Diode capacitances

Diode capacitances

- Electronic devices are inherently sensitive to **very high frequencies**.

- Most shunt capacitive effects that can be ignored at **lower frequencies** because the reactance $X_C = {}^{1}/_{2\pi fC}$ is very large (open circuit equivalent).

- This, however, cannot be ignored at **very high frequencies**. X_C will become sufficiently small due to the high value of f to introduce a low-reactance "shorting" path.

Diode capacitances

- In the p-n semiconductor diode, there are two capacitive effects to be considered.

- In the reverse-bias region we have the **transition- or depletion region capacitance (CT).**

- while in the forward-bias region we have the **diffusion (CD) or Storage capacitance.**

Diode capacitances

- Recall that the basic equation for the capacitance of a **parallelplate capacitor** is defined by

$$C = \in {}^{A}/_{d}$$

- where € is the permittivity of the dielectric (insulator) between the plates of area A separated by a distance d.
- In the reverse-bias region there is a depletion region that behaves essentially like an insulator between the layers of opposite charge.
- Since the depletion width (d) will increase with increased reverse-bias potential, the resulting transition capacitance will decrease.
- The fact that the **capacitance is dependent** on the applied reverse-bias potential has **application** in a number of electronic systems.

Diode capacitances

- Although the effect described above will also be present in the forward-bias region,

- it is over shadowed by a capacitance effect directly dependent on the rate at which charge is injected into the regions just outside the depletion region.

Transition and Diffusion Capacitance

- **Transition capacitance:** The capacitance which appears between positive ion layer in n-region and negative ion layer in p-region.
- **Diffusion capacitance**: This capacitance originates due to diffusion of charge carriers in the opposite regions.
- The transition capacitance is very small as compared to the diffusion capacitance.

- In reverse bias, transition capacitance is the dominant and is given by:

$$\boldsymbol{C_T} = \in \boldsymbol{A}/\boldsymbol{w}$$

where $\boldsymbol{C_T}$ - transition capacitance

A - diode cross sectional area

W - depletion region width

Transition and Diffusion Capacitance

In forward bias, the diffusion capacitance is the dominant and is given by:

$$C_D = dQ/dV = \tau^* dI/dV = \tau^* g = \tau/r \text{ (general)}$$

where C_D - diffusion capacitance

dQ - change in charge stored in depletion region

V - change in applied voltage

τ - time interval for change in voltage

g - diode conductance

r - diode resistance

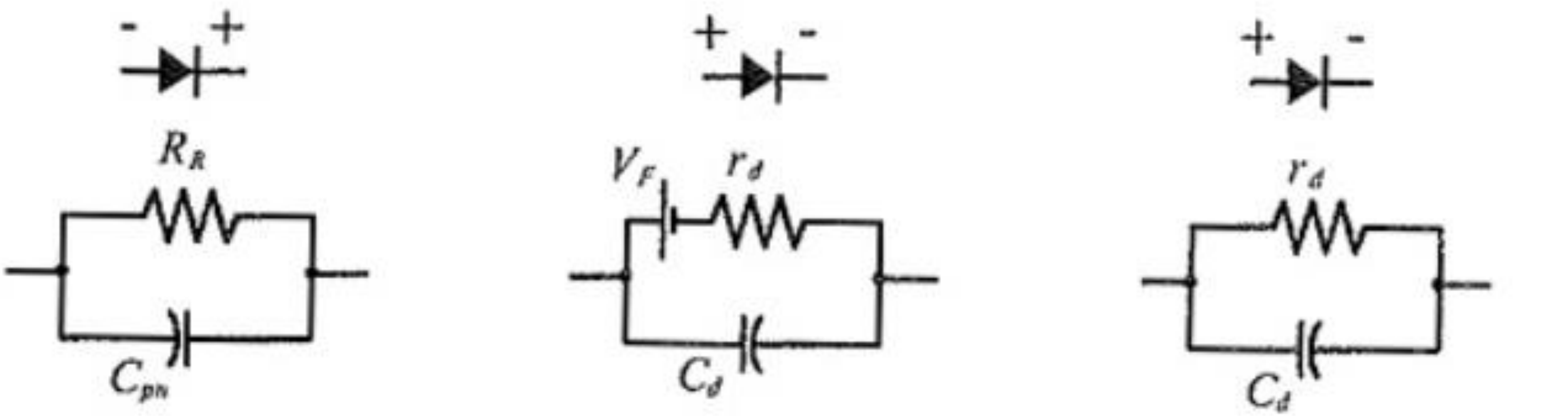
The diffusion capacitance at low frequencies is given by the formula:

$$C_D = \tau^* g/2 \text{ (low frequency)}$$

Equivalent circuit

- The capacitive effects described above are represented by a capacitor in parallel with the ideal diode,

- For low- or mid-frequency applications (except in the power area), however, the capacitor is normally not included in the diode symbol.



(a) Equivalent circuit for a reverse-biased diode

(b) Equivalent circuit for a forward-biase diode

(c) AC equivalent circuit for a forward-biased diode

Break Down Mechanisms

Break Down Mechanisms

- When an ordinary **P-N junction diode** is reverse biased, normally only very small reverse saturation current flows.

- This current is due to movement of **minority carriers**.

- It is almost **independent** of the voltage applied.

- However, if the reverse bias is increased, **a point** is reached when the junction breaks down and the reverse current increases abruptly.

- This current could be **large enough** to destroy the junction.

Break Down Mechanisms

- If the reverse current is **limited** by means of a **suitable series resistor**,
- the power dissipation at the junction will not be **excessive**, and the device **may be operated continuously** in its breakdown region to its normal (reverse saturation) level.

- It is found that for a **suitably designed diode**, the breakdown voltage is very stable over a wide range of reverse currents.

- This quality gives the breakdown diode many useful applications as a voltage reference source.

Break Down Mechanisms

- The critical value of the voltage, at which the breakdown of a P-N junction diode occurs, is called the *breakdown voltage*.

- The breakdown voltage depends on the **width of the depletion region**, which, in turn, depends on the **doping level.**

- The junction offers almost **zero resistance** at the breakdown point.

- There are two mechanisms by which breakdown can occur at a reverse biased P-N junction:

    1. ***Avalanche breakdown***

    2. ***Zener breakdown.***

Avalanche breakdown

- The **minority carriers**, under reverse biased conditions, flowing through the junction acquire a **kinetic energy** which increases with the increase in reverse voltage.
- At a sufficiently **high reverse voltage** (say 5V or more), the kinetic energy of minority carriers becomes **so large** that they **knock out electrons** from the covalent bonds of the semiconductor material.
- As a result of collision, the liberated electrons in turn **liberate more electrons** and the current becomes very large leading to the breakdown of the crystal structure itself. This phenomenon is called the avalanche breakdown.
- The breakdown region is the **knee of the characteristic curve**.
- Now the current is not controlled by the junction voltage but rather by the external circuit.

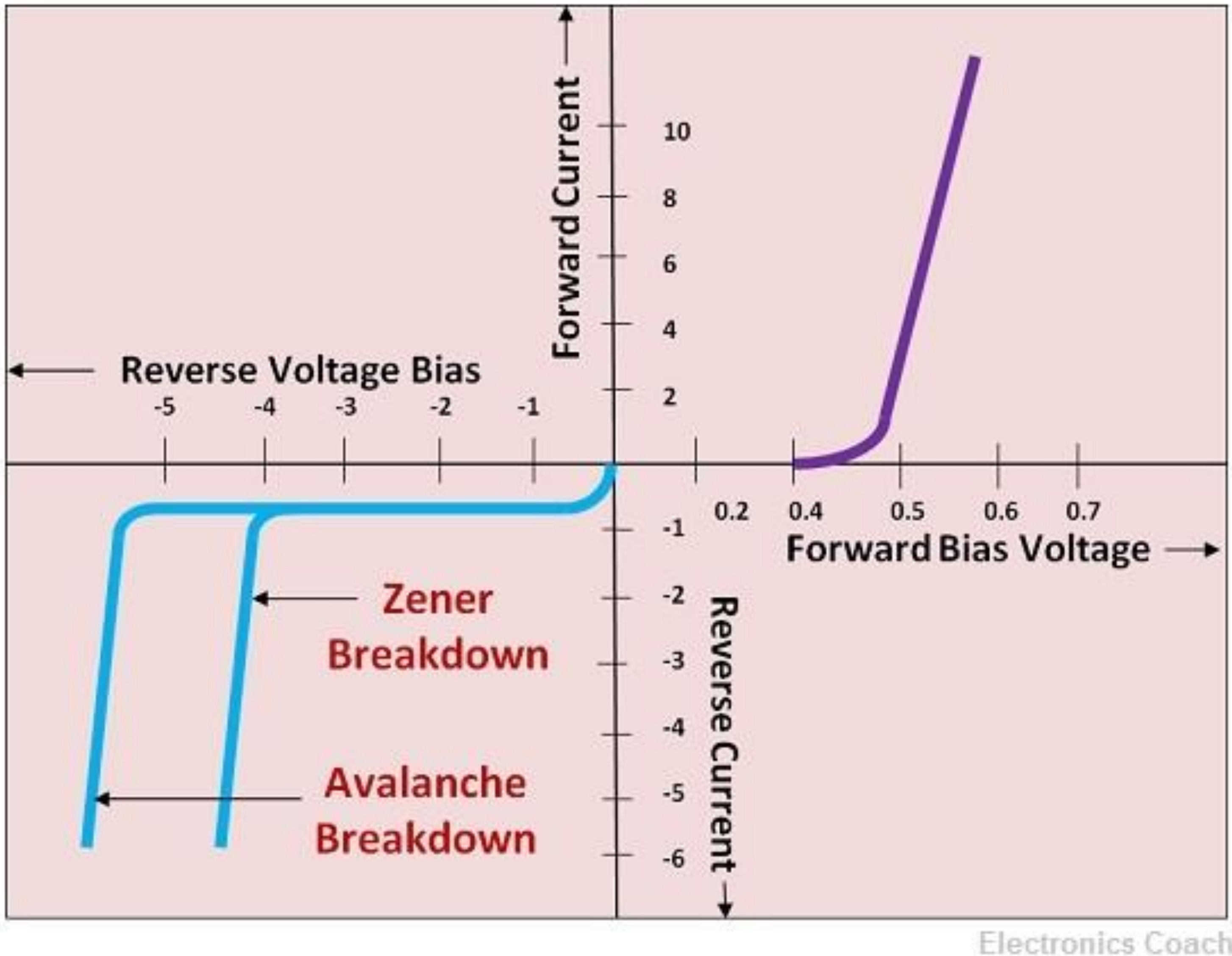
Zener breakdown

- Under a very high reverse voltage, the **depletion region expands** and the **potential barrier increases** leading to a ***very high electric field across*** the junction.

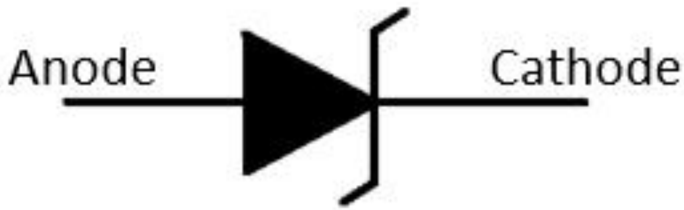
- The ***electric field*** will **break** some of the covalent bonds of the semiconductor atoms leading to a large number of **free minority** carriers, which suddenly increase the reverse current. This is called the Zener effect.

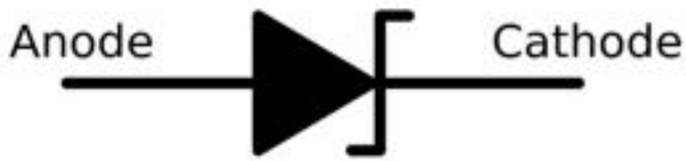
- The breakdown occurs at a particular and constant value of reverse voltage called the breakdown voltage, it is found that Zener breakdown occurs at electric field intensity of about 3×10^7 V/m.

I-V Characteristics



Zener Diode Symbol





Avalanche vs Zener breakdown

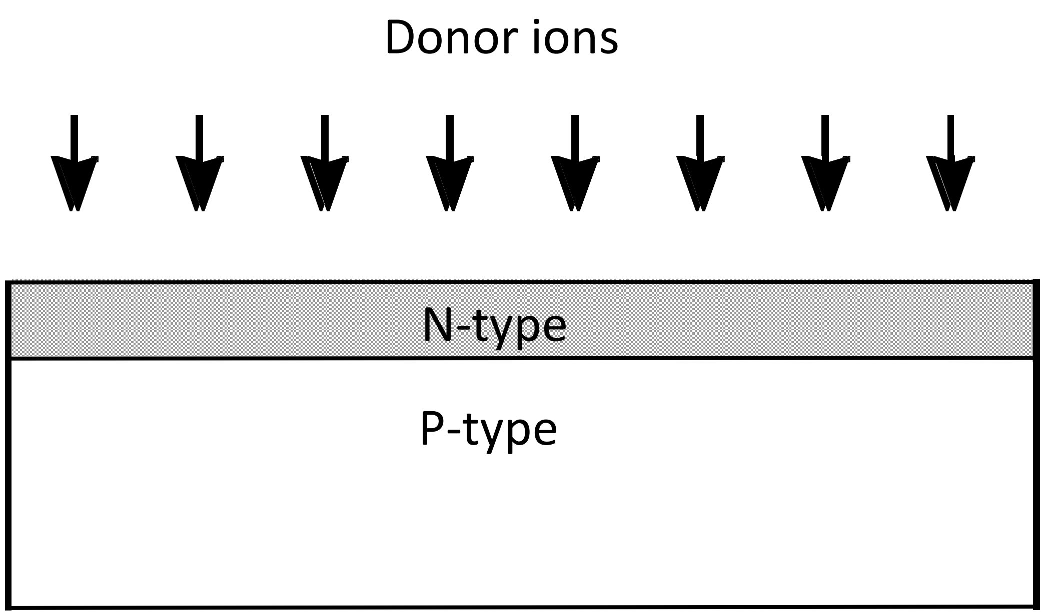
- Either of the two (Zener breakdown or avalanche breakdown) may occur **independently**, or **both** of these may occur simultaneously.
- Diode junctions that breakdown **below 5V** are caused by Zener effect.
- Junctions that experience breakdown **above 5V** are caused by avalanche effect.
- Junctions that breakdown **around 5V** are usually caused by combination of two effects.
- The Zener breakdown occurs in **heavily doped junctions** (P-type semiconductor moderately doped and N-type heavily doped), which produce narrow depletion layers.

Avalanche vs Zener breakdown

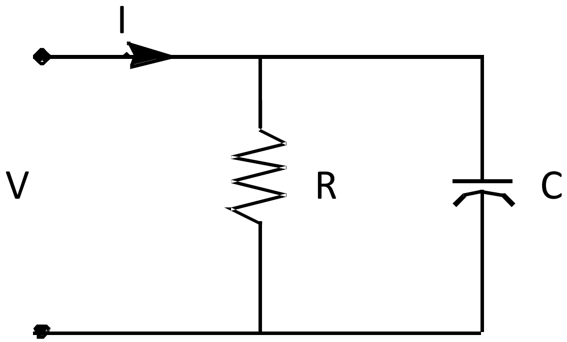
- The avalanche breakdown occurs in **lightly doped junctions**, which produce wide depletion layers.
- With the increase in junction temperature Zener breakdown voltage is reduced while the avalanche breakdown voltage increases.
- The Zener diodes have a **negative temperature coefficient** while avalanche diodes have a **positive temperature coefficient**.
- Diodes that have breakdown voltages around 5V have **zero temperature coefficient**.
- The breakdown phenomenon is **reversible and harmless** so long as the safe operating temperature is maintained.

Fabrication of PN Junction Diode

- a PN junction can be fabricated by implanting or diffusing donors into a P-type substrate such that a layer of semiconductor is converted into N type.
- Converting a layer of an N-type semiconductor into P type with acceptors would also create a PN junction



Small-signal Model of the Diode



$$G \equiv \frac{1}{R} = \frac{dI}{dV} = \frac{d}{dV} I_0 (e^{qV/kT} - 1) \approx \frac{d}{dV} I_0 e^{qV/kT}$$

$$= \frac{q}{kT} I_0 (e^{qV/kT}) = I_{DC} / \frac{kT}{q}$$

What is G at 300K and I_{DC} = 1 mA?

Diffusion Capacitance:

$$C = \frac{dQ}{dV} = \tau_s \frac{dI}{dV} = \tau_s G = \tau_s I_{DC} / \frac{kT}{q}$$

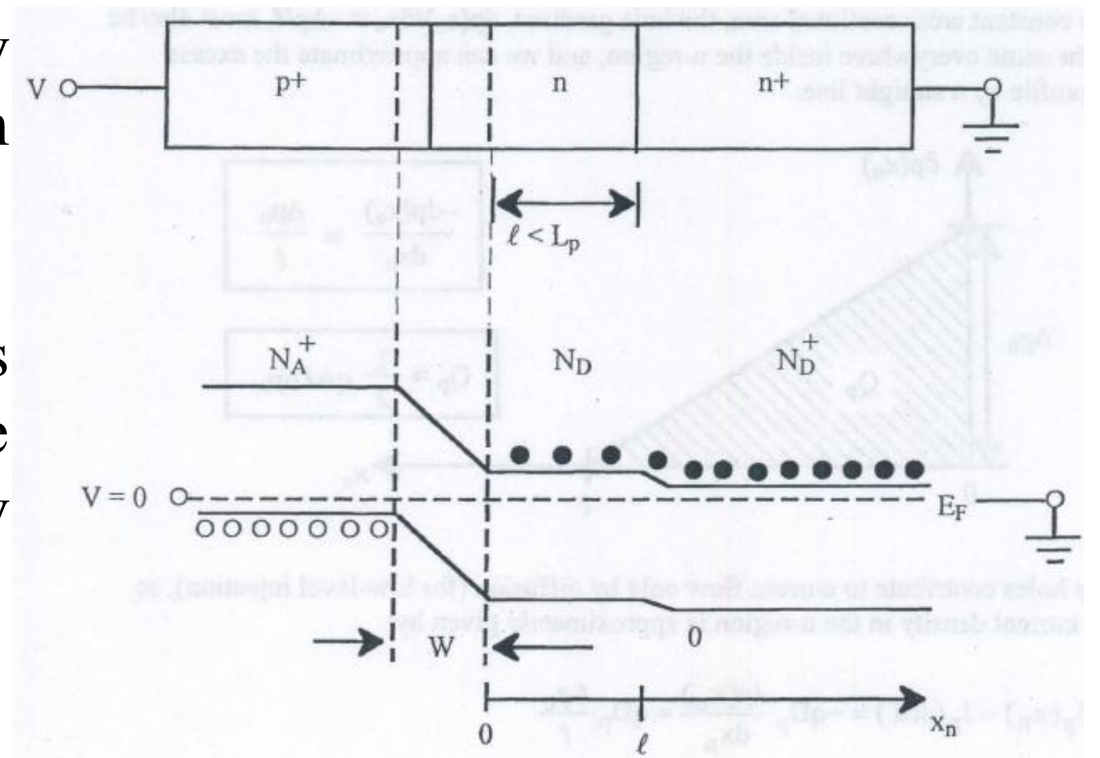
Narrow Base Diode

- The **narrow-base diode** is comprised of: **p+-n diode** and heavily doped **n+ contact**.

- Typically, the neutral portion of the lightly doped region is much less than the average hole diffusion length away.

- Neutral portion of lightly doped n-region is much less than Lp.

- Hole diffusion current is still dominant, as we expect, but the boundary conditions are altered.



Narrow Base Diode

- Minority holes cross Xn = l are assumed to recombine when they enter the n+ contact as the minority lifetime will be extremely small.
- The much larger change in hole concentration across the neutral n-region which sets up a **large diffusion**.
- We already know that only a few holes will recombine within the n-region.
- Each time this happens another electron must flow in from the n+ contact to preserve the charge neutrality.
- In the three terminal p+ - n - p device there exists a small electron base current corresponding to the sum of the electron injection and recombination currents which we can adjust to control the much large hole current.
- Therefore, we get **current multiplication**.