

Diodi

Materiali per l'elettronica

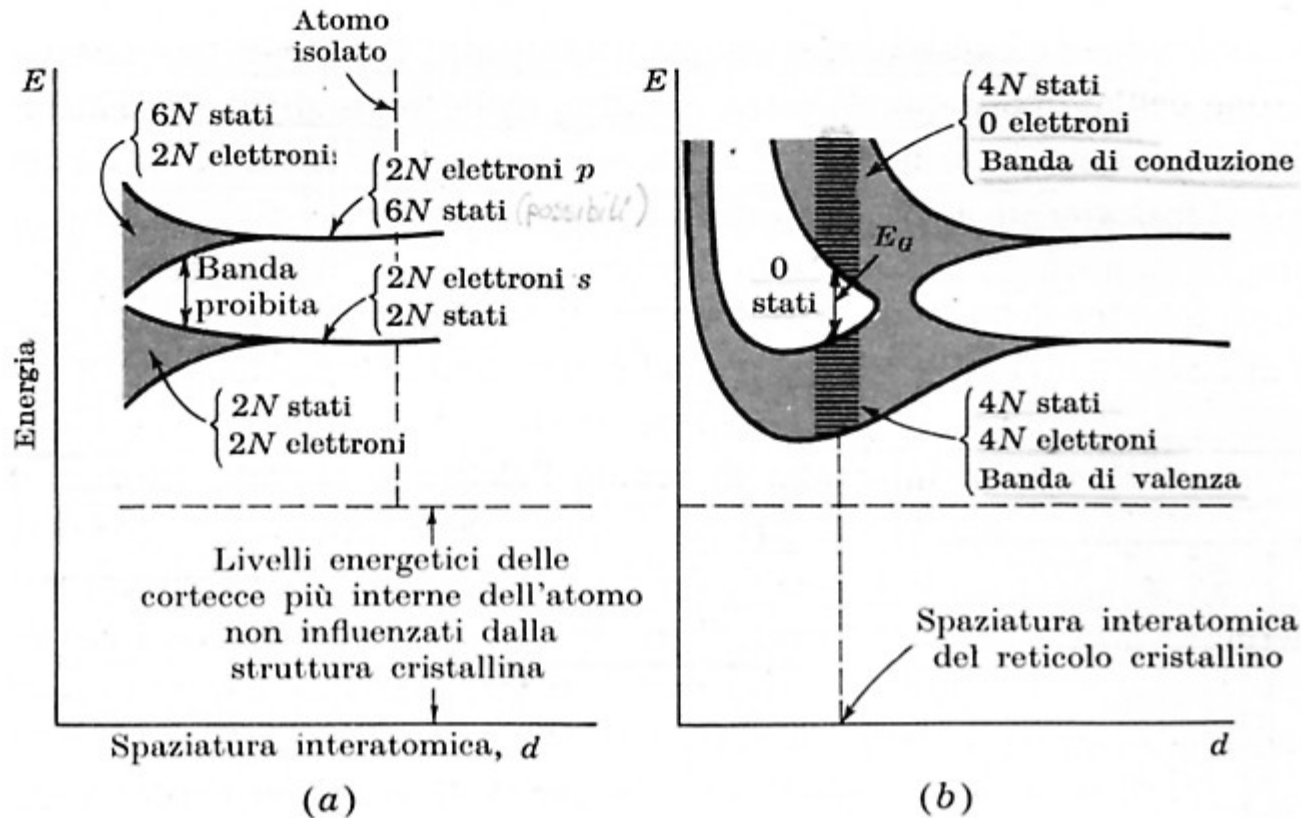
| | Resistività r (Ωcm) |
|----------------|---------------------------------------|
| Metalli | $r < 10^{-3}$ |
| Semiconduttori | $10^{-3} < r < 10^5$ |
| Isolanti | $r > 10^5$ |

- Semiconduttori intrinseci
- Semiconduttori estrinseci (drogati con impurezze)

Materiali semiconduttori per diodi

- Silicio (Si)
- Germanio (Ge)
- Arseniuro di Gallio (GaAs)

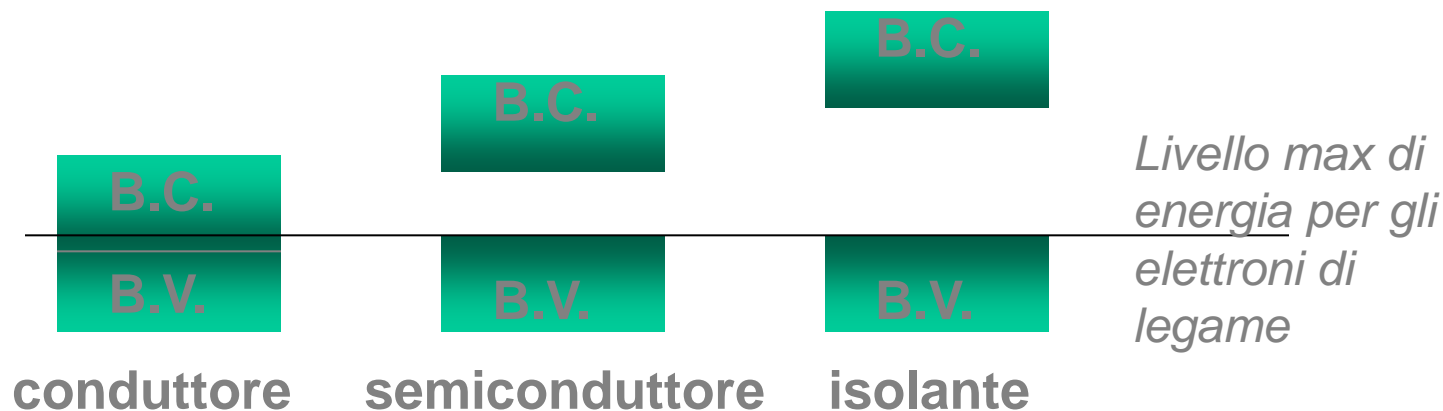
Bande di Energia nel silicio



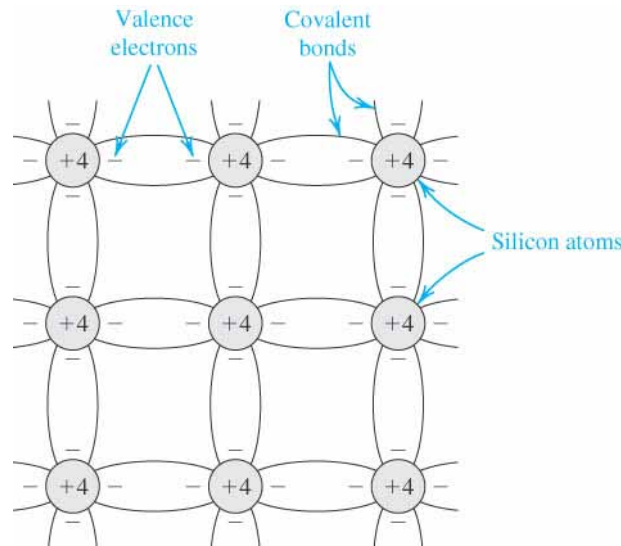
I livelli energetici degli atomi isolati si sparpagliano in intervalli (bande) di energia quando questi atomi sono portati in stretto contatto per formare un cristallo

Bande di Energia

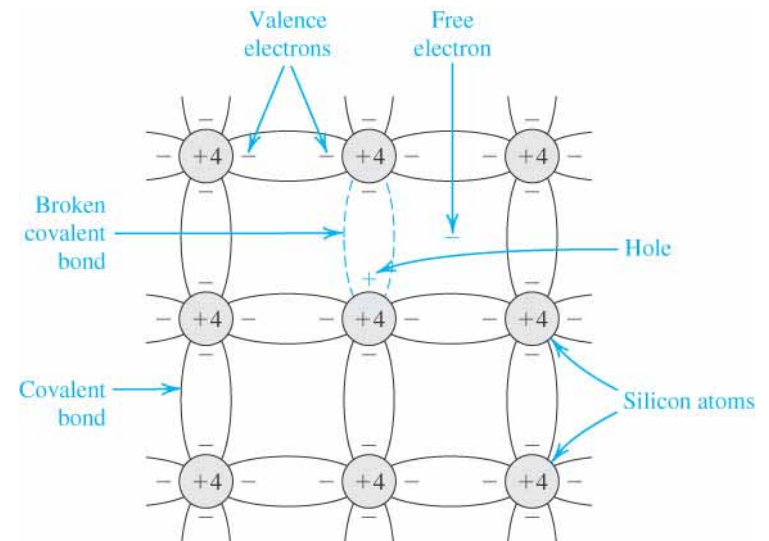
La differenza fondamentale tra materiali conduttori, semiconduttori e isolanti sta nel valore di energia di gap, banda di energia proibita per gli elettroni che separa banda di valenza (elettroni di legame) e banda di conduzione (elettroni liberi).



Silicio intrinseco



cristallo di silicio intrinseco a 0K



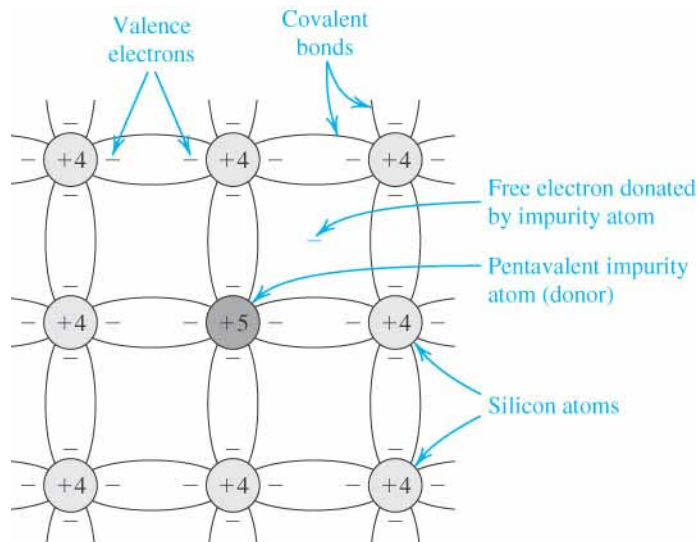
cristallo di silicio intrinseco a 300K
(temperatura ambiente)

$$n_i^2 = BT^3 e^{-E_G / kT} \quad \text{concentrazione intrinseca in un semiconduttore}$$

Per il silicio $n_i \approx 1.5 \cdot 10^{10}$ portatori/cm³

silicio drogato n-type

- drogaggio di tipo n: drogaggio con impurezze pentavalenti (Sb, P, As)
 - Impurezze che introducono livelli vicini alla banda di conduzione danno luogo a un solido in cui domina il trasporto di corrente per elettroni (cariche maggioritarie).
 - le cariche maggioritarie sono gli elettroni e le cariche minoritarie sono le lacune
 - l'atomo di impurezza di tipo n è detto donatore



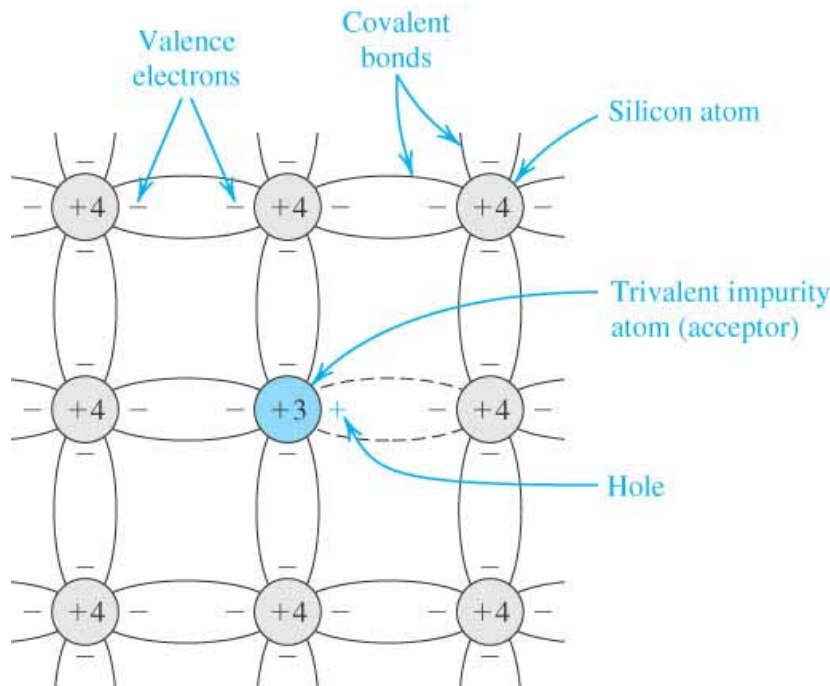
cristallo di silicio drogato con elemento pentavalente (di tipo n)



silicio drogato p-type

drogaggio di tipo p: drogaggio con impurezze trivalenti (B, Ga, In)

- Impurezze che introducono livelli vicini alla banda di valenza danno luogo a un drogaggio in cui domina il trasporto di corrente per lacune (cariche maggioritarie)
- l'atomo di impurezza di tipo p è detto accettore



cristallo di silicio drogato con elemento trivalente (di tipo p)



Corrente di drift

Sotto l'azione di un campo elettrico esterno E le cariche libere, elettroni e lacune si muovono in verso opposto, ma essendo di carica opposta contribuiscono alla corrente con due contributi dello stesso verso.

$$J_n = q m_n n E = s E \quad [\text{A/cm}^2]$$

$$J_p = q m_p p E = s E \quad [\text{A/cm}^2]$$

Dove:

m_n la mobilità degli elettroni, e m_p la mobilità delle lacune;

n e p numero di elettroni e lacune per cm^3 rispettivamente;

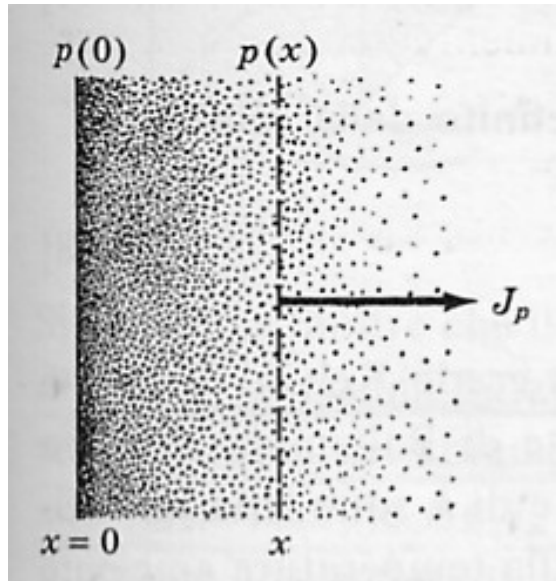
E il campo elettrico applicato in V/cm ;

q la carica dell'elettrone = $|1.6 \times 10^{-19}| \text{ C}$

s la conducibilità del materiale

Questa densità di corrente origina la corrente di conduzione, analoga a quella presente nei metalli

Corrente di diffusione



Dovuta alla presenza di un gradiente di concentrazione dei portatori di carica.
proporzionale alla differenza di concentrazione, tramite la costante di diffusione $D_{n,p}$.

$$J_n = qD_n \frac{dn}{dx} \text{ [A/cm}^2\text{]}$$

$$J_p = -qD_p \frac{dp}{dx} \text{ [A/cm}^2\text{]}$$

I coefficienti D , m sono legati tra di loro dalle relazioni di Einstein:

k è la costante di Boltzmann
 T la temperatura assoluta in kelvin.

$$D_p = \frac{kT}{q} \mu_p = V_T m_p$$

$$D_n = \frac{kT}{q} \mu_n = V_T m_n$$

Corrente totale

In un semiconduttore è possibile che esistano contemporaneamente sia una differenza di energia potenziale sia una differenza di concentrazione dei portatori di carica.

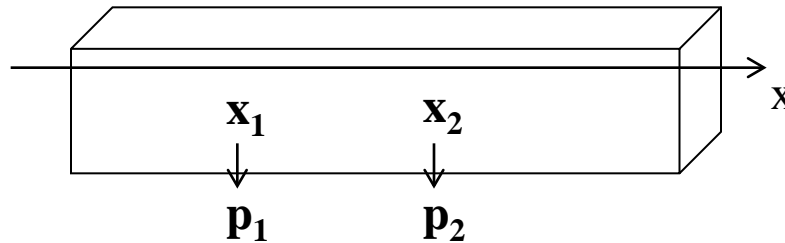
In questo caso la corrente totale delle lacune è somma di una corrente di deriva e di una corrente di diffusione:

$$J_p = qm_p E - qD_p dp/dx$$

Analogamente la corrente totale di elettroni vale:

$$J_n = qm_n E + qD_n dn/dx$$

Potenziale di contatto



$$J_p = qm_p E - qD_p dp/dx$$

Assenza di eccitazioni $J_p = 0$ $qm_p E = qm_p V_T dp/dx$

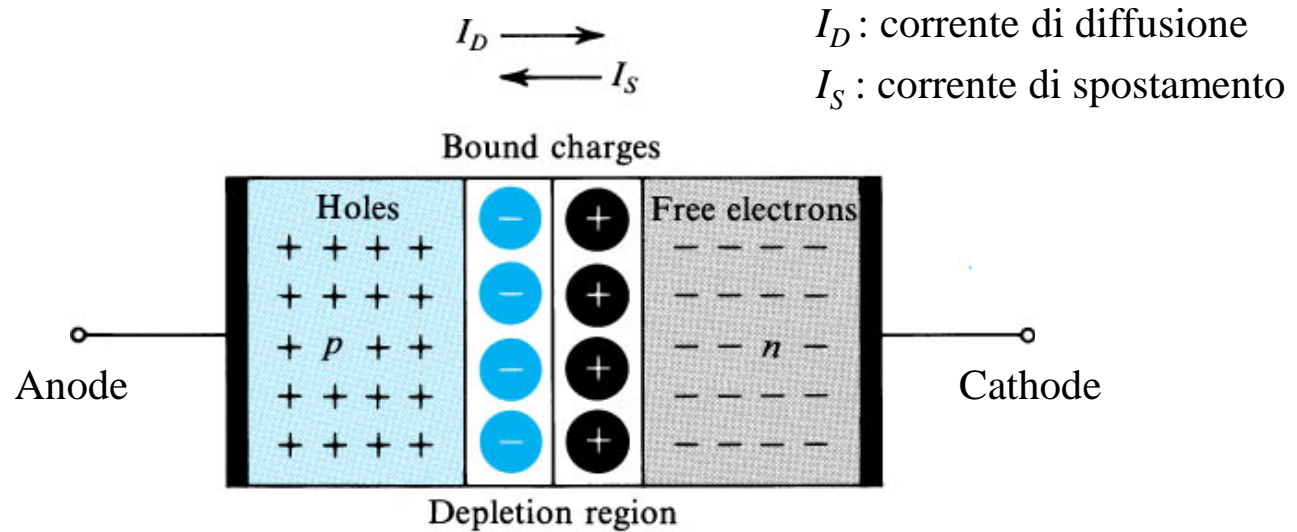
$$E = V_T/p dp/dx = - dV/dx$$

$$dV = V_2 - V_1 = V_0 = V_T \ln p_1/p_2$$

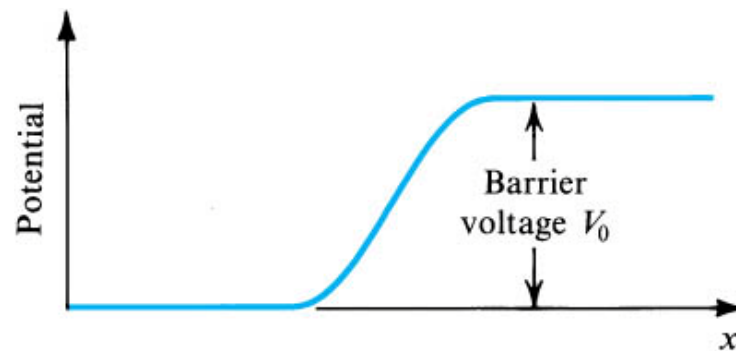
Analogamente la corrente totale di elettroni vale:

$$V_2 - V_1 = V_0 = V_T \ln n_2/n_1$$

Struttura semplificata di un diodo a giunzione: condizioni di circuito aperto



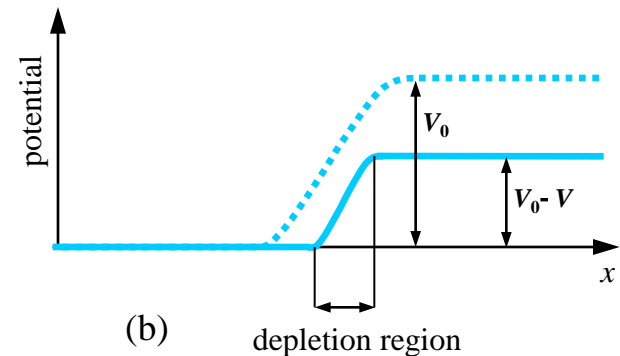
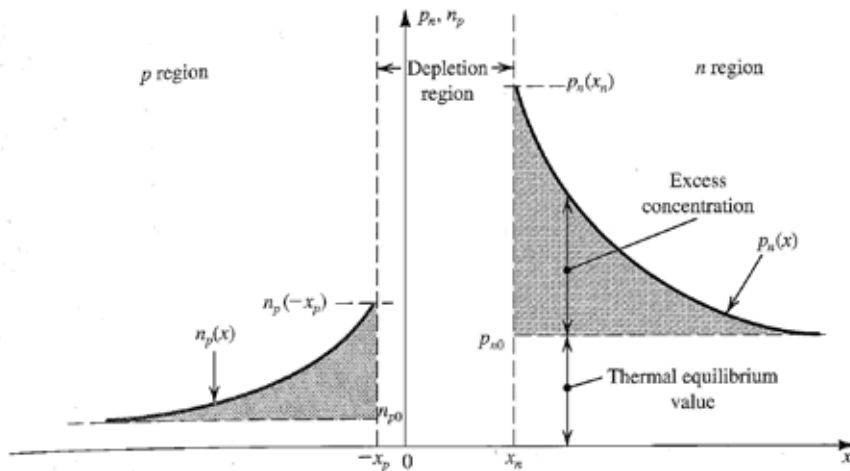
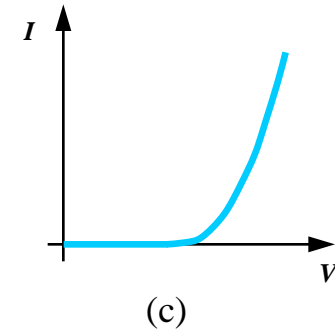
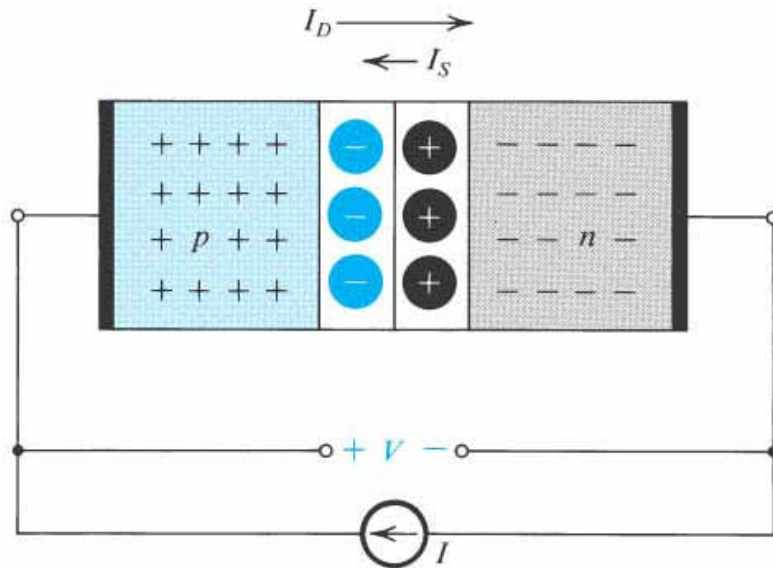
(a)



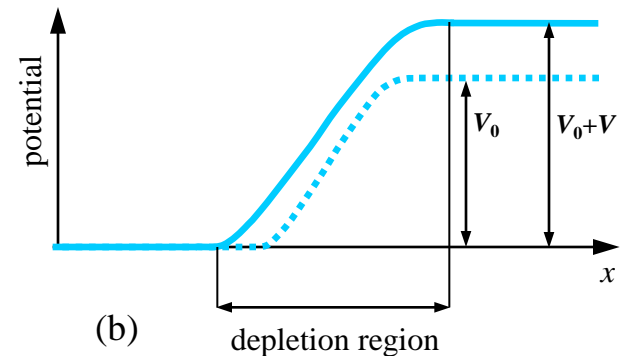
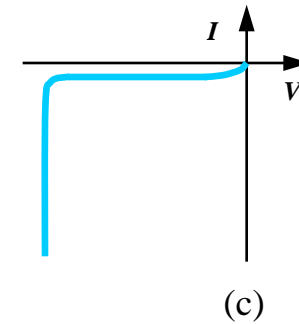
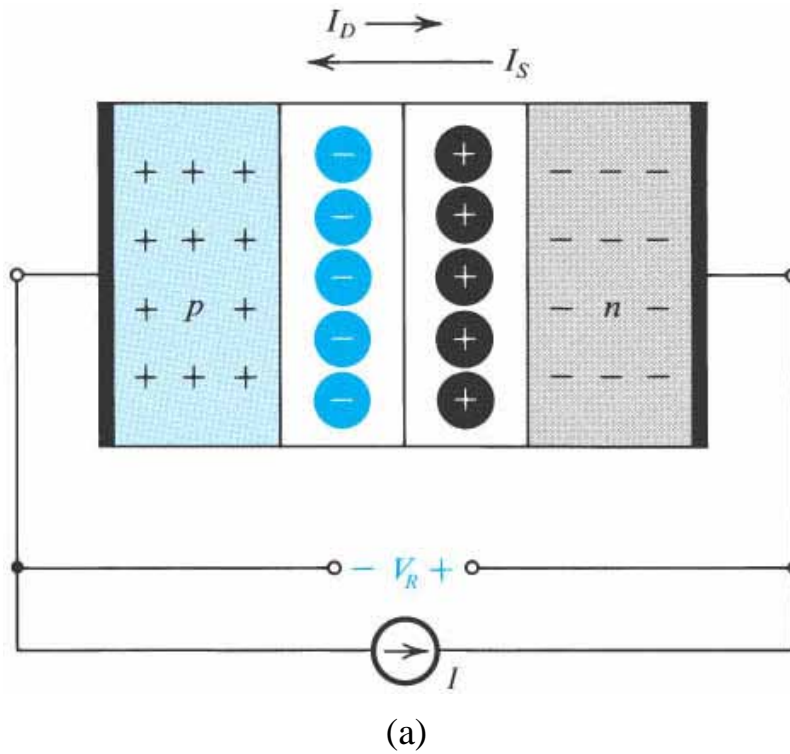
(b)

$$V_0 = V_T \ln \frac{N_A N_D}{n_i^2}$$

Giunzione *pn* in polarizzazione diretta



Giunzione *pn* in polarizzazione inversa



Caratteristica i-v del diodo reale (1/2)

$$i_D = I_S \left(e^{v_D / n V_T} - 1 \right) \quad \text{equazione del diodo di Shockley}$$

I_S : corrente inversa di saturazione del diodo (10^{-6} , 10^{-15} A)

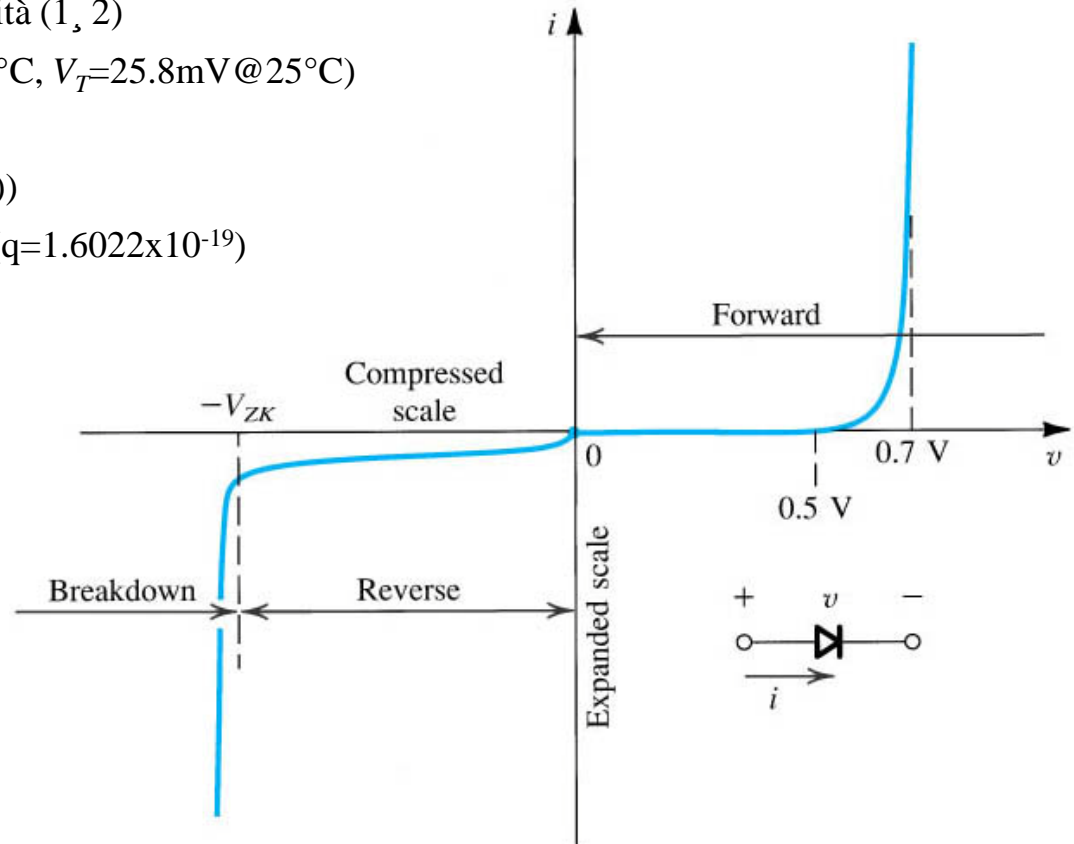
n : coefficiente di emissione o fattore di idealità (1, 2)

$V_T = kT/q$: tensione termica ($V_T = 25.2 \text{ mV} @ 20^\circ\text{C}$, $V_T = 25.8 \text{ mV} @ 25^\circ\text{C}$)

k : costante di Boltzmann ($k = 1.38 \times 10^{-23} \text{ J/K}$)

T : temperatura assoluta in kelvin ($273 + T(^{\circ}\text{C})$)

q : valore assoluto della carica dell'elettrone ($q = 1.6022 \times 10^{-19}$)



Caratteristica i-v del diodo reale (2/2)

per $i_D \gg I_S$ $\Rightarrow i_D \approx I_S e^{v_D / nV_T}$

$$\Rightarrow v_D = nV_T \ln \frac{i_D}{I_S}$$

espressione in forma logaritmica di v_D

per $v_D = V_{D1}$ $\Rightarrow I_{D1} \approx I_S e^{V_{D1} / nV_T}$

per $v_D = V_{D2}$ $\Rightarrow I_{D2} \approx I_S e^{V_{D2} / nV_T}$

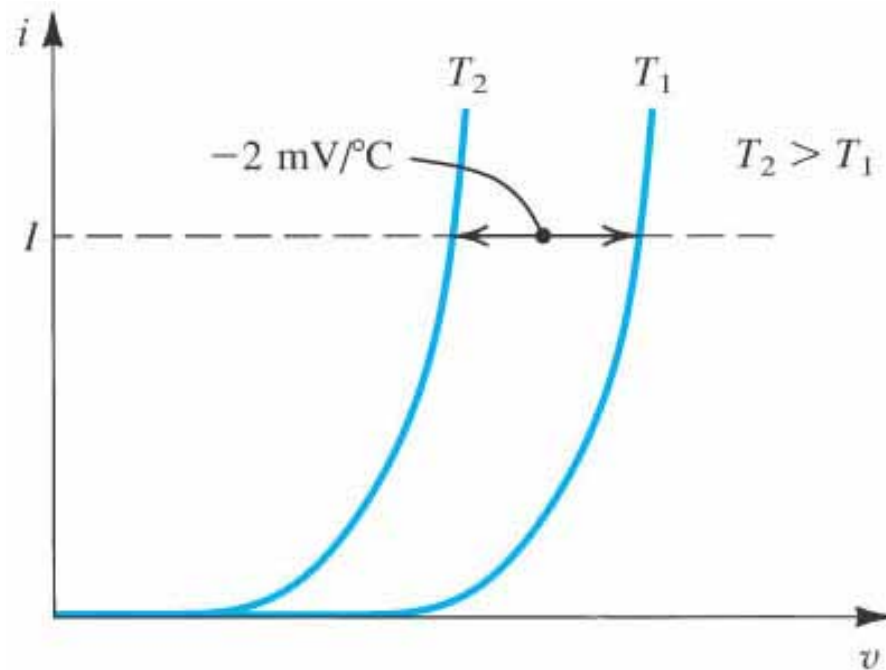
$$\frac{I_{D2}}{I_{D1}} \approx e^{(V_{D2} - V_{D1}) / nV_T}$$

$$V_{D2} - V_{D1} = nV_T \ln \frac{I_{D2}}{I_{D1}}$$

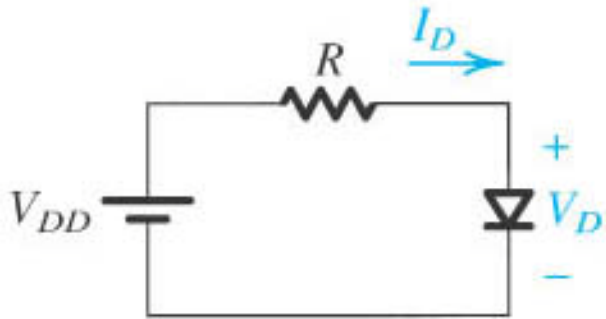
$$V_{D2} - V_{D1} = 2.3 nV_T \log \frac{I_{D2}}{I_{D1}}$$

variando la corrente nel diodo di una decade (cioè di un fattore 10) la tensione ai capi del diodo cambia solo di $2.3nV_T$

Effetti della temperatura

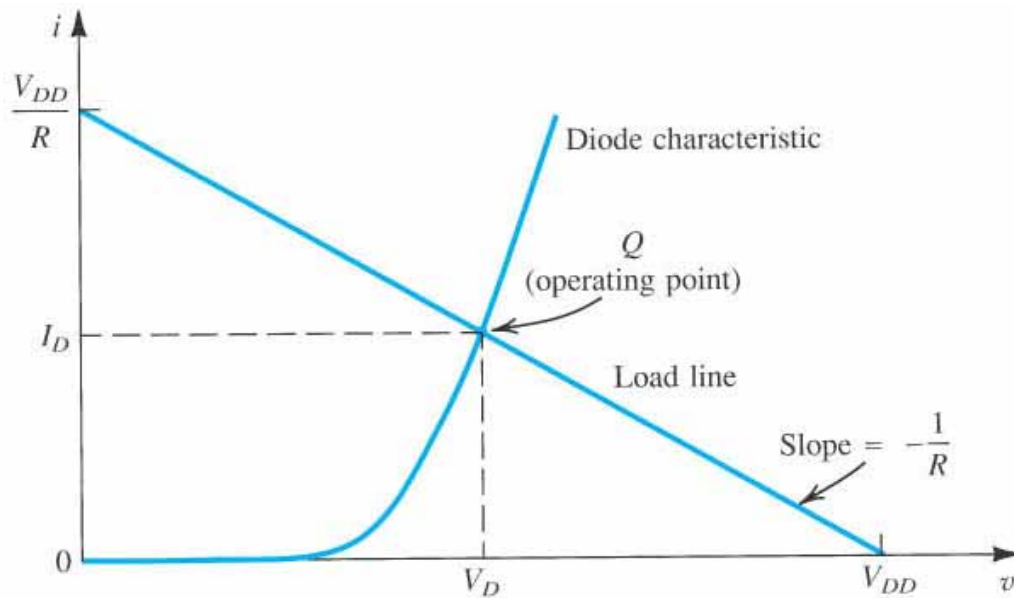


Analisi grafica di circuiti con diodi

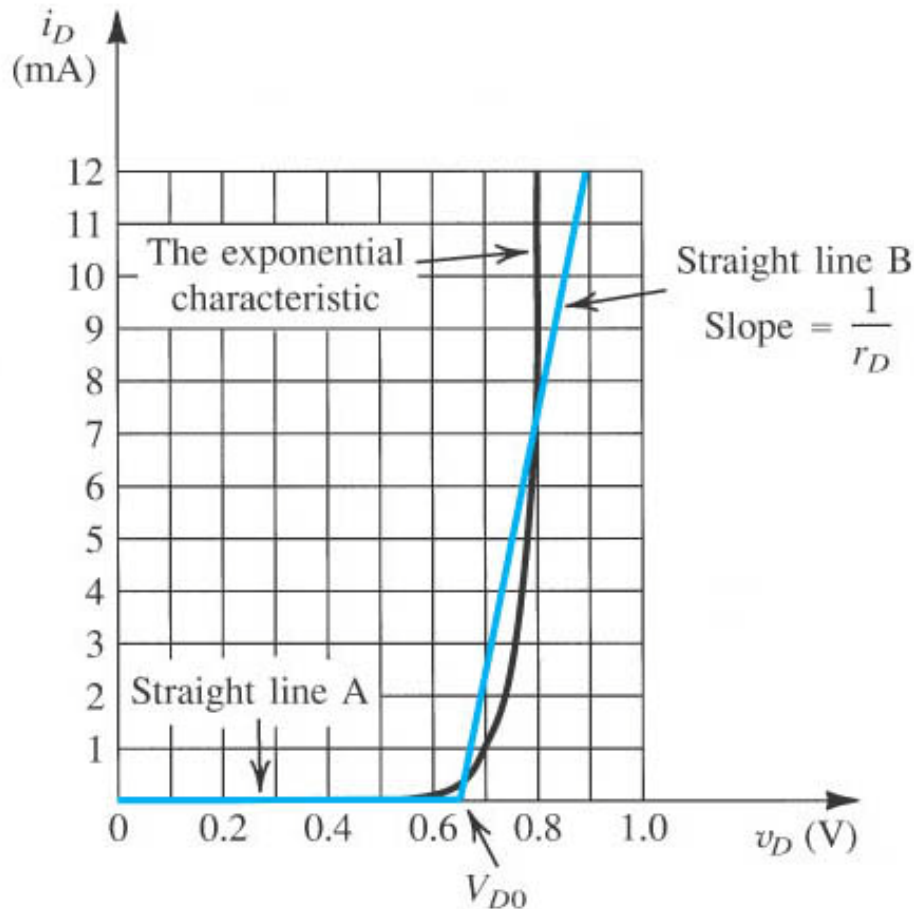


$$I_D @ I_S e^{V_D / nV_T}$$

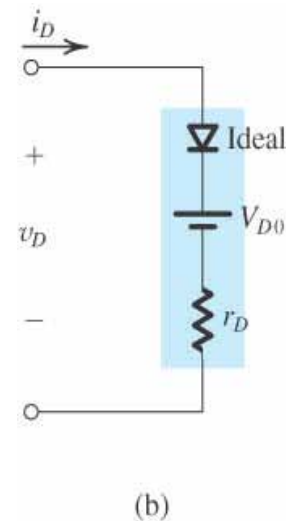
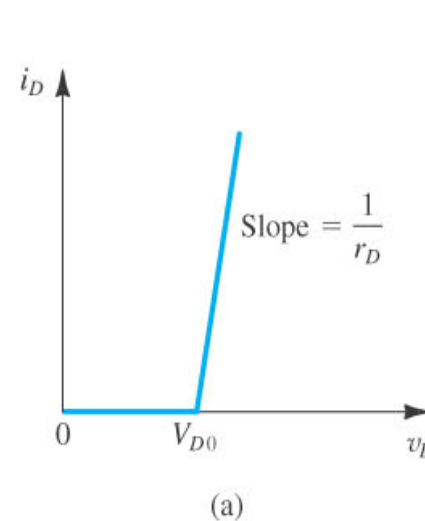
$$I_D = \frac{V_{DD} - V_D}{R}$$



Modello lineare a tratti del diodo



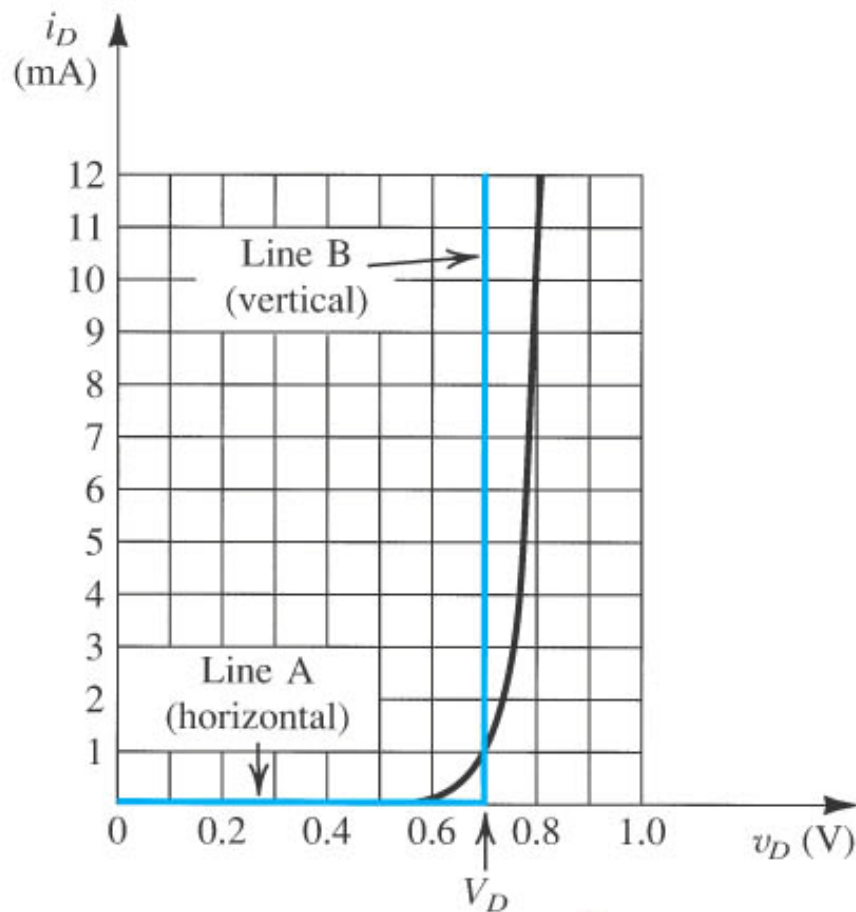
$$\begin{cases} i_D = 0 & \text{per } v_D \leq V_{D0} & \text{retta A} \\ i_D = \frac{v_D - V_{D0}}{r_D} & \text{per } v_D > V_{D0} & \text{retta B} \end{cases}$$



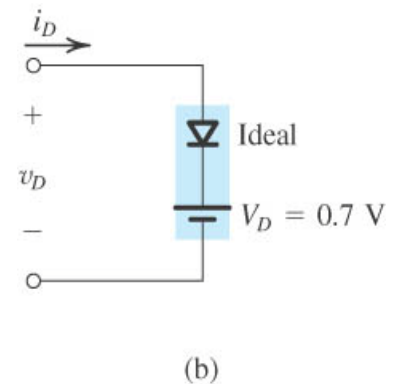
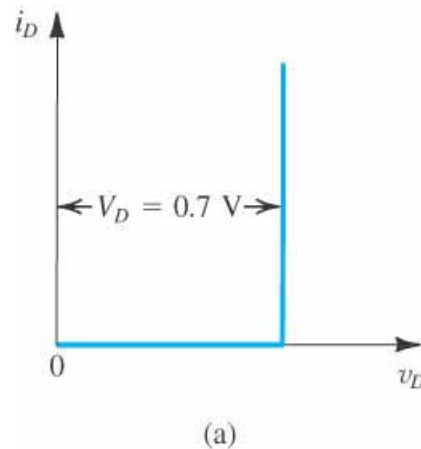
in questo caso $V_{D0} = 0.65 \text{ V}$

$r_D = 20 \text{ } \Omega$

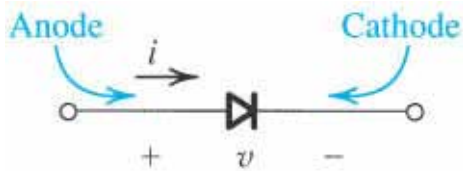
Modello a tensione costante del diodo



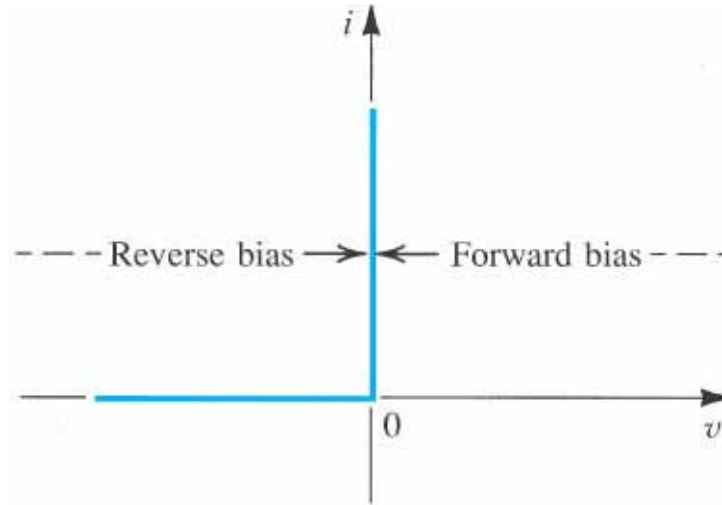
$$\begin{cases} v_D = 0 & \text{per } v_D < V_D \quad \text{retta A} \\ v_D = V_D & \text{per } v_D \geq V_D \quad \text{retta B} \end{cases}$$



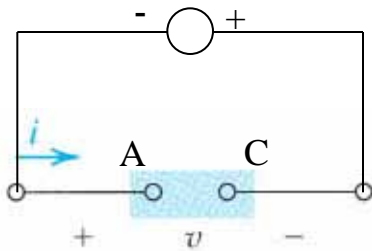
Il diodo ideale



(a)



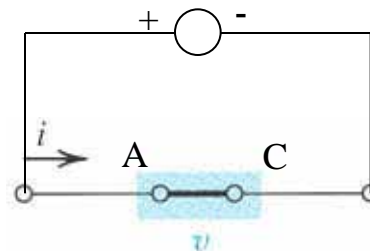
(b)



$$v < 0 \Rightarrow i = 0$$

(c)

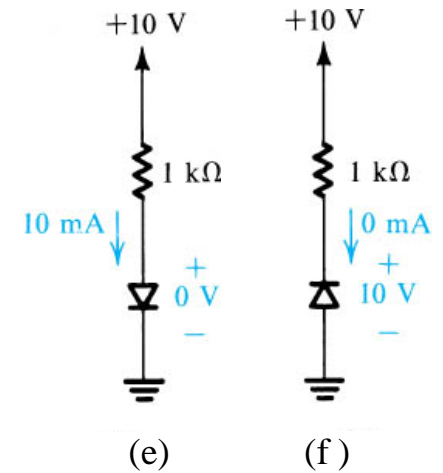
interdizione (stato off)



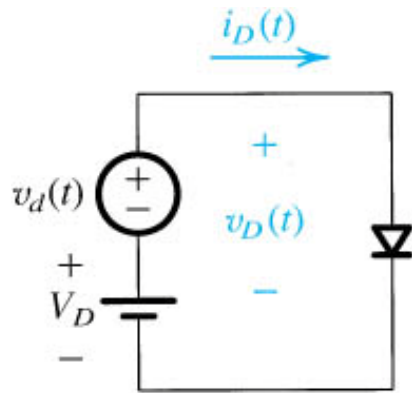
$$i > 0 \Rightarrow v = 0$$

(d)

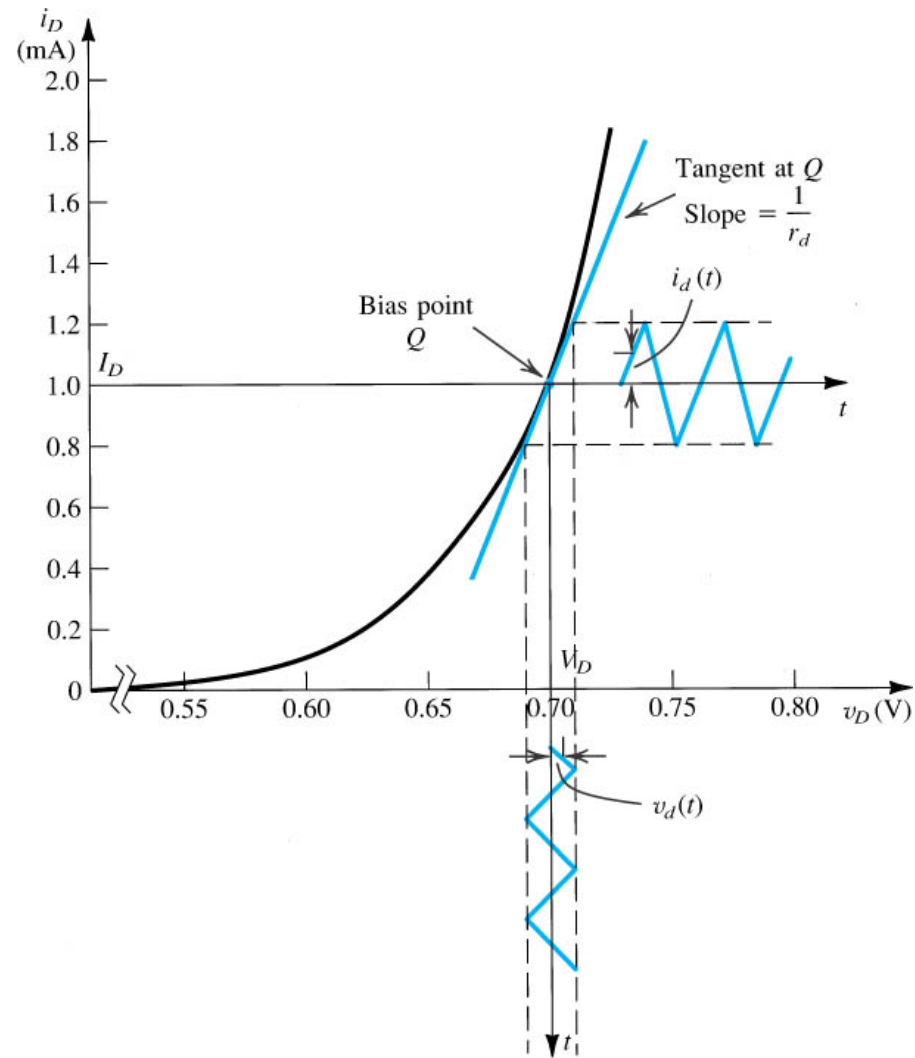
conduzione (stato on)



Modello del diodo per piccoli segnali

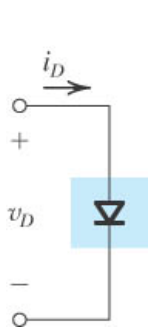
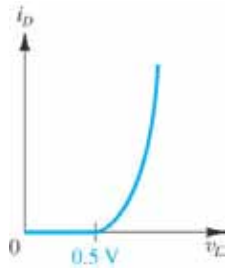


(a)



(b)

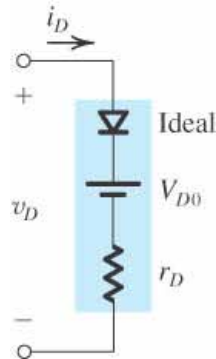
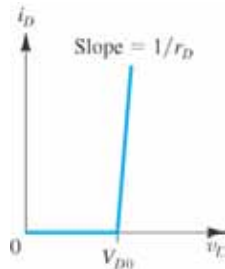
Modelli della caratteristica diretta del diodo



$$i_D = I_S e^{v_D / nV_T}$$

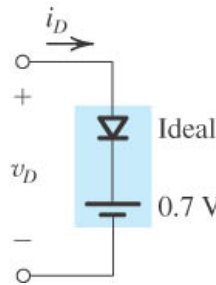
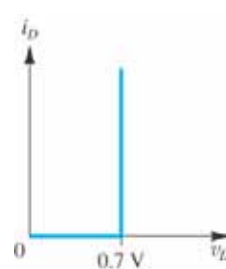
$$v_D = 2.3nV_T \log \frac{i_D}{I_S}$$

$$V_{D2} - V_{D1} = nV_T \ln \frac{I_{D2}}{I_{D1}}$$



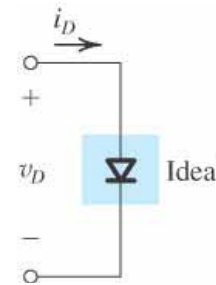
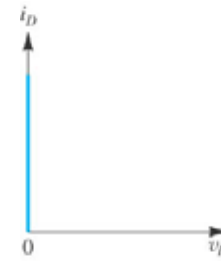
$$v_D < V_{D0} \Rightarrow i_D = 0$$

$$v_D \geq V_{D0} \Rightarrow i_D = \frac{v_D - V_{D0}}{r_D}$$



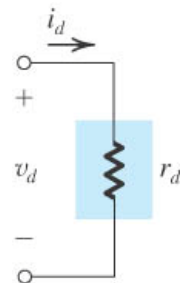
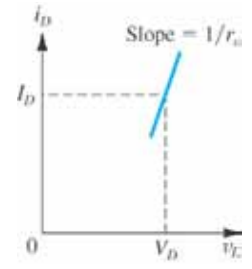
$$v_D < V_D \Rightarrow v_D = 0$$

$$i_D > 0 \Rightarrow v_D = V_D = 0.7$$



$$v_D < V_D \Rightarrow v_D = 0$$

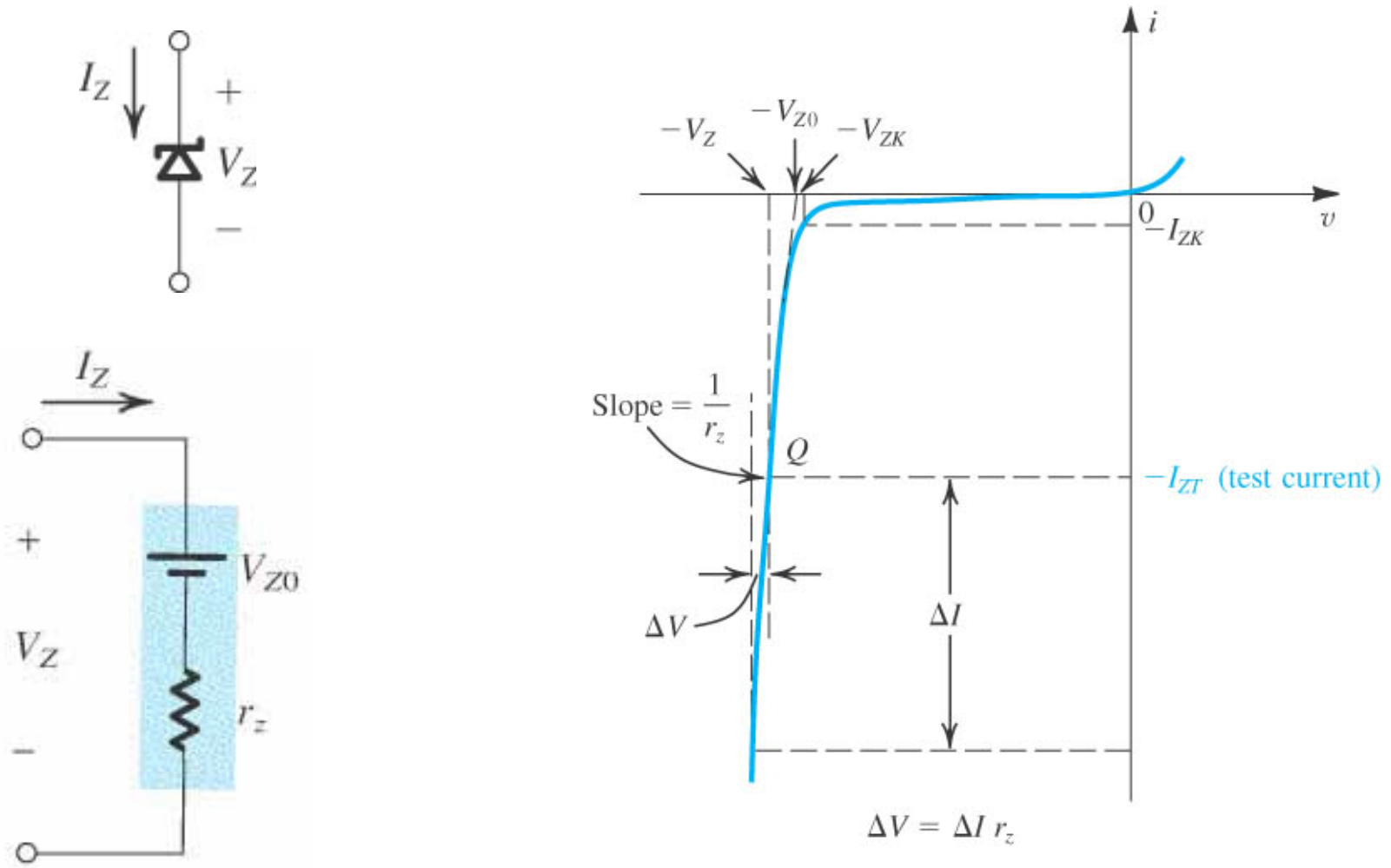
$$i_D > 0 \Rightarrow v_D = 0$$



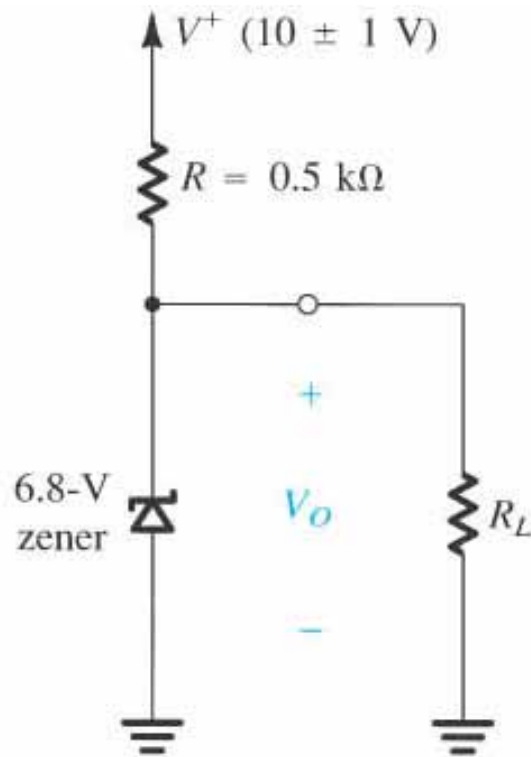
$$i_d = v_d / r_d$$

$$r_d = nV_T / I_D$$

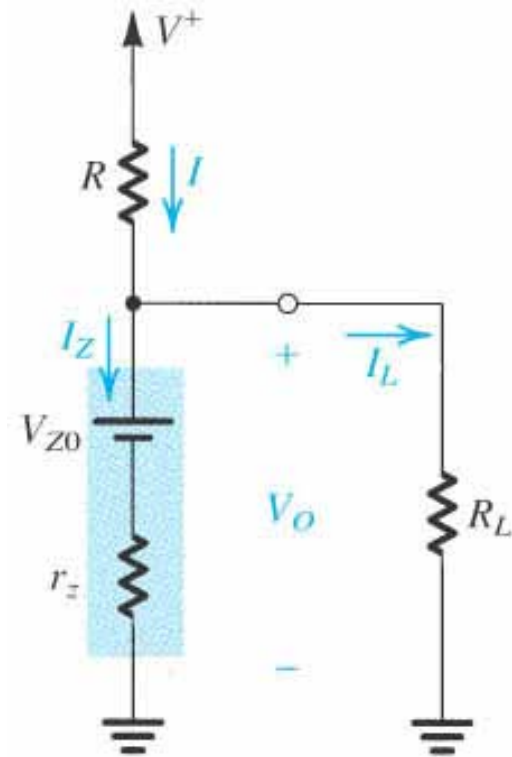
Diodo Zener



Regolatore di tensione con Zener (Es. 3.8)

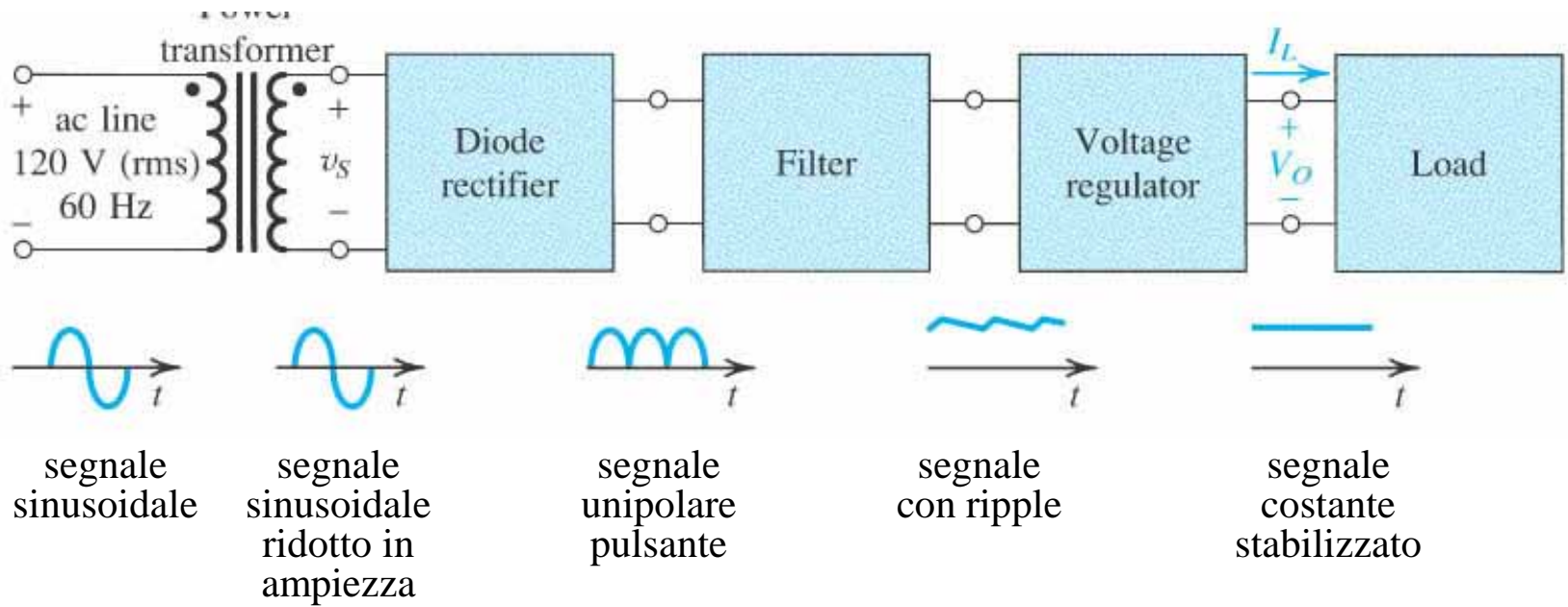


(a)

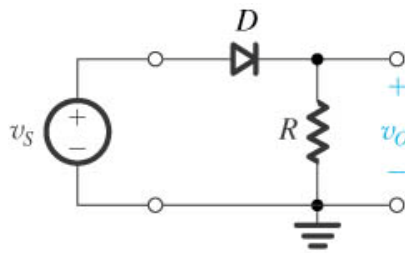


(b)

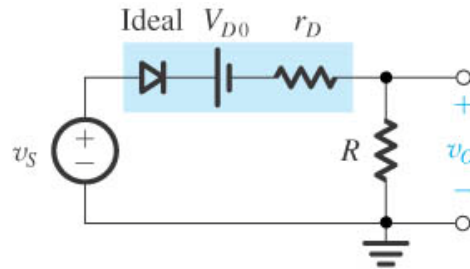
Diagramma a blocchi di un alimentatore in continua



Raddrizzatore a singola semionda



(a)

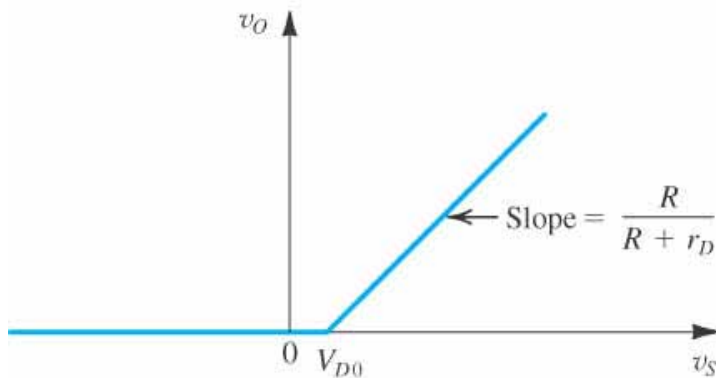


(b)

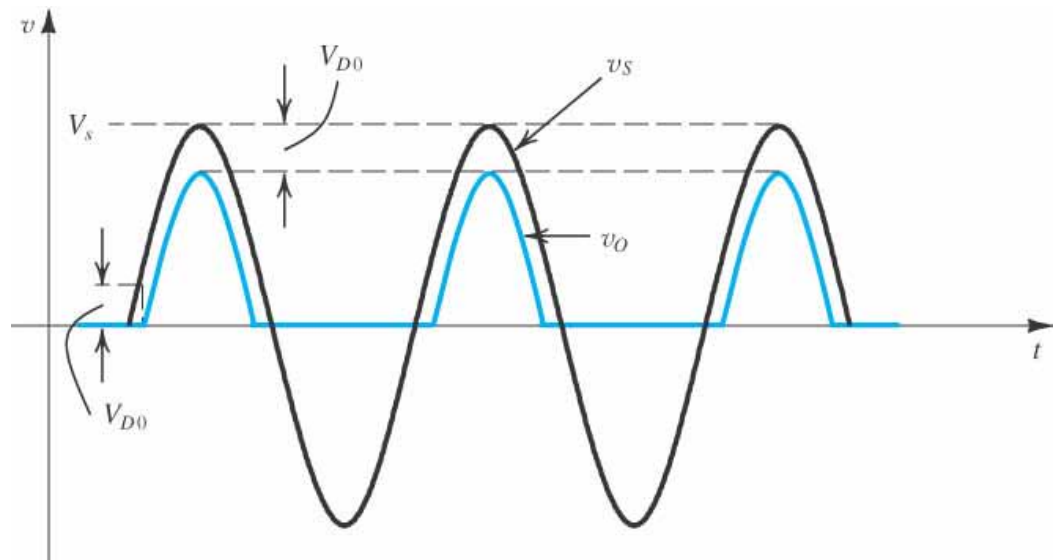
$$\begin{cases} v_O = 0 & \text{per } v_S \leq V_{D0} \\ v_O = (v_S - V_{D0}) \frac{R}{R + r_D} & \text{per } v_S > V_{D0} \end{cases}$$

Per $r_D \ll R$ $\Rightarrow v_O \approx v_S - V_{D0}$

$$\text{PIV} = V_s$$

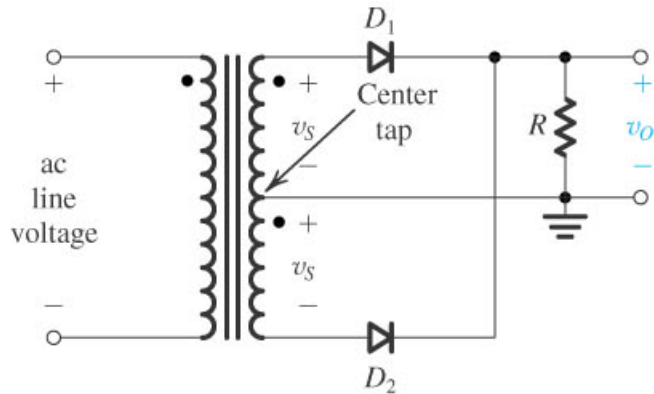


(c)



(d)

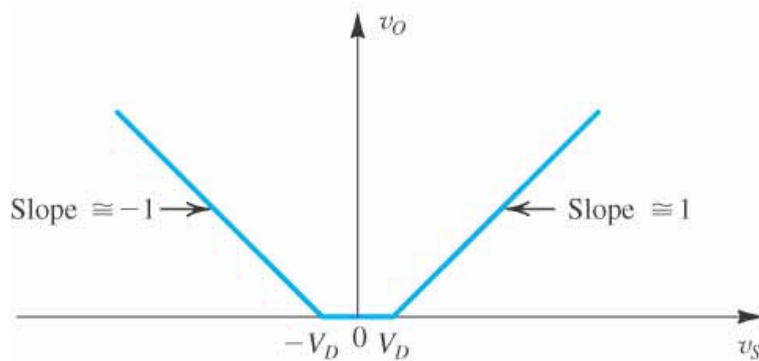
Raddrizzatore a doppia semionda



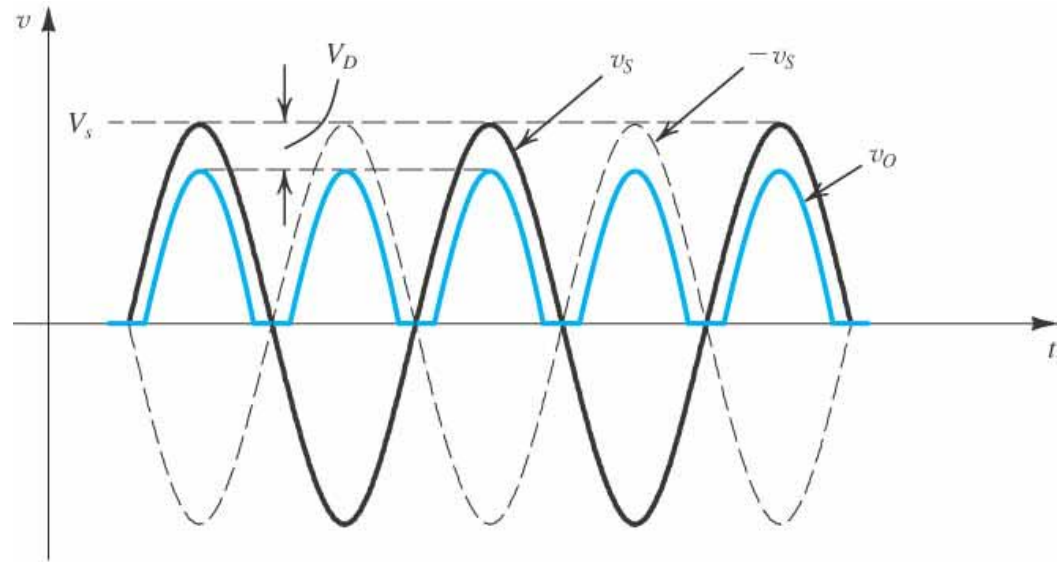
(a)

Per $r_D \ll R \Rightarrow v_O \approx v_S - V_{D0}$

$$\text{PIV} = 2V_s - V_{D0}$$

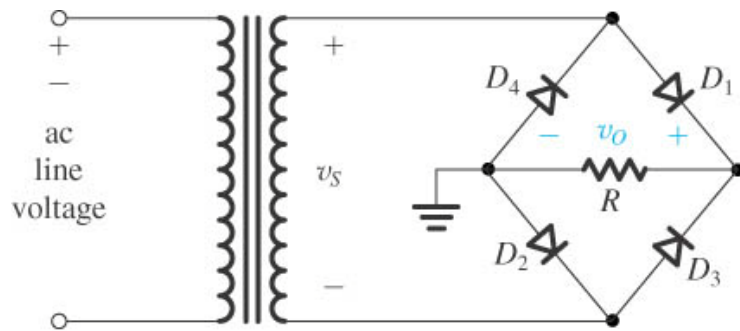


(b)



(c)

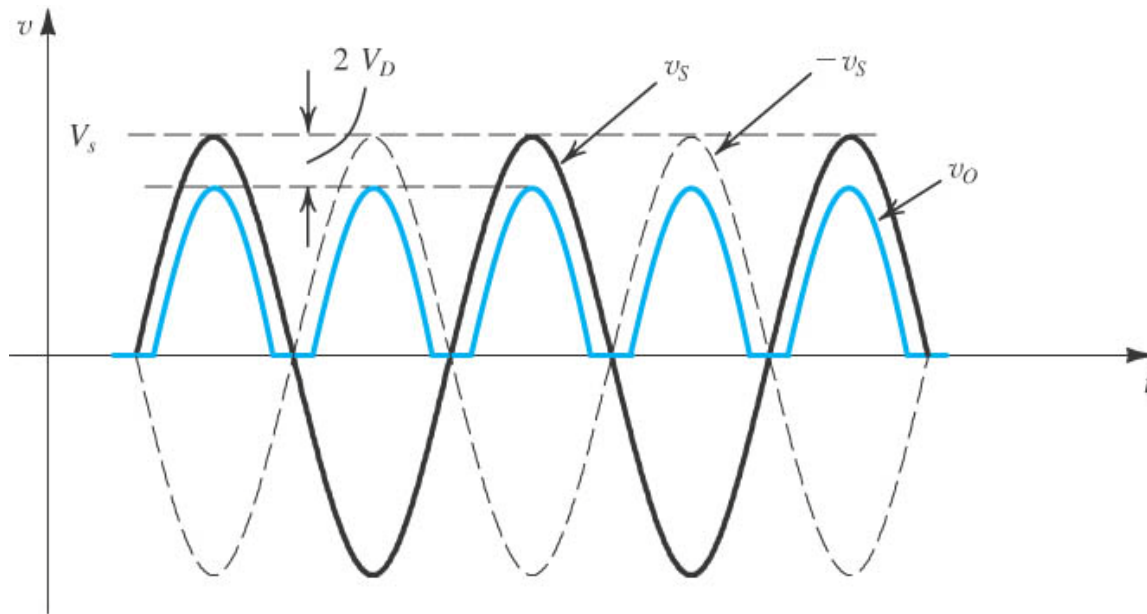
Raddrizzatore a ponte



(a)

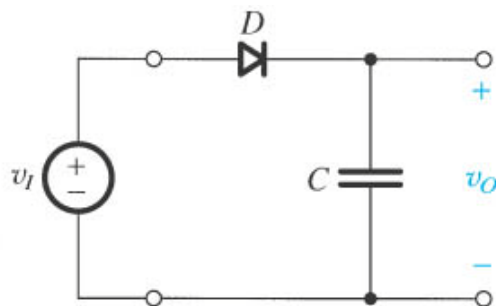
Per $r_D \ll R$ \triangleright $v_o \approx v_s - 2V_{D0}$

$$\text{PIV} = V_s - V_{D0}$$

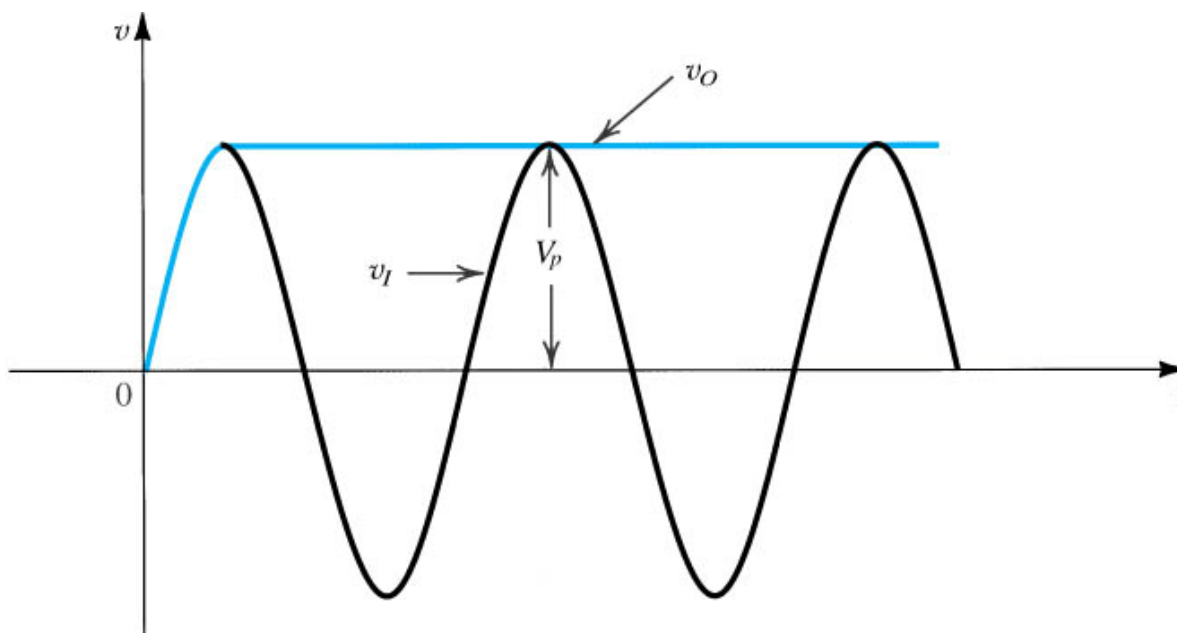


(b)

Concetto di filtro capacitivo

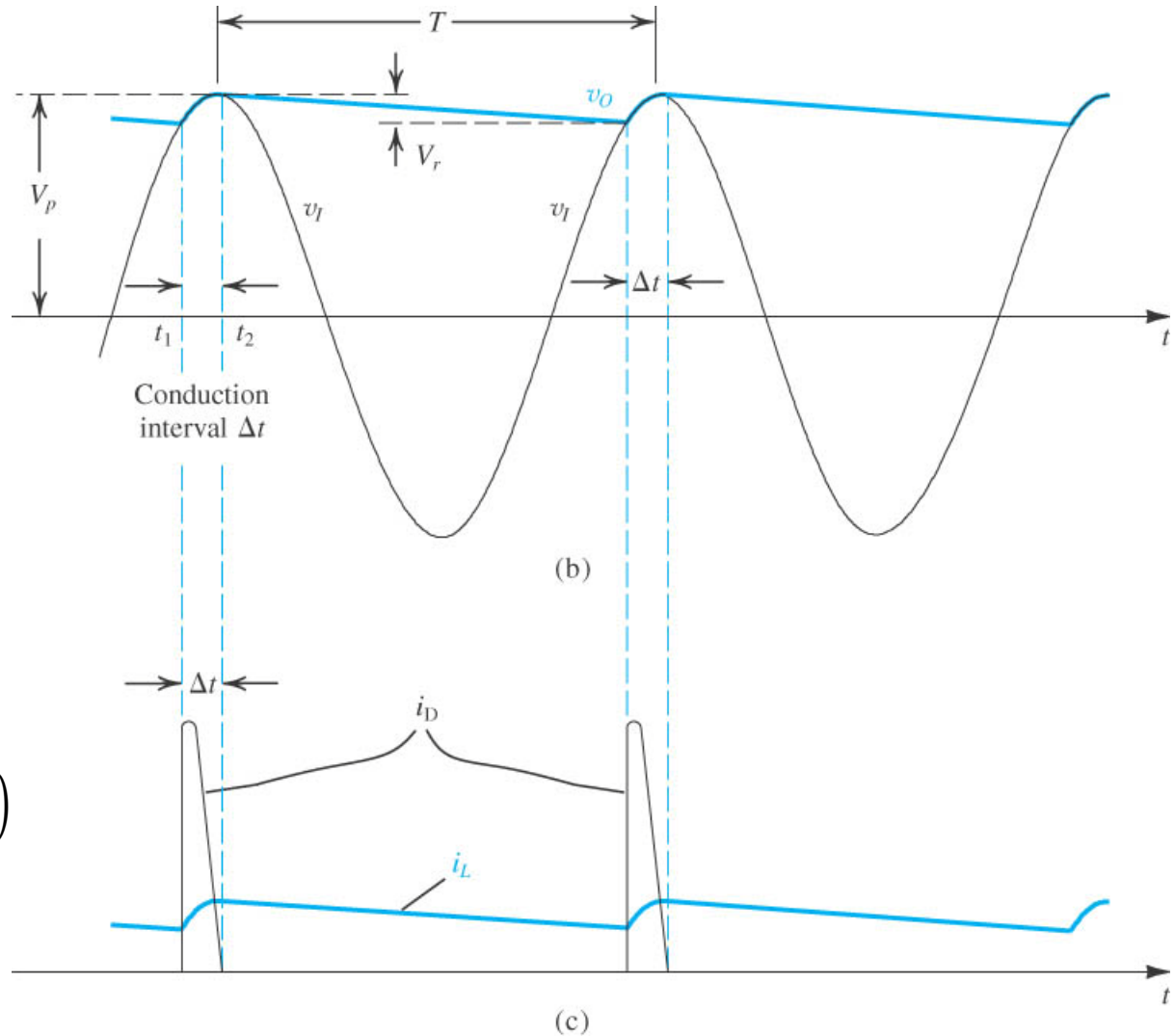
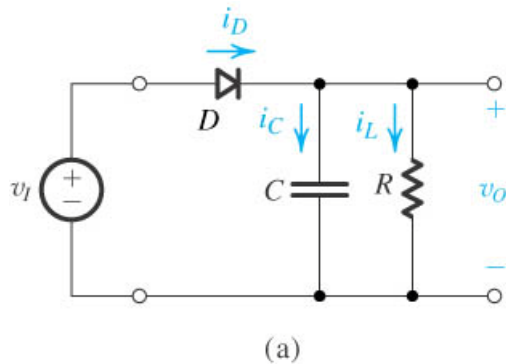


(a)



(b)

Raddrizzatore con condensatore di filtro

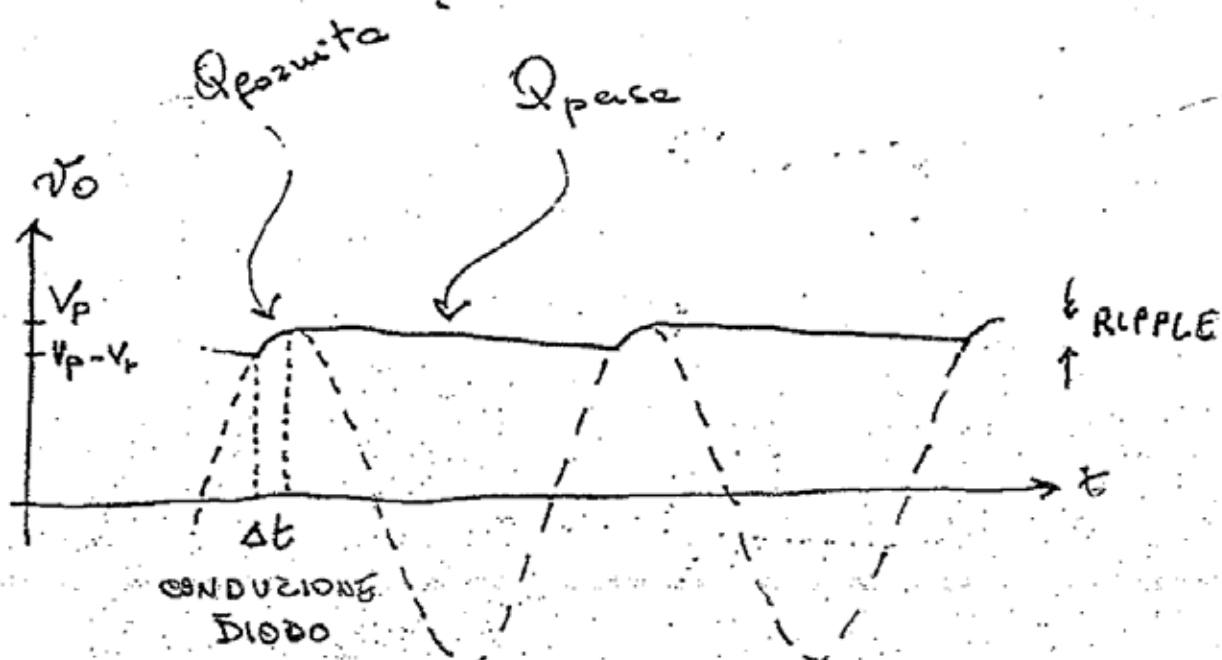


$$V_r = \frac{V_p}{fRC}$$

$$i_{Dav} = I_L \left(1 + \rho \sqrt{2V_p/V_r} \right)$$

$$i_{Dmax} = I_L \left(1 + 2\rho \sqrt{2V_p/V_r} \right)$$

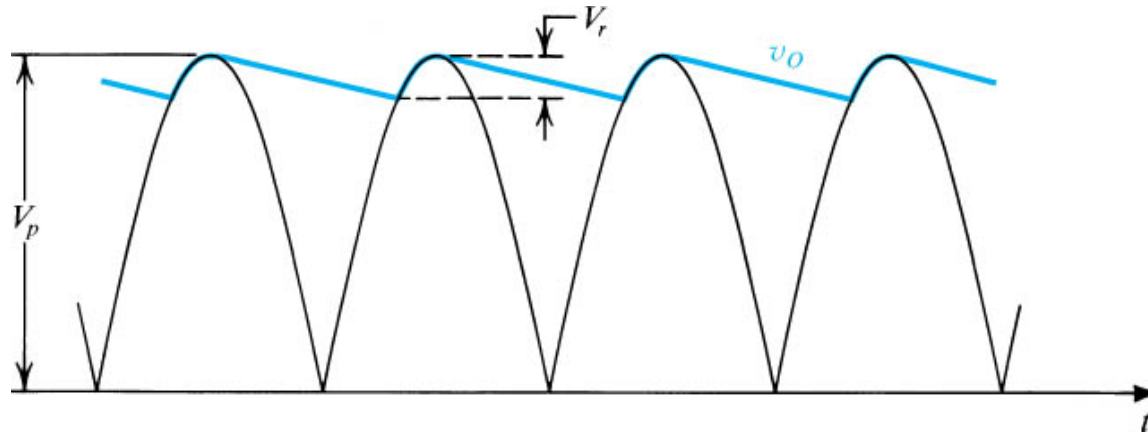
Raddrizzatore con condensatore di filtro



- Durante $T - \Delta t$ (interdizione diodo)
- Durante Δt (conduzione diodo)

$$Q_{fornita} / \Delta t \equiv Q_{presa} / (T - \Delta t)$$

Raddrizzatore di picco a doppia semionda



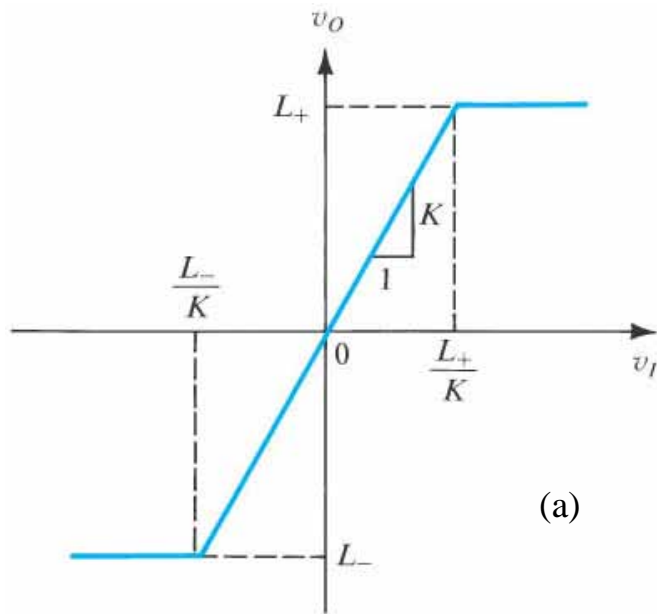
$$V_r = \frac{V_p}{2fRC}$$

$$i_{Dav} = I_L \left(1 + \rho \sqrt{V_p/V_r} \right)$$

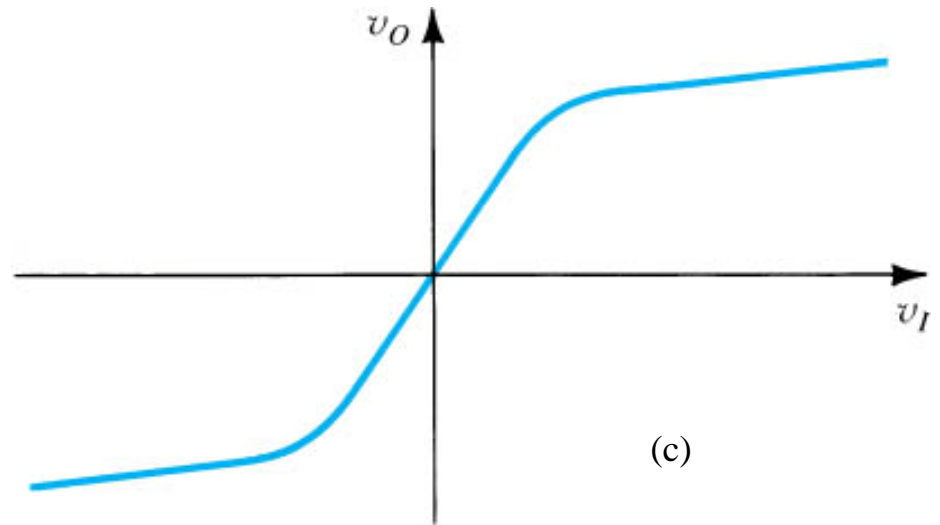
$$i_{Dmax} = I_L \left(1 + 2\rho \sqrt{2V_p/V_r} \right)$$



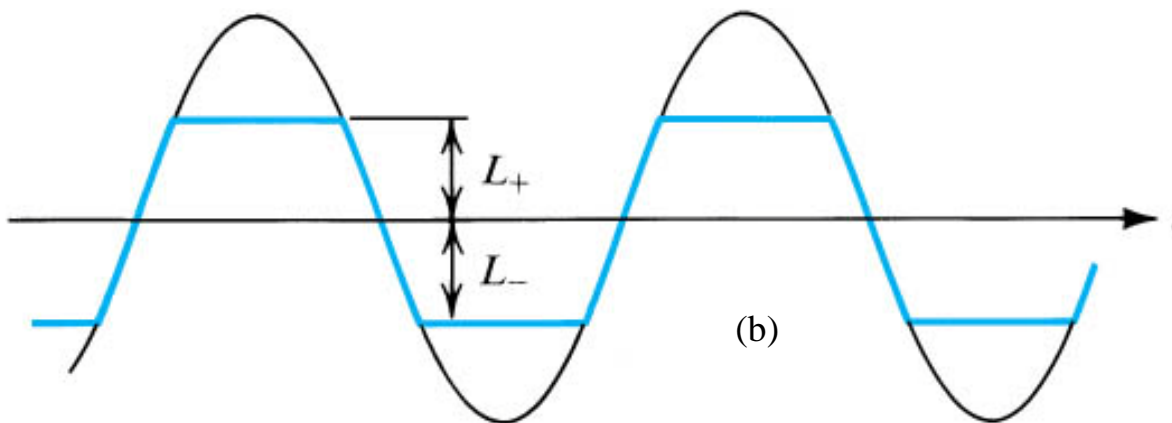
Circuiti limitatori



(a)

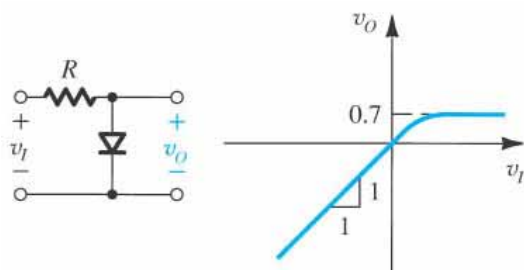


(c)

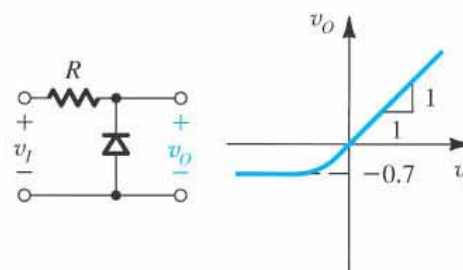


(b)

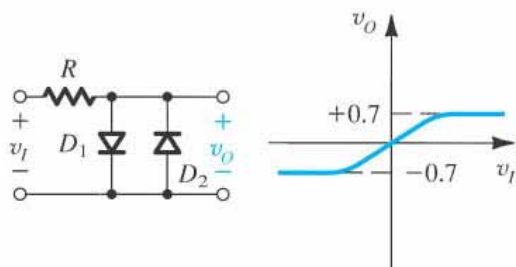
Semplici circuiti limitatori



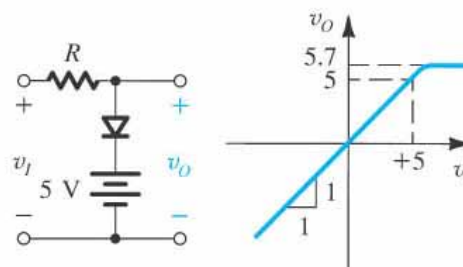
(a)



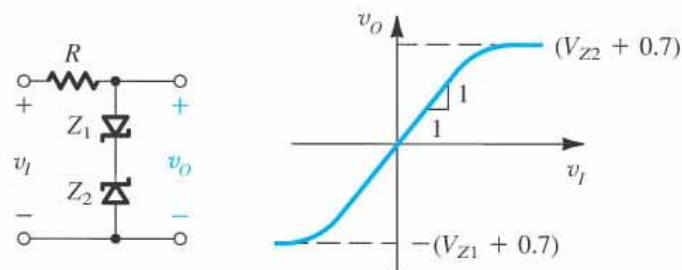
(b)



(c)

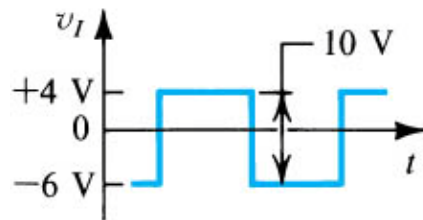


(d)

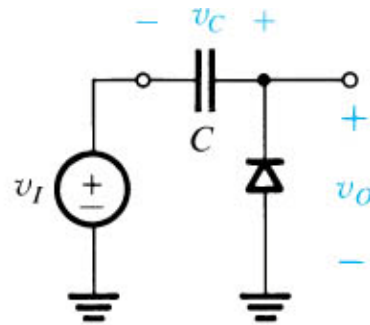


(e)

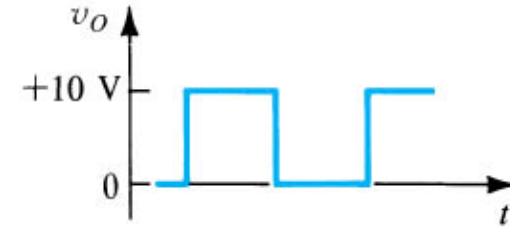
Circuiti di aggancio



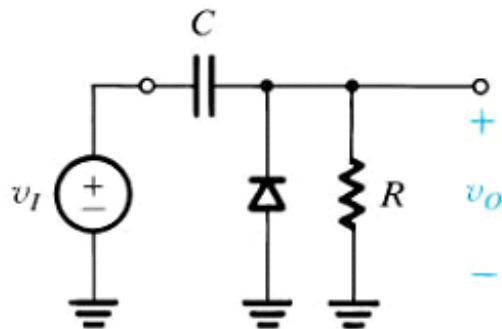
(a)



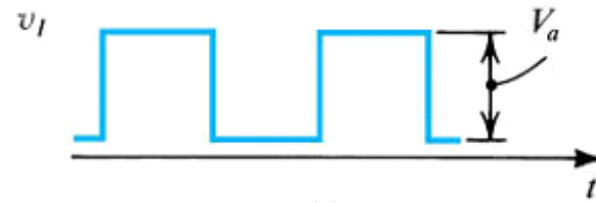
(b)



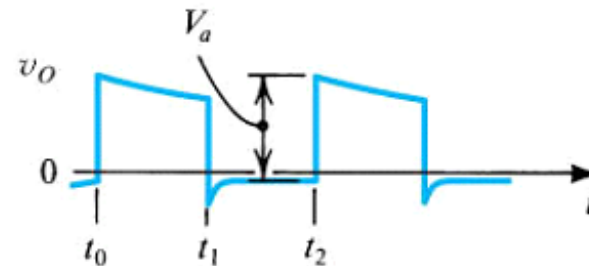
(c)



(d)

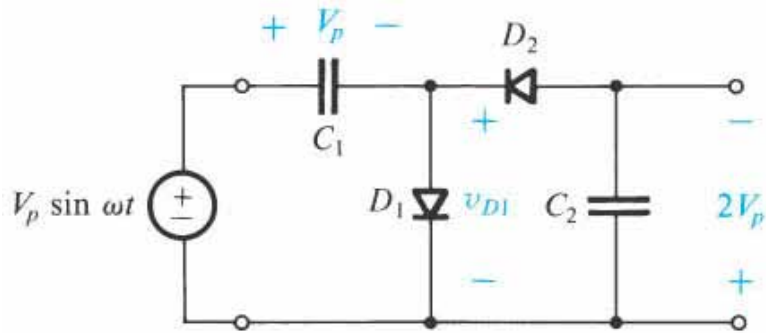


(e)

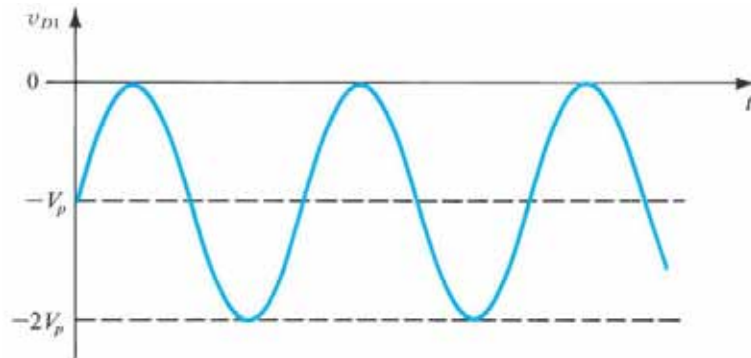


(f)

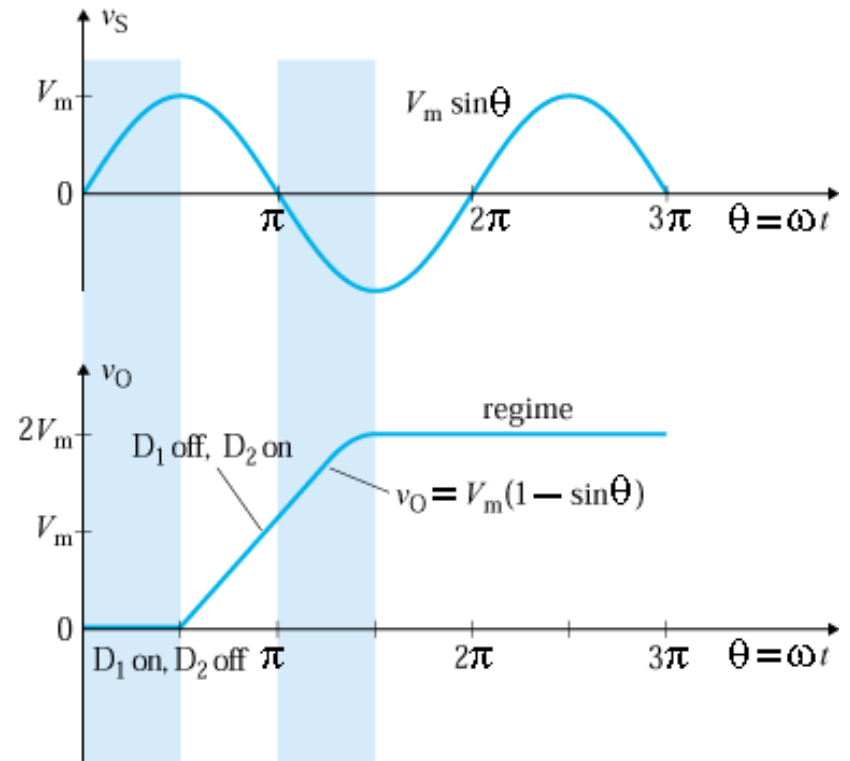
Duplicatore di tensione



(a)



(b)



(con $V_m = V_p$)