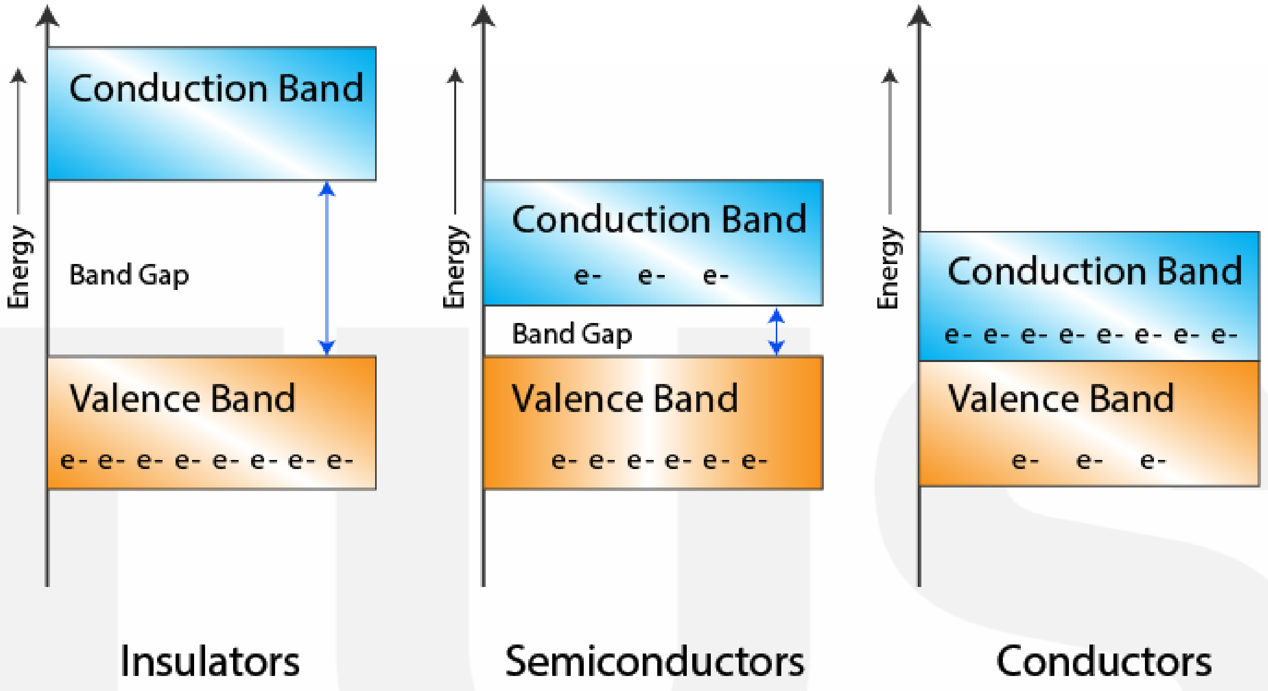
TUS

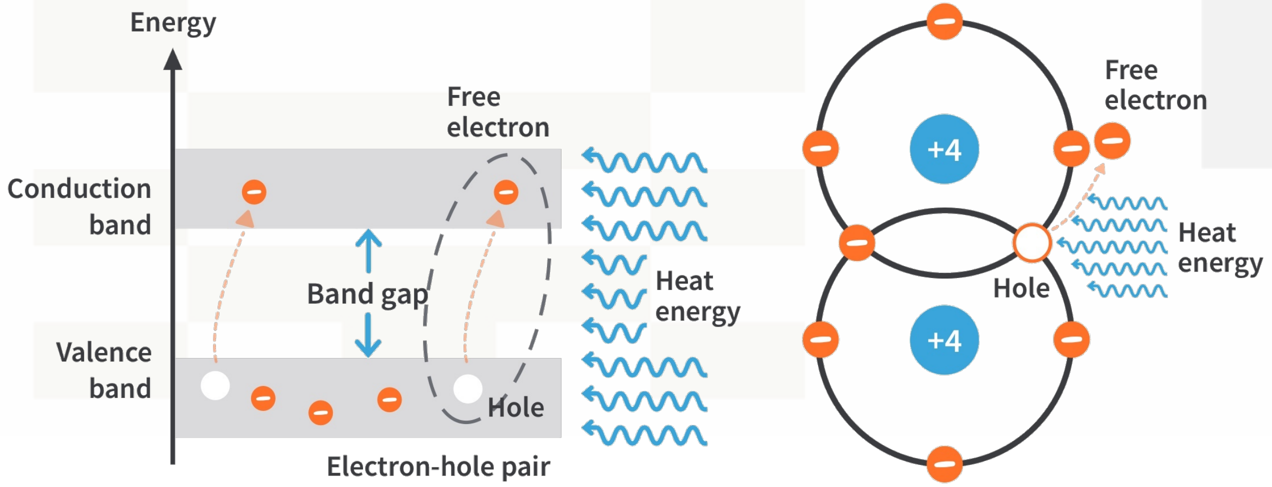
28th Engineering Week

Basic Principles and Applications of Semiconductor Technology

What Are Semiconductors?

- A special class of materials.
- Controllable electrical properties.
- The role of the "band gap".
- Intrinsic vs. extrinsic materials.



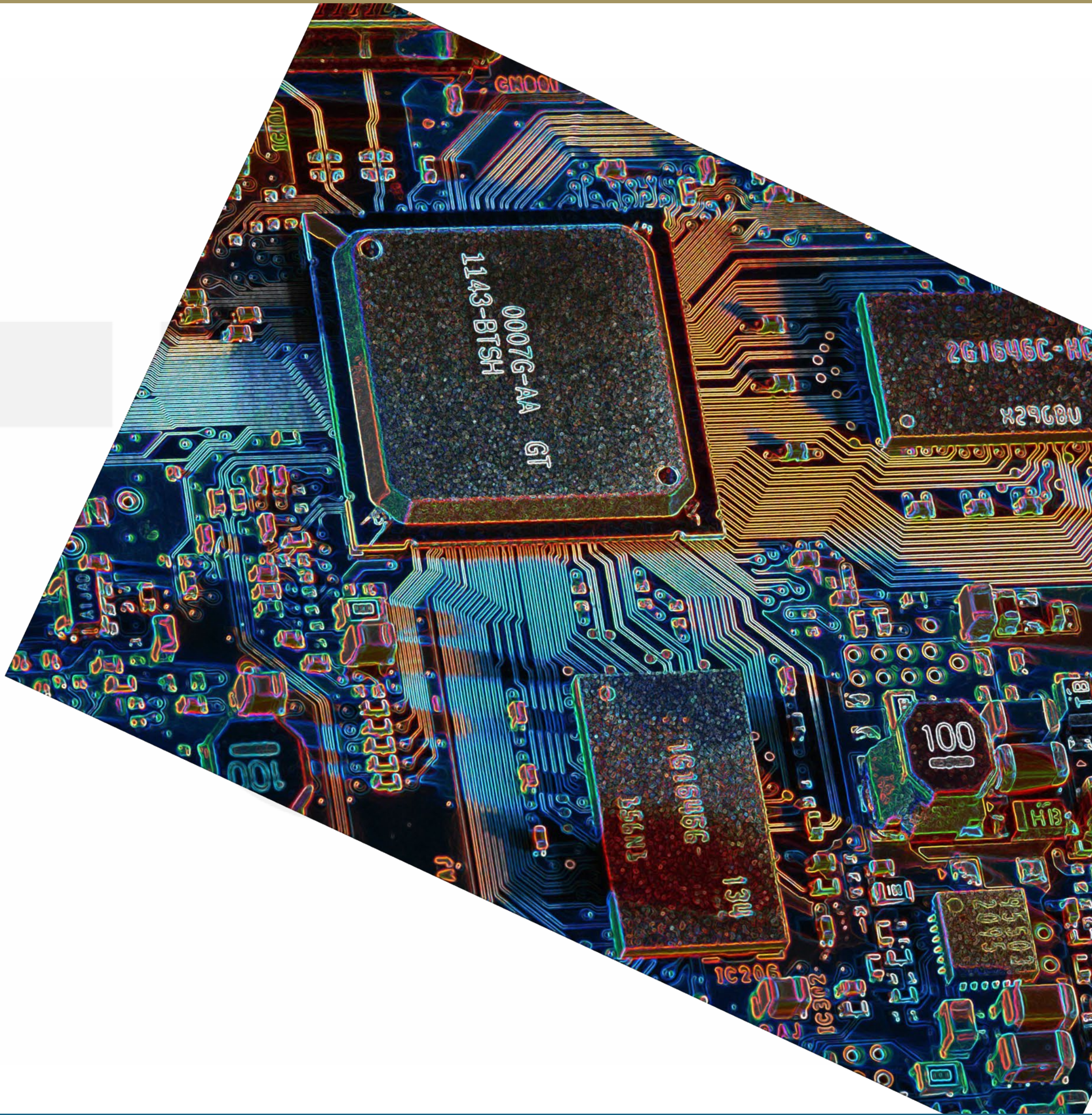


Common materials used:

- *Silicon (Si)* – the workhorse of electronics due to abundance and stability.
- *Gallium Arsenide (GaAs), Gallium Nitride (GaN), Silicon Carbide (SiC)* – used for high-frequency, high-power, or optical applications.

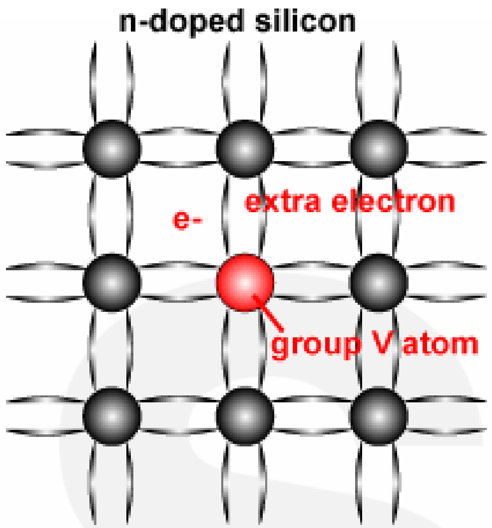
Why Semiconductors Matter

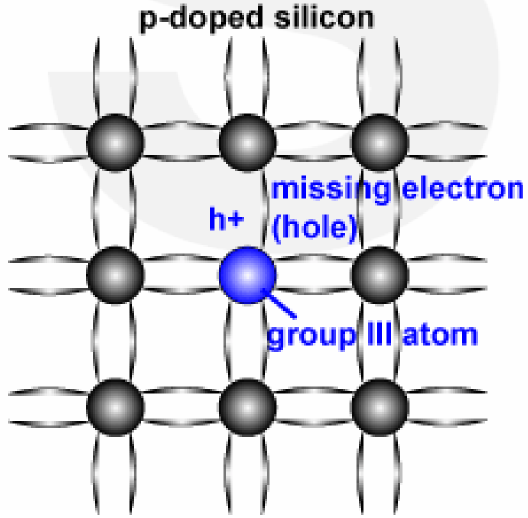
- The backbone of modern electronics.
- Enable miniaturisation and high-speed computing.
- Critical to global communication systems.
- Driving the energy transition.
- Revolutionising lighting and display technologies.
- Foundation for future technologies.



Doping — N-type and P-type

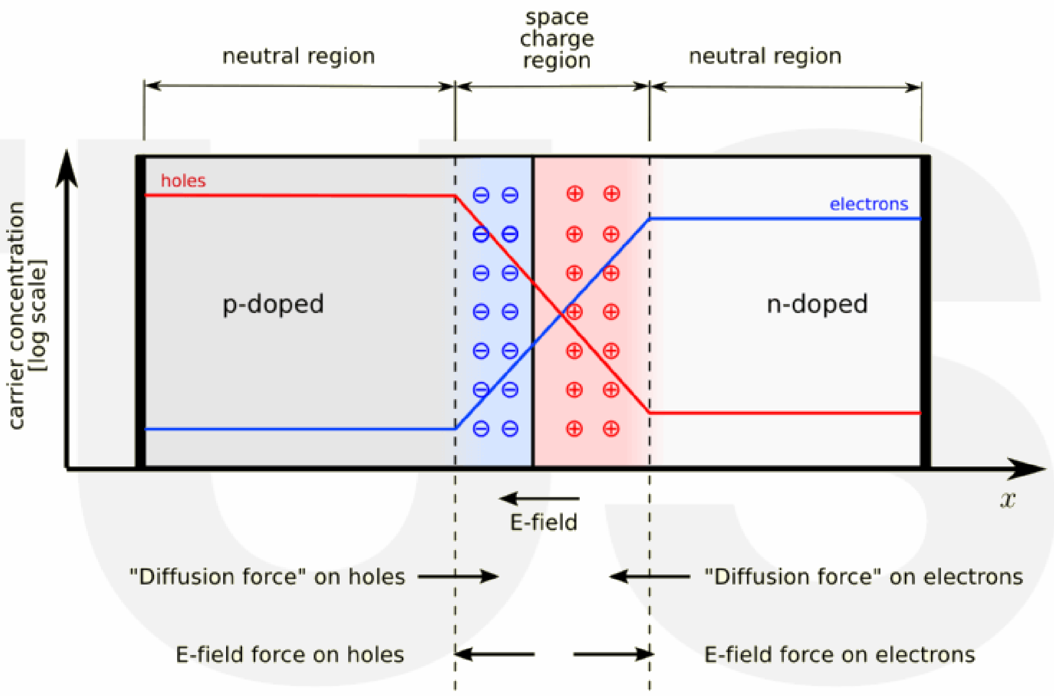
- Why doping matters.
  - Pure (intrinsic) semiconductors like silicon don't conduct very well at room temperature because they have very few free charge carriers.
- The goal of doping.
  - By carefully adding donor or acceptor atoms (typically only **1** impurity per **10^6** silicon atoms), the type and number of charge carriers in the crystal lattice can be changed without destroying its structure.
- N-type semiconductor.
  - Created by adding **donor atoms** with *five valence electrons* (e.g., phosphorus, arsenic).
- P-type semiconductor.
  - Created by adding **acceptor atoms** with *three valence electrons* (e.g., boron, gallium).
- Balance and control.
  - The ratio of donor to acceptor atoms determines the carrier concentration — and therefore, how conductive the semiconductor is.





P–N Junction Formation

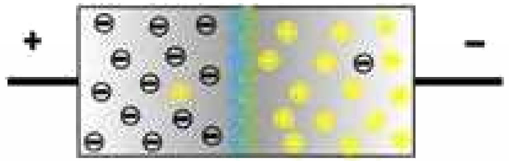
- Bringing opposites together.
  - **p-type** (rich in holes), **n-type** (rich in electrons) form a *p–n junction.*
- Initial carrier movement.
  - Electrons (n-type) & Holes (p-type) diffuse across the junction.
- Formation of the depletion region.
  - This diffusion creates a **depletion zone** — a region depleted of free charge carriers.
- Establishment of the potential barrier.
  - The electric field opposes further diffusion of electrons and holes.



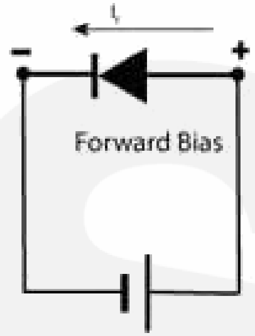
- Thermal equilibrium condition.
  - The junction remains stable with a small built-in voltage (typically around 0.6–0.7V for silicon).

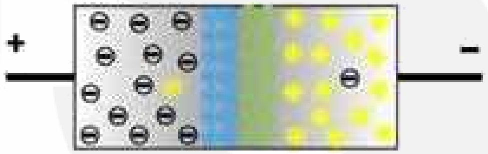
Biasing the P–N Junction

- Purpose of biasing.
  - By applying an external voltage to the p–n junction, we can alter the width of the depletion region and control whether current can flow.

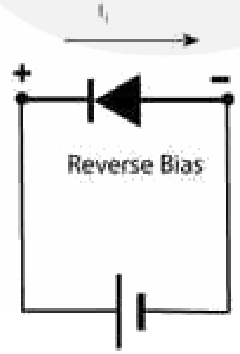


- Forward Bias — Turning the Junction “ON”.
  - The **positive terminal** of the power source is connected to the **p-type** side, and the **negative terminal** to the **n-type** side.
  - The depletion region **narrows**, reducing the barrier height.
  - Once the applied voltage exceeds the built-in potential (~0.6–0.7 V for silicon), charge carriers can easily cross the junction.



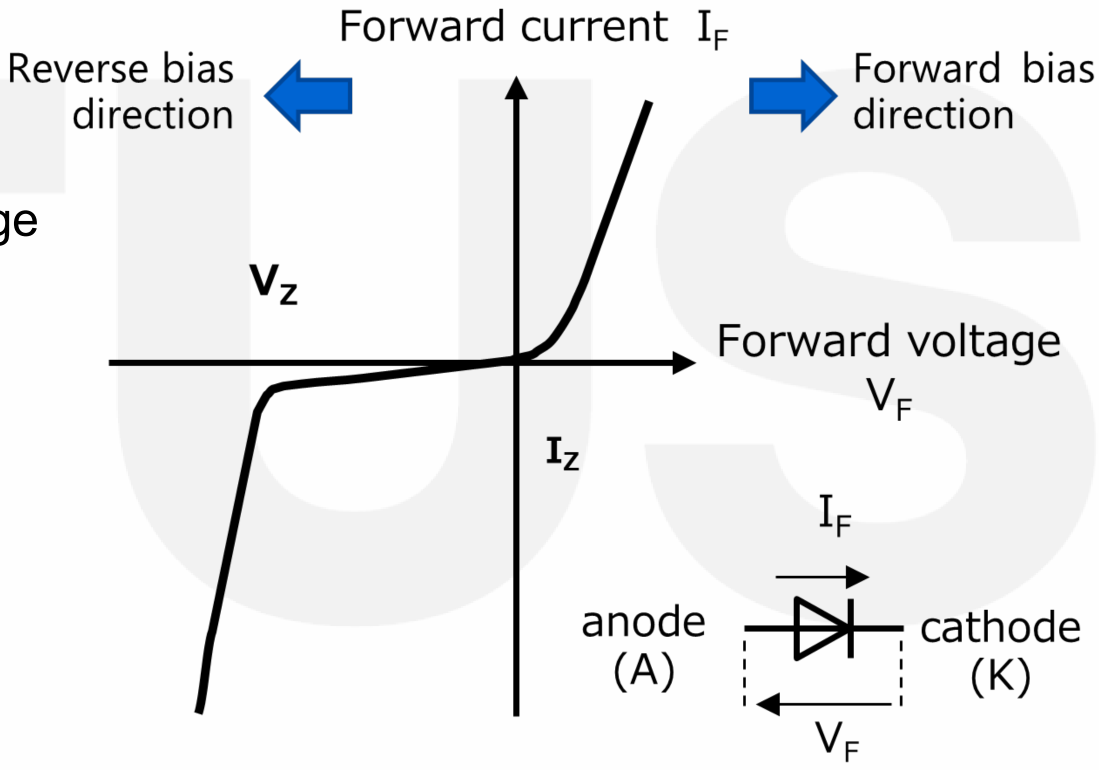


- Reverse Bias — Turning the Junction “OFF”.
  - The **positive terminal** is connected to the **n-type** side, and the **negative terminal** to the **p-type** side.
  - The depletion region **widens**, and the barrier becomes higher.
  - Only a very small **leakage current** flows due to minority carriers.



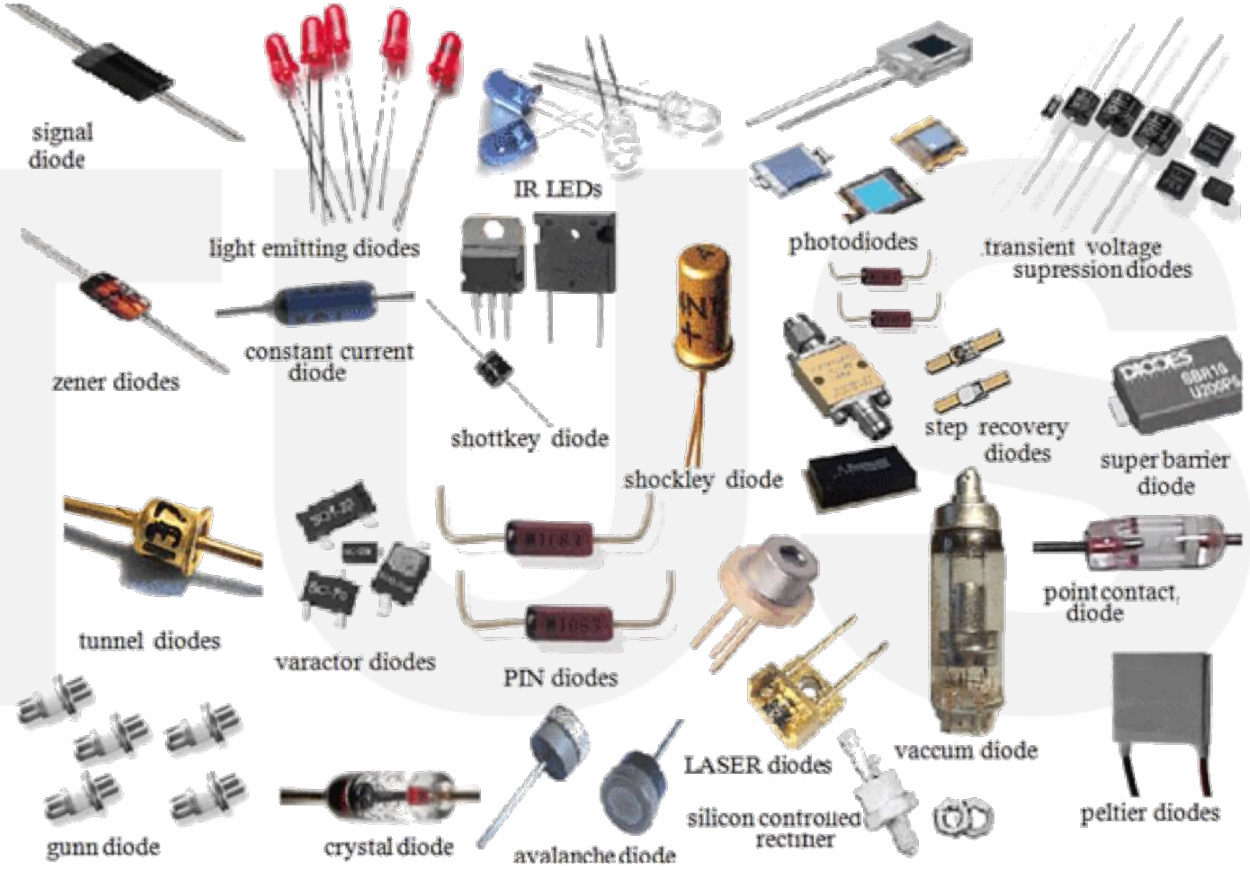
Diode Operation (Conceptual)

- Forward Bias — The Conducting State.
  - The external voltage **opposes** the diode's built-in potential barrier. The **depletion region** narrows. Conduction begins.
- Reverse Bias — The Blocking State.
  - The applied voltage **adds to** the built-in potential. The **depletion region** widens. Conduction halts (small leakage current)
- Breakdown Phenomena.
  - If the reverse voltage becomes sufficiently large, the electric field within the depletion region becomes strong enough to **free bound electrons** from the lattice.
  - This results in a sudden increase in current — known as **breakdown**.
  - Two primary mechanisms: **Avalanche** Breakdown - **Zener** Breakdown



Diode Types & Uses

- Rectifier Diodes — Turning AC into DC.
- Zener Diodes — Voltage Regulation by Design.
- Schottky Diodes — Speed and Efficiency.
- Light-Emitting Diodes (LEDs)
- Photodiodes — Light as a Signal.

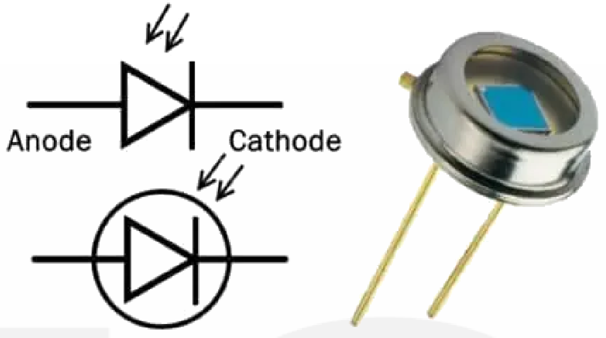


Optoelectronics: LEDs, Lasers, Photodiodes

- Light Emitting Diodes (LEDs).
  - When forward-biased, electrons and holes recombine across the junction.
  - This recombination releases energy as **photons** — a process called **electroluminescence**.
  - High **efficiency** and **long life** (no filament or gas).
  - Low **heat output** and **instant-on response**.
  - Different colour LEDs have different forward voltages.

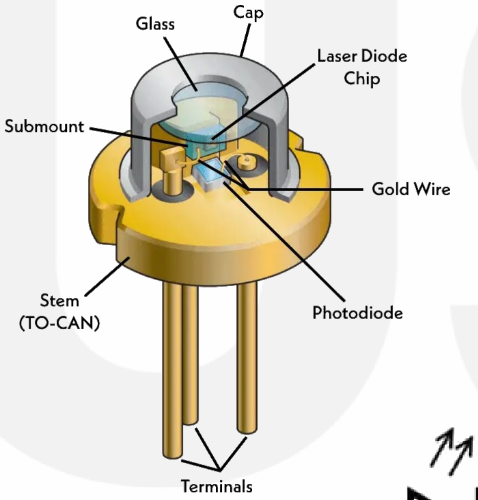
- Laser Diodes
  - Laser diodes operate on **stimulated emission**, where one photon triggers identical photons, producing a coherent light beam.
  - **Highly directional** and **coherent** (same phase and wavelength).
  - Can operate continuously or in pulses.

- Photodiodes — Detecting Light.
  - A **reverse-biased p–n junction** where incident photons

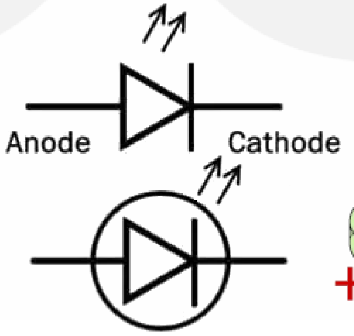


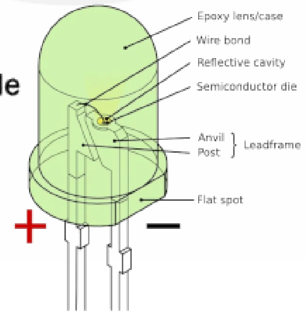
PhotoDiode

LaserDiode



LED



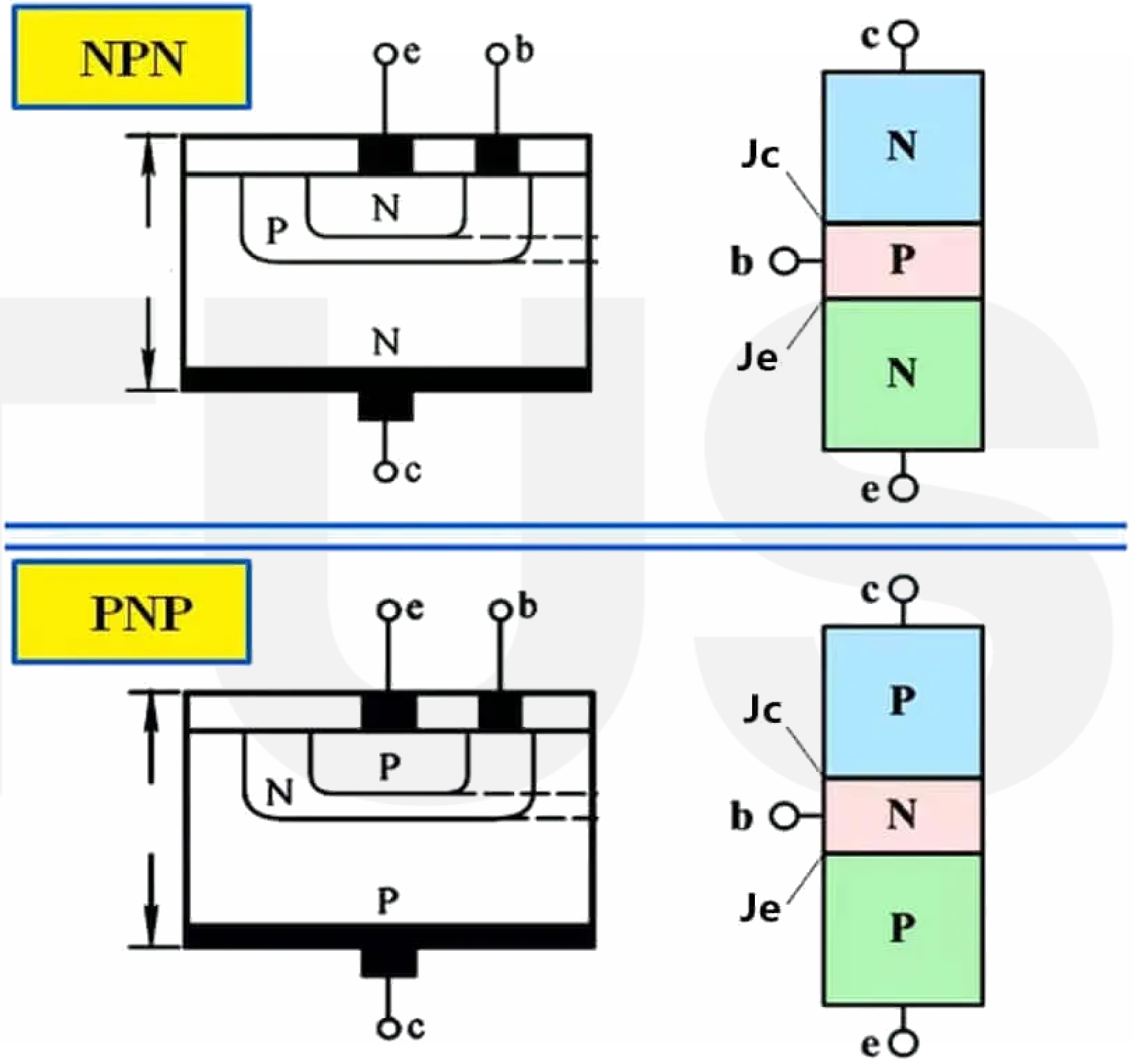


BJT — Conceptual Operation

- A Three-Layer, Two-Junction Device.
  - Emitter (E) Heavily doped; its job is to inject **charge carriers**.
  - Base (B) Very thin and lightly doped; acts as a **control gate** that regulates how many carriers pass through.
  - Collector (C) Moderately doped and larger area; collects the carriers.

  - NPN (N-type) – PNP (P-type)

- Current-Controlled Operation.
  - **base–emitter** junction is **forward biased**.
  - A **small base** current causes a much larger **collector current**.
  - **(I^c) = (I^B) * (β)**
  - **(I^e) = (I^B) + (I^c)**

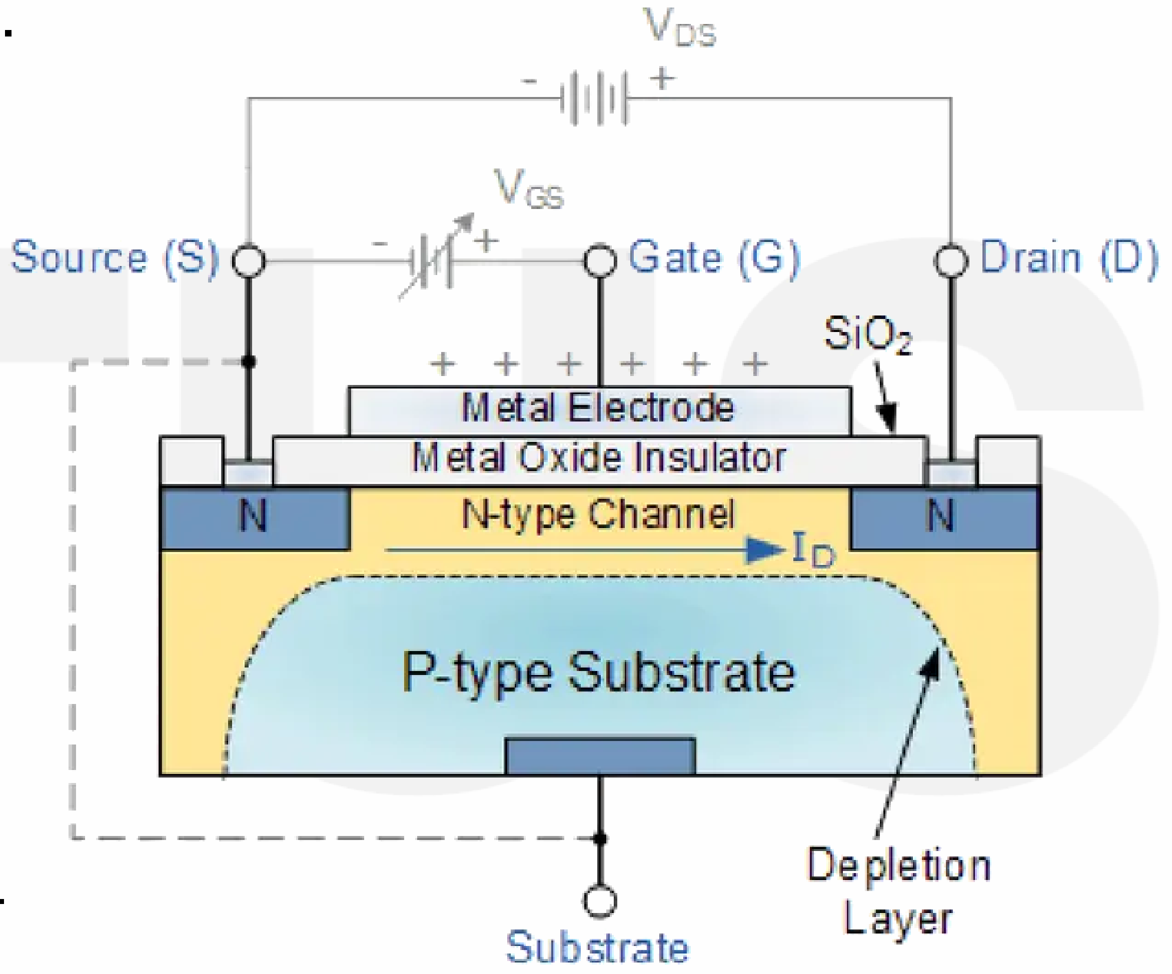


MOSFET — Conceptual Operation

- A Voltage-Controlled Semiconductor Switch.
  - **Source (S)** – where charge carriers enter.
  - **Drain (D)** – where carriers leave.
  - **Gate (G)** – a **metal electrode** insulated from the semiconductor channel by a thin **oxide layer.**

- How It Works
  - Applying a **gate voltage** induces an **electric field** in the semiconductor.
  - This **attracts charge carriers** toward the surface.
  - Once enough carriers accumulate, a **conductive channel forms**.

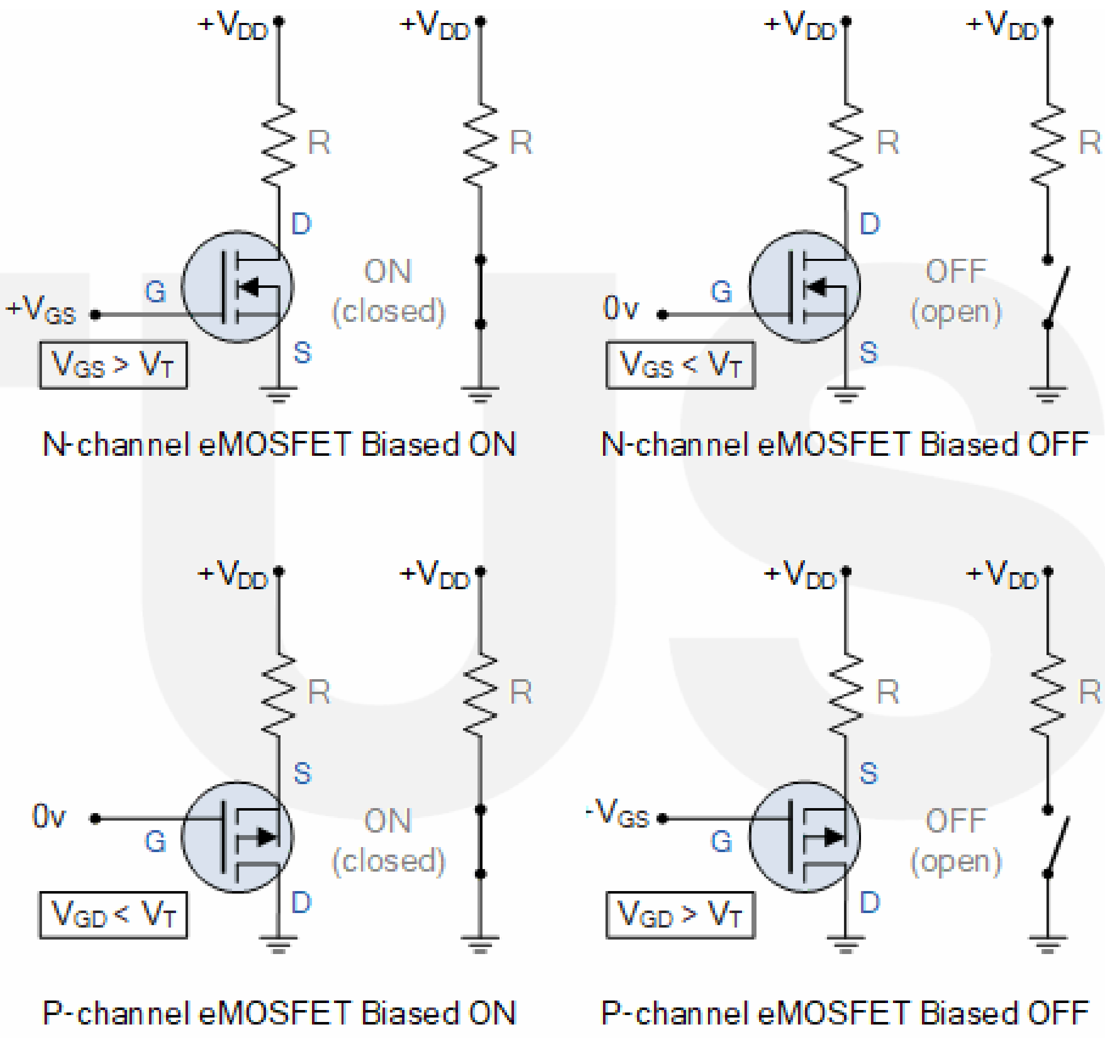
- Contrast with **BJT**.
  - BJT: Current-controlled, MOSFET: Voltage-controlled.
  - This makes MOSFETs easier to drive from microcontrollers or logic Ic’s.



MOSFET (Metal–Oxide–Semiconductor Field-Effect Transistor)

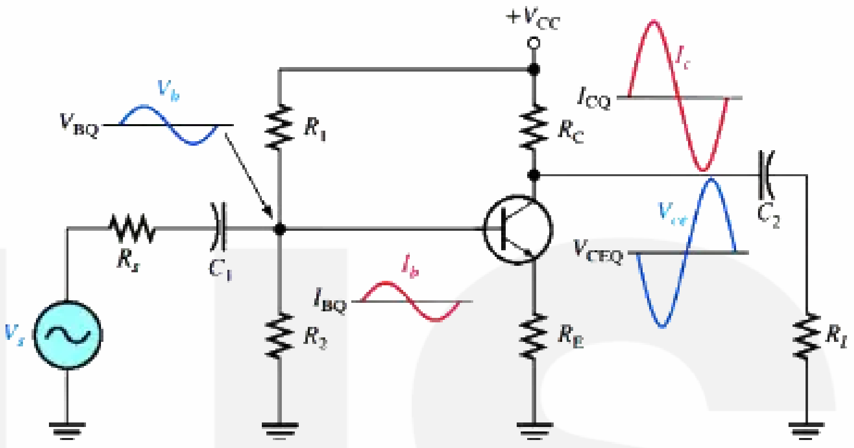
Transistor as a switch

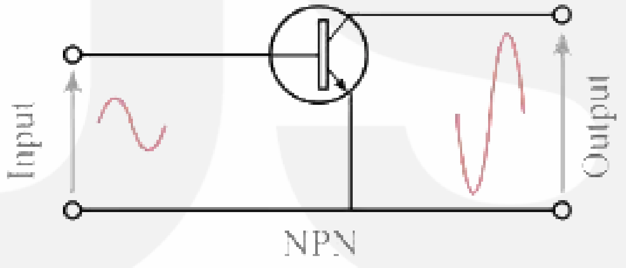
- In the **ON state**,
  - The transistor conducts heavily (BJT in **saturation**, MOSFET in **enhancement** mode).
  - Acts like a **closed switch**, allowing current to flow freely.
- In the **OFF state**,
  - It blocks current (BJT in **cutoff**, MOSFET with gate voltage removed (N) added (P).
  - Acts like an **open switch**, isolating the load.
- Advantages:
  - Transistors switch in **nanoseconds**, enabling GHz clock rates in processors.
  - Minimal energy wasted when fully on or off (especially with MOSFETs).
  - Solid-state operation means no moving parts — billions can operate simultaneously.

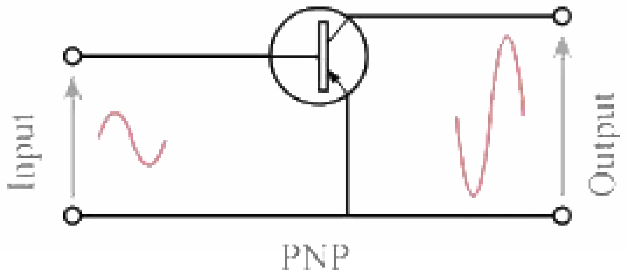


Transistor as an amplifier

- In analogue applications,
  - Transistors work in their **active region** (partially on), where small variations in input cause **proportional, larger variations** in output.
  - This enables **signal amplification** — boosting weak signals without distortion.
  - A **small base (or gate) signal** controls a **larger collector/drain current**.
  - The transistor acts as a **variable resistor or valve**, where the control voltage/current adjusts output flow.
  - The output signal maintains the same shape as the input, but with greater amplitude or power.
- Types:
  - **Common emitter / source:** Voltage amplifier (used in audio, sensor circuits).
  - **Common collector / drain:** Buffer stage (impedance matching).
  - **Common base / gate:** Current amplifier (high-frequency use).







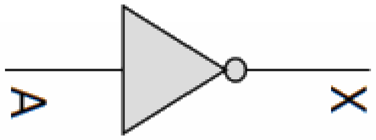
Logic Gates (Transistor)

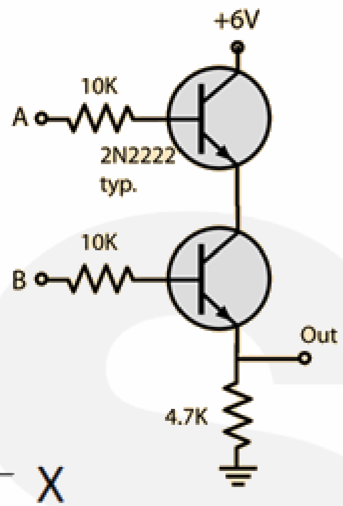
- Building Logic and Intelligence
  - Combining transistors in clever ways produces the basic logic functions (**AND**, **OR**, **NOT**, NAND, NOR, XOR, XNOR).
  - A simple inverter circuit → **NOT gate**.
  - Two MOSFETs in series → **AND gate** behaviour.
  - Two in parallel → **OR gate.**

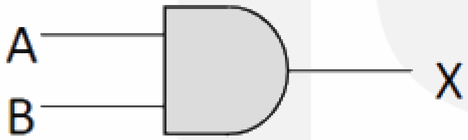
- Linking gates together:
  - *Sequential logic*: Such as **flip-flops** and **counters.**
  - *Arithmetic and control*: Such as **adders**, **multiplexers**, and **control units**, which underpin the architecture of **CPUs** and **microcontrollers.**

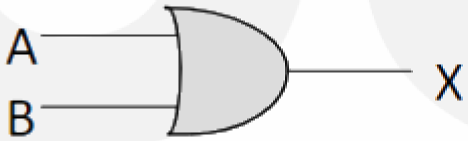
A single **microprocessor chip** may contain **tens of billions** of transistors, each switching billions of times per second.

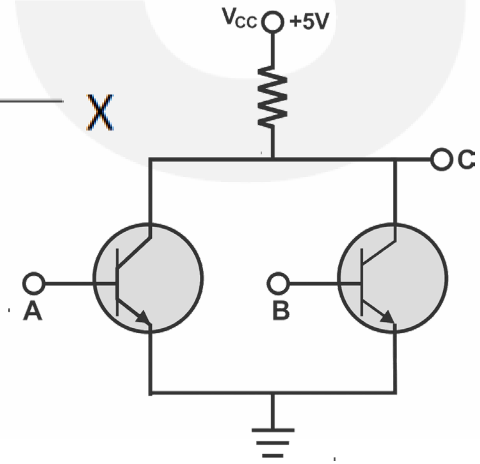
This scalability is what made the **Information Age** possible — from smartphones to AI.





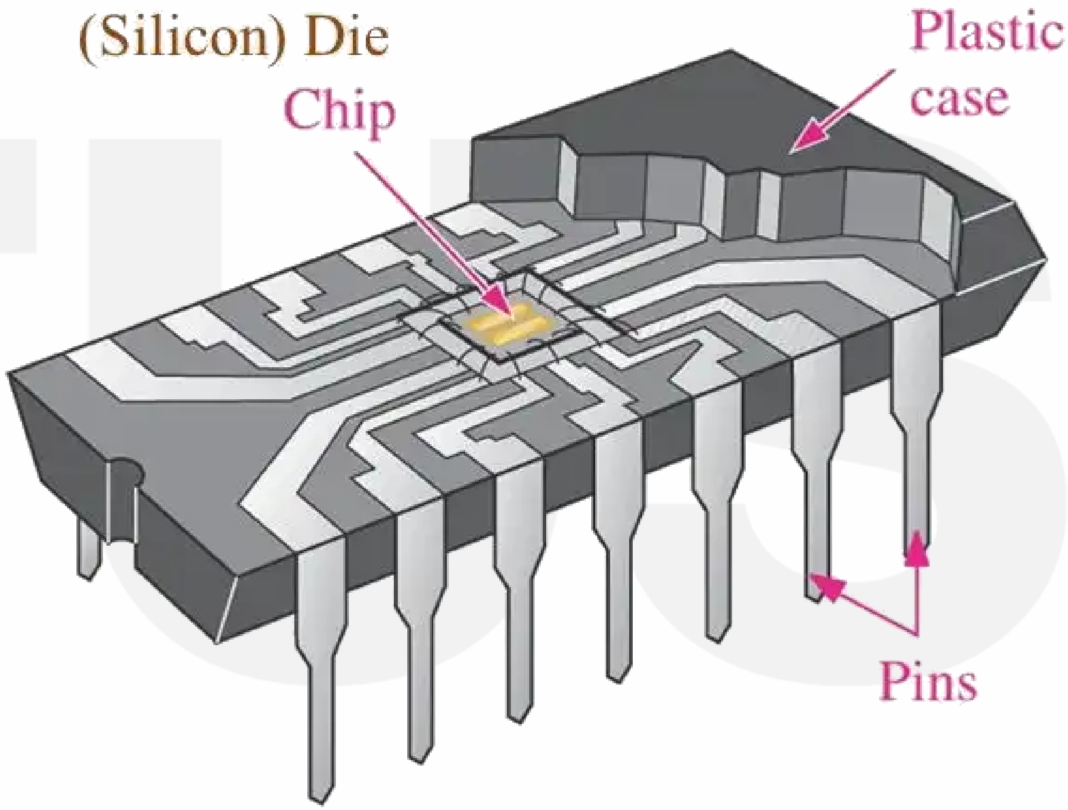






Integrated Circuits & Fabrication (High Level)

- An Integrated Circuit **(IC):**
  - Is a **complete electronic circuit** containing **many transistors and passive components** (resistors, capacitors) fabricated together on a **single piece of silicon**, called a **die**.
  - Reduces **size**, **cost**, and **power consumption** compared to discrete components.
  - Increases **speed and reliability** by eliminating long wiring paths.
  - Enables entire systems (CPUs, sensors, memory) to fit on one chip.
  - The invention of the IC (1958–1959) transformed electronics.



Integrated Circuits & Fabrication (High Level)

- How **IC**s Are Made**:**
  - A wafer is a **thin, polished disc of crystalline silicon** (typically 150–300 mm in diameter).
  - It serves as the **substrate** on which billions of transistor are built simultaneously.

- Fabrication process
  - Reduces **size**, **cost**, and **power consumption** compared to discrete components.
  - Increases **speed and reliability** by eliminating long wiring paths.
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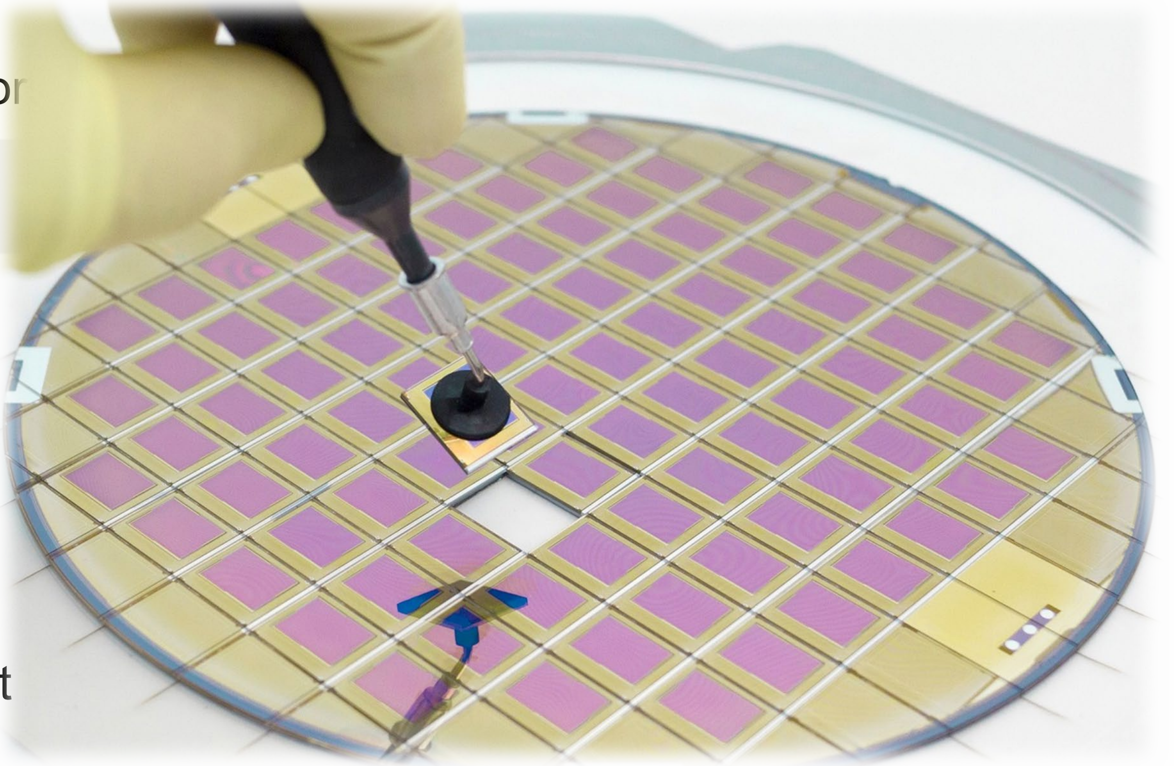


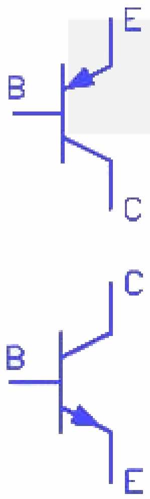
Semiconductor Sensors & IoT

Common uses:

- Inverters (DC ↔ AC Conversion):
- Motor Drivers:
- Electric Vehicles (EVs):
- Other applications:

BJT

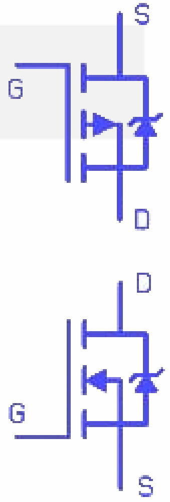
output current is a function of current signal into base



a current signal into base modulates the number of current carriers available to carry current thru device

FET

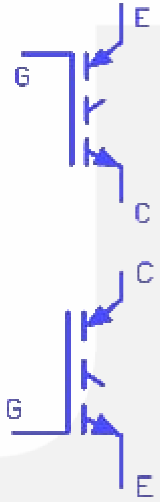
output current is a function of voltage signal at gate



a voltage signal at gate modulates channel resistance, and thus current thru device

IGBT

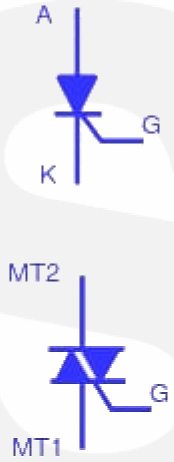
output current is a function of voltage signal at gate



a voltage signal at gate modulates both channel resistance and available current carriers, and thus current thru device

Thyristor

output latches *on* when triggered by pulse signal at gate



a small gate pulse triggers the device on. It stays latched on until the current thru the device drops below its holding current (I_H)

Emerging Materials & Trends

- **The Role of Semiconductors in Modern Sensing**.
  - Semiconductors are not only used for computing and power — they're also at the **heart of modern sensors**, converting physical quantities (like temperature, light, motion, or gas concentration) into **electrical signals**.
  - That same technology that builds transistors and ICs also builds **tiny, intelligent sensors**, forming the foundation of the **Internet of Things (IoT)**.

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