# Chapter 6

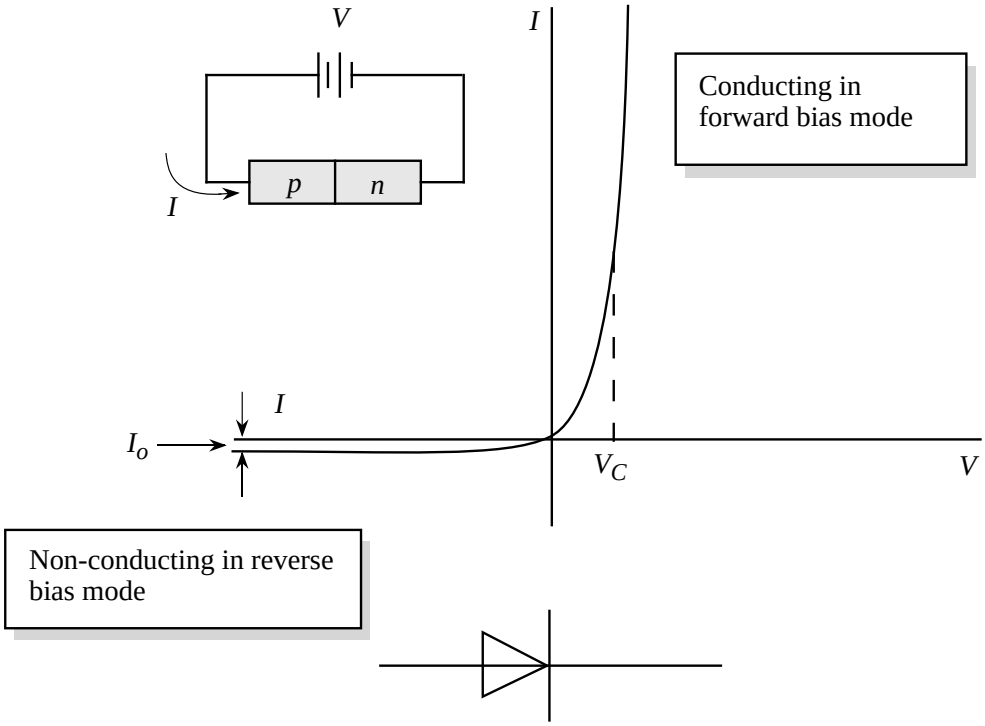
# P-N DIODES


Junctions between $n$- and $p$-type semiconductors are extremely important for a variety of devices. Diodes based on $p$-$n$ junctions produce nonlinear current voltage characteristics which can be exploited for numerous applications.

# P-N DIODE: NONLINEAR CURRENT-VOLTAGE

An ideal diode is conducting in one direction of bias and non-conducting in the reverse bias case.

- $V_C$, the cut-in voltage in forward bias should approach zero.
- $I_o$, the reverse bias current, should be zero.

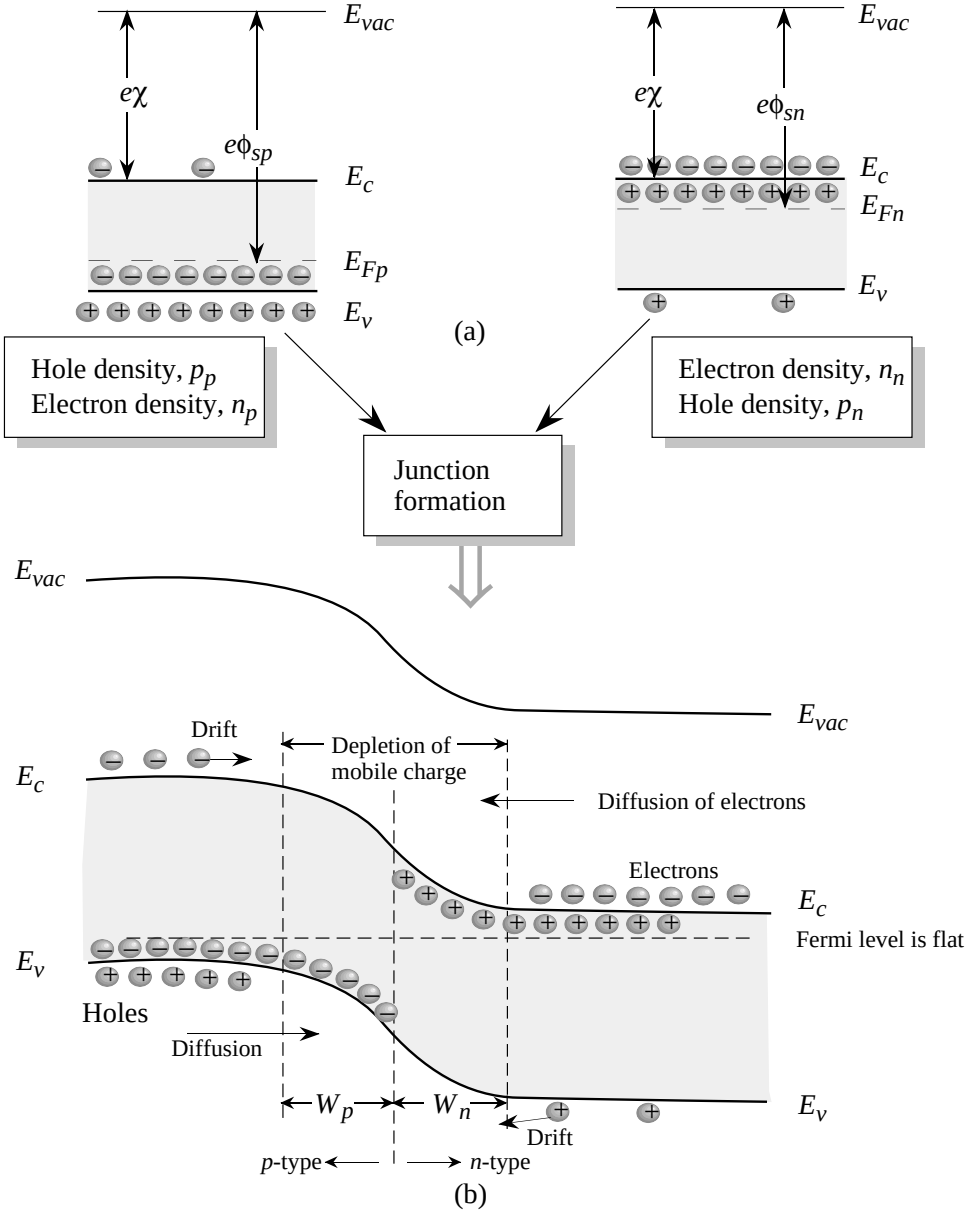



Diode symbol

# NON-IDEAL EFFECTS IN A P-N DIODE

A built-in voltage arises when a *p*-*n* junction is formed.

$$V_{bi} = k_B T \ ln \left( \frac{n_n p_p}{n_i^2} \right)$$




Mobile carriers (electrons on *n*-side, diodes on *p*-side) are swept away from the depletion region.

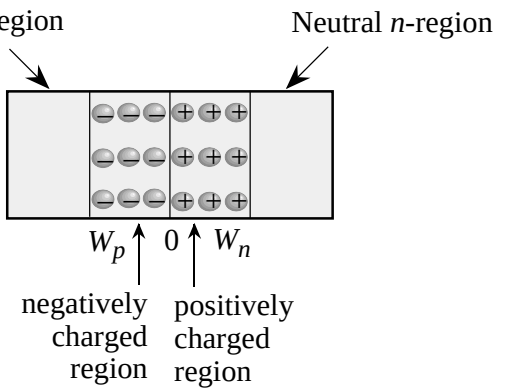
# DEPLETION REGION AND CURRENT FLOW

A *p*-*n* diode has a depletion region on the *n*-side and on the *p*-side.

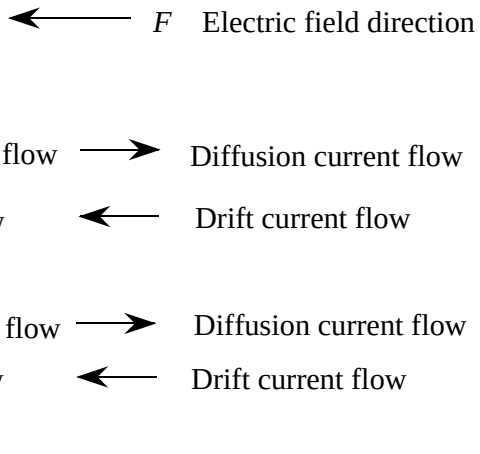
$$W_p(V) = \left\{ \frac{2\varepsilon\,(V_{bi} - V)}{e} \left[ \frac{N_d}{N_a\,(N_a + N_d)} \right] \right\}^{1/2}$$

$$W_n(V) = \left\{ \frac{2\varepsilon\,(V_{bi} - V)}{e} \left[ \frac{N_a}{N_d\,(N_d + N_a)} \right] \right\}^{1/2}$$

$$W(V) = \left\{ \frac{2\varepsilon\,(V_{bi} - V)}{e} \left[ \frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$$



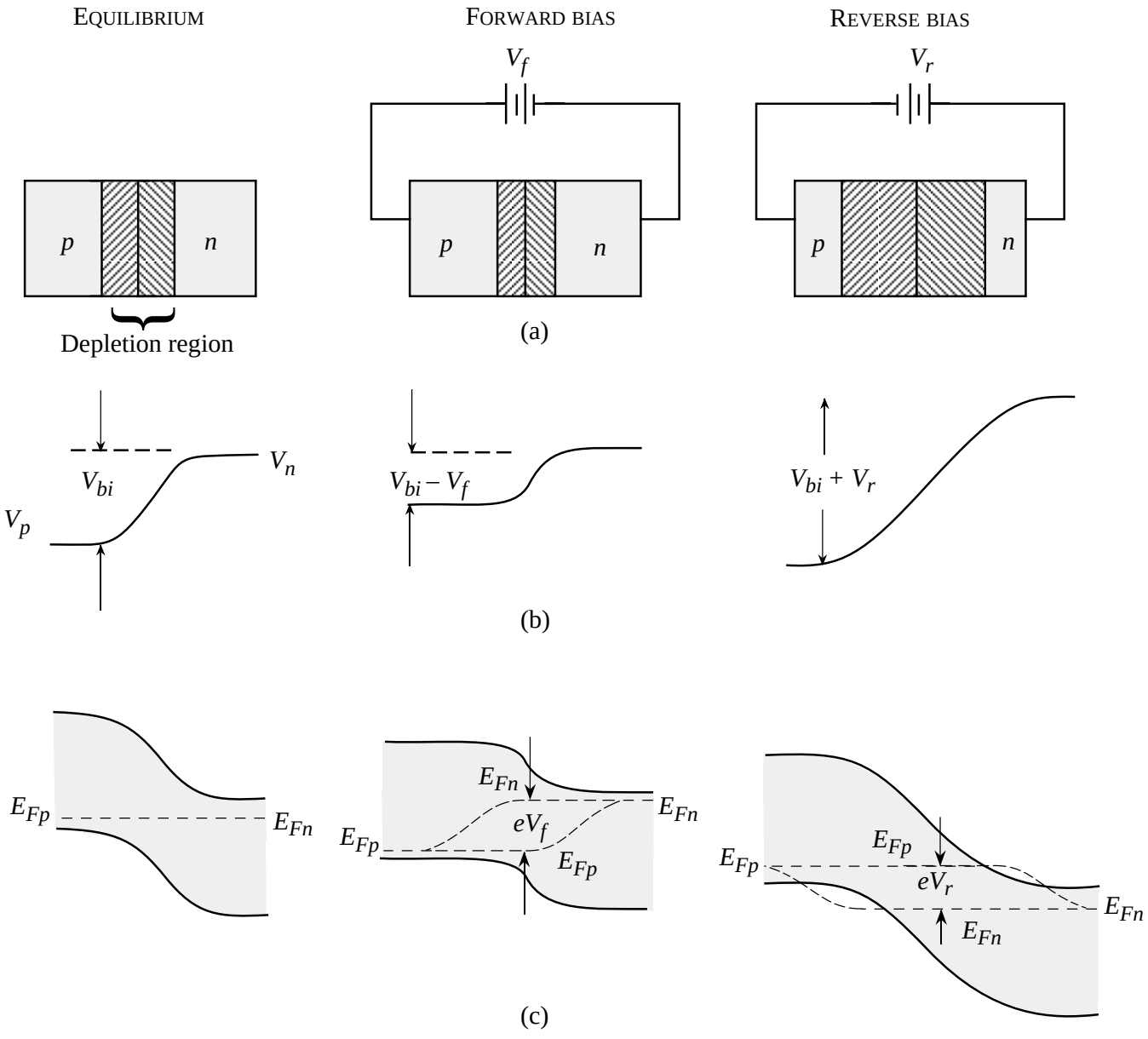

(a)




(b)

There are four terms in the current flow, as shown. At zero bias the total current is zero. At forward bias the minority current injected over the junction increases exponentially. At reverse bias the current saturates.

# BAND PROFILE IN A P-N DIODE




FORWARD BIAS: Depletion region decreases. Minority carriers injected (electrons injected from the *n*-side into the *p*-region + holes injected from the *p*-side into the *n*-region) control the current.

REVERSE BIAS: Depletion region width increases. Saturation current is made up of holes diffusing into the *p*-side (from the *n*-side) and electrons diffusing into the *n*-side from the *p*-side.

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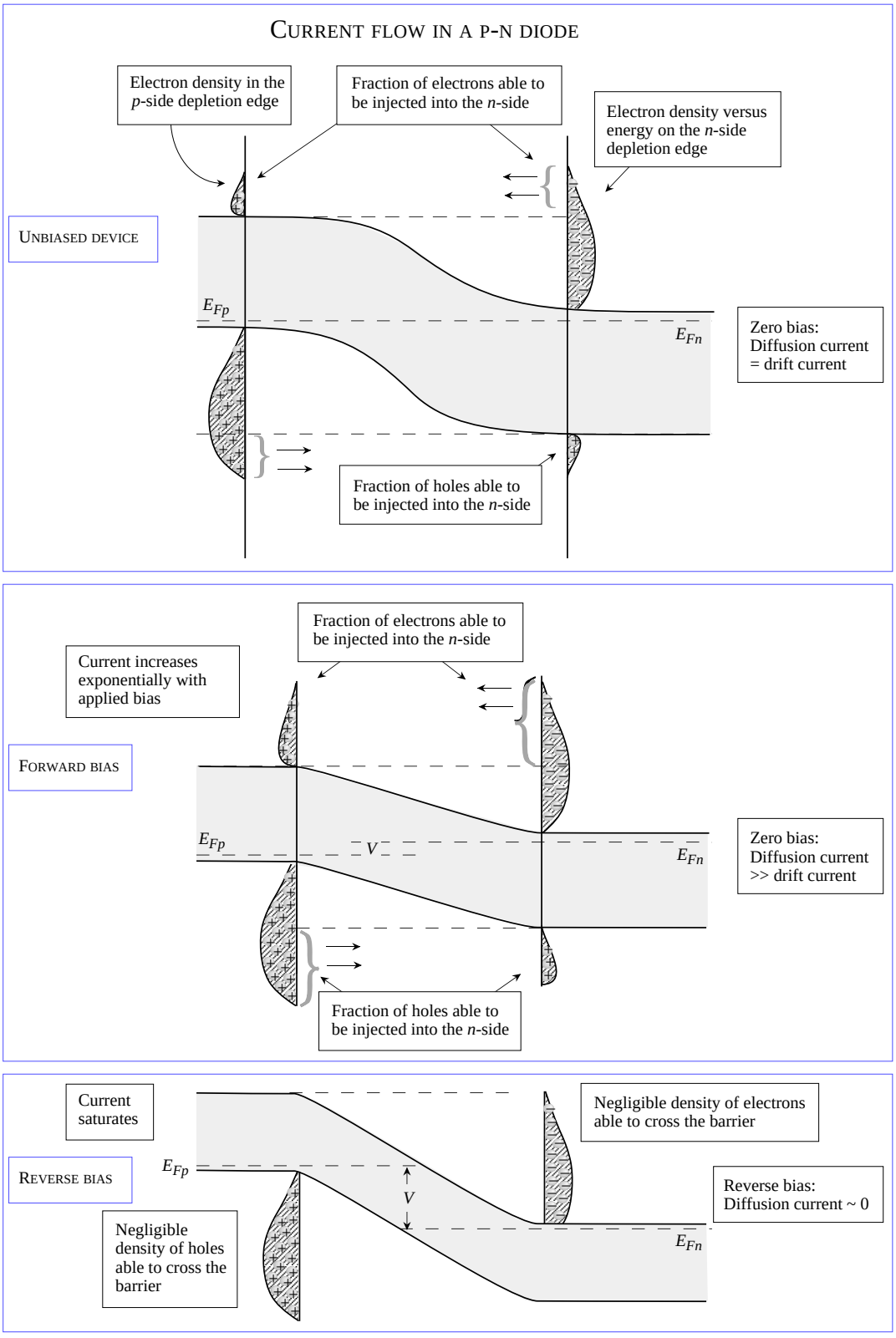
# CURRENT FLOW IN A P-N DIODE

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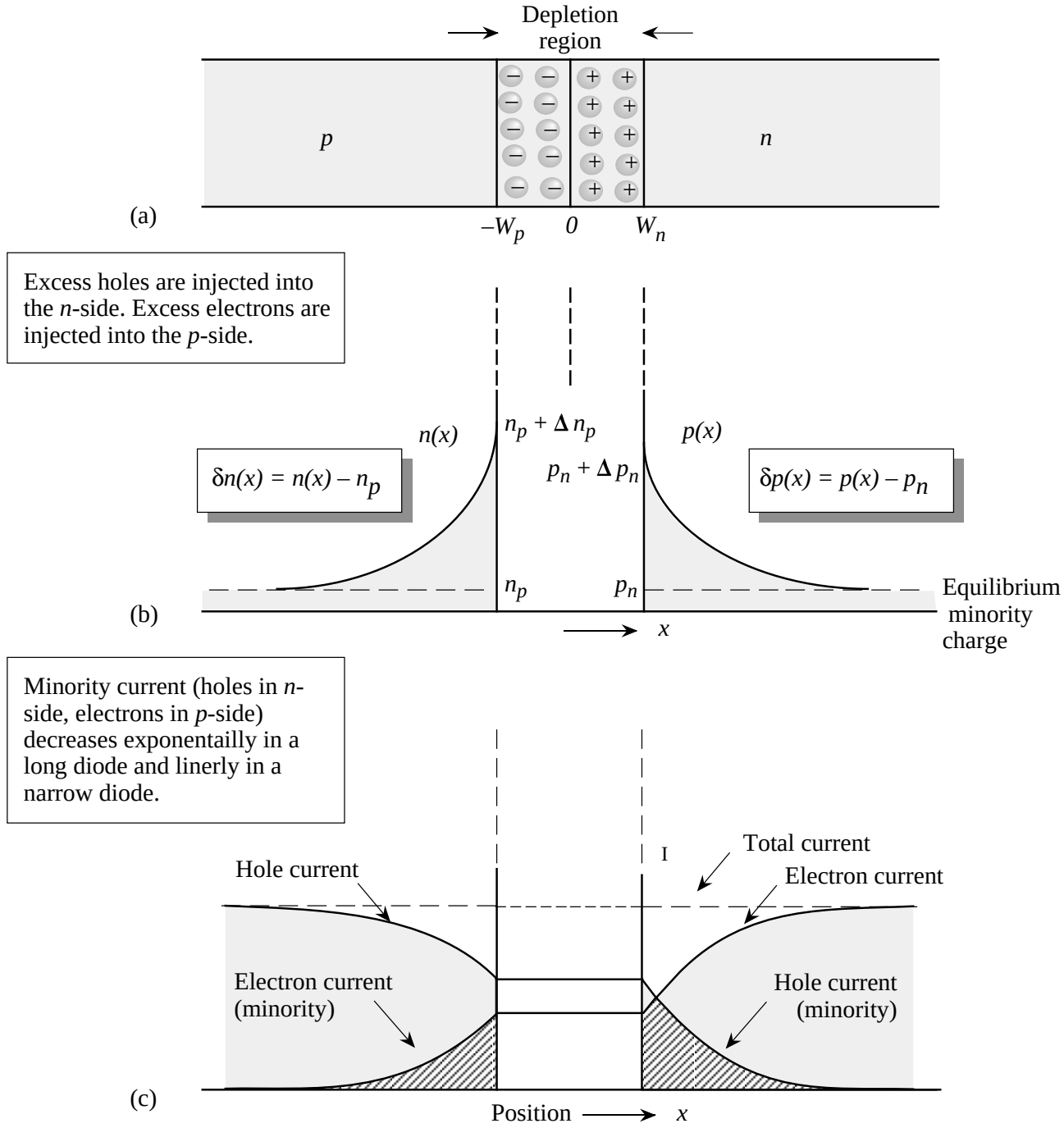
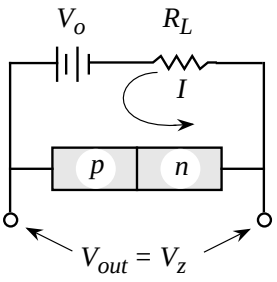
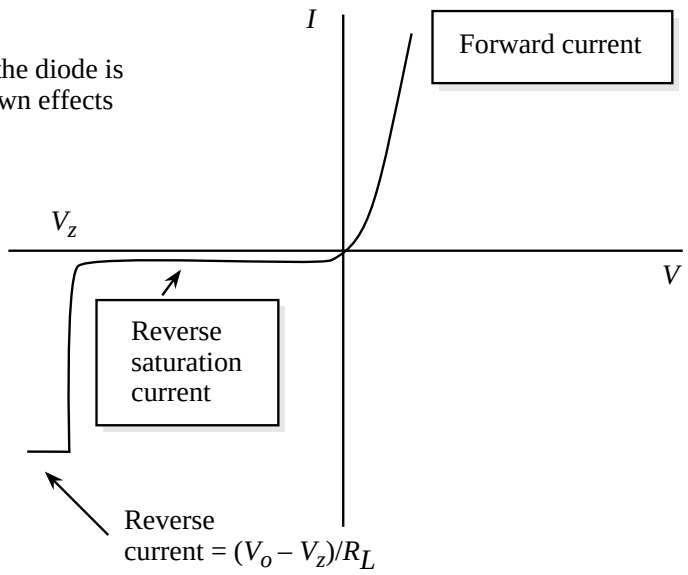
# MINORITY CHARGE DISTRIBUTION AND CURRENT IN A FORWARD BIAS DIODE



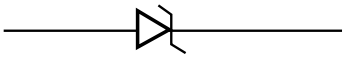
# CURRENT VOLTAGE IN A P-N DIODE

Reverse bias voltage across the diode is limited to $V_Z$ due to breakdown effects




(a)

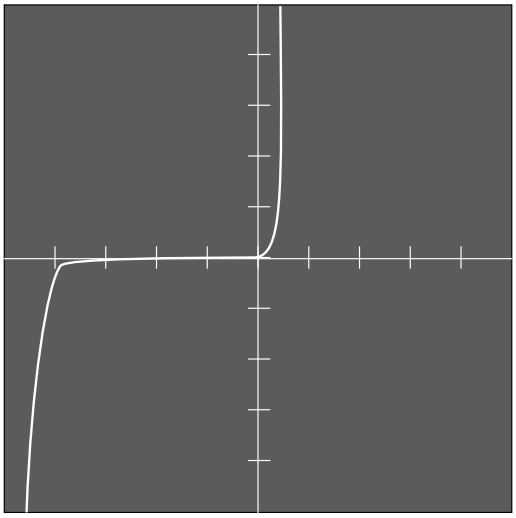


(Zener diode)

Forward bias:

$$I = I_S \left[ \exp \frac{eV}{nk_BT} - 1 \right]$$

$n$: non-ideality factor
$n = 1$ in ideal diode



Vertical: 5 mA/div
Horizontal: 5 V/div

(b)

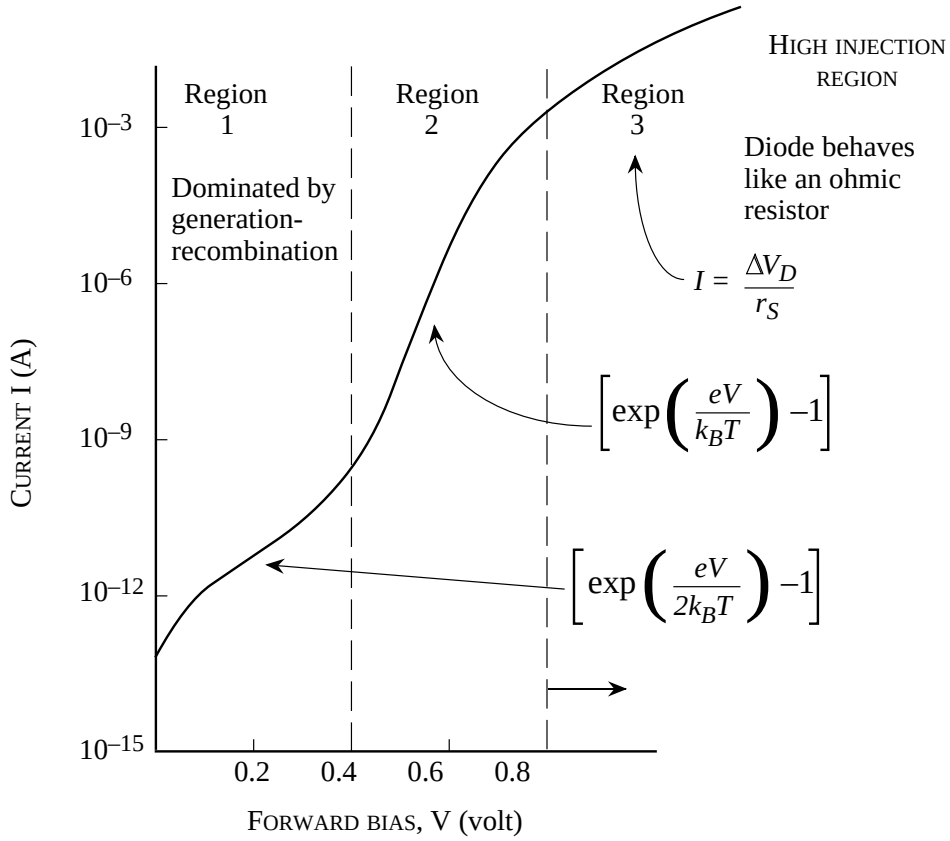
 

# NON-IDEAL EFFECTS IN A P-N DIODE

Recombination-generation effects in the depletion region allow current flow which has a behavior

$$I_{GR} = I^{\circ}_{GR}\left[\exp\left(\frac{eV}{2k_BT}\right)-1\right]$$

The total current voltage relation has the form shown below




Diode current:

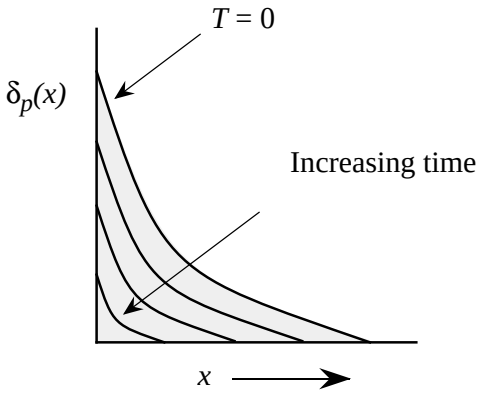
$$I = I_S\left[\exp\left(\frac{eV}{nk_BT}\right)-1\right]$$

In poor quality diodes $n \sim 2$
In high quality diodes $n \sim 1$

# IMPORTANT ISSUES CONTROLLING SWITCHING SPEEDS IN P-N DIODES

Excess minority charge is injected in a forward bias diode. This charge has to be removed to reverse-bias the diode.




Device response in minority carrier devices

How fast can minority charge be altered?

Recombination with majority carriers.

- $\tau \sim 10^{-6}$ sec for indirect gap materials
- $\tau \sim 10^{-9}$ sec for direct gap materials

Recombination via impurities or defects.

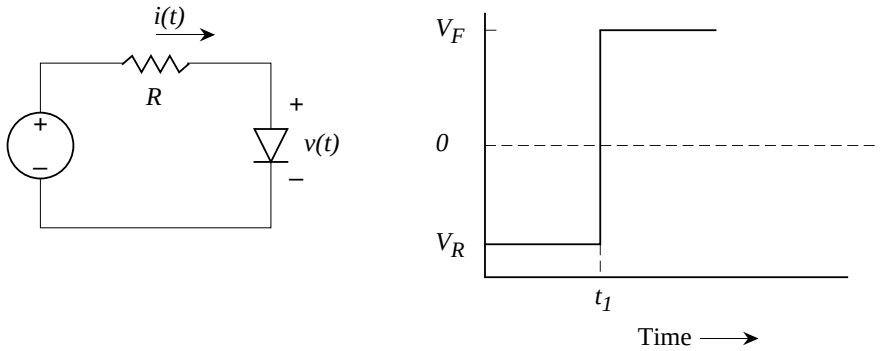
- $\tau$ can approach a few picoseconds

Narrow width devices to extract charge through contacts.

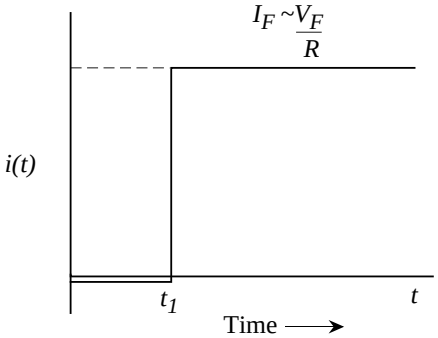
- $\tau$ dominated by transit time effects

# TURN-ON OF A P-N DIODE

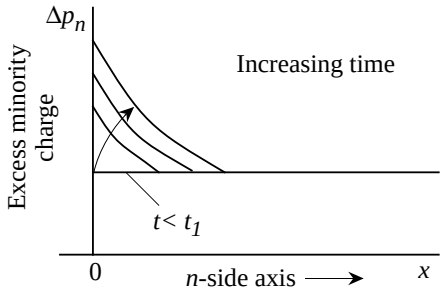



(a)



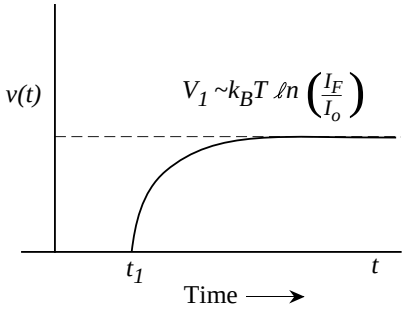

(b)

Current in the diode reaches $I_F$




(c)

Minority carrier density builds up on the *n*-side as the diode is forward biased




(d)

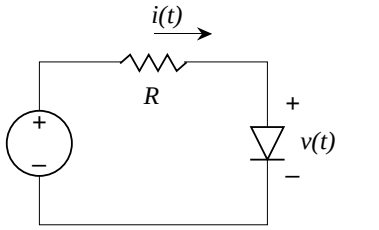
Voltage across the diode builds up to its final value

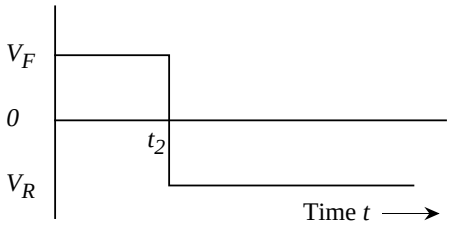
 

# TURN-OFF OF A P-N DIODE

IMPORTANT TIME CONSTANTS: Minority carrier lifetime (long diode) or minority carrier transit time to the contacts (narrow diode) + RC time constants for the reverse biased diode.

(a)

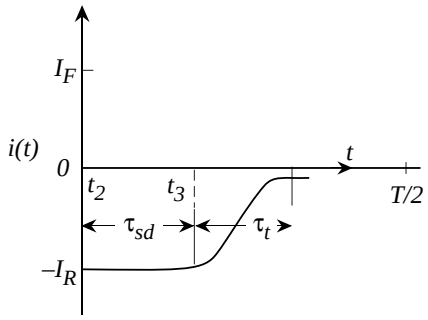


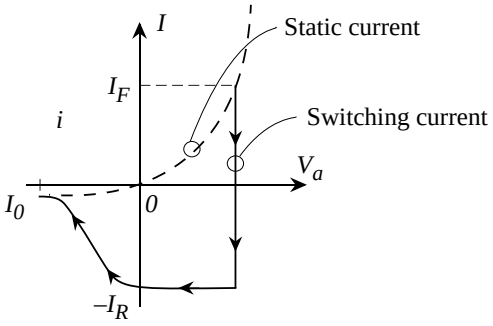




Diode current in time

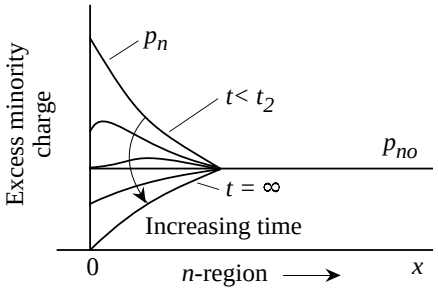
Diode current path

(b)



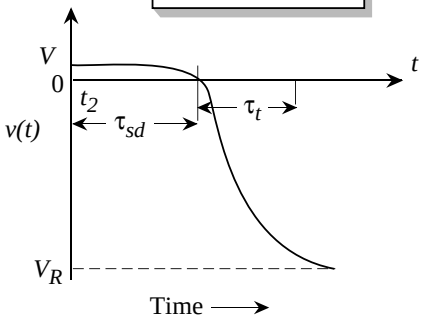

(c)




Excess minority charge is removed in a time $\tau_{sd}$

Diode voltage

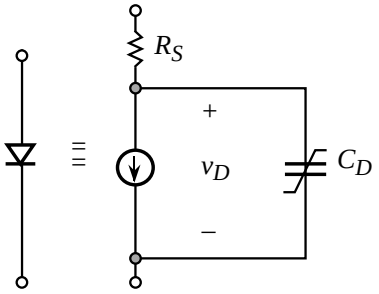
(d)




Voltage across the diode remains positive until all of the excess minority charge is extracted. $\tau_{sd}$ is the storage delay time and $\tau_t$ is the RC time constant

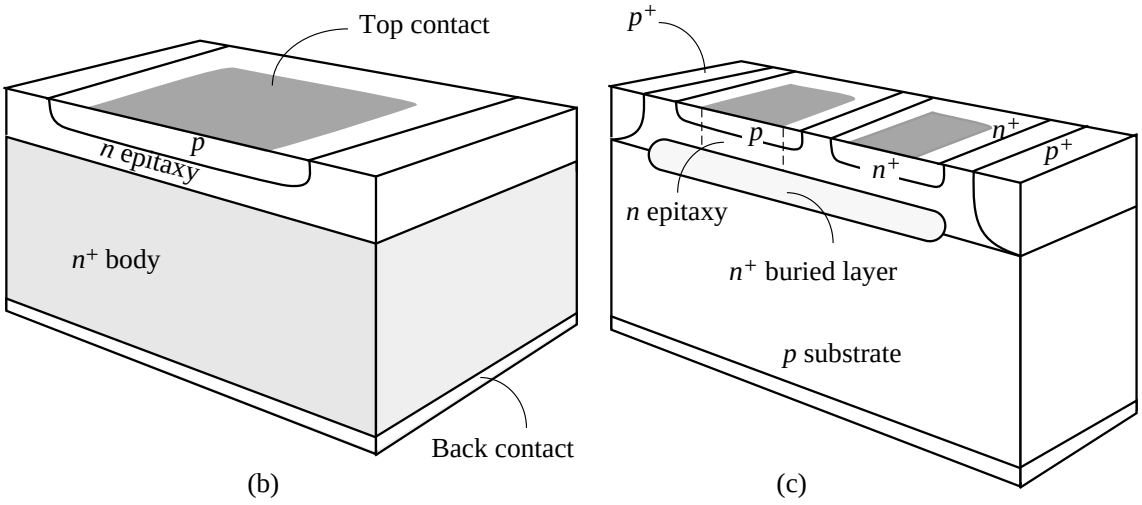
# A MODEL FOR A P-N DIODE USED IN SPICE




$$i_D = I_S\left[\exp\left(\frac{eV_D}{nk_BT}\right)-1\right]$$

$$C_D = \frac{e\tau_T}{k_BT} I_S\left[\exp\left(\frac{eV_D}{nk_BT}\right)-1\right] + C_{j0}\left(1-\frac{v_D}{V_0}\right)^m$$

(a)




DIODE CAPACITANCE: Diffusion capacitance (important in forward bias) + junction capacitance

$C_{diff} = \frac{e}{k_BT} I\tau$; $\tau$ = minority carrier lifetime (long diode)

$\tau$ = transit time to contact (narrow diode)

$$C_j = \frac{A\varepsilon}{W} = \frac{C_{jo}}{\left(1-\frac{V}{V_{bi}}\right)^m}$$

$m$ = 1/2 for abrupt doped diode

= 1/3 for linearly graded junctions

# A MODEL FOR A P-N DIODE USED IN SPICE