

Semiconductor Electronics: Reading Material for the Video Tutorial (Class 12)

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This reading material explains, in the same order as the video, how a semiconductor conducts, how a P-N junction diode works, and how diodes are used as rectifiers and special-purpose devices. Each section names the part of the video it goes with.

1. Conductors, semiconductors and insulators

Video: 0:46 to 1:24

Solids are grouped by how easily they carry electric current. Conductivity (σ) measures this, and resistivity (ρ) is its inverse, so a good conductor has high σ and low ρ .

Material	Resistivity ρ ($\Omega \text{ m}$)	Conductivity σ (S/m)	Examples
Metals (conductors)	10^{-2} to 10^{-8}	10^2 to 10^8	Copper, aluminium, silver
Semiconductors	10^{-5} to 10^6	10^5 to 10^{-6}	Silicon, germanium
Insulators	10^{11} to 10^{19}	10^{-11} to 10^{-19}	Glass, rubber, mica

- **Conductors** have a very large number of free electrons, so current flows easily.
- **Insulators** have almost no free charge carriers, so they offer very high resistance.
- **Semiconductors** lie between the two. Silicon (Si) and germanium (Ge) are the two most important ones.

Two properties make semiconductors useful. Their conductivity increases when temperature rises, which is the opposite of metals. And their conductivity can be changed by a very large factor by adding a tiny, controlled amount of impurity.

2. Energy bands

Video: 1:24 to 2:11

The size of the energy gap decides whether a solid is a conductor, a semiconductor or an insulator. In a single atom, electrons have sharp energy levels. In a solid, the atoms are so close that these levels spread into **energy bands**.

- **Valence band:** the band occupied by the valence electrons, which are held in bonds.
- **Conduction band:** the band above it. Electrons here are free to move and carry current.
- **Energy gap (E_g):** the gap between the top of the valence band and the bottom of the conduction band. No electron can have an energy inside this gap.

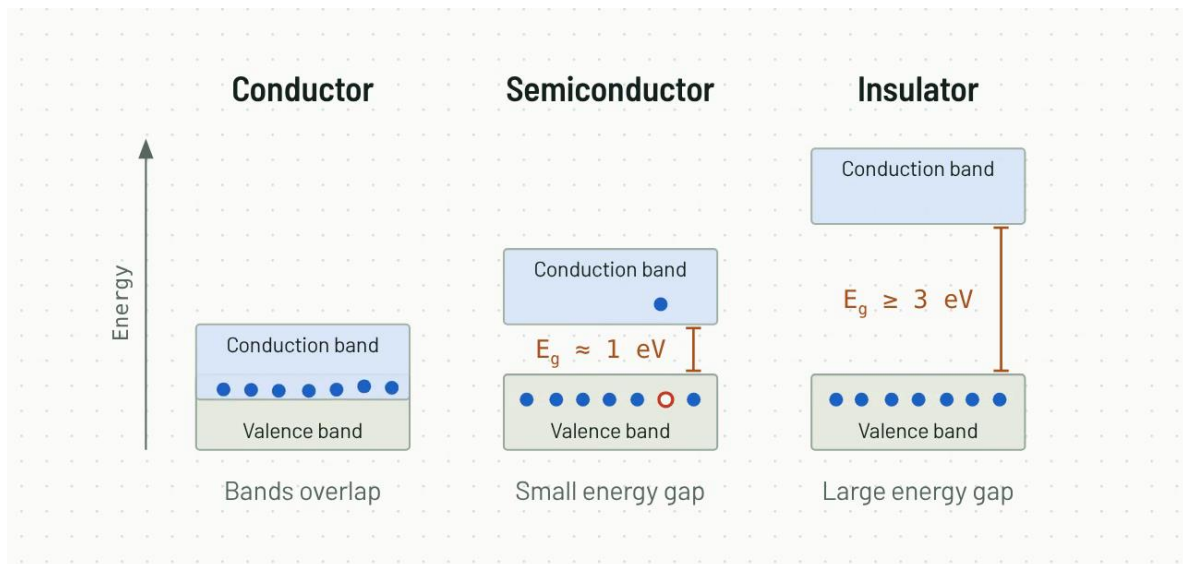


Figure 1. Energy bands of a conductor, a semiconductor and an insulator.

Material	Energy gap	What happens
Conductor	Bands overlap, or the conduction band is partly filled	Electrons move freely at any temperature
Semiconductor	Small, less than 3 eV (Si 1.1 eV, Ge 0.7 eV)	At room temperature some electrons gain enough energy to cross the gap
Insulator	Large, more than 3 eV	Practically no electron can cross the gap

At absolute zero a pure semiconductor behaves like an insulator, because no electron has enough energy to cross the gap. As temperature rises, more electrons reach the conduction band, so conductivity increases.

3. Intrinsic semiconductor

Video: 2:11 to 2:59

A pure semiconductor is called an **intrinsic semiconductor**, and it conducts through equal numbers of electrons and holes. Silicon and germanium each have four valence electrons. In the crystal, every atom shares one electron with each of its four neighbours, forming four **covalent bonds**.

- **At low temperature** all valence electrons stay in their bonds. There are no free carriers and the crystal does not conduct.
- **As temperature rises** some electrons gain enough thermal energy to break free. Each one becomes a **free electron**.
- **The vacancy left in the bond is called a hole**. It behaves like a positive charge.
- **A hole moves** when an electron from a neighbouring bond jumps into it. The hole then appears at the place that electron left.

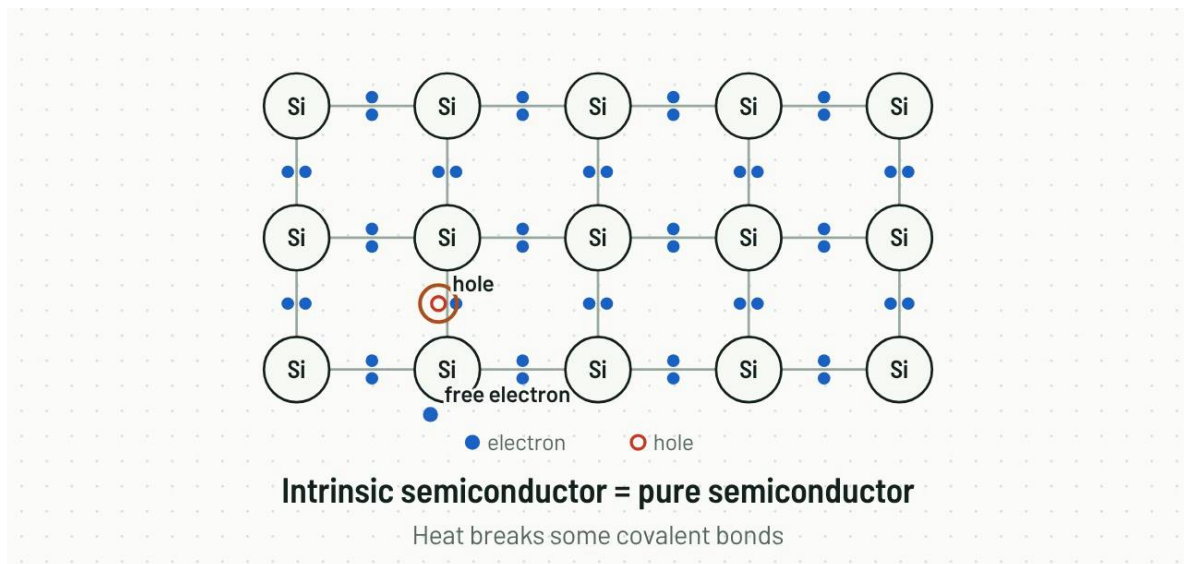


Figure 2. Heat breaks a covalent bond and creates one free electron and one hole.

Every broken bond gives one electron and one hole, so their numbers are always equal. This common value is the intrinsic carrier concentration.

$$n_e = n_h = n_i$$

In an electric field, electrons drift one way and holes drift the opposite way. Both add to the current in the same direction.

$$I = I_e + I_h$$

Free electrons also fall back into holes; this is called **recombination**. At a steady temperature, bonds break and recombine at the same rate.

4. Extrinsic semiconductors and doping

Video: 2:59 to 4:31

Adding a very small, controlled amount of a suitable impurity increases the conductivity of a pure semiconductor many times. The process is called **doping**, the impurity is the **dopant**, and the doped material is an **extrinsic semiconductor**. A few impurity atoms per million silicon atoms are enough.

N-type semiconductor. The dopant is pentavalent, with five valence electrons: arsenic (As), antimony (Sb) or phosphorus (P). Four electrons form bonds with the neighbouring silicon atoms. The fifth is only weakly bound and becomes free at room temperature. Because the impurity atom donates an electron, it is called a **donor**.

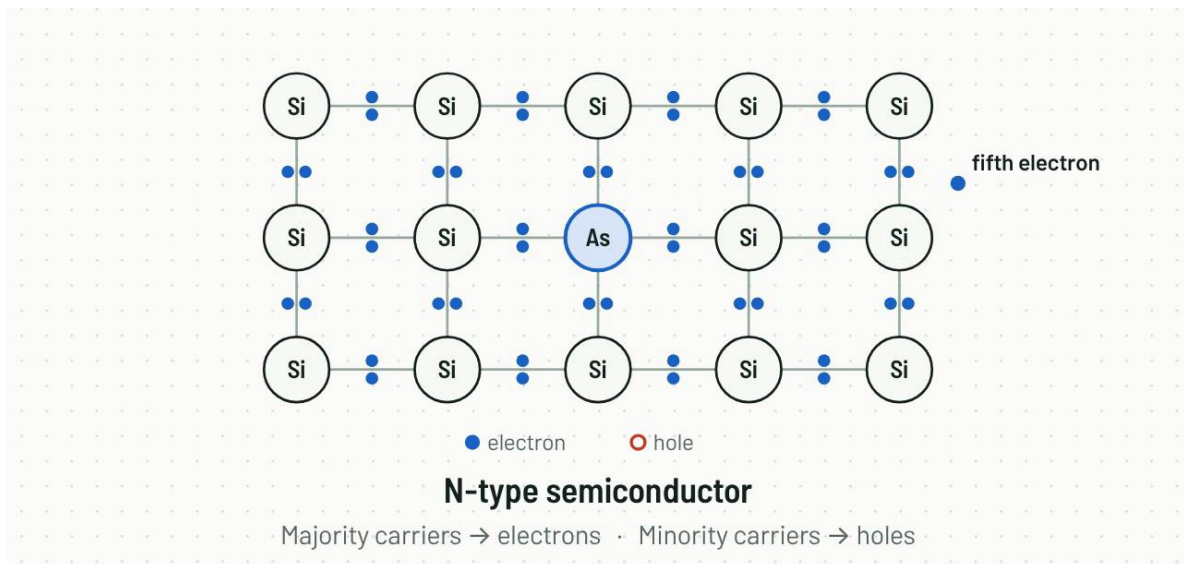


Figure 3. N-type: the fifth electron of the arsenic atom is free to move.

P-type semiconductor. The dopant is trivalent, with three valence electrons: indium (In), boron (B) or aluminium (Al). It can complete only three bonds. The fourth bond is one electron short, and this vacancy is a hole. Because the impurity atom accepts an electron from a neighbouring bond, it is called an **acceptor**.

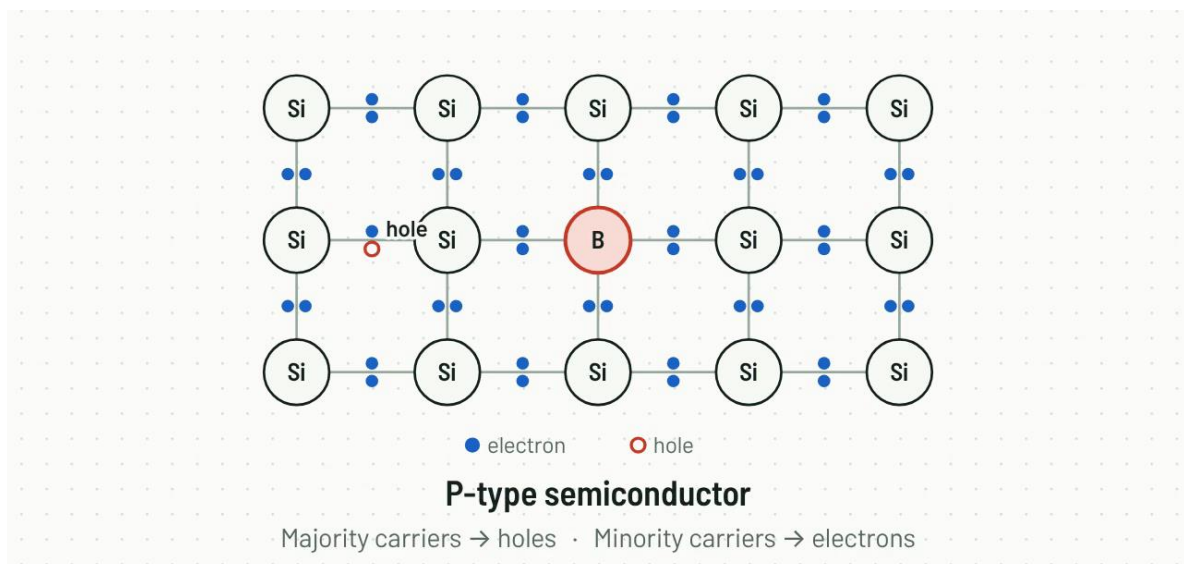


Figure 4. P-type: the boron atom leaves one bond incomplete, creating a hole.

	N-type	P-type
Impurity	Pentavalent (As, Sb, P)	Trivalent (In, B, Al)
Impurity is called	Donor	Acceptor
Majority carriers	Electrons	Holes
Minority carriers	Holes	Electrons
Carrier concentrations	Electrons far outnumber holes	Holes far outnumber electrons

Two points are often missed. First, a doped crystal is still electrically neutral: the extra carriers are balanced by the charge of the impurity ions fixed in the lattice. Second, at a given temperature the product of the two concentrations stays fixed.

$$n_e n_h = n_i^2$$

Worked example. Pure silicon has 5×10^{28} atoms per m^3 and is doped with 1 part per million of arsenic. Take $n_i = 1.5 \times 10^{16}$ per m^3 . Each arsenic atom gives one electron, so $n_e = 5 \times 10^{22}$ per m^3 . Then $n_h = n_i^2 / n_e = (2.25 \times 10^{32}) / (5 \times 10^{22}) = 4.5 \times 10^9$ per m^3 . The holes have become far fewer than in pure silicon.

5. The P-N junction

Video: 4:31 to 5:17

A P-N junction is the boundary inside one crystal where a P-type region meets an N-type region, and a thin carrier-free layer forms there by itself. It is the basic building block of diodes, transistors, LEDs and solar cells. The steps below happen as soon as the junction is made.

1. **Diffusion.** The P side has many holes and the N side has many electrons. Holes diffuse from P to N, and electrons diffuse from N to P. This movement is the diffusion current.
2. **Recombination.** Near the boundary, the electrons and holes that cross meet each other and recombine.
3. **Fixed ions are left behind.** An electron leaving the N side leaves a positive donor ion. A hole leaving the P side leaves a negative acceptor ion. These ions cannot move.
4. **Depletion region.** The layer on both sides of the junction is now emptied of mobile carriers. It is called the depletion region and is about one-tenth of a micrometre thick.
5. **Electric field and barrier.** The positive ions on the N side and negative ions on the P side set up an electric field directed from N to P. The field produces a potential difference across the junction called the **barrier potential**.
6. **Equilibrium.** The field pushes minority carriers across the junction (drift current), opposite to the diffusion current. When the two currents are equal, there is no net current.

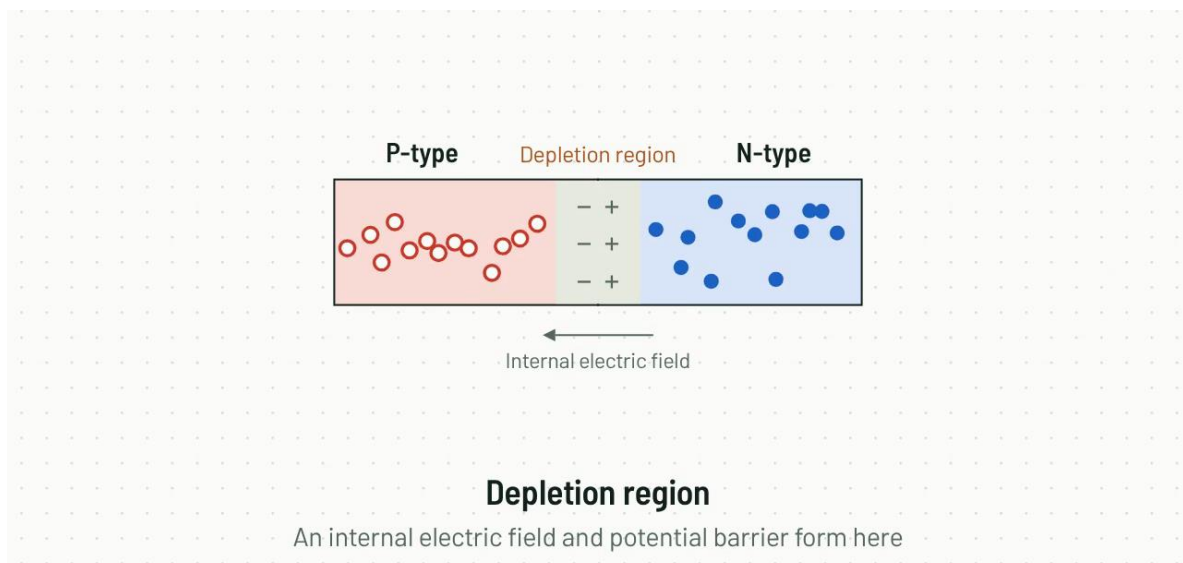


Figure 5. The depletion region contains fixed ions (shown as - and +) but very few mobile carriers.

The barrier acts like a hill for the majority carriers. An electron on the N side needs extra energy to climb it and reach the P side. External voltage can lower or raise this hill, which is the idea of biasing.

6. Forward bias, reverse bias and the diode characteristic

Video: 5:17 to 6:28

A P-N junction with a metal contact on each side is a **semiconductor diode**, and it conducts well in only one direction. In its symbol, the arrow points from P to N, which is the direction of conventional current when the diode conducts.

Forward bias. The P side is connected to the positive terminal of the battery and the N side to the negative terminal. The applied voltage opposes the barrier potential. The depletion region becomes narrower, the barrier becomes lower, and majority carriers cross the junction easily.

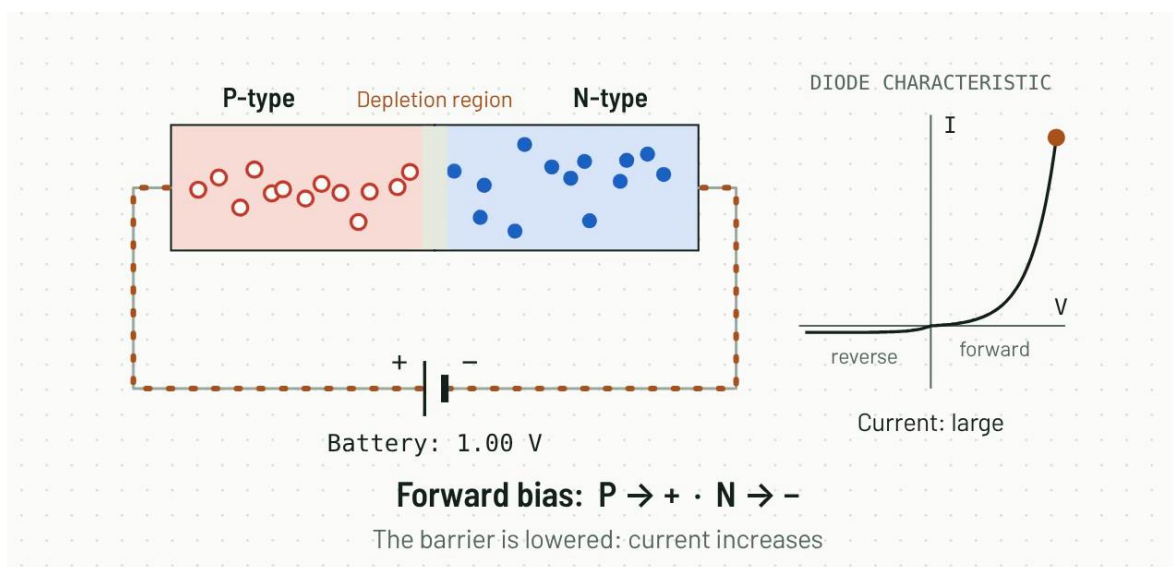


Figure 6. Forward bias: the depletion region is narrow and the current is large.

The forward current stays very small until the voltage reaches the **threshold voltage** (also called cut-in voltage). This is about 0.2 V for a germanium diode and 0.7 V for a silicon diode. Beyond it, the current rises very sharply and is measured in milliamperes.

Reverse bias. The P side is connected to the negative terminal and the N side to the positive terminal. The applied voltage now adds to the barrier potential. The depletion region widens and the majority carriers cannot cross.

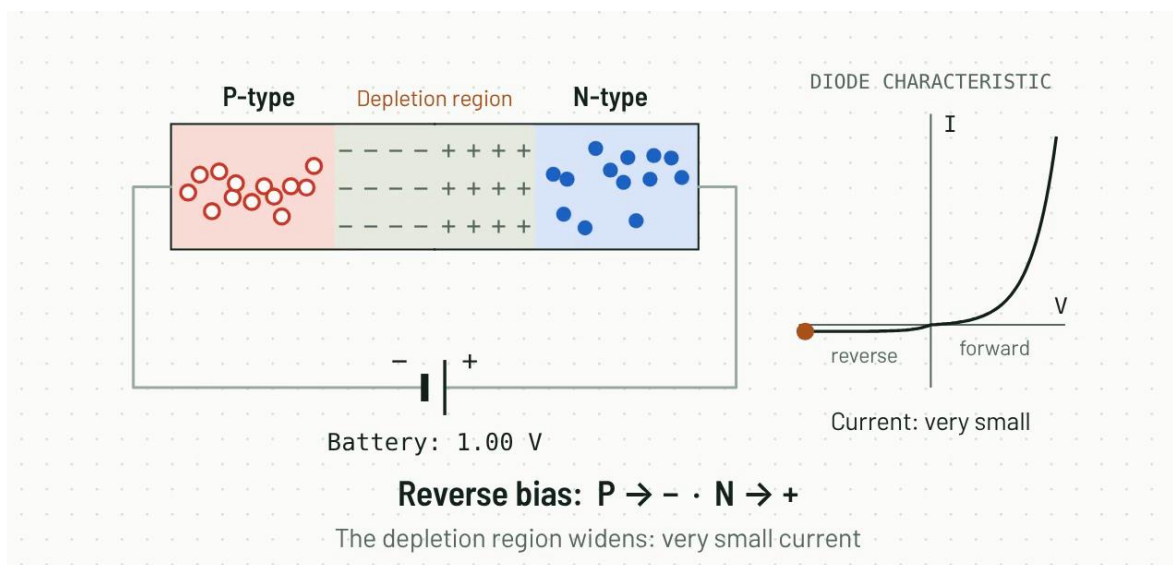


Figure 7. Reverse bias: the depletion region is wide and the current is very small.

A very small current still flows because the field sweeps minority carriers across the junction. It is called the **reverse saturation current**. It is of the order of microamperes and hardly changes with voltage. At a high reverse voltage, called the **breakdown voltage**, the current rises suddenly. An ordinary diode must be kept below this voltage or it overheats and is destroyed.

	Forward bias	Reverse bias
Connection	P to positive, N to negative	P to negative, N to positive

	Forward bias	Reverse bias
Effect on barrier	Lowered	Raised
Depletion region	Narrower	Wider
Current is due to	Majority carriers	Minority carriers
Size of current	Milliamperes, rising sharply after threshold	Microamperes, almost constant
Resistance of diode	Low	Very high

Dynamic resistance. The curve is not a straight line, so the diode does not obey Ohm's law. Its resistance at any point is defined as the ratio of a small change in voltage to the small change in current it produces.

$$r_d = \Delta V / \Delta I$$

7. Rectifiers

Video: 6:28 to 8:09

A rectifier converts alternating current (AC) into current that flows in one direction only, using the one-way conduction of the diode. This process is called **rectification**.

Half-wave rectifier. A single diode is connected in series with the load resistance R_L across the AC supply, usually the secondary of a transformer.

- During the positive half-cycle the diode is forward biased. It conducts, and current flows through the load.
- During the negative half-cycle the diode is reverse biased. It does not conduct, and the output is zero.

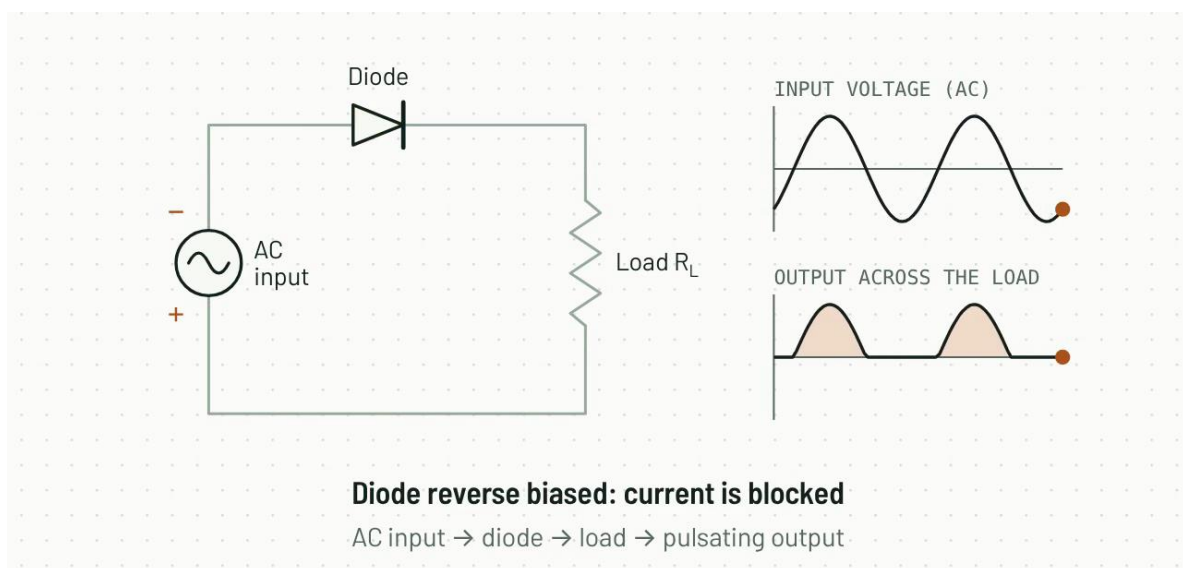


Figure 8. Half-wave rectifier: only one half of each cycle appears across the load.

The output is a series of pulses in one direction, one pulse for each input cycle. Half of the input is wasted. The diode chosen must have a reverse breakdown voltage higher than the peak AC voltage.

Full-wave rectifier. Two diodes, D1 and D2, are used with a transformer whose secondary winding has a **centre tap**. The two ends of the secondary go to the two diodes, and the load is connected between the joined diode outputs and the centre tap.

- During the positive half-cycle, end A is positive with respect to the centre tap. D1 is forward biased and conducts; D2 is reverse biased.
- During the negative half-cycle, end B is positive. D2 conducts; D1 is reverse biased.
- In both half-cycles the current passes through the load in the same direction.

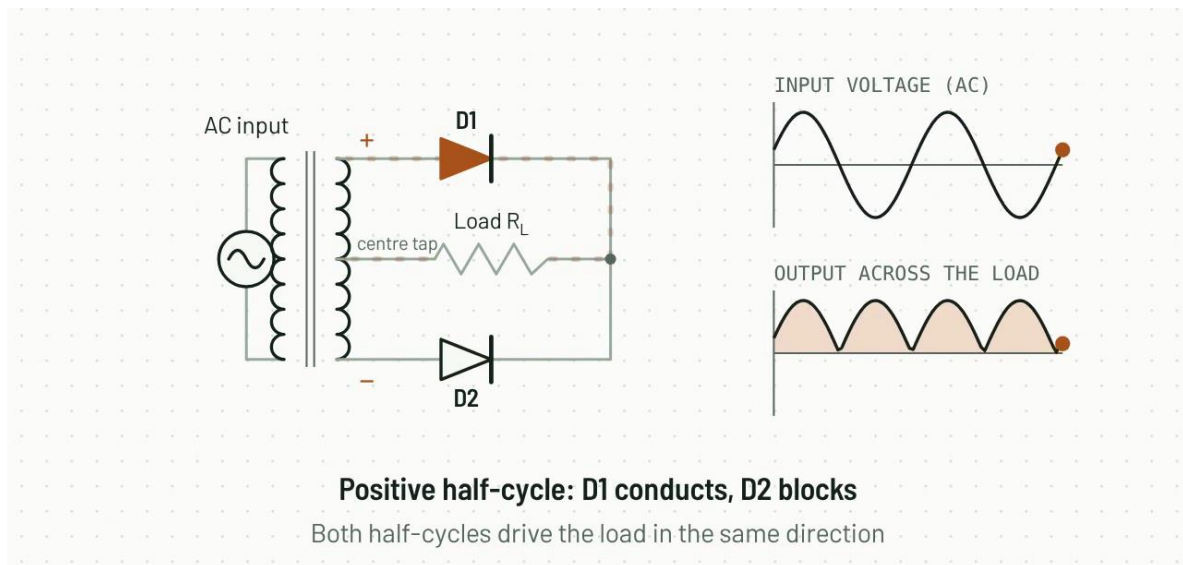


Figure 9. Full-wave rectifier: both half-cycles appear across the load.

	Half-wave	Full-wave (centre-tap)
Number of diodes	1	2
Transformer	Ordinary	Centre-tapped secondary
Diode conducts during	One half-cycle	D1 in one half-cycle, D2 in the other
Output pulses per input cycle	1	2
Pulse frequency for 50 Hz supply	50 Hz	100 Hz
Use of input	Half is wasted	Both halves are used

Filter capacitor. The rectified output still rises and falls, so it is not a steady DC. A capacitor connected across the load smooths it. The capacitor charges up to nearly the peak voltage while the output rises. When the rectifier output falls, the capacitor discharges slowly through the load and keeps the voltage up. The larger the capacitance and the load resistance, the smaller the remaining ripple.

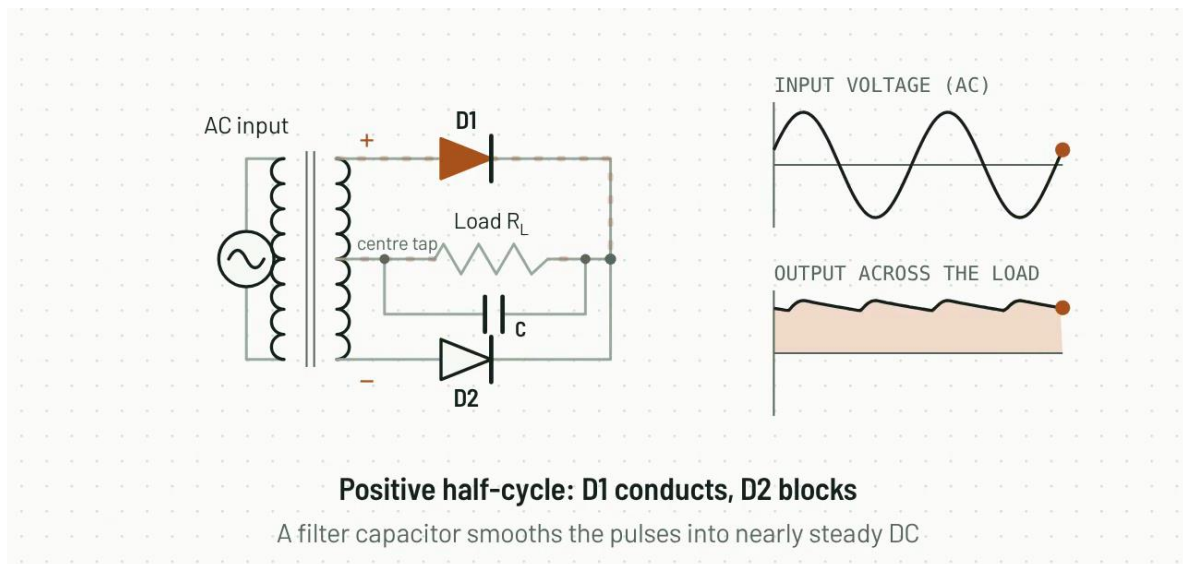


Figure 10. With a filter capacitor the output stays close to the peak voltage.

8. Special-purpose diodes

Video: 8:09 to 10:56

The four diodes below are the same P-N junction, made or biased differently so that it does one special job. This section goes beyond the current NCERT chapter, which ends at rectifiers.

8.1 Zener diode

A Zener diode is made to work in the reverse breakdown region without being damaged. Both its P and N sides are heavily doped, so the depletion region is very thin and the electric field across it is very strong, even at a few volts.

When the reverse voltage reaches the **Zener voltage** (V_Z), the field is strong enough to pull electrons out of their bonds. The reverse current then rises sharply. The important point is that the voltage across the diode stays almost equal to V_Z while the current changes over a wide range.

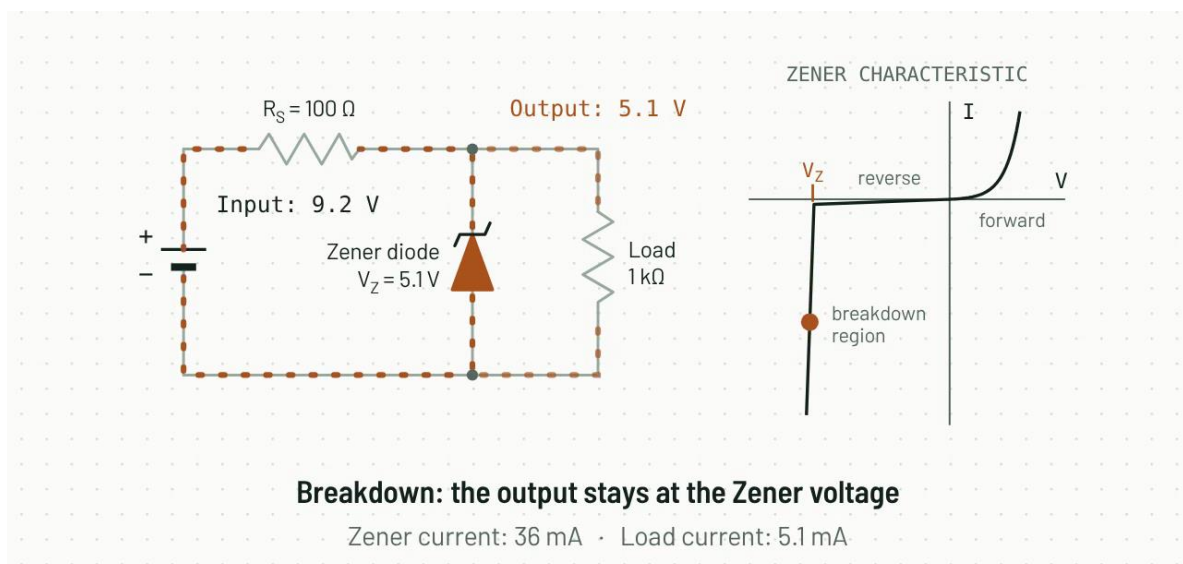


Figure 11. Zener diode as a voltage regulator, with example values.

Use as a voltage regulator. The Zener diode is connected in reverse bias across the load, with a series resistance R_S between it and the unregulated supply. If the input voltage rises, more current flows through R_S and the Zener diode. The extra voltage drops across R_S , and the load voltage stays at V_Z .

$$V_{in} = I R_S + V_Z$$

Worked example (values from Figure 11). $V_Z = 5.1 \text{ V}$, $R_S = 100 \Omega$, load = $1 \text{ k}\Omega$, input = 9.2 V . Current through $R_S = (9.2 - 5.1) / 100 = 41 \text{ mA}$. Load current = $5.1 / 1000 = 5.1 \text{ mA}$. Zener current = $41 - 5.1$, about 36 mA . If the input changes, the Zener current changes but the output stays 5.1 V .

8.2 Photodiode

A photodiode is a P-N junction with a transparent window, operated in reverse bias, whose current depends on the light falling on it.

- Light whose photon energy is greater than the energy gap creates electron-hole pairs in or near the depletion region.
- The junction field separates them before they recombine. Electrons go to the N side and holes to the P side.
- This gives a reverse current, called the photocurrent, which is proportional to the light intensity.

$$h\nu > E_g$$

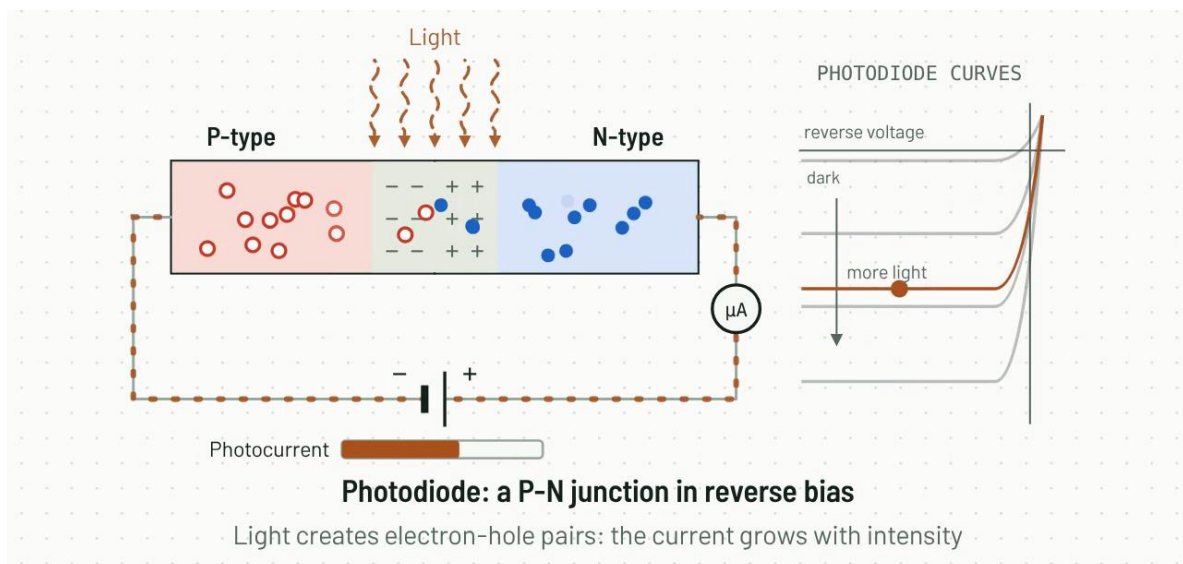


Figure 12. Photodiode: more light gives more reverse current.

Why reverse bias? In reverse bias the current without light is only a tiny minority-carrier current. The extra carriers created by light then make a large, easily measured change. In forward bias the same extra carriers would be lost in the much larger majority-carrier current.

8.3 Light emitting diode (LED)

An LED is a heavily doped P-N junction that gives out light when it is forward biased. Electrons from the N side and holes from the P side cross the junction and recombine. The energy released in each recombination comes out as a photon whose energy is close to the energy gap.

$$\lambda = hc / E_g$$

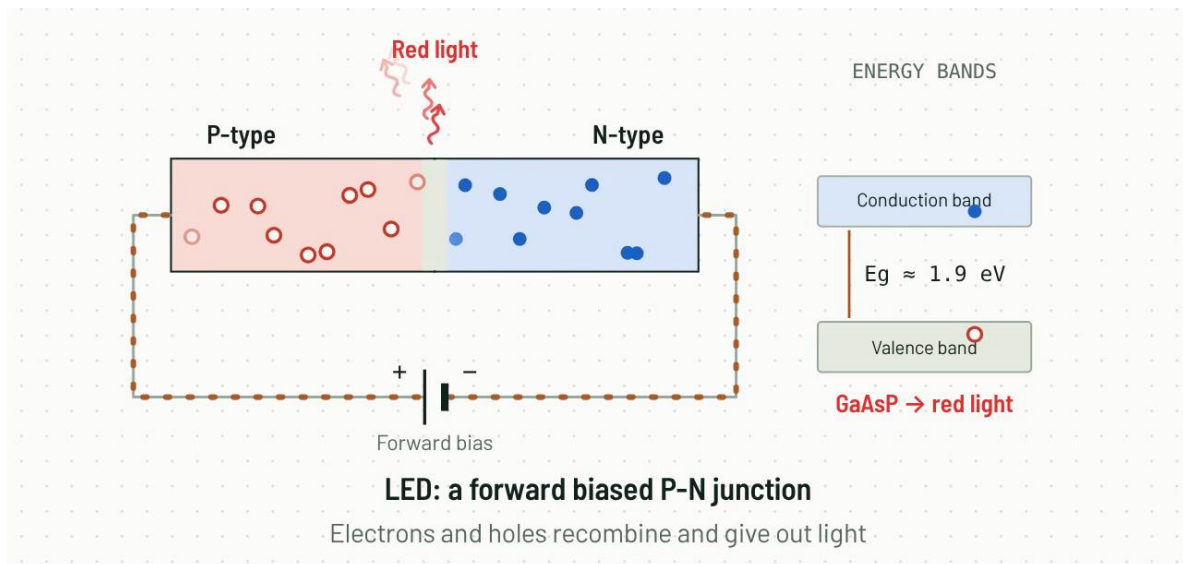


Figure 13. LED: recombination at the junction gives out light.

The colour therefore depends on the semiconductor. For visible light the energy gap must be at least about 1.8 eV. For example, with $E_g = 1.9$ eV, $\lambda = 1240 / 1.9$, about 650 nm, which is red.

Semiconductor	Light emitted
Gallium arsenide (GaAs), E_g about 1.4 eV	Infrared
Gallium arsenide phosphide (GaAsP), E_g about 1.9 eV	Red
Gallium phosphide (GaP)	Green
Indium gallium nitride (InGaN)	Blue

LEDs work at low voltage, use little power, switch on and off very fast, give nearly one colour and last long. They are used in indicators, displays, remote controls and lighting.

8.4 Tunnel diode

A tunnel diode is a P-N junction doped so heavily that its depletion region is only about 10 nm thick, and its current falls over a part of its curve as the voltage rises. Electrons can pass straight through such a thin barrier without having the energy to climb over it. This quantum effect is called **tunnelling**. The device was invented by Leo Esaki, so it is also called the Esaki diode.

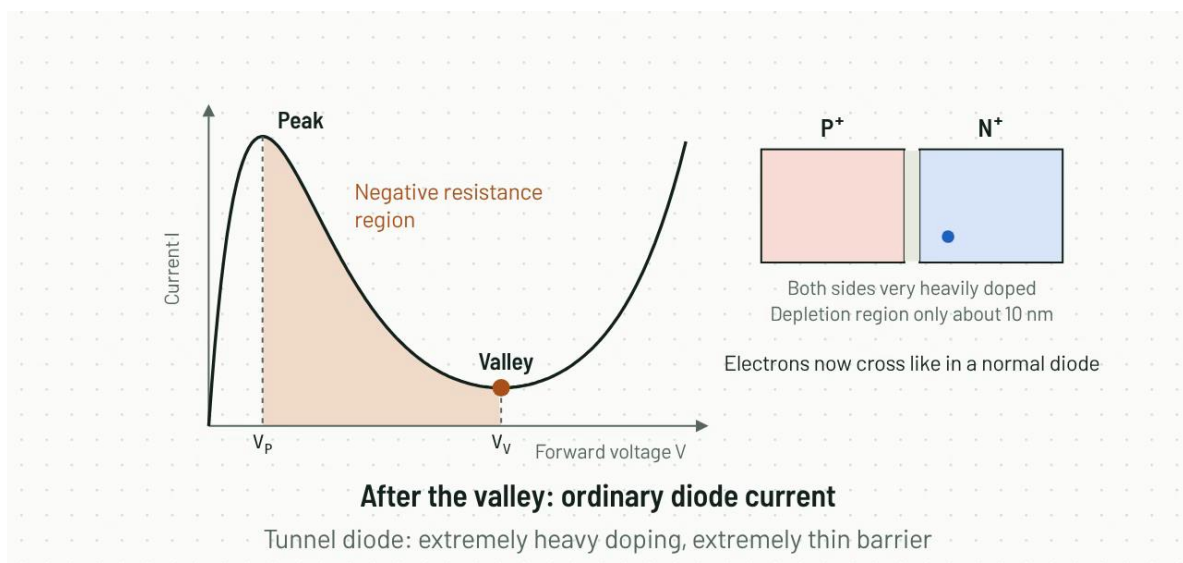


Figure 14. Tunnel diode characteristic.

1. As the forward voltage rises from zero, the tunnelling current rises quickly to a **peak** value.
2. With a further rise in voltage, fewer electrons can tunnel and the current falls to a **valley** value. In this part, voltage increases while current decreases, so it is called the **negative resistance region**.
3. Beyond the valley, the current rises again as in an ordinary diode.

Because tunnelling is extremely fast, tunnel diodes are used in high-frequency oscillators and fast switching circuits.

Summary of special diodes

Diode	Doping	Operated in	Key property	Use
Zener	Heavy	Reverse bias, at breakdown	Constant voltage over a wide current range	Voltage regulator
Photodiode	Normal	Reverse bias	Current proportional to light intensity	Light detector
LED	Heavy	Forward bias	Emits light on recombination	Indicators, displays, lighting
Tunnel diode	Very heavy	Small forward bias	Negative resistance, very fast	High-frequency oscillators, switching

Key points to remember

- Semiconductors have conductivity between that of conductors and insulators, and their energy gap is small (Si 1.1 eV, Ge 0.7 eV).
- In an intrinsic semiconductor the number of free electrons equals the number of holes.
- Doping with a pentavalent impurity gives N-type material (majority carriers electrons); a trivalent impurity gives P-type material (majority carriers holes).
- A doped semiconductor is electrically neutral.
- At a P-N junction, diffusion and recombination leave a depletion region with fixed ions, an electric field and a barrier potential.
- Forward bias lowers the barrier and gives a large current after the threshold voltage (about 0.7 V for silicon, 0.2 V for germanium).
- Reverse bias raises the barrier; only a tiny, nearly constant reverse saturation current flows until breakdown.
- A half-wave rectifier uses one diode and one half-cycle. A full-wave rectifier uses two diodes with a centre-tap transformer and both half-cycles. A filter capacitor smooths the output.
- A Zener diode holds a constant voltage in reverse breakdown, so it regulates voltage.
- A photodiode turns light into current in reverse bias; an LED turns current into light in forward bias.
- A tunnel diode shows negative resistance between its peak and valley and works at very high speed.

Glossary

The video keeps technical terms in English. Their Hindi textbook equivalents are given here for students who read the chapter in Hindi.

English term	Hindi term	Meaning in one line
Semiconductor	अर्धचालक	Material with conductivity between a conductor and an insulator
Valence band	संयोजकता बैंड	Energy band of the electrons held in bonds
Conduction band	चालन बैंड	Energy band in which electrons move freely
Energy gap	ऊर्जा अंतराल	Energy needed to lift an electron from the valence to the conduction band
Intrinsic semiconductor	नैज अर्धचालक	Pure semiconductor
Extrinsic semiconductor	अपद्रव्यी अर्धचालक	Doped semiconductor
Doping	मादन	Adding a controlled amount of impurity
Donor / Acceptor	दाता / ग्राही	Impurity that gives an electron / takes an electron
Hole	होल	Vacancy in a bond that acts as a positive charge
Majority / minority carriers	बहुसंख्यक / अल्पसंख्यक वाहक	The more numerous / less numerous charge carriers
Recombination	पुनर्संयोजन	A free electron filling a hole
Diffusion / Drift	विसरण / अपवाह	Carrier motion due to concentration difference / electric field
P-N junction	p-n संधि	Boundary between P-type and N-type regions
Depletion region	हासी क्षेत्र	Layer at the junction with no mobile carriers
Barrier potential	रोधिका विभव	Potential difference across the depletion region
Forward bias	अग्रदिशिक बायस	P to positive, N to negative
Reverse bias	पश्चदिशिक बायस	P to negative, N to positive
Threshold voltage	देहली वोल्टता	Forward voltage beyond which current rises sharply
Breakdown voltage	भंजन वोल्टता	Reverse voltage at which current rises suddenly
Rectifier	दिष्टकारी	Circuit that converts AC to DC
Half-wave / full-wave	अर्ध-तरंग / पूर्ण-तरंग	Using one half / both halves of the AC cycle
Voltage regulator	वोल्टता नियंत्रक	Circuit that keeps the output voltage constant
Tunnelling	सुरंगन	Passing through a thin barrier by a quantum effect
Negative resistance	ऋणात्मक प्रतिरोध	Current decreasing while voltage increases

Practice questions

Try each question before reading the answers that follow.

1. Why does the conductivity of a semiconductor increase when it is heated?

2. Silicon is doped with phosphorus. What type of semiconductor is formed, and what are its majority carriers?
3. Is an N-type semiconductor negatively charged? Give a reason.
4. What is the depletion region, and why does it contain no mobile carriers?
5. In which bias does the depletion region become wider?
6. The forward voltage of a diode changes from 0.7 V to 0.8 V, and the current changes from 10 mA to 20 mA. Find its dynamic resistance.
7. A rectifier is fed from a 50 Hz supply. What is the frequency of the output pulses for a half-wave and for a full-wave rectifier?
8. What does a filter capacitor do in a rectifier circuit?
9. A Zener diode with $V_Z = 6$ V is used with $R_S = 200\ \Omega$ and a load of 1.2 k Ω . The input is 10 V. Find the current through R_S , the load current and the Zener current.
10. Why is a photodiode operated in reverse bias?
11. An LED is made from a semiconductor with an energy gap of 2.5 eV. Find the wavelength of the light. Take $hc = 1240$ eV nm.
12. What is meant by the negative resistance region of a tunnel diode?

Answers

1. More covalent bonds break, so more electron-hole pairs are available to carry current.
2. N-type, because phosphorus is pentavalent. The majority carriers are electrons.
3. No. Each free electron is balanced by a positive donor ion fixed in the lattice, so the crystal is neutral.
4. It is the thin layer on both sides of the junction. Electrons and holes that diffuse across recombine there, leaving only fixed ions.
5. Reverse bias.
6. $r_d = \Delta V / \Delta I = 0.1\text{ V} / 10\text{ mA} = 10\ \Omega$.
7. 50 Hz for half-wave and 100 Hz for full-wave.
8. It charges to nearly the peak voltage and discharges slowly through the load, so the output becomes a nearly steady DC.
9. Current through $R_S = (10 - 6) / 200 = 20$ mA. Load current = $6 / 1200 = 5$ mA. Zener current = $20 - 5 = 15$ mA.
10. The current without light is very small in reverse bias, so the change produced by light is large and easy to measure.
11. $\lambda = 1240 / 2.5 = 496$ nm, which is blue-green light.
12. It is the part of the curve between the peak and the valley, where the current decreases as the forward voltage increases.

References

1. NCERT, Physics Part II, Textbook for Class XII, Chapter 14, "Semiconductor Electronics: Materials, Devices and Simple Circuits". [NCERT chapter PDF](#)
2. Ramesh Badoni, source script and notes for the video, "Semiconductor Electronics: Materials, Devices and Simple Circuits".
3. S. M. Sze and K. K. Ng, Physics of Semiconductor Devices, 3rd edition, Wiley, 2007.
4. L. Esaki, "New Phenomenon in Narrow Germanium p-n Junctions", Physical Review 109, 603 (1958).

The values in sections 1 to 7 were checked against reference 1. Section 8, the Hindi terms in the glossary and references 3 and 4 are written from memory and were not checked against a source.