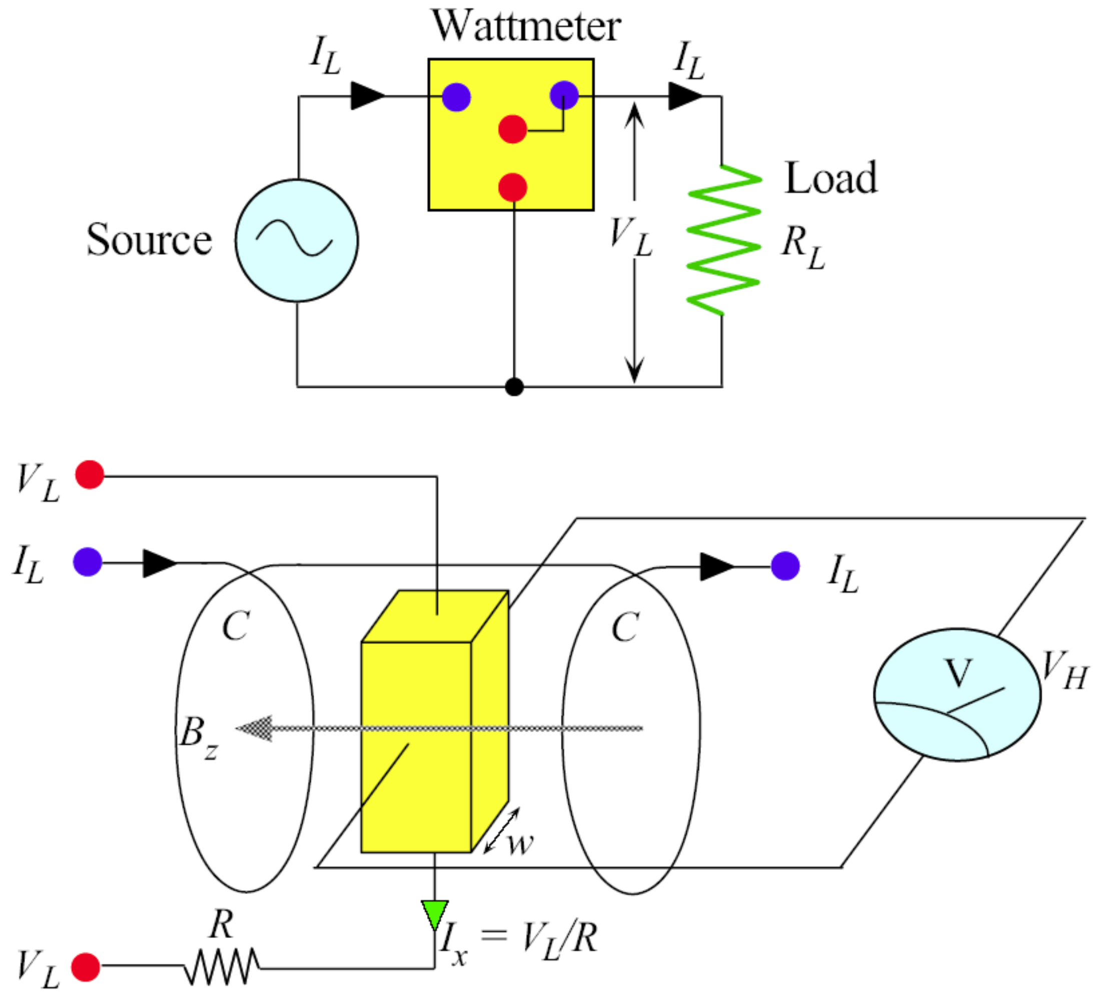
R_H = Hall coefficient, E_y = electric field in the y-direction, J_x = current density in the x-direction, B_z = magnetic field in the z-direction

Table 2.4 Hall coefficient and Hall mobility ($\mu_H = |\sigma R_H|$) of selected metals

Metal	n [m^{-3}] ($\times 10^{28}$)	R_H (Experimental) [m^3 A^{-1} s^{-1}] ($\times 10^{-11}$)	$\mu_H = \lvert\sigma R_H\rvert$ [m^2 V^{-1} s^{-1}] ($\times 10^{-4}$)
Ag	5.85	−9.0	57
Al	18.06	−3.5	13
Au	5.90	−7.2	31
Be	24.2	+3.4	?
Cu	8.45	−5.5	32
Ga	15.3	−6.3	3.6
In	11.49	−2.4	2.9
Mg	8.60	−9.4	22
Na	2.56	−25	53

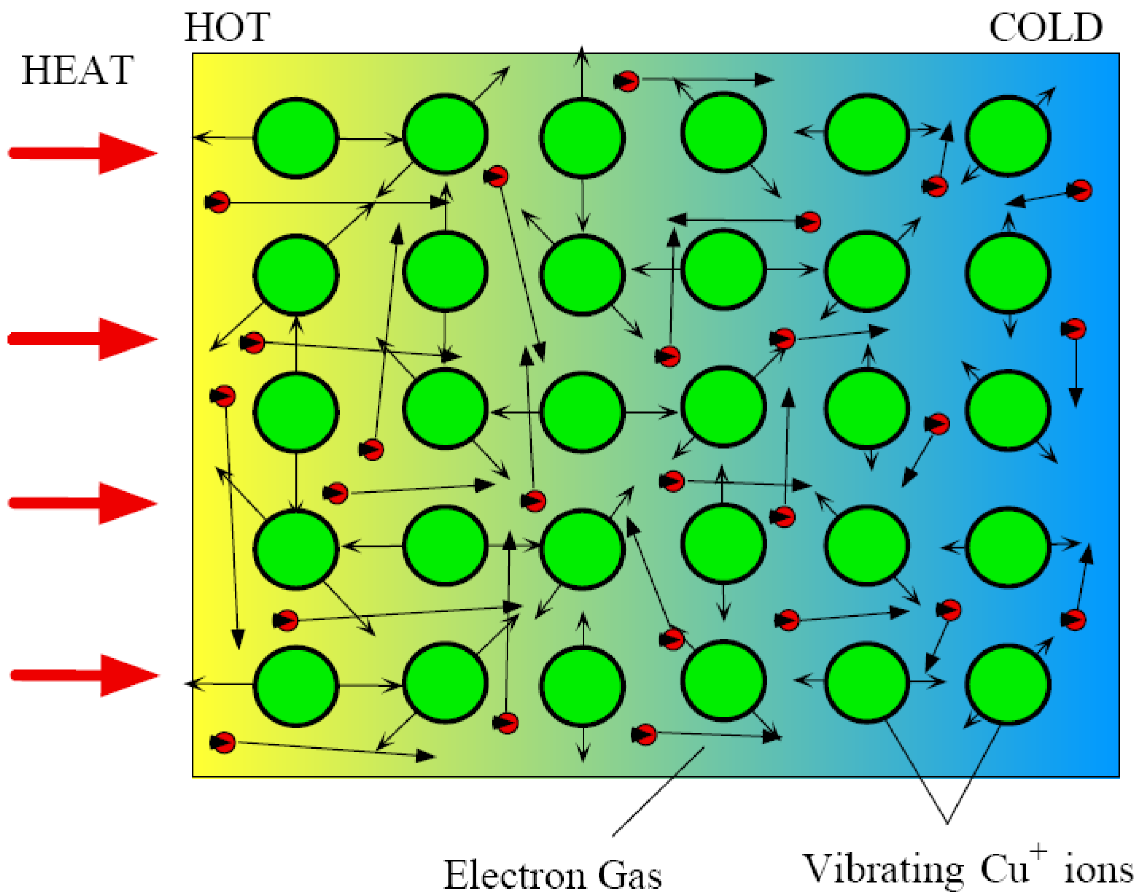


Magnetically operated Hall-effect position sensor as available from Micro Switch.



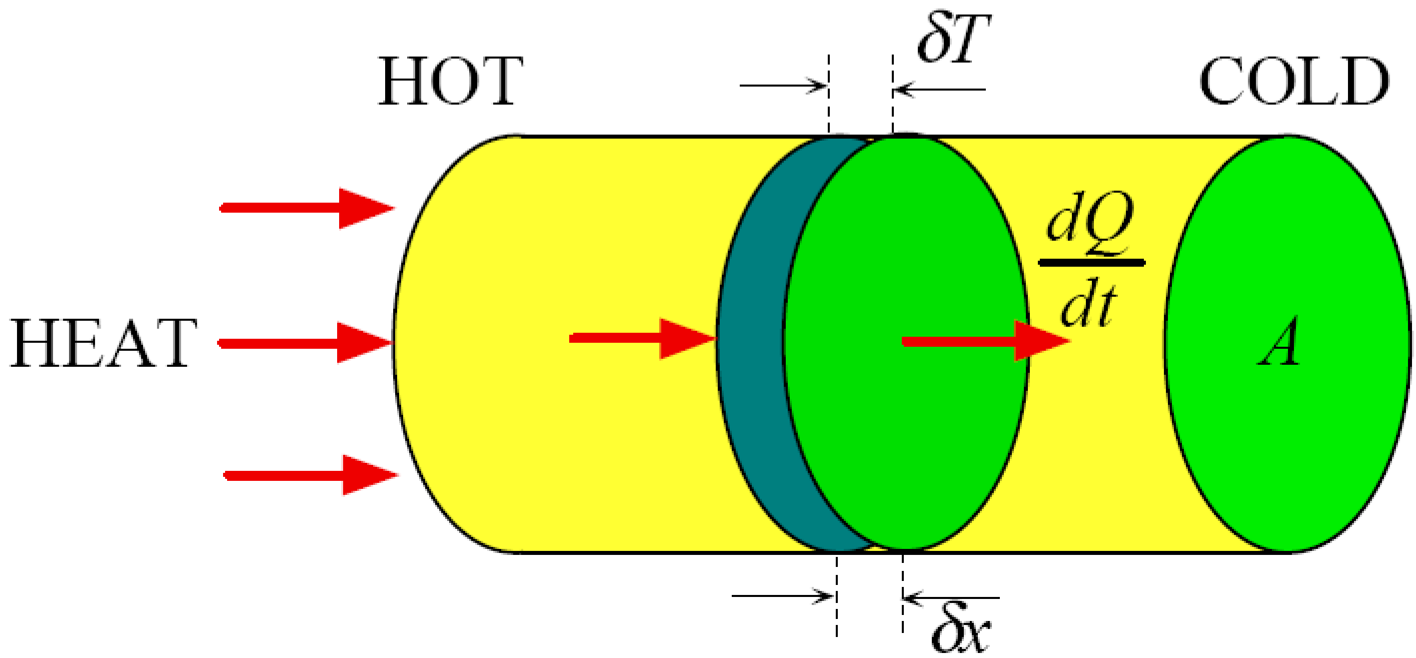
Wattmeter based on the Hall effect.
Load voltage and load current have L as subscript; C denotes the current coils for setting up a magnetic field through the Hall-effect sample (semiconductor).

Fig 2.18



Thermal conduction in a metal involves transferring energy from the hot region to the cold region by conduction electrons. More energetic electrons (shown with longer velocity vectors) from the hotter regions arrive at cooler regions and collide there with lattice vibrations and transfer their energy. Lengths of arrowed lines on atoms represent the magnitudes of atomic vibrations.

Fig 2.19



Heat flow in a metal rod heated at one end.
Consider the rate of heat flow, dQ/dt, across a thin section δx of the rod. The rate of Heat flow is proportional to the temperature gradient $\delta T/\delta x$ and the cross-sectional area A.

Fig 2.20

Fourier's Law of Thermal Conduction

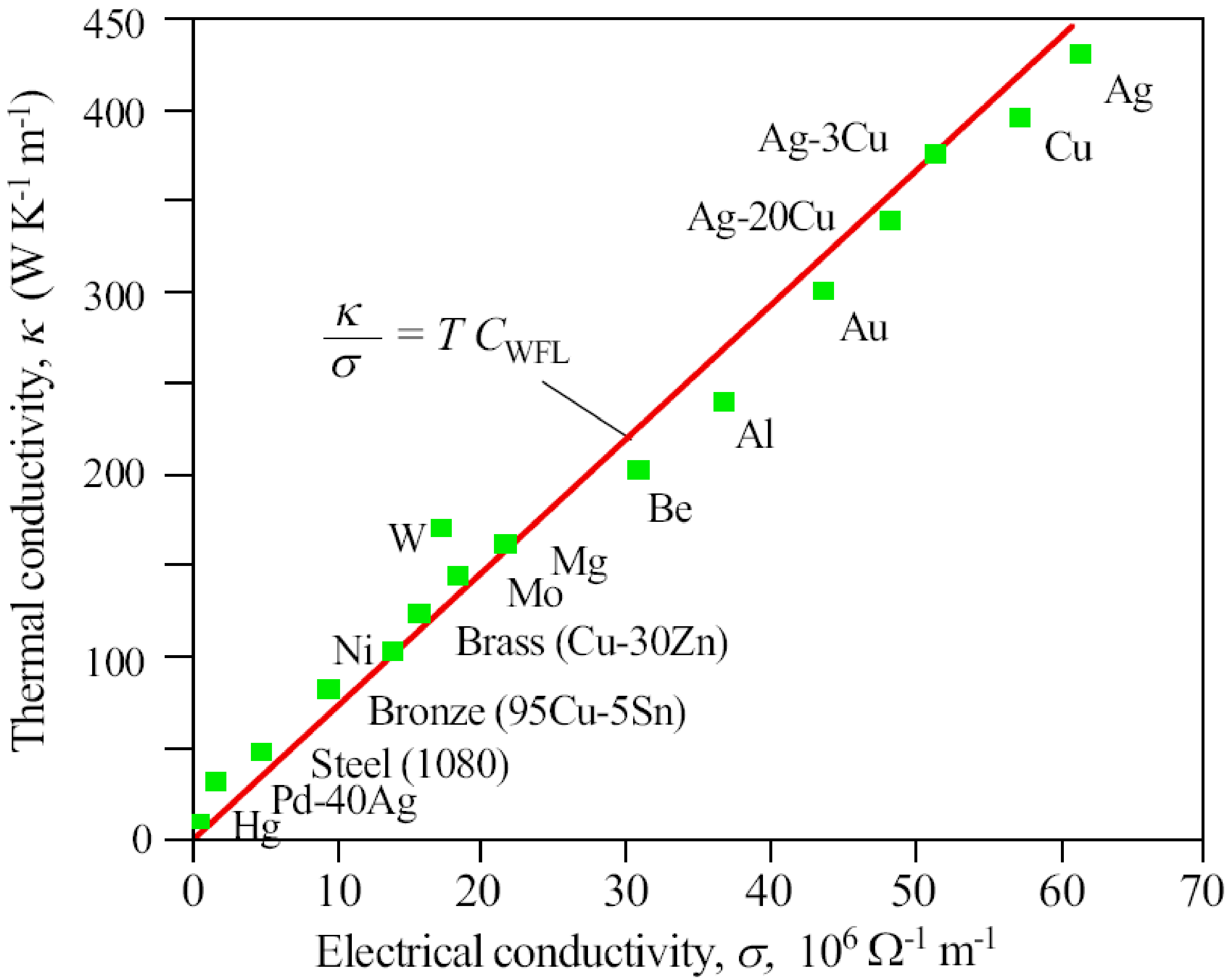
$$Q' = \frac{dQ}{dt} = -\kappa A \frac{\delta T}{\delta x}$$

Q' = rate of heat flow, Q = heat, t = time, κ = thermal conductivity, A = area through which heat flows, dT/dx = temperature gradient

Ohm's Law of Electrical Conduction

$$I = -A\sigma \frac{\delta V}{\delta x}$$

I = electric current, A = cross-sectional area, σ = electrical conductivity, dV/dx = potential gradient (represents an electric field), δV = change in voltage across δx, δx = thickness of a thin layer at x



Thermal conductivity κ versus electrical conductivity σ for various metals (elements and alloys) at 20 ˚C.

The solid line represents the WFL law with $C_{WFL} \approx 2.44 \times 10^8$ W Ω K^{-2}.

Fig 2.21

Wiedemann-Franz-Lorenz Law

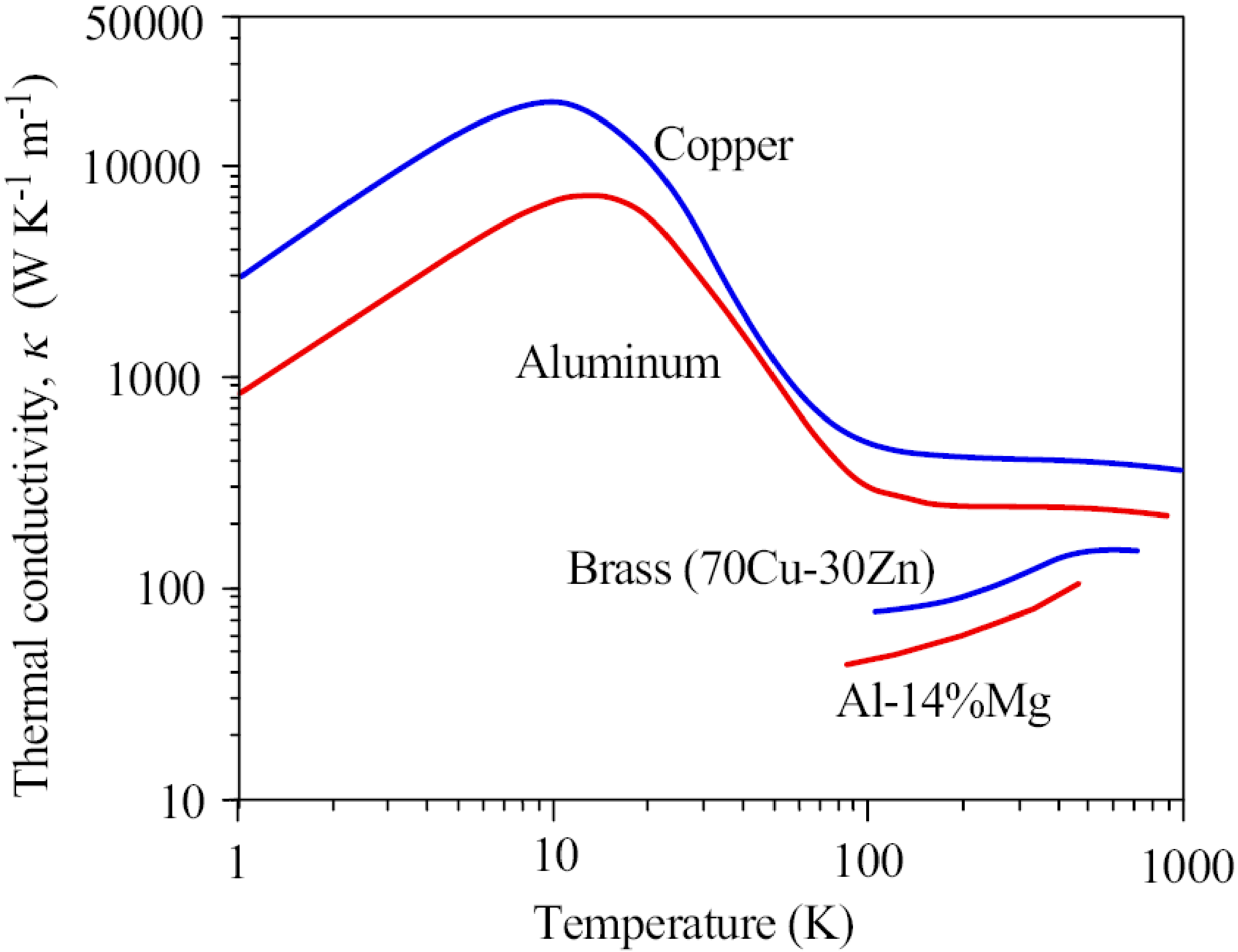
$$\frac{\kappa}{\sigma T} = C_{\mathrm{WFL}} = 2.45 \times 10^{-8}\ \mathrm{W\ \Omega\ K^{-2}}$$

κ = thermal conductivity

σ = electrical conductivity

T = temperature in Kelvins

C_{WFL} = Lorenz number



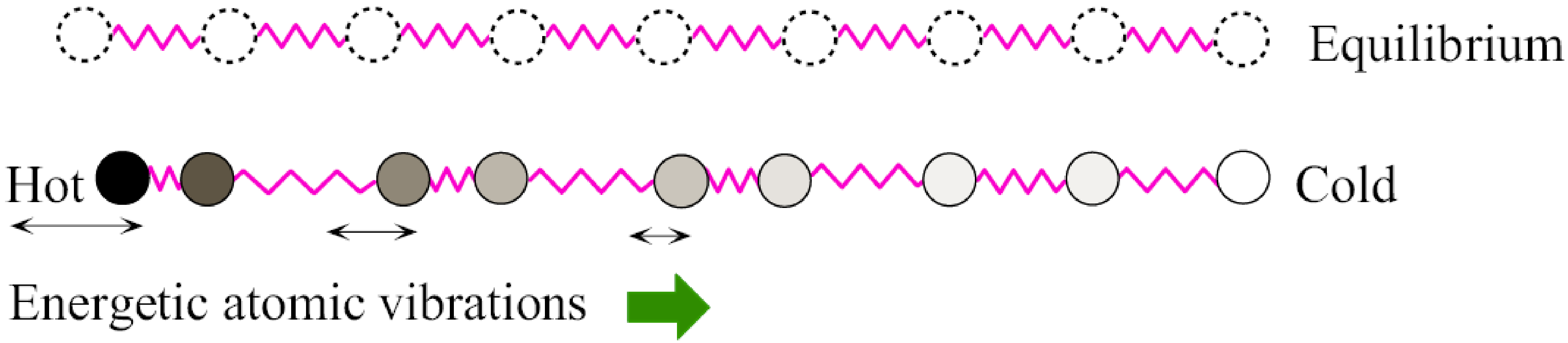
Thermal conductivity versus temperature for two pure metals (Cu and Al) and two Alloys (brass and Al-14% Mg).

SOURCE: Data extracted form I.S. Touloukian, et al., *Thermophysical Properties of Matter*, vol. 1: "Thermal Conductivity, Metallic Elements and Alloys, " New York: Plenum, 1970.

Fig 2.22

Table 2.5 Typical thermal conductivities of various classes of materials at 25 °C

Material	κ (W m^{-1} K^{-1})
Pure metal	
Nb	52
Fe	80
Zn	113
W	178
Al	250
Cu	390
Ag	420
Metal alloys	
Stainless steel	12–16
55% Cu–45% Ni	19.5
70% Ni–30% Cu	25
1080 steel	50
Bronze (95% Cu–5% Sn)	80
Brass (63% Cu–37% Zn)	125
Dural (95% Al–4% Cu–1% Mg)	147
Ceramics and glasses	
Glass-borosilicate	0.75
Silica-fused (SiO_2)	1.5
S_3N_4	20
Alumina (Al_2O_3)	30
Sapphire (Al_2O_3)	37
Beryllium (BeO)	260
Diamond	~1000
Polymers	
Polypropylene	0.12
PVC	0.17
Polycarbonate	0.22
Nylon 6,6	0.24
Teflon	0.25
Polyethylene, low density	0.3
Polyethylene, high density	0.5



Conduction of heat in insulators involves the generation and propagation of atomic Vibrations through the bonds that couple the atoms (an intuitive figure).

Fig 2.23

Fourier's Law

$$Q' = A\kappa \frac{\Delta T}{L} = \frac{\Delta T}{(L/\kappa A)}$$

Q' = rate of heat flow or the heat current, A = cross-sectional area, κ = thermal conductivity (material-dependent constant), ΔT = temperature difference between ends of component, L = length of component

Ohm's Law

$$I = \frac{\Delta V}{R} = \frac{\Delta V}{(L/\sigma A)}$$

I = electric current, ΔV = voltage difference across the conductor, R = resistance, L = length, σ = conductivity, A = cross-sectional area

Definition of Thermal Resistance

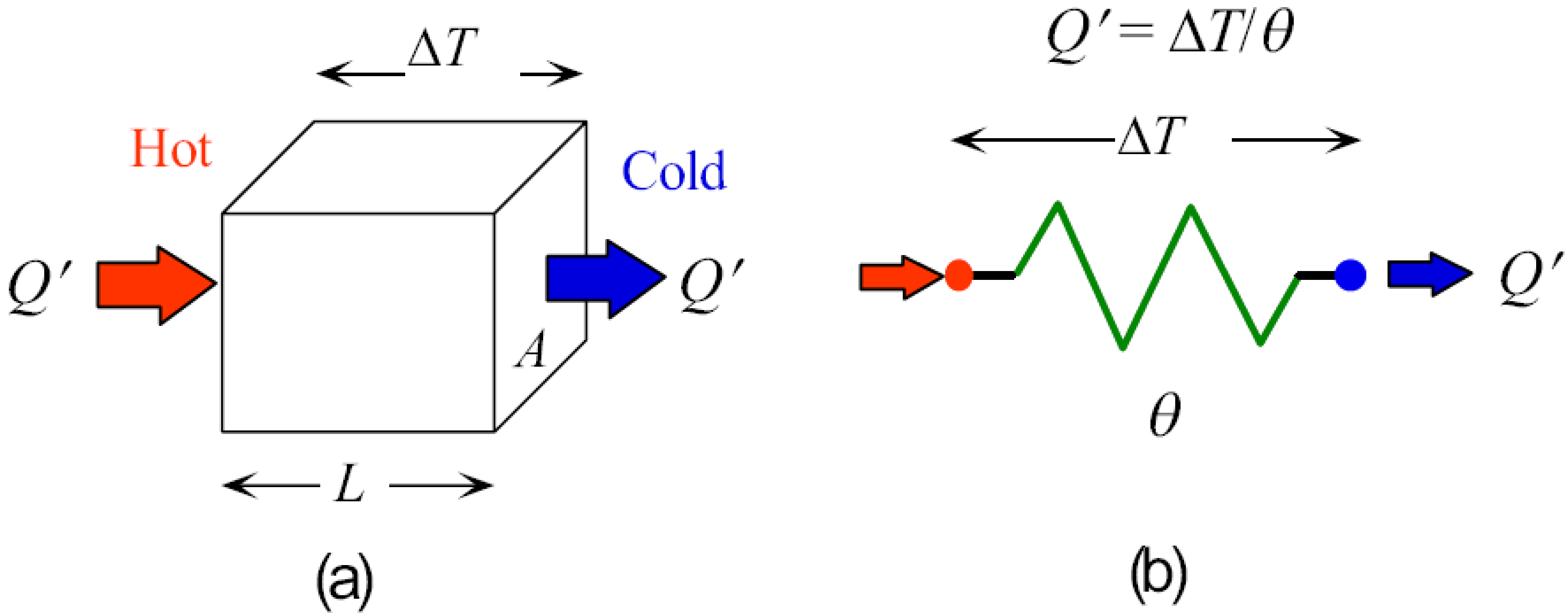
$$Q' = \frac{\Delta T}{\theta}$$

Q' = rate of heat flow, ΔT = temperature difference, θ = thermal resistance

Thermal Resistance

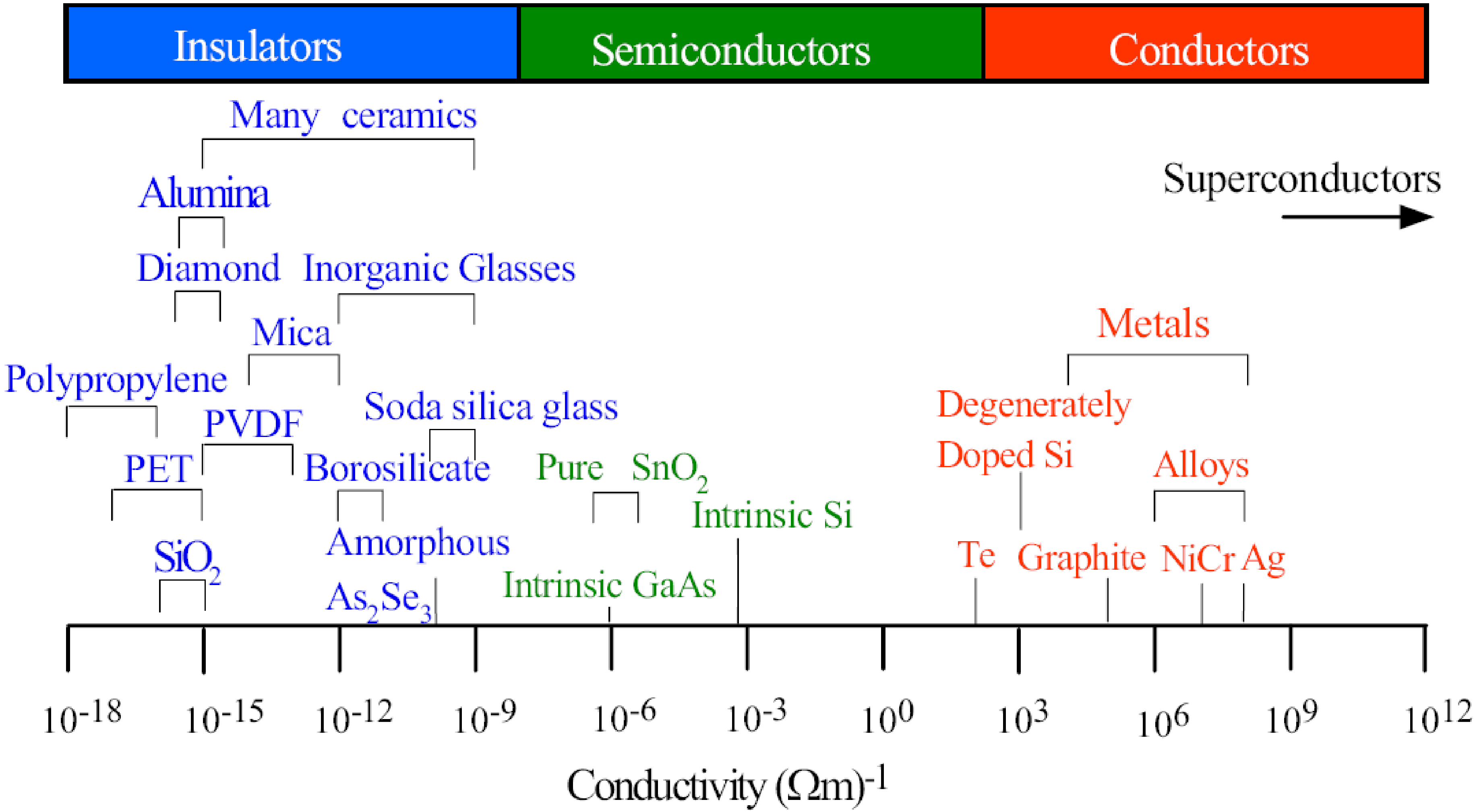
$$\theta = \frac{L}{A\kappa}$$

θ = thermal resistance, L = length, A = cross-sectional area, κ = thermal conductivity



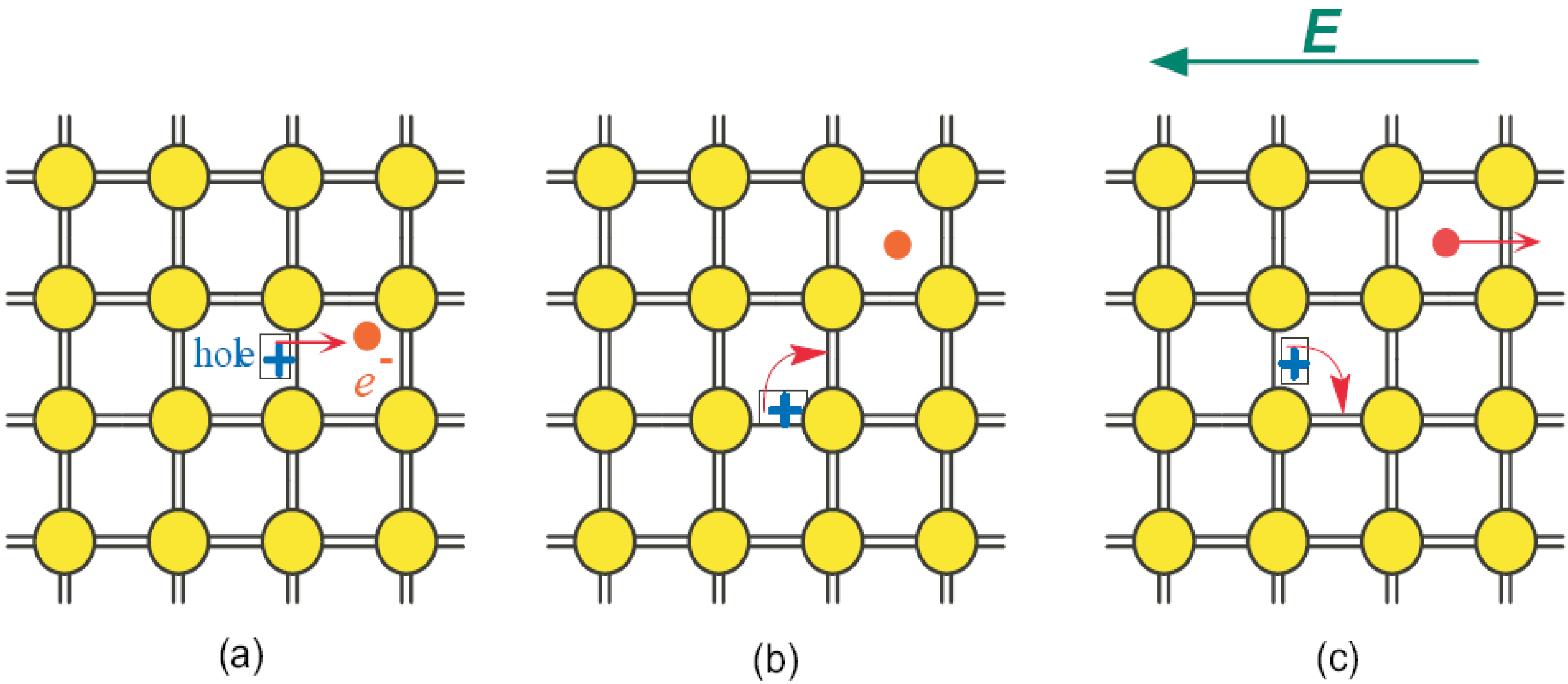
Conduction of heat through a component in (a) can be modeled as a thermal resistance θ shown in (b) where $Q' = \Delta T / \theta$

Fig 2.24



Range of conductivites exhibited by various materials

Fig 2.25



(a) Thermal vibrations of the atoms rupture a bond and release a free electron into the crystal. A hole is left in the broken bond which has an effective positive charge.
(b) An electron in a neighboring bond can jump and repair this bond and thereby create a hole in its original site; the hole has been displaced.
(c) When a field is applied both holes and electrons contribute to electrical conduction.

Fig 2.26

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Conductivity of a Semiconductor

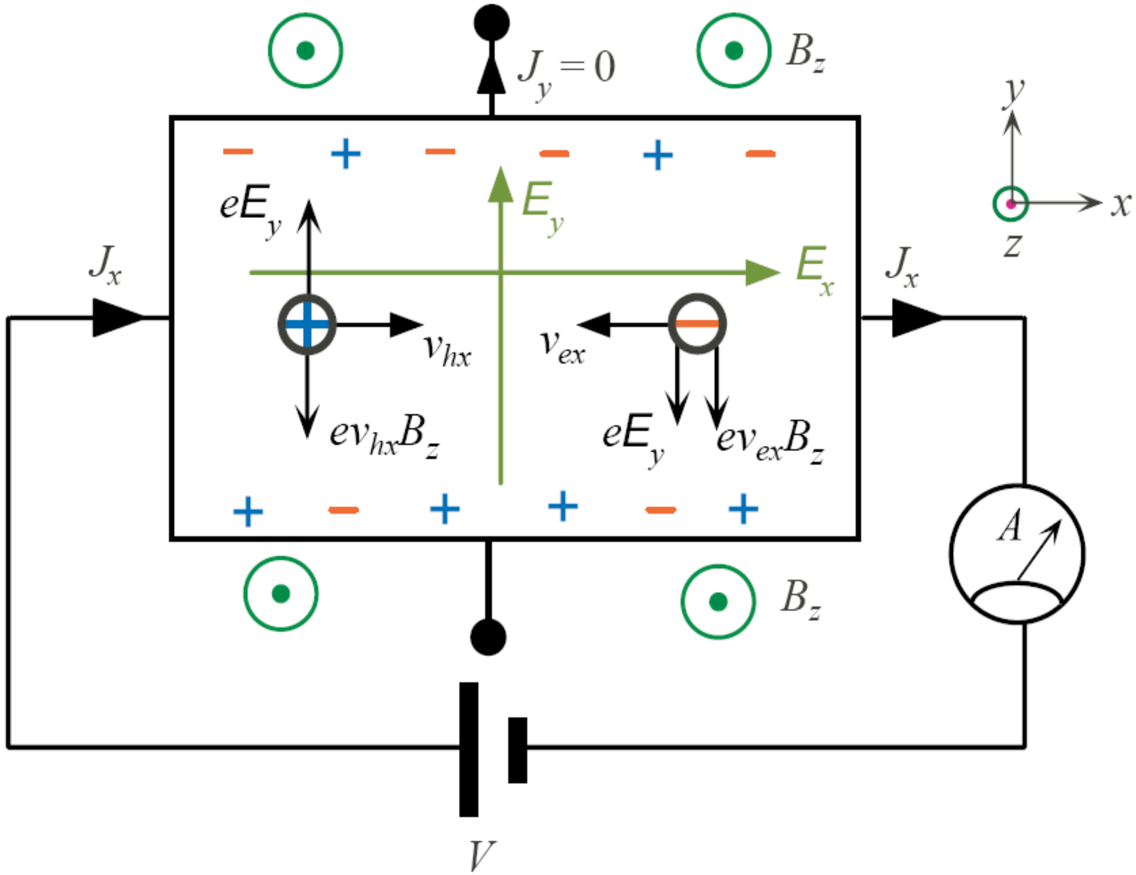
$$\sigma = en\mu_e + ep\mu_h$$

σ = conductivity, e = electronic charge, n = electron concentration, μ_e = electron drift mobility, p = hole concentration, μ_h = hole drift mobility

Drift Velocity and Net Force

$$v_e = \frac{\mu_e}{e} F_{\text{net}}$$

v_e = drift velocity of the electrons, μ_e = drift mobility of the electrons, e = electronic charge, F_{net} = net force



Hall effect for ambipolar conduction as in a semiconductor where there are both electrons and holes. The magnetic field B_z is out from the plane of the paper. Both electrons and holes are deflected toward the bottom surface of the conductor and consequently the Hall voltage depends on the relative mobilities and concentrations of electrons and holes.

Fig 2.27

Hall Effect for Ambipolar Conduction

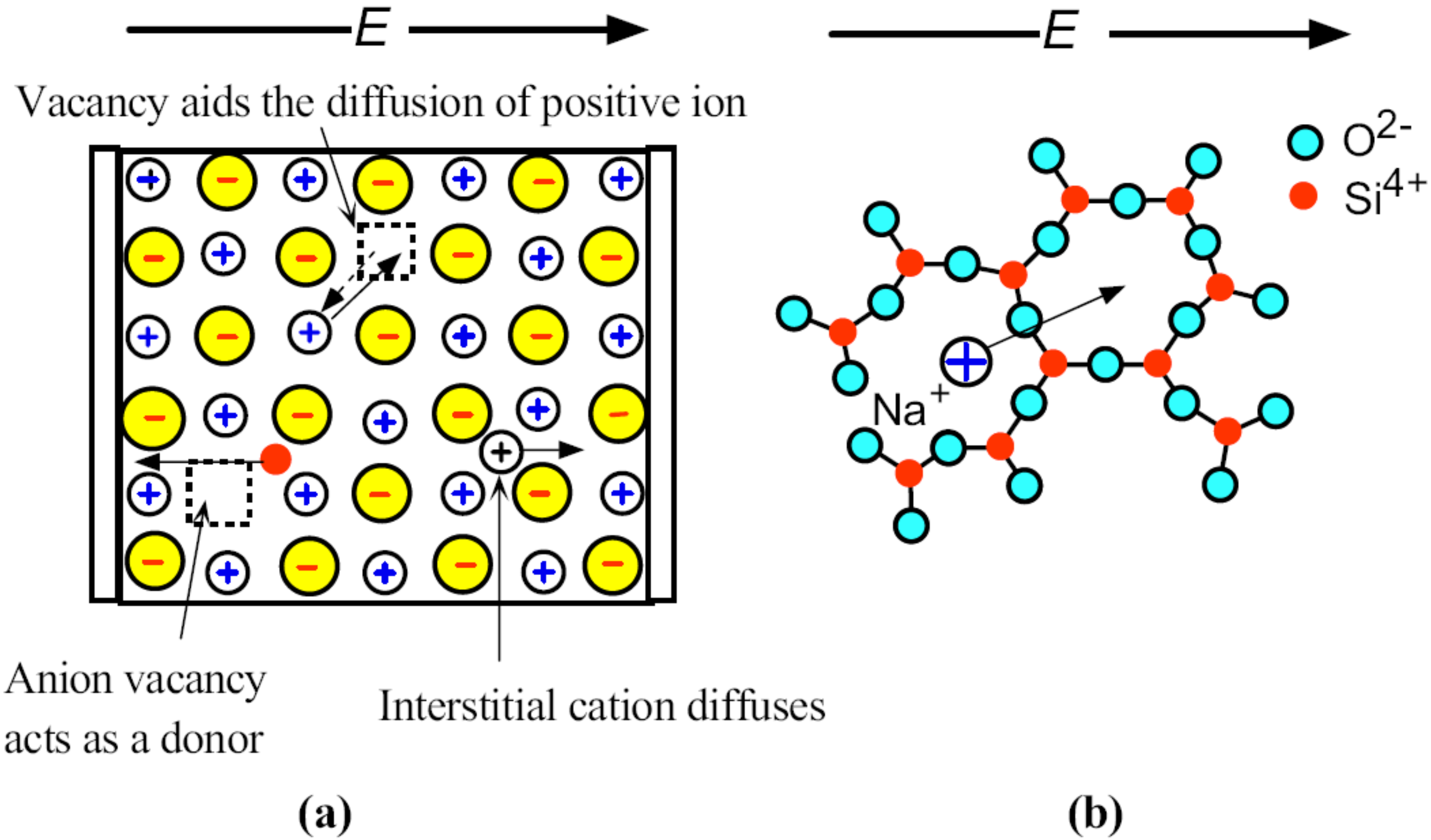
$$R_H = \frac{p\mu_h{}^2 - n\mu_e{}^2}{e(p\mu_h + n\mu_e)^2}$$

R_H = Hall coefficient, p = concentration of the holes, μ_h = hole drift mobility, n = concentration of the electrons, μ_e = electron drift mobility, e = electronic charge

OR

$$R_H = \frac{p - nb^2}{e(p + nb)^2}$$

$$b = \mu_e, / \mu_h$$



Possible contribution to the conductivity of ceramic and glass insulators.
(a) Possible mobile charges in a ceramic.
(b) An Na^+ ion in the glass structure diffuses and therefore drifts in the direction of the field.

Fig 2.28

General Conductivity

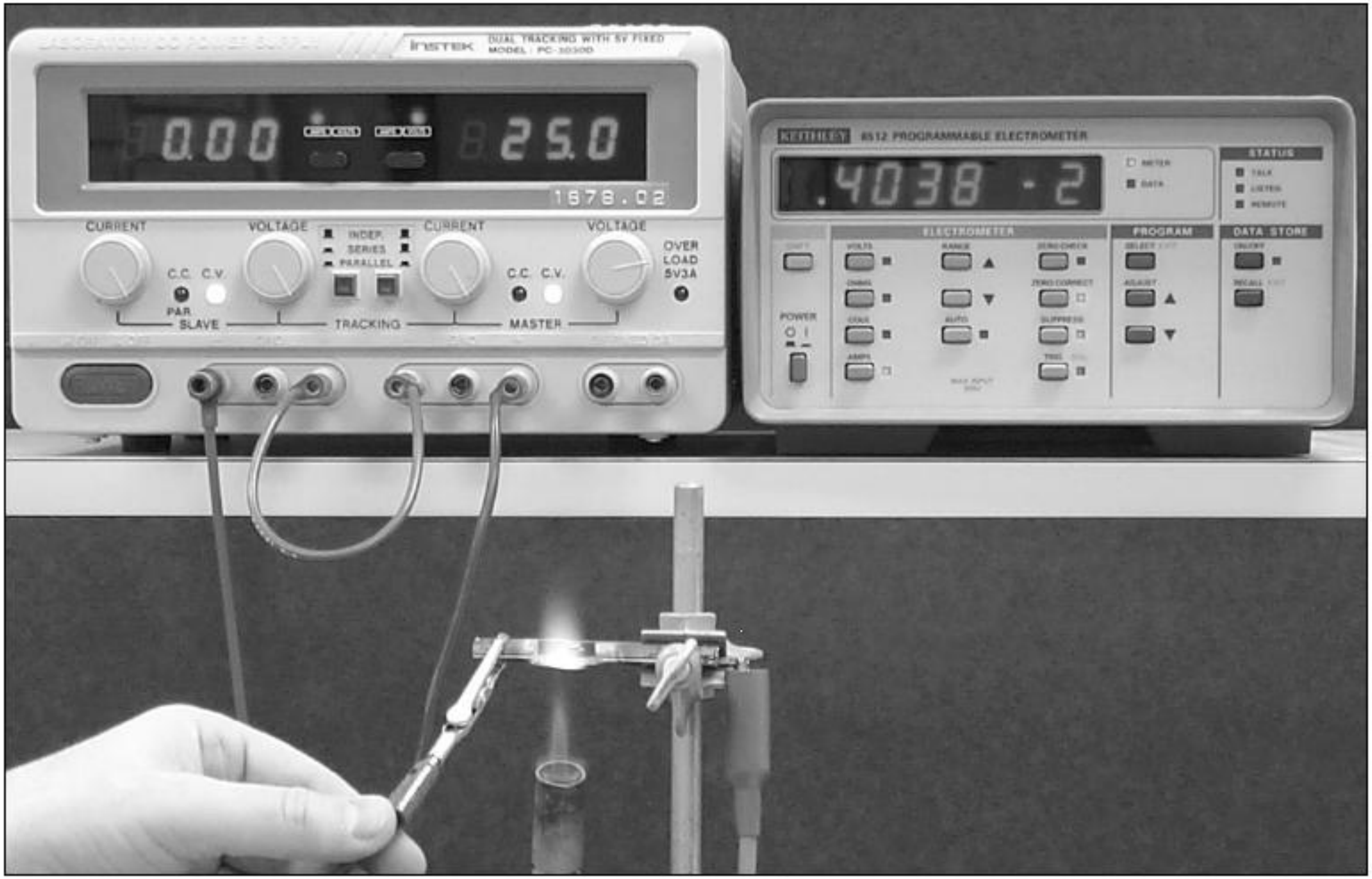
$$\sigma = \Sigma q_i n_i \mu_i$$

σ = conductivity

q_i = charge carried by the charge carrier species i (for electrons and holes $q_i = e$)

n_i = concentration of the charge carrier

μ_i = drift mobility of the charge carrier of species i



This soda glass rod when heated under a torch becomes electrically conducting. It passes 4 mA when the voltage is 50 V (2 × 25 V); a resistance of 12.5 kΩ! Ordinary soda glass at room temperature is an insulator but can be quite conducting at sufficiently high temperatures.

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

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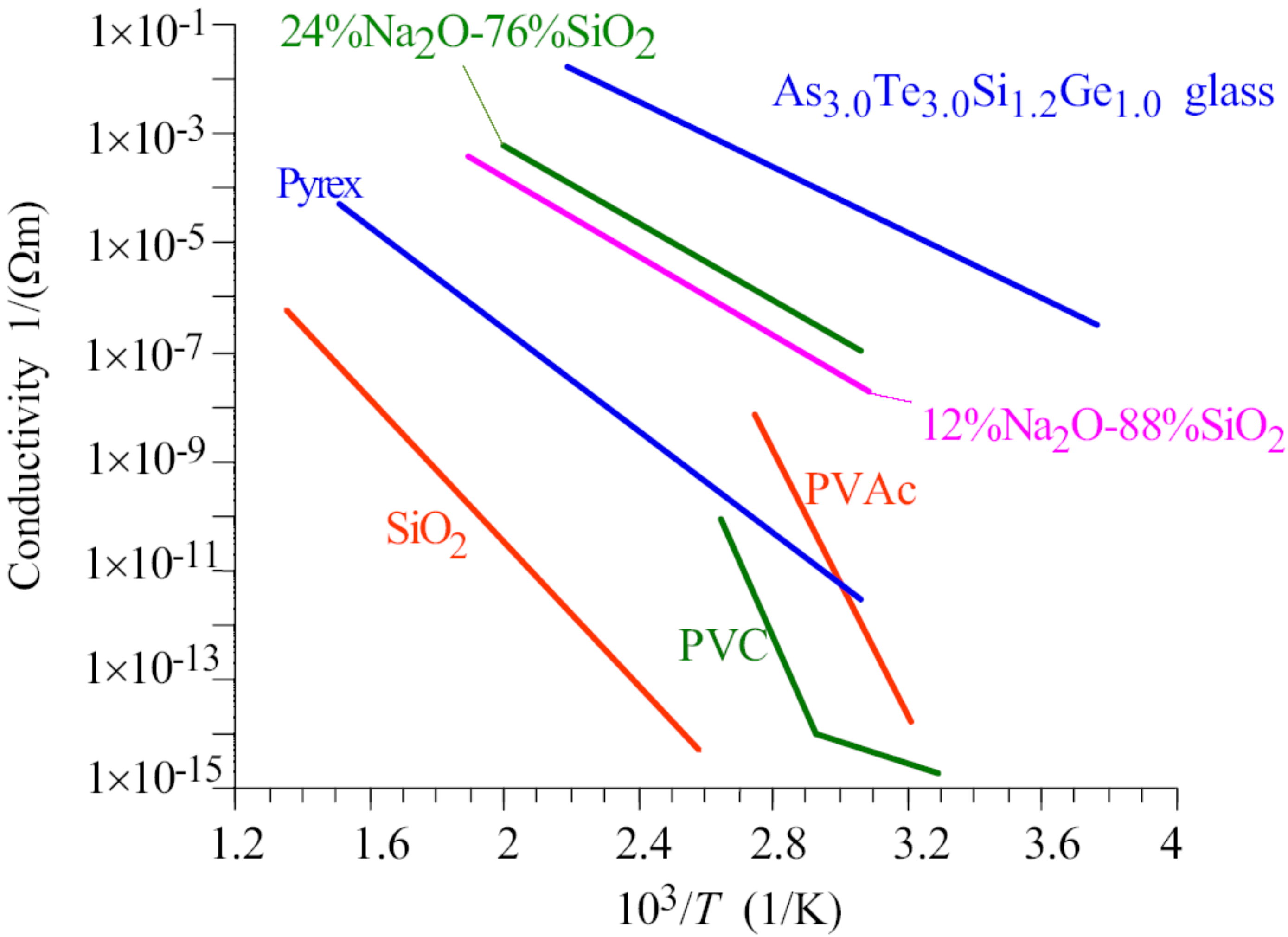


Conductivity versus reciprocal temperature for various low-conductivity solids
SOURCE: Data selectively combined from numerous sources.

Fig 2.29

Temperature Dependence of Conductivity

$$\sigma = \sigma_o \exp\left(-\frac{E_\sigma}{kT}\right)$$

σ = conductivity

σ_o = constant

E_σ = activation energy for conductivity

k = Boltzmann constant, T = temperature

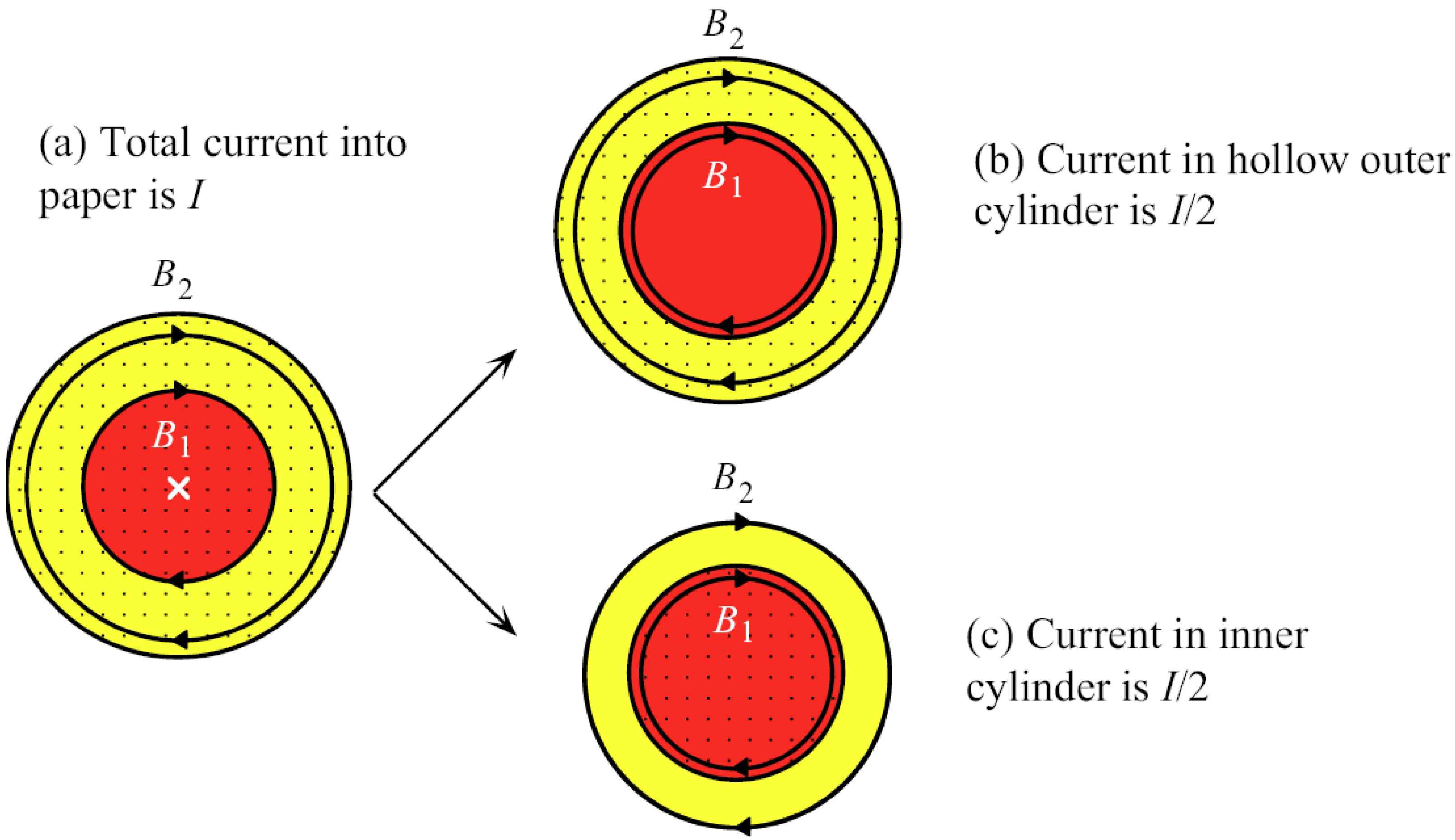
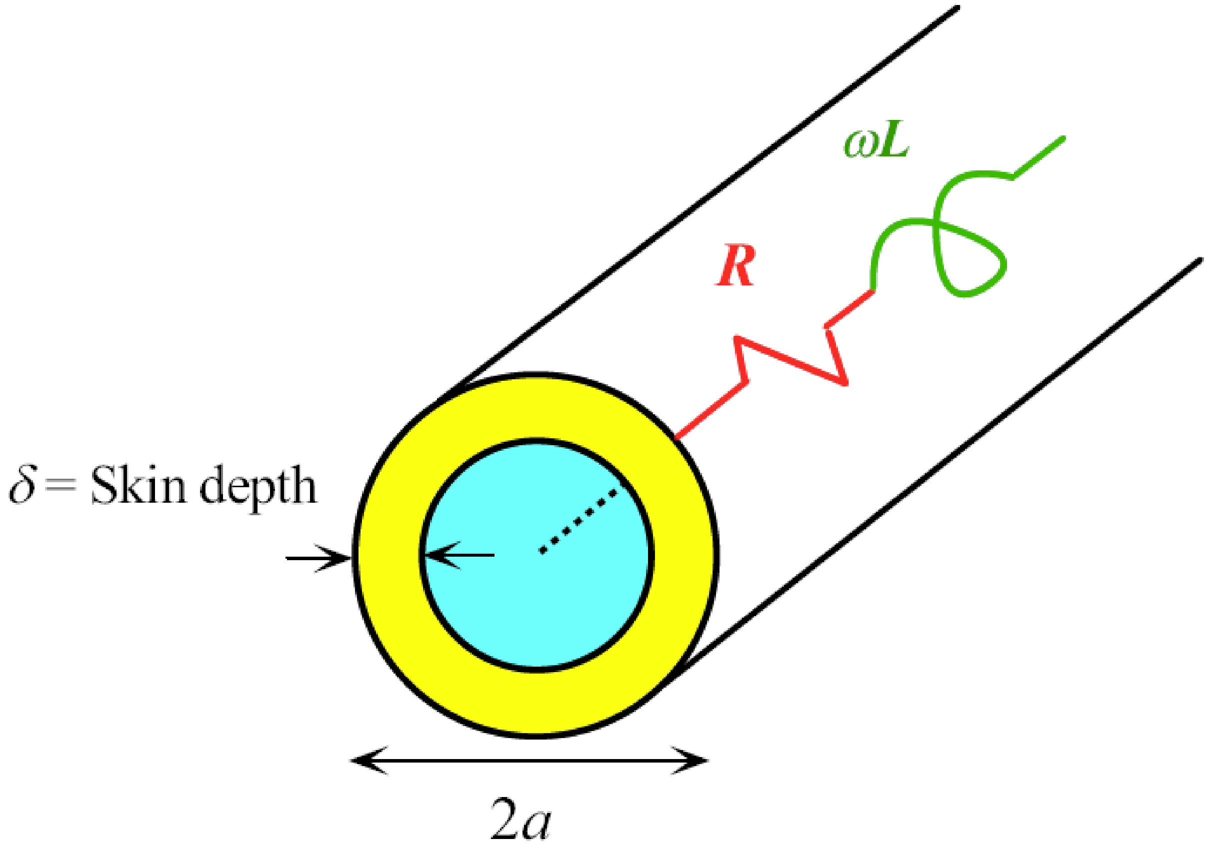


Illustration of the skin effect.
A hypothetical cut produces a hallow outer cylinder and a solid inner cylinder. Cut is placed where it would give equal current in each section. The two sections are in parallel so that the currents in (b) and (c) sum to that in (a).

Fig 2.30



At high frequencies, the core region exhibits more inductive impedance than the surface region, and the current flows in the surface region of a conductor defined approximately by the skin depth, δ.

Fig 2.31

Skin Depth for Conduction

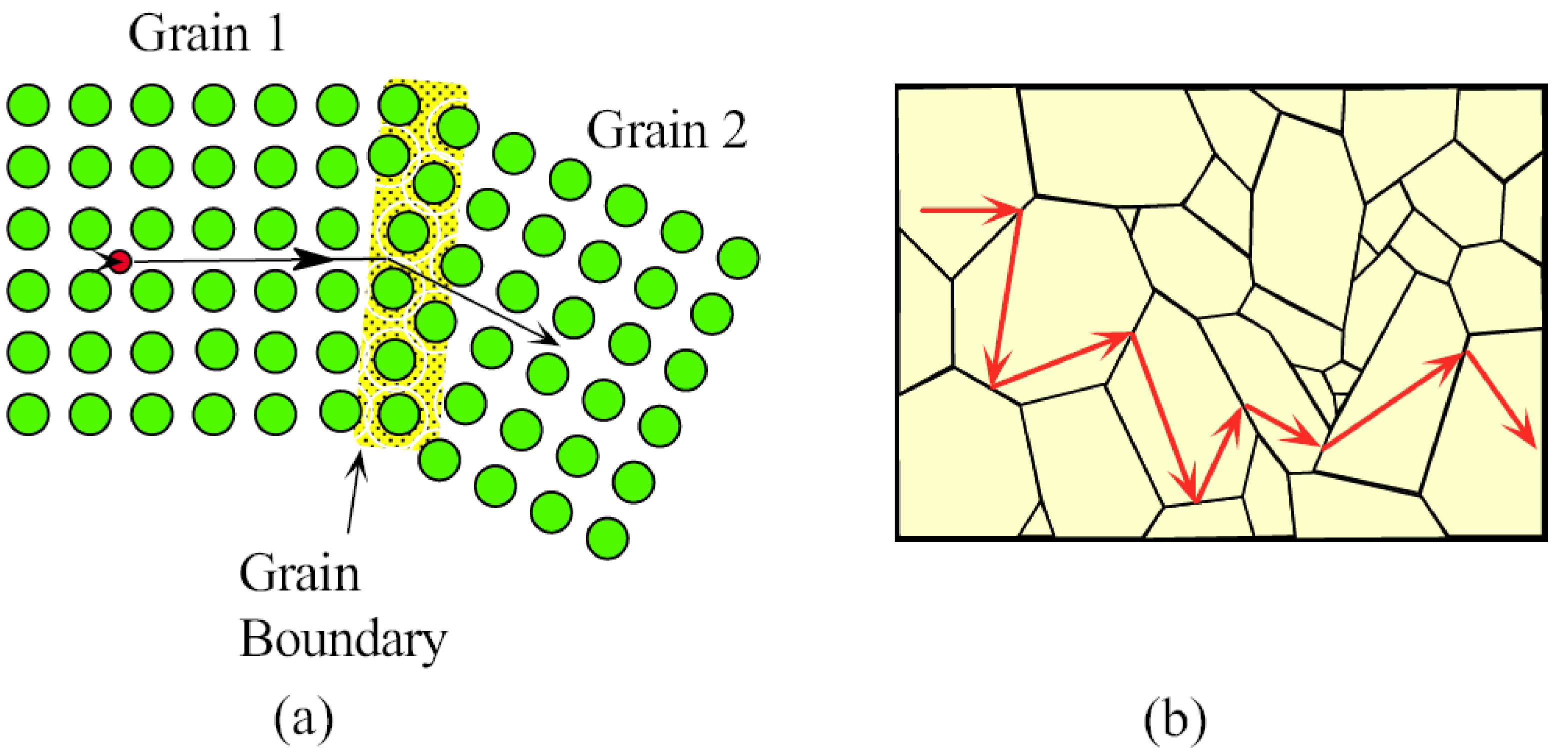
$$\delta = \frac{1}{\sqrt{\frac{1}{2}\omega\sigma\mu}}$$

δ = skin depth, ω = angular frequency of current, σ = conductivity, μ = magnetic permeability of the medium

HF Resistance per Unit Length Due to Skin Effect

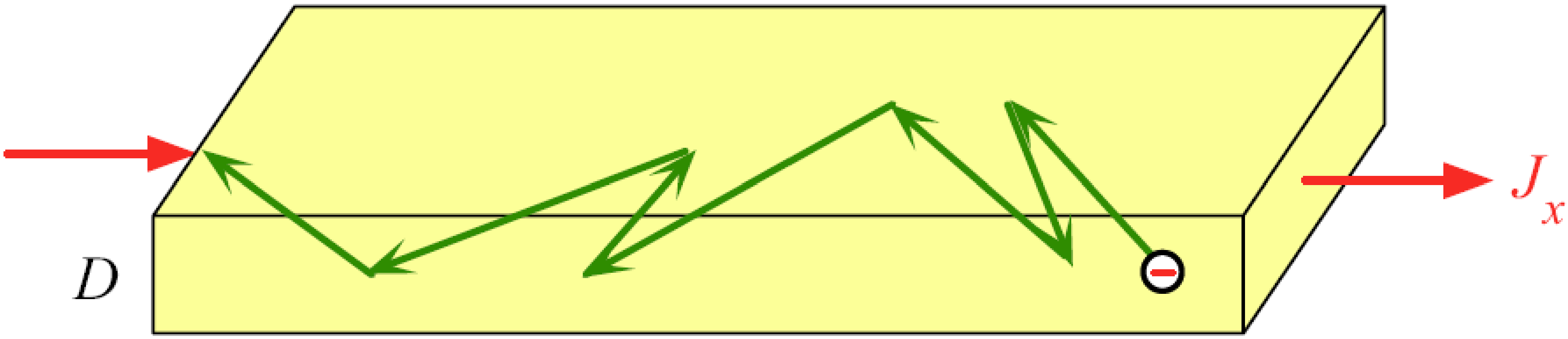
$$r_{\text{ac}} = \frac{\rho}{A} \approx \frac{\rho}{2\pi a\delta}$$

r_{ac} = ac resistance , ρ = resistivity, A = cross-sectional area, a = radius, δ = skin depth



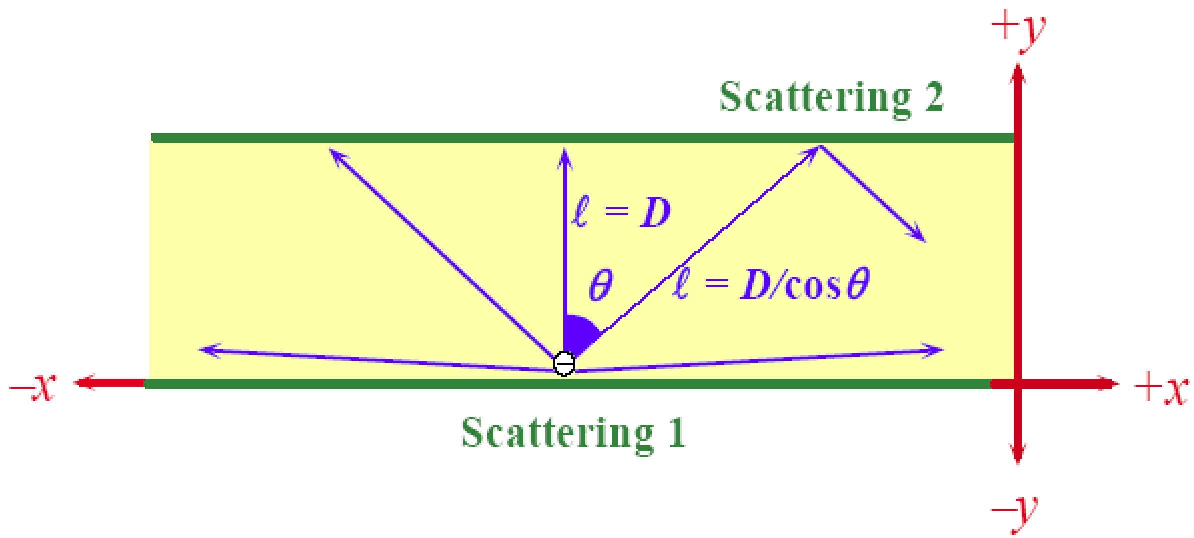
(a) Grain boundaries cause scattering of the electron and therefore add to the Resistivity by the Matthiessen's rule.
(b) For a very grainy solid, the electron is scattered from grain boundary to grain boundary and the mean free path is approximately equal to the mean grain diameter.

Fig 2.32



Conduction in thin films may be controlled by scattering from the surfaces

Fig 2.33



The mean free path of the electron depends on the angle θ after scattering.

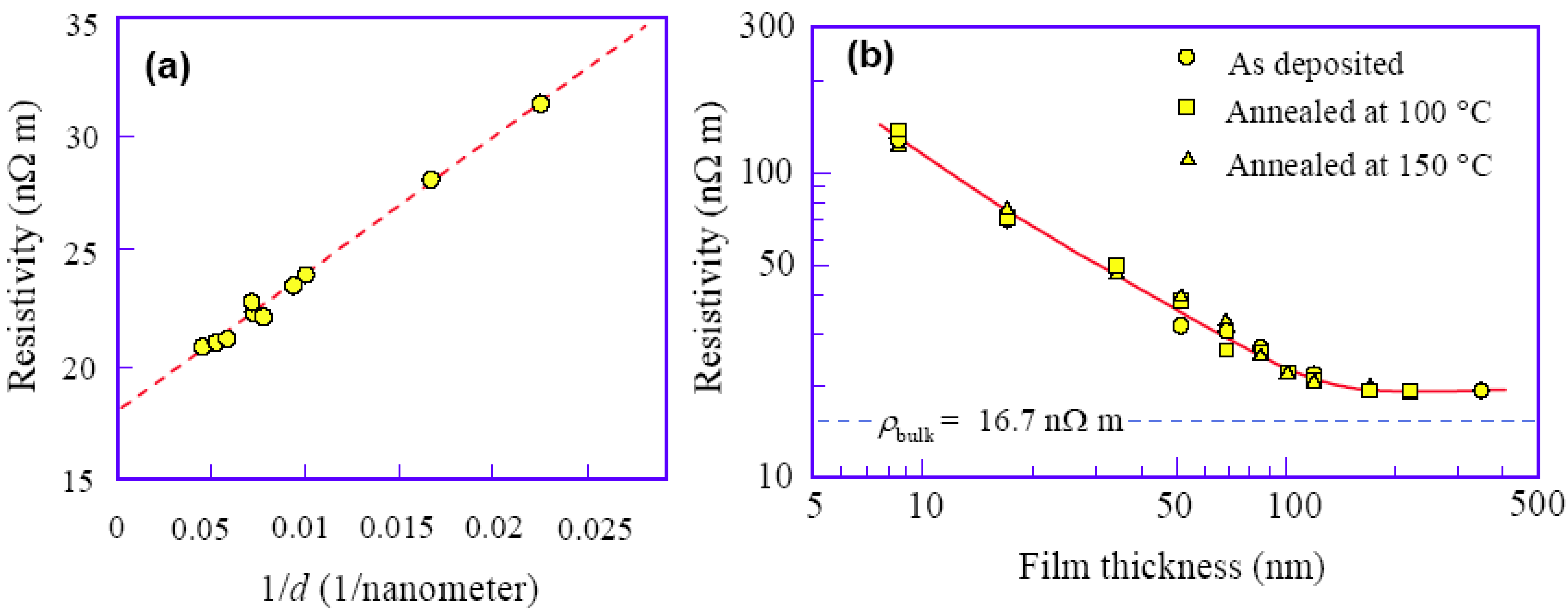
Fig 2.34

Table 2.6 Resistivities of some thin Cu and Au films at room temperature

Film	D (nm)	d (nm)	ρ (nΩ m)	Comment
Cu films (Polycrystalline)				
Cu on TiN, W, and TiW [1]	>250	186	21	Chemical vapor deposition (CVD).
		45	32	Substrate temperature 200 °C. ρ depends on d not $D = 250$–900 nm.
Cu on 500 nm SiO_2 [2]	20.5		35	Thermal evaporation. Substrate at RT.
	37		27	
Cu on Si (100) [3]	52		38	Sputtered Cu films. Annealing at 150 °C has
	100		22	no effect. $R \approx 0.40$ and $p \approx 0$.
Cu on glass [4]	40		50	As deposited
	40		29	Annealed at 200 °C
	40		25	Annealed at 250 °C
				All thermal evaporated and PC.
Au films				
Au epitaxial film on mica	30		25	Single crystal on mica. $p \approx 0.8$. Specular scattering.
Au PC film on mica	30		54	PC. Sputtered on mica. p is small.
Au film on glass	30		70	PC. Evaporated onto glass. p is small. Nonspecular scattering.
Au on glass [5]	40	8.5	92	PC. Sputtered films. $R = 0.27$–0.33.
	40	3.8	189	

NOTE: PC-polycrystalline film, RT-room temperature, D = film thickness, d = average grain size. At RT for Cu, $\lambda = 38$–40 nm, and for Au, $\lambda = 36$–38 nm.

SOURCES: Data selectively combined from various sources, including [1] S. Riedel *et al.*, *Microelec. Engin*. **33**, 165, 1997; [2] H. D. Liu *et al.*, *Thin Solid Films*, **34**, 151, 2001; [3] J. W. Lim *et al.*, *Appl. Surf. Sci.* **217**, 95, 2003. [4] R. Suri *et al.*, *J. Appl. Phys.*, **46**, 2574, 1975; [5] R. H. Cornely and T. A. Ali, *J. Appl. Phys.*, **49**, 4094, 1978.

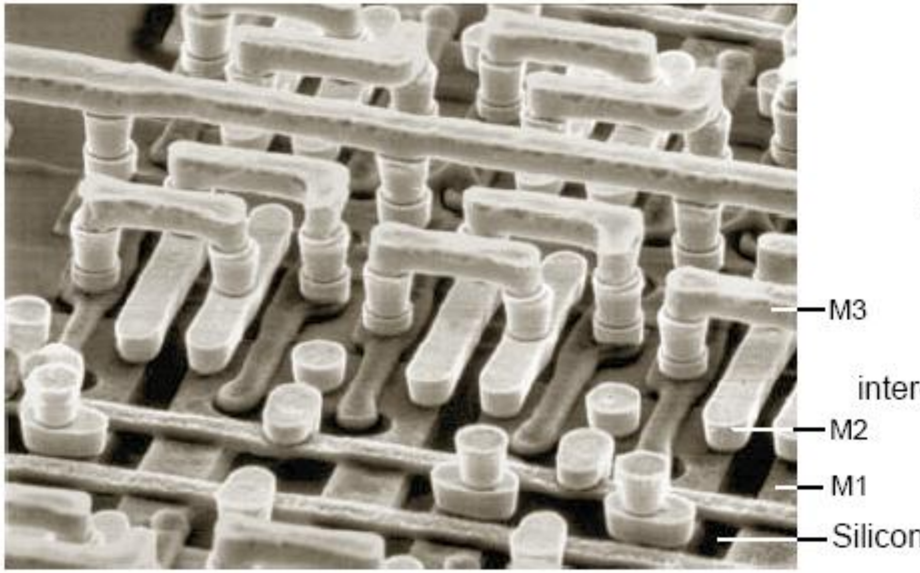


(a) ρ_{film} of the Cu polycrystalline films vs. reciprocal mean grain size (diameter), $1/d$. Film thickness D = 250 nm - 900 nm does not affect the resistivity. The straight line is ρ_{film} = 17.8 nΩ m + (595 nΩ m nm)($1/d$),

(b) ρ_{film} of the Cu thin polycrystalline films vs. film thickness D. In this case, annealing (heat treating) the films to reduce the polycrystallinity does not significantly affect the resistivity because ρ_{film} is controlled mainly by surface scattering.

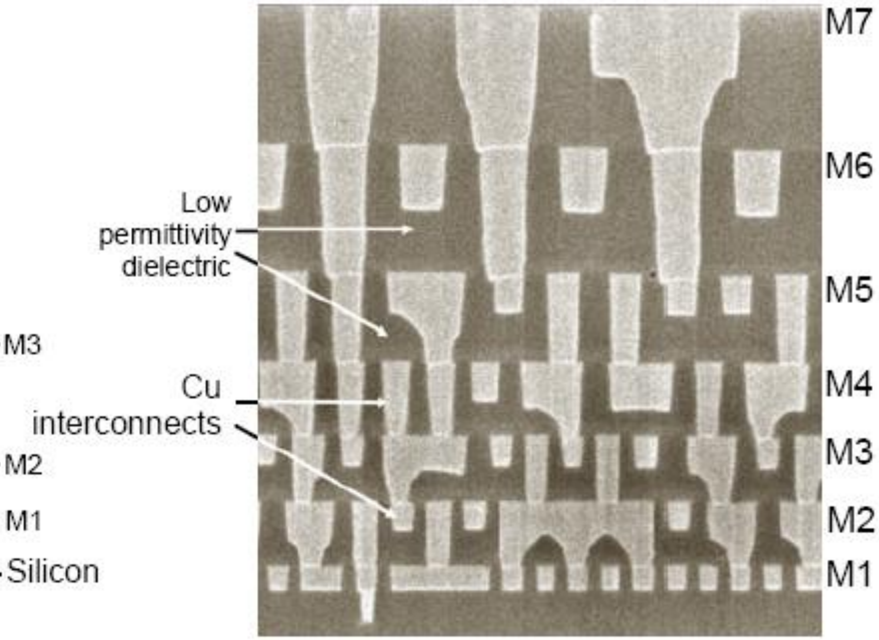
|SOURCE: Data extracted from (a) S. Riedel et al, *Microelec. Engin.* **33**, 165, 1997 and (b). W. Lim *et al*, *Appl. Surf. Sci.*, **217**, 95, 2003)

Fig 2.35



Metal interconnects wiring devices on a silicon crystal. Three different metallization levels M1, M2, and M3 are used. The dielectric between the interconnects has been etched away to expose the interconnect structure.

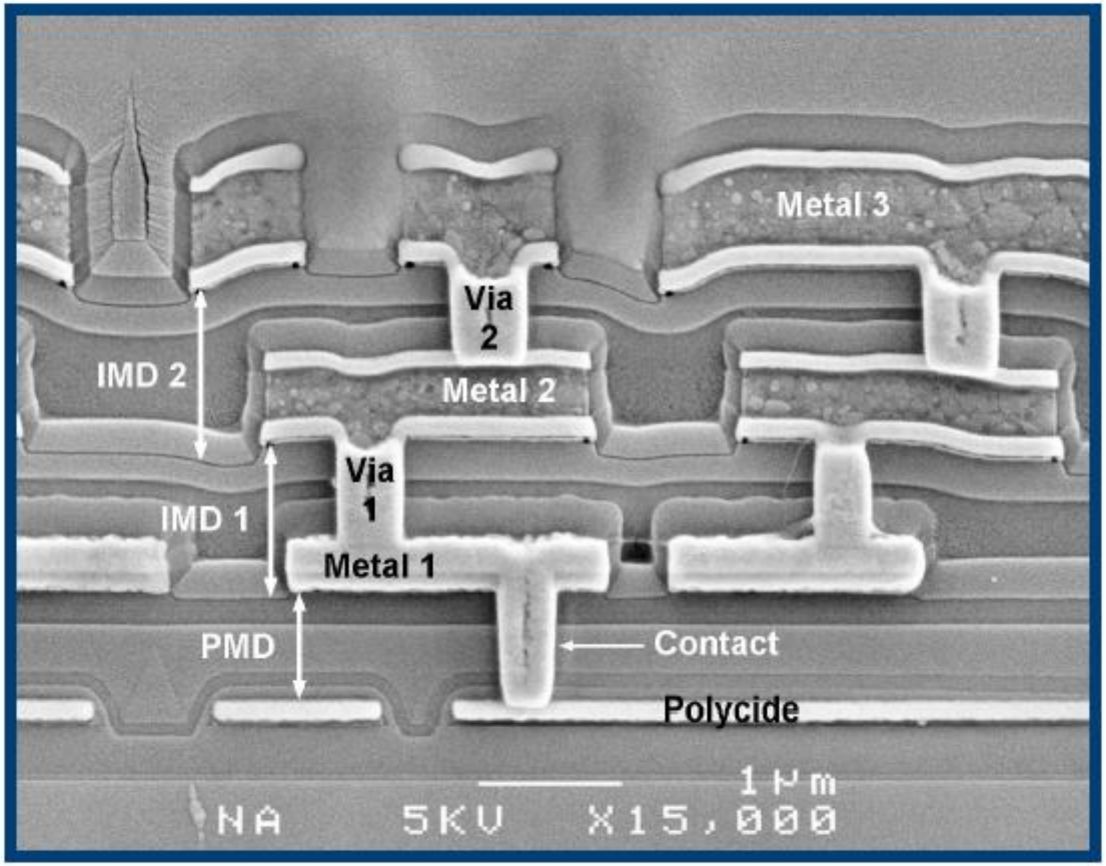
|SOURCE: Courtesy of IBM



Cross section of a chip with 7 levels of metallization, M1 to M7. The image is obtained with a scanning electron microscope (SEM).

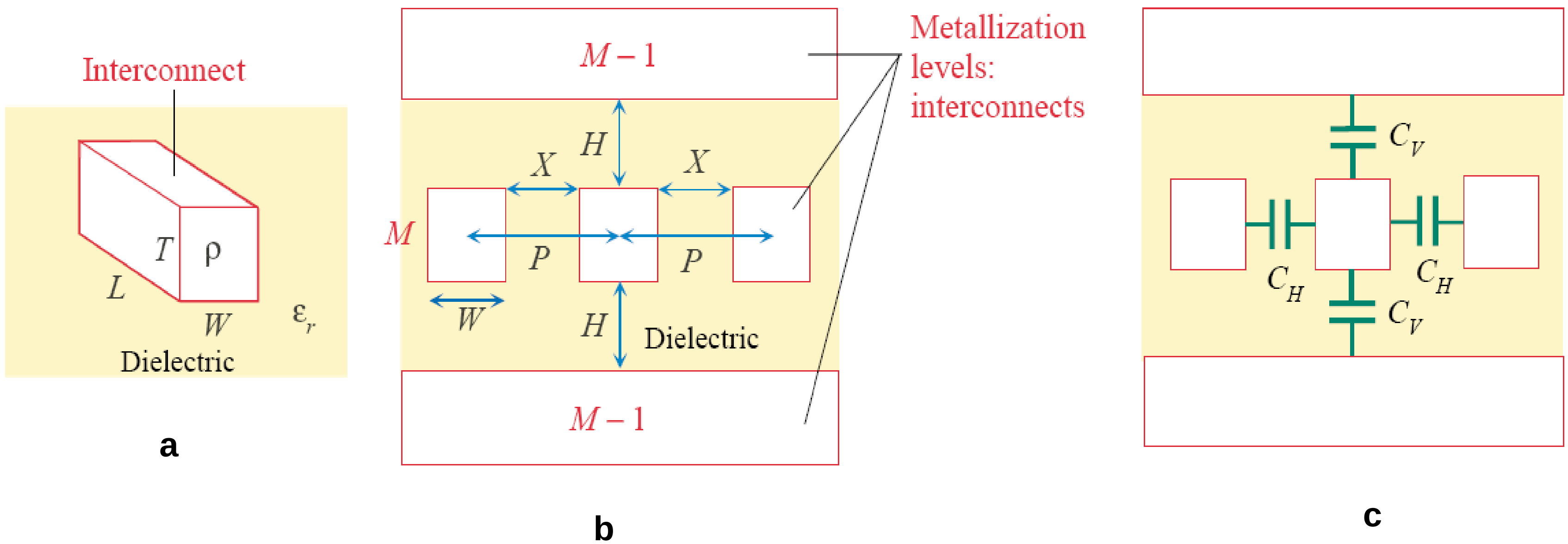
|SOURCE: Courtesy of Mark Bohr, Intel.

Fig 2.36



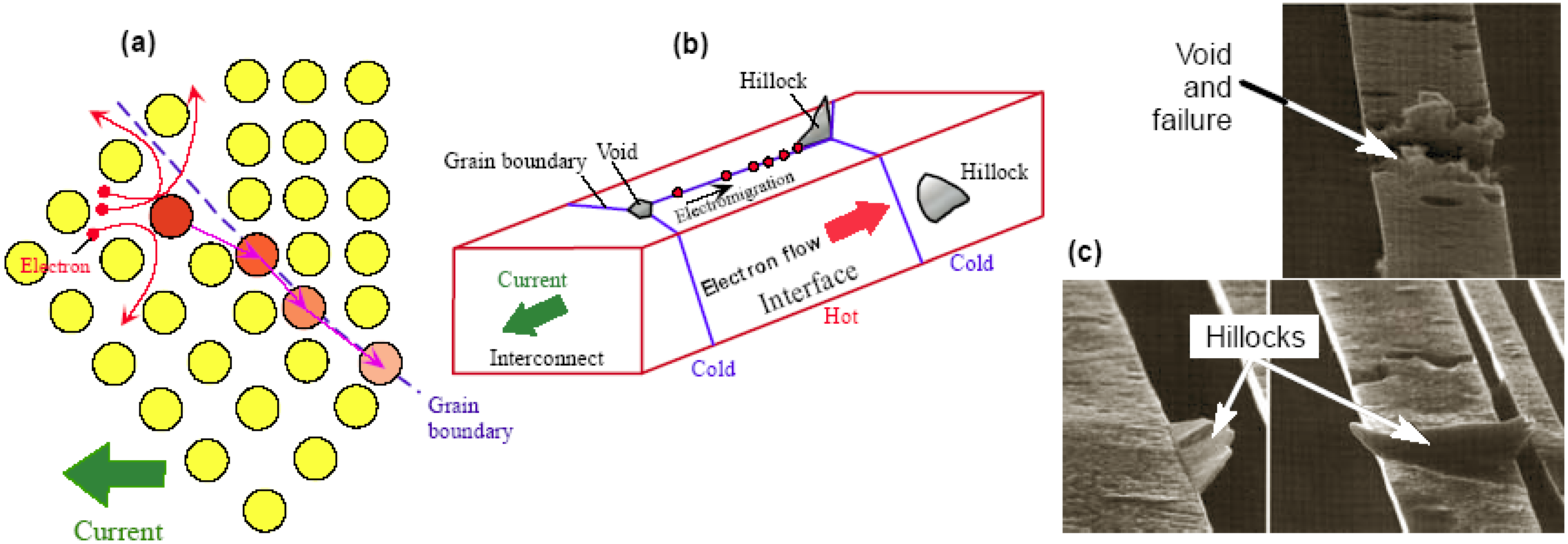
Three levels of interconnects in a flash memory chip. Different levels are connected through vias.

|SOURCE: Courtesy of Dr. Don Scansen, Semiconductor Insights, Kanata, Ontario, Canada



(a) A single line interconnect surrounded by dielectric insulation.
(b) Interconnects crisscross each other. There are three levels of interconnect: $M - 1$, M, and $M + 1$
(c) An interconnect has vertical and horizontal capacitances C_v and C_H.

Fig 2.37



(a) Electrons bombard the metal ions and force them to slowly migrate
(b) Formation of voids and hillocks in a polycrystalline metal interconnect by the electromigration of metal ions along grain boundaries and interfaces. (c) Accelerated tests on 3 mm CVD (chemical vapor deposited) Cu line. T = 200 ^{o}C, J = 6 MA cm^{-2}: void formation and fatal failure (break), and hillock formation.

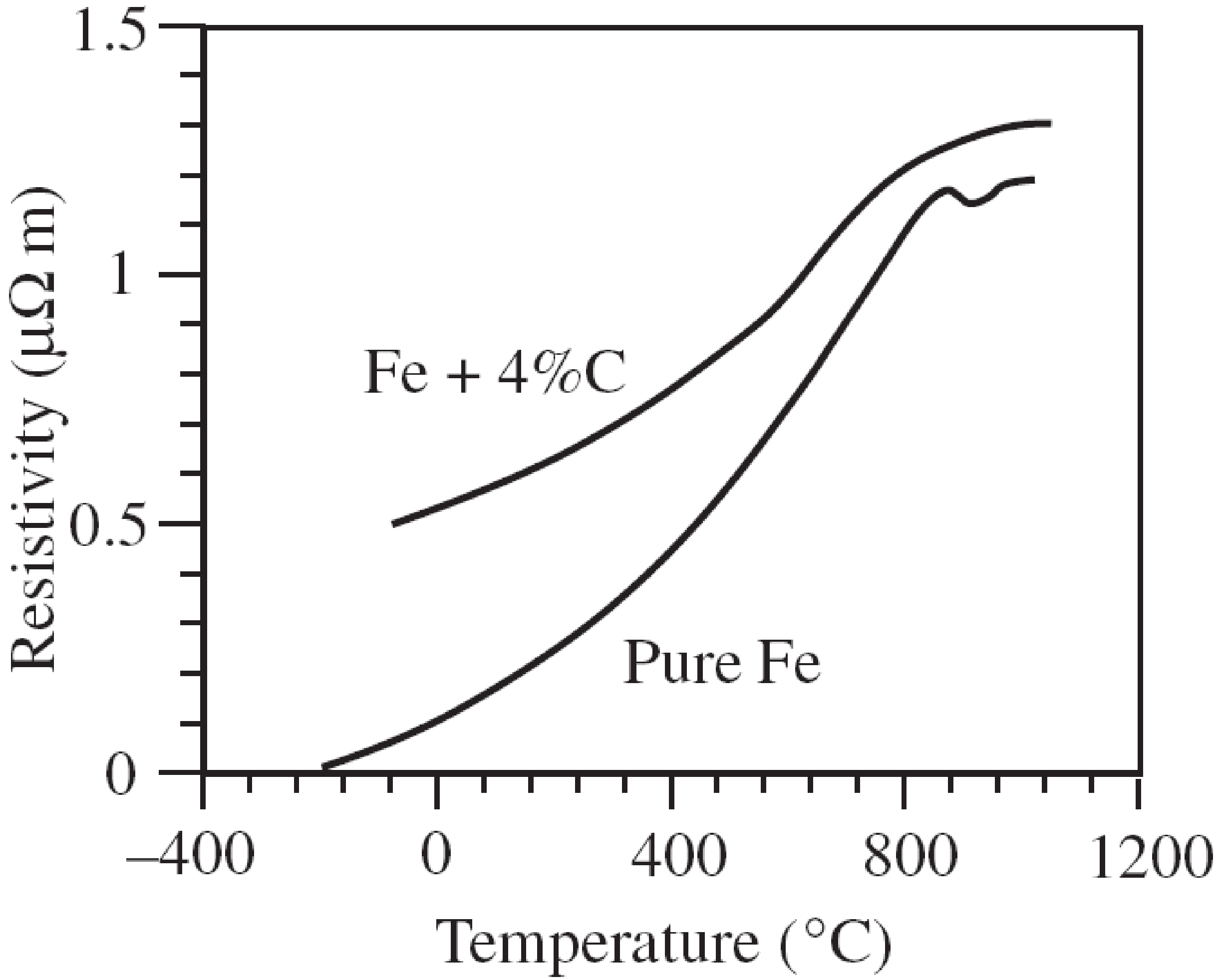
|SOURCE: Courtesy of L. Arnaud et al, *Microelectronics Reliability*, **40**, 86, 2000.

Fig 2.38

Table 2.7 Selection of metals from Groups I to IV in the Periodic Table

Metal	Periodic Group	Valency	Density ($g\ cm^{-3}$)	Resistivity ($n\Omega\ m$)	Mobility ($cm^2\ V^{-1}s^{-1}$)
Na	IA	1	0.97	42.0	53
Mg	IIA	2	1.74	44.5	17
Ag	IB	1	10.5	15.9	56
Zn	IIB	2	7.14	59.2	8
Al	IIIB	3	2.7	26.5	12
Sn	IVB	4	7.30	110	3.9
Pb	IVB	4	11.4	206	2.3

NOTE: Mobility from Hall-effect measurements.



Resistivity versus temperature for pure iron and 4% C steel.

Fig 2.39

From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005)

Table 2.8 Cu–Zn brass alloys

Zn at.% in Cu–Zn	0	0.34	0.5	0.93	3.06	4.65	9.66	15.6	19.59	29.39
Resistivity nΩ m	17	18.1	18.84	20.7	26.8	29.9	39.1	49.0	54.8	63.5

SOURCE: H. A. Fairbank, *Phys. Rev.*, **66**, 274, 1944.

Table 2.9 Resistivities of some solid solution metal alloys

	Alloy							
	Ag–Au	**Au–Ag**	**Cu–Pd**	**Ag–Pd**	**Au–Pd**	**Pd–Pt**	**Pt–Pd**	**Cu–Ni**
X (at.%)	8.8% Au	8.77% Ag	6.2% Pd	10.1% Pd	8.88% Pd	7.66% Pt	7.1% Pd	2.16% Ni
ρ_0 (nΩ m)	16.2	22.7	17	16.2	22.7	108	105.8	17
ρ at X (nΩ m)	44.2	54.1	70.8	59.8	54.1	188.2	146.8	50
C_{eff}								
X'	15.4% Au	24.4% Ag	13% Pd	15.2% Pd	17.1% Pd	15.5% Pt	13.8% Pd	23.4% Ni
ρ' at X' (nΩ m)								
ρ' at X' (nΩ m) Experimental	66.3	107.2	121.6	83.8	82.2	244	181	300

NOTE: First symbol (*e.g.*, Ag in AgAu) is the matrix (solvent) and the second (Au) is the added solute. X is in at.%, converted from traditional weight percentages reported with alloys. C_{eff} is the effective Nordheim coefficient in $\rho = \rho_o + C_{eff} X(1-X)$.

Table 2.10 Cu–Ni alloys, resistivity, and TCR

	Ni wt.% in Cu–Ni				
	0	2	6	11	20
Resistivity (nΩ m)	17	50	100	150	300
TCR (ppm $°C^{-1}$)	4270	1350	550	430	160

NOTE: ppm-parts per million, *i.e.*, 10^{-6}.

Table 2.11 Resistivity of Ag–Ni contact alloys for switches

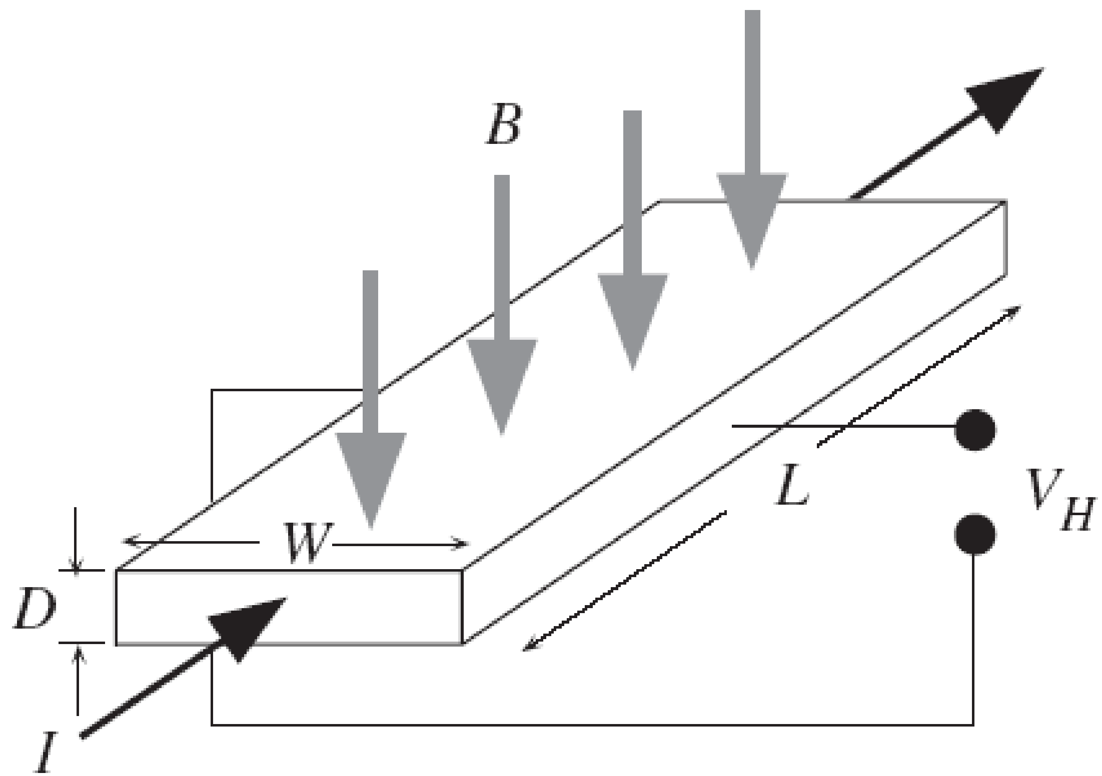
	Ni % in Ag–Ni					
	0	10	15	20	30	100
ρ(nΩ m)	16.9	20.9	23.6	25	31.1	71.4
d(g cm^{-3})	10.5	10.3	9.76	9.4	9.47	8.9
Hardness VHN	30	50	55	60	65	80

NOTE: Compositions are in wt.%. Ag–10% Ni means 90% Ag–10% Ni. Vickers hardness number (VHN) is a measure of the hardness or strength of the alloy, and d is density.

Table 2.12 Dependence of resistivity in Ag–W alloy on composition as a function of wt.% W

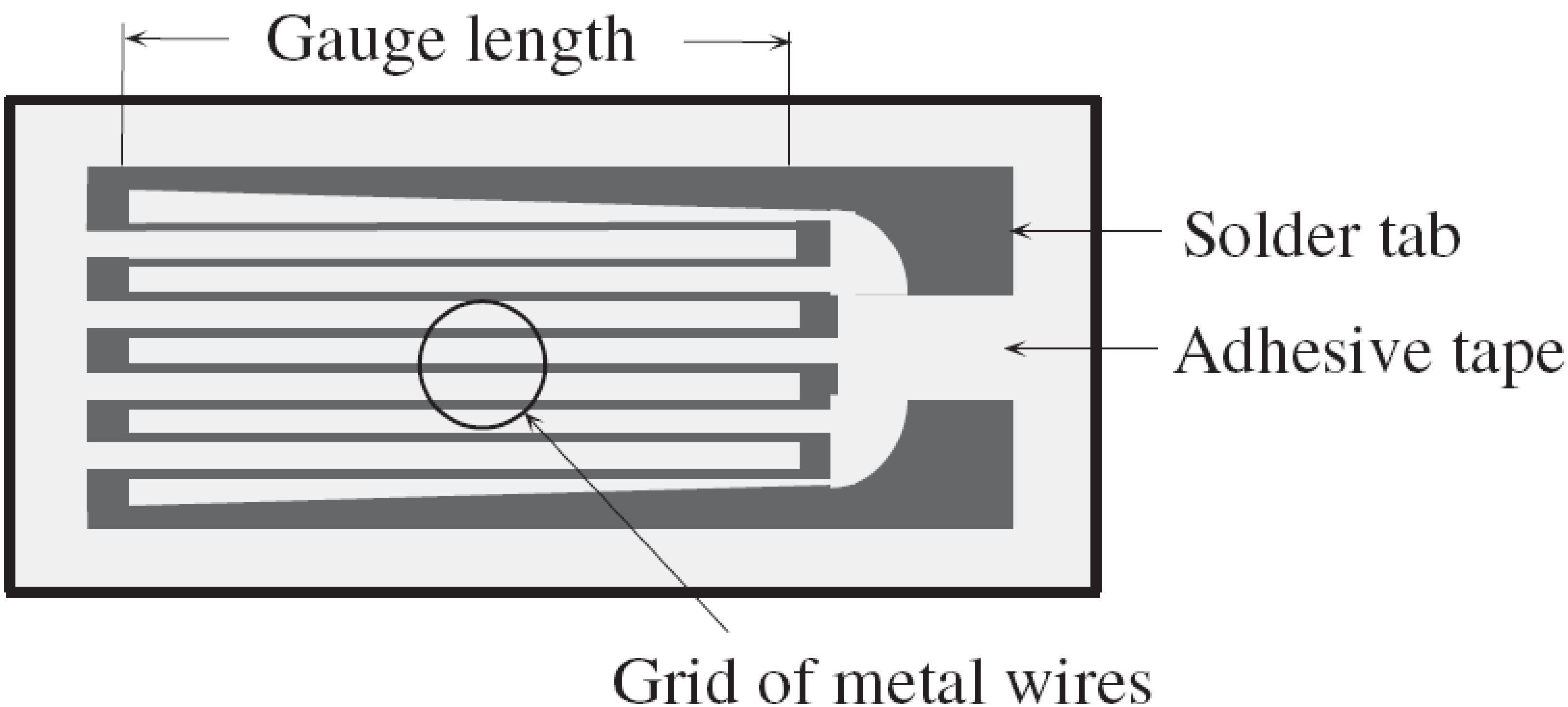
	W(wt.%)												
	0	**10**	**15**	**20**	**30**	**40**	**65**	**70**	**75**	**80**	**85**	**90**	**100**
ρ (nΩ m)	16.2	18.6	19.7	20.9	22.7	27.6	35.5	38.3	40	46	47.9	53.9	55.6
d (g cm^{-3})	10.5	10.75	10.95	11.3	12	12.35	14.485	15.02	15.325	16.18	16.6	17.25	19.1

NOTE: ρ = resistivity and d = density.



Hall effect in a rectangular material with length *L*, width*W*, and thickness *D*. The voltmeter is across the width *W*.

Fig 2.40



The strain gauge consists of a long, thin wire folded several times along its length to form a grid as shown and embedded in a self-adhesive tape. The ends of the wire are attached to terminals (solder pads) for external connections. The tape is stuck on the component for which the strain is to be measured.

Fig 2.41

Table 2.13 Resistivity ρ_{film} of a copper film as a function of thickness D.

D (nm)	8.61	17.2	34.4	51.9	69	85.8	102.6	120.3	173.2	224.3
ρ_{film} (nΩ m)	121.8	75.3	46.1	38.5	32.1	25.2	22.0	20.5	19.9	18.8

Table 2.14 Results of electromigration failure experiments on various Al and Cu interconnects

Al(Cu) [$J = 25$ mA/μm^2, $A = 0.35 \times 0.2$ (μm)^2]		Cu [$J = 25$ mA/μm^2, $A = 0.24 \times 0.28$ (μm)^2]		Cu [$J = 25$ mA/μm^2, $A = 1.3 \times 0.7$ (μm)^2]		Cu ($T = 370$ °C)	
T (°C)	**t_{50} (hr)**	**T (°C)**	**t_{50} (hr)**	**T (°C)**	**t_{50} (hr)**	**J mA μm^{-2}**	**t_{50} (hr)**
365	0.11	397	2.87	395	40.3	3.54	131.5
300	0.98	354	12.8	360	196	11.7	25.2
259	5.73	315	70.53	314	825	24.8	14.9
233	15.7	269	180	285	2098	49.2	4.28
		232	899			74.1	2.29
						140	0.69