JEE MAIN · PAPER 1 · PHYSICS

19 Electronic Devices

Formula & concept sheet

From energy bands to circuits: what makes a semiconductor, how doping and the p-n junction give a diode, how diodes rectify, what Zener diodes, LEDs, photodiodes and solar cells do, and how logic gates combine. Each idea is explained first, then the formulas, shortcuts and traps.

INSIDE THIS SHEET

1	Energy bands and semiconductors	2
2	The p-n junction diode	3
3	Rectifiers	4
4	Zener diode, LED, photodiode and solar cell	5
5	Logic gates	6
6	Worked examples	7
7	Last-minute checklist	7

READ ALONGSIDE NCERT XII · Semiconductor Electronics: Materials, Devices and Simple Circuits

HOW TO USE THIS SHEET

1. **Skim** — Read the Key ideas, then the formula cards.
2. **Memorise** — Learn the formulas and check every Trap box.
3. **Test** — Do the worked examples, then this chapter's PYQs.
4. **Revise** — Use the last-minute checklist before the exam.

Formula memorise · **Key idea** why it works · **Trap** marks lost here · **PYQ** how it is asked

Practise this chapter with real past-paper questions on Prep Vault. Written for revision, not as a first read.

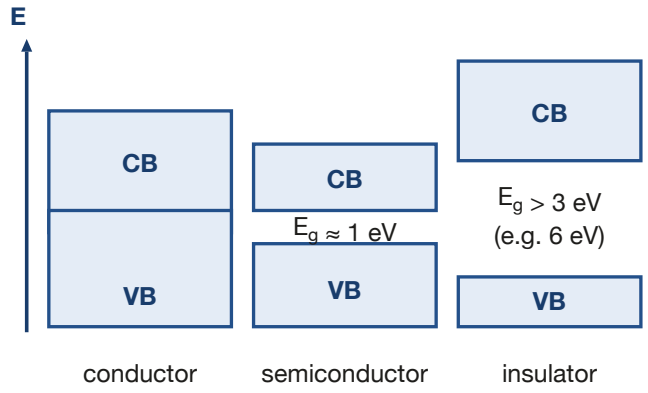
CHAPTER 19

Electronic Devices

NCERT XII · Semiconductor Electronics: Materials, Devices and Simple Circuits

Covers: energy bands · intrinsic and extrinsic semiconductors · p-n junction diode and its I-V characteristics · rectifiers · Zener diode as a regulator · LED, photodiode, solar cell · logic gates (OR, AND, NOT, NAND, NOR).

1 Energy bands and semiconductors



the size of the forbidden gap E_g separates conductors, semiconductors and insulators

ENERGY BANDS In a solid the electron energy levels merge into bands. The **valence band** is full; the **conduction band** above it is where electrons can carry current; between them lies the **forbidden gap** E_g. The size of the gap sorts materials: no gap in a conductor, a small gap (~ 1 eV) in a semiconductor, a large gap (> 3 eV) in an insulator.

CONDUCTOR, SEMICONDUCTOR, INSULATOR

	CONDUCTOR	SEMICONDUCTOR	INSULATOR
Bands	valence and conduction bands overlap	narrow gap: Si 1.1 eV, Ge 0.72 eV, GaAs 1.42 eV	wide gap, $E_g > 3$ eV
Resistivity (Ω m)	10^{-8} to 10^{-2}	10^{-5} to 10^{6}	10^{11} to 10^{19}
Effect of heating	resistance rises	resistance **falls** (more carriers)	little change

- **Intrinsic** (pure) semiconductor: each broken bond frees an electron and leaves a hole, so $n_e = n_h = n_i$. Heat or light across the gap makes pairs.
- **n-type**: doped with a pentavalent atom (P, As): the extra electron is a **donor** level just below the conduction band; majority carriers are electrons. **p-type**: doped with a trivalent atom (B, Al, In): an **acceptor** level just above the valence band; majority carriers are holes.
- Doped crystals are still **electrically neutral**; "n" or "p" names the majority carrier, not a net charge.

MASS-ACTION LAW

$$n_e n_h = n_i^2$$

at equilibrium for any doping: n-type with $N_D \gg n_i$: $n_e \approx N_D$, $n_h = \dfrac{n_i^2}{N_D}$

CONDUCTIVITY

$$\sigma = e(n_e\mu_e + n_h\mu_h), \quad \rho = \frac{1}{\sigma}$$

μ mobility; $v_d = \mu E$

PHOTON ACROSS THE GAP

$$\lambda_{max} = \frac{hc}{E_g} = \frac{1240}{E_g(\text{eV})} \text{ nm}$$

light of longer wavelength cannot lift an electron over the gap

TRAP

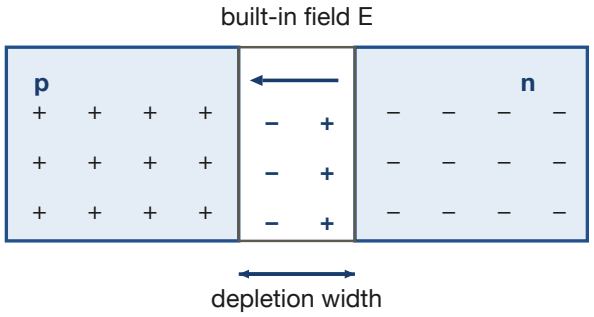
Heating **lowers** a semiconductor's resistance (more pairs), opposite to a metal. A crystal does not become charged by doping.

QUICK CHECK

Silicon has $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$ and is doped with $N_D = 10^{15}\ \text{cm}^{-3}$. Hole density?

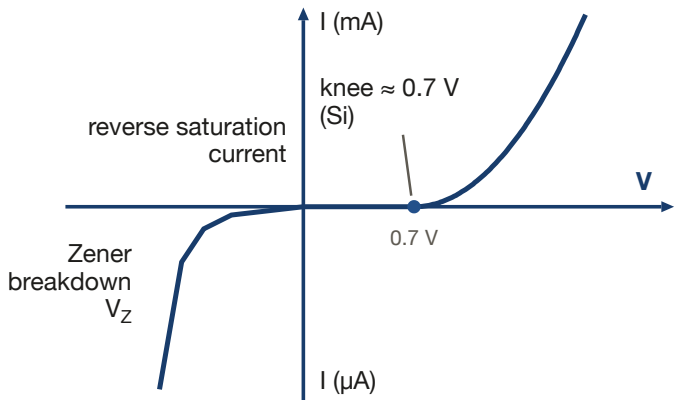
Answer: $n_h = \dfrac{n_i^2}{N_D} = \dfrac{2.25 \times 10^{20}}{10^{15}} = 2.25 \times 10^{5}\ \text{cm}^{-3}$.

2 The p-n junction diode



the depletion layer of fixed ions sets up the barrier potential (about 0.7 V in Si)

P-N JUNCTION Joining p and n material, holes diffuse into the n side and electrons into the p side. They leave behind fixed ions, so a **depletion layer** forms with no free carriers and an internal field that opposes further diffusion. The potential difference across it is the **barrier potential**, about 0.7 V for Si and 0.3 V for Ge.



forward conduction above the knee (≈ 0.7 V), tiny reverse current, sharp breakdown at V_Z

BIASING

- **Forward bias** (p to the positive terminal): the external voltage lowers the barrier and thins the depletion layer; current is negligible until the **knee** voltage, then rises steeply.
- **Reverse bias**: the barrier grows and the layer widens; only a tiny, nearly constant **reverse saturation current** of minority carriers flows, until breakdown at a large reverse voltage.
- An ideal diode is a wire in forward bias and an open gap in reverse.

DYNAMIC RESISTANCE

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

inverse slope of the forward curve at the operating point (very large in reverse)

KNEE VOLTAGE

Si ≈ 0.7 V, Ge ≈ 0.3 V

below it the forward current is negligible

DEPLETION WIDTH

$N_A x_p = N_D x_n$

the layer reaches farther into the more lightly doped side

DIODE IN A CIRCUIT

1. Decide for each diode whether it is forward biased (anode more positive than cathode by the knee voltage).
2. Replace a forward diode by a wire (or a 0.7 V drop); remove any reverse-biased diode.
3. Solve the resulting resistor circuit.

TRAP

Check the polarity before replacing a diode: a reverse-biased diode carries **no** current in the circuit problems. For a precise current use 0.7 V for silicon unless told otherwise.

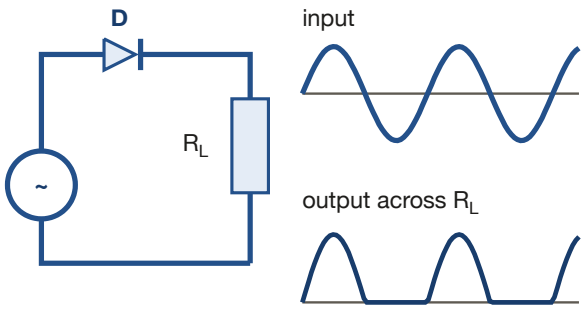
QUICK CHECK

A 10 V cell, a 1 kΩ resistor and a forward-biased silicon diode in series. Current?

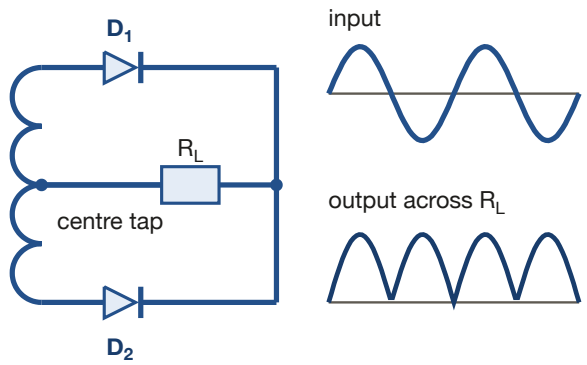
Answer: $I = \dfrac{10 - 0.7}{1000} = 9.3$ mA.

3 Rectifiers

A diode passes current only one way, so it turns alternating voltage into pulsating direct voltage: **rectification**. A capacitor across the load (a filter) smooths the pulses by charging at the peaks.



one diode passes only one half-cycle, so the output frequency equals the input frequency



each diode conducts on alternate half-cycles, so the output frequency is $2\times$ the input frequency

HALF-WAVE AGAINST FULL-WAVE (IDEAL DIODES, PEAK V_m)

	HALF-WAVE	FULL-WAVE
Diodes	one	two (centre-tap) or four (bridge)
Output frequency	f (same as input)	$2f$ (mains 50 Hz gives 100 Hz)
Average (dc) value	$V_{dc} = \dfrac{V_m}{\pi}$	$V_{dc} = \dfrac{2V_m}{\pi}$
Ripple factor	1.21	0.48
Efficiency	$\dfrac{4}{\pi^2} \approx 40.5\%$	$\dfrac{8}{\pi^2} \approx 81.1\%$

Books often quote 40.6% and 81.2% for the same ideal-diode efficiencies; use the value among the options.

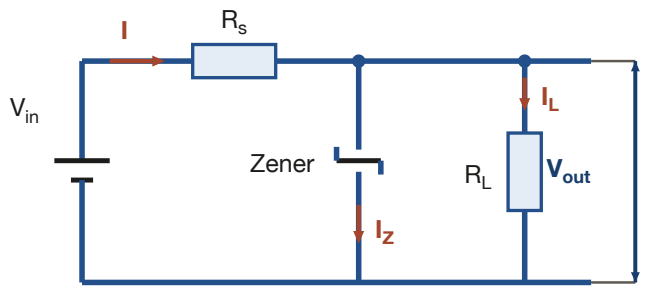
KEY IDEA

Full-wave rectification uses both half-cycles, so it has twice the frequency, twice the average value and a smoother output than half-wave.

TRAP

V_{dc} is the **average** of the output, not its RMS value. For a sine input the RMS is $V_m/\sqrt{2}$ (full-wave) or $V_m/2$ (half-wave).

4 Zener diode, LED, photodiode and solar cell



$I = I_Z + I_L$; the Zener keeps $V_{out} = V_Z$ while I_Z stays positive

ZENER DIODE A heavily doped diode designed to work in reverse **breakdown**, where the voltage across it stays almost fixed at V_Z while the current varies widely. In reverse bias it can hold a load at V_Z against changes in the supply: a voltage regulator.

REGULATOR CURRENTS

$$I_s = \frac{V_{in} - V_Z}{R_s}$$

$$I_L = \frac{V_Z}{R_L}, \quad I_Z = I_s - I_L$$

$I_Z \geq 0$ is needed for regulation

LARGEST ZENER CURRENT

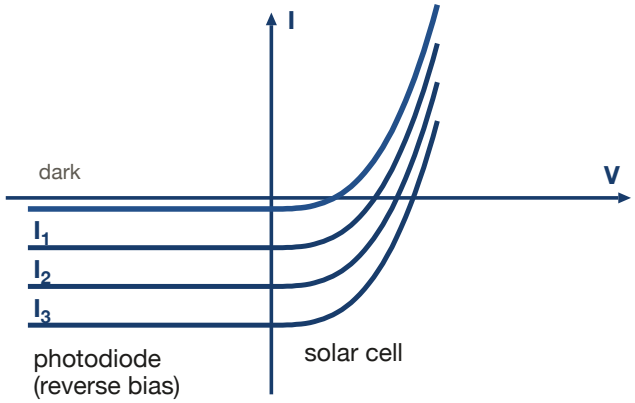
$$I_{Z,max} = \frac{P_{max}}{V_Z}$$

power rating over the Zener voltage

SAFE SERIES RESISTOR

$$R_{s,min} = \frac{V_{in} - V_Z}{I_{Z,max}}$$

worst case: the load is removed and the Zener takes all of I_s



reverse photocurrent grows with light intensity; in the fourth quadrant the device delivers power

LIGHT-SENSITIVE AND LIGHT-EMITTING DIODES

DEVICE	BIAS	ACTION
LED	forward	electrons and holes recombine at the junction and emit a photon of energy about E_g, $\lambda = \frac{1240}{E_g}$ nm
Photodiode	reverse	photons with $hf \geq E_g$ make pairs; reverse current rises with the light intensity
Solar cell	none	light makes pairs across the junction; the cell delivers power: I-V curve in the **fourth quadrant** (V_{oc}, I_{sc})

TRAP

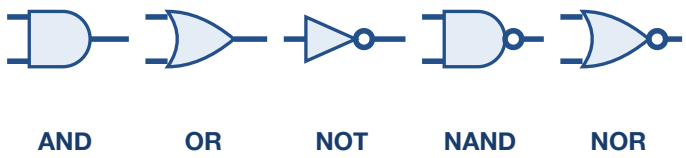
A Zener regulates in **reverse** breakdown; forward it is an ordinary diode. An LED is forward biased and emits; a photodiode is **reverse** biased and detects. A solar cell needs no bias.

QUICK CHECK

A 10 V, 0.4 W Zener runs from 15 V. Smallest safe series resistance?

Answer: $I_{Z,max} = \frac{0.4}{10} = 0.04$ A; $R_s = \frac{15 - 10}{0.04} = 125\ \Omega$.

5 Logic gates



bubble = inversion; $\overline{\text{NAND}}$ and NOR are universal gates, since any logic function can be built from either alone

LOGIC GATE A circuit with one or two inputs and one output, each either 0 (low) or 1 (high), whose output follows a fixed rule given by its **truth table**. A small circle (bubble) on a symbol means inversion: AND with a bubble is NAND, OR with a bubble is NOR.

TRUTH TABLES

A	B	OR	AND	NAND	NOR	NOT A
0	0	0	0	1	1	1
0	1	1	0	1	0	1
1	0	1	0	1	0	0
1	1	1	1	0	0	0

$Y = A + B$ (OR) · $Y = A \cdot B$ (AND) · $Y = \bar{A}$ (NOT) · $Y = \overline{A \cdot B}$ (NAND) · $Y = \overline{A + B}$ (NOR)

DE MORGAN

$$\overline{A + B} = \bar{A} \cdot \bar{B}$$
$$\overline{A \cdot B} = \bar{A} + \bar{B}$$

push a bar inward and swap $+$ and $\cdot$

IDENTITIES

$$A + \bar{A} = 1,\ A \cdot \bar{A} = 0$$
$$A + AB = A,\ \bar{\bar{A}} = A$$

also $A + A = A$ and $A \cdot A = A$

UNIVERSAL GATES

TO MAKE	FROM NAND	FROM NOR
NOT	tie the two inputs: $\overline{A \cdot A} = \bar{A}$	tie the two inputs: $\overline{A + A} = \bar{A}$
AND	NAND followed by a NOT	NOT on each input, then NOR
OR	NOT on each input, then NAND	NOR followed by a NOT

NAND and NOR can build every other gate, so each is called a **universal gate**.

A GATE CIRCUIT IN FOUR STEPS

1. Label every internal wire.
2. Fill the truth table column by column, wire by wire (four rows for two inputs, eight for three).
3. Match the output column to a named gate, or simplify with De Morgan first.
4. Shortcut: test the all-zero input; an output of 1 points to NAND or NOR style, 0 to AND or OR style. One mixed input then decides.

TRAP

Do not skip a bubble: it inverts the output. One wrong column in a table carries through to the answer; check each internal wire.

QUICK CHECK

$Y = \overline{A + B} + A\bar{B}$ with $A = 0$, $B = 1$. Value of Y?

Answer: $\overline{0 + 1} = 0$ and $A\bar{B} = 0 \cdot 0 = 0$, so $Y = 0$.

6 Worked examples

ZENER, TWO SUPPLIES

A 10 V Zener rated 0.5 W runs from 25 V. Series resistor to protect it?

$I_{Z,max} = \dfrac{0.5}{10} = 0.05$ A; $R_s = \dfrac{25 - 10}{0.05} = 300\ \Omega$

ZENER WITH A LOAD

$V_{in} = 20$ V, $R_s = 500\ \Omega$, $V_Z = 10$ V, $R_L = 1$ kΩ. Find I_s, I_L, I_Z.

$I_s = \dfrac{10}{500} = 20$ mA; $I_L = \dfrac{10}{1000} = 10$ mA; $I_Z = 20 - 10 = 10$ mA (≥ 0: regulating)

HALF-WAVE AVERAGE

A half-wave rectifier has a peak input of 10 V. Average output?

$V_{dc} = \dfrac{V_m}{\pi} = \dfrac{10}{\pi} \approx 3.18$ V

FULL-WAVE FREQUENCY

A full-wave rectifier is fed from 50 Hz mains. Output frequency?

$2 \times 50 = 100$ Hz

LED COLOUR

An LED has $E_g = 2.0$ eV. Wavelength emitted? And for GaAs (1.42 eV)?

$\dfrac{1240}{2.0} = 620$ nm (red); GaAs: $\dfrac{1240}{1.42} \approx 873$ nm (infrared)

DYNAMIC RESISTANCE

On the forward curve $\Delta V = 0.1$ V gives $\Delta I = 2$ mA. r_d?

$r_d = \dfrac{\Delta V}{\Delta I} = \dfrac{0.1}{2 \times 10^{-3}} = 50\ \Omega$

HOLE DENSITY

Silicon: $n_i = 1.5 \times 10^{10}$ cm^{-3}, $N_D = 10^{15}$ cm^{-3}. Minority carrier density?

$n_h = \dfrac{n_i^2}{N_D} = 2.25 \times 10^5$ cm^{-3} (mass-action law)

A GATE FROM NANDS

Two NAND gates: the first takes A and B; its output goes to both inputs of the second. Output?

first: $\overline{AB}$; second ties its inputs, so it inverts: $\overline{\overline{AB}} = AB$, an AND gate

7 Last-minute checklist

BEFORE YOU ANSWER

Which way is each diode biased? Is the quantity average or RMS? Which hc does the question give? Did you check every bubble on the gate symbols?

- Gap: conductor none, semiconductor about 1 eV, insulator > 3 eV; heating lowers a semiconductor's resistance.
- $n_e n_h = n_i^2$; $\sigma = e(n_e \mu_e + n_h \mu_h)$; n-type donors give electrons, p-type acceptors give holes; both neutral.
- Forward: knee 0.7 V (Si), 0.3 V (Ge); reverse: tiny saturation current; $r_d = \Delta V / \Delta I$.
- Half-wave: f, $V_{dc} = V_m/\pi$; full-wave: $2f$, $V_{dc} = 2V_m/\pi$.
- Zener (reverse): $I_{Z,max} = P/V_Z$, $R_s = (V_{in} - V_Z)/I_{Z,max}$; LED forward, photodiode reverse, solar cell fourth quadrant.
- OR $A + B$, AND AB, NOT $\bar{A}$, NAND $\overline{AB}$, NOR $\overline{A + B}$; De Morgan; NAND and NOR are universal.

Now test it. Practise this chapter with past-paper and bank questions on Prep Vault. **Practice this chapter →**