SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN

Term 7- Sept 2025

Nanoelectronics and Technology (01.119/99.503)-Week 1 Class 2

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18-Sept- 2025

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Outline

- Review of semiconductors- Silicon
- Carrier transport
- PN junction-Diodes
- Schottky Diodes
- Ohmic contact
- Introduction to MOS structure

Review of Semiconductors

- Semiconductors
  - Intrinsic Semiconductor
  - Extrinsic Semiconductor (Doped Semiconductor)
    - N-type Semiconductor
    - P-type Semiconductor

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Semiconductor Materials

- **Conductors**
- Gold
- Silver
- Copper
- Aluminum
- Cobalt

- **Semiconductors**
- Germanium
- Silicon
- Gallium Arsenide
- Carbon
- SiC
- GaN

- **Non-Conductors**
- Glass (3.8k)
- Air (1k)
- Silicon Dioxide (3.9k)
- Silicon Nitride (7.5k)
- Hafnium Dioxide (30k)

A **dielectric material** is a substance

that is a poor conductor of electricity, but an efficient supporter of electrostatic fields.
The **dielectric constant** , the extent to which a substance concentrates the electrostatic lines of flux

A **low-k** dielectric has a value of 3.9 or lower and a **high-k** a value of 4 or higher

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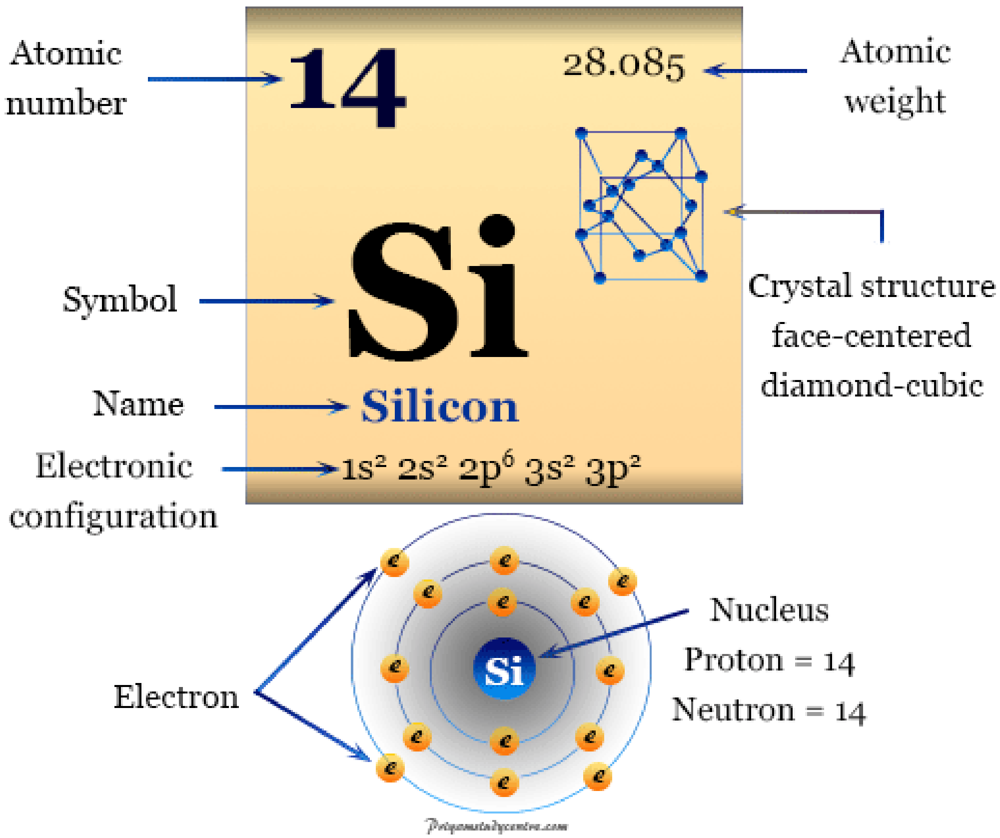
Silicon Semiconductor



Silicon is used for integrated circuits (ICs) because its properties as a semiconductor, such as

- a stable, optimal bandgap and excellent thermal stability, allow for reliable and complex electronic components.
- Its mechanical strength, abundance and cost-effectiveness make it ideal for mass production and integration into a wide range of electronic devices.

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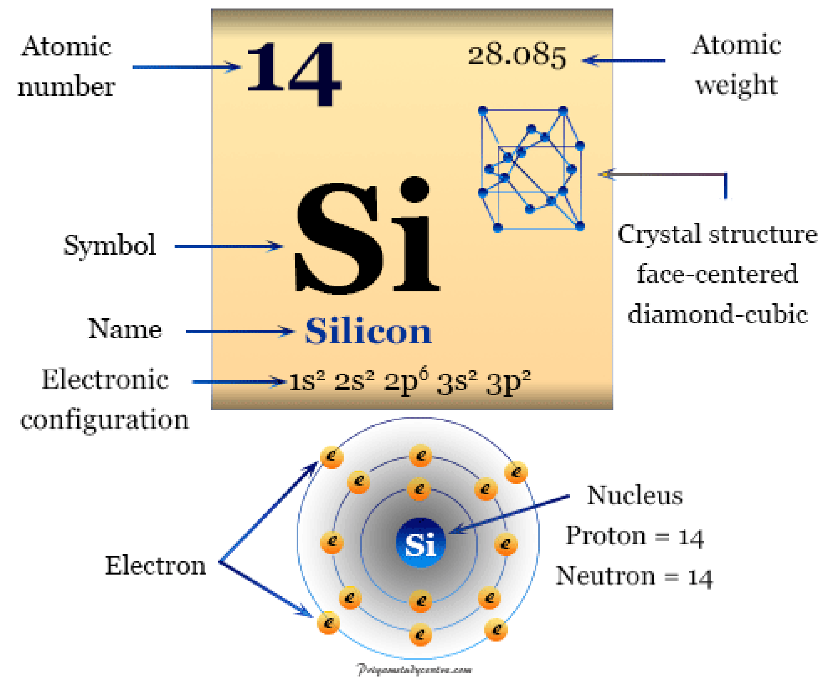
Silicon Semiconductor

- Si is a group 4 element, atomic no. 14 (14 protons & 14 electrons).
- 14 electrons in three shells config: 2) 8) 4 [orbital: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$].
- There are 4 electrons in the outer "bonding" shell (valence electrons).
- Si atom shares the valence electrons to form strong covalent bonds with 4 neighbors, forming a tetrahedral structure (pyramid).



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Silicon Semiconductor

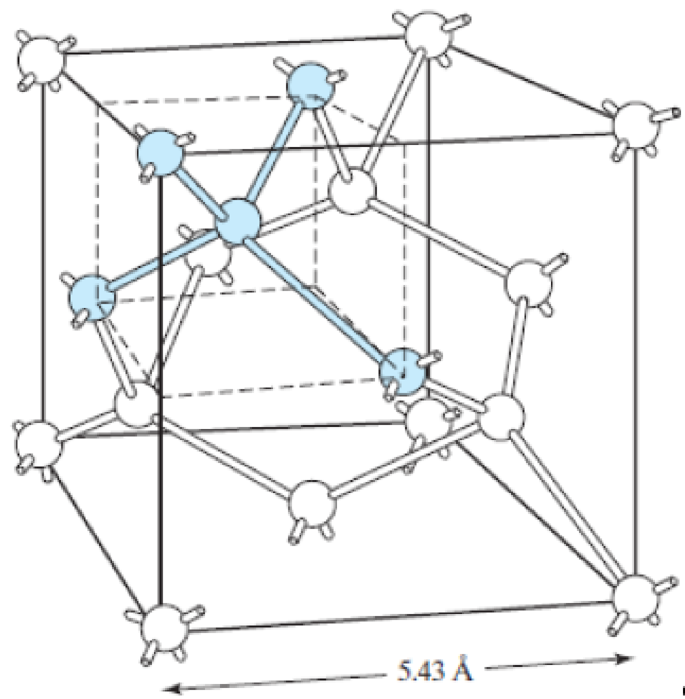
Lattice constant a = 5.431 Å.

Si atomic density is

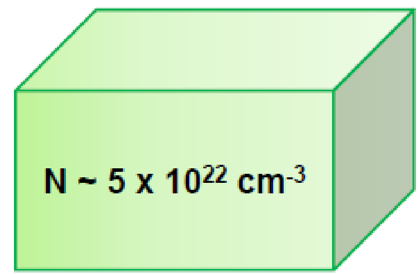
$$\frac{8}{(5.431\ \text{Å})^3} \approx 5 \times 10^{22}\ \text{cm}^{-3}$$

Silicon Crystal Structure

- ***Unit cell*** of silicon crystal is cubic.
- ***Each Si atom has 4 nearest neighbors.***



Modern Semiconductor Devices for Integrated Circuits (C. Hu)



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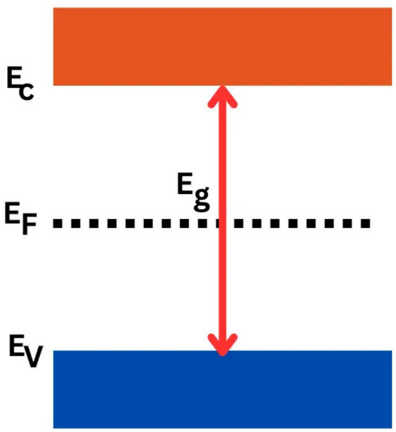
Silicon Semiconductor- Energy band



- E_c • Conduction Band
- E_V • Valence Band
- E_g • Forbidden Energy Gap
- E_F • Fermi Level

E_G	T=300K
Si	1.12eV

- The conduction band is the higher energy level band. This band is partially filled with electrons known as free electrons, as they are able to move anywhere within the solid.
- These electrons are responsible for the flow of current.
- There exists an energy gap between the conduction band and the valence band, and this difference in energy is referred to as the forbidden energy gap which determines the nature of a solid.
- At a temperature of 300ºK, silicon has a forbidden gap of 1.12 eV

https://www.electricalvolt.com/energy-bands-in-silicon/

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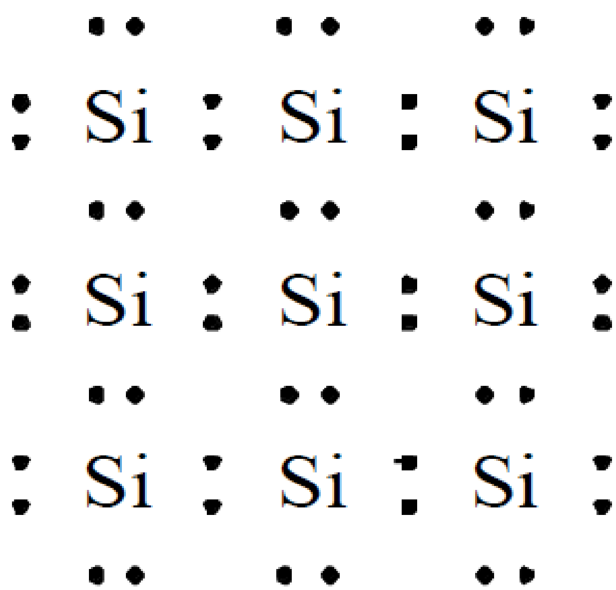
Silicon Semiconductor- Intrinsic

Intrinsic silicon – pure, perfect without impurities in the crystal.

All bonds unbroken at $T = 0$ K, free holes and electron concentration $p_o = n_o = 0$.



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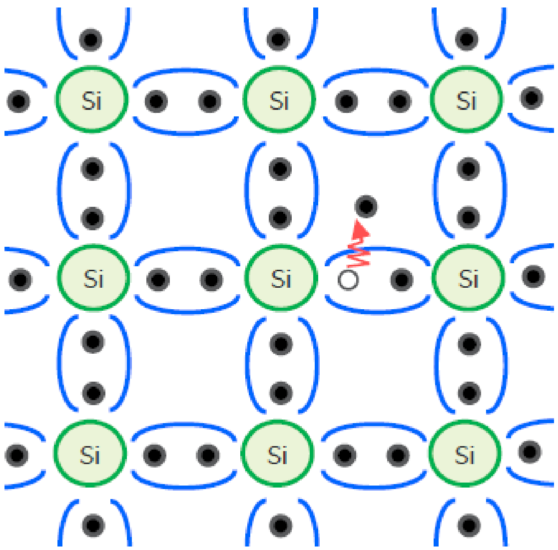
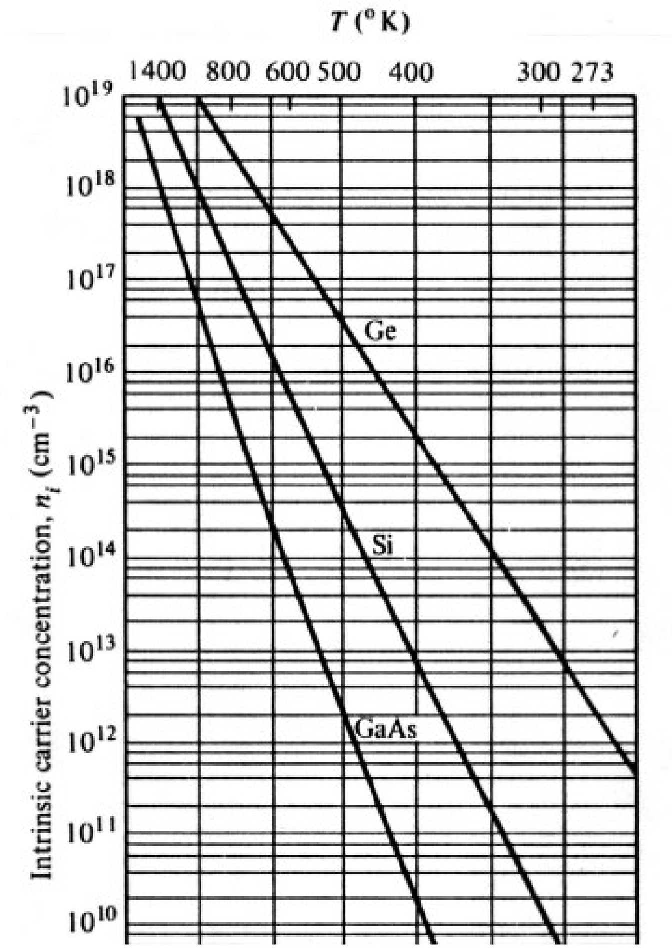


- Notice the temperature and bandgap dependency.

  At typical room temperature 300 K, Si $n_i(T) \cong 10^{10}\,\mathrm{cm}^{-3}$.

As T ↑, atoms vibrates which potentially break Si-Si bond and create a free electron and simultaneously it creates a vacant state (hole) ➔ n=p=n_i, measured in # cm^{-3}

Silicon Semiconductor- Intrinsic



Intrinsic carrier concentration is a material property that depends on temperature.

https://sites.chemengr.ucsb.edu/~ceweb/courses/che142242/pdfs/lecture_3_chex42.pdf

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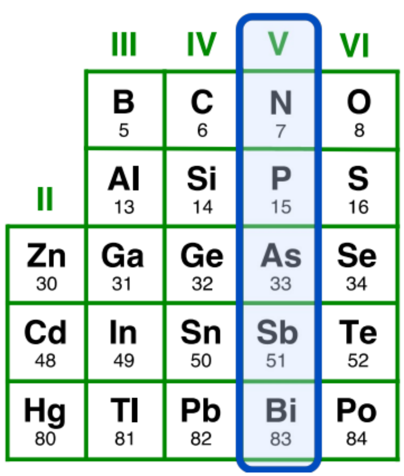
Doping of Silicon Semiconductors-Extrinsic

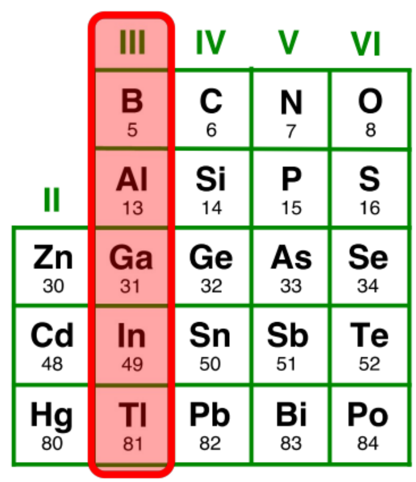
What is Doping?

- **Doping** is the intentional introduction of controlled impurities (dopant atoms) into pure silicon to tailor its electrical properties.
- Pure silicon is a **group IV element** with limited intrinsic conductivity. Adding small amounts of **group III (acceptors)** or **group V (donors)** elements changes the balance of charge carriers drastically.

Group V (donors)-N-type



Group III (acceptors)-P-type



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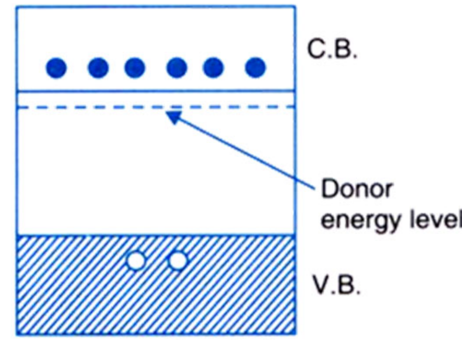
Doping of Silicon Semiconductors

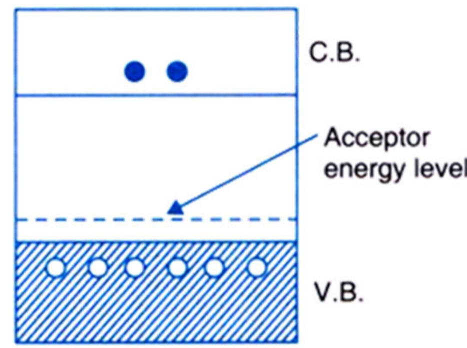
(a) n-type Doping

- Dopant: **Group V elements** (e.g., Phosphorus, Arsenic, Antimony).
- Each dopant atom contributes an **extra electron** (donor electron).
- Majority carriers: **Electrons**
- Minority carriers: **Holes**
- Fermi level shifts **closer to the conduction band.**



(b) p-type Doping

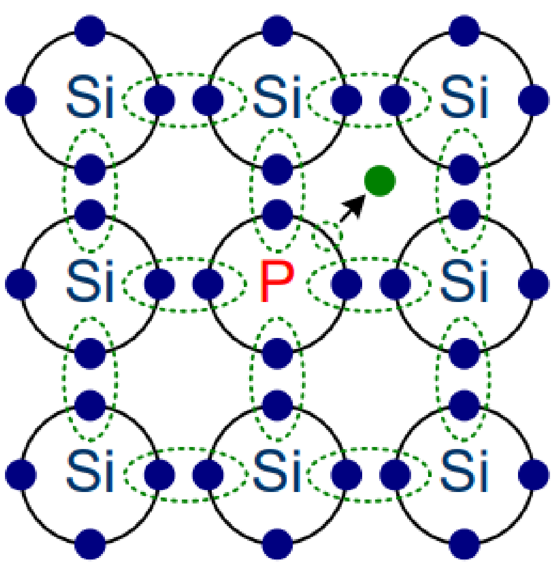
- Dopant: **Group III elements** (e.g., Boron, Gallium, Aluminum, Indium).
- Each dopant atom creates a **deficiency of an electron** → a **hole.**
- Majority carriers: **Holes**
- Minority carriers: **Electrons**
- Fermi level shifts **closer to the valence band.**



https://www.wiredfaculty.com/question/UTBKVFJVVk9VRWd4TWpBek9EZ3hPQT09

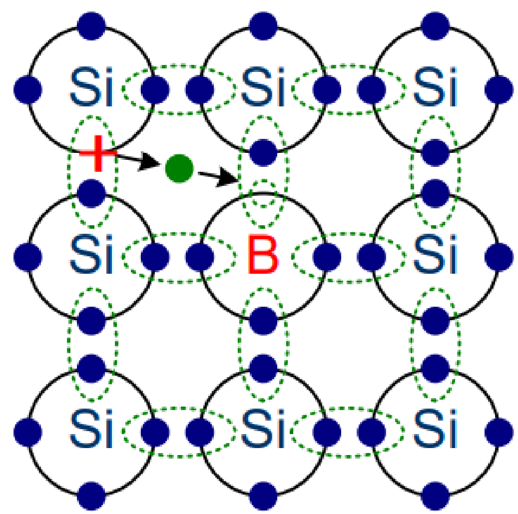
Doping of Silicon Semiconductors

(a) n-type Doping



n-doping with phosphorus

(b) p-type Doping



p-doping with boron

https://www.halbleiter.org/pdf/en/Fundamentals/Fundamentals%20-%20Doping.pdf

Doping of Silicon Semiconductors-Extrinsic

https://www.youtube.com/watch?v=5ZNeDxfgYAE

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Doping of Silicon Semiconductors-Extrinsic

1. Column V elements (P, As, Sb): "Donors", concentration N_d [unit : cm^{-3}]
2. Column III elements (B): "Acceptors", concentration N_a [unit : cm^{-3}]

At room temp almost all impurity atoms are ionized, so

- $N_d^+ \approx N_d$
- $N_a^- \approx N_a$

Simplified expressions for n and p in terms of n_i and E_F

$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = n_i e^{(E_i - E_F)/kT} \qquad \Rightarrow \qquad np = n_i^2$$

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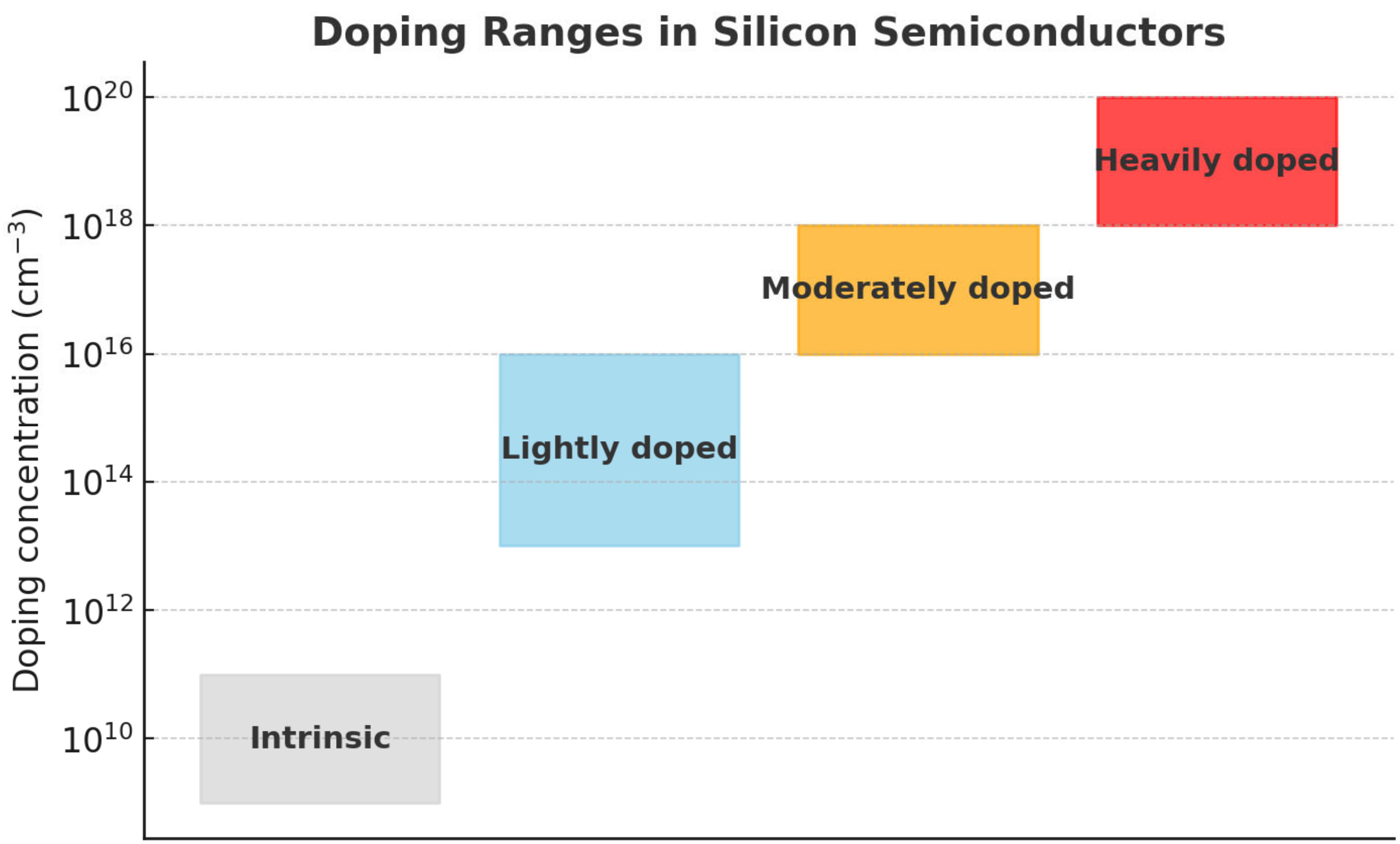
Doping of Silicon Semiconductors-Extrinsic



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Doping of Silicon Semiconductors-Extrinsic

Comparative Summary

Property	Lightly Doped	Heavily Doped
Dopant concentration	10^{13}–10^{16} cm^{-3}	10^{18}–10^{20} cm^{-3}
Resistivity	High	Low
Depletion width	Wide	Narrow
Switching speed	Slower	Faster
Common usage	Drift/channel regions, detectors	Source/drain, emitter, ohmic contact

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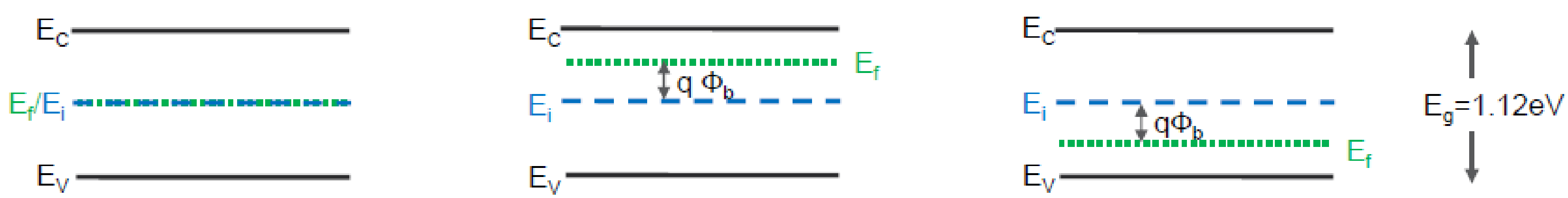
Energy Bands

E_f = Fermi level
E_i = Intrinsic Fermi level
E_C = Conduction band edge
E_V = Valence band edge
E_g = Band gap



Undoped Si	N-Type Si	P-Type Si
$n=p=n_i$	$n \gg p$	$n \ll p$

$| E_f - E_i | = q\,\Phi_b$ is known as Fermi potential (bulk potential), measure the doping strength

For Si, $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$

$$n = n_i\, e^{\frac{(E_f - E_i)}{kT}} = n_i e^{\frac{q\Phi_b}{kT}} \qquad p = n_i e^{\frac{(E_i - E_f)}{kT}} = n_i\, e^{\frac{q\Phi_b}{kT}}$$

Carrier Transport in Semiconductors

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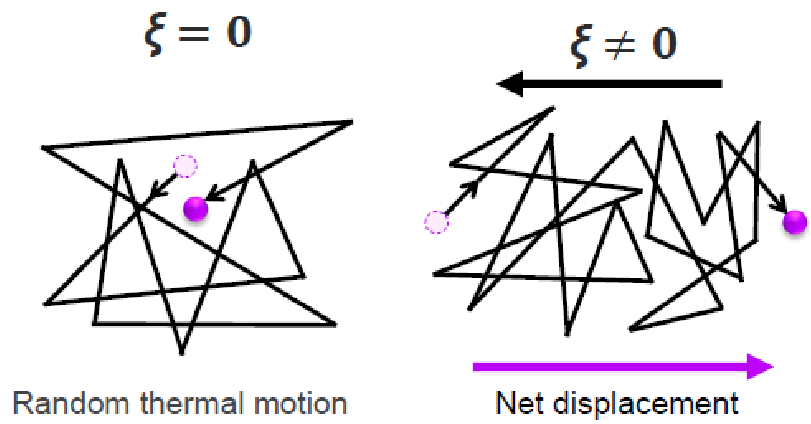
Thermal Equilibrium in Semiconductors

- In a semiconductor, thermal equilibrium is a steady state where the temperature is uniform and constant (no temperature gradient)
- No external forces such as voltages, electrical field, magnetic field
- No net motion of charges and energy

Drift Current

Carrier drift in semiconductors is the directed movement of electrons and holes in response to an applied electric field, resulting in a net drift current



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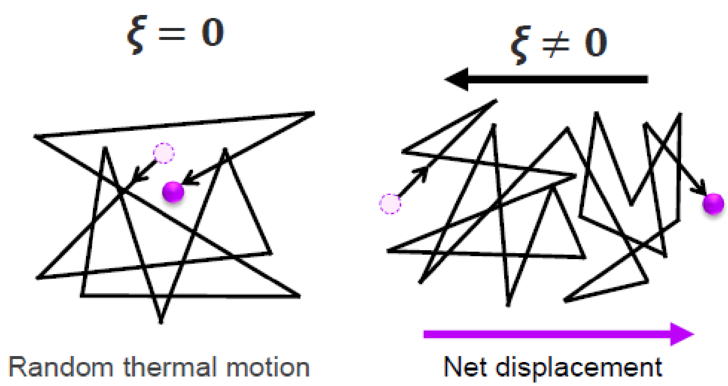

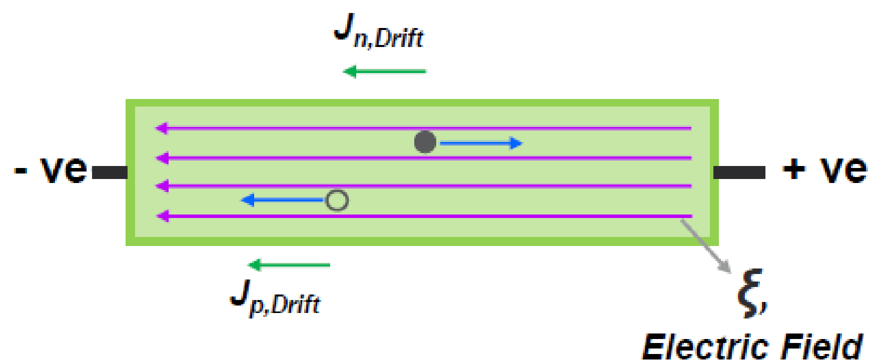

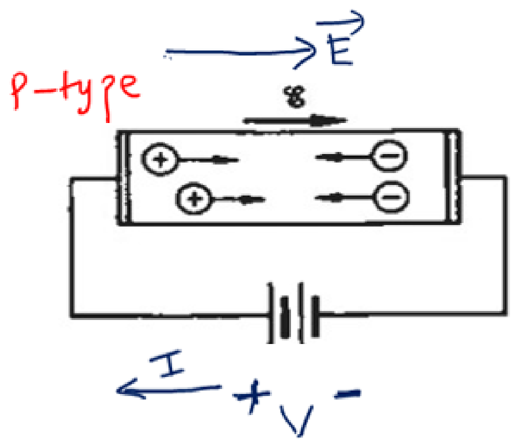

micron Educator Hub

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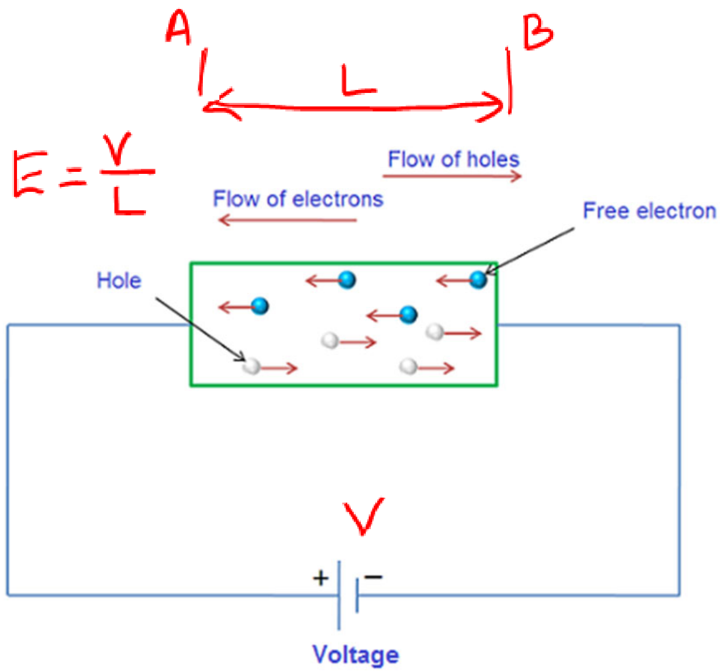
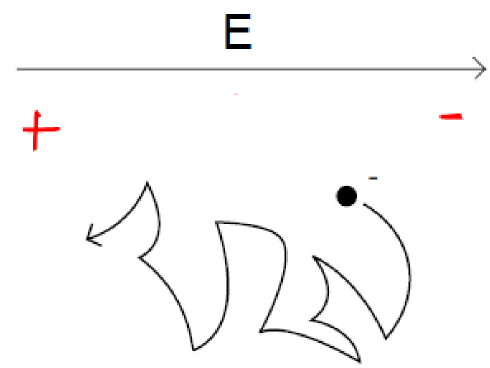
Drift Current

Holes and electrons acquire an average net velocity, proportional to the electric field E.



$$F = \pm qE$$



https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor/drift-current.html

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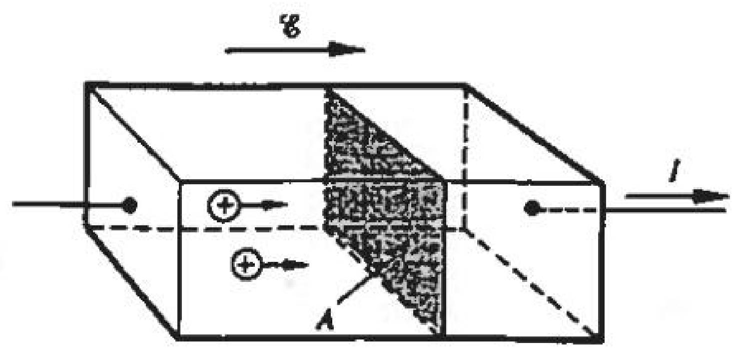
Drift Current

Holes: Towards the direction of Field Electron: Opposite to the direction of Field



Expanded view of a biased *p*-type semiconductor bar of cross-sectional area *A*.

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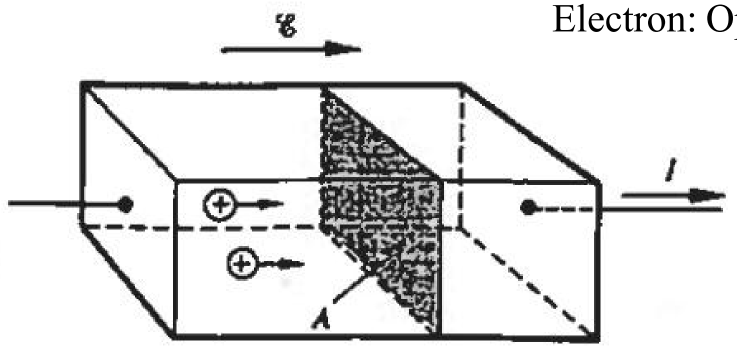
Drift Current

Holes: Towards the direction of Field
Electron: Opposite to the direction of Field



Expanded view of a biased *p*-type semiconductor bar of cross-sectional area *A*.

$v_d t$

... All holes this distance back from the v_d-normal plane will cross the plane in a time t.

$v_d t A$

... All holes in this volume will cross the plane in a time t.

$p v_d t A$

... Holes crossing the plane in a time t.

$q p v_d t A$

... Charge crossing the plane in a time t.

$q p v_d A$

... Charge crossing the plane per unit time.

$$I_{pdrift} = q p v_d A$$

$$J_{P|drift} = q p v_d$$

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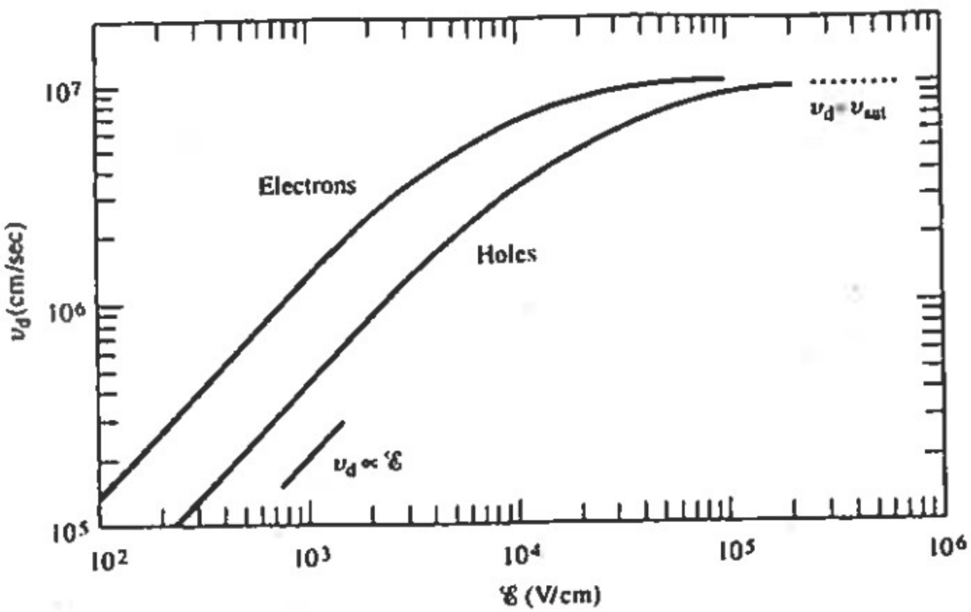
Carrier Mobility

$$v_d = \begin{cases} \mu_0 \mathscr{E} & \ldots \mathscr{E} \to 0 \\ v_{sat} & \ldots \mathscr{E} \to \infty \end{cases}$$



Measured drift velocity of the carriers in ultrapure silicon maintained at room temperature as a function of the applied electric field. Constructed from the data fits and the data respectively in Jacoboni et al.[4] and Smith et al.[5]

- **Mathematical Relation**:

$$\mu = \frac{q\langle\tau\rangle}{m^*}$$

  - $\langle\tau\rangle$: Mean free time between collisions.
  - m^*: Effective mass of carriers.

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Carrier Mobility

- Units ($\frac{cm^2}{Volt\ .sec}$)

Parameter	Silicon (Si)	Gallium Arsenide (GaAs)
Electron Mobility (μ_n)	1360 $cm^2/V \cdot s$	8000 $cm^2/V \cdot s$
Hole Mobility (μ_p)	460 $cm^2/V \cdot s$	400 $cm^2/V \cdot s$

Key Observation	$\mu_n > \mu_p$ for both Si and GaAs

- **Mathematical Relation**:

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  - $\langle\tau\rangle$: Mean free time between collisions.
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Mobility : Relationship to Scattering

Definition of Mobility: Measures ease of carrier motion in a crystal.

Impact of Scattering: Mobility decreases with increased motion-impeding collisions.

Types of Scattering:

Lattice Scattering: Collisions with thermally agitated lattice atoms. (Phonon Scattering)

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Ionized Impurity Scattering: Due to donor/acceptor-site ionization.

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$$\mu = \frac{q\langle \tau \rangle}{m^*}$$

  - $\langle \tau \rangle$: Mean free time between collisions.
  - m^*: Effective mass of carriers.

Mobility (μ) decreases as scattering increases.

Mobility (μ) decreases as carrier effective mass increases. ➔ Lighter carrier more readily

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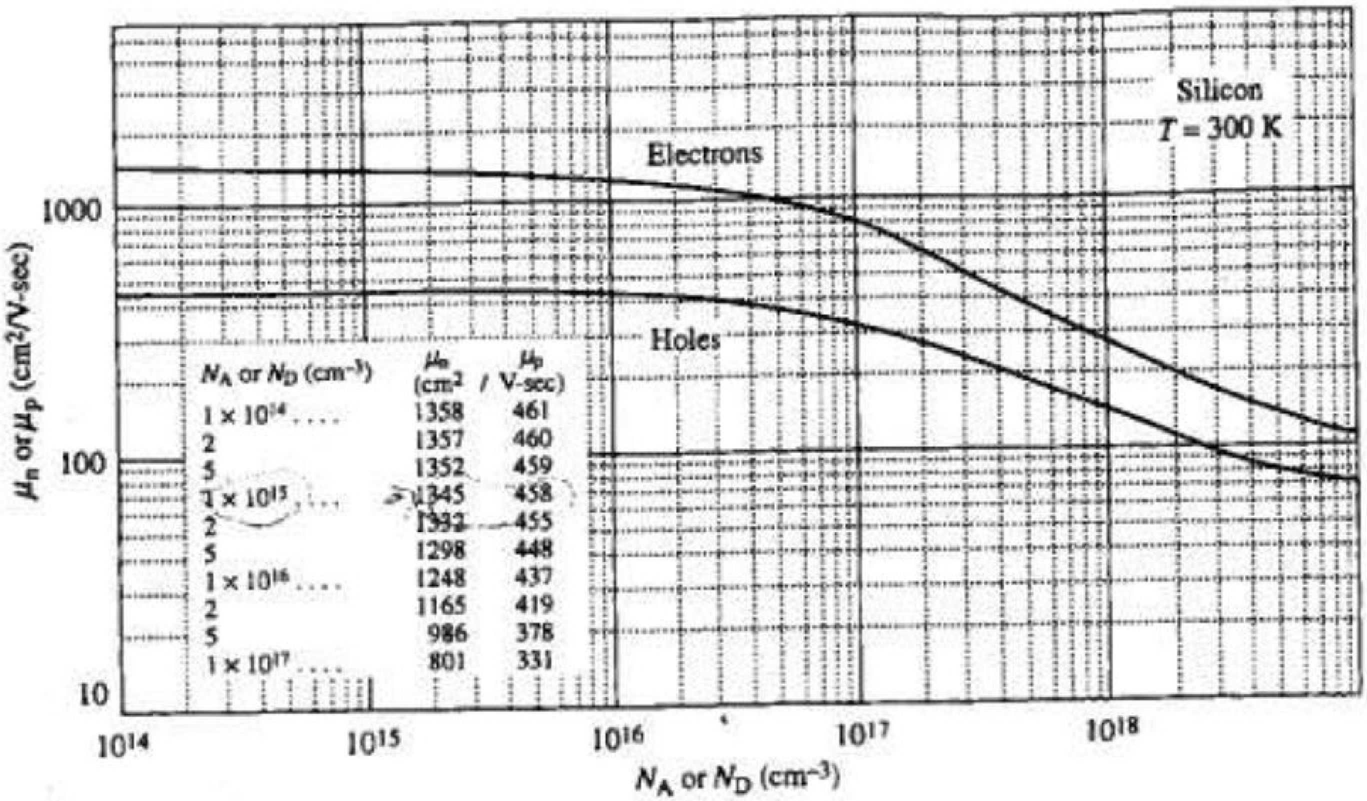
Mobility : Doping Dependence



$$\boxed{\mu = \frac{q\langle\tau\rangle}{m^*}}$$

Silicon

Room Temperature

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Mobility : Doping Dependence

•**General Trend**:

- Electron and hole mobilities in **semiconductors** show **doping dependence**.
- At **low doping** mobility is **independent** of doping.
- For **high doping**, mobility **decreases with increasing doping concentration.**

Key Takeaway:

- **Higher doping reduces mobility** due to **increased scattering centers** (acceptors/donors).
- This trade-off is crucial in semiconductor **device design** and **performance optimization**.

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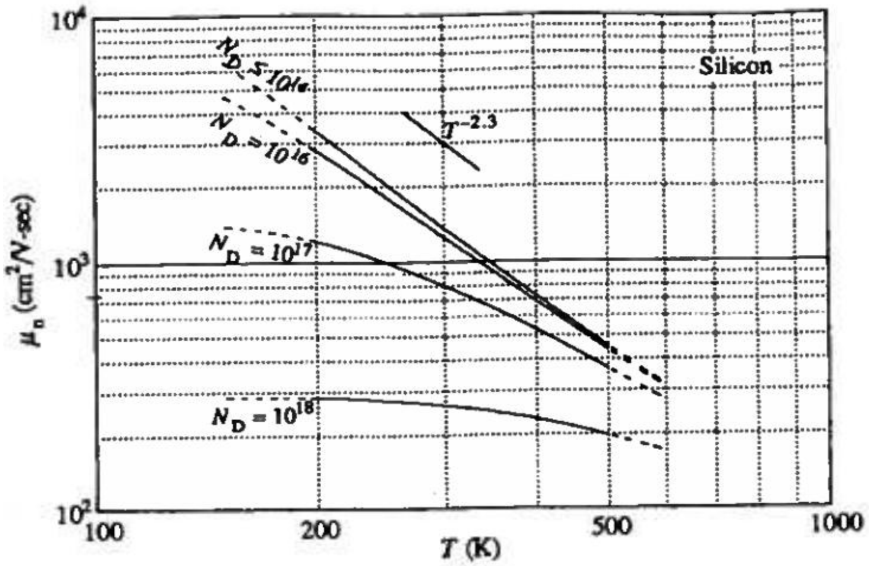
Mobility : Temperature Dependence (electrons)



(a)

Temperature dependence of (a) electron and (b) hole mobilities in silicon for dopings ranging from $\leq 10^{14}/\text{cm}^3$ to $10^{18}/\text{cm}^3$. The curves were constructed using the empirical fit relationships and parameters presented in Exercise 3.1. The dashed line portion of the curves correspond to a slight extension of the fit beyond the verified 200 K $\leq T \leq$ 500 K range of validity.

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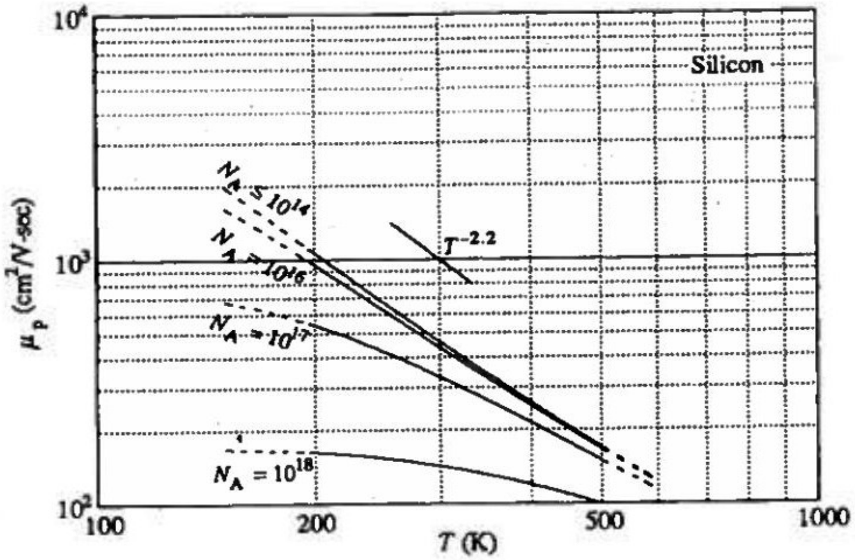
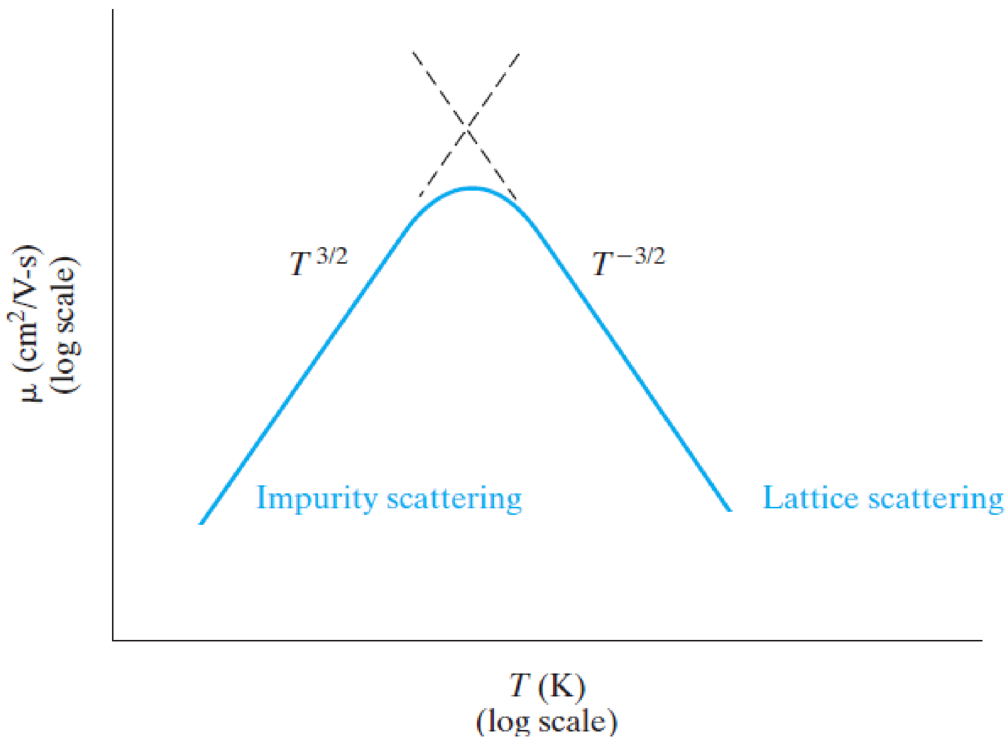
Mobility : Temperature Dependence (Holes)



(b)

Temperature dependence of (a) electron and (b) hole mobilities in silicon for dopings ranging from $\leq 10^{14}$/cm^3 to 10^{18}/cm^3. The curves were constructed using the empirical fit relationships and parameters presented in Exercise 3.1. The dashed line portion of the curves correspond to a slight extension of the fit beyond the verified 200 K $\leq T \leq$ 500 K range of validity.

Mobility : Temperature Dependence



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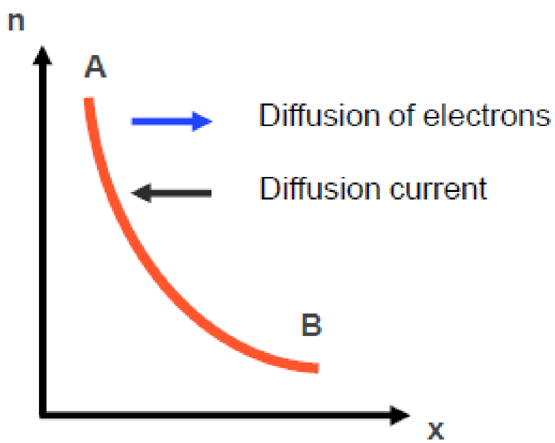
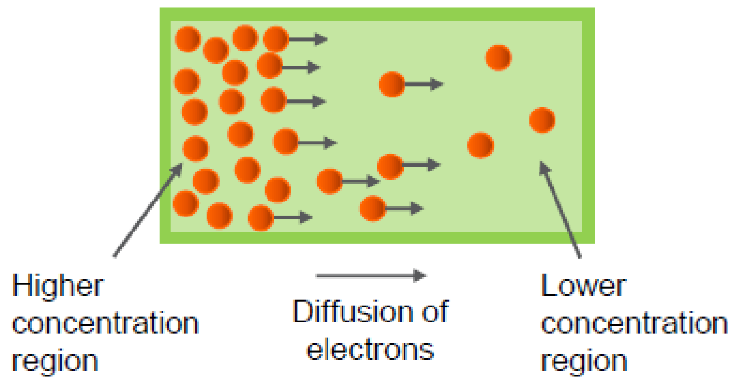
Diffusion Current

Electric current due to concentration gradients of carriers



N type



$$J_{n,Diff} \propto \frac{dn}{dx}$$

$$J_{n,Diff} = eD_n \frac{dn}{dx}$$

D_n : *Diffusion coefficient*

PN Junction diodes

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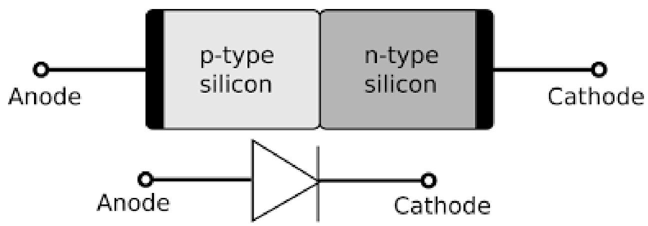
P-N Junction (Diode)

A p-n junction diode is a basic semiconductor device that controls the flow of electric current in a circuit. It has a positive (p) side and a negative (n) side created by adding impurities to each side of a silicon semiconductor.



- Current only flows in forward bias
- **Diodes** allow for current to flow in one direction and rectify (change AC to DC)

https://www.slideshare.net/slideshow/p-n-junctioneema/68227503

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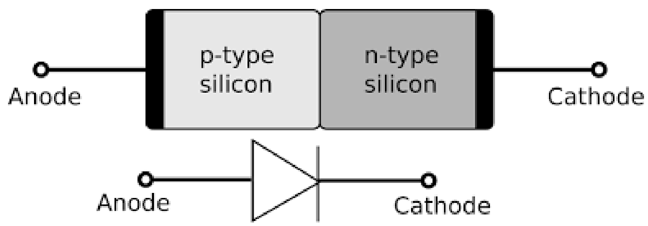

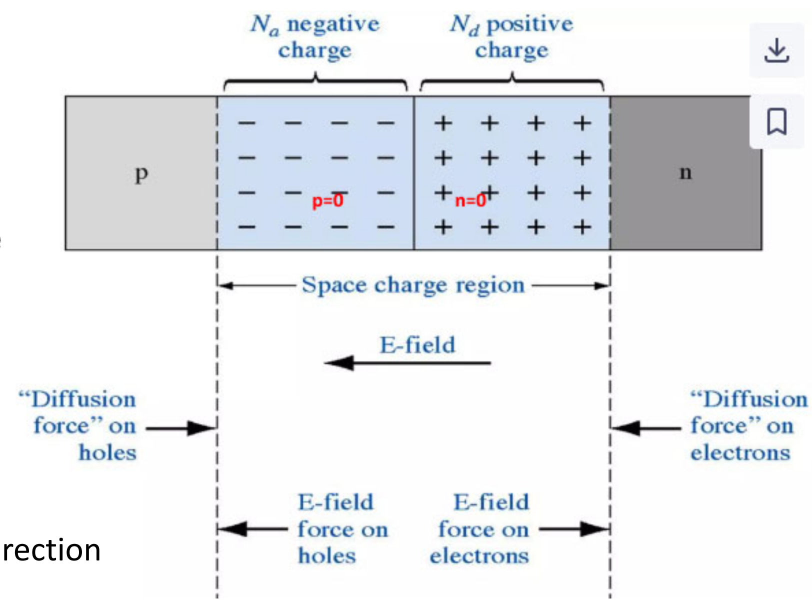

- Current only flows in forward bias
- **Diodes** allow for current to flow in one direction and rectify (change AC to DC)

https://www.slideshare.net/slideshow/p-n-junctioneema/68227503

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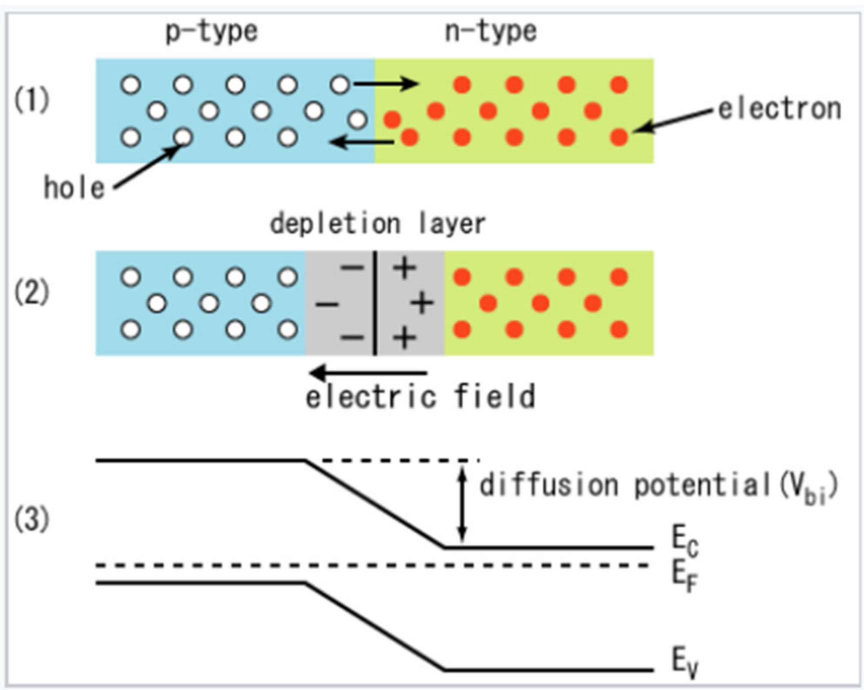
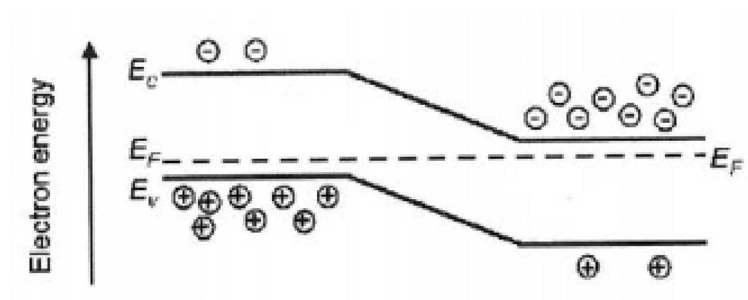
P-N Junction (Diode)-Built in potential

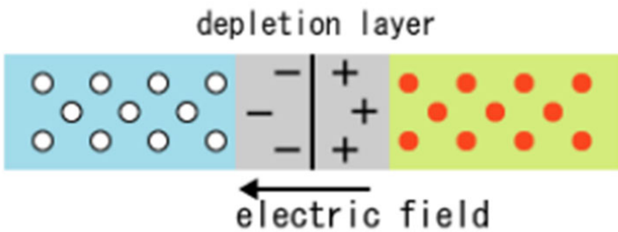


The built-in potential of a P-N junction is the potential difference that develops at the intersection of its p-type semiconductor material and n-type semiconductor material. This built-in potential develops in the depletion region.



https://study.com/academy/lesson/p-n-junction-diode-definition-properties.html

P-N Junction (Diode)-Built in potential



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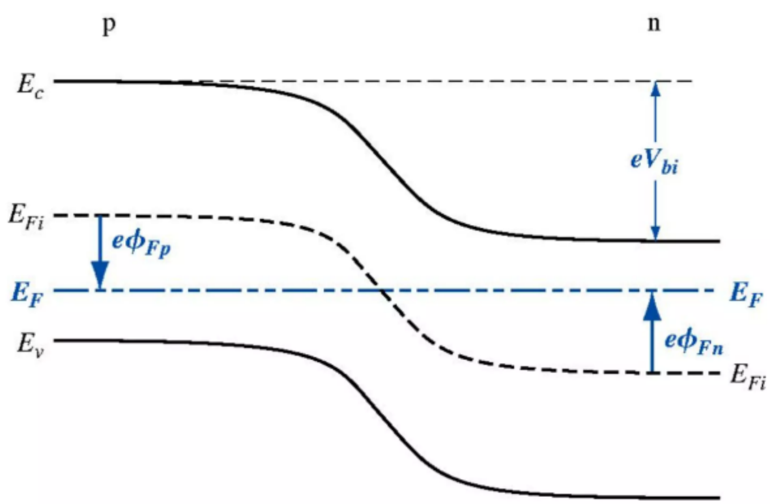

Formula

PN Junction Built-in Potential

$$V_{\text{built-in}} = \frac{kT}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

- $V_{\text{built-in}}$ → Built-in potential in volts
- N_D → n type - donor atoms concentration
- N_A → p type - acceptor atoms concentration
- n → concentration of electrons
- kT/q → thermal voltage
- T → temperature in Kelvin
- q → charges in coulombs

getcalc.com

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

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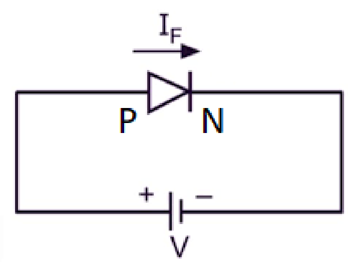
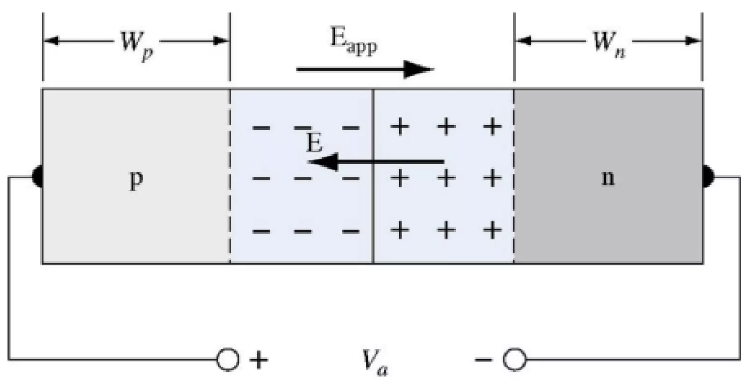
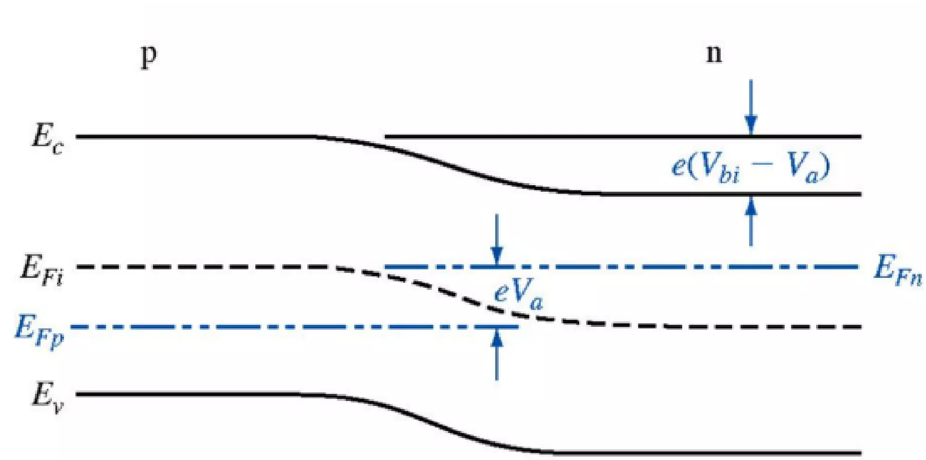
P-N Junction (Diode)-Forward Bias

When positive terminal of the source is connected to the P side and the negative terminal is connected to N side then the junction diode is said to be connected in forward bias condition.

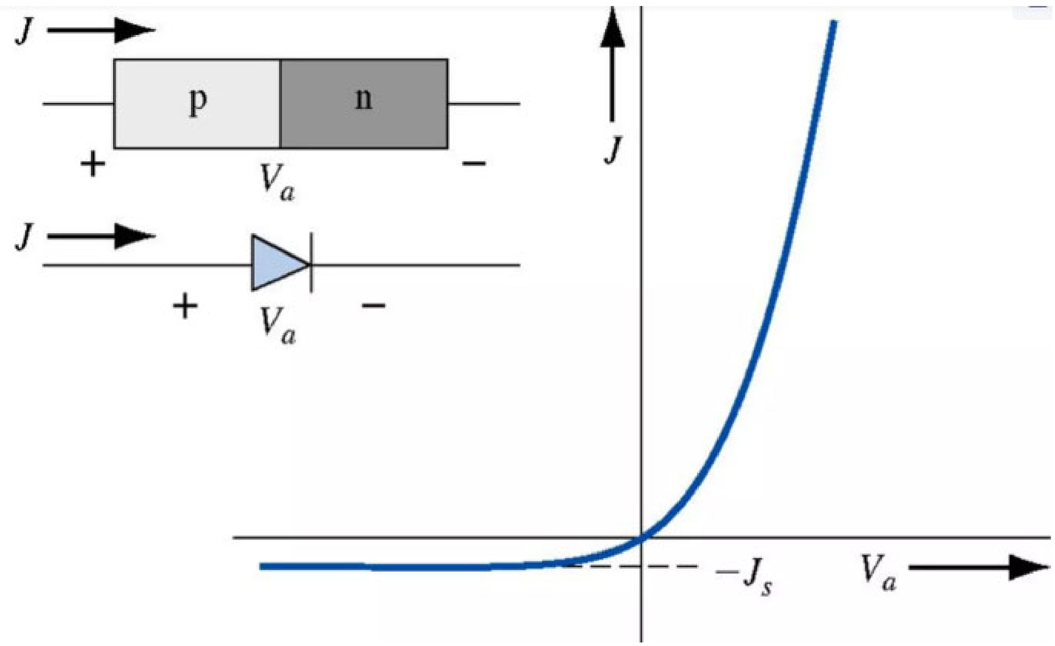


FORWARD BIAS PN JUNCTION





P-N Junction (Diode)-Forward Bias



$$J = J_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

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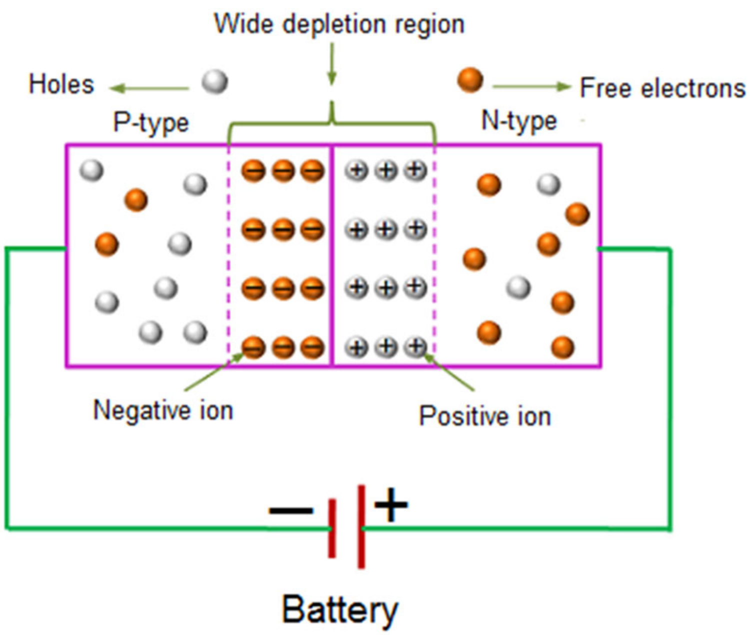
P-N Junction (Diode)-Reverse Bias



- Positive terminal attracts the electrons away from the junction in N side and negative terminal attracts the holes away from the junction in P side.
- As a result of it, the width of the potential barrier increases that impedes the flow of majority carriers in N side and P side.

https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor-diodes/reversebiaseddiode.html

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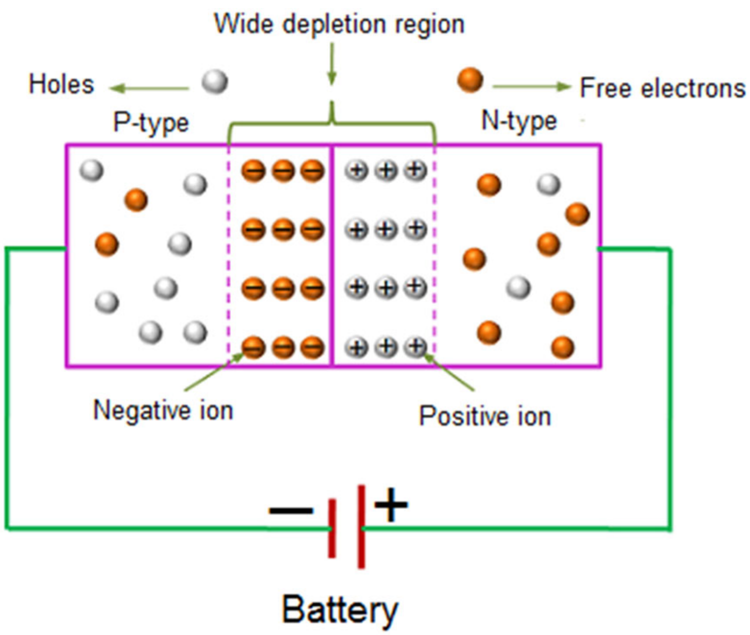
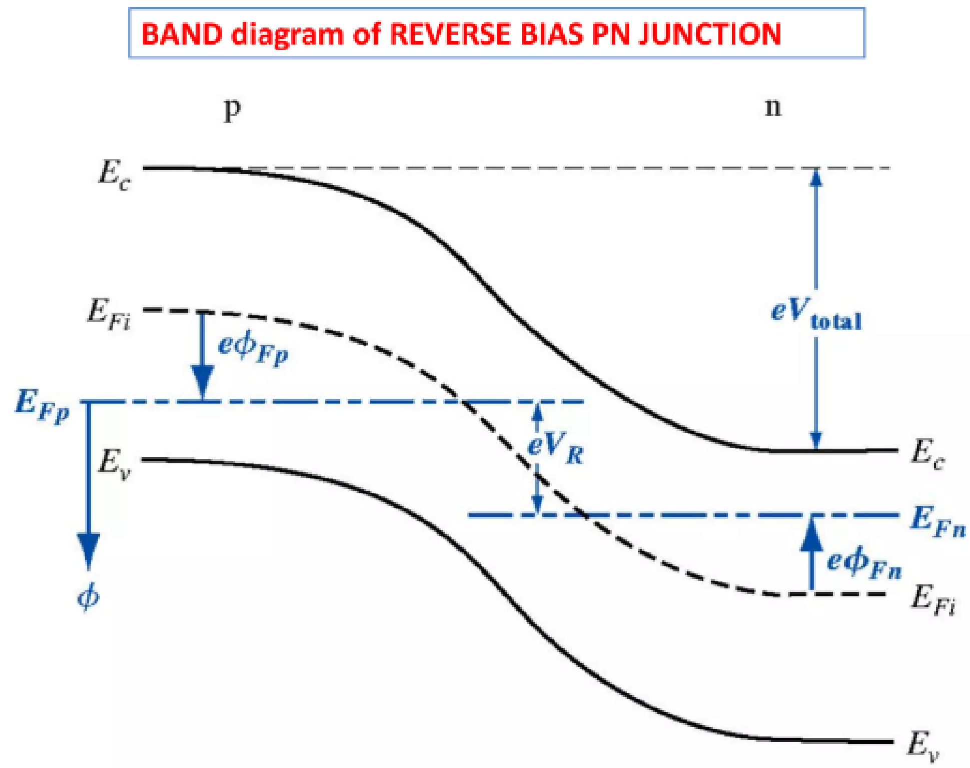
P-N Junction (Diode)-Reverse Bias





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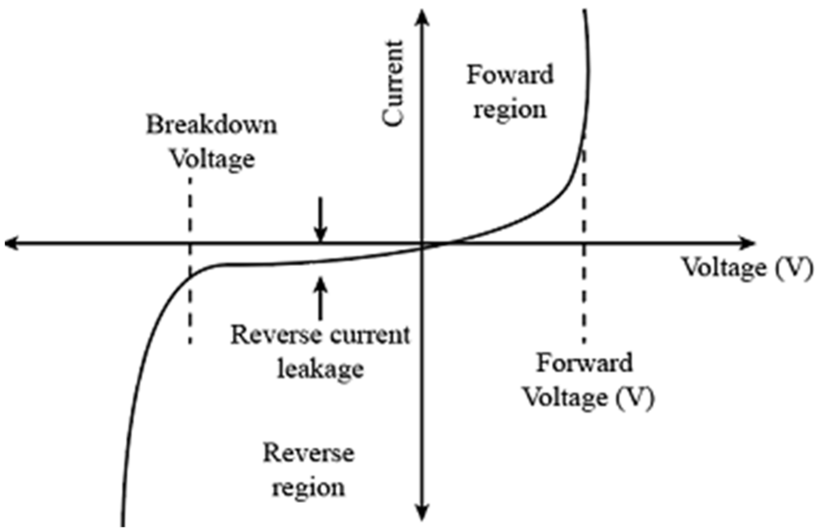
P-N Junction (Diode)-Reverse Bias

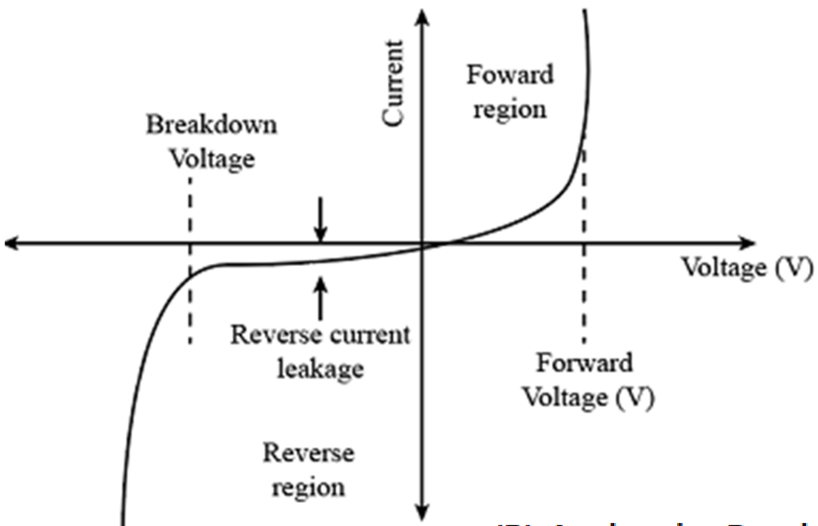


Breakdown occurs by two mechanisms.

(A) Zener Breakdown (Low Reverse Voltage, < ~5–6 V)

- Occurs in **heavily doped PN junctions** (narrow depletion region).
- Strong **electric field** develops across the narrow depletion layer.
- This field is strong enough to **break covalent bonds** and cause **quantum mechanical tunneling** of electrons from the valence band (P-side) into the conduction band (N-side).
- Result → sudden increase in current.
- Dominant in **low-voltage Zener diodes**.

P-N Junction (Diode)-Reverse Bias



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- Result → sudden increase in current.
- Dominant in **low-voltage Zener diodes**.

(B) Avalanche Breakdown (Higher Reverse Voltage, > ~6 V)

- Occurs in **lightly doped PN junctions** (wide depletion region).
- Minority carriers (electrons/holes) accelerated by the strong electric field gain enough energy to **ionize atoms** when they collide with the lattice.
- This generates **new electron-hole pairs**, which are again accelerated → **chain reaction (avalanche multiplication)**.
- Result → sharp rise in current.
- Dominant in **power diodes and high-voltage junctions.**

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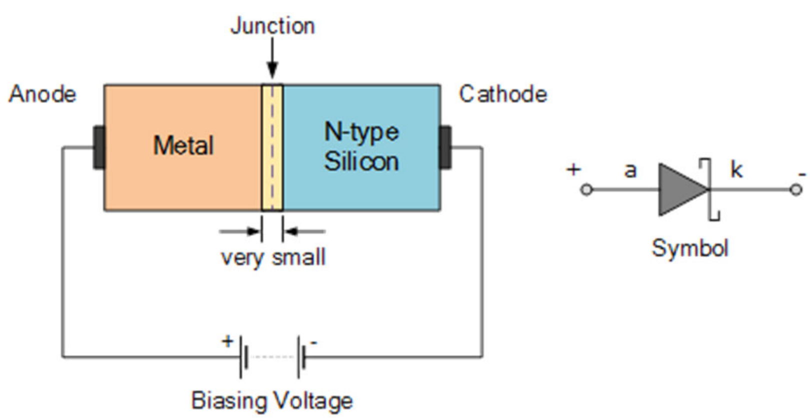
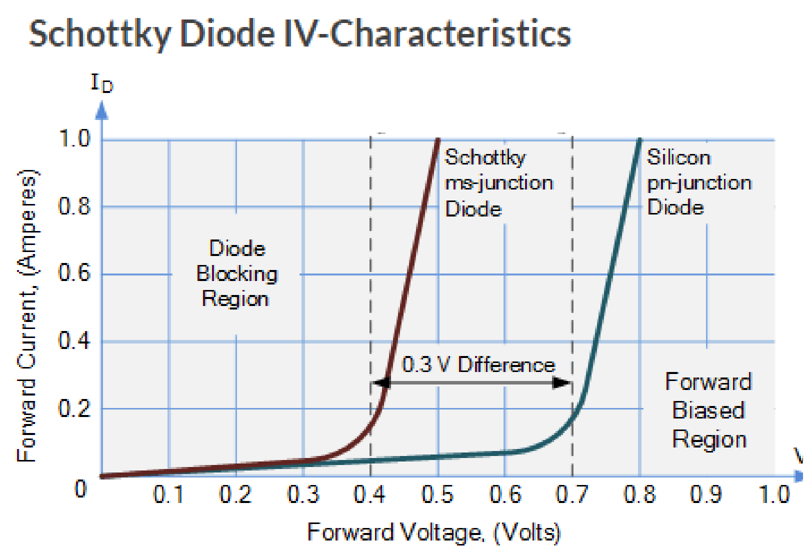
Schottky Diode: Metal-Semiconductor Junction

- The Schottky diode is a semiconductor diode formed by the junction of a semiconductor (N-type) with a metal.
- Current conduction is mainly due to **majority carriers** (usually electrons from the N-type side).
- It has a low forward voltage drop and a very fast switching action.
- The most common contact metal used for Schottky diode construction is “Silicide” which is a highly conductive silicon and metal compound.



https://www.electronics-tutorials.ws/diode/schottky-diode.html



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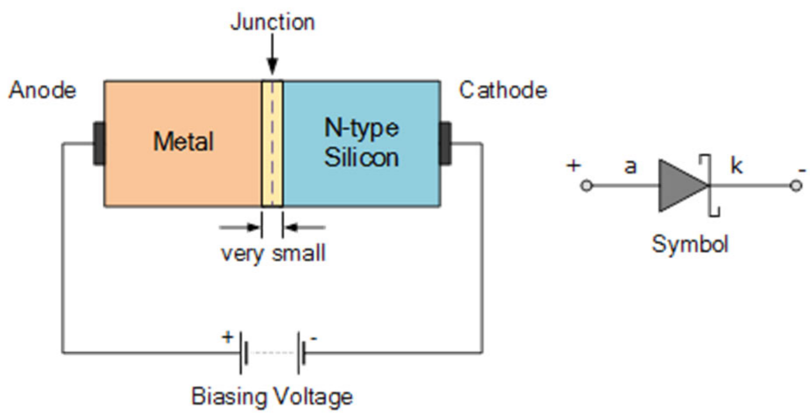
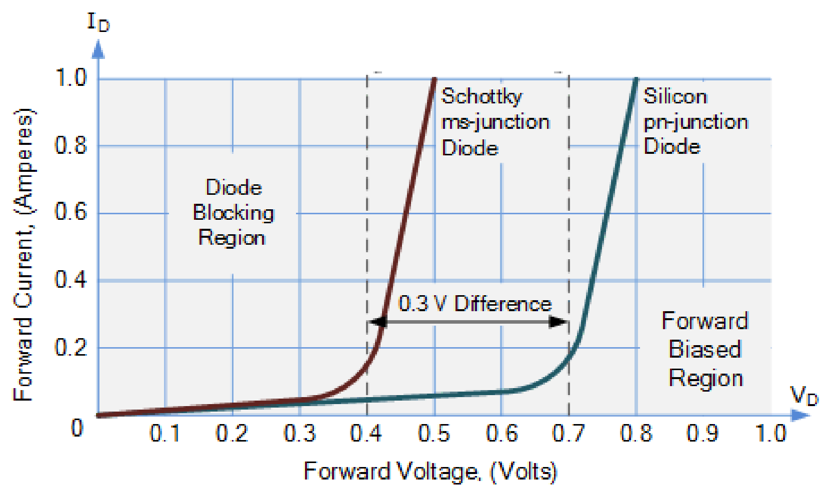
Schottky Diode: Metal-Semiconductor Junction

Barrier Potential

- **PN Diode:** Has a barrier potential of about **0.7 V (Si)**.
- **Schottky Diode:** Has a much lower barrier potential, typically **0.2–0.3 V**, because it is a metal–semiconductor junction.



Schottky Diode IV-Characteristics



https://www.electronics-tutorials.ws/diode/schottky-diode.html

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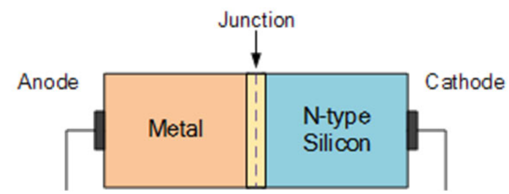
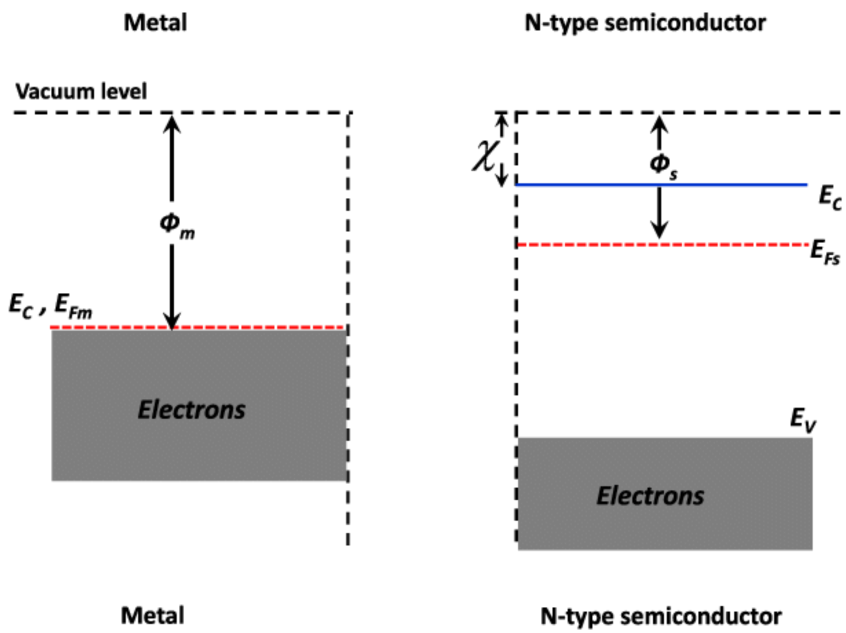
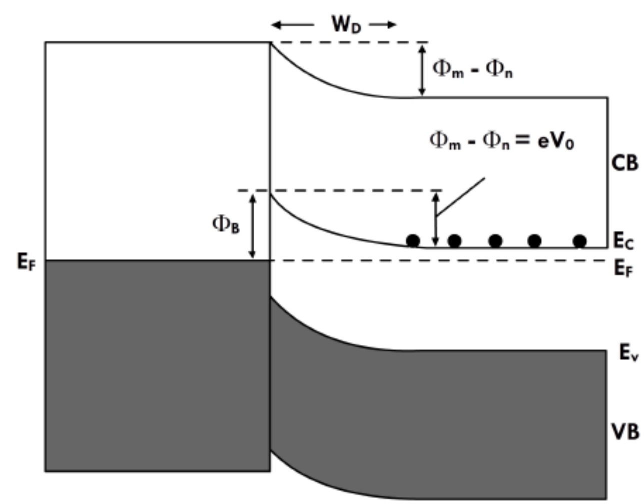
Schottky Diode: Metal-Semiconductor Junction



- **A Schottky junction is formed when the semiconductor has a lower work function than the metal.**



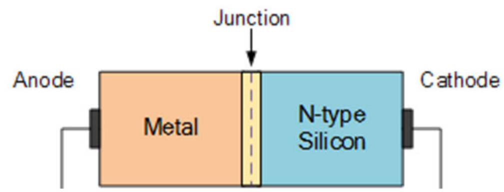


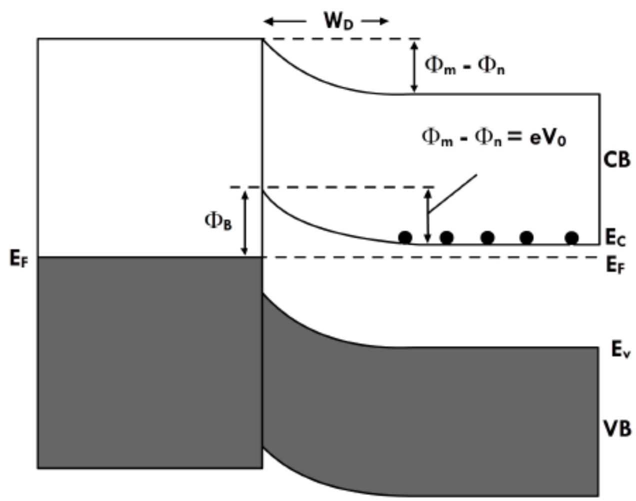
Equilibrium condition

https://www.electronics-tutorials.ws/diode/schottky-diode.html

https://www.icrfq.net/schottky-diode/

Schottky Diode: Metal-Semiconductor Junction

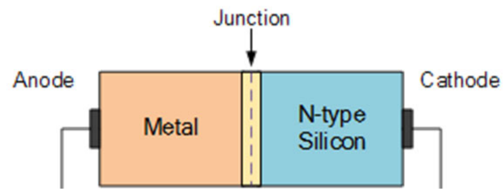


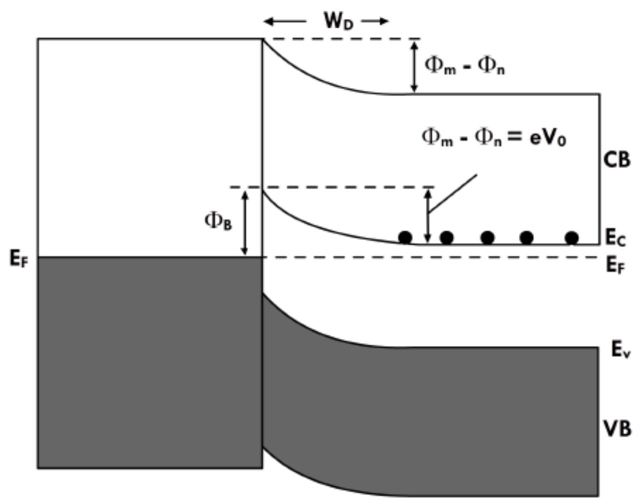


Equilibrium condition

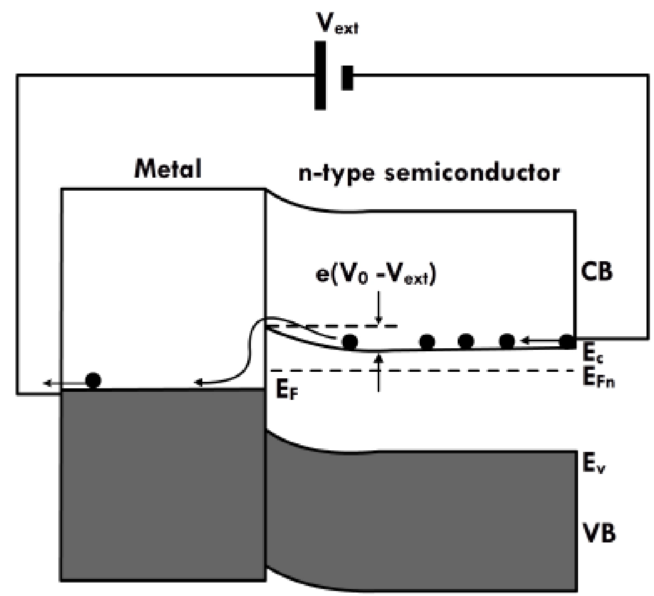
https://www.electronics-tutorials.ws/diode/schottky-diode.html

Schottky Diode: Metal-Semiconductor Junction (Forward Bias)





Equilibrium condition



Forward Bias

https://www.electronics-tutorials.ws/diode/schottky-diode.html

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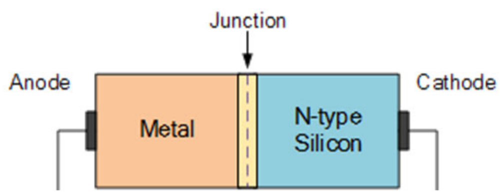
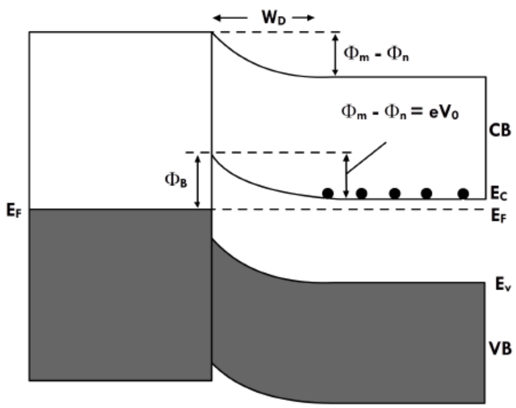
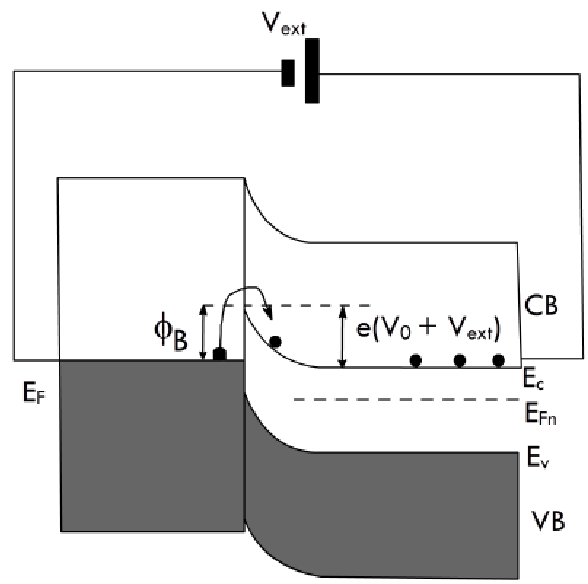
Schottky Diode: Metal-Semiconductor Junction (Reverse Bias)

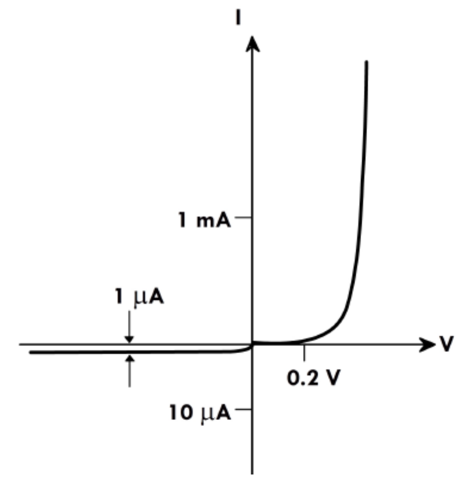




Equilibrium condition



Reverse Bias



https://www.electronics-tutorials.ws/diode/schottky-diode.html

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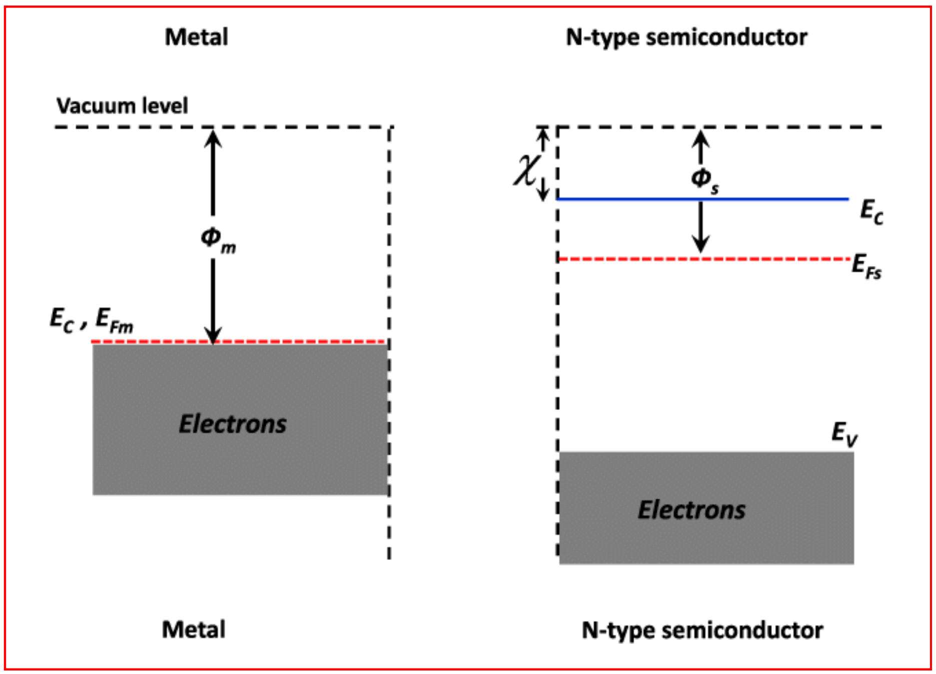
Ohmic Contact

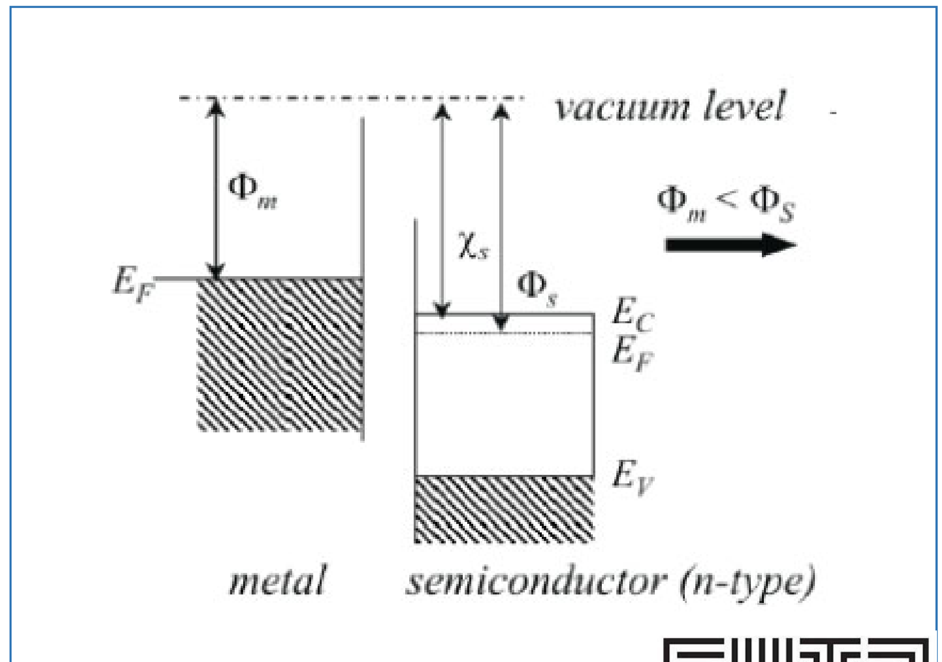
- A Schottky junction is formed when the semiconductor has a lower work function than the metal. When the semiconductor has a higher work function the junction formed is called the Ohmic junction.

Schottky junction



https://www.icrfq.net/schottky-diode/

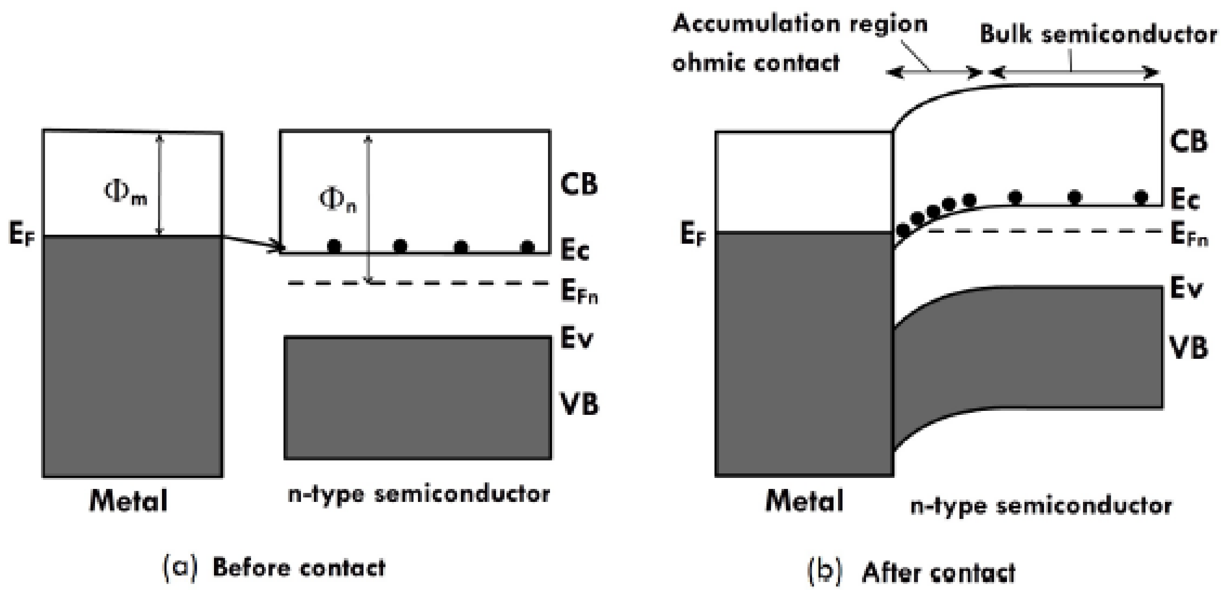
Ohmic junction



Ohmic Contact

- A Schottky junction is formed when the semiconductor has a lower work function than the metal. When the semiconductor has a higher work function the junction formed is called the Ohmic junction.

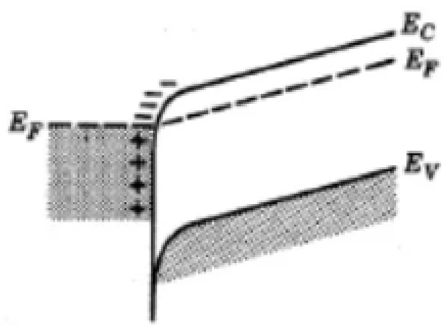
- Ohmic junction behaves as a resistor conducting in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor.



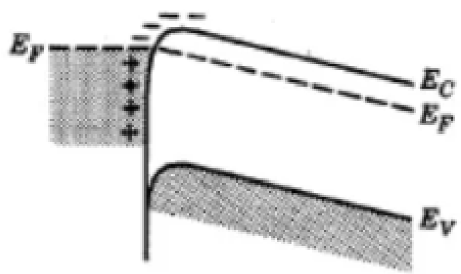
Ohmic Contact

Ohmic Contact (Forward bias and Reverse Bias)

Forward Bias (V_A>0V)



Reverse Bias (V_A<0V)



- When bias is applied, practically all applied voltage drops across the higher resistance region which is the bulk neutral semiconductor.
- Current is therefore determined by the resistance of the bulk, ie. measures property of device

- no depletion region
- ***accumulation of majority carriers*** near the semiconductor surface
- low resistance to current flow
- non-rectifying□ ohmic

Heavy doping near the junction (degenerate semiconductor): High doping narrows the depletion region, enabling **tunneling** of carriers → ohmic behavior even if a barrier exists.

https://www.slideserve.com/ehanley/metal-semiconductor-contact-powerpoint-ppt-presentation

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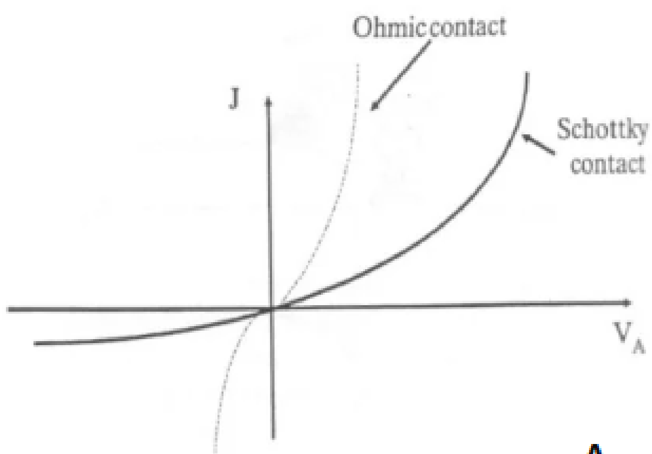
Ohmic Contact (Forward bias and Reverse Bias)

Current-Voltage Characteristics



Some discussions:

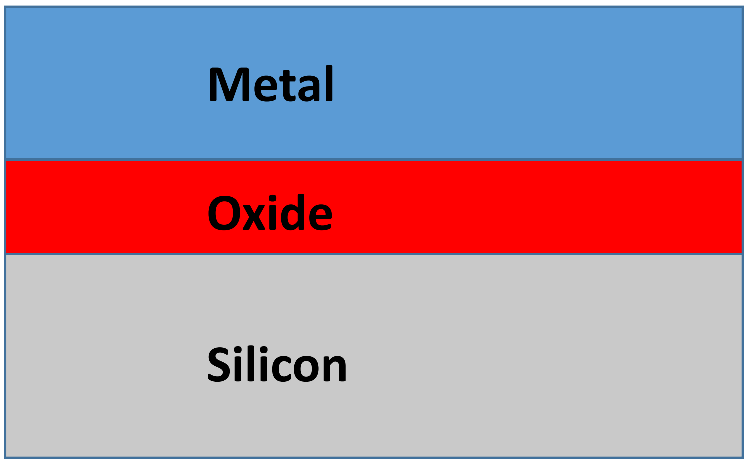
- Ohmic contacts have large current in both directions
- Typically, the resistance is very small
- Since the contact resistance is very small, the voltage will be dropped on the semiconductor

Applications

- Ohmic contacts are essential in **all semiconductor devices** (diodes, transistors, ICs).
- They provide the **electrical connection between metal electrodes and the semiconductor regions** (e.g., source, drain, emitter, collector).
- Without ohmic contacts, devices would behave like diodes at their terminals insteac of allowing proper current injection.

https://www.slideserve.com/ehanley/metal-semiconductor-contact-powerpoint-ppt-presentation

MOS structures



- Accumulation mode
- Depletion mode
- Inversion mode

MOS Capacitor

- MOS: Metal-oxide-semiconductor
  - Gate: metal (or polysilicon)
  - Oxide: silicon dioxide, grown on substrate
- MOS capacitor: two-terminal MOS structure