# Collegedunia NCERT Formula Sheet

*The Ultimate Formula Reference for Class 12 Physics*

## Chapter 14: Semiconductor Electronics

| Quantity / Material | Value |
|---|---|
| Band gap, $E_g$ (Si, 300 K) | $1.12$ eV |
| Band gap, $E_g$ (Ge, 300 K) | $0.67$ eV |
| Band gap, $E_g$ (GaAs) | $1.43$ eV |
| Diamond (insulator) $E_g$ | $\sim 6$ eV |
| Si intrinsic $n_i$ (300 K) | $\sim 1.5 \times 10^{16}$ /m$^3$ |
| Diode forward voltage (Si) | $\sim 0.7$ V |
| Diode forward voltage (Ge) | $\sim 0.3$ V |

## 1 Energy Bands in Solids

In a single atom, electrons occupy discrete levels. In a solid, these levels broaden into **bands**. The width of the gap between the last filled band and the next empty one classifies materials as conductors, semiconductors, or insulators (NCERT 14.2).

### Three classes of solids

**Conductor**: valence and conduction bands **overlap** ($E_g = 0$). Free electrons available at any temperature. Examples: Cu, Ag.
**Semiconductor**: small gap ($E_g \leq 3$ eV). Few thermally excited electrons at room temperature. Examples: Si ($E_g = 1.1$ eV), Ge ($E_g = 0.7$ eV).
**Insulator**: large gap ($E_g > 3$ eV). Almost no thermal excitation. Examples: diamond ($E_g \approx 6$ eV).

### Effect of temperature

**Conductors**: resistance **rises** with $T$ (more lattice scattering).
**Semiconductors / insulators**: resistance **falls** with $T$ (more carriers thermally promoted across the gap).
This opposite temperature behaviour is the standard test to distinguish a semiconductor from a metal.

## 2 Intrinsic & Extrinsic Semiconductors

A pure semiconductor has equal numbers of electrons and holes; doping shifts this balance to make n-type or p-type material (NCERT 14.3–14.4).

### Intrinsic semiconductor

$n_e = n_h = n_i$

In a pure (intrinsic) Si or Ge crystal, every thermally broken bond produces **one** electron and **one** hole. $n_i$ depends strongly on $T$ and $E_g$: $n_i \propto T^{3/2}\exp(-E_g/2k_BT)$.

### Doping

**n-type**: dope Si (group IV) with a **group-V** atom (P, As, Sb). Each donor atom contributes **one extra electron**. Majority: electrons. Minority: holes.
**p-type**: dope with a **group-III** atom (B, Al, Ga). Each acceptor atom creates **one extra hole**. Majority: holes. Minority: electrons.

### Mass-action law

$n_e\,n_h = n_i^2$

Holds in any doped semiconductor at thermal equilibrium. Doping increases majority carriers and **decreases** minority carriers, keeping the product constant.

### Conductivity

$\sigma = e(n_e\mu_e + n_h\mu_h)$

where $\mu_e, \mu_h$ = electron and hole mobilities (m$^2$/V/s).

Both electrons and holes contribute. In Si, $\mu_e \approx 0.135$ m$^2$/V/s; $\mu_h \approx 0.048$ m$^2$/V/s. Electrons are about 3× faster.

## 3 p–n Junction Diode

Joining p-type and n-type material creates a region depleted of mobile carriers — and a built-in electric field that controls one-way conduction (NCERT 14.5–14.6).

### Formation of the depletion layer

At the junction, electrons from n-side diffuse into p-side and recombine with holes; holes diffuse the other way. This leaves a region of **exposed ionised dopants** on each side — a **depletion layer** with no mobile carriers, only a built-in $\vec{E}$ field. The resulting potential barrier $V_b$ stops further diffusion in equilibrium.

### Built-in barrier potential

Si: $V_b \approx 0.7$ V; Ge: $V_b \approx 0.3$ V

Width: $W \sim 1\ \mu$m (typical); falls with doping.

No external voltage source — arises from the diffusion-drift balance at equilibrium. The diode ”wakes up” only when this barrier is crossed.

### Forward bias

Apply $V > V_b$ with **p-side at higher potential**. The applied field opposes the built-in field; the depletion layer **narrows**; majority carriers cross easily. Current rises sharply once $V$ exceeds $V_b$ — the **knee voltage**. Diode acts like a closed switch.

### Reverse bias

Apply $V$ with **n-side at higher potential**. The applied field adds to the built-in field; depletion layer **widens**. Almost no majority current flows; only a tiny **reverse saturation current** from minority carriers. Beyond a critical $V_z$ — breakdown — current rises catastrophically.

### Diode equation

$I = I_0\left[e^{eV/k_BT} - 1\right]$

where $I_0$ = reverse saturation current.

Strong asymmetry: $V > 0$ gives exponential growth; $V < 0$ saturates to $-I_0$. Captures the full $I$–$V$ curve.

### Dynamic resistance

$r_d = \dfrac{\Delta V}{\Delta I}$

Slope of $V$–$I$ characteristic at the operating point. Forward biased ($V > V_b$): $r_d$ is small (a few $\Omega$). Reverse biased: $r_d$ is enormous (M$\Omega$).

## 4 Rectifiers & Filtering

Diodes convert AC into pulsating DC. A capacitor across the load smooths the output (NCERT 14.7).

### Half-wave rectifier

A single diode in series with the AC source and load. Conducts during **one half-cycle only**; blocks the other. Output is **pulsating DC** with $f_{\text{out}} = f_{\text{in}}$. Inefficient; uses only half the input.

### Full-wave rectifier

Uses **two diodes** (with centre-tapped transformer) or **four diodes** in a bridge. Conducts during **both half-cycles**. Output: $f_{\text{out}} = 2f_{\text{in}}$. Twice as efficient as half-wave.

### Output of rectifier (smoothed)

$$V_{\text{DC}} = V_m - V_{\text{ripple}}$$

For full-wave with capacitor filter $C$ across load $R$: ripple shrinks as $C$ rises ($V_{\text{ripple}} \propto 1/fRC$).

Capacitor charges to $V_m$ during the peak, then slowly discharges through $R$ until the next peak. Larger $C$ or $R \Rightarrow$ smoother DC.

## 5 Special-Purpose Diodes

Diodes engineered for specific behaviours: voltage regulation, light emission, light detection, and energy conversion (NCERT 14.8).

### Zener diode

Heavily doped diode designed to operate in **reverse breakdown**, where $V$ stays nearly constant at $V_z$ over a wide range of currents. Used as a **voltage regulator**: a Zener in parallel with the load holds the output at $V_z$ even if the input or load fluctuates.

### Photodiode

A reverse-biased p–n junction with a transparent window. Incident photons with $h\nu > E_g$ create electron–hole pairs in the depletion region; the built-in field separates them, producing a photocurrent proportional to incident intensity. Used in **light meters, optical fibre receivers**.

### Light-emitting diode (LED)

A heavily doped, forward-biased p–n junction. As electrons recombine with holes across the junction, they release energy as photons of $h\nu \approx E_g$. Material choice ($E_g$) sets the colour: GaAs (IR), GaP (red), GaN/InGaN (blue, white). Highly efficient compared to filament bulbs.

### Solar cell

A large-area p–n junction operated **without external bias**. Sunlight creates electron–hole pairs; the built-in field separates them, and the current is collected by metal contacts. Generates a photovoltage $V_{\text{OC}}$ and short-circuit current $I_{\text{SC}}$. Maximum efficiency for Si: $\sim 25\%$ in lab.

### LED & photodiode wavelength relation

$$\lambda = \frac{hc}{E_g} = \frac{1240}{E_g\,(\text{eV})}\ \text{nm}$$

An LED with $E_g = 2$ eV emits $\sim 620$ nm (orange). A photodiode with $E_g = 1.1$ eV (Si) detects up to $\sim 1100$ nm (near-IR).

### JEE/NEET Extension: Choosing diode materials

**Visible LED**: need $E_g \approx 1.8$–3.1 eV → GaAsP, GaP, GaN.

**Solar cell**: Si ($E_g = 1.1$ eV) is well-matched to the solar spectrum's peak.

**Optical fibre**: 1300–1550 nm windows → InGaAs photodiodes.

The match between $E_g$ and the photon energy is the design principle behind every optoelectronic device.

### Bias direction

**Forward**: P at + and N at $-$ (**P**ositive–**P**-side).
**Reverse**: P at $-$ and N at +.

Forward biased $\Rightarrow$ depletion narrows $\Rightarrow$ current flows.
Reverse biased $\Rightarrow$ depletion widens $\Rightarrow$ no current (until breakdown).

### Doping does not change conductivity type

A pure (intrinsic) semiconductor has equal $n_e = n_h$ but is **still electrically neutral**. Doping creates **majority carriers** but the crystal as a whole **remains neutral** (the donor/acceptor ions balance). Don't confuse ”n-type” with ”negatively charged”.

# Quick Reference — Semiconductor Electronics

| **Quantity / Concept** | **Expression** | **Notes** |
|---|---|---|
| Band gap (Si / Ge) | 1.1 / 0.7 eV | At 300 K |
| Intrinsic relation | $n_e = n_h = n_i$ | Pure semiconductor |
| Mass-action law | $n_e n_h = n_i^2$ | Always at equilibrium |
| Conductivity | $e(n_e\mu_e + n_h\mu_h)$ | Both carriers |
| Built-in barrier (Si) | $\sim 0.7$ V | Knee voltage |
| Built-in barrier (Ge) | $\sim 0.3$ V | Smaller $E_g$ |
| Diode equation | $I_0[e^{eV/k_BT} - 1]$ | Asymmetric |
| Dynamic resistance | $\Delta V/\Delta I$ | Forward: small |
| Half-wave $f_{\text{out}}$ | $f_{\text{in}}$ | Single diode |
| Full-wave $f_{\text{out}}$ | $2f_{\text{in}}$ | Bridge or centre-tap |
| LED / photodiode $\lambda$ | $\frac{1240}{E_g}$ nm | For $E_g$ in eV |
| Zener regulator | $V_{\text{out}} = V_z$ | Reverse breakdown |
| Doping (n-type) | Group-V donor | Majority: electrons |
| Doping (p-type) | Group-III acceptor | Majority: holes |