# EC203 - Electronic Devices and Circuits-I

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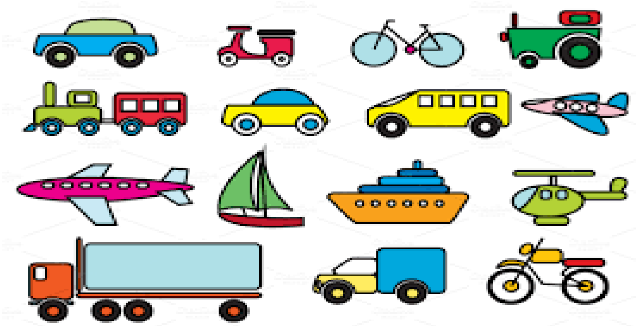
# COURSE OBJECTIVES

- Study and analyze the behavior of PN junction diodes.
- Characterize the current flow of a bipolar transistor in CB,CE and CC configurations
- Bias the transistors and FETs for amplifier applications.
- Realize simple amplifier circuits using BJT and FET.
- Analyse RC circuits for low pass and high pass filtering
- Understand the Negative Resistance behavior of semiconductor devices

# WHY WE NEED TO STUDY?



# SEMICONDUCTOR DIODES

- Band structure of pn junction, current components,
- Quantitative theory of pn diode,
- Volt-ampere characteristics and its temperature dependence,
- Narrow-base diode,
- Transition and diffusion capacitance of p-n junction diodes,
- Breakdown of junctions on reverse bias,
- Zener and Avalanche breakdowns.

# Electronic Devices and Circuits

**Electronic device** are widely used in almost all the industries for quality control and automation.

For example:

- Bio-medical applications
- Communication
- Computer's
- Aerospace etc.

# Electronic Devices and **Circuits**

- **Circuits:** Consisting an active and passive elements.

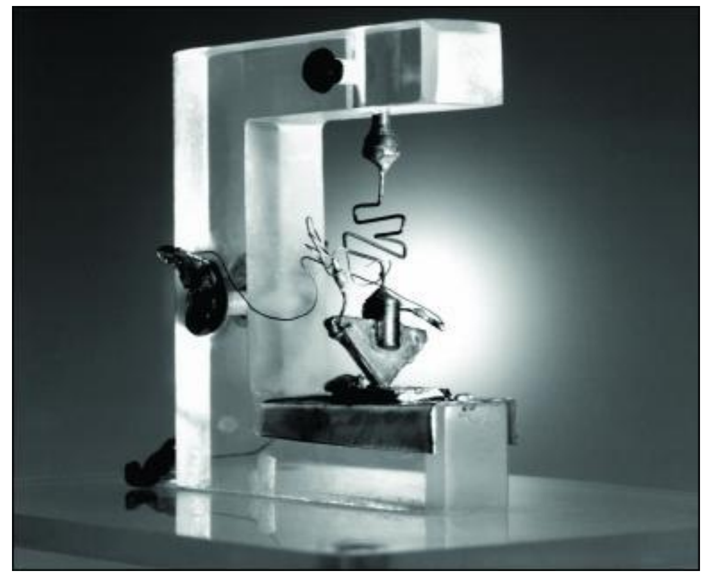
- **Active Elements:** BJT, MOSFET, Op-amp etc.

- **Passive Elements:** Resistor, capacitor and inductors

# The Start of the Modern Electronics Era

It can be said that the invention of the transistor and the subsequent development of the microelectronics have done more to shape the modern era than any other invention.

Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.



The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world

# Electronics Milestones

1874 Braun invents the solid-state rectifier

1906 DeForest invents triode vacuum tube.

1907-1927 First radio circuits developed from diodes and triodes.

1925 Lilienfeld field-effect device patent filed.

1947 Bardeen and Brattain at Bell Laboratories invent bipolar transistors.

1952 Commercial bipolar transistor production at Texas Instruments.

1956 Bardeen, Brattain, and Shockley receive Nobel prize.

1961 First commercial IC from Fairchild Semiconductor

1968 First commercial IC op-amp

1970 One transistor DRAM cell invented by Dennard at IBM.

1971 4004 Intel microprocessor introduced.

1978 First commercial 1-kilobit memory.

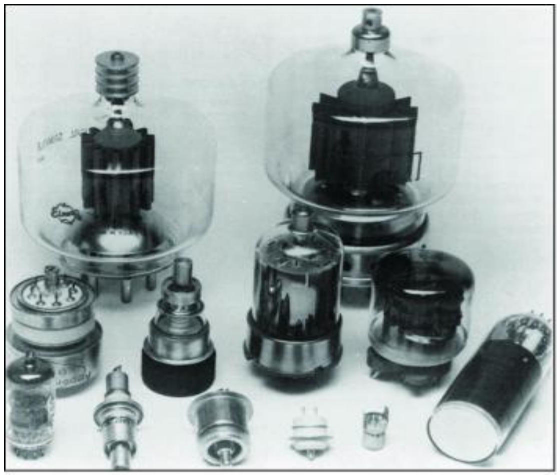
1974 8080 microprocessor introduced.

1984 Megabit memory chip introduced.

1995 Gigabite memory chip presented.

# Evolution of Electronic Devices

Vacuum Tubes



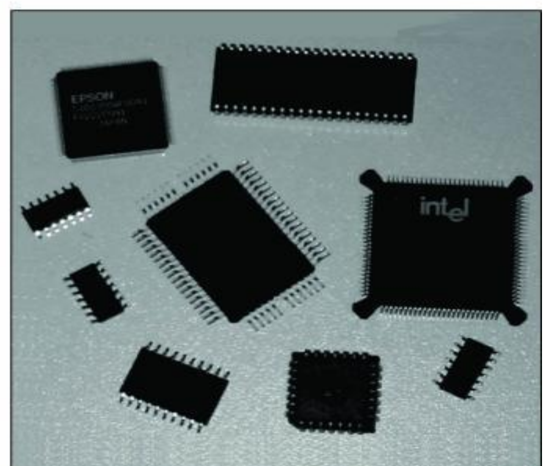
(a)

(b)

Discrete Transistors

SSI and MSI Integrated Circuits

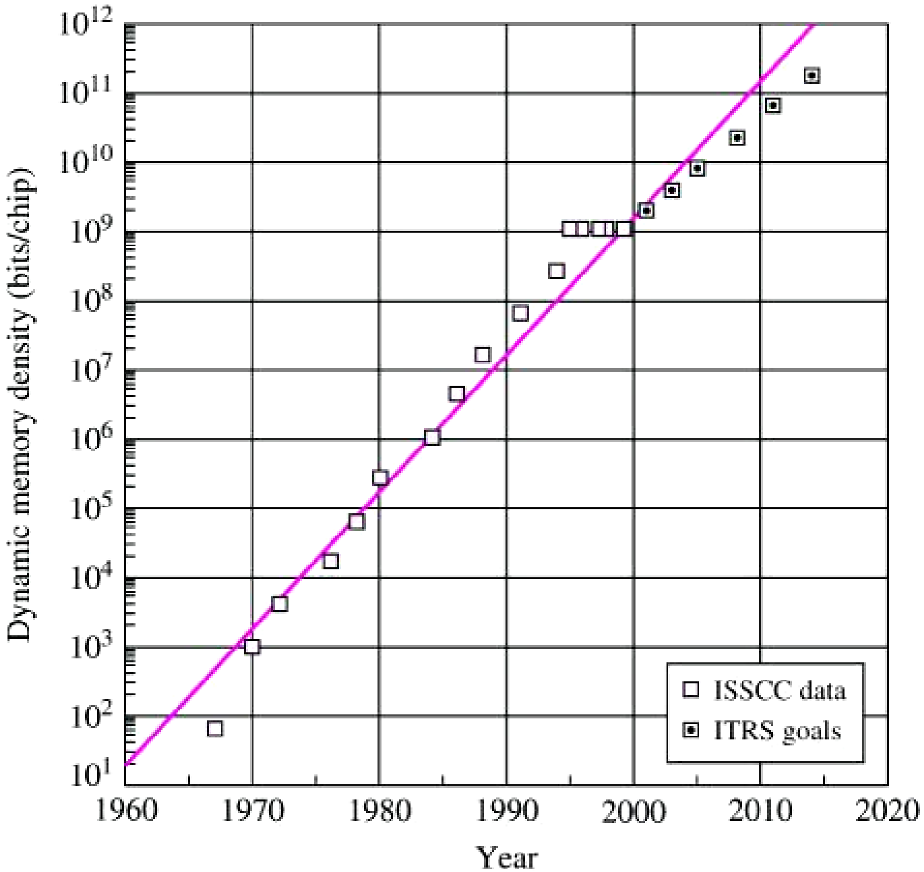
(c)



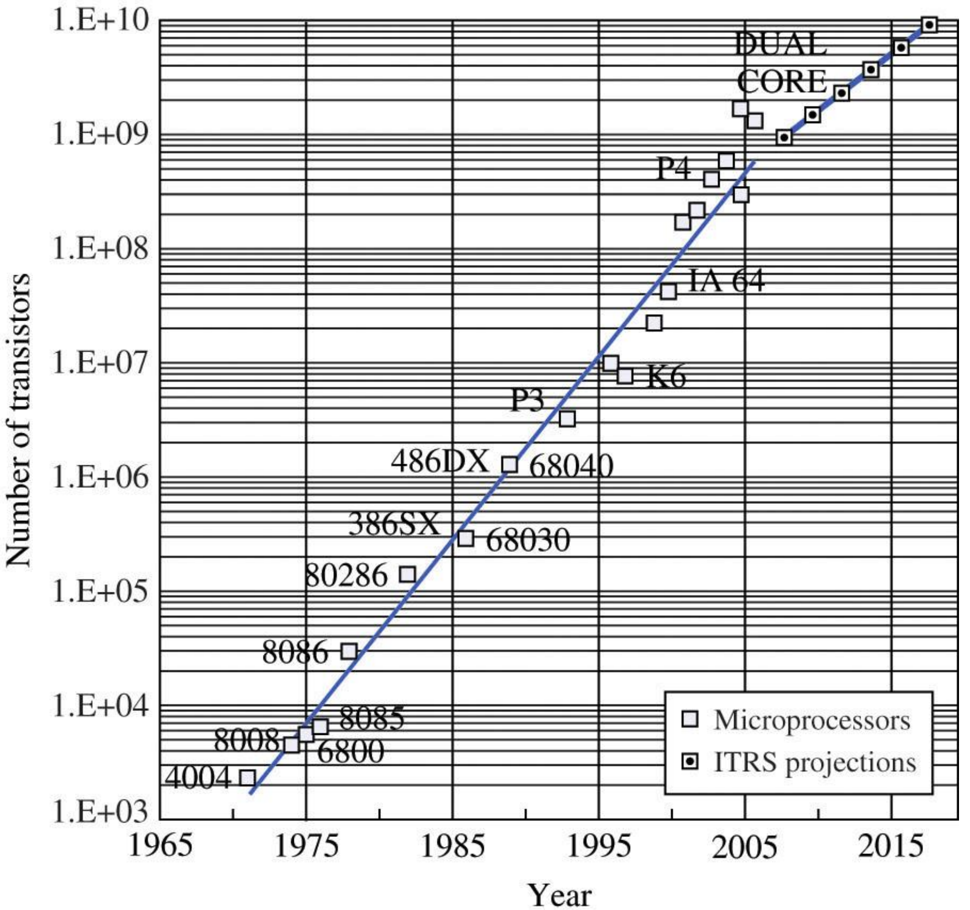

(d)

VLSI Circuits

# Rapid Increase in Density of Microelectronics

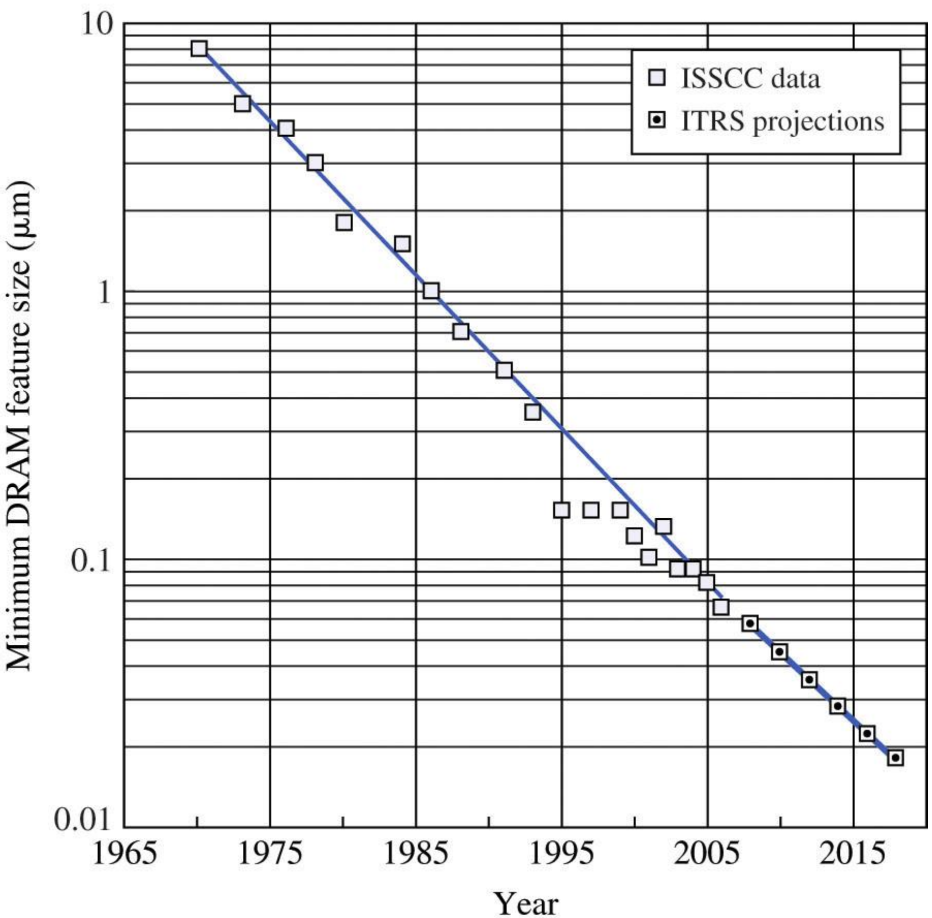



Memory chip density versus time.




Microprocessor complexity versus time.

# Device Feature Size

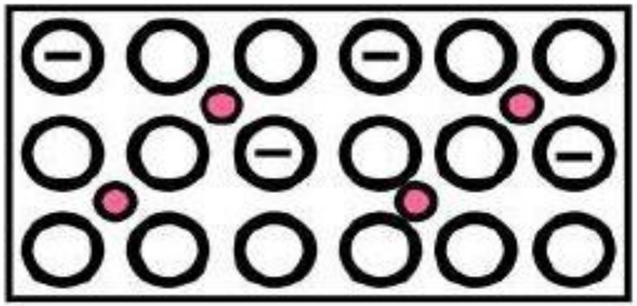


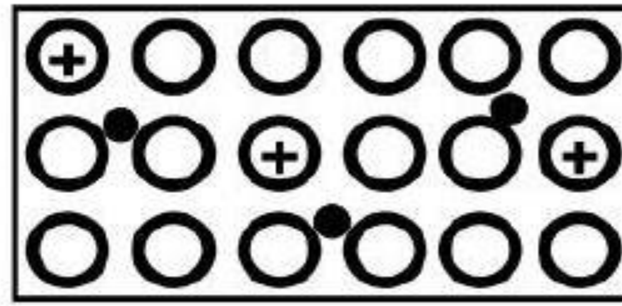

- Feature size reductions enabled by process innovations.
- Smaller features lead to more transistors per unit area and therefore higher density.
- SSI – small scale integration (< $10^2$)
- MSI – medium SI ($10^{2}$- $10^3$)
- LSI – large SI ($10^{3}$- $10^4$)
- VLSI – very large SI ($10^{4}$- $10^9$)
- ULSI & GSI– ultra large SI & giga-scale integration (> $10^9$)

# Introduction

- So far we learned the basics of semiconductor physics, concluding in the **Minority Carrier Diffusion Equation**
- We now encounter our simplest **electronic device**, a diode
- Understanding the principle requires the ability to draw band-diagrams
- Making this quantitative requires ability to solve MCDE (only exponentials!)
- Here we only do the equilibrium analysis

# P-N Junction Formation





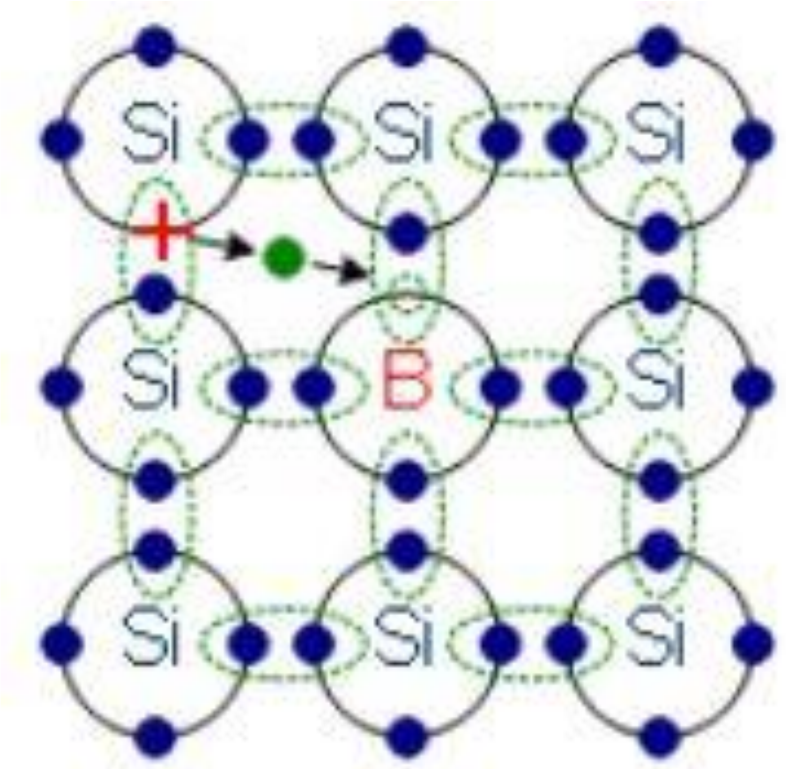
**p-type material**

- Semiconductor material doped with **acceptors**.
- Majority carrier are **holes**
- Material has **high hole** concentration
- Concentration of **free electrons** in p-type material  is **very low**.
- Contains **NEGATIVELY** charged acceptors (immovable) and **POSITIVELY** charged holes (free)
- Total charge = 0

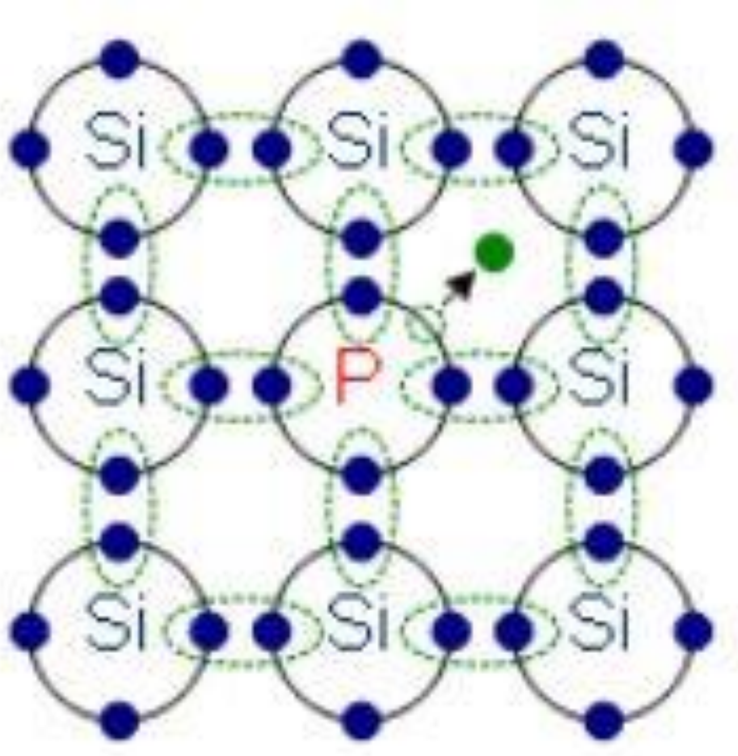
**n-type material**

- Semiconductor material doped with **donors**.
- Majority carrier are **electron**
- Material has high concentration of **free electrons**.
- Concentration of **holes** in n-type material is **very low**.
- Contains **POSITIVELY** charged donors (immovable) and **NEGATIVELY** charged free electrons.
- Total charge = 0

# Doping



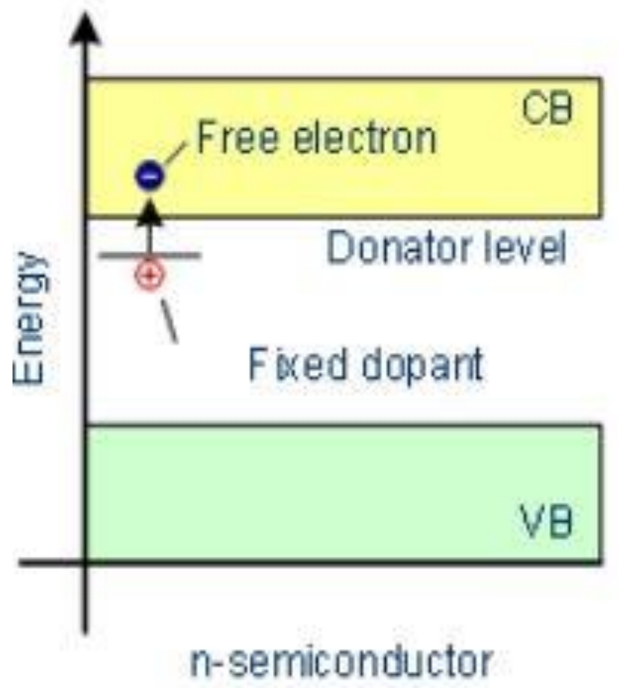

*p-doping with boron*

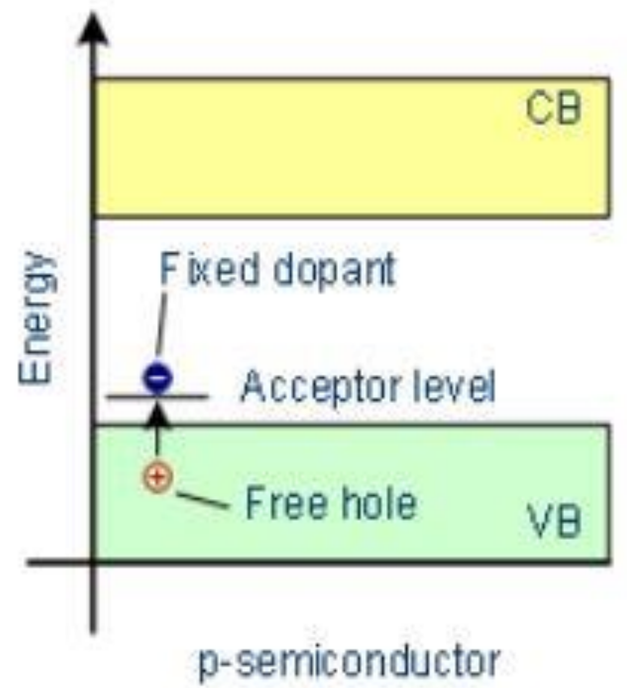



*n-doping with phosphorus*

# Band model of doped semiconductors

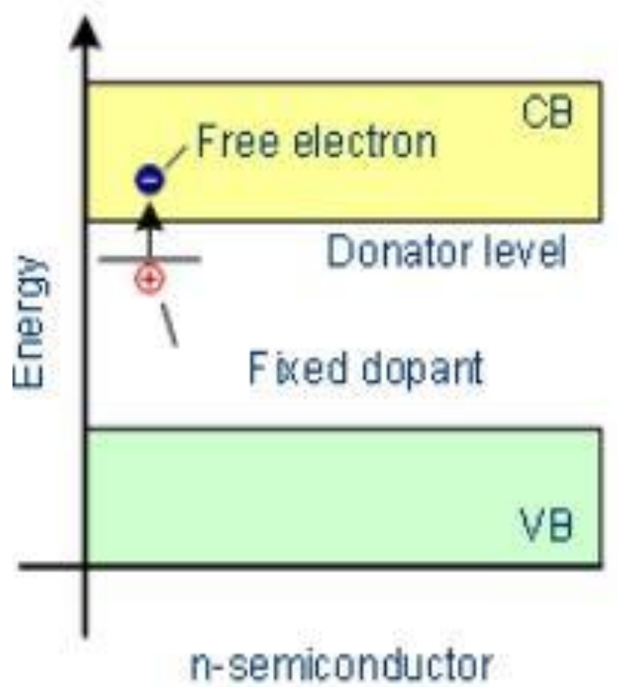
- dopant with five outer electrons, in n-doped semiconductors there is an electron in the crystal which is not bound and therefore can be moved with relatively little energy into the conduction band.
- n-doped semiconductors the donator energy level is close to the conduction band edge, the band gap to overcome is very small.

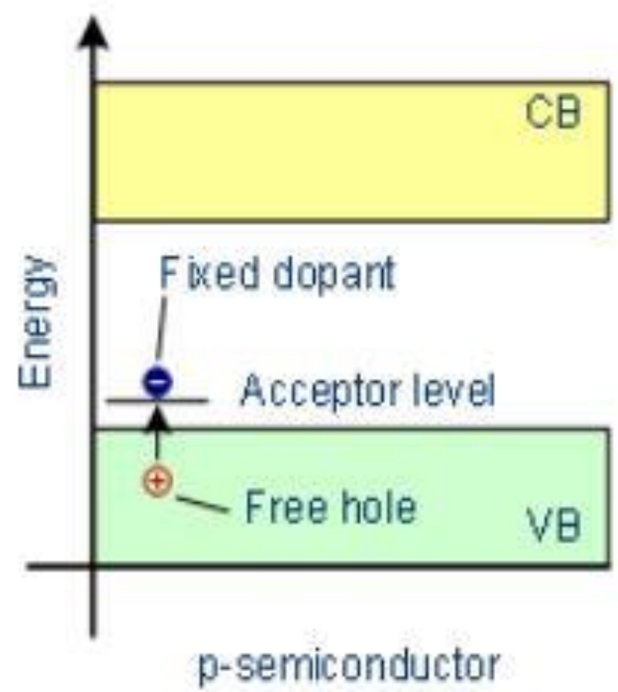


# Band model of doped semiconductors

- Analog, through introduction of a 3-valent dopant in a semiconductor, a hole is available, which may be already occupied at low-energy by an electron from the valence band of the silicon.
- For p-doped semiconductors the acceptor energy level is close the valence band.



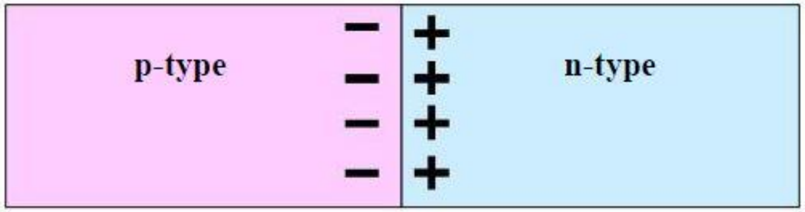
# P-N Junction Formation

- **What happens if n- and p-type materials are in close contact?**
- Being free particles, **electrons** start diffusing from n-type material into p-material and Being free particles, **holes,** too**,** start diffusing from p-type material into n-material
- eventually all the free electrons and holes had **uniformly distributed** over the entire compound crystal.
- However, every electrons **transfers** a negative charge (-q) onto the p-side and also leaves an uncompensated (+q) charge of the donor on the n-side.
- Every hole creates one **positive charge** (q) on the n-side and (-q) **negative charge** on the p-side

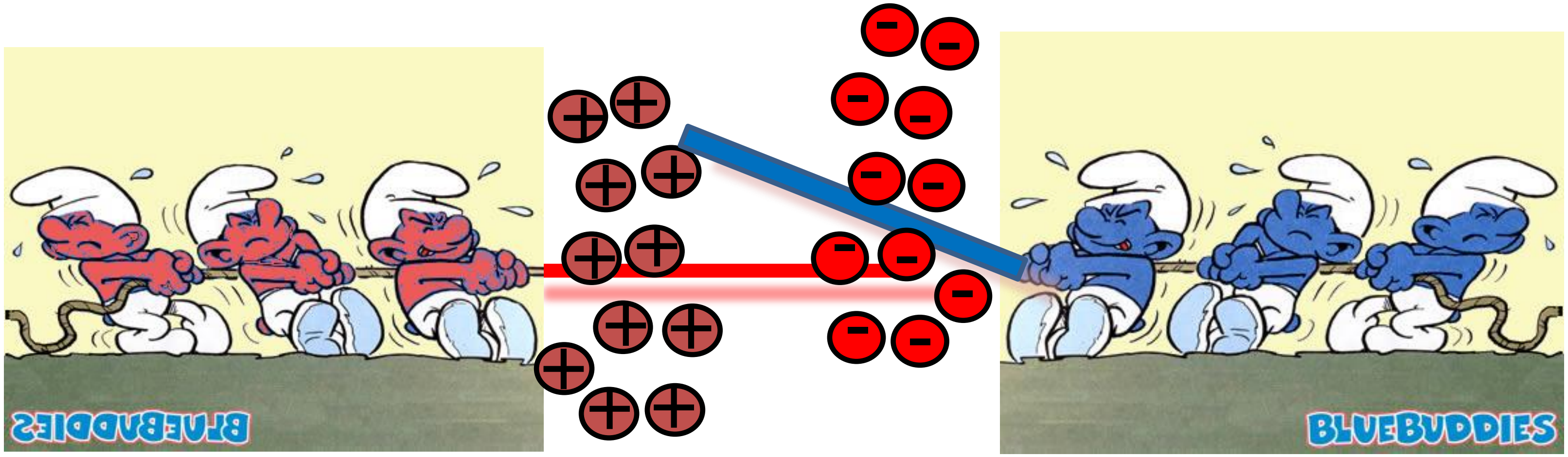
# Gradients drive diffusion


# P-N Junction Formation

- **What happens if n- and p-type materials are in close contact?**



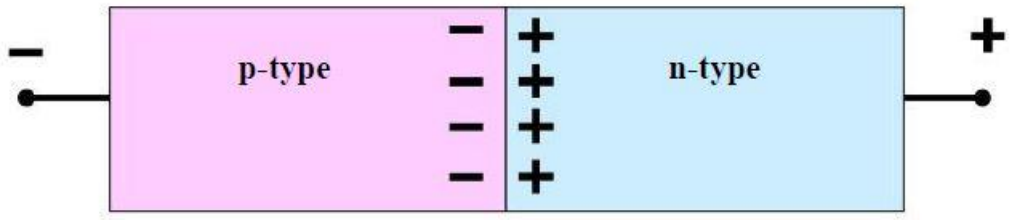

- Electrons and holes remain staying close to the p-n junction because negative and positive charges **attract each other**.
- Negative charge **stops** electrons from further diffusion and Positive charge **stops** holes from further diffusion
- **The diffusion forms a dipole charge layer at the p-n junction interface.**
- **There is a "built-in" VOLTAGE at the p-n junction interface that prevents penetration of electrons into the p-side and holes into the n-side.**




**But charges can't venture too far from the interface because their Coulomb forces pull them back!**

# P-N Junction Formation voltage characteristics

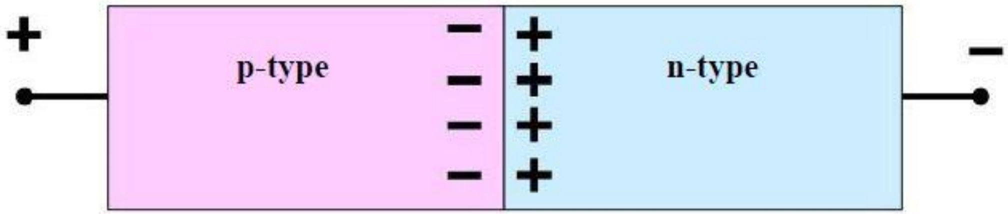
- **What happens when the voltage is applied to a p-n junction?**




- The polarity shown, attracts holes to the left and electrons to the right.
- According to the **current continuity law,** the current can **only** flow if all the charged particles move forming a closed loop
- However, there are very few holes in n-type material and there are very few electrons in the p-type material.
- There are very few carriers available to support the current through the junction plane
- **For the voltage polarity shown, the current is nearly zero**

# P-N Junction Formation voltage characteristics

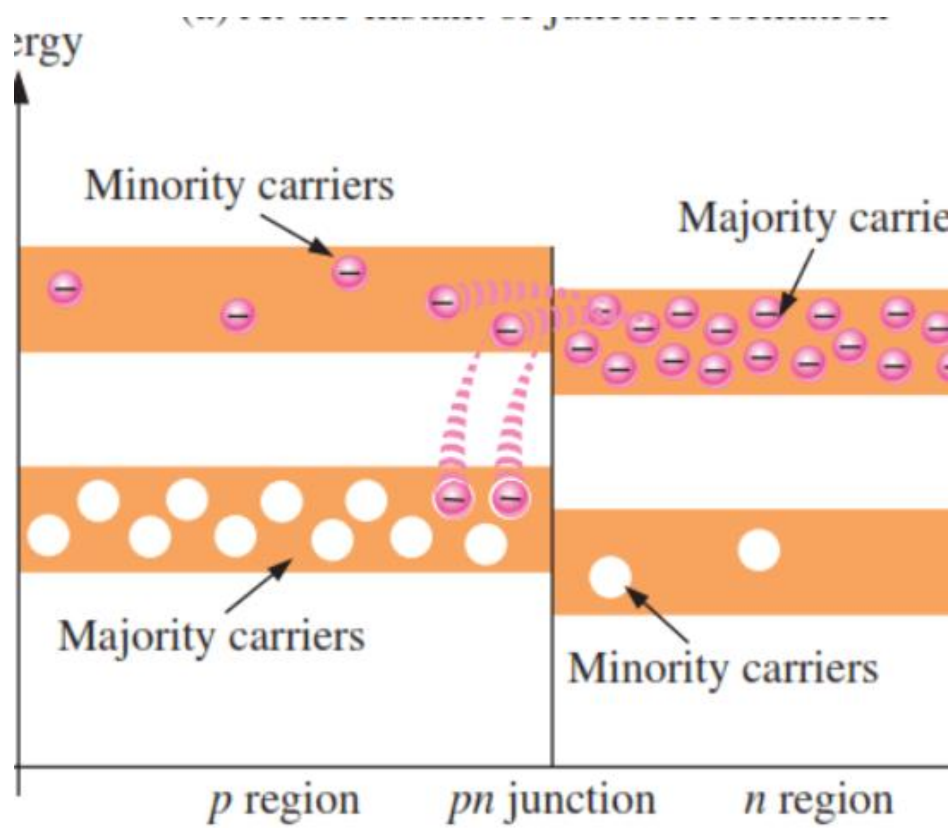
- **What happens if voltage of opposite polarity is applied to a p-n junction?**




- The polarity shown, attracts electrons to the left and holes to the right.
- There are plenty of electrons in the n-type material and plenty of holes in the p-type material.
- There are a lot of carriers available to cross the junction.
- **When the voltage applied is lower than the built-in voltage, the current is still nearly zero.**
- **When the voltage exceeds the built-in voltage, the current can flow through the p-n junction**

# Energy Band Diagrams of a PN Junction

- The valence and conduction bands in an n-type material are at slightly lower energy levels than the valence and conduction bands in a p-type material.
- The lower forces in p-type materials mean that the electron orbits are slightly larger and hence have greater energy than the electron orbits in the n-type materials.
- An energy diagram for a pn junction at the instant of formation is shown in Figure. As you can see, the valence and conduction bands in the n region are at lower energy levels than those in the p region, but there is a significant amount of overlapping.



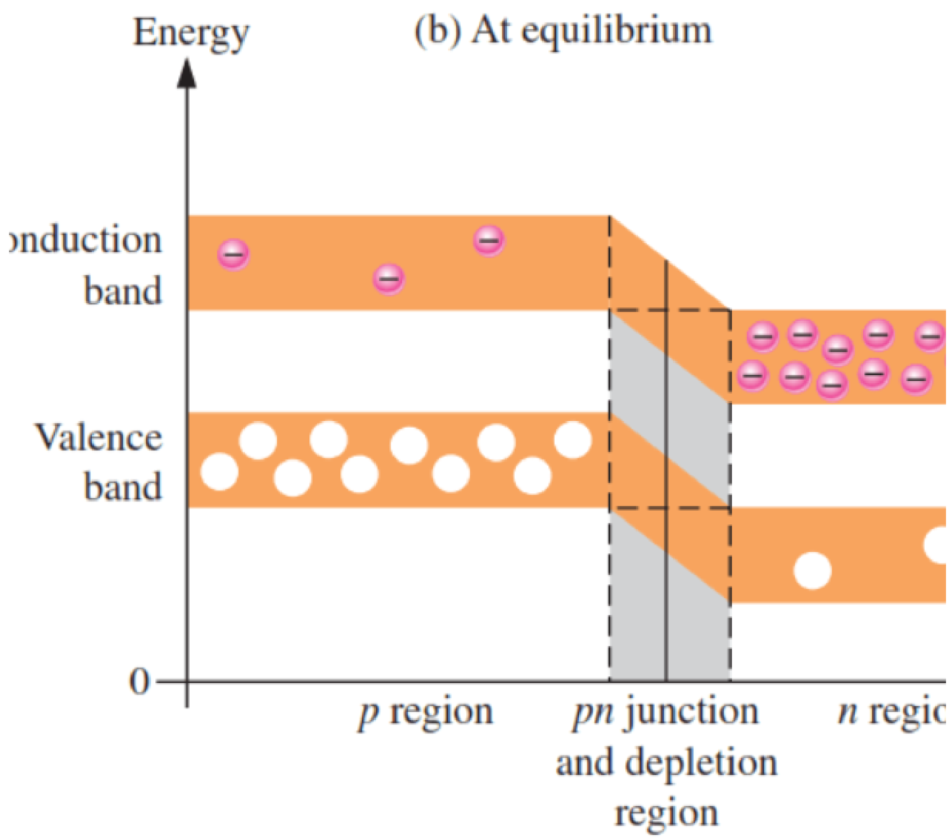
# Energy Band Diagrams of a PN Junction

- The free electron In the n region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the p-region conduction band.

- After crossing the junction, the electrons quickly lose energy and fall into the holes in the p-region valence band as indicated in Figure (a)

# Energy Band Diagrams of a PN Junction

- As the diffusion continues, the depletion region begins to form and the energy level of the n-region conduction band decreases.
- The decrease in the energy level of the conduction band in the n region is due to the loss of the higher energy electrons that have diffused across the junction to the p region.
- Soon, there are no electrons left in the n-region conduction band with enough energy to get across the junction to the p-region conduction band, as indicated by the alignment of the top of the n-region conduction band and the bottom of the p-region conduction band in Figure (b).



# Energy Band Diagrams of a PN Junction

- At this point, the junction is at equilibrium; and the depletion region is complete because diffusion has ceased. There is an energy gradiant across the depletion region which acts as an “energy hill” that an n-region electron must climb to get to the p region
- Notice that as the energy level of the n-region conduction band has shifted downward, the energy level of the valence band has also shifted downward.

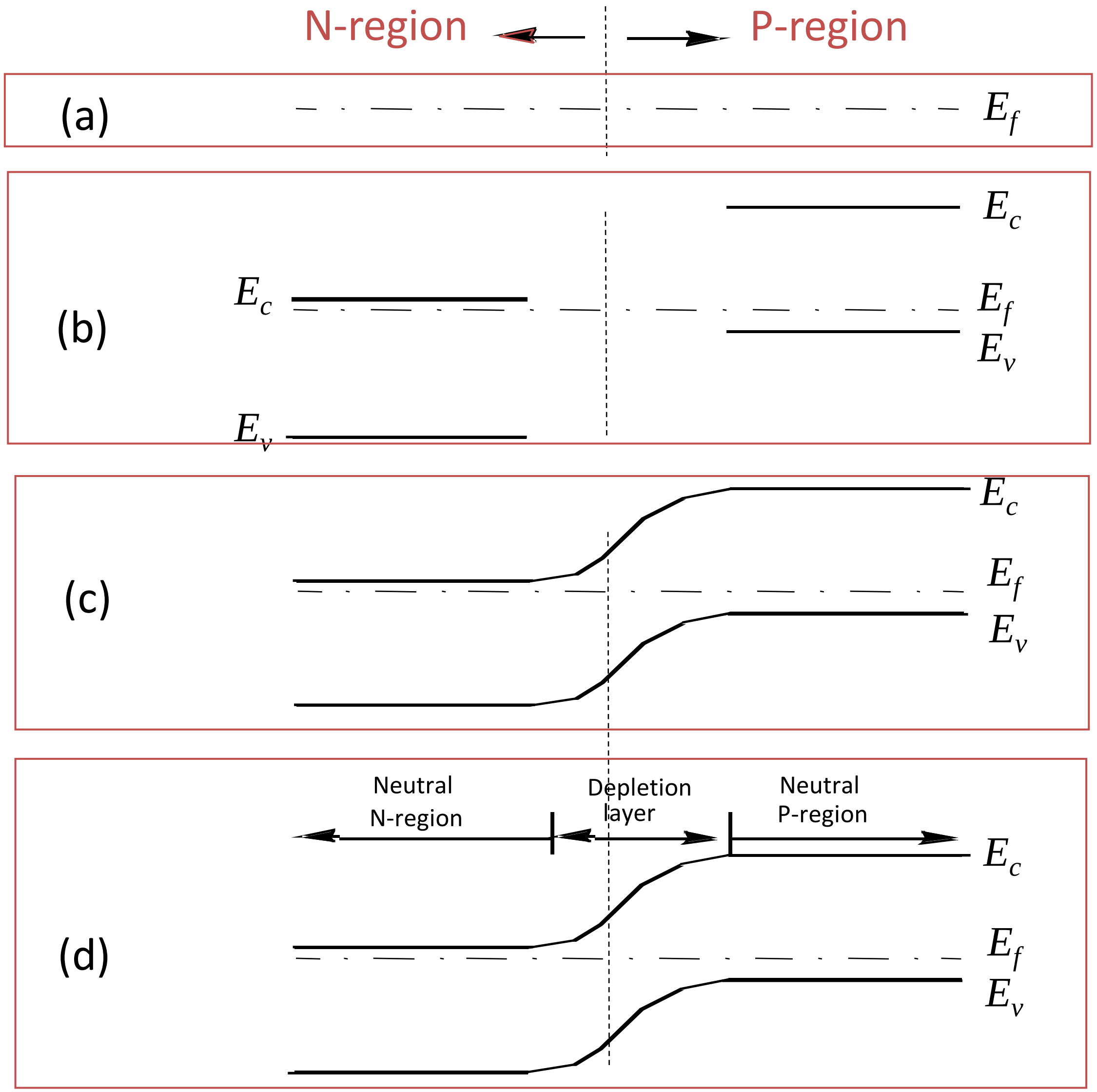
- It still takes the same amount of energy for a valence electron to become a free electron.
- In other words, the energy gap between the valence band and the conduction band remains the same.

# Energy Band Diagrams of a PN Junction

- For simplicity, it is usually assumed that the P and N layers are uniformly doped at **acceptor density *N*a**, and **donor density *N*d**, respectively.

- This idealized PN junction is known as a **step junction** or an **abrupt junction**.

# Energy Band Diagram of a PN Junction




$E_f$ is constant at equilibrium

$E_c$ and $E_v$ are known relative to $E_f$

$E_c$ and $E_v$ are smooth, the exact shape to be determined.

A depletion layer exists at the PN junction where $n \approx 0$ and $p \approx 0$.

# Work Function

- Valence bands and conduction bands are separated by the **band gap ($E_g$)**. This means the work function is now different from the **ionization energy** *(energy difference between valence bands maximum (VBM) and vacuum level)*.
- In a semiconductor, the Fermi level becomes a somewhat theoretical construct since there are no allowed electronic states within the band gap.
- The Fermi level refers to the point on the energy scale where the probability is just 50%. Even if there are no electrons right at the Fermi level in a semiconductor, the work function can be measured by photoemission spectroscopy(PES).

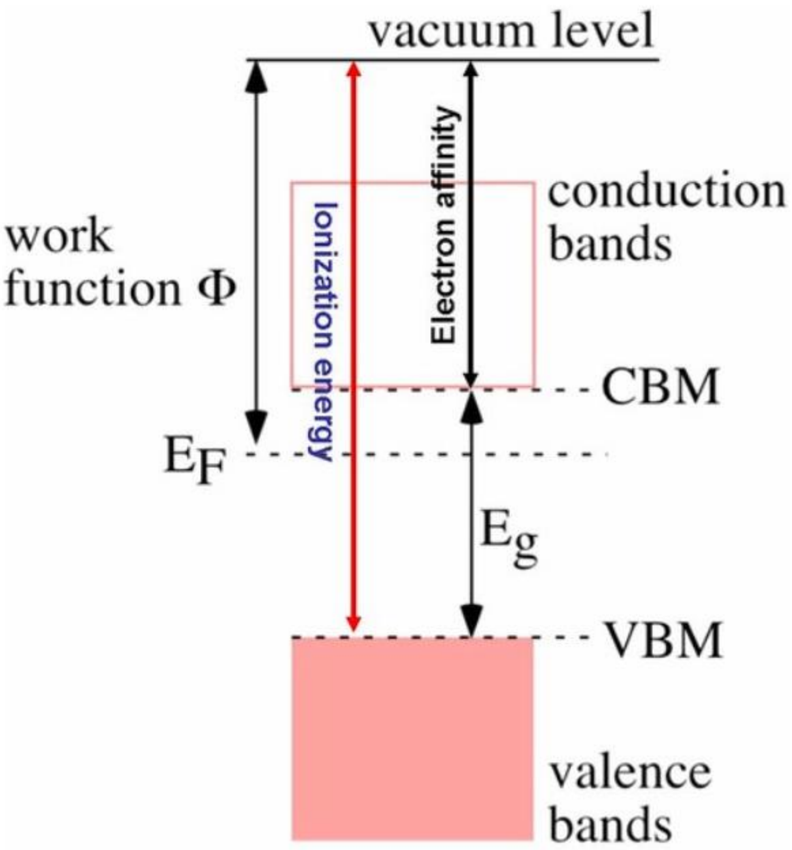
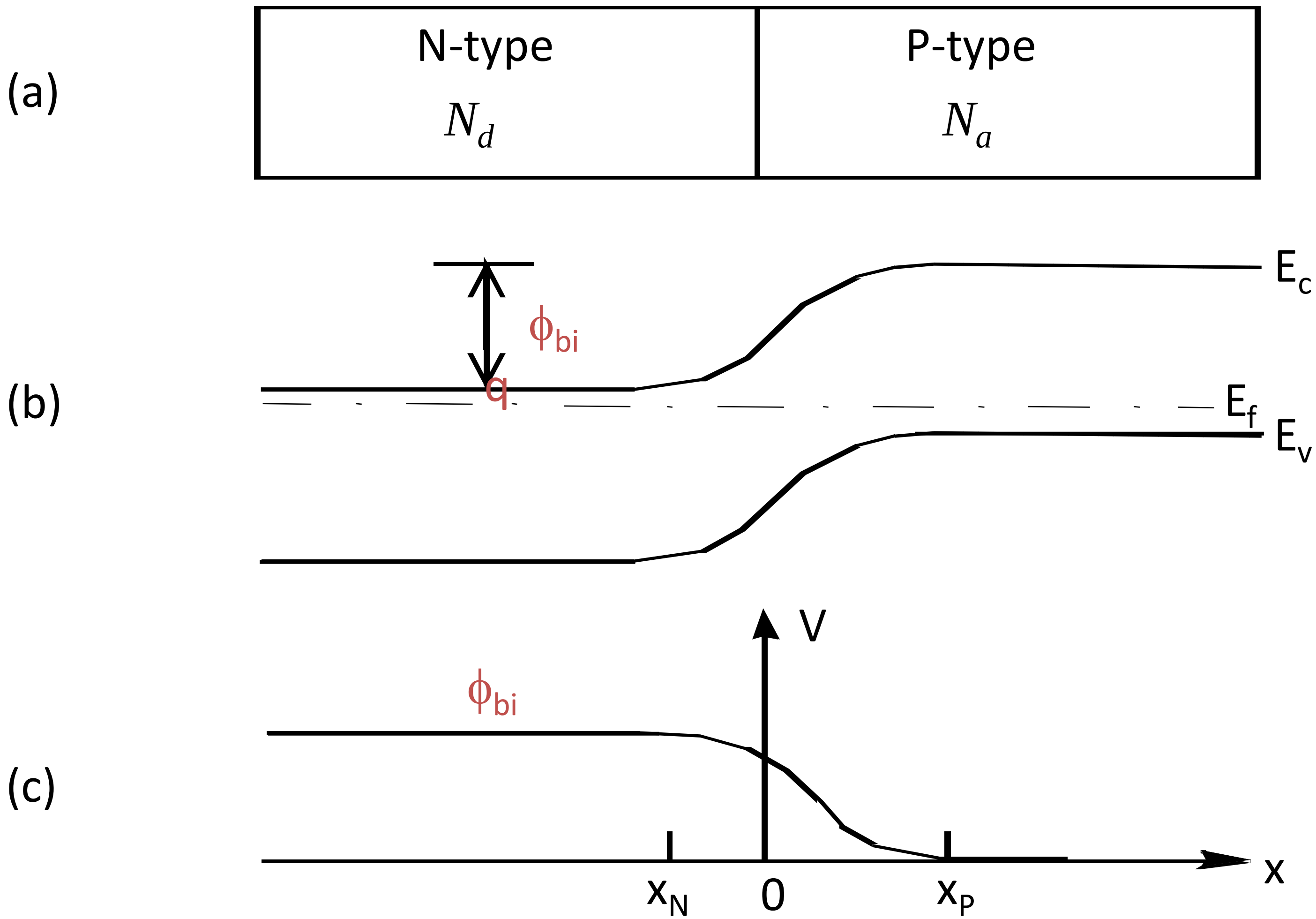



Figure: a schematic energy diagram of a n-type semiconductor.

# Built-in Potential




Can the built-in potential be measured with a voltmeter?

# Mass-Action Law

- $n_0$ : thermal-equilibrium concentration of electrons
- $p_0$ : thermal-equilibrium concentration of holes
- $n_0 p_0$ = ni ^2 = f(T) (function of temperature)
- The product of n0 and po is always a constant for a given semiconductor material at a given temperature.

# Equilibrium Electron and Hole Concentrations

- $n_0$ : thermal-equilibrium concentration of electrons
- $p_0$ : thermal-equilibrium concentration of holes
- $n_d$ : concentration of electrons in the donor energy state
- $p_a$ : concentration of holes in the acceptor energy state
- $N_d$ : concentration of donor atoms
- $N_a$ : concentration of acceptor atoms
- $N_d^+$ : concentration of positively charged donors (ionized donors)
- $N_a^-$ : concentration of negatively charged acceptors (ionized acceptors)

# Built-in Potential

**N-region** $$n = N_d = N_c e^{-qA/kT} \Rightarrow A = \frac{kT}{q}\ln\frac{N_c}{N_d}$$

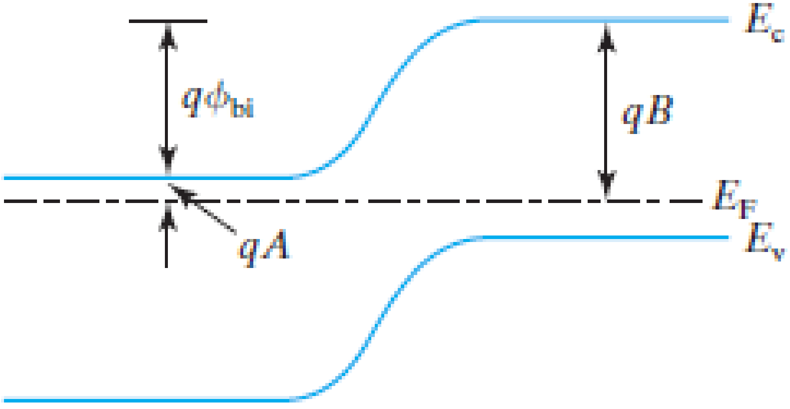
**donor density**

**P-region** $$n = \frac{n_i^2}{N_a} = N_c e^{-qB/kT} \Rightarrow B = \frac{kT}{q}\ln\frac{N_c N_a}{n_i^2}$$

**acceptor density**

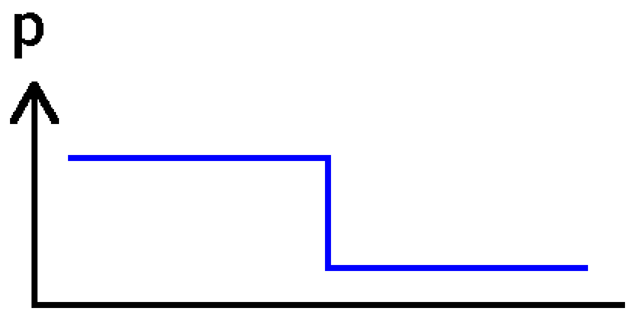
$$\phi_{bi} = B - A = \frac{kT}{q}\left(\ln\frac{N_c N_a}{n_i^2} - \ln\frac{N_c}{N_d}\right)$$

$$\boxed{\phi_{bi} = \frac{kT}{q}\ln\frac{N_d N_a}{n_i^2}}$$



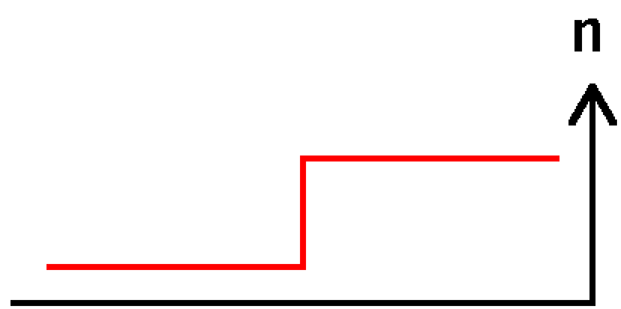
# Gradients drive diffusion

Hole gradient

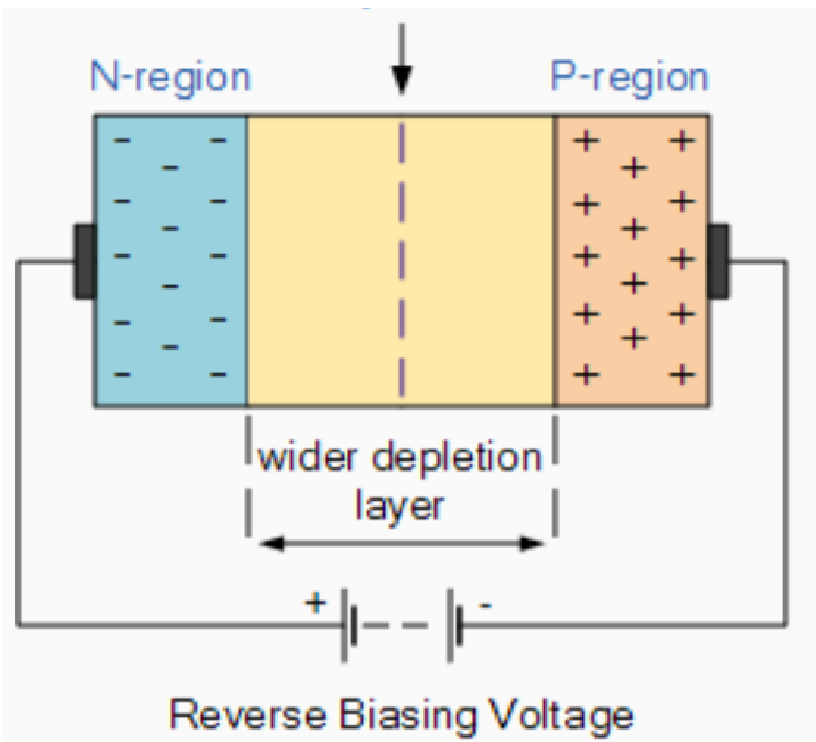


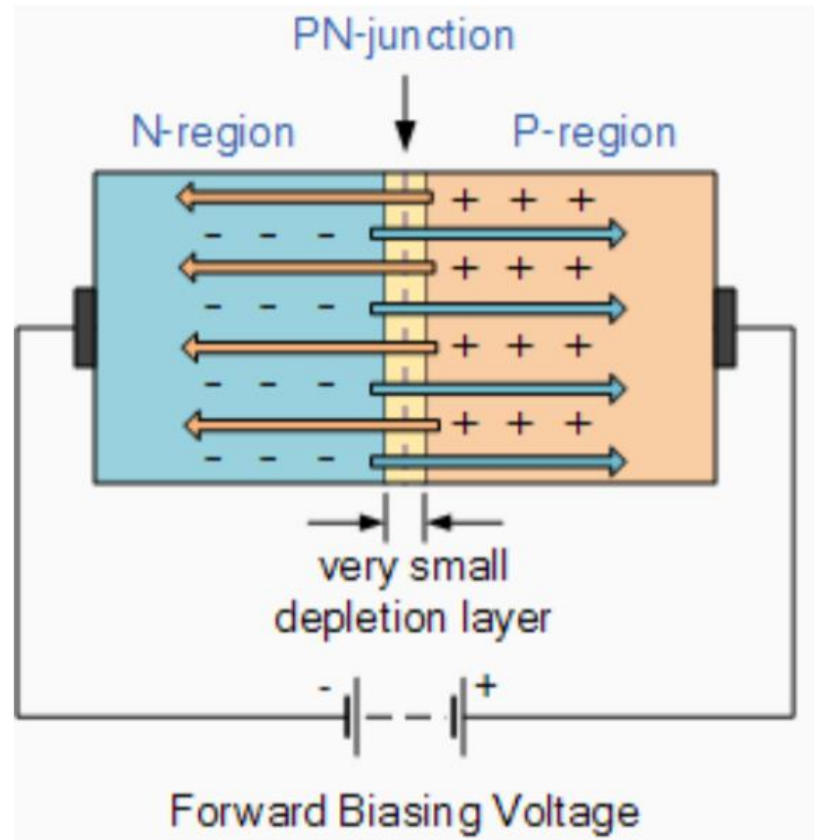

$J_{p,\ diffusion} = -qD_p\ dp/dx$ = current right, holes right

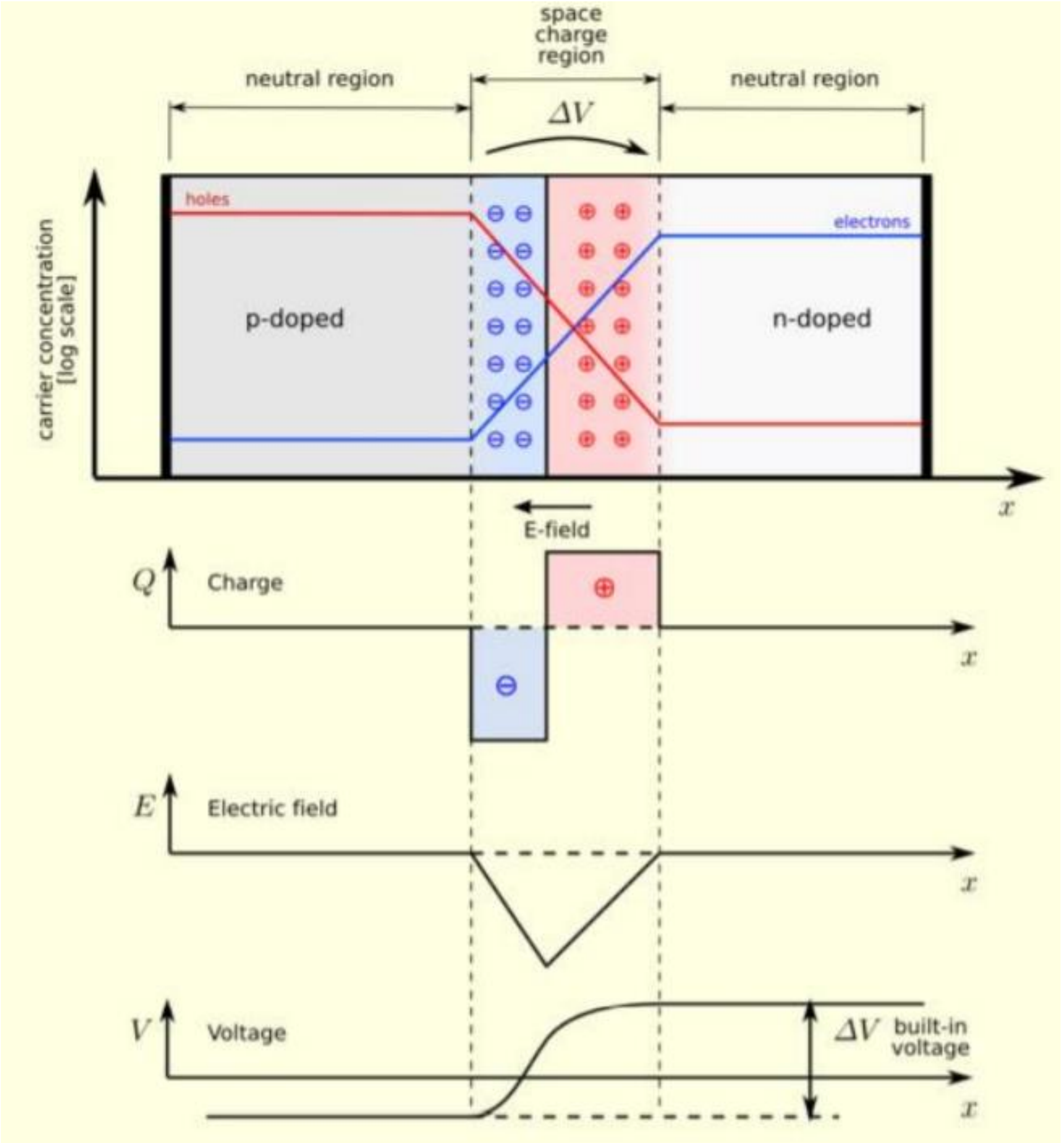
Electron gradient




$J_{n,diffusion} = -qD_n\ dn/dx$ = current right, electron left


N-region
P-region
wider depletion
layer
+
-
Reverse Biasing Voltage


PN-junction
N-region
P-region
very small
depletion layer
-
+
Forward Biasing Voltage



space
charge
region
neutral region
neutral region
$\Delta V$
holes
electrons
carrier concentration
[log scale]
p-doped
n-doped
$x$
E-field
$Q$
Charge
$x$
$E$
Electric field
$x$
$V$
Voltage
$\Delta V$ built-in
voltage
$x$

# DIFFUSION CURRENT

- It is possible for an electric current to flow in a semiconductor even in the absence of the applied voltage provided a concentration gradient exists in the material.
- A **concentration gradient exists** if the number of either elements or holes is greater in one region of a semiconductor as compared to the rest of the Region.
- the change carriers have the **tendency to move** from the region of higher concentration to that of lower concentration of the same type of charge carriers.
- Thus the movement of charge carriers takes place resulting in a current called **diffusion current**.
- Since the hole density p(x) decreases with increasing x, dp/dx is negative and the minus sign in equation is needed in order that Jp has positive sign in the positive x direction

Diffusion current density = Charge × Carrier flux

Diffusion current density due to electron Jn and holes $Jp$ is given by

$$J_n^{diff} = qD_n \frac{dn}{dx} \quad A/cm^2$$

$$J_p^{diff} = -qD_p \frac{dp}{dx} \quad A/cm^2$$

$Dp = \lambda_2/\tau_c$ is the diffusion coefficient

Average carrier velocity = $Vth$ = 10^7 cm/s
Average interval between collisions = τc = 10-13 s = 0.1 picoseconds
mean free path = λ = $Vth\ \tau_C$ = 10^-6 cm = 10 nm

# DIFFUSION CURRENT

# DRIFT CURRENT

- When an electric field is applied across the semiconductor material, the charge carriers attain a certain drift velocity Vd , which is equal to the product of the mobility of the charge carriers and the applied Electric Field intensity E .

- Drift velocity Vd = mobility of the charge carriers X Applied Electric field intensity. (Vd = -μnE)

- Holes move towards the negative terminal of the battery and electrons move towards the positive terminal of the battery. This combined effect of movement of the charge carriers constitutes a current known as **— the drift current.**

- Thus the drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

- Drift current due to the charge carriers such as free electrons and holes are the current passing through a square centimeter perpendicular to the direction of flow.

Drift current density: ∝ Carrier drift velocity

∝ Carrier concentration

∝ Carrier charge

$$J_n^{drift} = -qnv_{dn} = qn\mu_n E$$

$$J_p^{drift} = qpv_{dp} = qp\mu_p E$$

n - Number of free electrons per cubic centimetre

P - Number of holes per cubic centimetre

μ(n) – Mobility of electrons in cm2 / Vs

μ(p) – Mobility of holes in cm2 / Vs

E – Applied Electric filed Intensity in V /cm

q – Charge of an electron = 1.6 x 10-19 coulomb.

# DRIFT CURRENT

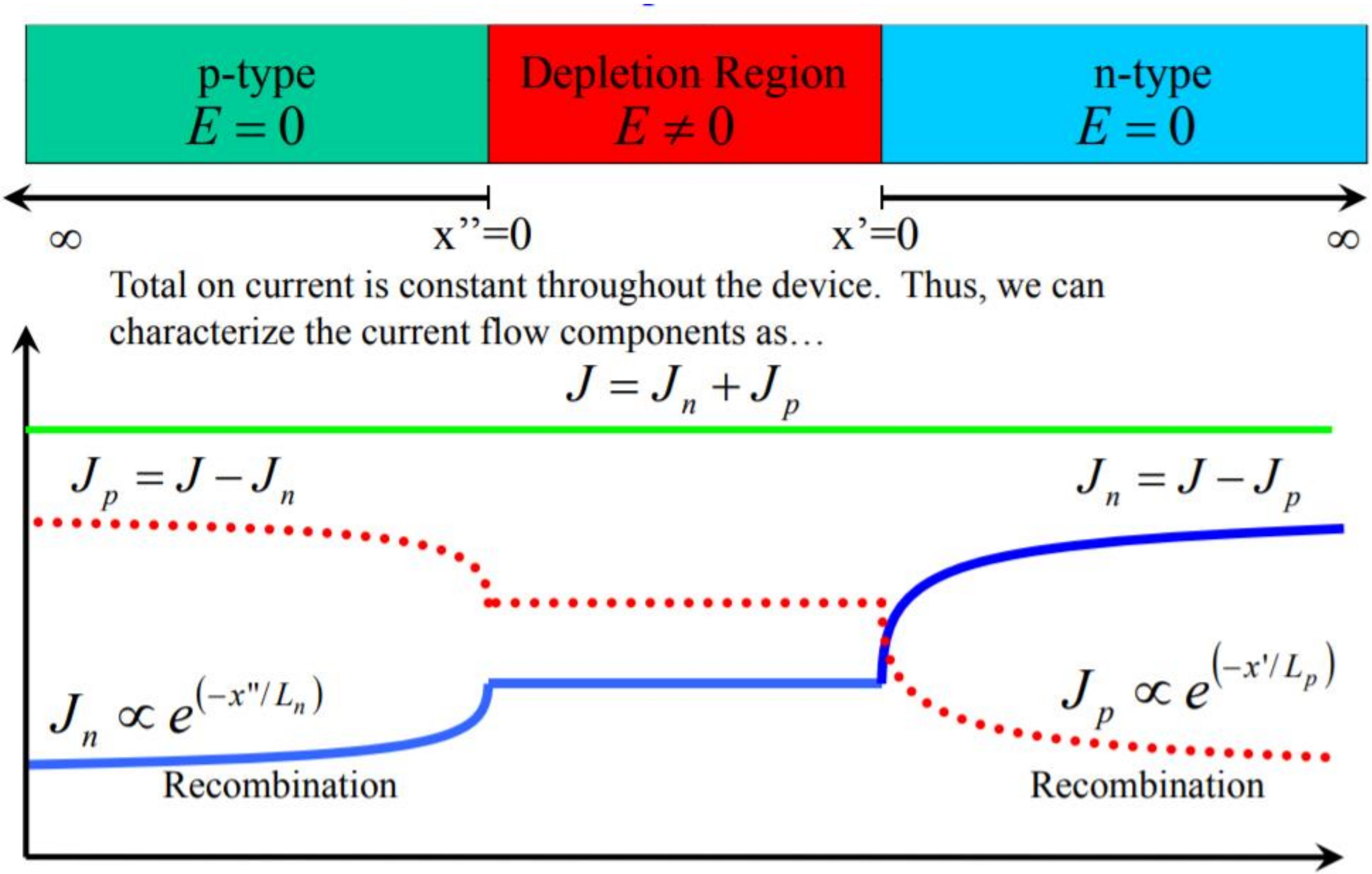
# Total Current

The total current in a semiconductor (N type and P type) is the sum of both drift and diffusion currents that is given by

$$\mathbf{J_n = J_n^{drift} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}}$$

$$\mathbf{J_p = J_p^{drift} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}}$$

# Quantitative PN Diode Solution



# PN Diode Current

Thus, evaluating the current components at the depletion region edges, we have…

$$\mathrm{J} = \mathrm{J_n}(\mathrm{x''}=0) + \mathrm{J_p}(\mathrm{x'}=0) = \mathrm{J_n}(\mathrm{x''}=0) + \mathrm{J_p}(\mathrm{x''}=0) = \mathrm{J_n}(\mathrm{x'}=0) + \mathrm{J_p}(\mathrm{x'}=0)$$

$$\mathrm{J} = q\left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}\right)\left(e^{qV_A/kT} - 1\right) \quad \textit{for all } x$$

*or*

$$\boxed{\begin{array}{c} \mathrm{I} = I_o\left(e^{qV_A/kT} - 1\right) \quad \textit{where } I_o = qA\left(\dfrac{D_n n_i^2}{L_n N_A} + \dfrac{D_p n_i^2}{L_p N_D}\right) \\ I_o \textit{ is the "reverse saturation current"} \end{array}}$$

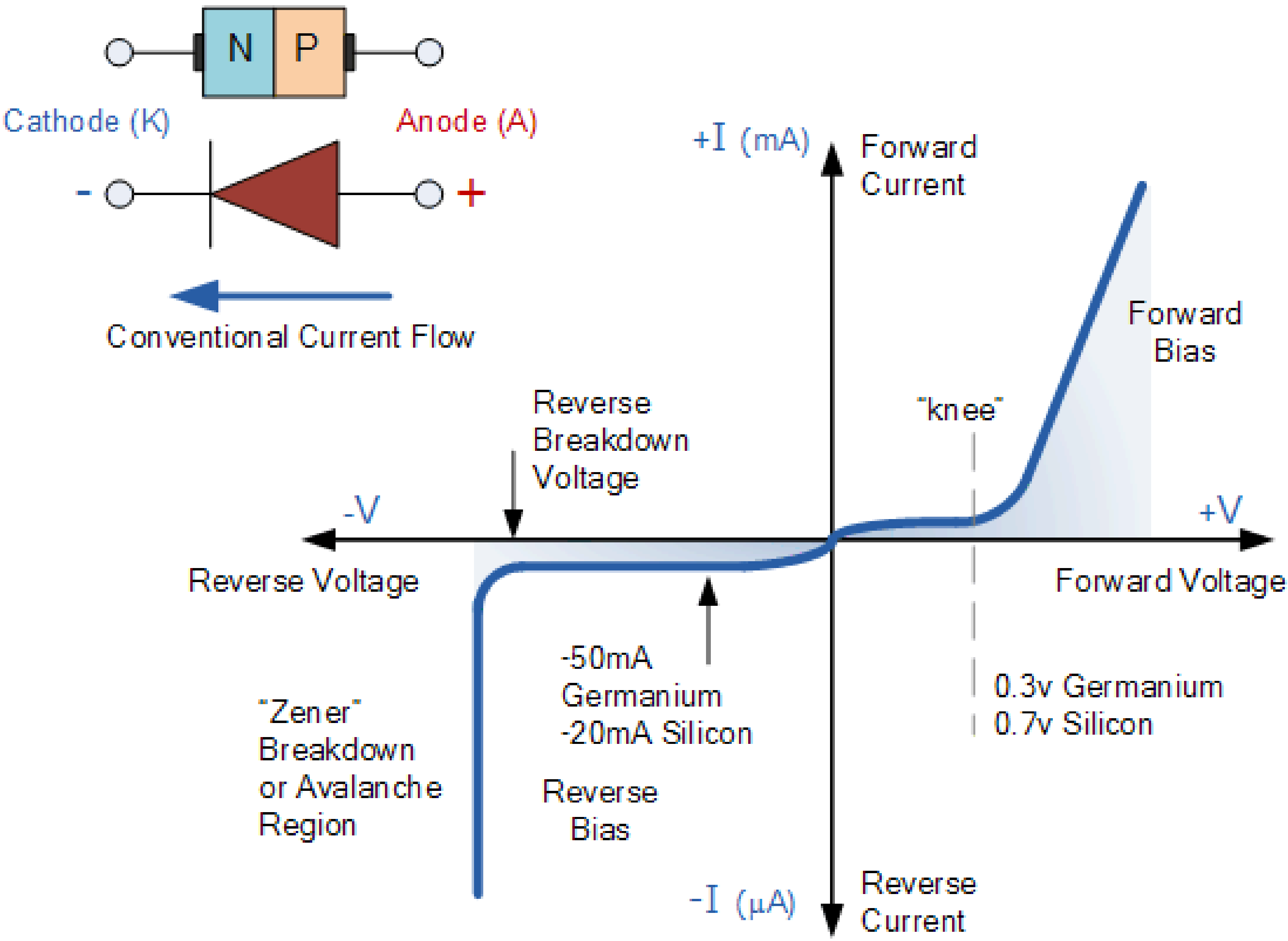
# PN Diode Current

- Diode is **non-linear component** of an electrical circuit, which allow current in forward biasing and block current in reverse biasing.
- The behavior of a diode can be identified using VI characteristic. Current of the diode depends upon the voltage across the diode.
- The diode current can be expressed in the form of diode current equation.

$$\boldsymbol{I = I_0\,[e^{V/\eta V_T} - 1]}$$

- I – Diode Current
- Io- Diode reverse saturation current at room temperature
- V- External Voltage applied to the diode
- η – A constant, two for Silicon and one for Germanium
- $V_T - \frac{kT}{q}$ = T/11600 Volts-equivalent of temperature, thermal voltage

# V-I Characteristics of PN Junction Diode



# V-I Characteristics of PN Junction Diode Reverse Bias