PN Junction Diode

- **P-N junction diode** is the most fundamental and the simplest electronics device.
- When one side of an intrinsic semiconductor is doped with acceptor i.e, one side is made p-type by doping with n-type material, a p-n junction diode is formed.
- This is a two terminal device.
- It appeared in 1950's. **P-N junction** can be step graded or linearly graded. In step graded the concentration of dopants both, in n - side and in p - side are constant up to the junction. But in linearly graded junction, the doping concentration varies almost linearly with the distance from the junction.

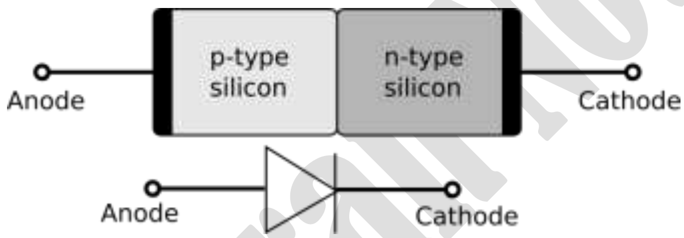


Figure 1 PN Junction Diode

- When the **P-N diode** is in unbiased condition that is no voltage is applied across it, electrons will defuse through the junction to p-side and holes will defuse through the junction to n-side and they combine with each other. Thus the acceptor atom near the p-side and donor atom near n-side are left unutilized. An electron field is generated by these uncovered charges. This opposes further diffusion of carriers. So, no movement of region is known as space charge or depletion region.
- If, we apply forwards bias to the p-n junction diode. That means if positive side of the battery is connected to the p – side, then the depletion regions width decreases and carriers flow across the junction.
- If the bias is reversed the depletion width increases and no charge can flow across the junction.

Properties

- The p–n junction possesses some interesting properties that have useful applications in modern electronics. A p-doped semiconductor is relatively conductive. The same is true of an n-doped semiconductor, but the junction between them can become depleted of charge carriers, and hence non-conductive, depending on the relative voltages of the two semiconductor regions.

- By manipulating this non-conductive layer, p–n junctions are commonly used as diodes: circuit elements that allow a flow of electricity in one direction but not in the other (opposite) direction.
- *Bias* is the application of a voltage across a p–n junction; *forward bias* is in the direction of easy current flow, and *reverse bias* is in the direction of little or no current flow.

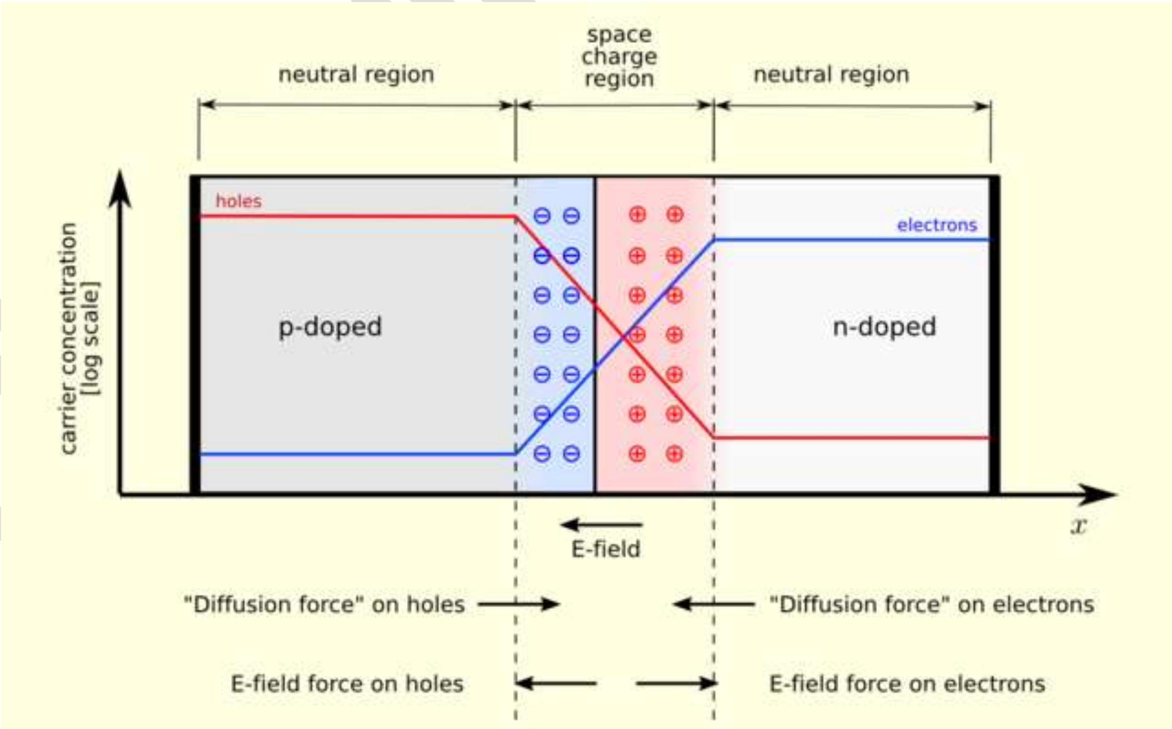
Equilibrium (zero bias)

- In a p–n junction, without an external applied voltage, an equilibrium condition is reached in which a potential difference is formed across the junction. This potential difference is called built-in potential.
- After joining p-type and n-type semiconductors, electrons from the n region near the p–n interface tend to diffuse into the p region leaving behind positively charged ions in the n region and being recombined with holes, forming negatively charged ions in the p region. Likewise, holes from the p-type region near the p–n interface begin to diffuse into the n-type region, leaving behind negatively charged ions in the p region and recombining with electrons, forming positive ions in the n region.
- The regions near the p–n interface lose their neutrality and most of their mobile carriers, forming the space charge region or depletion layer.
- A p–n junction in thermal equilibrium with zero-bias voltage applied. Electron and hole concentration are reported with blue and red lines, respectively. Gray regions are charge-neutral. Light-red zone is positively charged. Light-blue zone is negatively charged. The electric field is shown on the bottom, the electrostatic force on electrons and holes and the direction in which the diffusion tends to move electrons and holes. (The log concentration curves should actually be smoother with slope varying with field strength.)
- The electric field created by the space charge region opposes the diffusion process for both electrons and holes. There are two concurrent phenomena: the diffusion process that tends to generate more space charge and the electric field generated by the space charge that tends to counteract the diffusion. The carrier concentration profile at equilibrium is shown in figure A with blue and red lines. Also shown are the two counterbalancing phenomena that establish equilibrium.

- A p–n junction in thermal equilibrium with zero-bias voltage applied. Under the junction, plots for the charge density, the electric field, and the voltage are reported. (The log concentration curves should actually be smoother, like the voltage.)
- The space charge region is a zone with a net charge provided by the fixed ions (donors or acceptors) that have been left*uncovered* by majority carrier diffusion. When equilibrium is reached, the charge density is approximated by the displayed step function. In fact, since the y-axis of figure A is log-scale, the region is almost completely depleted of majority carriers (leaving a charge density equal to the net doping level), and the edge between the space charge region and the neutral region is quite sharp (see figure B, Q(x) graph). The space charge region has the same magnitude of charge on both sides of the p–n interfaces, thus it extends farther on the less doped side in this example (the n side in figures A and B).

Forward bias

- In forward bias, the p-type is connected with the positive terminal and the n-type is connected with the negative terminal.
- PN junction operation in forward-bias mode, showing reducing depletion width. The panels show **energy band diagram**, **electric field**, and **net charge density**. Both p and n



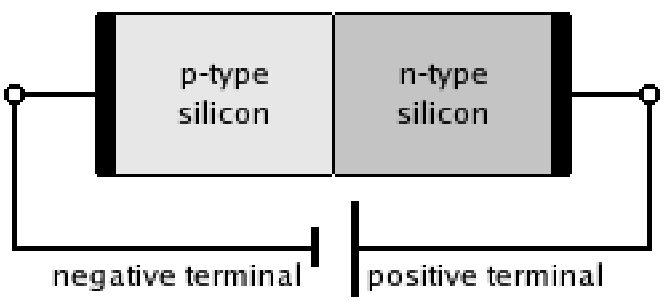
junctions are doped at a 1e15/cm3 (0.00016C/cm^3) doping level, leading to built-in potential of ~0.59 V. Reducing depletion width can be inferred from the shrinking charge profile, as fewer dopants are exposed with increasing forward bias.

- With a battery connected this way, the holes in the p-type region and the electrons in the n-type region are pushed toward the junction and start to neutralize the depletion zone, reducing its width. The positive potential applied to the p-type material repels the holes, while the negative potential applied to the n-type material repels the electrons. The change in potential between the p side and the n side decreases or switches sign. With increasing forward-bias voltage, the depletion zone eventually becomes thin enough that the zone's electric field cannot counteract charge carrier motion across the p–n junction, which as a consequence reduces electrical resistance. The electrons that cross the p–n junction into the p-type material (or holes that cross into the n-type material) will diffuse into the nearby neutral region. The amount of minority diffusion in the near-neutral zones determines the amount of current that may flow through the diode.
- Only majority carriers (electrons in n-type material or holes in p-type) can flow through a semiconductor for a macroscopic length. With this in mind, consider the flow of electrons across the junction. The forward bias causes a force on the electrons pushing them from the N side toward the P side. With forward bias, the depletion region is narrow enough that electrons can cross the junction and *inject* into the p-type material. However, they do not continue to flow through the p-type material indefinitely, because it is energetically favorable for them to recombine with holes. The average length an electron travels through the p-type material before recombining is called the *diffusion length*, and it is typically on the order of micrometers.[2]
- Although the electrons penetrate only a short distance into the p-type material, the electric current continues uninterrupted, because holes (the majority carriers) begin to flow in the opposite direction. The total current (the sum of the electron and hole currents) is constant in space, because any variation would cause charge buildup over time (this is Kirchhoff's current law). The flow of holes from the p-type region into the n-type region is exactly analogous to the flow of electrons from N to P (electrons and holes swap roles and the signs of all currents and voltages are reversed).

- Therefore, the macroscopic picture of the current flow through the diode involves electrons flowing through the n-type region toward the junction, holes flowing through the p-type region in the opposite direction toward the junction, and the two species of carriers constantly recombining in the vicinity of the junction. The electrons and holes travel in opposite directions, but they also have opposite charges, so the overall current is in the same direction on both sides of the diode, as required.
- The Shockley diode equation models the forward-bias operational characteristics of a p–n junction outside the avalanche (reverse-biased conducting) region.

Reverse bias

- A silicon p–n junction in reverse bias.
- Connecting the *p-type* region to the *negative* terminal of the battery and the *n-type* region to the *positive* terminal corresponds to reverse bias. If a diode is reverse-biased, the voltage at the cathode is comparatively higher than at the anode. Therefore, very little current will flow until the diode breaks down. The connections are illustrated in the diagram to the right.



- Because the p-type material is now connected to the negative terminal of the power supply, the 'holes' in the p-type material are pulled away from the junction, leaving behind charged ions and causing the width of the depletion region to increase. Likewise, because the n-type region is connected to the positive terminal, the electrons will also be pulled away from the junction, with similar effect. This increases the voltage barrier causing a high resistance to the flow of charge carriers, thus allowing minimal electric current to cross the p–n junction. The increase in resistance of the p–n junction results in the junction behaving as an insulator.
- The strength of the depletion zone electric field increases as the reverse-bias voltage increases. Once the electric field intensity increases beyond a critical level, the p–n junction depletion zone breaks down and current begins to flow, usually by either the Zener or the avalanche breakdown processes. Both of these breakdown processes are

non-destructive and are reversible, as long as the amount of current flowing does not reach levels that cause the semiconductor material to overheat and cause thermal damage.

- This effect is used to advantage in Zener diode regulator circuits. Zener diodes have a low breakdown voltage. A standard value for breakdown voltage is for instance 5.6 V. This means that the voltage at the cathode cannot be more than about 5.6 V higher than the voltage at the anode (although there is a slight rise with current), because the diode will break down – and therefore conduct – if the voltage gets any higher. This in effect limits the voltage over the diode.
- Another application of reverse biasing is Varicap diodes, where the width of the depletion zone (controlled with the reverse bias voltage) changes the capacitance of the diode.

Summary

- The forward-bias and the reverse-bias properties of the p–n junction imply that it can be used as a diode.
- A p–n junction diode allows electric charges to flow in one direction, but not in the opposite direction; negative charges (electrons) can easily flow through the junction from n to p but not from p to n, and the reverse is true for holes.
- When the p–n junction is forward-biased, electric charge flows freely due to reduced resistance of the p–n junction.
- When the p–n junction is reverse-biased, however, the junction barrier (and therefore resistance) becomes greater and charge flow is minimal.

Applications

- PN Junction diode is used in many electronic circuits such as Rectifier, Clippers, and Clampers etc.
- PN junction in reverse biased configuration is sensitive (generates an electron-hole pair) to light from 400-1000nm which includes VISIBLE Light (400nm to 700nm). So all/most of the sensors involving capturing light information will use a photodiode. PN junction in reverse biased configuration is the ***most widely used sensor*** compared to any other sensor. For example

  - all the digital cameras use an array of photodiodes to capture light and produce an image.
  - Solar Cells
- PN junction (which has direct energy bandgap) in forward biased condition produces light when biased with a current. All LED lighting uses a PN junction diode.
- Voltage across PN junction biased at a constant current has a negative temperature coefficient. Difference between the PN junction voltages of two differently biased diodes has a positive temperature coefficient. These properties are used to create Temperature Sensors, Reference voltages (Bandgap).
- Various circuits like Rectifiers, Varactors for Voltage Controlled Oscillators (VCO) etc.