# Chapter 8. Transient response

The diodes are used as switches in many applications. Of prime concern is the speed at which the pn junction diode can be made to switch from "off" to "on" state and vice versa.

For a $p^+n$ diode, under steady state forward biased condition, there will be an excess charge ($Q_p$) stored in the n-region. When the diode is turned off, the excess charge does not go to zero instantaneously. There are two methods by which this excess charge can decay to zero.

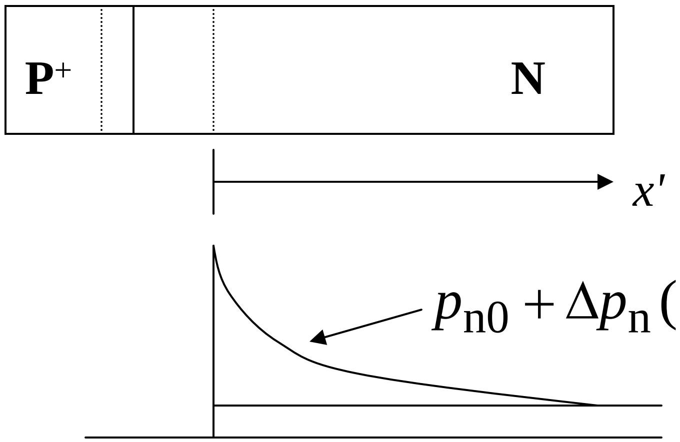
- By current flow (i.e, flow of charge)

- By recombination

In equation form:

$$\frac{dQ_p}{dt} = i(t) - \frac{Q_p}{\tau_p}$$

# Turn-off transient




$$p_{n0} + \Delta p_n(0)\, e^{-\frac{x'}{L_P}} \quad \text{and} \quad \Delta p_n(0) = p_{n0}\left(e^{\frac{qV_A}{kT}} - 1\right)$$

$$Q_p = qA \int_0^{\infty} \Delta p_n(x')\, dx' = qA \int_0^{\infty} \Delta p_n(0)\, e^{-x'/L_p}\, dx' = qAL_p \Delta p_n(0)$$

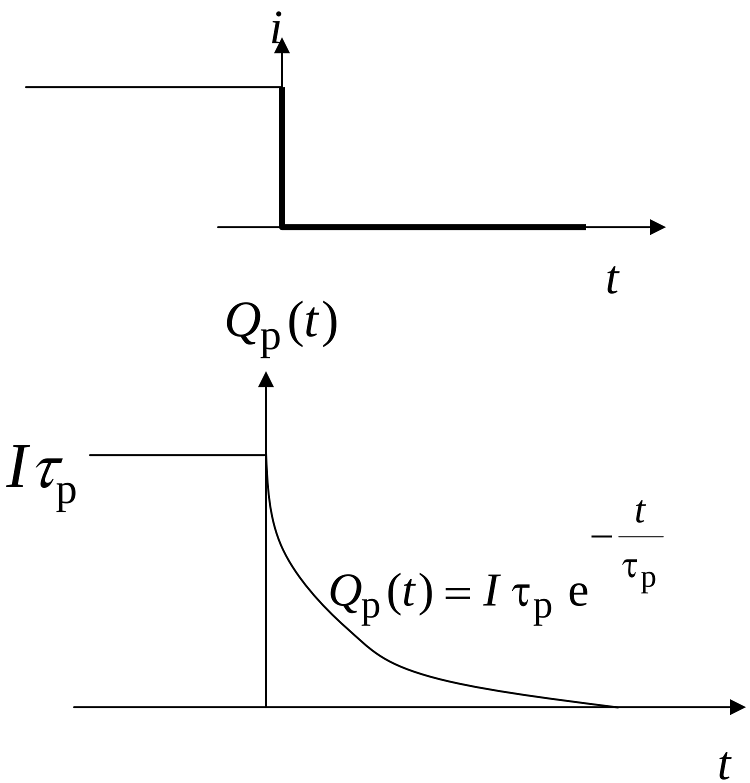
To maintain this charge, a current $I = \dfrac{qAL_p \Delta p_n(0)}{\tau_p}$ must be supplied at $x' = 0$

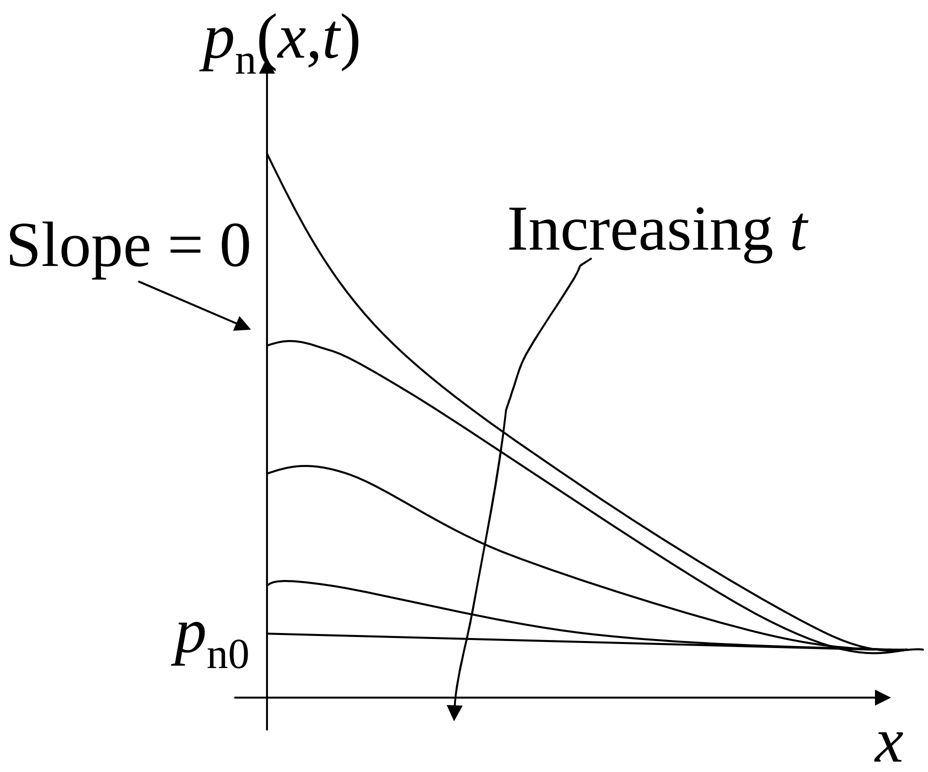
# Turn-off transient with $I = 0$

If the current is zero, $Q_p(t) = Q_p(0)e^{-t/\tau_p}$

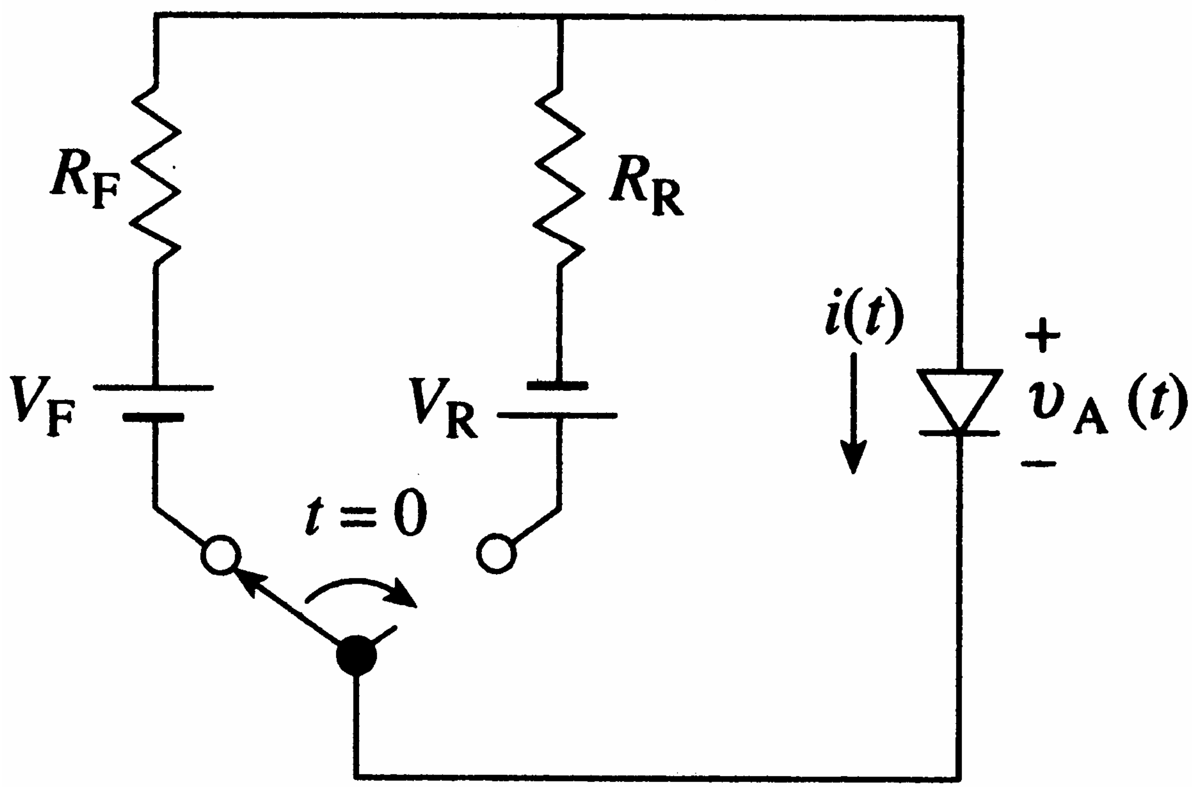
But $Q_p = I\,\tau_p$ for $t < 0$. Therefore $Q_p(t) = I\tau_p\, e^{-t/\tau_p}$

**Excess charge exponentially decays to zero, and it takes several lifetimes (several μs in Si).**



# Idealized representation of a switching circuit




(a)

Figure 8.1

# Diode current- and voltage-time transients

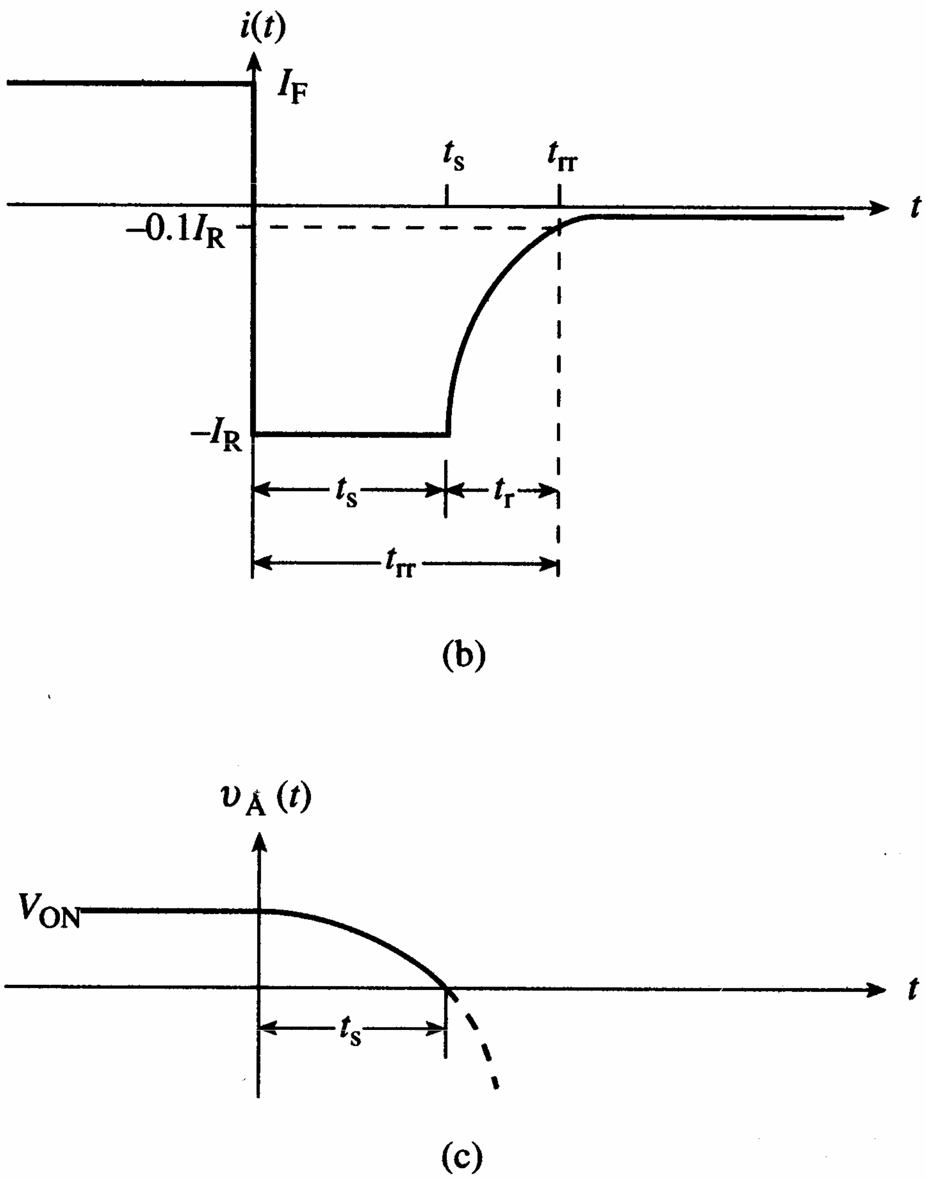


Figure 8.1

$$I_F = \frac{V_F - V_{on}}{R_F} \approx \frac{V_F}{R_F}$$

$$I_R = \frac{V_R + v_A(t)}{R_R} \approx \frac{V_R}{R_R}$$

***Note***: the current does not change to $I_0$ (reverse saturation current), $I_0$, instantaneously. $t_s$ is the storage time or storage delay time.

# Stored minority charge causing switching delay

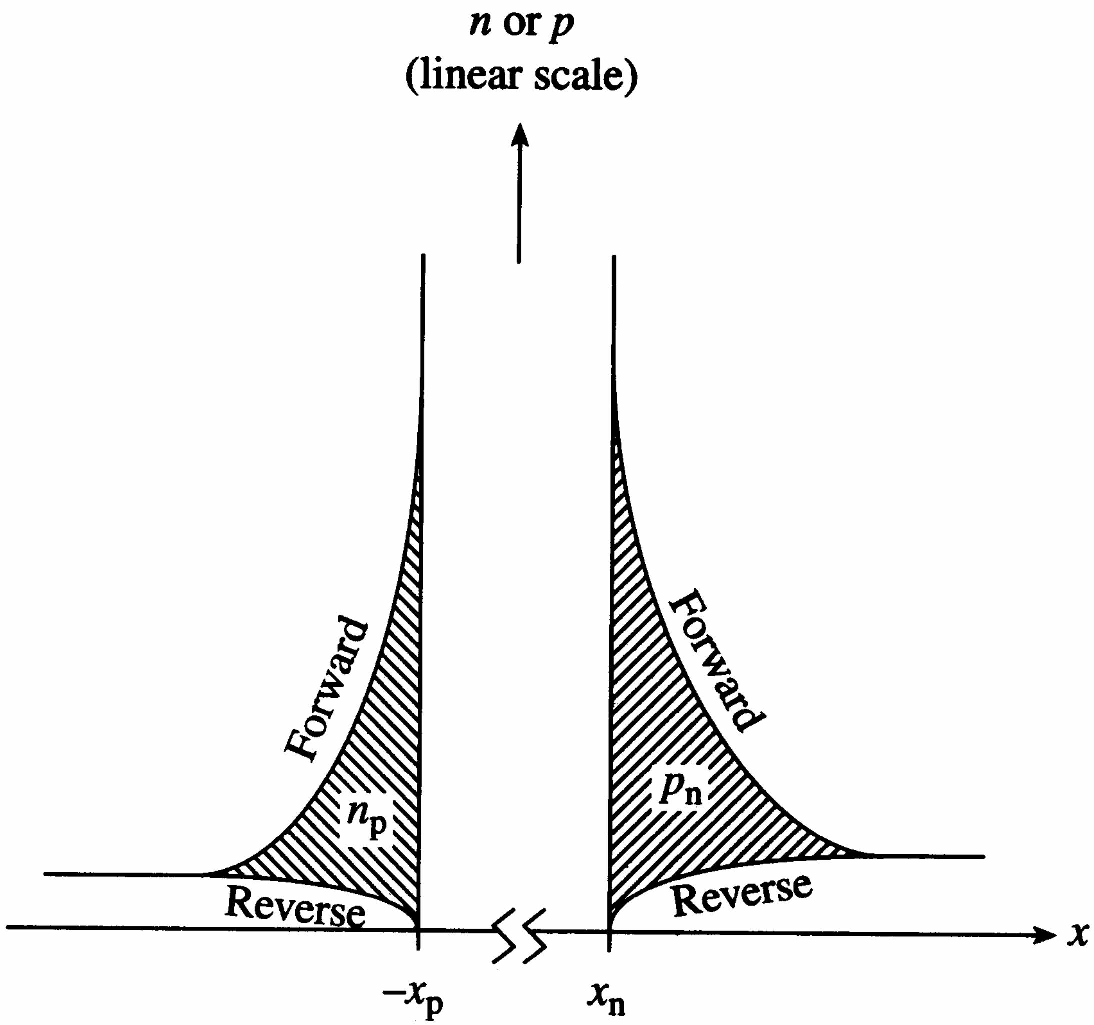



Figure 8.2

# Decay of stored hole charge in a pn junction

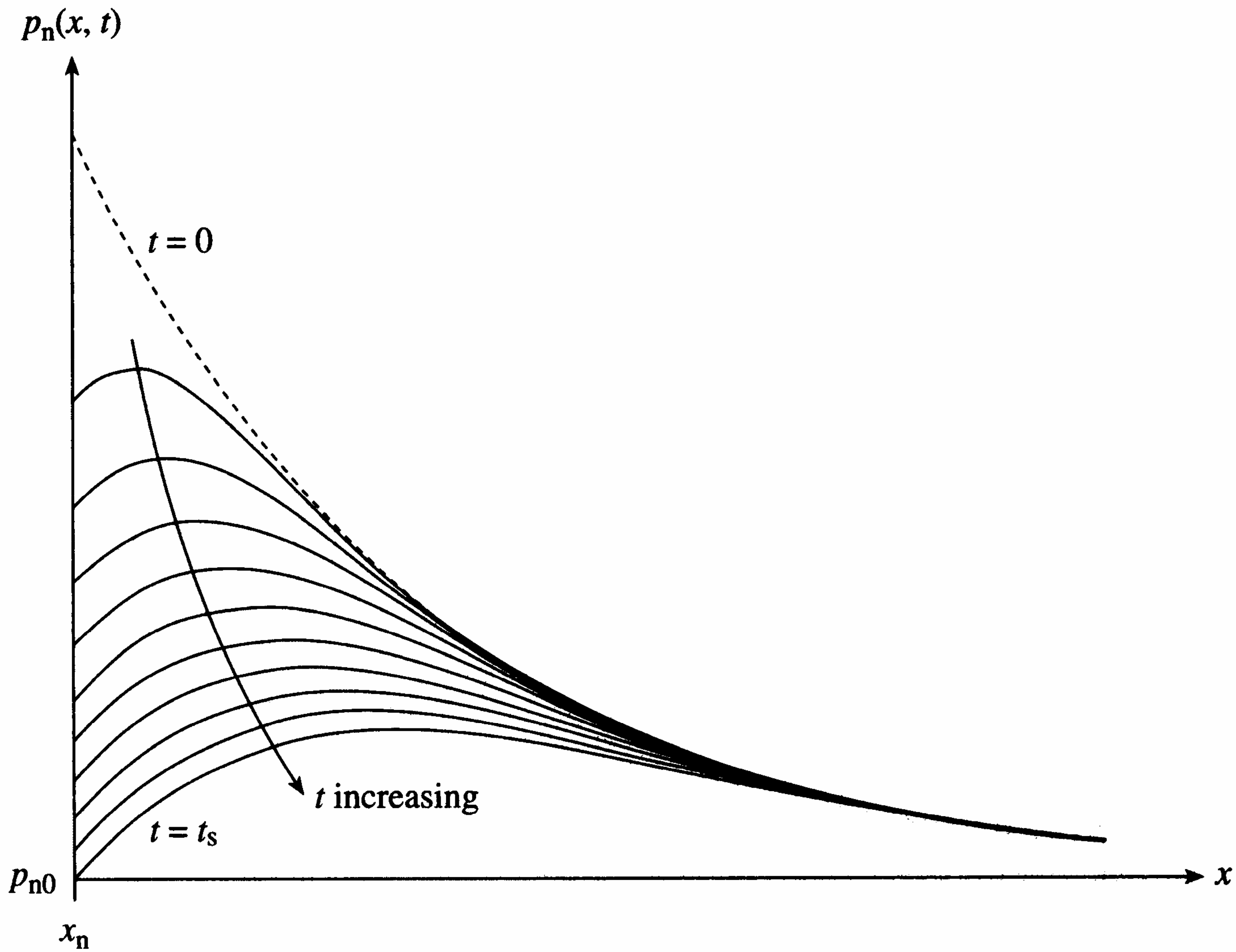



Figure 8.3

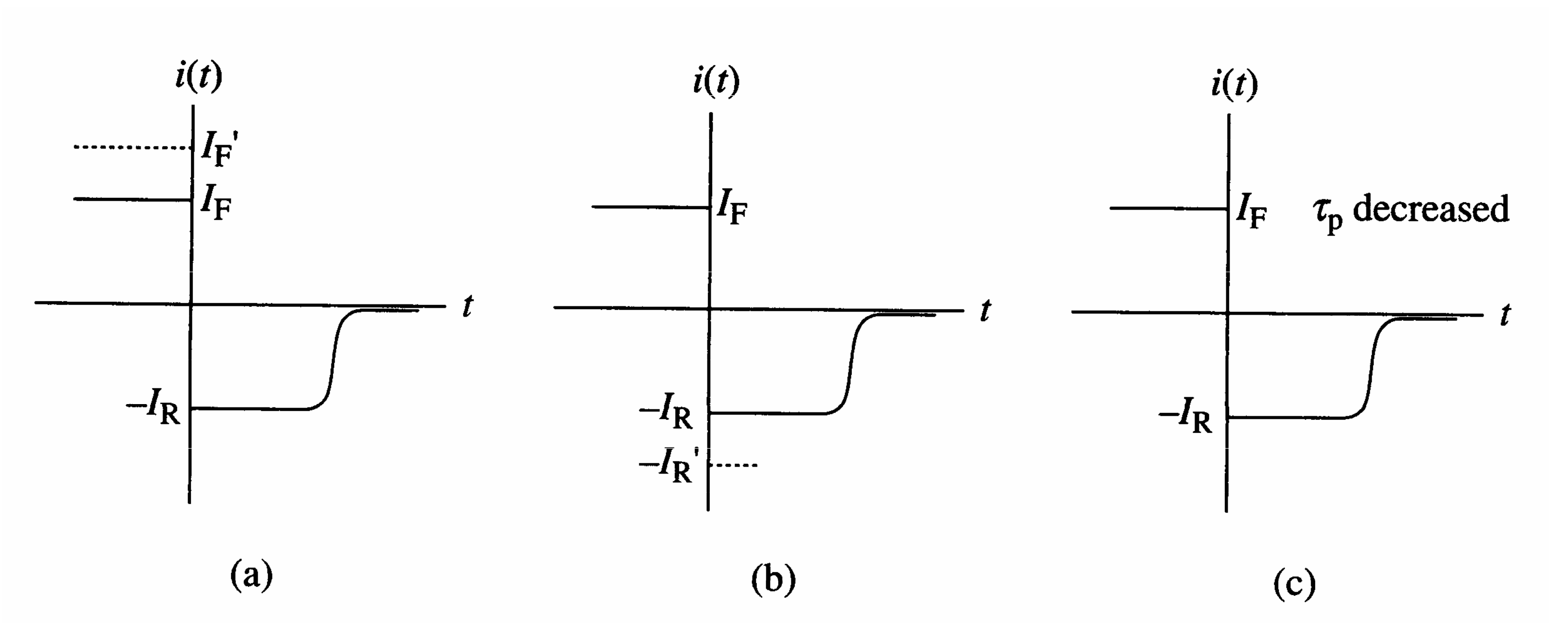
# Example 1

The baseline *i*-vs.-*t* transient is shown below for a diode. At $t = 0$, the diode is switched in reverse direction. Indicate what happens to the *i*-*t* transient if:

(a) If $I_F$ is increased to $I_F'$

(b) If $I_R$ is increased to $I_R'$

(c) If $\tau_p$ is decreased, lifetime made shorter



# Example 1: Solution

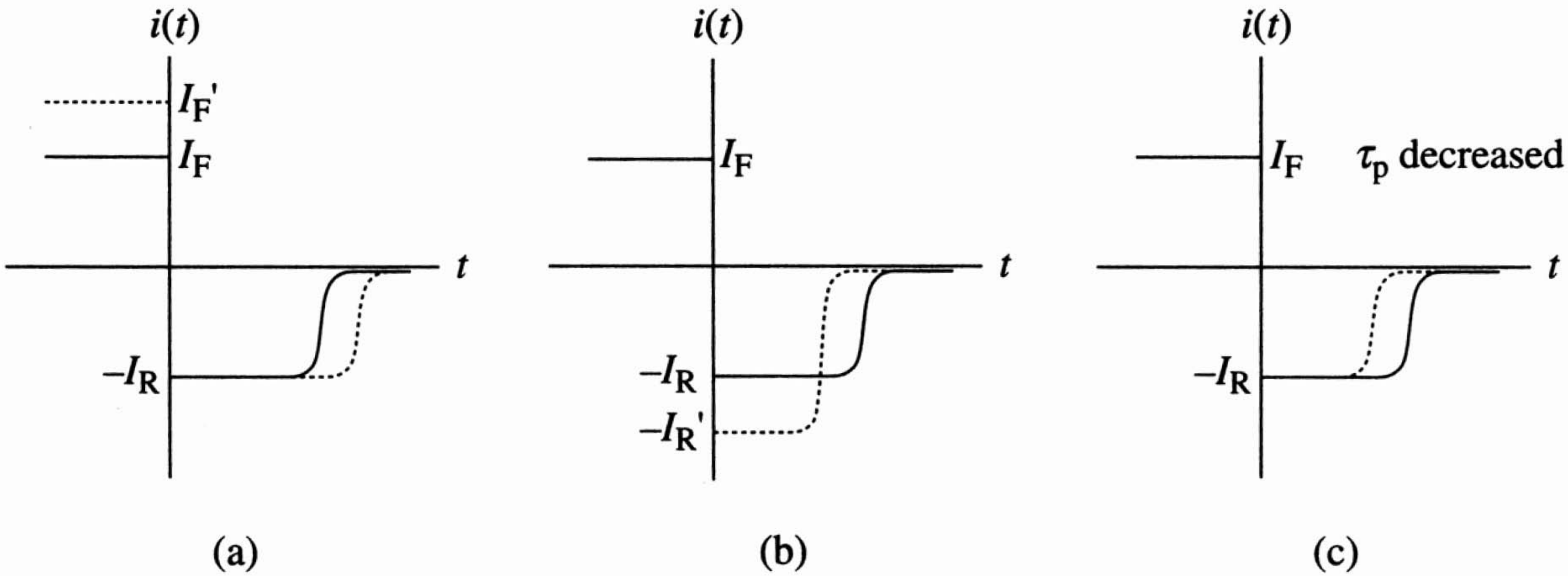



Figure E8.1

# Storage delay time: Quantitative analysis

Consider a p$^+$n diode.

$$\frac{\mathrm{d}Q_\mathrm{p}}{\mathrm{d}t} = i - \frac{Q_\mathrm{p}}{\tau_\mathrm{p}} \qquad i = \frac{\text{charge removed}}{\text{unit time}}$$

$$= -I_\mathrm{R} - \frac{Q_\mathrm{p}}{\tau_\mathrm{p}} \qquad 0 < t < t_\mathrm{s}$$

$$\int_{Q_\mathrm{p}(t=0)}^{Q_\mathrm{p}(t=t_\mathrm{s})} \frac{\mathrm{d}Q_\mathrm{p}}{I_\mathrm{R} + \frac{Q_\mathrm{p}}{\tau_\mathrm{p}}} = -\int_0^{t_\mathrm{s}} \mathrm{d}t = -t_\mathrm{s}$$

# Storage delay time: Quantitative analysis

$$t_s = -\tau_p \ln\left(I_R + \frac{Q_p}{\tau_p}\right)\Bigg|_{Q_p(t=0)}^{Q_p(t=t_s)} = \tau_p \ln\left(\frac{I_R + \dfrac{Q_p(0^+)}{\tau_p}}{I_R + \dfrac{Q_p(t_s)}{\tau_p}}\right)$$

Since $Q_p(t = 0) = I_f\,\tau_p$ and if we assume that $Q_p(t = t_s) \approx 0$, then

$$t_s = \tau_p \ln\left(1 + \frac{I_F}{I_R}\right)$$

Minority carrier lifetimes can be measured using this method.

# Transient response measurement system

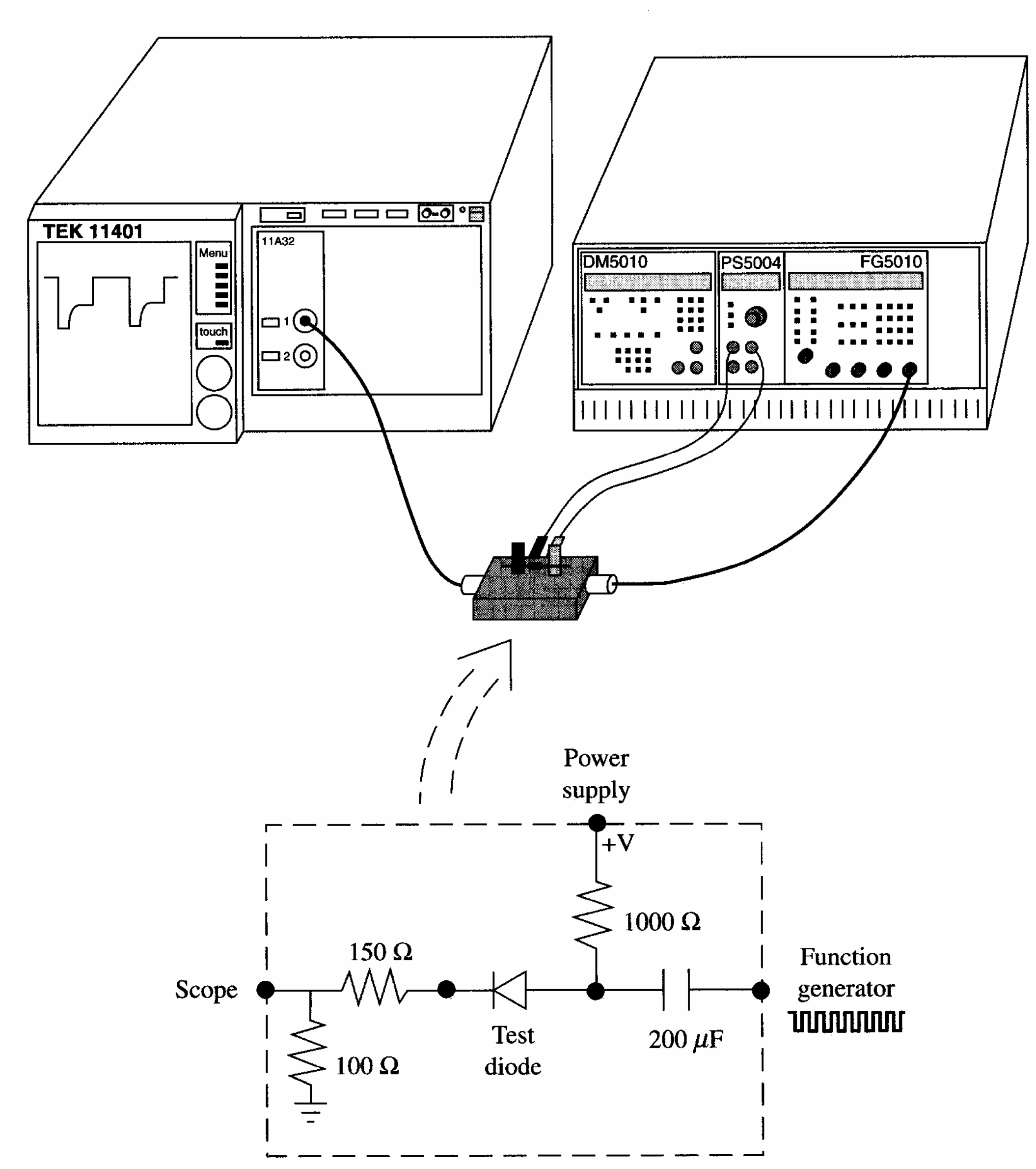



Figure 8.4

# Sample current-time turn-off transient

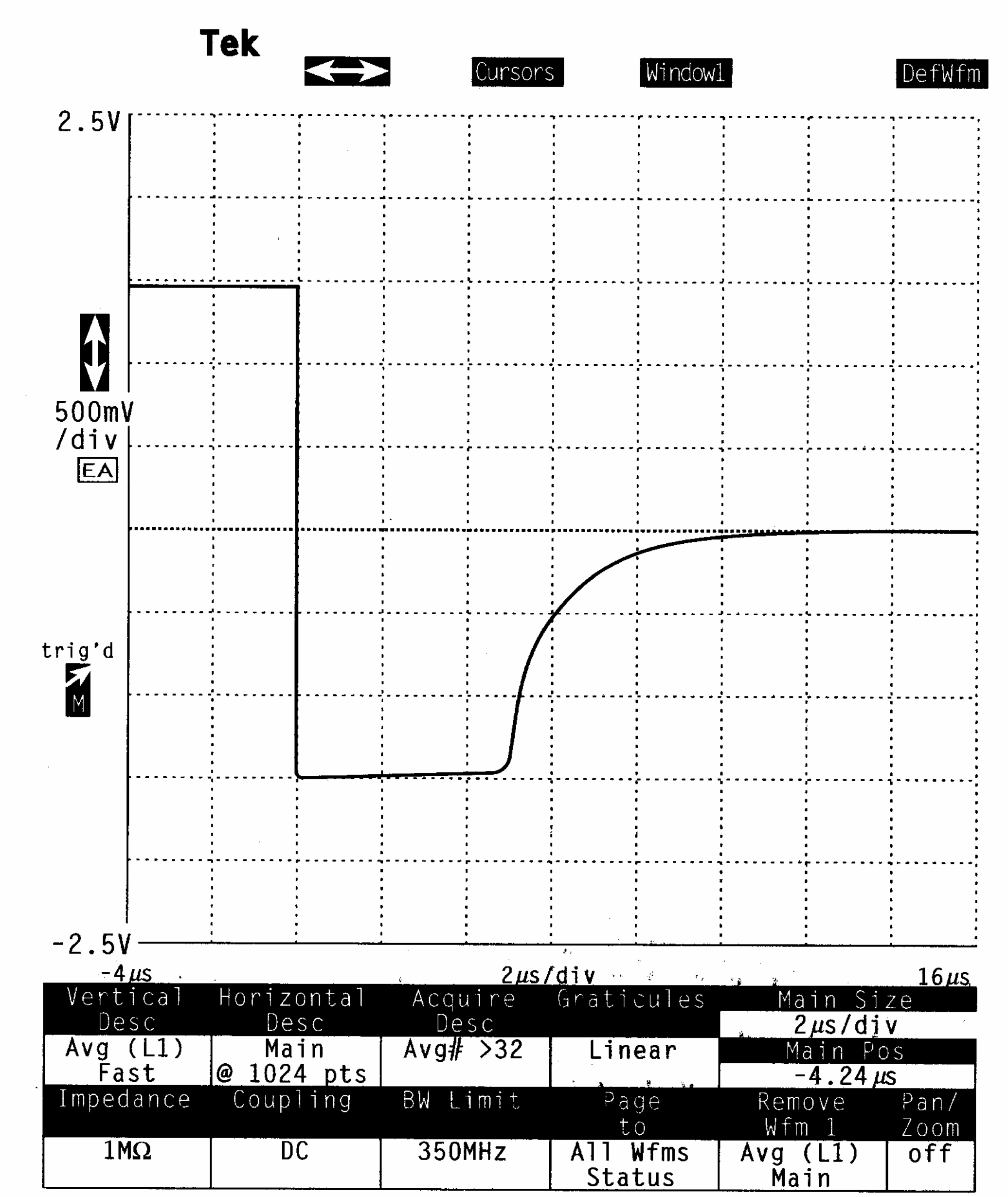



Figure 8.5