Shockley equation

In Shockley model of pn junction:

- The junction is assumed to be an abrupt, whereas the region out of the space charge region is neutral.
- The carrier densities at the boundaries are related to the potential distribution.
- The injected minority carrier density is small in comparison to the majority carrier density.
- The depletion region is free of charge, and so generation or recombination cannot occur.

The current density passing through an ideal pn-junction diode due to applying a voltage (V) is described by the Shockley equation

$$I = qAn_i^2 . \left(\frac{D_h}{L_h N_D} + \frac{D_e}{L_e N_A}\right)\left[\exp\left(\frac{V}{V_T}\right) - 1\right]$$

q : electron charge
A : diode area
D : diffusion coefficient
L : diffusion length
V_T : thermal voltage
The subscripts p and n refer to holes and electrons.

$$V_T = \frac{K_B T}{q}$$

At room temperature, $V_T = 26\ mV$.

The current

$$I = I_s\left[exp\left(\frac{V}{V_T}\right) - 1\right]$$

I_s is called the saturation

$$I_s = qAn_i^2 . \left(\frac{D_h}{L_h N_D} + \frac{D_e}{L_e N_A}\right)$$

The Shockley equation of a diode gives a precise variation of I versus an applied voltage.

$I - V$ Characteristics

- A plot of a current passing through a diode against an applied voltage is referred to as current – voltage ($I - V$) characteristics of the diode.
- Two different regions are seen: forward and reverse region.
- At the point A: the forward current is zero at zero-bias condition.
- At the point B: The current increases slightly until reaches approximately 0.7 V at the knee of the curve.
  After point A point, the change in the forward voltage becomes not noticeable.
- At the point C : the forward current increases rapidly.
- The forward voltage at the point C is approximately equal to the built-in-voltage.

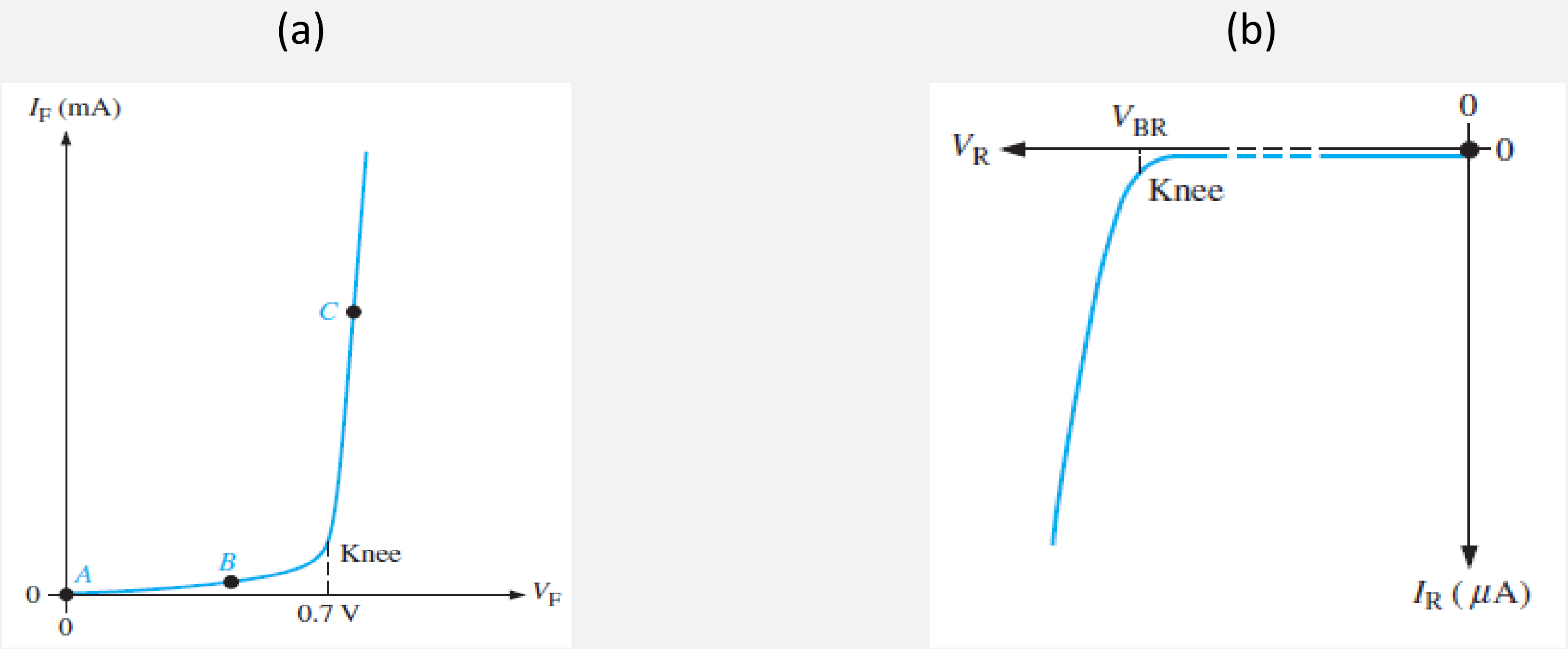
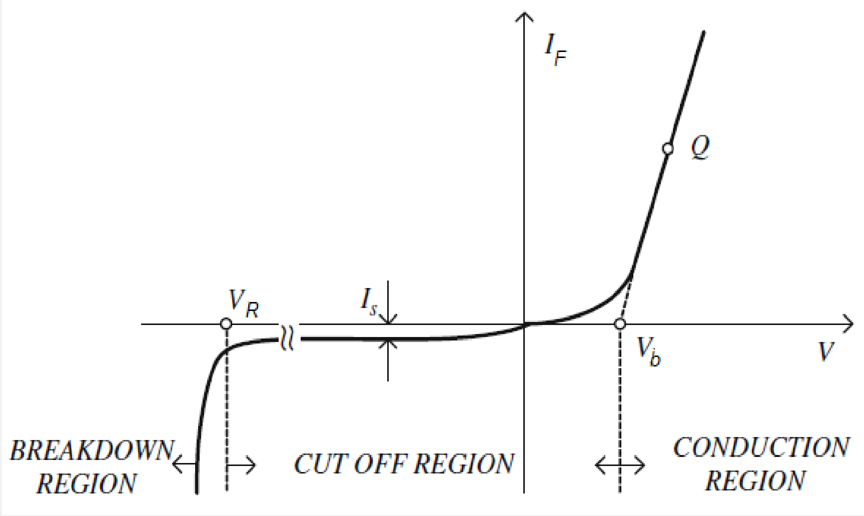


Fig. 3.10. $I - V$ Characteristics of an ideal pn-junction diode in forward and reverse bias.

- At zero-bias condition, the reverse current is strongly diminished.
- If the reverse-bias voltage is increased, a very small reverse current is seen.
- The reverse current increases rapidly, when only the applied voltage accedes a certain value called breakdown voltage (V_R).

Fig. 3.11. $I - V$ Characteristics of an ideal pn-junction diode.



Circuit Analysis of a *pn* Junction Diode

When we need to analyze a *pn*-junction, it would be better to represent it as an ideal diode with a parasitic elements depending on the biasing polarity.

- when a diode is biased with a forward voltage, it is described as an ideal diode connected serially with a forward diode resistance r_d.

I_f, passes through r_d which is connected to a built-in-voltage source.

- In reverse bias: an ideal reverse-biased diode connected to a reverse resistance r_R with flowing a reverse current, I_R, through the circuit.

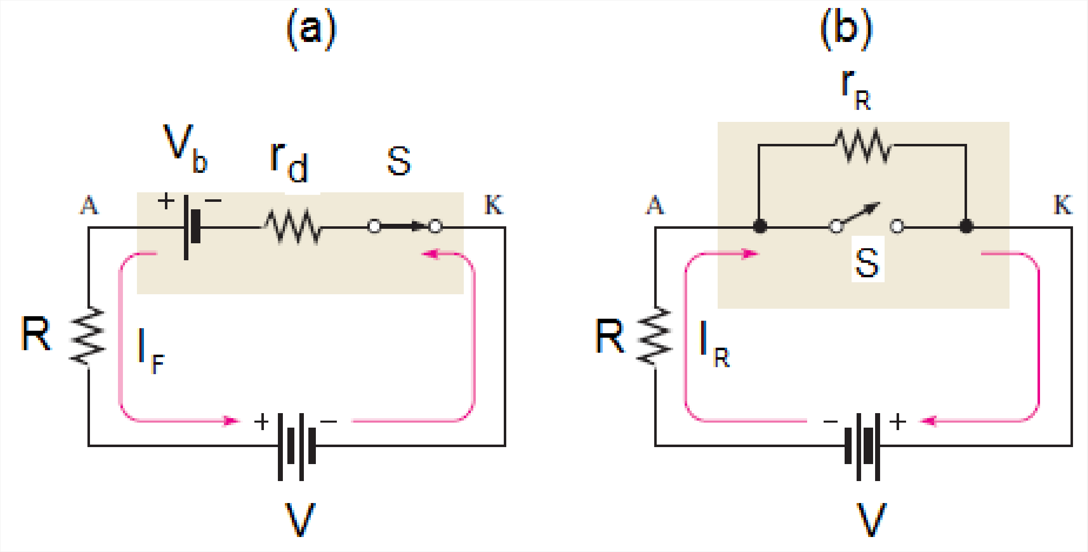


Fig. 3.13. Equivalent circuit of a practical *pn*-junction diode,
(a) forward-biased diode and (b) reverse-biased diode.

Quality Factor a *pn* Junction Diode

- This may indicate to the deviation of a practical diode from the ideal behavior of a diode.
- By measuring the dark $\mathrm{I-V}$ characteristics, the ideality factor can be extracted.
- Shockley equation can be written in terms of ideality factor, n, by

$$I = I_s\left[exp\left(\frac{qV}{nK_BT}\right) - 1\right]$$

If $\mathrm{V \geq 3qK_BT}$, the equation reduces to

$$I \approxeq I_s\, exp\left(\frac{qV}{nK_BT}\right),$$

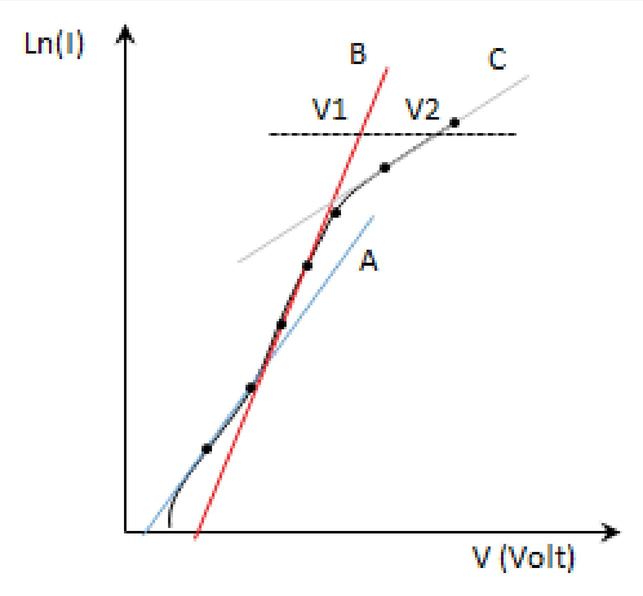
in terms of natural log

$$Ln(I) = Ln\,(I_s) + \left(\frac{q}{nK_BT}\right)V$$

$Ln(I)$ against V gives the slope of the curve that is equal to q/nK_BT, and the intercept gives $Ln\,(I_s)$.

- The ideal value of n =1.
- The ideality factor is a powerful tool for the characterization of a diode.
- The ideality factor ≠ 1 indicates that either recombination mechanisms occur.

(a)



(b)

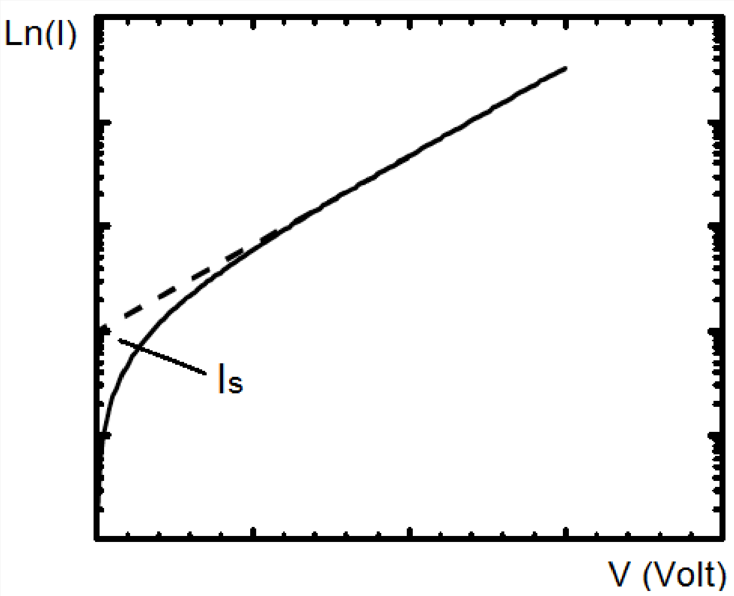


Fig. 3.12. (a) Semi log $I - V$ Characteristics of a practical *pn*-junction diode. Two regions in the forward bias can be seen: (a) low linear region and (b) exponential region. (b) Semi log $I - V$ Characteristics of a practical *pn*-junction diode demonstrating the reverse-saturation current.

- In a practical diode such behavior departs slightly from the ideality because of participation of other parasitic such as the resistance of the PN junction.
- In semilog $I - V$ characteristics of a practical diode: three distinct regions in the forward bias:

Forward Recombination Region

- At low forward voltage (Region (A)):
- The depletion width contracts leading to diffuse some majority carriers across the junction.
- These carriers may recombine inside the depletion region before crossing the junction.
- A small forward current would flow called the forward recombination region.
- The ideality factor almost gives a value between 1.5 and 2.0.

Diffusion Region

- A slight increase of voltage.
- Diffusion of charges is dominant and thence more current, in µA range, passes through the junction.
- In the diffusion region the value of the quality factor may equal to unity.

High Level Injection Region

- The upper most region is called high level injection region.
- The majority carrier concentrations on both sides of the depletion region change.
- A higher current will flow due to a negligible resistance of the diode.
- The series resistance of the diode becomes measurable.
- The ideality factor to be about 2.0 or more.

Series and Dynamic Resistances

- Series resistance, R_S, is one of the significant parasitic causes a difference between real and ideal diodes.
- The series resistance reduces the voltage across the junction with amount of IR_S.
- The resistance is given by

$$R_S = \frac{V_2 - V_1}{I_F}$$

The dynamic diode resistance is given in terms of the reciprocal of the dynamic diode conductance by

$$r_d = \left(\frac{1}{dI/dV}\right)_{V=cons}$$

$$\frac{dI}{dV} = \frac{d}{dV} I_s \, exp\left(\frac{V}{V_T}\right)$$

$$\frac{dI}{dV} = \frac{I_s}{V_T} exp\left(\frac{V}{V_T}\right)$$

$$\frac{dI}{dV} = \frac{I}{V_T}$$

$$r_d = \frac{1}{I/V_T}$$

$$r_d = \frac{V_T}{I}$$

(a) (b) (c)

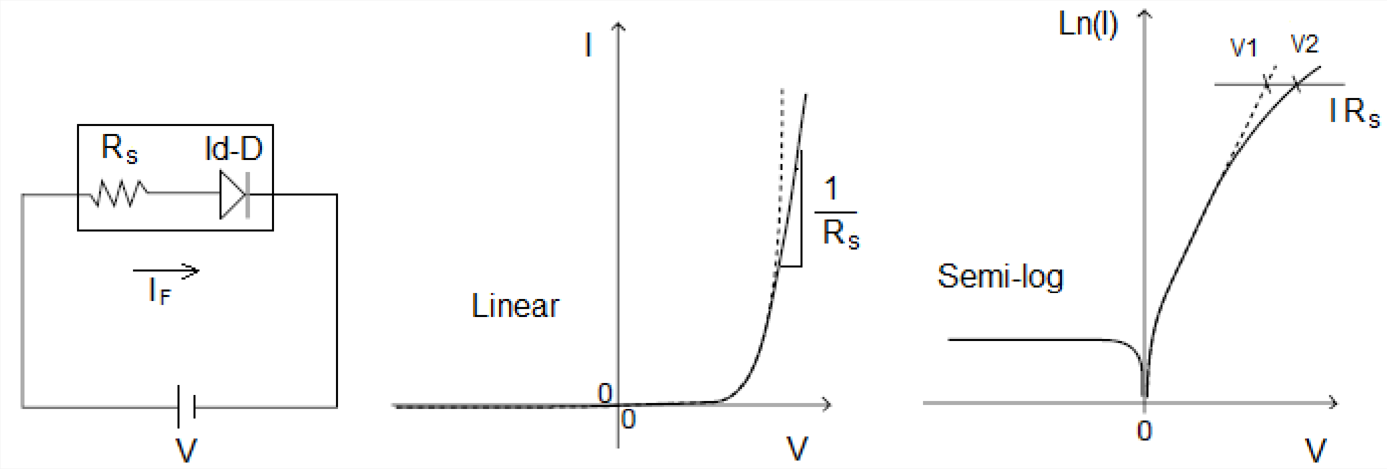


Fig. 3.13. (a) A practical pn junction diode in forward bias. R_S is the series resistance. $I - V$ Characteristics of pn junction in (b) linear and (c) semi-logarithmic scales.