Introduction to
Semiconductor Physics

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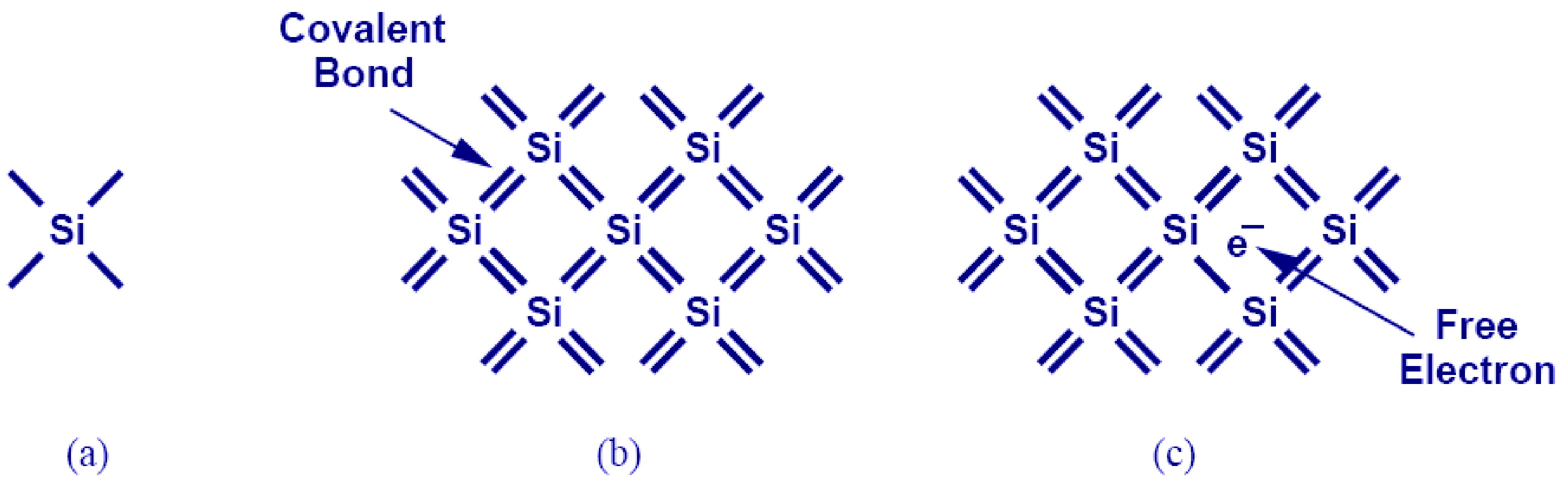
Silicon

- Atomic density: 5×10^{22} atoms/cm^3
- Si has four valence electrons. Therefore, it can form covalent bonds with four of its nearest neighbors.
- When temperature goes up, electrons can become free to move about the Si lattice.



Electronic Properties of Si

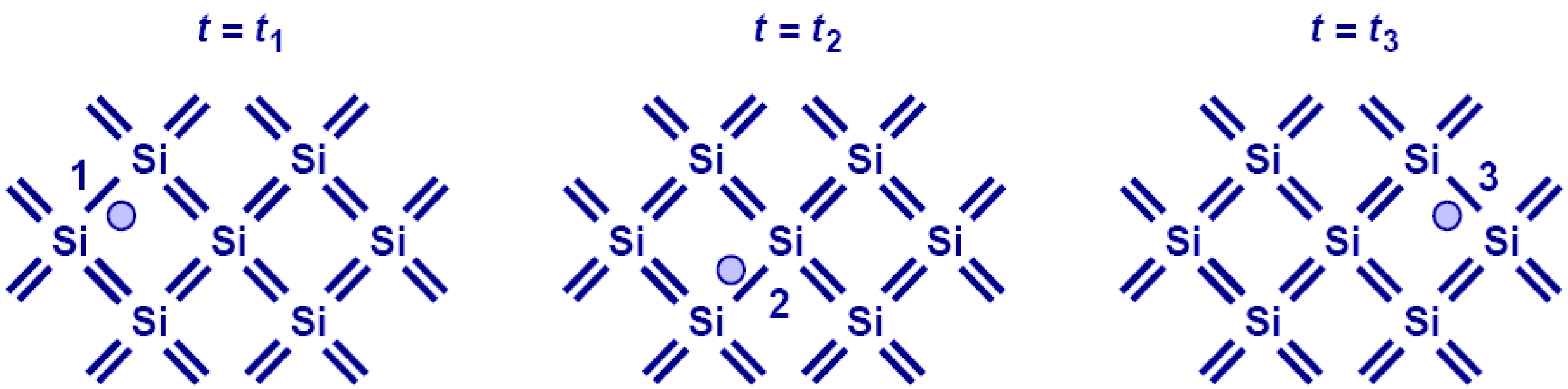
- **Silicon is a semiconductor material.**
  - Pure Si has a relatively high electrical resistivity at room temperature.

- **There are 2 types of mobile charge-carriers in Si:**
  - ***Conduction electrons*** are negatively charged;
  - ***Holes*** are positively charged.

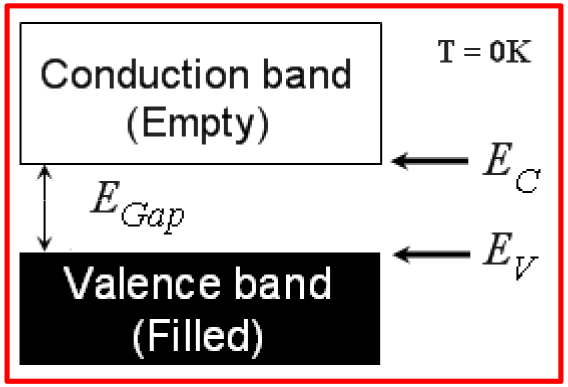
- **The concentration (/cm^3) of conduction electrons & holes in a semiconductor can be modulated in several ways:**
  1. **by adding special impurity atoms (*dopants*)**
  2. **by applying an electric field**
  3. **by changing the temperature**
  4. **by irradiation**

Electron-Hole Pair Generation

- When a conduction electron is thermally generated, a "hole" is also generated.
- A hole is associated with a positive charge, and is free to move about the Si lattice as well**.**



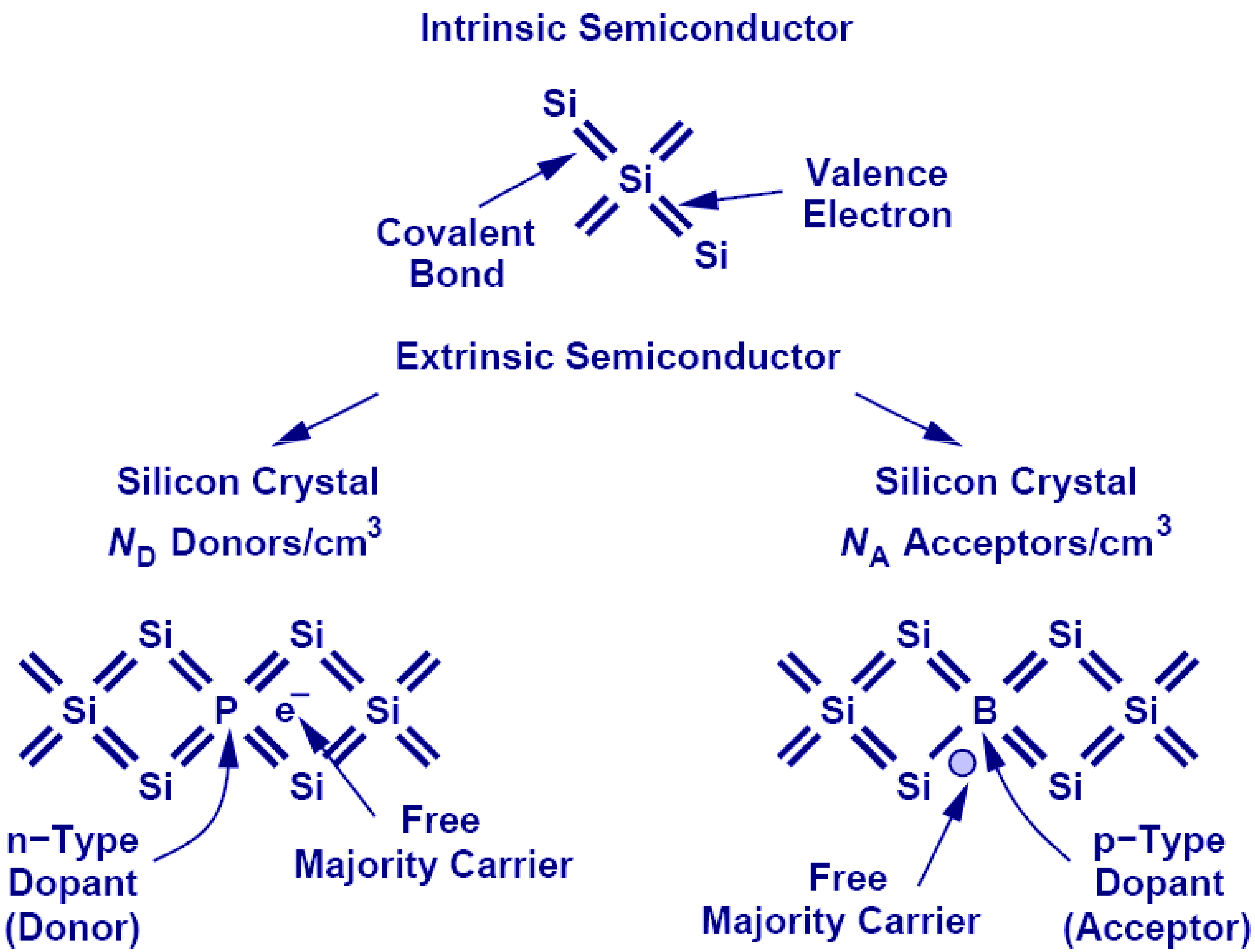
- The highest energy band completely filled with electrons (at T = 0 K) is called the ***Valence Band***
- The next band is called the ***Conduction Band***
- The energy difference between the bottom of the ***Conduction*** and the top of the ***Valence*** bands is called the ***Band Gap***



Conduction

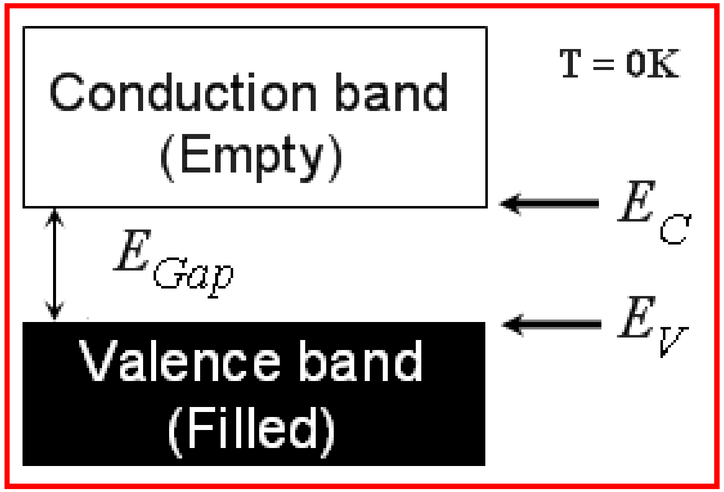
- ***Electron Conduction*** is easy to imagine: electrons (in the conduction band) move almost like free particles
- ***Hole Conduction*** is due to positively charged particles in the valence band

Summary of Charge Carriers

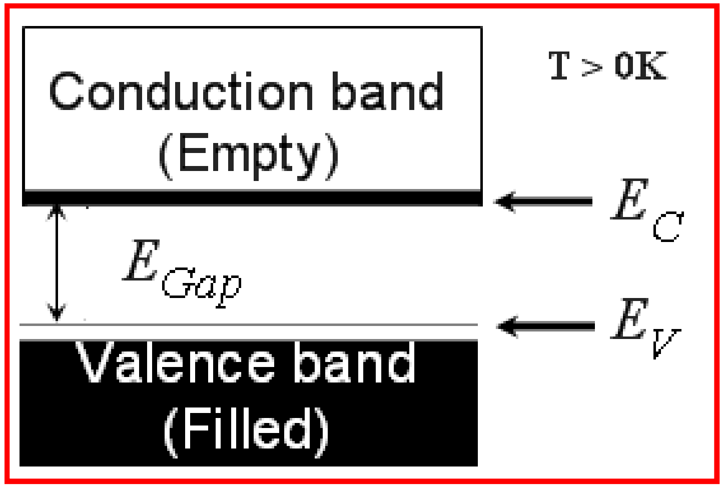


Intrinsic Semiconductors

- 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



Calculation of Carrier concentration in an intrinsic semiconductor:

a) Carrier concentration in Conduction band:

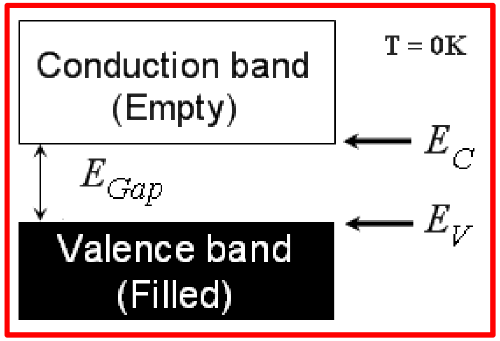
Let 'dn' be the number of electrons available between energy states 'E' and 'E+dE' in the conduction band.

dn= Z(E) F(E)dE, where Z(E) dE is the density of states in the energy interval E and E+dE and F(E) is the electron occupancy probability.

If E_c is the energy corresponding to the bottom of the conduction band then the number of electrons in the conduction band is given by

$$n = \int_{E_c}^{\infty} Z(E)F(E)dE$$

where the density of states is given by



Since the electron is moving in a periodic potential, 'm' should be the effective mass.

Since the energy E starts at E_c

$$Z(E)dE = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}(E - E_c)^{1/2}\, dE$$

The Fermi – Dirac distribution function, gives probability of an electron occupying an energy state 'E'

$$F(E) = \frac{1}{1 + exp\left(\frac{E - E_f}{k_B T}\right)}$$

where E_f is the Fermi level.

If

$$(E - E_f) >> k_B T \qquad F(E) \cong exp\left(\frac{E_f - E}{k_B T}\right)$$

$$\therefore n = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}\int_{E_c}^{\infty}(E - E_c)^{1/2}\exp\left(\frac{E_f - E}{k_B T}\right)dE$$

$$= \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}\exp\left(E_f \big/ k_B T\right)\int_{E_c}^{\infty}(E - E_c)^{1/2}\exp\left(\frac{-E}{k_B T}\right)dE$$

To solve this integral we put

$$E - E_c = x$$

$dE = dx$

$$\therefore E = E_c + x;$$

$$\therefore n = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2} \exp\left(E_f \big/ k_B T\right)\int_0^\infty x^{1/2} \exp\left(\frac{-E_c - x}{k_B T}\right)dx$$

Using Gamma function

.

, the integral part is equal to

$$\left(k_B T\right)^{3/2} \frac{\pi^{1/2}}{2}$$

$$= \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2} \exp\left(\frac{E_f - E_c}{k_B T}\right)\int_0^\infty x^{1/2} e^{\frac{-x}{k_B T}} dx$$

$$\therefore n = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2} \exp\left(\frac{E_f - E_c}{k_B T}\right)\left(k_B T\right)^{3/2} \frac{\pi^{1/2}}{2}$$

$$= 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} exp\left(-\frac{E_c - E_f}{k_B T}\right)$$

$$= N_c\, exp\left[-\frac{\left(E_c - E_f\right)}{k_B T}\right]$$

where N_c is a pseudo constant.

Concentration of holes in the valence band of an intrinsic semiconductor:

Let dp be the number of holes in the energy interval E and E+ dE in the valence band.

$$dp = Z(E)[1 - F(E)]dE$$

$1 - F(E)$ gives the probability that an electron will be missing from an energy state E (i.e) a hole is created.

.

$$1 - F(E) = 1 - \frac{1}{1 + exp\left(\frac{E - E_f}{k_B T}\right)}$$

for

$$(E - E_f) >> k_B T$$

$$[1 - F(E)] \cong exp\left(\frac{E - E_f}{k_B T}\right)$$

$$Z(E)dE = \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2} E^{\frac{1}{2}} dE$$

Since E_V is the energy of the top of the valence band

$$Z(E)dE = \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2}\left(E_V - E\right)^{1/2} dE$$

The number of holes (per unit volume) in the valence band is given by

$$P = \int_{-\infty}^{E_V} \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2}\left(E_V - E\right)^{1/2} \exp\left(\frac{E - E_f}{k_B T}\right) dE$$

$$= \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2} \exp\left(\frac{-E_f}{k_B T}\right)\int_{-\infty}^{E_V} \left(E_V - E\right)^{1/2} \exp\left(\frac{E}{k_B T}\right) dE$$

To solve this integral; put $E_V - E = x$

or $E = E_V - x$; $dE = -dx$.

$$\therefore P = \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2} \exp\left(\frac{-E_f}{k_B T}\right)\int_{\infty}^{0} x^{1/2} \exp\left(\frac{E_V - x}{k_B T}\right)(-dx)$$

$$= \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2} \exp\left(\frac{E_V - E_f}{k_B T}\right)\int_0^\infty x^{1/2} \exp\left(\frac{-x}{k_B T}\right) dx$$

$$= \frac{4\pi}{h^3}\left(2m_h^*\right)^{3/2} \exp\left(\frac{E_V - E_f}{k_B T}\right)\left(k_B T\right)^{3/2} \frac{\pi^{1/2}}{2}$$

$$= 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} exp\left[\frac{-\left(E_f - E_V\right)}{k_B T}\right]$$

$$= N_V \, exp \left[\frac{-\left(E_f - E_V\right)}{k_B T}\right]$$

Where

$$N_V = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2}$$

is a pseudo constant.

Fermi level and the intrinsic carrier concentration:

Since n = p for intrinsic semiconductors,

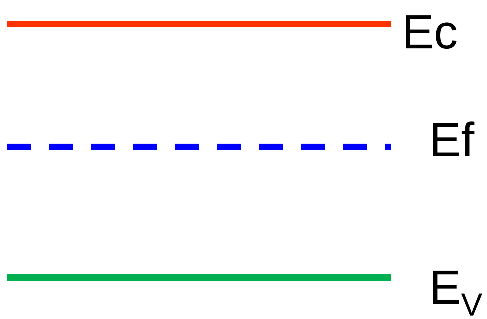
$$2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} \exp\left[\frac{E_f - E_C}{k_B T}\right] = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} exp\left[\frac{E_V - E_f}{k_B T}\right]$$

$$\Rightarrow \frac{exp\left(\dfrac{E_f - E_C}{k_B T}\right)}{exp\left(\dfrac{E_V - E_f}{k_B T}\right)} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

$$\Rightarrow exp\left[\frac{2E_f - (E_C + E_V)}{k_B T}\right] = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

Taking log on both sides and simplifying

$$E_f = \frac{E_C + E_V}{2} + \frac{3k_B T}{4} log\left(\frac{m_h^*}{m_e^*}\right)$$



If

$$m_h^* = m_e^*$$

or T=0ºK

$$E_f = \frac{E_C + E_V}{2}$$

Thus the Fermi level is located half way between the conduction and valance bands in an intrinsic semi conductor.

In Intrinsic semiconductors

$$n = p = n_i$$

where n_i is the intrinsic carrier concentration

$$\therefore n_i^2 = np \longrightarrow \text{Mass action law}$$

$$\therefore n^2{}_i = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} \exp\left[\frac{E_f - E_C}{k_B T}\right] \bullet 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} exp\left[\frac{E_V - E_f}{k_B T}\right]$$

$$= 4\left(\frac{2\pi k_B T}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{3/2} exp\left(\frac{E_V - E_C}{k_B T}\right)$$

$$= 4\left(\frac{2\pi k_B T}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{3/2} exp\left(\frac{-E_g}{k_B T}\right)$$

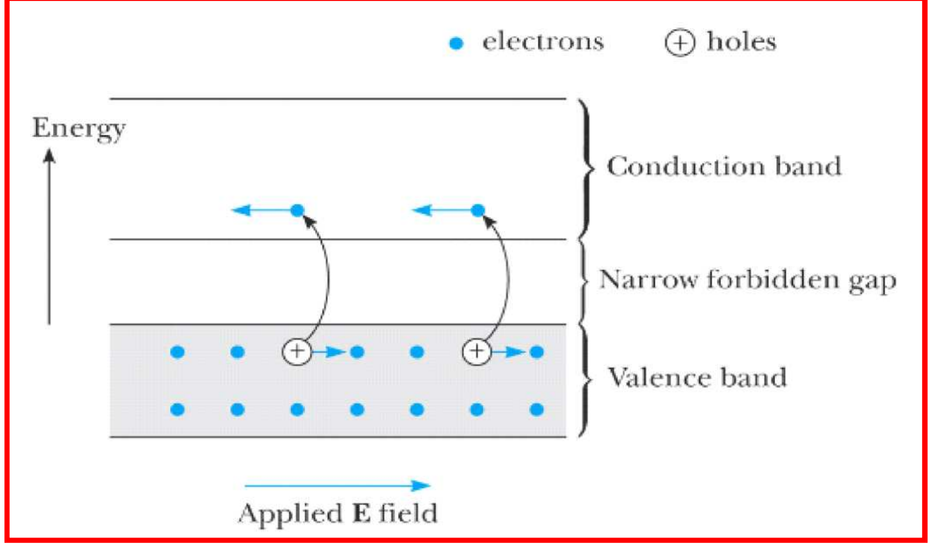
Where $E_C - E_V = E_g$ the forbidden energy gap.

$$\therefore n_i = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2} \left(m_e^* m_h^*\right)^{3/4} exp\left(\frac{-E_g}{2k_B T}\right)$$

Intrinsic Semiconductors at T >0 K

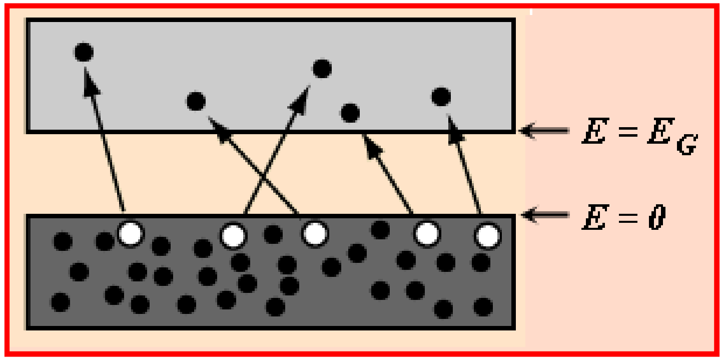
- Electrons and holes contribute to the current when a voltage is applied

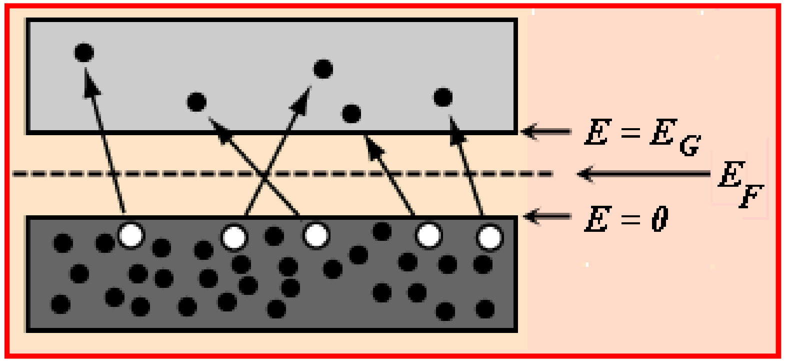
$$\boxed{\sigma = \frac{e^2 n_e \tau_n}{m_e^*} + \frac{e^2 n_h \tau_p}{m_h^*}}$$



Carrier Concentrations at T >0 K

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





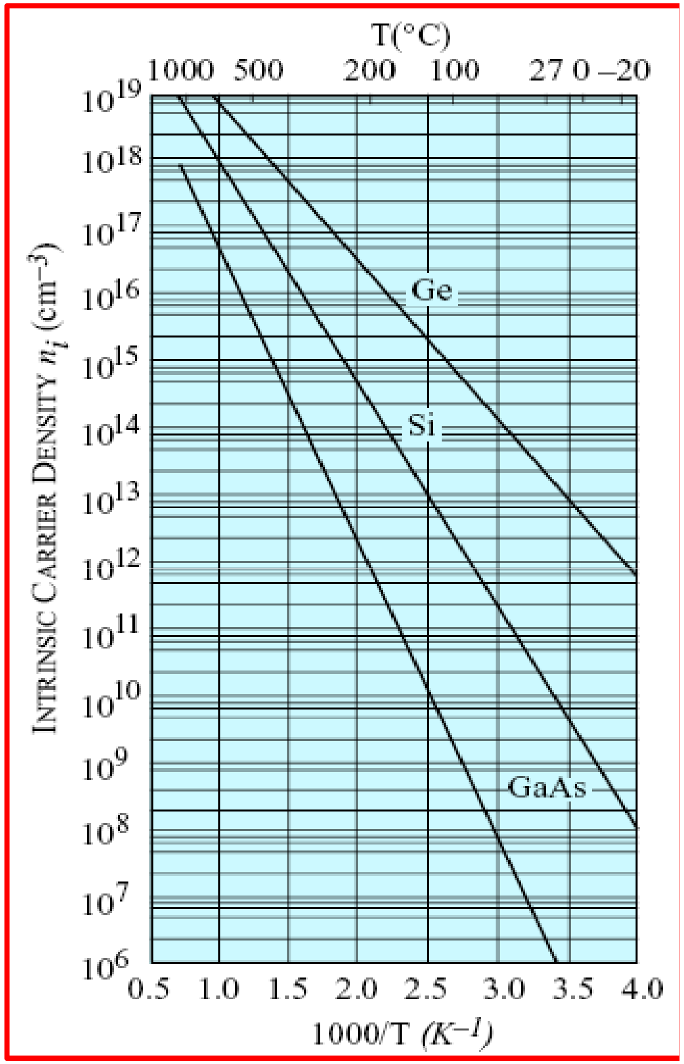
- The number of electrons equals the number of holes, $n_e = n_h$
- The Fermi level lies in the middle of the band gap

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

- $n_e = n_h$ 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

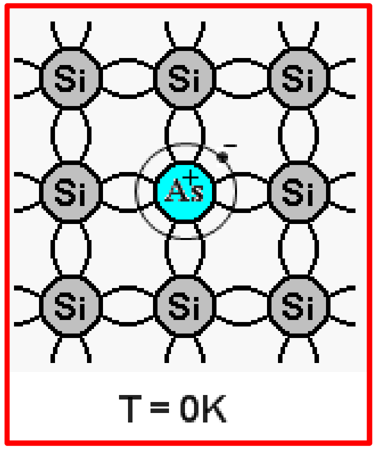
- ***Electrical Properties of semiconductors can be altered drastically by adding minute amounts of suitable impurities to the pure crystals***
- Impurities: Atoms of the elements different from those forming solid
  - Interstitial: "foreign" atoms "squeezed" between regular sites crystal sites
  - Substitutional: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

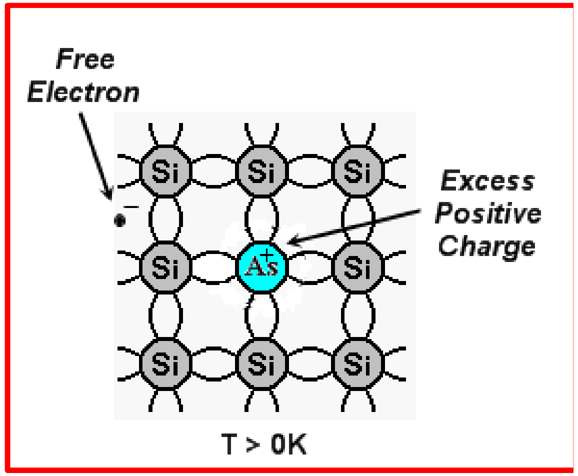
Donors/ doping N-type

- 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

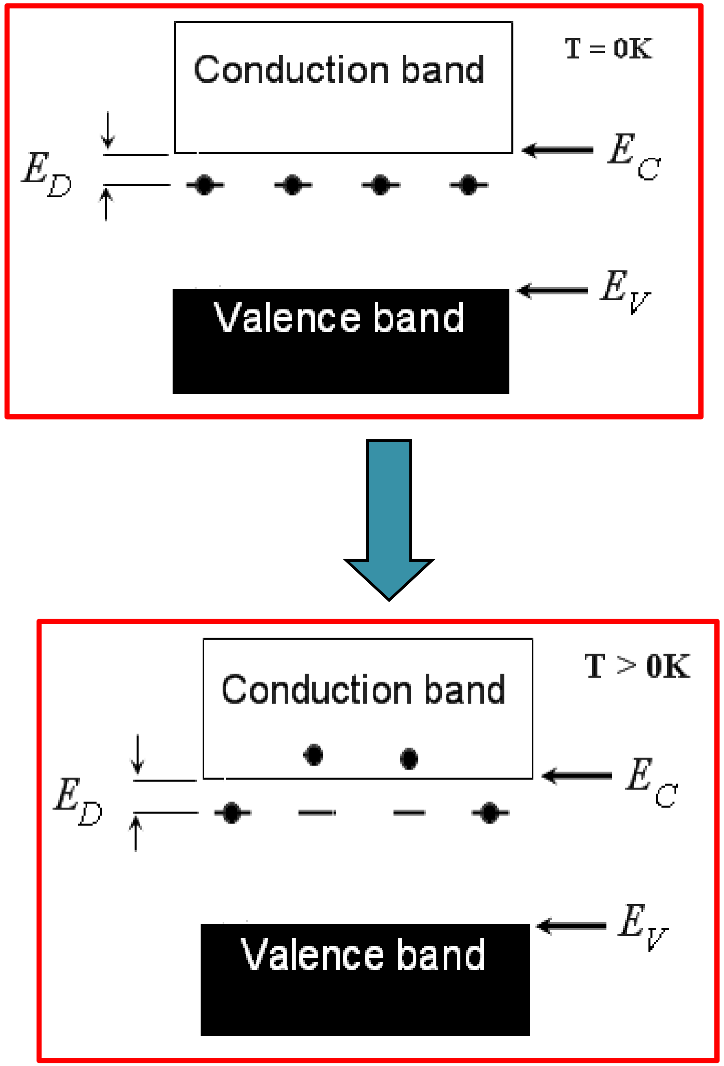
- The remaining electron will not be very tightly bound, and can be easily ionized at T > 0K
- Ionized electron is free to conduct
  - In term of the band structure, this electron is now in the conduction band
- Such Group V impurities are called ***Donors***, since they "donate" electrons into the Conduction Band
  - ***Semiconductors doped by donors are called n-type semiconductors***

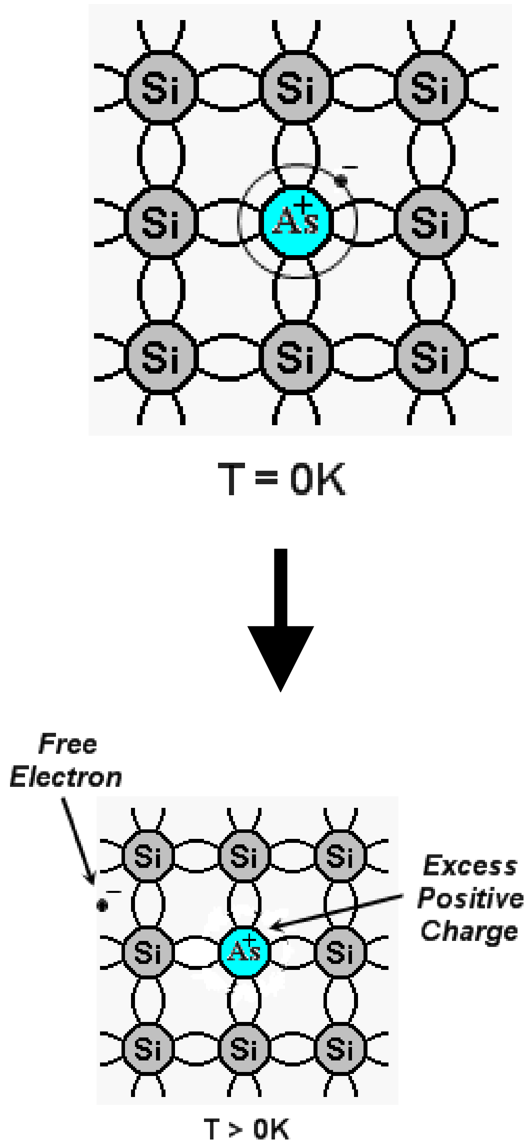


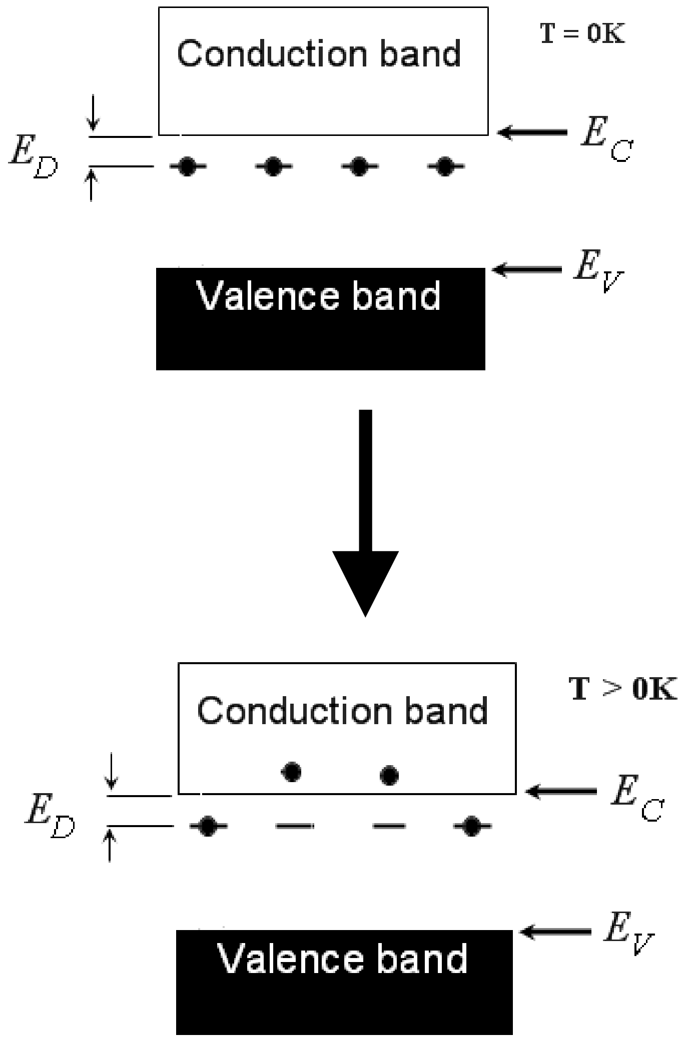


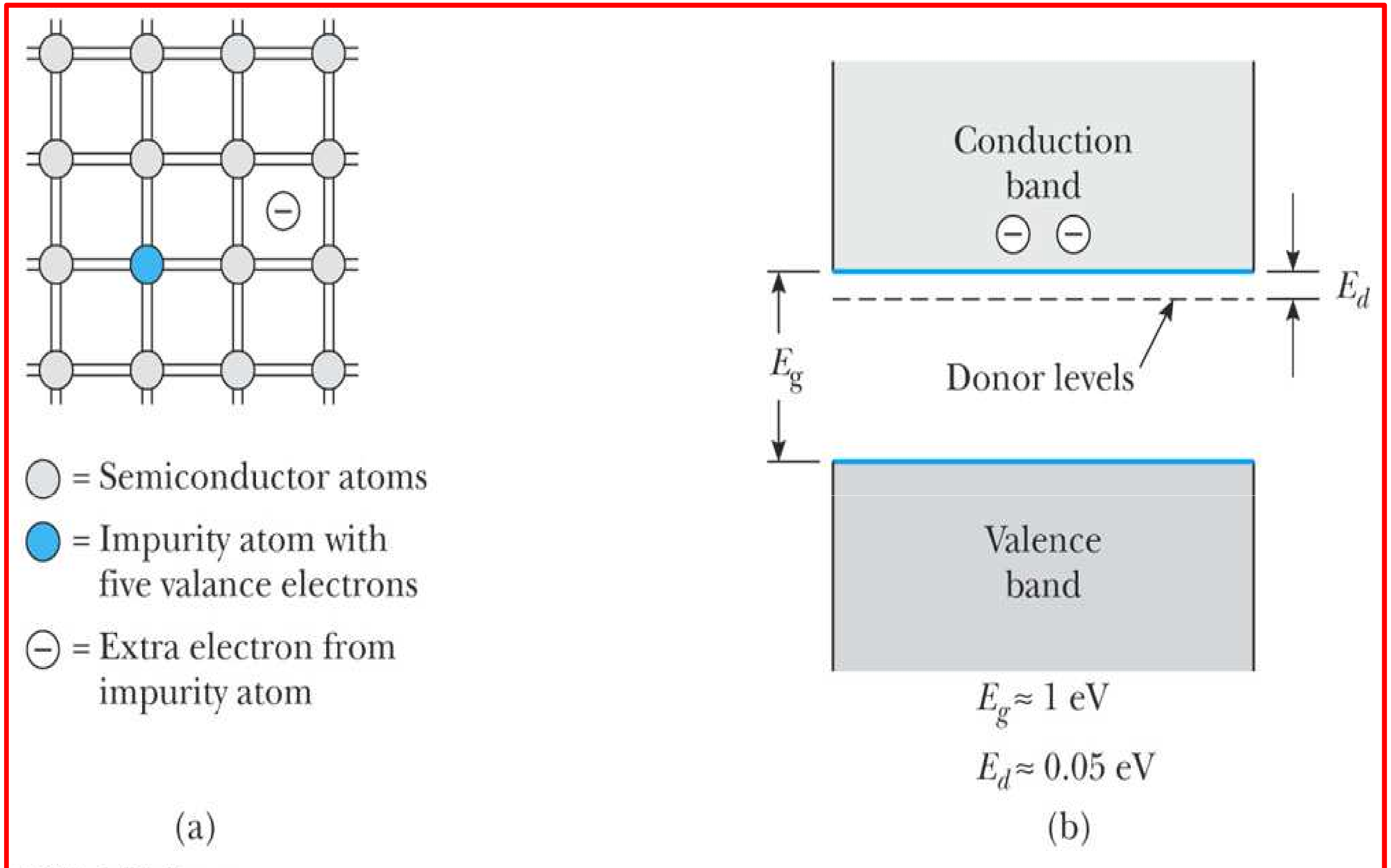
Donors: Energy Levels

- 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
Free Electron
Excess Positive Charge
T > 0K

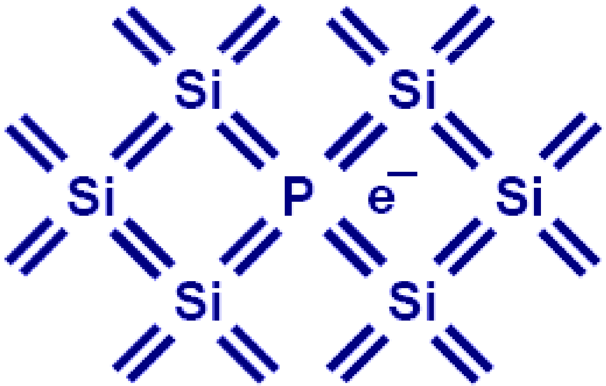

Conduction band
T = 0K
E_D
E_C
Valence band
E_V
Conduction band
T > 0K
E_D
E_C
Valence band
E_V

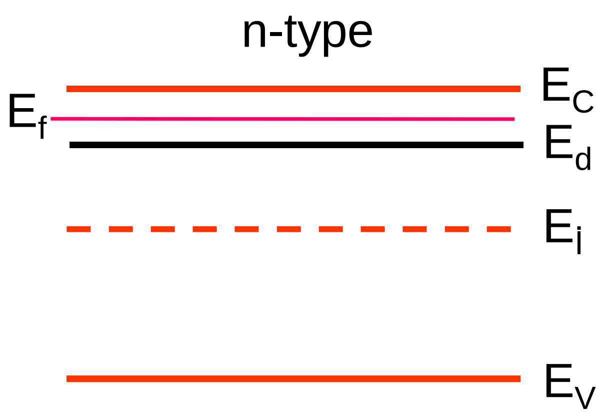


= Semiconductor atoms
= Impurity atom with five valance electrons
= Extra electron from impurity atom
(a)
Conduction band
Donor levels
E_g
E_d
Valence band
$E_g \approx 1$ eV
$E_d \approx 0.05$ eV
(b)

Doping (N type) contd..

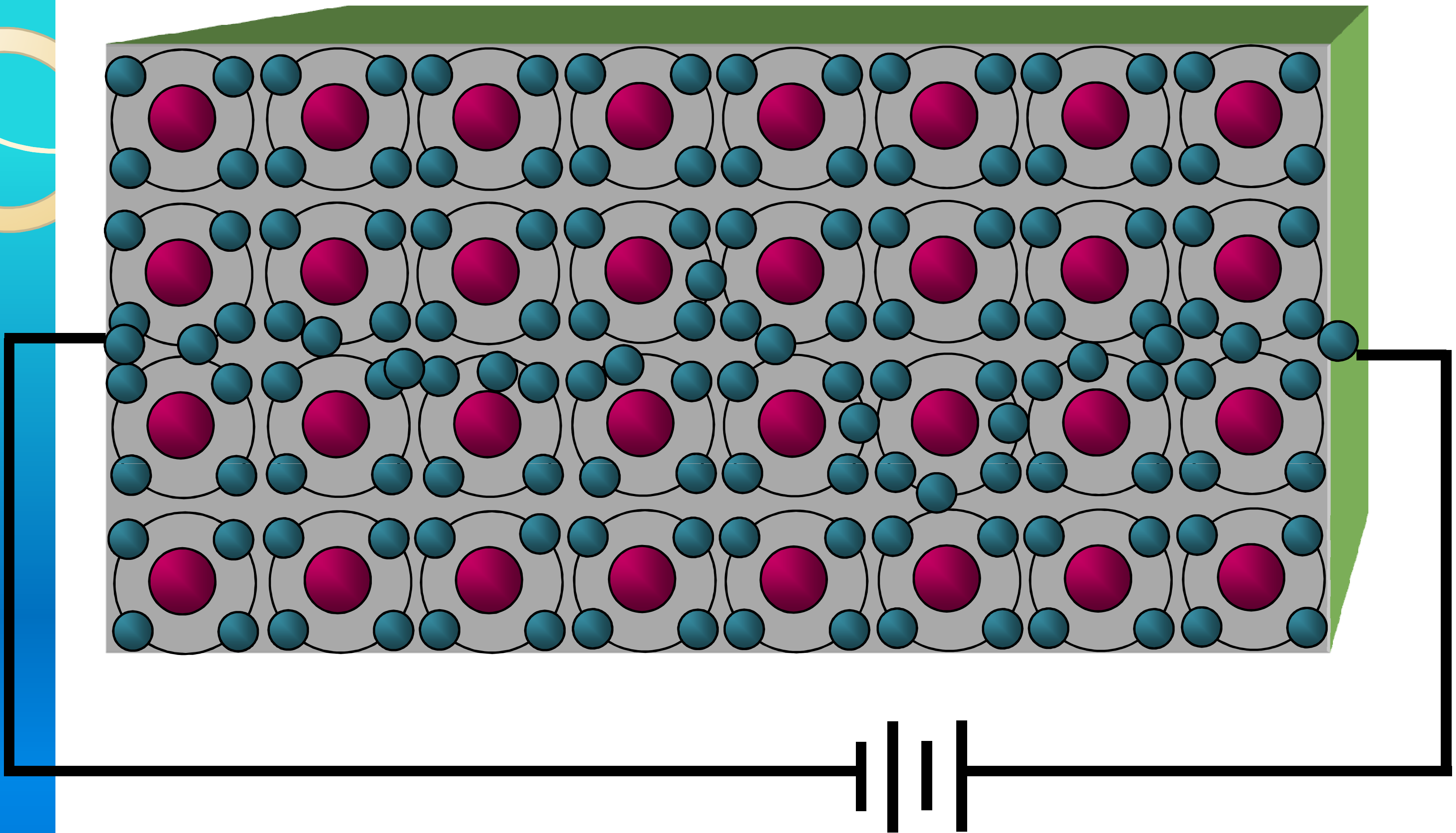
- Si can be "doped" with other elements to change its electrical properties.
- For example, if Si is doped with phosphorus (P), each P atom can contribute a conduction electron, so that the Si lattice has more electrons than holes, *i.e.* it becomes "N type":





Notation:
n = conduction electron concentration

This crystal has been doped with a pentavalent impurity.



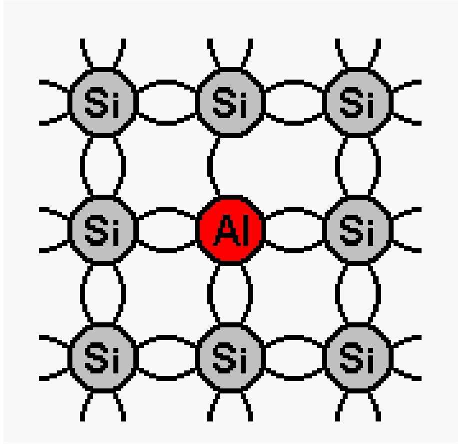
The free electrons in n type silicon support the flow of current.

Acceptors

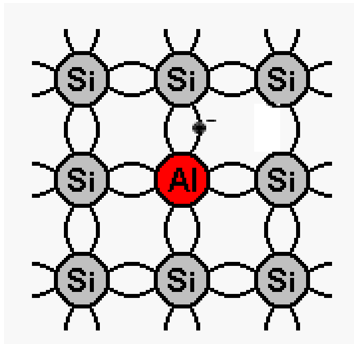
- Use Silicon (Si) as an example
  - Substitute one Group III atom (e.g. Al or In) with a Si (Group IV) atom
  - Si atoms have four valence electrons that participate in the covalent bonding
  - When a Group III atom replaces a Si atom, it cannot complete a tetravalent bond scheme
  - An "electronic 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 t 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



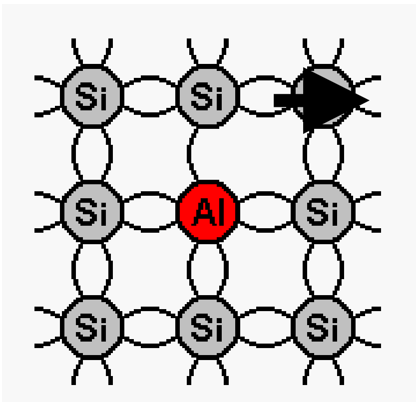
T = 0K



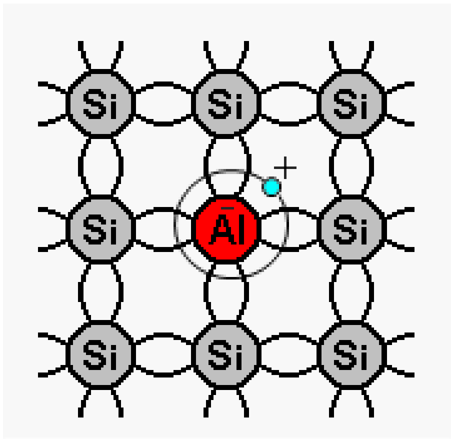
T > 0K

Acceptors

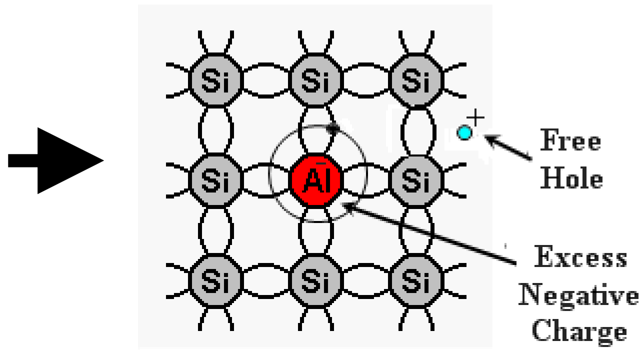
- By “incorporating” the electron into the impurity atom we can represent this (T = 0 K) as a negative charge in the core with a positive charge (hole) outside the core attracted by its [Coulomb] potential
- At T > 0 K this hole can be ionized
- Such semiconductors are called ***p-type semiconductors***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



T = 0K



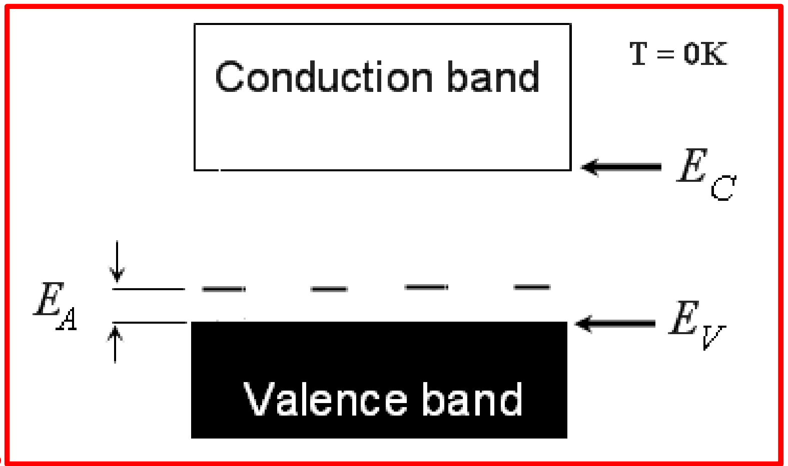
T = 0K

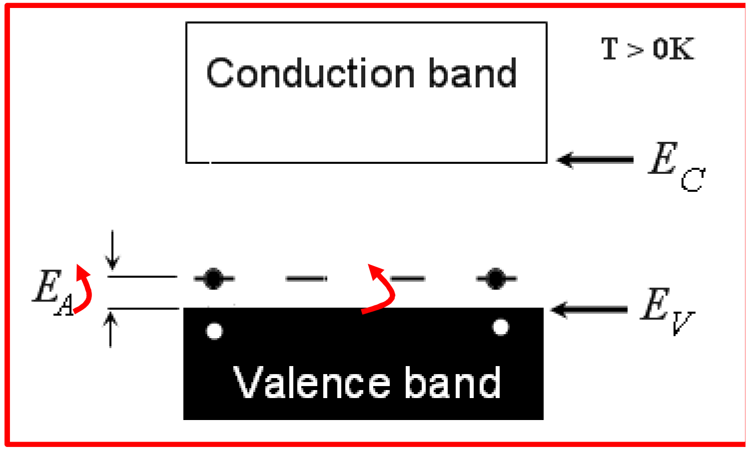


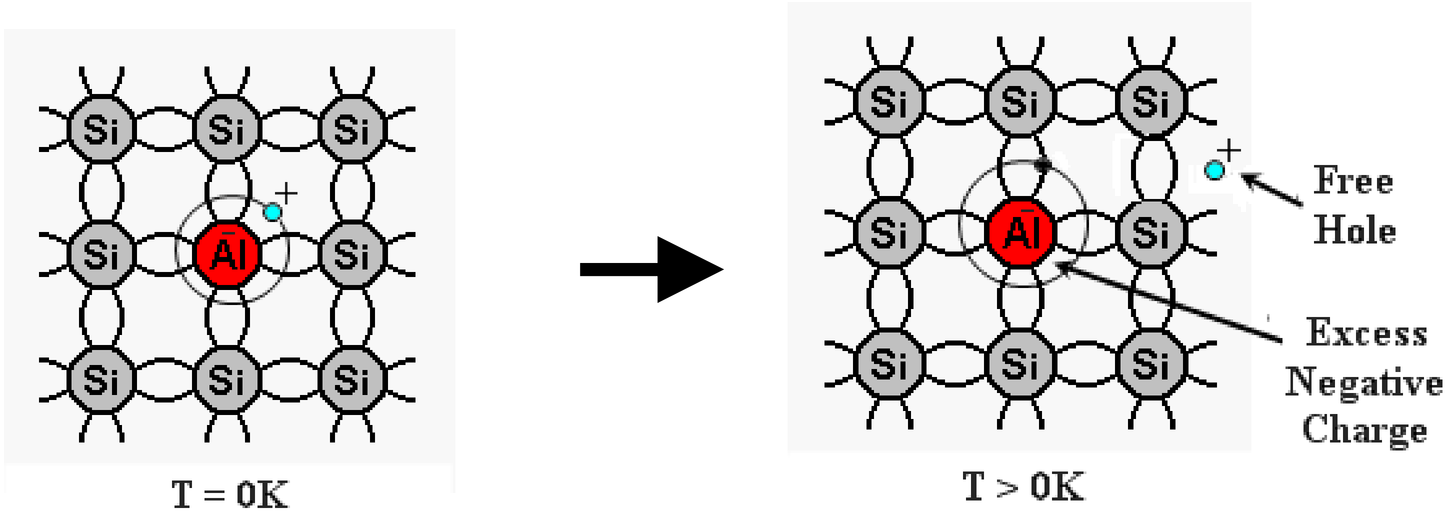
T > 0K

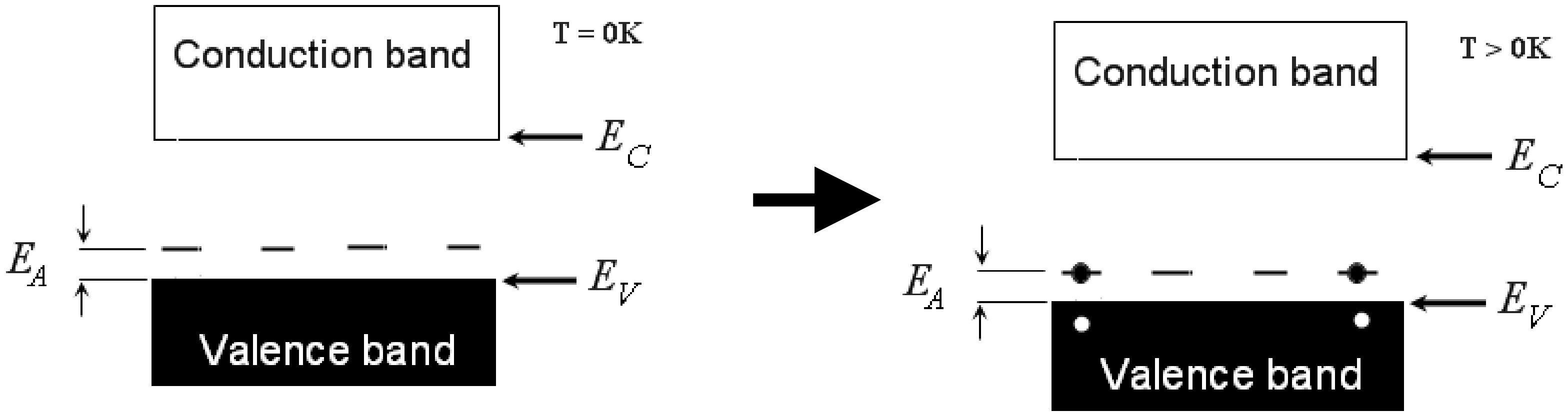
Acceptor: Energy Levels

- 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

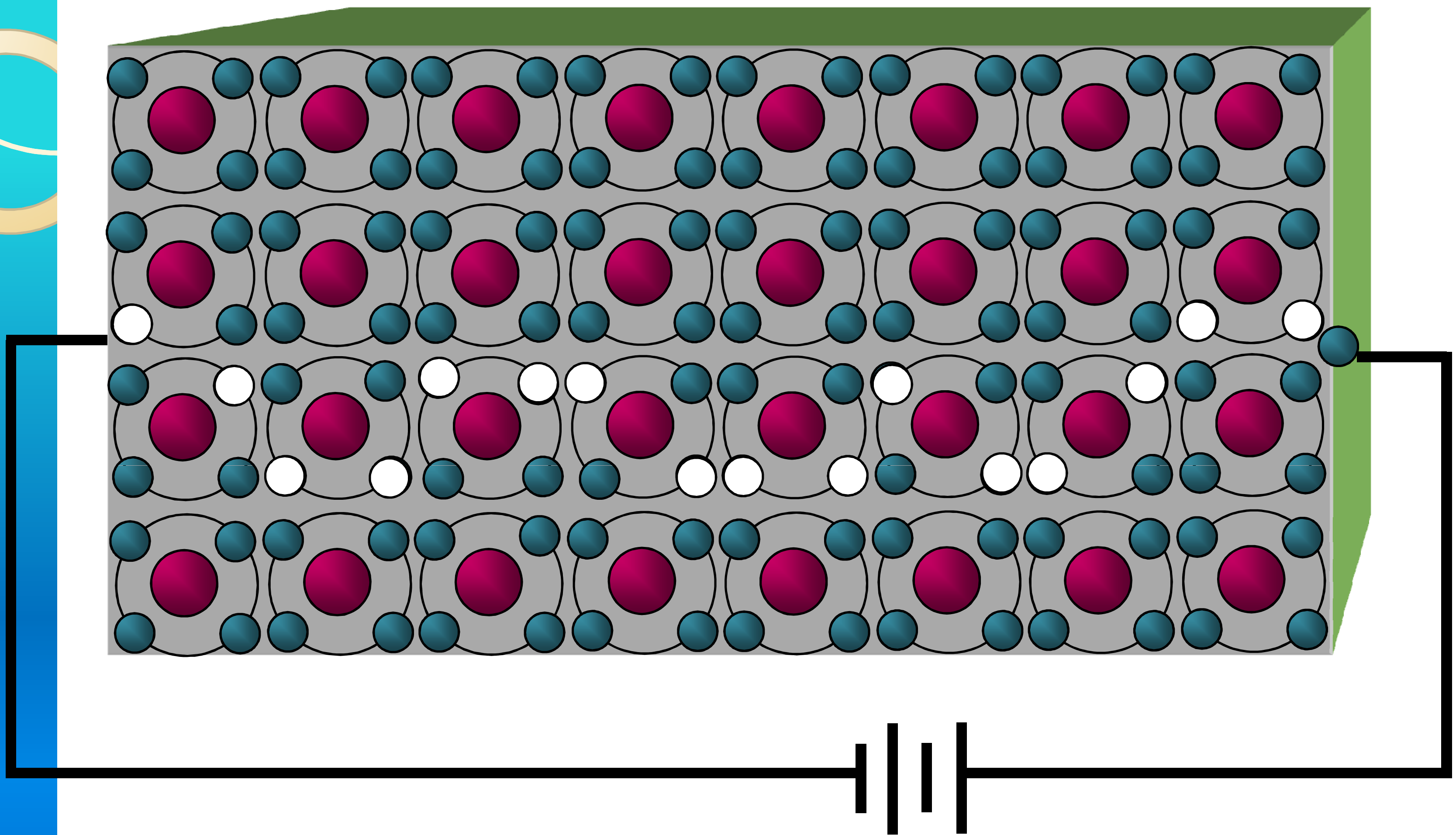





Si
Al
T = 0K
Free
Hole
Excess
Negative
Charge
T > 0K

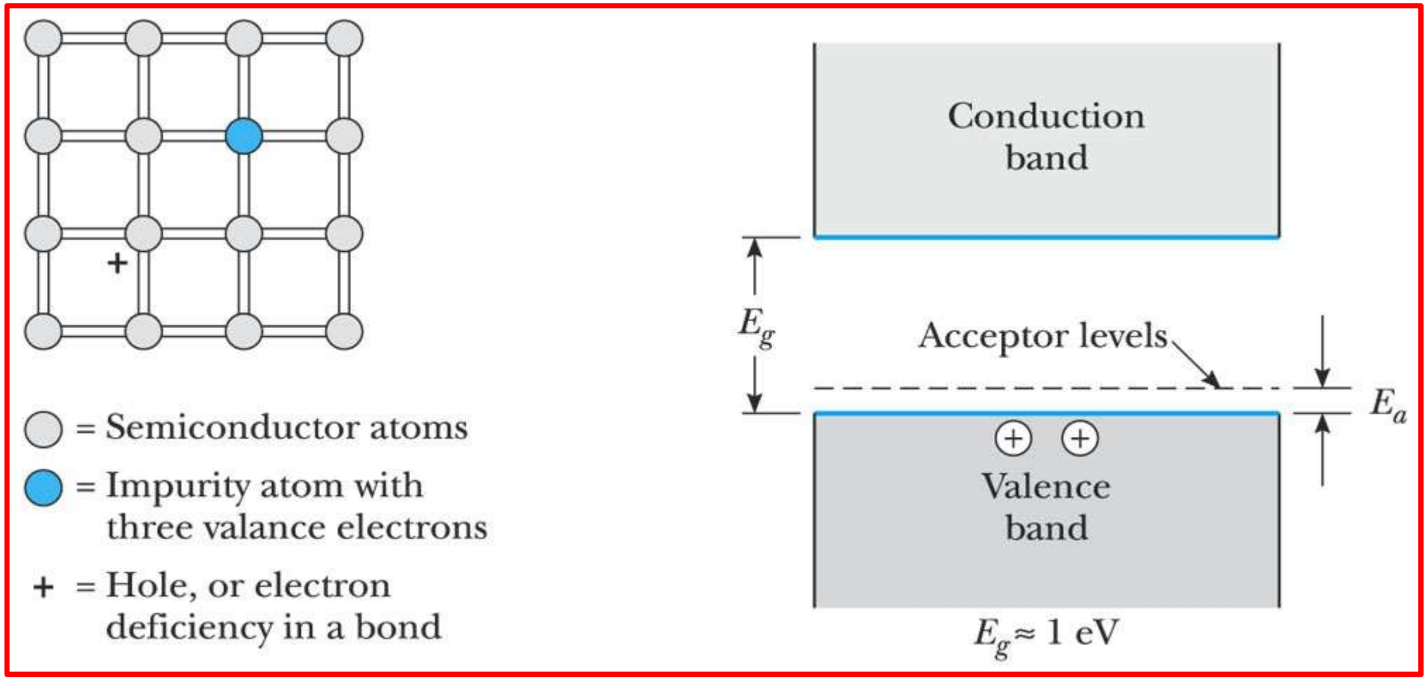

Conduction band
T = 0K
E_C
E_A
E_V
Valence band
Conduction band
T > 0K
E_C
E_A
E_V
Valence band

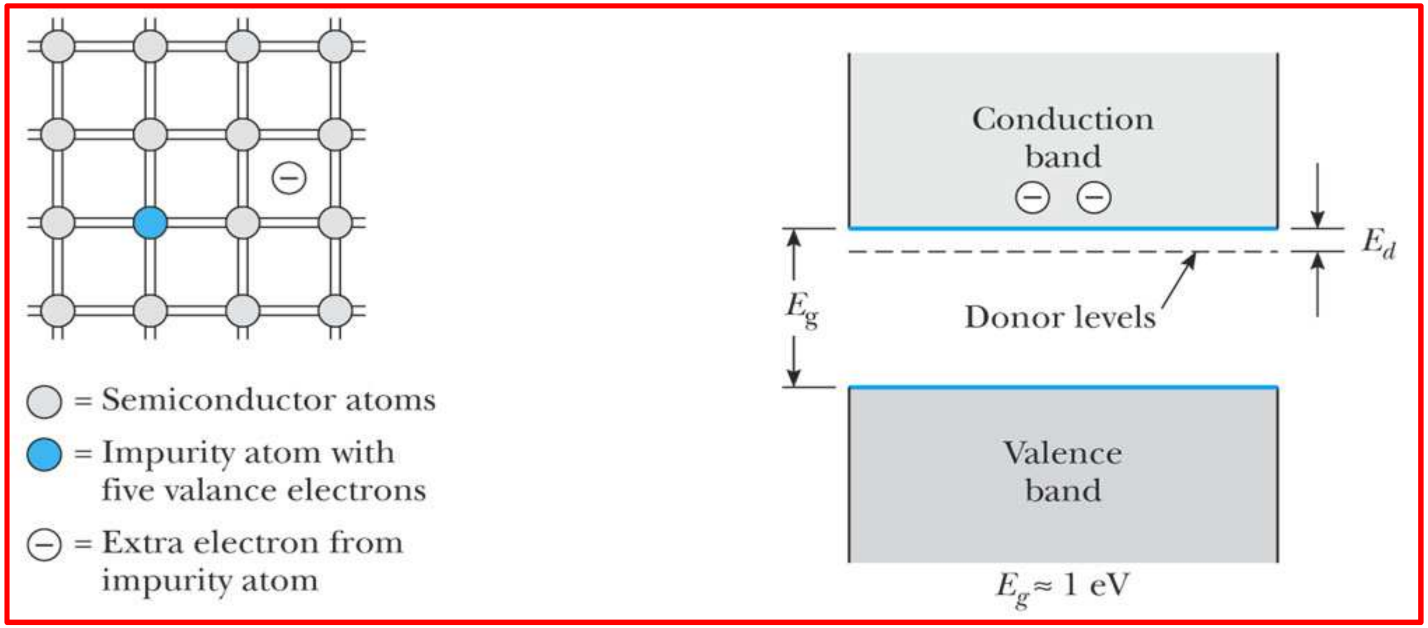
This crystal has been doped with a trivalent impurity.



The holes in p type silicon contribute to the current.

Note that the hole current direction is <u>opposite</u> 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
Acceptor levels
Valence band
E_g
E_a
$E_g \approx 1$ eV


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

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

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

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

- For impurity semiconductors

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

- 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

p – n junction

- The p-n junction is the basic element of all bipolar devices. Its main electrical property is that it rectifies (allow current to flow easily in one direction only).The p-n junction is often just called a DIODE. Applications;

- photodiode, light sensitive diode,
- LED- ligth emitting diode,
- varactor diode-variable capacitance diode

The formation of p-n junction :

- The p-n junction can be formed by pushing a piece of p-type silicon into close contact with a piecce of n-type silicon. But forming a p-n junction is not so simply. Because;

1) There will only be very few points of contact and any current flow would be restricted to these few points instead of the whole surface area of the junction.

2) Silicon that has been exposed to the air always has a thin oxide coating on its surface called the "native oxide". This oxide is a very good insulator and will prevent current flow.

3) Bonding arrangement is interrupted at the surface; dangling bonds.

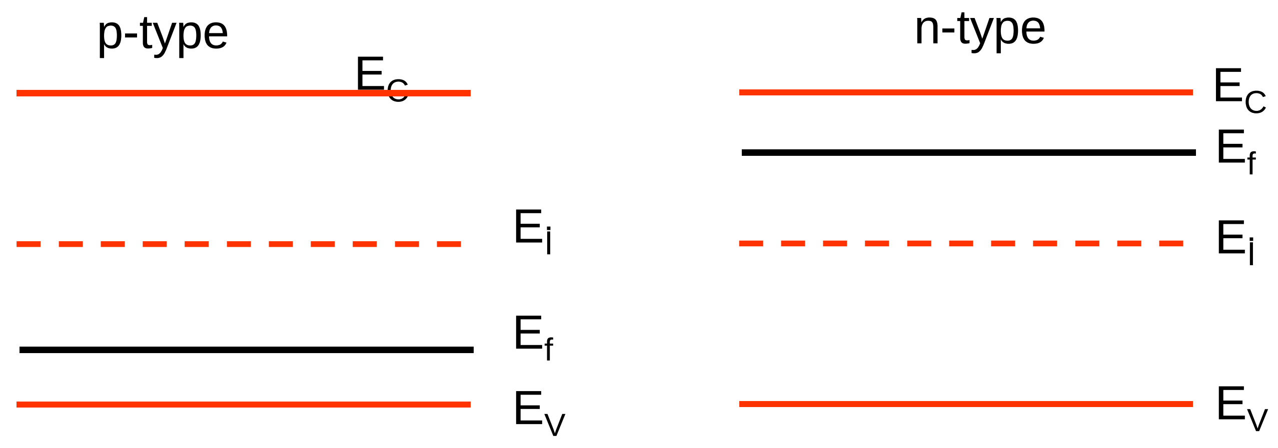
Surface states

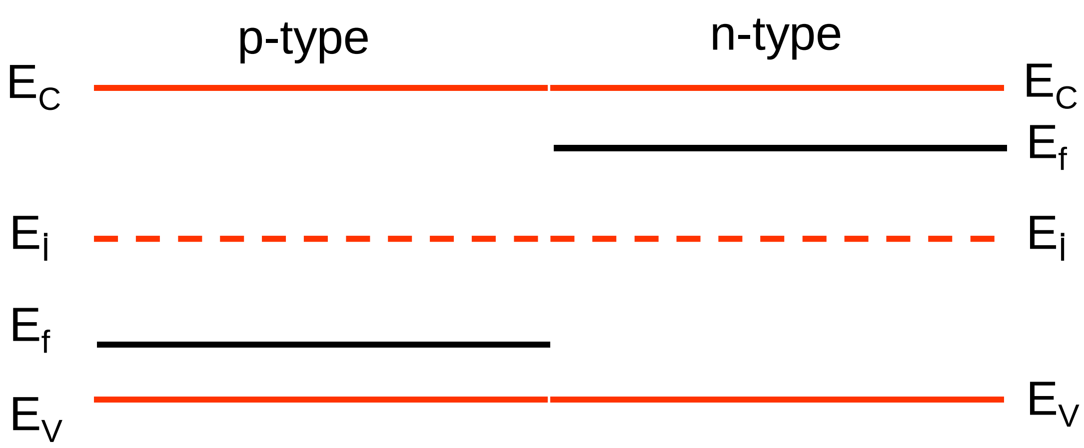
To overcome these surface states problems

↓

p-n junction can be formed in the bulk of the semiconductor, away from the surface as much as possible.

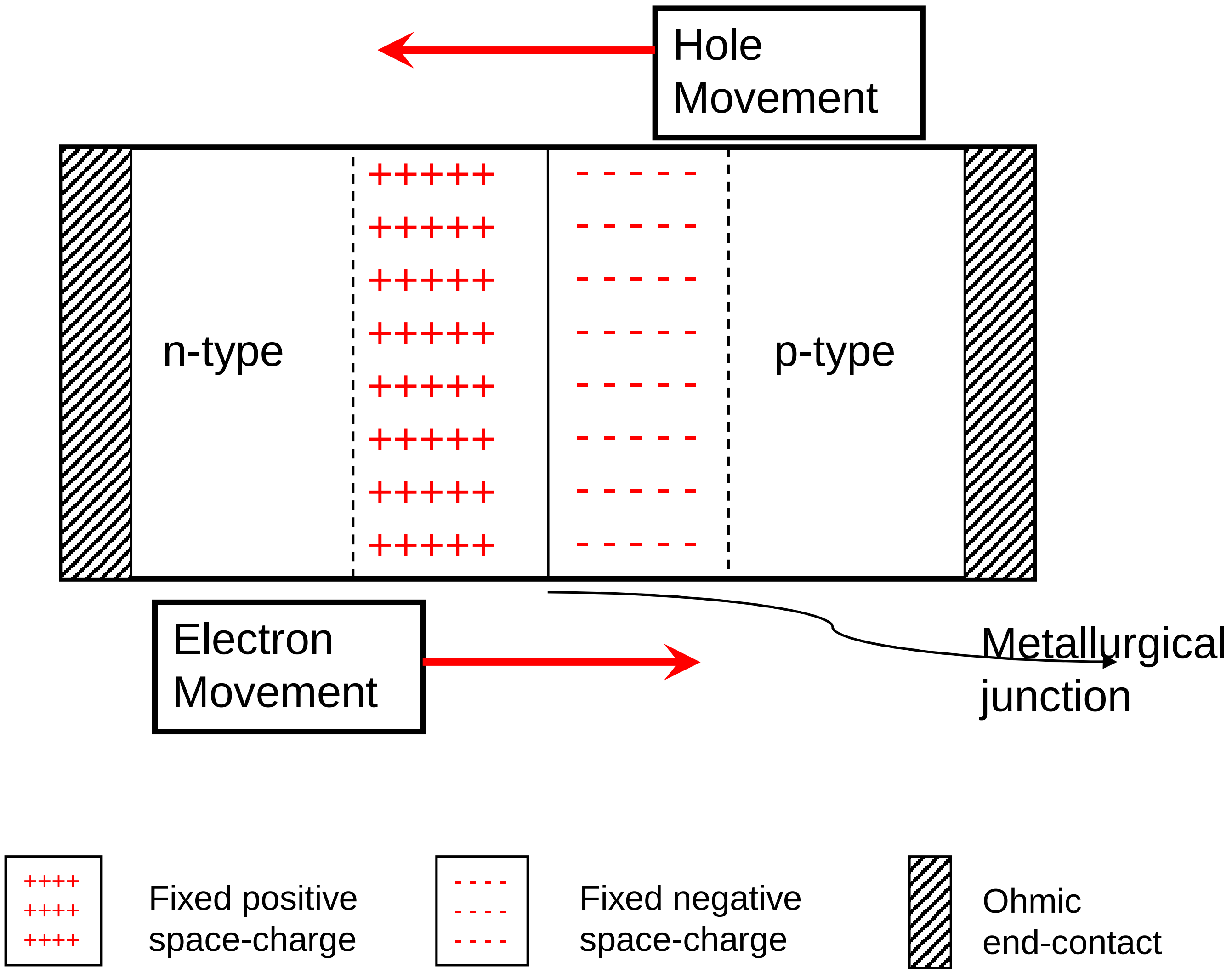
p – n junction





There is a big discontinuity in the fermi level accross the p-n junction.

Idealized p-n junction; recombination of the carrier and carrier diffusion



p – n junction

- Lots of electrons on the left hand side of the junction want to diffuse to the right and lots of holes on the right hand side of the junction want to move to the left.

- The donors and acceptors fixed,don’t move (unless you heat up semiconductors, so they can diffuse) because they are elements (such as arsenic and boron) which are incorporated to lattice.

- However, the electrons and holes that come from them are free to move.

Idealized p-n junction

- Holes diffuse to the left of the metalurgical junction and combine with the electrons on that side. They leave behind negatively charged acceptor centres.

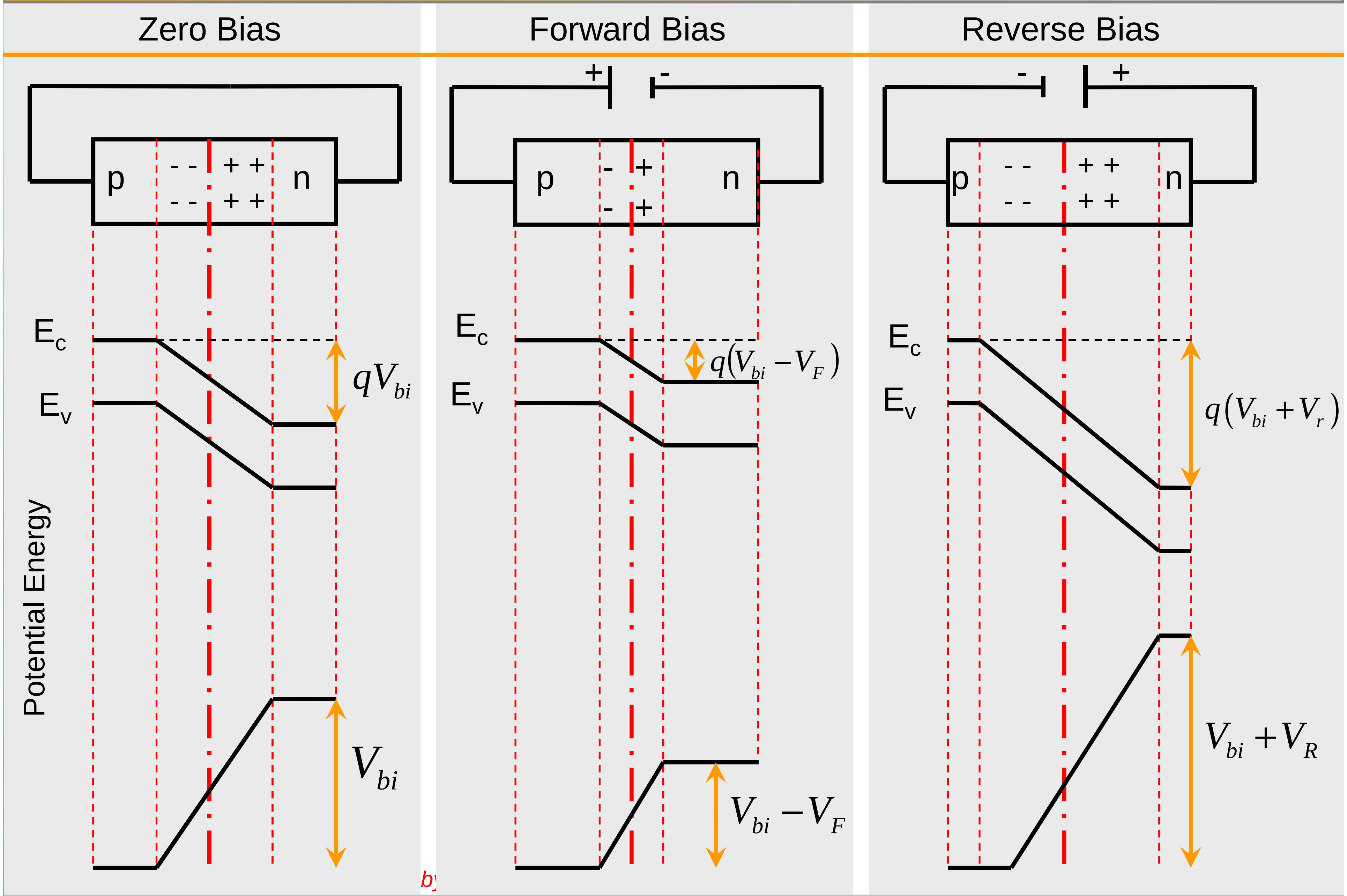
- Similarly, electrons diffusing to the right will leave behind positively charged donor centres. This diffusion process can not go on forever. Because, the increasing amount of fixed charge wants to electrostatically attract the carriers that are trying to diffuse away(donor centres want to keep the electrons and acceptor centres want to keep the holes). Equlibrium is reached.

- This fixed charges produce an electric field which slows down the diffusion process.

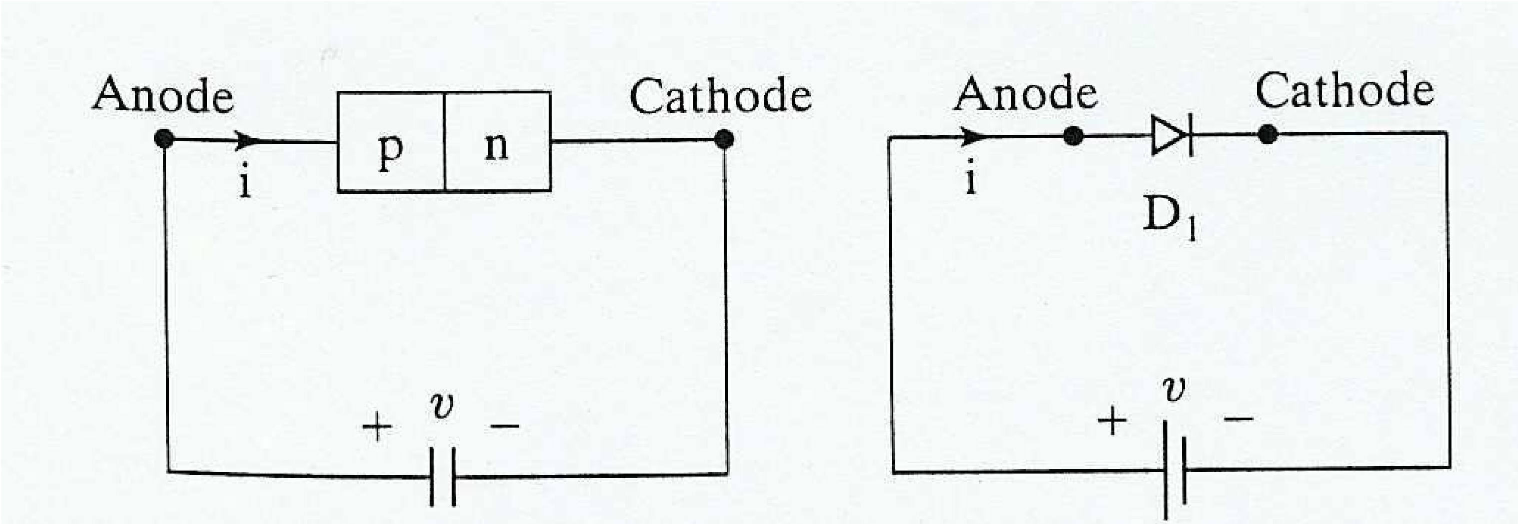
- This fixed charge region is known as depletion region or space charge region which is the region the free carriers have left.

- It is called as depletion region since it is depleted of free carriers.

Applying bias to p-n junction



PN-Junction Diode Characteristics



Forward Bias --- External battery makes the Anode more positive than the Cathode --- Current flows in the direction of the arrow in the symbol.

Reverse Bias --- External battery makes the Cathode more positive than the Anode --- A tiny current flows opposite to the arrow in the symbol.

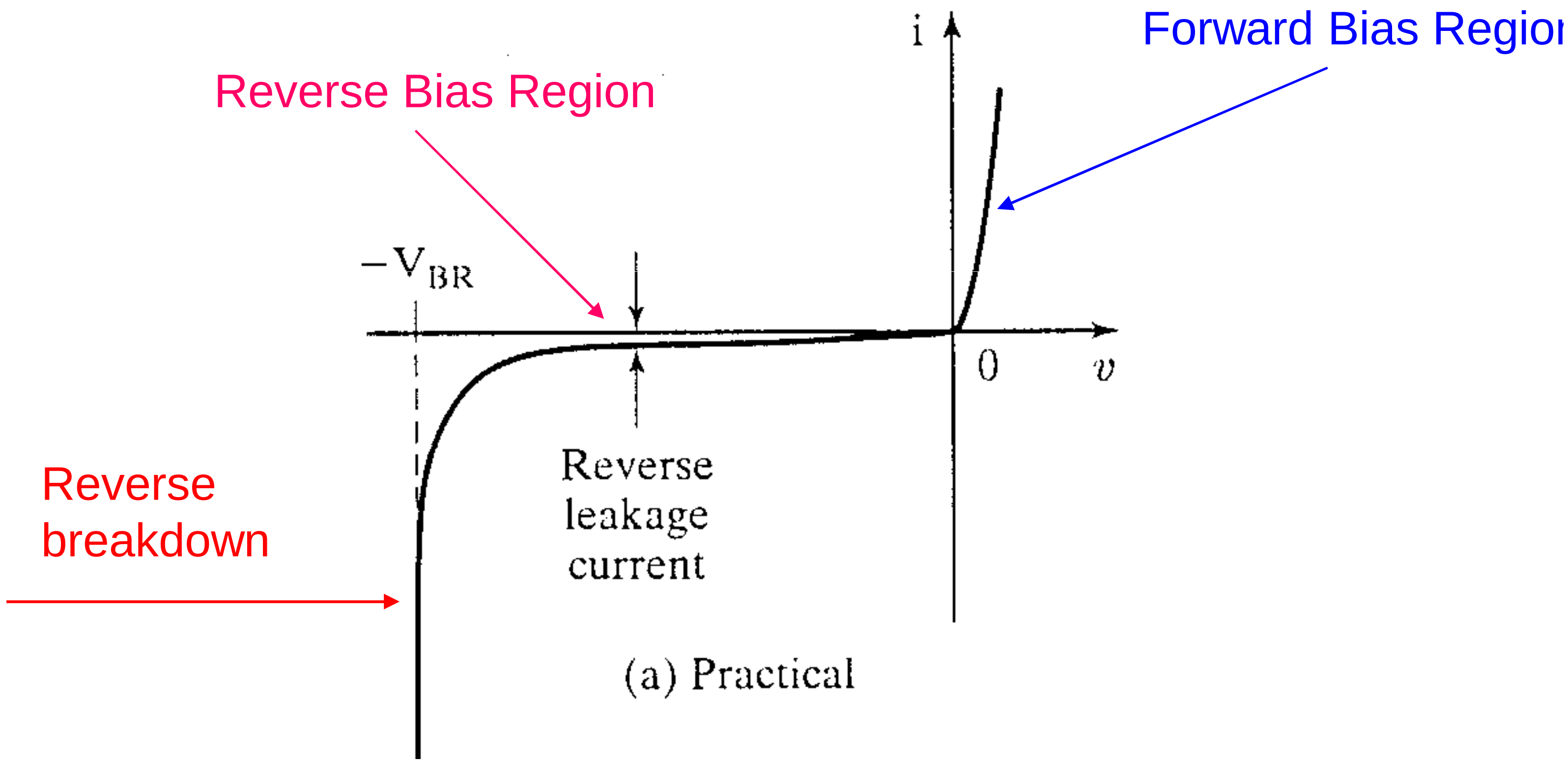
Forward Bias

- Mnemonic. Connect positive terminal to p-side for forward bias.
- Junction potential reduced
- Enhanced hole diffusion from p-side to n-side compared with the equilibrium case.
- Enhanced electron diffusion from n-side to p-side compared with the equilibrium case.
- Drift current flow is similar to the equilibrium case.
- Overall, a large diffusion current is able to flow.

Reverse Bias

- Mnemonic. Connect positive terminal to n-side for reverse bias.
- Junction potential increased
- Reduced hole diffusion from p-side to n-side compared with the equilibrium case.
- Reduced electron diffusion from n-side to p-side compared with the equilibrium case
- Drift current flow is similar to the equilibrium case.
- Overall a very small reverse saturation current flows.

Graphical
PN-Junction Diode V-I Characteristic



(a) Practical

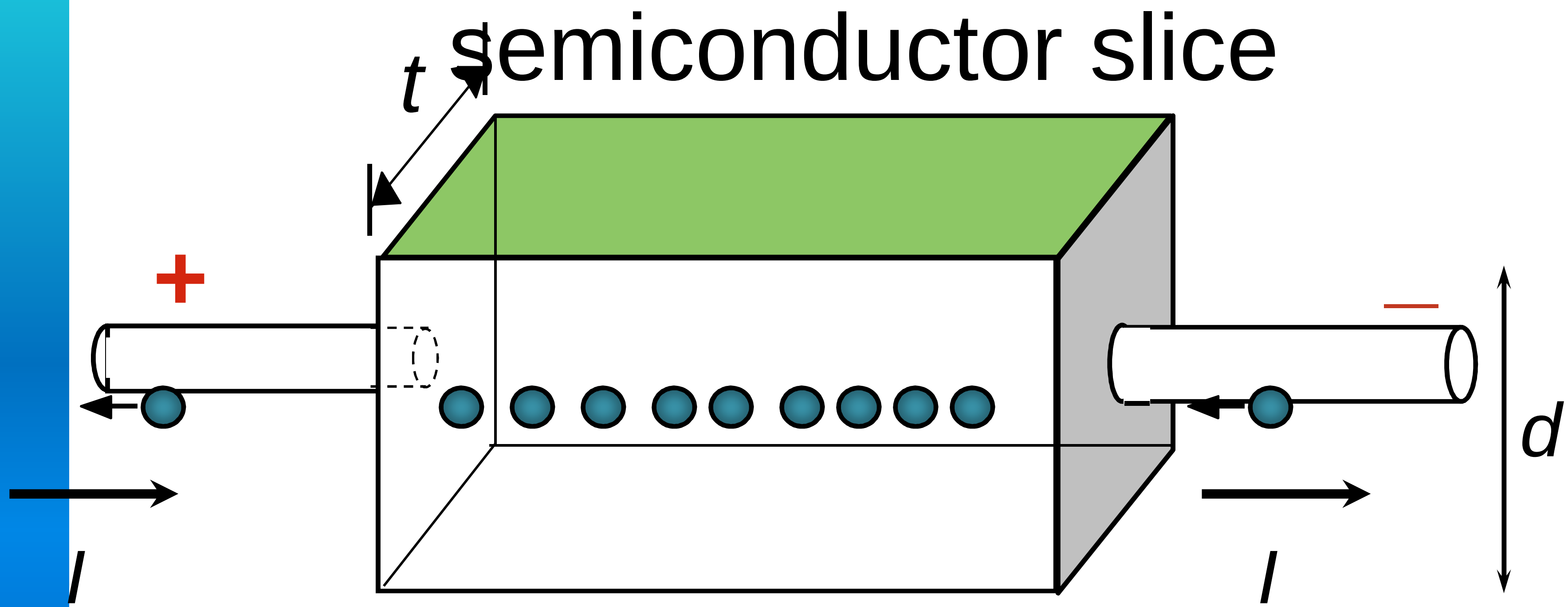
Hall Effect

The **Hall effect** is the production of a voltage difference (the **Hall voltage**) across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current. It was discovered by Edwin Hall in 1879.

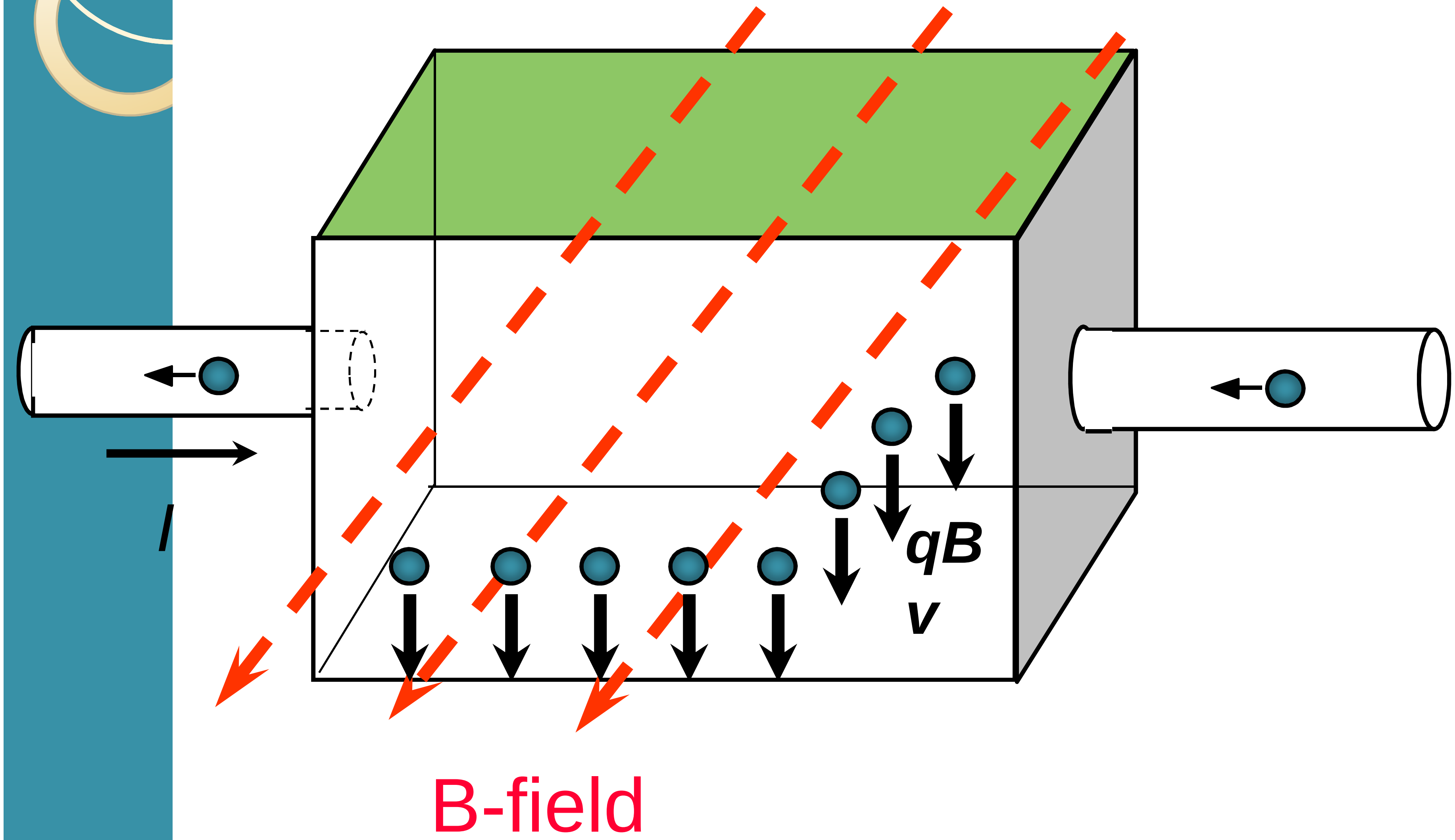
The Hall coefficient is defined as the ratio of the induced electric field to the product of the current density and the applied magnetic field. It is a characteristic of the material from which the conductor is made, since its value depends on the type, number, and properties of the charge carriers that constitute the current.

- Identify either semiconductor is n-type or p-type
- To calculate the no of chare carriers
- To calculate the mobility

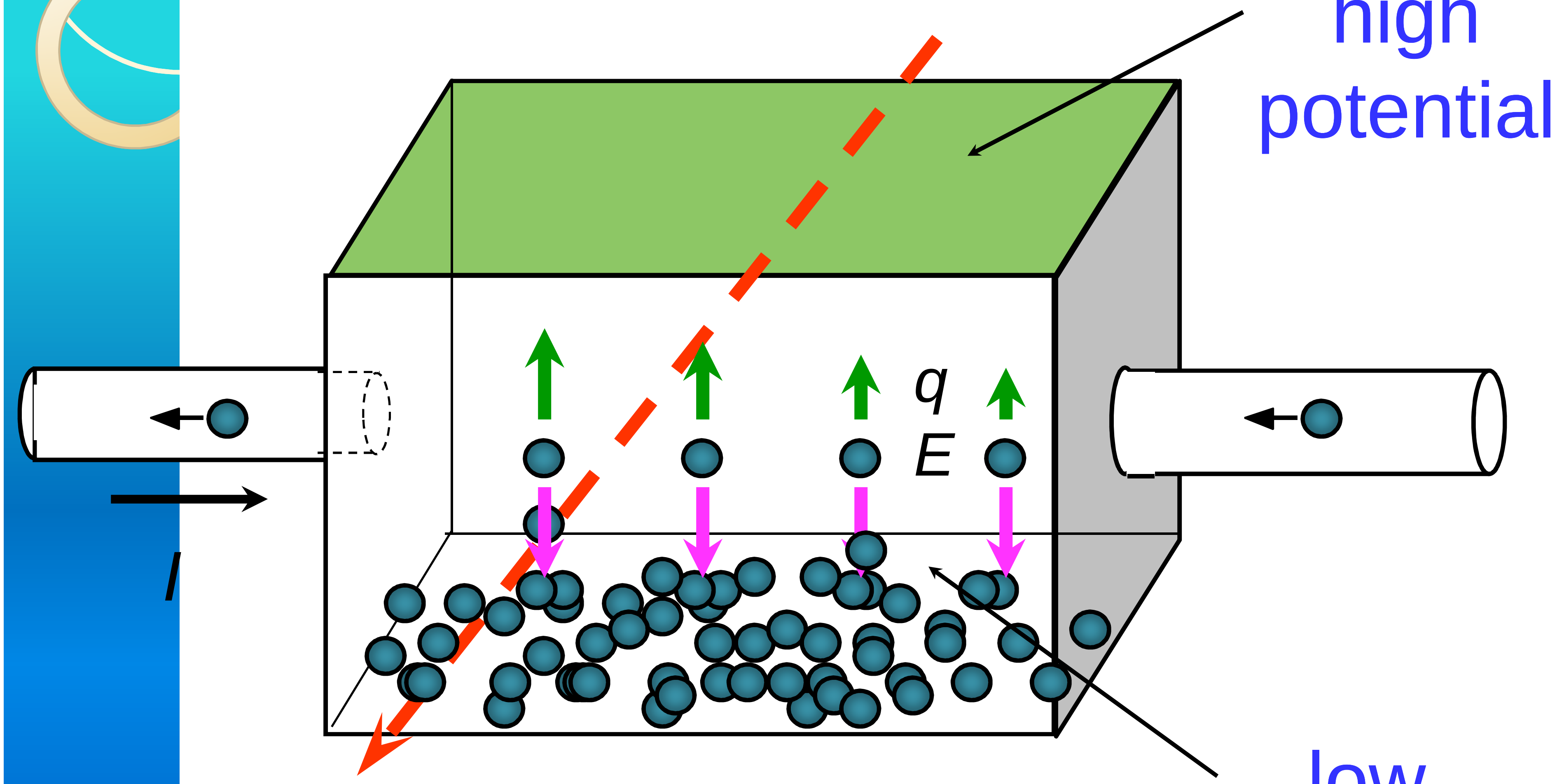
When electrons flow without magnetic field...



When the magnetic field is turned on ...

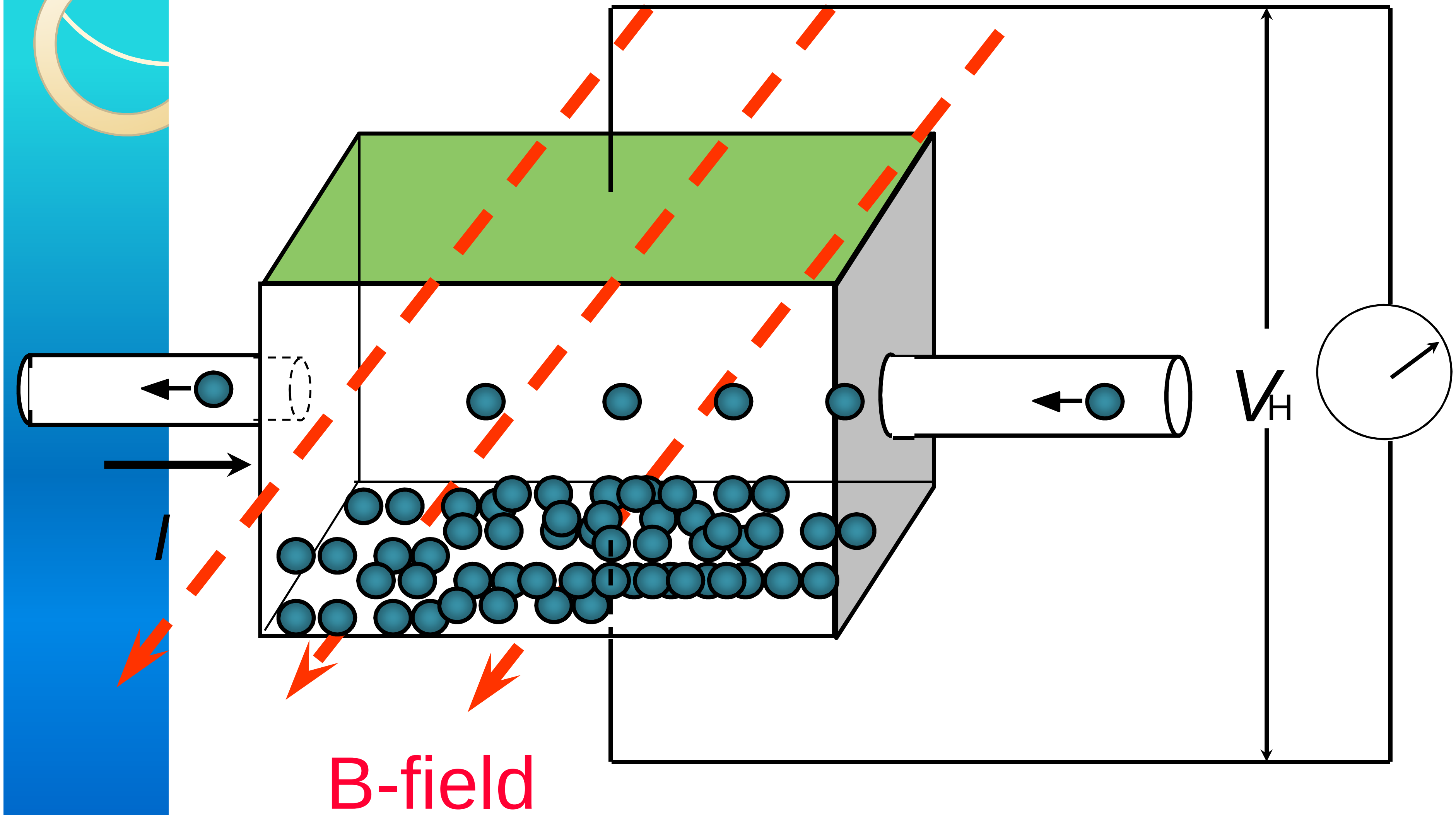


As time goes by...



$$qBv = qE$$

Finally...



Mathematical analysis:

Electric force balanced by the Magnetic fore

$$qE = q(vXB)$$

$$qE_H = qv_d B$$ E_H = Hall electric field, B= Magnetic induction field

$$E_H = v_d B$$

$$\because J = nqv_d$$ J= Current density, vd= Drift velocity, n= no of charge carriers

$$E_H = \frac{J}{nq} B$$

$$R_H = \frac{E_H}{JB} = \frac{1}{nq} = Hall \text{ Coefficient}$$

For metals R_H value is smaller compared to Semiconductors

$$\because\ E_H = \frac{J}{nq} B$$

since J=I/A and $E_H = v_d B$

then

$$n = \frac{IB}{qldE_H}$$

How to calculate the Hall voltage?

- A current of 50A is established in a slab of cu 0.5 cm thick and 2 cm wide. The slab is placed in a magnetic field B of 1.5T. The magnetic filed is perpendicular to the plane of the slab and current. The free electron concentration in copper is 8.48×10^{28}. electron/m3. What will be the magnitude of Hall Voltage across the width of the slab

$$V_H = \frac{BI}{nqt}$$

V_H=1.116 µV

Thank You