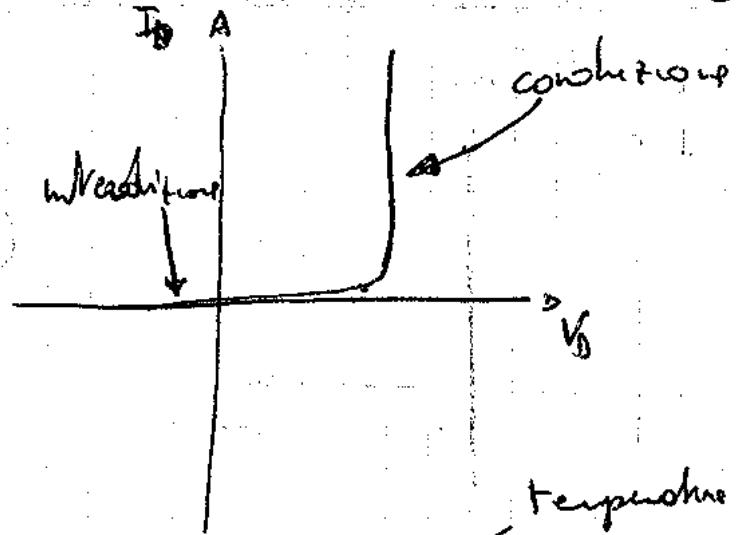
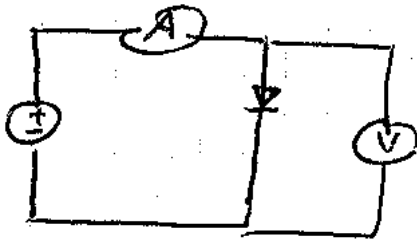
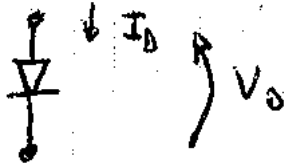


# DIODI

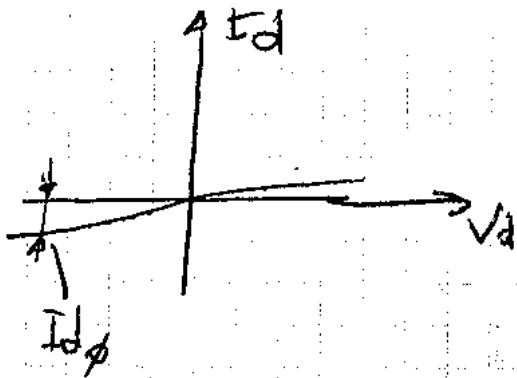


$$I_D = I_{D\phi} \left[ e^{\frac{V_D}{\eta V_T}} - 1 \right] \quad V_T = \frac{k_B T}{q} \text{ - carica elettrica}$$

$\eta$  fattore di idealità del diodo ( $1 < \eta < 2$ )  
 $\eta_{Si} \approx 1$

$I_{D\phi}$  corrente di saturazione inversa del diodo

$V_T$  equivalente in tensione della temperatura.  
 Zone inversione ( $V_T (27^\circ C) \approx 26 \text{ mV}$ )



Diodo aperto

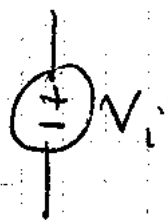
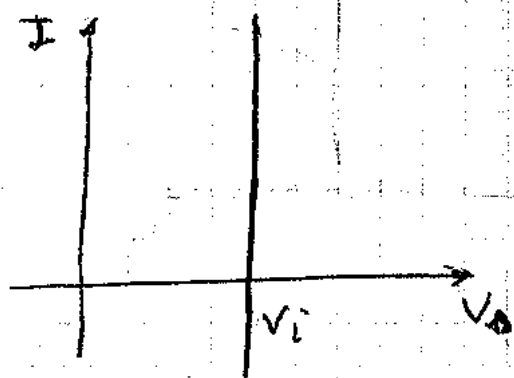
$$I_D = -I_{D\phi}$$

$$I_D \approx I_{D\phi} e^{\frac{V_D}{\eta V_T}}$$

$I_{D\phi}$  dipende da Area <sup>del diodo</sup> e temperatura.

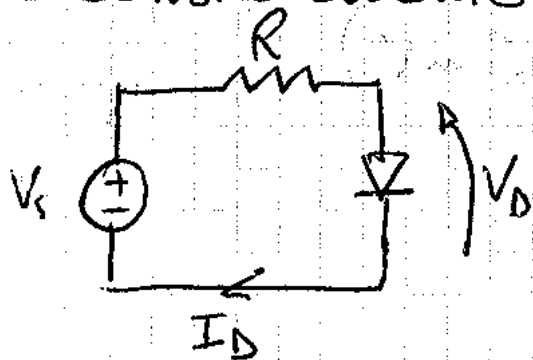
$$n \text{ A} < I_{D\phi} (27^\circ C) < \mu \text{ A}$$

il diodo anodico ad un generatore ideale di tensione



il diodo aperto si comporta quasi come un circuito aperto. Più opportuno emularlo ad un generatore di corrente  $I_{D\phi}$ .

Consideriamo il circuito



$$\begin{cases} I_D = I_{D\phi} \left[ \exp\left(\frac{V_D}{n V_T}\right) - 1 \right] \\ I_D = \frac{V_s - V_D}{R} \end{cases}$$

$$\frac{V_s}{R} - \frac{V_D}{R} = I_{D\phi} \left[ \exp\left(\frac{V_D}{n V_T}\right) - 1 \right]$$

Bisogna risolverlo per vie numerica.

Facciamo riferimento a spettro per ovviare al

problema.

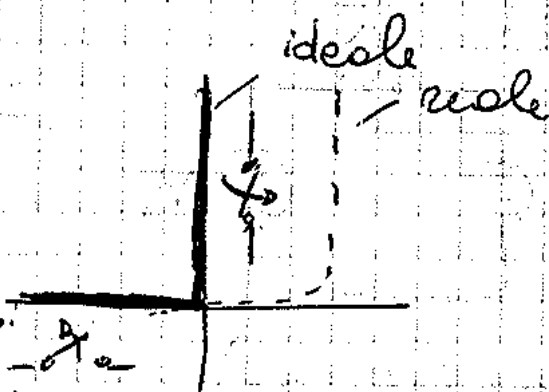
Modelli:

• Diodo ideale

$V_D < 0 \Rightarrow I_D = 0$

$V_D = 0 \Rightarrow I_D = \text{qualsiasi}$

$V_D > 0$  non ci sono correnti.



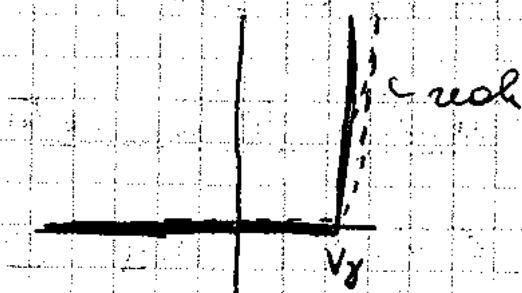
• Diodo a caduta di tensione

$V_D < V_g \Rightarrow I_D = 0$

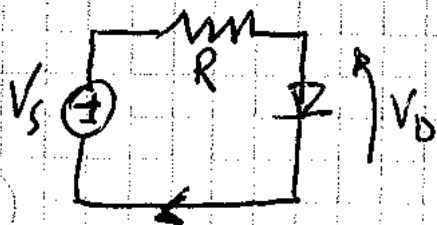
$V_D = V_g \Rightarrow I_D \text{ qualsiasi}$

$V_D > V_g$  non definito

$0,6 \text{ V} < V_g < 1 \text{ V}$



Analizziamo il circuito precedente con modello diodo ideale:

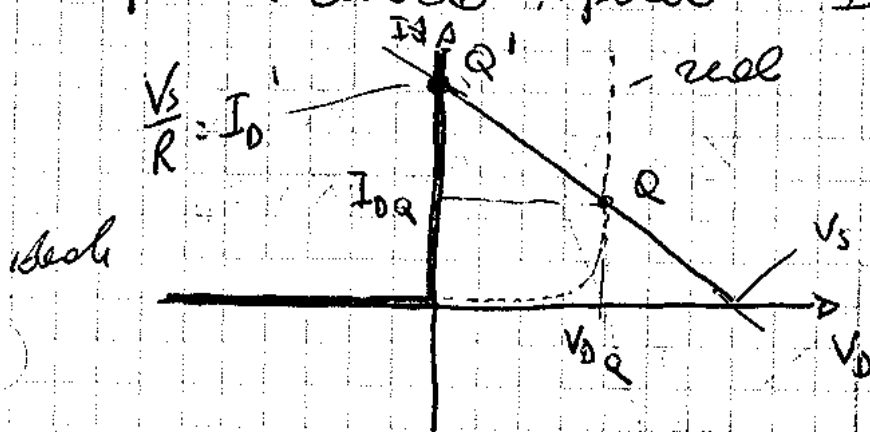


ipotesi: diodo eccesso in conduzione

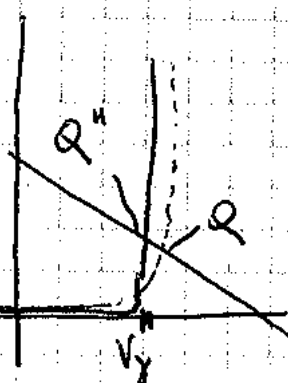
$I_D = \frac{V_s}{R}$

ipotesi: diodo aperto

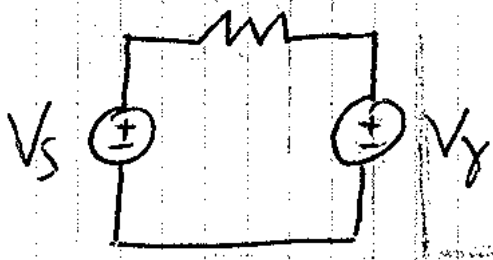
$I_D = 0 \quad V_D = V_s$



diodo e real di tensione



Se  $V_s > V_y$  passaggio di corrente all'interno del diodo



$$I_D'' = \frac{V_s - V_y}{R}$$

$$Q''(V_y, I_D'')$$

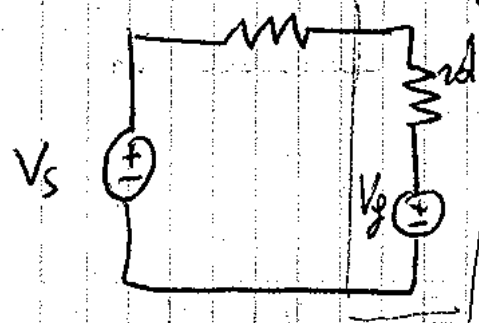
$0.6V < V_y < 1V$  diodi in commercio

Modello della retta tangente

$$V_D < V_g \Rightarrow I_D = 0$$

$$V_D \geq V_g \Rightarrow I_D = I_{D0} + g_D (V_D - V_g)$$

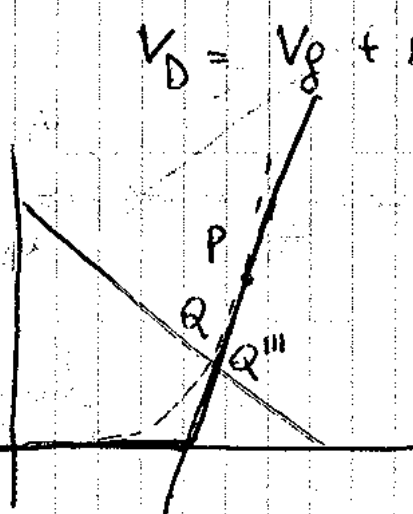
$$g_D = \left. \frac{\partial I_D}{\partial V_D} \right|_P = \frac{I_{D0}}{n V_T} \left( \frac{V_D}{n V_T} \right)$$



$$R_D = \frac{1}{g_D}$$

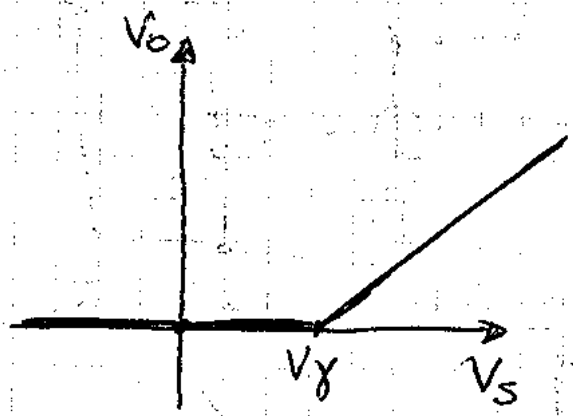
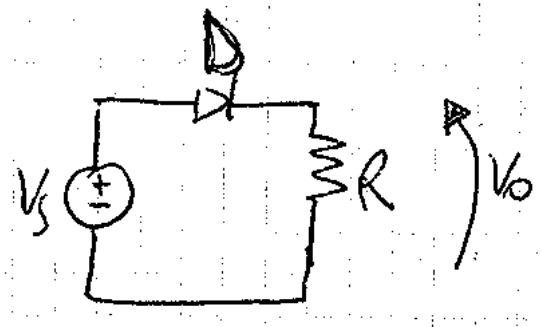
$$I_D = \frac{V_s - V_g}{R + R_D}$$

$$V_D = V_g + R_D \frac{V_s - V_g}{R + R_D}$$



In conduzione possiamo dire che (7)

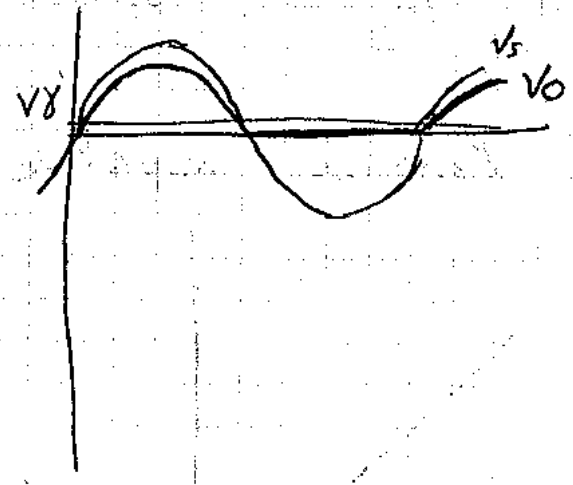
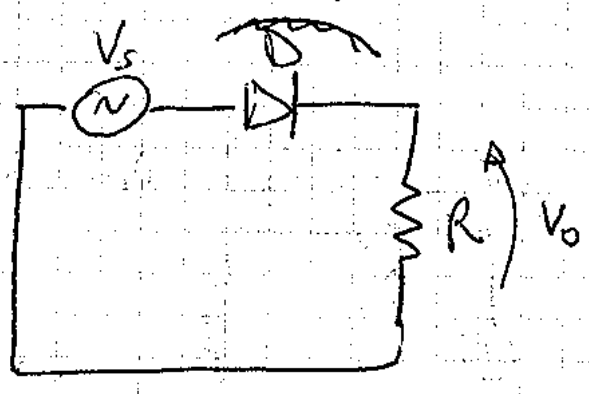
$$P_D \approx \frac{I_{DP}}{\eta V_T}$$



uso modello a caduta di tensione -

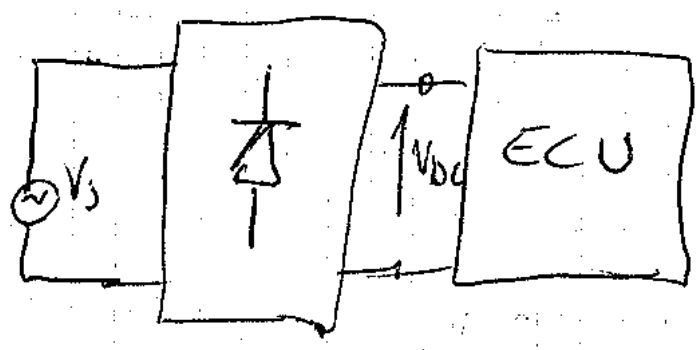
$$V_o = R I_D$$

$$V_o = V_s - V_\gamma \text{ se diodo in conduzione}$$

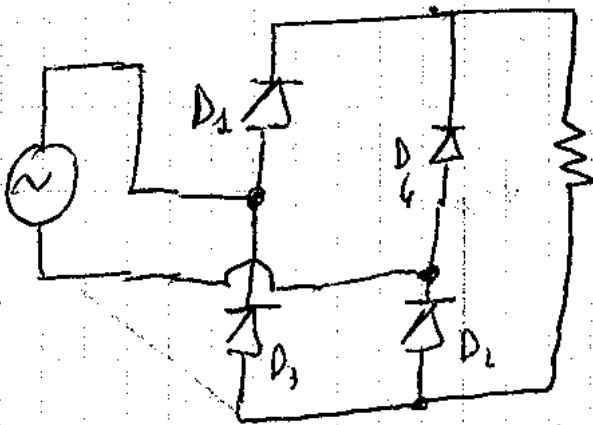


$$\overline{V_s} = 0 \quad \overline{V_o} \neq 0$$

Il diodo è utilizzato per addurre la corrente

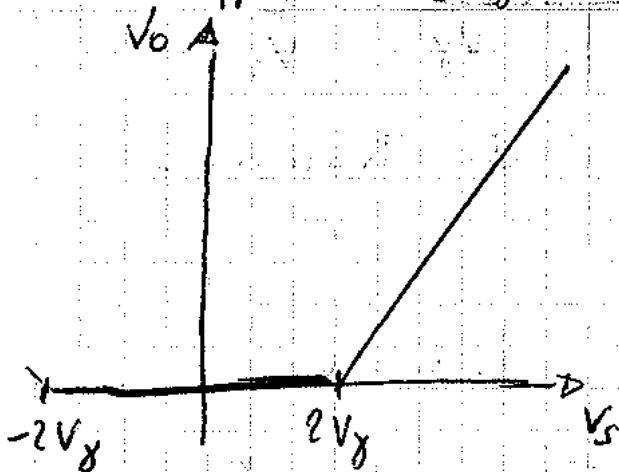


# Circuito rettificatore

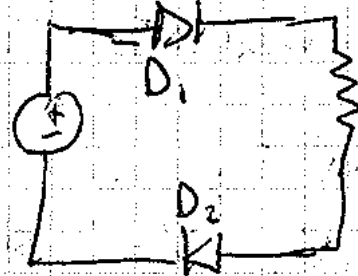


Rettificatore a  
doppie-semionde

Supponiamo  $V_s$  generatore di corrente costante.



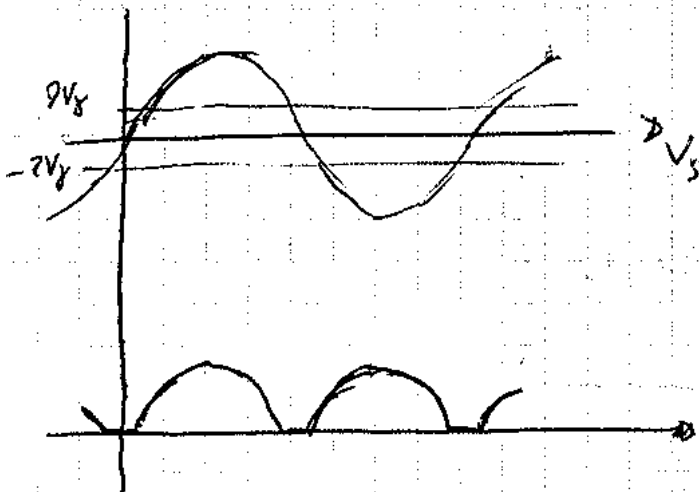
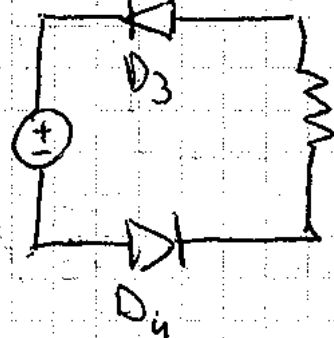
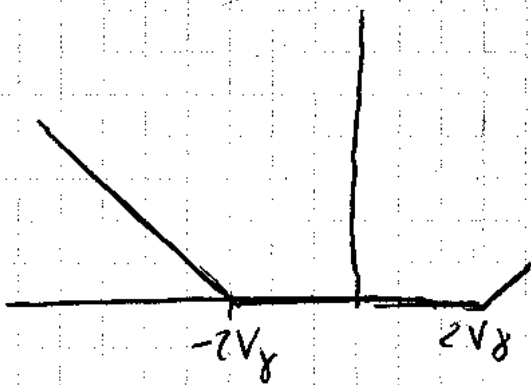
Superate  $2V_g$

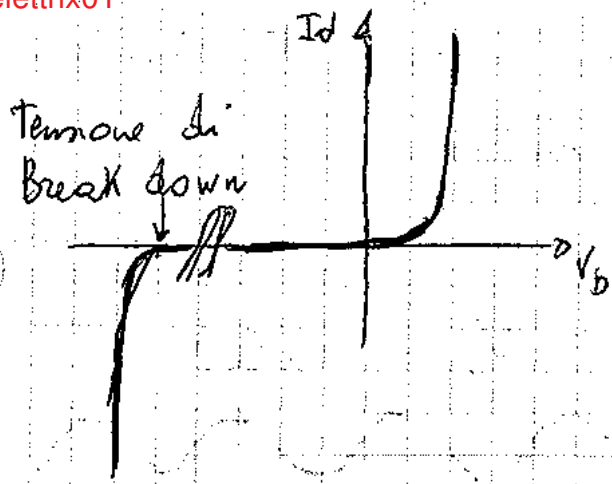


$V_o$   
 $V_o = V_s - 2V_g$

Per tensioni negative

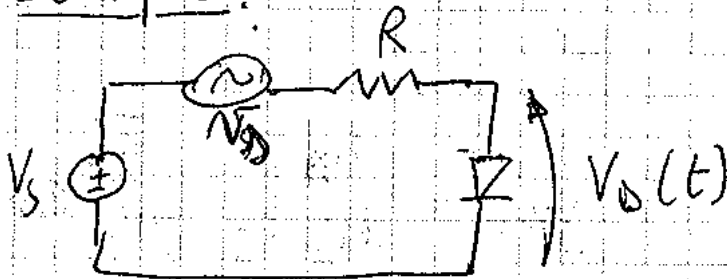
( $V_s < -2V_g$ )  $D_3 - D_4$  in cond.





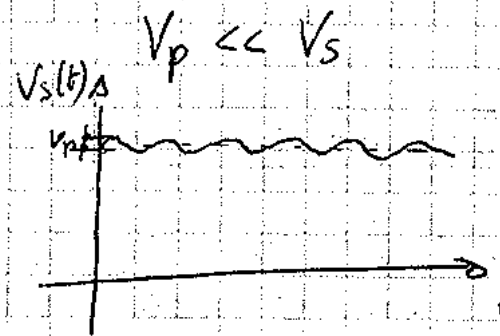
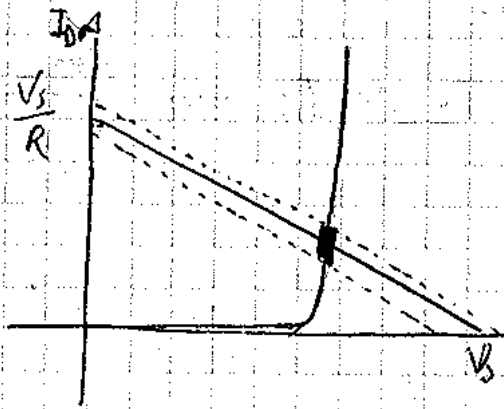
talvolta può essere utile descrivere il diodo mediante circuiti equivalenti semplificati

Esempio:



$$v_S = V_s + v_S(t)$$

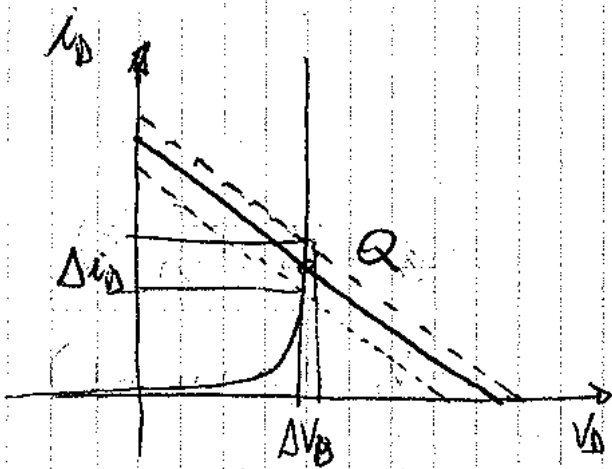
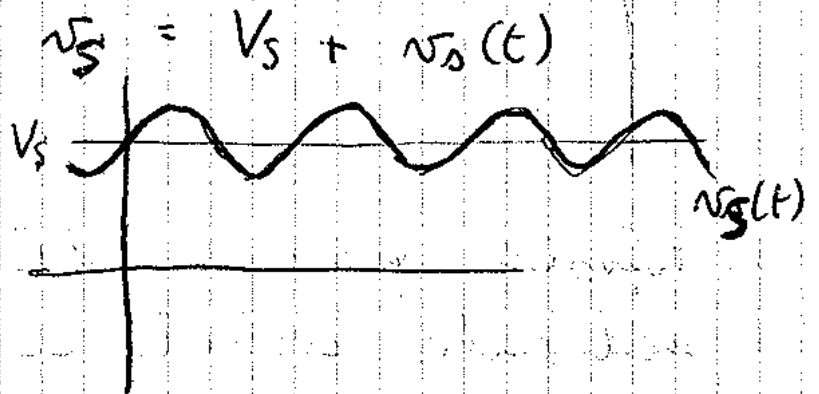
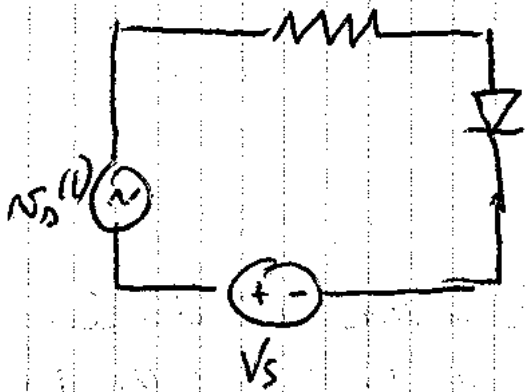
$$= V_s + V_p \sin(\omega t)$$



$\Delta V_s = 2V_p$  meglio trovare  $\Delta V_D$  approssimando con  
 rette rg.

$$\Delta V_D = \frac{r_D}{r_D + R} \Delta V_s$$

Esistono numerosi circuiti in cui il diodo non è usato come interruttore



$$I_D = \frac{V_s - V_D}{R}$$

$$g_{DQ} = \left. \frac{dI_D}{dV_D} \right|_Q = \frac{I_s}{\eta V_T} \exp\left(\frac{V_{DQ}}{\eta V_T}\right)$$

diodo in cond.

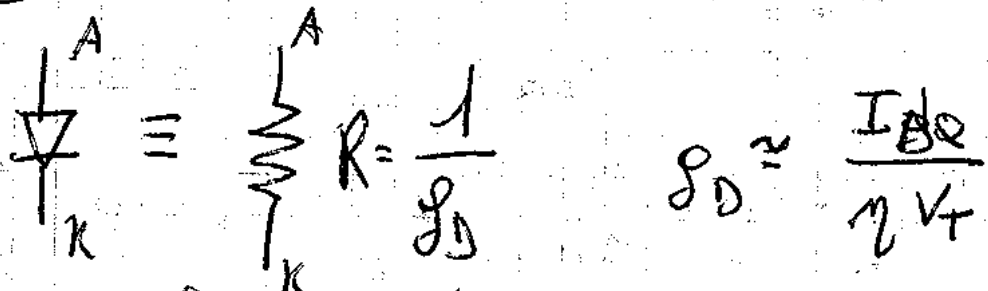
$$I_{DQ} \approx I_s \exp\left(\frac{V_{DQ}}{\eta V_T}\right)$$

## Analisi dei circuiti

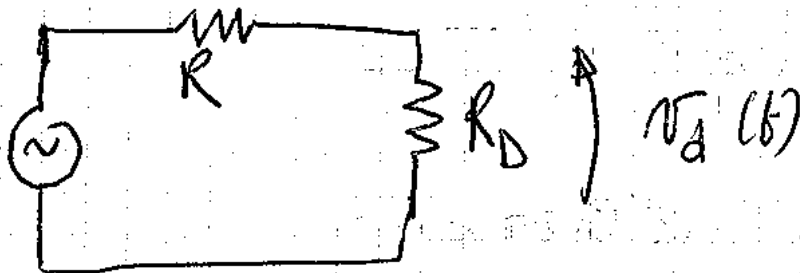
- ① Calcolo punto di lavoro dei componenti non lineari ( $E_s$ ,  $V_{DQ}$ ,  $I_{DQ}$ )
- ② Per calcolare le variazioni di tensione e di corrente in un diodo (o di un componente non lineare) posso usare un modello per le variazioni.



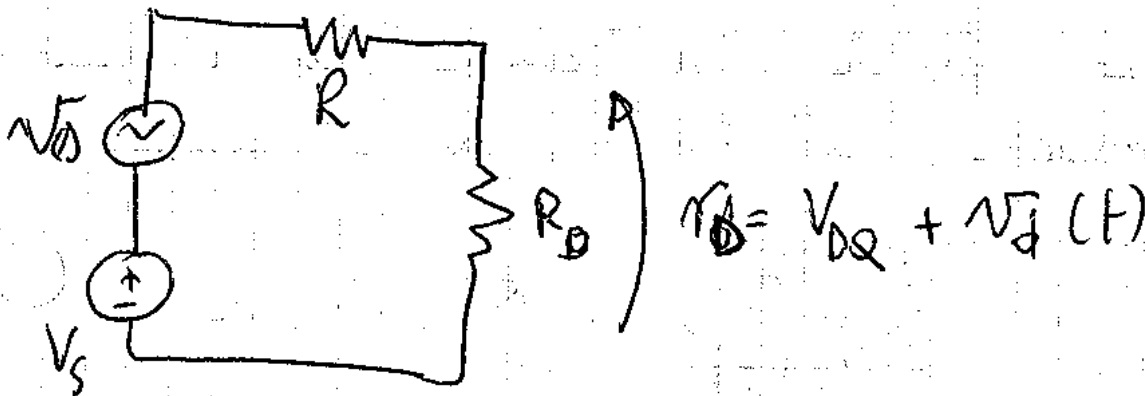
Modello di PICCOLO SEGNALE del DIODO:  
 se diodo polarizzato ed in conduzione  
 allora



Solo e fronte di una variazione.



$$v_d(t) = \frac{R_D}{R + R_D} v_s(t)$$



Limiti di validità:

Sappiamo che

$$i_D = I_S \left[ \exp\left(\frac{V_D}{\eta V_T}\right) - 1 \right] =$$

$$I_S \left[ \exp\left(\frac{V_{DQ}}{\eta V_T}\right) \exp\left(\frac{v_d(t)}{\eta V_T}\right) - 1 \right]$$

$$i_D \approx I_S \left[ \exp\left(\frac{V_{DQ}}{\eta V_T}\right) \left[ 1 + \frac{v_D(t)}{\eta V_T} + \frac{1}{2} \left(\frac{v_D(t)}{\eta V_T}\right)^2 + \dots \right] - 1 \right] =$$

$$= \overbrace{I_S \left[ \exp\left(\frac{V_{DQ}}{\eta V_T}\right) - 1 \right]}^{I_{DQ}} + \overbrace{I_S \exp\left(\frac{V_{DQ}}{\eta V_T}\right)}{\approx I_{DQ}} \left[ \frac{v_D(t)}{\eta V_T} + \frac{1}{2} \left(\frac{v_D(t)}{\eta V_T}\right)^2 + \dots \right]$$

Nel modello che utilizziamo

$$i_D \approx I_{DQ} + I_{DQ} \left[ \frac{v_D(t)}{\eta V_T} + \frac{1}{2} \left(\frac{v_D(t)}{\eta V_T}\right)^2 + \dots \right]$$

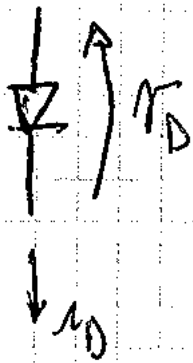
consideriamo solo il termine di 1° grado  
 è valido finché il termine di 1° grado  
 è  $\gg$  rispetto al termine di 2° grado

$$\frac{v_D(t)}{\eta V_T} \gg \frac{1}{2} \frac{v_D^2}{(\eta V_T)^2} \quad \text{Quindi se}$$

$$|v_D| \ll 2 \eta V_T$$

$$V_T|_{27^\circ\text{C}} \approx 26 \text{ mV} \quad \eta|_{\text{Si}} = 1$$

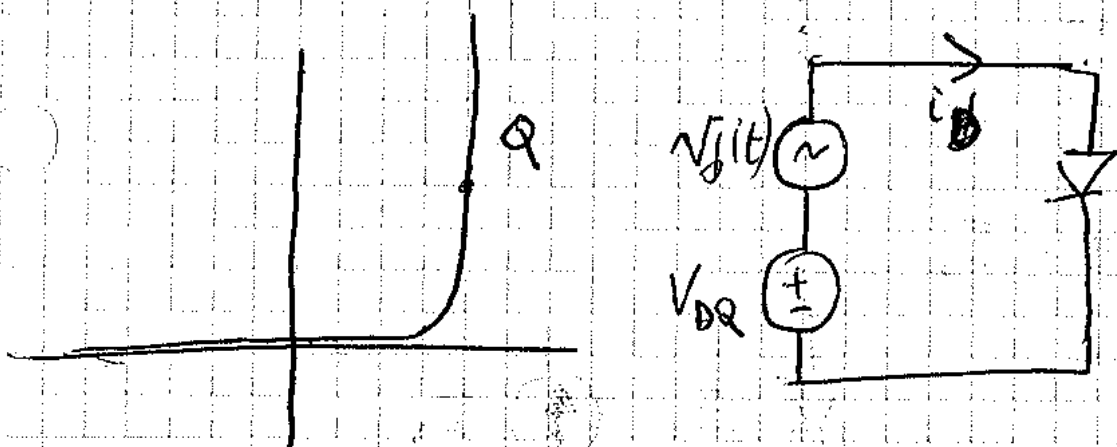
$$\text{Quindi } |v_D| \ll 52 \text{ mV}$$



Quanto detto fino ad ora  
 è valido in condizioni  
 statiche!

Abbiamo visto anche con  
 tensione modulata (variazioni  
 piccole e lentamente

variabili nel tempo).

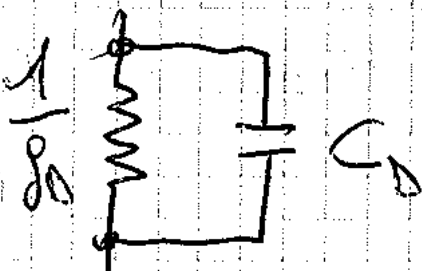


Se aumentiamo la frequenza di  $V_d(t)$   
 si ha che

$$I_D = I_{DQ} + g_D v_d(t)$$

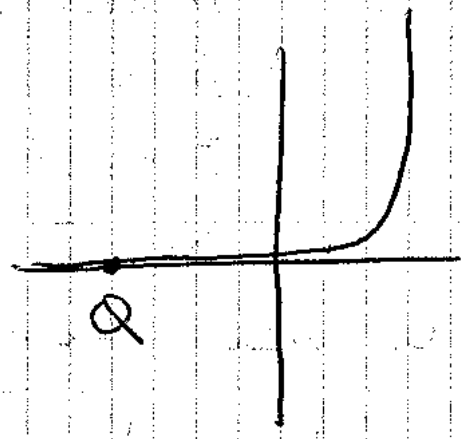
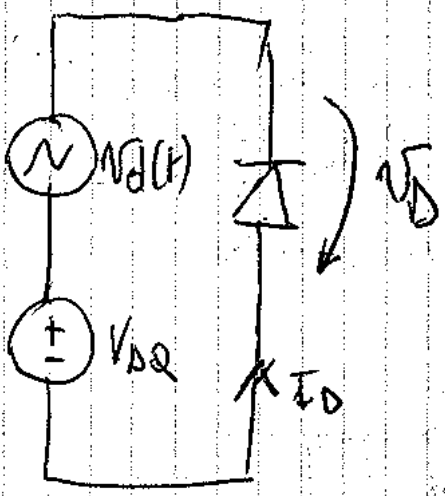
NON È PIÙ VALIDO!!!

### Modello di alta frequenza del Diodo (-Piccola $g_D$ )



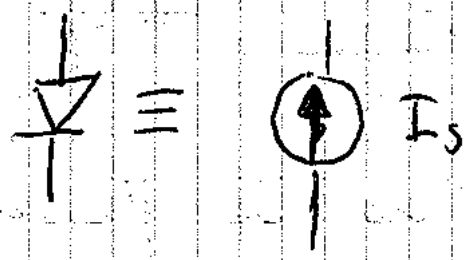
capacità di diffusione  
 del diodo (legata al  
 tempo di spostamento all'interno  
 del giunzione degli elettroni)

$$G_D = (V_D - I_{DQ} R) / V_T$$



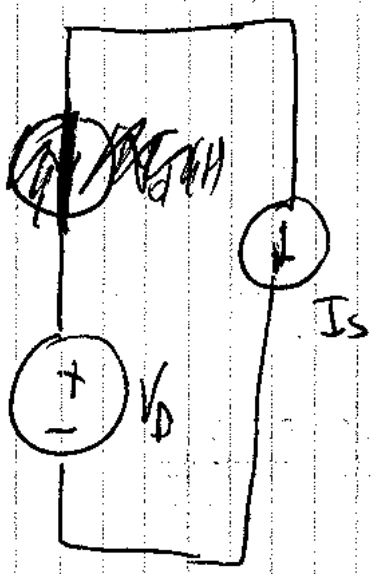
$$I_{DQ} = -I_S$$

Quindi:



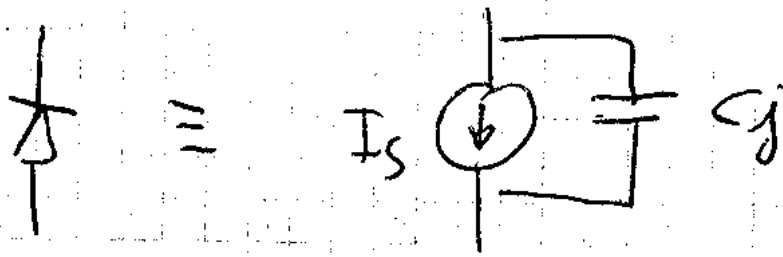
$$10^{-8} < I_S < 10^{-6}$$

$I_S$  dipende dalla temperatura e cresce in modo esponenziale con la temperatura.



Per variazioni continue nel tempo  $I_S$  rimane costante.

Se la frequenza di risonanza di  $N$  è alta, MODELLO ALTA FREQ. DIODO POLARIZZATO INVERSAMENTE



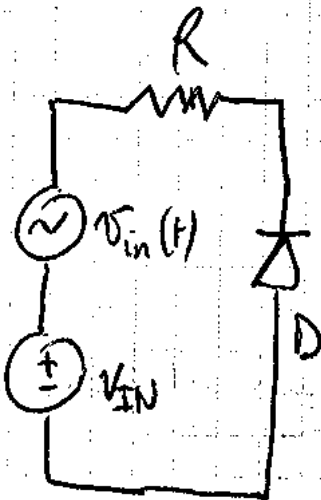
$$C_j = C_{j0} / \left[ 1 + \frac{|V_D|}{\phi_0} \right]^m$$

$$m = \frac{1}{2} \quad \phi_0 = 0,5 \text{ V}$$

$C_{j0}$  ( $V_D = 0$ ) cioè ~~già~~  $C_j$  questo

$$V_D = 0$$

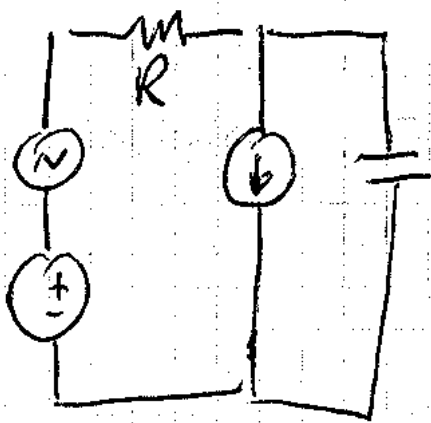
Capacità minime se  $V_D = 0$  e cresce verso e meno che si allontanano dalla origine.



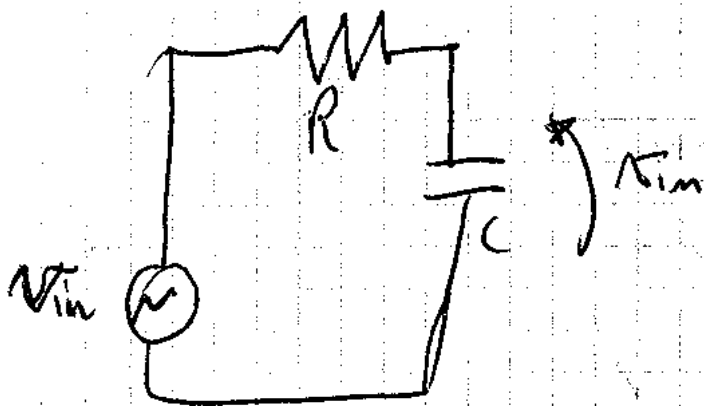
$$V_Y = 90 \text{ V}$$

$$V_{IN} = 10 \text{ V}$$

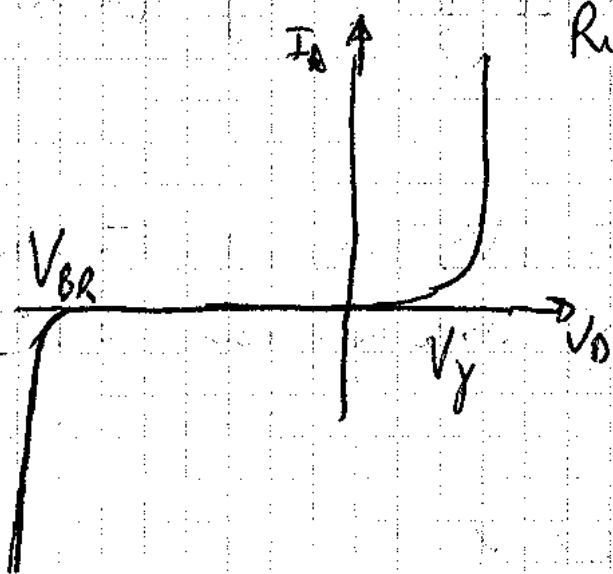
$$|V_{in}| = 1 \text{ V}$$



Per analizzare le  
variazioni: eliminando  
componenti continue



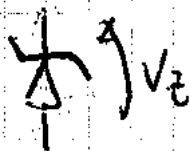
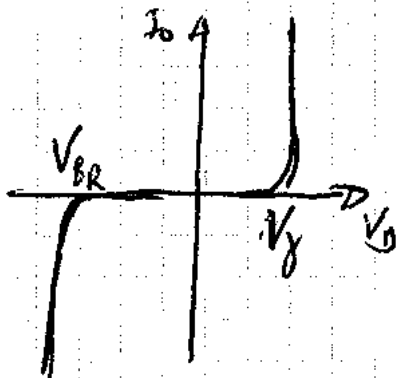
C dipende dalla  
temperatura e dai  
capi.



Ricordare

$$|V_{BR}| > 30 \text{ V}$$

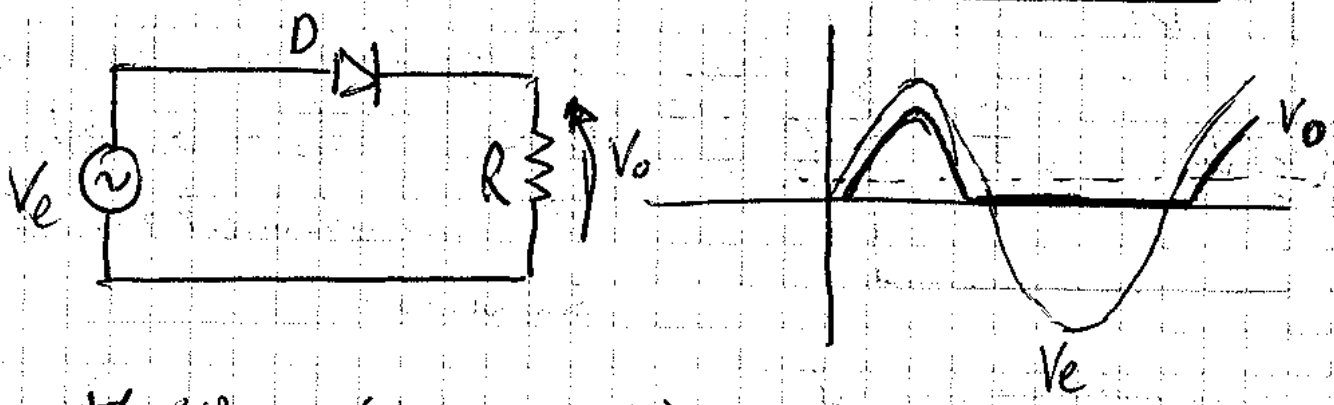
DIODO ZENER



pensare sia per whetto ma  
in polarizzazione  
diretta sia per  
break-down

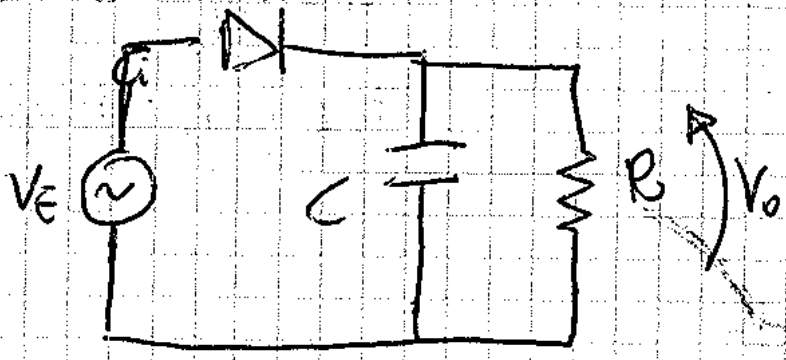
$$1 \text{ V} < |V_{BR}| < 30 \text{ V}$$

# Utilizzo dei diodi come interruttori

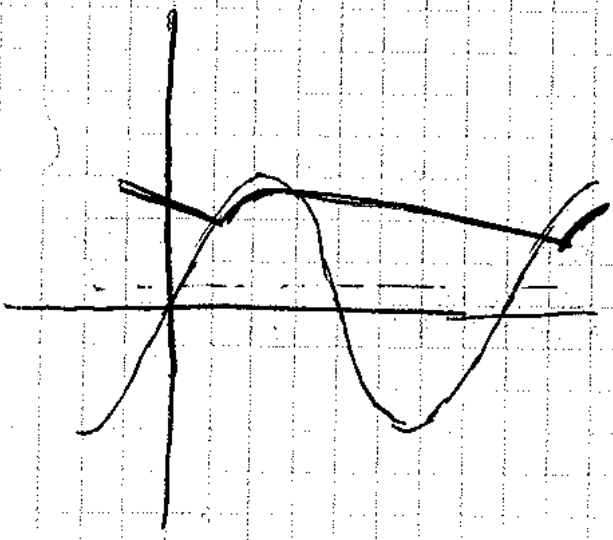


$$V_e(t) = V_p \sin(\omega t)$$

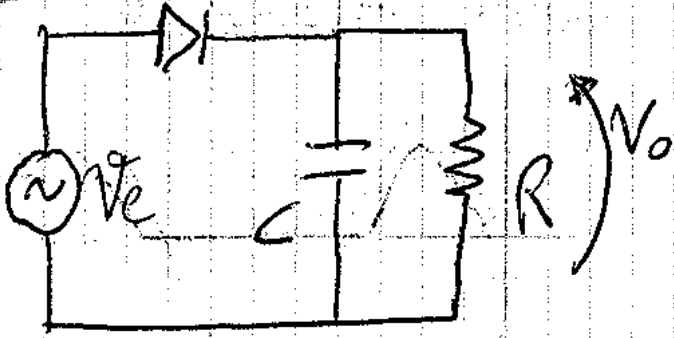
$$V_o(t) = \begin{cases} V_e \sin(\omega t) - V_g & V_e > V_g \\ 0 & \text{otherwise} \end{cases}$$



Se  $RC > T$   
 periodo segnale  
 di ingresso



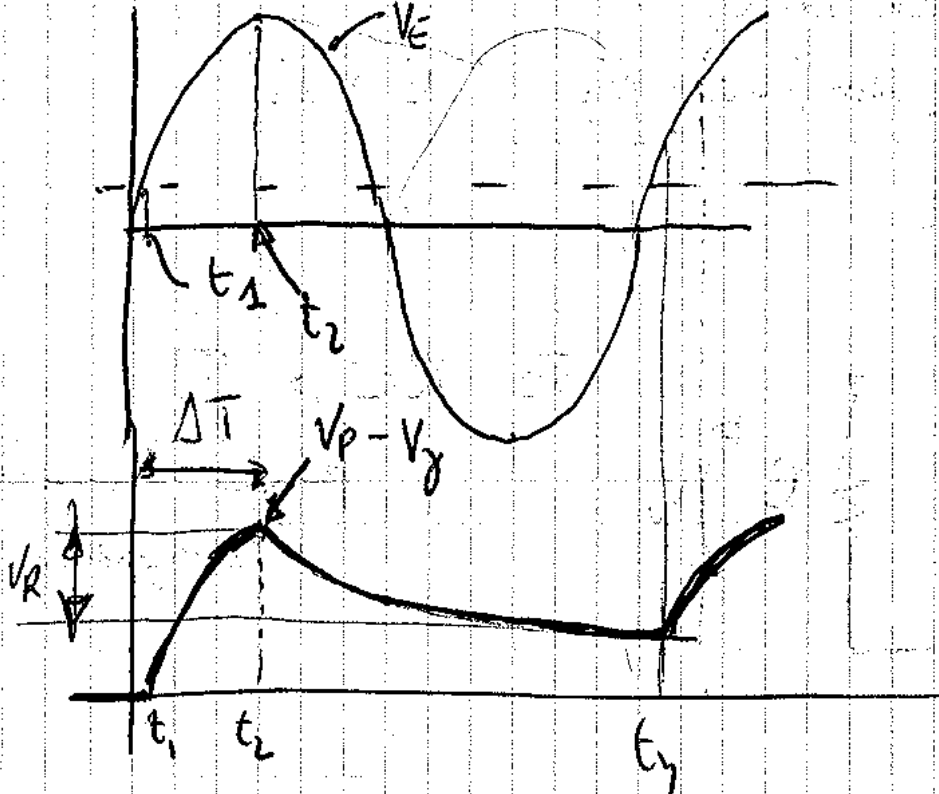
# Analisi di un circuito non lineare dinamico



Supponiamo che in  $t=0$   $V_0 = 0$  ed il condensatore è scarico!

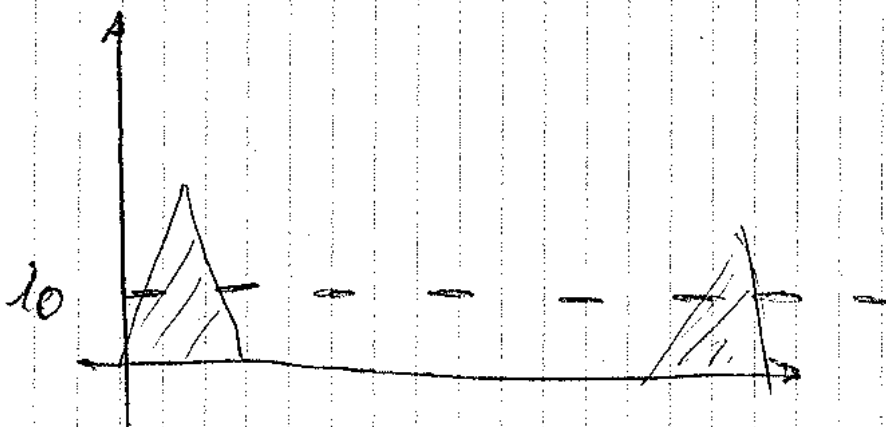
Consideriamo il

$$v_E = V_p \sin(\omega t)$$



$t_1 \leq t < t_2 \rightarrow V_0 = v_E - V_D$   
 $t_2 \leq t < t_3 \rightarrow D$  spento

In  $\Delta T$  il diodo è in conduzione. Durante fase di scarica del condensatore il diodo è un ~~condensatore~~ <sup>interruttore</sup> aperto!



$$\left\{ \begin{aligned} I_0 &= \frac{V_0}{R} \\ i_0 &= -C \frac{dV_0}{dt} \end{aligned} \right.$$



$$\frac{dV_o}{dt} + \frac{1}{RC} V_o = 0$$

(13)

$$V_o(t) = K \exp\left(-\frac{t-t_0}{RC}\right)$$

con  $t_0$  costante in cui inizia il decadimento

$$V_o(t_0) = K = V_p - V_y$$

⇓

$$V_o(t) = (V_p - V_y) e^{-\frac{t-t_0}{RC}}$$

$T - \Delta T \ll RC$  perché se così non fosse il decadimento della funzione d'onda si avvicina molto a quella senza condensatore.

$$V_{Ripple} = (V_p - V_y) - (V_p - V_y) e^{-\frac{t-\Delta t}{RC}}$$

Se ho e' ipotesi  $T - \Delta T \ll RC$  p' più

$$V_{Ripple} \approx [V_p - V_y] \left[ 1 - \left( 1 - \frac{T - \Delta T}{RC} \right) \right] =$$

$$(V_p - V_y) \frac{T - \Delta T}{RC}$$

$$\text{Se } \Delta T \ll T \Rightarrow V_{Ripple} \approx (V_p - V_y) \frac{T}{RC}$$

RICAVARE  $\Delta T$  (tempo di conduzione del diodo)

$$(V_p - V_\gamma) e^{-\frac{T - \Delta T}{RC}} = V_p \cos(\omega(T - \Delta T)) - V_\gamma$$

$$(V_p - V_\gamma) \left[ 1 - \frac{T - \Delta T}{RC} \right] = V_p \left[ 1 - \omega^2 \frac{\Delta T^2}{2} \right] - V_\gamma$$

$$(V_p - V_\gamma) \left[ 1 - \frac{T - \Delta T}{RC} \right] = V_p - V_\gamma - V_p \frac{\omega^2 \Delta T^2}{2}$$

~~$$\frac{\Delta T}{RC} = \frac{V_p \omega^2 \Delta T^2}{2(V_p - V_\gamma)}$$~~

$$\Delta T = \left( \frac{2(V_p - V_\gamma)}{V_p} \cdot \frac{T}{RC} \right)^{\frac{1}{2}} \cdot \frac{1}{\omega}$$

$$V_{R_{eff}} = (V_p - V_\gamma) \frac{T}{RC}$$

$$\Delta T = \frac{1}{\omega} \cdot \left( \frac{2V_R}{V_p} \right)^{\frac{1}{2}}$$

Esempio

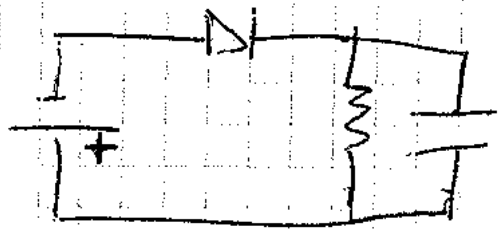
$$T = 10^{-3} \text{ s}$$

$$\Delta T = 100 \text{ } \mu\text{s}$$

$$\bar{i}_e = 10 \text{ mA}$$

$$\bar{i}_e T = \frac{\Delta T}{2} I_p \Rightarrow I_p = 2 \frac{\bar{i}_e T}{\Delta T} = 0,2 \text{ A}$$

Considera tensione ai capi nel diodo al momento del p.c.o. negativo delle correnti alternate. (16)



$$V_c \approx (V_p - V_g)$$

diodo polarizzato inversamente

$$|-V_p - V_c| \ll |V_{BR}| \text{ altrimenti il}$$

diodo va in conduzione per break-down (diodo non deve essere portato nelle regioni di break-down)

potenza media dissipata nel diodo

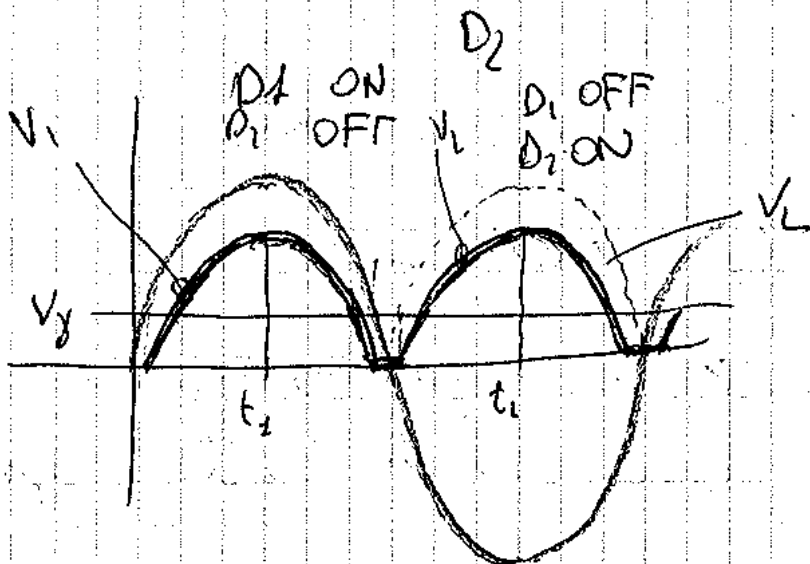
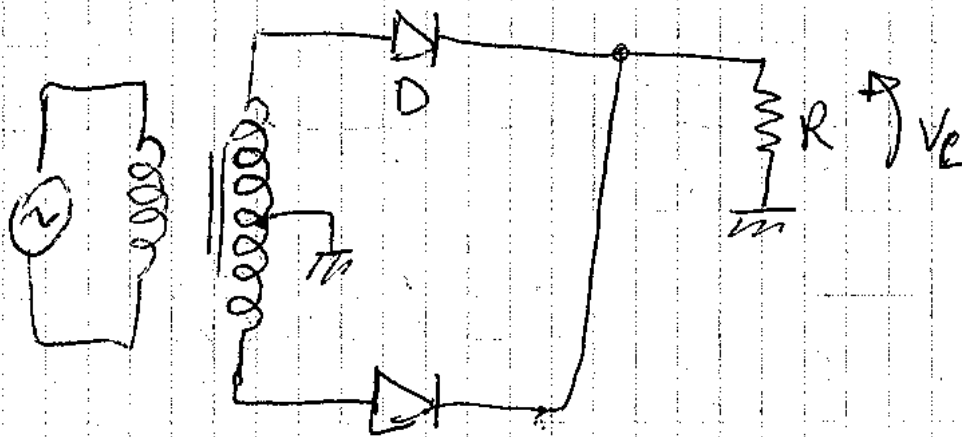
$$\bar{P}_D = \frac{1}{T} \int_0^T P_D(x) dx = \frac{1}{T} \int_{T-\Delta T}^T P_D(x) dx =$$

$$= \frac{1}{T} \int_{T-\Delta T}^T V_g i_D(x) dx = \frac{1}{T} V_g \frac{\Delta T}{2} \bar{I}_p$$

$$\bar{I}_L = \frac{\Delta T}{2} \bar{I}_p$$

$$\bar{I}_p = \frac{2 \bar{I}_e T}{\Delta T}$$

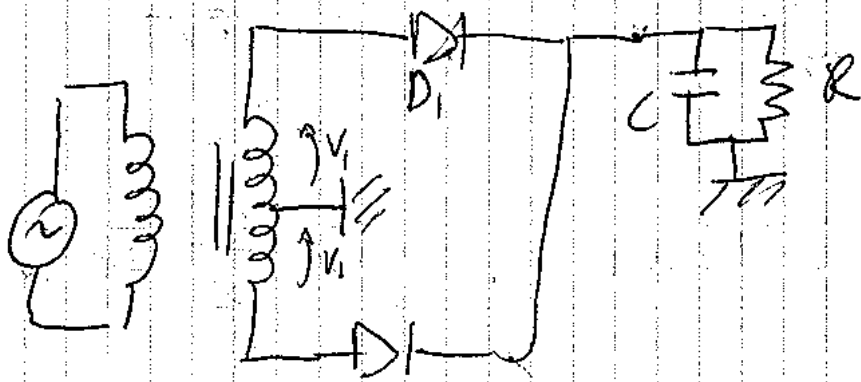
$$\bar{P}_D = \frac{1}{T} V_g \frac{\Delta T}{2} \frac{2 \bar{I}_e T}{\Delta T} = V_g \cdot \bar{I}_e$$



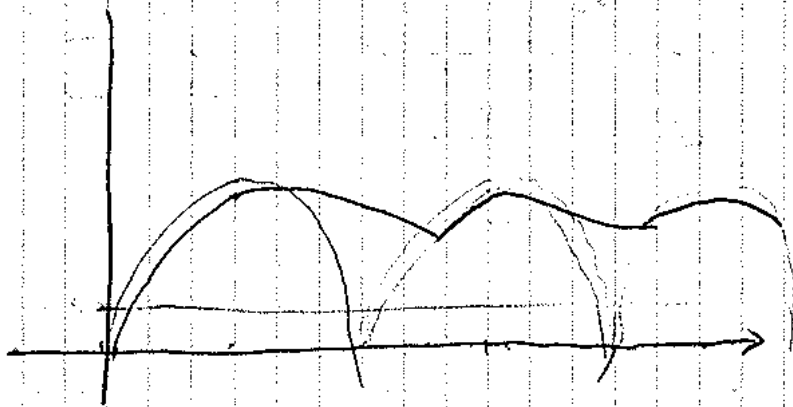
$$V_i = V_p \sin(\omega t)$$

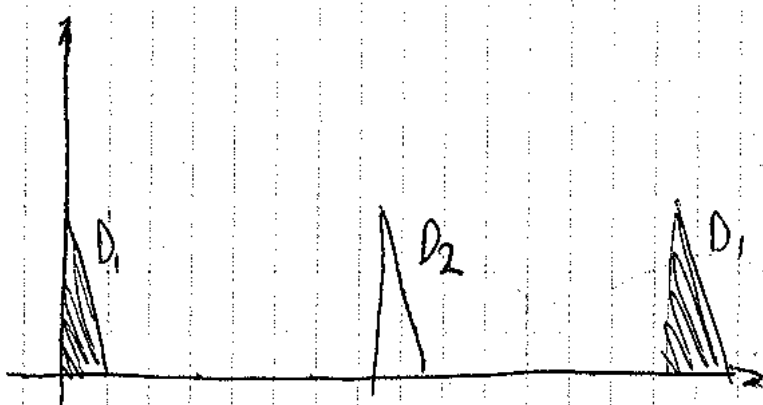
$$V_e = -V_p \sin(\omega t)$$

$$V_{D2}(t_1) = -2V_p + V_g = V_{D1}(t_2)$$



$$RC \gg \frac{I_s}{2} - \Delta T$$





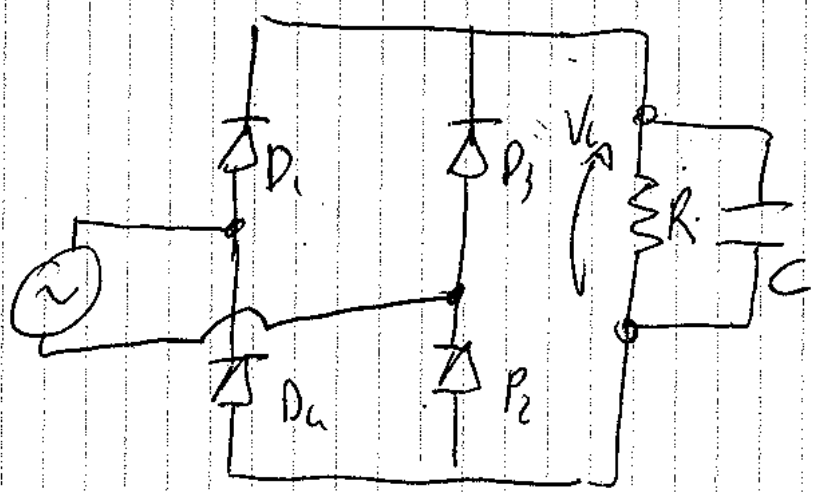
$$\overline{I_L T} = I_P \frac{\Delta T}{2} \chi$$

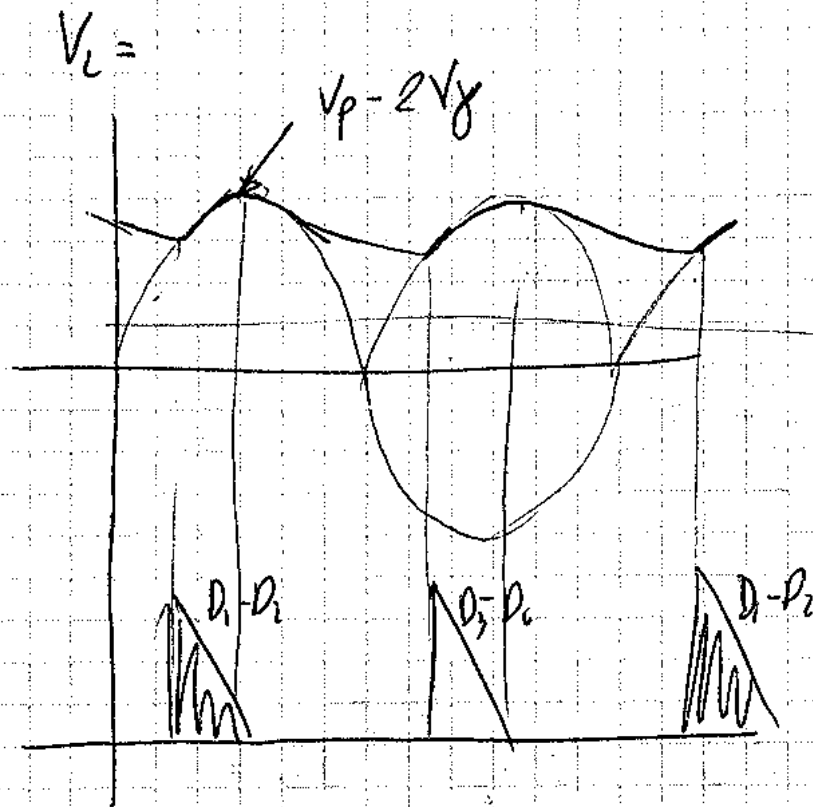
$$I_P = \frac{\overline{I_L T}}{\Delta T}$$

$$P_{D1} = \frac{1}{T} \int_0^T P_{D1}(t) dt = \frac{1}{T} V_g \frac{\Delta T}{2} I_P =$$

$$= \frac{1}{T} V_g \frac{\Delta T}{2} \frac{\overline{I_L T}}{\Delta T} = \frac{V_g \overline{I_L}}{2}$$

PONTE di Greps





$$\overline{P}_{D_1} = \frac{V_g \overline{I}_c}{2}$$

$$\overline{P}_t = 2V_g \overline{I}_c$$

dissipa il doppio di potenza rispetto al raddrizzatore precedente.