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The PN Junction Diode

The One-Way Street of Electricity in Modern Electronics

- L1 Computer Engineering
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1. Introduction

What is a Diode?

→ Semiconductor Device

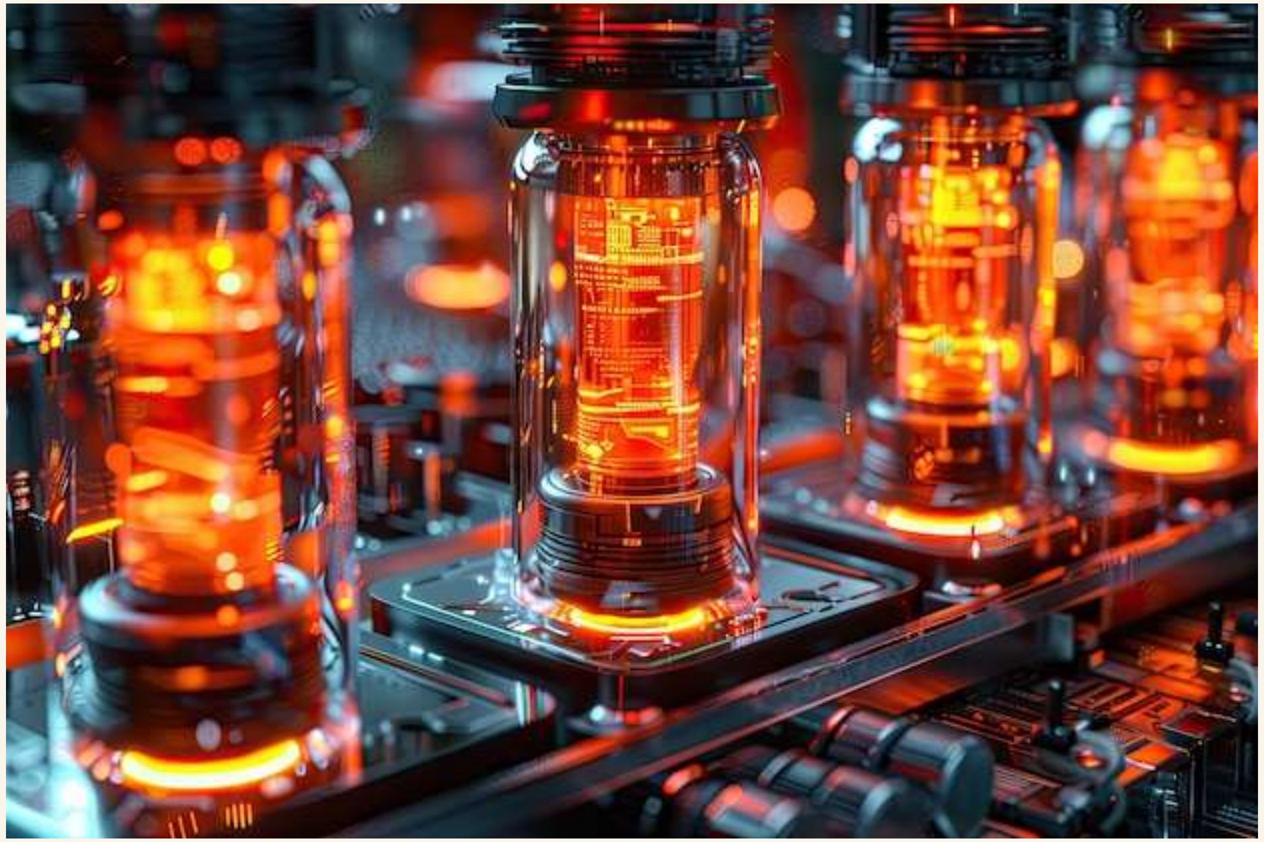
A device constructed from semiconductor materials (typically silicon) designed to actively control the flow of electrical current within a circuit.

→ One-Way Valve

It functions analogously to a one-way mechanical valve, permitting electrical current to flow easily in one direction (forward bias) while strictly blocking it in the opposite direction (reverse bias).

→ Electronic Foundation

The diode is an indispensable, fundamental building block underpinning nearly all modern electronic circuits and systems, from power supplies to logic gates.



The Junction formation

Part 1

The operation of a diode relies on the precise combination of two distinct, doped semiconductor materials:

P-type Material

*Created by doping pure silicon with Group III impurities, such as Boron or Gallium. This process introduces an abundance of **"holes"**, which act as mobile positive charge carriers.*

N-type Material

*Created by doping pure silicon with Group V impurities, such as Phosphorus or Arsenic. This results in an excess of **free electrons**, which act as mobile negative charge carriers.*

These individual doped materials, while conductive, possess limited functional utility until they are physically joined to form a junction.

Part 2

The critical component is the boundary formed when the P-type and N-type materials are brought into intimate contact.

Joining the Materials

The P-type material (holes) and N-type material (electrons) are fabricated adjacently to create a seamless PN junction interface.

Diffusion Occurs

Due to the concentration gradient, free electrons from the N-side immediately diffuse across the junction to combine with and fill the holes on the P-side.

Depletion Region Formation

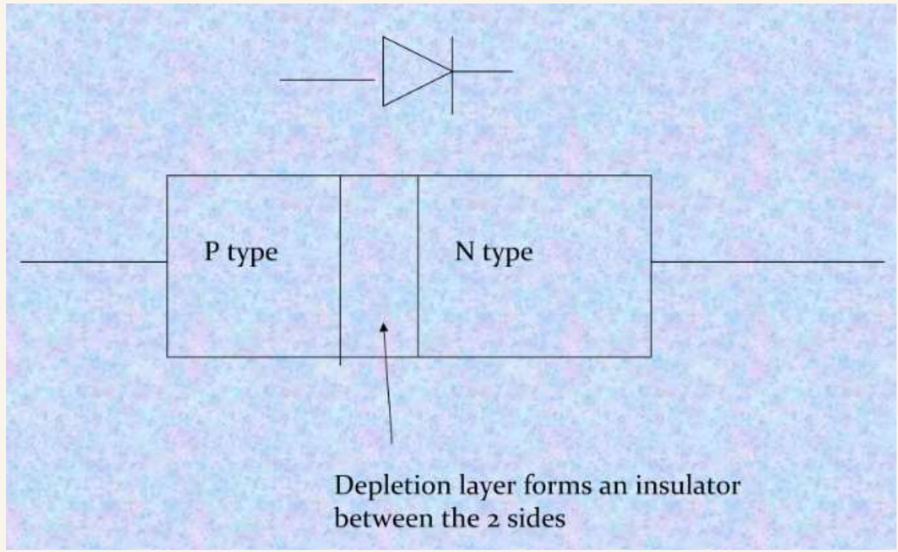
*This recombination process leaves behind immobile, fixed ions on both sides of the junction. This area, now devoid of mobile charge carriers, is called the **depletion region**.*

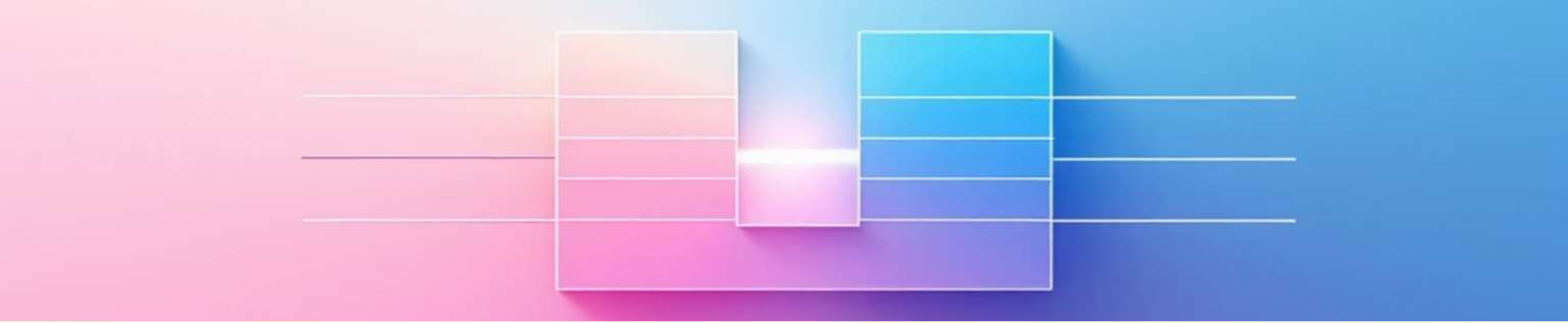
Internal Electric Field

The fixed ions create a permanent internal electric field and potential difference, known as the built-in potential, which opposes further charge carrier movement.

Part 3

- *The depletion region forms at the PN junction due to the diffusion of electrons and holes. This area is void of free charge carriers, creating an electric field that opposes further carrier movement. The width of this region influences the junction's barrier potential and is critical in controlling the current flow under different biasing conditions.*
- *A PN junction is a device formed by joining p-type (doped with B, Al) with n-type (doped with P, As, Sb) semiconductors and separated by a thin junction is called PN junction diode or junction diode.*
- *Electronic symbol : triangle shows indicated the direction of current.*
- *In PN junction diode, N is at right and P is at left, (N region: electrons, P region: holes)*





Electrostatics of the PN Junction

Charge density distribution

- *Charge density profile in the depletion region. Relationship with doping concentrations*

Electric field distribution

- *Electric field profile in the depletion region. Maximum electric field at the junction.*

Potential distribution

- *Potential variation across the depletion region. Calculation of the built-in-potential.*

2. Biasing of a PN Junction diode

Forward bias effects

Describes the effects of applying a positive voltage to the p-side and a negative voltage to the n-side of a PN junction, including depletion region reduction and increased current flow.

Reverse bias characteristics

Details the impact of applying a reverse bias (negative to p-side and positive to p-side), focusing on deplention region widening and current suppression.

Breakdown voltage limits

Explains the PN junction behavior at high reverse voltages, including avalanche and Zener breakdown, and the limit actions on reverse bias voltage.

Forward Bias: Opening the Floodgates

To enable current flow, an external voltage must overcome the internal barrier:

1

Connection

Positive voltage is applied to the P-side (anode) and negative voltage to the N-side (cathode).

2

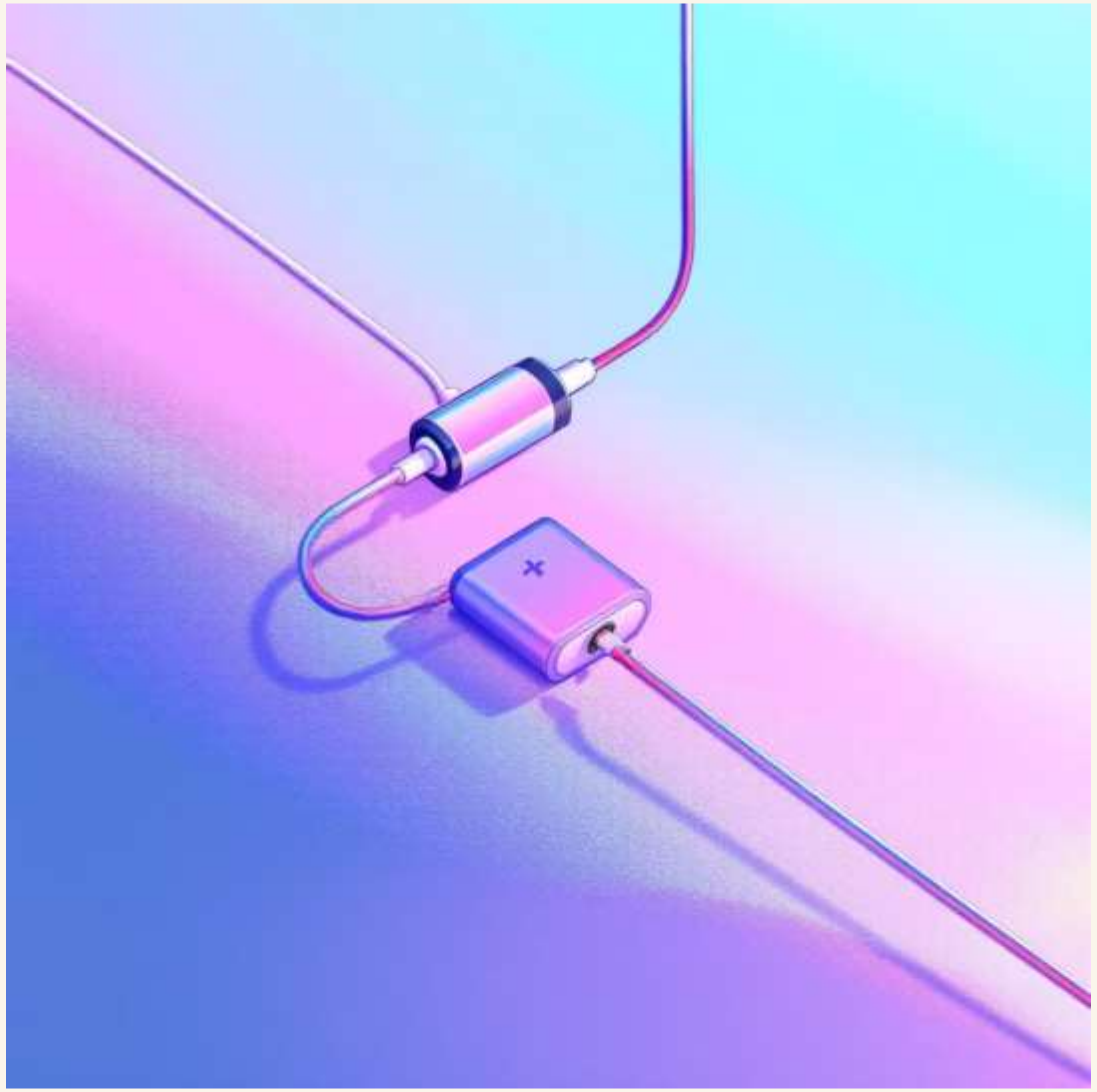
Barrier Reduction

The applied voltage opposes the built-in potential, significantly narrowing the depletion region.

3

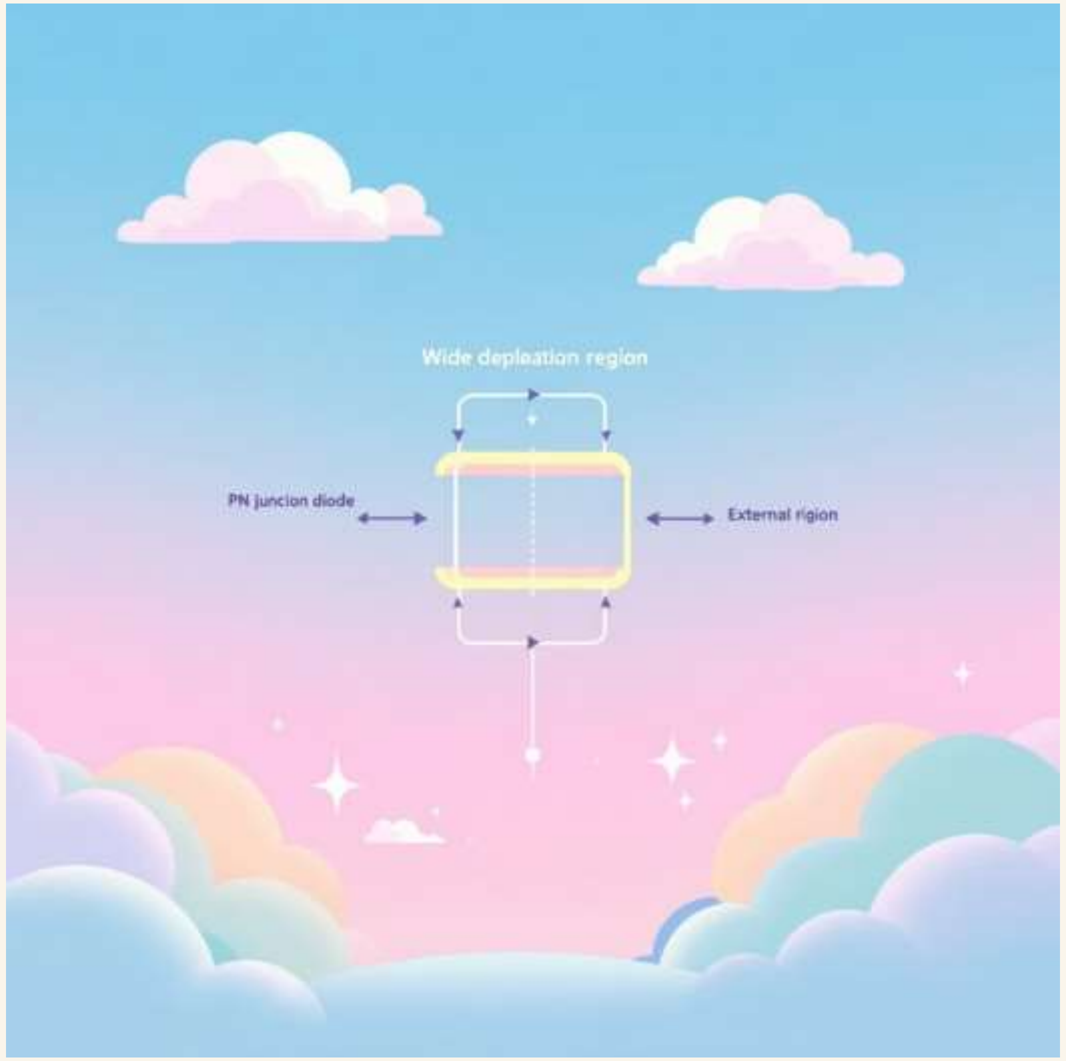
Conduction

Once the voltage reaches the knee voltage (approx. 0.7V for Silicon), the barrier collapses, allowing substantial current to flow.



> *Key Threshold: For silicon diodes, a voltage greater than 0.7V is required to maintain forward conduction.*

Reverse Bias: Blocking the Flow



Reverse bias reinforces the internal barrier, preventing current passage:

Polarity Reversed

Negative voltage is applied to the P-side, and positive voltage to the N-side.

Depletion Widening

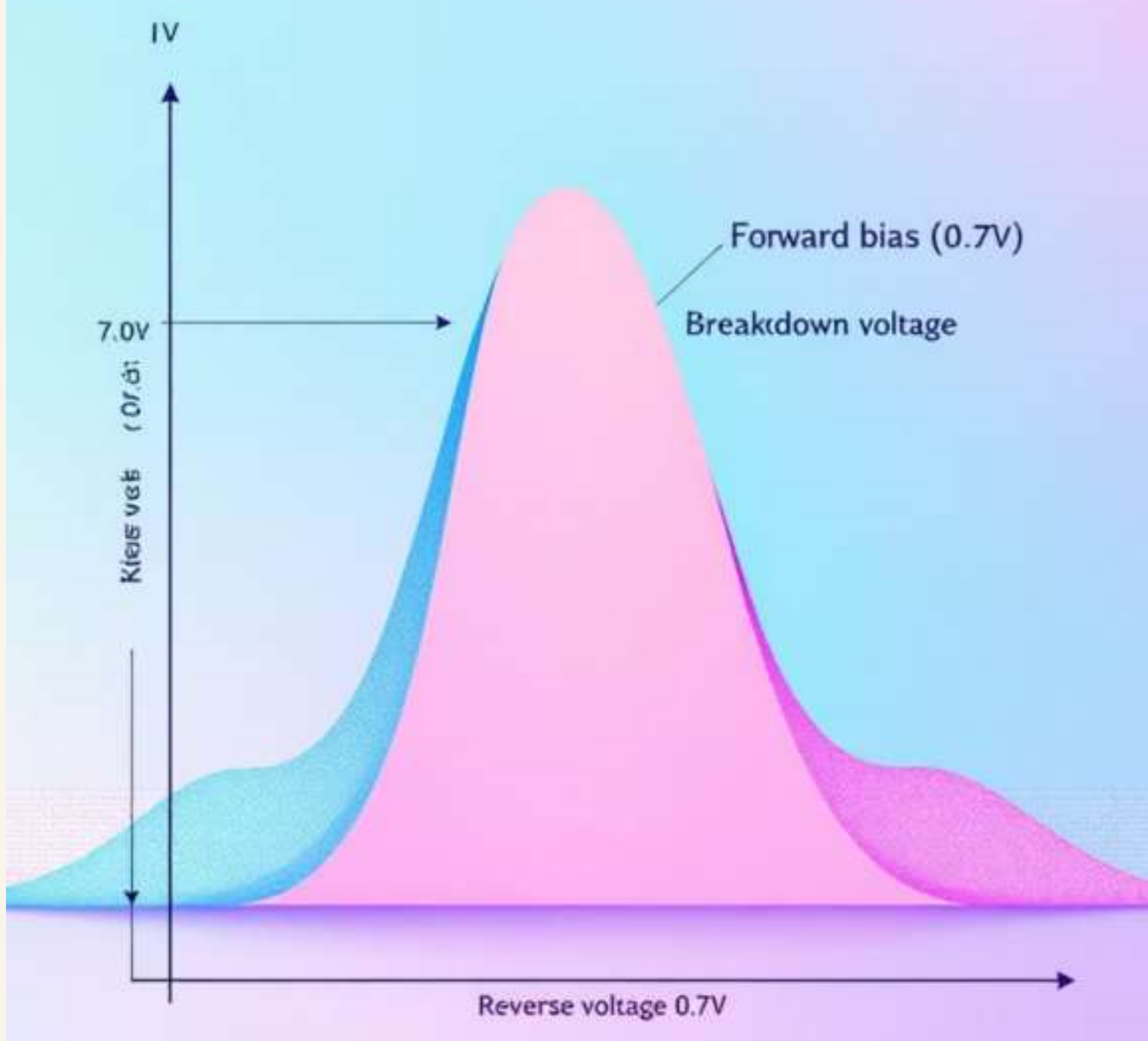
The applied voltage adds to the built-in potential, pulling the mobile carriers away from the junction and drastically widening the depletion region.

Minimal Current

The resulting resistance is extremely high, allowing only a minute, temperature-dependent "leakage current" to flow.

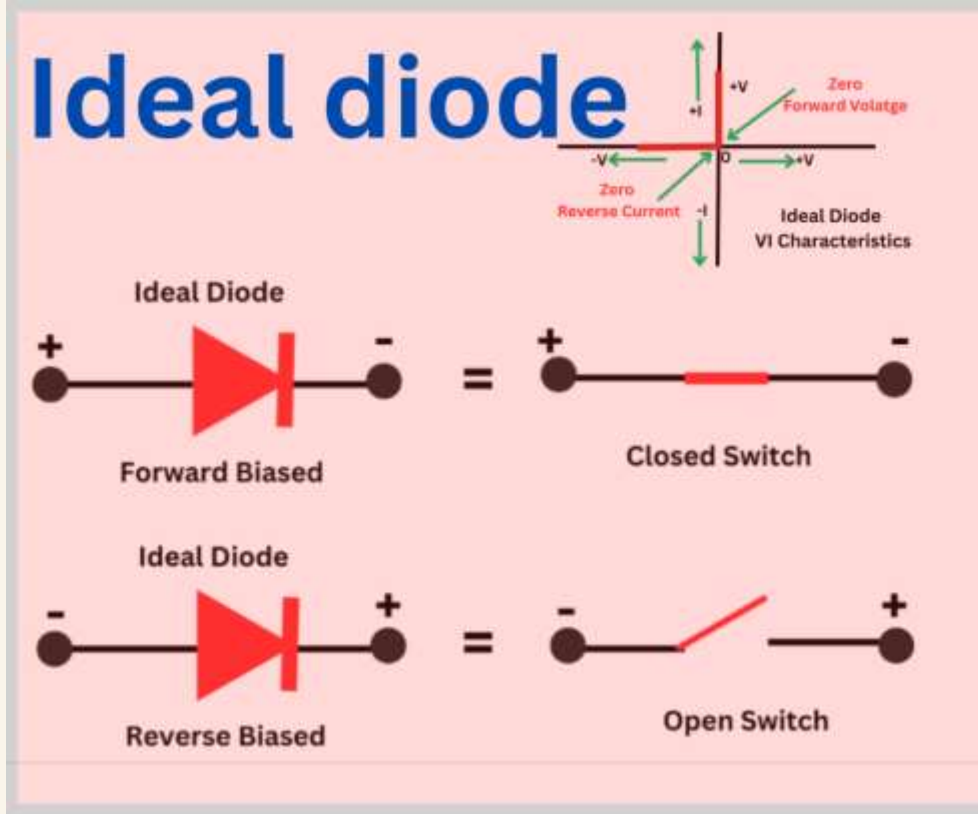
The Diode's Personality: Current vs. Voltage

The I-V curve graphically represents the diode's behaviour: exponential current growth in forward bias after the knee voltage, and near-zero current until the catastrophic reverse breakdown voltage is reached.



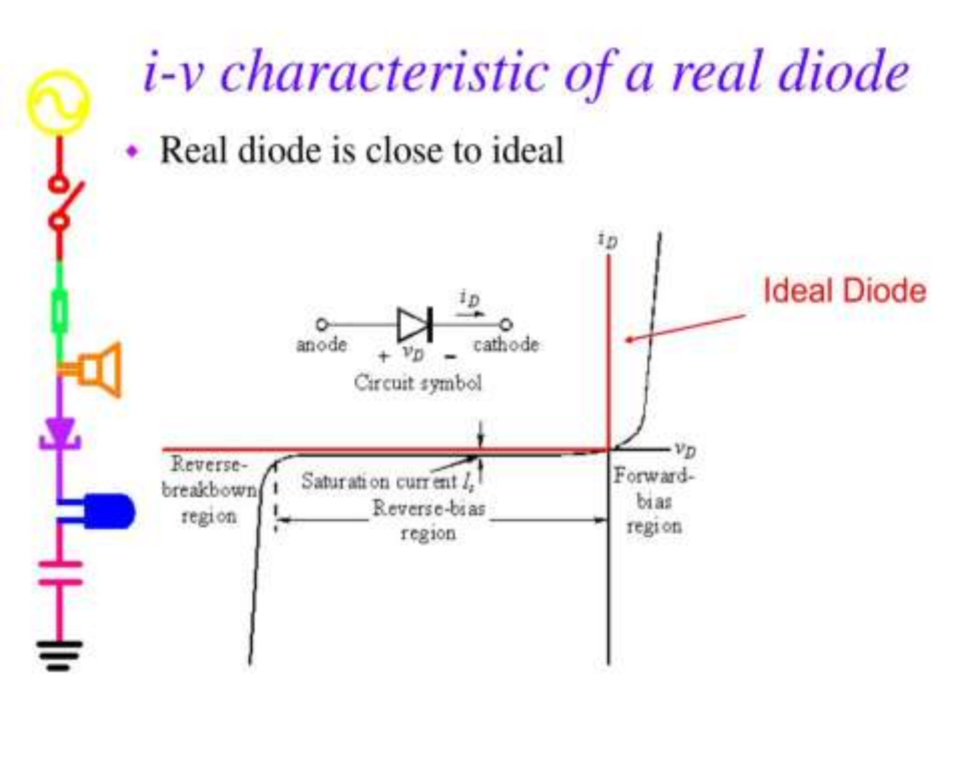
Ideal Diode Model

- ✓ *I-V Characteristics: Ideal case*
Perfect conductor in forward bias, perfect insulator in reverse bias, ideal I-V curve.
- ✓ *Limitations of ideal model in real-world appliactions, neglecting volatge drop in forward bias and small reverse current.*



Real Diode Model

- ✓ ***Shockley diode equation***
Mathematical representation of the diode current-voltage relationship, saturation current, applied voltage, and thermal voltage
- ✓ ***Forward bis characteristics***
Volatge dependency on the forward current, voltage drop across the real diode in forward bis
- ✓ ***Reverse bias characteristics***
Reverse saturation current and its temperature dependences, breakdown voltage and its impact on diode operations, leakage current considerations.



3. Applications: The Diode at Work

The unique directional conductivity of the diode makes it crucial for a vast range of electronic functions:

Rectification

Converting alternating current (AC) into pulsating direct current (DC), essential for all modern power supplies and adapters.

Digital Switching

Acting as a high-speed electronic switch to control current flow in digital logic gates, memory chips, and processing units.

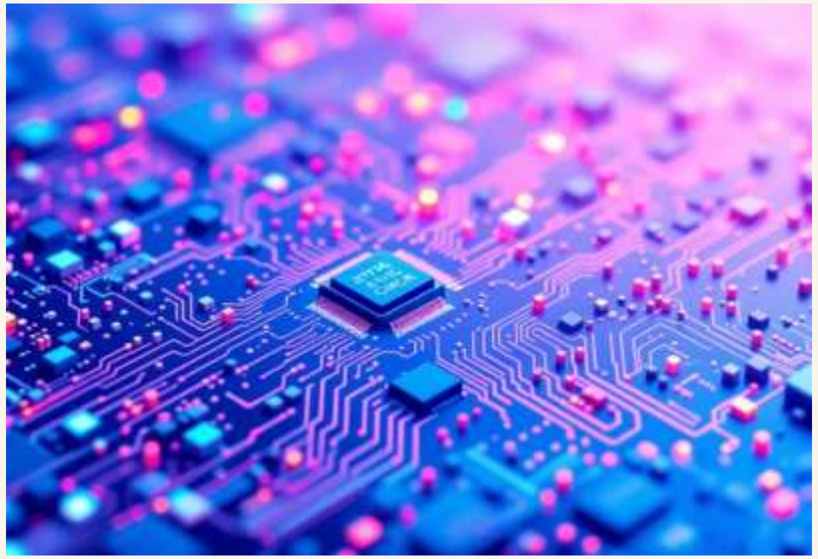
Signal Demodulation

Used in older radio circuits to separate the information signal (audio) from the high-frequency carrier wave.

Voltage Regulation

Specialised Zener diodes are designed to operate in reverse breakdown, maintaining a precise, constant output voltage across a circuit.

4. The Future of Diodes: Small, Smart, and Essential



Foundation of Integration

Diodes remain fundamental components for continued miniaturisation and ultra-dense integration within complex integrated circuits (ICs).

Enabling Advanced Tech

Their principles underpin advanced photonics (LEDs, laser diodes) and energy harvesting (solar cells), driving future technological breakthroughs.

The simple PN junction diode is, and will remain, an irreplaceable cornerstone of all electronic engineering.

5. Conclusion

Advantages

PN junction diodes are inexpensive, reliable, and have a simple structure. They are widely available, have a long lifespan, and are easy to integrate into electronic circuits.

Disadvantages

PN junction diodes have a limited power handling capability, and their performance can be affected by temperature changes. They also have a relatively slow switching speed compared to more advanced semiconductor devices.