

# Power Electronics Devices (and Components)

Dr Bikash Sah



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- 2 Physics of Basic Semiconductor Devices
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  - Power bipolar junction transistor (BJT)
- 5 Conventional Power Semiconductor Devices

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- 1 An initial overview of of the course

# Power Electronics Devices and Components

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# Course Overview

The course will be in 6 modules.

- ▶ Module I: Basics of Electronics Devices.
- ▶ Module II: Towards Power Semiconductor Devices- Introduction.
- ▶ Module III: Conventional Power Semiconductor Devices.
- ▶ Module IV: Next Generation Power Semiconductor Devices.
- ▶ Module V: Passive Components.
- ▶ Module VI: Way forward- Power Modules, Reliability, and Thermal Management

## **Pattern of class:**

Day: Thursday, every week

Time: 4 pm to 6 pm (theory) and 6 pm to 8 pm (tutorial) (ideally but it can change)

Holidays: 1st May, 29 May, and 19 June 2025. As required classes will be rescheduled.

# The teaching team



Bikash Sah



Andreas Sack

## Contact

- ▶ Email: see [chair's homepage](#)
- ▶ Offices: H-A building, 4th floor
- ▶ Individual appointments on request (remote or personally)
- ▶ Multiple relevant courses are offered by the Chair. [Check link!](#)

\*\* Future follow-up courses are planned to be introduced in next semester- High Frequency Power Electronics, etc.

# Module I: Basics of Electronics Devices

# What are "Electronic Devices"?

## Electronic Devices

Electronic devices are hardware components which leverage the property of materials to control the flow of electrons or charge.

- ▶ Have a long history of development- started with the invention of vacuum tube or Thermionic valve in 1904 by J.A. Fleming.
- ▶ The first transistor was invented in 1947 by J.Bardeen, W.H. Brattain and W.S. Shockley in Bell Labs.
- ▶ The first integrated circuit was invented in 1958 by J. Kilby and R. Noyce – On and it goes

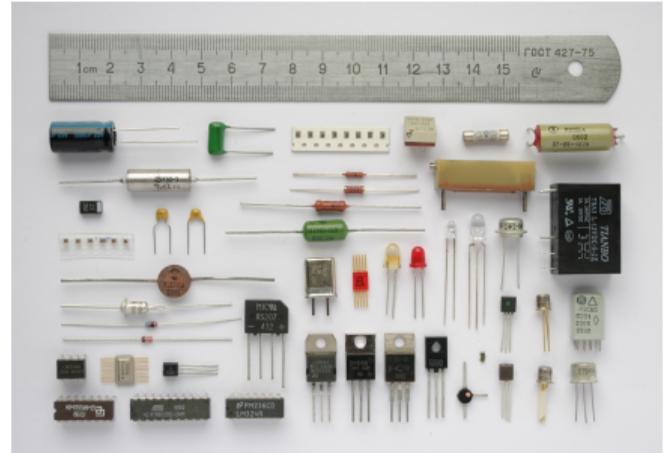


Fig. 1.1: Example of electronic components (source: [Wikimedia Commons](#), Kae, public domain)

# General classification of "Electronic Devices" ?

- ▶ Active devices: These are the devices which can control the flow of current and mainly consists of **semiconductor** materials. Examples: Transistor, Diode, etc.
- ▶ Passive devices: These are the devices which cannot control the flow of current and perform operation like consuming, storing, or releasing power. Examples: Resistor, Capacitor, Inductor, etc.

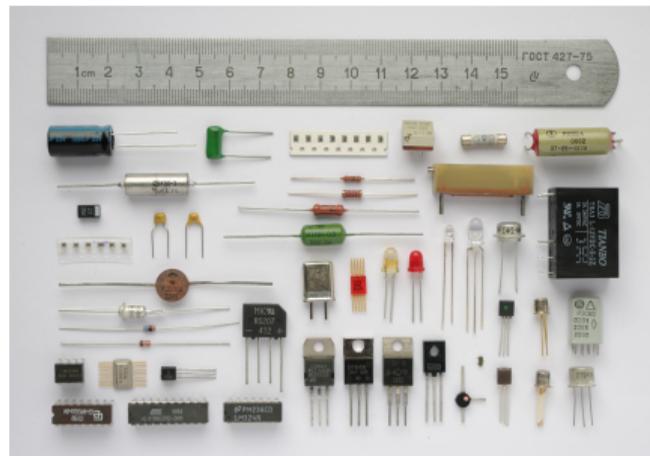


Fig. 1.2: Example of electronic components (source: [Wikimedia Commons](#), Kae, public domain)

# Comparison of Electronics and Power Electronics

Tab. 1.1: Comparison between Electronics and Power Electronics

<b>Feature</b>	<b>Electronics</b>	<b>Power Electronics</b>
<b>Primary Focus</b>	Signal processing, computation, communication	Energy conversion, control, and delivery
<b>Power Levels</b>	$\mu\text{W}$ to a few watts	Tens of watts to megawatts
<b>Speed</b>	High-speed logic, RF, GHz range	Lower switching frequency (kHz–MHz), but high voltage/current
<b>Core Devices</b>	BJTs, MOSFETs, ICs, Op-Amps, Logic Gates	Diodes, IGBTs, Power MOSFETs, SCRs, SiC/GaN devices
<b>Applications</b>	Microprocessors, audio amps, sensors, mobile phones	EVs, solar inverters, motor drives, HVDC systems
<b>Design Challenges</b>	Noise, bandwidth, gain, low power	Efficiency, thermal stress, EMI, ruggedness
<b>Energy Handling</b>	Information carriers (signals)	Bulk power carriers (watts, kilowatts, megawatts)

# Locating active and passive components in real world



(a) Example charging station (source: Wikimedia Commons, CC BY 2.0)



(b) Public mobile charging machine (source: Wikimedia Commons, Raysonho, CC0 1.0)

# Locating active and passive components in real world



(a) Generic mobile phone charger (source: [Wikimedia Commons](#), Radio Mayak Pervouralsk, CC BY-SA 4.0)



(b) Example electric vehicle (source: [Wikimedia Commons](#), Raysonho CCo 1.0)

## Locating active and passive components in real world



(a) Thorntonbank Wind Farm, using 5 MW turbines REpower 5M in the North Sea off the coast of Belgium (source: [Wikimedia Commons](#), © Hans Hillewaert, [CC BY-SA 4.0](#))



(b) Thyristor valve in an HVDC (source: [Wikimedia Commons](#), Marshelec, [CC BY-SA 3.0](#))

# Locating active and passive components in real world



(a) A solar PV plant in (source: [Wikimedia Commons](#), Claus Ableiter, CC BY-SA 3.0)



(b) Internal view of a solar inverter (source: [Wikimedia Commons](#), Russell Neches, CC BY 2.0)

# Why is knowledge about power electronics devices is important?

## Power Electronics more relevant than ever

Knowledge of power electronics devices is crucial for designing efficient systems that convert, control, and deliver electrical energy. It enables innovation in EVs, renewable energy, robotics, and industrial automation by optimizing performance, minimizing losses, and ensuring reliable operation.

## Power electronics is the key to efficiency and sustainability

Power electronic systems handle and convert more than 70% of global electricity across industries such as transportation, energy, and automation (source: [International Energy Agency](#)). With rising demands for electrification, advancing device efficiency and reliability is critical to minimizing energy losses, improving system performance, and enabling sustainable technologies across the globe.

# Looking inside to define objectives!

A PV Inverter

Components

- Active
- Passive

Semiconductors

P-N junctions

Energy bands

Crystal lattice

- Atoms
  - Electrons, protons, & neutrons

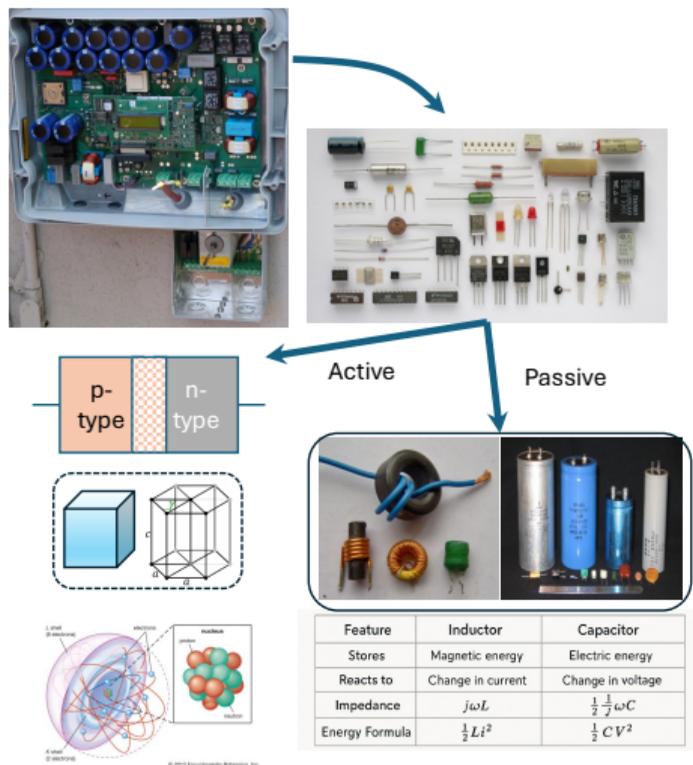


Fig. 1.7: Definition of course and need (source: PV inverter, components, inductors, and capacitors  
[Wikimedia Commons](#), multiple sources, public domain)

## Learning objectives

- ▶ Understand and explain the role of power electronics in modern energy systems, electrification, and sustainable technologies.
- ▶ Understand the working principles of each device and components in power electronics.
- ▶ Analyze the physics of semiconductor materials and devices, including band theory, carrier transport, junction behavior, and breakdown mechanisms.
- ▶ Differentiate and evaluate the characteristics, structures, and operation principles of power semiconductor devices.
- ▶ Interpret and model switching characteristics, conduction behavior, and thermal limitations of conventional and wide-bandgap power devices (Si, SiC, GaN).
- ▶ Select and model active and passive components such as capacitors, inductors, transformers, and filters with consideration of frequency, losses, and application context.
- ▶ Have fun learning about power electronics devices and components.

## Necessary prior knowledge for this course

You should have a basic understanding of the following topics:

- ▶ Basic electrical engineering knowledge (e.g., Ohm's law, Kirchhoff's laws, etc.)
- ▶ Basic understanding of physics in electronics
- ▶ Algebra and complex numbers
- ▶ Basic signal theory knowledge (e.g., Fourier series, Laplace transform)
- ▶ No advanced knowledge of semiconductors or programming is needed — this course builds those concepts from scratch and applies them to real systems.

What we will not cover, but you do not need to know (covered in separate courses):

- ▶ Power converter circuits and topologies.
- ▶ Power electronics in depth involving analysis and controller design.

## Recommended reading

- ▶ Baliga, B. Jayant. Fundamentals of power semiconductor devices. Springer Science & Business Media, 2010.
- ▶ Lutz, Josef, Heinrich Schlangenotto, Uwe Scheuermann, and Rik De Doncker. "Semiconductor power devices." Physics, characteristics, reliability 2 (2011).
- ▶ Baliga, B. Jayant, ed. Wide Bandgap Semiconductor Power Devices: Materials, Physics, Design, and Applications. Woodhead Publishing, 2018.
- ▶ K. Niayesh, M. Runde, "Power Switching Components Theory, Applications and Future Trends", 1. Ed., Springer, 2018.

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## 2 Physics of Basic Semiconductor Devices

# Physics of basic semiconductor devices

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# What will you learn?

- ▶ Materials
  - ▶ Atoms and materials used in semiconductors
  - ▶ Flow of electrons and holes
  - ▶ Conductors, insulators, and semiconductors
  - ▶ Energy bands, Fermi level, doping
  - ▶ Intrinsic and extrinsic semiconductors
- ▶ Fundamental properties
  - ▶ Carrier concentration
  - ▶ Carrier mobility
  - ▶ The Hall effect
  - ▶ Drift and diffusion currents
  - ▶ Breakdown voltage, temperature dependence, etc.
- ▶ pn junctions
  - ▶ What is a pn junction?
  - ▶ Diodes and their characteristics
  - ▶ Physics of operation, properties and IV characteristics of diodes.

# Atoms

- ▶ All matter is made up of atoms.
- ▶ Atoms are the smallest unit of matter that retains the properties of an element.
- ▶ Two models of atom exist: classical and quantum.
- ▶ The classical model of the atom is based on the idea that atoms are made up of a nucleus (protons and neutrons) surrounded by electrons that orbit the nucleus in fixed paths- Rutherford's Atomic Model
- ▶ The quantum model of the atom is based on the principles of quantum mechanics, which describe the behaviour of particles at the atomic and subatomic quantised energy levels- Bohr's Atomic Model:
- ▶ Both model states: atoms consist of a nucleus (protons & neutrons) & electrons that orbit the nucleus.

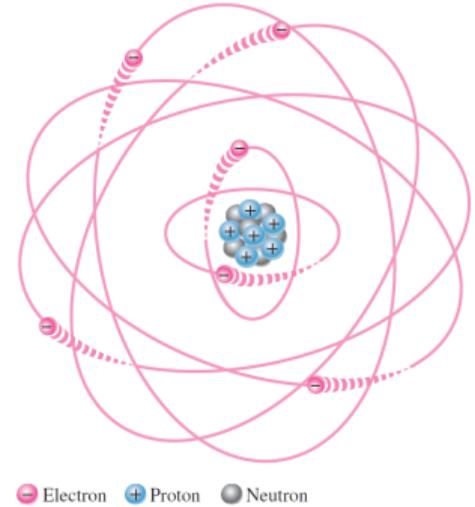


Fig. 2.1: The Bohr model of an atom (Adapted from [Electronic Devices \(Electron Flow Version\)](#), 10th edition)

# Atoms

- ▶ The number of protons in the nucleus determines the element (e.g., hydrogen, oxygen, etc.).
- ▶ Electrons are arranged in energy levels or shells around the nucleus.
- ▶ Electrons are negatively charged, while protons are positively charged.
- ▶ Number of protons in the nucleus is equal to the number of electrons in the atom, making it electrically neutral.
- ▶ Outermost shell of an atom is called the valence shell.
- ▶ Number of electrons in the valence shell, also called valence electrons determines the chemical properties of the atom.
- ▶ Atoms can gain or lose electrons to form ions, which are charged particles.

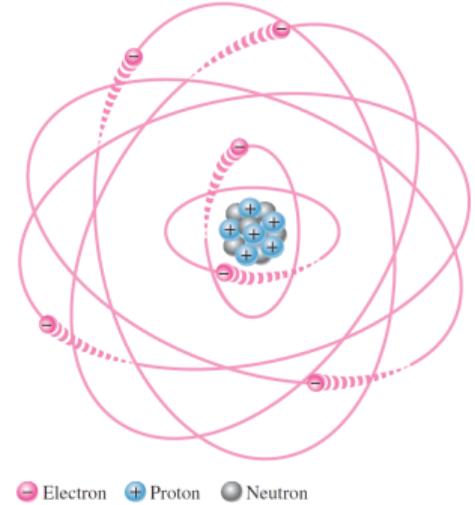


Fig. 2.2: The Bohr model of an atom (Adapted from [Electronic Devices \(Electron Flow Version\)](#), 10th edition)

# Ionisation energy

- ▶ The energy required to remove an electron from an atom is called ionisation energy.
- ▶ The ionisation energy varies for different elements and is generally higher for elements with more protons in the nucleus.
- ▶ The ionisation energy is also affected by the distance of the electron from the nucleus and the number of electrons in the valence shell- outermost shell is more vulnerable to ionisation!
- ▶ Atoms with low ionisation energy tend to lose electrons easily and form positive ions, while atoms with high ionisation energy tend to gain electrons and form negative ions.
- ▶ The ionisation energy is an important factor in determining the chemical reactivity of an element.

# Materials in electronics

- ▶ The electrical properties of materials are determined by the arrangement and behaviour of their atoms and electrons.
- ▶ Example: Carbon (C) has 4 valence electrons.
- ▶ Nucleus of C: has 6 protons and 6 neutrons. 2 electrons in the inner shell/core make a charge of +4 in the core.
- ▶ 4 valence electrons in the outer shell, forms covalent bonds with other atoms.
- ▶ In solids like diamond or any organic compounds, each carbon atom is tightly bonded to 4 others in a 3D lattice — **no free electrons to move around**.
- ▶ So, carbon is a non-metal and is a poor conductor of electricity.

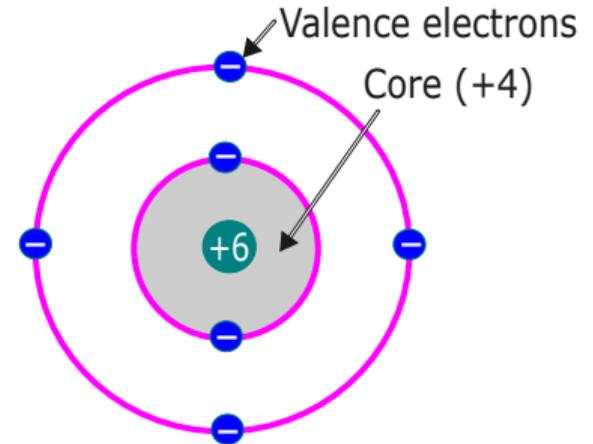


Fig. 2.3: Carbon atom with four valence electrons- used in resistors but if you **change crystal structure** (example graphite, where one electron is free to move due to flat layers of carbon atoms)

## Materials in electronics

- ▶ The electrical properties of materials can be classified into three categories based on their ability to conduct electricity:
  - ▶ **Insulators** have valence electrons tightly bound to the atoms and do not have free electrons to conduct electricity. Insulators have a **very high ionisation energy**, meaning they require a lot of energy to remove an electron from the atom. So they are bad conductors of electricity. Examples: rubber, glass, and plastic.
  - ▶ **Conductors** have a large number of loosely bounded electrons that can move easily through the material, allowing them to conduct electricity well. Conductors have a **low ionisation energy**, meaning they require very little energy to remove an electron from the atom. So, they have a low resistance to the flow of electric current. Examples: metals like copper (Cu) and aluminum (Al).
  - ▶ **Semiconductors\*** in pure or intrinsic state is neither a good conductor nor a good insulator. They have to be synthesized as compounds or made extrinsic by adding impurities (doping) to change their electrical properties. Examples: Silicon (Si) and Germanium (Ge) as intrinsic and gallium arsenide, indium phosphide, gallium nitride, silicon carbide are extrinsic.

\*Semiconductors can conduct electricity under certain conditions, such as when they are doped with impurities or when they are exposed to light or heat.

## Example explanation based on Bohr model of atom

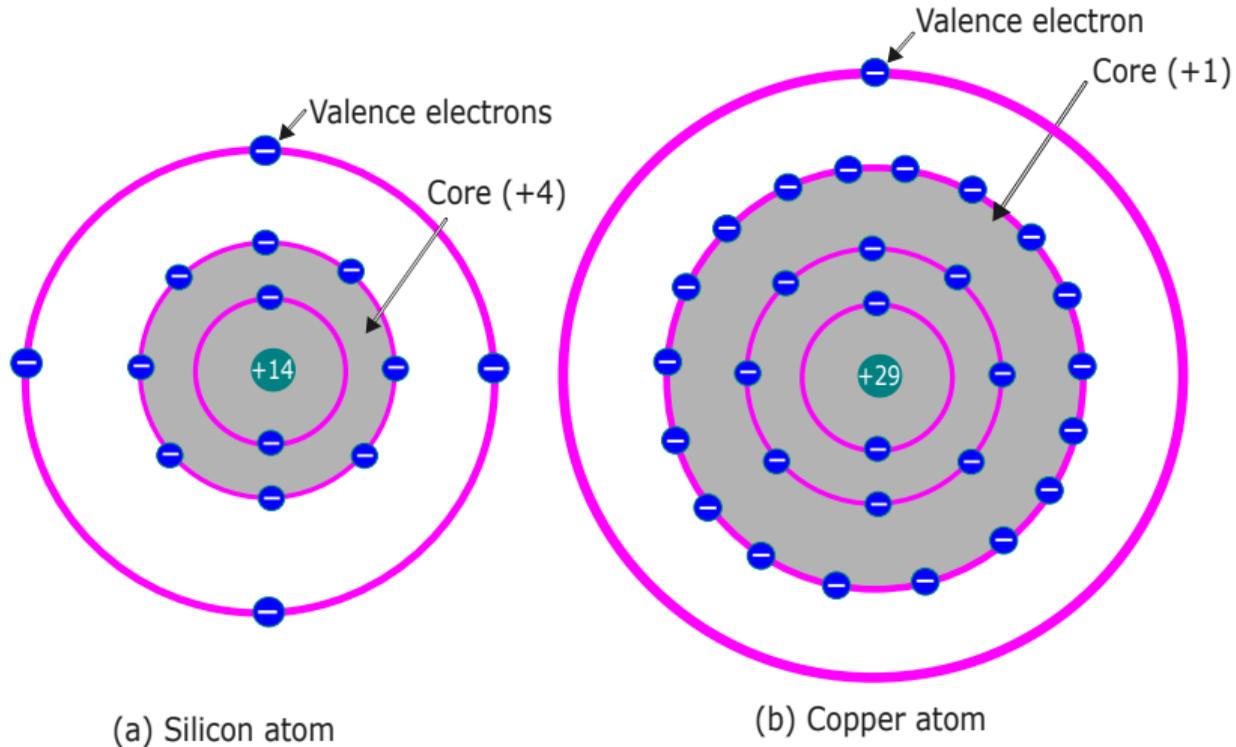


Fig. 2.4: (a) Silicon atom with four valence electrons, (b) Copper atom with one valence electron

# Example explanation based on Bohr model of atom

- ▶ **Semiconductor:** Silicon
- ▶ Silicon (Si) has 4 valence electrons.
- ▶ Nucleus of Si: has 14 protons and 14 neutrons. 10 electrons in the inner shell/core make a charge of +4 in the core.
- ▶ 4 valence electrons in the outer shell, forms covalent bonds with other atoms.
- ▶ In solids like those forming an organic compounds, each silicon atom is tightly bonded to 4 others in a 3D lattice — **no free electrons to move around.**
- ▶ So, silicon is a non-metal and is a poor conductor of electricity.

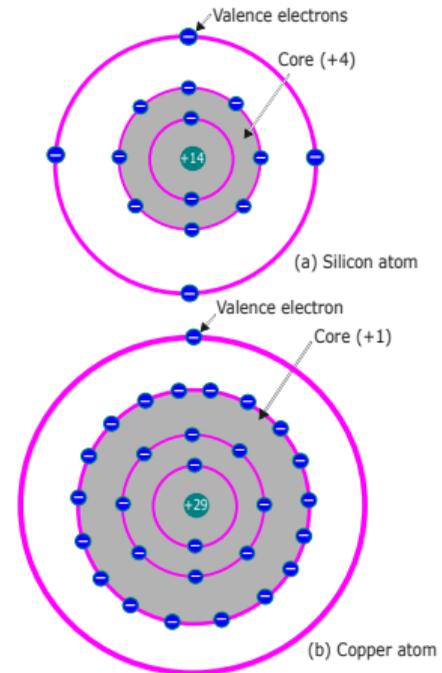


Fig. 2.5: (a) Silicon atom with four valence electrons, (b) Copper atom with one valence electron

# Example explanation based on Bohr model of atom

- ▶ **Conductor:** Copper
- ▶ Copper (Cu) has 1 valence electron.
- ▶ Nucleus of Cu: has 29 protons and 29 neutrons. 28 electrons in the inner shell/core make a charge of  $+1$  in the core.
- ▶ 1 valence electron in the outer shell, forms metallic bonds with other atoms.
- ▶ In solids like copper, each copper atom is loosely bonded to other atoms in a 3D lattice — **free electrons to move around.**
- ▶ So, copper is a metal and is a good conductor of electricity.

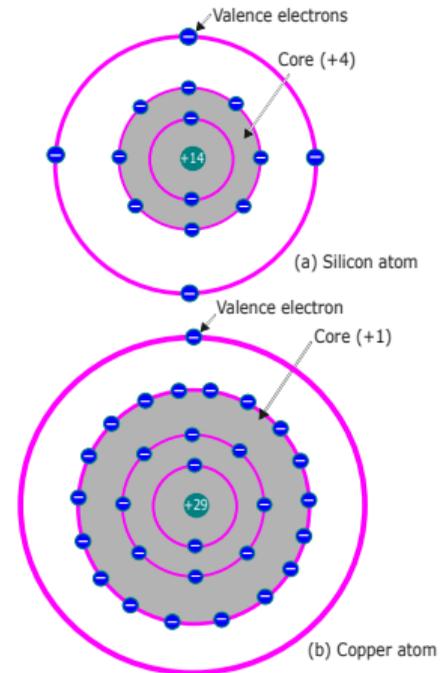


Fig. 2.6: (a) Silicon atom with four valence electrons, (b) Copper atom with one valence electron

## Energy of electron in an orbit

- ▶ The energy of an electron in an orbit is determined by the distance of the electron from the nucleus and the number of protons in the nucleus.
- ▶ Electrons in orbits closer to the nucleus have lower energy than those in orbits farther away.
- ▶ The energy of an electron in an orbit is also affected by the presence of other electrons in the atom.
- ▶ Electrons in the same shell repel each other, which can increase their energy and make them more likely to be ionised.
- ▶ **Why is electron having a negative charge?**

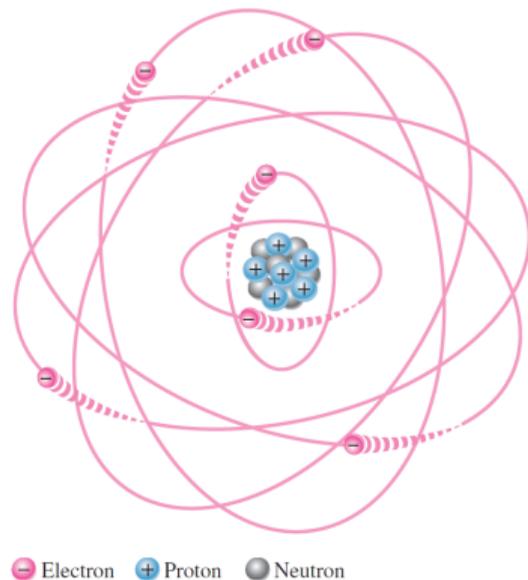


Fig. 2.7: The Bohr model of an atom  
(Adapted from [Electronic Devices \(Electron Flow Version\)](#), 10th edition)

## Total energy of the electron

- ▶ The planetary model of atom developed by **Niels Bohr** in 1913, where electrons are thought to orbit the nucleus like planets orbiting the sun. *The nucleus is considered fixed in space.*
- ▶ We aim to derive the total energy  $W$  of the electron.
- ▶ Electrostatic force of attraction between the electron and the nucleus (Coulomb's law):

$$\frac{q^2}{4\pi\epsilon_0 r^2} \quad (2.1)$$

where  $q$  is the charge of the electron,  $\epsilon_0$  is the permittivity of free space, and  $r$  is the distance between the electron and the nucleus.

- ▶ Centripetal force of electron in circular motion assuming mass  $m$  and  $v$  is its velocity:

$$\frac{mv^2}{r} \quad (2.2)$$

- ▶ Equating forces (from Newton's second law of motion):

$$\frac{q^2}{4\pi\epsilon_0 r^2} = \frac{mv^2}{r} \quad (2.3)$$

## Total energy of the electron

- ▶ Potential energy of the electron at a distance  $r$  from the nucleus:

$$U = -\frac{q^2}{4\pi\epsilon_0 r} \quad (2.4)$$

- ▶ Kinetic energy:

$$K = \frac{1}{2}mv^2 \quad (2.5)$$

- ▶ Total Energy:

$$W = K + U = \frac{1}{2}mv^2 - \frac{q^2}{4\pi\epsilon_0 r} \quad (2.6)$$

- ▶ From 2.3 we can substitute for  $mv^2$ :

$$mv^2 = \frac{q^2}{4\pi\epsilon_0 r} \quad (2.7)$$

- ▶ Substituting in 2.6 gives:

$$W = \frac{1}{2} \cdot \frac{q^2}{4\pi\epsilon_0 r} - \frac{q^2}{4\pi\epsilon_0 r} \quad (2.8)$$

- ▶ Simplifies to:

$$W = -\frac{q^2}{8\pi\epsilon_0 r} \quad (2.9)$$

## Interpretation of $W = -\frac{q^2}{8\pi\epsilon_0 r}$

- ▶ The energy levels are **quantized**, meaning that electrons can only occupy certain energy levels and cannot exist in between them.
- ▶ Total energy of the electron is negative, which means that the electron is bound state to the nucleus and cannot escape without an external energy input- energy must be supplied to remove it from the atom.
- ▶ Energy  $\propto \frac{-1}{r}$ , the closer the electron is to the nucleus (smaller  $r$ ), the more negative (tightly bound) its energy becomes.
- ▶ As  $r \rightarrow \infty$ ,  $W \rightarrow 0$ , meaning the electron is free from the nucleus and has zero energy.
- ▶ Atomic stability: at equilibrium, electrons sit at a stable radius with a specific energy — this defines discrete energy levels in atoms.
- ▶ **How do we connect all with the material properties we discussed earlier?**

# Connecting dots to material properties- energy levels

- ▶ The energy levels of electrons in an atom are quantized, meaning that they can only occupy certain discrete energy levels.
- ▶ Typically what we learnt (planetary model) is true for classical mechanics.
- ▶ As per classical laws of electromagnetism, electrons are charged particles and should radiate energy as they move in circular orbits around the nucleus, causing them to spiral inward and eventually collide with the nucleus.
- ▶ However, this does not happen in reality, and electrons do not lose energy in this way.
- ▶ This is because electrons are also subject to the principles of **quantum mechanics\***, which govern their behaviour at the atomic and subatomic levels.

\*Quantum mechanics describes the behaviour of electrons in terms of wave functions, which represent the probability of finding an electron in a particular location and energy state.

## Solution to the problem- The Bohr model and energy levels

Postulates of the Bohr model of the atom:

- ▶ **Quantized Energy Levels:** Electrons can only occupy certain discrete energy states. When in these stationary states, electrons do not emit radiation.
- ▶ **Radiation via Transition:** Electrons emit or absorb energy only when transitioning between stationary states:

$$f = \frac{W_2 - W_1}{h} \quad (2.10)$$

where  $f$  is frequency and  $h$  is Planck's constant.

- ▶ **Quantized Angular Momentum:** Electron's angular momentum is quantized:

$$mvr = \frac{nh}{2\pi} \quad (2.11)$$

where  $n$  is a positive integer (principal quantum number).

## Solution to the problem- The Bohr model and energy levels

Energy level in the Bohr model:

- ▶ Combining equations 2.3, 2.11, we get:

$$W_n = -\frac{mq^4}{8h^2\epsilon_0^2} \cdot \frac{1}{n^2} \quad (2.12)$$

- ▶ Shows that energy levels quantised and are inversely proportional to  $n^2$ .
- ▶ Radius of the lowest state (ground state) is approximately  $0.5 \text{ \AA}$  (Angstrom).
- ▶ Negative values indicate bound states.

**Let's move from discrete atomic energy levels to energy bands in solids!**

## From discrete atomic energy levels to energy bands in solids

- ▶ In isolated atoms (like in the Bohr model), electrons occupy discrete levels.
- ▶ In crystalline solids, atoms are close together – their orbitals overlap, and these discrete energy levels broaden into bands.

<b>Bohr atom</b>	<b>Solid material</b>
Quantized orbits ( $n = 1, 2, \dots$ )	Continuous energy bands
Negative $W_n = \text{bound}$	Valence band (bound states)
Ionization limit $W = 0$	Bottom of conduction band

Tab. 2.1: Comparison between Bohr atom model and solid-state materials

- ▶ Bohr's quantum model forms a foundation for understanding electrical behavior in materials — especially in semiconductors and insulators.

## The energy band formation and the role of quantum number $n$

- ▶ Valence band: Derived from the outermost electron levels (e.g.,  $n=2,3$ ) of atoms.
- ▶ Conduction band: Formed from higher unoccupied energy states – analogous to free or nearly free electrons.
- ▶ Band gap ( $E_g$ ): Energy difference between the valence band and conduction band. Determines electrical properties of materials.
- ▶ **Energy bands**: In Bohr's model,  $n$  defined specific orbits and energies but in solids, energy levels are not discrete but form bands due to the overlap of atomic orbitals. The energy bands are separated by band gaps, which determine the electrical properties of the material.

# Energy band diagram and classification of materials

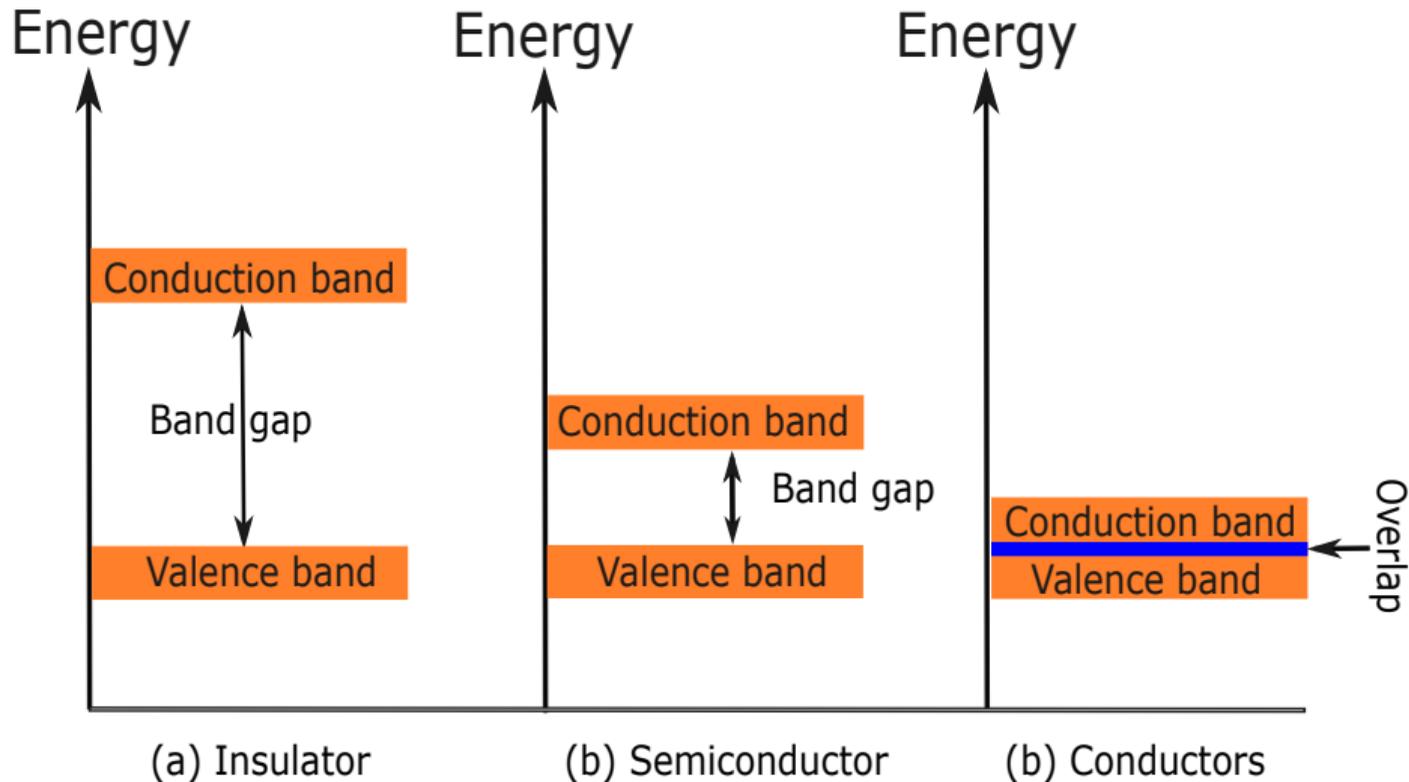


Fig. 2.8: Energy band diagram showing the classification of materials

# Energy band diagram and classification of materials

- ▶ Energy band diagram shows the energy levels of electrons in a solid material.
- ▶ The energy bands are separated by band gaps, which determine the electrical properties of the material.
- ▶ Materials can be classified based on their energy band structure:
  - ▶ Conductors: No band gap, electrons can move freely.
  - ▶ Semiconductors: Small band gap, electrons can be excited to the conduction band with some energy input.
  - ▶ Insulators: Large band gap, electrons cannot move freely without significant energy input.

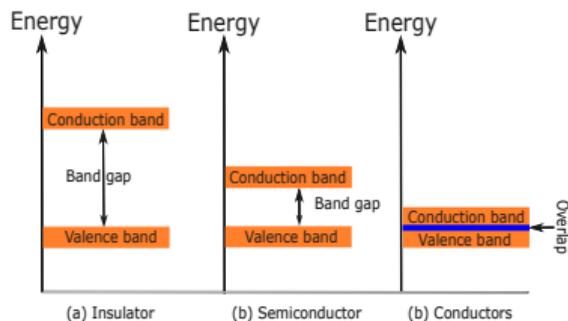


Fig. 2.9: Energy band diagram showing the classification of materials

# Conclusion on types of materials

- ▶ We learnt in two ways about classification of materials:
  - ▶ Based on the number of valence electrons.
  - ▶ Based on the energy band structure.

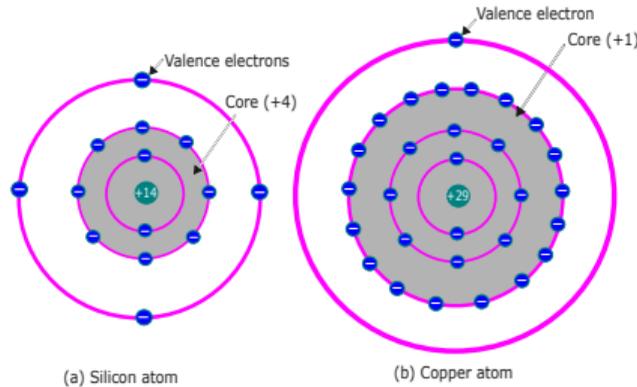


Fig. 2.10: (a) Silicon atom with four valence electrons, (b) Copper atom with one valence electron

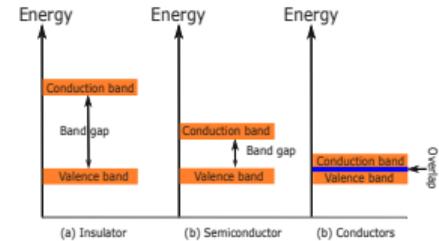


Fig. 2.11: Energy band diagram showing the classification of materials

**What next? → We will learn about the flow of electrons and holes in semiconductors.**

## Free electrons and holes in semiconductors

- ▶ In semiconductors, the energy band gap is small enough that some electrons can be thermally excited from the valence band to the conduction band at room temperature.
- ▶ This process creates **free electrons** (also called **conduction electrons**) in the conduction band and **holes** (a vacant state that behaves like a positive charge) in the valence band.
- ▶ Example: At room temperature, intrinsic silicon has enough thermal energy to excite some valence electrons across the band gap.
- ▶ This process results in **electron-hole pairs**.
- ▶ Free electrons and holes drift under electric fields and contribute to electrical conductivity.
- ▶ The concentration of free electrons and holes in a semiconductor can be controlled by doping with impurities.

## Electron current in semiconductors

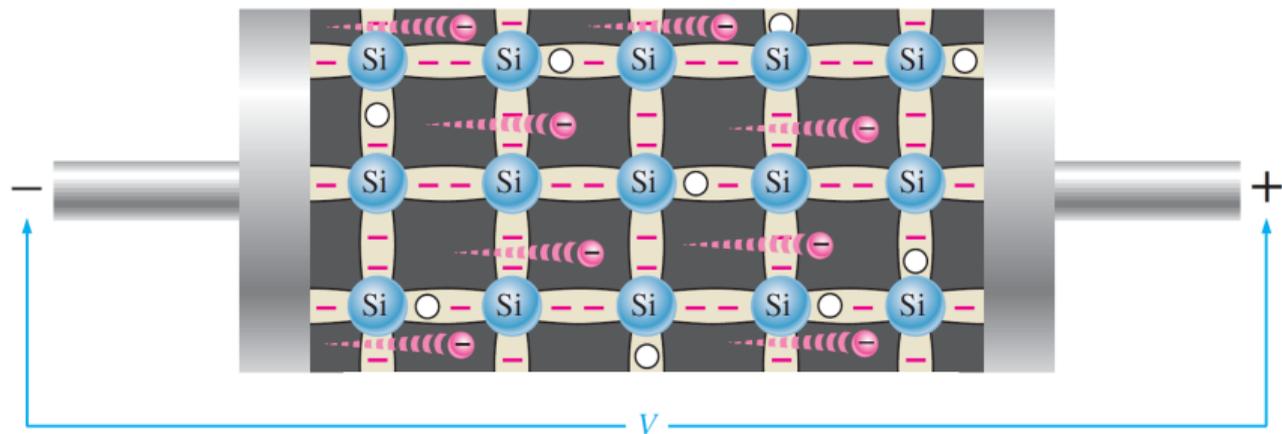
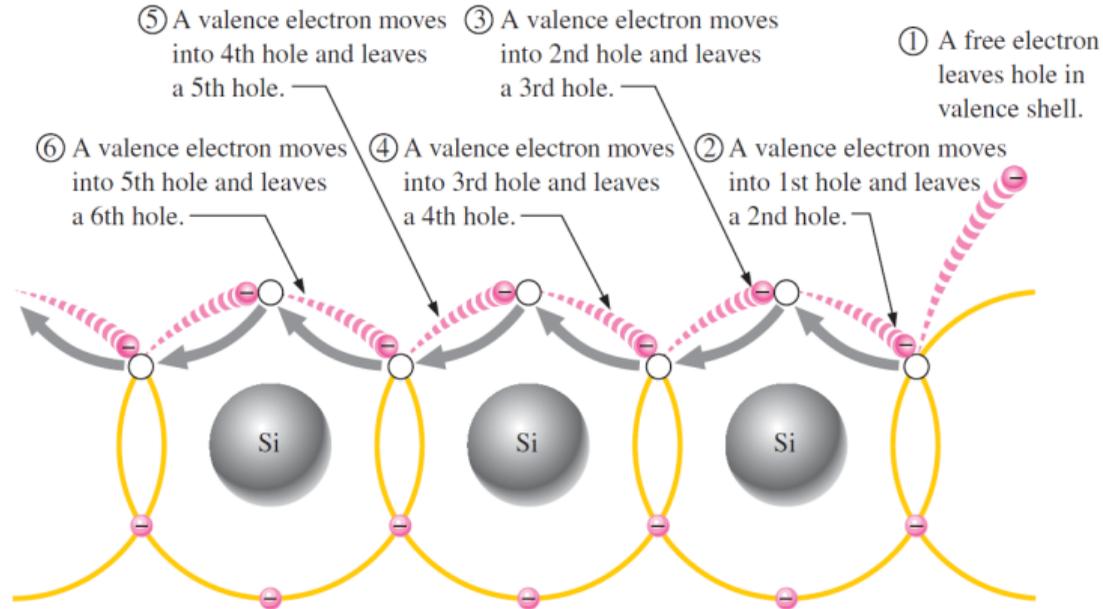


Fig. 2.12: Electron current in semiconductors (intrinsic Si) (Adapted from [Electronic Devices \(Electron Flow Version\)](#), 10th edition)

**The current we speak in general is the flow of electrons in a conductor. In semiconductors, the current is due to the flow of both electrons and holes.**

# Electron current in semiconductors



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

Fig. 2.13: Hole current in semiconductors (intrinsic Si) (Adapted from [Electronic Devices \(Electron Flow Version\)](#), 10th edition)

# N-type and P-type semiconductors

- ▶ **Doping:** The process of adding impurities to a intrinsic (pure) semiconductor to change its electrical properties.
- ▶ N-type semiconductors are formed by doping intrinsic semiconductors with elements that have more valence electrons (e.g., phosphorus (P), arsenic (As)).
- ▶ In N-type semiconductors, the majority carriers are free electrons, while in P-type semiconductors, the majority carriers are holes.
- ▶ P-type semiconductors are formed by doping intrinsic semiconductors with elements that have fewer valence electrons (e.g., boron (B), gallium (Ga)).
- ▶ The minority carriers in N-type semiconductors are holes, while in P-type semiconductors, the minority carriers are free electrons.

# Understanding the doping process- Donor and Acceptor atoms

- ▶ **Donor atoms:** Atoms that donate extra electrons to the semiconductor lattice, creating N-type semiconductors.
- ▶ **Example of donor:**
  - ▶ Consider Germanium (Ge) as the intrinsic semiconductor. It is a group IV element with 4 valence electrons.
  - ▶ When doped with Phosphorus (P), a group V element with 5 valence electrons, the extra electron from P becomes a free electron in the conduction band of Ge.
  - ▶ This creates an N-type semiconductor with a higher concentration of free electrons than holes.
  - ▶ The energy required to detach the extra electron from the donor atom is very small, so it is easily ionised at room temperature. For example, the ionisation energy of P in Ge is about 0.01 eV and for Si is about 0.045 eV.

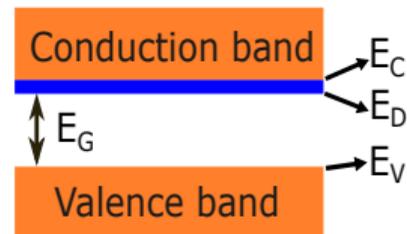


Fig. 2.14: Energy band diagram of an n-type semiconductor- allowable energy levels introduced in the conduction band.  $E_D$  is also called Fermi level ( $E_F$ ).

# Understanding the doping process- Donor and **Acceptor atoms**

- ▶ **Acceptor atoms:** Atoms that accept electrons from the semiconductor lattice, creating P-type semiconductors.
- ▶ **Example of Acceptor:**
  - ▶ Consider Silicon (Si) as the intrinsic semiconductor. It is a group IV element with 4 valence electrons.
  - ▶ When doped with Boron (B), a group III element with 3 valence electrons, the missing electron from B creates a hole in the valence band of Si.
  - ▶ This creates a P-type semiconductor with a higher concentration of holes than free electrons.
  - ▶ The energy required to fill the hole is very small, so it is easily ionised at room temperature. For example, the ionisation energy of B in Si is about 0.045 eV and for Ga is about 0.1 eV.

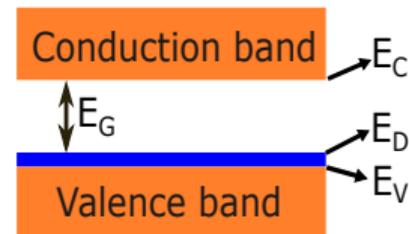


Fig. 2.15: Energy band diagram of an p-type semiconductor- allowable energy levels introduced in the valence band.  $E_D$  is also called Fermi level ( $E_F$ )

## Acceptor and donor atoms in a semiconductor- example

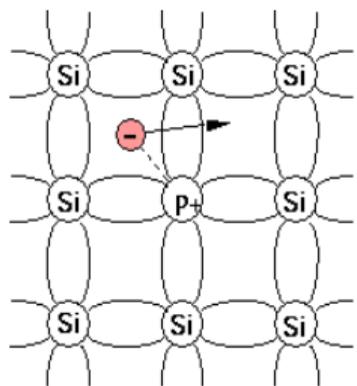


Fig. 2.16: Phosphorus atom acting as a donor in the simplified 2D silicon lattice. (Source: from Karolkalna at the English Wikipedia, CC BY-SA 3.0)

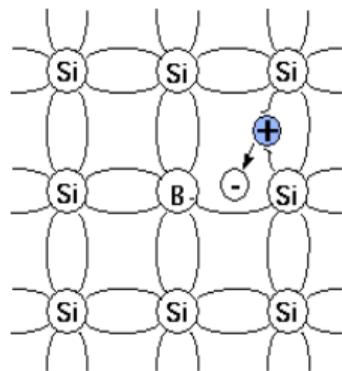


Fig. 2.17: Boron atom acting as an acceptor in the simplified 2D silicon lattice- (Source: from Karolkalna at the English Wikipedia, CC BY-SA 3.0)

## Mass action law

- ▶ The mass action law states that the product of the concentrations of electrons and holes in a semiconductor is constant at a given temperature.
- ▶ This relationship can be expressed mathematically as:

$$n \cdot p = n_i^2 \quad (2.13)$$

where  $n$  is the concentration of free electrons,  $p$  is the concentration of holes, and  $n_i$  is the intrinsic carrier concentration.

- ▶ The intrinsic carrier concentration ( $n_i$ ) is a measure of the number of electron-hole pairs generated in an intrinsic semiconductor at thermal equilibrium.

# Charge Neutrality in Semiconductors

- ▶ Electrical neutrality:

$$N_D + p = N_A + n \quad (2.14)$$

- ▶ For **n-type material** ( $N_A = 0$ ):

$$n \approx N_D \quad (2.15)$$

- ▶ Thus, free-electron concentration equals donor atom concentration.

- ▶ More clearly written with subscripts:

$$n_n \approx N_D \quad (2.16)$$

- ▶ Hole concentration:

$$p_n = \frac{n_i^2}{N_D} \quad (2.17)$$

## p-Type Semiconductors and Doping

- ▶ For **p-type semiconductors**:

$$p_p \approx N_A, \quad n_p = \frac{n_i^2}{N_A} \quad (2.18)$$

- ▶ Equal donor and acceptor concentrations ( $N_D = N_A$ )  $\Rightarrow$  intrinsic behavior.
- ▶ Doping can switch material type depending on relative  $N_D$  and  $N_A$ .
- ▶ For  $N_D > N_A$ , p-type becomes n-type.
- ▶ Adjusted neutrality (general case):

$$N_D + p = N_A + n \Rightarrow N_D - N_A = n - p \quad (2.19)$$

# Conductivity and Carrier Mobility

▶ Semiconductors are **bipolar**: conduction via both electrons and holes.

▶ Current density:

$$J = (n\mu_n + p\mu_p)q\mathcal{E} = \sigma\mathcal{E} \quad (2-16)$$

▶  $n, p$ : carrier concentrations;  $\mu_n, \mu_p$ : mobilities.

▶ Conductivity:

$$\sigma = (n\mu_n + p\mu_p)q \quad (2-17)$$

▶ Intrinsic case:  $n = p = n_i$

# Intrinsic Carrier Concentration and Temperature Dependence

- ▶ As temperature increases, intrinsic carrier concentration increases:

$$n_i^2 = A_0 T^3 e^{-E_{G0}/kT} \quad (2-18)$$

- ▶ Temperature-dependent bandgap:

$$E_G(T) = 1.21 - 3.60 \times 10^{-4}T \quad (\text{Si}) \quad (2-19)$$

$$E_G(T) = 0.785 - 2.23 \times 10^{-4}T \quad (\text{Ge}) \quad (2-20)$$

- ▶ As  $T$  increases:
  - ▶  $E_G$  decreases
  - ▶  $n_i$  increases
  - ▶ Conductivity increases

# The Hall Effect

- ▶ When a semiconductor carries a current  $I$  in a transverse magnetic field  $B$ , an electric field  $\mathcal{E}$  develops perpendicular to both  $I$  and  $B$ .
- ▶ This phenomenon is known as the **Hall Effect**.
- ▶ Used to determine:
  - ▶ Whether a semiconductor is **n-type** or **p-type**
  - ▶ The carrier concentration
  - ▶ The mobility  $\mu$  of carriers
- ▶ A potential difference, called the **Hall voltage**  $V_H$ , appears across the sample.

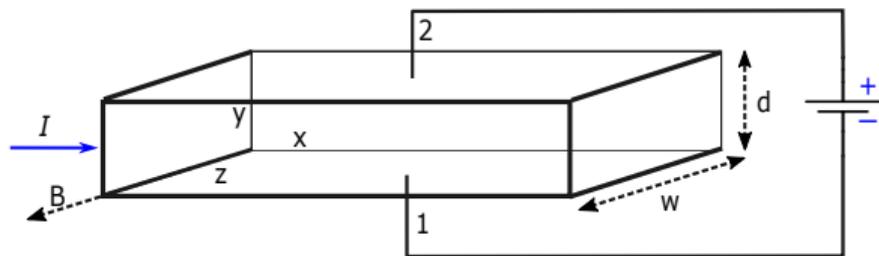


Fig. 2.18: Schematic diagram of Hall setup showing force on charge carriers

## Lorentz Force and Hall Field

- ▶ Consider a semiconductor sample placed in a magnetic field  $\vec{B}$  in the  $z$ -direction.
- ▶ A current  $I$  is passed in the  $x$ -direction, perpendicular to  $\vec{B}$ .
- ▶ Charge carriers (electrons or holes) moving with velocity  $\vec{v}$  experience a force:

$$\vec{F} = q(\vec{v} \times \vec{B}) \quad (2.20)$$

- ▶ This Lorentz force deflects carriers in the  $+y$  direction, creating:
  - ▶ Negative charge on the  $+y$  side (if electrons dominate)
  - ▶ Positive charge on the  $-y$  side
- ▶ This generates an electric field  $E_H$  opposing the Lorentz force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = 0 \quad (2.21)$$

For simplicity, let's represent  $\vec{E} = \mathcal{E}$

## Hall Voltage and Carrier Type

- ▶ Solving Eq. 2.21 gives the Hall field:

$$\mathcal{E} = v_x B_z \quad (2.22)$$

- ▶ This field gives rise to a Hall voltage:

$$V_H = d\mathcal{E} = dv_x B_z \quad (2.23)$$

- ▶  $d$ : width of the semiconductor sample
- ▶ Since current  $I \propto qv_x$ , the sign of  $V_H$  indicates:
  - ▶  $V_H > 0$ : Majority carriers are electrons (n-type)
  - ▶  $V_H < 0$ : Majority carriers are holes (p-type)
- ▶ Thus, **Hall effect enables determination of carrier type** in semiconductors

## Experimental Determination of $\mu$ (mobility of charge carrier) and $\rho$ (charge density)

- ▶ In the equilibrium state the electric field intensity  $\mathcal{E}$  due to Hall effect must be equal to the magnetic force:

$$q\mathcal{E} = Bqv \quad (2-21)$$

- ▶ Using  $\mathcal{E} = \frac{V_H}{d}$  and  $J = \rho v = \frac{I}{wd}$ , where  $\rho$  is the charge density,  $w$  is the width of the sample, and  $J$  is the current density:

$$V_H = \mathcal{E}d = Bvd = \frac{BJd}{\rho} = \frac{BI}{\rho w} \quad (2-22)$$

- ▶ Hence  $\rho$  can be expressed as:

$$\rho = \frac{BI}{V_H w} \Rightarrow R_H = \frac{1}{\rho} = \frac{V_H w}{BI} \quad (2-23, 2-24)$$

where  $R_H$  is the Hall coefficient.

## Hall Coefficient and Mobility

- ▶ Conductivity:  $\sigma = \rho\mu$  (for single carrier type)
- ▶ Therefore, mobility:

$$\mu = \sigma R_H \quad (2-26)$$

- ▶ If random thermal motion is accounted for:

$$\mu = \left(\frac{8\sigma}{3\pi}\right) R_H \quad (2.24)$$

- ▶ Hall effect allows complete characterization of a semiconductor.

# Applications and Conductivity Modulation

- ▶ Applications:
  - ▶ Magnetic field sensors (Hall-effect meters)
  - ▶ Hall-effect multipliers (measure product of two signals)
- ▶ Conductivity  $\sigma$  can be modulated by:
  - ▶ Varying temperature
  - ▶ Doping to increase  $n$  or  $p$
  - ▶ Illumination to generate electron-hole pairs
- ▶ Reiterates Eq. (2-17):  $\sigma = (n\mu_n + p\mu_p)q$

## Carrier Generation and Recombination

- ▶ **Generation:** Creation of electron-hole pairs (EHPs)
  - ▶ Due to thermal energy or light (photons)
- ▶ **Recombination:** Annihilation of an electron with a hole
- ▶ At equilibrium, generation rate  $G$  equals recombination rate  $R$
- ▶ Important for determining carrier lifetime  $\tau$ : Average time a carrier exists before recombination.
- ▶ **Auger recombination:** Involves three carriers (two electrons and one hole or vice versa).
  - ▶ It is transfer of the energy and momentum released by the recombination of an electron-hole pair to a third mobile particle- electrons in the case of heavily doped N-type material and holes in the case of heavily doped P-type material.
  - ▶ It is a non-radiative process and is the dominant recombination mechanism in heavily doped semiconductors.
  - ▶ Auger recombination is a significant factor in determining the efficiency of semiconductor devices, especially in **high-power and high-frequency applications**.
- ▶ **Radiative recombination:** Involves emission of a photon.

## Carrier Diffusion

- ▶ Caused by spatial concentration gradients of charge carriers
- ▶ Electrons and holes move from regions of high to low concentration
- ▶ Electron diffusion current density:

$$J_n^{\text{diff}} = qD_n \frac{dn}{dx} \quad (2.25)$$

- ▶ Hole diffusion current density:

$$J_p^{\text{diff}} = -qD_p \frac{dp}{dx} \quad (2.26)$$

- ▶ Where:

- ▶  $q$ : elementary charge
- ▶  $D_n, D_p$ : diffusion coefficients of electrons and holes
- ▶  $\frac{dn}{dx}, \frac{dp}{dx}$ : gradients of electron and hole concentrations with respect to position  $x$

# Carrier Drift

- ▶ Caused by an applied electric field  $\mathcal{E}$  across the semiconductor
- ▶ Electron drift current:

$$J_n^{\text{drift}} = qn\mu_n\mathcal{E} \quad (2.27)$$

- ▶ Hole drift current:

$$J_p^{\text{drift}} = qp\mu_p\mathcal{E} \quad (2.28)$$

- ▶ Where:

- ▶  $n, p$ : concentrations of electrons and holes
- ▶  $\mu_n, \mu_p$ : mobilities of electrons and holes
- ▶  $\mathcal{E}$ : electric field (V/m)
- ▶ Drift current is proportional to the electric field and carrier concentration
- ▶ Drift and diffusion currents are the two main mechanisms of charge transport in semiconductors

## Distinction: Drift vs Diffusion Currents

### Comparison of Drift and Diffusion Currents

Aspect	Drift Current	Diffusion Current
Driving Force	Electric field ( $\mathcal{E}$ )	Concentration gradient ( $\frac{dn}{dx}$ or $\frac{dp}{dx}$ )
Direction	Field direction	High to low concentration
Equation	$qn\mu\mathcal{E}$ or $qp\mu\mathcal{E}$	$qD\frac{dn}{dx}$ or $-qD\frac{dp}{dx}$
Occurs Due To	External bias	Inhomogeneous doping or illumination
Field Requirement	Required	Not required

## How mobility and diffusion are related of charge carrier are related?

- ▶ **Mobility** ( $\mu$ ): Measure of how quickly charge carriers (electrons or holes) can move through a semiconductor material in response to an electric field.
- ▶ **Diffusion coefficient** ( $D$ ): Measure of how quickly charge carriers can spread out in a semiconductor material due to concentration gradients.
- ▶ **Einstein relation**: Connects mobility and diffusion coefficient:

$$D = \frac{kT}{q} \mu \quad (2.29)$$

- ▶ Where:
  - ▶  $k$ : Boltzmann constant
  - ▶  $T$ : Absolute temperature (in Kelvin)
  - ▶  $q$ : Elementary charge (charge of an electron)
- ▶ This relation shows that the diffusion coefficient is directly proportional to the mobility of charge carriers and the temperature.
- ▶ Higher mobility leads to higher diffusion rates, which is important for understanding charge transport in semiconductors.

## Relevance of Einstein relation?

- ▶ The Einstein relation is a fundamental concept that bridge the microscopic thermal motion of carriers with their macroscopic electrical behavior, and is essential for modeling how semiconductors behave under various conditions.
- ▶ **Unifies Drift and Diffusion:** Shows that mobility (drift due to electric field) and diffusion (due to concentration gradient) are inherently linked by thermal motion.
- ▶ **Device Modeling:** Essential for modeling carrier transport in semiconductors such as diodes, BJTs, and MOSFETs where both drift and diffusion processes coexist.
- ▶ **Simplifies Analysis:** If one parameter (e.g., mobility) is known, diffusion coefficient can be calculated, reducing experimental complexity.
- ▶ **Temperature Dependence:** Since  $D \propto T$  and  $\mu \propto T^{-m}$  (where  $m \approx 1.5$ ), the Einstein relation captures how transport properties change with temperature — crucial for thermal sensor and reliability design.
- ▶ **Measurement and Material Characterization:** Enables calculation of diffusion coefficient  $D$  from mobility  $\mu$  measured using Hall effect.

## Deriving Einstein Relation

- ▶ The Einstein relation connects the diffusion coefficient ( $D$ ) and the mobility ( $\mu$ ) of charge carriers in thermal equilibrium.

- ▶ For electrons:

$$D_n = \frac{kT}{q} \mu_n, \quad \text{and for holes: } D_p = \frac{kT}{q} \mu_p \quad (2.30)$$

- ▶ **Start with the drift current:**

$$J_n^{\text{drift}} = qn\mu_n\mathcal{E} \quad (2.31)$$

- ▶ **In equilibrium**, the total electron current must be zero:

$$J_n^{\text{drift}} + J_n^{\text{diff}} = 0 \Rightarrow qn\mu_n\mathcal{E} + qD_n \frac{dn}{dx} = 0 \quad (2.32)$$

## Deriving Einstein Relation. Contd.

- ▶ From Boltzmann distribution:

$$n(x) \propto e^{-q\phi(x)/kT} \Rightarrow \frac{dn}{dx} = \frac{qn\mathcal{E}}{kT} \quad (2.33)$$

- ▶ Substituting back into current balance:

$$\begin{aligned}qn\mu_n\mathcal{E} + qD_n \left( \frac{qn\mathcal{E}}{kT} \right) &= 0 \\ \Rightarrow qn\mathcal{E} \left( \mu_n + \frac{qD_n}{kT} \right) &= 0\end{aligned}$$

- ▶ Since  $qn\mathcal{E} \neq 0$  in general, we get:

$$D_n = \frac{kT}{q}\mu_n \quad (2.34)$$

- ▶ Similarly, for holes:

$$D_p = \frac{kT}{q}\mu_p \quad (2.35)$$

# Continuity Equation

- ▶ Expresses conservation of charge carriers over time and space and ensured that the total charge in a semiconductor remains constant or the law of **conservation of charge**.

- ▶ For electrons:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} + G_n - R_n \quad (2.36)$$

- ▶ Where:

- ▶  $n$ : electron concentration (per unit volume)
- ▶  $J_n$ : electron current density
- ▶  $G_n$ : electron generation rate
- ▶  $R_n$ : electron recombination rate

- ▶ Similar form exists for holes

- ▶ Important in analyzing transient or steady-state carrier dynamics

## Continuity Equation- relevance

- ▶ Models **transient behavior** in devices (e.g., switching in transistors, photodiode response), basically how quickly a device responds to changes in input.
- ▶ Describes **steady-state operation** when  $\partial n/\partial t = 0$ , hence used in diode forward and reverse bias analysis, minority carrier injection in BJTs.
- ▶ Forms the backbone of **minority carrier analysis** in diodes and BJTs
- ▶ Extends to holes:  $\frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} + G_p - R_p$ , together with the electron equation, allows for a complete description of carrier dynamics in semiconductors.
- ▶ Couples with Poisson's equation (describes how the electric potential varies in space due to the presence of electric charge within the material) for **complete device modeling**
- ▶ Core equation in numerical tools like TCAD, COMSOL, Silvaco

## Impact Ionization

- ▶ **Impact ionization:** Process where a high-energy electron collides with an atom, creating an electron-hole pair.
- ▶ This process can lead to a chain reaction, where the newly created electrons also gain enough energy to create more electron-hole pairs.
- ▶ Impact ionization is a high-field carrier generation mechanism leading to **avalanche multiplication**.
- ▶ It occurs when electrons or holes in a strong electric field gain sufficient kinetic energy to ionize atoms, creating electron-hole pairs.
- ▶ Fundamental in determining the **breakdown voltage** in devices like diodes and power MOSFETs.
- ▶ Before we proceed, just a short thought on how a device conducts current.
  - ▶ In forward bias, due to diffusion of majority carriers, the depletion region shrinks and the current increases exponentially with voltage.
  - ▶ In reverse bias, If voltage is low and doping is high → Zener breakdown,  
If voltage is high and doping is low → Avalanche breakdown

# Table of contents

## 3 p-n junctions and diodes

# p-n junctions and diodes

Dr Bikash Sah



# What have you learnt and what you will learn?

- ▶ What you have learnt so far?
  - ▶ How do a material behave as a conductor, semiconductor and insulator?
  - ▶ How the current flows in a semiconductor?
  - ▶ Mathematics of the current flow in a semiconductor?
  - ▶ Properties of a intrinsic and extrinsic semiconductors?
  - ▶ What is doping and **individual properties of n-type and p-type semiconductors?**
- ▶ What you will learn in this lecture?
  - ▶ What is a p-n junction? **How n-type and p-type semiconductors work together?**
  - ▶ What is the depletion region?
  - ▶ What is the built-in potential?
  - ▶ What is the forward and reverse bias?
  - ▶ What is the current-voltage characteristics of a diode?
  - ▶ What are the different types of diodes?
  - ▶ What are the applications of diodes?

# Band diagrams of p-n junctions

- ▶ A p-n junction is formed when a p-type semiconductor and an n-type semiconductor are brought into contact.
- ▶ The energy band diagrams of a p-n junction can be represented as follows:
  - ▶ Before contact: The energy bands of the p-type and n-type semiconductors are separate.
  - ▶ After contact: The energy bands of the p-n junction align, creating a depletion or space charge region at the interface.
  - ▶ The conduction band and valence band of the n-type semiconductor are higher in energy than those of the p-type semiconductor.
  - ▶ The Fermi level of the n-type semiconductor is higher than that of the p-type semiconductor before contact.
  - ▶ After contact, the Fermi level becomes constant across the junction, indicating thermal equilibrium.
- ▶ The energy band diagram of a p-n junction can be represented as follows:

# Band diagrams of p-n junctions

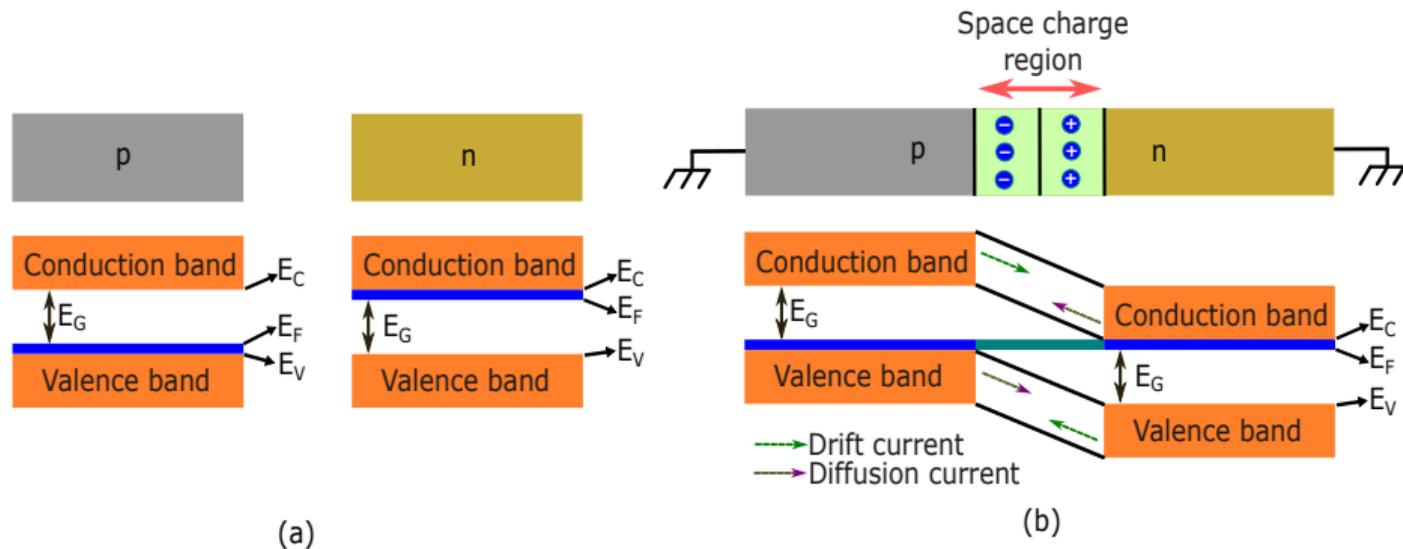


Fig. 3.1: Energy band diagram of a (a) discrete p and n (b) p-n junction.

- ▶ The energy band diagram of a p-n junction shows the conduction band, valence band, and Fermi level of both the p-type and n-type semiconductors before and after contact.
- ▶ The depletion region is formed at the interface, where the majority carriers (holes in p-type and electrons in n-type) recombine, creating a region with no free charge carriers.

# Band diagrams of p-n junctions

## ► Step 1: Diffusion Due to Concentration Gradient

- p-side: High hole concentration
- n-side: High electron concentration
- Result: Holes diffuse from p to n, electrons from n to p

## ► Step 2: Ions Left Behind → Space Charge

- As mobile carriers leave, fixed ionized dopants remain:
  - Negative acceptor ions in the p-region
  - Positive donor ions in the n-region

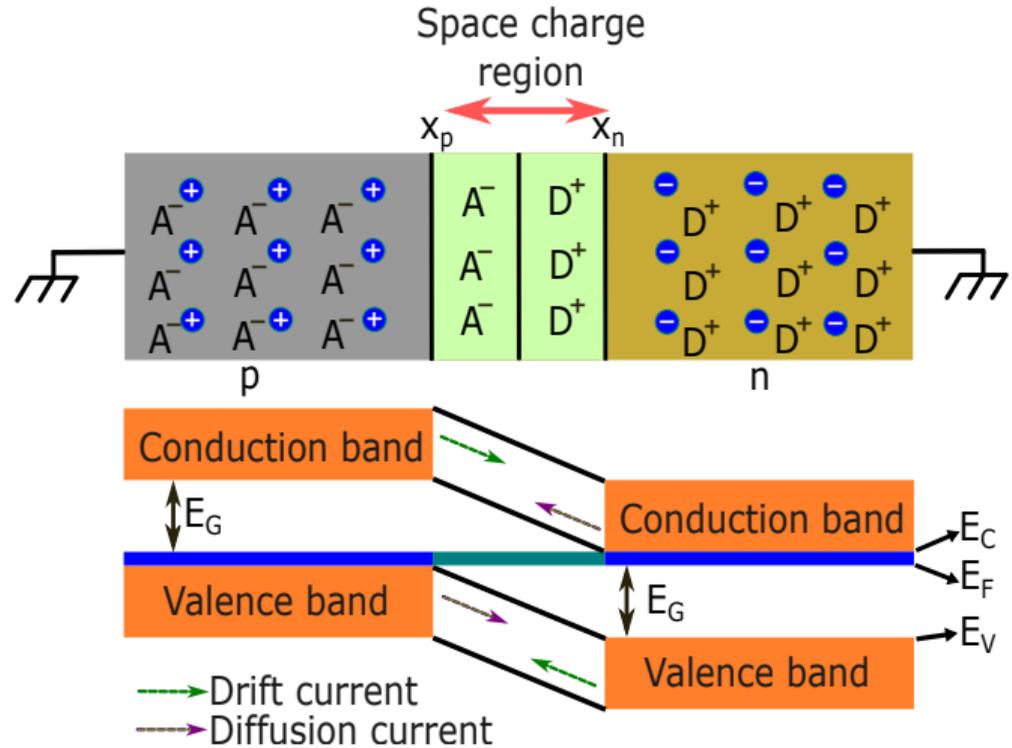


Fig. 3.2: Energy band diagram of a p-n junction.

# Band diagrams of p-n junctions

- ▶ **Step 1: Diffusion Due to Concentration Gradient**
- ▶ **Step 2: Ions Left Behind → Space Charge**
  - ▶ Creates a region with net charge — the **space charge region**
- ▶ **Step 3: Built-in Electric Field Forms**
  - ▶ The space charge generates an electric field  $\mathcal{E}_{bi}$  (from n to p)
  - ▶ This field opposes further carrier diffusion
- ▶ **Step 4: Dynamic Balance Achieved**
  - ▶ Eventually, drift current (due to  $\mathcal{E}_{bi}$ ) balances diffusion current
  - ▶ Net current = 0: system reaches **thermal equilibrium**

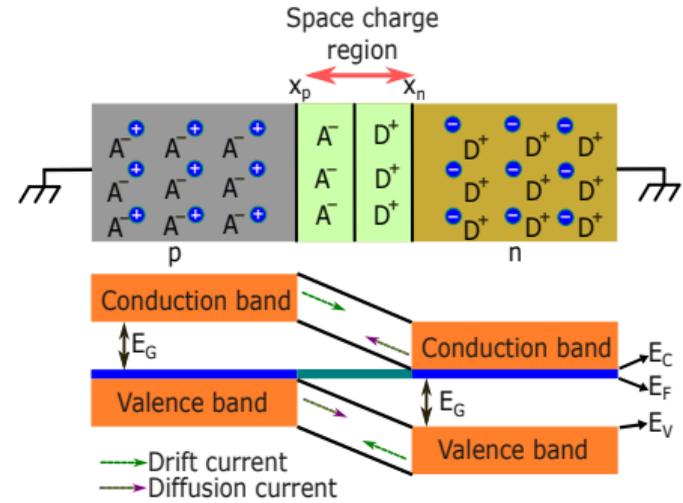


Fig. 3.3: Energy band diagram of a p-n junction.

# Key Insights into Charge Movement

- ▶ Initial carrier flow is driven by **concentration gradients**, not electric forces.
- ▶ Opposite charges do not attract each other across the junction initially.
- ▶ The **electric field is a result of diffusion**, not the cause of it.
- ▶ The depletion region is characterized by:
  - ▶ No free carriers
  - ▶ Net space charge from fixed dopants
- ▶ The system reaches an equilibrium defined by the **built-in potential**  $V_{bi}$ .

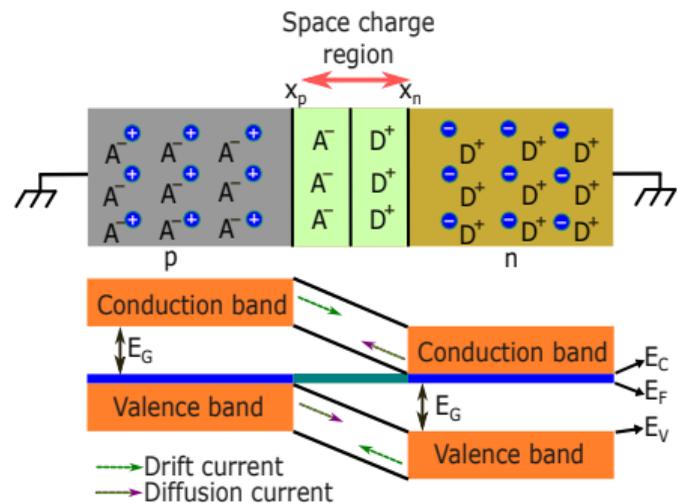


Fig. 3.4: Energy band diagram of a p-n junction.

## Electric Field Intensity in the space charge region

- ▶ The depletion region in a pn junction contains **uncompensated dopant ions** (donors in n-side, acceptors in p-side).
- ▶ This fixed charge distribution creates a **space-charge density**  $\rho(x)$ , giving rise to an electric field.
- ▶ According to **Poisson's equation**:

$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\epsilon} \quad (3.1)$$

where  $V$  is the electrostatic potential and  $\epsilon$  is the permittivity.

- ▶ Integrating Poisson's equation yields the electric field:

$$\mathcal{E}(x) = \int_{x_p}^x \frac{\rho(x_n)}{\epsilon} dx \quad (3.2)$$

where  $x_p$  is the reference point where  $\mathcal{E}(x_p) = 0$ .

## Electric Field Intensity in the space charge region

- ▶ **Electric field direction:**
  - ▶ Points from n-side (positive charge) to p-side (negative charge).
  - ▶ Corresponds to **negative field intensity** if potential decreases from n to p.
- ▶ The electric field acts like an **internal dipole layer**, enabling the concept of **built-in potential**  $V_0$ .
- ▶ **Equilibrium condition:**
- ▶ At thermal equilibrium, i.e. the steady-state condition at a given temperature with no external excitations, the individual electron and hole currents flowing across the junctions are identically zero. Thus, for each type of carrier the drift current due to the electric field must exactly cancel the diffusion current due to the concentration gradient.

$$j_n = j_p = 0 \Rightarrow j_n + j_p = 0 \quad (3.3)$$

- ▶ The total current density is given by:

$$j = j_n(\text{drift}) + j_p(\text{diffusion}) = q \left( \mu_n n \mathcal{E} + D_n \frac{dn}{dx} - \mu_p p \mathcal{E} - D_p \frac{dp}{dx} \right) = 0 \quad (3.4)$$

## Built-in Voltage: Einstein Relation and Carrier Distribution

- ▶ From the Einstein relation, the drift-diffusion equations become:

$$j_n = q\mu_n \left( n\mathcal{E} + \frac{kT}{q} \frac{dn}{dx} \right) \quad (3.5)$$

$$j_p = q\mu_p \left( p\mathcal{E} - \frac{kT}{q} \frac{dp}{dx} \right) \quad (3.6)$$

- ▶ At equilibrium ( $j_p = 0$ ), using integration of the expression inside the bracket gives:

$$p(x) = p(x_p) e^{-\frac{qV(x)}{kT}} \quad (3.7)$$

- ▶ With  $V(x) = -\int_{x_p}^x \mathcal{E}(x') dx'$

- ▶ Similarly for electrons:

$$n(x) = n(x_n) e^{\frac{qV(x)}{kT}} \quad (3.8)$$

- ▶ These distributions are referred to as the **Boltzmann distribution** under equilibrium.

## Derivation of Built-in Potential $V_{bi}$

- ▶ Carrier product at any point:

$$n \cdot p = n_i^2 \quad (3.9)$$

- ▶ Built-in potential is given by:

$$V_{bi} = V(x_n) = \frac{kT}{q} \ln \left( \frac{p(x_p)}{p(x_n)} \right) = \frac{kT}{q} \ln \left( \frac{p(x_p) \cdot n(x_n)}{n_i^2} \right) \quad (3.10)$$

- ▶ Assuming complete ionization at boundaries:

$$V_{bi} \cong \frac{kT}{q} \ln \left( \frac{N_A(x_p) \cdot N_D(x_n)}{n_i^2} \right) \quad (3.11)$$

- ▶ This shows that  $V_{bi}$  depends only on the doping levels and intrinsic carrier concentration.
- ▶ Important for setting the electrostatic barrier preventing further diffusion across the junction.

# Key Insights from Built-in Potential Derivation

## ▶ 1. Drift-Diffusion Balance at Equilibrium

- ▶ Currents consist of drift + diffusion components.
- ▶ At equilibrium:  $j_n = j_p = 0 \Rightarrow$  drift current = - diffusion current.

## ▶ 2. Carrier Densities Follow Boltzmann Distributions

- ▶  $p(x) = p(x_p)e^{-\frac{qV(x)}{kT}}$ ,  $n(x) = n(x_n)e^{\frac{qV(x)}{kT}}$
- ▶ Potential  $V(x)$  governs spatial variation in carrier concentration.

## ▶ 3. Mass Action Law Holds: $n(x) \cdot p(x) = n_i^2$ everywhere in depletion region

## ▶ 4. Built-in Voltage Expression:

$$V_{bi} = \frac{kT}{q} \ln \left( \frac{N_A(x_p) \cdot N_D(x_n)}{n_i^2} \right) \quad (3.12)$$

- ▶ Depends only on doping densities and intrinsic carrier concentration.
- ▶ Sets up internal electrostatic barrier to prevent further diffusion.

## ▶ 5. Interpretation:

- ▶ Defines equilibrium energy band bending and barrier height.
- ▶ Logarithmic dependence allows efficient doping control of  $V_{bi}$ .

## Biasing of p-n junctions

All discussions in the previous slides were based on the assumption of thermal equilibrium and no external fields.

The behavior of a p-n junction can be controlled by applying an external voltage across the junction.

**Biasing** refers to the application of an external voltage across a p-n junction to control its operation. The two main types of biasing are:

► **Forward Bias:** Positive voltage applied to the p-side and negative voltage to the n-side.



Fig. 3.5: Forward bias of a p-n junction.

► **Reverse Bias:** Positive voltage applied to the n-side and negative voltage to the p-side.



Fig. 3.6: Reverse bias of a p-n junction.

## Reverse bias in a $p$ - $n$ Junction

**Key Concept:** Reverse bias widens the depletion region and blocks majority carrier flow.

- ▶ **Biasing:** Negative terminal to  $p$ -side, positive to  $n$ -side (Fig. 3.6).
- ▶ **Effect:** Drives majority carriers (holes in  $p$ , electrons in  $n$ ) away from the junction.
- ▶ **Depletion Region:** Widens due to carrier drift, increasing the electric field barrier.
- ▶ **Steady State:** Cannot sustain continuous diffusion without replenishment  $\Rightarrow$  nominally zero current.
- ▶ **Reverse Saturation Current  $I_0$ :**
  - ▶ Small current due to minority carriers thermally generated.
  - ▶  $I_0$  increases with temperature, but is *independent* of applied reverse voltage.
- ▶ **Physical Insight:** Potential barrier increases by  $qV \Rightarrow$  blocks majority carriers, but allows minority carriers to flow.
- ▶ **Reverse Bias Breakdown:** If reverse voltage exceeds a critical value, breakdown occurs (Zener or avalanche breakdown).

## Forward bias in a $p$ - $n$ Junction

**Key Concept:** Forward bias lowers the potential barrier and allows majority carrier injection.

- ▶ **Biasing:** Positive terminal to  $p$ -side, negative to  $n$ -side.
- ▶ **Effect:** Lowers the junction barrier height by  $qV$ , aiding carrier diffusion.
- ▶ **Depletion Region:** Narrows, reducing the internal electric field.
- ▶ **Carrier Movement:**
  - ▶ Holes from  $p$  move into  $n$ -side  $\Rightarrow$  *injected minority current*
  - ▶ Electrons from  $n$  move into  $p$ -side  $\Rightarrow$  *minority current in opposite direction*
- ▶ **Current Flow:** Resultant current = sum of hole and electron minority currents.
- ▶ **Diode Equation:**  $I = I_0 (e^{qV/kT} - 1)$  (derived later)

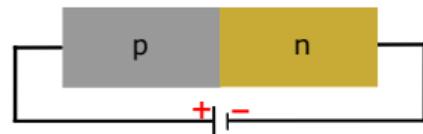


Fig. 3.7: Forward bias of a  $p$ - $n$  junction.

# Ohmic Contacts in p-n Junctions

**Definition:** *Ohmic contacts* are special metal-semiconductor interfaces engineered to allow current to flow freely in both directions, without rectification behavior.

## Key Assumptions:

- ▶ In practical  $p$ - $n$  diodes, external bias is applied via metal contacts to both the  $p$  and  $n$  regions.
- ▶ These contacts create metal-semiconductor junctions — which, in general, could have their own contact potential.
- ▶ **Ohmic contacts** are designed to ensure:
  - ▶ Contact potential remains **constant**, irrespective of current direction or magnitude.
  - ▶ There is **no barrier to carrier flow** at the metal-semiconductor interface.

# Ohmic Contacts in p-n Junctions cont..

## Physical Insight: Justification of Bias Assumption:

- ▶ Because the ohmic contacts are nonrectifying and the voltage drop across the bulk crystal is negligible,
- ▶  $\Rightarrow$  **Entire external bias appears across the p-n junction barrier.**
- ▶ This simplifies analysis: bias voltage directly modifies the potential barrier height.

## Conclusion:

- ▶ Ohmic contacts are **essential** for accurate modeling of diode behavior under applied bias.
- ▶ They ensure that changes in applied voltage affect only the junction, not the metal-semiconductor interfaces.

# Short-Circuited and Open-Circuited p-n Junction

**Physical Insight:** The behavior of a  $p$ - $n$  junction under short-circuit ( $V = 0$ ) or open-circuit conditions ( $I = 0$ ) reveals fundamental principles of equilibrium electrostatics and energy conservation.

## Key Points:

- ▶ When  $V = 0$  is applied across the  $p$ - $n$  diode (Fig. 3.7 or Fig. 3.6), the junction is **short-circuited**.
- ▶ Under thermal equilibrium, this implies:
  - ▶ Net current  $I = 0$
  - ▶ Junction potential  $V_0$  remains unchanged.
- ▶ **Energy conservation argument:**
  - ▶ If current  $I \neq 0$ , metal wire heats up.
  - ▶ No external energy source exists, so energy must come from  $p$ - $n$  bar  $\Rightarrow$  thermal cooling of bar.
  - ▶ **Contradiction:** Can't have metal heating and bar cooling simultaneously in equilibrium.
  - ▶ **Conclusion:**  $I = 0$

# Short-Circuited and Open-Circuited p-n Junction

## ▶ Voltage Loop Consistency:

- ▶ Total voltage drop across closed loop must be zero.
- ▶  $V_0$  is exactly compensated by contact potentials at ohmic contacts.
- ▶ Even if wire is cut, voltage drop remains zero.

▶ **Implication:**  $V_0$  cannot be measured directly by a voltmeter.

**Conclusion:** *Built-in potential  $V_0$  exists, but is internally balanced by metal-semiconductor junctions; it is not externally measurable.*

# The current components in a $p$ - $n$ Junction

## Key Idea: Minority carrier injection under forward bias

- ▶ When a forward voltage  $V$  is applied:
  - ▶ Holes are injected from  $p$  to  $n$  region.
  - ▶ Electrons are injected from  $n$  to  $p$  region.

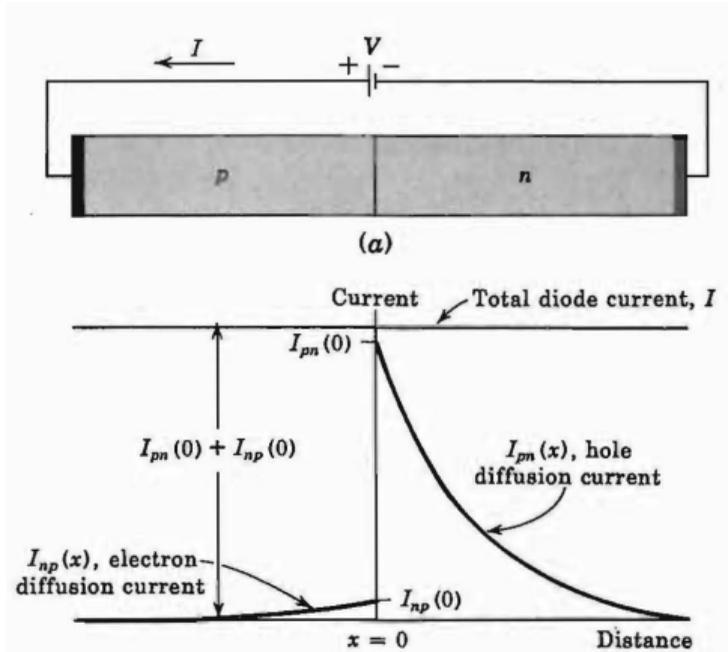


Fig. 3.8: The hole- and electron-current diffusion components vs. distance in a  $p$ - $n$  junction diode; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

## Minority Currents in a $p$ - $n$ Junction

- ▶ Minority carrier current in  $n$ -type region:

$$I_{pn}(0) = \frac{AqD_p}{L_p} [p_n(0) - p_{n0}] \quad (3.13)$$

where:

- ▶  $D_p$  = hole diffusion coefficient
  - ▶  $L_p$  = hole diffusion length
  - ▶  $p_n(0)$  = hole concentration at  $x = 0$
  - ▶  $p_{n0}$  = equilibrium minority hole concentration
- ▶ From law of the junction:

$$p_n(0) = p_{n0} e^{\frac{V}{V_T}} \quad (3.14)$$

## Minority Currents in a $p$ - $n$ Junction

- ▶ Substituting Eq. 3.14 into Eq. 3.13 gives:

$$I_{pn}(0) = \frac{AqD_p p_{n0}}{L_p} \left( e^{\frac{V}{V_T}} - 1 \right) \quad (3.15)$$

- ▶ Similarly for electron diffusion:

$$I_{np}(0) = \frac{AqD_n n_{p0}}{L_n} \left( e^{\frac{V}{V_T}} - 1 \right) \quad (3.16)$$

- ▶ **Total diode current:**

$$I = I_0 \left( e^{\frac{V}{V_T}} - 1 \right) \quad (3.17)$$

where:

$$I_0 = \frac{Aq}{L_p} D_p p_{n0} + \frac{Aq}{L_n} D_n n_{p0}$$

- ▶  $I_0$  is the reverse saturation current.

# Majority Carrier Currents and Total Current Distribution

## Current Continuity and Carrier Profile:

- ▶ Under forward bias, minority carrier current varies with  $x$ :
  - ▶  $I_{pn}(x)$  (hole current) decreases exponentially in  $n$ -region.
  - ▶  $I_{np}(x)$  (electron current) decreases exponentially in  $p$ -region.

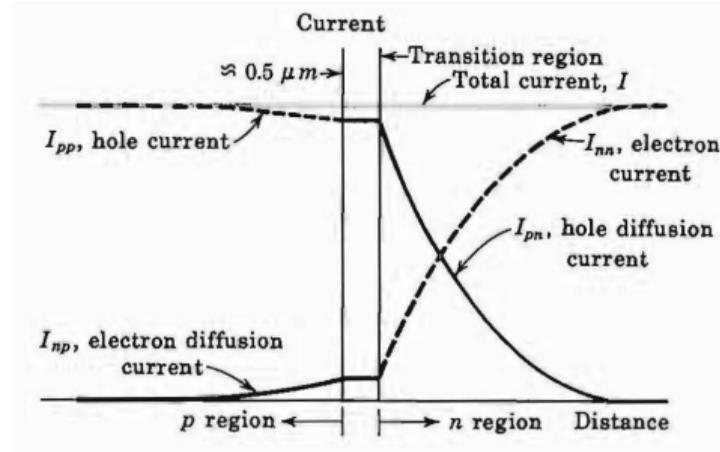


Fig. 3.9: The minority (solid) and the majority (dashed) currents vs. distance in a p-n diode. It is assumed that no recombination takes place in the very narrow depletion region.; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

# Majority Carrier Currents and Total Current Distribution

- ▶ **To maintain constant total current  $I$  across the junction:**

$$I_{nn}(x) = I - I_{pn}(x), \quad I_{pp}(x) = I - I_{np}(x) \quad (3.18)$$

where:

- ▶  $I_{nn}(x)$  is majority (electron) current in  $n$  region
- ▶  $I_{pp}(x)$  is majority (hole) current in  $p$  region
- ▶ **Total current is bipolar in nature:**
  - ▶ Composed of hole and electron contributions
  - ▶ Varies spatially due to recombination
- ▶ Transition region assumed to have negligible recombination width (valid for Si)

# Volt-Ampere Characteristic of a $p-n$ Diode

## General Current Equation:

$$I = I_0 \left( e^{\frac{V}{\eta V_T}} - 1 \right) \quad (3.19)$$

- ▶  $I_0$  = reverse saturation current
- ▶  $V$  = applied voltage
- ▶  $V_T = \frac{kT}{q}$  = thermal voltage ( $\approx 26$  mV at 300 K)
- ▶  $\eta$  = ideality factor ( $\approx 1$  for Ge,  $\approx 2$  for Si)

## Interpretation:

- ▶ For  $V \gg V_T$ : exponential current rise (forward bias)
- ▶ For  $V < 0$ :  $I \approx -I_0$  (reverse saturation current)

# Reverse Saturation Current and Breakdown Behavior

## ▶ Reverse Saturation Current ( $I_0$ ):

- ▶ For reverse bias  $V < 0$ , diode current saturates to  $I = -I_0$ .
- ▶  $I_0$  is weakly dependent on reverse voltage.
- ▶ Caused by thermally generated minority carriers.
- ▶ Germanium diodes have  $I_0 \sim 1000\times$  larger than silicon.

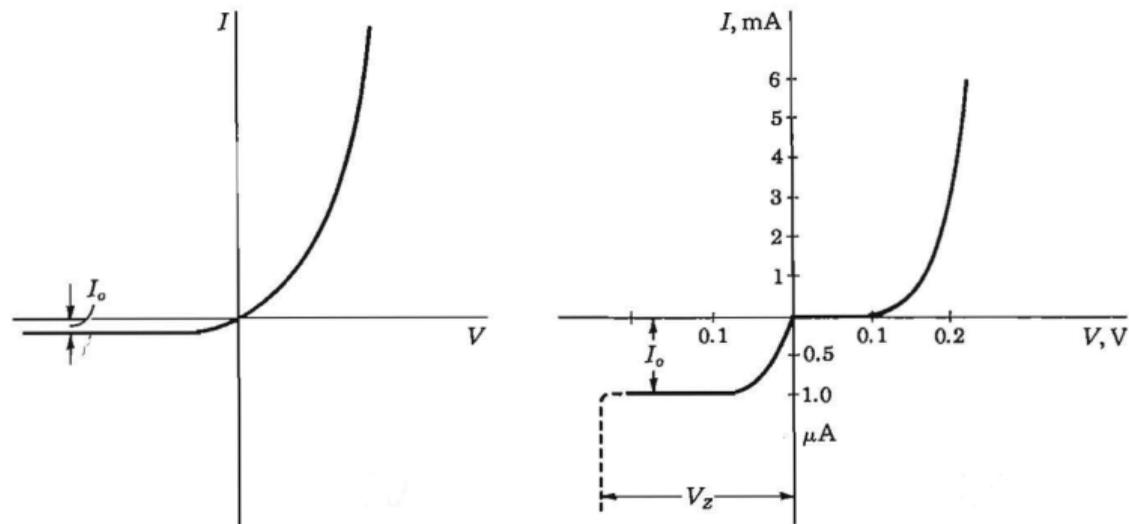


Fig. 3.10: The volt-ampere characteristic of an ideal p-n diode and the volt-ampere characteristic for a germanium; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

# Reverse Saturation Current and Breakdown Behavior

## ► Breakdown Region:

- At a reverse voltage  $V_Z$ , breakdown occurs  $\Rightarrow$  sudden increase in  $I$ .
- Caused by impact ionization or Zener effect.
- Fig. 3-6b illustrates abrupt transition at  $V_Z$ .

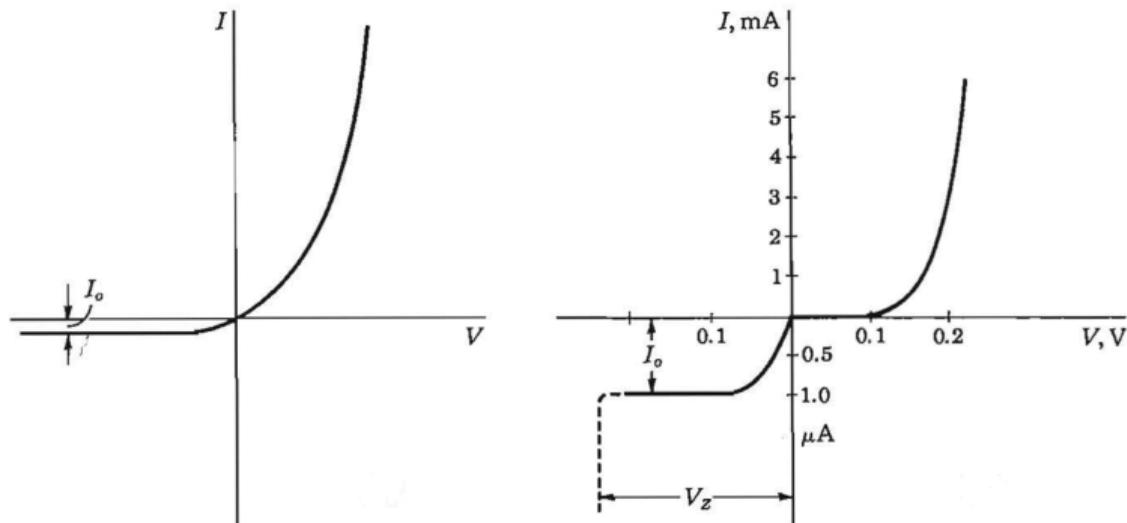


Fig. 3.11: The volt-ampere characteristic of an ideal p-n diode and the volt-ampere characteristic for a germanium; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

# Cut-in Voltage and Material Comparison

## ► Cut-in / Threshold Voltage ( $V_\gamma$ ):

- Minimum forward bias for noticeable current.
- Typically  $V_\gamma \approx 0.2 \text{ V}$  (Ge),  $\approx 0.6 \text{ V}$  (Si).
- Beyond  $V_\gamma$ , current increases rapidly  $\Rightarrow$  exponential growth.

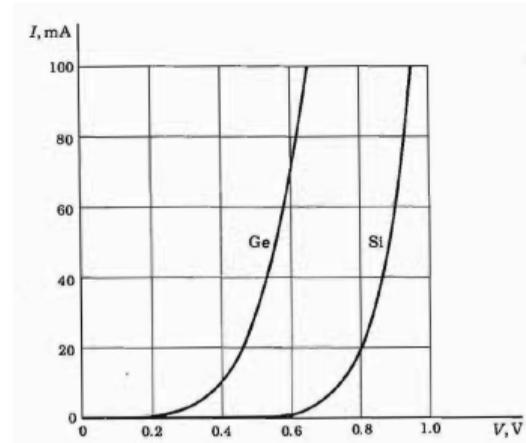


Fig. 3.12: Forward VI characteristics of Si and Ge; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

# Cut-in Voltage and Material Comparison

## ► Material Differences:

- Ge diodes: Lower  $V_\gamma$ , larger  $I_0$ , steeper characteristics.
- Si diodes: Higher  $V_\gamma$ , lower  $I_0$ , more thermal stability.

- **Fig. 3.13:** Comparative  $I$ - $V$  of 1N270 (Ge) vs 1N3605 (Si).

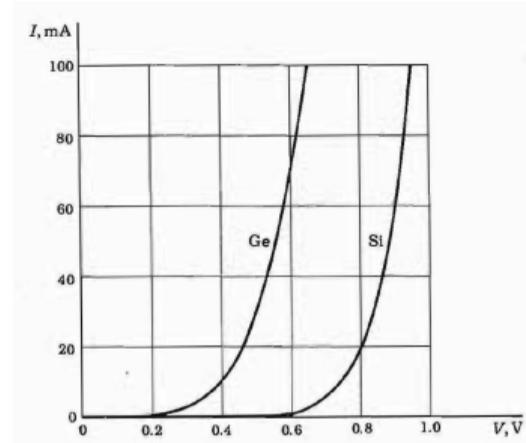


Fig. 3.13: Forward VI characteristics of Si and Ge; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

# Temperature Dependence and $I_0$

- ▶  $I_0$  increases with temperature:
  - ▶  $I_0(T) = I_{01} \times 2^{(T-T_1)/10}$
  - ▶  $\Rightarrow$  doubles for every  $10^\circ\text{C}$  rise.
- ▶ **Thermal Impact:**
  - ▶  $V_T = \frac{T}{11600} \text{ V}$
  - ▶ At room temp ( $300\text{K}$ ),  $V_T = 26 \text{ mV}$
  - ▶  $\left| \frac{dV}{dT} \right| \approx 2.5 \text{ mV}/^\circ\text{C}$
- ▶ Fig. 3.14 shows  $I$ - $V$  shifts with temperature: Higher  $T \Rightarrow$  lower  $V_\gamma$

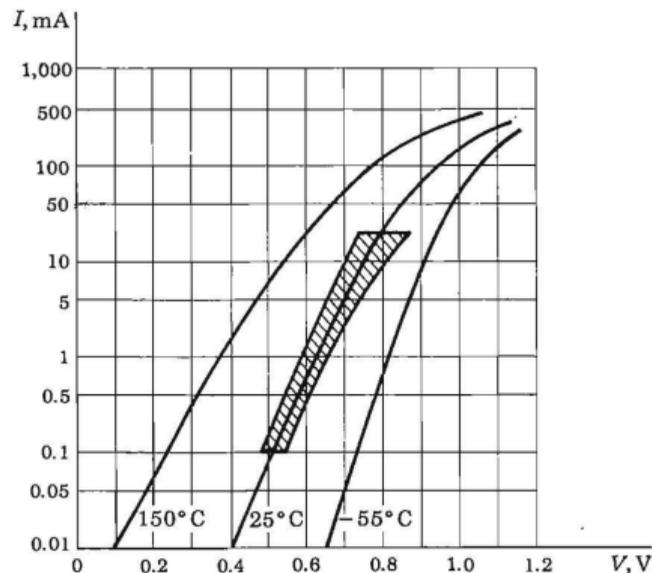


Fig. 3.14: VI characteristics at three different temperatures for a silicon diode; adapted from Millman, J., & Halkias, C. C. Integrated Electronics: Analog and Digital Circuits and Systems.

# Diode Resistance and Piecewise Linear Model

▶ **Static Resistance:**  $R = V/I$  — not reliable.

▶ **Dynamic Resistance:**

$$r = \frac{\eta V_T}{I}$$

▶ **Dynamic Conductance:**

$$g = \frac{1}{r} = \frac{I + I_0}{\eta V_T}$$

▶ **Piecewise Linear Model:**

▶ Diode  $\sim$  open circuit if  $V < V_\gamma$

▶ For  $V > V_\gamma$ :  $r = dV/dI$  constant  $\Rightarrow R_f$

▶ Fig. 3.11: Diode modeled with  $V_\gamma$  and slope  $1/R_f$

## Transition Capacitance ( $C_T$ )

- ▶ Under reverse bias, depletion region widens  $\Rightarrow$  increase in uncovered charge.
- ▶ Defined as:

$$C_T = \left| \frac{dQ}{dV} \right|$$

- ▶ **Corresponding Current:**

$$i = C_T \frac{dV}{dt}$$

- ▶  $C_T$  is voltage dependent, unlike a linear capacitor.
- ▶ Important in high-frequency and switching circuits.

# Diffusion Capacitance: Concept and Static Derivation

## ▶ When forward biased:

- ▶ Excess charge is injected into the neutral region.
- ▶ Results in large capacitance — called **diffusion capacitance**,  $C_D$ .

## ▶ Definition:

$$C_D = \left. \frac{dQ}{dV} \right|_{\text{forward bias}} \quad (\text{rate of change of stored charge w.r.t. voltage})$$

## ▶ Using:

$$C_D = \tau \frac{dI}{dV} = \tau g = \frac{\tau}{r} \quad (3-27)$$

$$\Rightarrow C_D = \frac{\tau I}{\eta V_T} \quad (3-28)$$

## ▶ Here:

- ▶  $\tau$  = carrier lifetime (mean time minority carrier remains mobile)
- ▶  $I$  = diode current (assumed due to holes)
- ▶  $\eta$  = ideality factor ( $\approx 1$  for Ge,  $\approx 2$  for Si)
- ▶  $V_T = \frac{kT}{q}$  = thermal voltage

# Dynamic Diffusion Capacitance: Arbitrary and Sinusoidal Inputs

► **Implication:**  $C_D \propto I$  (linearly dependent on current)

► **Time constant:**

$$rC_D = \tau \quad (3-29)$$

where  $r = \eta V_T / I$  is the diode dynamic resistance.

► **In general:**

$$i = \frac{dQ'}{dt} = C'_D \frac{dV}{dt} \quad (3-30)$$

►  $C'_D < C_D$  when input varies rapidly.

► **Dynamic capacitance:**

$$i \neq \frac{dQ}{dt}, \quad i \neq C_D \frac{dV}{dt} \quad (3-31)$$

since  $Q'$  accounts only for instantaneously injected charge, not steady-state.

# Dynamic Diffusion Capacitance: Arbitrary and Sinusoidal Inputs

## ► For sinusoidal voltage input:

- Low frequency ( $\omega\tau \ll 1$ ):

$$C'_D = \frac{1}{2}\tau g \quad (3-32)$$

- High frequency ( $\omega\tau \gg 1$ ):

$$C'_D = \left(\frac{\tau}{2\omega}\right)^{1/2} g \quad (3-33)$$

- $g = dI/dV =$  diode conductance

## ► Key Insight:

- $C'_D$  is frequency-dependent.
- Decreases as frequency increases.
- Must solve continuity equations to fully describe  $C'_D(x, t)$  under general conditions.

# Table of contents

- 4 Introduction to Power Semiconductor Devices
  - Power diodes
  - Power bipolar junction transistor (BJT)

# Introduction to power semiconductor devices

Dr Bikash Sah



# Normal vs Power Semiconductor Devices: Key Differences

## 1. Physical Design:

- ▶ **Normal Devices:** Small device areas, thin active regions for fast operation.
- ▶ **Power Devices:** Large device areas, thick drift regions to support high voltages; trade-off between speed and ruggedness.

## 2. Key Parameters:

- ▶ **Normal Devices:** Optimize *speed, gain, integration density*.
- ▶ **Power Devices:** Optimize *breakdown voltage, on-resistance, thermal management*.

## 3. Material and Fabrication:

- ▶ **Normal Devices:** Primarily Silicon (Si).
- ▶ **Power Devices:** Silicon (Si), but also wide bandgap materials like Silicon Carbide (SiC) and Gallium Nitride (GaN) for superior performance.

## 4. Examples:

- ▶ **Normal Devices:** CMOS transistors, Bipolar Junction Transistors (BJTs).
- ▶ **Power Devices:** MOSFETs, IGBTs, Diodes (Schottky, PIN), SiC MOSFETs, GaN HEMTs.

# Conceptual idea of a power semiconductor devices physics

## 1. Charge Carriers:

- ▶ Power devices rely on the transport of **electrons** and **holes**.
- ▶ Key mechanisms: **drift** (due to electric fields) and **diffusion** (due to concentration gradients).

## 2. Energy Bands and Junctions:

- ▶ Junctions (e.g., p-n junctions, Schottky barriers) control carrier flow.
- ▶ Band bending creates potential barriers essential for device blocking and switching behavior.

## 3. Electric Field Distribution:

- ▶ High electric fields are engineered to manage breakdown and switching.
- ▶ **Critical electric field** ( $E_{crit}$ ) defines breakdown limits.

# Conceptual idea of a power semiconductor devices physics cond..

## 4. Key Physical Processes:

- ▶ **Avalanche Multiplication:** Carrier generation at high fields.
- ▶ **Recombination-Generation:** Determines carrier lifetimes.
- ▶ **Tunneling:** Important in very high field conditions (Zener breakdown).

## 5. Device Performance Metrics:

- ▶ **Blocking Voltage:** Ability to withstand high reverse voltages.
- ▶ **On-State Resistance:** Determines conduction losses.
- ▶ **Switching Speed:** Influenced by carrier lifetimes and device capacitances.

## Summary:

*Power semiconductor devices are engineered by carefully controlling material properties, doping profiles, junction designs, and carrier dynamics to optimize switching behavior, conduction losses, and voltage handling capabilities.*

# Classification of types of power semiconductor devices

## Based on number of terminals:

### ▶ Two-terminal devices:

- ▶ Diodes (e.g., Schottky, Zener, and standard rectifier diodes).

### ▶ Three-terminal devices:

- ▶ Insulated Gate Bipolar Transistor (IGBT).
- ▶ Thyristors (SCRs).

### ▶ Four-terminal devices:

- ▶ IGBT with Kelvin connection.
- ▶ Cascode structures (e.g., GaN HEMT with a low-voltage MOSFET).

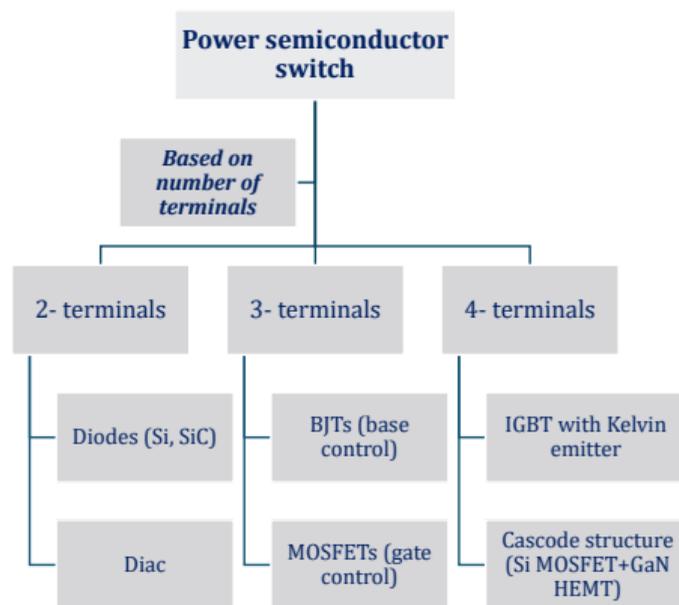


Fig. 4.1: Classification of power semiconductor devices based on number of terminals.

# Classification of types of power semiconductor devices

## Based on number of layer/junctions:

### ▶ **Two-layer devices:**

- ▶ Diodes (e.g., Schottky, Zener, and standard rectifier diodes).

### ▶ **Three-layers devices:**

- ▶ BJTs.
- ▶ MOSFETs.

### ▶ **Four-layers devices:**

- ▶ GTOs
- ▶ SCRs.

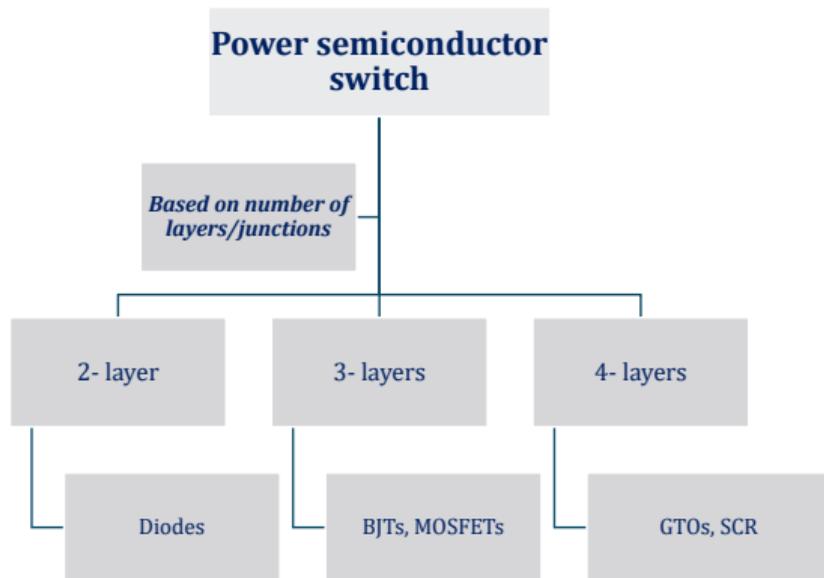


Fig. 4.2: Classification of power semiconductor devices based on number of layers.

# Classification of types of power semiconductor devices

## Based on controllability:

### ► Uncontrolled:

- Diodes (e.g., Schottky, Zener, and standard rectifier diodes).

### ► Semicontrolled:

- SCRs.

### ► Fully controlled:

- BJTs.
- MOSFETs.

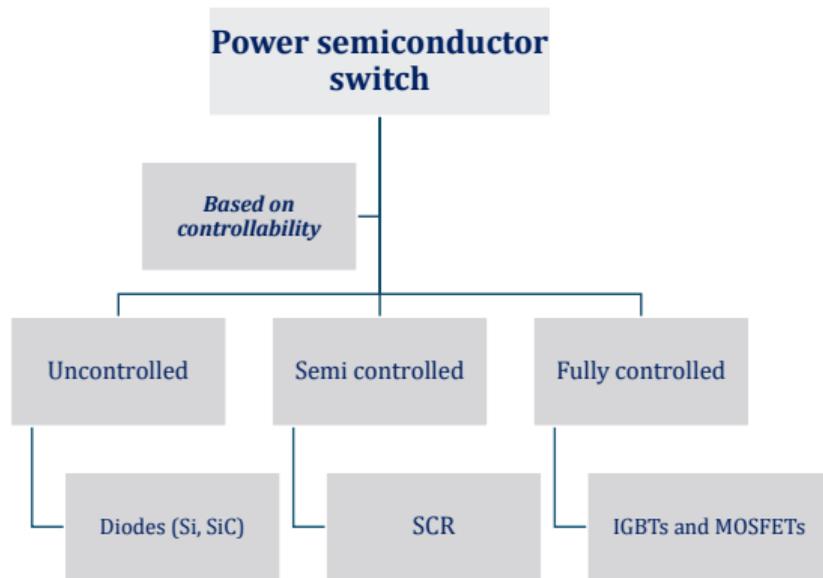


Fig. 4.3: Classification of power semiconductor devices based on controllability.

# Classification of types of power semiconductor devices

## Based on quadrant of operation:

### ▶ Single quadrant:

- ▶ Diodes (e.g., Schottky, Zener, and standard rectifier diodes).

### ▶ Two quadrant:

- ▶ Current bidirectional devices (e.g., MOSFETs).
- ▶ Voltage bidirectional devices (e.g., MOSFET with a series diodes).

### ▶ Four quadrant:

- ▶ By combination of two or more devices (e.g., using IGBTs and MOSFETs).
- ▶ MOSFETs.

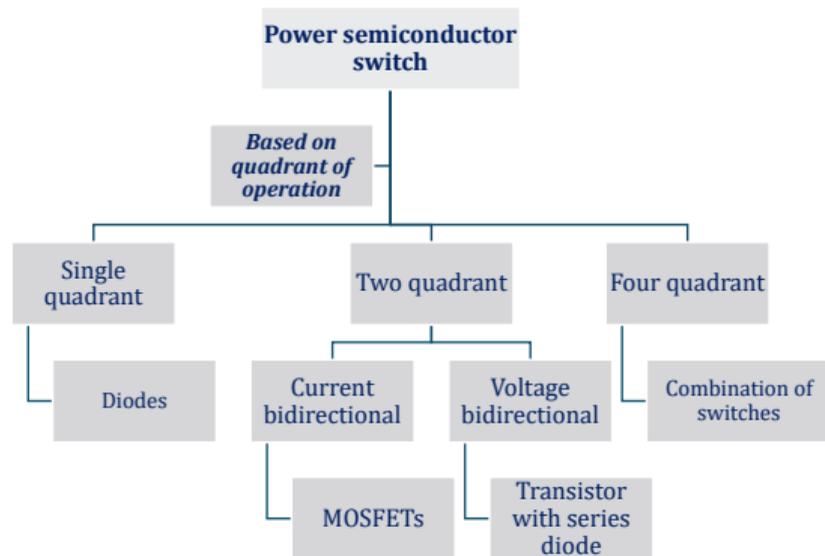


Fig. 4.4: Classification of power semiconductor devices based on quadrant of operation.

# Power Diodes

## 1. Definition:

*A power diode is a semiconductor device that allows current to flow in one direction while blocking it in the opposite direction. It is designed to handle high voltages and currents, making it suitable for power applications.*

## 2. Key Characteristics:

- ▶ **Forward Voltage Drop ( $V_f$ ):** The voltage drop across the diode when it is conducting.
- ▶ **Reverse Breakdown Voltage ( $V_{BR}$ ):** The maximum reverse voltage the diode can withstand before breakdown occurs.
- ▶ **Reverse Recovery Time ( $t_{rr}$ ):** The time taken for the diode to switch from conducting to blocking state.

## 3. Types of Power Diodes:

- ▶ **Standard Rectifier Diodes:** Used in AC-DC conversion.
- ▶ **Schottky Diodes:** Low forward voltage drop and fast switching; used in high-frequency applications.
- ▶ **Zener Diodes:** Used for voltage regulation and protection against overvoltage conditions.

# Power Diodes- basic structure

## ► Basic Structure:

- Inclusion of a lightly doped  $n^-$  drift region.
  - the lightly doped  $n^-$  layer (drift region) allows the depletion region to expand widely under reverse bias.
  - Allows the diode to have high voltage blocking capability
- Thick epitaxial layer and high current capacity.
  - Epitaxial growth and cross-sectional area are tailored to high current rating.
  - Larger devices use 4-inch wafers.

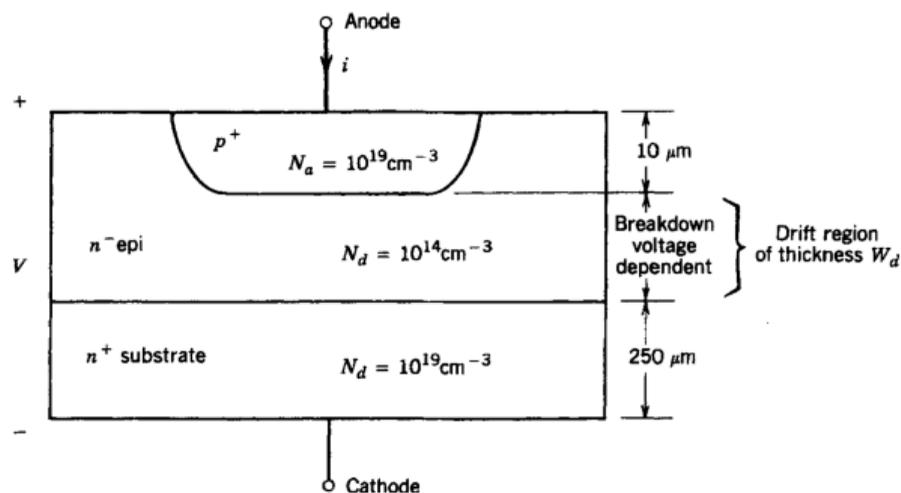


Fig. 4.5: Cross section of pn junction diode; adapted from Mohan, Undeland, Robbins, "Power Electronics: Converters, Applications and Design - 2nd Edition".

# Power Diodes- Static characteristics

## ▶ Linear forward conduction:

- ▶ high forward current flows through the lightly doped drift region, introducing significant series resistance  $R_{on}$ .
- ▶ The characteristic is linear rather than exponential beyond  $\approx 1V$ .

## ▶ Reverse bias and avalanche breakdown:

- ▶ Under reverse bias, a small leakage current flows until the breakdown voltage  $BV_{BD}$  is reached.
- ▶ Beyond  $BV_{BD}$  avalanche multiplication causes current to rise rapidly while the voltage remains approximately constant.

## ▶ Breakdown operation must be avoided!.

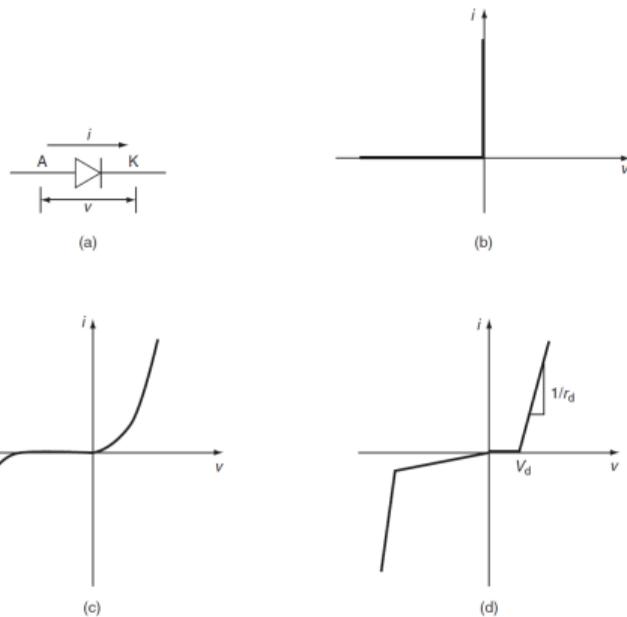
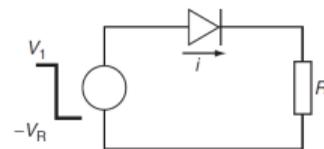


Fig. 4.6: (a) symbol of diode, (b) ideal VI characteristics, (c) VI characteristics of a practical diode (d) piece wise linear model; adapted from Umanand, L., Power Electronics: Essentials & Applications.

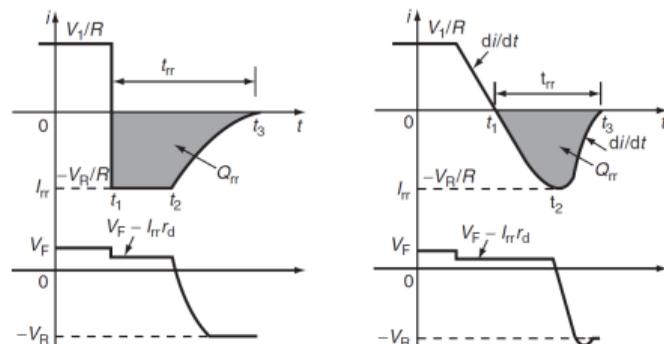
# Power Diodes- Dynamic characteristics

## Turn-OFF of Diode:

- ▶ When a forward-biased diode is suddenly reverse biased, excess carriers in the diffusion region (space-charge region) must be removed.
- ▶ The diode voltage remains in the ON-state initially due to stored charge.
- ▶ Reverse current flows until charges are removed at time  $t_2$ , after which the junction becomes reverse biased.
- ▶ The time interval from  $t_1$  to  $t_2$  is termed **storage time**, and  $t_{rr}$  (total duration of reverse recovery) is crucial for switching applications.



(a)



(b)

(c)

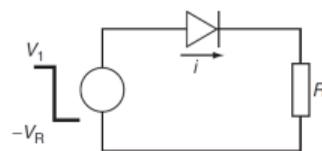
Fig. 4.7: (a) test circuit- turn-off, (b) ideal dynamic characteristics, (c) practical diode dynamic characteristics-turn-off; adapted from Umanand, L., Power Electronics: Essentials & Applications.

# Power Diodes- Dynamic characteristics

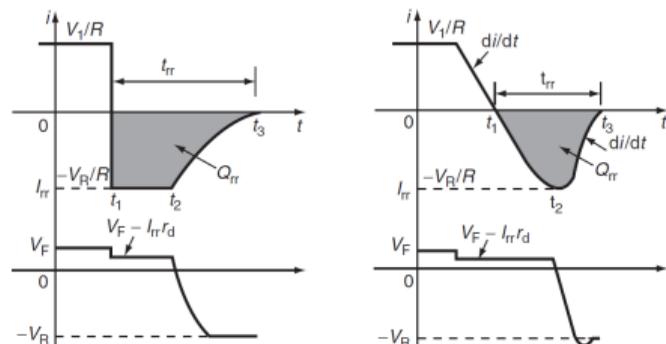
## Turn-ON of Diode:

- ▶ If a diode under reverse bias is forward biased, the transition requires a time known as **turn-ON time** or **forward recovery time**.
- ▶ Charges redistribute from to establish steady-state conduction.
- ▶ This process is generally faster than charge removal during turn-OFF, hence  $t_{ON} < t_{OFF}$ .

*Note: In practical circuits, reverse recovery can be slowed by parasitic inductance.*



(a)



(b)

(c)

Fig. 4.8: (a) test circuit- turn-off, (b) ideal dynamic characteristics, (c) practical diode dynamic characteristics-turn-off; adapted from Umanand, L., Power Electronics: Essentials & Applications.

# Classification and Parameters of Power Diodes

## Diode Classifications

- ▶ Classification is based on reverse recovery time  $t_{rr}$ , indicating how quickly a diode can switch off.
- ▶ **Types of Diodes:**
  - ① **Rectifier Diodes:**  $t_{rr}$  in the microsecond range.
  - ② **Fast Recovery Diodes:**  $t_{rr}$  between 200–500 ns.
  - ③ **Ultra-Fast Recovery Diodes:**  $t_{rr} \sim 30\text{--}200$  ns.
  - ④ **Schottky Diodes:** Metal-semiconductor junction,  $t_{rr} < 30$  ns.
- ▶ For high-frequency applications (e.g. SMPS, converters), use types 2–4 based on frequency and voltage ratings.

## Applications:

- ▶ Type 1 is suitable for low-frequency mains rectification.
- ▶ Types 2–4 used in fast-switching converters.

# Datasheet Parameters for Diode Selection

## Key Diode Parameters:

- ① Average forward current,  $I_{Fav}$
- ② RMS forward current,  $I_{Frms}$
- ③ Peak forward current,  $I_F$
- ④ Surge current,  $I_{FSM}$
- ⑤ Breakdown or reverse voltage,  $V_{RRM}$
- ⑥ Forward voltage drop,  $V_F$
- ⑦ Dynamic resistance,  $r_d$
- ⑧ Reverse recovery time,  $t_{rr}$
- ⑨ Thermal endurance:  $I^2t$  rating

## Important Notes:

- ▶ For sinusoidal operation,  $I_{Fav}$ ,  $I_{Frms}$ ,  $I_F$  relations are well-known.
- ▶ For non-sinusoidal waveforms, these values must be derived from fundamentals.
- ▶ Choose diode ratings higher than the worst-case circuit values.

# Surge Current

## Surge Current:

- ▶ Diodes can handle overload currents briefly without damage.
- ▶ Key datasheet specs:  $I_{FSM}$  (max peak half-cycle non-repetitive current) and  $I^2t$  (energy dissipation).
- ▶ Surge current often arises when rectifier filters switch on with high peak voltages.
- ▶ Limiting devices (e.g., series resistors or fuses) ensure surge stays below  $I^2t$  limit.

# Thermal Viewpoint of Diodes

## Thermal Viewpoint:

▶ Total power loss:  $P_d = P_{\text{on}} + P_{\text{off}} + P_{\text{switching}}$

▶ **On-state loss:**

$$P_{\text{on}} = \frac{1}{T} \int_0^T v(t)i(t) dt \approx (V_d \times I_{\text{avg}}) + (I_{\text{rms}}^2 \times r_d) \quad (4.1)$$

▶ **Switching loss:**

$$P_{\text{switching}} = E_{\text{switching}} \cdot f_s = \left( \frac{1}{2} Q_{rr} V_R \right) f_s \quad (4.2)$$

▶ Reverse recovery charge:

$$Q_{rr} = \frac{1}{2} t_{rr} I_{rr} \Rightarrow P_{\text{switching}} = \frac{1}{4} I_{rr} V_R t_{rr} f_s \quad (4.3)$$

▶ Junction temperature must remain below datasheet limit (e.g., 150°C).

# Modeling a Power Diode: Steady-State and Transient Behavior

**Objective:** To model both static and dynamic characteristics of a diode for simulation and design purposes.

## ► Steady-State Behavior:

- Current-voltage ( $i_d$ - $V_d$ ) relationship is exponential:

$$i_d = I_0 \left( e^{\frac{V_d}{nV_T}} - 1 \right)$$

- $R_s$ : Series resistance due to bulk and contact resistance (non-zero in practice).

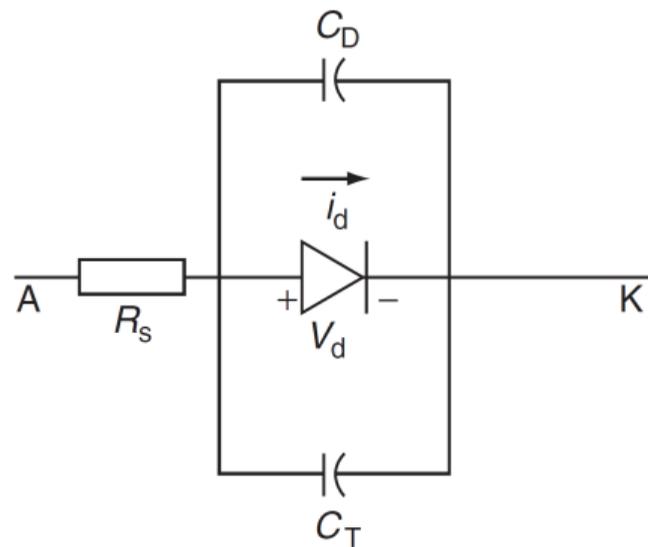


Fig. 4.9: Model of diode; adapted from Umanand, L., Power Electronics: Essentials & Applications.

# Modeling a Power Diode: Steady-State and Transient Behavior

## ► Dynamic Behavior:

### ► Diffusion Capacitance ( $C_D$ ):

- Appears during transition from forward to reverse bias.
- Models the excess mobile charge that must be removed.

### ► Transition Capacitance ( $C_T$ ):

- Relevant when transitioning from reverse to forward bias.
- Models mobile charge accumulation at the junction.

## ► Capacitance Non-Linearity:

- Both  $C_D$  and  $C_T$  are non-linear and depend on the charge distribution.
- Circuit simulators implement these models dynamically.

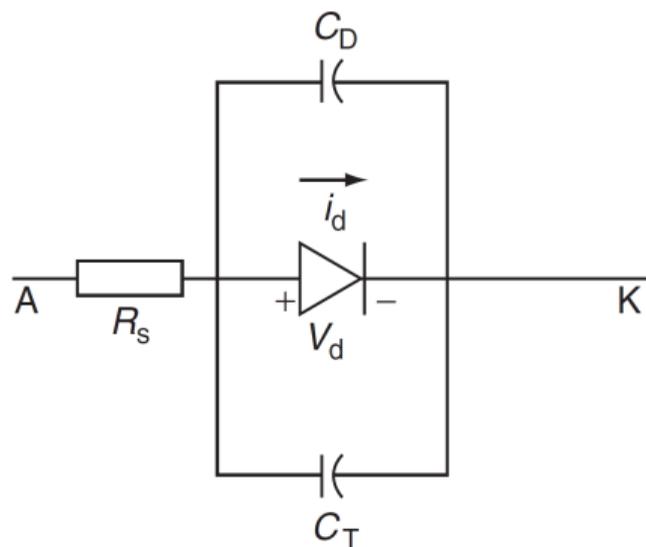


Fig. 4.10: Model of diode; adapted from Umanand, L., Power Electronics: Essentials & Applications.

# Introduction to punch-through vs non-punch-through power diodes

## Differences: Punch through vs non-punch-through:

Characteristic	Punch-through (PT)	Non-punch-through (NPT)
Drift Region	Thinner, moderately doped	Thicker, lightly doped
Electric Field Profile	Extends through drift region (reaches anode)	Ends before reaching the anode
Breakdown Mechanism	Abrupt avalanche breakdown	Gradual breakdown onset
Switching Speed	Faster reverse recovery	Slower but more robust
On-State Voltage Drop	Lower	Slightly higher
Reverse Recovery Loss	Lower	Higher
Application Voltage Range	Medium (e.g., 600–1200 V)	High (e.g., $\geq$ 1200 V)
Example Devices	Transient Voltage Suppression and Schottky barrier diodes	1N400x

**Design Implication:** Choice depends on switching frequency, voltage class, and thermal constraints.

# Avalanche Breakdown in Step Junctions

**Concept:** Reverse bias in a  $p-n$  junction causes the electric field to drop entirely across the depletion region. As the field strength increases, it approaches a critical value  $E_{BD}$  where impact ionization begins  $\Rightarrow$  Avalanche Breakdown.

## Key Definitions:

- ▶ **Breakdown Voltage** ( $BV_{BD}$ ): Reverse-bias voltage at which impact ionization becomes significant.
- ▶ **Critical Field Strength** ( $E_{BD}$ ): Electric field at which avalanche multiplication starts.

## Breakdown Condition:

$$E_{\max} \approx E_{BD} \quad (4.4)$$

## Where:

- ▶  $E_{\max}$ : Maximum electric field in the depletion region.

## Breakdown Voltage Expression for Step Junction

$$BV_{BD} = \phi_c + \left[ \frac{W_0 E_{BD}}{2\varepsilon} \right]^2 - \phi_c \approx \frac{\varepsilon(N_A + N_D)E_{BD}^2}{2qN_A N_D} \quad (4.5)$$

### Parameters:

- ▶  $W_0$ : Depletion width
- ▶  $E_{BD}$ : Breakdown electric field
- ▶  $\varepsilon$ : Permittivity of the semiconductor
- ▶  $N_A, N_D$ : Acceptor and donor concentrations
- ▶  $q$ : Electron charge
- ▶  $\phi_c$ : Contact potential

**Observation:** Breakdown voltage depends strongly on doping concentrations and junction profile (e.g., step, graded, diffused).

# Breakdown Voltage in Non-Punch-Through (NPT) Diodes

## Structure Concept:

- ▶ **Non-punch-through diode:** Drift region thickness  $W_d$  is *greater than* depletion width at breakdown.
- ▶ Depletion region does **not reach** the heavily doped  $n^+$  substrate.

## Simplified Breakdown Voltage Equation:

$$BV_{BD} \approx \frac{\varepsilon E_{BD}^2}{2qN_D} \quad (4.6)$$

- ▶  $E_{BD}$ : Breakdown electric field
- ▶  $N_D$ : Doping concentration of drift region (lightly doped  $n$ )
- ▶  $\varepsilon$ : Permittivity of the semiconductor

# Breakdown Voltage in Non-Punch-Through (NPT) Diodes

Numerical Estimation for Silicon:

$$BV_{BD} \approx \frac{1.3 \times 10^{17}}{N_D} \quad (4.7)$$

(for  $N_D$  in  $\text{cm}^{-3}$ ,  $BV_{BD}$  in volts)

Depletion Width at Breakdown:

$$W_d \approx \frac{2BV_{BD}}{E_{BD}} \approx 10^{-5} BV_{BD} \quad (\text{in cm}) \quad (4.8)$$

Design Implications:

- ▶ High breakdown voltages  $\Rightarrow$  require very **light doping** ( $\sim 10^{14} \text{ cm}^{-3}$ ).
- ▶ Drift region width for 1000 V breakdown  $\approx 100 \mu\text{m}$ .
- ▶ Trade-off between **blocking capability** and **on-resistance**.

# Punch-Through Diode Breakdown Mechanism

**Definition:** Punch-through occurs when the reverse bias extends the depletion region entirely across the lightly doped  $n^-$  drift region up to the heavily doped  $n^+$  region.

- ▶ Reverse bias pushes the depletion edge to contact  $n^+$ , beyond which it cannot grow.
- ▶ The electric field profile changes shape — not triangular anymore.
- ▶ Breakdown voltage is reached when  $E_1 + E_2 = E_{BD}$ .

**Key Point:** The  $n^+$  layer's heavy doping blocks further depletion region growth.

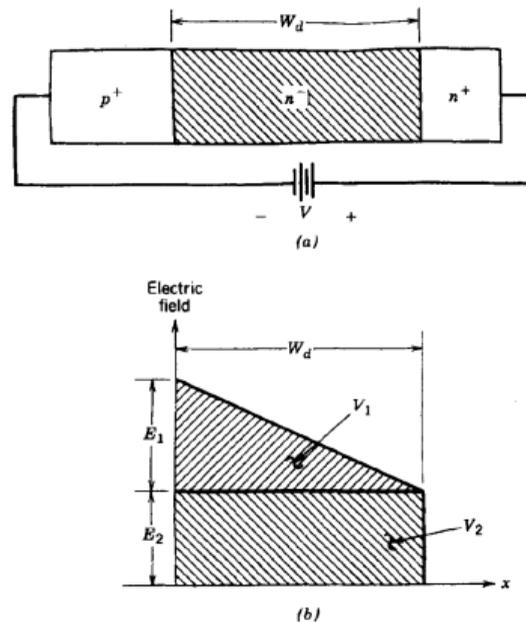


Fig. 4.11: Punch-through diode under reverse bias: (a) Depletion layer extends fully across the drift region (punch-through condition); (b) Electric field profile. Adapted from Mohan et al., *Power Electronics, 2nd Ed.*

# Electric Field & Voltage Profile in Punch-Through Diode

► Electric field profile:

► Triangular portion:  $E_1 = \frac{qN_dW_d}{\epsilon}$

► Rectangular portion:  $E_2$

► Breakdown voltage:

$$V_1 = \frac{qN_dW_d^2}{2\epsilon}, \quad V_2 = E_2W_d \quad (4.9)$$

$$BV_{BD} = V_1 + V_2 = E_{BD}W_d - \frac{qN_dW_d^2}{2\epsilon} \quad (4.10)$$

**Observation:** When  $V_1 \ll V_2$ , then  $BV_{BD} \approx E_{BD}W_d$

# Implications of Punch-Through Design

- ▶ Allows shorter  $W_d$  for same  $BV_{BD}$   $\rightarrow$  compact device.
- ▶ Higher resistivity in drift region increases  $R_{on}$ :
  - ▶ Higher conduction loss compared to non-punch-through.
- ▶ **Important:** No conductivity modulation under on-state — no conductivity injection from minority carriers.
- ▶ Results in higher  $R_{on}$  under on-state condition.

**Conclusion:** Useful for high-speed, high-frequency operation despite higher on-resistance.

# Schottky Diode: Structure and Principle of Operation

## Structure:

- ▶ Formed by placing a metal in contact with an  $n$ -type semiconductor.
- ▶ The metal acts as the anode and the semiconductor as the cathode.
- ▶ Only majority carriers (electrons in  $n$ -type) participate — no hole injection.

## Principle of Operation:

- ▶ Barrier formed due to work function difference.
- ▶ Equilibrium is reached when electron flow from metal to semiconductor balances opposite flow.
- ▶ No minority carriers  $\Rightarrow$  no charge storage  $\Rightarrow$  fast switching.

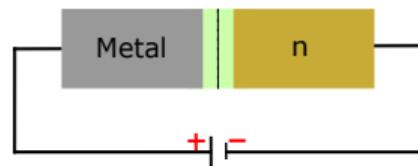


Fig. 4.12: Schottky diode structure and energy band diagram; adapted from Mohan et al., *Power Electronics, 2nd Ed.*

# I-V Characteristics of Schottky Diode

**Equation:**

$$I = I_s \left( e^{\frac{qV}{nkT}} - 1 \right) \quad (4.11)$$

**Key Observations:**

- ▶ Forward drop: 0.3–0.4 V (lower than silicon  $p$ - $n$  junction).
- ▶ High reverse leakage current due to majority-carrier injection.
- ▶ Not suitable beyond 100–200 V breakdown.

**Advantage:** Very fast ON/OFF response due to absence of stored charge.

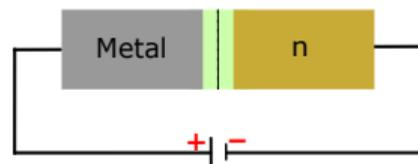


Fig. 4.13: Schottky diode structure and energy band diagram; adapted from Mohan et al., *Power Electronics, 2nd Ed.*

# Ohmic vs Rectifying Contact in Metal–Semiconductor Junctions

## Ohmic Contact:

- ▶ No rectifying behavior; linear I-V characteristics.
- ▶ Occurs when metal work function  $\phi_m < \phi_s$ .
  - ▶ The work function  $\phi$  is the minimum energy needed to remove an electron from the Fermi level to vacuum.
  - ▶  $\phi_m$  = work function of metal
  - ▶  $\phi_s$  = work function (or electron affinity + energy gap position) of the semiconductor
- ▶ Heavy doping or tunneling required to minimize barrier.

## Rectifying (Schottky) Contact:

- ▶ Barrier prevents majority carriers  $\Rightarrow$  diode action.
- ▶ No minority carrier injection  $\Rightarrow$  low switching loss.

# Breakdown Behavior of Schottky Diodes

- ▶ Geometry and electric field crowding limits breakdown voltage.
- ▶ Surface effects and field curvature reduce breakdown to  $\sim 200$  V.
- ▶ No conductivity modulation  $\Rightarrow$  higher drift region resistance.
- ▶ Trade-off: High  $V_{BD} \Rightarrow$  low doping  $\Rightarrow$  high  $R_{on}$ .

**Comparison:**  $p$ - $n$  junction diodes can go to  $\sim 5$  kV due to conductivity modulation.

- ▶ Geometry and electric field crowding limits breakdown voltage.
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**Comparison:**  $p$ - $n$  junction diodes can go to  $\sim 5$  kV due to conductivity modulation.

# Switching Characteristics of Schottky Diodes

- ▶ Turn-ON and turn-OFF are extremely fast (no minority carrier storage).
- ▶ No reverse recovery current unlike  $p-n$  diodes.
- ▶ Higher junction capacitance  $\Rightarrow$  small voltage overshoot if  $di/dt$  is large.

**Applications:** Preferred in high-frequency power converters and fast rectifiers.

## Schottky Diode: Key Takeaways

- ▶ Majority-carrier device with fast switching.
- ▶ Lower forward voltage drop (0.3–0.4 V).
- ▶ Poor high-voltage blocking ( $< 200$  V).
- ▶ Higher reverse leakage current than  $p-n$  diodes.
- ▶ Ideal for low-voltage, high-speed power circuits.

# Table of contents

- 4 Introduction to Power Semiconductor Devices
  - Power diodes
  - Power bipolar junction transistor (BJT)

# Power bipolar junction transistor (BJT)

## 1. Definition:

*A power BJT is a three-terminal semiconductor device that can amplify or switch electronic signals and electrical power. It consists of two p-n junctions and is designed to handle high voltages and currents, making it suitable for power applications.*

- ▶ Power BJTs require high blocking voltage in OFF state and high current capacity in ON state.
- ▶ Structure differs from logic-level BJTs to meet power handling demands.
- ▶ Exhibits distinct  $i-v$  characteristics and switching behavior compared to signal BJTs.
- ▶ Applications include:
  - ▶ Power converters
  - ▶ Motor drives
  - ▶ High-voltage switching circuits

# Bipolar Power Transistors (BJT)

- ▶ BJTs are three-terminal current-controlled devices with:
  - ▶ Emitter (E)
  - ▶ Base (B)
  - ▶ Collector (C)
- ▶ Two types: **NPN** and **PNP**
- ▶ Current controlled: Small base current controls large collector current
- ▶ Can only conduct in one direction:
  - ▶ NPN:  $C \rightarrow E$
  - ▶ PNP:  $E \rightarrow C$
- ▶ Structure: vertically oriented layers with heavily doped emitter and lightly doped collector

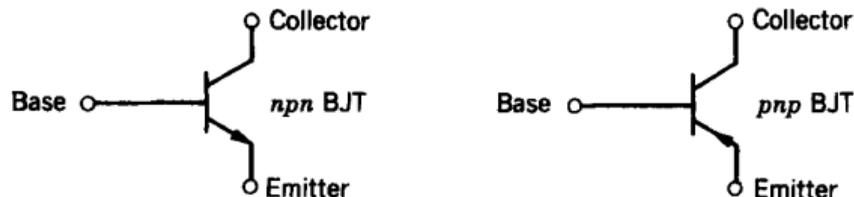


Fig. 4.14: BJT structure and symbol, adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Vertical Power Transistor Structure

- ▶ 4-layer vertical structure with alternating  $p$  and  $n$ -type regions.
- ▶ Base input, collector output, emitter common terminal.
- ▶ Vertical layout reduces  $R_{on}$  and thermal resistance.
- ▶ Enhances current flow and reduces power dissipation.
- ▶ Common-emitter configuration used in power circuits.

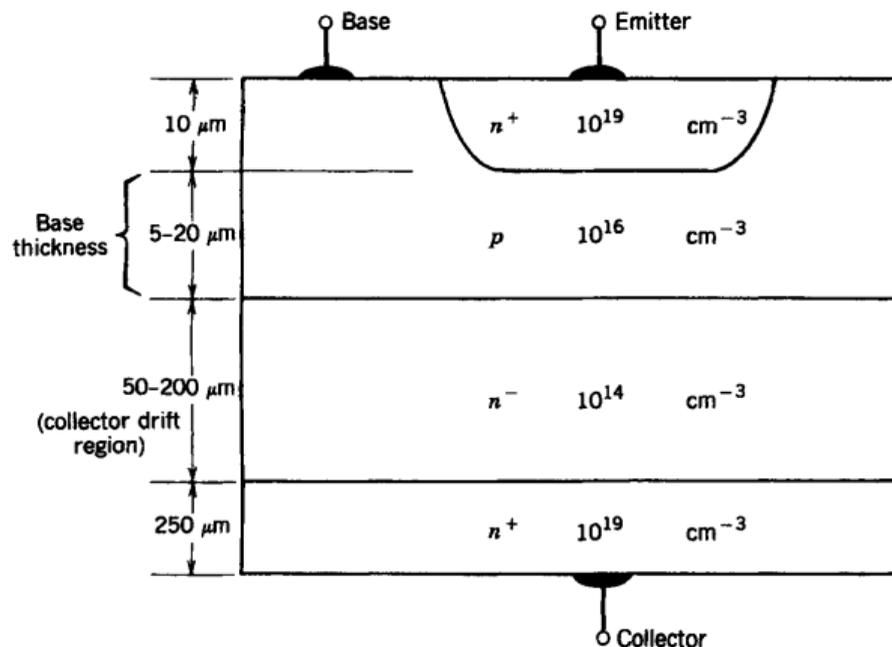


Fig. 4.15: Cross-section of a typical vertical  $npn$  power BJT, adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Doping and Thickness in Vertical BJTs

- ▶ Emitter: Heavily doped  $n^+$  ( $\sim 10^{19} \text{ cm}^{-3}$ )
- ▶ Base: Moderately doped  $p$ -type ( $\sim 10^{16} \text{ cm}^{-3}$ )
- ▶ Collector drift: Lightly doped  $n^-$  ( $\sim 10^{14} \text{ cm}^{-3}$ ), width = 50–200  $\mu\text{m}$
- ▶ Collector contact:  $n^+$  ( $\sim 10^{19} \text{ cm}^{-3}$ )

## Design Considerations:

- ▶ Base kept thin (5–20  $\mu\text{m}$ ) for high current gain.
- ▶ Drift region determines breakdown voltage.

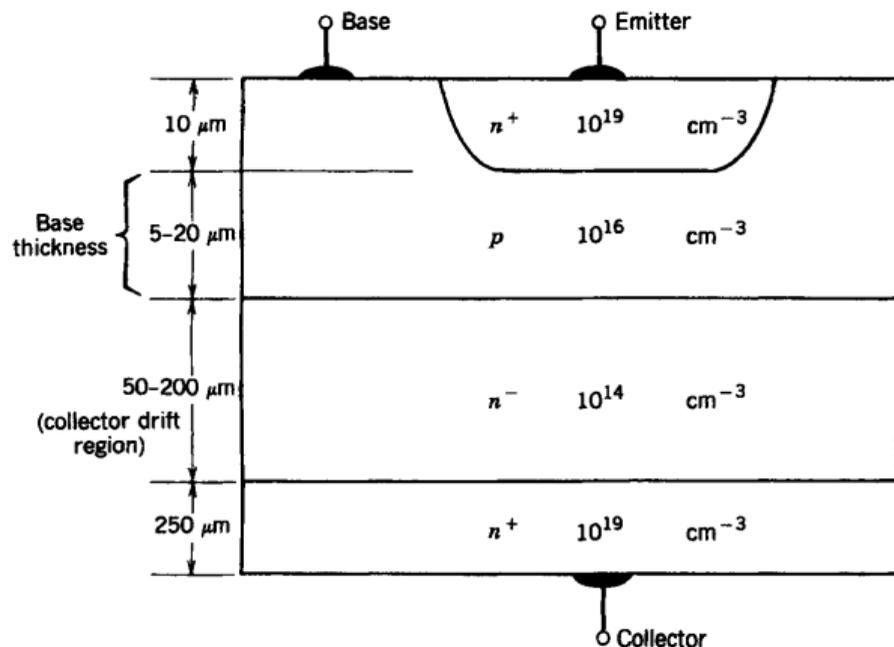


Fig. 4.16: Cross-section of a typical vertical *npn* power BJT, adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd Edition.

# NPN Transistor: Operating Principle

## Operation:

- ▶ Emitter–Base junction forward-biased → injects electrons into base.
- ▶ Base–Collector junction reverse-biased → collects electrons.
- ▶ Base is thin and lightly doped to minimize recombination.
- ▶ Electrons diffuse across base and are swept into collector.
- ▶ Base current  $I_B$  is small; Collector current  $I_C$  is large.

## Collector current:

$$I_C = \alpha_F I_E - I_{CO}(e^{V_{CE}/V_T} - 1) \quad (4.12)$$

## Emitter current:

$$I_E = \alpha_R I_C - I_{EO}(e^{V_{EC}/V_T} - 1) \quad (4.13)$$

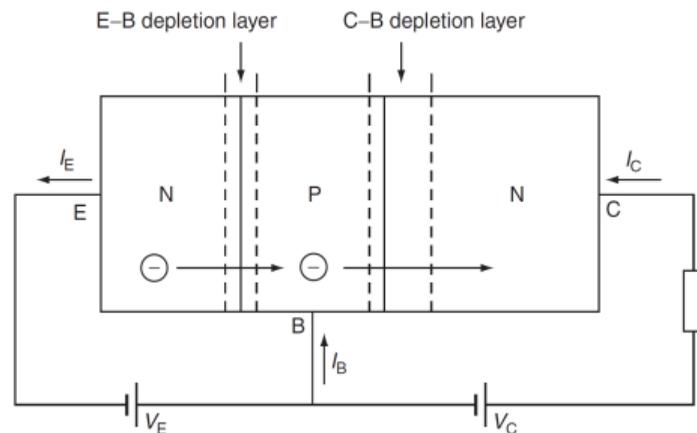


Fig. 4.17: NPN BJT operation under forward active mode; adapted from Mohan et al., *Power Electronics, 2nd Ed.*

# BJT Current Components and Ebers-Moll Model

- ▶ BJT modeled using Ebers-Moll equivalent circuit
- ▶ Includes forward and reverse  $\alpha$  parameters
- ▶ Defines base, collector, and emitter currents via diode current equations

$$I_C = \alpha_F I_F - I_{CO}(e^{V_{CE}/V_T} - 1)$$

$$I_E = \alpha_R I_R - I_{EO}(e^{V_{EC}/V_T} - 1)$$

## Current continuity:

$$I_C + I_E + I_B = 0$$

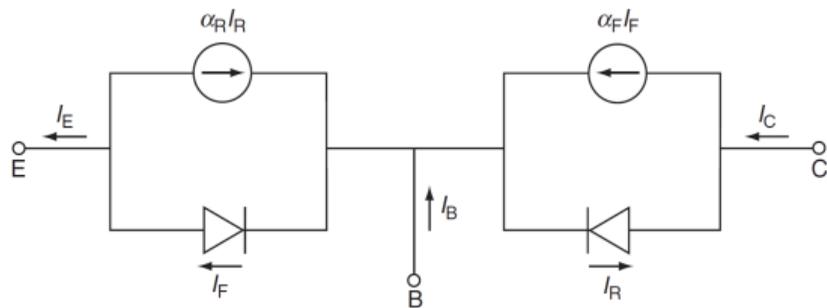


Fig. 4.18: Ebers-Moll equivalent circuit of NPN BJT

## Key Parameters and Insights

- ▶  $\alpha_F = \frac{I_C}{I_E}$  (forward common-base current gain), typically 0.9 to 0.98
- ▶  $\alpha_R = \frac{I_E}{I_R}$  (reverse common-base current gain), typically 0.02 to 0.1
- ▶  $\alpha_R$  is usually much smaller than  $\alpha_F$ .
- ▶  $\beta = \frac{I_C}{I_B}$  (common-emitter current gain), typically 50 to 200
- ▶ Higher  $\alpha \rightarrow$  better carrier injection from emitter
- ▶ Thin base  $\rightarrow$  high efficiency but increased risk of punch-through
- ▶  $I_B$  is small but essential for switching control

**Conclusion:** BJT operates via minority carrier injection and diffusion under strong forward bias conditions. It is highly efficient for amplification and switching when designed with proper base width and doping gradients.

# BJT Current Gain Mechanism and Base Transport

## Active Region Operation:

- ▶ In the active mode of a BJT, the base-emitter junction is forward biased, and the base-collector junction is reverse biased.
- ▶ Electrons are injected from the emitter ( $n^+$ ) into the base ( $p$ ) and then diffuse toward the collector.
- ▶ The base is intentionally kept very thin and lightly doped to minimize recombination and ensure most electrons reach the collector.
- ▶ The resulting collector current  $I_C$  is almost equal to the emitter current  $I_E$ , while the base current  $I_B$  remains small.

**Implication:** The small base current and large collector current results in current gain  $\beta = \frac{I_C}{I_B}$ .

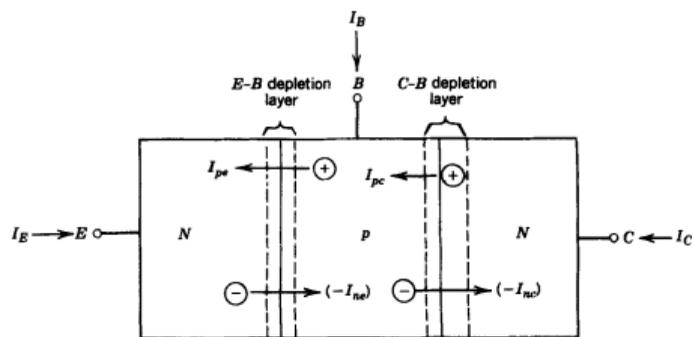


Fig. 4.19: Simplified cross-sectional model of BJT and current components; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Diffusion Currents and Stored Charge Distribution

- ▶ The injected electrons from the emitter diffuse through the base to the collector, supported by the electric field across the reverse-biased base-collector junction.
- ▶ Recombination in the base is minimized due to short base width and high diffusion constant.
- ▶ Stored charge distribution within the base and collector regions affects dynamic response and switching.
- ▶ The base current includes three components:
  - ▶  $I_{ne}$ : diffusion of electrons injected from emitter to base.
  - ▶  $I_{nc}$ : recombination in the collector depletion layer.
  - ▶  $I_{pe}$ : holes injected into emitter to maintain charge neutrality.

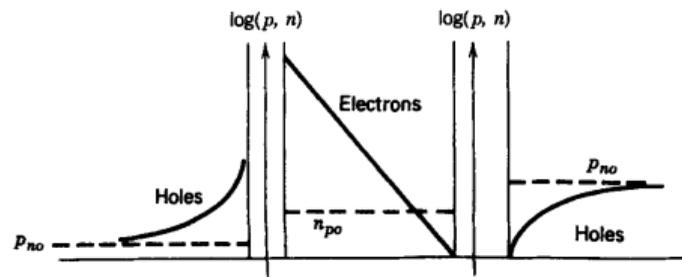


Fig. 4.20: Stored charge vs.  $\log(p, n)$  profile; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Expression for Current Gain and Beta

## Terminal Current Definitions:

$$I_C = I_{nc}$$

$$I_E = I_{ne} + I_{pe}$$

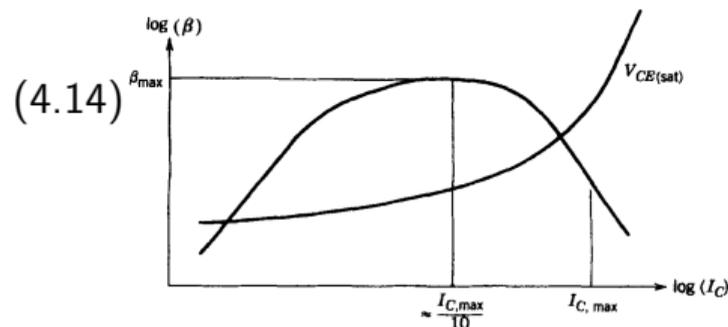
$$I_B = I_E - I_C = I_{ne} - I_{nc} + I_{pe}$$

## Gain Expression:

$$\frac{I_B}{I_C} = \frac{I_{ne} - I_{nc}}{I_{nc}} + \frac{I_{pe}}{I_{nc}} \Rightarrow \beta = \left( \frac{I_B}{I_C} \right)^{-1}$$

## Optimization:

- ▶ Large  $\beta$  requires: small  $I_{pe}$  (via heavy emitter doping), minimal  $(I_{ne} - I_{nc})$  (via long electron lifetime in base).
- ▶ Thin base to reduce recombination path and ensure efficient electron diffusion.



(4.15) Fig. 4.21: Variation of BJT  $\beta$  and  $V_{CE(sat)}$ , as a function of dc collector current; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Emitter Current Crowding and its Impact on Beta

- ▶ Emitter current does not flow uniformly due to geometry and lateral resistance in the base.
- ▶ The voltage drop across the base-emitter junction is higher near the emitter edge, leading to current crowding.
- ▶ Result: Increased base current density at the emitter edge  $\Rightarrow$  early onset of high-level injection  $\Rightarrow$  fall in  $\beta$ .
- ▶ Modern power BJTs mitigate this by using interleaved emitter-base finger structures.

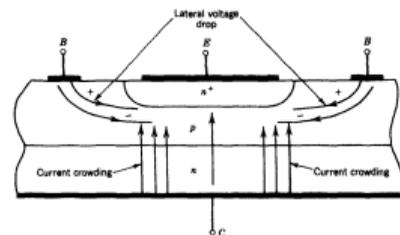


Fig. 4.22: Forward-biased emitter current crowding due to lateral base resistance; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Quasi-Saturation in Power BJTs

- ▶ At high  $I_C$ , the voltage drop across the drift region increases due to  $R_d$ .
- ▶ The base-collector junction becomes weakly forward biased.
- ▶ Hole injection from base to collector drift occurs, and space-charge neutrality requires electron injection as well.
- ▶ Drift region begins to accumulate charge on one side only — this is quasi-saturation.

$$i_C = \frac{V_{CE}}{R_d}$$

(4.16)

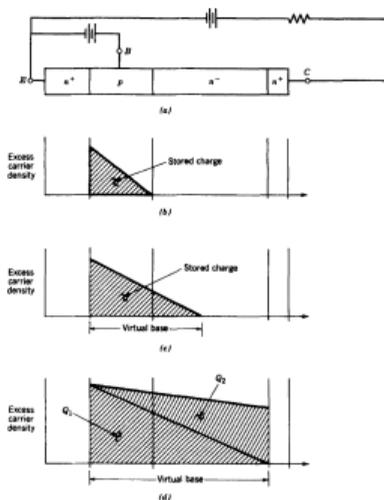


Fig. 4.23: Charge profile showing virtual base in quasi-saturation; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Static Characteristics of BJT

- ▶ A BJT is a current-controlled device.
- ▶ Its output characteristic  $i_C$  versus  $V_{CE}$  depends on the base current  $i_B$ :

$$i_C = f(V_{CE}, i_B)$$

- ▶ The collector current is ideally  $i_C = \beta i_B$ , where  $\beta$  is the current gain of the transistor.
- ▶ However, due to the Early effect (modulation of base width with  $V_{CE}$ ),  $\beta$  is not constant.
- ▶ This leads to variation in  $i_C$  for the same  $i_B$  as  $V_{CE}$  increases.

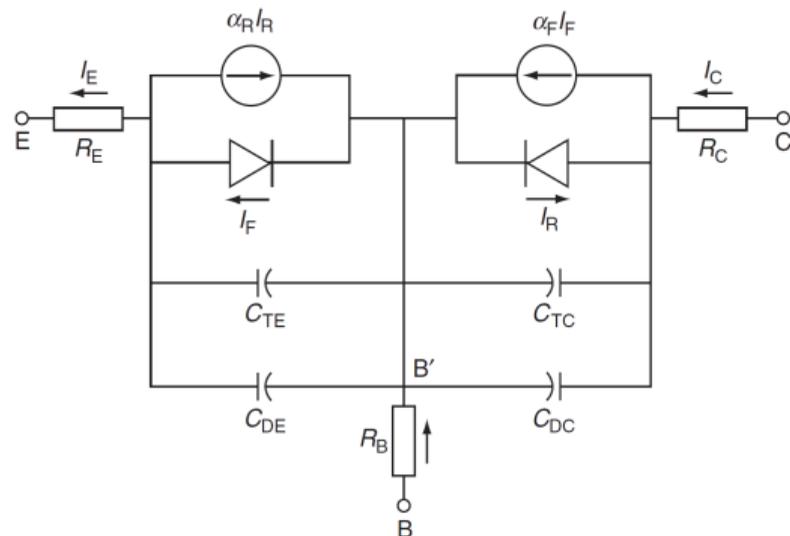


Fig. 4.24: BJT equivalent circuit with resistances and capacitances; ; adapted from Mohan et al., *Power Electronics, 2nd Ed.*

# Output Characteristics of a Transistor

- ▶ The  $i_C$  vs  $V_{CE}$  curve reveals three operating regions:
  - ① **Saturation Region:** Very low  $V_{CE}$ , high  $i_C$ , transistor fully ON.
  - ② **Active Region:**  $i_C \approx \beta i_B$ , transistor used for amplification.
  - ③ **Cutoff Region:**  $i_B \approx 0$ , thus  $i_C \approx 0$ , transistor OFF.
- ▶ The Load Line on the output characteristic intersects the  $i_C$ - $V_{CE}$  curves based on  $i_B$ .
- ▶ Used to find the Q-point in analog design.

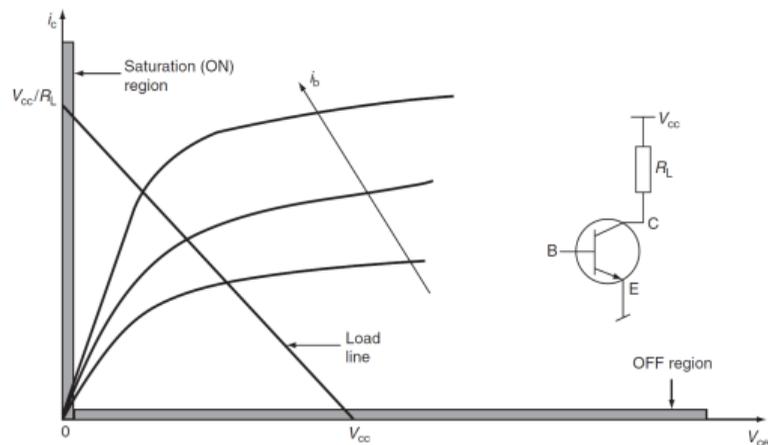


Fig. 4.25: Output characteristics of a BJT; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

# Power BJT – Static Characteristics

- ▶ Power BJTs exhibit similar  $i_C$ - $V_{CE}$  behavior but with effects like:
  - ▶ **Quasi-saturation:** due to the lightly doped collector drift region.
  - ▶ **Second breakdown:** due to localized thermal hotspots under high  $i_C$ .
- ▶ Three major regions are:
  - ① Active region: Used for amplification.
  - ② Quasi-saturation: Forward-biased  $C$ - $B$  junction begins to conduct.
  - ③ Hard saturation: Excess carrier injection across drift region.
- ▶ Breakdown voltages:
  - ▶  $BV_{CBO}$ : Collector-base with emitter open.
  - ▶  $BV_{CEO}$ : Collector-emitter with base open.
  - ▶  $BV_{SUS}$ : Sustaining voltage after breakdown onset.

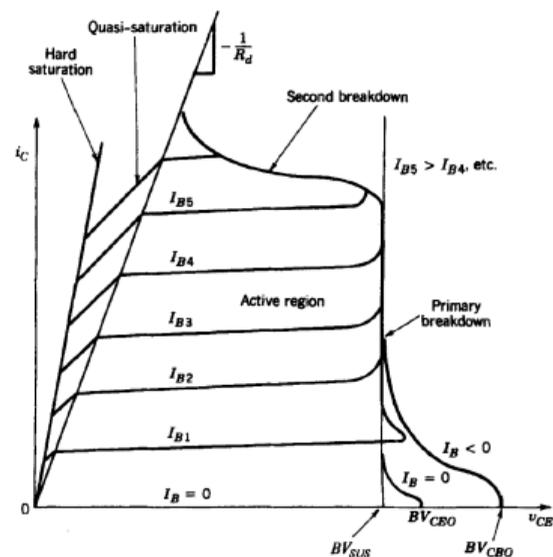


Fig. 4.26:  $i_C$ - $V_{CE}$  curves with  $I_B$  steps; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Current Gain and Load Line Intersection

- ▶ For a given  $i_B$ , collector current  $i_C = \beta i_B$  in the active region.
- ▶  $\beta$  is affected by:
  - ▶ Injection efficiency (related to emitter doping)
  - ▶ Base transport factor (related to recombination and diffusion in base)
- ▶ Load line defined by:

$$i_C = \frac{V_{CC} - V_{CE}}{R_L}$$

- ▶ Intersection of load line and transistor characteristic determines Q-point.

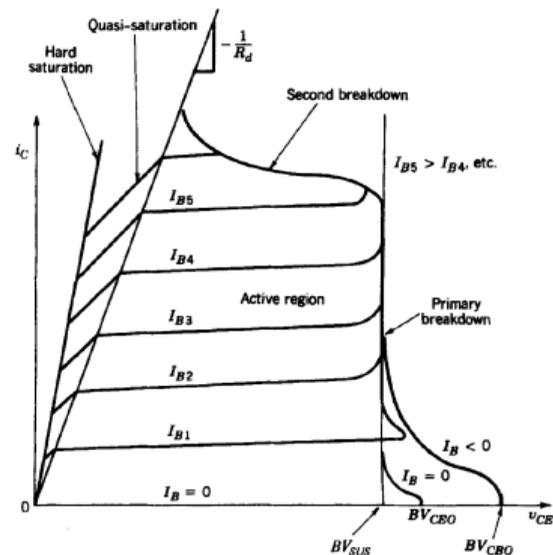


Fig. 4.27:  $i_C$ - $V_{CE}$  curves with  $I_B$  steps; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Key Observations in Power BJT Static Behavior

- ▶ Unlike small-signal BJTs, power BJTs show:
  - ▶ **Lower current gain  $\beta$** , especially in quasi-saturation.
  - ▶ **Voltage fall-off due to second breakdown.**
  - ▶ **Load line may enter second breakdown zone**, leading to thermal failure.
- ▶ Quasi-saturation is due to double carrier injection in the collector drift region.
- ▶ Proper thermal and current limiting design is critical in power BJTs.

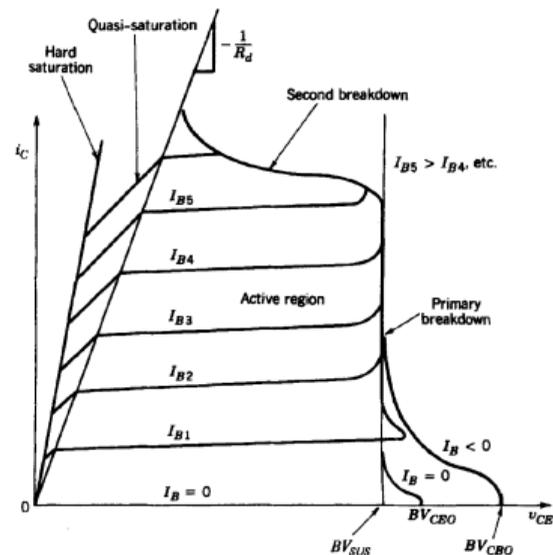


Fig. 4.28:  $i_C$ - $V_{CE}$  curves with  $I_B$  steps; adapted from Ned Mohan, Tore M. Undeland, and William P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd Edition.

# Dynamic Characteristics of BJT

**In the ON-state, a transistor stores three main charges:**

- ①  $Q_b$ : Charge stored in the base region.
- ②  $Q_{ce}$ : Charge in the collector region beneath the emitter.
- ③  $Q_{cb}$ : Charge in the collector region beneath the base contact.

These charges define the transient behavior during switching. When transitioning to the OFF-state, all three must be removed for the transistor to fully block current.

Fig. 4.29: [Add diagram showing positions of  $Q_b$ ,  $Q_{ce}$ , and  $Q_{cb}$ ]

## Charge Dependency on $V_{CE}$ and $I_C$

- ▶  $Q_b$  is largely independent of  $V_{CE}$ , but increases with  $I_C$ .
- ▶  $Q_{ce}$  increases with  $I_C$  but decreases as  $V_{CE}$  increases.
- ▶  $Q_{cb}$  grows rapidly as  $V_{CE}$  drops — marking the onset of saturation.

**Implication:** Charge buildup significantly affects collector-emitter voltage and switching speed.

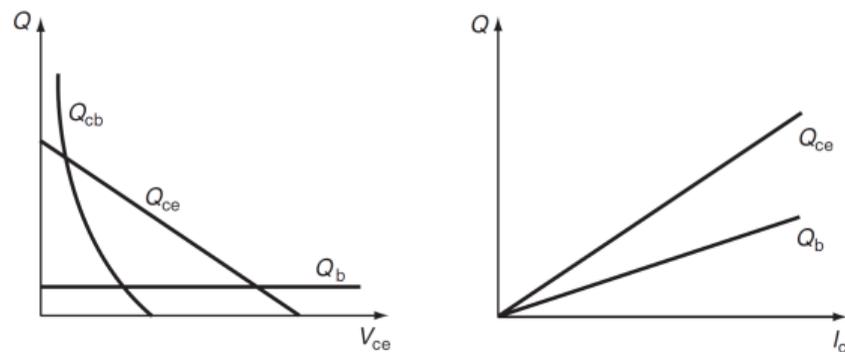


Fig. 4.30:  $Q$  vs  $V_{CE}$  and  $Q$  vs  $I_C$ ; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

## Turn-OFF of BJT – Physical Process

- ▶ Turn-off begins when base drive is removed or reversed.
- ▶  $Q_b$  is removed first, starting from edges near the emitter.
- ▶  $Q_{ce}$  and  $Q_{cb}$  follow, shrinking towards the center.
- ▶ Residual charge  $Q_r$  creates a *tail current*, affecting turn-off time.

**Storage time**  $t_s$ : Time during which current still flows due to residual charge even after base drive is removed.

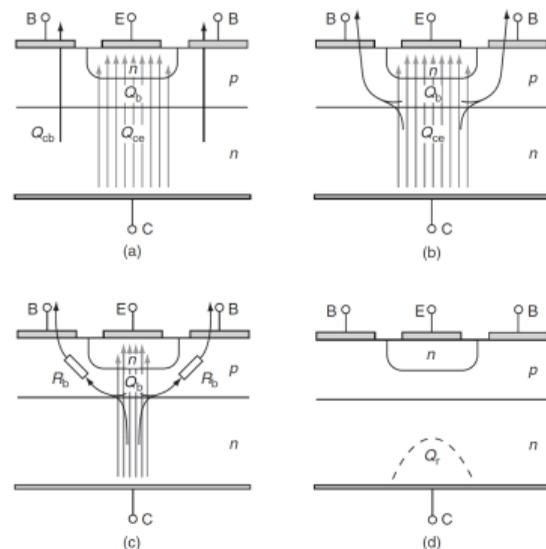


Fig. 4.31: BJT Turn-off process: charge removal sequence; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

# Turn-ON of BJT – Dynamics

- ▶ In OFF-state, there are no stored charges.
- ▶ A positive base pulse injects  $Q_{ce}$ , reducing  $V_{CE}$  rapidly.
- ▶ A sharp peak in base current is ideal for quick charge buildup.
- ▶ Faster ON-switching means lower energy loss.

**Switching losses during turn-ON** depend on:

- ▶ Time to establish  $Q_{ce}$  and  $Q_b$ .
- ▶ Load characteristics (resistive or inductive).

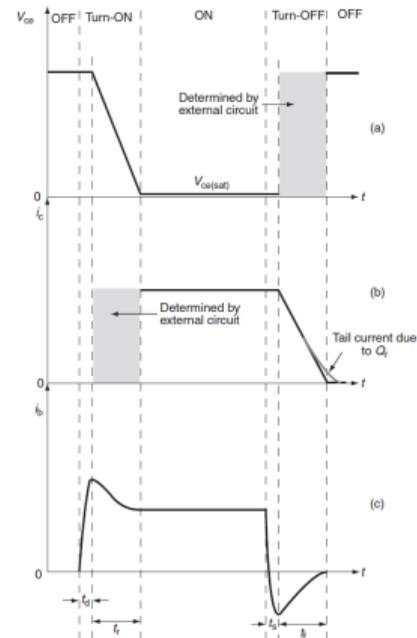


Fig. 4.32: BJT Turn-on process: charge buildup sequence; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

# Power Dissipation in BJT

## Total Power Dissipation:

$$P_d = P_{on} + P_{off} + P_{switching}$$

## ON-state Loss:

$$P_{on} = V_{CE(sat)} \times I_C \times D$$

where  $D$  is the duty cycle.

## Switching Loss (OFF $\rightarrow$ ON):

$$P_{OFF-ON} = \frac{V_{cc} I_C t_f f_s}{6}$$

## Switching Loss (ON $\rightarrow$ OFF):

$$P_{ON-OFF} = \frac{V_{cc} I_C t_r f_s}{6}$$

## Total Switching Loss:

$$P_{switching} = \frac{V_{cc} I_C f_s (t_r + t_f)}{6}$$

# Safe Operating Area (SOAR)

**SOAR:** Region where transistor operates safely under given voltage-current conditions.

- ▶ Forward SOAR (FSOAR): With positive base drive.
- ▶ Reverse SOAR (RSOAR): With negative base drive (turn-off).
- ▶ Delimits power dissipation, collector voltage, and current density.

## Key Constraints:

- ▶ Second breakdown limit.
- ▶ Thermal limits (hot spot prevention).
- ▶ Switching-induced crowding.

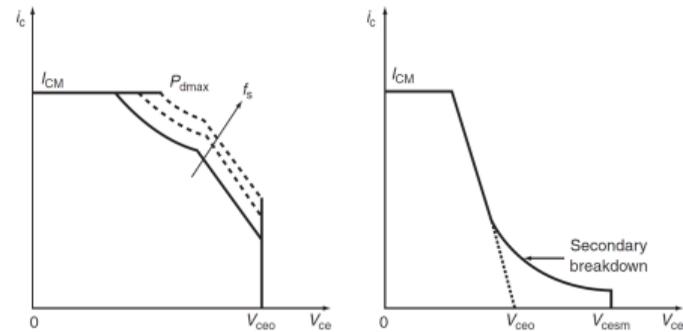


Fig. 4.33: SOAR and RSOAR curves for a power BJT; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

## Breakdown Voltages in BJTs

- ▶ In the blocking state, the C–B junction must withstand the applied voltage.
- ▶ The B–E junction has a lower breakdown voltage (5–20 V) due to heavy emitter doping to achieve high  $\beta$ .
- ▶ To withstand high voltages, a lightly doped collector drift region is used.
- ▶ Base width is minimized to maintain gain but limited to avoid reach-through breakdown.

**Design Trade-off:** Thin base for high gain vs. thick base for high voltage. **Breakdown Voltage Expressions:**

- ▶ In common-emitter configuration:  $BV_{CEO} < BV_{CBO}$
- ▶ Relationship:

$$BV_{CEO} = \frac{BV_{CBO}}{\beta^{1/n}} \quad \text{where } n = 4 \text{ for } npn, n = 6 \text{ for } pnp$$

- ▶ Due to reverse-bias current  $I_{CBO}$  at B–E junction, impact ionization rate increases in emitter-open mode.

## Second Breakdown, Thermal Runaway and Localized Hotspots

- ▶ Occurs at high  $V_{CE}$  and  $I_C$  despite staying below primary breakdown.
- ▶ Triggered by localized thermal runaway and current filamentation.
- ▶ Exponential increase in power dissipation with temperature due to:

$$n_i \propto \exp\left(-\frac{E_g}{2kT}\right)$$

- ▶ Dangerous due to steep  $V_{CE}$  drop and rapid localized heating.

### Thermal Runaway and Localized Hotspots

- ▶ Filamentation: nonuniform current density leads to  $J_A > J_B$
- ▶ Result:  $T_A > T_B \Rightarrow$  runaway due to positive feedback
- ▶ Region A may exceed intrinsic temperature  $T_i$  causing catastrophic failure.
- ▶ Preventive measures:
  - ▶ Use of snubbers and freewheeling diodes.
  - ▶ Narrow emitter stripes.
  - ▶ Controlled  $di/dt$  and  $dv/dt$  during switching.

## On-State Losses

- ▶ Dominated by conduction loss:

$$P_{on} = I_C \cdot V_{CE(sat)}$$

- ▶  $V_{CE(sat)}$  increases with  $I_C$  due to:

$$V_{CE(sat)} = V_{BE(on)} - V_{BC(sat)} + V_d + I_C(R_e + R_c)$$

- ▶ Main contributor:  $V_d$  across collector drift region.
- ▶  $V_d$  depends on carrier lifetime; trade-off between low  $V_d$  and fast switching.

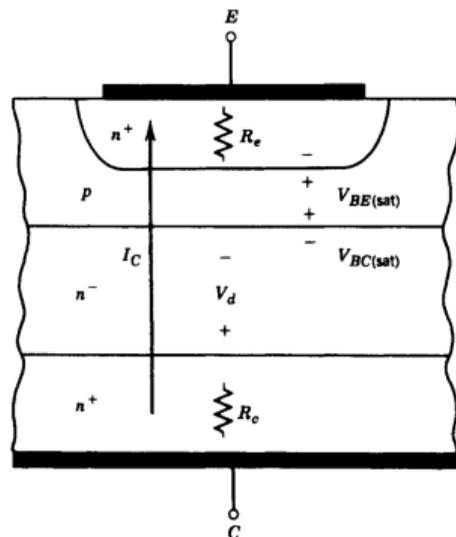


Fig. 4.34: On-state losses in a BJT; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

# Paralleling of BJTs

- ▶ Used in high-current applications to share load.
- ▶ Risk: thermal runaway due to negative temp. coeff. of  $V_{BE}$ .
- ▶ Solution: Add emitter resistance  $R$  for negative feedback.

$$V_{be1} = V_{be2} + R(I_{c1} - I_{c2}) \Rightarrow \Delta V_{be} = R\Delta I_c$$

- ▶ Limit  $\Delta V_{be}$  to  $\approx 0.2$  V to allow  $\Delta I_C \leq 0.5$  A.

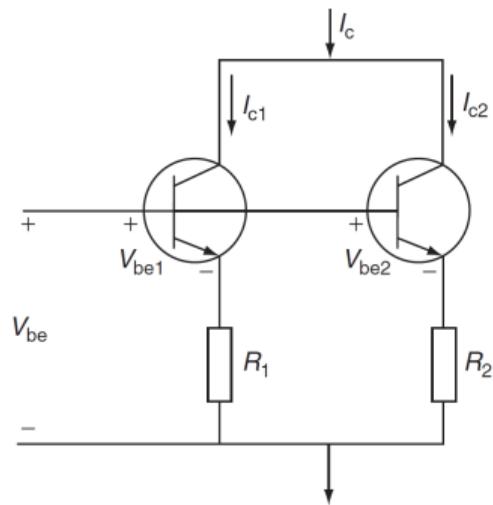


Fig. 4.35: Paralleling of BJT; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

# Darlington Connection

- ▶ Used to boost current gain:

$$I_B = \frac{I_C}{\beta_1 \cdot \beta_2}$$

- ▶ Higher  $V_{CE(sat)} \approx 1\text{--}1.2\text{ V}$  compared to  $0.4\text{--}0.6\text{ V}$  for single BJT.
- ▶ Ideal for high-power applications where base drive must be minimized.
- ▶ Trade-off: higher power loss and slower switching.

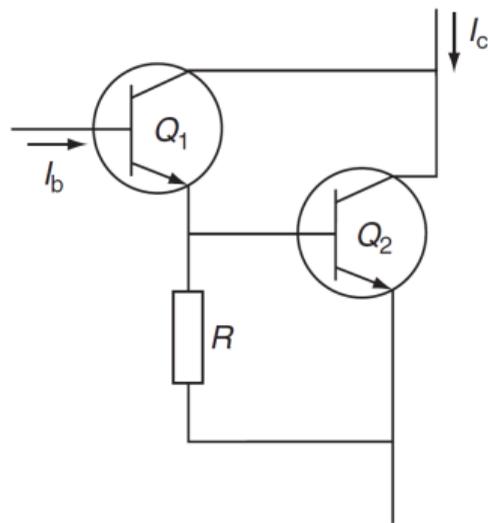


Fig. 4.36: Darlington; adapted from Umanand, L., *Power Electronics, Essentials and Applications*.

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## 5 Conventional Power Semiconductor Devices

# Conventional Power Semiconductor Devices

Dr Bikash Sah



# Introduction to Power MOSFETs

- ▶ Power MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistors) are widely used in power electronics since the early 1980s.
- ▶ They offer high on-state current capability and off-state voltage blocking, making them suitable for high-speed switching applications.
- ▶ Replacing BJTs in many applications, especially those requiring fast switching, due to their voltage-controlled nature.
- ▶ Understanding the differences between BJTs and MOSFETs is crucial for effective circuit design.
- ▶ This section introduces the physical structure, voltage and current limits, and failure mechanisms of MOSFETs.

**Figure Placeholder:** *Power MOSFET application context diagram (optional).*

## Basic Structure of Power MOSFET

- ▶ The MOSFET is constructed with alternating p-type and n-type layers:  $n^+ - p - n^- - n^+$ .
- ▶ The  $n^+$  (source and drain), p-body, and  $n^-$  (drift region) form the core active structure.
- ▶ Gate terminal is insulated from the body by silicon dioxide ( $\text{SiO}_2$ ) forming the gate oxide.
- ▶ Applying a positive voltage to the gate induces an n-channel in the p-body, allowing current flow.
- ▶ The drift region ( $n^-$ ) is lightly doped to handle high blocking voltages.

**Figure Placeholder:** *MOSFET cross-section with labels for source, gate, drain, body, and drift region.*

## Perspective View of a Power MOSFET

- ▶ Power MOSFETs consist of thousands of small identical cells connected in parallel.
- ▶ Each cell includes source diffusion, gate conductor, field oxide, and drain contact.
- ▶ High current handling is achieved by maximizing the number of cells and gate width.
- ▶ This configuration is often referred to as VDMOS (Vertical Diffused MOSFET).
- ▶ Parasitic elements like a BJT and integral body diode are naturally formed.

**Figure Placeholder:** *Figure 22-1(b): Perspective structure showing MOSFET cellular layout.*

## Channel Formation and Operation

- ▶ The p-body prevents current flow until a gate voltage is applied.
- ▶ Applying  $V_{GS} > V_{th}$  induces an n-channel in the p-body.
- ▶ This connects the source to the drain allowing electron flow (n-channel enhancement).
- ▶ No minority carrier injection occurs—enabling fast switching.
- ▶ The MOSFET operates as a unidirectional voltage-controlled switch.

**Figure Placeholder:** *Figure 22-2(a): Accumulation layer in ON-state.*

## Gate Metallization and Field Plate Action

- ▶ Gate metallization overlaps the  $n^-$  drift region to serve two purposes:
  - ① Enhances conductivity during ON-state by forming accumulation layer.
  - ② Acts as a field plate to reduce electric field curvature in OFF-state.
- ▶ This helps to minimize on-resistance and improves breakdown voltage.
- ▶ Design strategies include optimizing gate width-to-length ratio to maximize gain.

**Figure Placeholder:** *Figure 22-2(b): Field plate action during OFF-state.*

## Inversion Layers and the Field Effect

- ▶ The gate region of the MOSFET is composed of:
  - ▶ Gate metallization (e.g., Al or polysilicon)
  - ▶ Gate oxide ( $SiO_2$ )
  - ▶ Silicon substrate beneath the oxide
- ▶ This gate stack acts as a high-quality MOS capacitor.
- ▶ Applying a small positive  $V_{GS}$  causes:
  - ▶ Positive charge on gate metal
  - ▶ Negative charge induced on silicon side
  - ▶ Formation of a depletion region by repelling holes
- ▶ The structure acts as a capacitor inducing a field across the gate oxide.

**Note:** The inversion layer forms only after depletion is sufficient.

# Formation of Depletion and Inversion Layers

- ▶ As  $V_{GS}$  increases:
  - ① Depletion region widens (Fig. 22-5a)
  - ② Electrons begin to accumulate at oxide–silicon interface (Fig. 22-5b)
  - ③ Inversion layer forms when electron density exceeds hole density (Fig. 22-5c)
- ▶ Inversion layer has **n-type** conductivity and enables conduction between source and drain.
- ▶ This defines the MOSFET's enhancement mode behavior.

# Threshold Voltage and Oxide Capacitance

- ▶ Threshold voltage  $V_{GS(th)}$  is the point at which an inversion layer is just formed.
- ▶ As  $V_{GS} > V_{GS(th)}$ , inversion layer:
  - ▶ Becomes thicker
  - ▶ Becomes more conductive
  - ▶ Screens the underlying depletion region
- ▶ Major factor: oxide capacitance per unit area:

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

- ▶ Other influencing factors:
  - ▶ Work function difference (metal vs silicon)
  - ▶ Fixed/trapped charge
  - ▶ Body doping and oxide thickness

## Gate Control of Drain Current Flow

- ▶ With  $V_{GS} > V_{GS(th)}$  and small  $V_{DS}$ :
  - ▶ MOSFET operates in the ohmic (linear) region.
  - ▶ Inversion layer has nearly uniform thickness along the channel.
  - ▶ Drain current  $I_D$  increases linearly with  $V_{DS}$ .
- ▶ Voltage drop along the channel varies:

$$V_{ox}(x) = V_{GS} - V_{CS}(x)$$

- ▶ As  $V_{DS}$  increases,  $V_{CS}(x)$  increases toward the drain end.
- ▶ This leads to non-uniform channel thickness and begins shaping current characteristics.

## Channel Pinch-Off and Saturation Region

- ▶ As  $V_{DS}$  increases such that:

$$V_{GS} - V_{DS} = V_{GS(th)}$$

the channel is **pinched off** at the drain end.

- ▶ No inversion layer exists at the drain end—carrier velocity becomes saturated.
- ▶ Device enters saturation (active) region:
  - ▶  $I_D$  becomes independent of  $V_{DS}$
  - ▶ Minimum inversion layer thickness is maintained by high electric field
- ▶ Channel length modulation and velocity saturation effects begin.

## Electric Field and Velocity Saturation

- ▶ At high electric fields, carrier velocity saturates:

$$v_{\text{drift}} \approx 8 \times 10^6 \text{ cm/s at } E \approx 1.5 \times 10^4 \text{ V/cm}$$

- ▶ This saturation leads to constant  $I_D$  in the saturation region:

$$I_D = K(V_{\text{GS}} - V_{\text{GS(th)}})^2$$

with

$$K = \mu_n C_{\text{ox}} \frac{W}{2L}$$

- ▶  $\mu_n$  is carrier mobility;  $W/L$  is width-to-length ratio of the channel.
- ▶ Design goal: maximize  $W/L$  to minimize on-state losses and improve gain.

## Deviation from Square Law Model

- ▶ Square-law  $I_D$ - $V_{GS}$  relationship:

$$I_D \propto (V_{GS} - V_{GS(th)})^2$$

- ▶ Breaks down at high  $I_D$  due to:
  - ▶ Velocity saturation (as per  $v_{drift}$  curve)
  - ▶ Reduction in mobility  $\mu_n$  due to:
    - ▶ Increased electric field in inversion layer
    - ▶ Increased electron density near gate
    - ▶ Carrier-carrier scattering effects
- ▶ At high currents, the relationship becomes approximately linear.