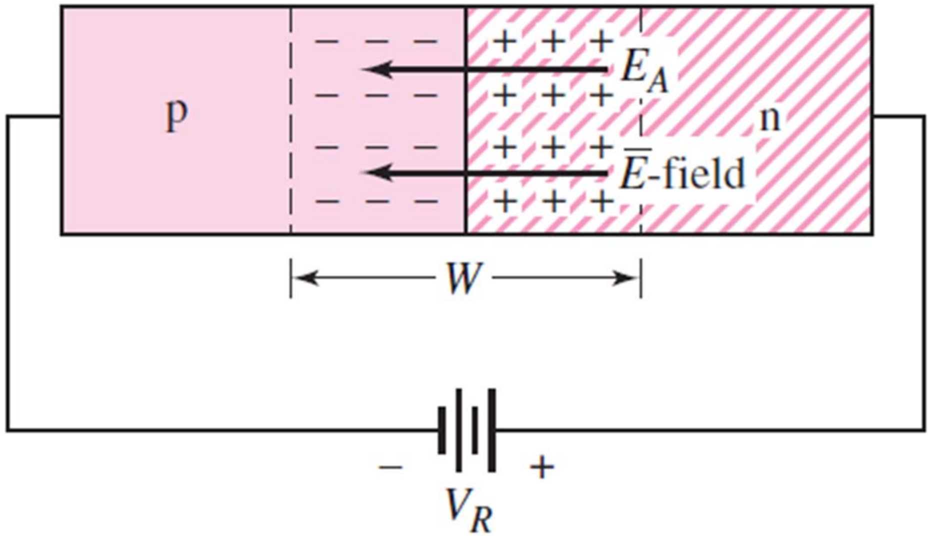
pn Junction

Reverse-bias pn Junction:

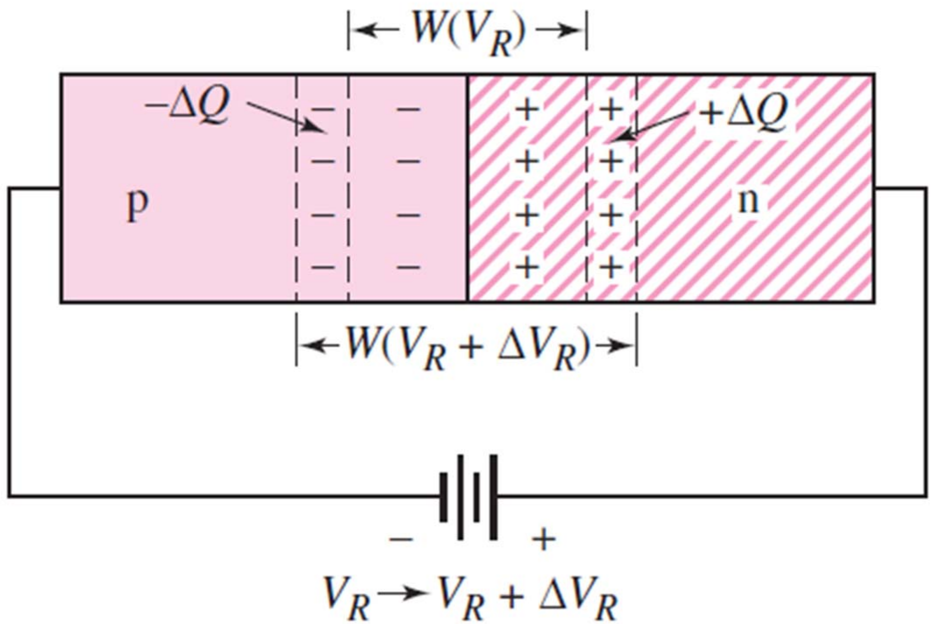
- Positive voltage is applied to the n-region of a pn junction and negative to the p-region



- V_R introduces an electric field E_A
- The direction of this applied field is the same as that of the electric field in the depletion region

- The magnitude of the electric field in the depletion region increases above the equilibrium value.

- Physically, such a increase must be represented by increase in positive and negative ions
  - This can happen only by an increase in the width of the depletion region (as carrier concentration does not change)
  - The width increase happens as electrons (in n-type) and holes (in p-type) are move towards their voltage terminals leaving behind the ions.



- This increased field further holds back the holes in the p-region and the electrons in the n-region, preventing diffusion.

However, a drift current due to minority carrier flow exists, attracted by the extra opposite polarity charge on the other side!

- This drift current is measurable across the material due to the electron flow into p-type & out of n-type by the applied external voltage.

Junction capacitance:

There is a capacitance associated with the charge variation in the depletion layer is called the junction capacitance. The capacitance value changes when additional positive and negative charges are induced:

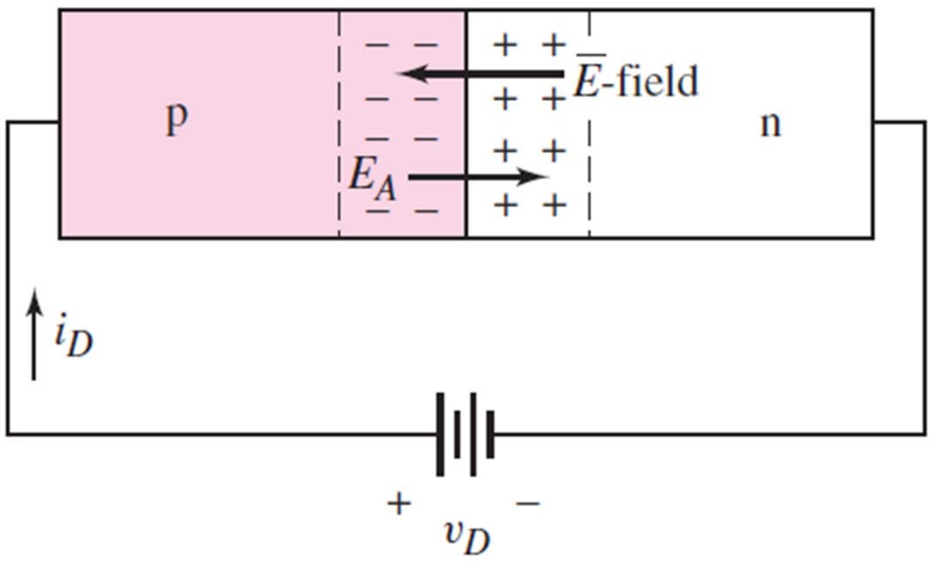
$$C_j = C_{jo}\left(1 + \frac{V_R}{V_{bi}}\right)^{-1/2}$$

Junction capacitance at zero applied voltage

Neither the electric field in the space-charge region nor the applied reverse-bias voltage can increase indefinitely because at some point, breakdown will occur and a large reverse bias current will be generated. [LATER]

Forward-bias pn Junction:

- Positive voltage is applied to the p-region of a pn junction and negative to the n-region.



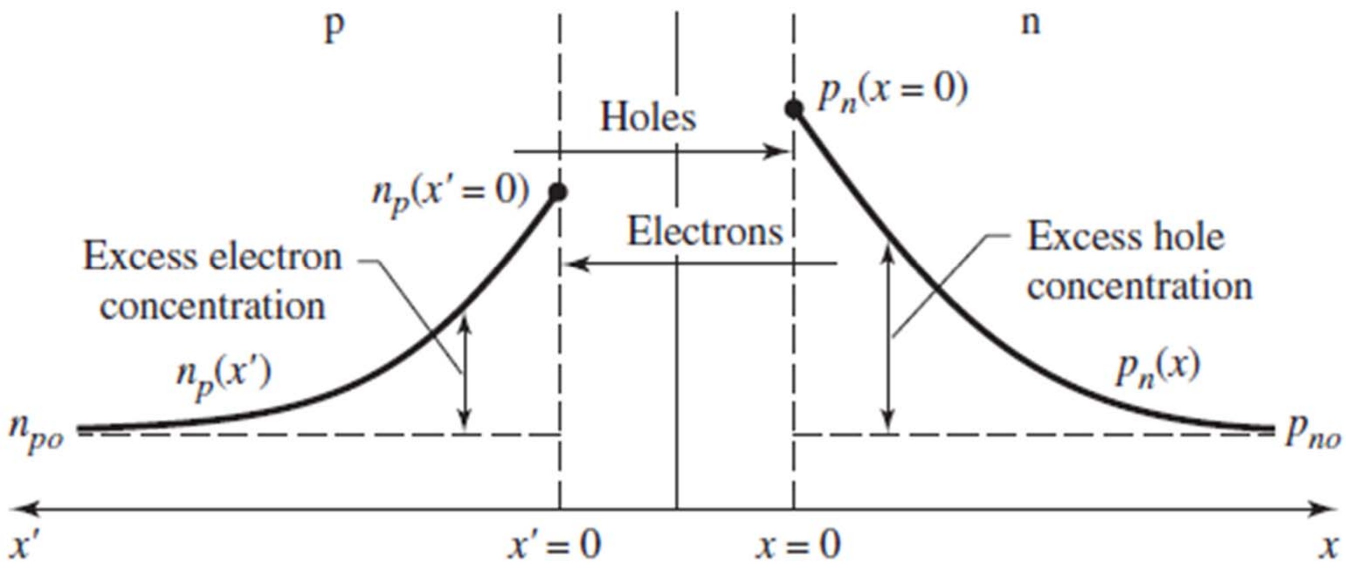
- V_R introduces an electric field E_A
- The direction of this applied field is the opposite to that of the electric field in the depletion region
- This upsets the delicate balance between diffusion (majority carrier) and the electric field force (minority carrier drift).

- Majority carrier electrons from the n-region diffuse into the p-region, and majority carrier holes from the p-region diffuse into the n-region. This continues as long as the external voltage is applied.

- Physically, when forward bias voltage is applied, electrons /holes in n-region /p-region are hurled towards the junction for recombination with the ions, resulting in width reduction of the depletion layer.

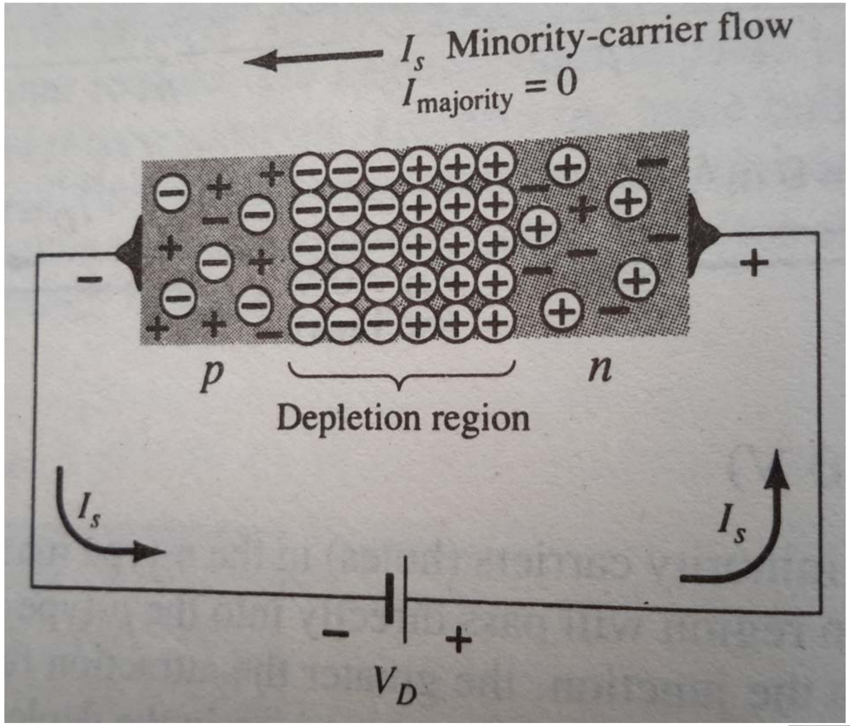
Depletion width reduction --> reduction in junction Electric field --> start of majority carrier diffusion

- The building of more ions on either side due to diffusion is counteracted by constant recombination
- The diffused electrons and holes into p-region and n-region, do not contribute to rise in minority carrier drift current.
  - This is because they are recombined with holes/ electrons in the neutral p-region/ n-region.



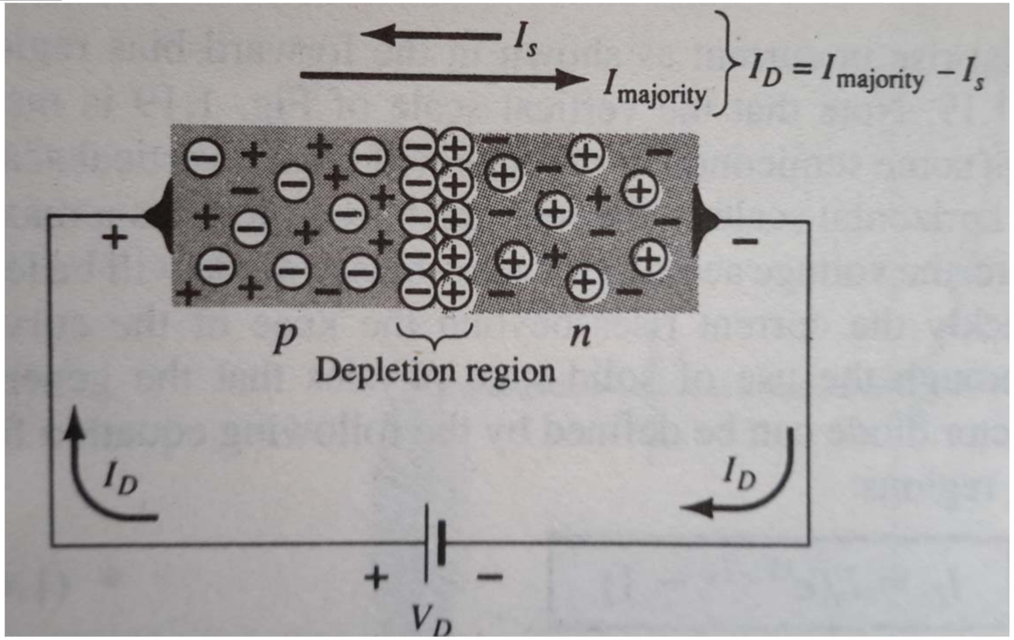
- Reduced (as junction field is decreased) minority carrier flow and drift current exist across the junction.

- The overall current flowing through the devise is diffusion current – drift current



→ Reverse bias

Forward bias ←



Ideal current-voltage relationship:

- The theoretical relationship between the voltage and the current in the pn junction is given as:

$$i_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right]$$

V_T = 0.026 V, I_S is the reverse-bias saturation current.

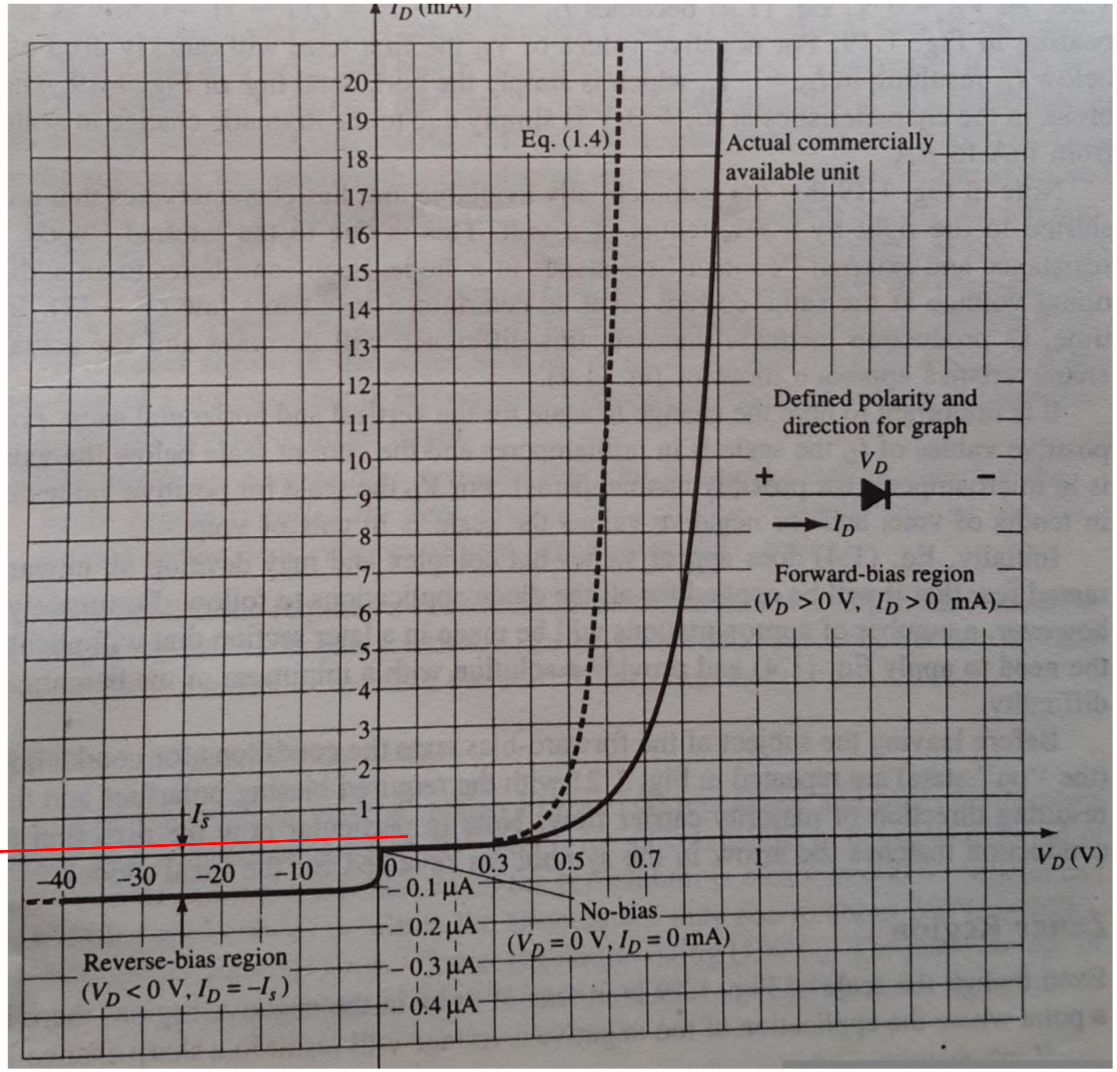
The emission coefficient n = 1to 2 takes into account any recombination of electrons and holes in the space-charge region.

This pn junction, with nonlinear rectifying current characteristics, is called a pn junction diode.

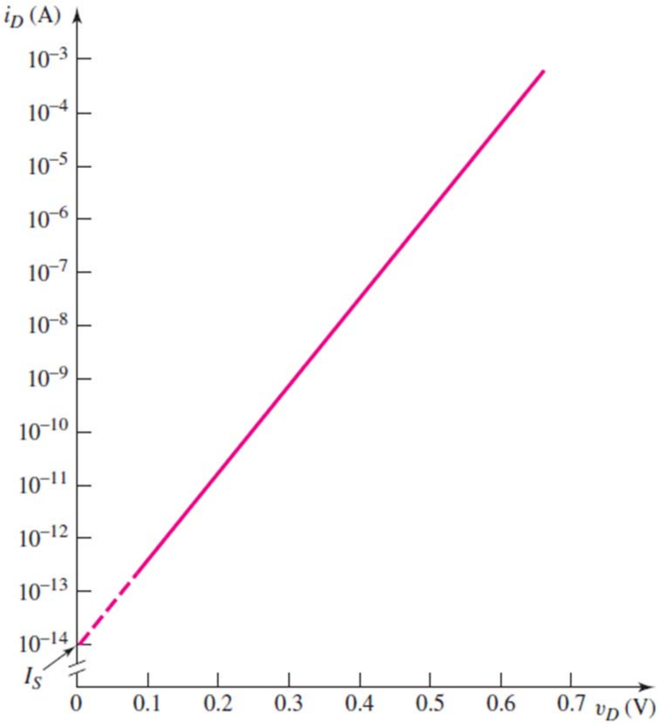
pn-junction diode:

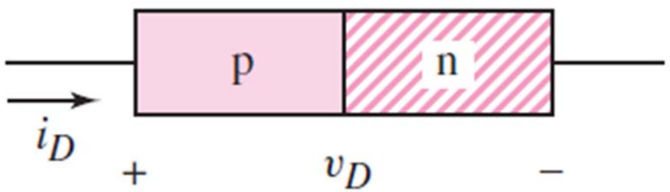
The derived current–voltage characteristics of a pn junction (silicon shown):

For a forward-bias voltage $v_D > +0.1$ V

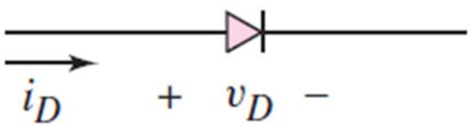


In log scale:





(a)



(b)

The diode circuit symbol and the conventional current direction and voltage polarity

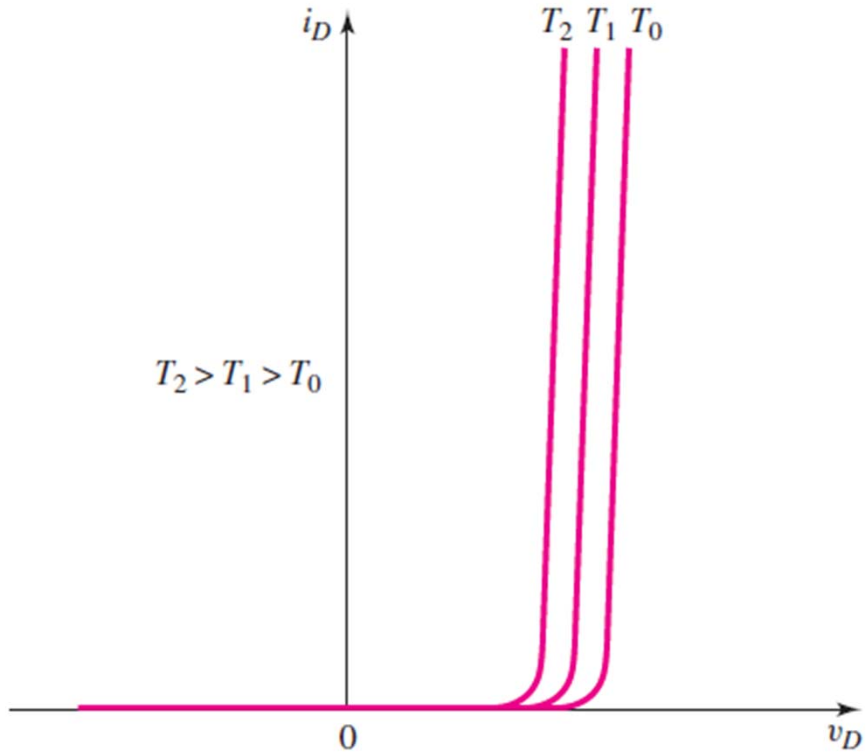
- When a diode is reverse-biased by at least 0.1 V, the diode current is $I_D = -I_S$. As it is constant, hence the name reverse-bias saturation current.

- Real diodes, however, exhibit reverse-bias currents that are considerably larger than I_S. This additional current is called a generation current and is due to electrons and holes being generated within the space-charge region.

The diode can be thought of and used as a voltage controlled switch that is "off" for a reverse-bias voltage and "on" for a forward-bias voltage. In the forward-bias or "on" state, a relatively large current is produced by a fairly small applied voltage; in the reverse-bias, or "off" state, only a very small current is created.

Temperature Effect:

Both I_S and V_T are functions of temperature.



I_S is a function of the intrinsic carrier concentration n_i, which in turn is strongly dependent on temperature.

The actual reverse-bias diode current, as a general rule, doubles for every 10 °C rise in temperature.

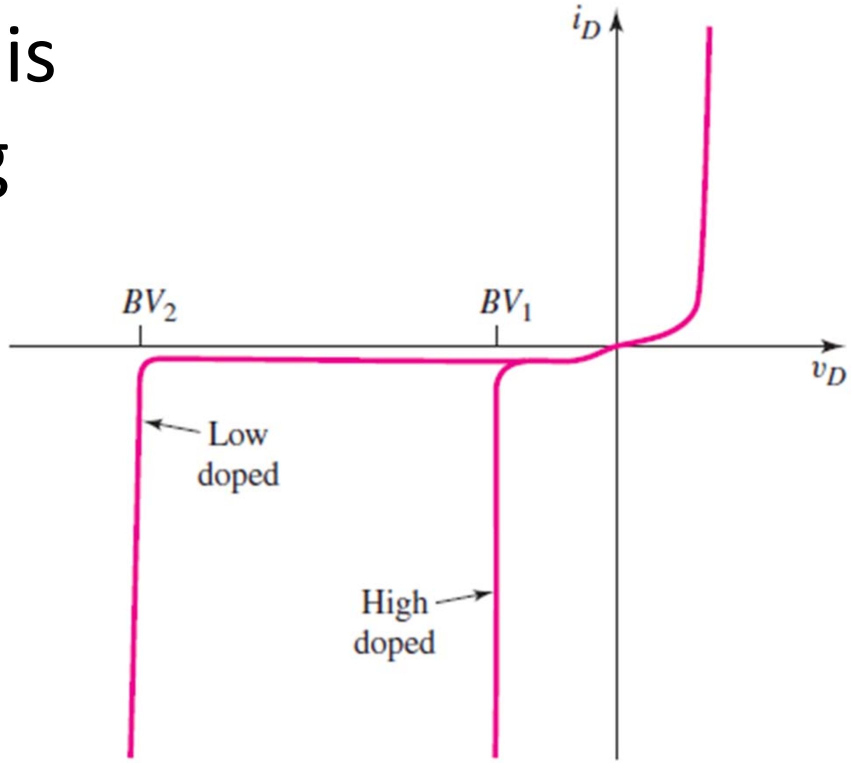
Breakdown Voltage:

When a reverse-bias voltage is applied to a pn junction, the electric field in the space-charge region increases. The electric field may become large enough that covalent bonds are broken and electron–hole pairs are created.

Electrons are swept into the n-region and holes are swept into the p-region by the electric field, generating a large reverse bias current.

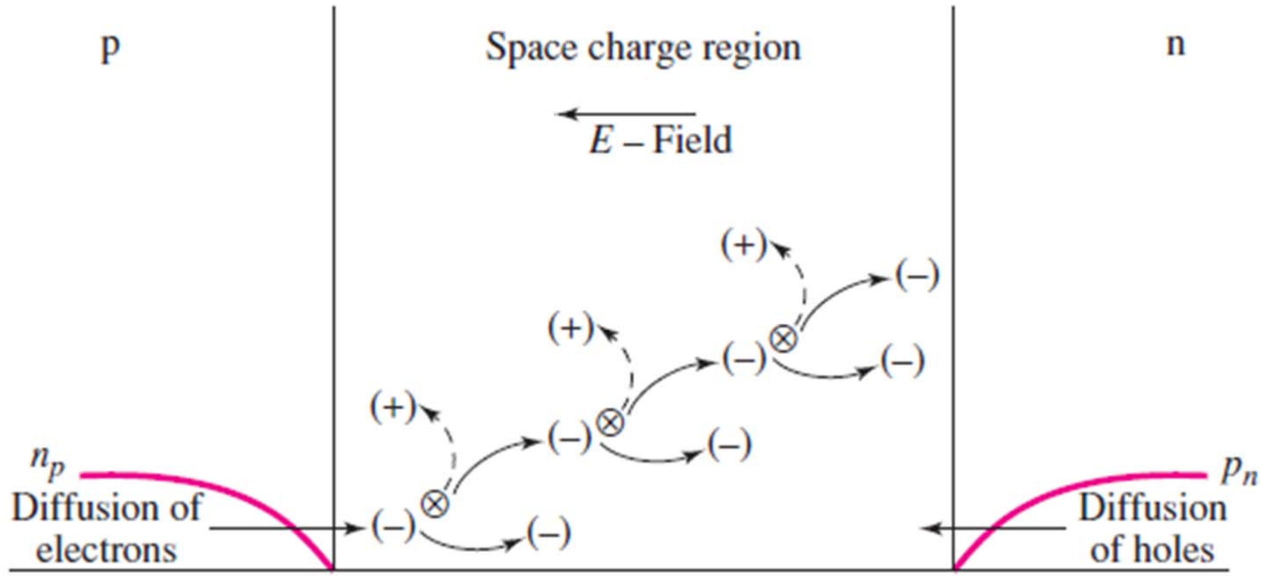
This phenomenon is called breakdown. Can cause physical damage to the device!

The breakdown voltage is a function of the doping concentration.



Avalanche breakdown:

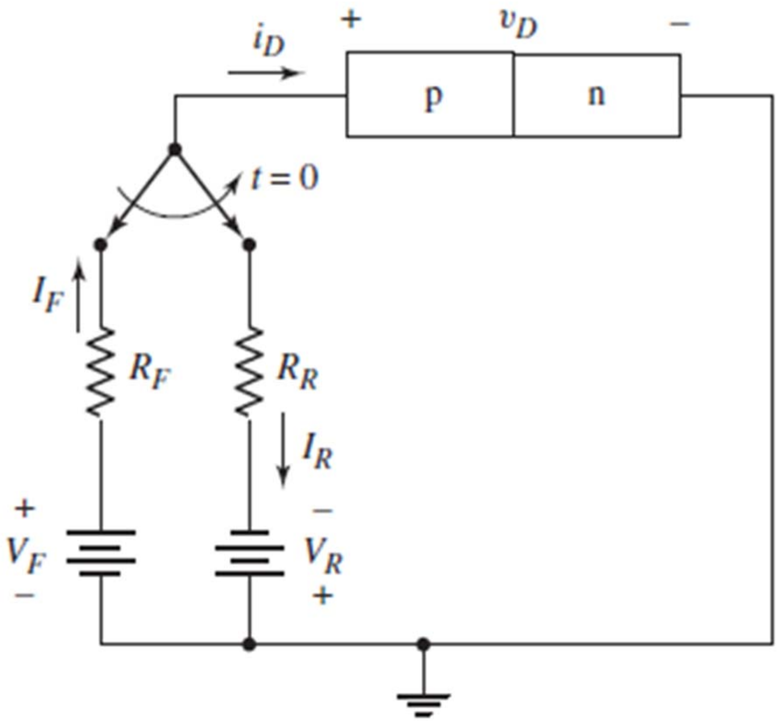
Carriers crossing the space charge region gain sufficient kinetic energy from the high electric field to be able to break covalent bonds during a collision process. More carriers generated which further add to the process.



Avalanche breakdown can happen without –
"The electric field may become large enough that covalent bonds are broken and electron–hole pairs are created."
This breakdown in particular is called Zener breakdown, which happens at Zener potential

The peak inverse voltage (PIV) of a diode must never be exceeded in circuit operation if reverse breakdown is to be avoided.

Switching Transient:

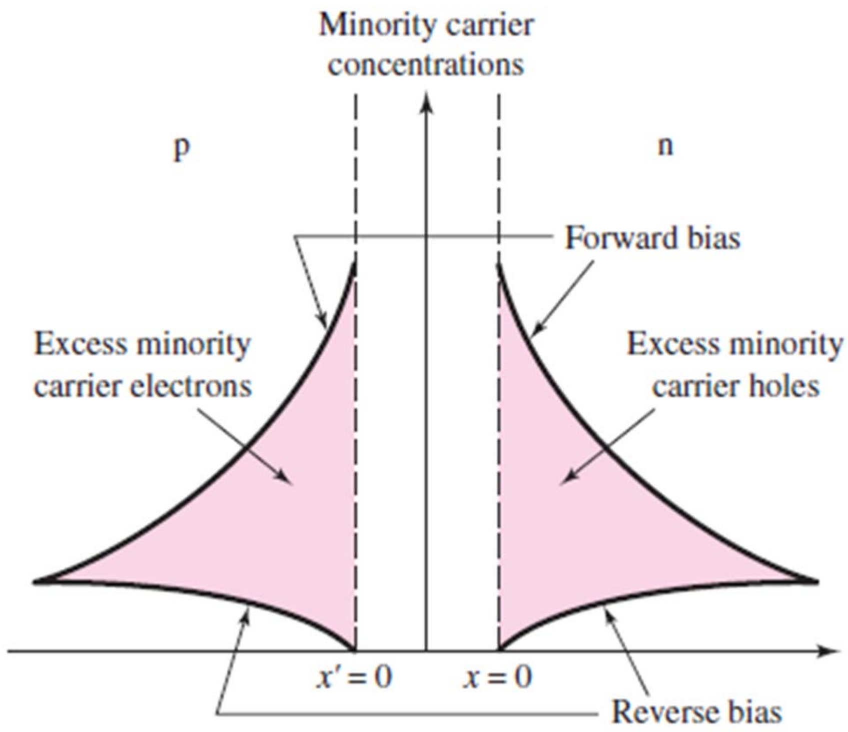


At forward-bias:

$$i_D = I_F = \frac{V_F - v_D}{R_F}$$

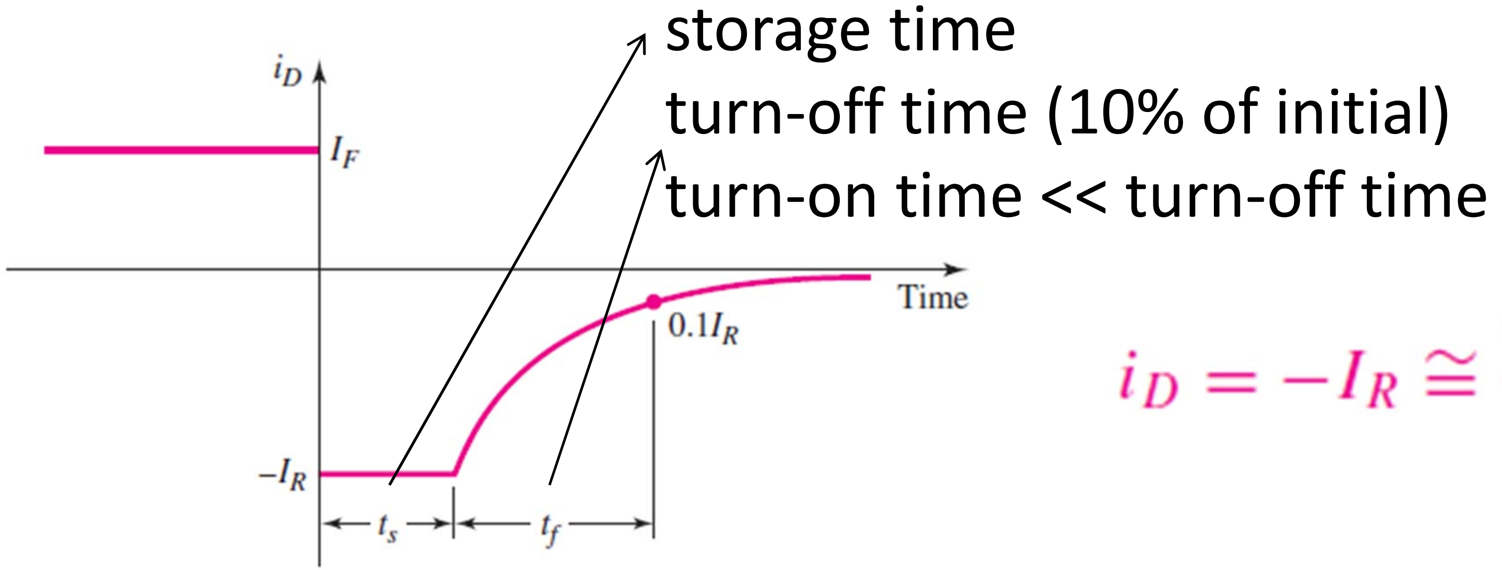
Speed and characteristics of diode as a switch. Forward-bias “on” state to the reverse-bias “off” state, or the opposite.

Ignoring the depletion layer width change, the difference between the minority carrier concentrations during forward bias and during reverse bias in neutral regions needs to be eliminated (charge must be removed)



As the forward-bias voltage is removed, relatively large diffusion currents are created in the reverse-bias direction.

Due to the excess minority carrier electrons flow back across the junction into the n-region, and the excess minority carrier holes flow back across the junction into the p-region.



$$i_D = -I_R \cong \frac{-V_R}{R_R}$$