SEMICONDUCTOR

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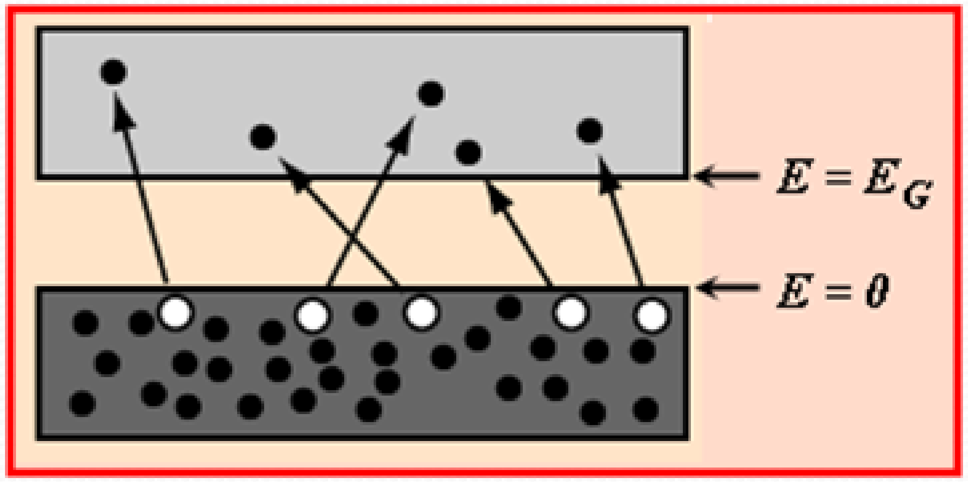
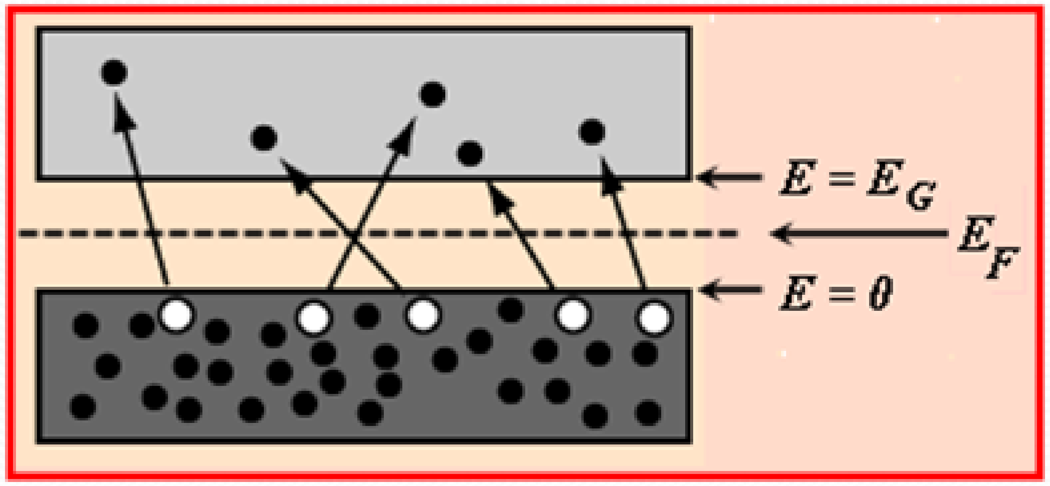
Carrier Concentrations at T >0 K

- Let's take $E_V = 0$, then $E_C = E_G$





- The number of electrons equals the number of holes, $n_e = n_h$
- The Fermi level lies in the middle of the band gap

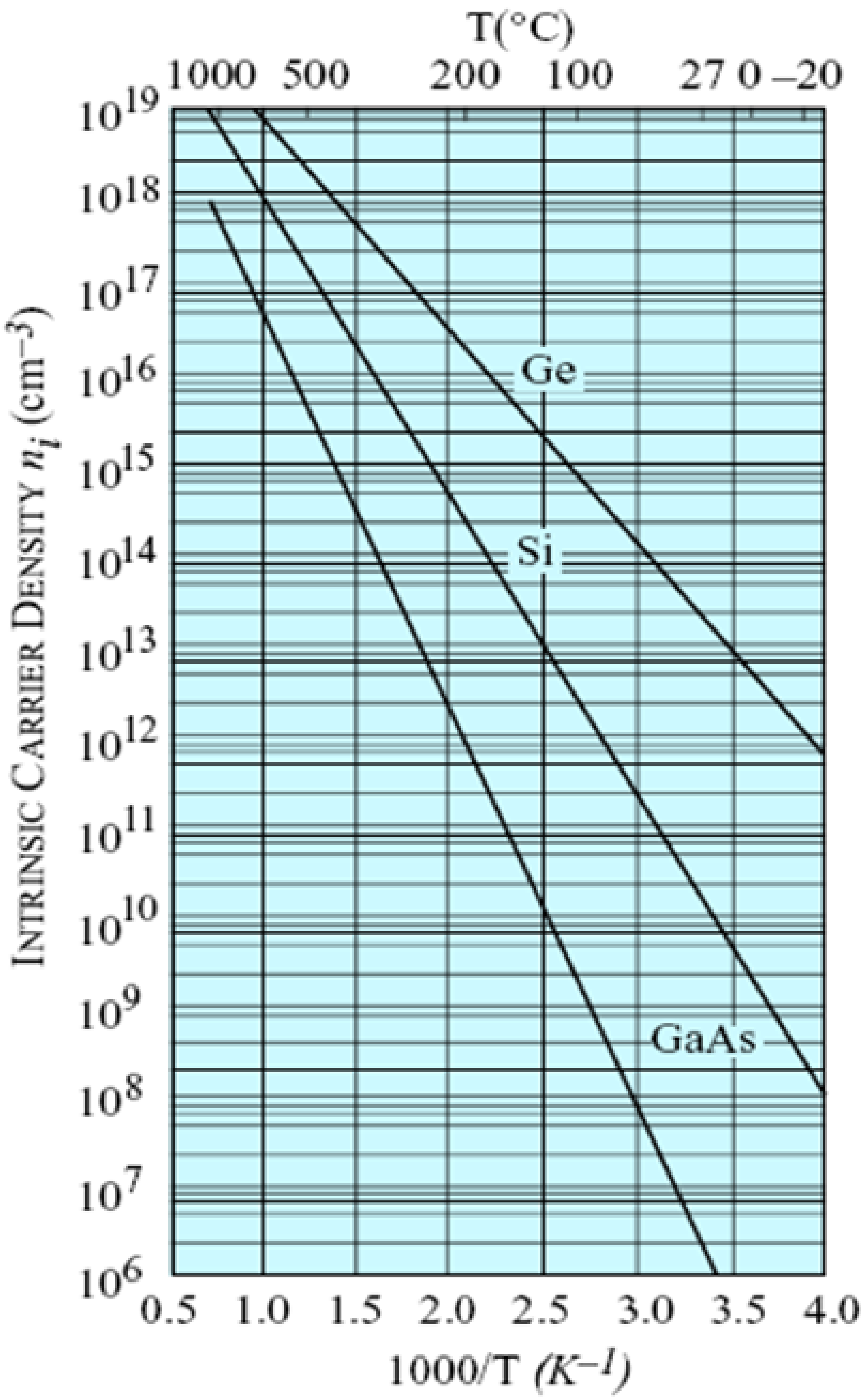
$$\boxed{n_e = n_h = \left(\frac{1}{2}\right)^{1/2} \left(\frac{kT}{\hbar^2 \pi}\right)^{3/2} \left(m_e^* m_h^*\right)^{3/4} \exp\left[-\frac{E_G}{2kT}\right]}$$

- $n_e = n_h$ increase rapidly with temperature

Carrier Concentrations

- E_G of selected semiconductors
  - Si: 1.1eV
  - Ge: 0.7eV
  - GaAs: 1.4eV
  - ZnSe: 2.7eV
- Carrier effective masses for selected semiconductors
  - GaAs: $m_e^* = 0.067m_0$; $m_h^* = 0.45m_0$
  - Si: $m_e^* = 0.26m_0$; $m_h^* = 0.49m_0$
  - Ge: $m_e^* = 0.04m_0$; $m_h^* = 0.28m_0$
  - ZnSe: $m_e^* = 0.21m_0$; $m_h^* = 0.74m_0$

Carrier concentration falls with 1/T, i.e. increase with T



Doping

- Semiconductors can be easily doped
- **Doping** is the incorporation of [substitutional] impurities into a semiconductor according to our requirements

- In other words, impurities are introduced in a controlled manner

Impurities change the conductivity of the material so that it can be fabricated into a device

Extrinsic Semiconductors

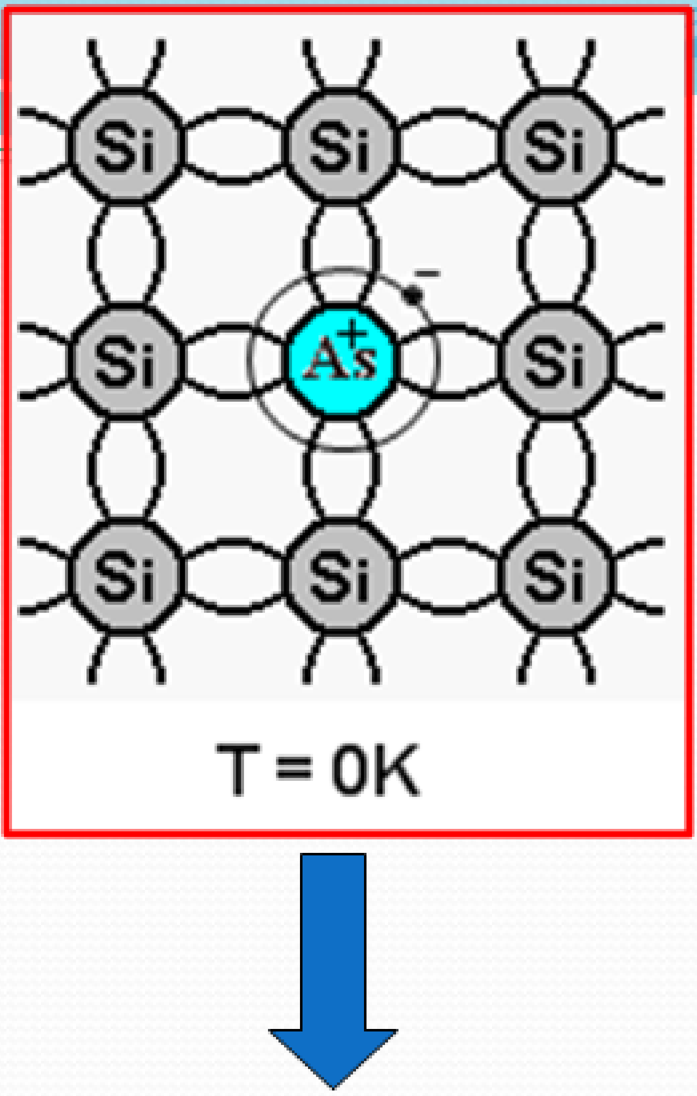
- *Electrical Properties of Semiconductors can be altered drastically by adding minute amounts of suitable impurities to the pure crystals*
- Impurities: Atoms of the elements different from those forming solid
  - Interstitial: "foreign" atoms "squeezed" between regular sites crystal sites
  - Substitutional: "foreign" atoms occupying the sites of host atoms

Donors

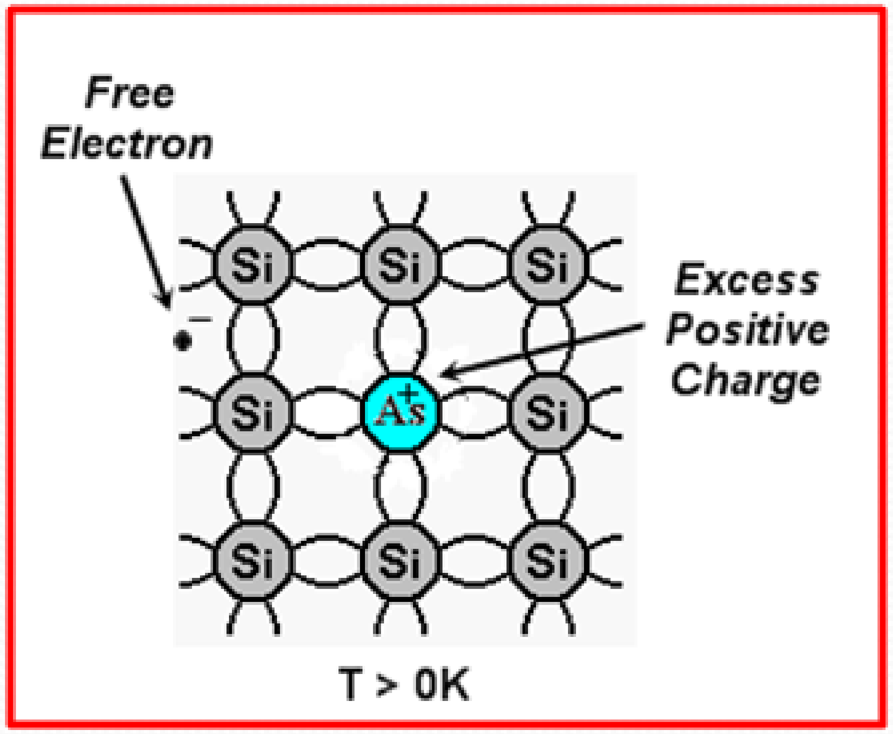
- We use Silicon (Si) as an example
  - Substitute one Si (Group IV) atom with a Group V atom (e.g. As or P)
  - Si atoms have four valence electrons that participate in covalent bonding
  - When a Group V atom replaces a Si atom, it will use four of its electrons to form the covalent bonding
  - What happens with the remaining electron?

Donors

- The remaining electron will not be very tightly bound, and can be easily ionized at T > 0K

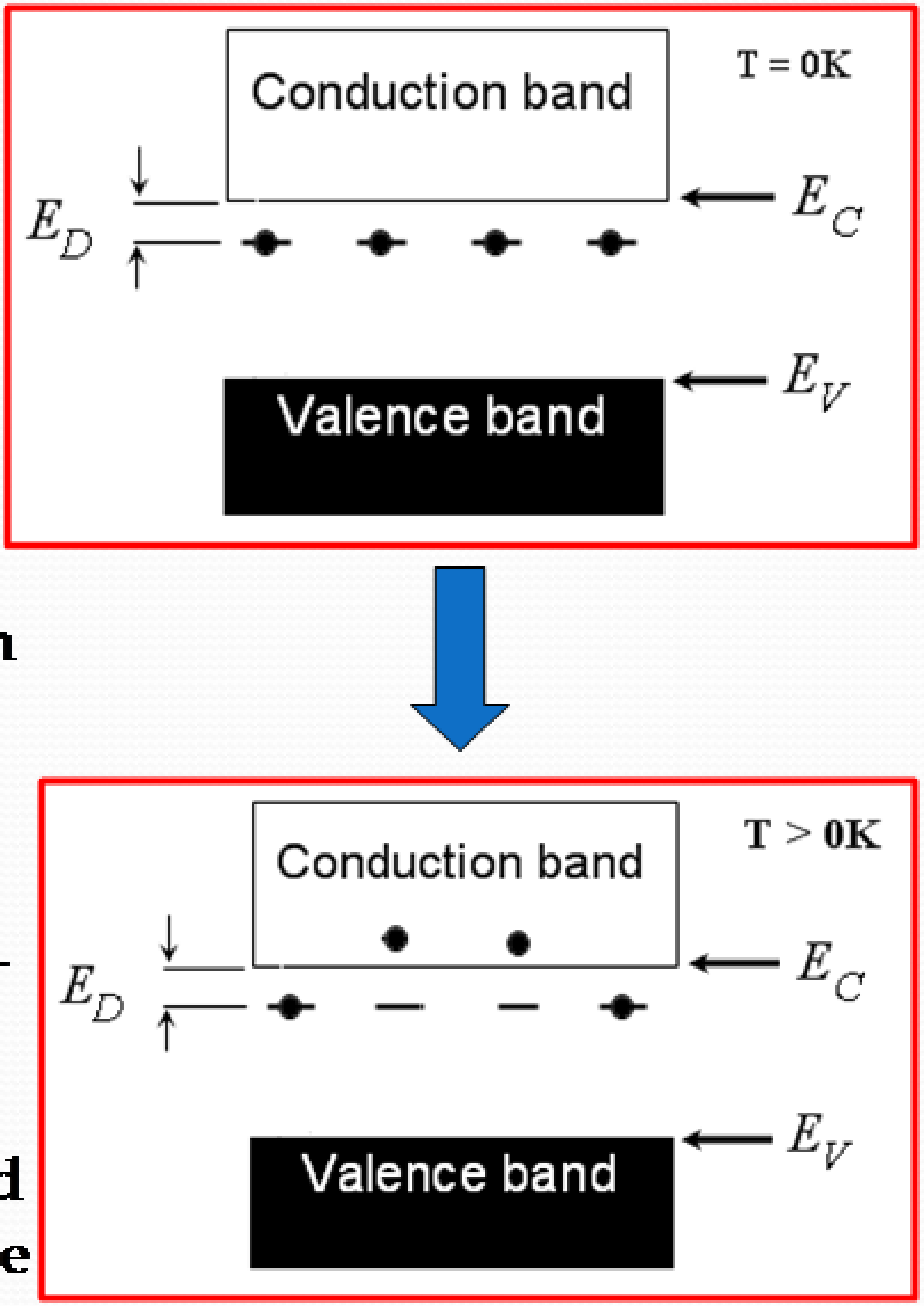


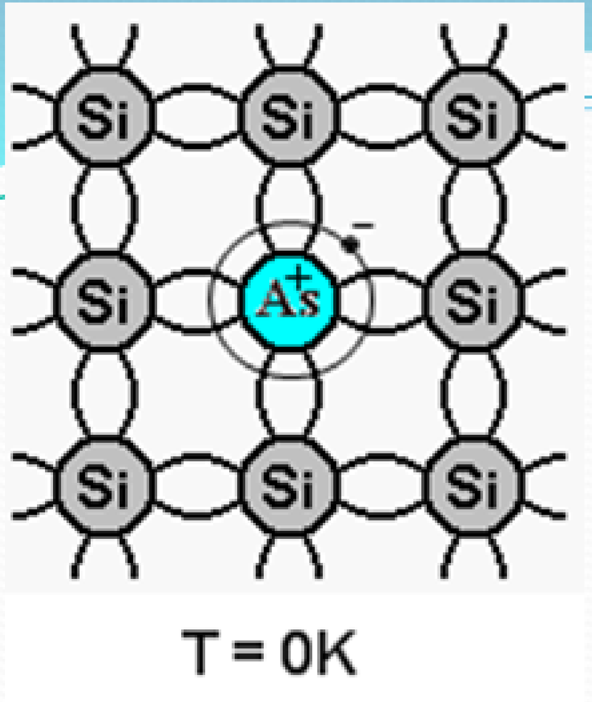
- Ionized electron is free to conduct
  - **In term of the band structure, this electron is now in the conduction band**
- Such Group V impurities are called ***Donors***, since they "donate" electrons into the Conduction Band
  - ***Semiconductors doped by donors are called n-type semiconductors***

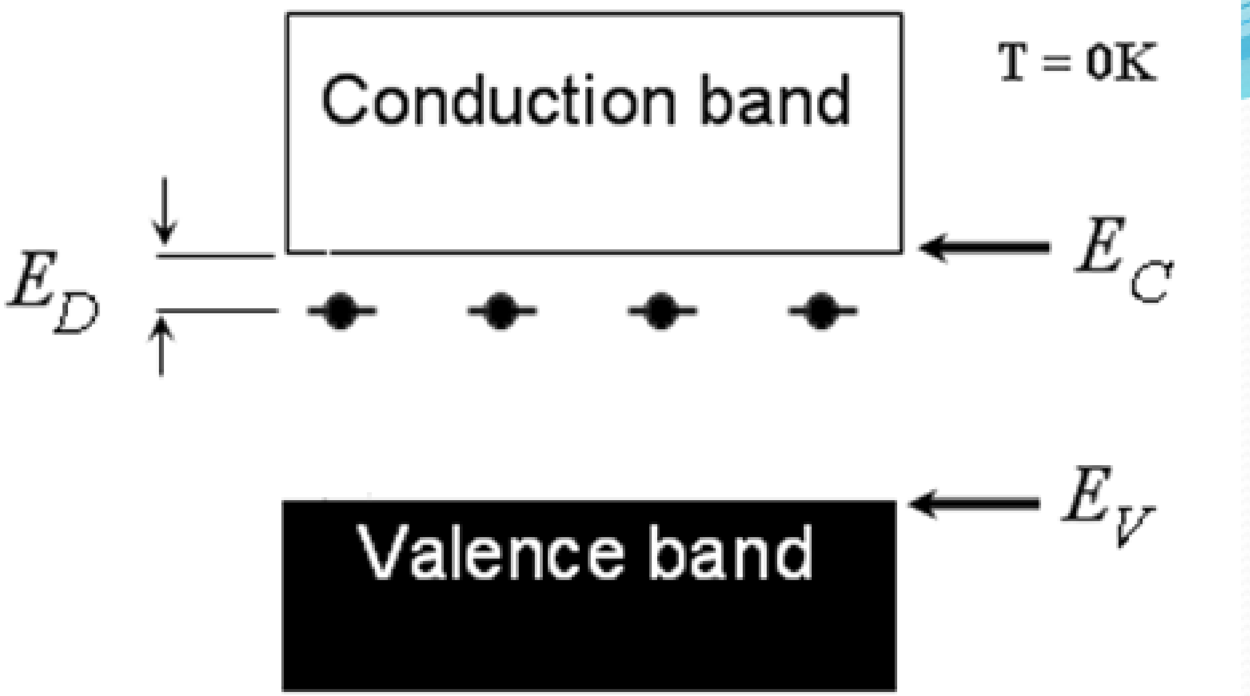


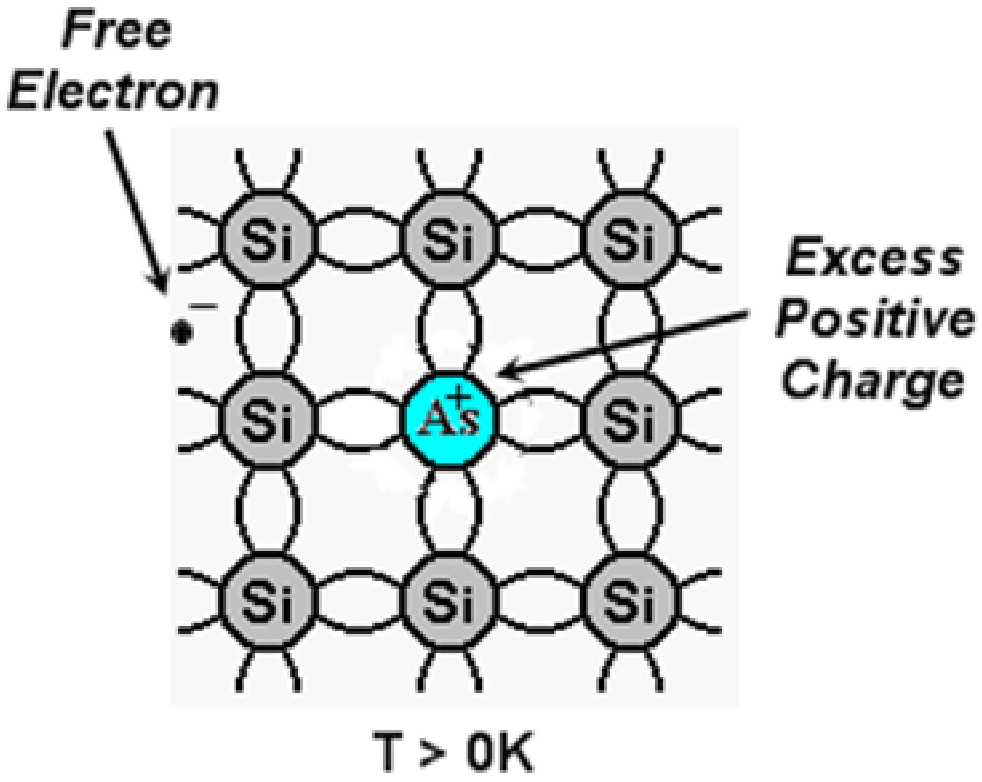
Donors: Energy Levels

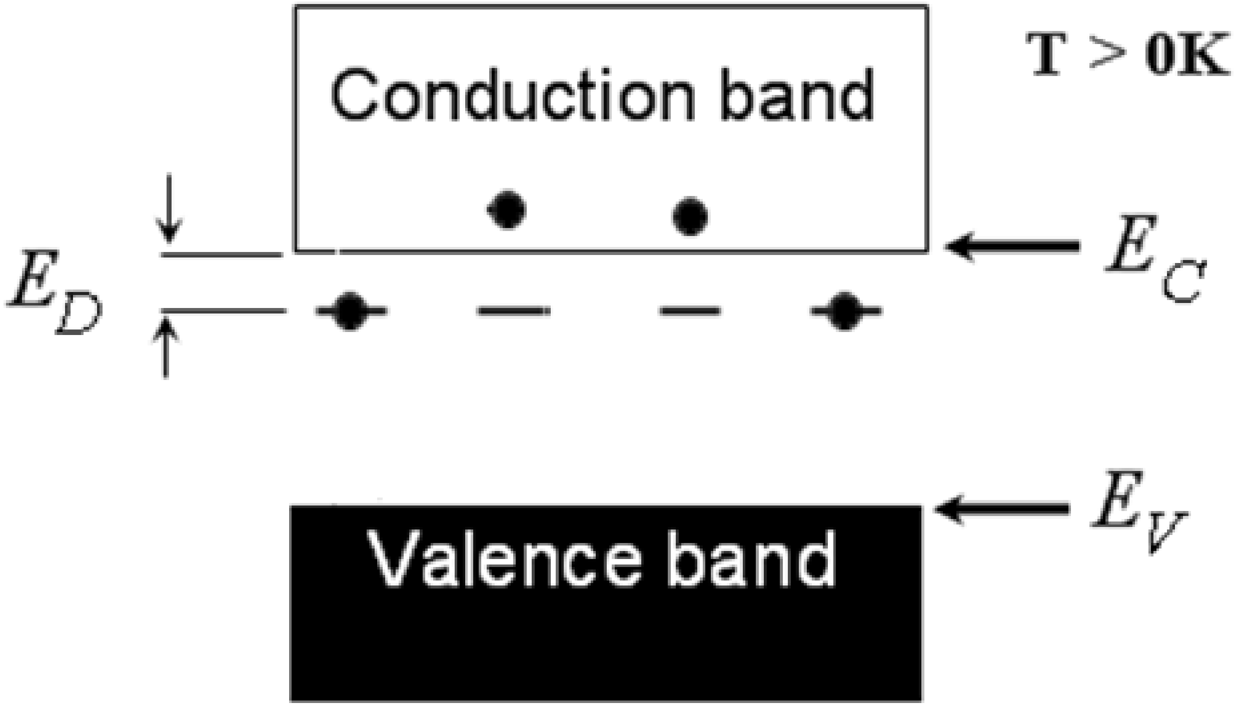
- The Band Structure View
  - Such impurities "create" an energy level within the band gap, close to the conduction band
- A donor is similar to a hydrogen atom
  - A positive charge with a single electron within its potential
  - Such impurities are called ***hydrogenic*** donors
  - They create so-called "shallow" levels - the levels that are very close to the conduction band, so the energy required to ionize the atom is small and a sizable fraction of donor atoms will be ionized at room temperature

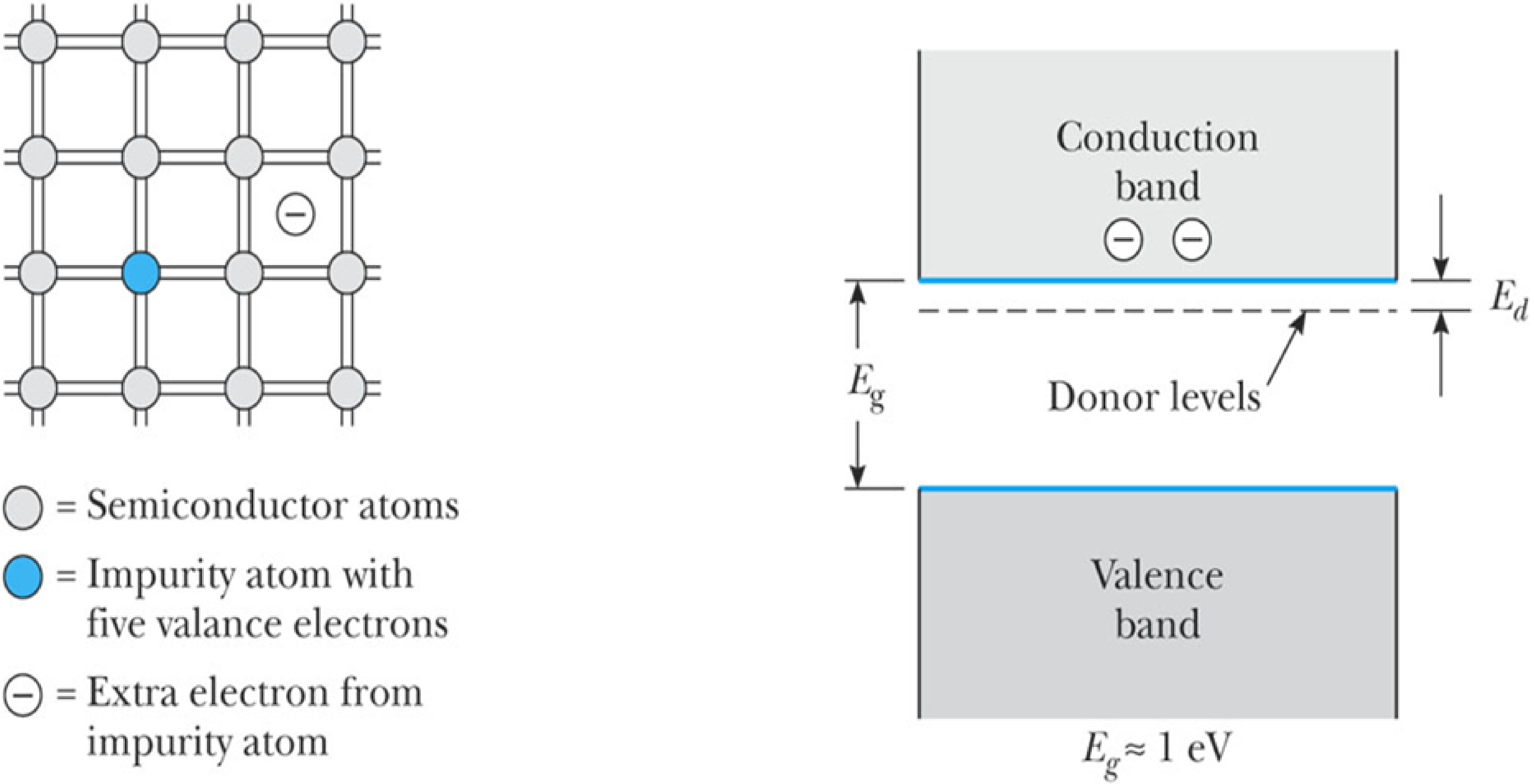



Si
As
T = 0K


Conduction band
T = 0K
E_D
E_C
E_V
Valence band


Free Electron
Excess Positive Charge
Si
As
T > 0K


Conduction band
T > 0K
E_D
E_C
E_V
Valence band

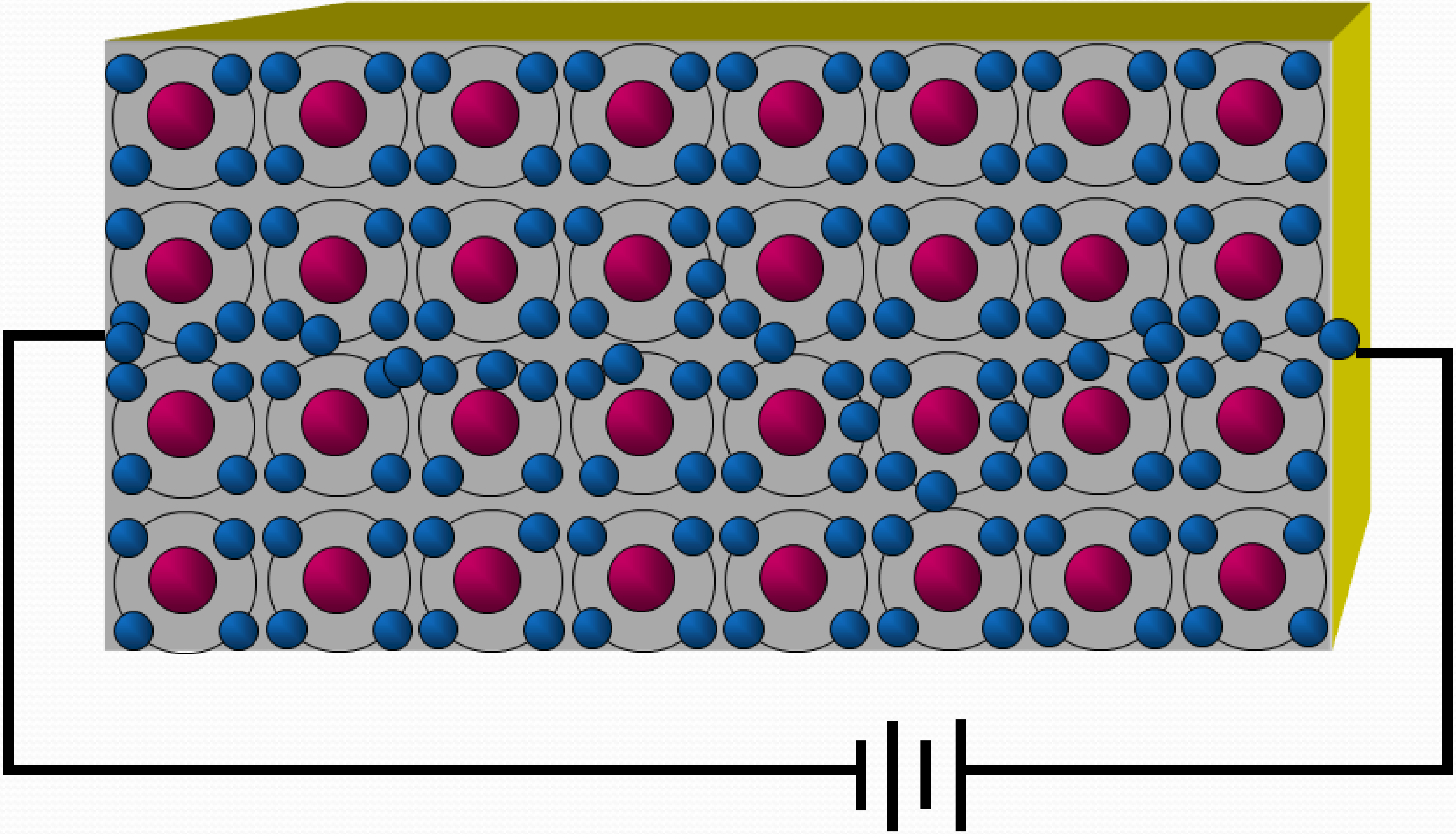


○ = Semiconductor atoms

● = Impurity atom with five valance electrons

⊖ = Extra electron from impurity atom

This crystal has been doped with a pentavalent impurity.



The free electrons in n type silicon support the flow of current.

Semiconductors

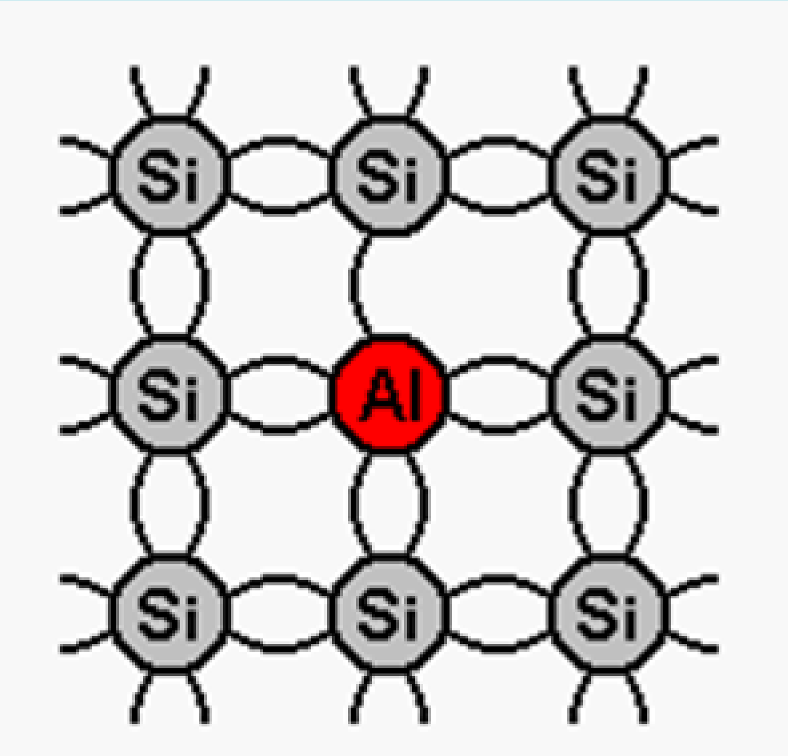
- Semiconductors are materials that essentially can be conditioned to act as good conductors, or good insulators, or any thing in between.
- Common elements such as **carbon, silicon**, and **germanium** are semiconductors.
- Silicon is the best and most widely used semiconductor.

Acceptors

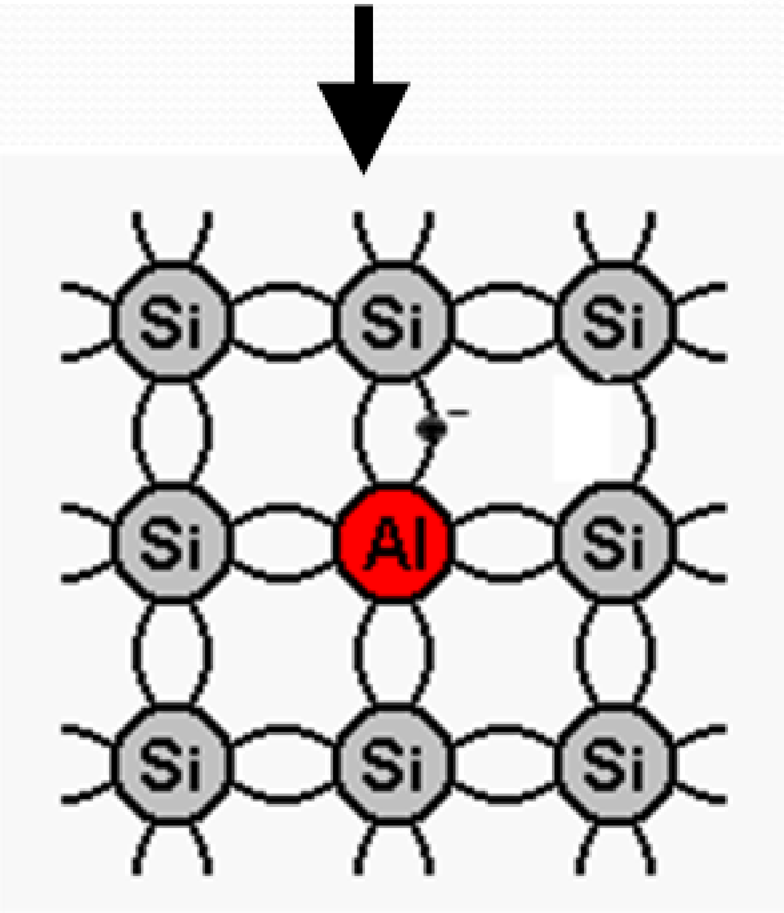
- Use Silicon (Si) as an example
  - Substitute one Group III atom (e.g. Al or In) with a Si (Group IV) atom
  - Si atoms have four valence electrons that participate in the covalent bonding
  - When a Group III atom replaces a Si atom, it cannot complete a tetravalent bond scheme
  - An "electronic vacancy" – hole – is formed when an electron from the valence band is grabbed by the atom so that the core is negatively charged, the hole created is then attracted the negative core
  - At T = 0 K this hole "stays" with atom – localized hole
  - At T > 0 K, electron from the neighboring Si atom can jump into this hole – the hole can then migrate and contribute to the current

Acceptors

- At T > 0 K, electron from the neighboring Si atom can jump into this hole – the hole starts to migrate, contributing to the current
- We can say that this impurity atom accepted an electron, so we call them **Acceptors**
- Acceptors accept electrons, but "donate" free holes



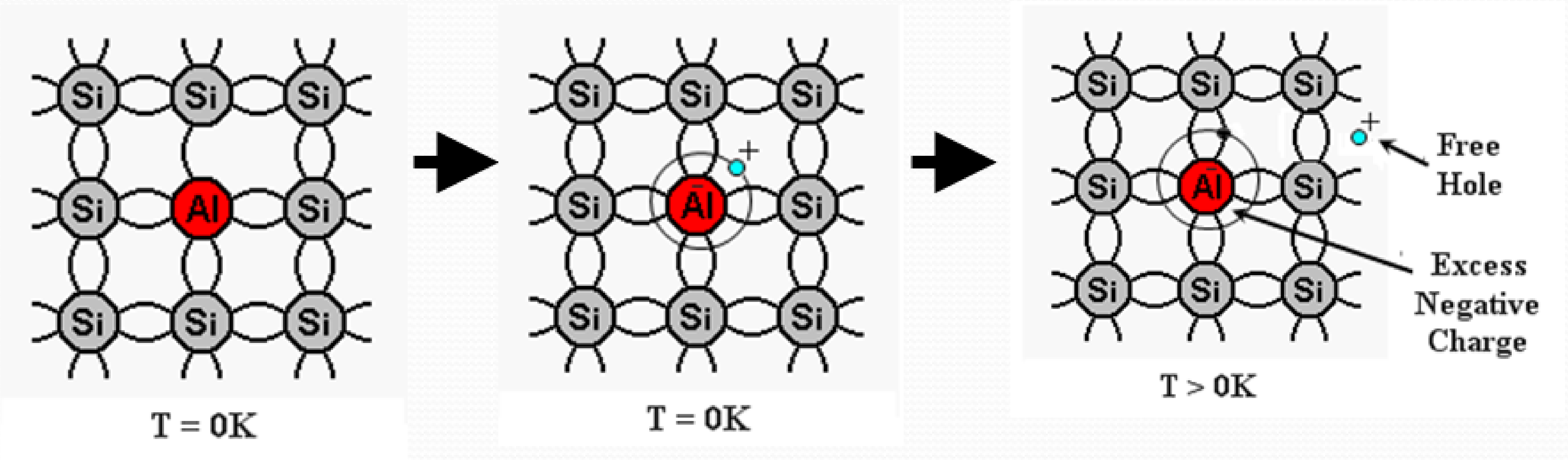
T = 0K



T > 0K

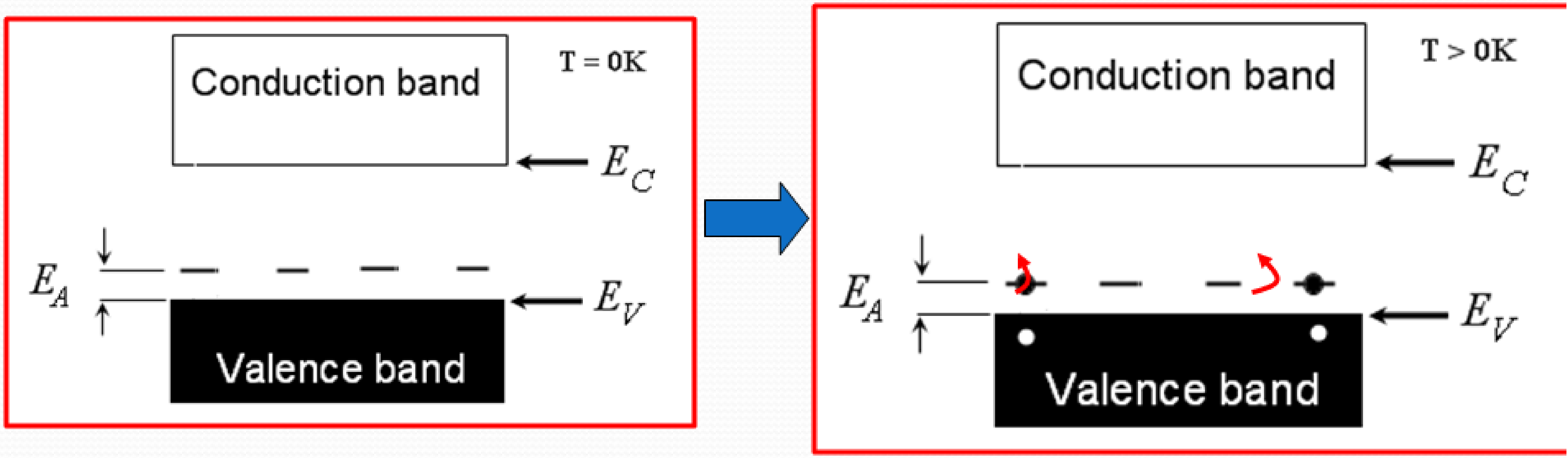
Acceptors

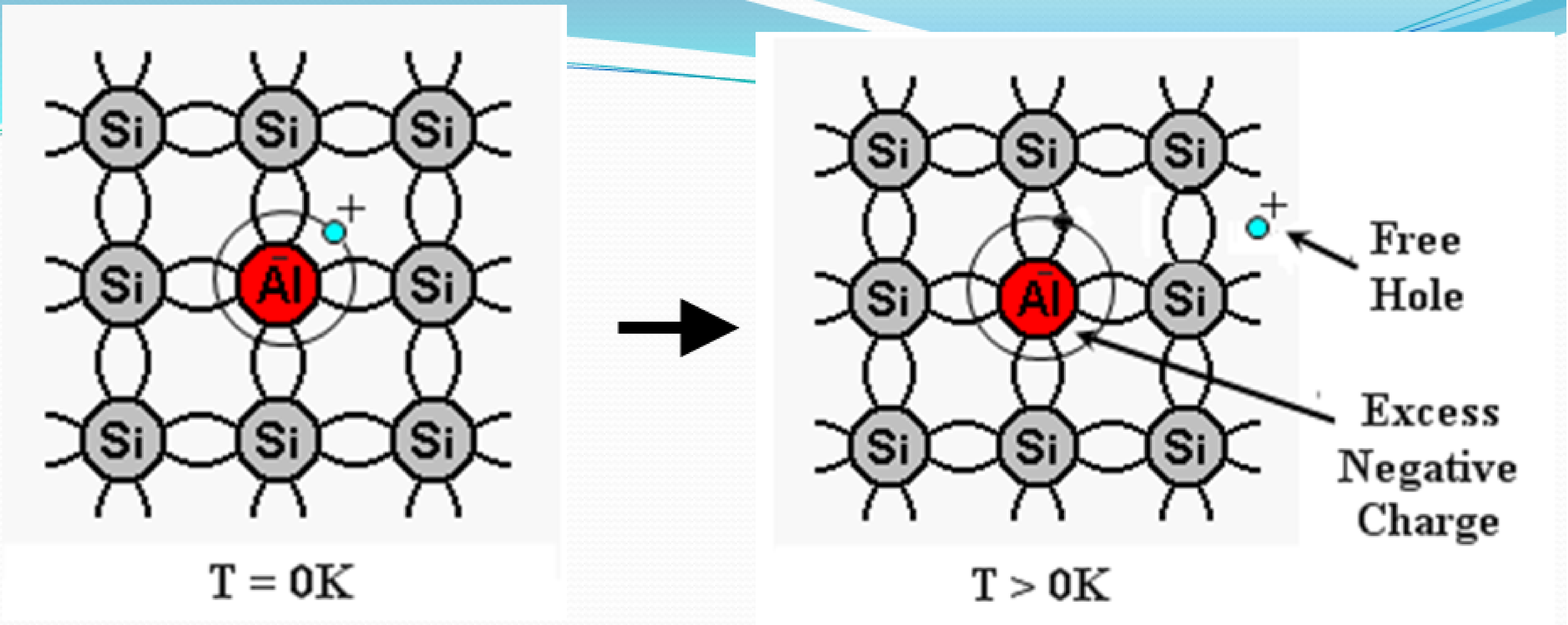
- By "incorporating" the electron into the impurity atom we can represent this (T = 0 K) as a negative charge in the core with a positive charge (hole) outside the core attracted by its [Coulomb] potential
- At T > 0 K this hole can be ionized
- Such semiconductors are called ***p-type semiconductors*** since they contribute positive charge carriers



Acceptor: Energy Levels

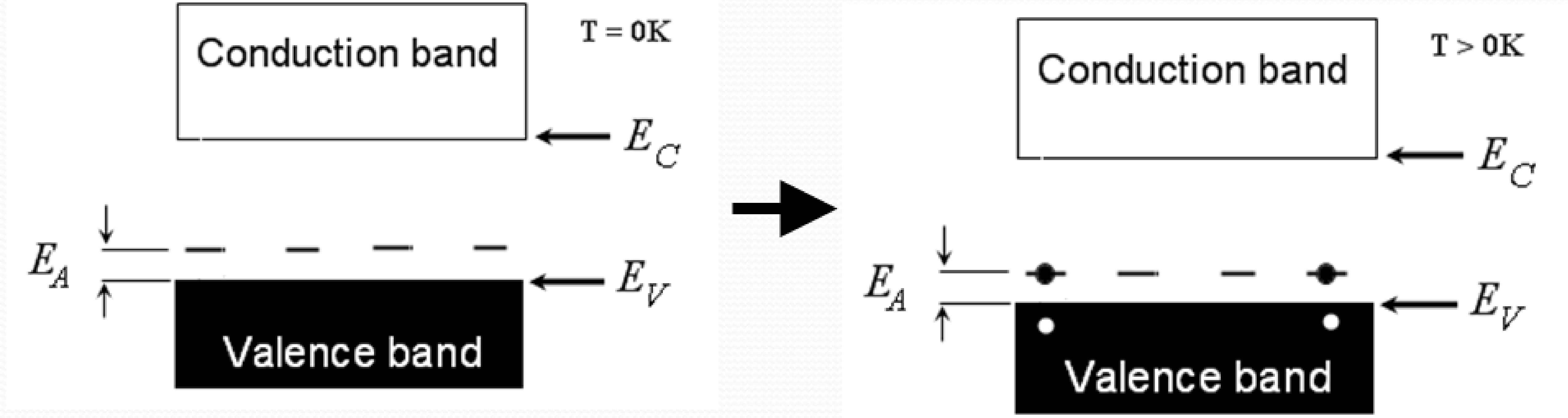
- From the Band Structure View
  - Such impurities “create” energy levels within the band gap, close to the valence band
  - They are similar to “negative” hydrogen atoms
  - Such impurities are called hydrogenic acceptors
  - They create “shallow” levels - levels that are very close to the valence band, so the energy required to ionize the atom (accept the electron that fills the hole and creates another hole further from the substituted atom) is small





T = 0K

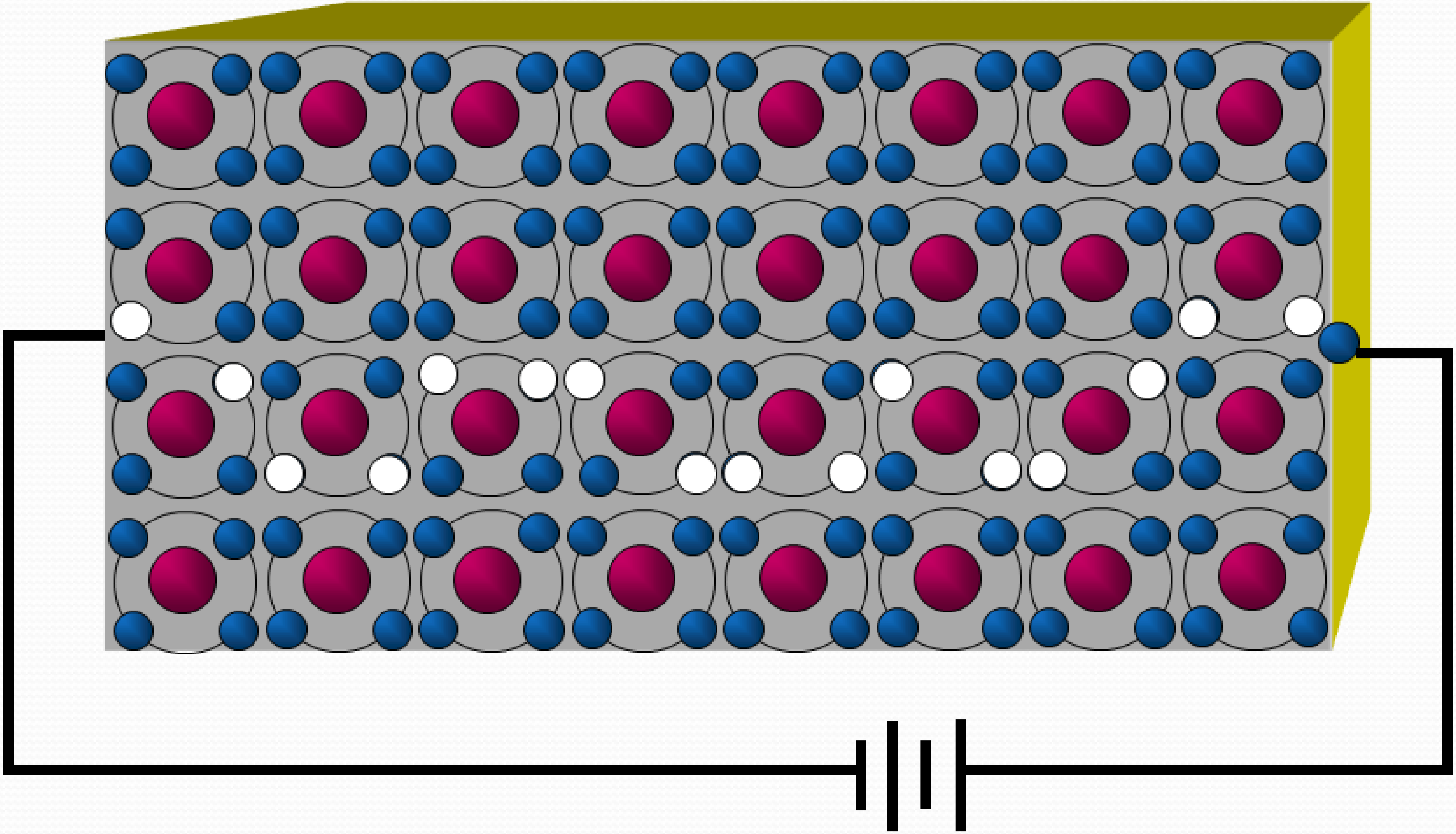
T > 0K



T = 0K

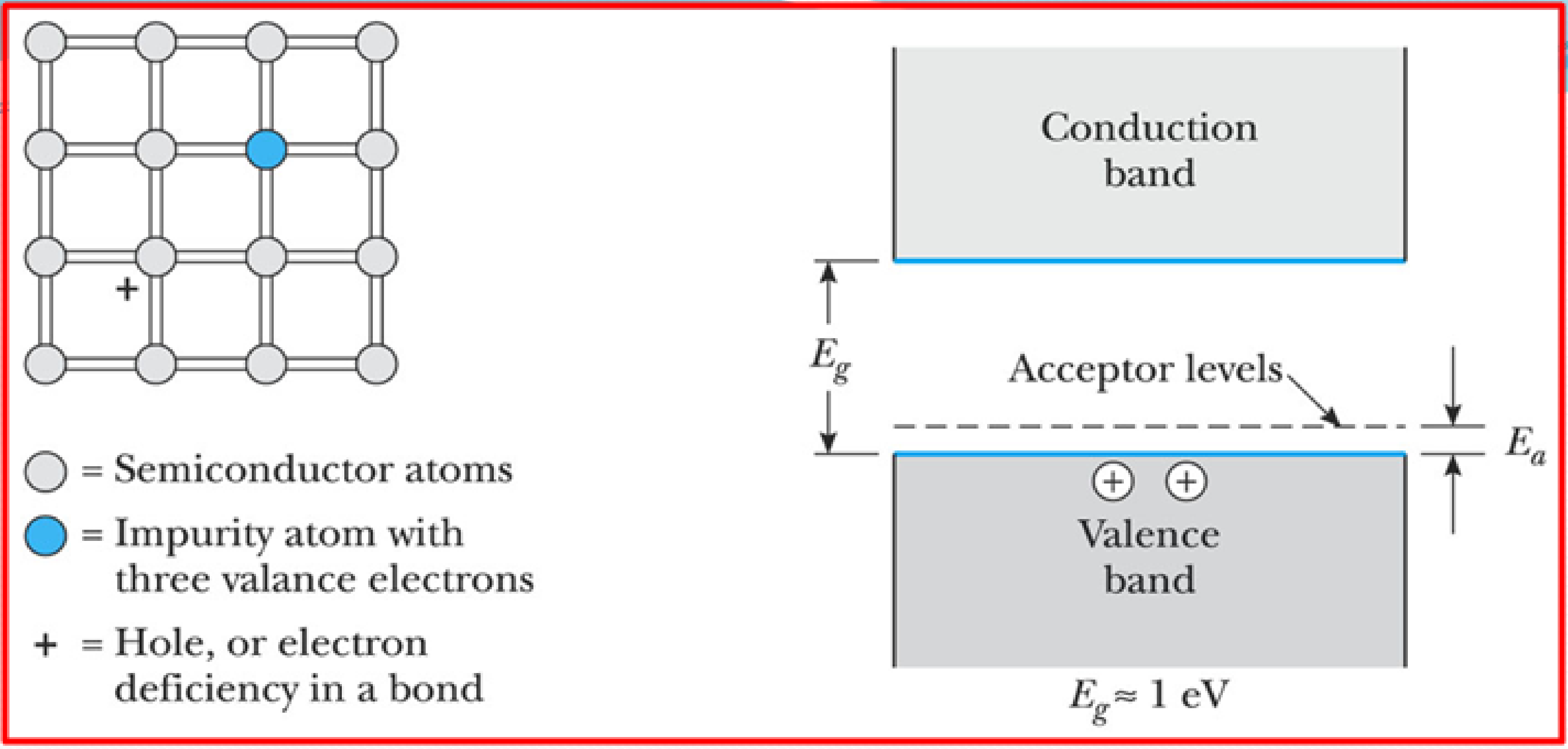
T > 0K

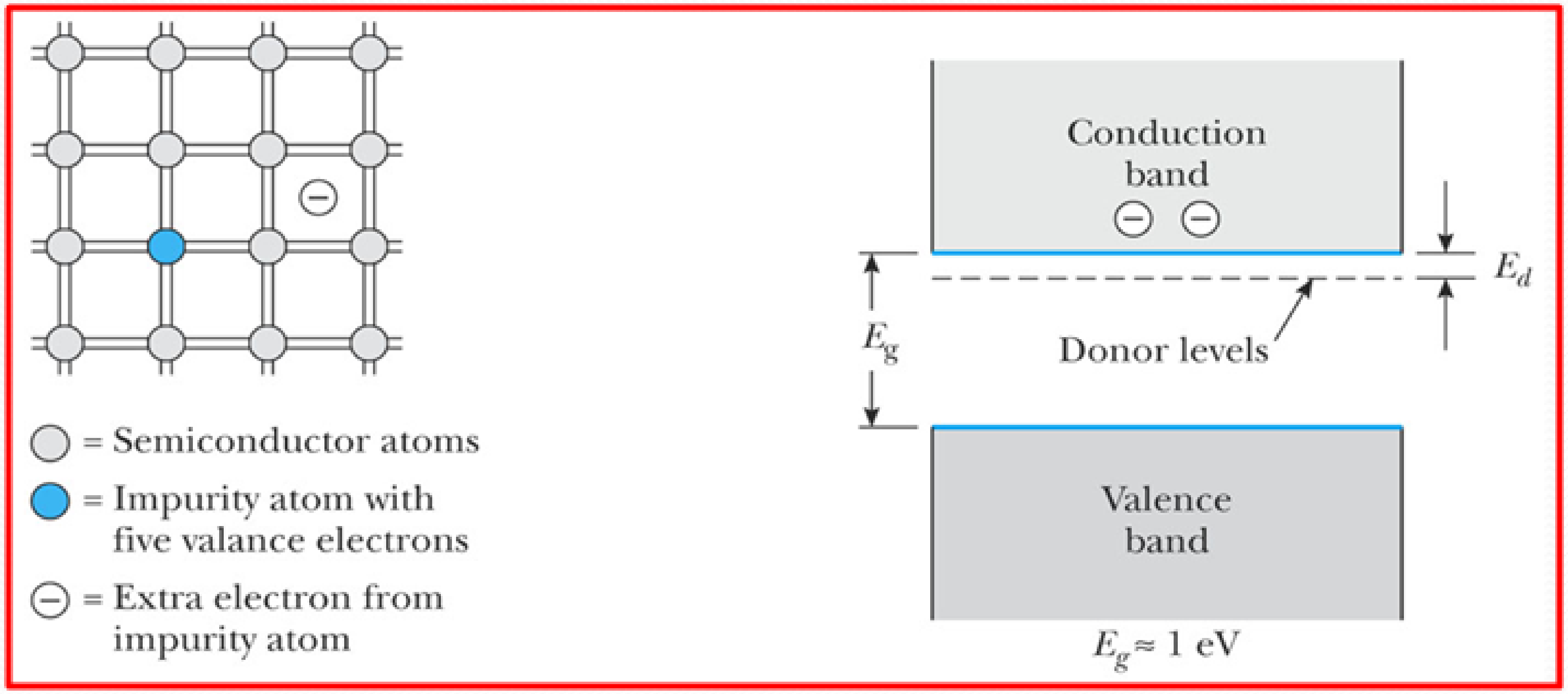
This crystal has been doped with a trivalent impurity.



The holes in p type silicon contribute to the current.

Note that the hole current direction is opposite to electron current so the electrical current is in the same direction


+
○ = Semiconductor atoms
● = Impurity atom with three valance electrons
+ = Hole, or electron deficiency in a bond
Conduction band
E_g
Acceptor levels
E_a
⊕ ⊕
Valence band
$E_g \approx 1$ eV


⊖
○ = Semiconductor atoms
● = Impurity atom with five valance electrons
⊖ = Extra electron from impurity atom
Conduction band
⊖ ⊖
E_d
E_g
Donor levels
Valence band
$E_g \approx 1$ eV

Carrier Concentrations in Extrinsic Semiconductors

- The carrier densities in extrinsic semiconductors can be very high
- It depends on doping levels ([net] dopant concentration) and ionization energy of the dopants
- Often both types of impurities are present
    - If the total concentration of donors (N_D) is larger than the total concentration of acceptors (N_A) have an ***n-type semiconductor***
    - In the opposite case have a ***p-type semiconductor***

Charge Neutrality Equation

- To calculate the charge concentration, the charge neutrality condition is used, since the net charge in a uniformly doped semiconductor is zero
  - Otherwise, there will be a net flow of charge from one point to another resulting in current flow

$$\boxed{p + N_D^{+} = n + N_A^{-}}$$

  - p is the concentration of holes in the valence band
  - n is the electron concentration
  - N_D^+ is the ionized donor concentration
  - N_A^- is the ionized acceptor concentration

Resisitivity of Semiconductors

$$\boxed{\rho_n^{-1} = \sigma_n = \frac{q^2 n \tau}{m^*}}$$

- The carrier concentration and thus the conductivity is dominated by its essentially exponential dependence on temperature
- For intrinsic semiconductors

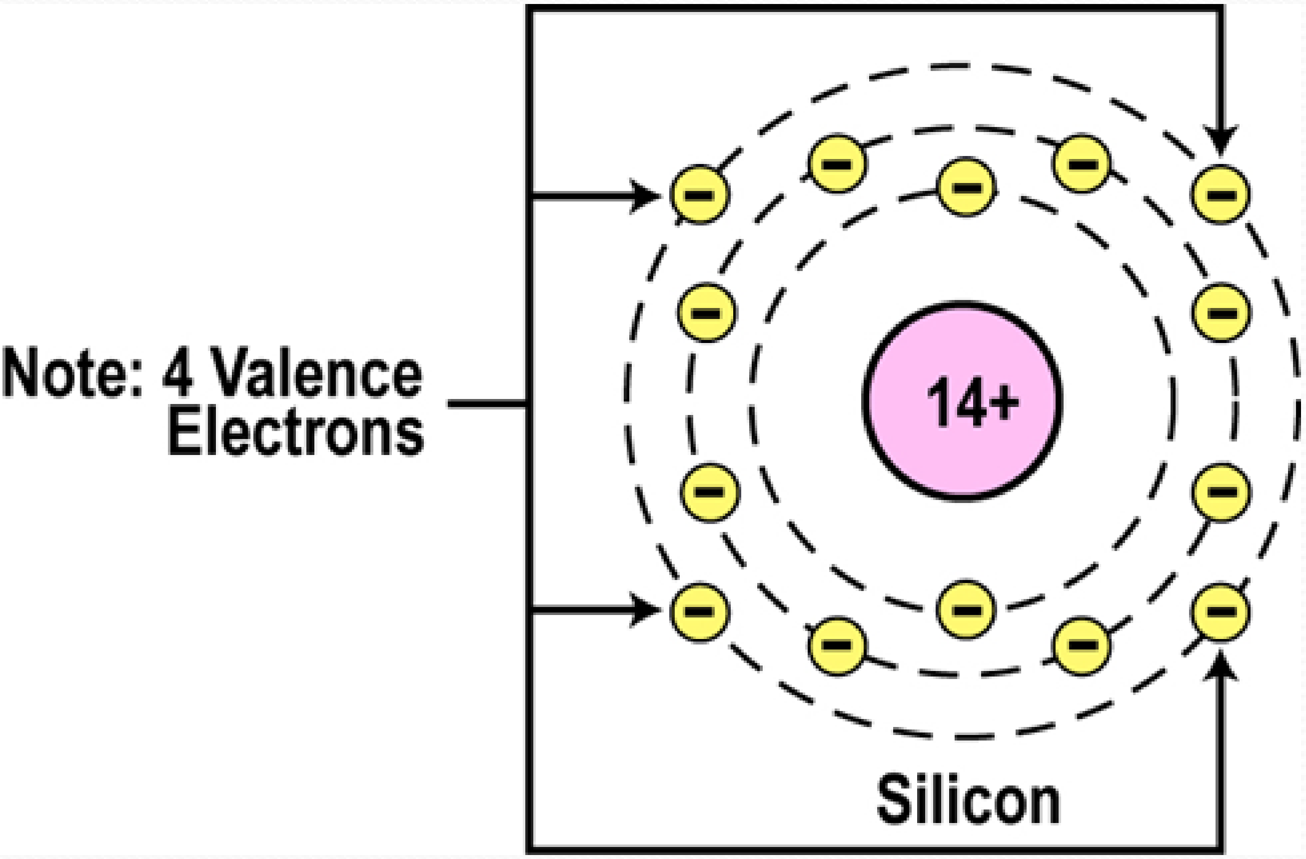
$$\boxed{\rho_n^{-1} = \sigma_n = \frac{q^2 n \tau}{m^*} = \mathrm{constant}\ \ \exp[-\frac{\mathrm{E_g}}{\mathrm{2kT}}]}$$

- For impurity semiconductors

$$\boxed{\rho_n^{-1} = \sigma_n = \frac{q^2 n \tau}{m^*} = \mathrm{constant}\ \ \exp[-\frac{(\mathrm{E_g} - \mathrm{E_F})}{\mathrm{2kT}}]}$$

- E_F is first between the impurity level and the band edge and then approaches $E_g/2$ after most of the impurities are ionized

Semiconductor Valence Orbit

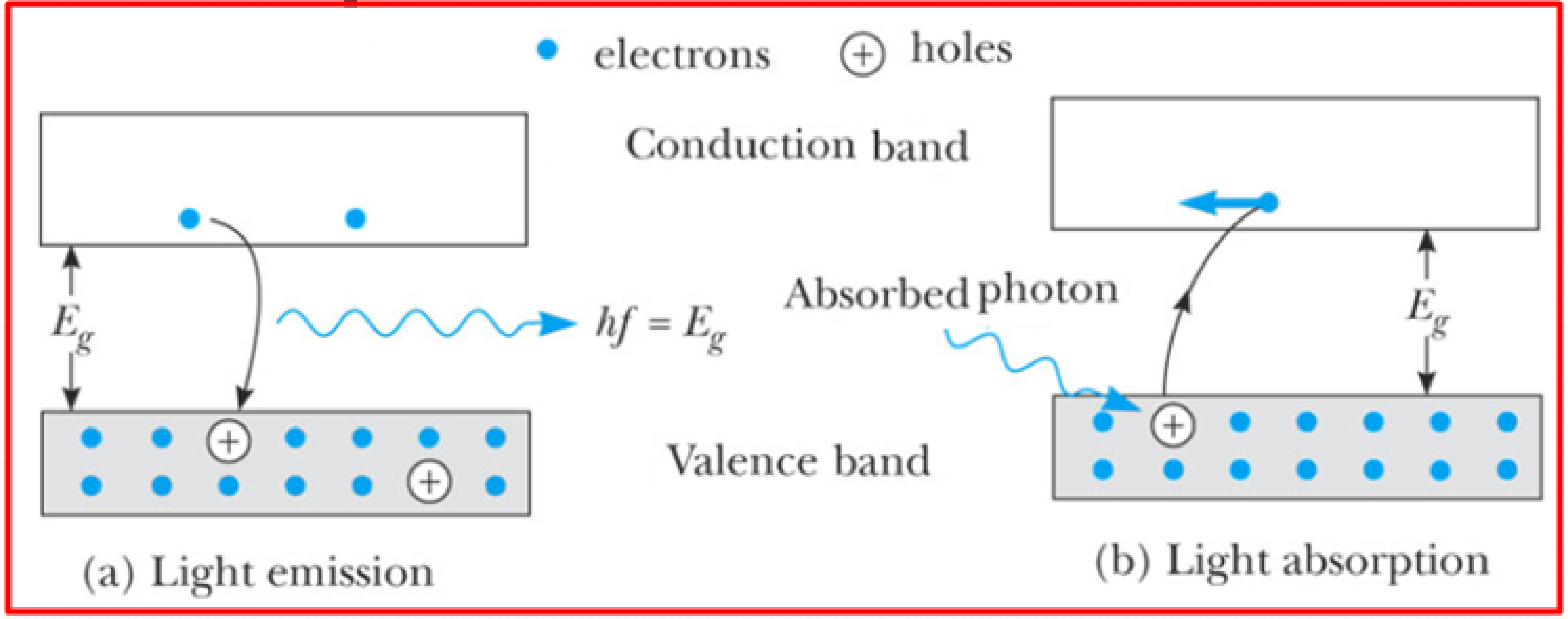


- The main characteristic of a semiconductor element is that it has <u>four electrons</u> in its outer or valence orbit.

Semiconductors in Summary

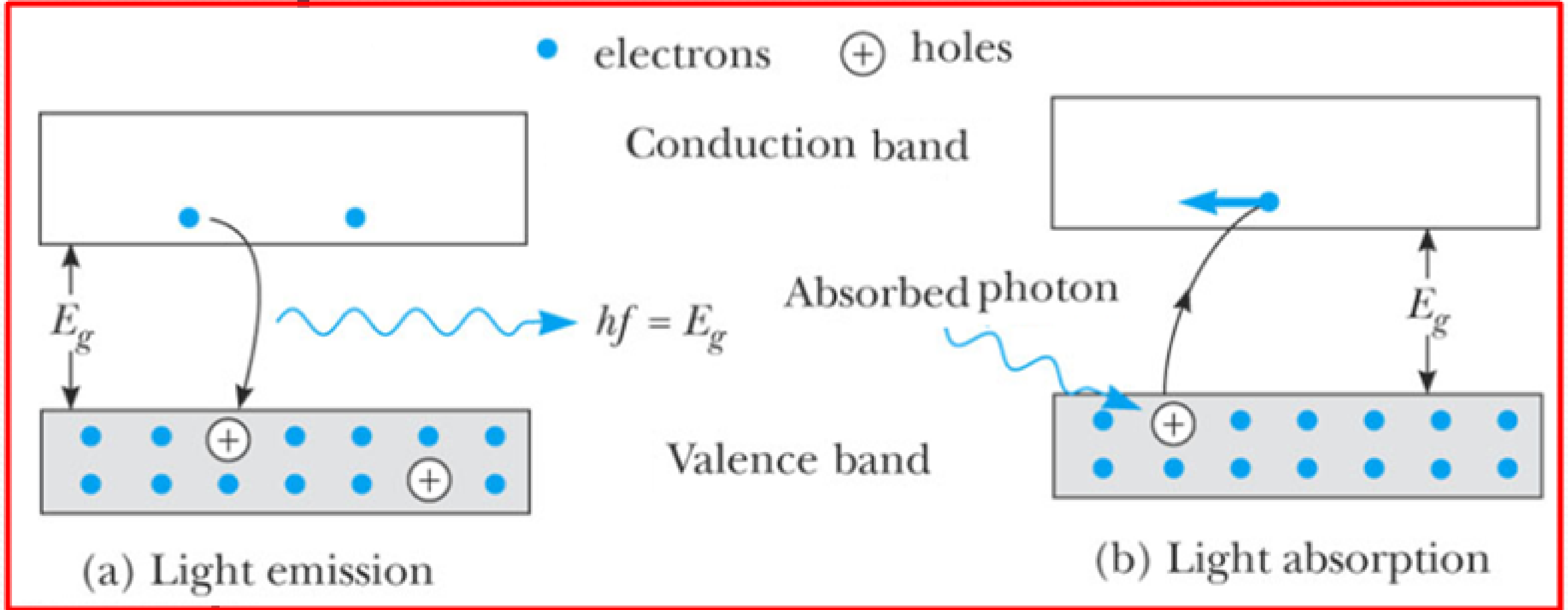
- **The most widely used material is silicon**
- **Pure crystals are <u>intrinsic</u> semiconductors**
- **Doped crystals are <u>extrinsic</u> semiconductors**
- **Crystals are doped to be n type or p type**
- **n type semiconductors have few *minority* carriers (*holes*).**
- **p type semiconductors have few *minority* carriers (*electrons*).**

Optical Properties



- If semiconductor or insulator does not have many impurity levels in the band gap, photons with energies smaller than the band gap energy can't be absorbed
  - **There are no quantum states with energies in the band gap**
- This explains why many insulators or wide band gap semiconductors are transparent to visible light, whereas narrow band semiconductors (Si, GaAs) are not

Optical Properties

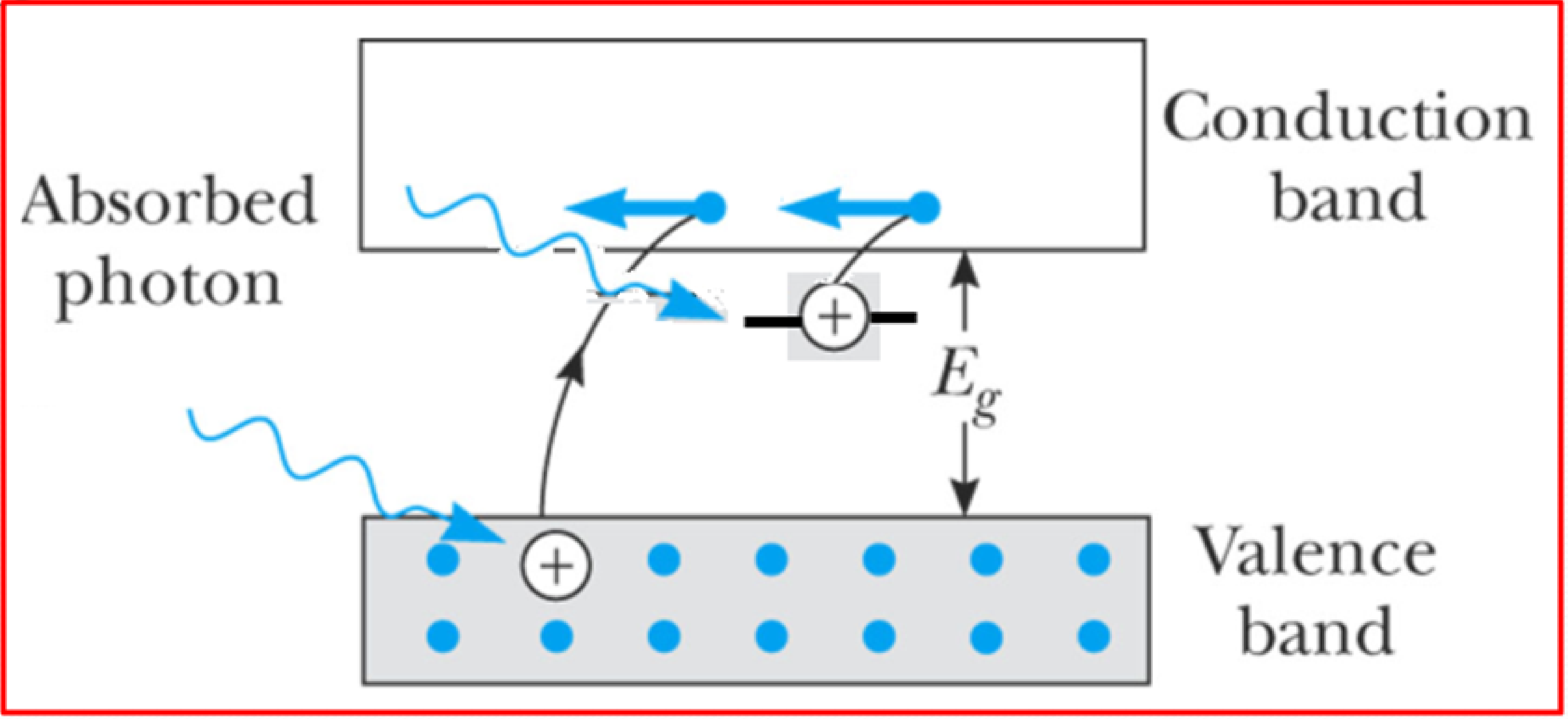


(a) Light emission

(b) Light absorption

- Some applications
  - Emission: light emitting diode (LED) and Laser Diode (LD)
  - Absorption: Filtering
    - **Sunglasses**
    - **Si filters: transmission of infra red light with simultaneous blocking of visible light**

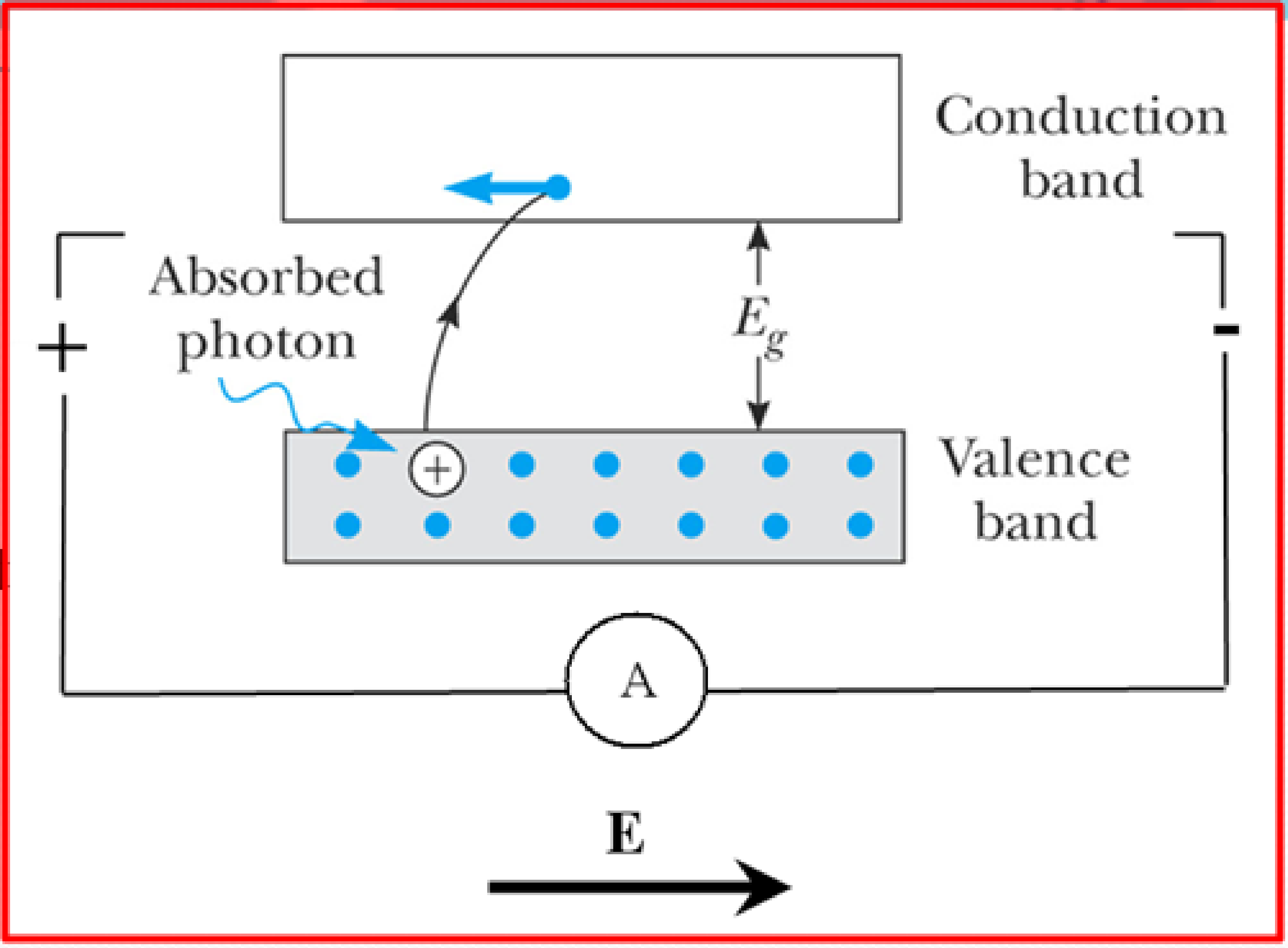
Optical Properties



- If there are many impurity levels the photons with energies smaller than the band gap energy can be absorbed, by exciting electrons or holes from these energy levels into the conduction or valence band, respectively
  - **Example: Colored Diamonds**

Photoconductivity

- Charge carriers (electrons or holes or both) created in the corresponding bands by absorbed light can also participate in current flow, and thus should increase the current for a given applied voltage, i.e., the conductivity increases
- This effect is called *Photoconductivity*



- Want conductivity to be controlled by light. So want few carriers in dark → semiconductor
- But want light to be absorbed, creating photoelectrons
- → Band gap of intrinsic photoconductors should be smaller than the energy of the photons that are absorbed

Photoconductivity

- Important Applications
  - Night vision systems imaging IR radiation
  - Solar cells
  - Radiation detectors
  - Photoelectric cells (e.g., used for automatic doors)
  - Xerography
  - CCD ("Digital Cameras")

Charge carriers in semiconductors

- Electrons and holes
  - Electrons (e) we know about, but what is a hole (h)?
    - When an electron receives enough energy to jump from the valence band to the conduction band it leaves behind an empty state. This creates an electron-hole pair (EHP)
    - Hole current is really due to an electron moving in the opposite direction in the valence band.
    - Electron current is an electron moving from state to state in the conduction band.

$$k_h = -k_e$$

$$\in_h \left(k_h\right) = - \in_e \left(k_e\right)$$

$$v_h = v_e$$

$$m_h = -m_e$$

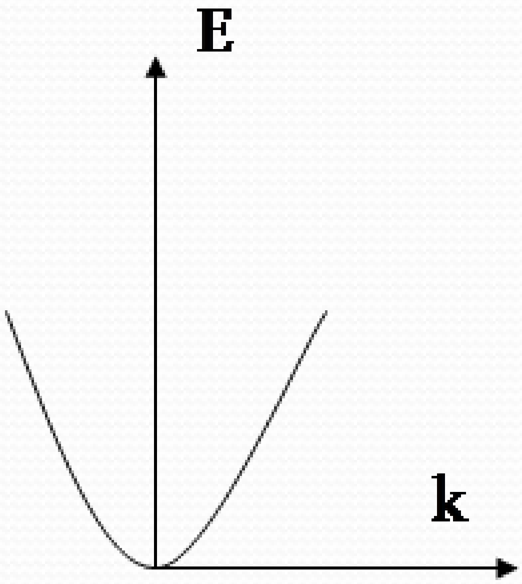
$$\left.\begin{aligned} \hbar \frac{d\vec{K}_h}{dt} &= \vec{F}_h = e(E + \frac{1}{c} V_h x B) \\ \hbar \frac{d\vec{K}_e}{dt} &= \vec{F}_e = -e(E + \frac{1}{c} V_e x B) \end{aligned}\right\} \vec{F}_h = -\vec{F}_e$$

Charge carriers in semiconductors

- Effective mass
  - Electrons in a crystal are not totally free.
  - The periodic crystal affects how electrons move through the lattice.
  - We use and effective mass to modify the mass of an electron in the crystal.

Charge carriers in semiconductors

- Effective mass



$$p = mv = \hbar k$$

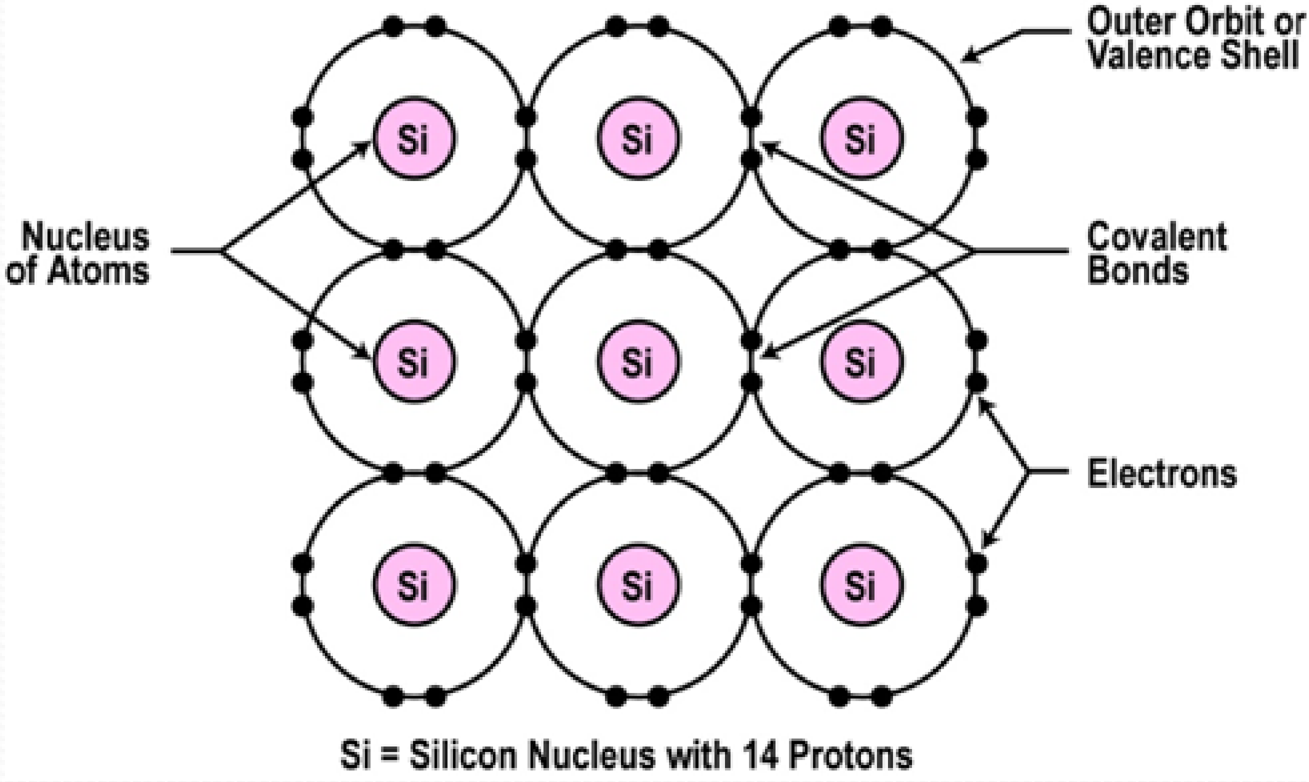
$$E = \frac{1}{2}mv^2 = \frac{\hbar^2}{2m}k^2$$

$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

$$m^* = \frac{\hbar^2}{\frac{d^2E}{dk^2}}$$

Crystal Lattice Structure

- The unique capability of semiconductor atoms is their ability to link together to form a physical structure called a crystal lattice.
- The atoms link together with one another sharing their outer electrons.
- These links are called <u>covalent bonds</u>.



2D Crystal Lattice Structure

- The double derivative of E is a constant
- Not all semiconductors have a perfectly parabolic band structure
- The different atomic spacing in each direction gives rise to different effective masses in different crystal directions. This can be compensated by using an average value of effective mass.

- Effective mass (for density of states calculation)

	Ge	Si	GaAs
m_n^*	0.55 m_0	1.1 m_0	0.067 m_0
m_p^*	0.37 m_0	.56 m_0	0.48 m_0

Charge carriers in semiconductors

Intrinsic material

- A perfect semiconductor crystal
  - no impurities or defects
- No charge carriers at 0K
  - valence band is filled, conduction band empty
- Heat (lattice vibrations can break a covalent bond and push an electron into the conduction band)
- This electron is moving several lattice constants away in a QM probability distribution.

- Each electron pumped up to the valence band leaves an empty state behind, thus for intrinsic material the electron concentration in the conduction band (n_e/cm^3)=the hole concentration in the valence band (p_h/cm^3)

$$n = p = n_i$$

- If this relation is to hold then the generation rate of EHP's must equal the recombination rate of EHP's

$$n = p = n_i$$

$$r_i = g_i$$

$$r_i = \alpha_r n_0 p_0 = \alpha_r n_i^2 = g_i$$

Charge carriers in semiconductors

- Extrinsic material
  - Intrinsic material is not very useful except for devices which change their conductivity based on optical or thermal excitation. There is no gain mechanism involved and thus large areas are needed to detect the effect, thus are slow.
  - One can create extrinsic material by replacing semiconductor atoms in the lattice with atoms from different groups in the periodic table.

Charge carriers in semiconductors

- Extrinsic material.

II	III	IV	V	VI
	B	C		
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In		Sb	Te

- Elements from group V give rise to energy levels close the the conduction band in Si and Ge and is completely filled at oK. It only takes a little energy to make an electron jump from this level to the conduction band. This new energy level donates an electron and so group V elements are know as donors (with respect to Si and Ge)

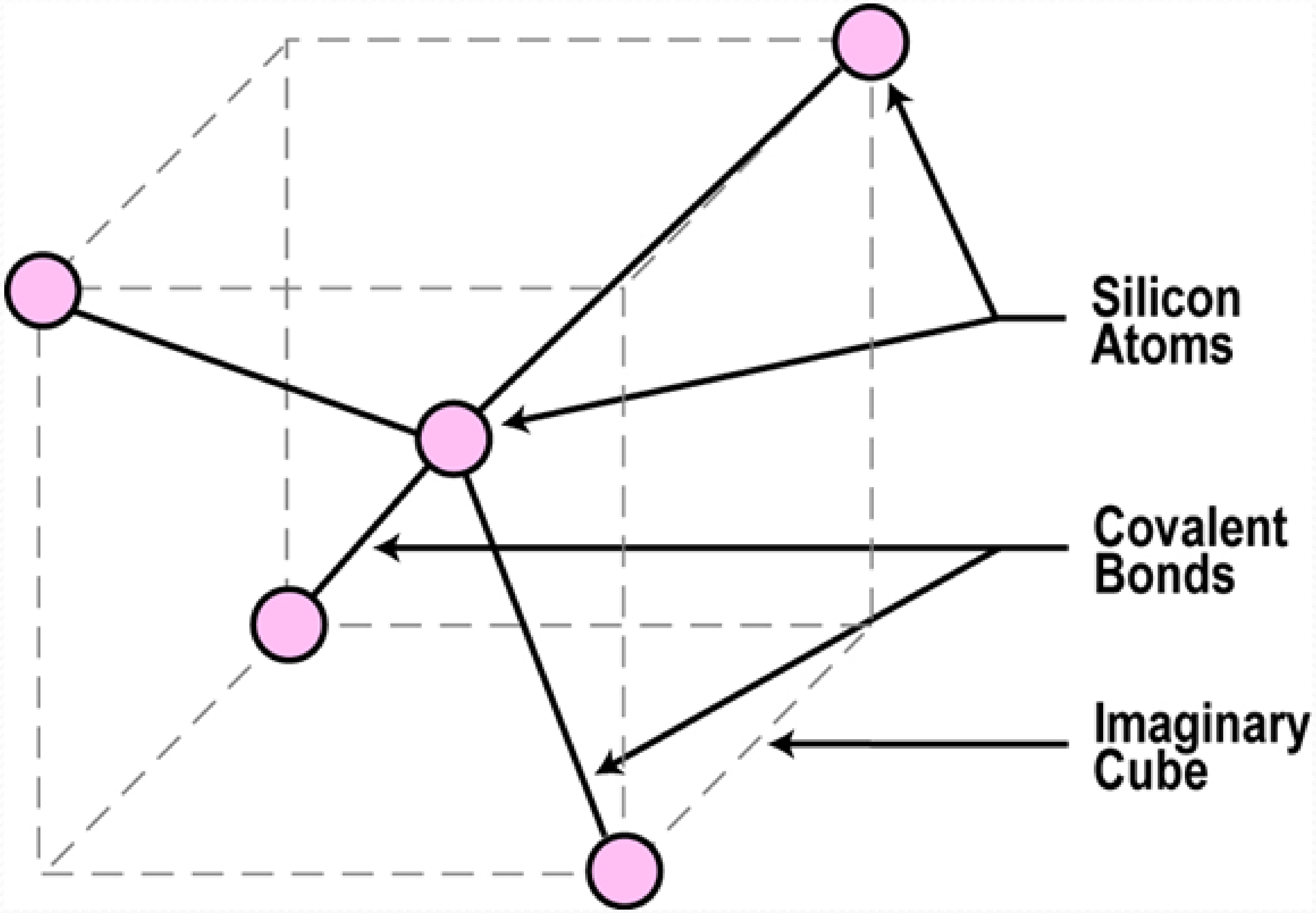
- Extrinsic material.
  - Elements from group III give rise to energy levels close the the valence band in Si and Ge and is completely empty at oK. It only takes a little energy to make an electron jump from the valence band to this new level. This new energy level accepts an electron and so group III elements are knows as acceptors (with respect to Si and Ge)

Problem

- Calculate the concentrations of free carriers in intrinsic silicon at *T*=350 K and the change of it if the temperature changes:
  a) 0.2 %,
  b) 20 %.

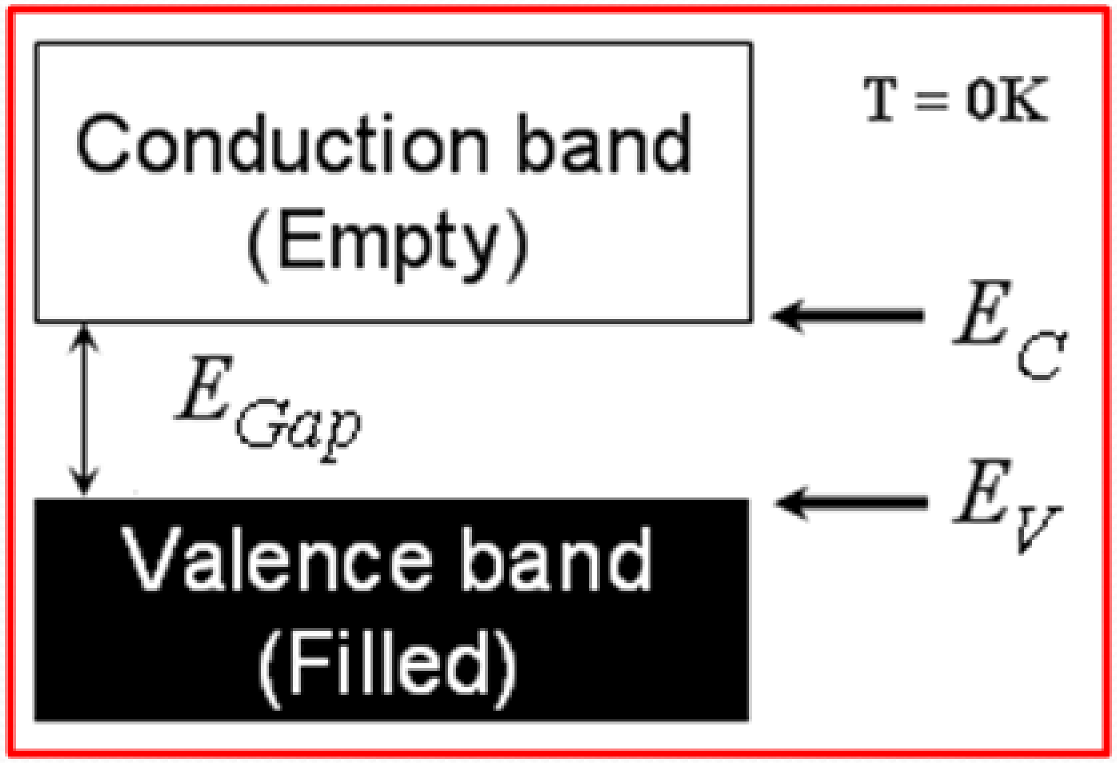
$$n_i = C \cdot T^{3/2} \cdot \exp\left(-\frac{E_{G0}}{2 \cdot k \cdot T}\right)$$

3D Crystal Lattice Structure



- The highest energy band completely filled with electrons (at T = 0 K) is called the ***Valence Band***
- The next band is called the ***Conduction Band***

- The energy difference between the bottom of the ***Conduction*** and the top of the ***Valence*** bands is called the ***Band Gap***

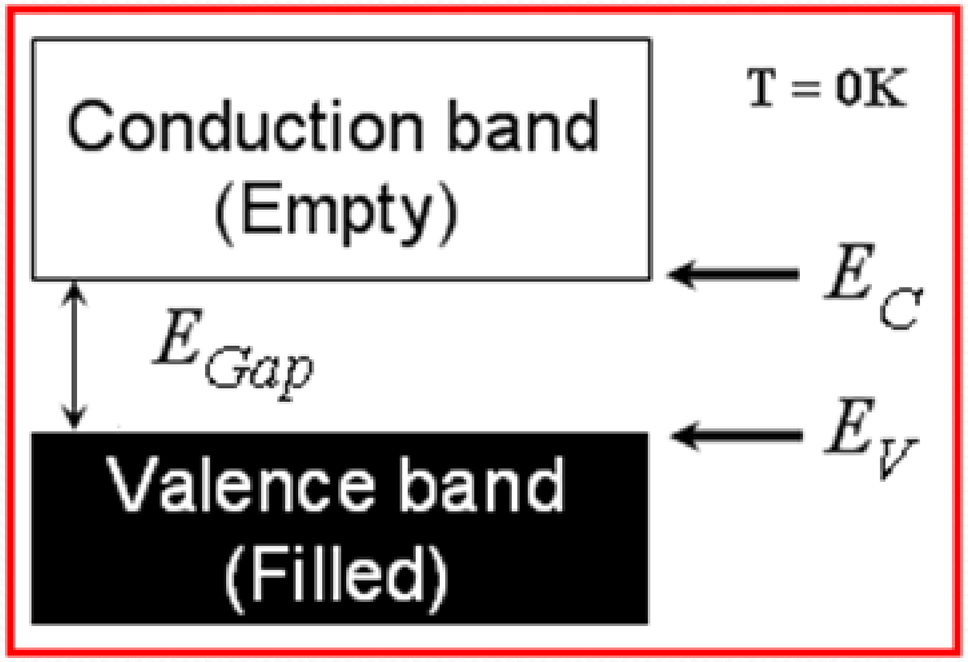


Conduction

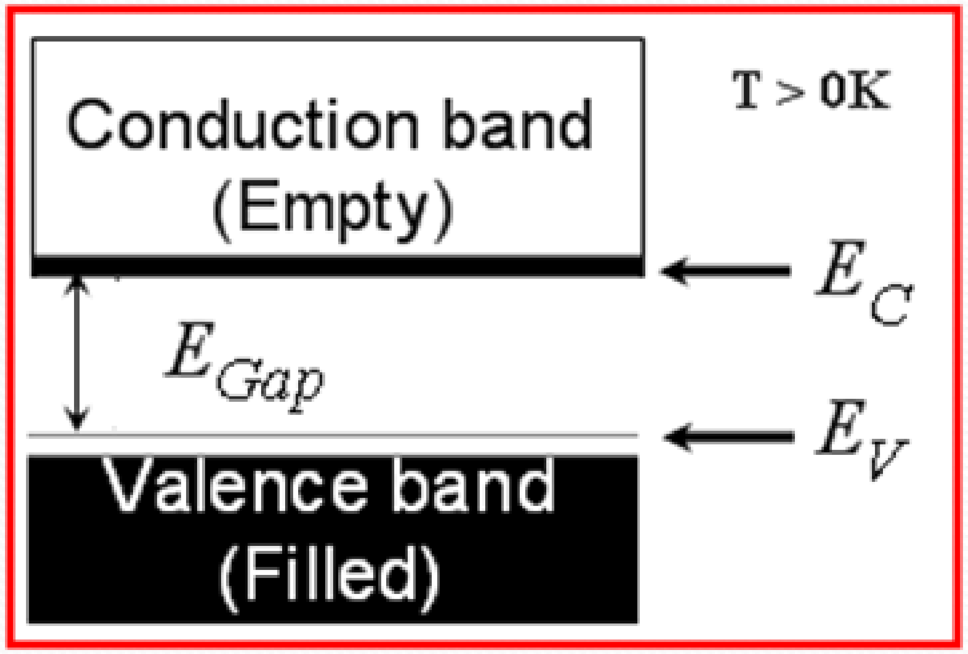
- ***Electron Conduction*** is easy to imagine: electrons (in the conduction band) move almost like free particles
- ***Hole Conduction*** is due to positively charged particles in the valence band

Intrinsic Semiconductors

- Consider nominally pure semiconductor at T = 0 K
- There is no electrons in the conduction band



- At T > 0 K a small fraction of electrons is thermally excited into the conduction band, “leaving” the same number of holes in the valence band



Intrinsic Semiconductors at T >0 K

- Electrons and holes contribute to the current when a voltage is applied

$$\sigma = \frac{e^2 n_e \tau_n}{m_e^*} + \frac{e^2 n_h \tau_p}{m_h^*}$$