Theory of Semiconductor Devices (반도체 소자 이론)

Lecture 10. The PN diodes (2)

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The "Short" Diode

In the previous section, we assumed that both p and n regions were long compared with the minority carrier diffusion lengths. In many pn junction structures, one region may be short compared with the minority carrier diffusion length.

One of the n and p region is shorter than minority carrier diffusion length

$$W_n << L_p$$

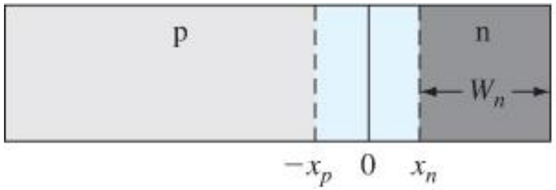


Figure 8.11 | Geometry of a "short" diode.

Steady-state excess minority carrier hole concentration in the n region :

$$\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0 \qquad (x > x_n) \quad \Longrightarrow \quad \delta p_n(x) = p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} \qquad (x \geq x_n)$$

$$\Longrightarrow \quad \delta p_n(x) = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\frac{\sinh\left[(x_n + W_n - x)/L_p\right]}{\sinh\left[W_n/L_p\right]}$$

Boundary conditions:

$$p_n(x_n) = p_{n0}\exp\left(\frac{eV_a}{kT}\right)$$

$$p_n(x = x_n + W_n) = p_{n0}$$

$$\Longrightarrow \quad \delta p_n(x) = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\left(\frac{x_n + W_n - x}{W_n}\right)$$

$$\sinh\left(\frac{x_n + W_n - x}{L_p}\right) \approx \left(\frac{x_n + W_n - x}{L_p}\right)$$

$$\sinh\left(\frac{W_n}{L_p}\right) \approx \left(\frac{W_n}{L_p}\right)$$

Minority carrier hole diffusion current density is :

$$J_p = -eD_p\frac{d(\delta p_n(x))}{dx} \quad = \quad J_p(x) = \frac{eD_p p_{n0}}{W_n}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

- Larger current for short diode

- Constant current → no recombination of minority carriers in the short n region.

The recombination rate of excess electrons and holes, given by the Shockley-Read-Hall recombination theory, was written as

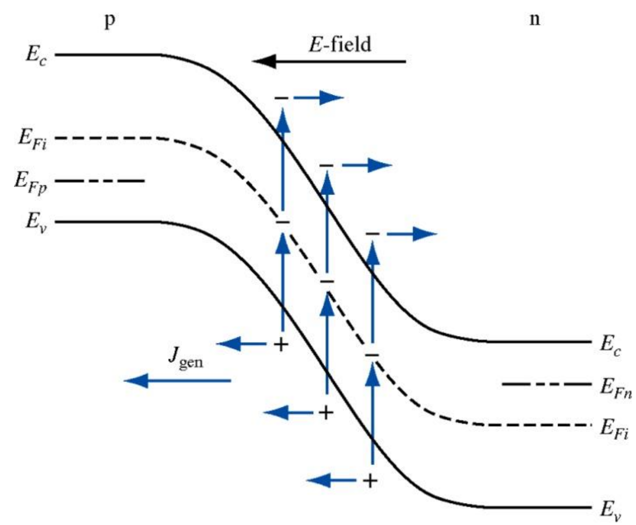
$$R_n = R_p = \frac{C_n C_p N_t (np - n_i^2)}{C_n(n+n') + C_p(p+p')} \equiv R = \frac{\delta n}{\tau} \qquad R = \frac{-C_n C_p N_t n_i^2}{C_n n' + C_p p'}$$

Reverse-biased Generation Current

For a pn junction under reverse bias, mobile electrons and holes are swept out of depletion region. (within the depletion region, $n \approx p \approx 0$)
→ Generation of electron and hole is needed to reestablish thermal equilibrium.

$$J_{\text{gen}} = \frac{e n_i W}{2\tau_0} \qquad J_R = J_s + J_{\text{gen}}$$

J_S : independent of the reverse bias voltage
J_{gen} : dependent on the depletion width.

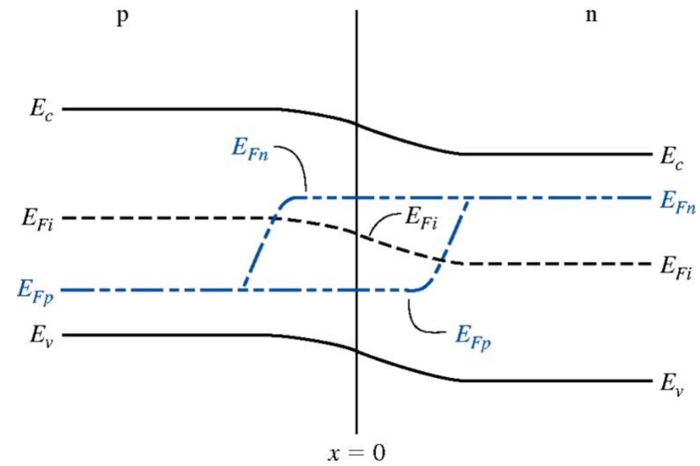


The ideal reverse-saturation current density is independent of the reverse-biased voltage. However, J_{gen} is a function of the depletion width W, which in turn is a function of the reverse-biased voltage.

$$R = \frac{-n_i}{\frac{1}{N_t C_p} + \frac{1}{N_t C_n}} \qquad R = \frac{-n_i}{\tau_{p0} + \tau_{n0}} \qquad \tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2} \qquad R = \frac{-n_i}{2\tau_0} \equiv -G \qquad J_{\text{gen}} = \int_0^W eG\,dx$$

Forward bias Recombination Current

Under forward bias, some excess carriers injected across the depletion region exist.
→ Some of these electrons and holes will recombine within the space charge region and not become part of the minority carrier distribution.



$$J_{\text{rec}} = \frac{eWn_i}{2\tau_0} \exp\left(\frac{eV_a}{2kT}\right) = J_{r0} \exp\left(\frac{eV_a}{2kT}\right)$$

$$R = \frac{C_n C_p N_t (np - n_i^2)}{C_n(n + n') + C_p(p + p')}$$

$$R = \frac{np - n_i^2}{\tau_{p0}(n + n') + \tau_{n0}(p + p')}$$

$$n = n_i \exp\left[\frac{E_{Fn} - E_{Fi}}{kT}\right] \qquad p = n_i \exp\left[\frac{E_{Fi} - E_{Fp}}{kT}\right]$$

$$(E_{Fn} - E_{Fi}) + (E_{Fi} - E_{Fp}) = eV_a$$

At the center, $E_{Fn} - E_{Fi} = E_{Fi} - E_{Fp} = \dfrac{eV_a}{2}$

$$n = n_i \exp\left(\frac{eV_a}{2kT}\right) \qquad p = n_i \exp\left(\frac{eV_a}{2kT}\right)$$

$$R_{\max} = \frac{n_i \quad [\exp(eV_a/kT) - 1]}{2\tau_0\,[\exp(eV_a/2kT) + 1]}$$

$$J_{\text{rec}} = \int_0^W eR\,dx$$

Total Forward bias Current

The total forward bias current density is the sum of the recombination and the ideal diffusion current densities :

$$J = J_{\text{rec}} + J_D$$

J_{rec} : recombination current density
J_D : ideal diffusion current density.

Because of recombination, additional holes from the *p* side must be injected into the space charge region to establish the minority carrier hole concentration in the *n* region.

$$J_D = J_s \exp\left(\frac{eV_a}{kT}\right)$$

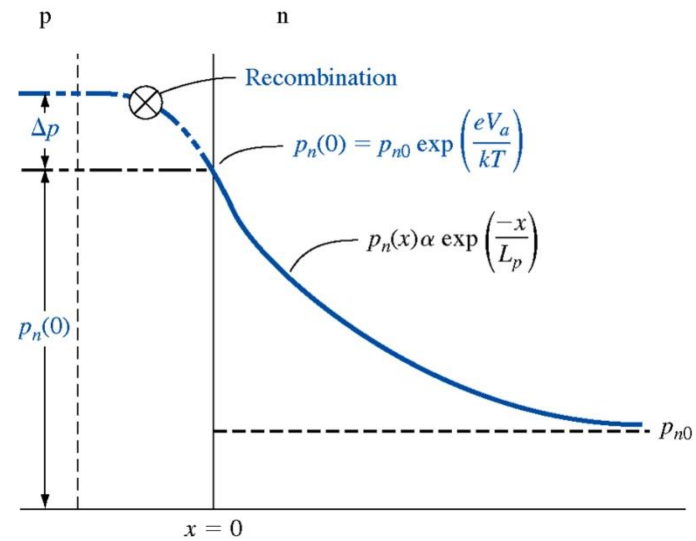
J_S : ideal reverse saturation current density

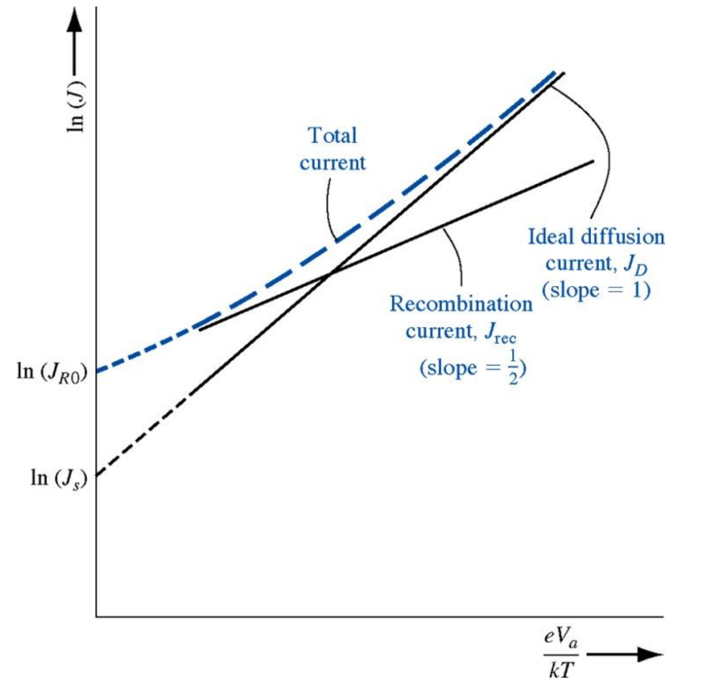
$$\ln J_{\text{rec}} = \ln J_{r0} + \frac{eV_a}{2kT} = \ln J_{r0} + \frac{V_a}{2V_t}$$

$$\ln J_D = \ln J_s + \frac{eV_a}{kT} = \ln J_s + \frac{V_a}{V_t}$$

$$\Longrightarrow \quad I = I_s\left[\exp\left(\frac{eV_a}{nkT}\right) - 1\right]$$

n ≒ 1 at diffusion dominates
n ≒. 2 at low forward bias





High-level injection

Low level injection implies that the excess minority carrier concentrations are always much less than the majority carrier concentration.
However, as the forward-bias voltage increases, the excess carrier concentrations increase and may become comparable or even greater than the majority carrier concentration.

$$n = n_i \exp\left[\frac{E_{Fn} - E_{Fi}}{kT}\right] \qquad p = n_i \exp\left[\frac{E_{Fi} - E_{Fp}}{kT}\right]$$

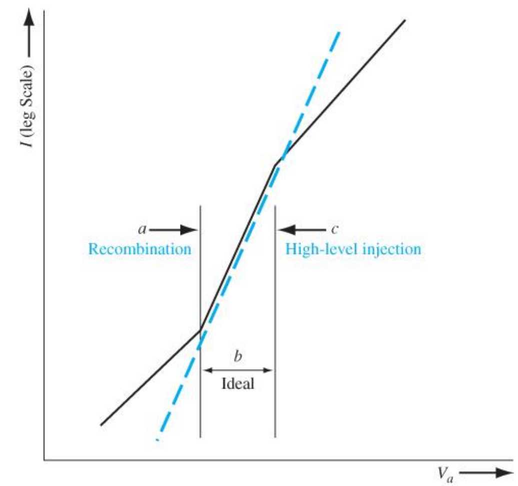
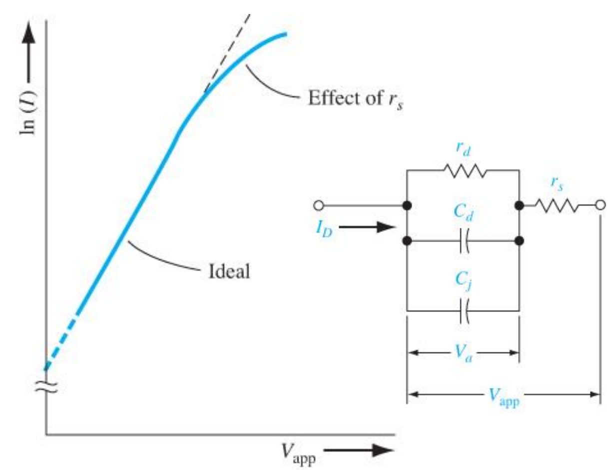
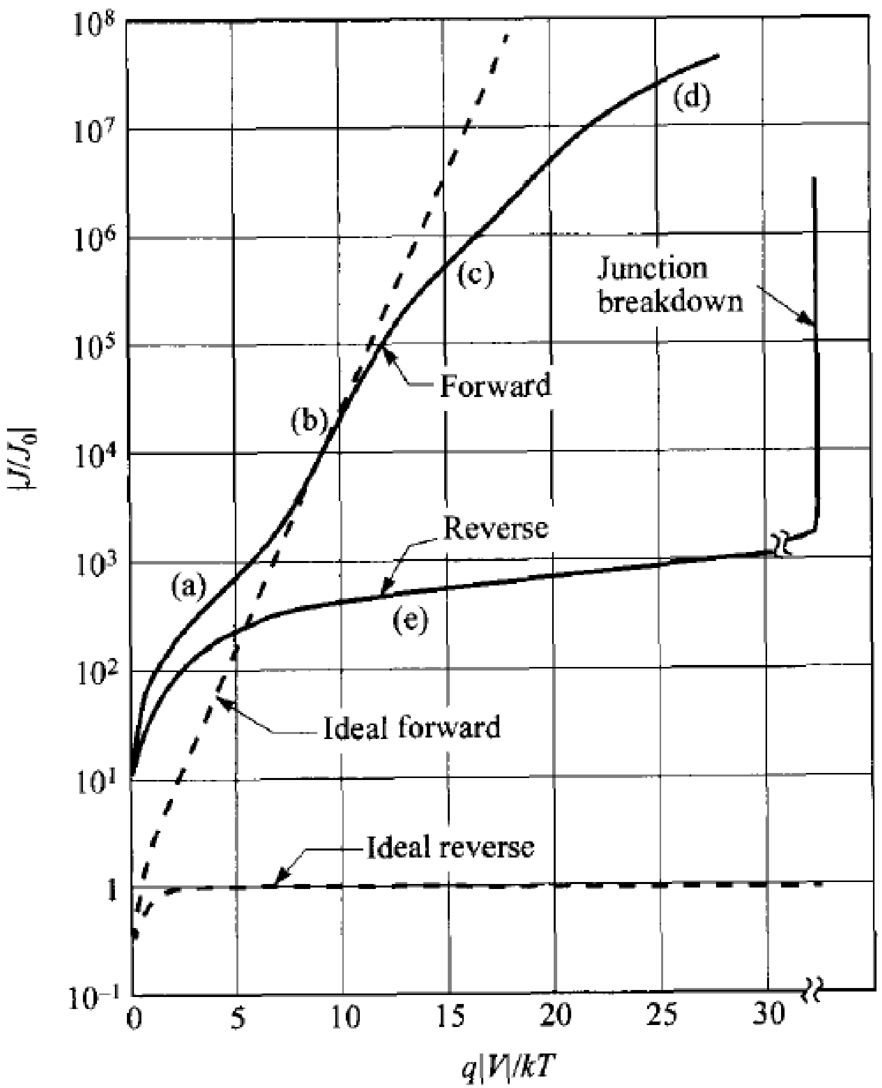


Figure 8.17 | Forward-bias current versus voltage from low forward bias to high forward bias.

Series-resistance

The neutral n and p regions have finite resistances so the actual pn junction will include a series resistance.
A larger applied voltage is required to achieve the same current value when a series resistance is included.





Current-voltage characteristics of a practical Si diode.

(a) Generation-recombination current region.

(b) Diffusion-current region

(c) High-injection region

(d) Series-resistance effect

(e) Reverse leakage current due to generation-recombination and surface effects.

Small-signal model of the pn junction

We have been considering the dc characteristics of the pn junction diode. When semiconductor devices with pn junctions are used in linear amplifier circuits, for example, sinusoidal signals are superimposed on the dc currents and voltages, so that the small-signal characteristics of the pn junction become important.

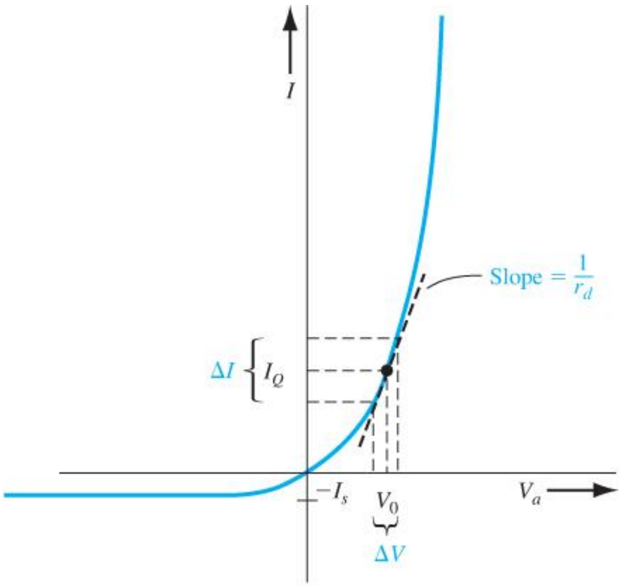


Figure 8.18 | Curve showing the concept of the small-signal diffusion resistance.

Diffusion Resistance

$$I_D = I_s\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

I_D : Diode current
I_s : diode reverse-saturation current

The ratio of sinusoidal current to sinusoidal voltage is called the incremental conductance. The small-signal incremental conductance is just the slope of the dc current-voltage curve.
If we assume that the diode is biased sufficiently far in the forward-bias region, then the (-1) term can be neglected and the incremental conductance becomes,

$$g_d = \left.\frac{dI_D}{dV_a}\right|_{V_a=V_0} = \left(\frac{e}{kT}\right)I_s \exp\left(\frac{eV_0}{kT}\right) \approx \frac{I_{DQ}}{V_t}$$

Then, the small-signal incremental resistance is the reciprocal function,

$$r_d = \left.\frac{dV_a}{dI_D}\right|_{I_D=I_{DQ}} = \frac{V_t}{I_{DQ}}$$

The incremental resistance is also known as the diffusion resistance.

Small-signal model of the pn junction

Diffusion capacitance

The mechanism of charging and discharging of holes in the n region and electrons in the p region leads to a capacitance. This capacitance is called diffusion capacitance.
The physical mechanism of this diffusion capacitance is different from that of the junction capacitance. We show that the magnitude of the diffusion capacitance in a forward-biased pn junction is usually substantially larger than the junction capacitance.

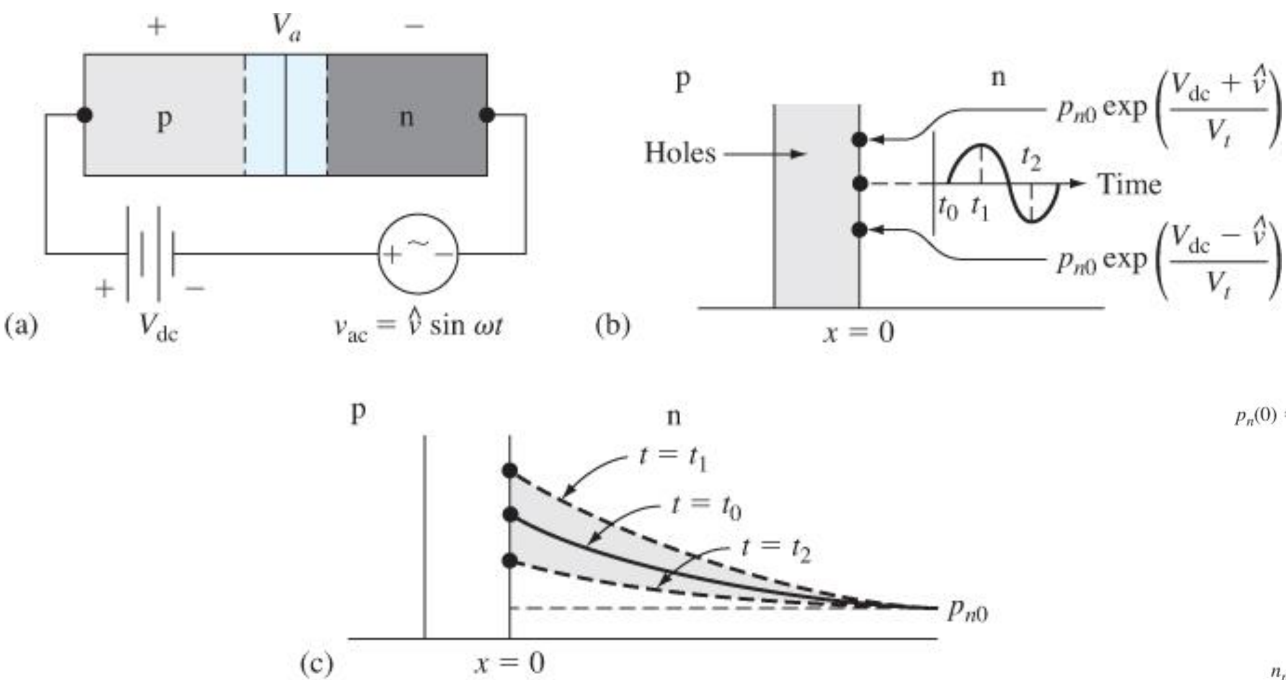


Figure 8.19 | (a) A pn junction with an ac voltage superimposed on a forward-biased dc value; (b) the hole concentration versus time at the space charge edge; (c) the hole concentration versus distance in the n region at three different times.

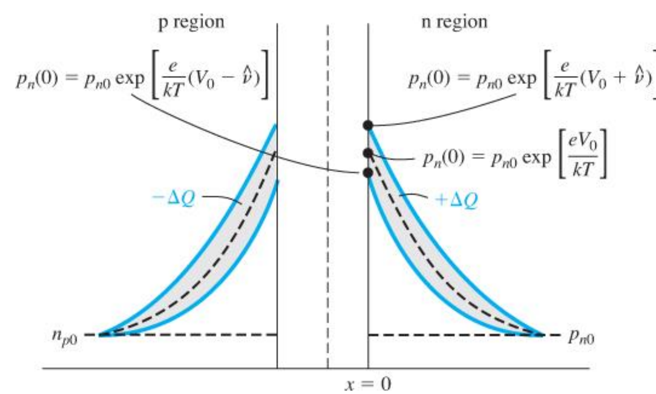


Figure 8.21 | Minority carrier concentration changes with changing forward-bias voltage.

Transient Analysis of Diode

The speed of the pn junction diode in switching state is determined by the short transient time between "on" and "off" states.

$$I = I_F = \frac{V_F - V_a}{R_F}$$

$$I = -I_R \approx \frac{-V_R}{R_R}$$

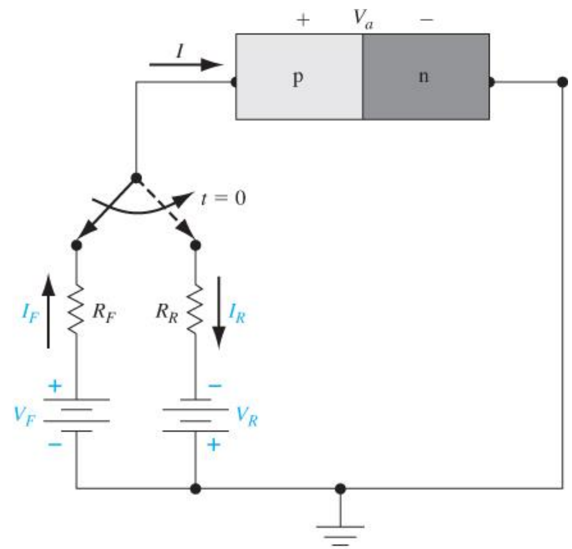


Figure 8.24 | Simple circuit for switching a diode from forward to reverse bias.