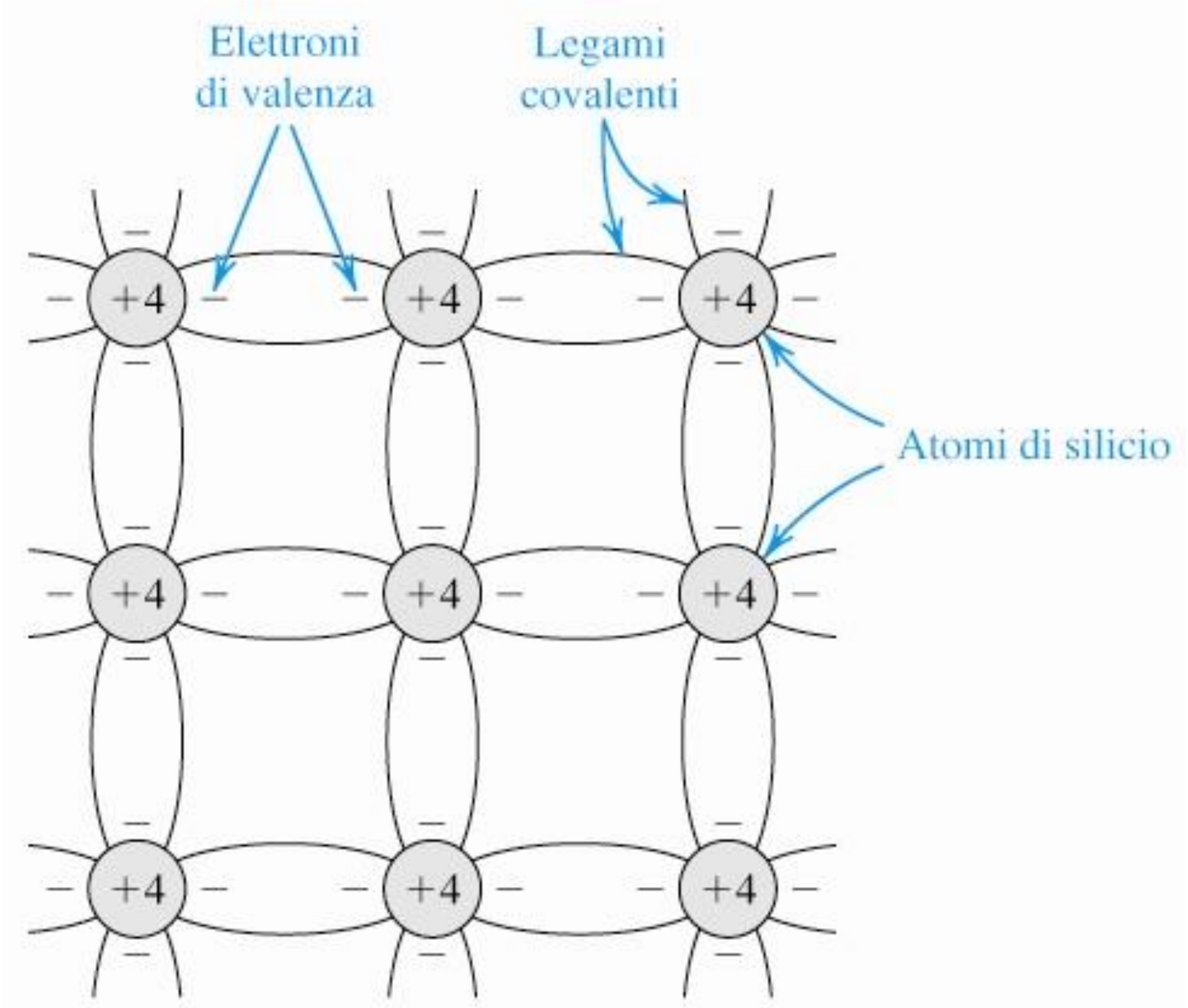
A.A. 2021-2022

Elementi di Elettronica (INF)

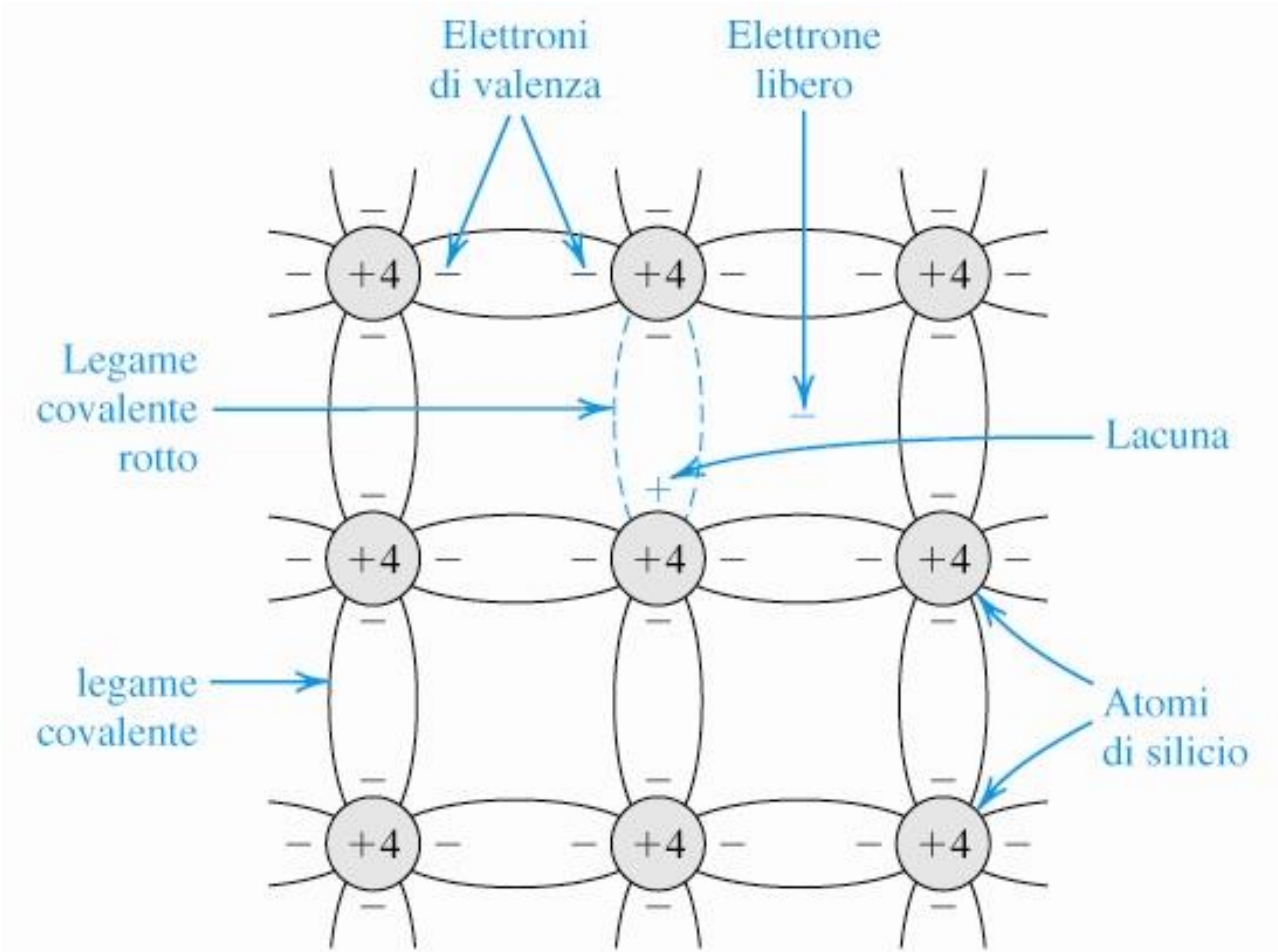
Prof. Paolo Crippa

Diodo

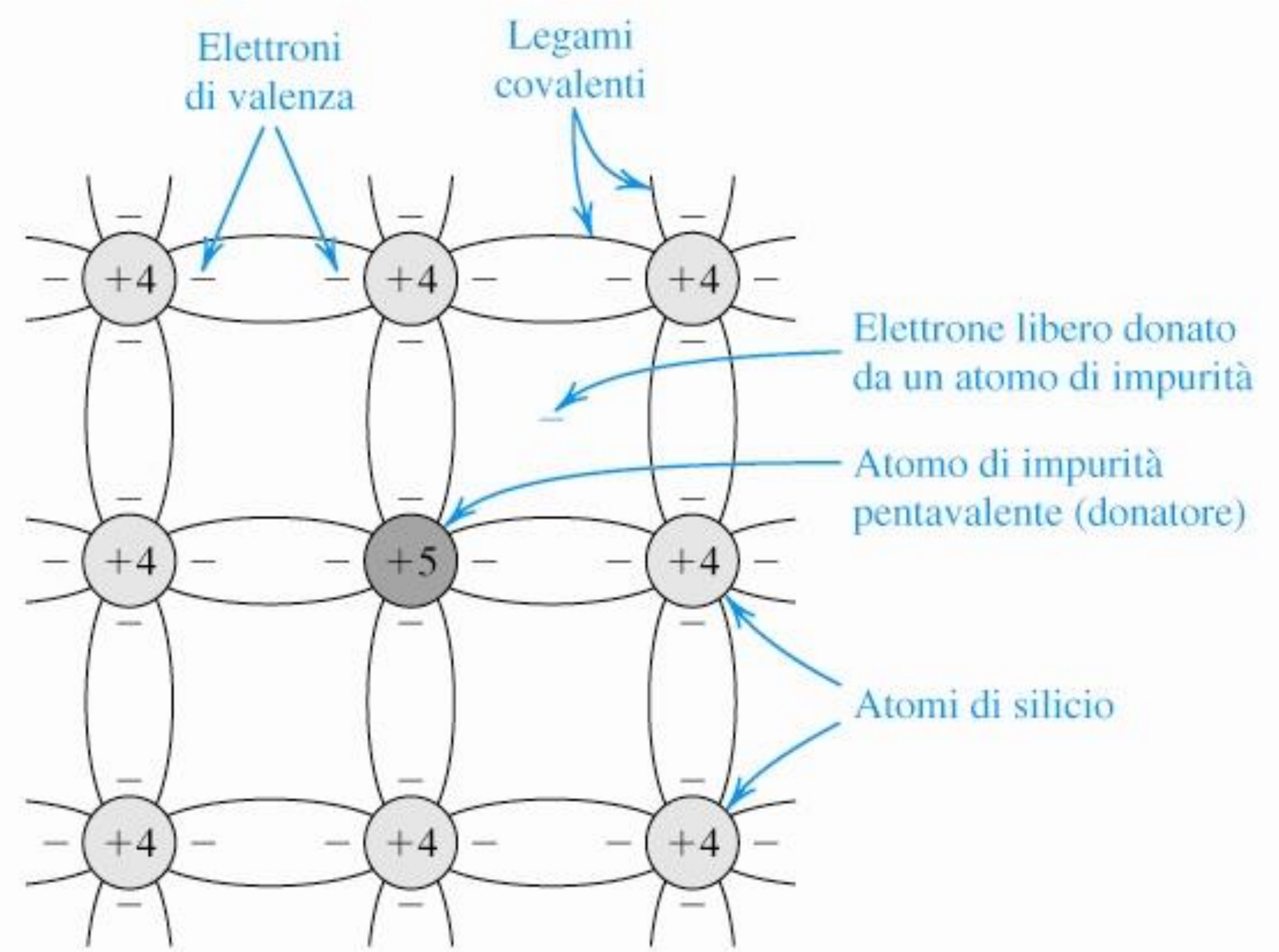
Il Silicio


Elettroni di valenza
Legami covalenti
Atomi di silicio
+4
+4
+4
+4
+4
+4
+4
+4
+4

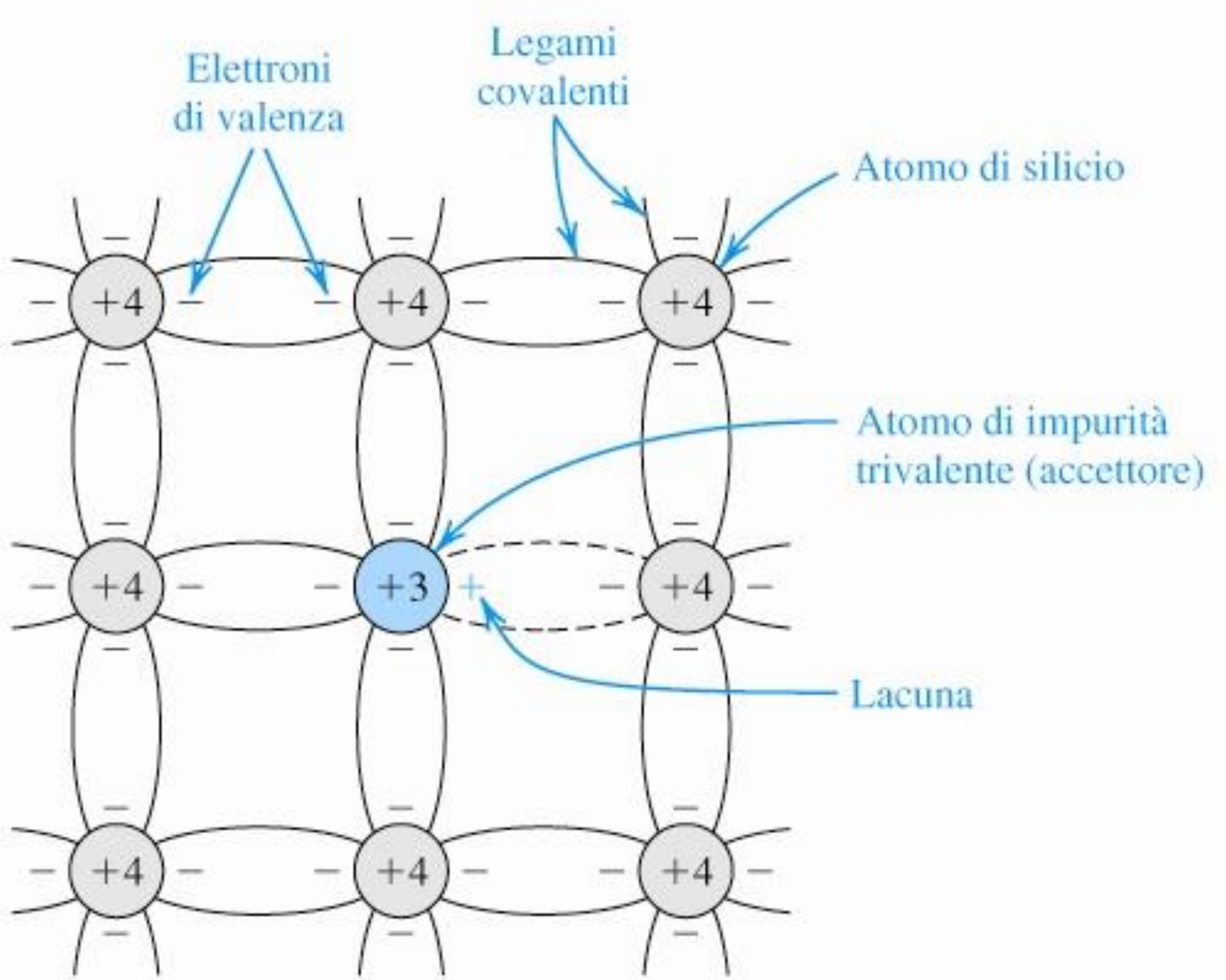
Il Silicio


Elettroni
di valenza
Elettrone
libero
Legame
covalente
rotto
Lacuna
legame
covalente
Atomi
di silicio
+4

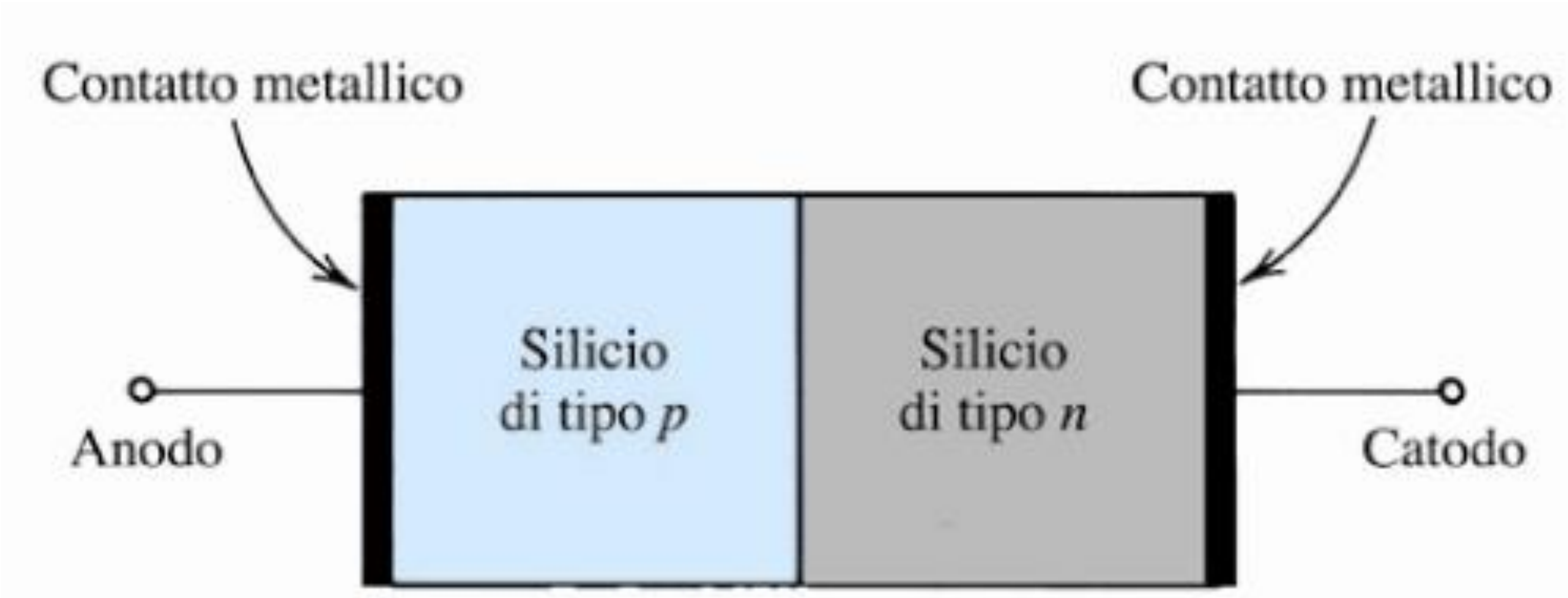
Il Silicio


Elettroni di valenza
Legami covalenti
+4
+5
Elettrone libero donato da un atomo di impurità
Atomo di impurità pentavalente (donatore)
Atomi di silicio

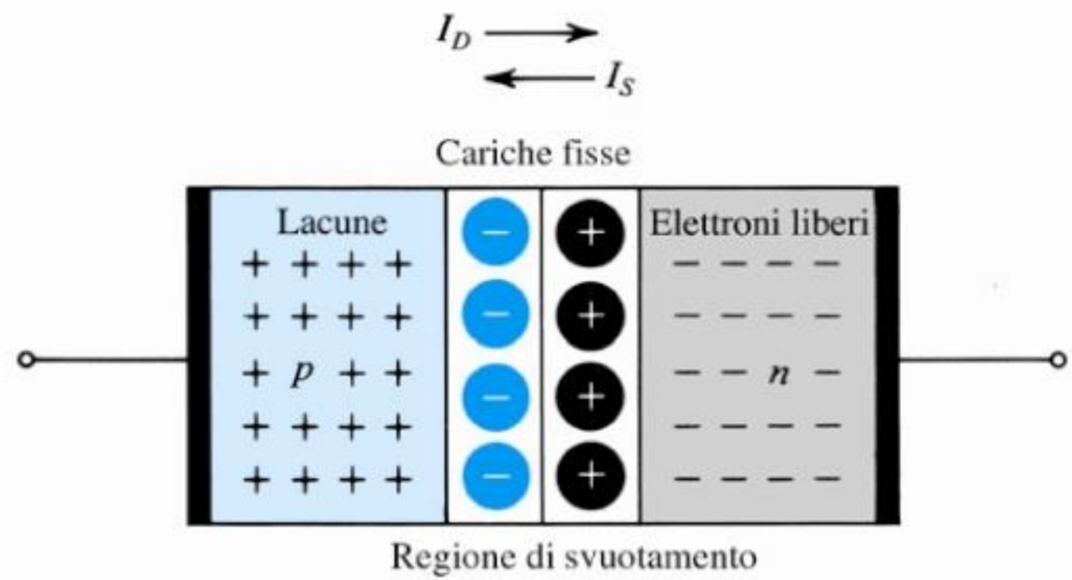
Il Silicio


Elettroni di valenza
Legami covalenti
Atomo di silicio
Atomo di impurità trivalente (accettore)
Lacuna
+4
+3
+

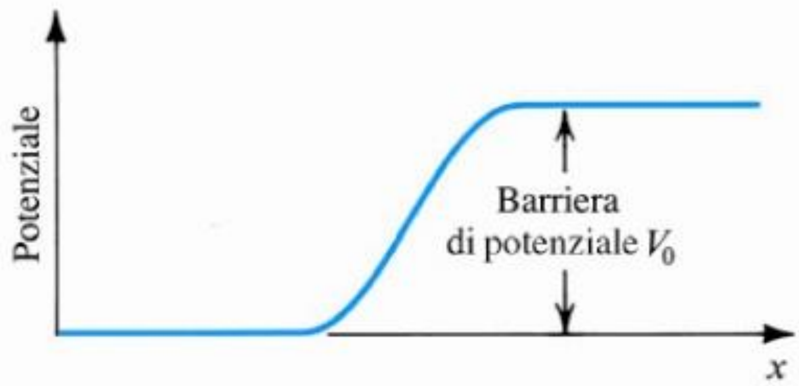
Il Diodo al Silicio



Il Diodo al Silicio

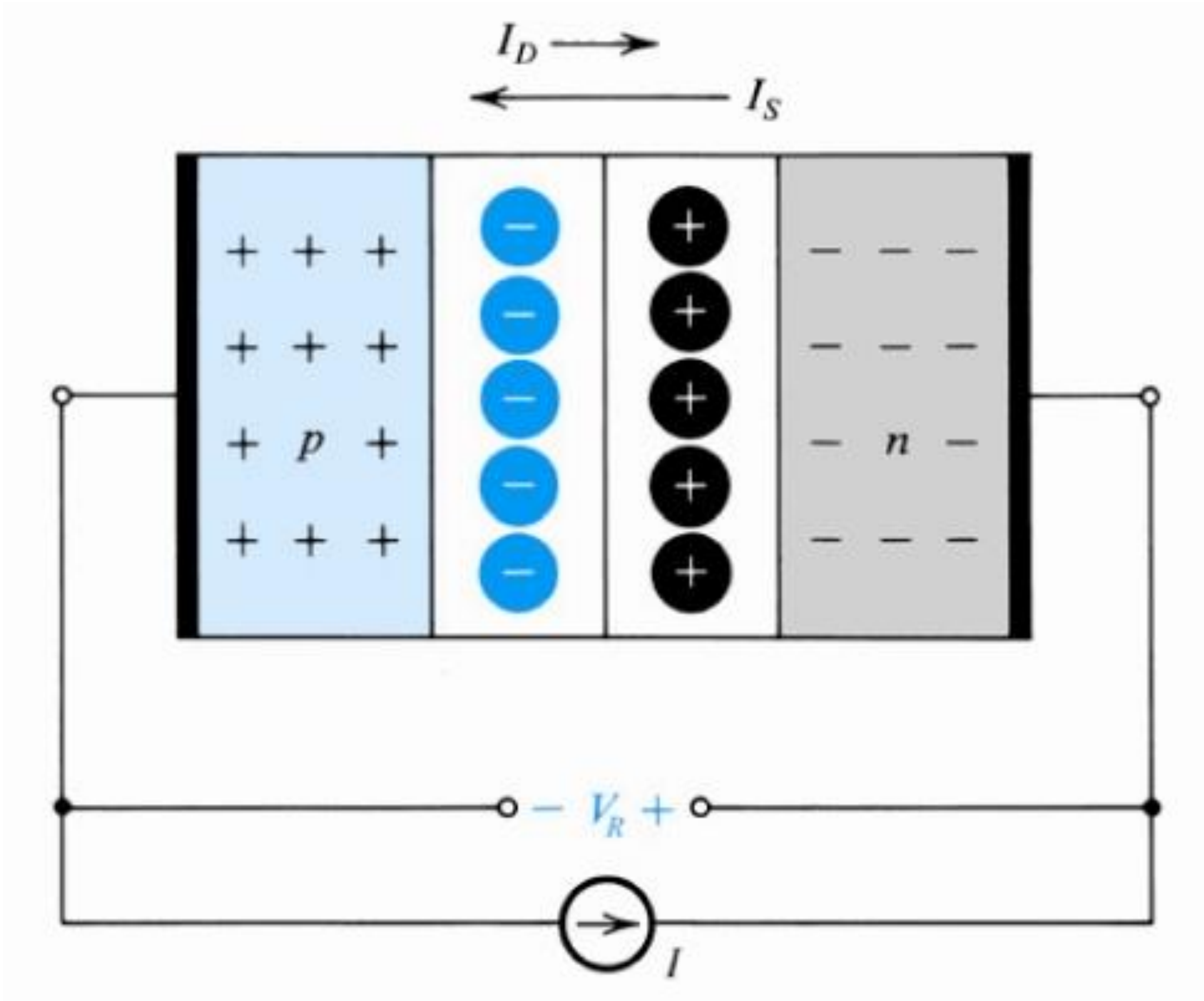


(a)

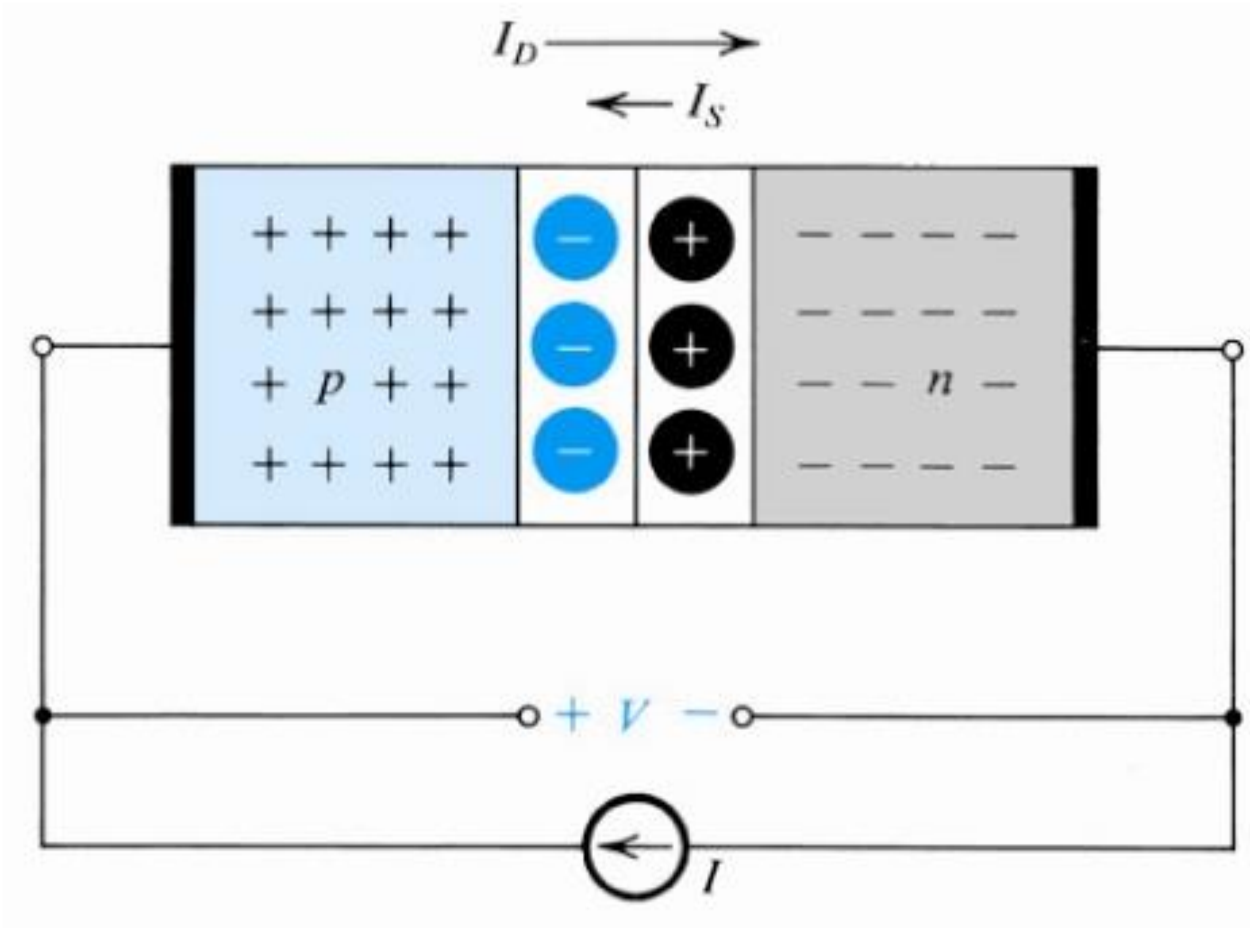


(b)

Il Diodo al Silicio

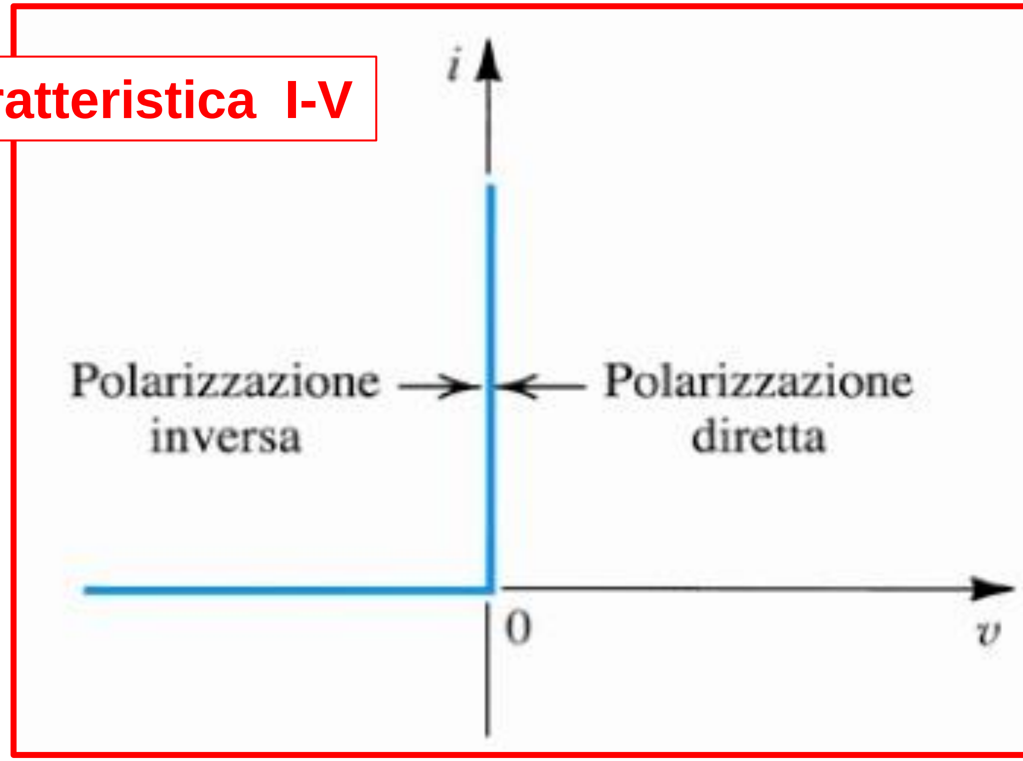


Il Diodo al Silicio

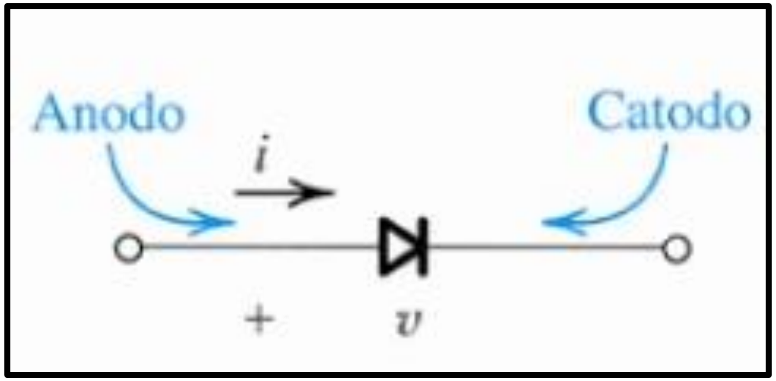


Il Diodo Ideale

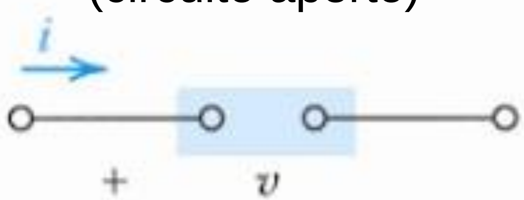
Caratteristica I-V



Simbolo Circuitale

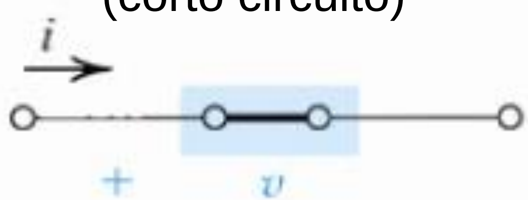


Circuito equivalente in polarizzazione inversa (circuito aperto)



$v < 0 \Rightarrow i = 0$

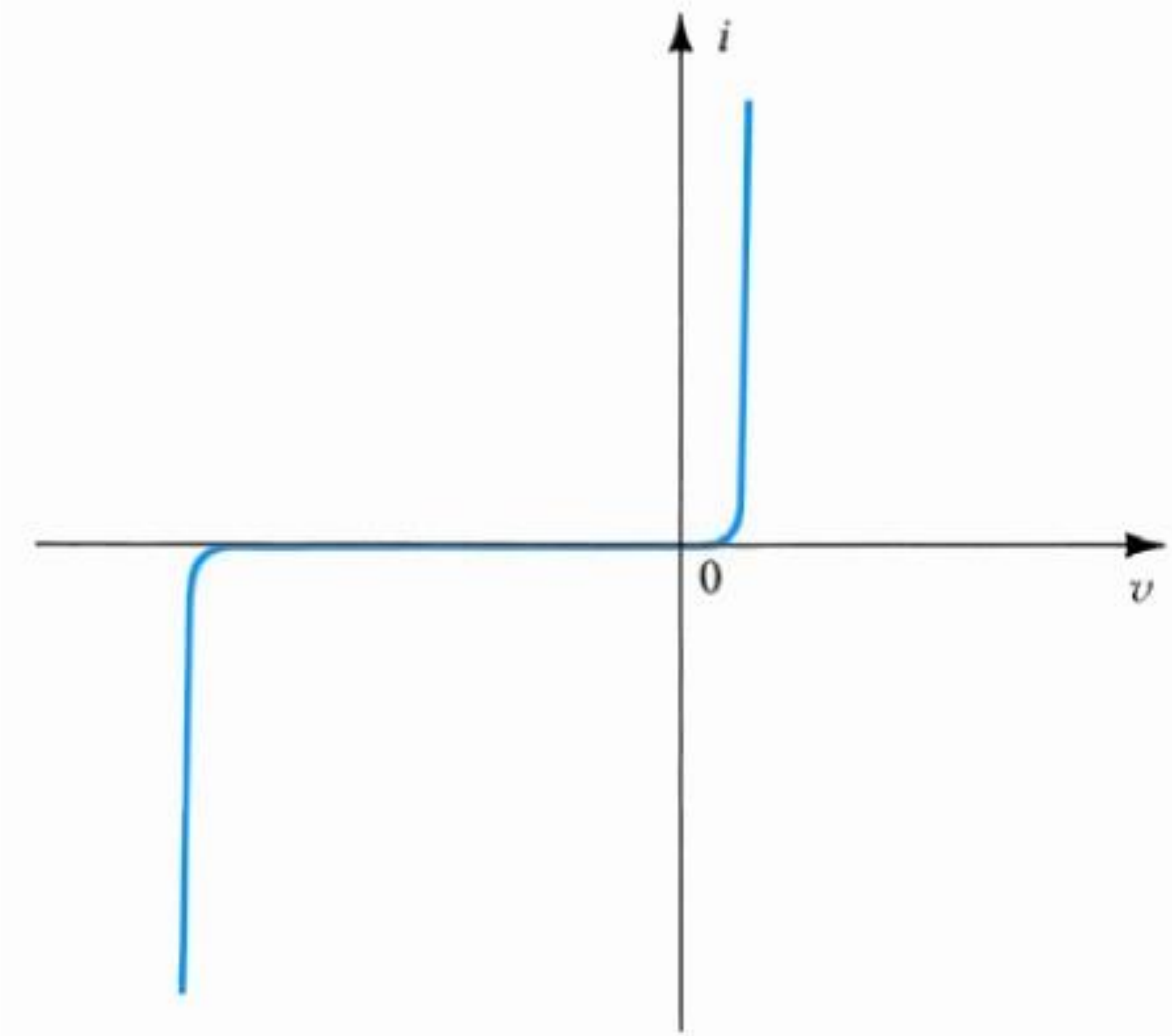
Circuito equivalente in polarizzazione diretta (corto circuito)



$i > 0 \Rightarrow v = 0$

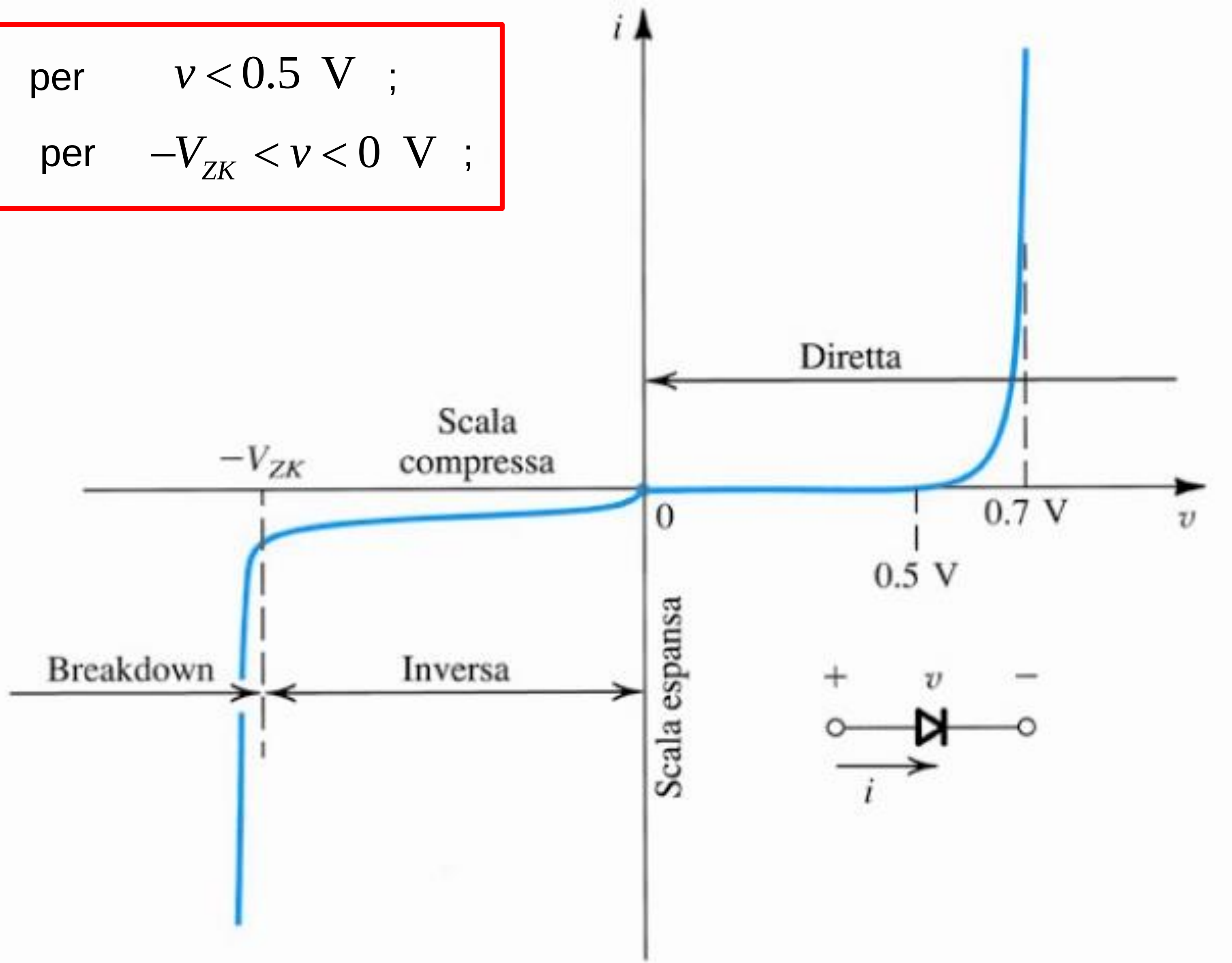
Il Diodo Reale

Caratteristica I-V (corrente-tensione) del diodo al silicio reale



Il Diodo Reale

- $i \simeq 0$ per $v < 0.5 \ \text{V}$;
- $i \simeq I_S$ per $-V_{ZK} < v < 0 \ \text{V}$;



Il Diodo: Equazione di Shockley

$$\boxed{i = I_S \left(e^{v/nV_T} - 1 \right)}$$

$$I_S = J_S A$$

J_S = densità di corrente

A = area del dispositivo

I_S corrente di saturazione

$V_T = \dfrac{kT}{q}$ tensione termica

k = costante di Boltzmann = $1.38 \cdot 10^{-23}$ J/K

T = temperatura assoluta in K = 273 + temp. in °C

q = carica dell'elettrone = $1.602 \cdot 10^{-19}$ C

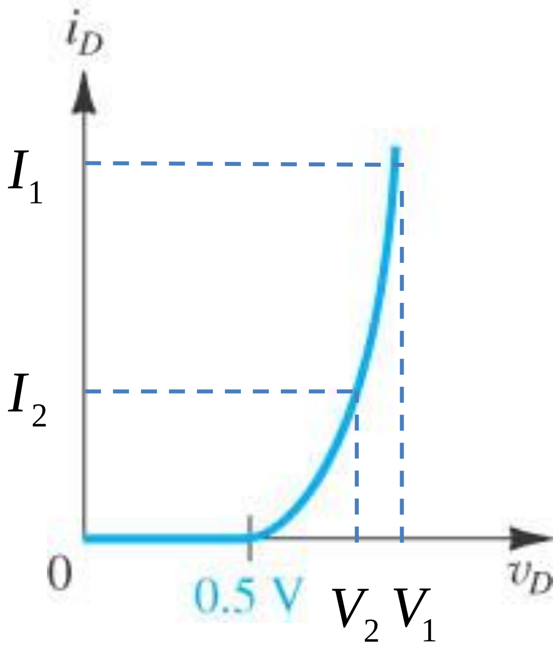
$$V_T \left(20\,°\mathrm{C} \right) = 25.2 \text{ mV} \cong 25 \text{ mV}$$

$n = 1 \div 2$ parametro dipendente dalla tecnologia

$$\boxed{v = V_T \ln \frac{i}{I_S}}$$

Il Diodo

Consideriamo due valori di corrente :



$$I_1 = I_S\left(e^{V_1/V_T} - 1\right)$$

$$I_2 = I_S\left(e^{V_2/V_T} - 1\right)$$

$$\frac{I_1}{I_2} = e^{(V_1 - V_2)/V_T}$$

Da cui : $$V_1 - V_2 = V_T \ln\frac{I_1}{I_2}$$

$$\boxed{V_1 - V_2 = 2.3\,V_T \log\frac{I_1}{I_2}}$$

se $\dfrac{I_1}{I_2} = 10 \quad \Rightarrow \quad V_1 - V_2 \cong 58\ \text{mV}$

se $\dfrac{I_1}{I_2} = 100 \quad \Rightarrow \quad V_1 - V_2 \cong 115\ \text{mV}$

Il Diodo

Valori tipici di corrente in un circuito elettronico

$$v = V_T \ln \frac{i}{I_S} \quad , \qquad I_S = 10^{-15} \ \text{A}$$

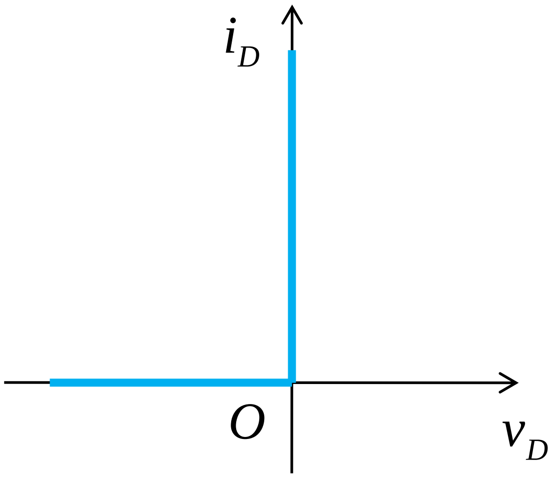
$$v = V_T \ln \frac{i_M}{I_S} = 25 \cdot 10^{-3} \ln \frac{10^{-3}}{10^{-15}} = 0.69 \ \text{V}$$

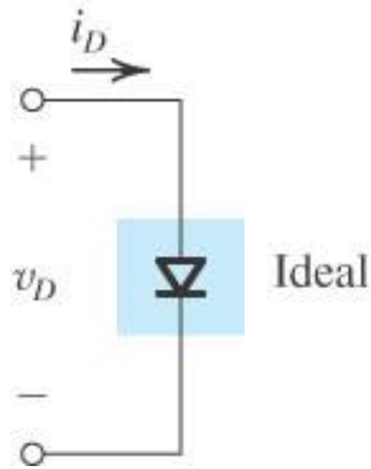
$$v = V_T \ln \frac{i_m}{I_S} = 25 \cdot 10^{-3} \ln \frac{10^{-6}}{10^{-15}} = 0.52 \ \text{V}$$

$$\boxed{v \sim 0.5 \div 0.7 \ \text{V}}$$

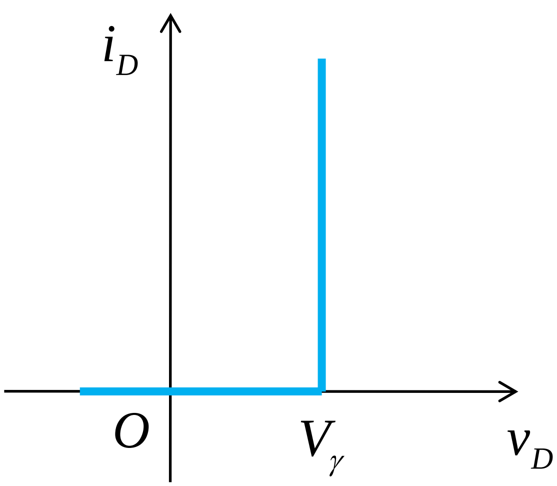
I	***V***
10 mA	0.748 V
1 mA	0.691 V
100 μA	0.633 V
10 μA	0.576 V
1 μA	0.518 V
100 nA	0.460 V
10 nA	0.403 V
1 nA	0.345 V

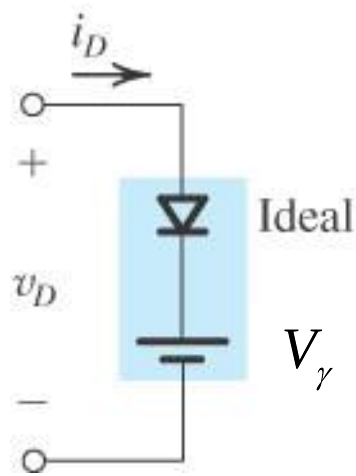
Il Diodo: Modelli Semplificati





$$\begin{cases} i_D = 0 & v_D \le 0 \\ v_D = 0 & i_D \ge 0 \end{cases}$$

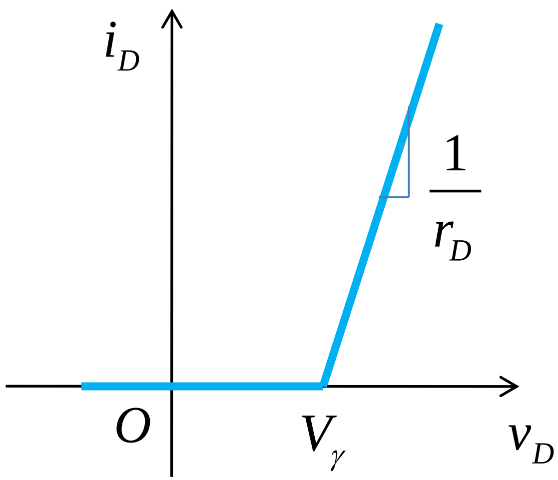


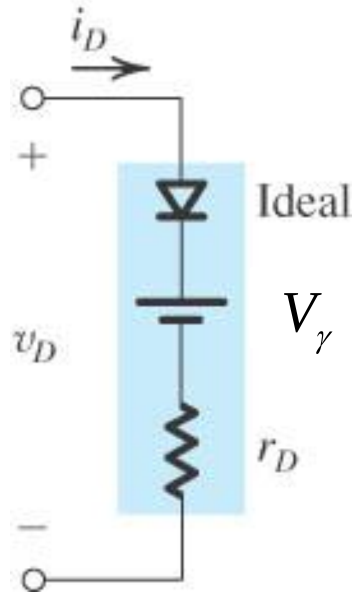


$$\begin{cases} i_D = 0 & v_D \le V_\gamma \\ v_D = V_\gamma & i_D \ge 0 \end{cases}$$

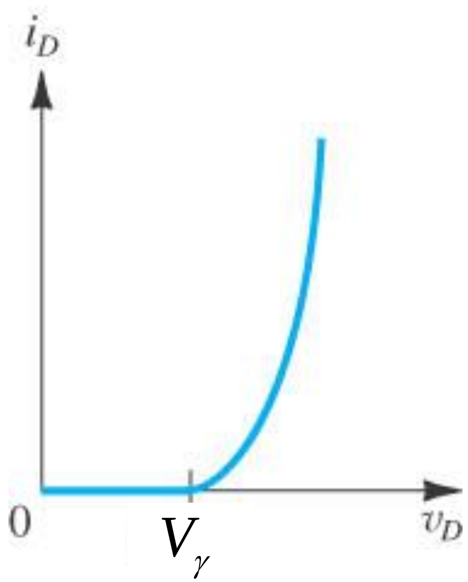
$$V_\gamma \sim 0.5 \div 0.7$$

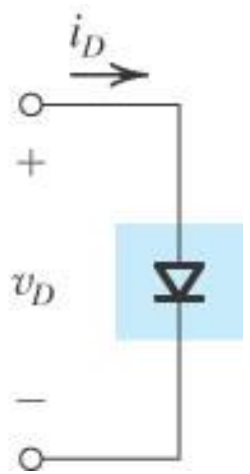
Il Diodo: Modelli Semplificati



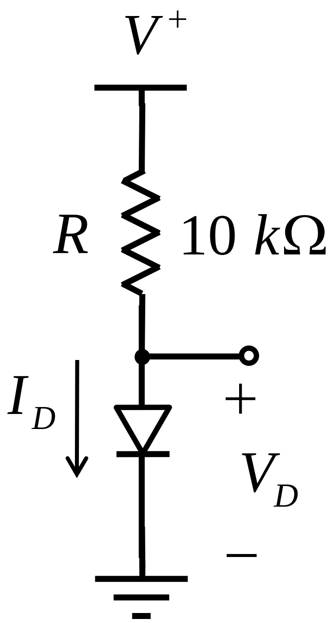


$$\begin{cases} i_D = 0 & v_D \le V_\gamma \\ i_D = \dfrac{1}{r_D}\left(v_D - V_\gamma\right) & v_D \ge V_\gamma \end{cases}$$





$$i = I_S\left(e^{v/nV_T} - 1\right)$$



Determinare I_D nei seguenti casi:

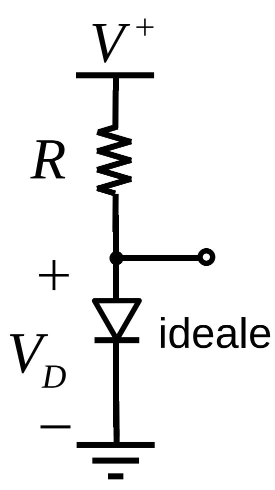
a) **$V^+ = 10$ V;**

b) **$V^+ = 1$ V;**

usando i diversi modelli del diodo.

Caso a) $V^+ = 10\ \text{V}$

1)

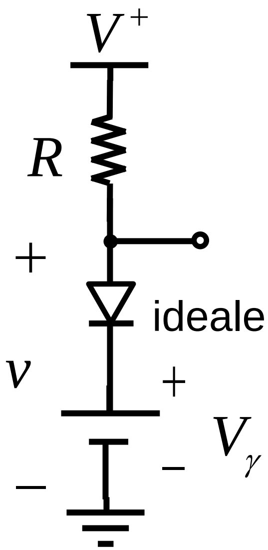


$$V_D = 0\ \text{V} \quad , \quad I_D = \frac{V^+}{R} = \frac{10}{10 \cdot 10^3} = 1\ \text{mA}$$

$$\text{se} \quad v \le 0 \ , \quad i = 0 \quad \Rightarrow \quad V_D = V^+ > 0 \qquad \text{NO!}$$

Circuiti con Diodi

2)

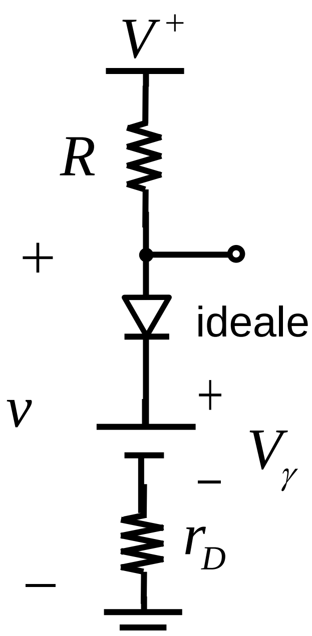


$$V_\gamma = 0.6 \text{ V}$$

$$I_D = \frac{V^+ - V_\gamma}{R} = \frac{10 - 0.6}{10 \cdot 10^3} = 0.94 \text{ mA}$$

$$\text{se} \quad v \le V_\gamma \quad , \quad i = 0 \quad \Rightarrow \quad v = V^+ > 0 \qquad \text{NO!}$$

3)

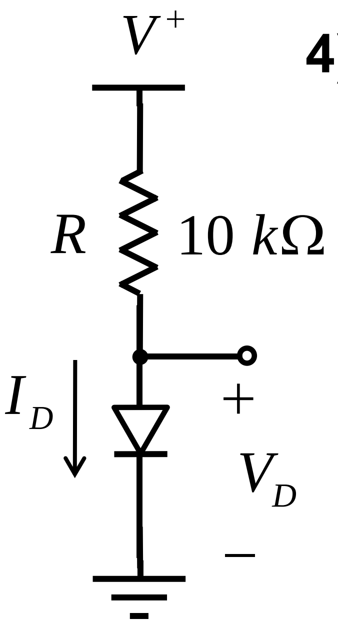


$$V_\gamma = 0.6 \text{ V} \qquad r_D = 200\ \Omega$$

$$I_D = \frac{V^+ - V_\gamma}{R + r_D} = \frac{10 - 0.6}{(10 + 0.2) \cdot 10^3} = 0.92 \text{ mA}$$

$$\text{se} \quad v \le V_\gamma \quad , \quad i = 0 \quad \Rightarrow \quad v = V^+ > 0 \qquad \text{NO!}$$

Circuiti con Diodi



4) Algoritmo di risoluzione dell'equazione esatta

$$\boxed{\begin{aligned} I_D &= I_S\, e^{V_D/V_T} \\ I_S &= 10^{-15}\ \text{A} \end{aligned}}$$

$$V^+ = R\, I_D + V_D = R\, I_D + V_T \ln \frac{I_D}{I_S}$$

$$I_D = \frac{1}{R}\left(V^+ - V_T \ln \frac{I_D}{I_S} \right)$$

risolvendo iterativamente si ottiene il valore esatto:

$$I_D^{(k+1)} = 10^{-4}\left(10 - 25 \cdot 10^{-3} \ln \frac{I_D^k}{10^{-15}} \right)$$

$$I_D^{(0)} = 0.94\ \text{mA}$$

$$I_D^{(1)} = 0.931\ \text{mA}$$

$$I_D^{(2)} = 0.931\ \text{mA}$$

Soluzione: $\boxed{I_D = 0.931\ \text{mA}}$

Circuiti con Diodi

Caso b) $V^+ = 1\ \text{V}$

1) $V_D = 0\ \text{V}$, $I_D = \dfrac{V^+}{R} = \dfrac{1}{10 \cdot 10^3} = 0.1\ \text{mA}$

2) $V_\gamma = 0.6\ \text{V}$ $\quad I_D = \dfrac{V^+ - V_\gamma}{R} = \dfrac{1 - 0.6}{10 \cdot 10^3} = 0.04\ \text{mA}$

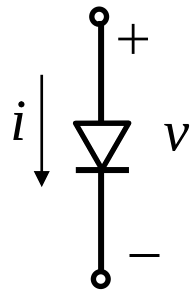
3) $V_\gamma = 0.6\ \text{V}$ $\quad r_D = 200\ \Omega$ $\quad I_D = \dfrac{V^+ - V_\gamma}{R + r_D} = \dfrac{1 - 0.6}{(10 + 0.2) \cdot 10^3} = 0.039\ \text{mA}$

4) $I_D = 0.039\ \text{mA}$

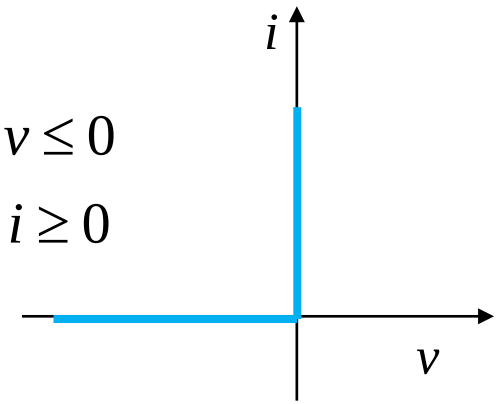
Il modello 1) dà risultati soddisfacenti solo quando la V^+ è elevata rispetto a V_γ

Circuiti con Diodi

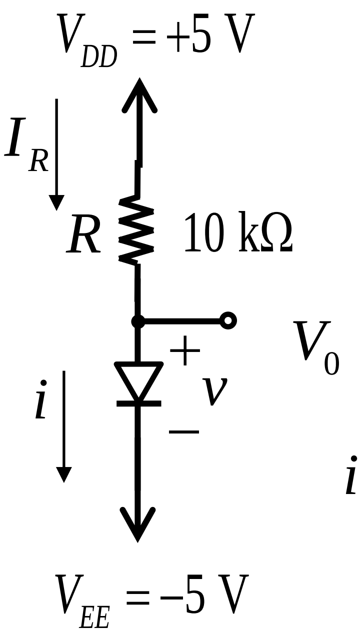
Diodo ideale



$$\begin{cases} i = 0 & v \le 0 \\ v = 0 & i \ge 0 \end{cases}$$



Es.1

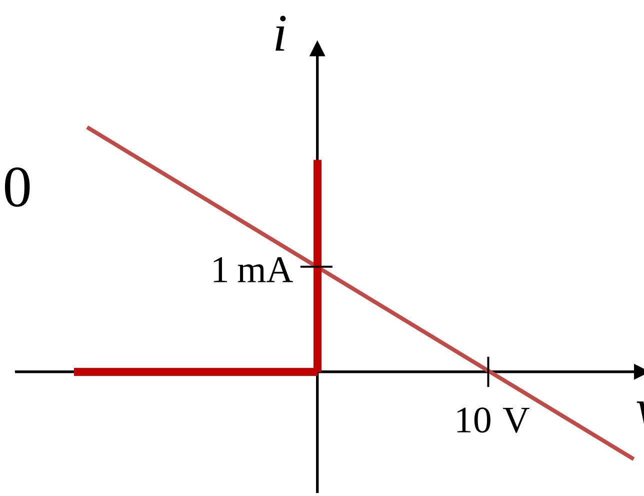


$$i\ ,\ V_0\ =\ ?$$

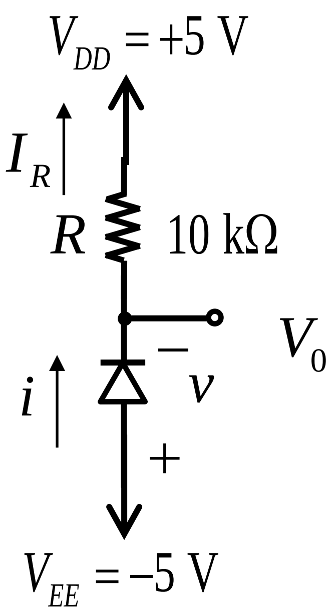
$$i \ge 0 \quad \Rightarrow \quad v = 0 \quad \Rightarrow \quad V_0 = V_{EE} = -5\ \mathrm{V}$$

$$i = I_R = \frac{V_{DD} - V_O}{R} = \frac{10}{10 \cdot 10^3} = 1\ \mathrm{mA} > 0$$

Graficamente $\qquad 10 = Ri + v$



Es.2



$$i\ ,\ \ V_0\ \ =\ \ ?$$

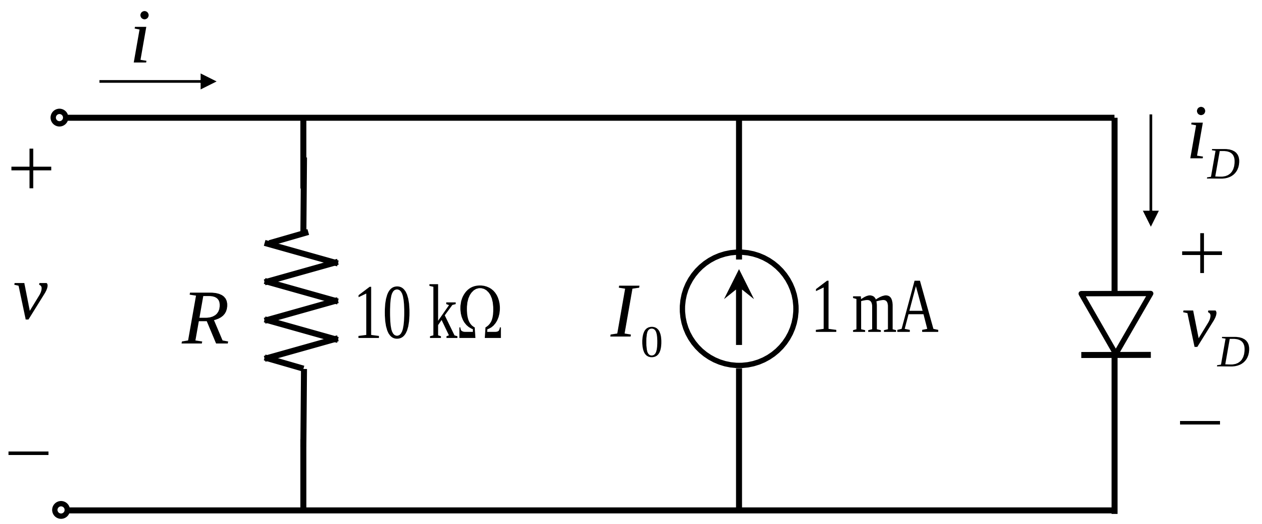
$$i \geq 0 \quad \Rightarrow \quad v = 0 \quad \Rightarrow \quad V_0 = V_{EE} = -5\ \text{V}$$

$$i = I_R = \frac{V_O - V_{DD}}{R} = \frac{-10}{10 \cdot 10^3} = -1\ \text{mA} < 0 \qquad \text{NO!}$$

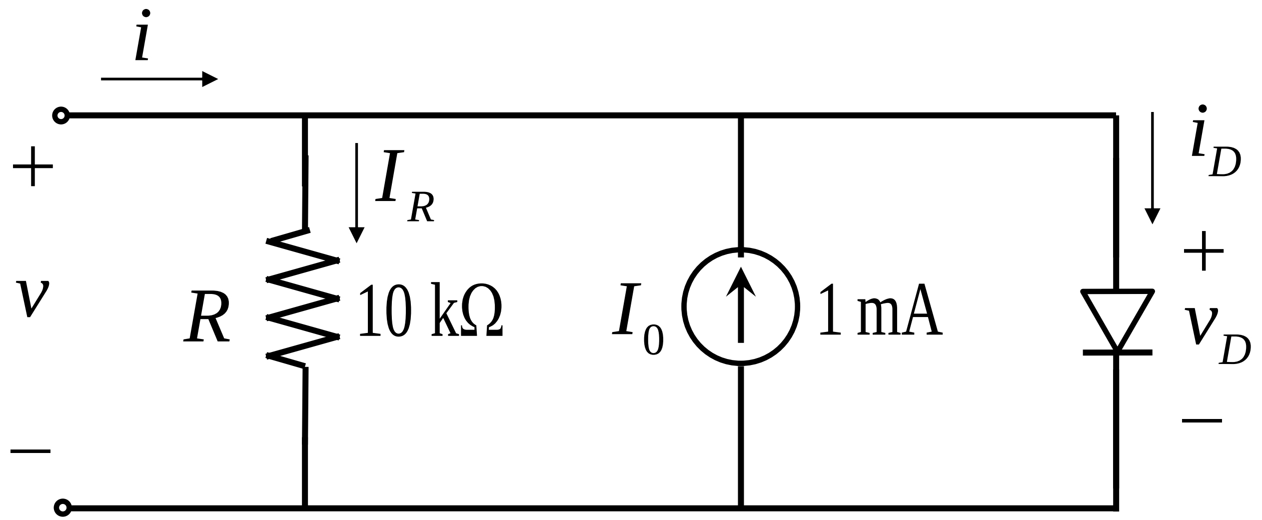
$$v < 0 \quad \Rightarrow \quad i = 0 \quad \Rightarrow \quad V_0 = 5\ \text{V} \quad \Rightarrow \quad v = -10\ \text{V} < 0 \qquad \text{SI!}$$

Es.3

Determinare analiticamente e graficamente la caratteristica I-V del seguente bipolo:



Circuiti con Diodi



$$v = v_D \quad , \qquad i = +I_R - I_0 + i_D = \frac{v}{R} - I_0 + i_D$$

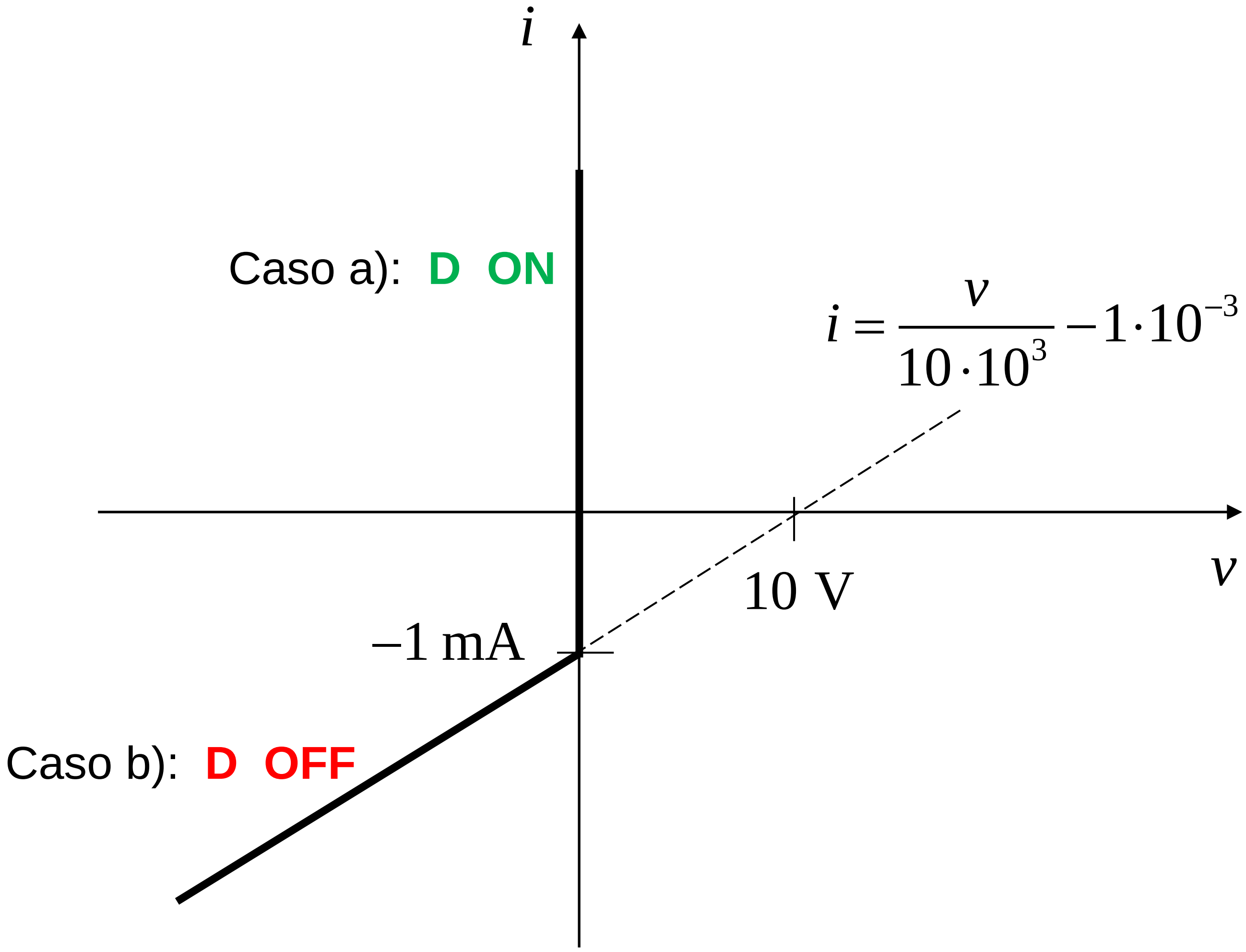
Caso a): **D ON**

$$i_D \geq 0 \, , \; v_D = 0 \quad \Rightarrow \quad \boxed{v = 0 \;,} \quad i = -I_0 + i_D \qquad i_D = i + I_0 \geq 0 \qquad \boxed{i \geq -I_0}$$

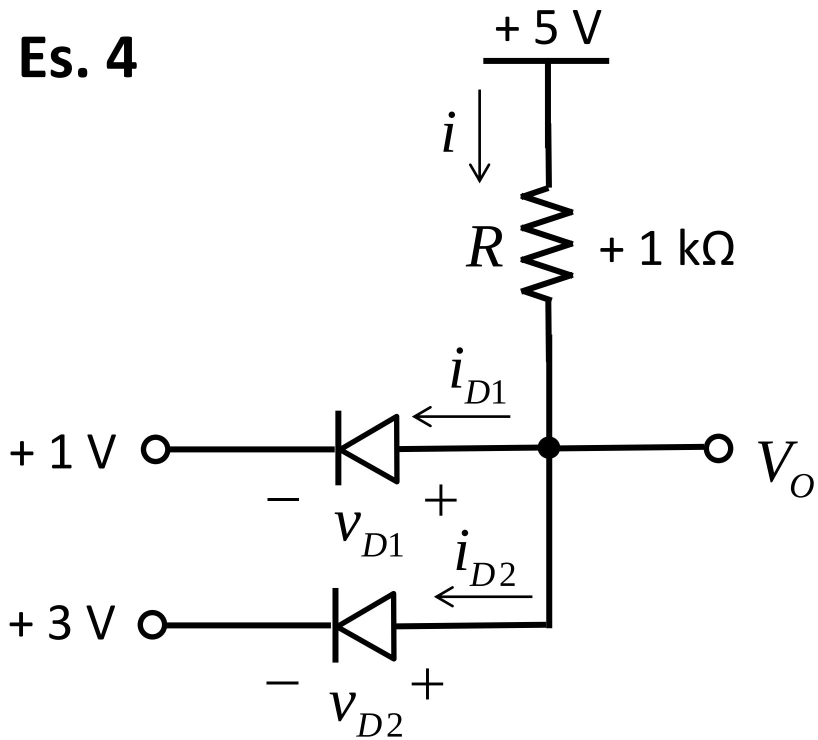
Caso b): **D OFF**

$$v_D \leq 0 \;\; , \; i_D = 0 \quad \Rightarrow \quad \boxed{i = \frac{v}{R} - I_0} \qquad \boxed{v \leq 0}$$

Circuiti con Diodi



Es. 4



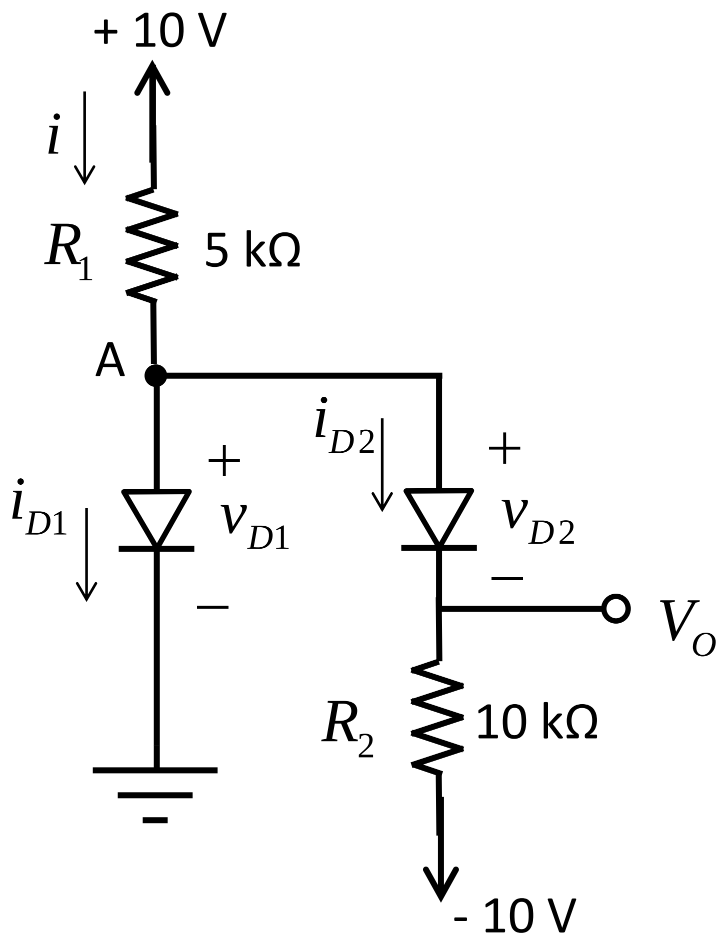
$$i_{D1} > 0\ ,\ i_{D2} > 0 \quad \Rightarrow \quad v_{D1} = v_{D2} = 0 \quad \Rightarrow \quad V_0 = 1\ ,\ 3\ \text{V} \qquad \text{NO!}$$

$$i_{D1} > 0\ ,\ v_{D2} < 0 \quad \Rightarrow \quad v_{D1} = 0\ ,\ i_{D2} = 0 \quad \Rightarrow \quad V_0 = 1\ \text{V}$$

$$\Rightarrow \quad v_{D2} = -2\ \text{V} < 0 \quad , \quad i_{D1} = i = \frac{5-1}{1k} = 4\ \text{mA} > 0 \qquad \text{SI!}$$

Circuiti con Diodi

Es. 5

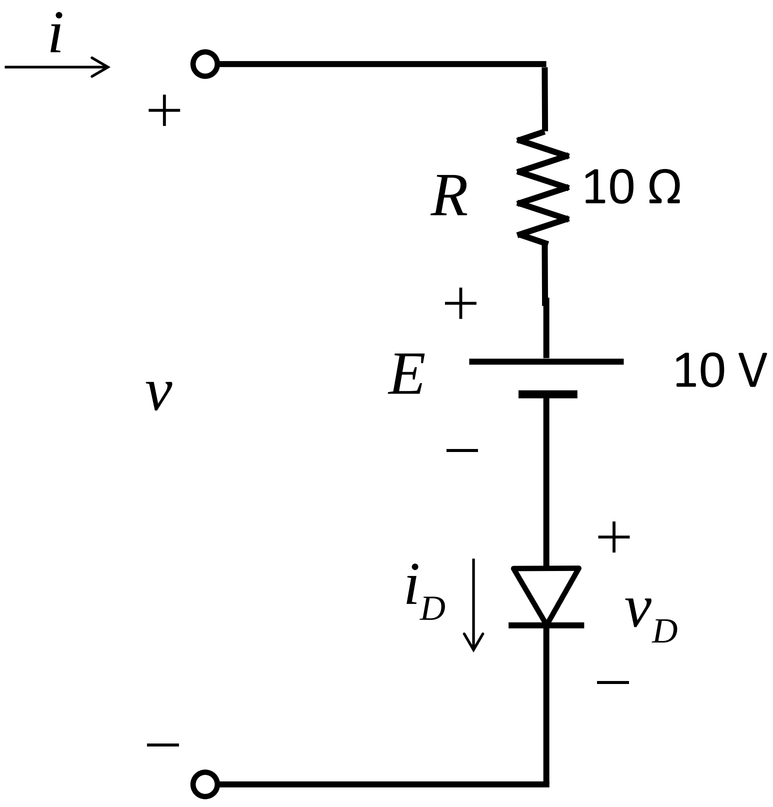


$$i_{D1} > 0 \;,\; i_{D2} > 0 \quad \Rightarrow \quad v_{D1} = v_{D2} = 0 \quad \Rightarrow \quad V_A = 0 \text{ V} \;,\; V_0 = 0 \text{ V}$$

$$\Rightarrow i_{D2} = \frac{10}{10k} = 1 \text{ mA} > 0 \qquad i = \frac{10}{5k} = 2 \text{ mA} \quad \Rightarrow \quad i_{D1} = 1 \text{ mA} > 0 \qquad \text{SI!}$$

Es. 6

Determinare analiticamente e graficamente la caratteristica I-V del seguente bipolo:



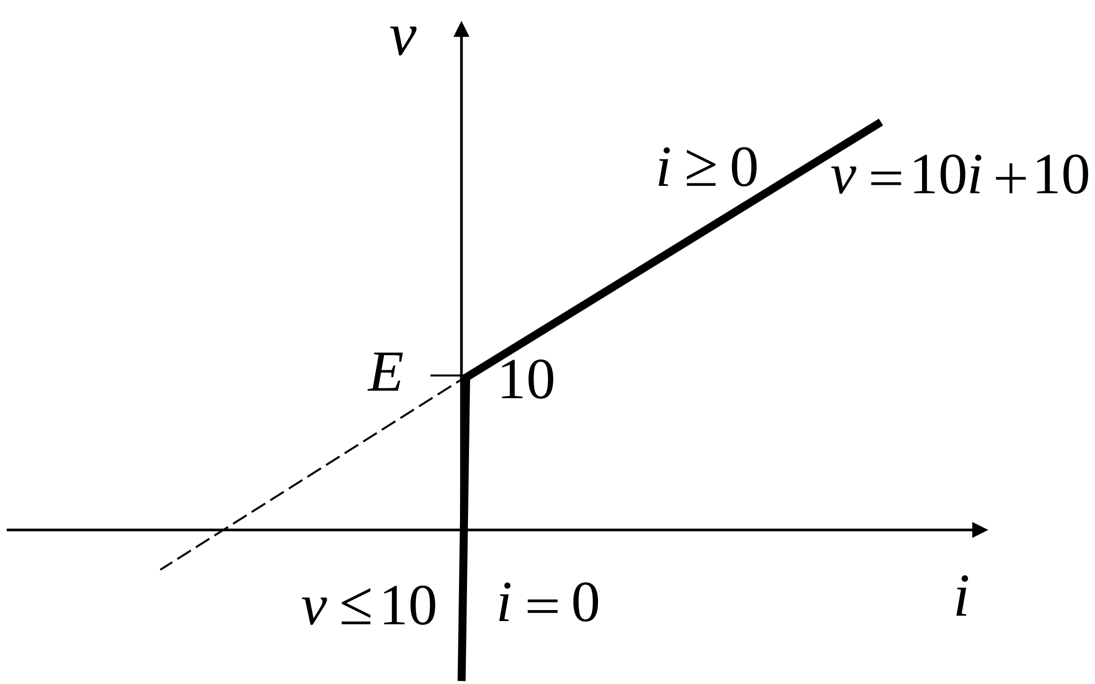
Circuiti con Diodi

Caso a): **D ON**

$$i_D \geq 0 \ , \ v_D = 0 \quad \Rightarrow \quad \boxed{v = Ri + E = 10i + 10} \qquad\qquad i = i_D \quad \Rightarrow \quad \boxed{i \geq 0}$$

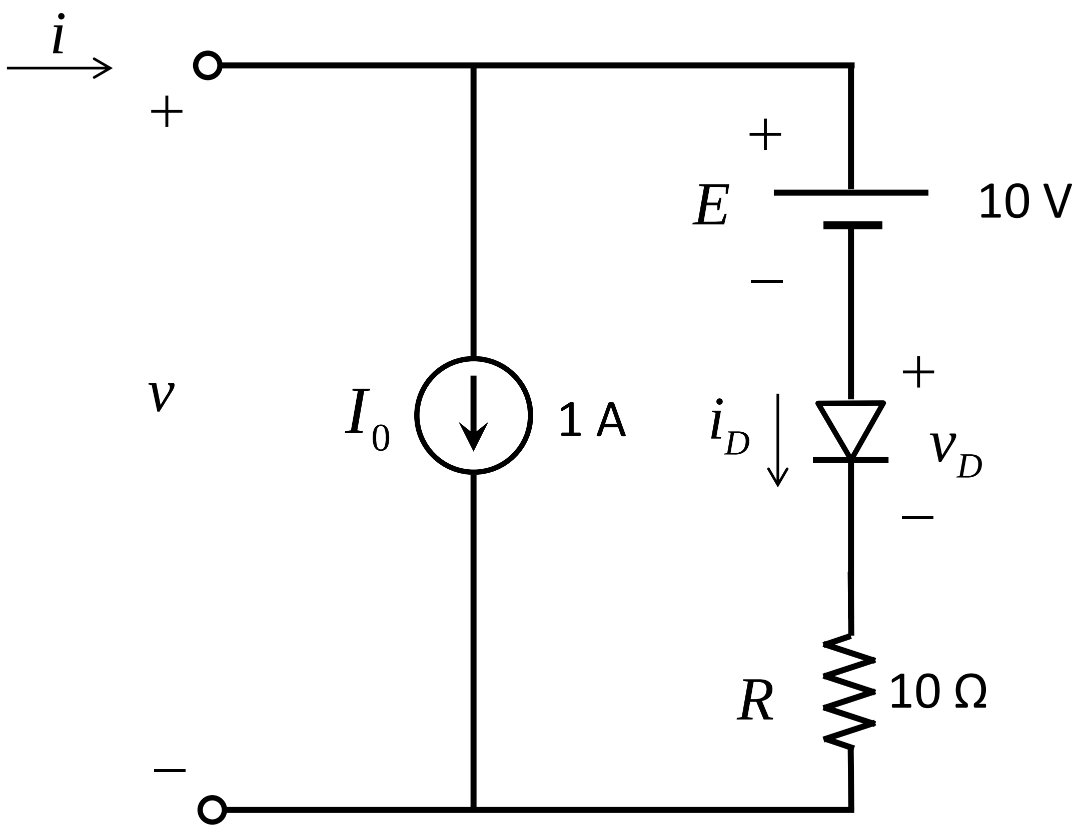
Caso b): **D OFF**

$$v_D \leq 0 \ , \ i_D = 0 \quad \Rightarrow \quad \boxed{i = 0} \qquad\qquad v_D = v - E \leq 0 \quad \Rightarrow \quad \boxed{v \leq E = 10}$$

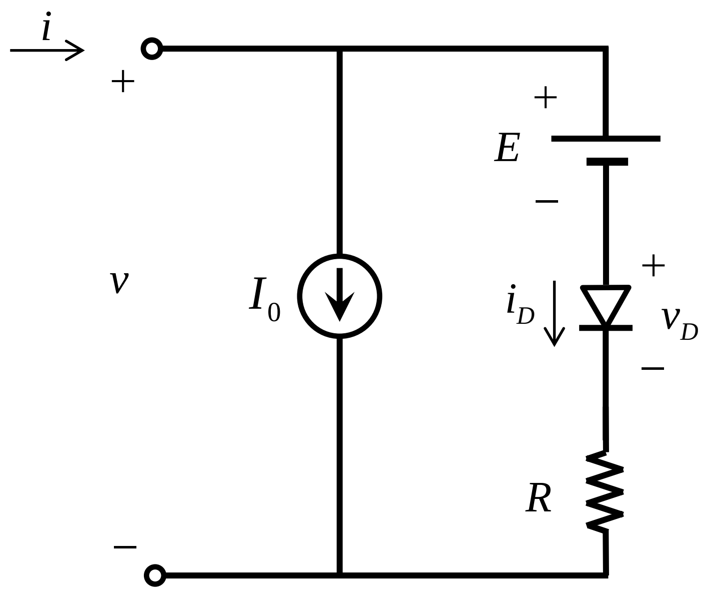


Es. 7

Determinare analiticamente e graficamente la caratteristica I-V del seguente bipolo:



Circuiti con Diodi



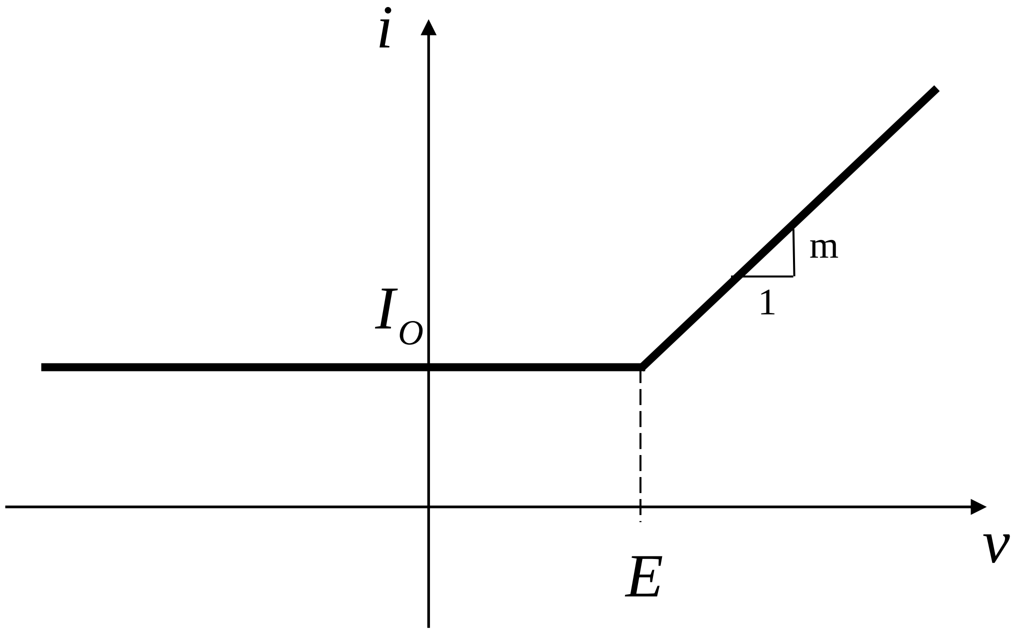
Caso a): **D OFF**

$$v_D \le 0\ ,\ \ i_D = 0 \quad \Rightarrow \quad \boxed{i = I_0} \quad v = E + v_D \quad \Rightarrow \quad v_D = v - E \le 0 \quad \Rightarrow \quad \boxed{v \le E}$$

Caso b): **D ON**

$$i_D \ge 0\ ,\ \ v_D = 0 \quad \Rightarrow \quad \boxed{i = I_0 + \frac{v-E}{R}} \quad m = \frac{1}{R} \quad i_D = \frac{v-E}{R} \ge 0 \quad \Rightarrow \quad \boxed{v \ge E}$$

Circuiti con Diodi



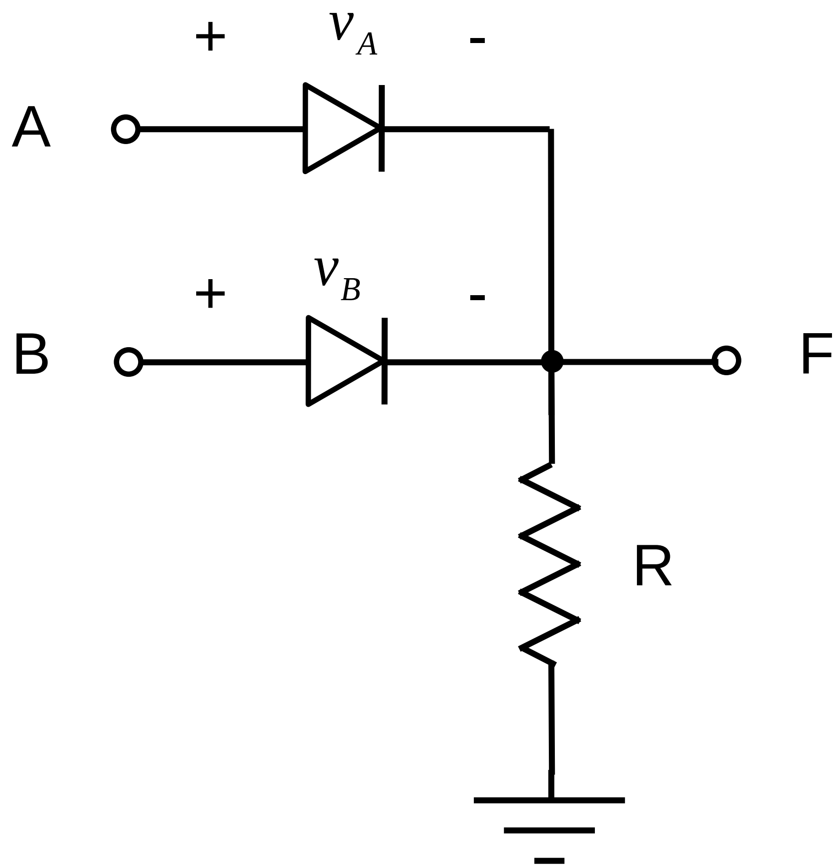
$$v \le E \qquad i = I_O$$

$$v \ge E \qquad i = m\left(v - E\right) + I_O$$

$$m = \frac{1}{R}$$

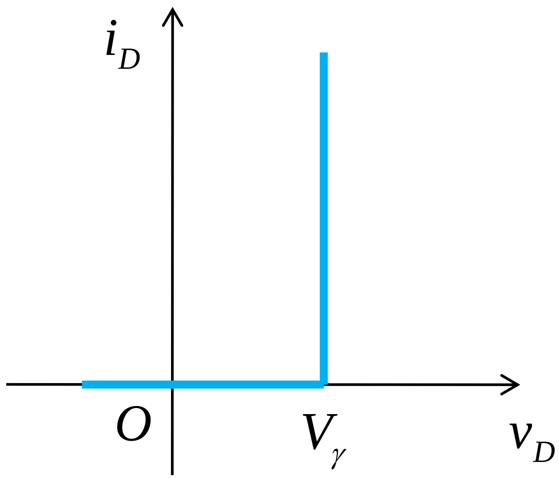
Logica a Diodi

Porta OR



$$V = 0 \text{ V} \quad \Leftrightarrow \quad 0 \text{ logico}$$

$$V = 5 \text{ V} \quad \Leftrightarrow \quad 1 \text{ logico}$$

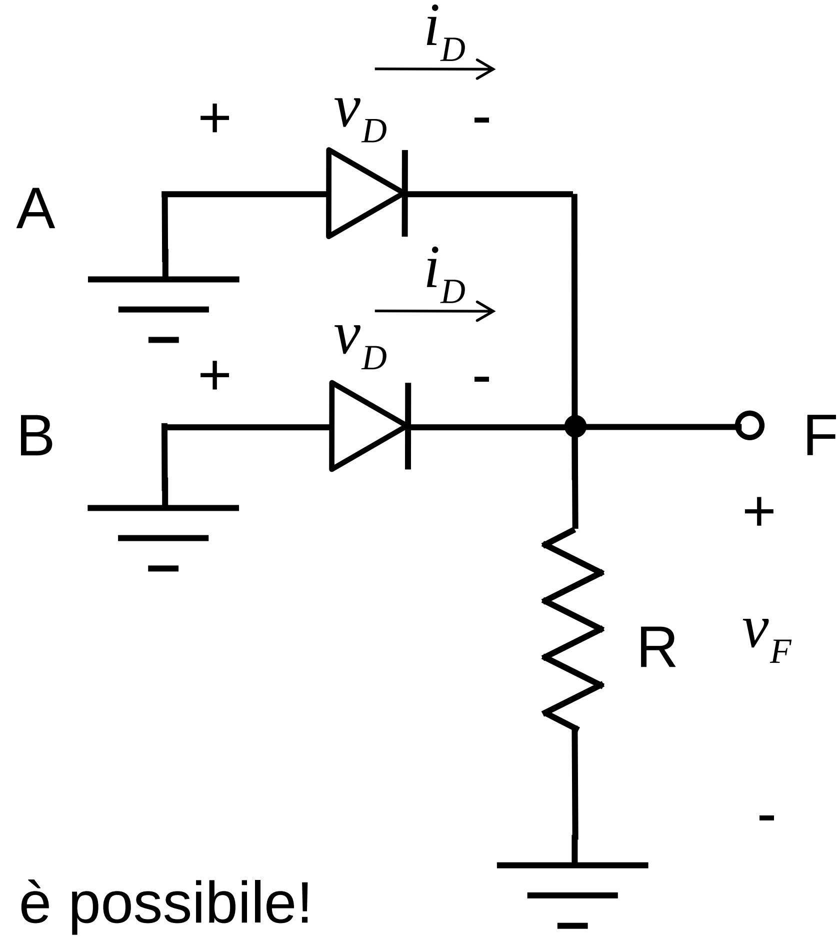


$$\begin{cases} i_D = 0 & v_D \le V_\gamma \\ v_D = V_\gamma & i_D \ge 0 \end{cases}$$

$$V_\gamma = 0.7 \text{ V}$$

Logica a Diodi

1) $V_A = V_B = 0\ \mathrm{V}$



se $i_D \geq 0$ $v_D = V_\gamma$

$\Rightarrow \quad v_F = 2 i_D R > 0\ \mathrm{V}$

ma $v_F + v_D = 0\ \mathrm{V}$

$\Rightarrow \quad v_D = V_\gamma = -v_F < 0\ \mathrm{V}$ Non è possibile!

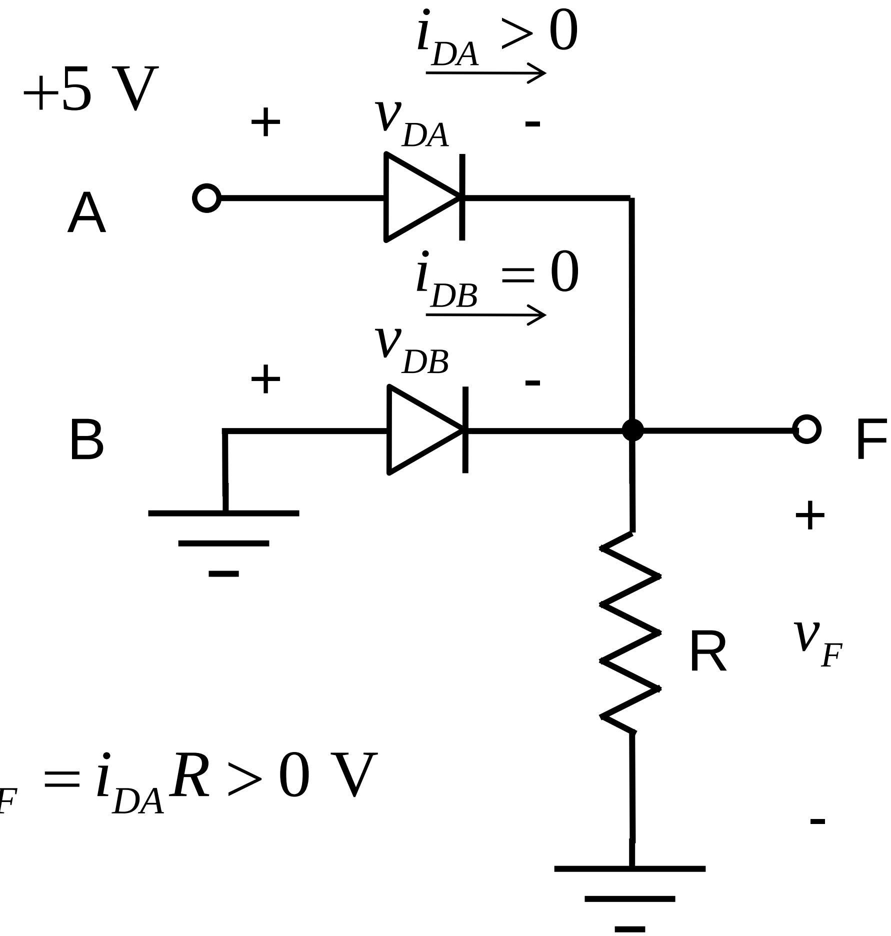
Allora: $v_D \leq V_\gamma \quad i_D = 0 \quad \Rightarrow \boxed{v_F = 0\ \mathrm{V}}$

OK

Logica a Diodi

2) $V_A = 5\text{ V}$

$V_B = 0\text{ V}$



se $\quad i_{DA} \geq 0 \quad v_{DA} = V_\gamma \qquad v_{DB} \leq V_\gamma \quad i_{DB} = 0$

$$\Rightarrow \quad v_F = i_{DA} R > 0\text{ V}$$

Allora $\quad v_{DB} = -v_F \leq V_\gamma \quad \Rightarrow \quad \boxed{v_F = 5\text{ V} - V_\gamma = 4.3\text{ V}}$

OK

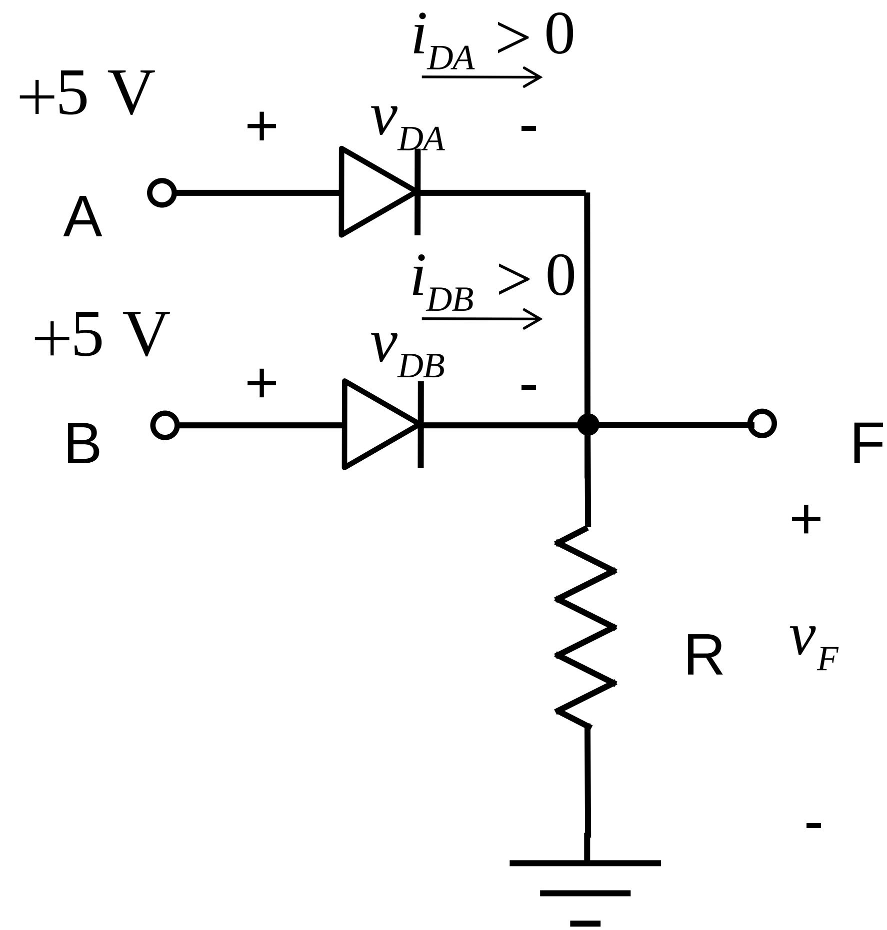
Logica a Diodi

3) $V_A = 0 \text{ V}$

$V_B = 5 \text{ V}$

$\Rightarrow \boxed{v_F = 4.3 \text{ V}}$ Analogo al caso 2)

4) $V_A = V_B = 5\text{V}$



se $i_{DA} \geq 0 \quad v_{DA} = V_\gamma$

$i_{DB} \geq 0 \quad v_{DB} = V_\gamma$

$$\Rightarrow \boxed{v_F = 5 \text{ V} - V_\gamma = 4.3 \text{ V}} > 0$$

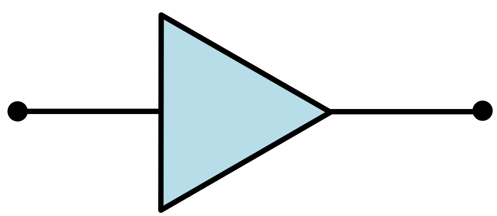
$$v_F = 2 i_{DA} R > 0 \text{ V}$$

OK

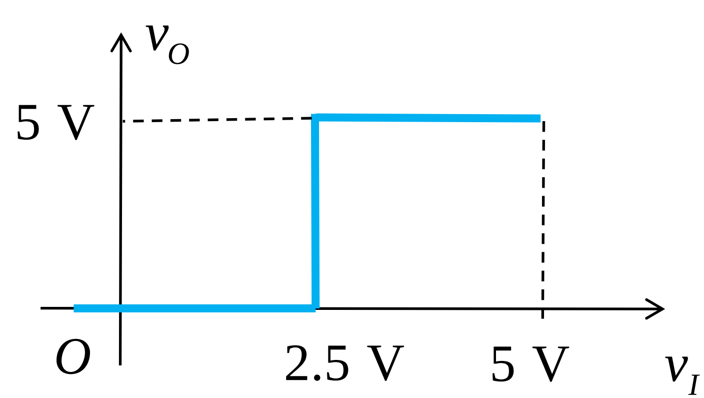
Logica a Diodi

V_A	V_B	v_F	Caso ideale $V_\gamma = 0$
0 V	0 V	0 V	0 V
5 V	0 V	4.3 V	5 V
0 V	5 V	4.3 V	5 V
5 V	5 V	4.3 V	5 V

- Si ha una riduzione del livello in uscita a causa di V_γ
- Per ripristinare il livello di 5 V in uscita è necessario un circuito amplificatore

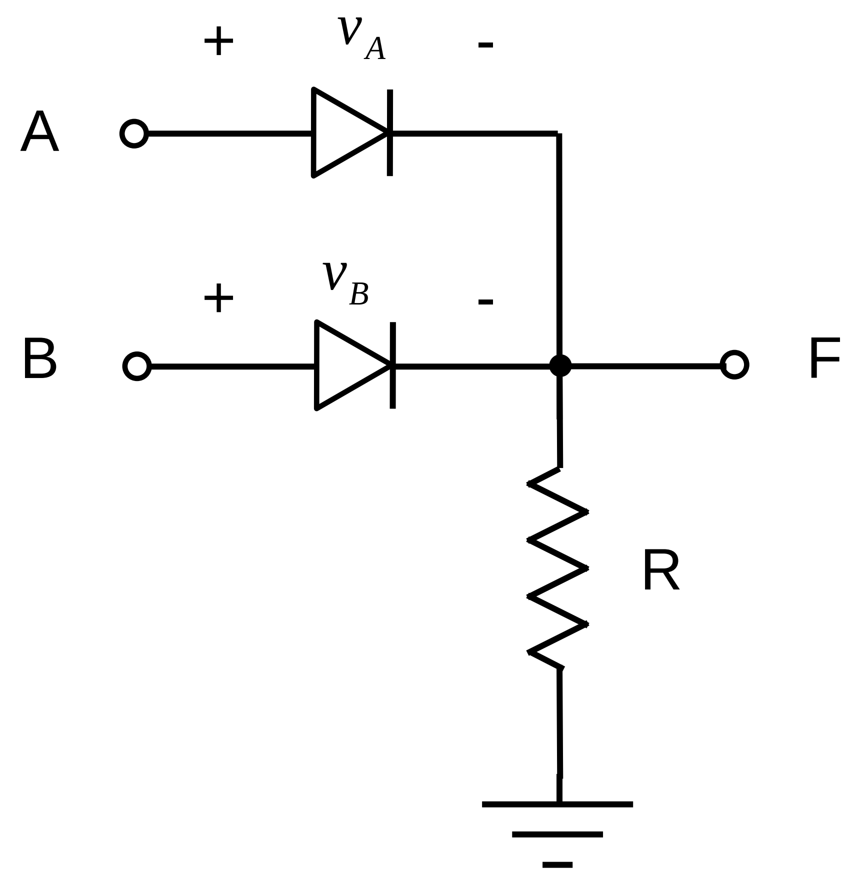


$$\begin{cases} v_O = 0\ \text{V}\ , & v_I < 2.5\ \text{V} \\ v_O = 5\ \text{V}\ , & v_I \geq 2.5\ \text{V} \end{cases}$$



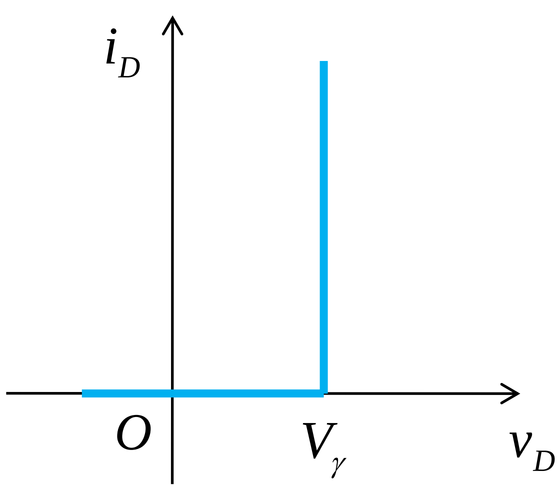
Logica a Diodi

Porta OR



$$V = 0 \text{ V} \quad \Leftrightarrow \quad 0 \ \text{logico}$$

$$V = 5 \text{ V} \quad \Leftrightarrow \quad 1 \ \text{logico}$$

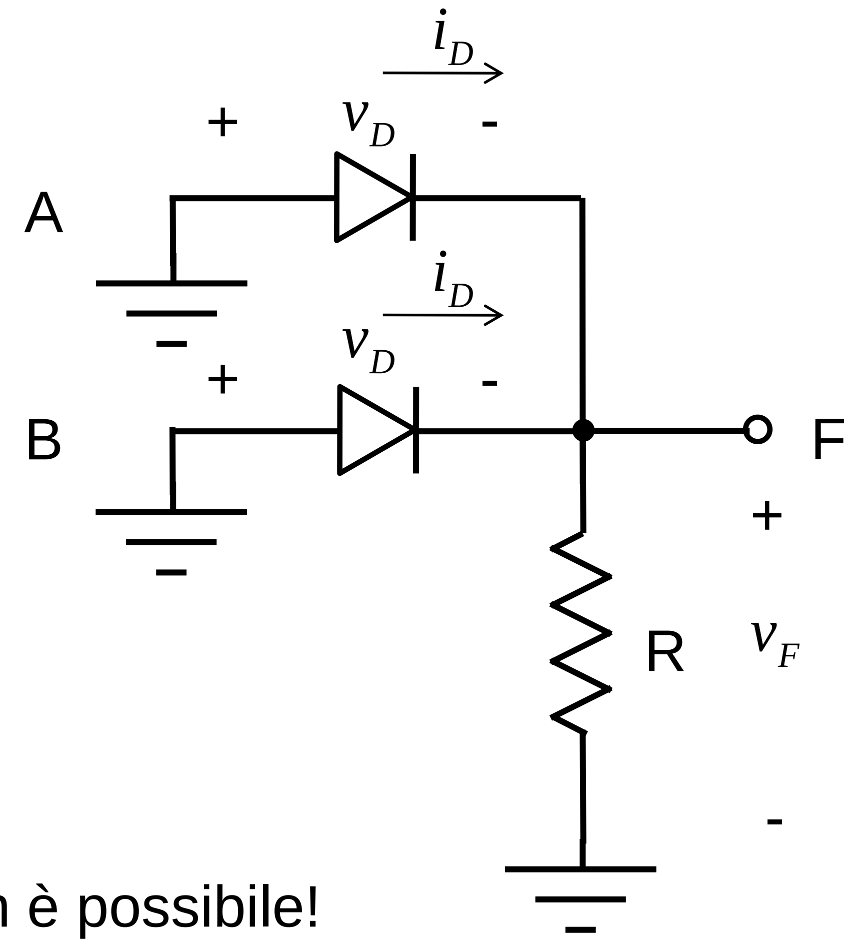


$$\begin{cases} i_D = 0 & v_D \le V_\gamma \\ v_D = V_\gamma & i_D \ge 0 \end{cases}$$

$$V_\gamma = 0.7 \text{ V}$$

Logica a Diodi

1) $V_A = V_B = 0\ \text{V}$



se $i_D \geq 0$ $v_D = V_\gamma$

$\Rightarrow$ $v_F = 2 i_D R > 0\ \text{V}$

ma $v_F + v_D = 0\ \text{V}$

$\Rightarrow$ $v_D = V_\gamma = -v_F < 0\ \text{V}$ Non è possibile!

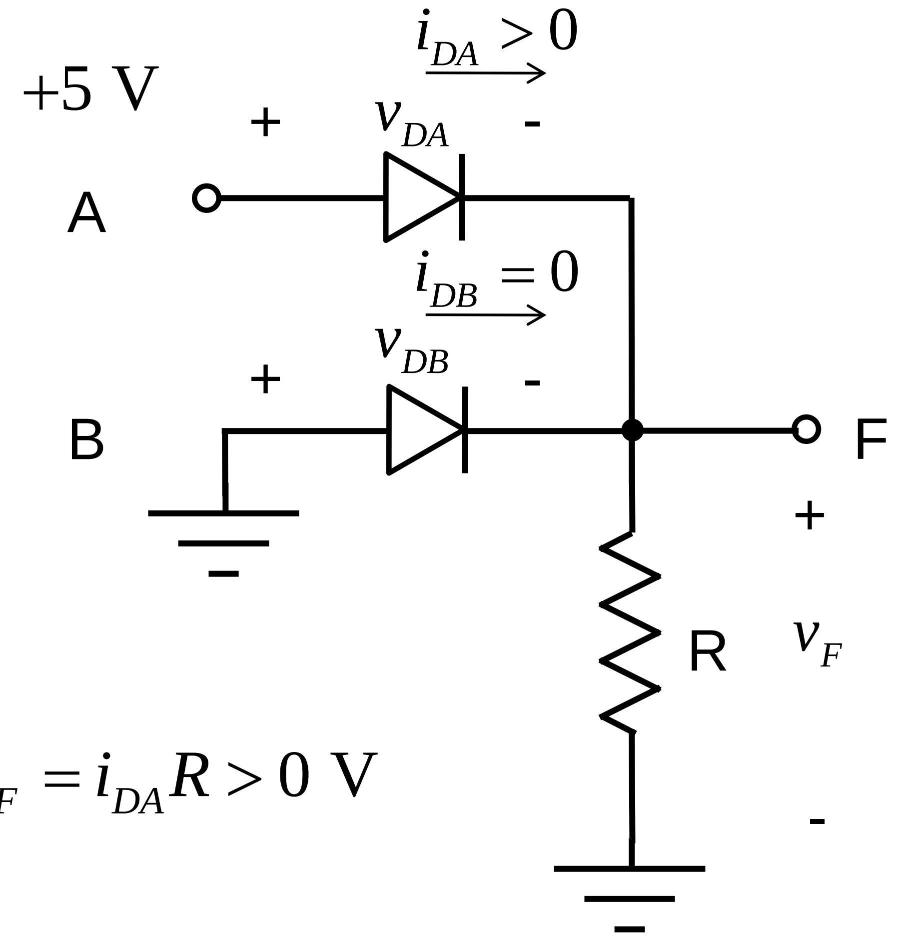
Allora: $v_D \leq V_\gamma$ $i_D = 0$ $\Rightarrow \boxed{v_F = 0\ \text{V}}$

OK

Logica a Diodi

2) $V_A = 5\ \text{V}$

$V_B = 0\ \text{V}$



se $\quad i_{DA} \geq 0 \quad v_{DA} = V_\gamma$

$\quad\;\; v_{DB} \leq V_\gamma \quad i_{DB} = 0$ $\quad \Rightarrow \quad v_F = i_{DA} R > 0\ \text{V}$

Allora $\quad v_{DB} = -v_F \leq V_\gamma \quad \Rightarrow \quad \boxed{v_F = 5\ \text{V} - V_\gamma = 4.3\ \text{V}}$

OK

Logica a Diodi

3) $V_A = 0 \text{ V}$

$V_B = 5 \text{ V}$ $\Rightarrow \boxed{v_F = 4.3 \text{ V}}$ Analogo al caso 2)

4) $V_A = V_B = 5\text{V}$

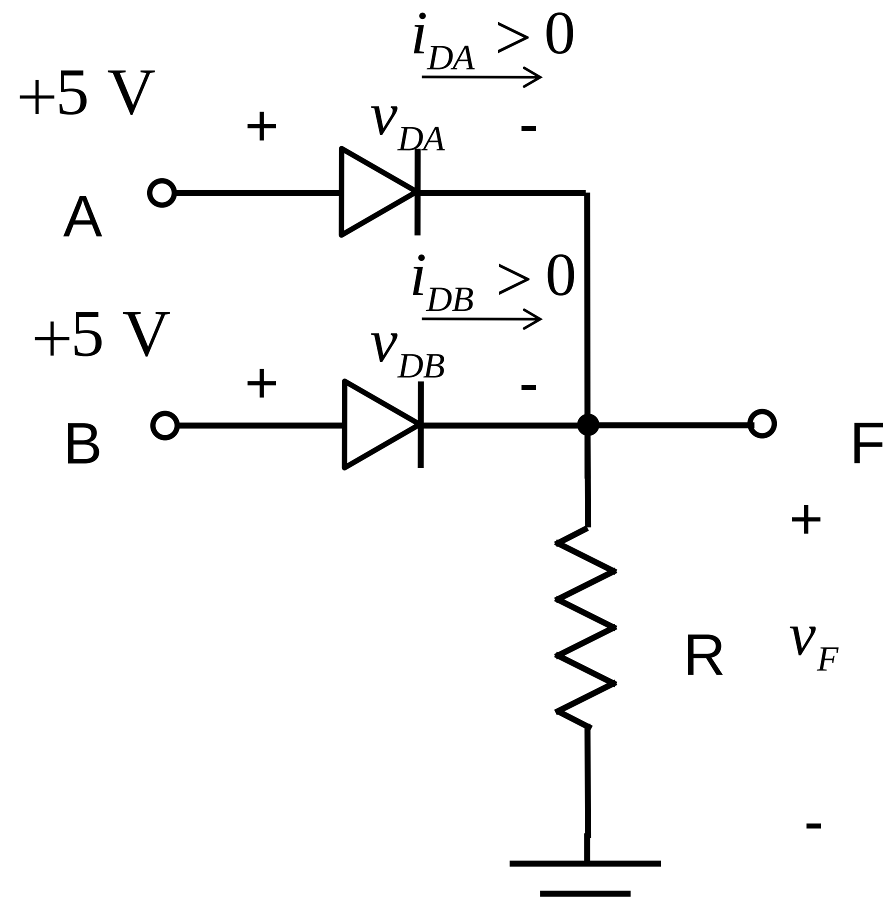
se $i_{DA} \geq 0 \quad v_{DA} = V_\gamma$

$i_{DB} \geq 0 \quad v_{DB} = V_\gamma$

$$\Rightarrow \boxed{v_F = 5 \text{ V} - V_\gamma = 4.3 \text{ V}} > 0$$

$$v_F = 2 i_{DA} R > 0 \text{ V}$$

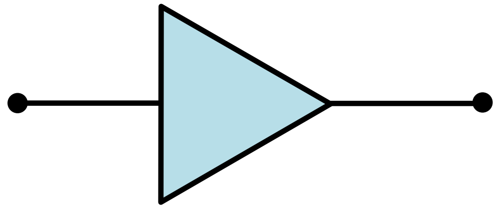
OK



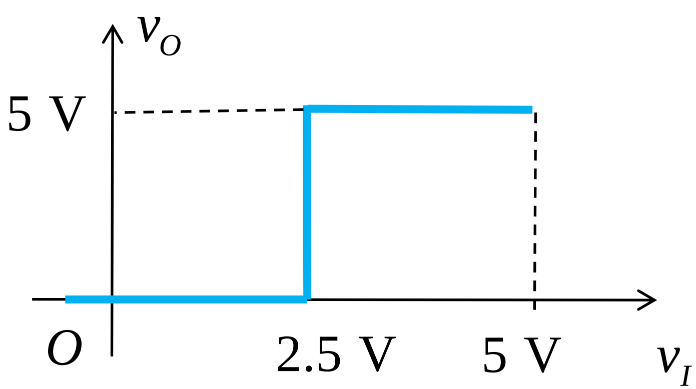
Logica a Diodi

V_A	V_B	v_F	Caso ideale $V_\gamma = 0$
0 V	0 V	0 V	0 V
5 V	0 V	4.3 V	5 V
0 V	5 V	4.3 V	5 V
5 V	5 V	4.3 V	5 V

- Si ha una riduzione del livello in uscita a causa di V_γ
- Per ripristinare il livello di 5 V in uscita è necessario un circuito amplificatore

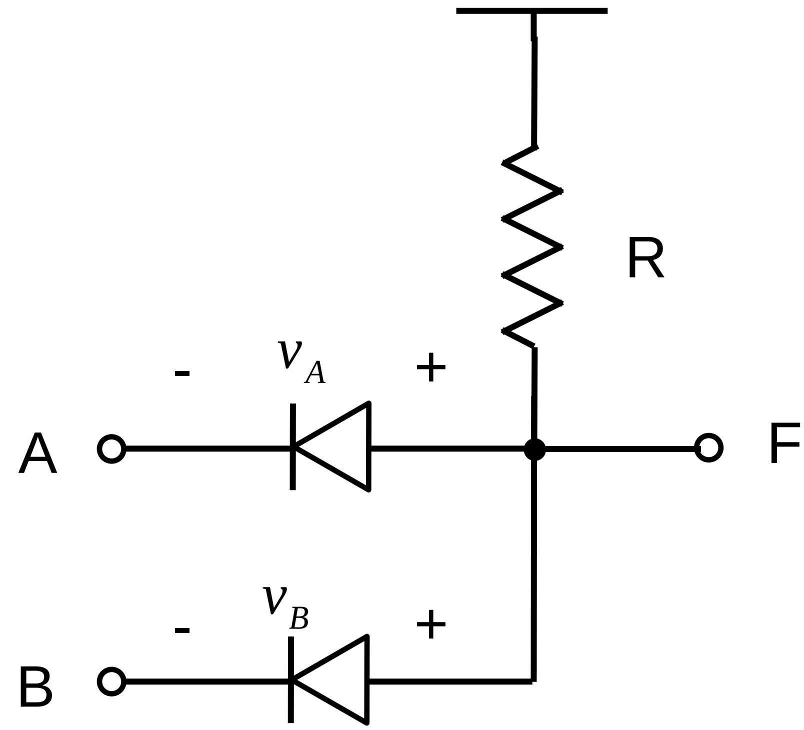


$$\begin{cases} v_O = 0\ \text{V}, & v_I < 2.5\ \text{V} \\ v_O = 5\ \text{V}, & v_I \geq 2.5\ \text{V} \end{cases}$$

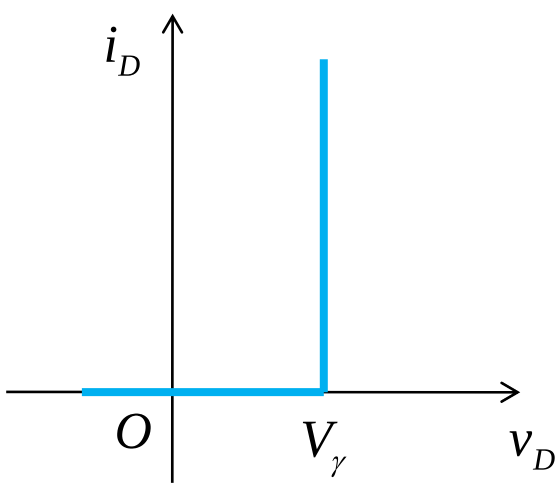


Logica a Diodi

Porta AND



$$V = 0\ \text{V} \quad \Leftrightarrow \quad 0\ \text{logico}$$
$$V = 5\ \text{V} \quad \Leftrightarrow \quad 1\ \text{logico}$$



$$\begin{cases} i_D = 0 & v_D \le V_\gamma \\ v_D = V_\gamma & i_D \ge 0 \end{cases}$$

$$V_\gamma = 0.7\ \text{V}$$

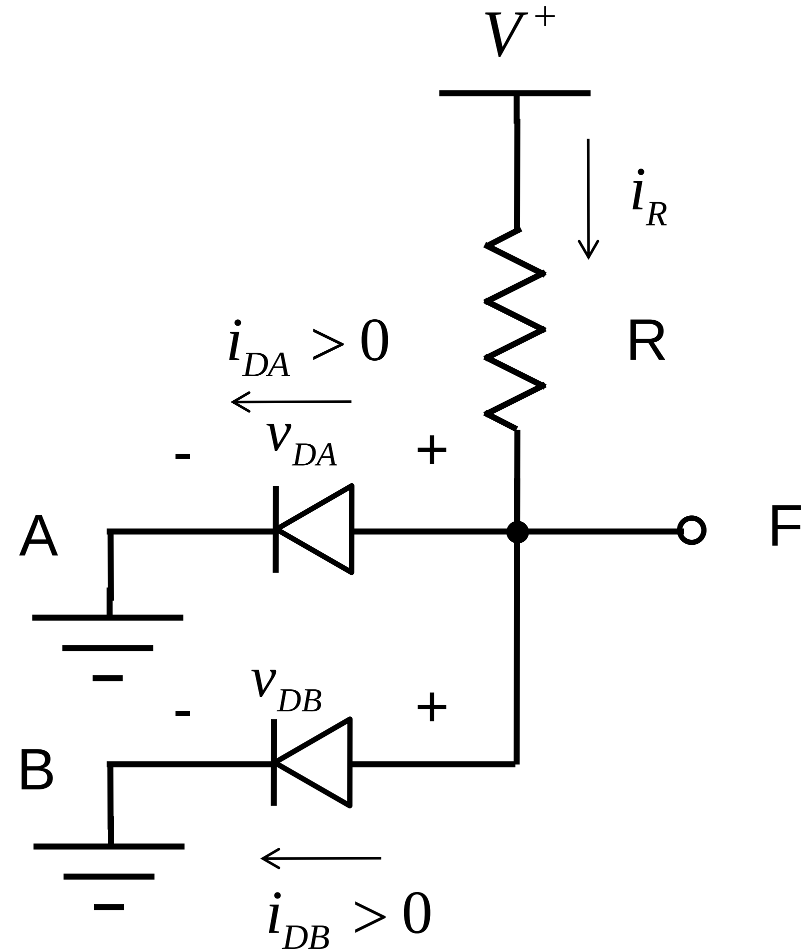
Logica a Diodi

1) $V_A = V_B = 0 \text{ V}$

$$i_{DA}\ ,\ \ i_{DB} \geq 0 \quad \Rightarrow \quad D_A\,,\ D_B \ \rightarrow \ \text{ON}$$

$$i_{DA} = i_{DB} = i_D$$

$$v_{DA} = v_{DB} = V_\gamma = v_F \qquad \boxed{v_F = 0.7 \text{ V}}$$



$$i_R = \frac{V^+ - v_F}{R} = \frac{V^+ - V_\gamma}{R} = 2 i_D > 0$$

OK

Logica a Diodi

2) $V_A = 5\ \text{V}$

$V_B = 0\ \text{V}$

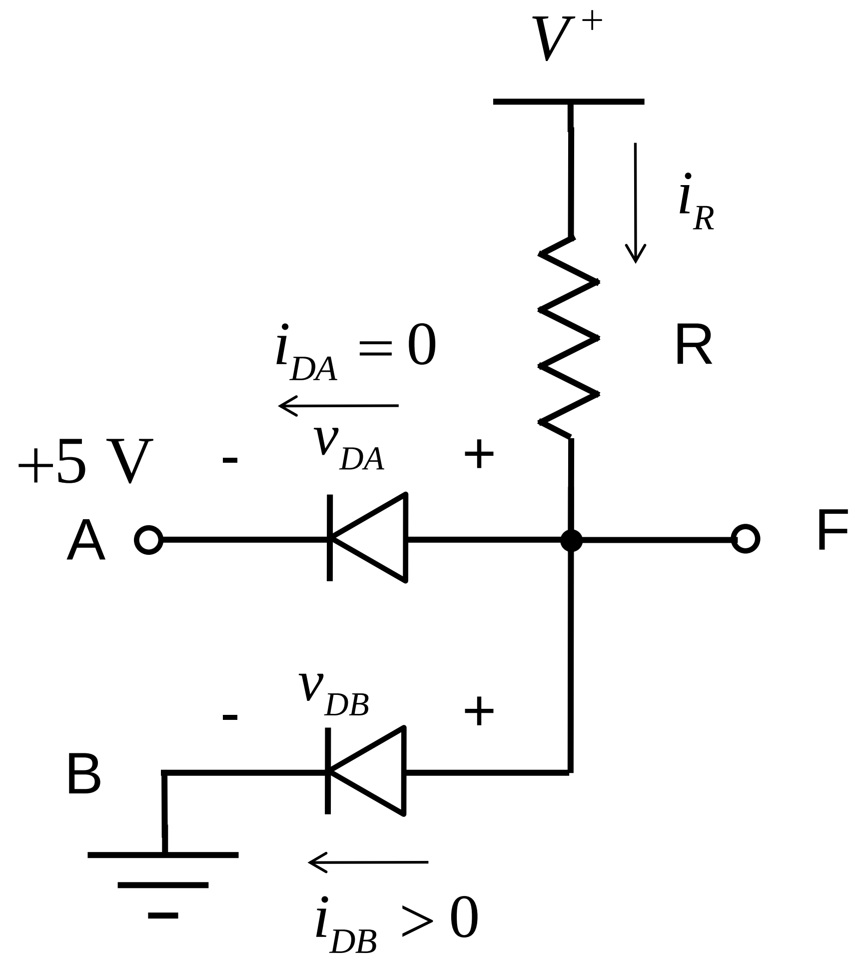
$i_{DB} \geq 0 \qquad v_{DB} = V_\gamma \quad D_B \rightarrow \text{ON}$

$v_{DA} = v_F - V^+ < 0 \Rightarrow \quad D_A \rightarrow \text{OFF}$

$v_F = V_\gamma$

$$i_R = \frac{V^+ - V_\gamma}{R} = i_{DB} > 0$$

$$\boxed{v_F = 0.7\ \text{V}}$$



OK

Logica a Diodi

3) $V_A = 0\ \text{V}$

$V_B = 5\ \text{V}$

$$\boxed{v_F = V_\gamma = 0.7\ \text{V}}$$

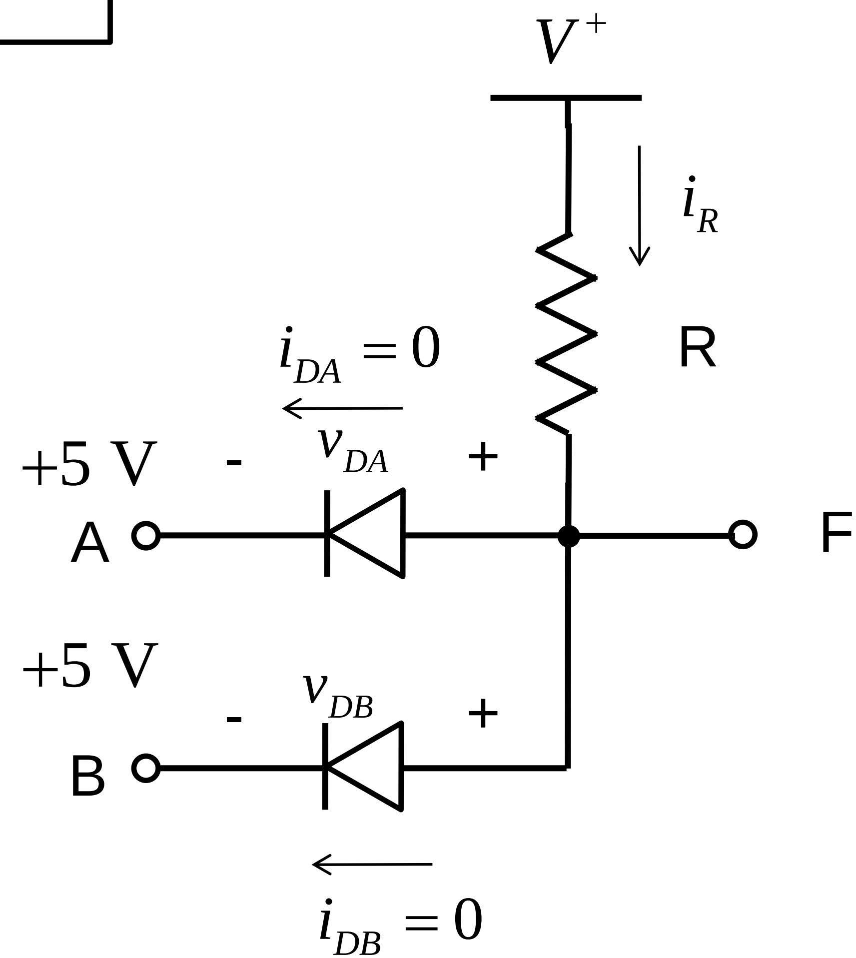
4) $V_A = V_B = 5\,\text{V}$

$$v_{DA},\ v_{DB} < V_\gamma$$

$$\Rightarrow\quad D_A\ ,\ D_B \rightarrow \text{OFF}$$

$$i_{DA} = i_{DB} = 0 = i_R$$

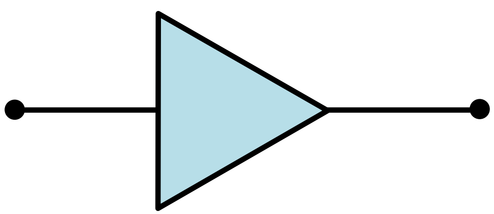
$$\boxed{v_F = V^+ = 5\ \text{V}}$$



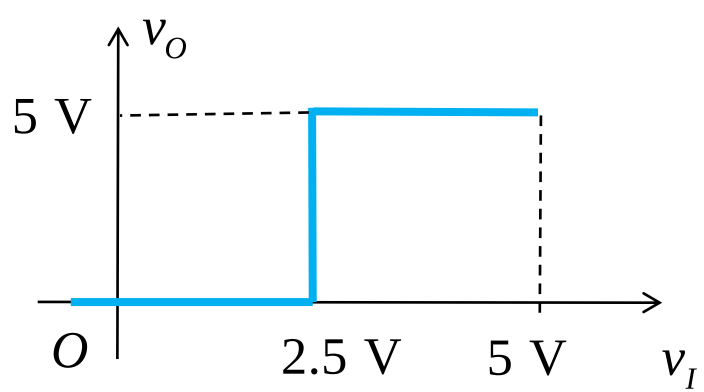
OK

Logica a Diodi

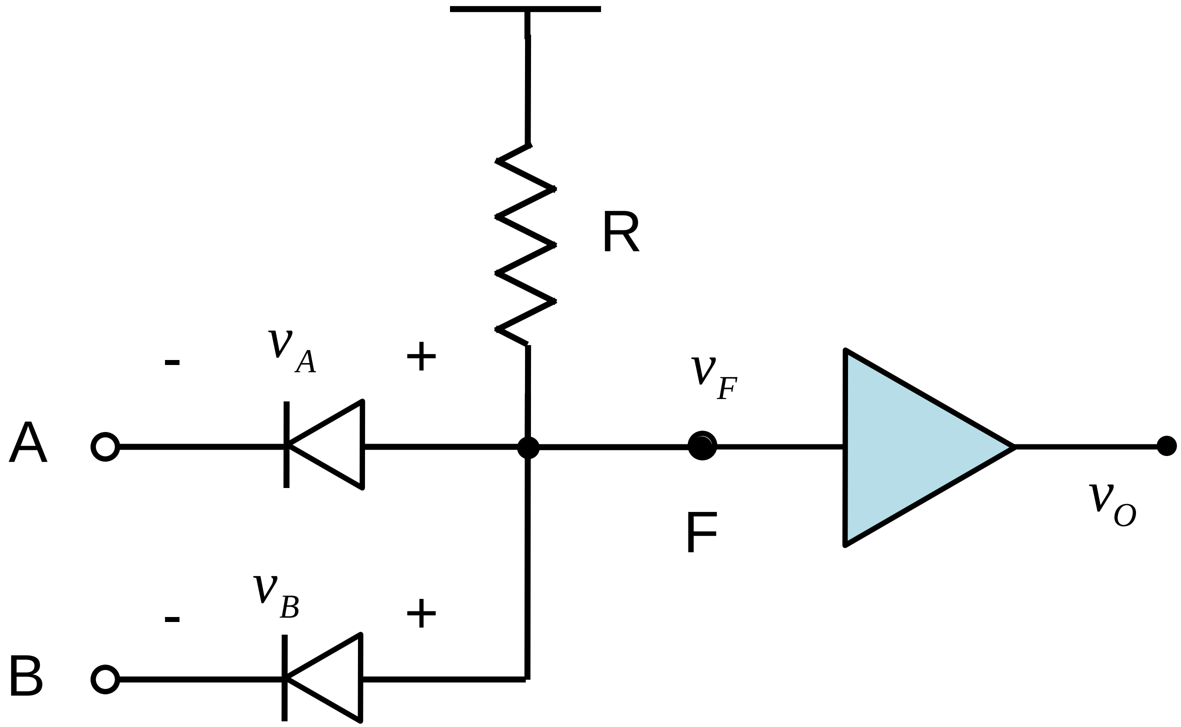
V_A	V_B	v_F	Caso ideale $V_\gamma = 0$
0 V	0 V	0.7 V	0 V
5 V	0 V	0.7 V	0 V
0 V	5 V	0.7 V	0 V
5 V	5 V	5 V	5 V

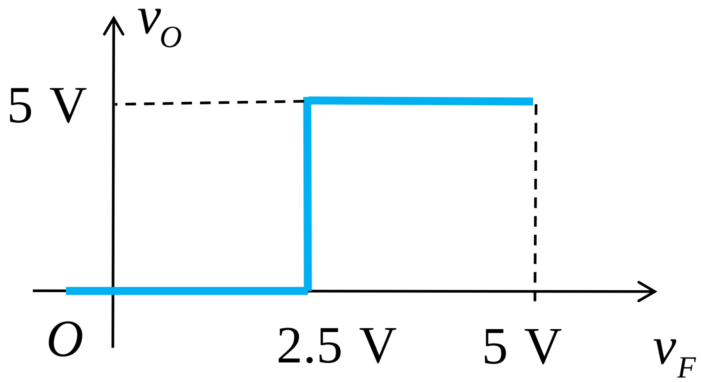


$$\begin{cases} v_O = 0\ \text{V}\ , & v_I < 2.5\ \text{V} \\ v_O = 5\ \text{V}\ , & v_I \geq 2.5\ \text{V} \end{cases}$$



Logica a Diodi





V_A	V_B	v_O
0 V	0 V	0 V
5 V	0 V	0 V
0 V	5 V	0 V
5 V	5 V	5 V

- L'insieme AND, OR non è completo:
- Si deve realizzare il NOT (amplificatore invertente)

Il Diodo: Dipendenza della Temperatura

$$i_D = I_D \qquad v_D = V_T \ln\left(\frac{I_D}{I_S}\right) = \frac{kT}{q}\ln\left(\frac{I_D}{I_S}\right)$$

$$\frac{dv_D}{dT} = \frac{v_D}{T} - V_T \frac{I_S}{I_D}\frac{I_D}{I_S^2}\frac{dI_S}{dT} = \frac{v_D}{T} - V_T\left(\frac{1}{I_S}\frac{dI_S}{dT}\right)$$

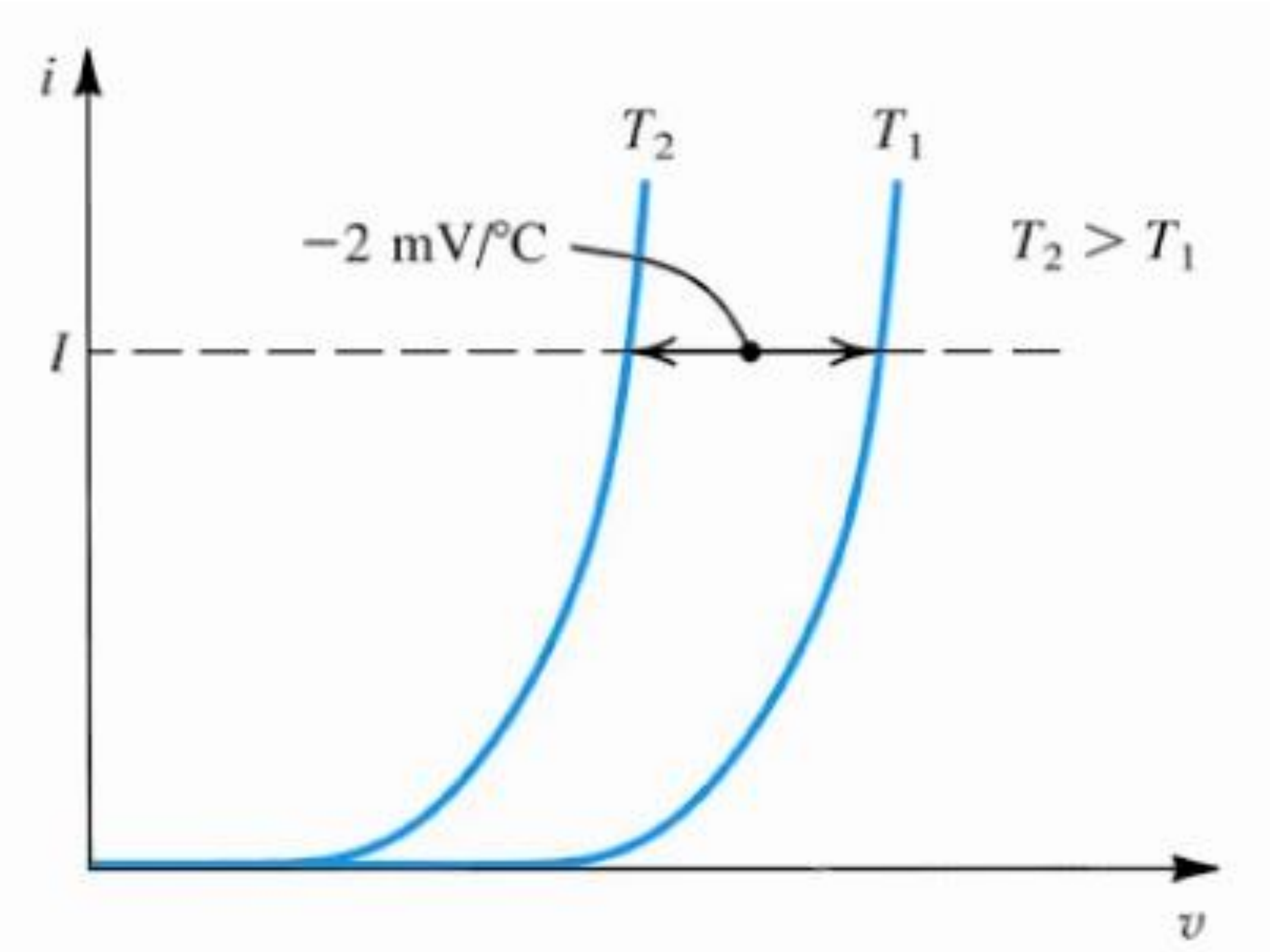
$$= \frac{v_D}{T} - \frac{3V_T}{T} - \frac{V_G}{T} = -\frac{V_G - v_D}{T} - \frac{3V_T}{T}$$

$$V_G = E_G/q \qquad v_D \approx V_D = 0.6\ \text{V} \qquad E_G = 1.12\ \text{eV}$$

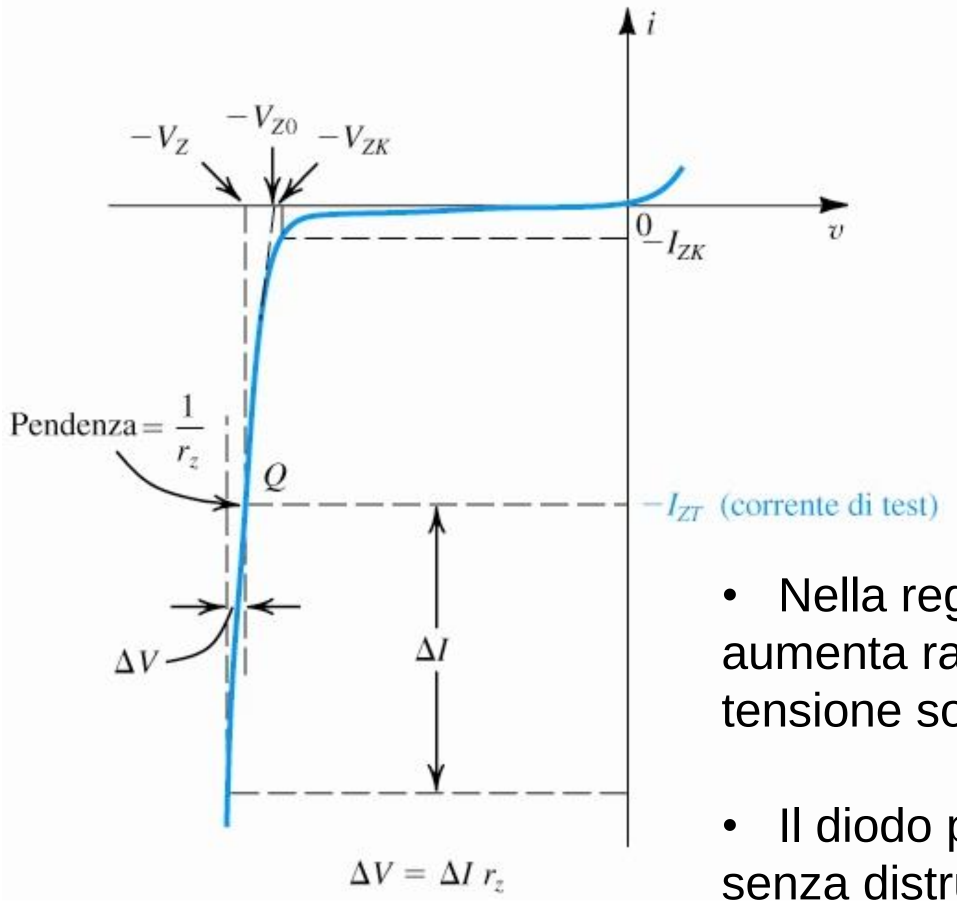
per $T = 300\ \text{K}$

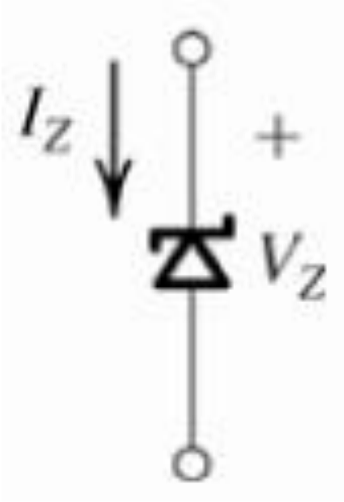
$$\boxed{\frac{dv_D}{dT} = -2.3\ \text{mV/°C}}$$

Il Diodo: Dipendenza della Temperatura



Il Diodo Zener



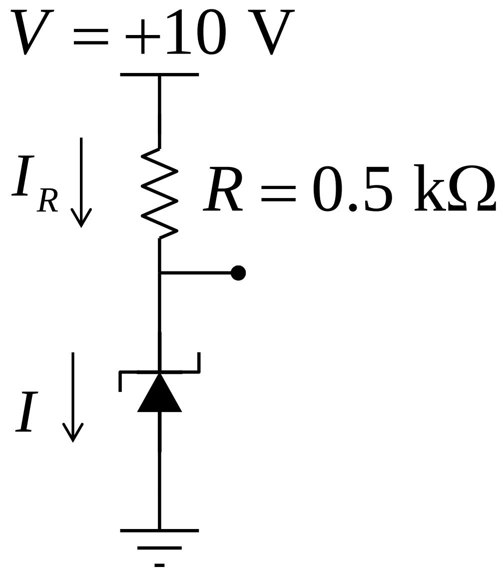


- Nella regione di breakdown la corrente inversa aumenta rapidamente e i corrispondenti incrementi di tensione sono molto piccoli;

- Il diodo può lavorare nella regione di breakdown senza distruggersi, purché la potenza dissipata nel diodo venga opportunamente limitata da un circuito esterno ad un livello di guardia (il suo valore viene specificato nel data-sheet);

- I diodi che vengono costruiti appositamente per lavorare in questa regione vengono detti “**diodi zener**”.

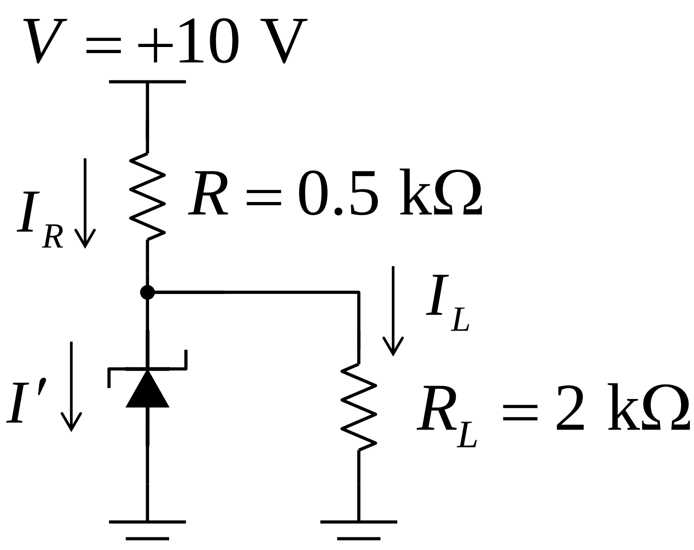
Il Diodo Zener come Regolatore di Tensione



$$V_{ZK} = 6.8\ \text{V}$$

$$I = \frac{10 - 6.8}{0.5 \cdot 10^3} = 6.4\ \text{mA}$$

- Inseriamo un carico R_L

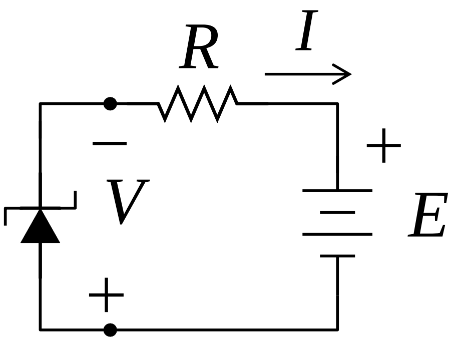


$$I_L = \frac{6.8}{2 \cdot 10^3} = 3.4\ \text{mA} \qquad V_Z \cong V_{ZK} = 6.8\ \text{V}$$

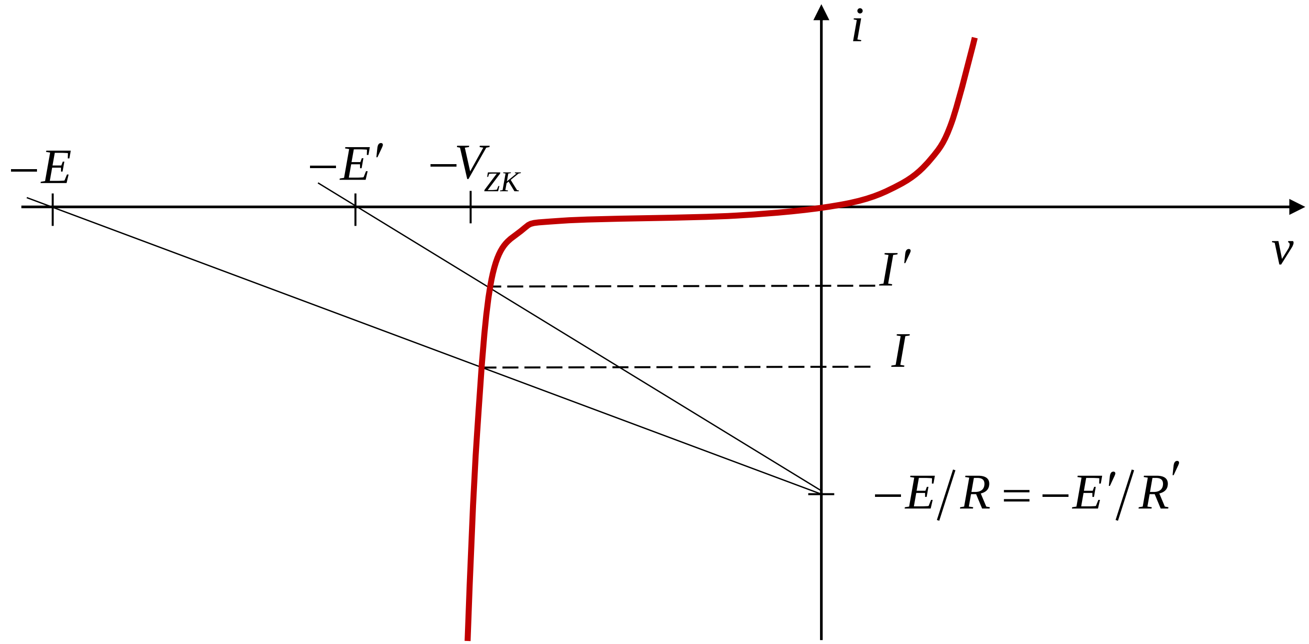
La corrente sul diodo cambia

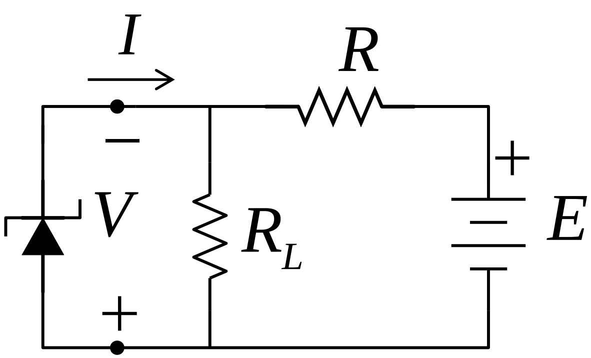
$$I' = I_R - I_L = 6.4 - 3.4 = 3\ \text{mA} \qquad I' < I$$

Il Diodo Zener come Regolatore di Tensione

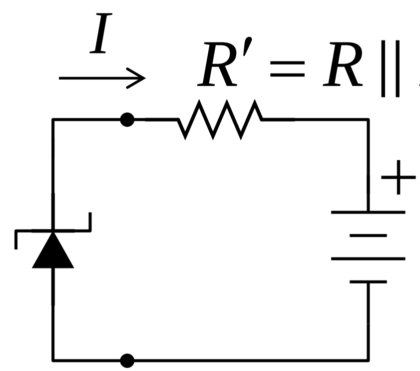


$$I = -\frac{V+E}{R}$$





$\Rightarrow$



$$R' = R \,||\, R_L = \frac{RR_L}{R+R_L}$$

$$E' = E\frac{R_L}{R+R_L}$$

$$I = -\frac{V+E'}{R'}$$

$$R' < R$$

$$E' < E$$

$$\frac{E'}{R'} = E\frac{R_L}{R+R_L}\frac{R+R_L}{RR_L} = \frac{E}{R}$$

Convenzioni sulle Notazioni

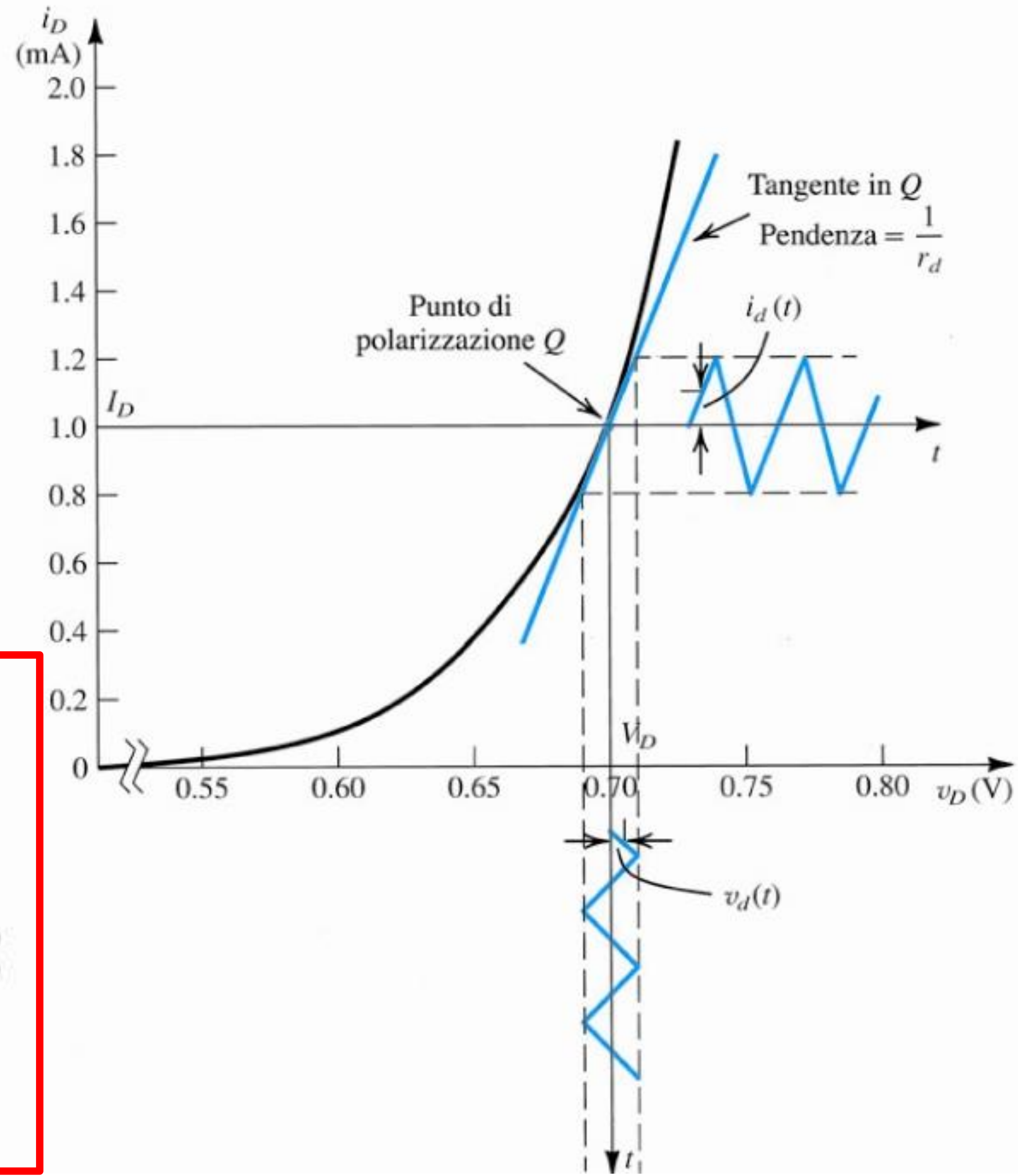
$$i_D = I_D + i_d$$

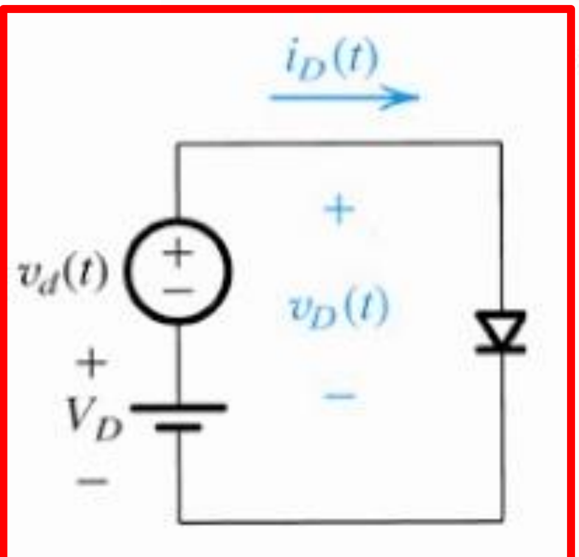
$$v_{AB} = V_{AB} + v_{ab}$$

$$i_D(t) = I_{D,0} + i_d(t)$$

$$v_{AB}(t) = V_{AB,0} + v_{ab}(t)$$

Il Diodo: Circuito alle Variazioni





Il Diodo: Circuito alle Variazioni

Regione di polarizzazione diretta: $$\boxed{I_D = I_S e^{V_D/nV_T}}$$

$$v_D(t) = V_D + v_d(t) \qquad i_D(t) = I_D + i_d(t)$$

$$i_D(t) = I_S e^{v_D(t)/nV_T}$$

$$i_D(t) = I_S e^{(V_D + v_d(t))/nV_T}$$

$$V_T = \frac{kT}{q}$$

$$i_D(t) = I_S e^{V_D/nV_T} e^{v_d(t)/nV_T}$$

$$i_D(t) = I_D e^{v_d(t)/nV_T}$$

Approssimazione di piccolo segnale

$$\frac{v_d(t)}{nV_T} \ll 1 \quad \overset{e^x \approx 1 + x}{\Rightarrow} \quad i_D(t) \simeq I_D\left(1 + \frac{v_d(t)}{nV_T}\right)$$

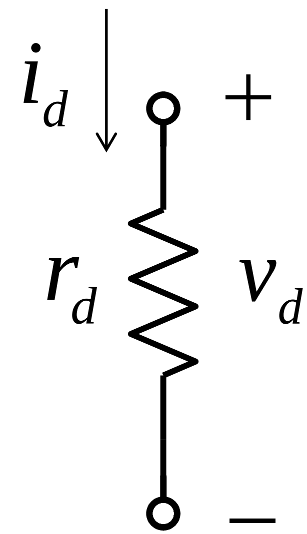
Il Diodo: Circuito alle Variazioni

$$i_D(t) = I_D + \frac{I_D}{nV_T} v_d(t)$$

$$i_D(t) = I_D + i_d(t)$$

$$\boxed{i_d(t) = \frac{I_D}{nV_T} v_d(t)}$$

MODELLO DEL DIODO PER PICCOLO SEGNALE



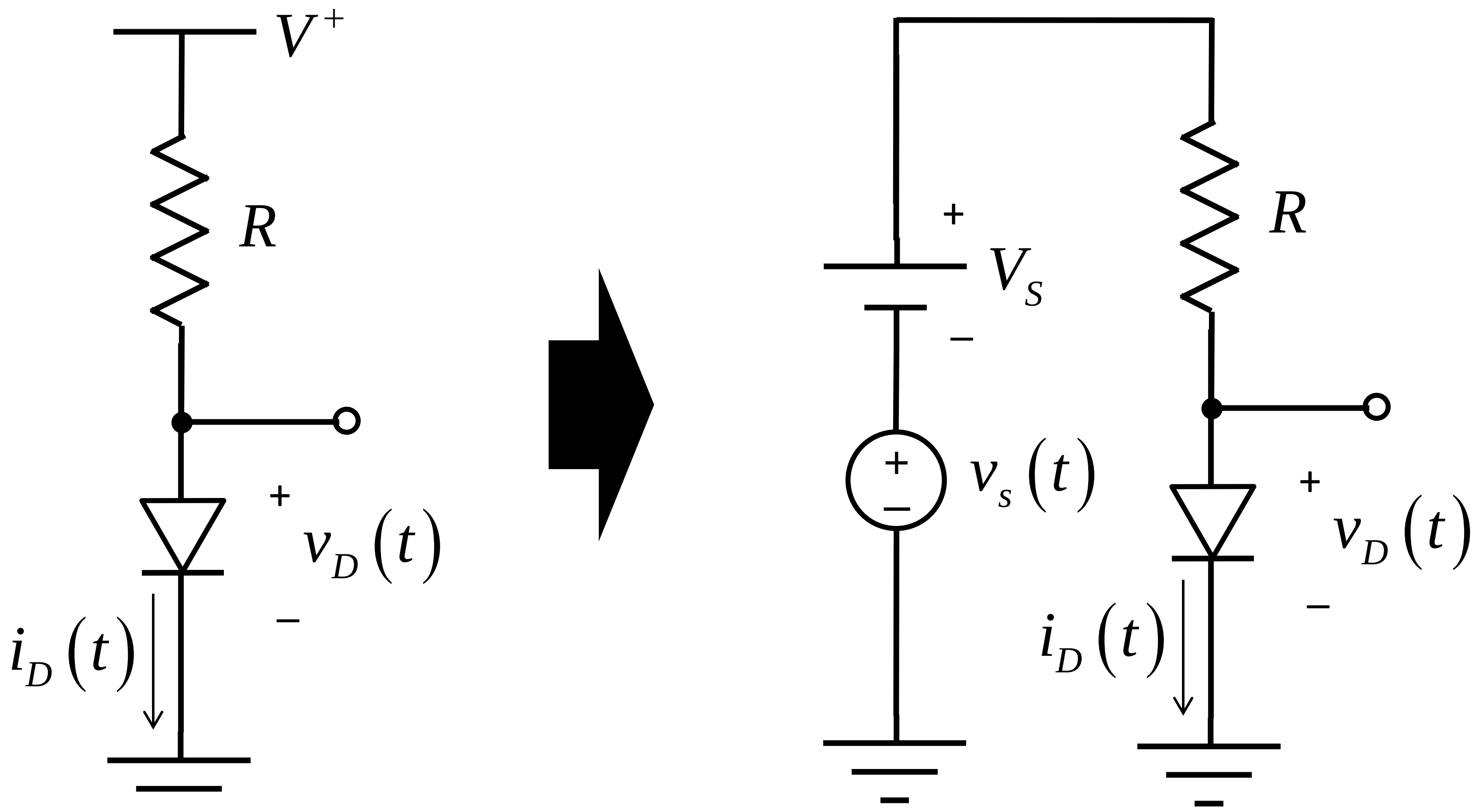
Resistenza del diodo per piccolo segnale o resistenza differenziale

$$\boxed{r_d = \frac{nV_T}{I_D}}$$

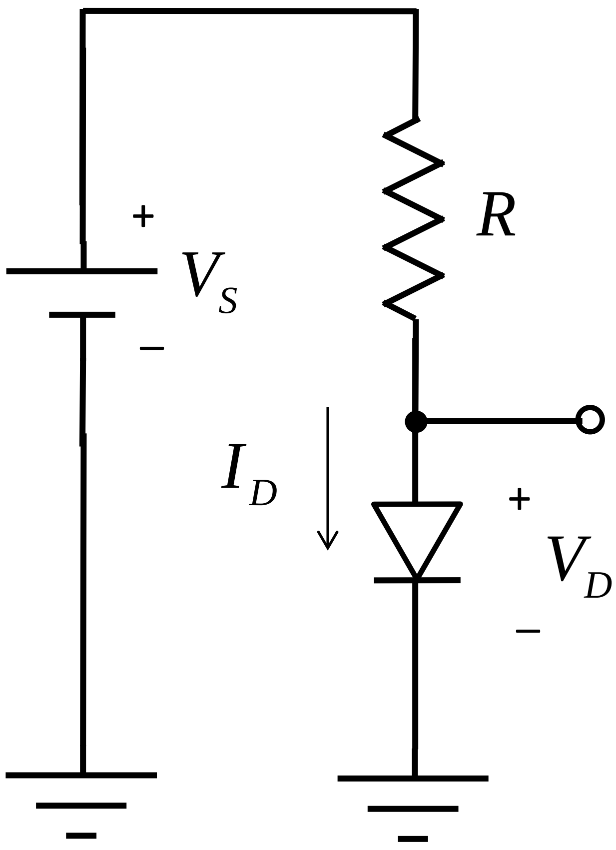
$$\boxed{r_d = 1 \Big/ \left[\frac{\partial i_D}{\partial v_D}\right]_{i_D = I_D}}$$

Il Diodo: Analisi Circuitale Completa

- Si consideri il circuito riportato qui sotto nel caso in cui sia R = 10 kΩ. L'alimentazione V^+ fornisce una tensione continua di 10 V sulla quale è sovrapposta una sinusoide a 60 Hz con ampiezza di picco di 1 V (tale componente di segnale della tensione di alimentazione è un'imperfezione del progetto dell'alimentatore ed è conosciuta come ***ripple*** (ondeggiamento) dell'alimentazione).
- Calcolare sia la tensione in continua del diodo che il segnale sinusoidale che si presenta ai suoi capi. Si ipotizzi che il diodo abbia una caduta di tensione di 0.7 V in corrispondenza di una corrente di 1 mA e che sia *n* = 2.



Il Diodo: Analisi del Circuito in DC



$$v_s(t) = 0 \qquad R = 10\ \text{k}\Omega$$

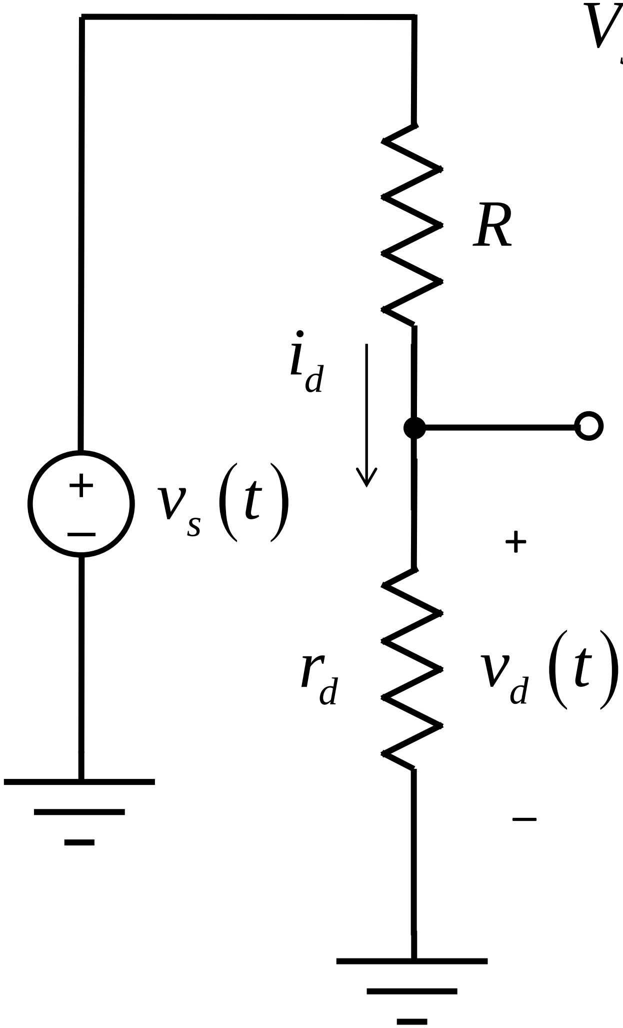
$$V_S = V^+ = 10\ \text{V}$$

$$V_D = V_\gamma = 0.7\ \text{V}$$

$$I_D = \frac{V^+ - V_\gamma}{R} = \frac{10 - 0.7}{10 \cdot 10^{-3}} = 0.93\ \text{mA}$$

soluzione in DC (punto di riposo)

Il Diodo: Analisi del Circuito alle Variazioni



$$V_S = 0 \text{ V} \qquad I_{DQ} = I_D = 0.93 \text{ mA} \qquad R = 10 \text{ k}\Omega$$

$$v_s(t) = \hat{V}_s \sin(2\pi f_c t) \qquad f_c = 60 \text{ Hz}$$

$$r_d = \frac{nV_T}{I_D} = \frac{2 \cdot 25 \cdot 10^{-3}}{0.93 \cdot 10^{-3}} = 53.8\ \Omega$$

$$v_d(t) = \frac{r_d}{r_d + R} v_s(t) \qquad i_d(t) = \frac{v_s(t)}{r_d + R}$$

$$v_d(t) = \hat{v}_d \cdot \sin(2\pi f_c t)$$

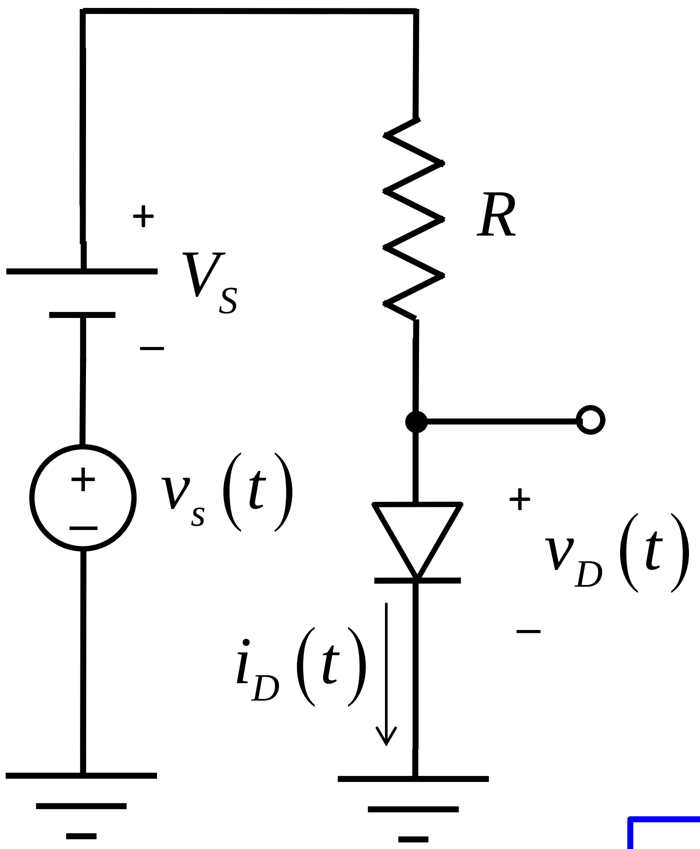
$$\hat{v}_d(picco) = \hat{V}_s \frac{r_d}{r_d + R} = 5.35 \text{ mV}$$

$$i_d(t) = \hat{i}_d \cdot \sin(2\pi f_c t)$$

$$\hat{i}_d(picco) = \frac{\hat{V}_s}{r_d + R} = 99.46\ \mu\text{A}$$

soluzione alle variazioni

Il Diodo: Analisi Completa



soluzione completa

$$v_D(t) = 0.7 + 5.35 \cdot 10^{-3} \sin(2\pi 60 t)$$

$$i_D(t) = 0.93 \cdot 10^{-3} + 99.46 \cdot 10^{-6} \sin(2\pi 60 t)$$