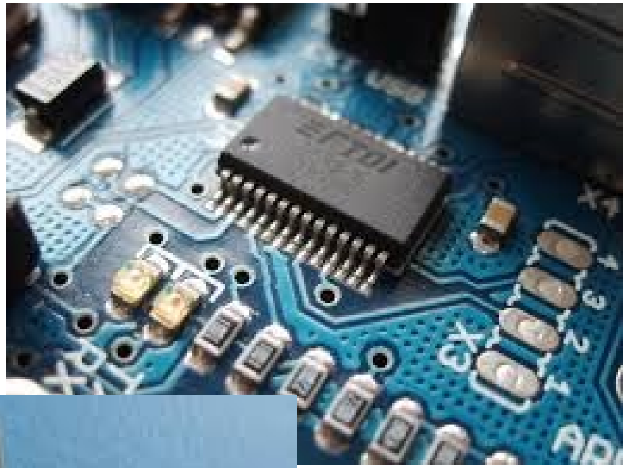
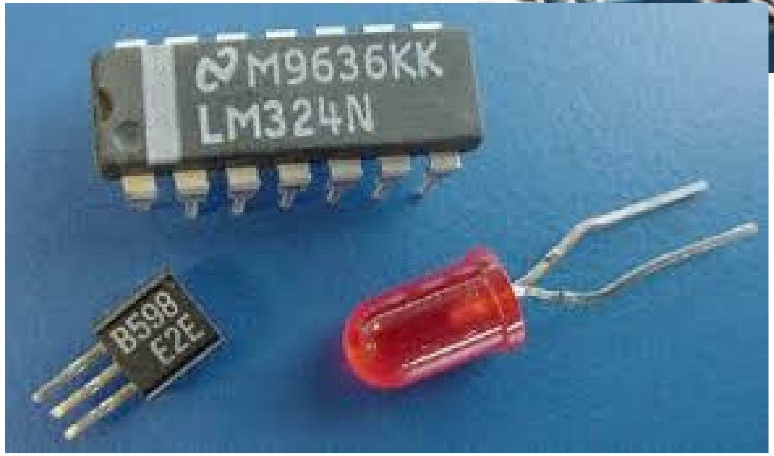
CHAPTER 11

Electronic Materials

What are they?

- Materials that conduct electricity
- **Used** in electrical industries, electronics and microelectronics, and the substances for the building up of integrated circuits, circuit boards, packaging materials, communication cables, optical fibres, displays, and various controlling and monitoring devices.





Ohm’s Law

$$V = IR$$

- Where V is the voltage (volts, V), I is the current (amperes or amps, A), and R is the resistance (ohms).

$$R = \rho \frac{l}{A} = \frac{l}{\sigma A}$$

- where l is the length (cm) of the resistor, A is the cross-sectional area (cm^2) of the resistor, ρ is the electrical resistivity (ohm.cm), and , which is the reciprocal of σ, is the electrical conductivity ($ohm^{-1}\ cm^{-1}$).
- Metals: High conductivity
- Insulators: Low Conductivity
- Semiconductors: Conductivity can be varied by several orders of magnitude.

Using Ohm’s law

$$P = IV = I^2R$$

The electrical power **P** (in watts, W) lost when a current flows through a resistance.

$$J = \frac{I}{A} = \sigma\frac{V}{l} = \sigma E = \mathrm{nq}v; \qquad v = \frac{l}{t}$$

$$\mu = \frac{v}{E} = \frac{\sigma}{nq}$$

J: Current density(A/cm^2)

E: Electric field (V/cm)

n: number of charge carriers (carriers/cm^3)

q: charge on each carrier (1.6×10^{-19} C)

v:the average drift velocity (cm/s) at which the charge carriers move

μ: Mobility (cm^2 /V s)

Example

- A voltage of 1700 V is applied to a gold wire 25 m in length. Calculate the diameter of wire and current density if the resistance is 3 ohm

- $V = 1700\ V$
- $R = 3\ \Omega$
- $l = 25\ m = 2500\ \text{cm}$
- $\sigma_{Au} = 4.26 \times 10^{5} \Omega^{-1} cm^{-1}$

Diameter of the wire?

Current density?

Example

- Design an electrical transmission line 1500 m long and diameter of 1 cm that will carry a current of 50 A with no more than 5×10^5 W loss in power.

Material	Conductivity ($\Omega^{-1}\,m^{-1}$)
Aluminum	3.5×10^7
Copper	6.0×10^7
Gold	4.1×10^7
Iron	1.0×10^7
Silver	6.2×10^7
Tungsten	1.8×10^7
Nichrome*	6.7×10^5
Carbon	2.9×10^4

What is the maximum conductivity for this power loss?

- $l = 1500\ m$
- $d = 1\ cm = 0.01\ \mathrm{m}$
- $I = 50\ A$
- $P = 5 \times 10^5\ W$

Material	Conductivity ($\Omega^{-1}\mathrm{m}^{-1}$)
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Copper	6.0×10^7
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Iron	1.0×10^7
Silver	6.2×10^7
Tungsten	1.8×10^7
Nichrome*	6.7×10^5
Carbon	2.9×10^4

Example

- A current density of 5000 A/cm2 is applied to a Aluminum wire. If half of the valence electrons serve as charge carriers, calculate the average drift velocity of the electrons

- $J = 5000 \frac{A}{cm^2}$
- $Al\ is\ FCC$
- $a_0 = 4.04 \times 10^{-8}\ cm$

q: charge on each carrier (1.6×10−19 C)

Drift velocity?

How does conductivity work?

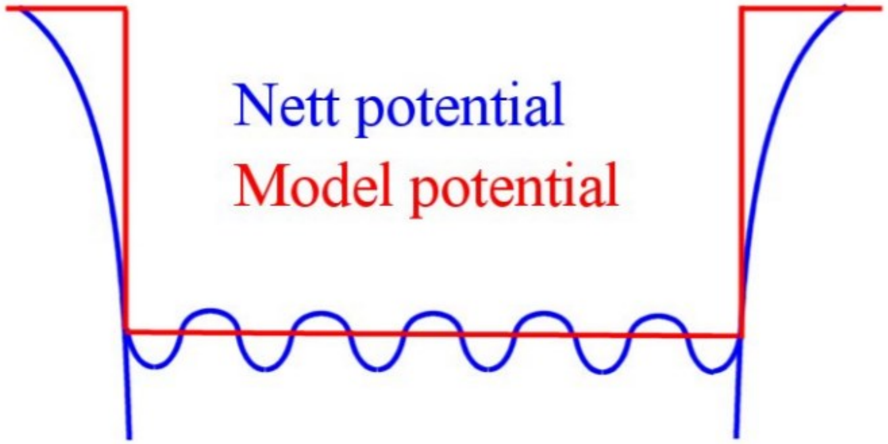
1. FREE ELECTRON MODEL

Assumptions: e- are not interacting with each other

e- respond equally to an external field

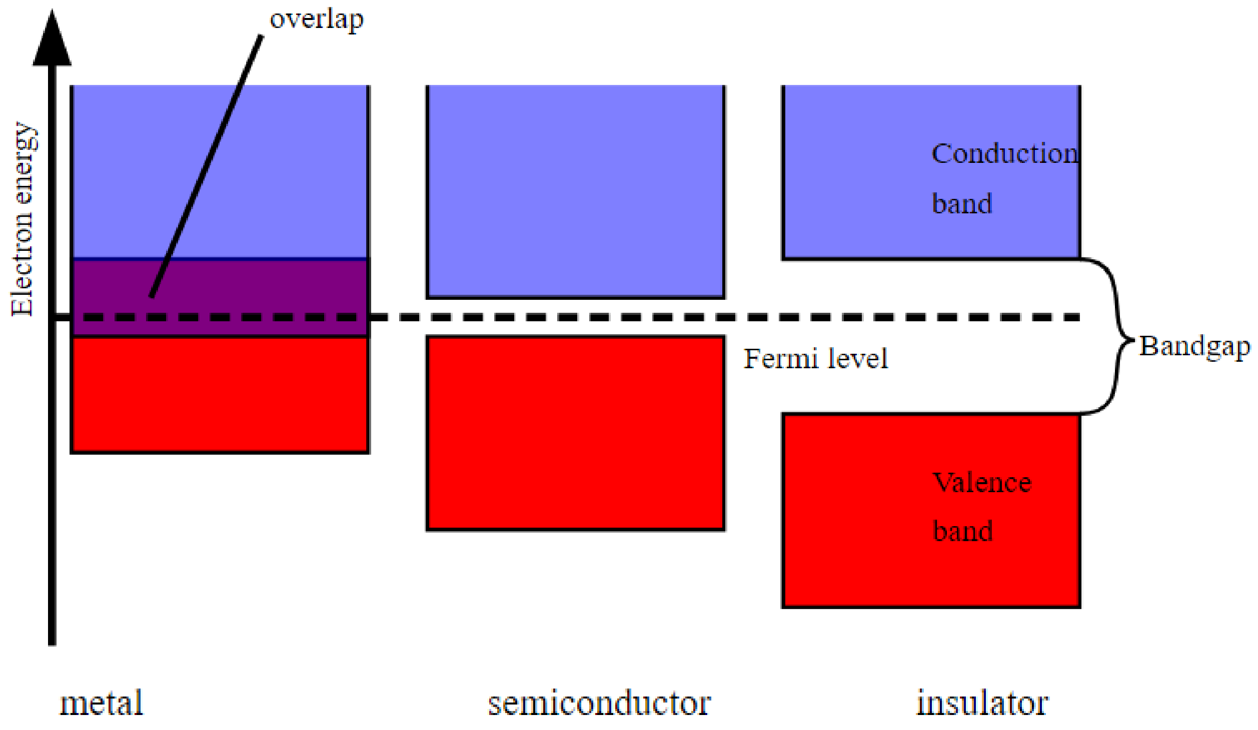
inner e- are localized

Constant potential



How does conductivity work?

- BAND THEORY
- Describes the conduction in terms of the energy to excite an e-



BAND THEORY

- In order for e- to jump from one band to another, the energy must accelerate the e- enough to promote it to energy empty states.

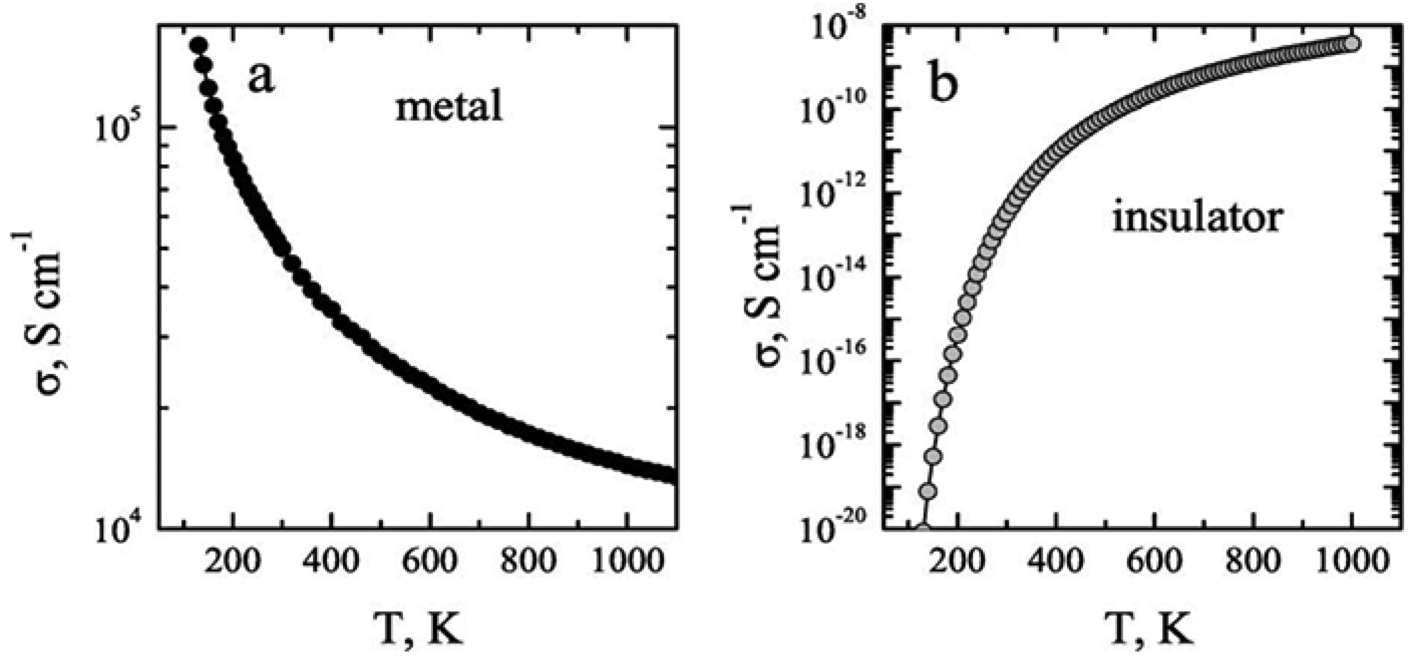
- <u>Fermi Energy (Ef):</u> Energy level at which only half of the energy levels in the band are field at ABSOLUTE ZERO

- What happens with Non-metals? Due to covalent bonding the energy needed to excite an e- will form a hybrid band between s and p levels.

Response to temperature

By the way
Siemens is a resistivity unit

S = Ω^{-1}



Example

- If all valence e- contribute to the current flow in Cu, calculate:

a) Mobility of e- and, b) average drift velocity of e- in 100cm long wire when 10V are applied

- a_o= 3.51E-18 cm
- FCC structure
- σ= 5.98E5 Ω^{-1} cm^{-1}

Mobility?

a_o= 3.51E-18 cm
FCC structure
Valence=1
σ= 5.98E5 Ω^{-1} cm^{-1}

b) Drift velocity?

a_o= 3.51E-18 cm
FCC structure
Valence=1
σ= 5.98E5 Ω^{-1} cm^{-1}
V=10 v
L=100 cm

Conductivity of Metals and Alloys

- Conductivity is defined by the electronic structure of the material, if and only, the material is pure and defect-free.

$$\sigma = \mathrm{nq}\mu$$

- The paths of electrons are influenced internal fields due to the atoms present in the solid and imperfections present in the lattice.

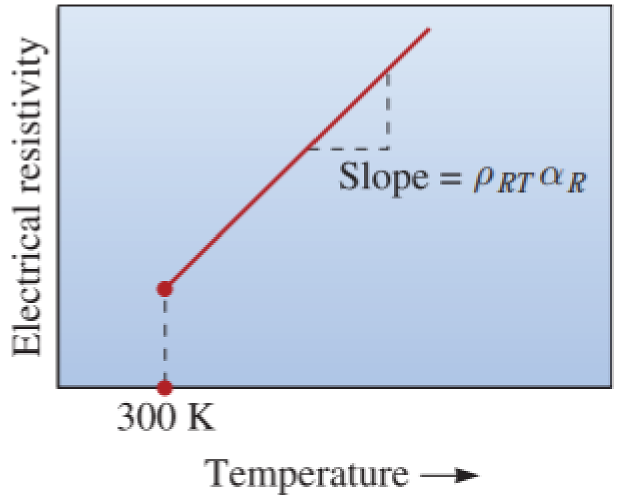
$$\lambda_e = \tau\upsilon$$

- λ_e: Mean free path
- τ: Average time between collisions

Conductivity of Metals and Alloys: Temperature effect

$\Uparrow$ T ⟶ $\Downarrow \lambda_e$ $\Downarrow \mu$ $\Downarrow \sigma$

$$\frac{1}{\sigma} = \rho = \rho_{RT}(1 + \alpha_R(T - 25°\mathrm{C}))$$



ρ_{RT}: Resistivity at room temperature (Ω*cm)
α_R: Temperature resistivity coefficient (Ω/ Ω °C)
T: New temperature (°C)

Example

- After finding the electric conductivity of cobalt at 0 °C, we decide to double the conductivity. To what temperature must we cool the metal?

TABLE 19-3 *The temperature resistivity coefficient α_R for selected metals*

Metal	Room Temperature Resistivity (ohm · cm)	Temperature Resistivity Coefficient (α_R) [ohm/(ohm · °C)]
Be	4.0×10^{-6}	0.0250
Mg	4.45×10^{-6}	0.0037
Ca	3.91×10^{-6}	0.0042
Al	2.65×10^{-6}	0.0043
Cr	12.90×10^{-6} (0°C)	0.0030
Fe	9.71×10^{-6}	0.0065
Co	6.24×10^{-6}	0.0053
Ni	6.84×10^{-6}	0.0069
Cu	1.67×10^{-6}	0.0043
Ag	1.59×10^{-6}	0.0041
Au	2.35×10^{-6}	0.0035
Pd	10.8×10^{-6}	0.0037
W	5.3×10^{-6} (27°C)	0.0045
Pt	9.85×10^{-6}	0.0039

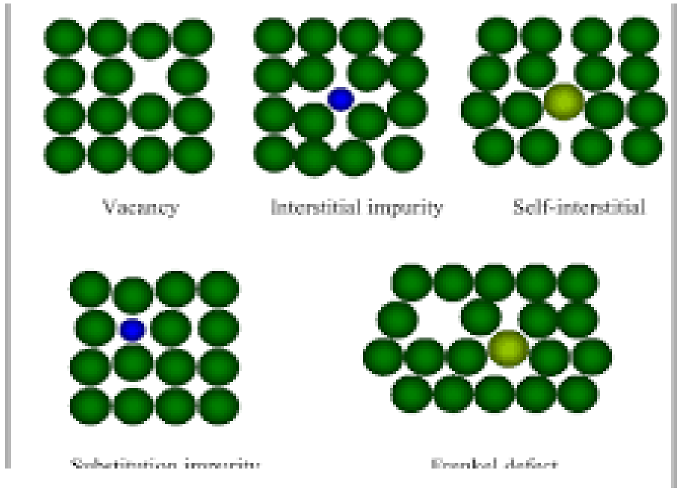
Conductivity at $0°C$

- $\rho_{RT}(Co) = 6.24 \times 10^{-6} \Omega\ cm$
- $\alpha_{Rt} = 0.0053 \frac{1}{°C}$
- $T_1 = 0°C$

- $\rho_{RT}(Co) = 6.24 \times 10^{-6}\Omega\ cm$
- $\alpha_{Rt} = 0.0053\frac{1}{°C}$
- $T_1 = 0°C$

If we wish to double the conductivity, what temperature should we use?

Conductivity of Metals and Alloys: Defects effect

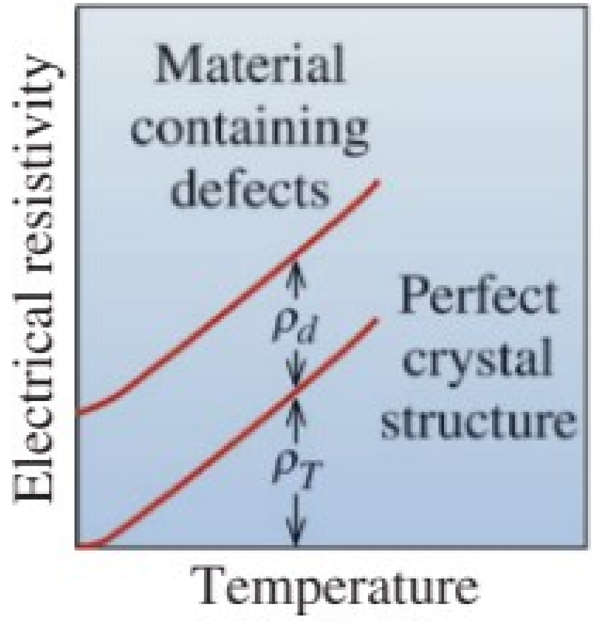


$\uparrow$ defects $\longrightarrow$ $\downarrow \lambda_e$ $\quad \downarrow \mu$ $\quad \downarrow \sigma$

$$\rho_d = bx(1 - x)$$

ρ_d: Resistivity due to defects(Ω*cm)
b: Defect resistivity coefficient (Ω*cm)
x: fraction of impurity

$$\rho = \rho_t + \rho_d$$



Example

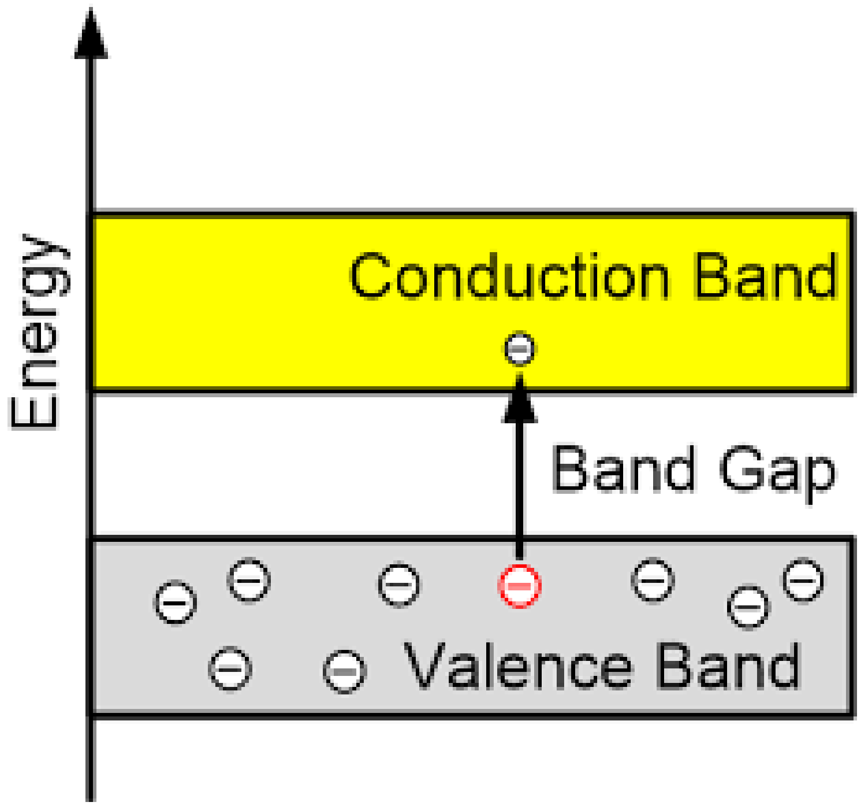
- The electrical resistivity of beryllium alloy containing 5at% of an alloying element is found to be 50E6 Ω cm at 400ºC.
- Determine the contributions to resistivity due to temperature and due to impurities by finding the expected resistivity of pure beryllium at 400ºC, the resistivity due to impurities, and the defect resistivity coefficient.
- What would be the electrical resistivity if beryllium contained 10 at% of the same alloying element at 200ºC?
  - ρ_{RT}: 4E-6 Ω cm
  - α_R: 0.025 1/ºC

- $\rho_{400°\mathrm{C}} = 50 \times 10^{-6}\ \Omega \cdot \mathrm{cm}$
- $\rho_{RT} = 4 \times 10^{-6}\ \Omega \cdot \mathrm{cm}$
- $\alpha_R = 0.025\ 1/°\mathrm{C}$
- $\chi = 0.05$

- $\rho_{RT} = 4 \times 10^{-6}\ \Omega \cdot \mathrm{cm}$
- $\alpha_R = 0.025\ 1/°\mathrm{C}$
- $\chi = 0.1$
- $b = 1.79 \times 10^{-4}\ \Omega \cdot \mathrm{cm}$

Semiconductors

- Any of a class of crystalline solids intermediate in electrical conductivity between a conductor and an insulator.
- Key elements for the majority of electronic systems, serving communications, signal processing, computing, and control applications in both the consumer and industrial markets.
- Energy gap (Eg) between the valence and conduction bands is relatively small.
- **Intrinsic semiconductors**: Properties independent of the impurities.
- **Extrinsic semiconductors**: Temperature stable and can be controlled by ion implantation or diffusion of impurities known as dopants.



Intrinsic semiconductors

- For every electron promoted to the conduction band, there is a hole left in the valence band.

$$\sigma = n_i \mathrm{q}\left(\mu_n + \mu_p\right)$$

- n_i: Concentration of e-
- μ_n: Mobility of e-
- μ_p: Mobility of holes (h+)

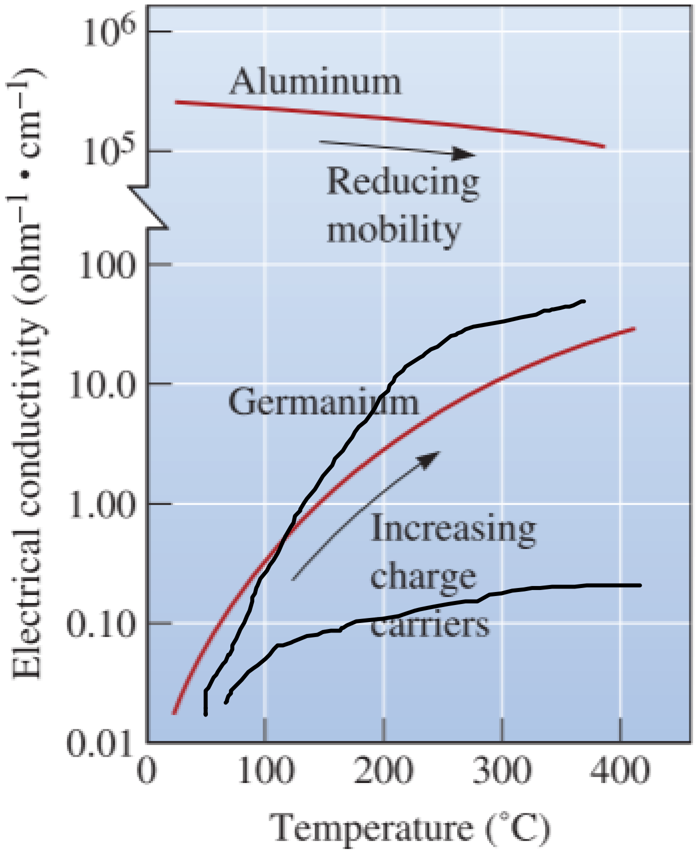
$$\mu_n > \mu_p$$

Intrinsic semiconductors: Temperature effect

$$n_i = n_0 exp\left(\frac{-E_g}{2k_B T}\right) \quad n_0 = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4}$$

$$\sigma = n_0 q(\mu_n + \mu_p)\, exp\left(\frac{-E_g}{2k_B T}\right)$$

k_B: Boltzmann's constant (1.38×10^{-23} m^2 kg s^{-2} K^{-1} or **8.63×10^{-5} eV/K**)
h: Planck's constant (6.63×10^{-34} m^2 kg / s)
m_n^*: Effective mass of e-
m_p^*: Effective mass of h+



Example

For germanium and silicon, compare, at 25°C, the number of charge carriers per cubic centimeter, the fraction of the total # electrons in the valence band that are excited into the conduction band, and the constant no

TABLE 19-5 *Properties of commonly encountered semiconductors at room temperature*

Semiconductor	Bandgap (eV)	Mobility of Electrons (μ_n) $\left(\frac{cm^2}{V\text{-}s}\right)$	Mobility of Holes (μ_p) $\left(\frac{cm^2}{V\text{-}s}\right)$	Dielectric Constant (k)	Resistivity ($\Omega \cdot cm$)	Density $\left(\frac{g}{cm^2}\right)$	Melting Temperature (°C)
Silicon (Si)	1.11	1350	480	11.8	2.5×10^5	2.33	1415
Amorphous Silicon (a:Si:H)	1.70	1	10^{-2}	~11.8	10^{10}	~2.30	—
Germanium (Ge)	0.67	3900	1900	16.0	43	5.32	936
SiC (α)	2.86	500		10.2	10^{10}	3.21	2830
Gallium Arsenide (GaAs)	1.43	8500	400	13.2	4×10^8	5.31	1238
Diamond	~5.50	1800	1500	5.7	$> 10^{18}$	3.52	~3550

ao (Si) = 5.43E-8 cm
ao (Ge) = 5.66E-8 cm

Germanium @ 25°C

- $\rho_{RT}(Ge) = 43\ \Omega\ cm$
- $\sigma_{RT}(Ge) = 0.0233\ \Omega^{-1} cm^{-1}$
- $Eg = 0.67\ eV$
- $\mu_n = 3900 \frac{cm^2}{Vs}$
- $\mu_p = 1900 \frac{cm^2}{Vs}$
- $2k_bT = 0.0514\ eV$
- $a_0 = 5.66 \times 10^{-8} cm$
- $DC \rightarrow 8 \frac{at}{uc}$
- Oxidation number =4

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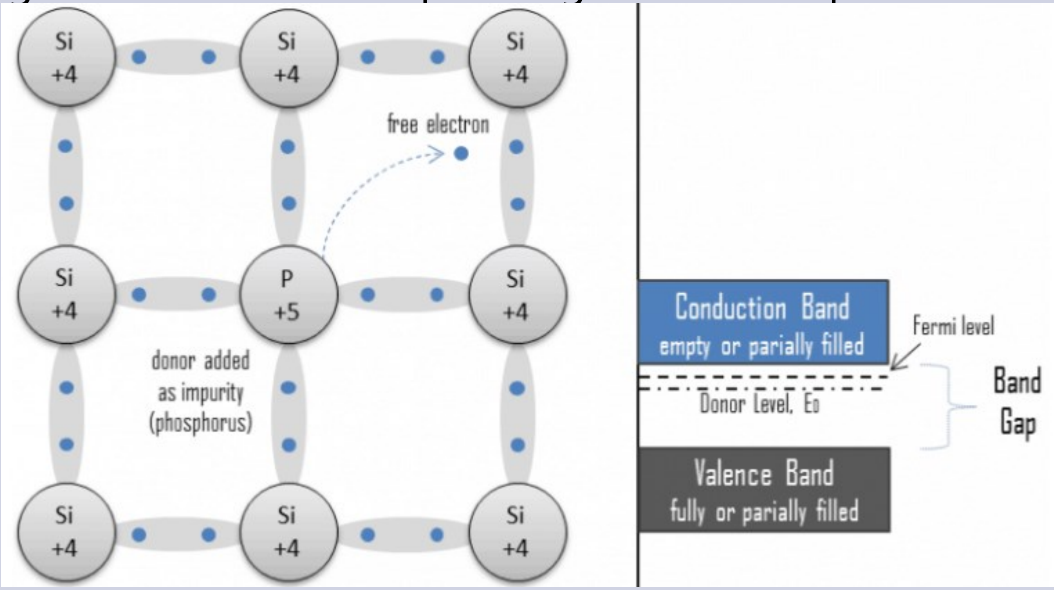
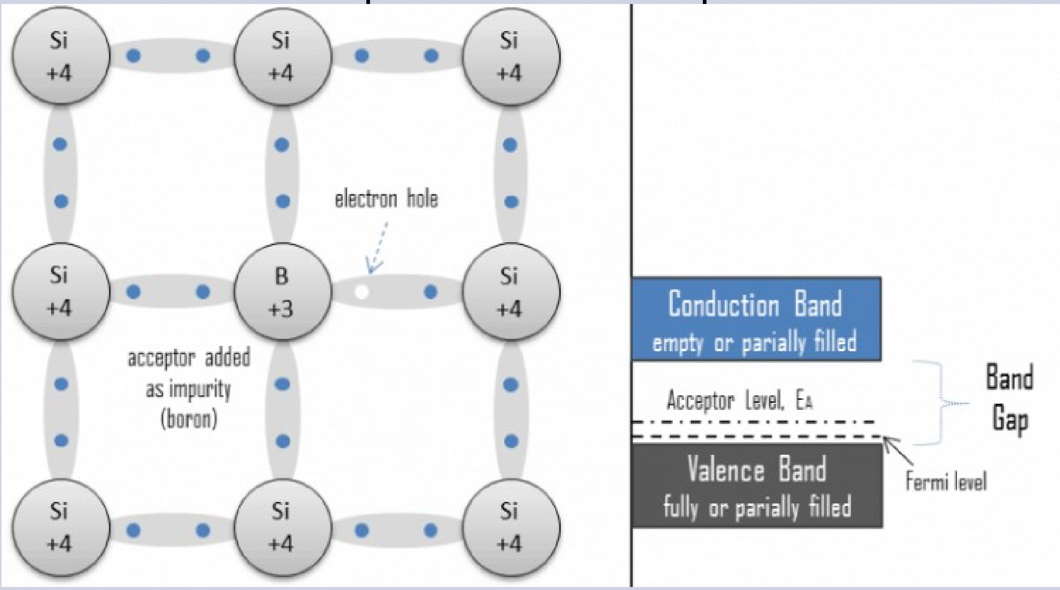
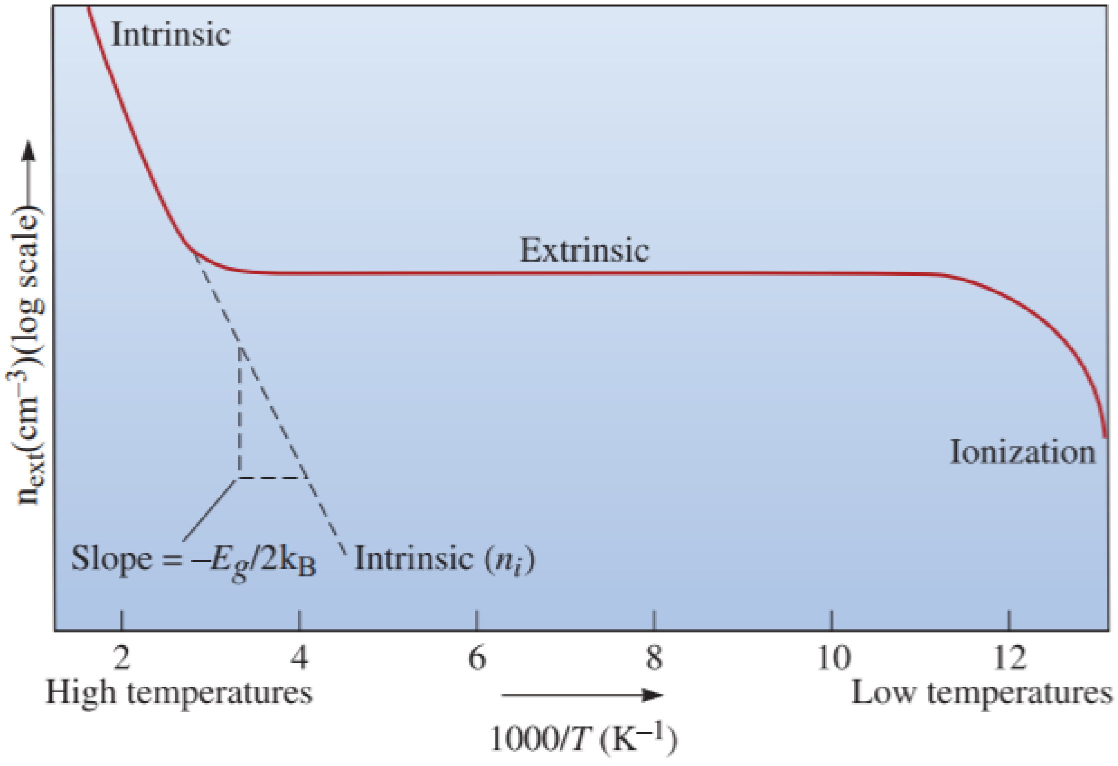
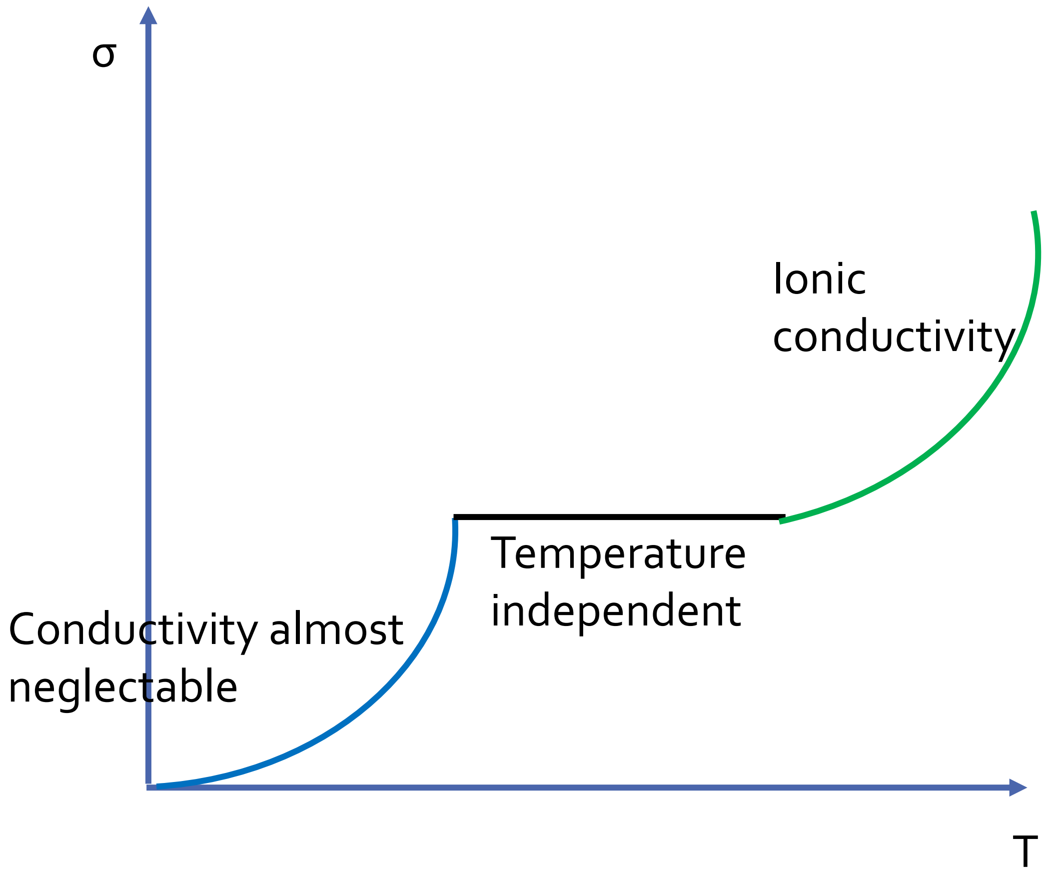
Extrinsic Semiconductors

- Conductivity is based on the addition of impurities (Doping)
- Conductivity can be independent of temperature

n-Type	p-Type
Negative: Valence of dopant is greater than 4	Positive: Valence of dopant is less than 4
	

Extrinsic Semiconductors: Temperature dependence





Example

- Determine the electrical conductivity of silicon when 0.0001at% Sb is added as a dopant. Compare it to the electrical conductivity when the same percentage of In is added.

TABLE 19-6 ■ *The donor and acceptor energy levels (in electron volts) when silicon and germanium semiconductors are doped*

	Silicon		Germanium	
Dopant	E_d	E_a	E_d	E_a
P	0.045		0.0120	
As	0.049		0.0127	
Sb	0.039		0.0096	
B		0.045		0.0104
Al		0.057		0.0102
Ga		0.065		0.0108
In		0.160		0.0112

P-Type (In)

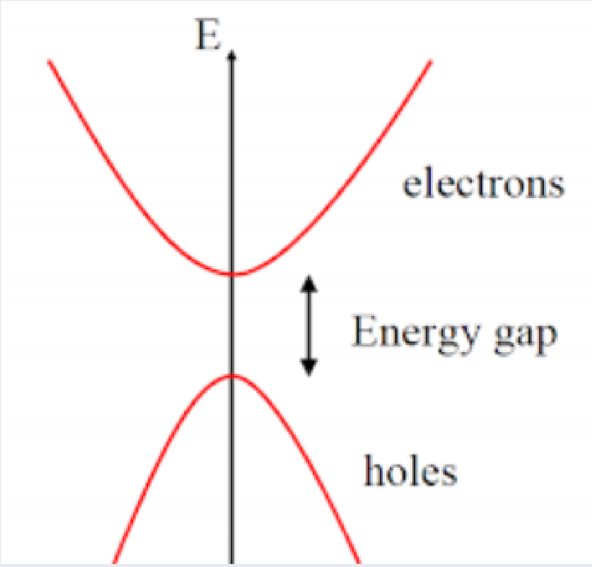
- *In in Silicon Ea*$\rightarrow \mu_p$
- $\mu_p = 480 \frac{cm^2}{Vs}$
- $a_0 = 5.43 \times 10^{-8} cm$
- $DC \rightarrow 8 \frac{at}{uc}$
- 0.0001at% In

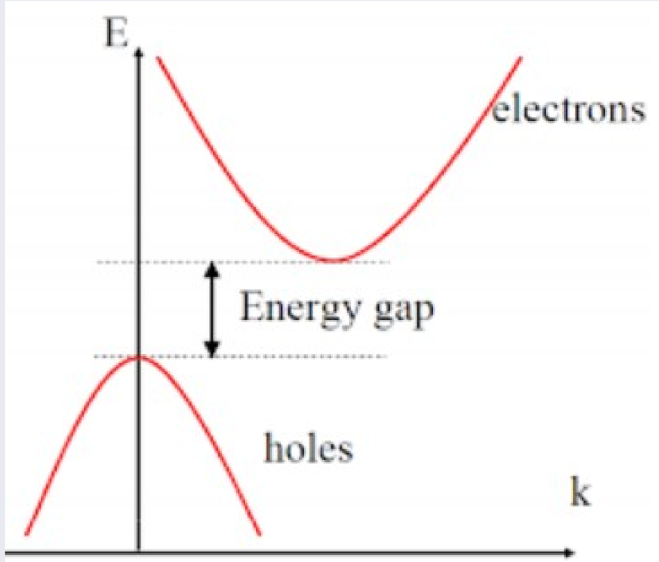
N-Type (Sb)

- $Sb\ in\ Silicon\ Ed \rightarrow \mu_n$
- $\mu_n = 1350 \frac{cm^2}{Vs}$
- $a_0 = 5.43 \times 10^{-8} cm$
- $DC \rightarrow 8 \frac{at}{uc}$
- 0.0001at% Sb

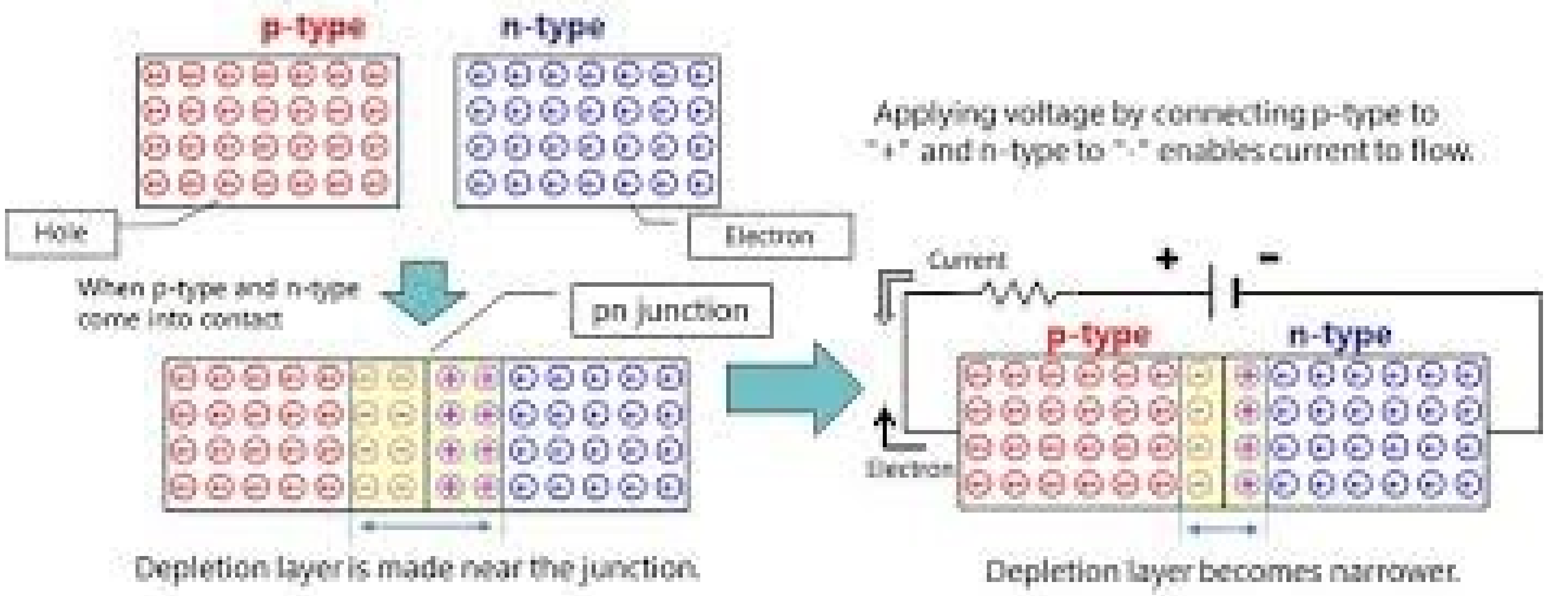
Bandgap Semiconductors

Direct (DBG) semiconductor	Indirect (IBG) semiconductor
• The maximum energy level of the valence band aligns with the minimum energy level of the conduction band. • The probability of a radiative recombination is high. • DBG semiconductors are always preferred over IBG for making optical sources. • Example, Gallium Arsenide (GaAs).	• The maximum energy level of the valence band and the minimum energy level of the conduction band are misaligned. • Heat • Example, Silicon and Germanium.

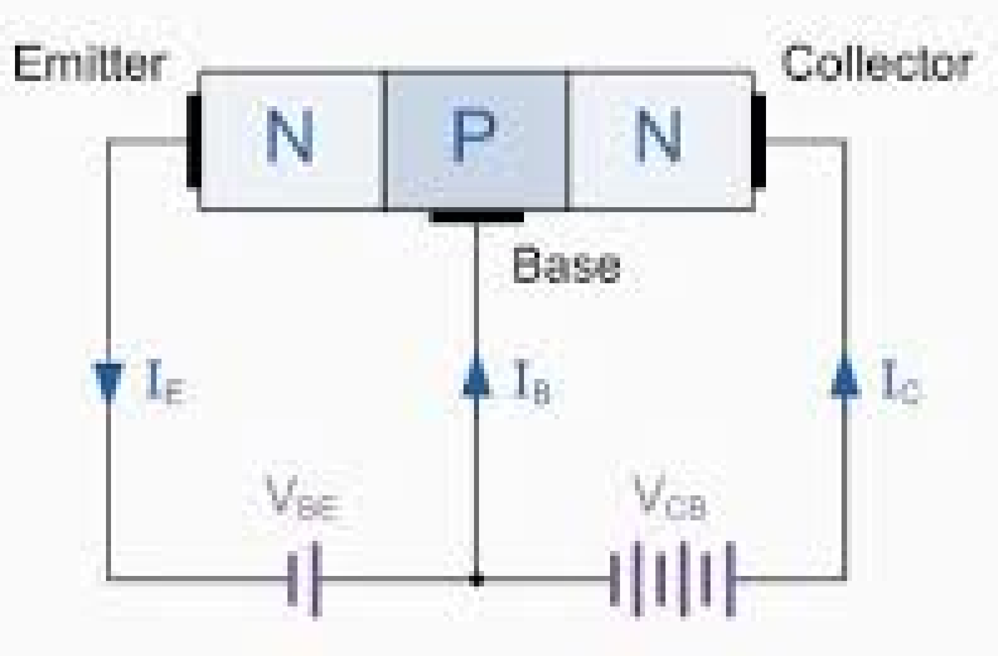


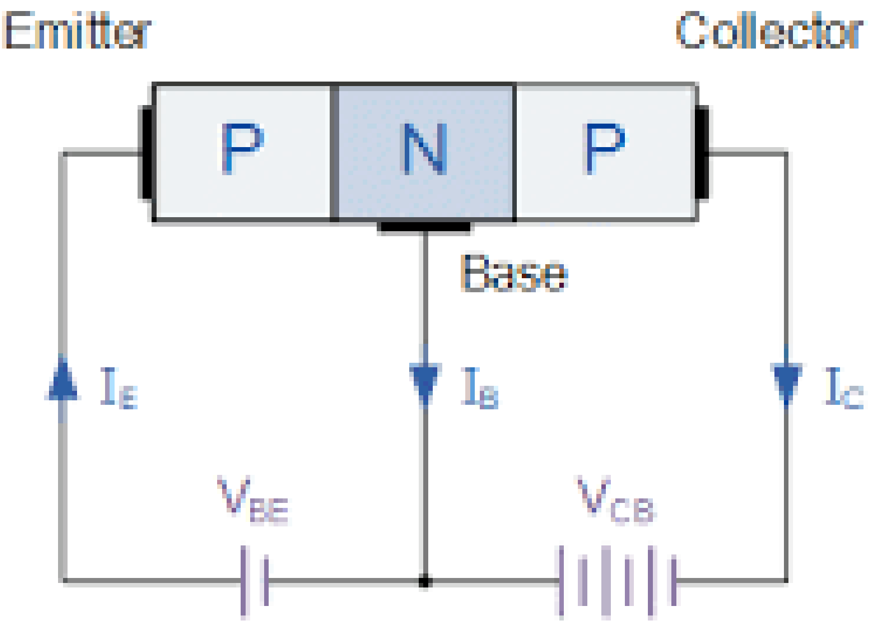


p-n Junction


p-type
n-type
Hole
Electron
When p-type and n-type come into contact
pn junction
Depletion layer is made near the junction.
Applying voltage by connecting p-type to "+" and n-type to "-" enables current to flow.
Current
+
-
p-type
n-type
Electron
Depletion layer becomes narrower.

Transistors

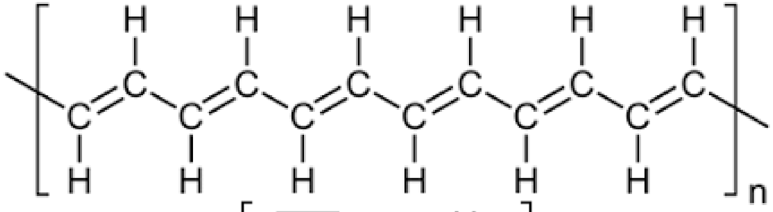




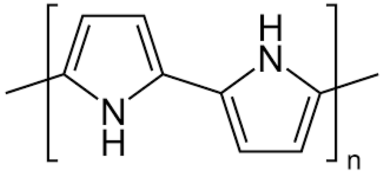
Conductivity in other materials: Polymers

- - 10^{-8}, 10^{-12} Ω^{-1} cm^{-1}
- - Covalent bonds
- + **Composite materials:**
- Powders
- Coatings

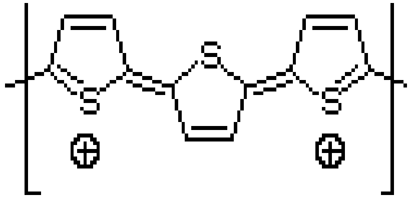
Polyacetylene



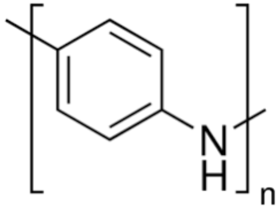
Polypyrrole



Polythiophene



Polyaniline



Dope with:

ClO_4^-

I_3

AsF_5

Conductivity in other materials: Ceramics

- - Ionic material
- - entire ions move, not just e-

$$\mu = \frac{zqD}{k_B T} \qquad \sigma = n_i z q \mu$$

$$\boxed{D = D_0 exp\left(\frac{-Q}{RT}\right)}$$

Z: valence of the ion
q: charge on each carrier (1.6×10-19 C)
D: diffusion coefficient
ni: concentration of diffusing ions

Example

Suppose that the electrical conductivity of MgO is determined primarily by the diffusion of the Mg2+ ions. Estimate the mobility of the Mg2+ ions and calculate the electrical conductivity of MgO at 1500°C.

D_0=0.705 10^{-13} [cm^2 s^{-1}]

Q= 1.25 10^5 J

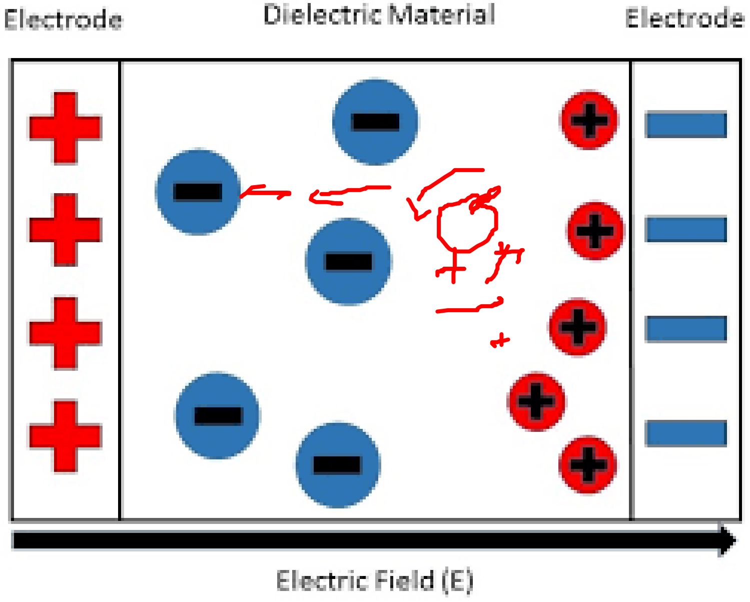
ao=3.96E-8 cm

- $D_0 = 0.705 \times 10^{-13}\ \mathrm{cm^2 \cdot s^{-1}}$
- $Q = 1.25 \times 10^5\ \mathrm{J}$
- $a_0 = 3.96 \times 10^{-8}\mathrm{cm}$
- $T = 1500°\mathrm{C} = 1773\mathrm{K}$
- $\mathrm{Mg^{2+}} \to 2e^- \to z = 2$

- $D_0 = 0.705 \times 10^{-13}\ \mathrm{cm}^2 \cdot \mathrm{s}^{-1}$
- $Q = 1.25 \times 10^5\ \mathrm{J}$
- $a_0 = 3.96 \times 10^{-8}\mathrm{cm}$
- $T = 1500°\mathrm{C} = 1773\mathrm{K}$
- $\mathrm{Mg}^{2+} \to 2e^- \to z = 2$

Dielectric and insulating materials: Polarization

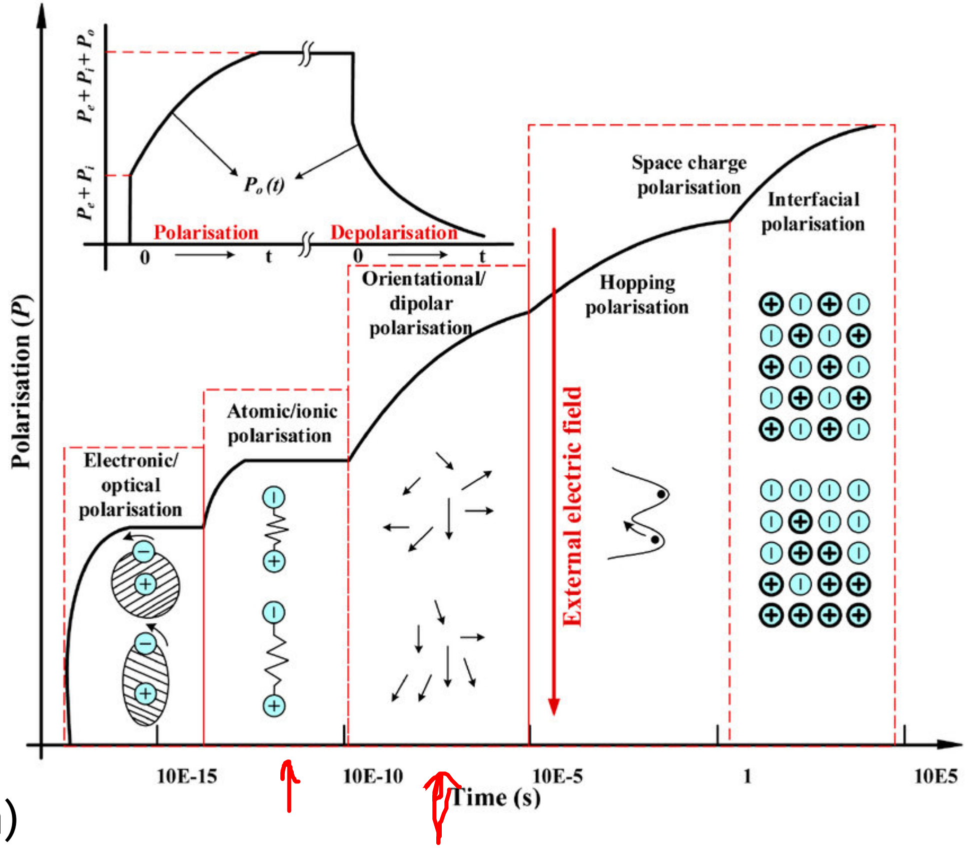
Charge separation!



$$U = qd$$

$$P = zqd$$

P: polarization
z: Number of charges displaced per unit volume
d: average displacement (m)



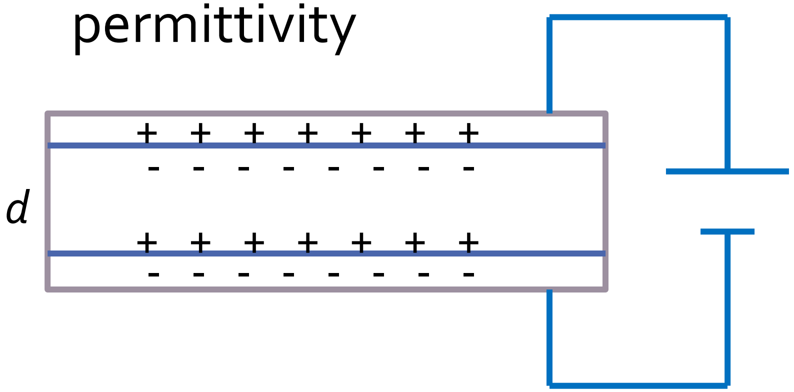
Example

- Calculate the displacement of e- if the polarization of Al is 2E-8 C m^{-2}
  - Atomic number: 13
  - ao: 4.04E-8 cm
  - FCC structure

- Atomic number: 13
- $a_0 = 4.04 \times 10^{-8}$ cm
- FCC structure
- $P = 2 \times 10^{-8}\ \mathrm{C/m^2}$

Dielectric constant (k)

- Also known as Relative permittivity



$$Q = CV \qquad k = \frac{\varepsilon}{\varepsilon_0}$$

$$C = \varepsilon \frac{A}{d} \qquad C = k\varepsilon_0 \frac{A}{d}$$

Q: Stored charge (C)
C: capacitance (Farad)
V: voltage (V)

A: Surface area (m2)
d: average displacement (m)
ε: permittivity of material (F/m)

ε_0: Permittivity of vacuum (8.85E-12 F/m)

Example

- A simple parallel plate capacitor is designed to store 5E-6 C at a potential of 8000 V. The distance between plates if 0.30 mm. Calculate the area of the plates if a) there is vacuum in between and b) alumina is the chosen dielectric material, if the permittivity of this material is 9 times the vacuum permittivity.

$Q = 5 \times 10^{-6}\ C$
$V = 8000\ V$
$d = 0.30\ mm$

$Q = 5 \times 10^{-6}\ C$
$V = 8000\ V$
$d = 0.30\ mm$

Example

Design a capacitor that is capable of storing 1 μF when 1000 V is applied, producing an electric field of 250 V/m and the distance between plates is a fifth of the side of a plate.

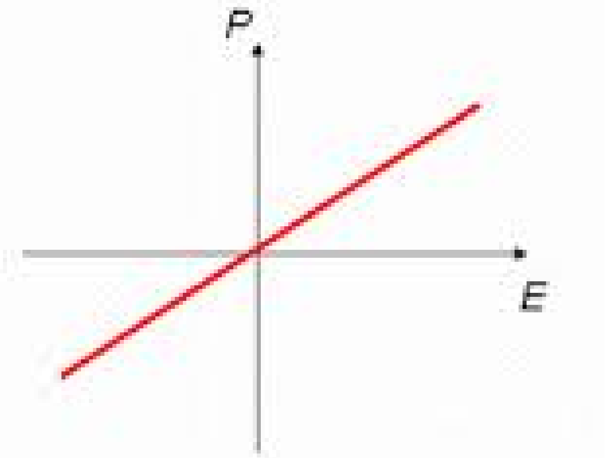
$C = 1 \times 10^{-6} F$
$V = 1000\ V$
$E = 250\ V/m$

Distance between plates is a fifth of the side of a plate

k?

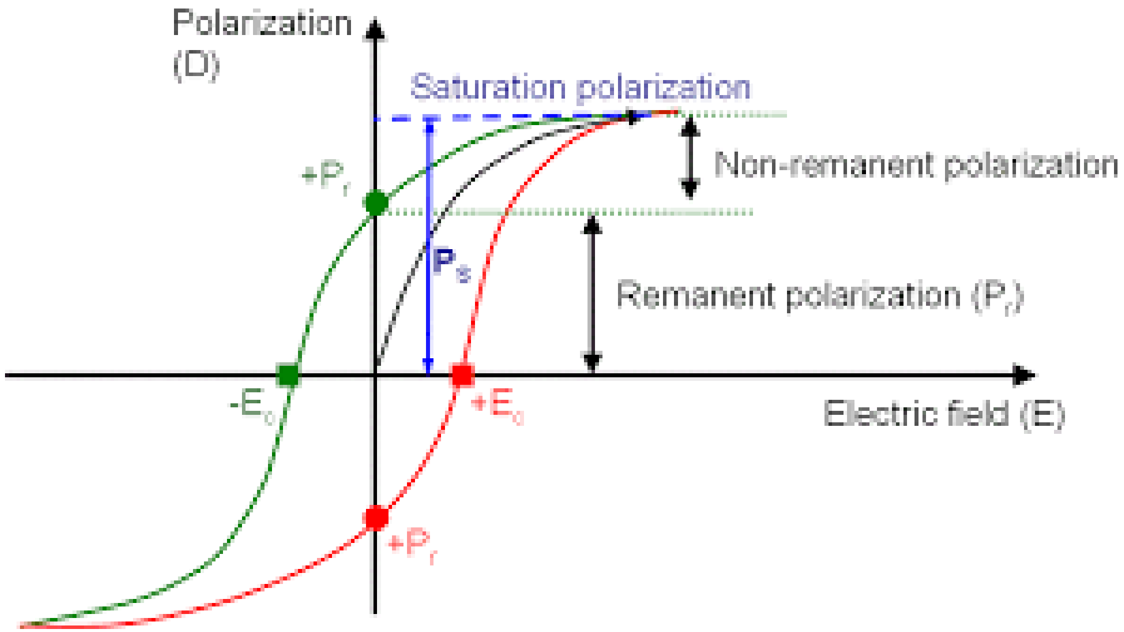
Linear and non-Linear dielectrics

- Polarization only occurs when an electric field is applied
- $P = (k-1)\varepsilon_0 E$ V= Ed
- $x = (k-1)$: Dielectric susceptibility



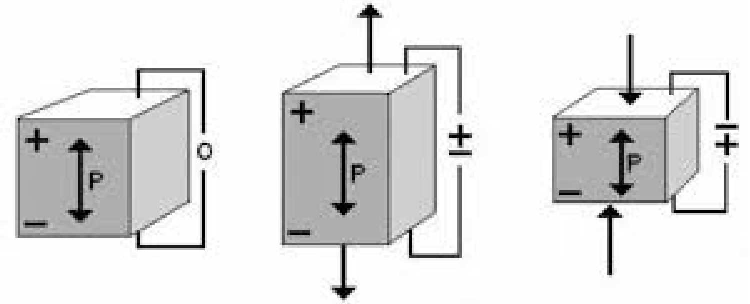
- E: Electric field (V/m)

Polarization has a remnant even after the electric field is removed

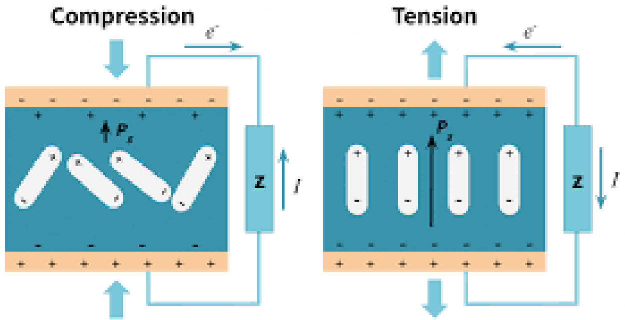


Non-Linear dielectrics

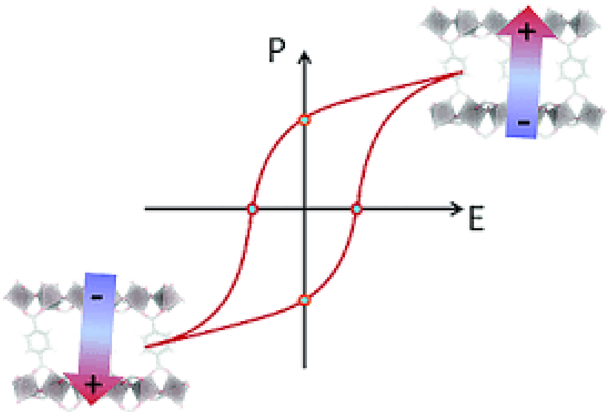
- Electrostricticity: Dimensional change in the material when there is E.



- Piezoelectricity: Application of stress on some materials can produce polarization



- Ferroelectricity: Spontaneous and reversible dielectric polarization (Ps).



Example

A 2-mm-thick alumina dielectric is used in a 60 Hz circuit. Calculate the voltage required to produce a polarization of 5E-7 C/m²

TABLE 19-7 ■ ***Properties of selected dielectric materials***

	Dielectric Constant		Dielectric		
Material	(at 60 Hz)	(at 10^6 Hz)	Strength (10^6 V/m)	tan δ (at 10^6 Hz)	Resistivity (ohm · cm)
Polyethylene	2.3	2.3	20	0.00010	$> 10^{16}$
Teflon	2.1	2.1	20	0.00007	10^{18}
Polystyrene	2.5	2.5	20	0.00020	10^{18}
PVC	3.5	3.2	40	0.05000	10^{12}
Nylon	4.0	3.6	20	0.04000	10^{15}
Rubber	4.0	3.2	24		
Phenolic	7.0	4.9	12	0.05000	10^{12}
Epoxy	4.0	3.6	18		10^{15}
Paraffin wax		2.3	10		10^{13}–10^{19}
Fused silica	3.8	3.8	10	0.00004	10^{11}–10^{12}
Soda-lime glass	7.0	7.0	10	0.00900	10^{15}
Al_2O_3	9.0	6.5	6	0.00100	10^{11}–10^{13}
TiO_2		14–110	8	0.00020	10^{13}–10^{18}
Mica		7.0	40		10^{13}
$BaTiO_3$		2000–5000	12	~0.0001	10^{8}–10^{15}
Water		78.3			10^{14}

P= 5E-7 C/m²

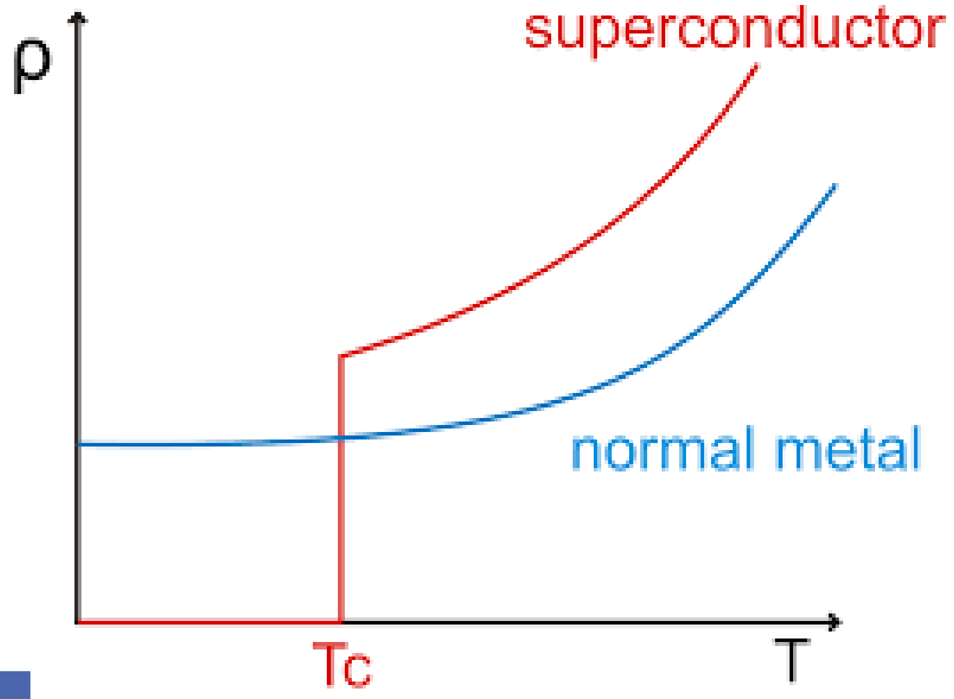
d= 2 mm = 2E-3 m

From the table

k= 9

Superconductivity

- Zero resistance
- Temperature dependent
- Meissner effect: Response of the superconductor to a magnetic field. A new opposing field.
- Critical magnetic field: Magnitude of field needed to eliminate the superconductivity property of the material.



Type I	Type II
Ideal metals (most of them)	Intermetallic compounds
Completely expel magnetic field	Able to lose superconductivity