ENGG103 – Materials in Design
Dr Ciara O’Driscoll

UNIVERSITY
OF WOLLONGONG
IN DUBAI

University of Wollongong in Dubai

ENGG103 – Materials in Design

Week 10: Lecture 10 – Electrical properties

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Consultation hours:

Monday 10:30 – 12:30

Please email first for appointment.

Electrical conductivity

- **Electrical conductivity** is defined as the ease with which a solid material conducts electricity.
- Current passing through a conductor is due to the movement of charged particles (electrons) under the influence of an electric field.
- These charged particles encounter resistance to their passage through the crystal lattice as a result of interactions between the conduction electrons and other particles, dislocations, vacancies, impurity atoms and crystalline imperfections.
- **Ohm's law** relates the current (or time rate of charge passage) to the applied voltage:

$$\boxed{V = IR}$$

volts

amperes

ohms

where: ***V*** is the potential or applied electric field (V);
I is the current passing through the conductor (A); and
R is the resistance of the material through which current is flowing (Ω).

Electrical Conduction

- Ohm's Law:

$$V = I R$$

voltage drop (volts = J/C)
C = Coulomb

current (amps = Coulomb/sec)

resistance (Ohms)

- **Electric** current is the flow of electrons though a material, and **electrical conductivity** is the ability of **electric** current to flow through a material.

- Conductors, such as copper & other metals, have a high **electrical conductivity** and therefore can easily have electrons pass through them.

Electrical Conduction

- Resistivity, ρ: measure of the resistance of a given size of a specific material to electrical conduction
  - -- a material property that is independent of sample size and geometry

independent of specimen geometry - **intrinsic property**

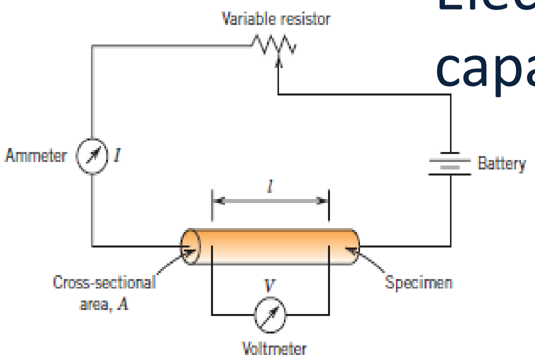
$$\rho = R\frac{A}{l}$$

surface area of current flow

current flow path length

SI unit: ohm meter (Ω·m)

- Conductivity, σ
  - Electrical conductivity, σ, is the ease with which a material is capable of conducting electric current.



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

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SI unit for electrical conductance is siemens per meter (S/m), where $S = \Omega^{-1}$

Conductivity: Comparison

- Room temperature values $(\text{Ohm-m})^{-1} = (\Omega \text{ - m})^{-1}$

METALS	conductors
Silver	6.8×10^{7}
Copper	6.0×10^{7}
Iron	1.0×10^{7}

SEMICONDUCTORS	
Silicon	4×10^{-4}
Germanium	2×10^{0}
GaAs	10^{-6}
Gallium arsenide	semiconductors

CERAMICS	
Soda-lime glass	10^{-10}-10^{-11}
Concrete	10^{-9}
Aluminum oxide	$<10^{-13}$

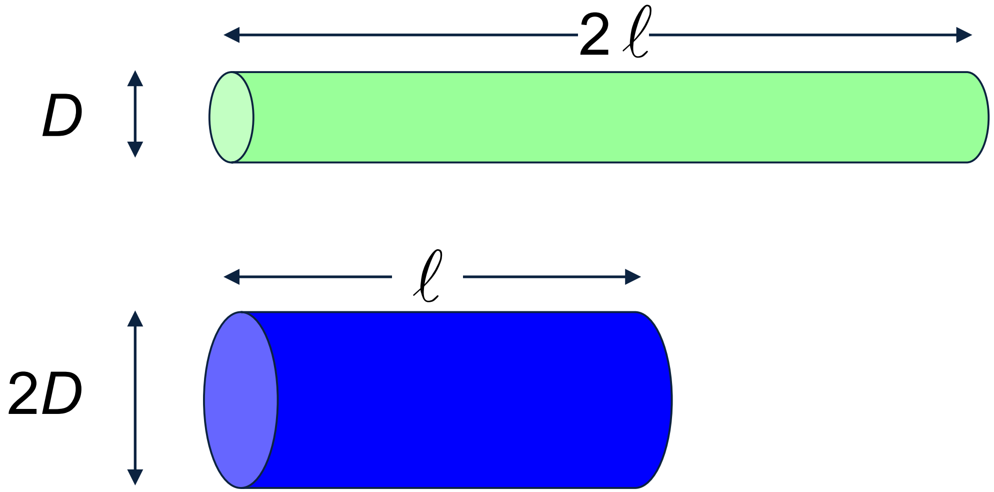
POLYMERS	
Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}-10^{-17}
	insulators

Selected values from Tables 18.1, 18.3, and 18.4, *Callister & Rethwisch 8e.*

Electrical Properties

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

- Which will have the greater resistance?



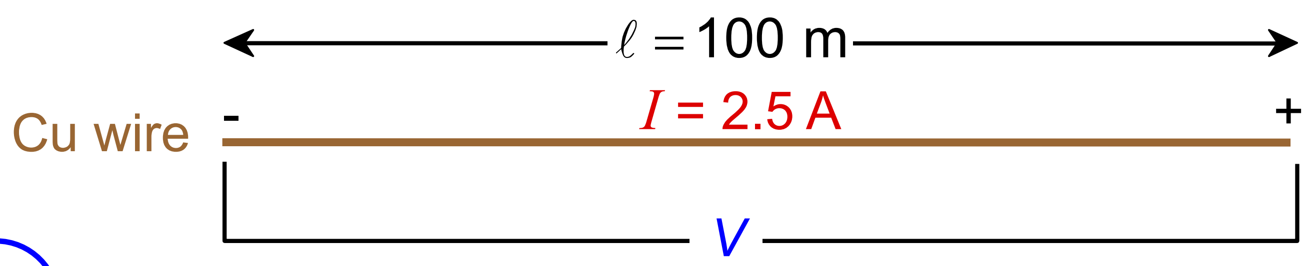
$$R_1 = \frac{2\rho\ell}{\pi\left(\frac{D}{2}\right)^2} = \frac{8\rho\ell}{\pi D^2}$$

$$R_2 = \frac{\rho\ell}{\pi\left(\frac{2D}{2}\right)^2} = \frac{\rho\ell}{\pi D^2} = \frac{R_1}{8}$$

- Analogous (comparable in certain respects)to flow of water in a pipe
- Resistance depends on sample geometry and size.

Exam Example: Conductivity Problem

What is the minimum diameter (D) of the wire so that $V < 1.5$ V?



Conductivity

- Room temperature values (

METALS	conductors
Silver	6.8 x 10^7
Copper	6.0 x 10^7
Iron	1.0 x 10^7

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

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

$$V = I R$$

$$R = \frac{\ell}{A\sigma} = \frac{V}{I}$$

ℓ = 100 m

V < 1.5 V

I = 2.5 A

$A = \frac{\pi D^2}{4}$

σ = 6.07 x 10^7 (Ohm-m)$^{-1}$

Solve to get $D > 1.87$ mm

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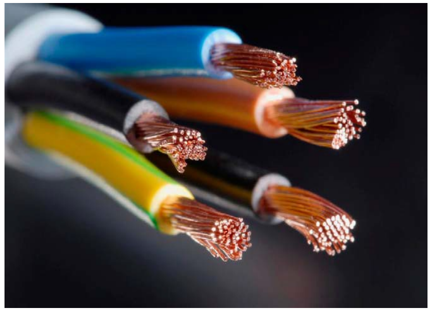


Electrical resistivity

- The **electrical power, *P***, is related to the resistance of the conductor by Joule's law of heating:

$$P = \frac{V^2}{R}$$

SI unit: Watt (W) , 1W = 1J / 1s

- Since *V* = *IR*, power can also be expressed as:

$$P = I^2R$$

- ***V*** is the potential or applied electric field (V);
- ***I*** is the current passing through the conductor (A); and
- ***R*** is the resistance of the material through which current is flowing (Ω).

Electrical resistivity

Example 10.1:

Annealed copper wire with a diameter of 2 mm is used for a 240 V household circuit. The electrical resistivity of copper at room temperature is 1.7 x $10^{-8}\Omega$.m.

(a) What is the resistance per meter length of this wire?

(b) How much electrical energy is used if a heating device with a resistance of 5 Ω, connected to 20 m of this wire, operates for 8 hours?

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

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

$$V = IR$$

$$P = \frac{V^2}{R}$$

Exam examples: Electrical resistivity

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

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

$$V = I R$$

$$P = \frac{V^2}{R}$$

Example 10.1:

Annealed copper wire with a diameter of 2 mm is used for a 240 V household circuit. The electrical resistivity of copper at room temperature is 1.7 x $10^{-8}\,\Omega$.m.

(a) What is the resistance per meter length of this wire?

(b) How much electrical energy is used if a heating device with a resistance of 5 Ω, connected to 20 m of this wire, operates for 8 hours?

Answer:

(a) $\rho = \frac{RA}{L}$

$$\therefore\ R = \frac{\rho L}{A} = \frac{(1.7\text{x}10^{-8}\,\Omega\text{.m})(1\text{ m})}{\left(\frac{\pi}{4}\,(2\text{x}10^{-3})\right)^2\text{m}^2} = 5.4\text{ x }10^{-3}\ \Omega/\text{m}$$

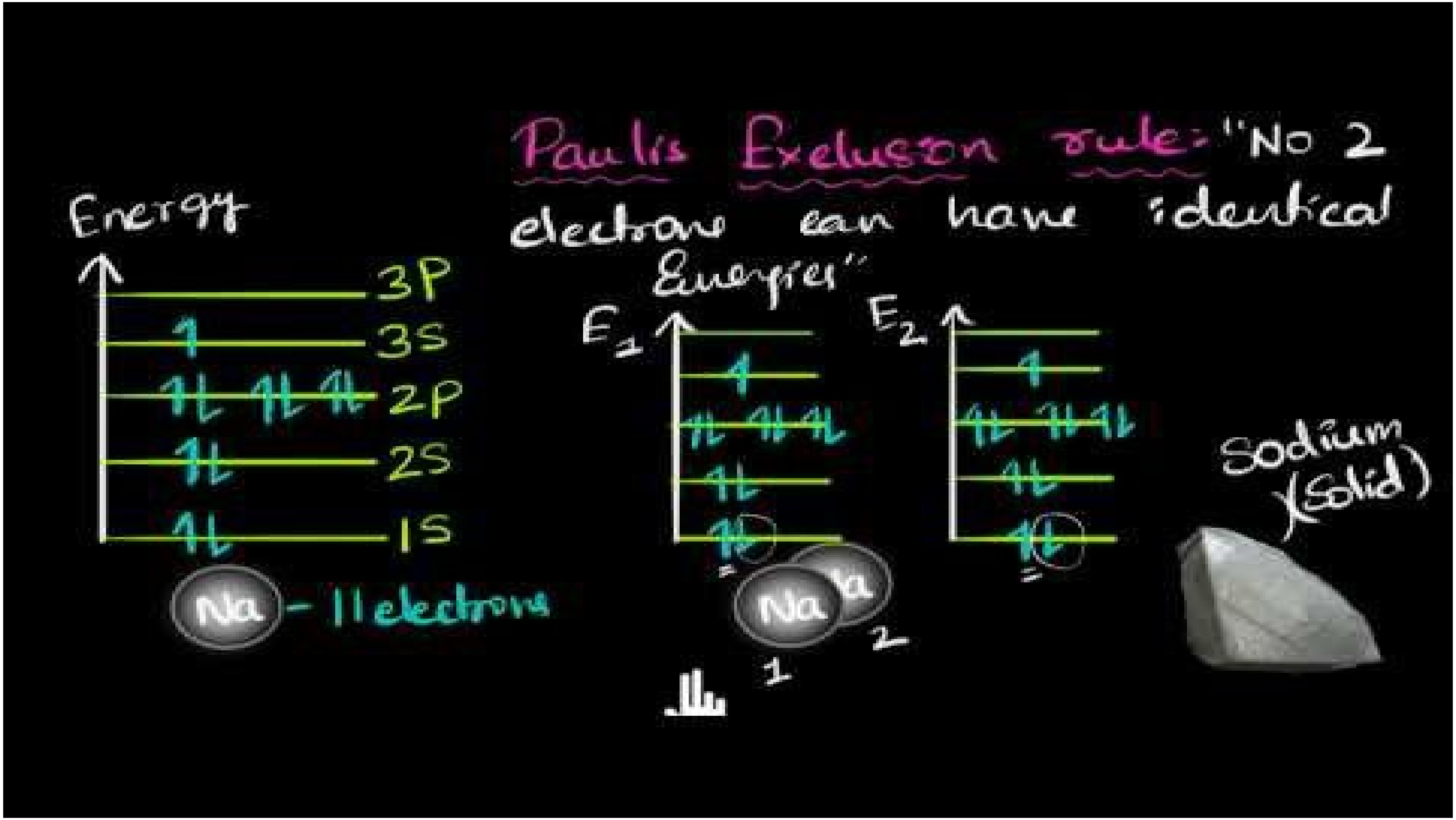
(b) R_{wire} = (5.4 x $10^{-3}\,\Omega$/m)(20 m) = 1.08 x $10^{-1}\,\Omega$

$R_{total} = R_{wire} + R_{device}$ = 0.108 Ω + 5 Ω = 5.108 Ω

$$\therefore\ P = \frac{V^2}{R} = \frac{(240\text{ V})^2}{5.108\,\Omega} = 11276\text{ W} = 11.3\text{ kW}$$

$\therefore$ Electrical energy = (Power)(time) = (11.3)(8) = **90.4 kW.hr**

Why atomic theory doesn't work for solids



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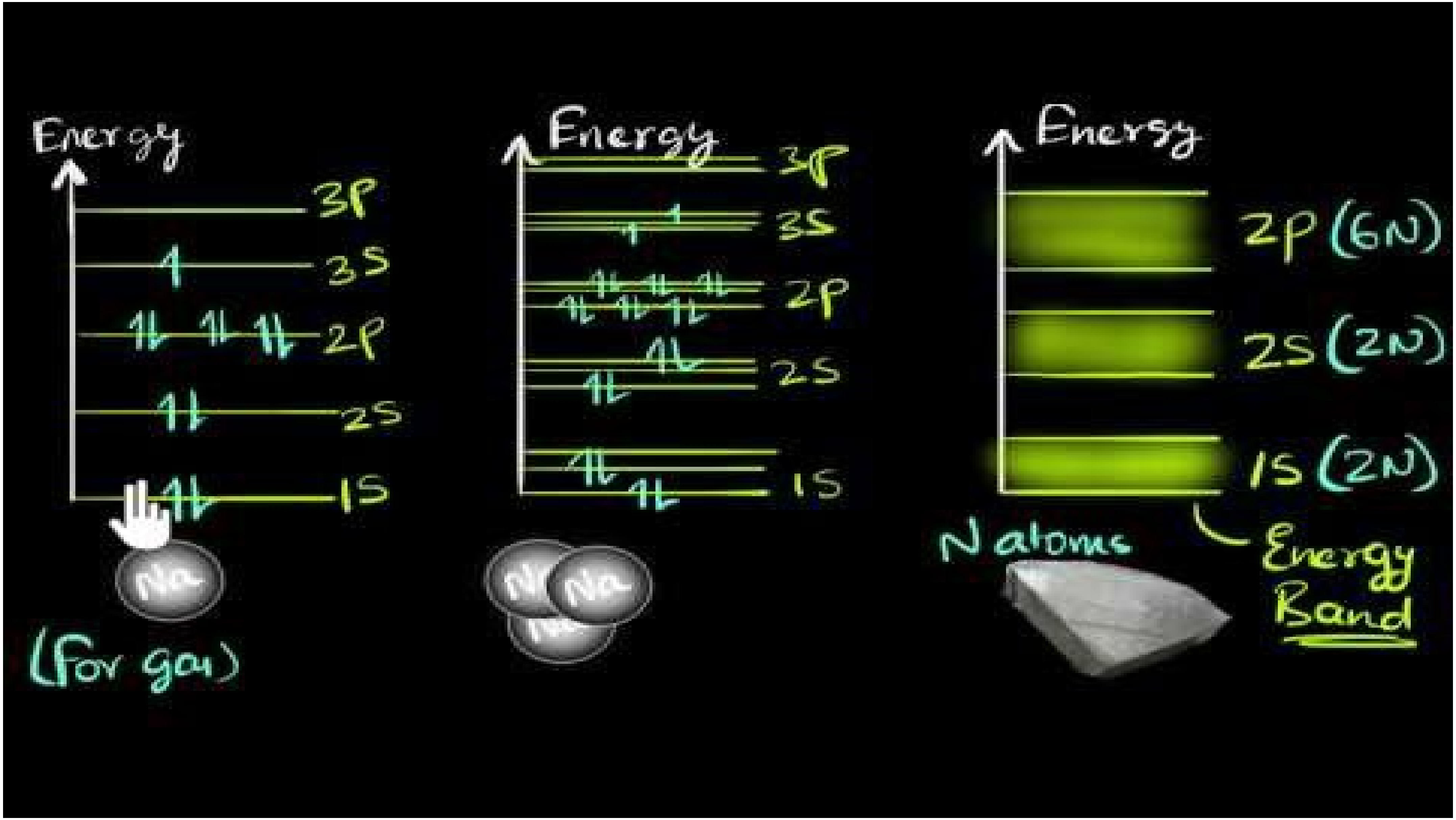
Band theory of solids



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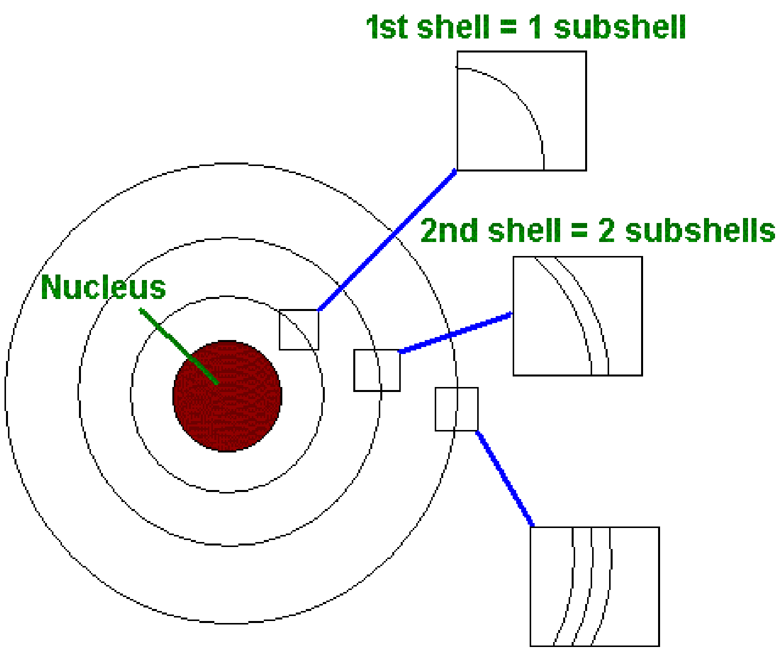
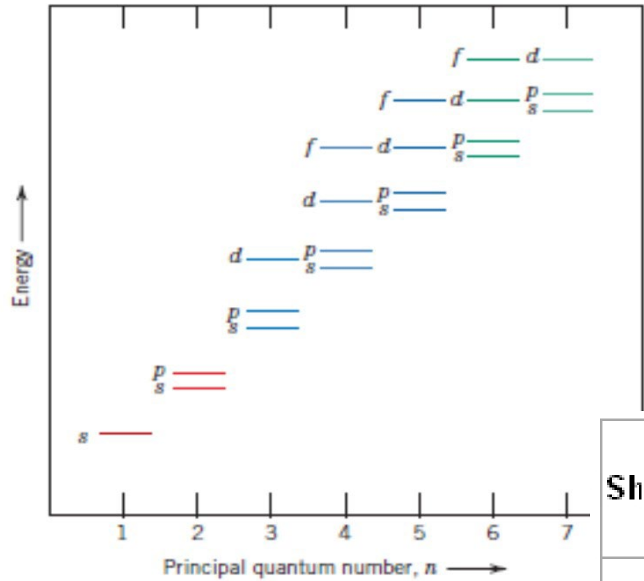
Electron configurations:

- Electrons are *quantized* – that is, electrons are only permitted to have specific values of energy (energy levels or states), limiting them to specific orbitals (shells and subshells) at discrete distances from the nucleus.
- An electron can change energy, but it must make a quantum jump to an allowed higher energy level (with absorption of energy) or to a lower energy level (with emission of energy).





- **Maximum number of electrons in each subshell:**
  - *s*: 2
  - *p*: 6
  - *d*: 10
  - *f*: 14

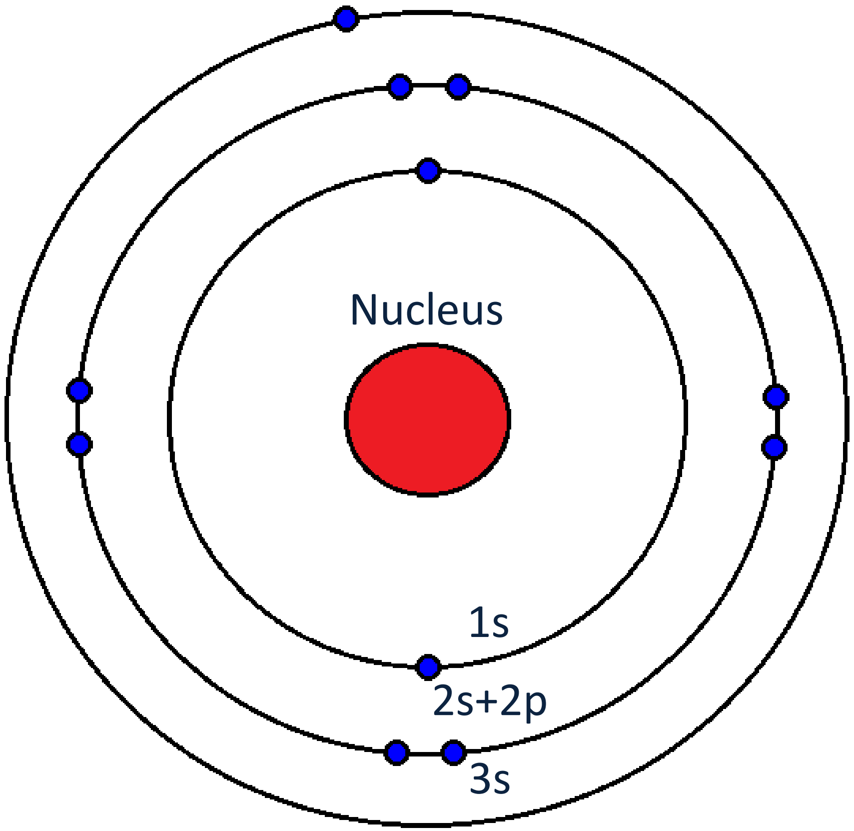
Shell number	Maximum Number of Electrons
1	2 ($1s^2$)
2	8 ($2s^2, 2p^6$)
3	18 ($3s^2, 3p^6, 3d^{10}$)
4	32 ($4s^2, 4p^6, 4d^{10}, 4f^{14}$)
5	50 ($5s^2, 5p^6, 5d^{10}, 5f^{14}, 5g^{18}$)
6	72 ($6s^2, 6p^6, 6d^{10}, 6f^{14}, 6g^{18}, 6h^{22}$)
7	98 ($7s^2, 7p^6, 7d^{10}, 7f^{14}, 7g^{18}, 7h^{22}, 7i^{26}$)

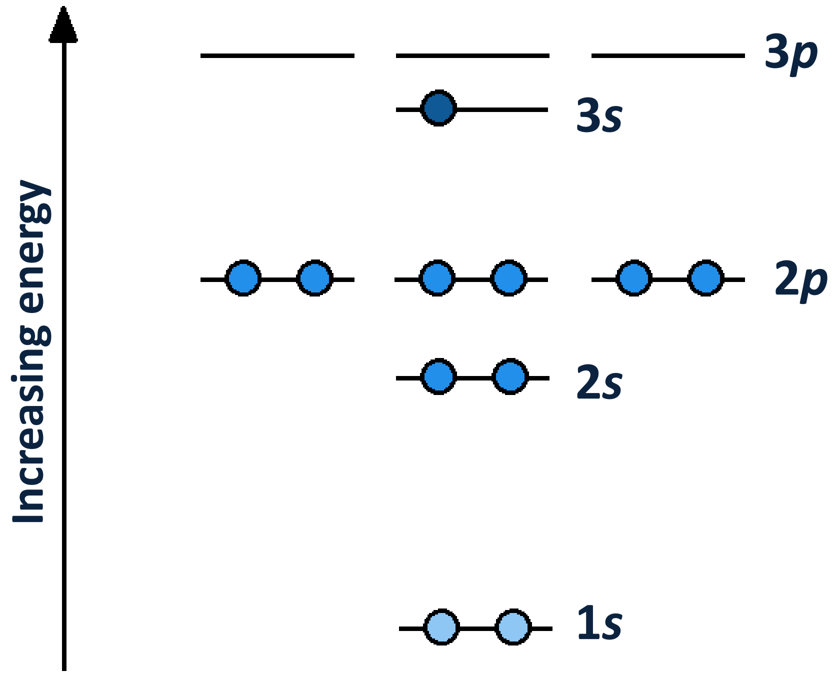
ry

<u>Example</u>: Sodium (Na)

$1s^2 2s^2 2p^6 3s^1$

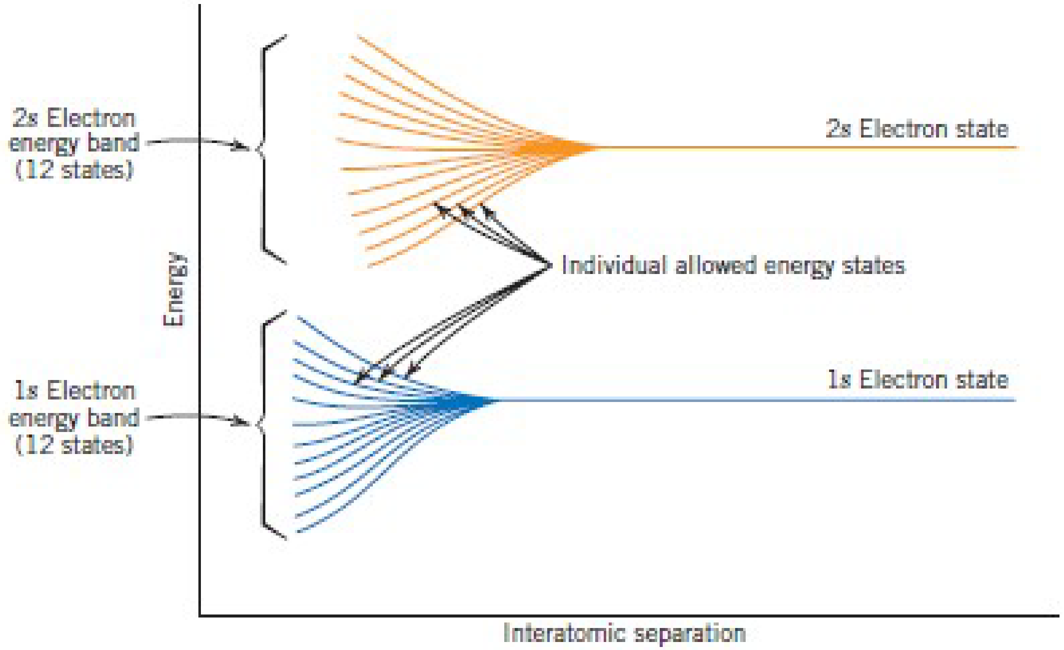
Filled and lowest unfilled energy states for a Na atom:





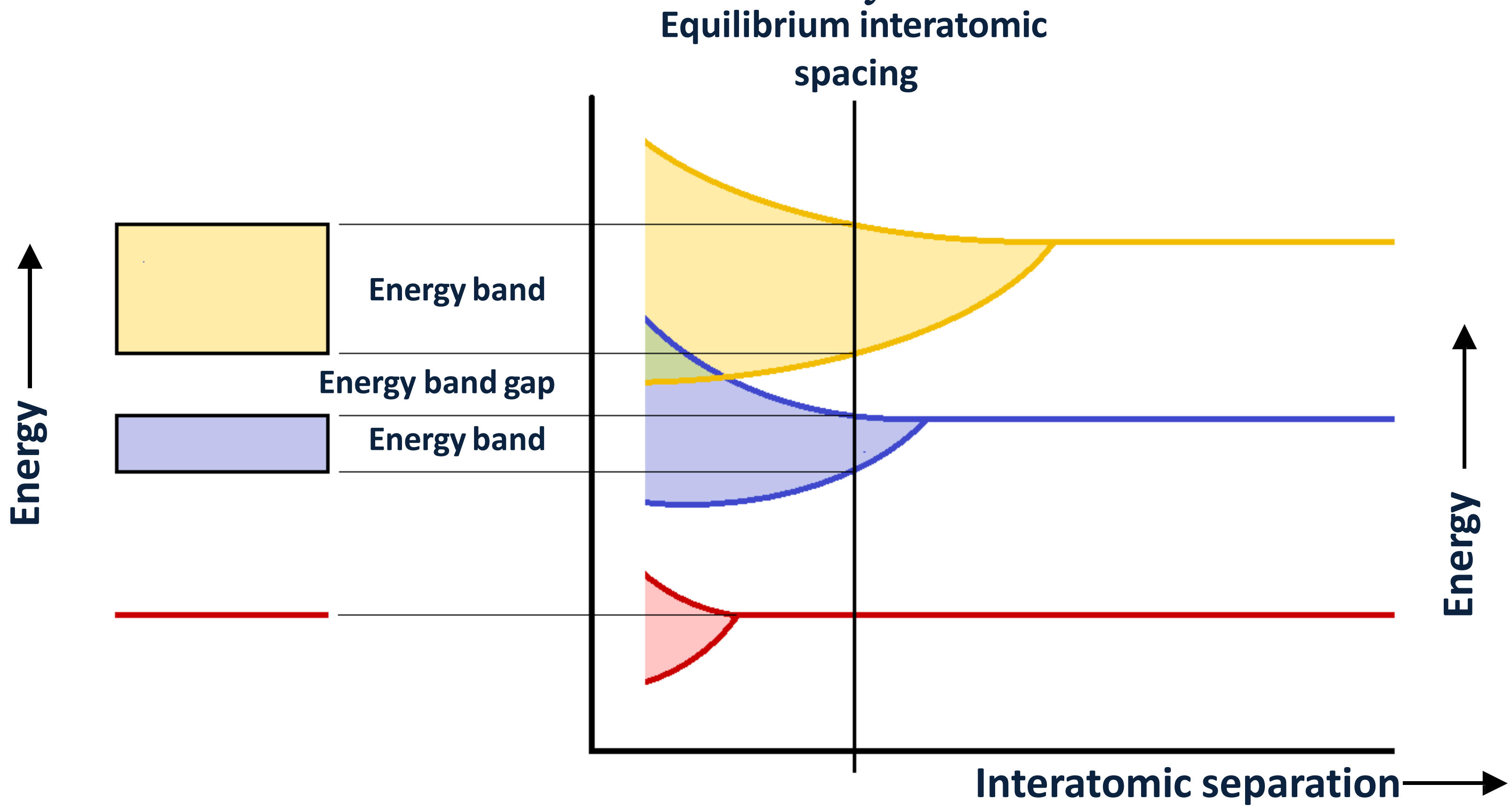
Band theory

- When atoms are joined in a metallic bond, their electron structures no longer behave in a classical orbital sense.
- The inner-shell electrons remain essentially unchanged, but the outer valence shell splits into a number of energy levels. **Valence electrons** are those that occupy the outermost shell.
- The uppermost band is called the **conduction band** if it is partially filled.



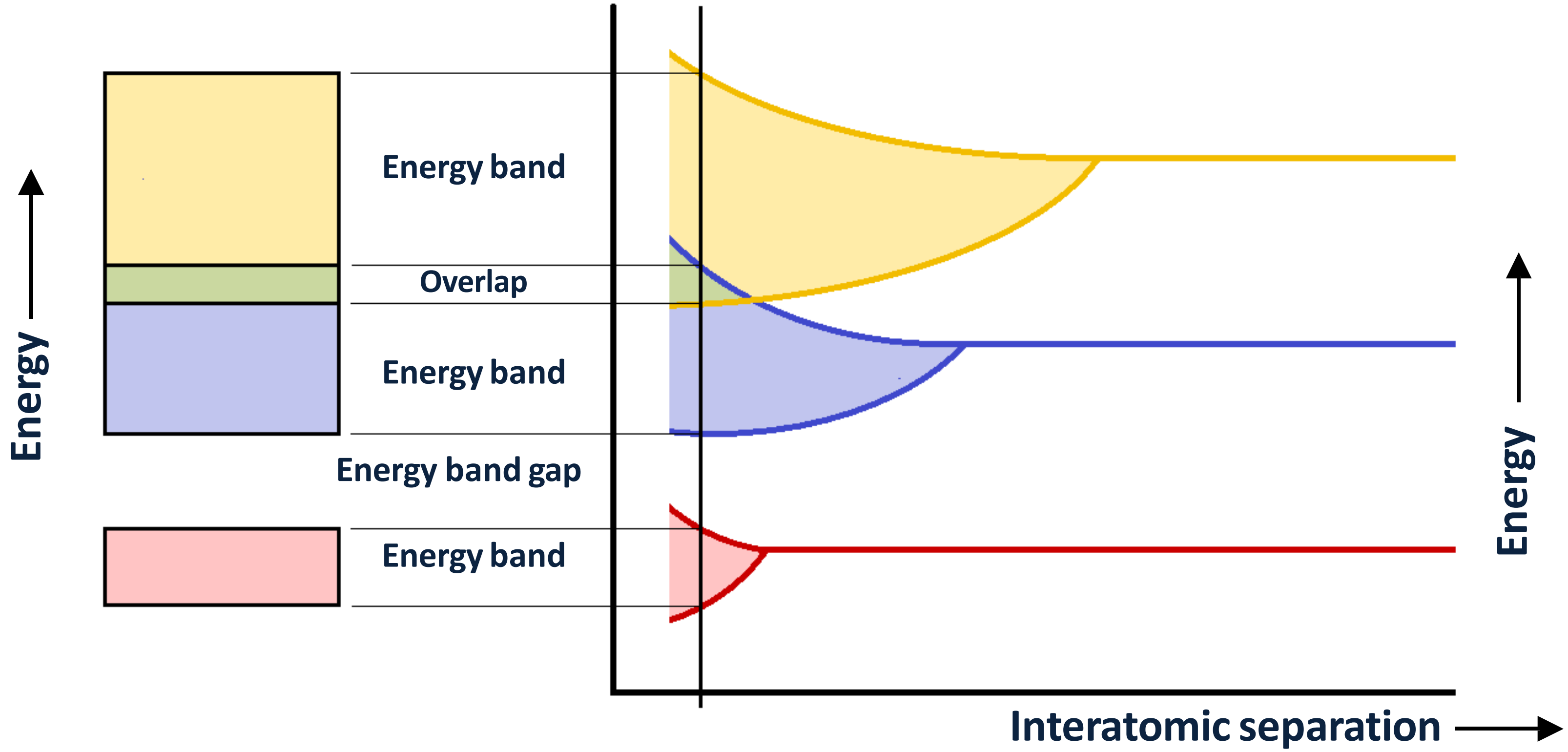
- The extent of splitting depends on interatomic separation and begins with the outermost electron shells.

Band theory



- At the equilibrium spacing, band formation may not occur for the electron subshells nearest to the nucleus.
- Gaps may exist between adjacent bands (energies lying in band gaps are not available for electron occupancy).

Band theory



- Gaps and overlaps may exist between adjacent bands.

Band theory

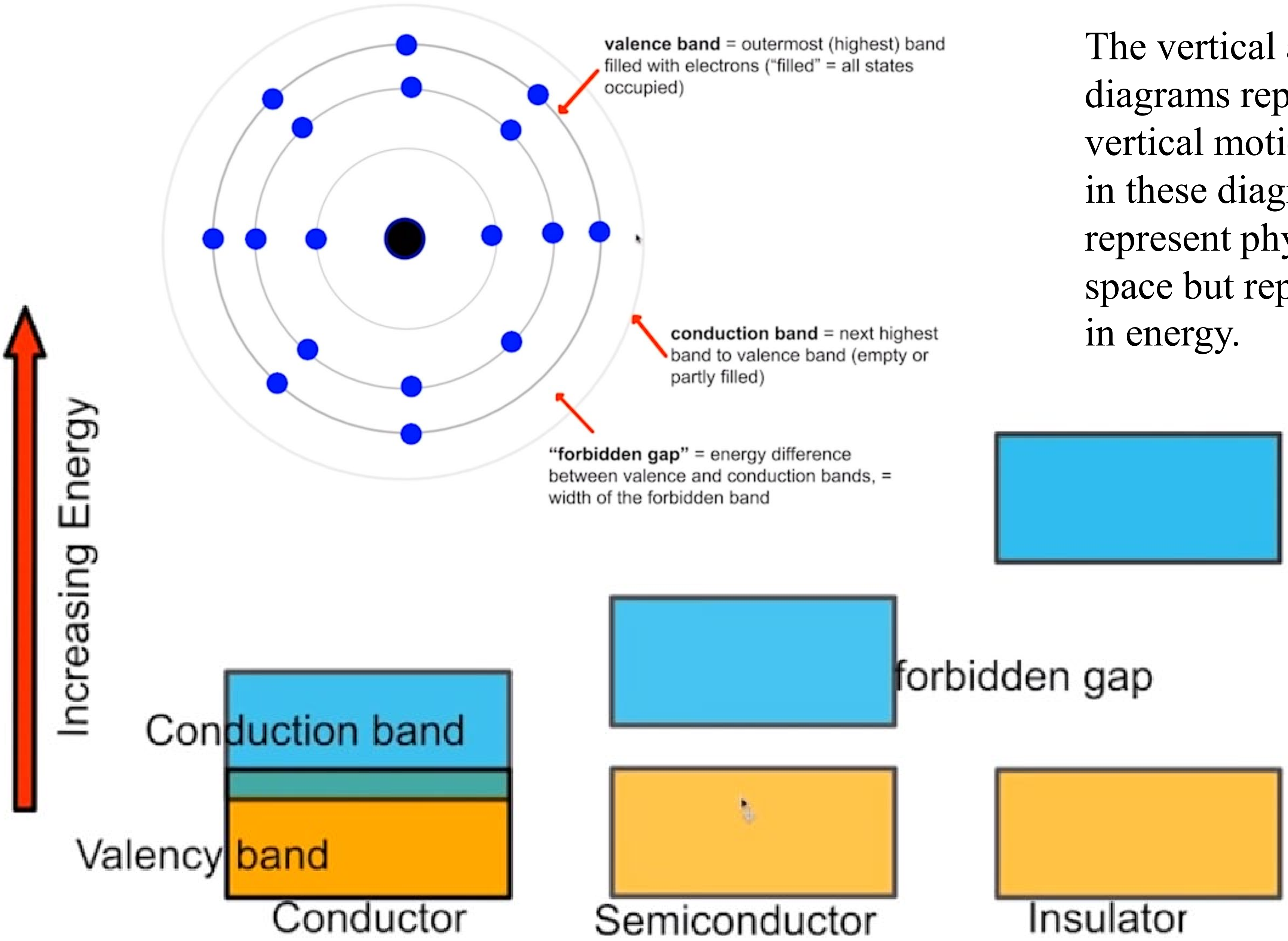
- A useful way to visualize the **difference** between **conductors**, **insulators** and **semiconductors** is to plot the **available energies** for electrons in the materials.
- Available energy states form **bands**.
- Crucial to the **conduction process** is whether or not there are electrons in the conduction band.
- In **insulators** the electrons in the valence band are separated by a large gap from the conduction band, in **conductors** like metals the valence band overlaps the conduction band.
- **Semiconductors** there is a small enough gap between the valence and conduction bands that thermal or other excitations can bridge the gap.
- With such a small gap, the presence of a small percentage of a doping material can increase conductivity dramatically.

Band Theory

The motion of electrons in solids is complex.

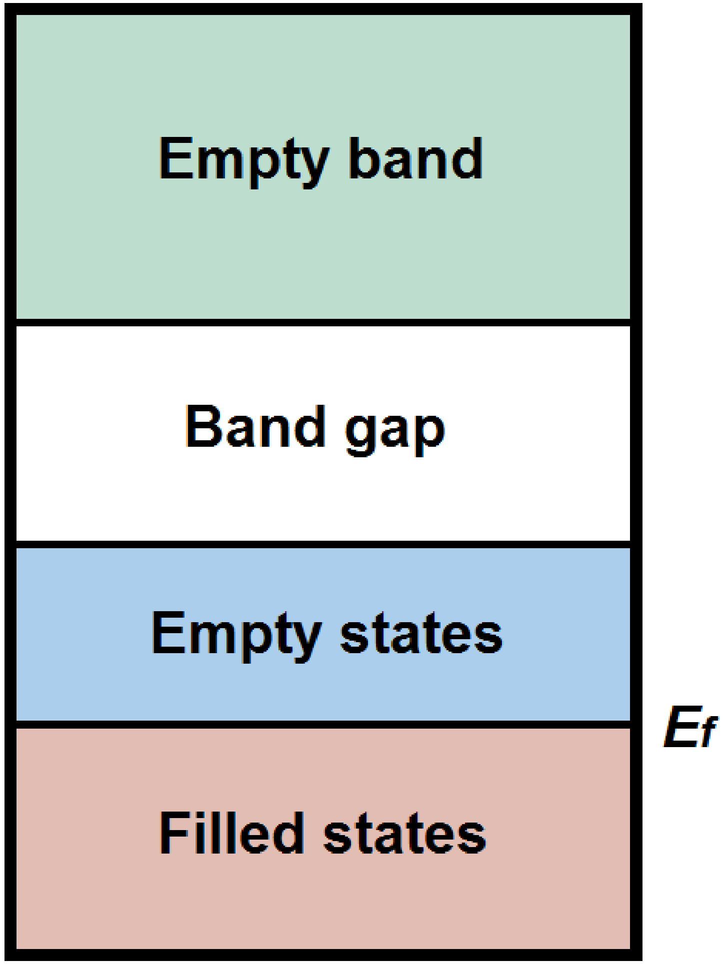
The vertical axis in band diagrams represents energy; vertical motion of electrons in these diagrams does not represent physical motion in space but represents a change in energy.

Resource Link



Possible electron band structures

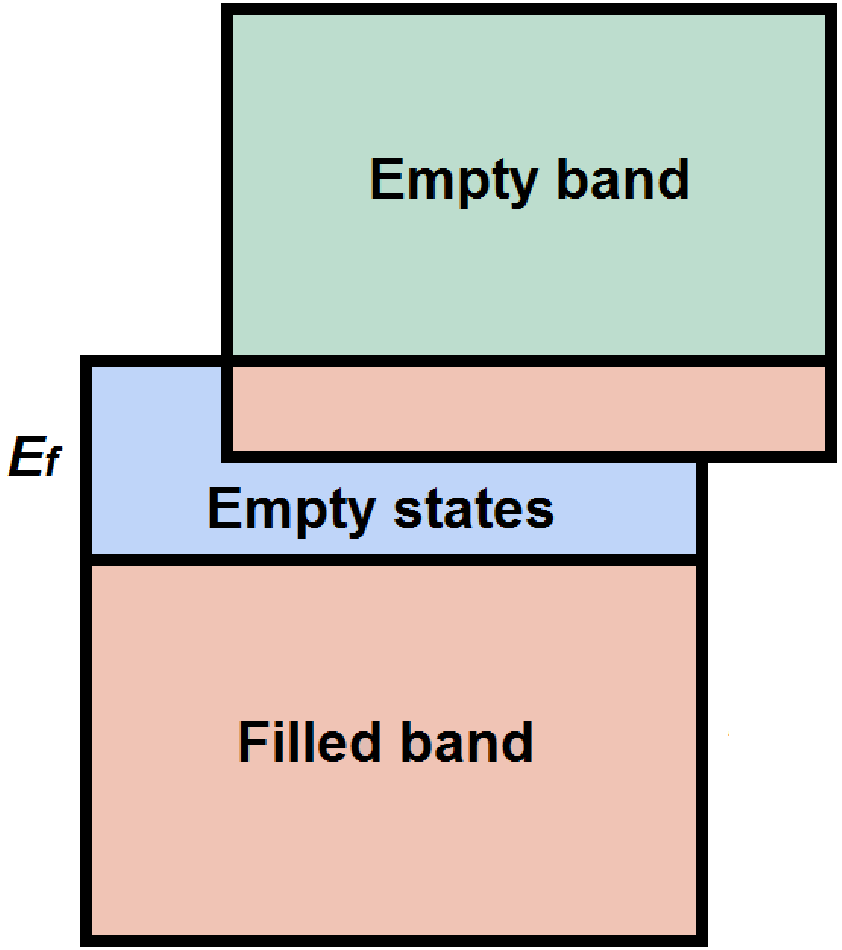
(a) The electron band structure found in metals such as Copper



- One outermost band is only partially filled with electrons (usually a single *s* valence electron).
- Unoccupied higher-energy states are available in the band to which electrons may rise in response to an applied field.
- The energy corresponding to the highest filled state at 0 Kelvin is called the **Fermi** energy (E_f).
- **Example**: Copper (partially filled 4*s* band).
- **Good conductors.**

Possible electron band structures

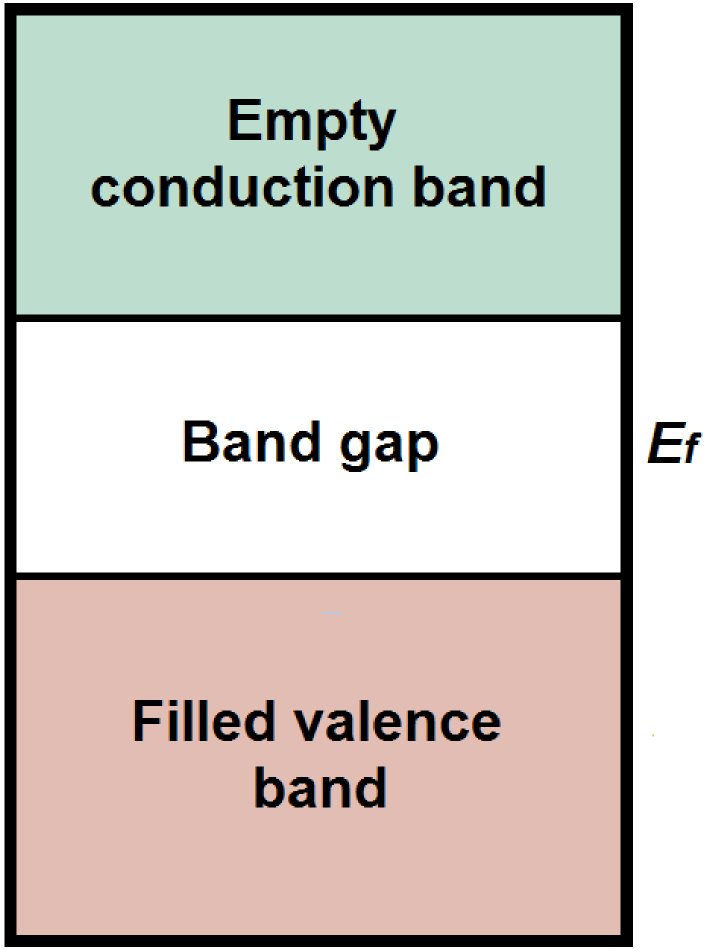
(b) The electron band structure found in metals such as Magnesium



- Overlap of a filled band and an empty band.
- The unoccupied states in these bands serve as higher-energy states for electrons during conduction.
- Only electrons with energies greater than the Fermi energy can be accelerated in an electric field.
- Example: In magnesium the 3*s* and 3*p* bands overlap. Some electrons spill over into the second band.
- **Good conductors**.

Possible electron band structures

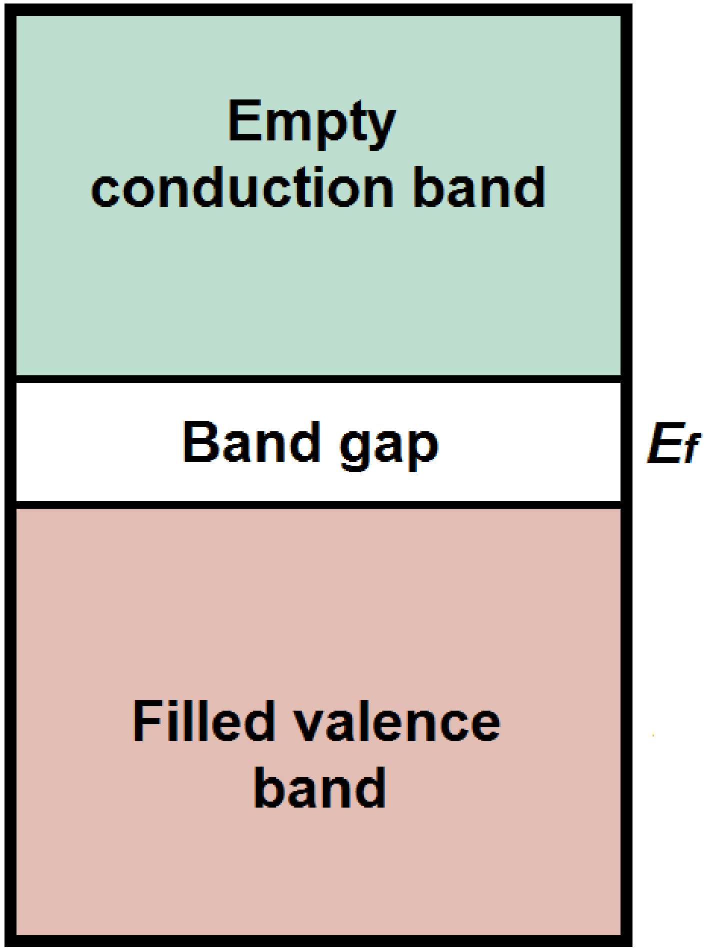
(c) The electron band structure found in Insulators



- The valence band is completely filled with electrons and separated from an empty conduction band by a forbidden band gap.
- **Wide energy gap – <u>Insulator</u>.**

Possible electron band structures

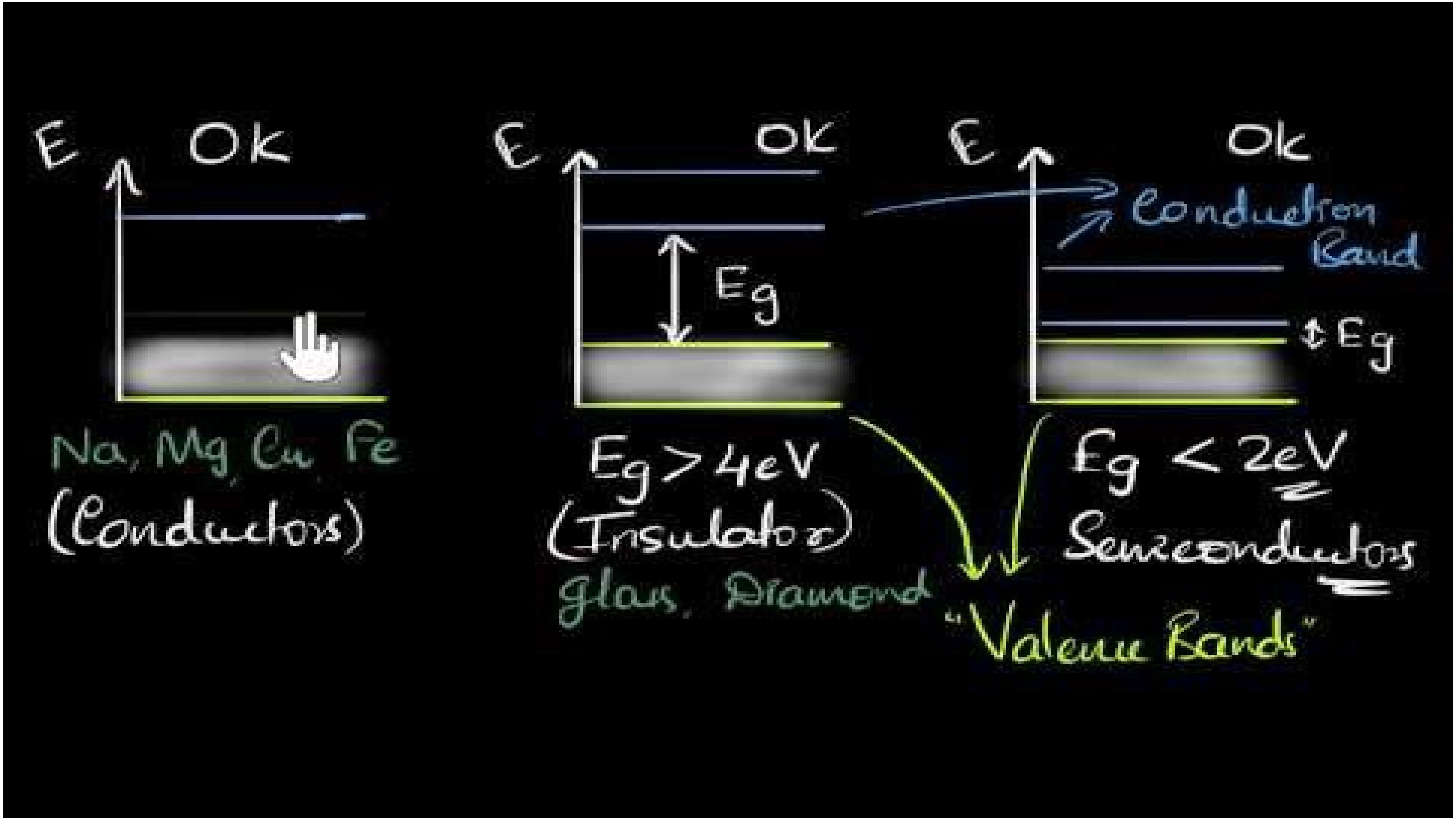
(d) The electron band structure found in semiconductor



- The valence band is completely filled with electrons and separated from an empty conduction band by a band gap.
- **Narrow energy gap – Semiconductor.**
- Over time, scientists discovered that they could control the conductivity of certain materials, turning a good insulator into a decent conductor by changing certain attributes, such as the temperature of the substance or the amount of impurities found in it.

Resource Link

Conductors, insulators, and semiconductors



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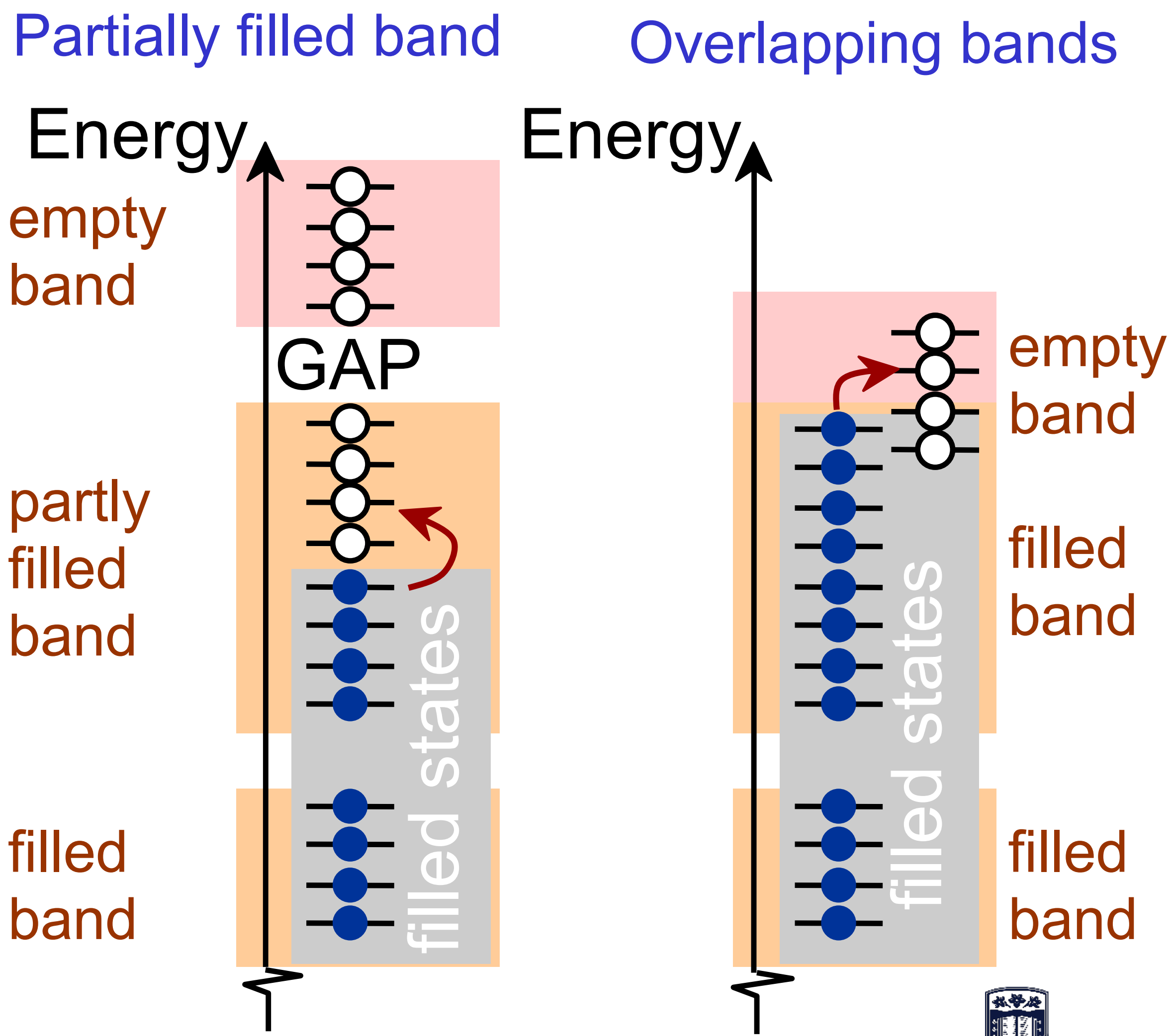
Conduction & Electron Transport

- Metals (Conductors):

-- for metals empty energy states are adjacent to filled states.

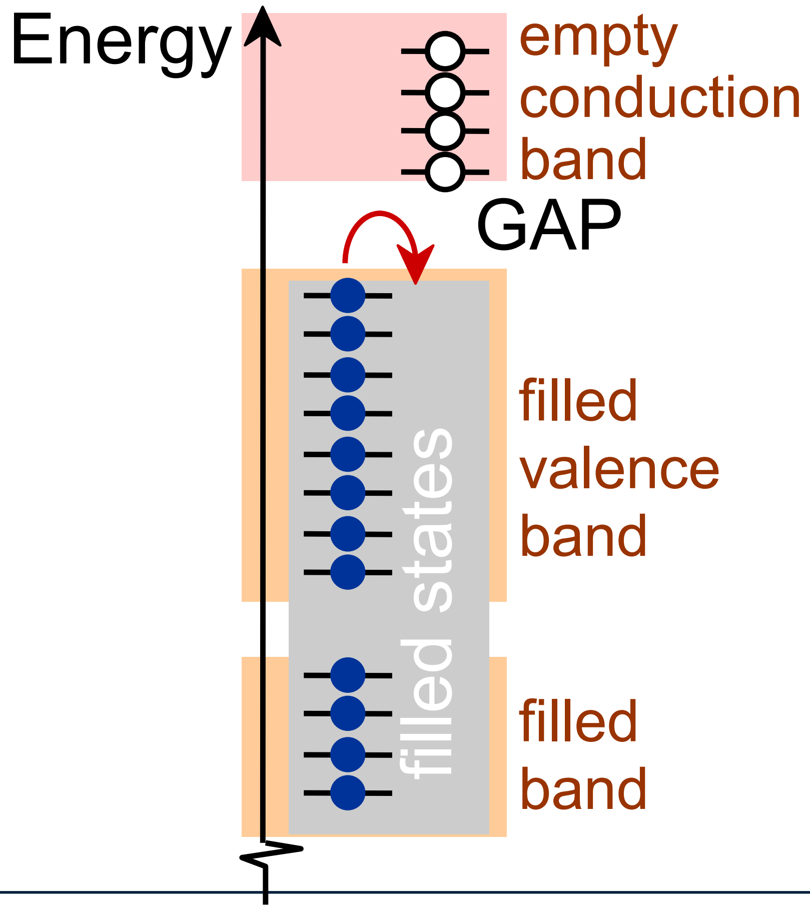
-- thermal energy excites electrons into empty higher energy states.

-- two types of band structures for metals
- partially filled band
- empty band that overlaps filled band

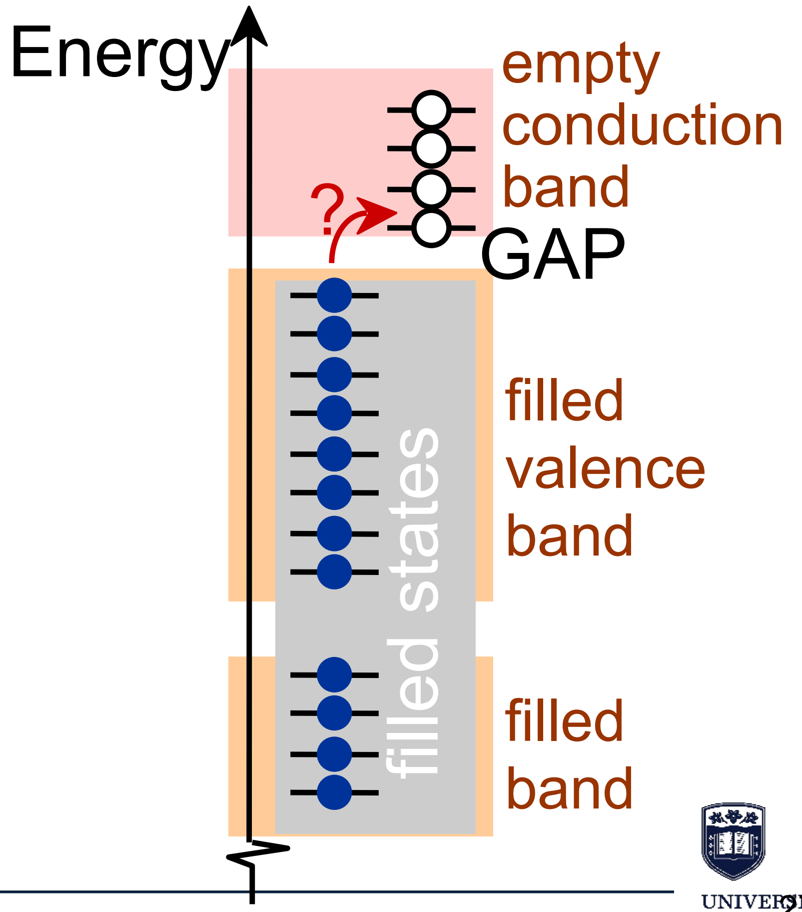


Energy Band Structures: Insulators & Semiconductors

- **Insulators**:
  -- wide band gap (> 2 eV)
  -- few electrons excited across band gap



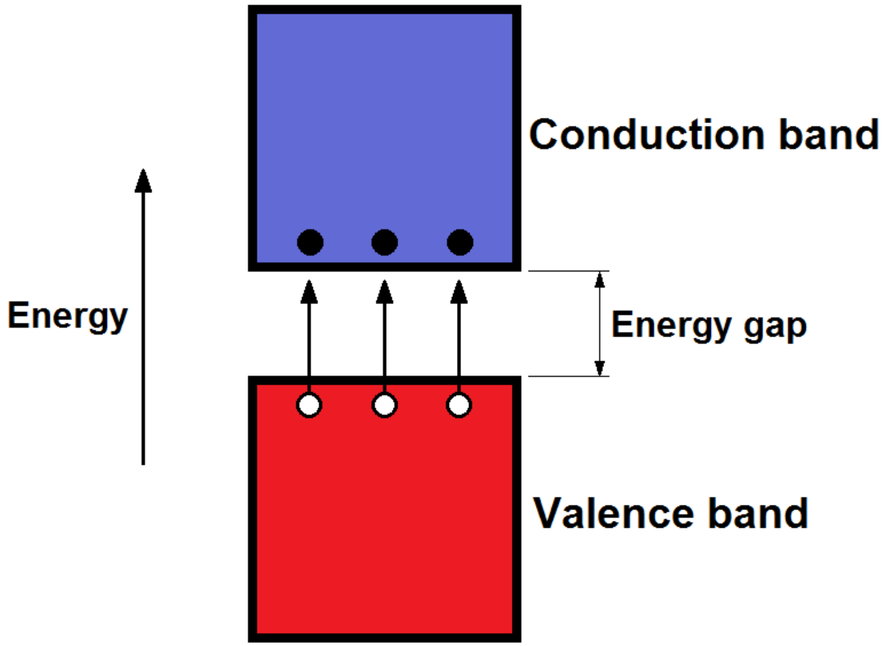
- **Semiconductors**:
  -- narrow band gap (< 2 eV)
  -- more electrons excited across band gap



Semiconductivity

- Materials with a full valence band separated from the conduction band by an energy gap can only conduct charge if some of the electrons cross the energy gap.

- In semiconductor materials the energy gap is relatively small.



- Electromagnetic fields (voltage), electromagnetic radiation, heat and magnetic fields are potential energy sources for electrons to jump across the gap.

- Two types of semiconductors: **intrinsic** and **extrinsic** semiconductors.

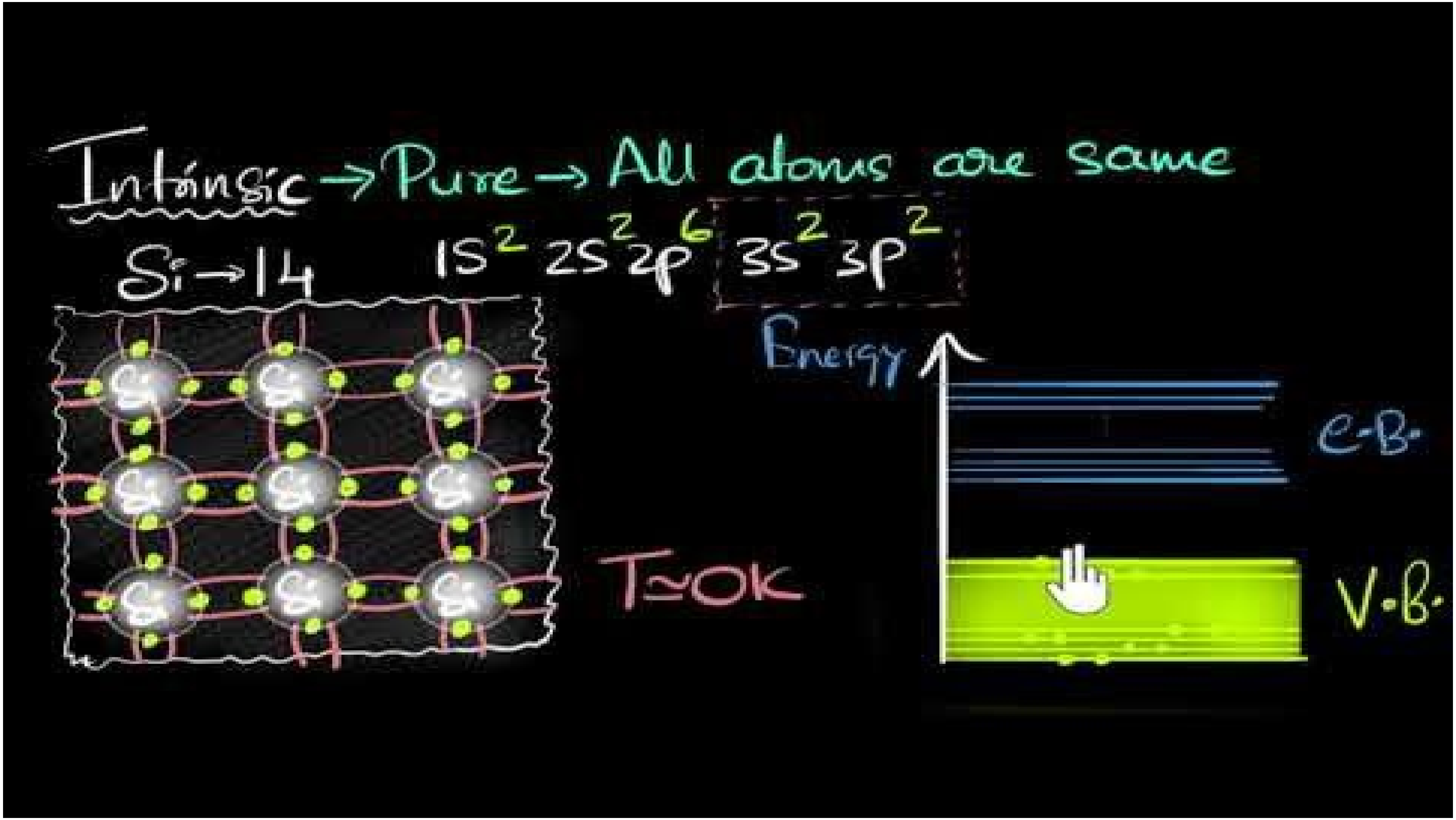
The difference between conduction in **semiconductors** and conduction in **conductors** is evident in the **effect of temperature on resistance**.

Resistance increases (and conductivity decreases) as a resistor gets hot. Heating any device results in more atomic vibrations. If the atomic cores are vibrating more, electrons will have decreased mobility. Voila - increased resistance.

The resistance of **semiconductors** depends upon temperature in an additional manner. Increasing the temperature of intrinsic semiconductors provides more thermal energy for electrons to absorb, and thus will increase the number of conduction electrons. Voila - **decreased resistance**. This second effect in semiconductors is much greater than the effect of atomic vibrations, so increasing the temperature of a semiconductor ends up decreasing its resistance.

Resource Link

Intrinsic semiconductors



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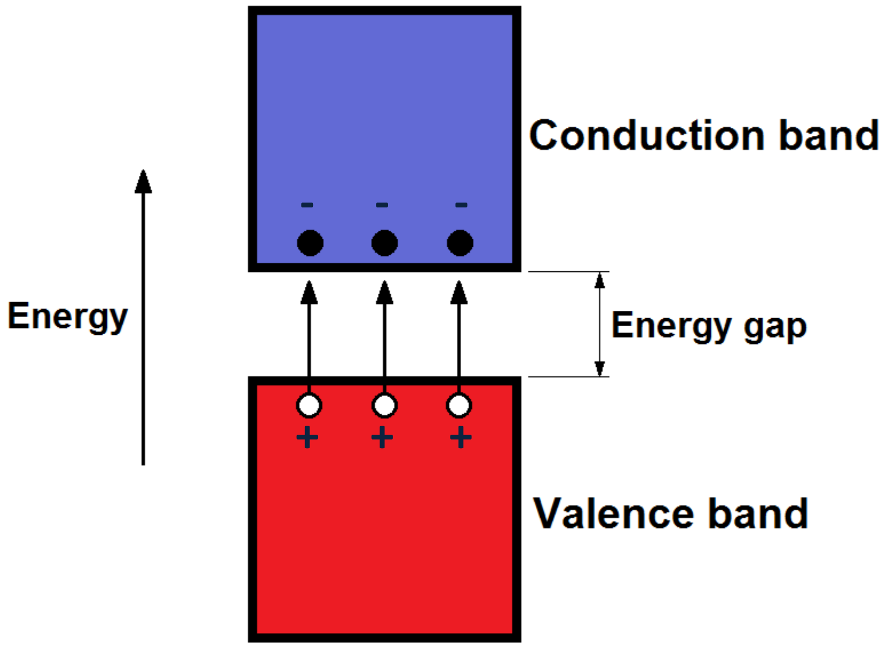
Intrinsic semiconductors

- Characterised by a **completely filled valence band**, separated from an **empty conduction band** by a relatively **narrow forbidden band gap** (less than 2 eV).
- Some of the valence electrons can be excited to the conduction band, leaving behind an electron hole that behaves like a positive charge.
- Very pure, near-perfect crystals are required (with impurity levels controlled to 1 ppm or less) as electrons are scattered by lattice imperfections.
- Silicon, germanium, gray tin selenium and tellurium. Also Cu_2O, ZnO, Fe_2O_3, GaAs, InSb, CdS, ZnTe and PbTe.

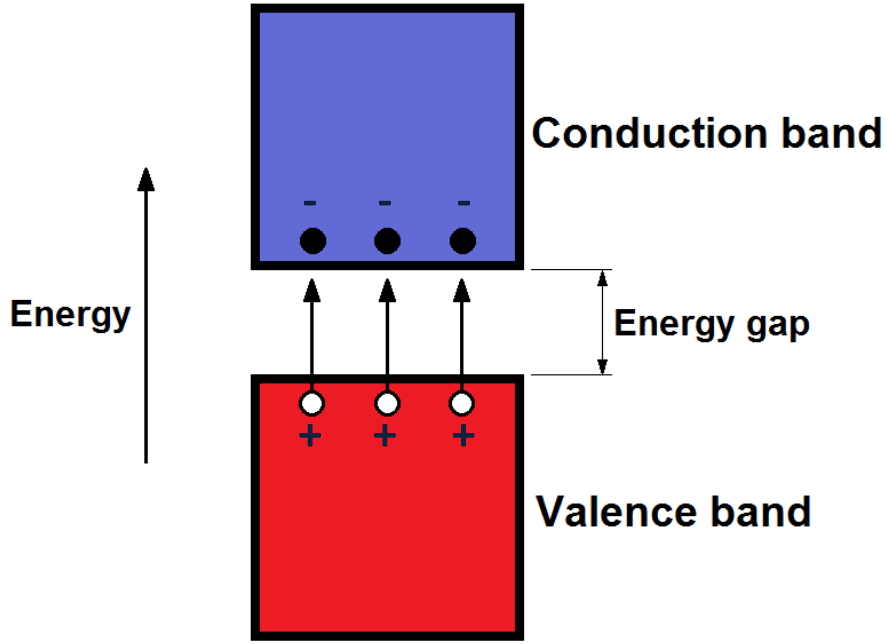


Band gap energies:

Silicon (Si):	1.1 eV
Germanium (Ge):	0.7 eV

Intrinsic semiconductors

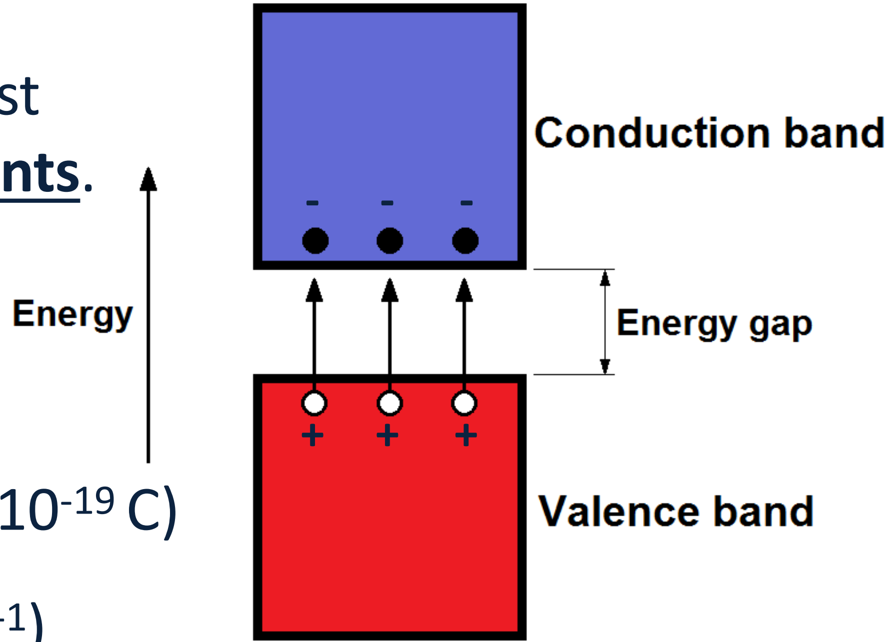
- For every electron excited into the conduction band, a missing electron (**hole**) is left behind in one of the covalent bonds.
- Under the influence of an electric field, the position of the hole may be thought of as moving by the motion of other valence electrons repeatedly filling the incomplete bond.
- A hole has the same charge as an electron, but of opposite sign.
- In the presence of an electric field, excited electrons and holes move in opposite directions.



Intrinsic semiconductors

Because there are <u>two</u> types of charge carriers (free electrons and holes), the expression for **electrical conduction** must **account for the electron and hole currents**.

$$\sigma = |q|\mu_p p + |q|\mu_n n$$
$$= |q|(\mu_p p + \mu_n n)$$



where: q = charge of an electron (-1.6×10^{-19} C)

μ_p = mobility of holes ($m^2V^{-1}s^{-1}$)

μ_n = mobility of electrons ($m^2V^{-1}s^{-1}$)

p = number of holes per m^3

n = number of electrons per m^3

For **intrinsic** semiconductors:

$$n = p = n_i \longrightarrow \sigma = |q|n_i(\mu_p + \mu_n)$$

where: n_i = intrinsic charge carrier concentration

Intrinsic semiconductors

Example:

If the conductivity of pure silicon in determined to be 5 x 10^{-4} $S.m^{-1}$, estimate the concentration of conduction electrons per m^3 in this material if the electron mobility in silicon is 0.14 $m^2.V^{-1}.s^{-1}$ and the hole mobility is 0.05 $m^2.V^{-1}.s^{-1}$.

$$\boxed{\sigma = |q| n_i (\mu_p + \mu_n)}$$

Intrinsic semiconductors

Example:

If the conductivity of pure silicon in determined to be 5 x 10^{-4} S.m^{-1}, estimate the concentration of conduction electrons per m^3 in this material if the electron mobility in silicon is 0.14 m^2.V^{-1}.s^{-1} and the hole mobility is 0.05 m^2.V^{-1}.s^{-1}.

$$\boxed{\sigma = |q| n_i (\mu_p + \mu_n)}$$

Answer:

Rearrange:

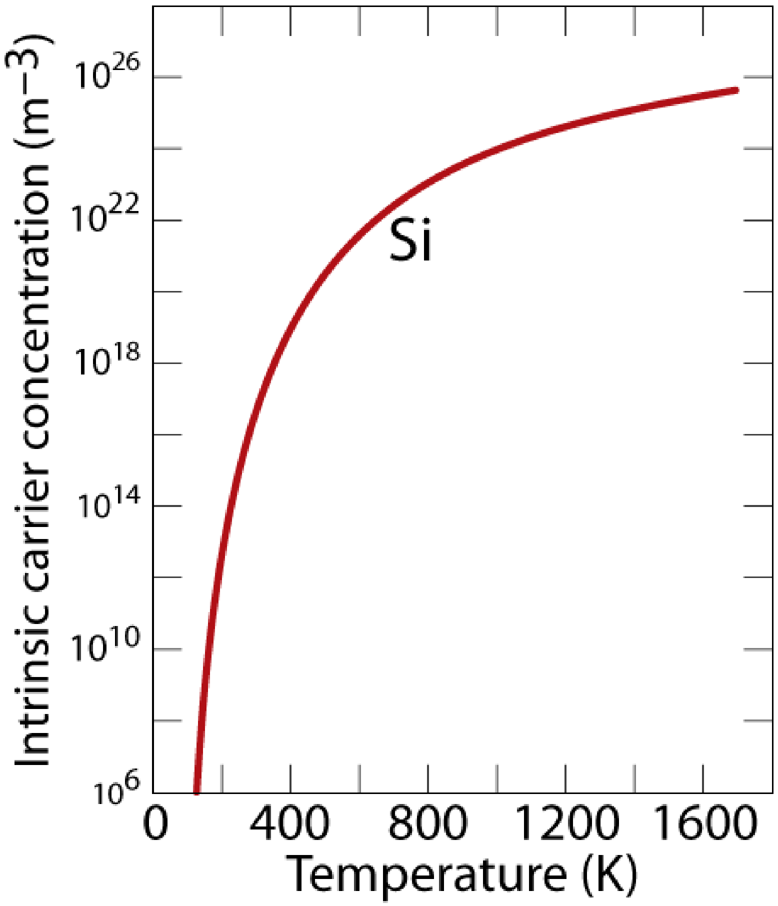
$$n = \frac{\sigma}{|q|(\mu_p + \mu_n)} \qquad \therefore\ n = \frac{(5 \times 10^{-4}\ S.m^{-1})}{(0.16 \times 10^{-18}\ C)(0.14 + 0.05\ m^2 V^{-1} s^{-1})}$$

$$\therefore\ n = 1.64 \times 10^{16}\ \text{carriers.m}^{-3}$$

$$\therefore\ n_i = \mathbf{1.64 \times 10^{10}\ carriers.cm^{-3}}$$

Intrinsic Semiconductors: Conductivity vs *Temp*

- Data for Pure Silicon:
  -- σ increases with T
  -- opposite to metals



$$\sigma = n_i |e| (\mu_e + \mu_h)$$

$$n_i \propto e^{-E_{gap}/kT}$$

material	band gap (eV)
Si	1.11
Ge	0.67
GaP	2.25
CdS	2.40

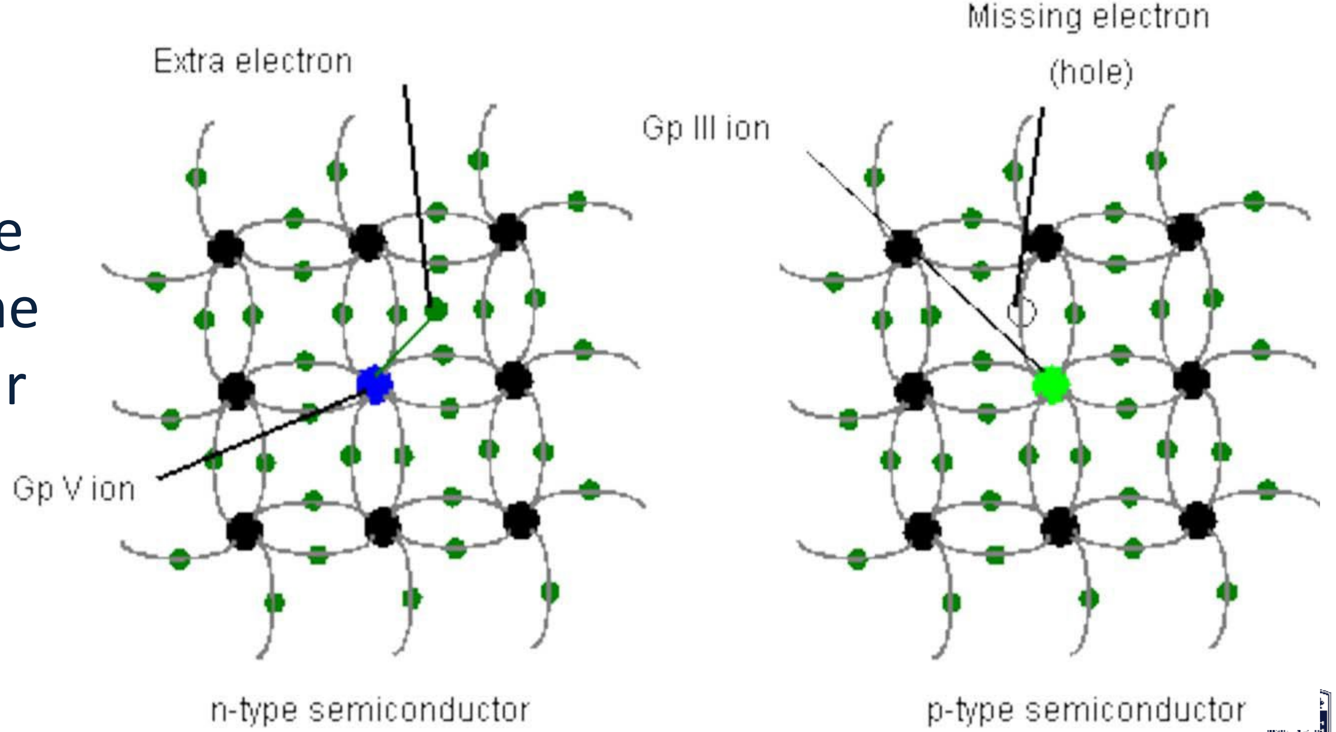
Selected values from Table 18.3, *Callister & Rethwisch 8e.*

Adapted from Fig. 18.16, *Callister & Rethwisch 8e.*

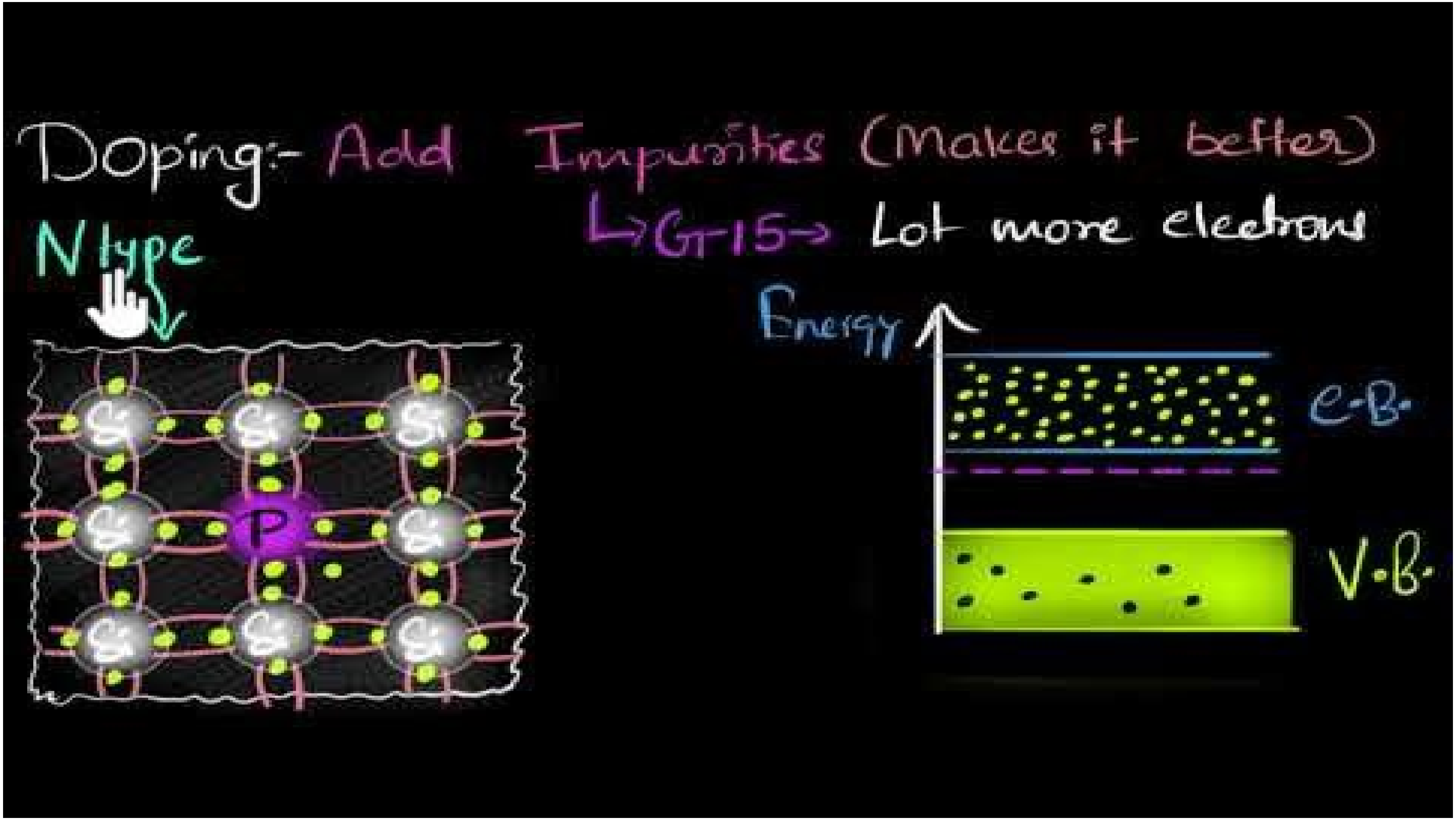
Extrinsic semiconductors

- The **electrical behaviour** is determined by **impurities** that, even in very low concentrations, **introduce excess *electrons* or *holes*** into the atomic structure.
- Impurity atoms act as *donors* or *acceptors* in the crystal lattice.
- An impurity concentration of 1 atom in 10^{12} is sufficient to render silicon extrinsic at room temperature.

- Virtually all commercial semiconductors are extrinsic; that is, the electrical behaviour is determined by impurities



Extrinsic semiconductors N-type



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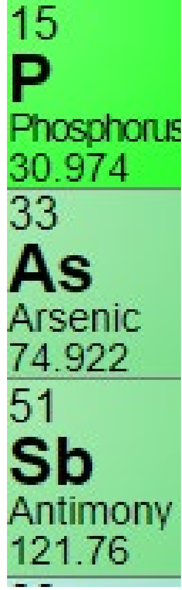
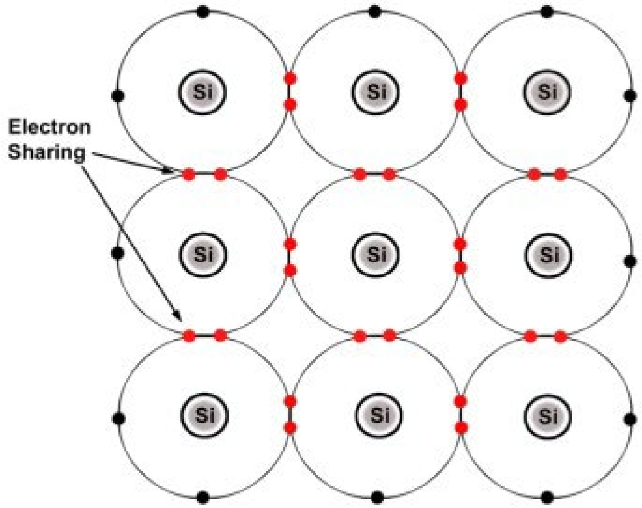
n-type extrinsic semiconductors

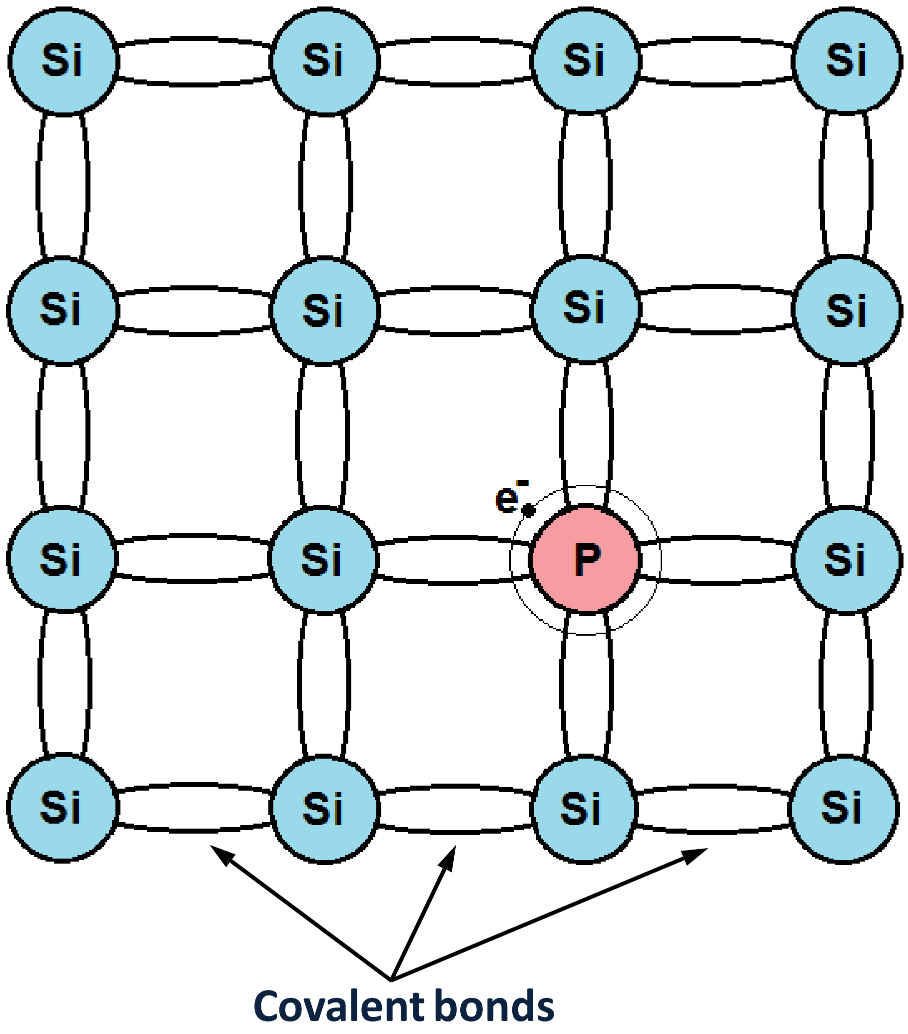


- An **extra non-bonded electron** (or electrons) is **supplied by impurity atoms.**
- **Example:** Silicon has four valence electrons, each of which is bonded to one of four adjacent silicon atoms. If an impurity atom with a valence of five (such as P, As or Sb) is added as a substitutional impurity, only four of the five valence electrons of the impurity atom can participate in bonding because there are only four bonds possible with adjacent atoms.
- The nonbonding atom is loosely bound to the region around the impurity atom (binding energy of only about 0.01 eV). It can easily be removed from the impurity atom to become a free or conducting electron



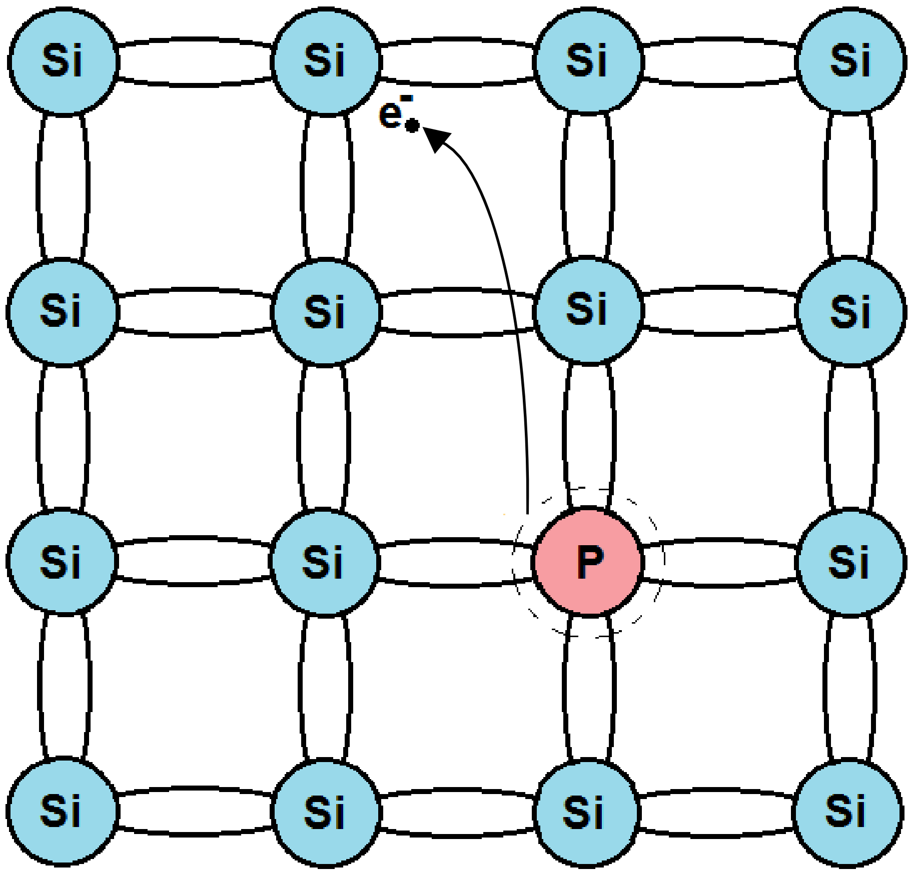
Covalent bonding in the Si lattice structure.

n-type extrinsic semiconductors



- Silicon lattice (tetravalent) containing a phosphorus impurity (pentavalent).
- Four phosphorus valence electrons form covalent bonds with adjacent Si atoms.
- The fifth phosphorus valence electron is loosely bonded to the donor atom (P) and is easily excited into the conduction band.

n-type extrinsic semiconductors



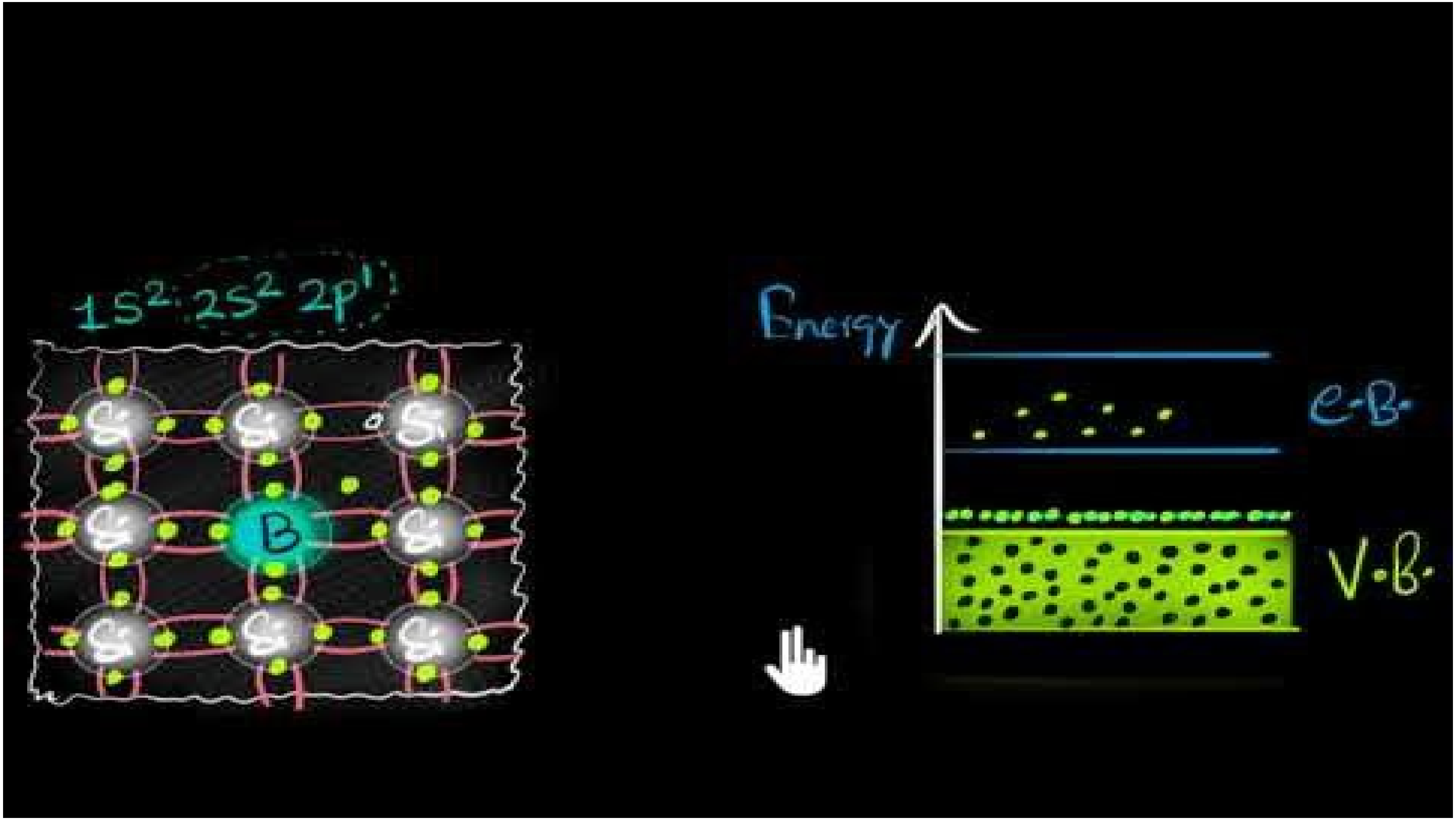
- The impurity is known as a ***donor***, because it produces conduction electrons without leaving holes in the valence band.
- Electrons are the majority charge carriers, while holes are minority carriers.

→ *n*-type extrinsic semi-conductor

$$\boxed{\sigma = |q|\, n\, \mu_n}$$

where: $\boldsymbol{q}$ = charge of an electron (-1.6×10^{-19} C)
μ_n = mobility of electrons ($m^2V^{-1}s^{-1}$)
$\boldsymbol{n}$ = number of electrons per cm^3

Extrinsic semiconductors P-type



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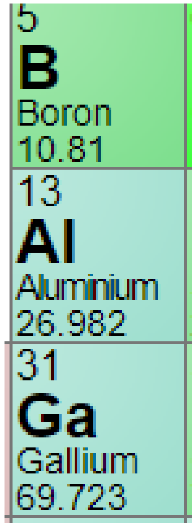
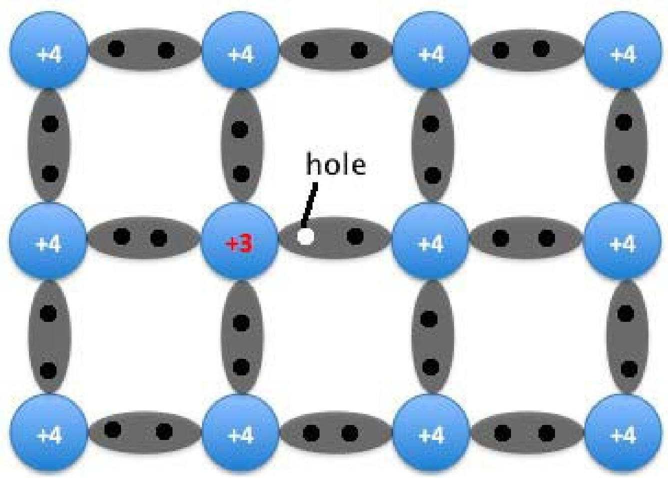
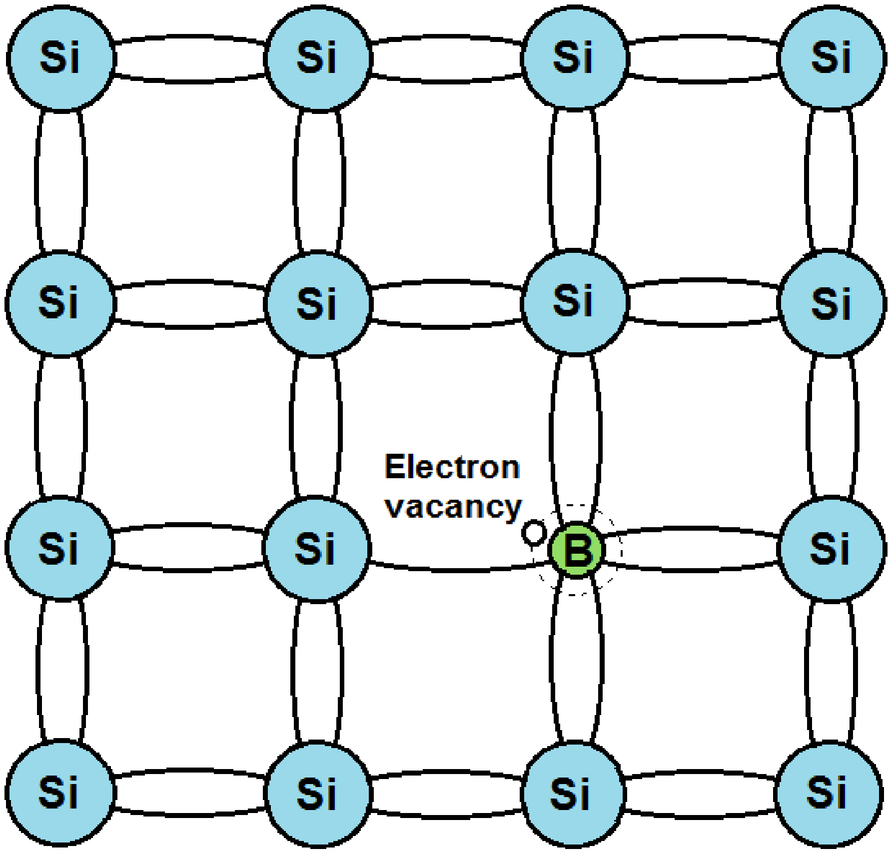
p-type extrinsic semiconductors



- An **electron deficiency is caused by the presence of impurity atom**s.
- **Example:** Silicon has four valence electrons, each of which is bonded to one of four adjacent silicon atoms. If an impurity atom with a valence of three (such as Al, B or Ga) is added as a substitutional impurity, all three of the valence electrons of the impurity atom participate in bonding.
- One of the covalent bonds around each of these atoms is deficient in an electron. Such a deficiency may be viewed as a hole that is weakly bonded to the impurity atom.
- This hole may be liberated from the impurity atom by the transfer of an electron from an adjacent bond (the hole and electron exchange positions).
- A moving hole is considered to be in an excited state and participates in conduction.

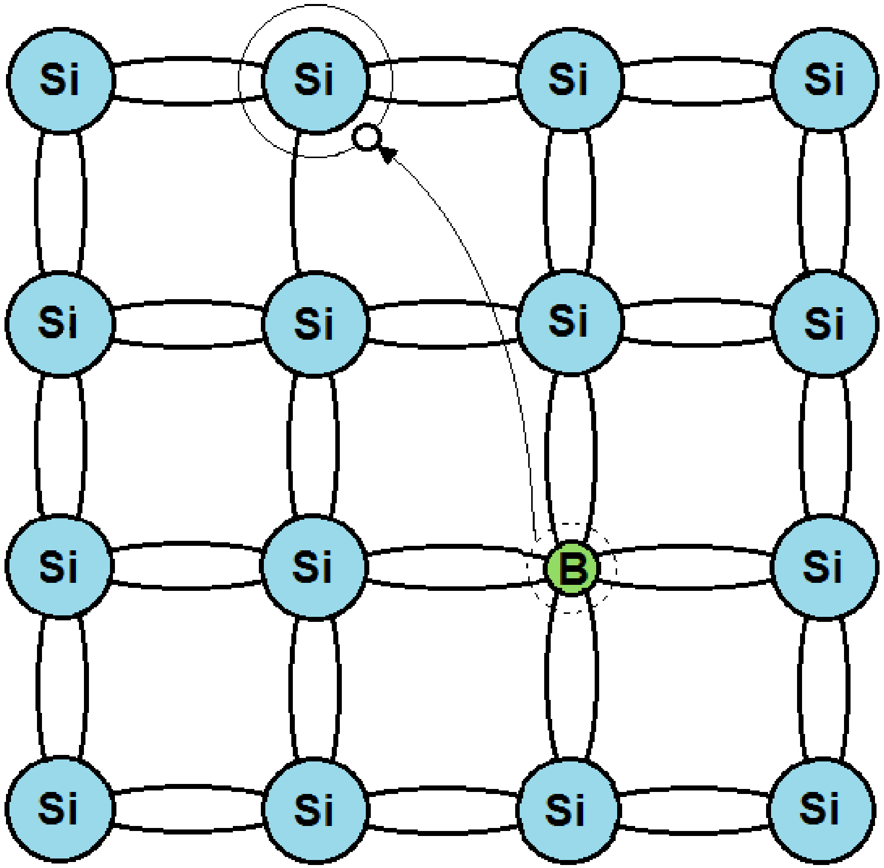


p-type extrinsic semiconductors



- Silicon lattice (tetravalent) containing a boron impurity (trivalent).
- Three phosphorus valence electrons form covalent bonds with adjacent Si atoms.
- An electron deficiency (hole) around the impurity results in an incomplete covalent bond.

p-type extrinsic semiconductors



- A hole exists in the valence state of the impurity atom. If the hole moves away from the impurity, the bonding state is filled by accepting a valence electron from a tetravalent atom.
- The impurity is termed an **acceptor**.
- The majority charge carriers are holes.

→ ***p*-type extrinsic semi-conductor**

$$\boxed{\sigma = |q|\, p\, \mu_p}$$

where: $\boldsymbol{q}$ = charge of an electron (-1.6×10^{-19} C)
$\boldsymbol{\mu_p}$ = mobility of holes ($m^2V^{-1}s^{-1}$)
$\boldsymbol{p}$ = number of holes per cm^3

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Extrinsic semiconductors

Example:

Pure silicon is doped with 0.5×10^{22} aluminium atoms per m^3 (0.1 ppm). If the conductivity of pure Si is 5×10^{-4} S/m and the carrier mobility 0.05 $m^2.V^{-1}.s^{-1}$, how does the Al addition affect the conductivity of silicon?

Extrinsic semiconductors

Example:

Pure silicon is doped with 0.5×10^{22} aluminium atoms per m^3 (0.1 ppm). If the conductivity of pure Si is 5×10^{-4} S/m and the carrier mobility $0.05\ m^2.V^{-1}.s^{-1}$, how does the Al addition affect the conductivity of silicon?

Answer:

The addition of trivalent atoms to silicon produces holes which are available for conduction (*p*-type extrinsic semiconductor).

$$\sigma = |q| p \mu_p$$

$$= (0.16 \times 10^{-18}\ C)(0.5 \times 10^{22}\ atoms.m^{-3})(0.05\ m^2.V^{-1}.s^{-1})$$

$$= 40\ (\Omega.m)^{-1}$$

$$\mathbf{= 40\ S/m}$$

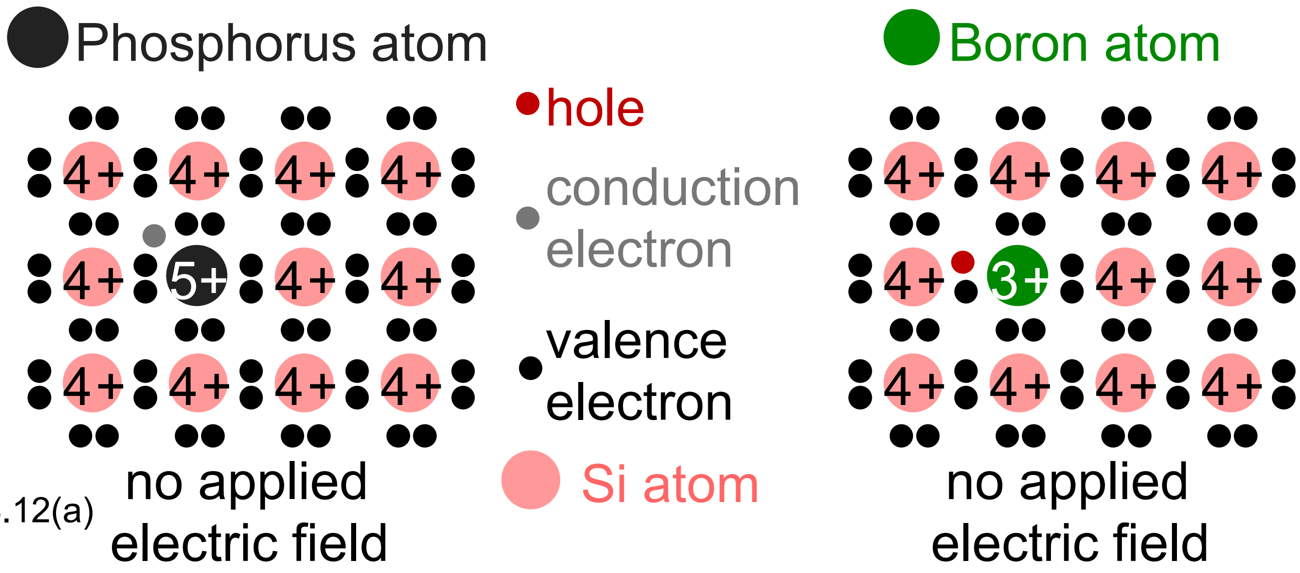
This shows that the addition of just 0.1 ppm aluminium to silicon increases its conductivity by 80 000 times!

Intrinsic vs Extrinsic Conduction

- Intrinsic:
  -- case for pure Si
  -- # electrons = # holes ($n = p$)
- Extrinsic:
  -- electrical behavior is determined by presence of impurities that introduce excess electrons or holes
  -- $n \neq p$

- *n*-type Extrinsic: ($n >> p$)
- *p*-type Extrinsic: ($p >> n$)

$$\sigma \approx n|e|\mu_e$$



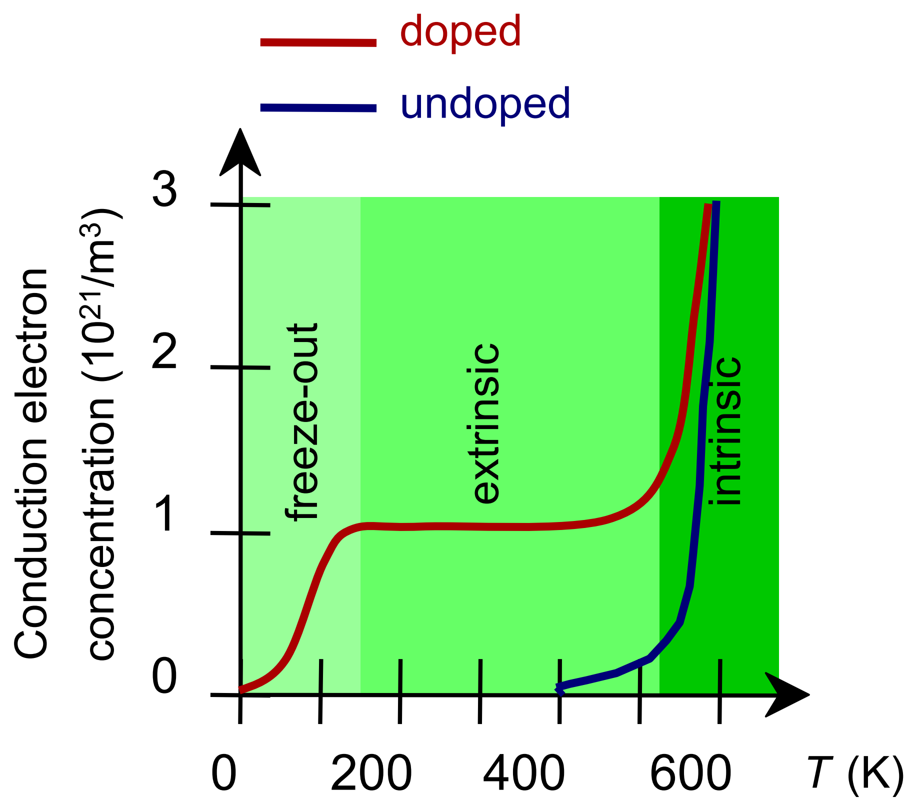
$$\sigma \approx p|e|\mu_h$$

Adapted from Figs. 18.12(a) & 18.14(a), *Callister & Rethwisch 8e.*

Extrinsic Semiconductors: Conductivity vs. Temperature

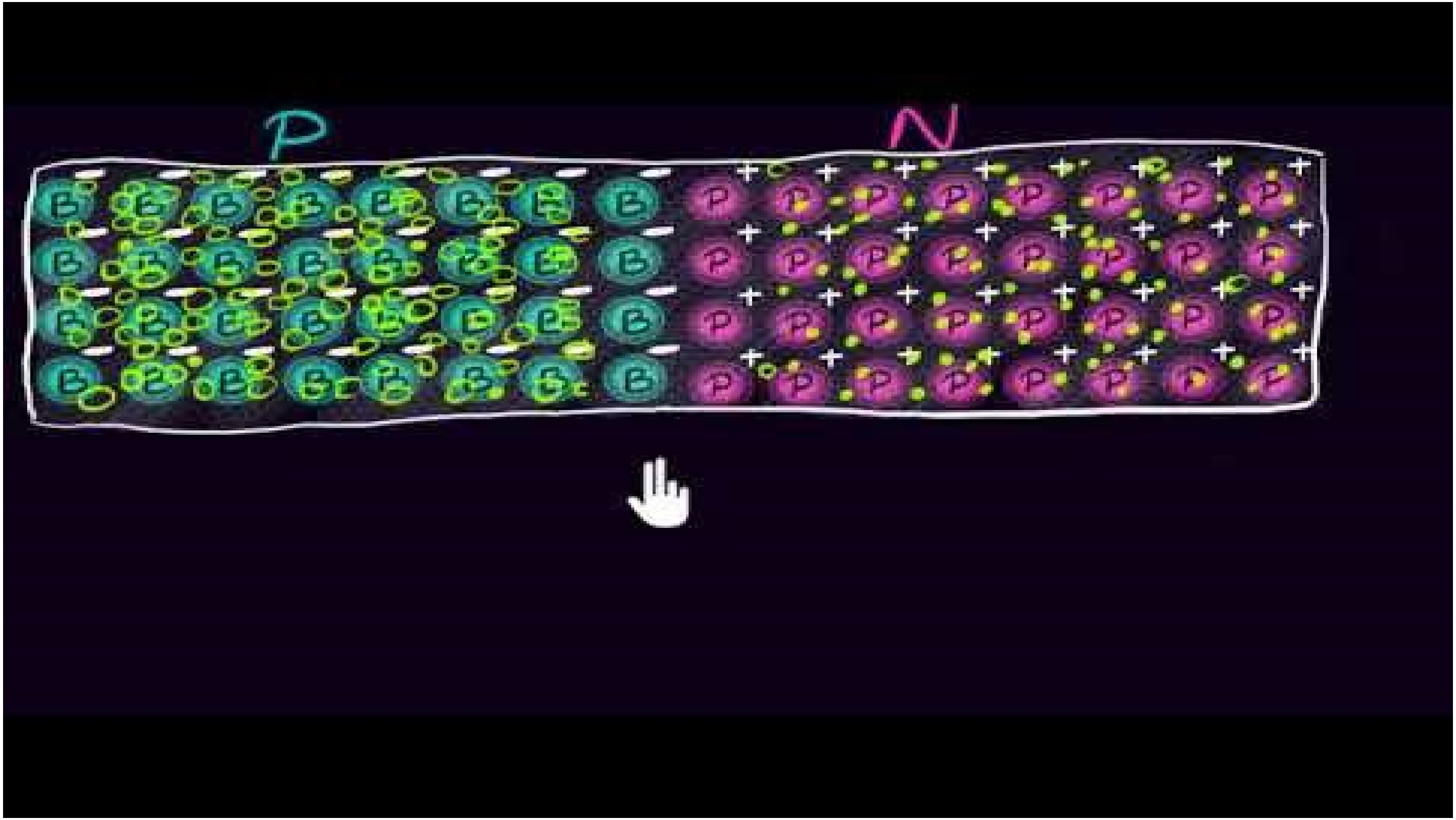
- Data for Doped Silicon:
  - -- σ increases doping
  - -- reason: imperfection sites lower the activation energy to produce mobile electrons.

- Comparison: intrinsic vs extrinsic conduction...
  - -- extrinsic doping level: $10^{21}/m^3$ of a *n*-type donor impurity (such as P).
  - -- for *T* < 100 K: "freeze-out“, thermal energy insufficient to excite electrons.
  - -- for 150 K < *T* < 450 K: "extrinsic"
  - -- for *T* >> 450 K: "intrinsic"



Adapted from Fig. 18.17, *Callister & Rethwisch 8e.* (Fig. 18.17 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

The PN junction



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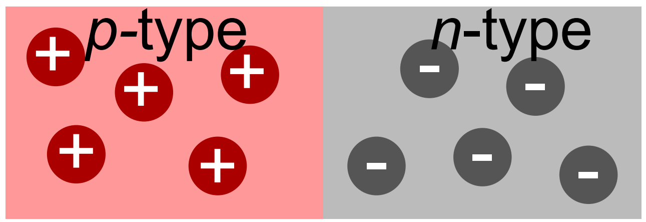
p-n Rectifying Junction

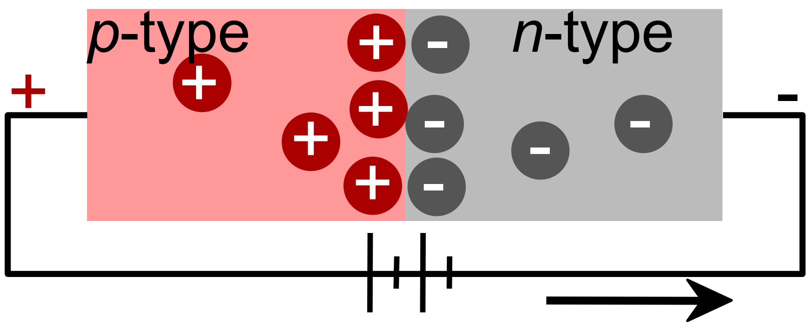
- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current).
- Processing: diffuse P into one side of a Boron-doped crystal.

-- No applied potential: no net current flow.

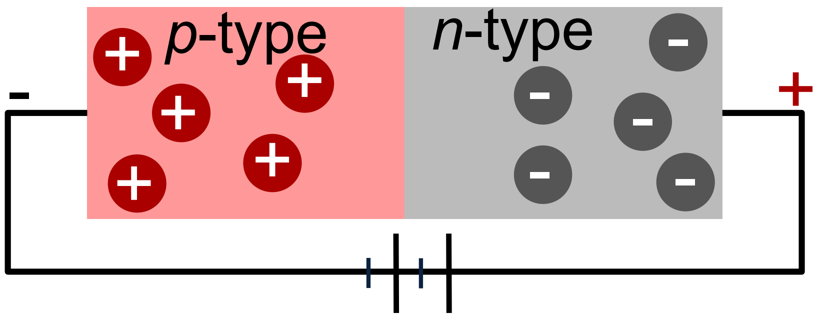


Adapted from Fig. 18.21 Callister & *Rethwisch 8e.*

-- Forward bias: carriers flow through *p*-type and *n*-type regions; holes and electrons recombine at *p-n* junction; current flows.

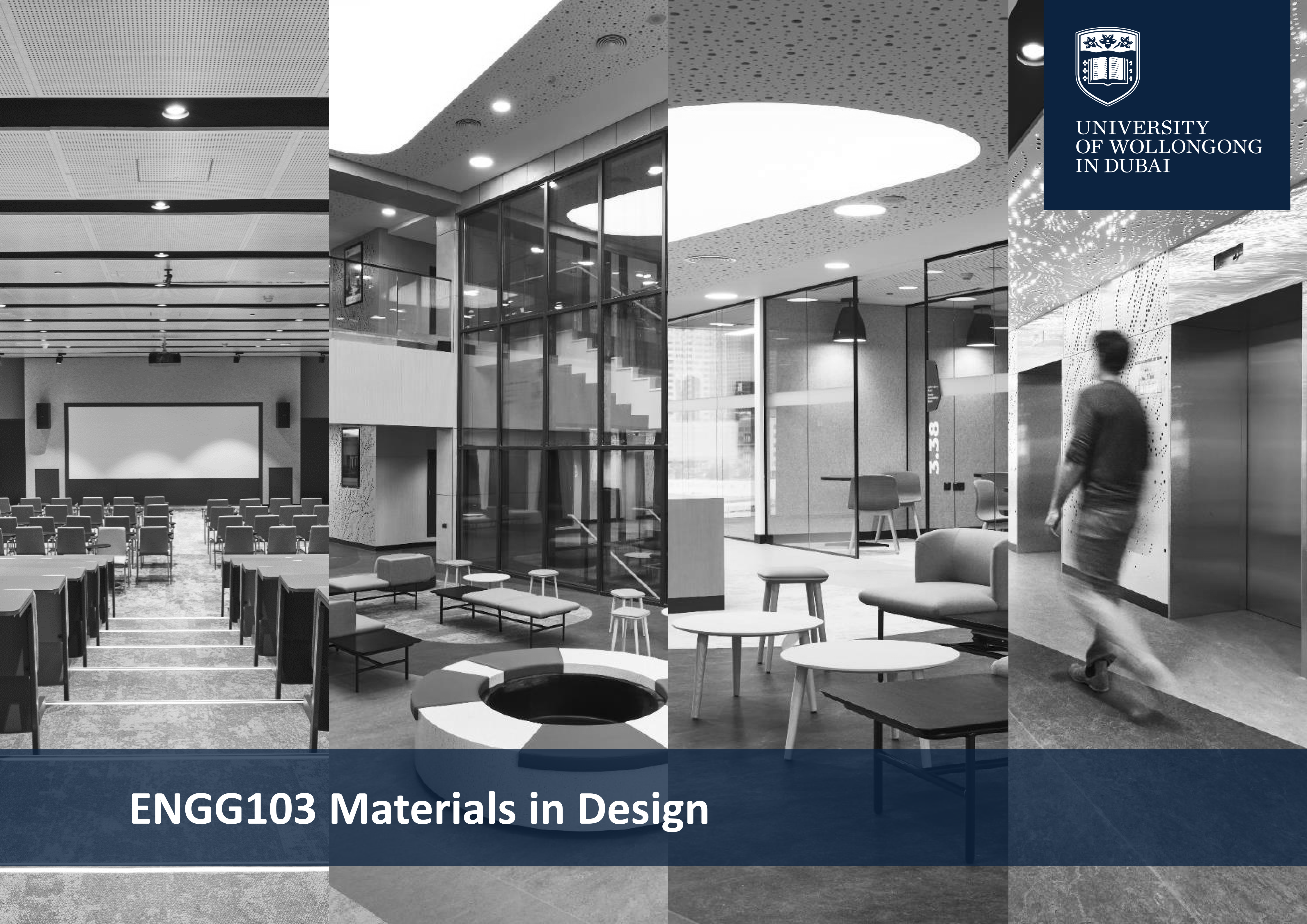


-- Reverse bias: carriers flow away from *p-n* junction; junction region depleted of carriers; little current flow.



Summary

- Electrical *conductivity* and *resistivity* are:
  -- material parameters
  -- geometry independent
- Conductors, semiconductors, and insulators...
  -- differ in range of conductivity values
  -- differ in availability of electron excitation states
- For metals, *resistivity* is increased by
  -- increasing temperature
  -- addition of imperfections
  -- plastic deformation
- For pure semiconductors, *conductivity* is increased by
  -- increasing temperature
  -- doping [e.g., adding B to Si (*p*-type) or P to Si (*n*-type)]



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