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.

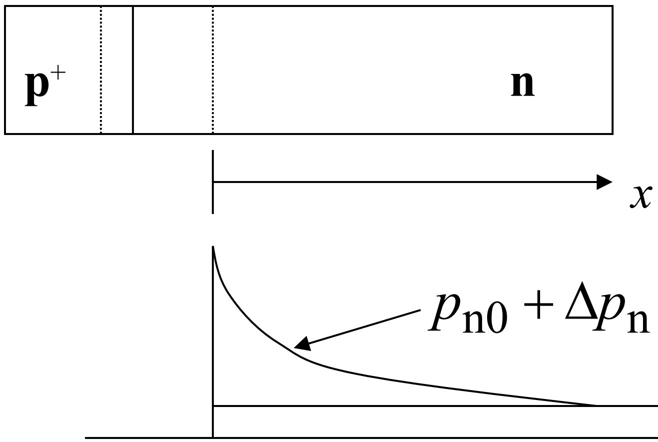
- By current flow (i.e, flow of charge)

- By recombination

In equation form:

$$\frac{\mathrm{d}Q_p}{\mathrm{d}t} = i(t) - \frac{Q_p}{\tau_p}$$

Turn-off transient



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

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

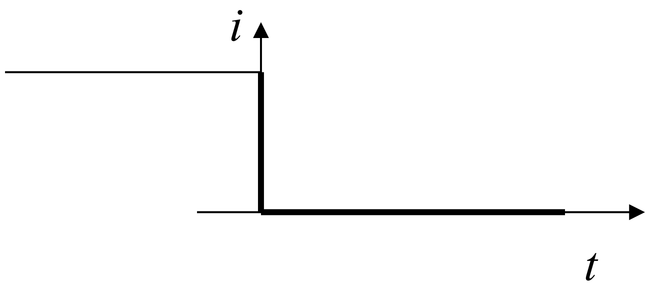
To maintain this charge, a current $I = \dfrac{qAL_p\Delta p_n(0)}{\tau_p}$ must be supplied at $x' = 0$

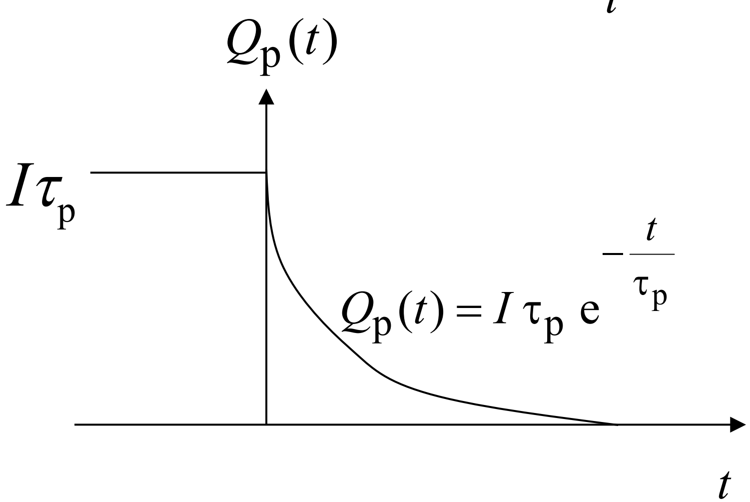
Turn-off transient with $I = 0$

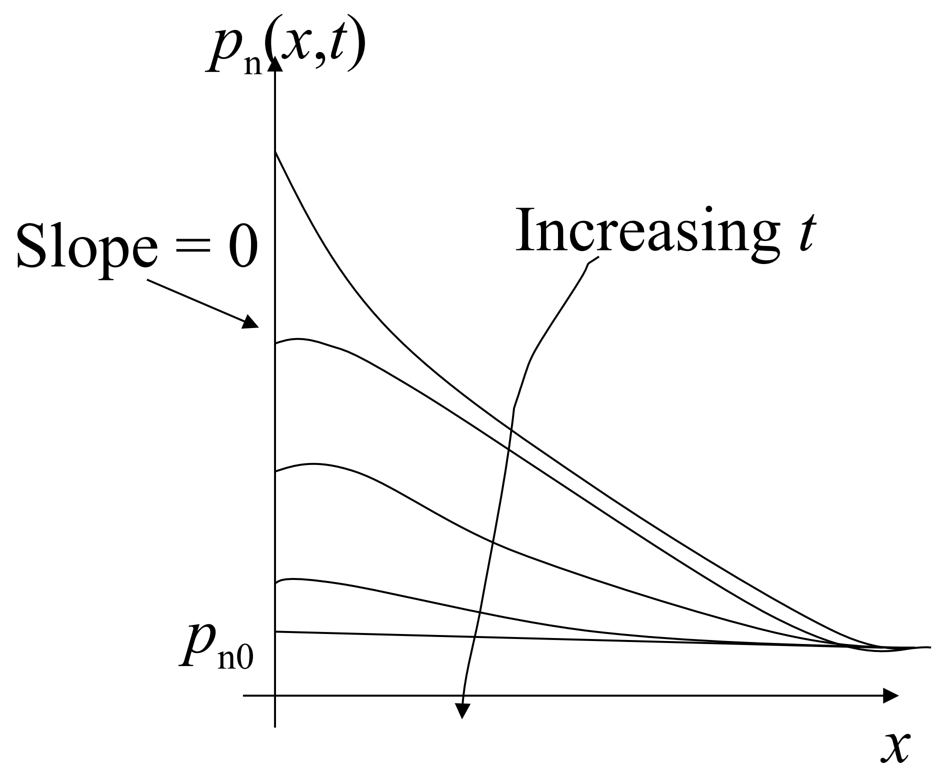
If the current is zero, $Q_p(t) = Q_p(0)e^{-t/\tau_p}$

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

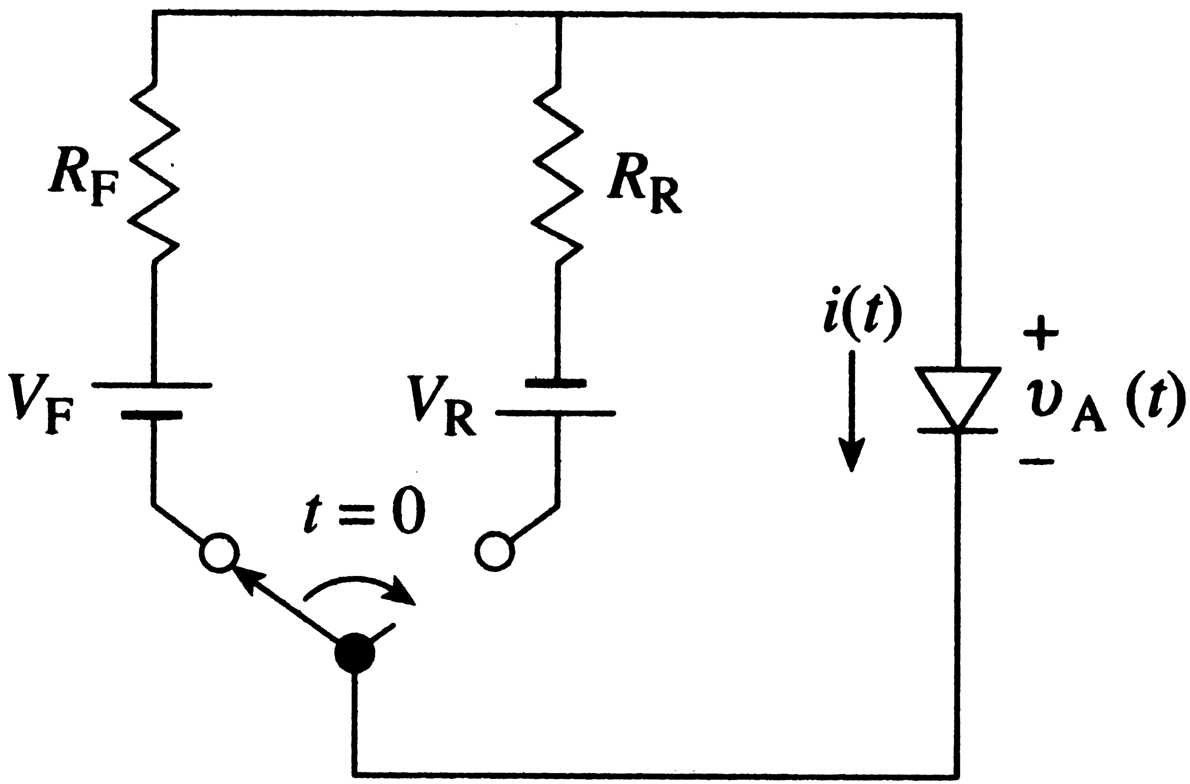
Excess charge exponentially decays to zero, and this takes several lifetimes (several μs in Si)







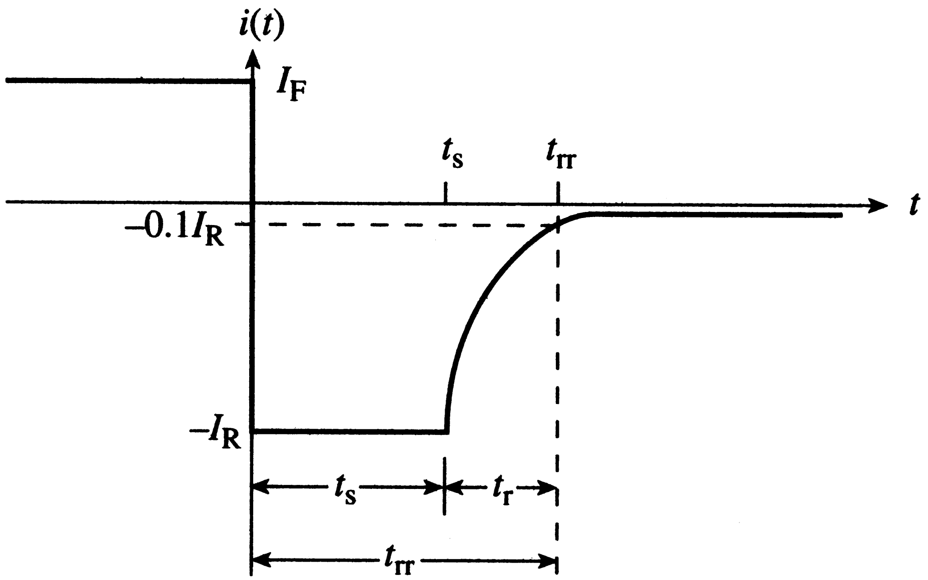
Idealized representation of a switching circuit



(a)

Figure 8.1

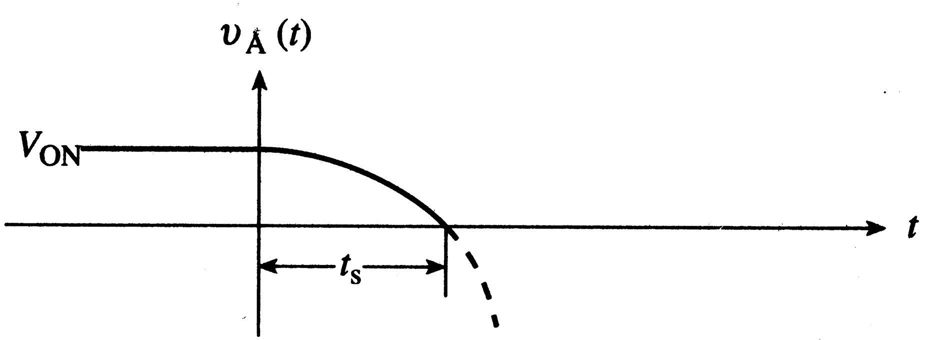
Diode current- and voltage-time transients



(b)

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

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



(c)

Figure 8.1

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

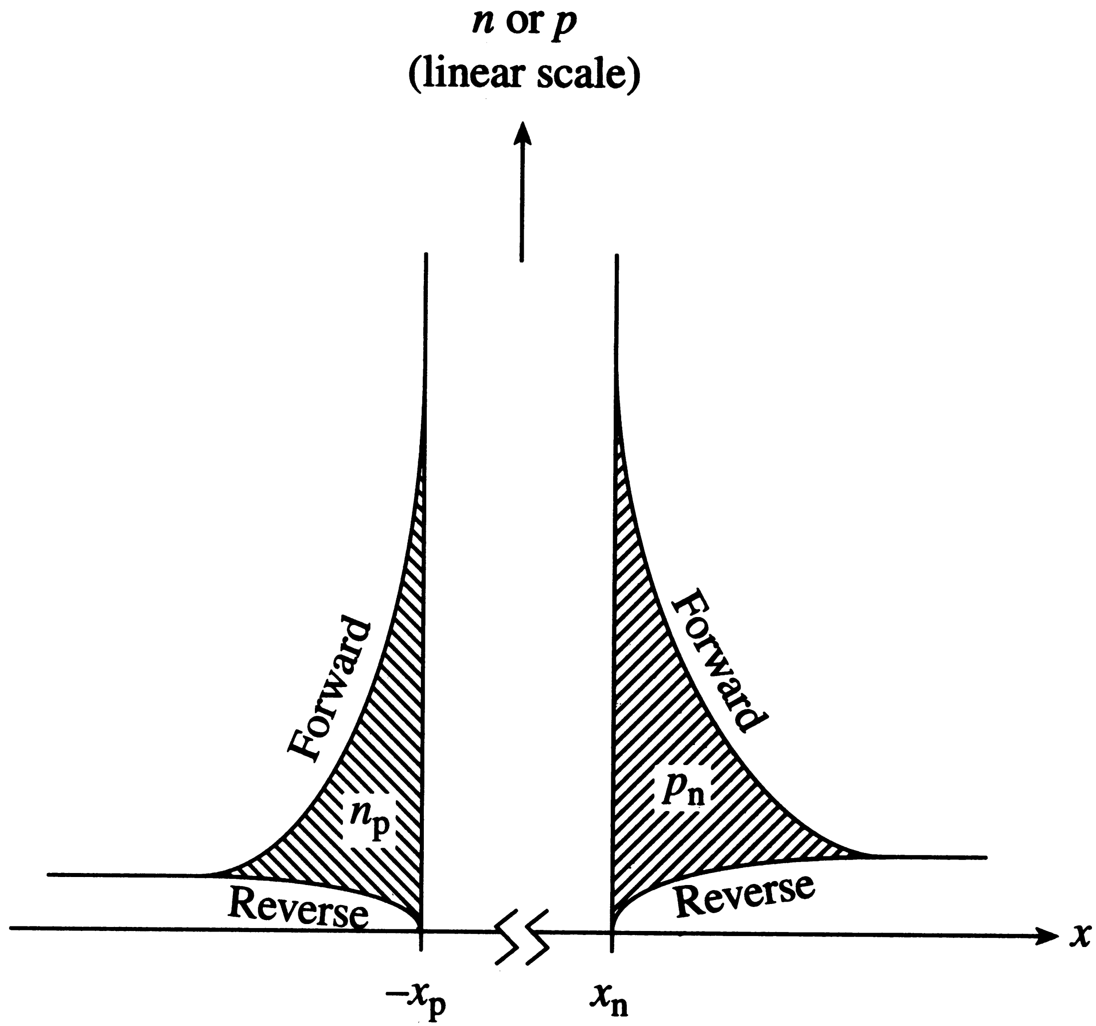


Figure 8.2

Decay of stored hole charge in a pn junction

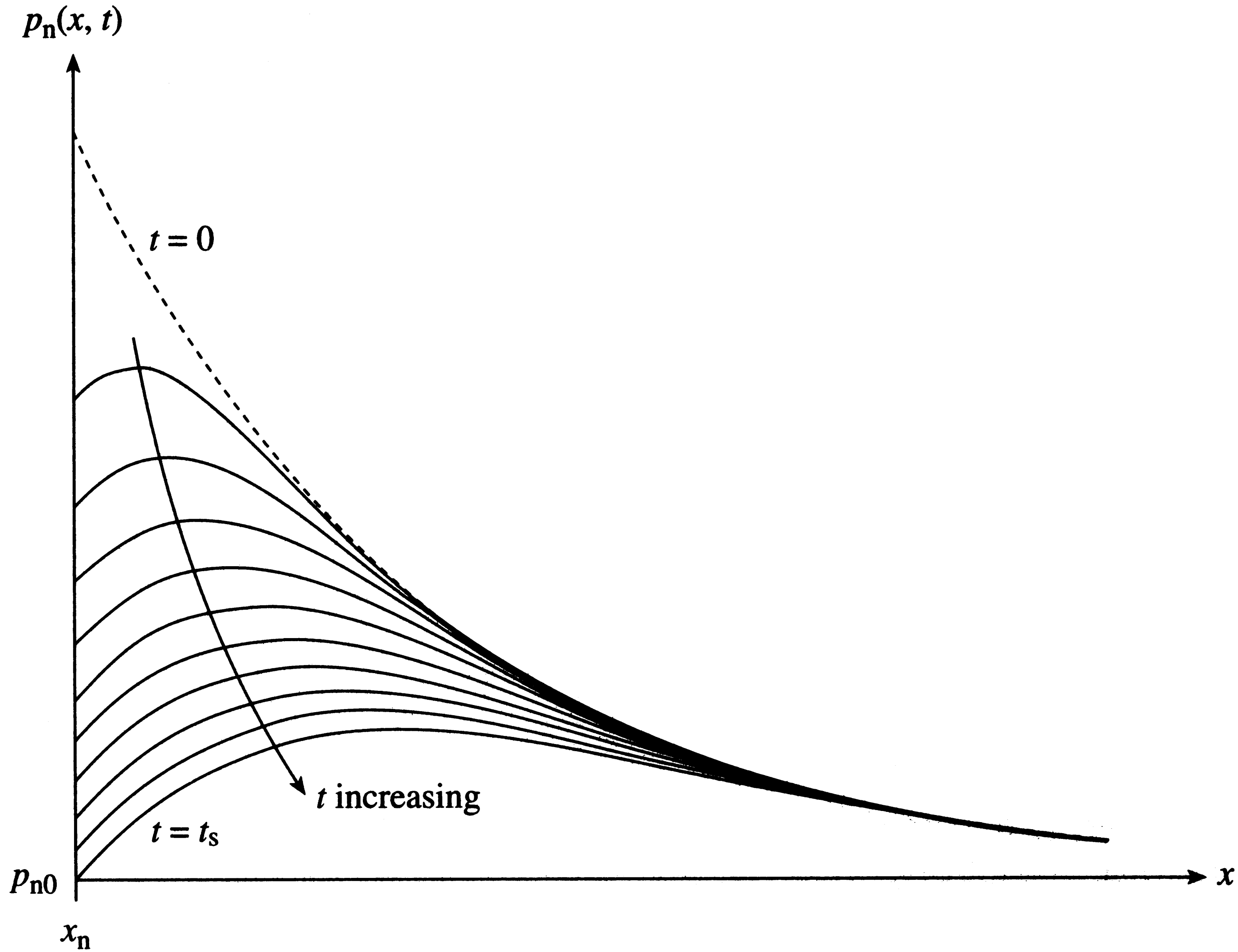


Figure 8.3

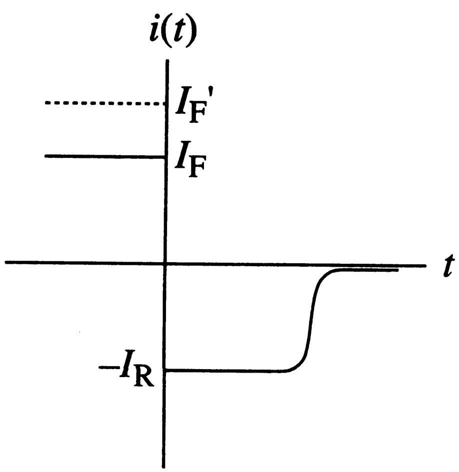
Example 1

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

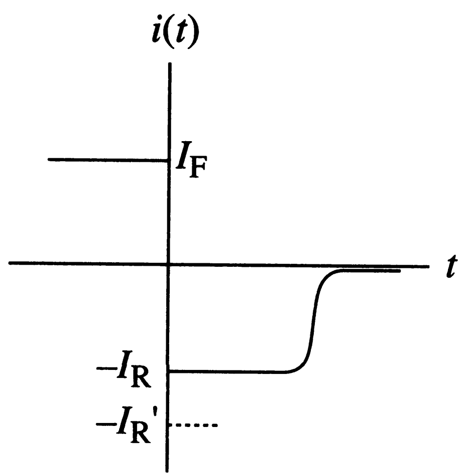
(a) If I_F is increased to I_F'

(b) If I_R is increased to I_R'

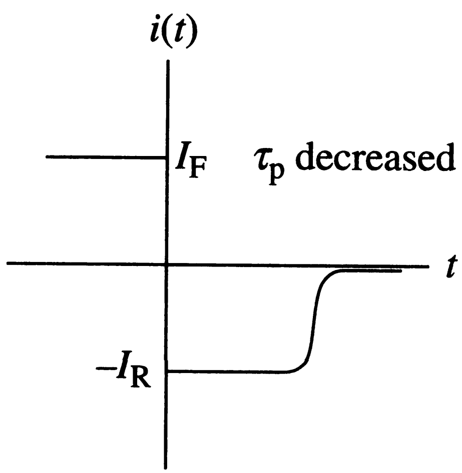
(c) If τ_p is decreased, lifetime made shorter



(a)



(b)



(c)

Example 1: Solution

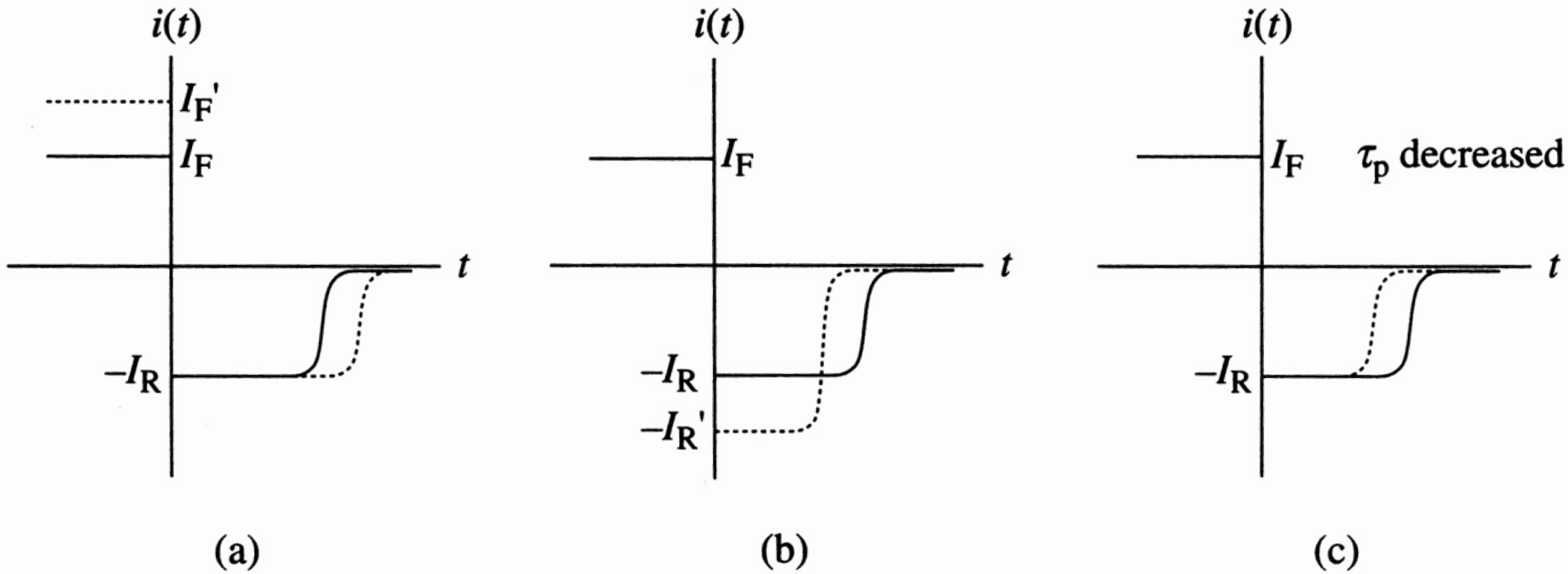


Figure E8.1

Storage delay time: Quantitative analysis

Consider a p$^+$n diode.

$$\frac{\mathrm{d}Q_\mathrm{p}}{\mathrm{d}t} = i - \frac{Q_\mathrm{p}}{\tau_\mathrm{p}}$$

$$i = \frac{\text{charge removed}}{\text{unit time}}$$

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

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

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

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

Minority carrier lifetimes can be measured using this method.

Transient response measurement system

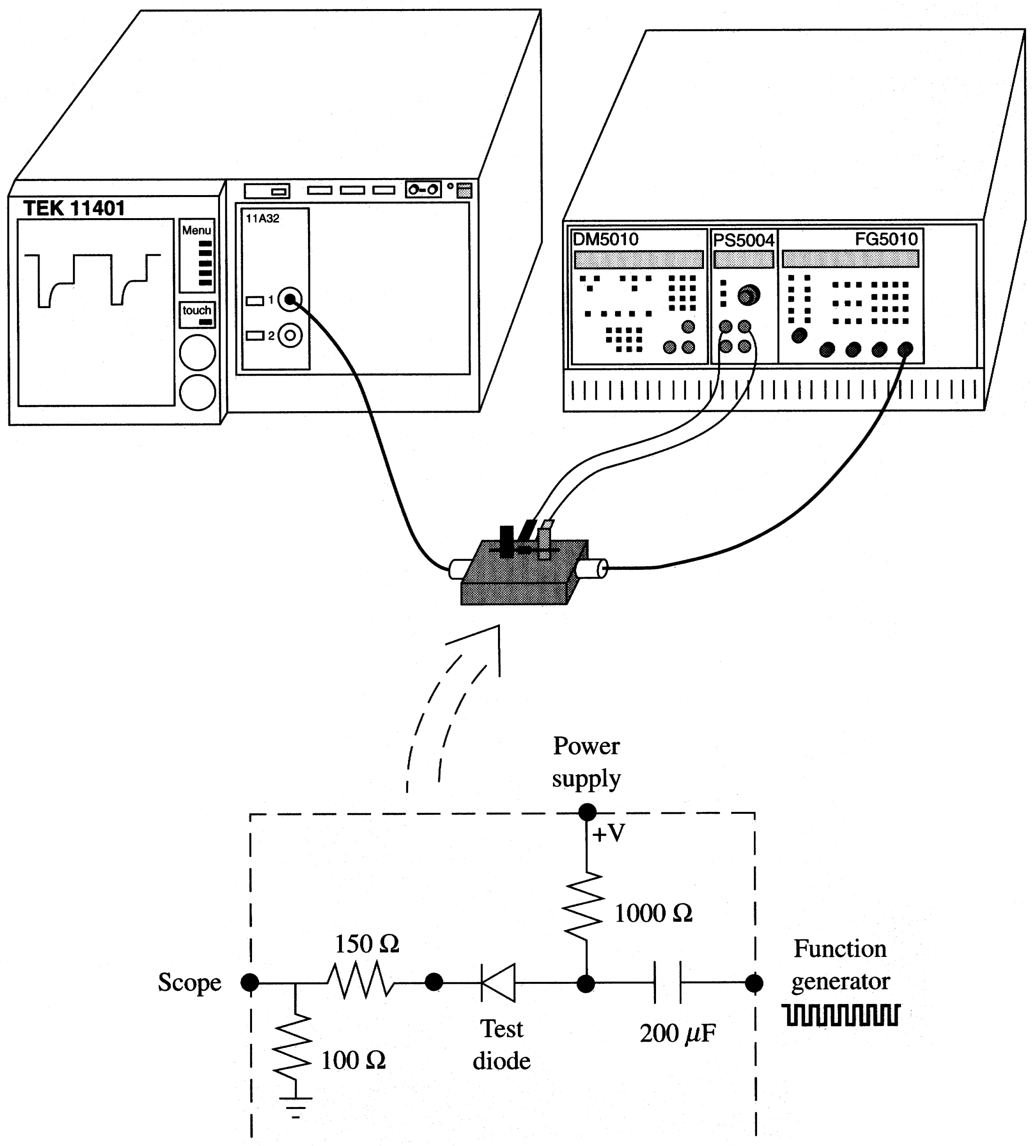


Figure 8.4

Sample current-time turn-off transient

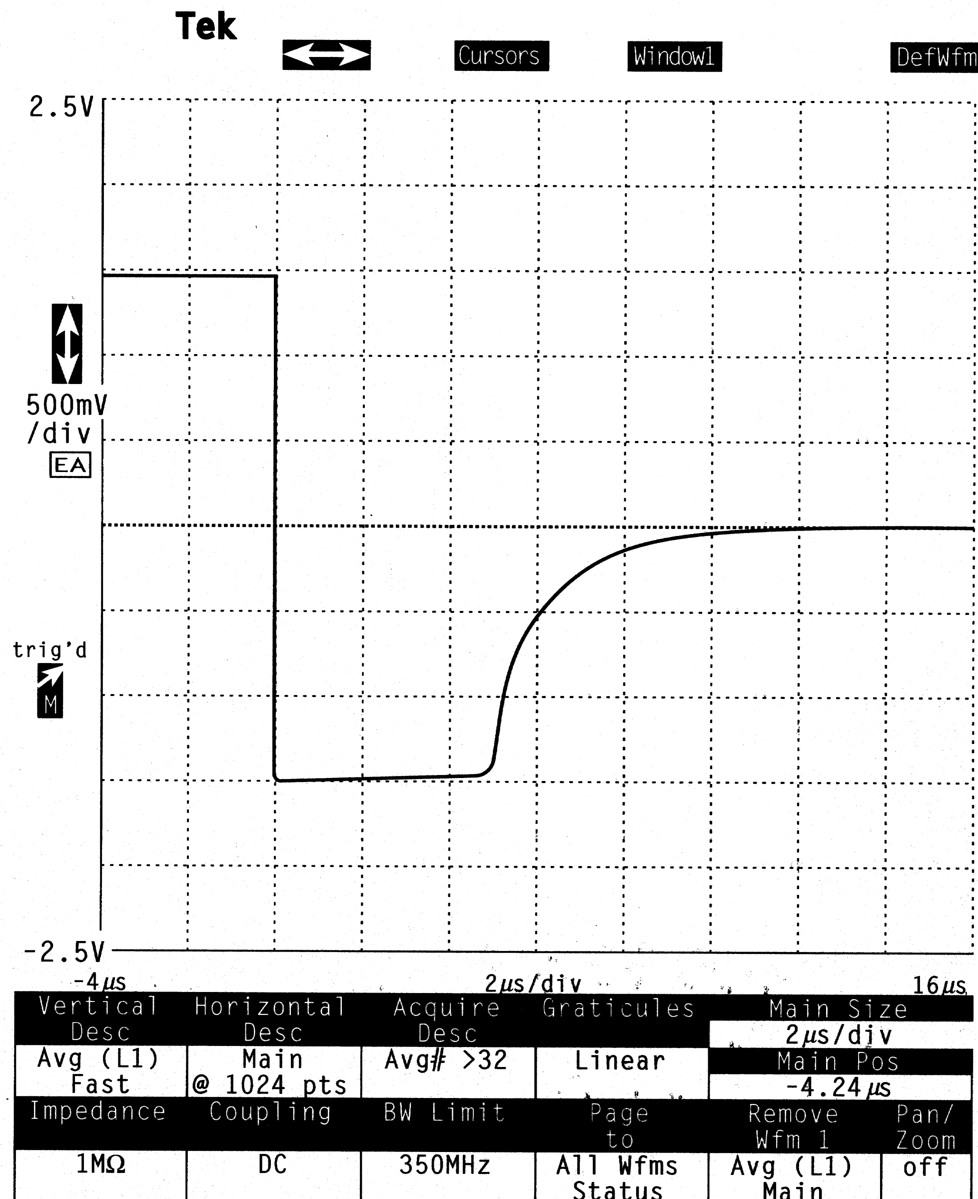


Figure 8.5

Chapter 9. PN-junction diodes: Applications

Diode applications:

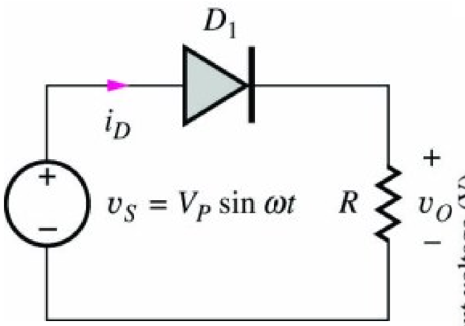
- Rectifiers
- Switching diodes
- Zener diodes
- Varactor diodes (Varactor = Variable reactance)

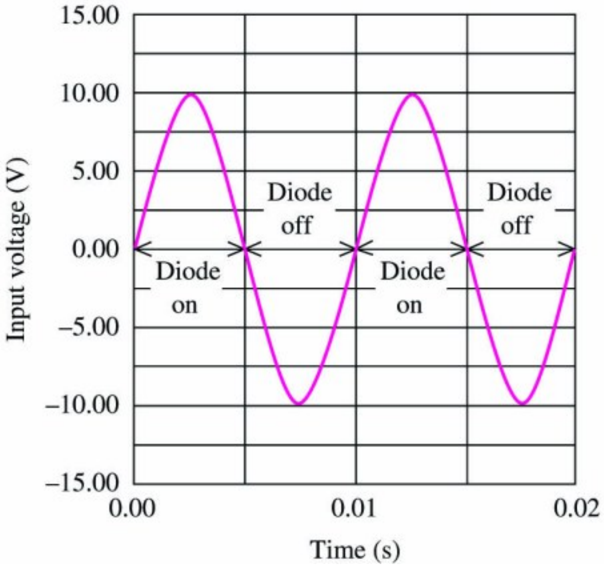
Photodiodes

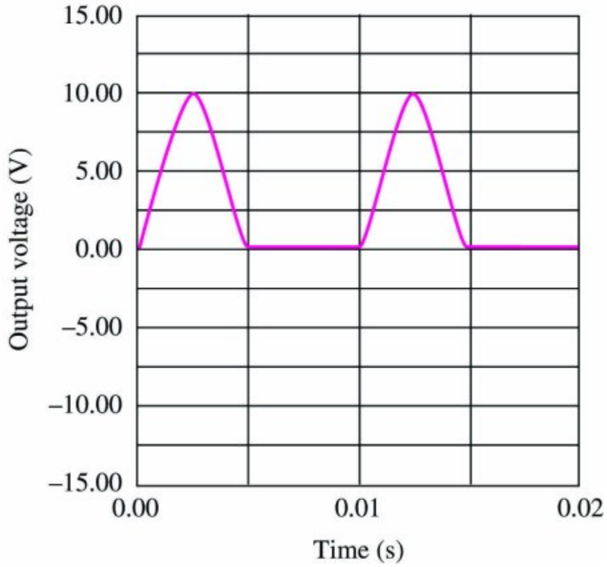
- pn junction photodiodes
- p-i-n and avalanche photodiodes

Solar Cells

Half-Wave Rectifier Circuit with Resistive Load







For positive half-cycle of input, source forces positive current through diode, diode is on, $v_o = v_s$.

During negative half cycle, negative current can't exist in diode, diode is off, current in resistor is zero and $v_o = 0$.

Rectifiers

Low R in forward direction:

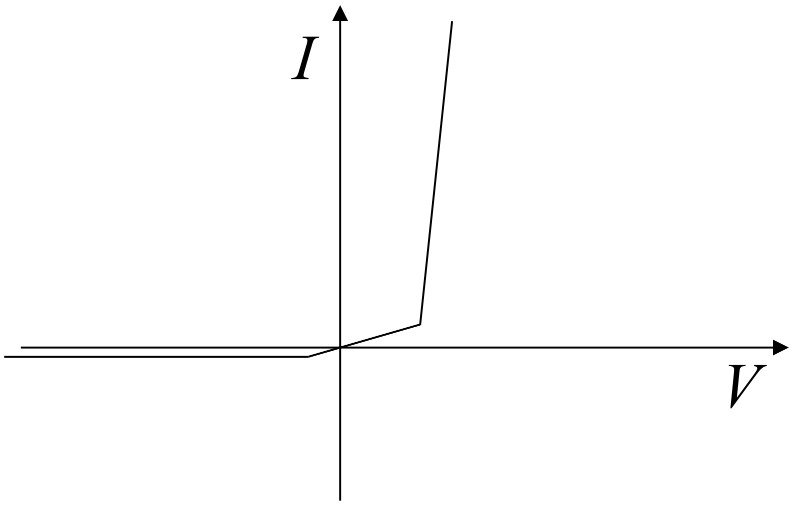
- p^+-n-n^+ structure preferred
- The p^+ and n^+ regions reduce the parasitic resistance.

Low I_0 in reverse:

- Ge is worse than Si. Why?

High voltage breakdown in reverse:

- p^+-n-n^+ structure
- Higher bandgap materials preferred. Why?



Switching diodes

- Diodes can be used as switching devices
- Need to change from conducting to non-conducting at high speed
- Storage time or turn-off transients should be small
- Add recombination centers to reduce minority carrier lifetimes

  For example adding $10^{15}\mathrm{cm}^{-3}$ gold (Au) to Si reduces hole lifetime to 0.01 μs from 1 μs!

- Use narrow-base diodes

  Amount of charge stored in the neutral region of the diode will be small.

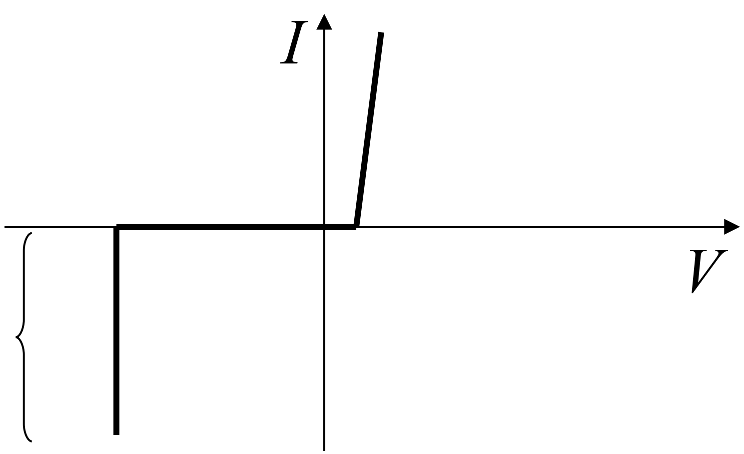
Zener diodes

The breakdown characteristics of diodes can be tailored by controlling the doping concentration

Heavily doped p^+ and n^+ regions result in low breakdown voltage (Zener effect)

Used as reference voltage in voltage regulators

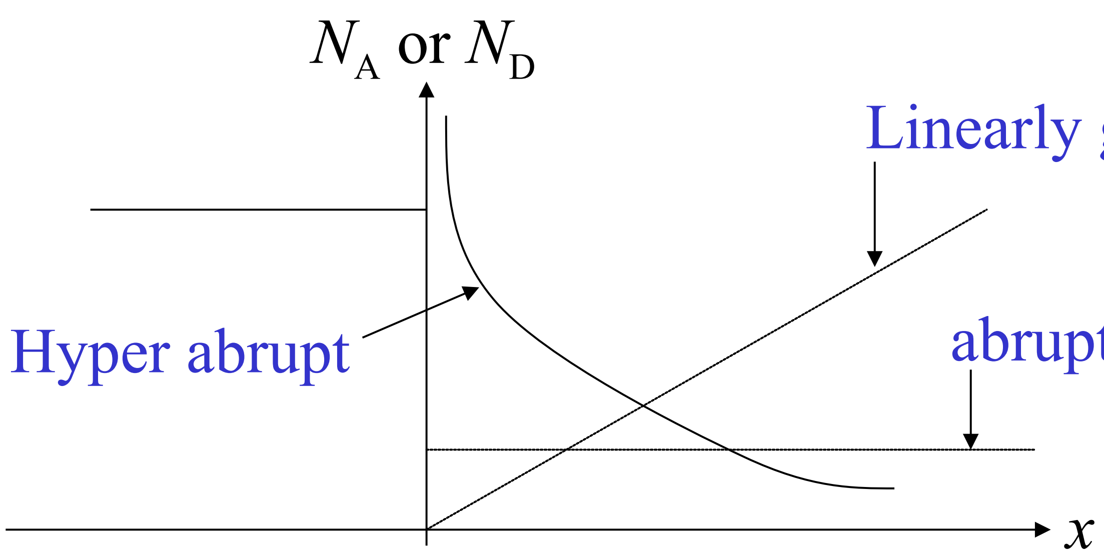
Region of operation



Varactor diodes (**Var**iable re**act**ance diode)

Voltage-controlled capacitance of a pn junction can be used in tuning stage of a radio or TV receiver.

$C_J \propto (V_A)^{-n}$, where $n = 1/2$ for an abrupt pn junction. However, n can be made higher than 1/2 by suitably changing the doping profile.



Opto-electronic diodes

Many of these diodes involve semiconductors other than Si. Use *direct* bandgap semiconductors.

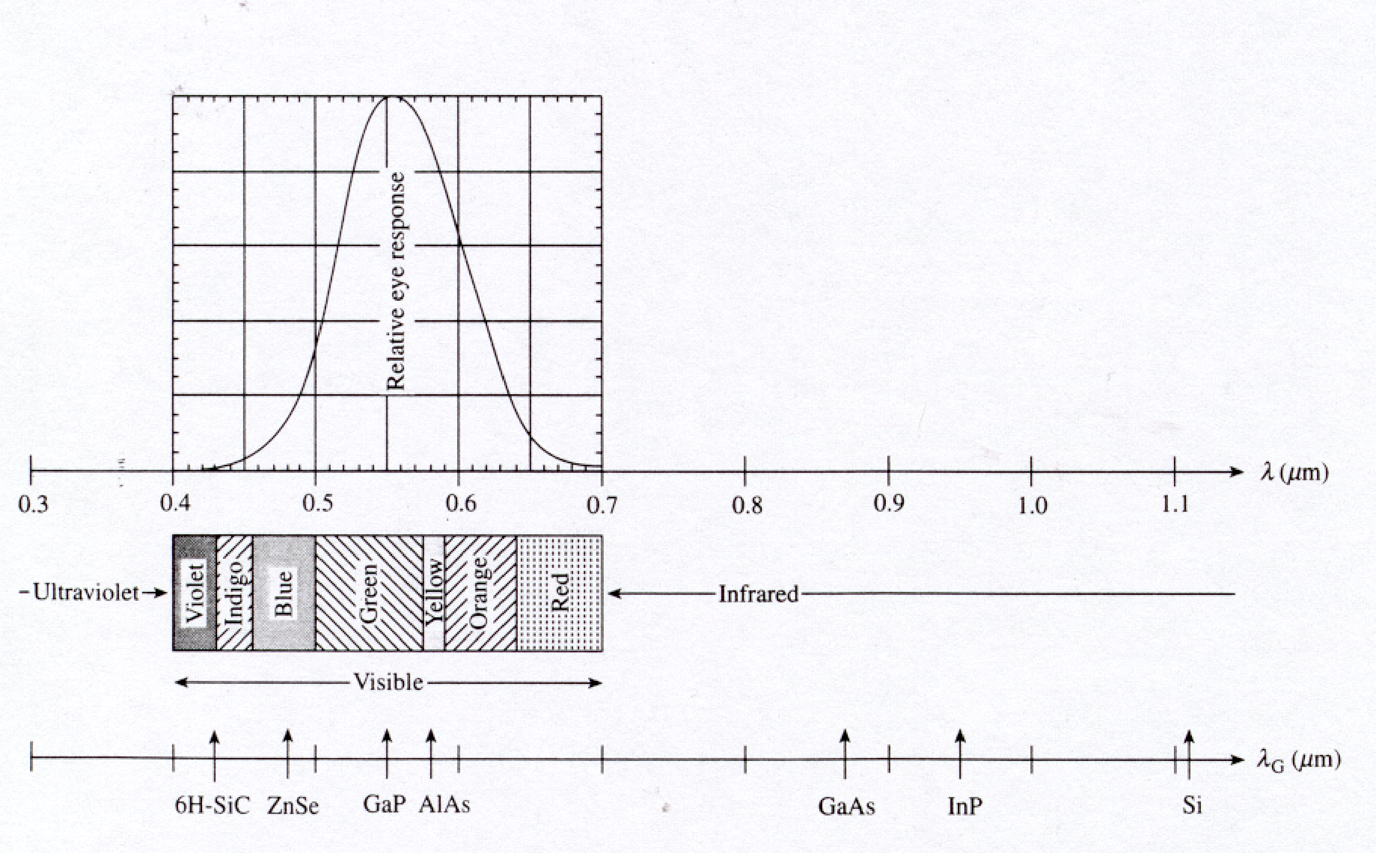
Devices to convert optical energy to electrical energy
- photodetectors: generate electrical signal
- Solar cells: generate electrical power

Devices to convert electrical energy to optical energy
- light emitting diodes (LEDs)
- laser diodes

Optical spectrum correlated with relative eye sensitivity

Photon energy $E_{ph} = hc/\lambda$

Inserting numerical values for h and c yields $E_{ph} = 1.24\ \text{eV}\ \mu\text{m}/\lambda$



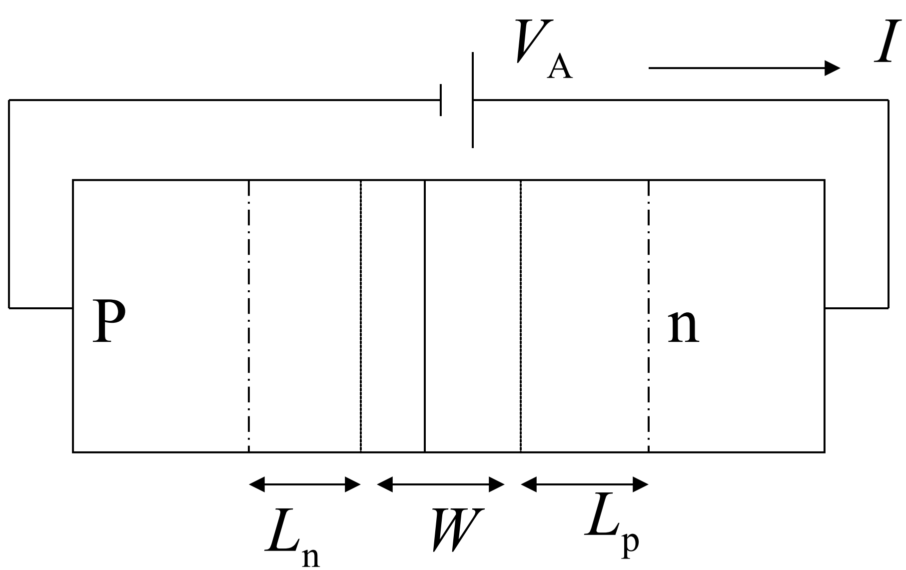
Note: Our eye is very sensitive to green light

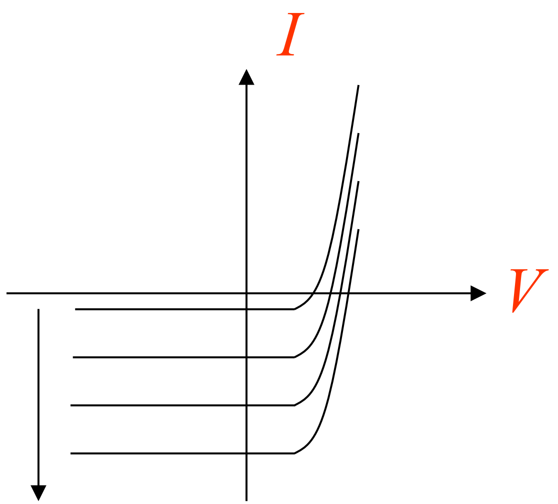
Photodiodes

Specifically designed for detector application and light penetration

$I_L = -q\,A\,(L_N + W + L_P)\,G_L$ assuming uniform photo-generation rate, G_L

$I = I_{dark} + I_L$





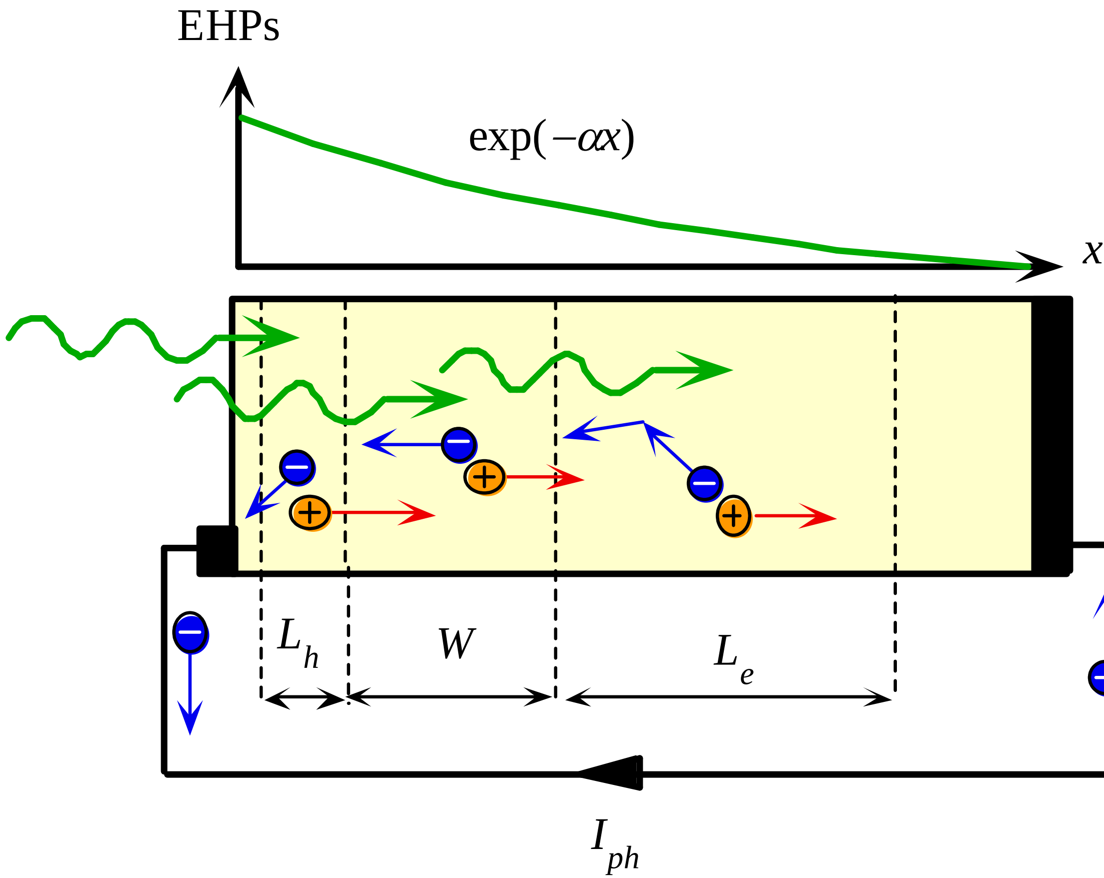
Photodiodes

If the depletion width is negligible compared to $L_n + L_p$, then I_L is proportional to light intensity.

Spectral response - an important characteristic of any photo-detector. Measures how the photocurrent, I_L varies with the wavelength of incident light.

Frequency response - measures how rapidly the detector can respond to a time varying optical signal. The generated minority carriers have to diffuse to the depletion region before an electrical current can be observed externally. Since diffusion is a slow process, the maximum frequency response is a few tens of MHz for pn junctions. Higher frequency response (a few GHz) can be achieved using p-i-n diodes.

Fundamentals of Solar Cell



Photogenerated carriers within the volume $L_h + W + L_e$ give rise to a photocurrent I_{ph}. The variation in the photegenerated EHP concentration with distance is also shown where α is th absorption coefficient at the wavelength of interest.