PN-Junction Diode

Outline

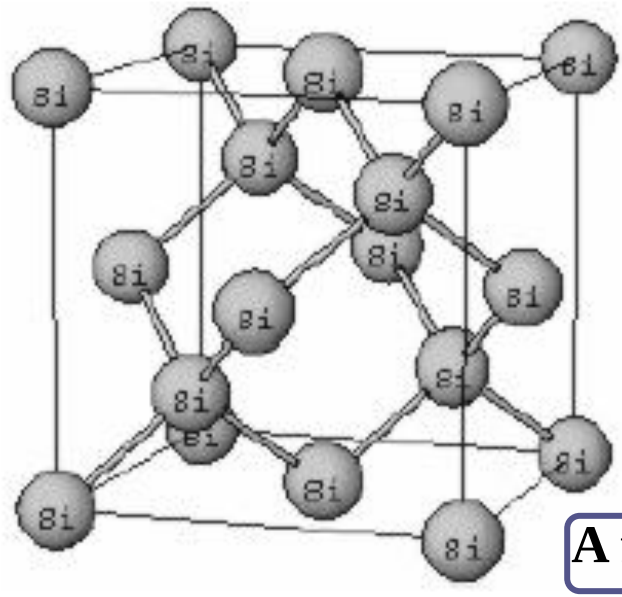
- The PN-Junction Diode
- Analysis of diode circuits
- I-V characteristic of *pn* junction
  - Terminal characteristic of junction diode.
  - Physical operation of diode.
- Applications of diode circuits
  - Rectification
    - Half wave Rectifiers
    - Full wave Rectifiers
      - Centre-tap
      - Bridge

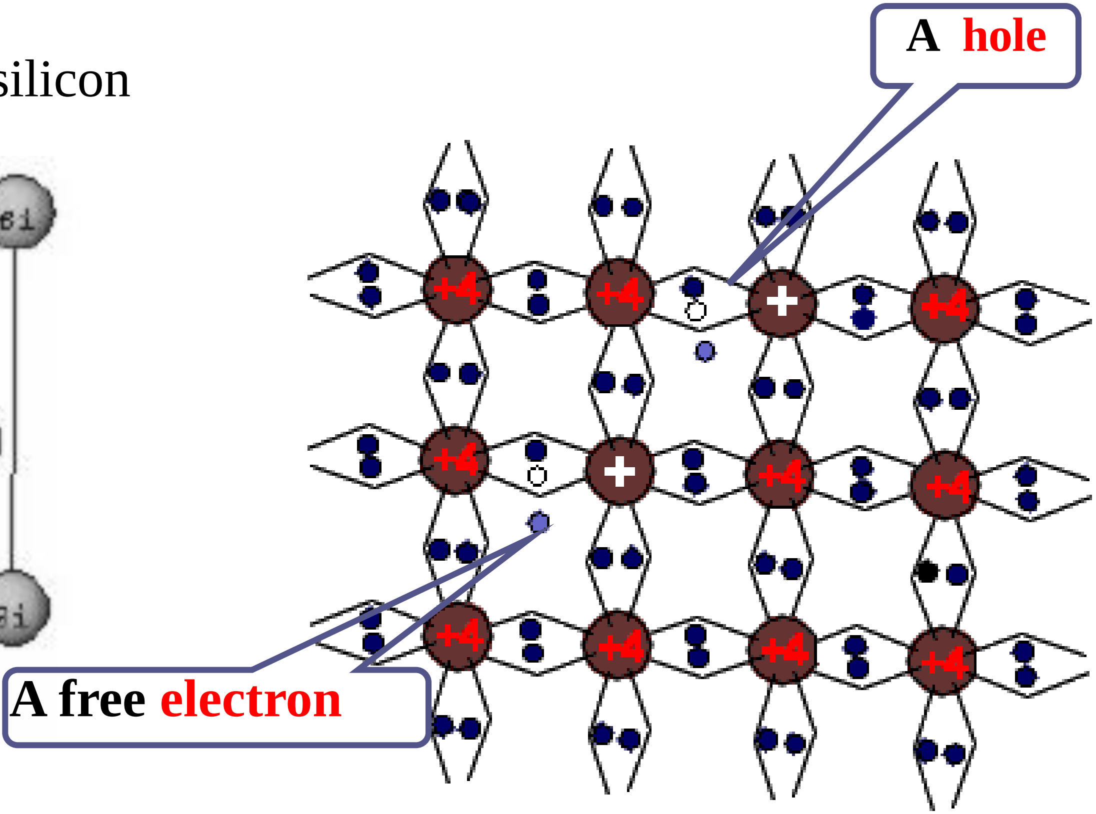
Previous Lecture

- Semiconductor
  - Intrinsic
  - Doping
  - Extrinsic
    - N-type
    - P-type

Intrinsic (pure) Semiconductors

- Intrinsic(pure) silicon





• An electron-hole pair is created when an electron get excited by thermal or light energy;

• Recombination occurs when an electron loses energy and falls back into a hole.

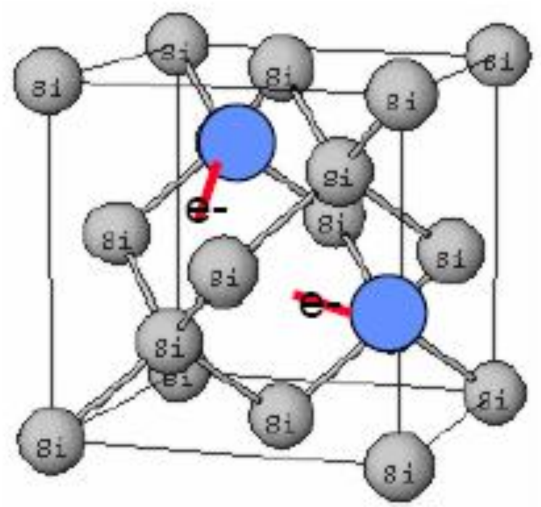
Intrinsic (pure) Semiconductors

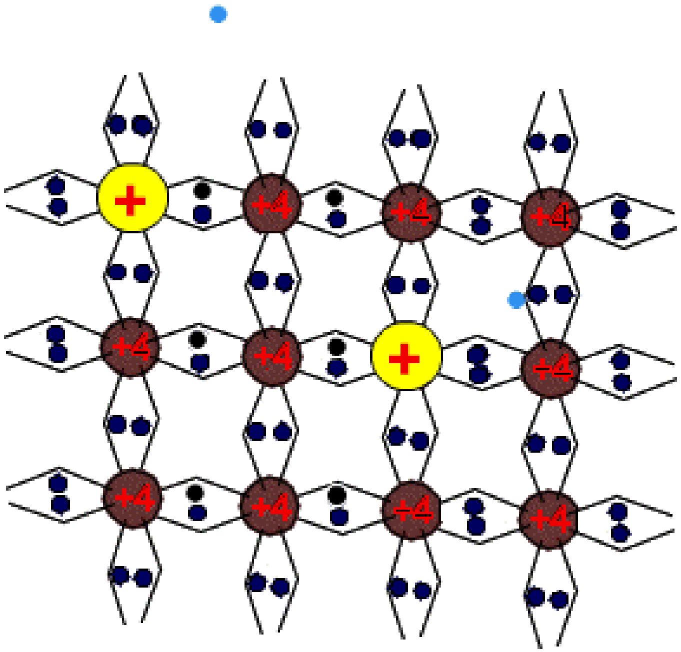
- Holes also conduct current. In reality, it’s the movement of all the other electrons. The hole allows this motion.
- Holes have positive charge.
- Current flows in the same direction as the holes move.

- Both electrons and holes carry current-- **carriers**.
- In intrinsic semiconductors the electron and hole concentrations are equal because carriers are created in pairs
- The intrinsic concentration depends exponentially on temperature.
- At room temp (300K), the intrinsic carrier concentration of silicon is:

$$n_i = 1.5 \times 10^{10} / cm^3$$

Phosphorus Doping (N-type)





• Phosphorus has 5 valence electrons.

• P atoms will sit in the location of a Si atom in the lattice, to avoid breaking symmetry, but each will have an extra electron that does not bond in the same way. And these extra electrons are easier to excite (and can move around more easily)

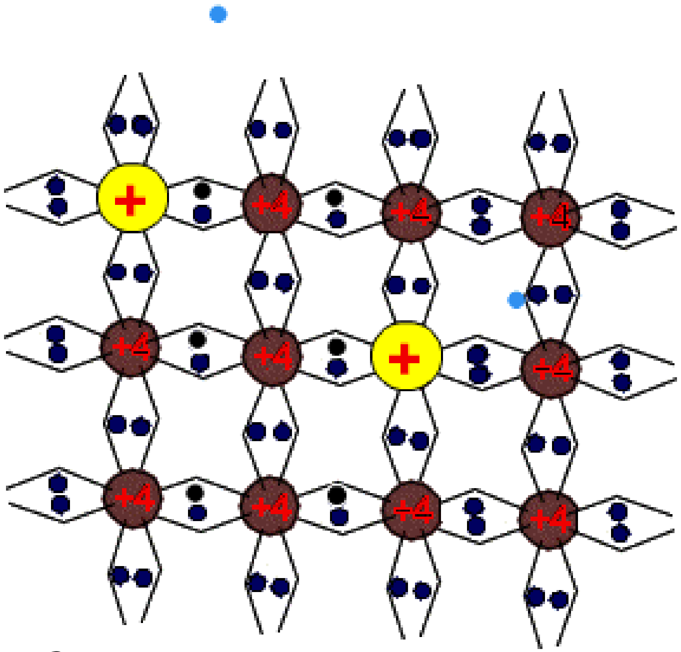
• These electrons depends on the amounts of the two materials.

Phosphorus Doping (N-type)

Electrons---Majority carrier.

Holes---Minority carrier

Phosphorus---**Donor materials.**



- In equilibrium, $pn = p_i n_i = p_i^2 = n_i^2$
- At room temp (300K), if $1/10^{10}$ donors are added to the intrinsic silicon, then the electron carrier concentration is about 10^{13}cm^{-3}; the hole carrier concentration is about 10^{6}cm^{-3}.

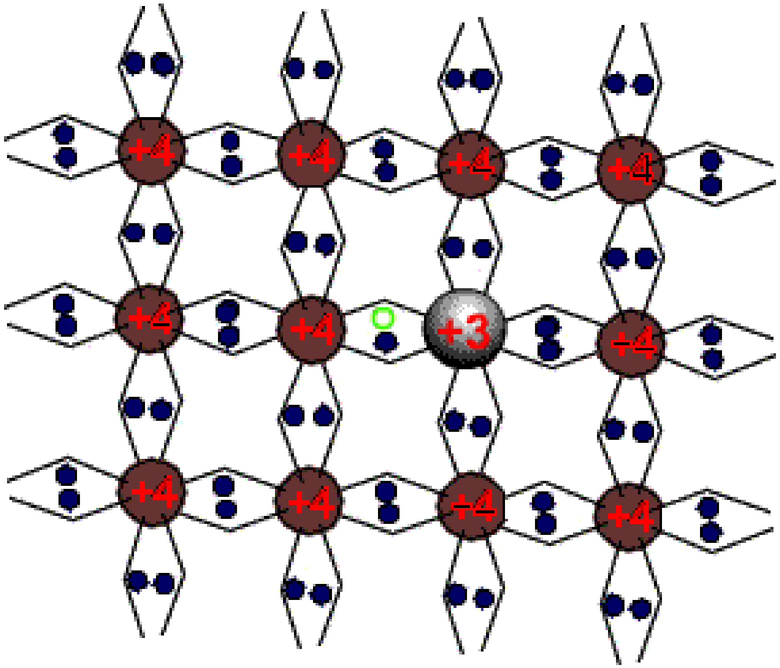
Phosphorus $\rho \approx 89.3\Omega \cdot cm$; Intrinsic silicon $\rho \approx 2.14 \times 10^5 \Omega \cdot cm$

Boron Doping (P-type)

Holes---Majority carrier;

Electrons---Minority carrier

Boron---**acceptor materials.**



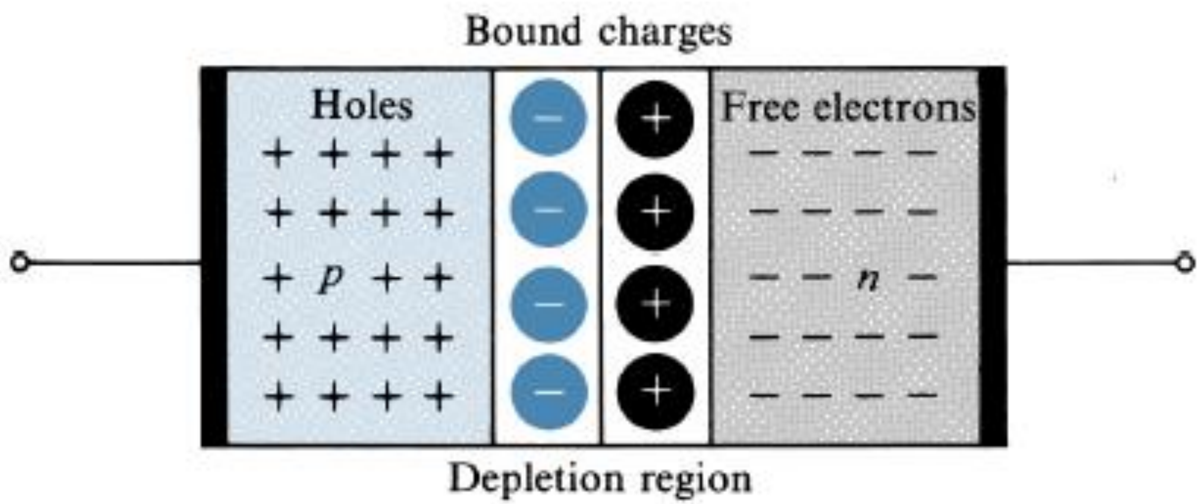
• Boron has 3 valence electrons.

• B will sit at a lattice site, but the adjacent Si atoms lack an electron to fill its shell. This creates a hole.

PN Junction

- N-type materials: Doping Si with a Group V element, providing extra electrons (n for negative) .
- P-type materials: Doping Si with a Group III element, providing extra holes (p for positive).

What happens when P-type meets N-type?



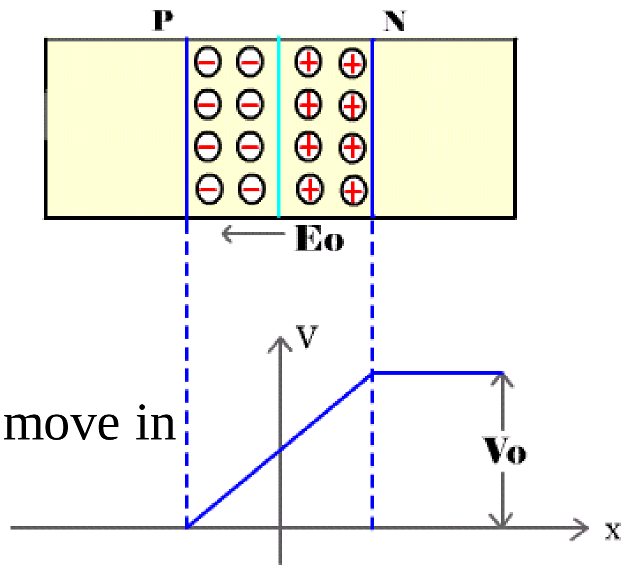
PN Junction

What happens when P-type meets N-type?

- Holes diffuse from the P-type into the N-type, electrons diffuse from the N-type into the P-type, creating a diffusion current.
- Once the holes [electrons] cross into the N-type [P-type] region, they recombine with the electrons [holes].
- This recombination "strips" the n-type [P-type] of its electrons near the boundary, creating an electric field due to the positive and negative bound charges.
- The region "stripped" of carriers is called the space-charge region, or depletion region.
- V_0 is the contact potential that exists due to the electric field. Typically, at room temp, V_0 is 0.5~0.8V.
- Some carriers are generated (thermally) and make their way into the depletion region where they are whisked away by the electric field, creating a drift current.

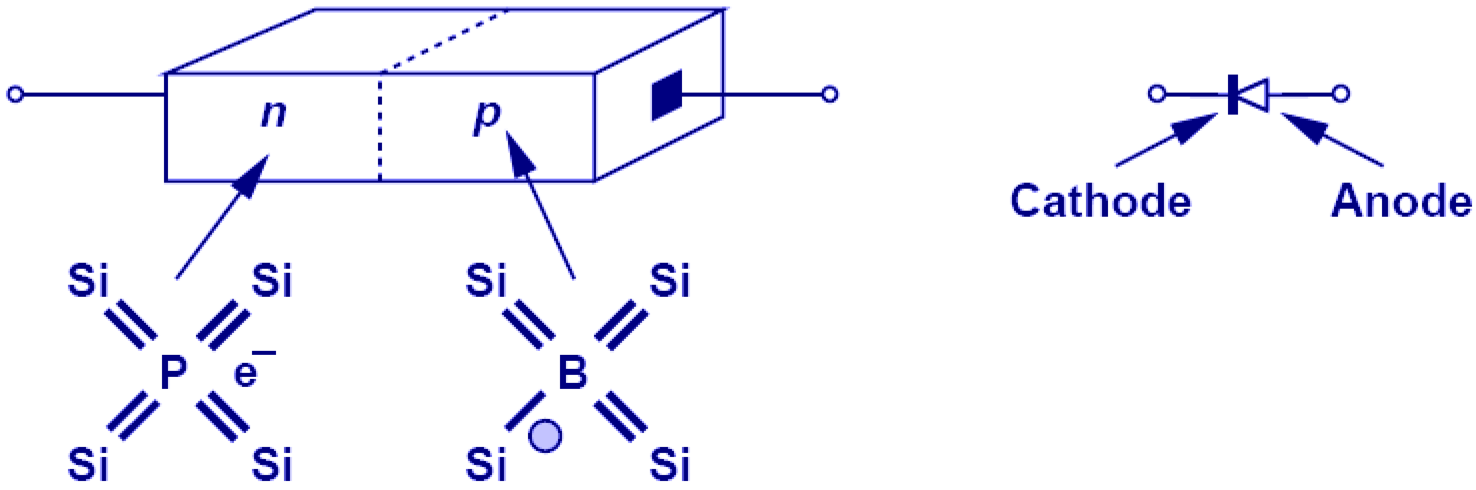
PN Junction

What happens when P-type meets N-type?



- There are two mechanisms by which mobile carriers move in semiconductors – resulting in current flow
  - Diffusion
    - Majority carriers move (diffuse) from a place of higher concentration to a place of lower concentration
  - Drift
    - Minority carrier movement is induced by the electric field.
- In equilibrium, diffusion current (I_D) is balanced by drift current (I_S). So, there is no net current flow.

PN Junction (Diode)



(a) (b)

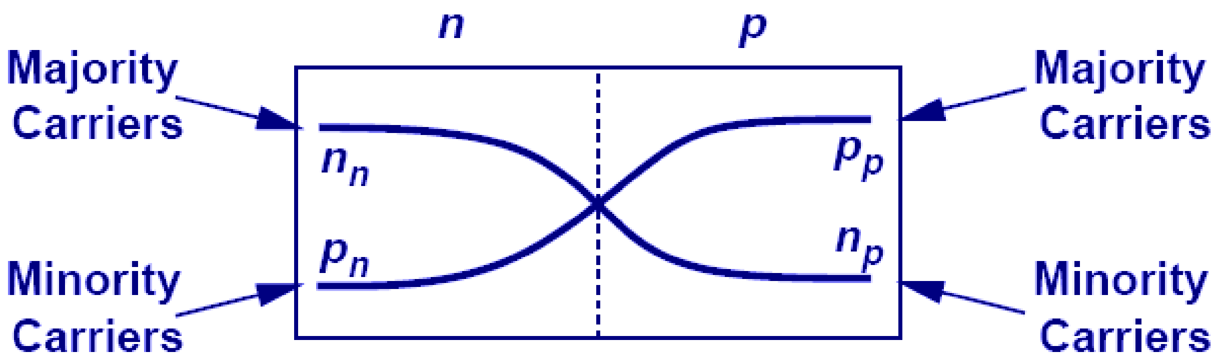
- When N-type and P-type dopants are introduced side-by-side in a semiconductor, a PN junction or a diode is formed.

Diode’s Three Operation Regions

PN Junction in Equilibrium		PN Junction Under Reverse Bias		PN Junction Under Forward Bias
• Depletion Region • Built−in Potential	⇨	• Junction Capacitance	⇨	• I/V Characteristics

- In order to understand the operation of a diode, it is necessary to study its three operation regions: equilibrium, reverse bias, and forward bias.

Current Flow Across Junction: Diffusion



n_n : Concentration of electrons on n side

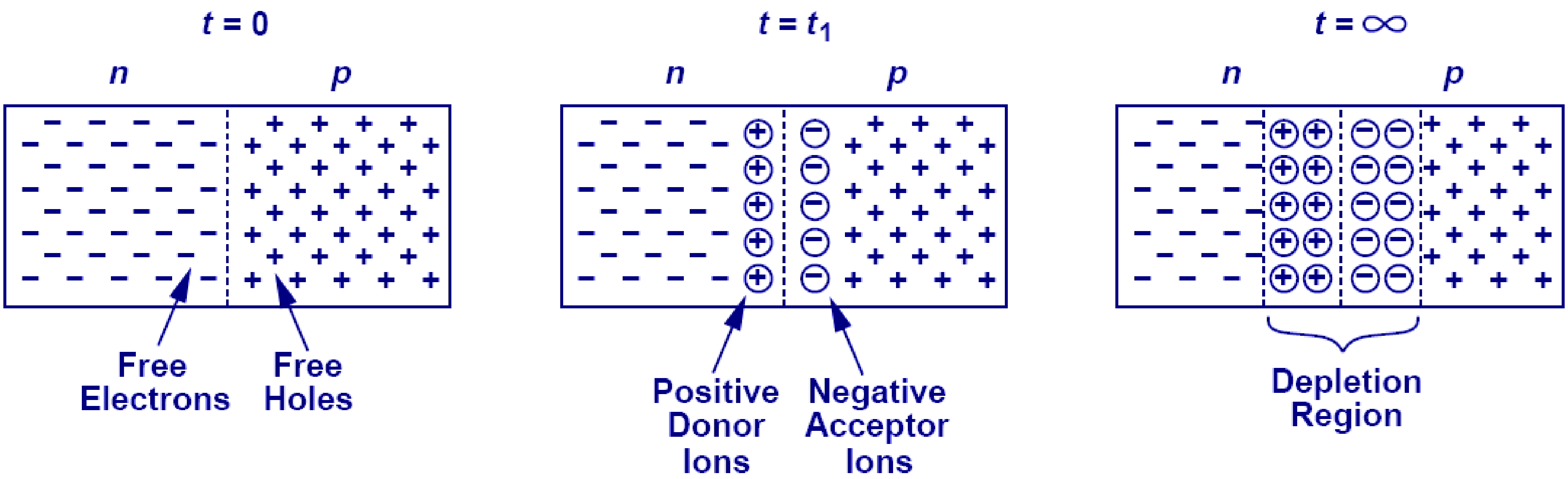
p_n : Concentration of holes on n side

p_p : Concentration of holes on p side

n_p : Concentration of electrons on p side

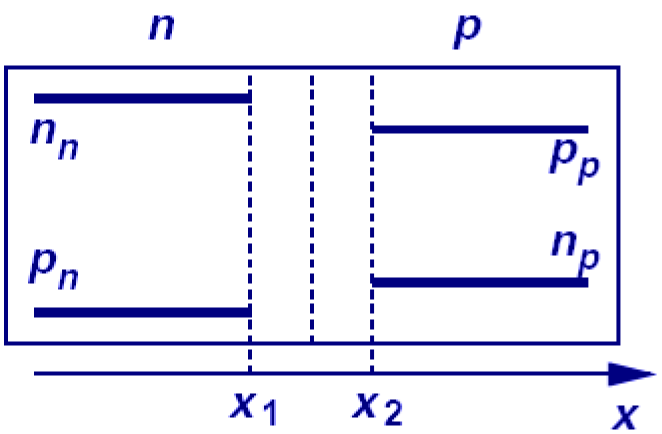
- Because each side of the junction contains an excess of holes or electrons compared to the other side, there exists a large concentration gradient. Therefore, a diffusion current flows across the junction from each side.

Depletion Region



- As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the "depletion region."

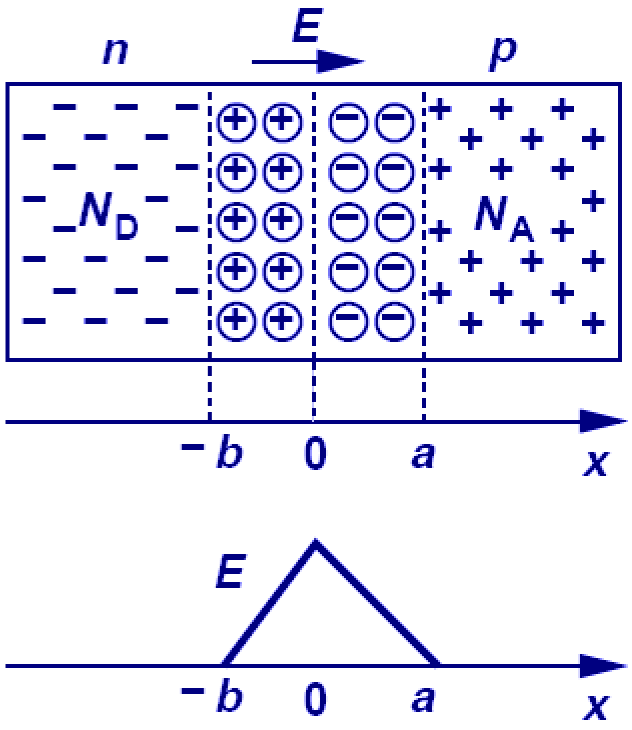
Current Flow Across Junction: Equilibrium



$$I_{drift,p} = I_{diff,p}$$
$$I_{drift,n} = I_{diff,n}$$

- At equilibrium, the drift current flowing in one direction cancels out the diffusion current flowing in the opposite direction, creating a net current of zero.
- The figure shows the charge profile of the PN junction.

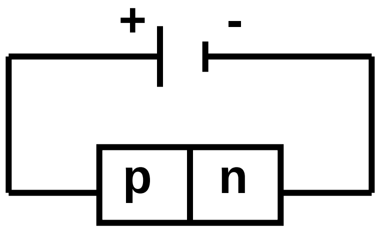
Current Flow Across Junction: Drift



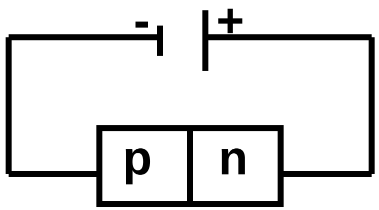
- The fixed ions in depletion region create an electric field that results in a drift current.

Biasing a PN Junction Diode

Appliying bias to p-n junction



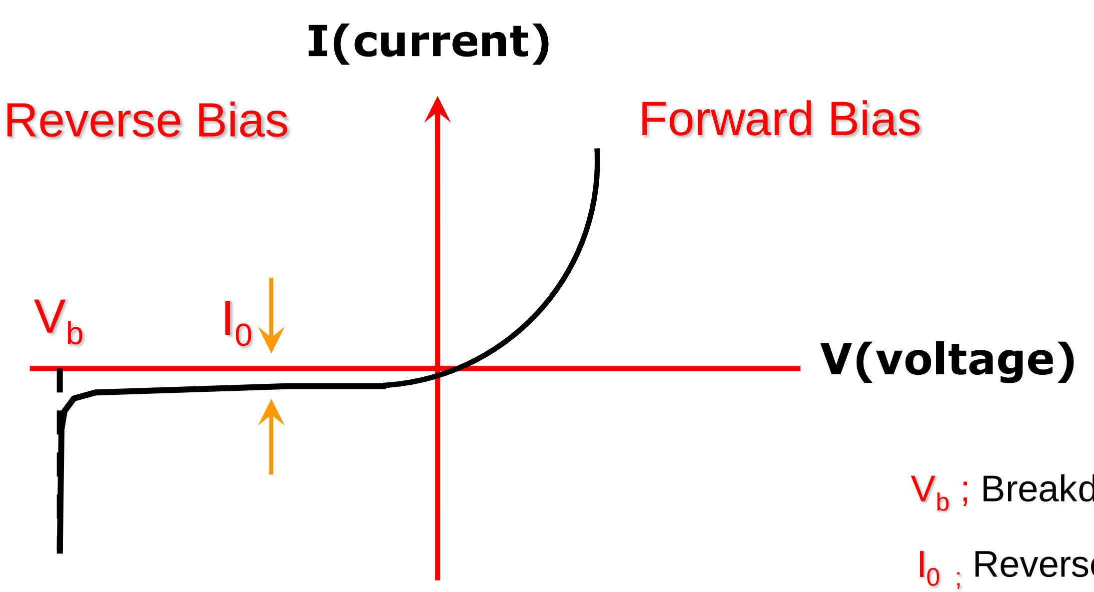
forward bias



reverse bias

- How current flows through the p-n junction when a bias (voltage) is applied.
- The current flows all the time whenever a voltage source is connected to the diode. But the current flows rapidly in forward bias, however a very small constant current flows in reverse bias case.

Appliying bias to p-n junction

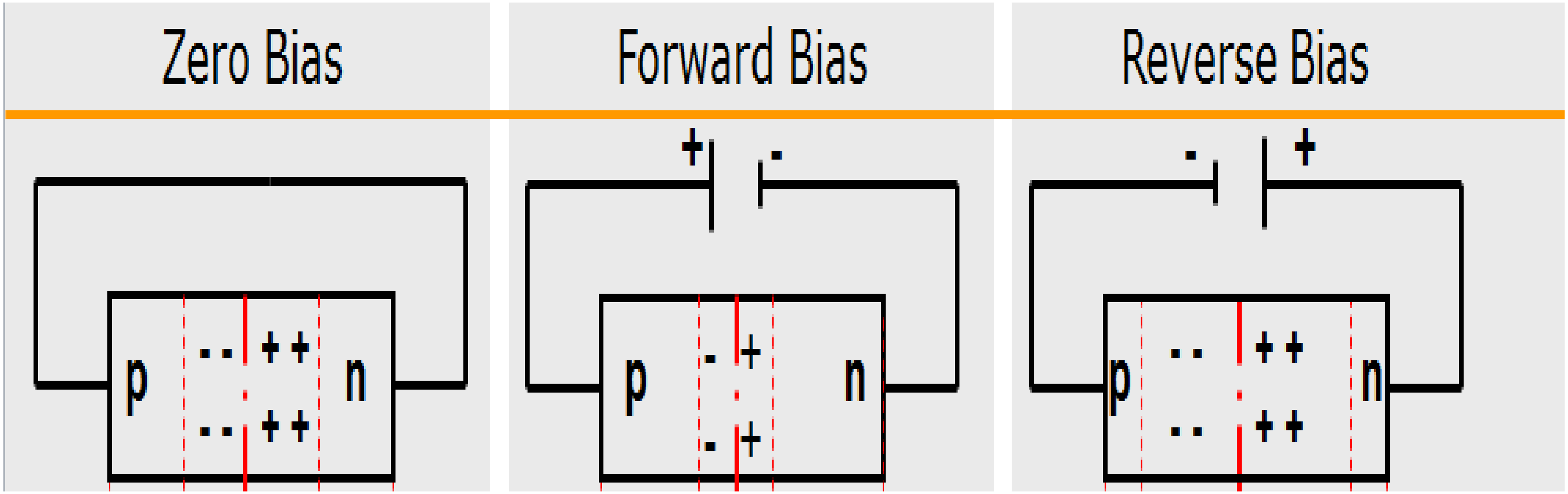


V_b ; Breakdown voltage

I_0 ; Reverse saturation current

- There is no turn-on voltage because current flows in any case. However , the turn-on voltage can be defined as the forward bias required to produce a given amount of forward current.
- If 1 m A is required for the circuit to work, 0.7 volt can be called as turn-on voltage.

Biasing PN Junction Diode



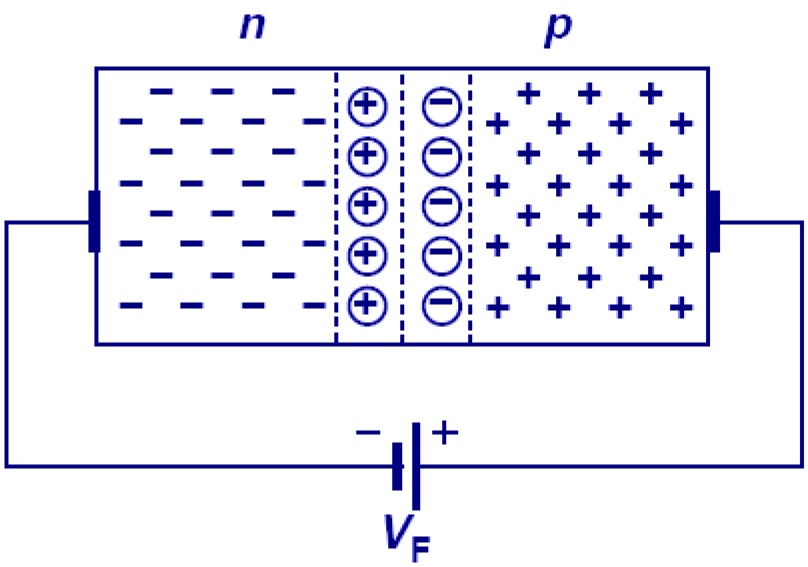
Appliying bias to p-n junction

$$V_F \rightarrow \text{forward voltage}$$

$$V_R \rightarrow \text{reverse voltage}$$

- When a voltage is applied to a diode , bands move and the behaviour of the bands with applied forward and reverse fields are shown in previous diagram.

Diode in Forward Bias



Add more majority carriers to both sides →shrink the depletion region→ lower V_0 →diffusion current increases.

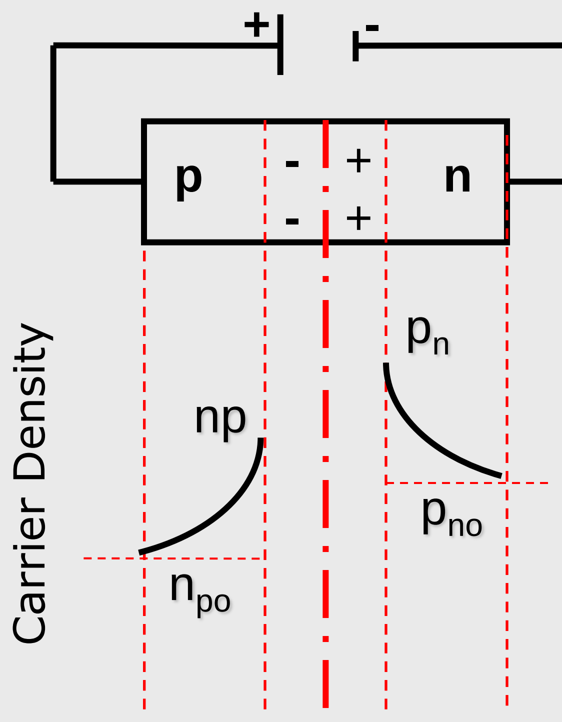
- Decrease the built-in potential, lower the barrier height.
- Increase the number of carriers able to diffuse across the barrier
- Diffusion current increases
- Drift current remains the same. The drift current is essentially constant, as it is dependent on temperature.
- Current flows from p to n

- When the N-type region of a diode is at a lower potential than the P-type region, the diode is in forward bias.
- The depletion width is shortened and the built-in electric field decreased.

- Junction potential reduced
- Enhanced hole diffusion from p-side to n-side compared with the equilibrium case.
- Enhanced electron diffusion from n-side to p-side compared with the equilibrium case.
- Drift current flow is similar to the equilibrium case.
- Overall, a large diffusion current is able to flow.
- Mnemonic. Connect positive terminal to p-side for forward bias.

- Drift current is very similar to that of the equilibrium case. This current is due to the minority carriers on each side of the junction and the movement minority carriers is due to the built in field accross the depletion region.

Qualitative explanation of forward bias



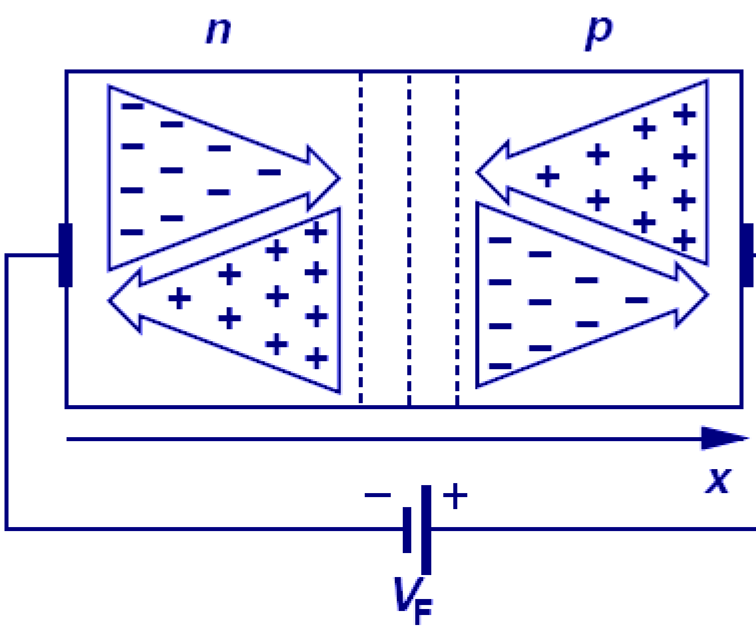
p-n junction in forward bias

- Junction potential is reduced
- By forward biasing a large number of electrons are injected from n-side to p-side accross the depletion region and these electrons become minority carriers on p-side, and the minority recombine with majority holes so that the number of injected minority electrons decreases (decays) exponentially with distance into the p-side.

- Similarly, by forward biasing a large number of holes are injected from p-side to n-side across the DR. These holes become minority carriers at the depletion region edge at the n-side so that their number (number of injected excess holes) decreases with distance into the neutral n-side.

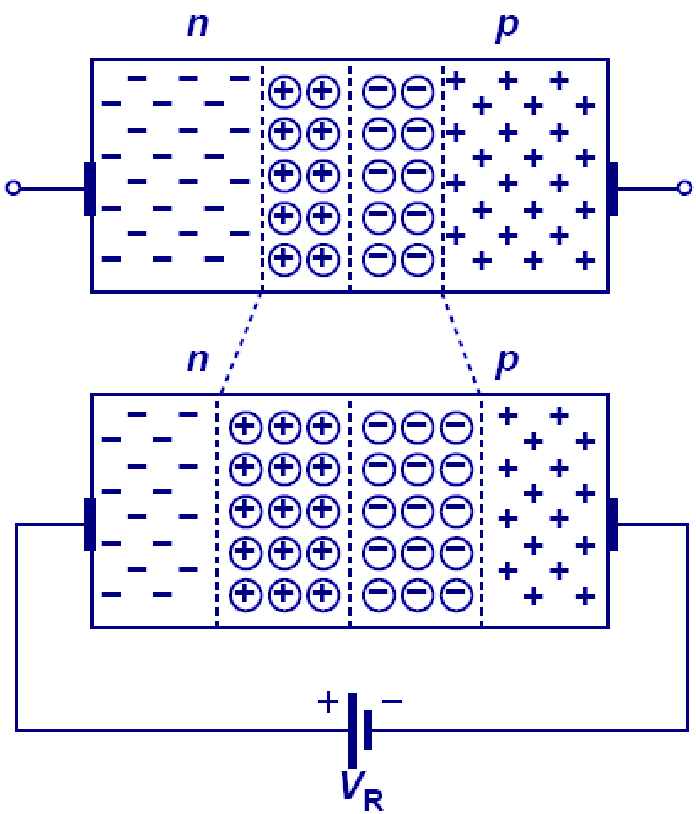
- In summary, by forward biasing in fact one injects minority carriers to the opposite sides. These injected minorites recombine with majorities.

Forward Bias Condition: Summary



- In forward bias, there are large diffusion currents of minority carriers through the junction. However, as we go deep into the P and N regions, recombination currents from the majority carriers dominate. These two currents add up to a constant value.

Diode in Reverse Bias



- Increase the built-in potential, increase the barrier height.
- Decrease the number of carriers able to diffuse across the barrier.
- Diffusion current decreases.
- Drift current remains the same
- Almost no current flows. Reverse leakage current, I_S, is the drift current, flowing from N to P.

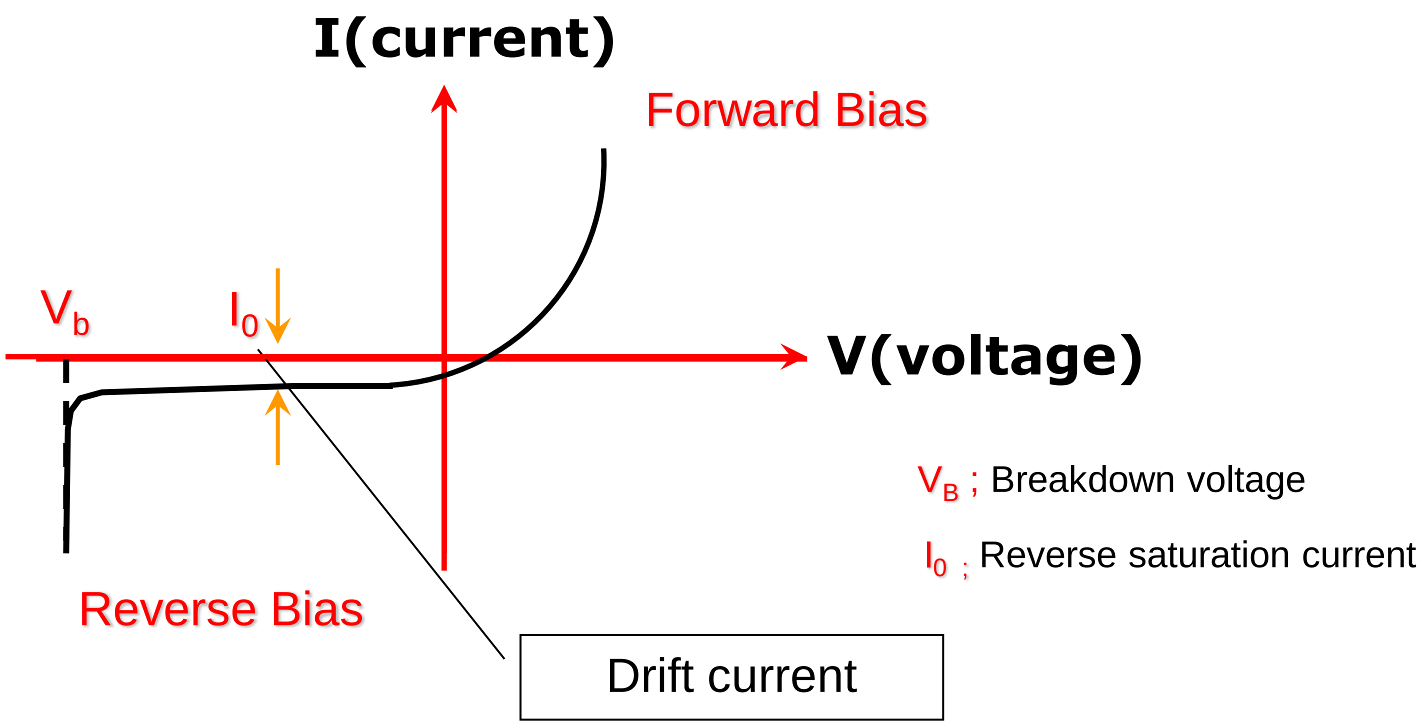
- When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under reverse bias, which results in wider depletion region and larger built-in electric field across the junction.

Reverse Bias

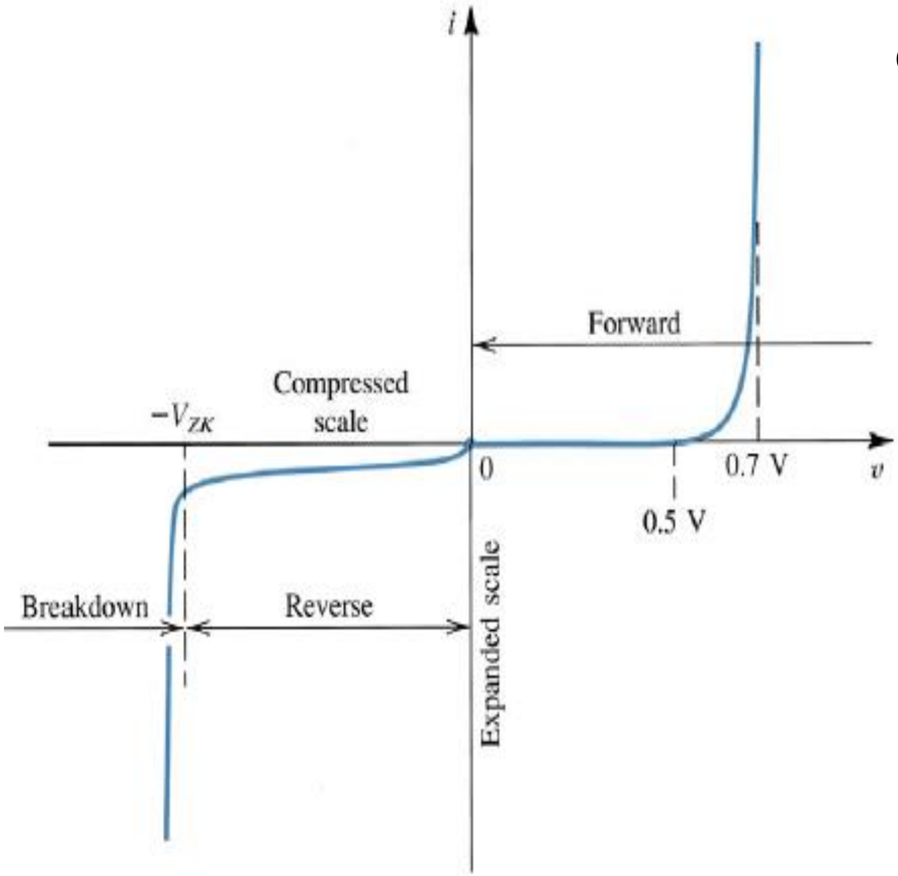
- Junction potential increased
- Reduced hole diffusion from p-side to n-side compared with the equilibrium case.
- Reduced electron diffusion from n-side to p-side compared with the equilibrium case
- Drift current flow is similar to the equilibrium case.
- Overall a very small reverse saturation current flows.
- Mnemonic. Connect positive terminal to n-side for reverse bias.

p-n junction in reverse bias

- The flow of these minorities produces the reverse saturation current and this current increases exponentially with temperature but it is independent of applied reverse voltage.



PN Junction Diode I-V Characteristic



Typical PN junction diode volt-ampere characteristic is shown on the left.

- In forward bias, the PN junction has a "turn on" voltage based on the "built-in" potential of the PN junction. turn on voltage is typically in the range of 0.5V to 0.8V
- In reverse bias, the PN junction conducts essentially no current until a critical breakdown voltage is reached. The breakdown voltage can range from 1V to 100V. Breakdown mechanisms include avalanche and zener tunneling.

The current and voltage relationship of a PN junction is exponential in forward bias region, and relatively constant in reverse bias region.

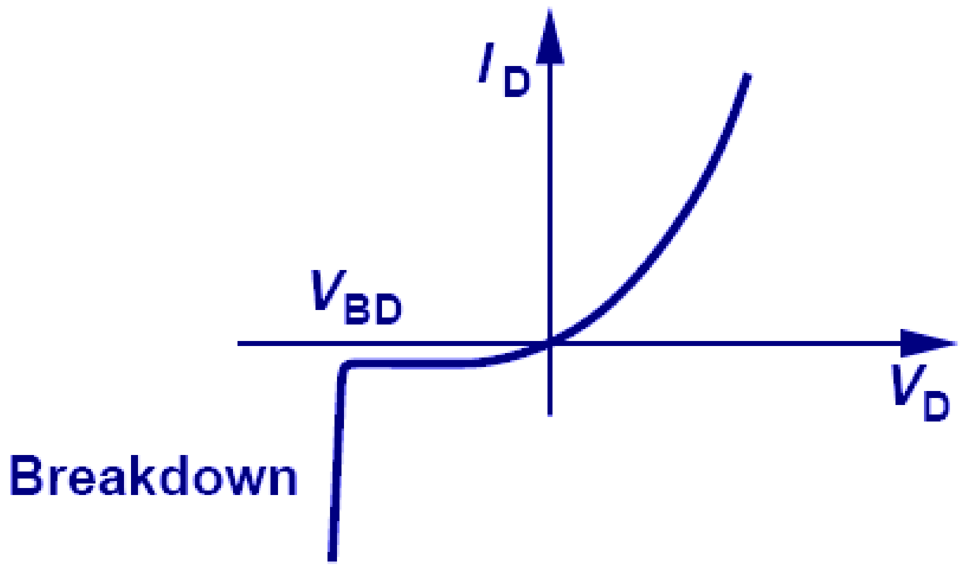
Junction breakdown or reverse breakdown

- An applied reverse bias (voltage) will result in a small current to flow through the device.
- At a particular high voltage value, which is called as breakdown voltage V_B, large currents start to flow. If there is no current limiting resistor which is connected in series to the diode, the diode will be destroyed. There are two physical effects which cause this breakdown.

1) Zener breakdown is observed in highly doped p-n junctions and occurs for voltages of about 5 V or less.

2) Avalanche breakdown is observed in less highly doped p-n junctions.

Reverse Breakdown



- When a large reverse bias voltage is applied, breakdown occurs and an enormous current flows through the diode.

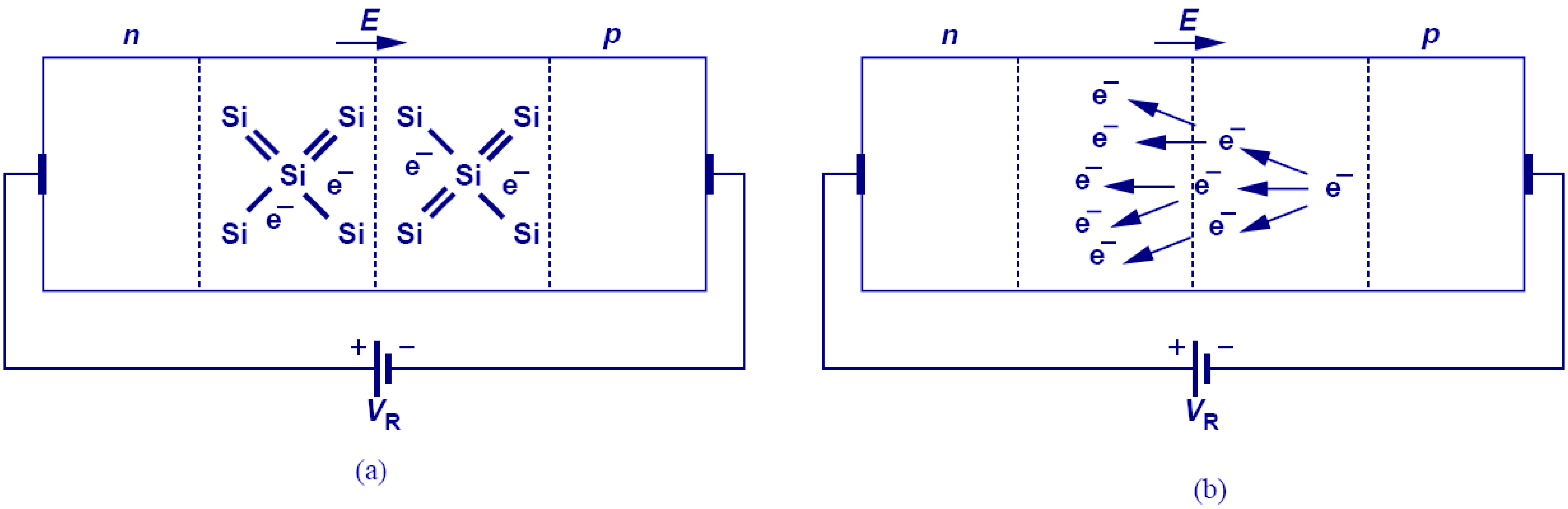
Zener breakdown

- Zener breakdown occurs at highly doped p-n junctions with a tunneling mechanism.
- In a highly doped p-n junction the conduction and valance bands on opposite side of the junction become so close during the reverse-bias that the electrons on the p-side can tunnel into the n-side.

Avalanche Breakdown

- Avalanche breakdown mechanism occurs when electrons and holes moving through the DR and acquire sufficient energy from the electric field to break a bond i.e. create electron-hole pairs by colliding with atomic electrons within the depletion region.
- The newly created electrons and holes move in opposite directions due to the electric field and thereby add to the existing reverse bias current. This is the most important breakdown mechanism in p-n junction.

Zener vs. Avalanche Breakdown



- Zener breakdown is a result of the large electric field inside the depletion region that breaks electrons or holes off their covalent bonds.
- Avalanche breakdown is a result of electrons or holes colliding with the fixed ions inside the depletion region.

Lab Experiment

I-V Characteristics of PN Junction Diode

Components

- Diode
- Variable Resistor
- Ammeter
- Voltmeter
- Voltage Supply (Signal Generator)

Diode

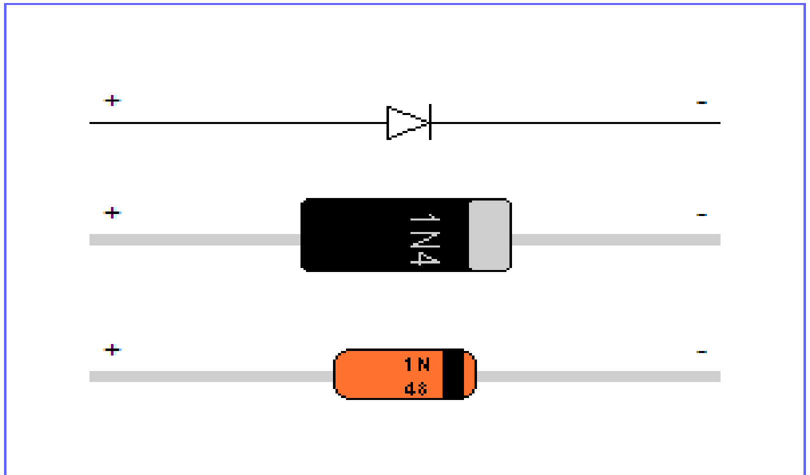
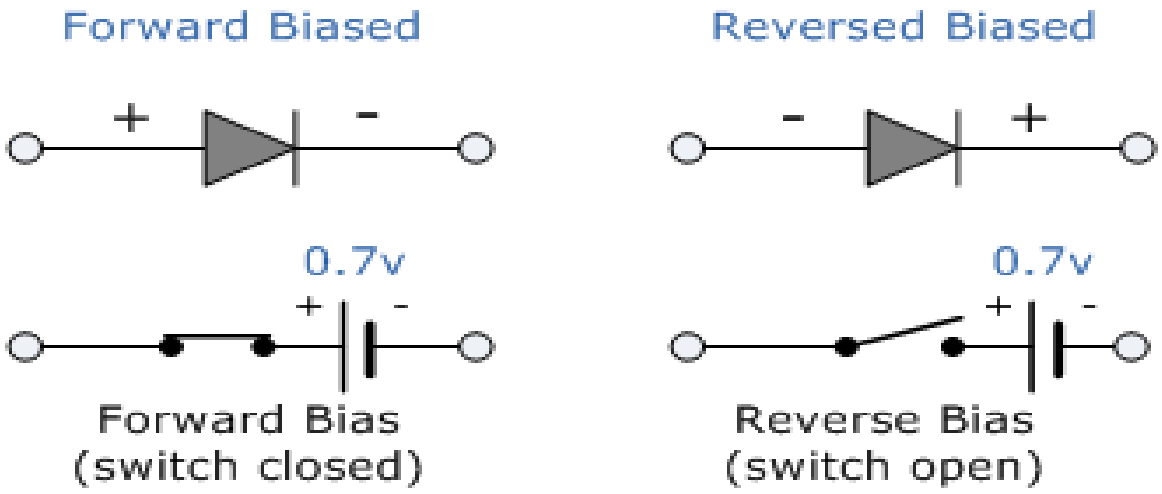


Figure 2: Orientation of diodes

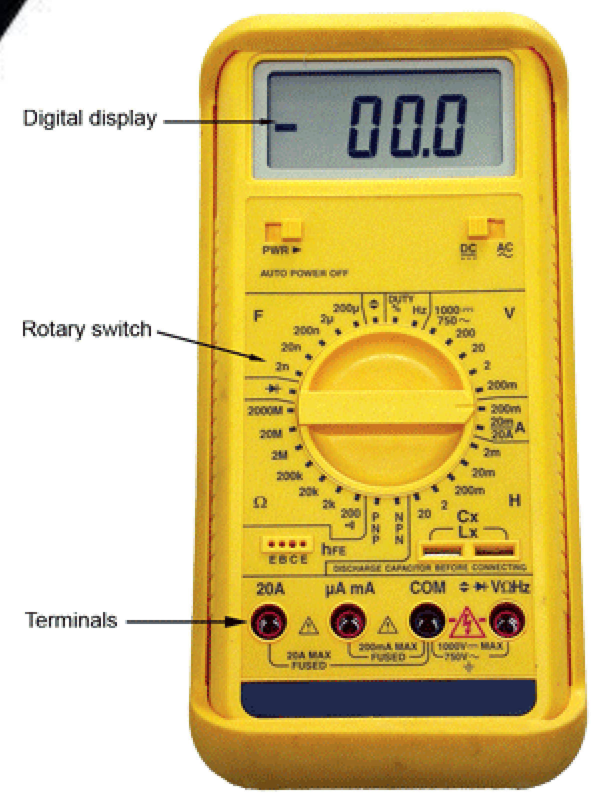


Variable Resistor

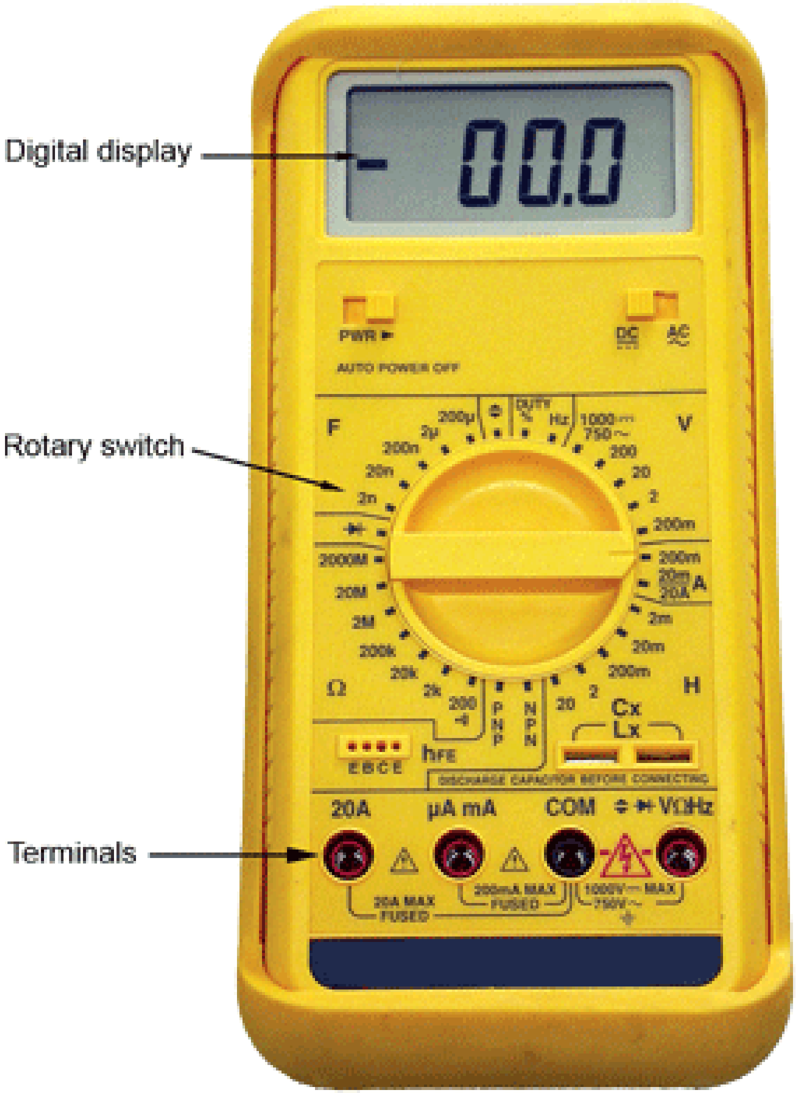
Ammeter


0
1
2
3
0.2
0
0.2
0.4
0.6
A


40
20
0
20
40
50
μA
50


Digital display
00.0
Rotary switch
Terminals
20A
μA mA
COM

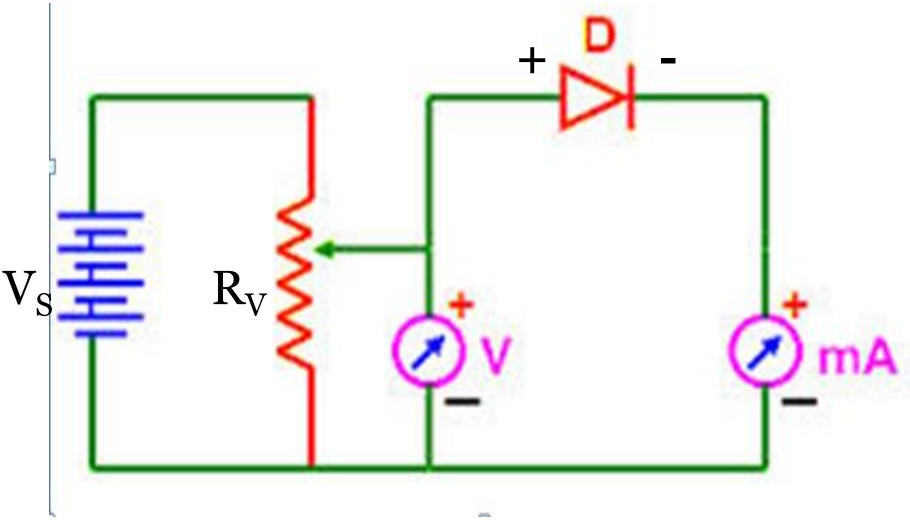
Voltmeter



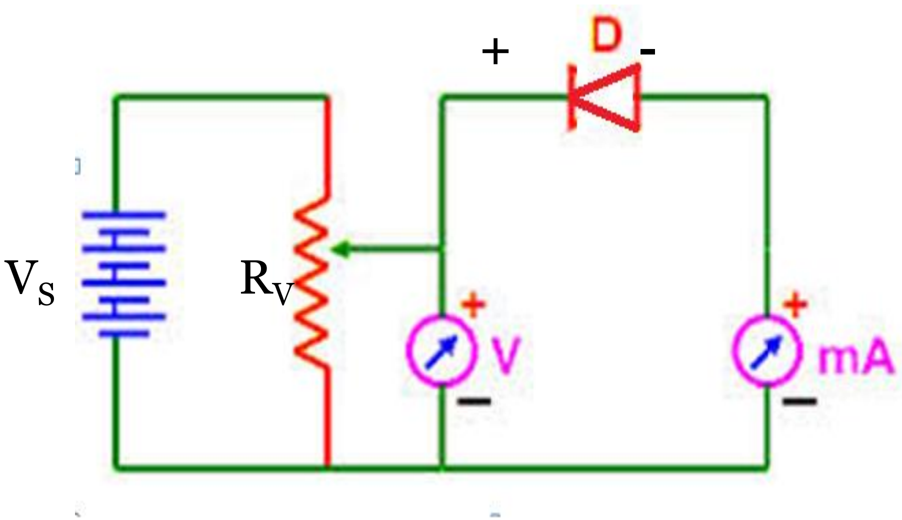
Voltage Supply (Signal Generator)

Experimental Setup

Forward Bias

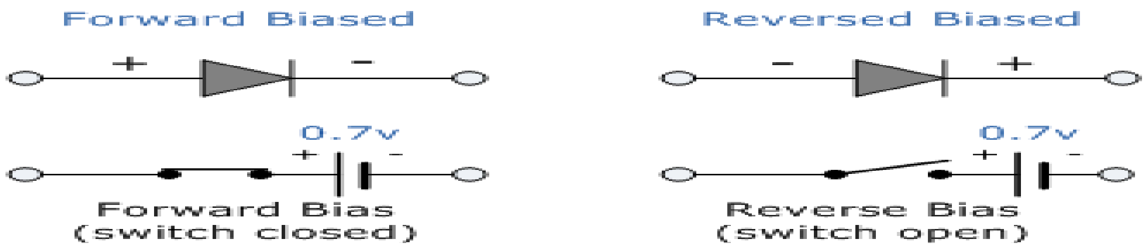


Reverse Bias



Vs = Supply Voltage
Rv = Variable Resistor
V = Voltmeter
mA/uA = Ammeter

I-V characteristics of PN junction Diode



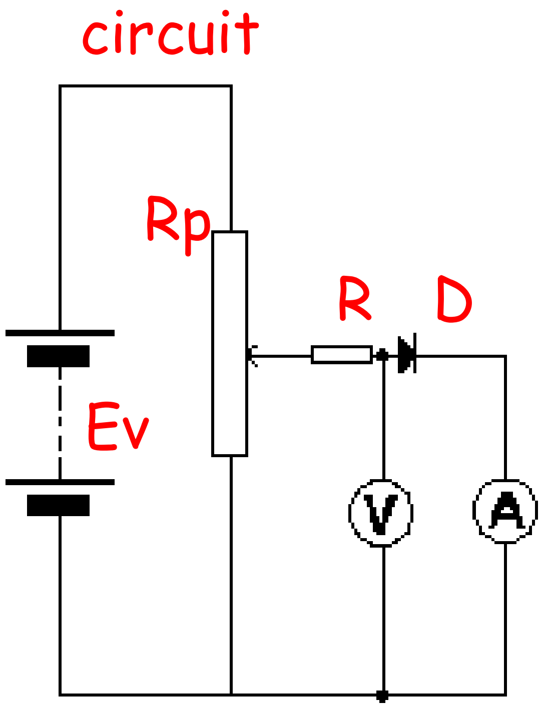
Forward Bias

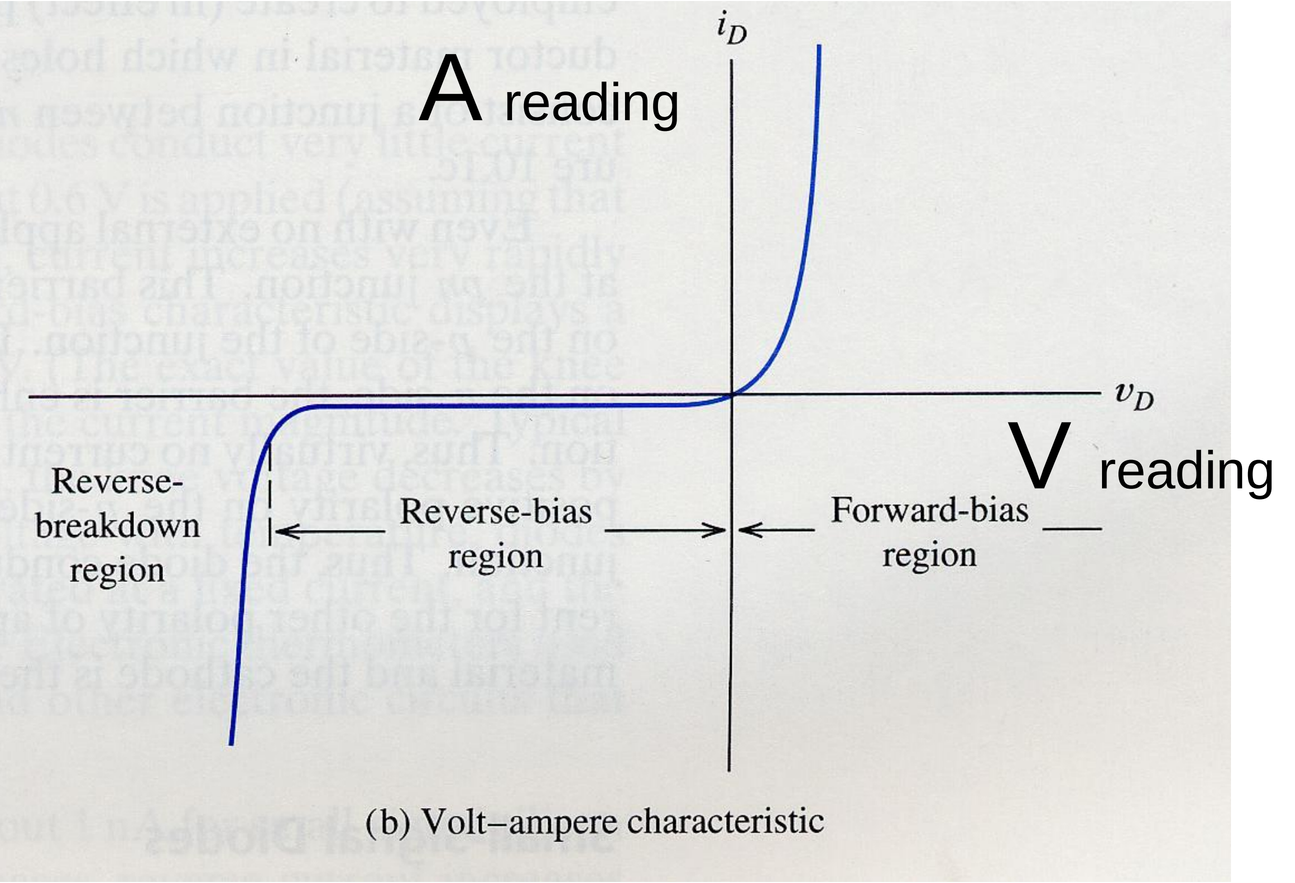
Test	Voltmeter Reading	Ammeter Reading

Reverse Bias

Test	Voltmeter Reading	Ammeter Reading

Diode Characteristic





(b) Volt–ampere characteristic

A diode is a nonlinear device and typical linear circuit analysis methods do not apply!

…that's all folks…
…thanks for your time…