Universidade Federal de Uberlândia
Engenharia Eletrônica e de Telecomunicações

- Eletrônica Analógica 1 -

Capítulo 1: Diodos

Prof. Alan Petrônio Pinheiro

Sumário

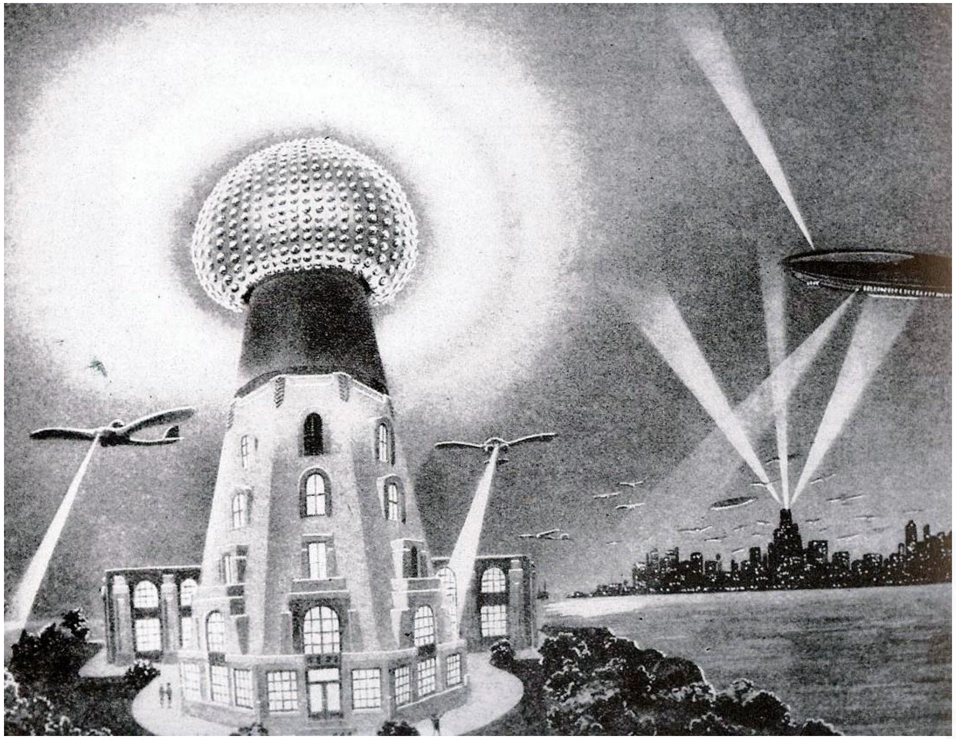
Parte 1: teoria de diodos

- O diodo ideal
- Física dos semicondutores
- Resistência e modelos equivalentes
- Capacitância e tempos do diodo
- Diodo de Zener
- Interpretação de folha de dados
- Modelos e testes com diodos
- Tipos especiais de diodos
- Exercícios e exemplos

Parte 2: Circuitos com diodos

- Grampeadores de tensão
- Multiplicadores de tensão
- Diodo Zener: projeto
- Outras aplicações
- Projeto básico fontes de alimentação

Transistor: tudo começou com um “fracasso”



The True Wireless

By NIKOLA TESLA

Written Exclusively for The Electrical Experimenter

EVER since the announcement of Maxwell's electro-magnetic theory scientific investigators all the world over had been bent on its experimental verification. They were convinced that it would be done and lived in an atmosphere of eager expectancy, un-

Alternator of 10,000 Cycles p.s., Capacity 10 K.W., Which Was Employed by Tesla in His First Demonstrations of High Frequency Phenomena Before the American Institute of Electrical Engineers at Columbia College, May 20, 1891. Fig. 1.

usually favorable to the reception of any evidence to this end. No wonder then that the publication of Dr. Heinrich Hertz's results caused a thrill as had scarcely ever been experienced before. At that time I was in the midst of pressing work in connection with the commercial introduction of my system of power transmission, but, nevertheless, caught the fire of enthusiasm and fairly burned with desire to behold the miracle with my own eyes. Accordingly, as soon as I had freed myself of these imperative duties and resumed research work in my laboratory on Grand Street, New York, I began, parallel with high frequency alternators, the

proved appliances. Similar phenomena were noted, greatly magnified in intensity, but they were susceptible of a different and more plausible explanation. I considered this so important that in 1892 I went to Bonn, Germany, to confer with Dr. Hertz in regard to my observations. He seemed disappointed to such a degree that I regretted my trip and parted from him sorrowfully. During the succeeding years I made numerous experiments with the same object, but the results were uniformly negative. In 1900, however, after I had evolved a wireless transmitter which enabled me to obtain electro-magnetic activities of many millions of horse-power, I made a last desperate attempt to prove that the disturbances emanating from the oscillator were ether vibrations akin to those of light, but met again with utter failure. For more than eighteen years I have been reading treatises, reports of scientific transactions, and articles on Hertz-wave telegraphy, to keep myself informed, but they have always imprest me like works of fiction.

The history of science shows that theories are perishable. With every new truth that is revealed we get a better understanding of Nature and our conceptions and views are modified. Dr. Hertz did not discover a new principle. He merely gave material support to a hypothesis which had

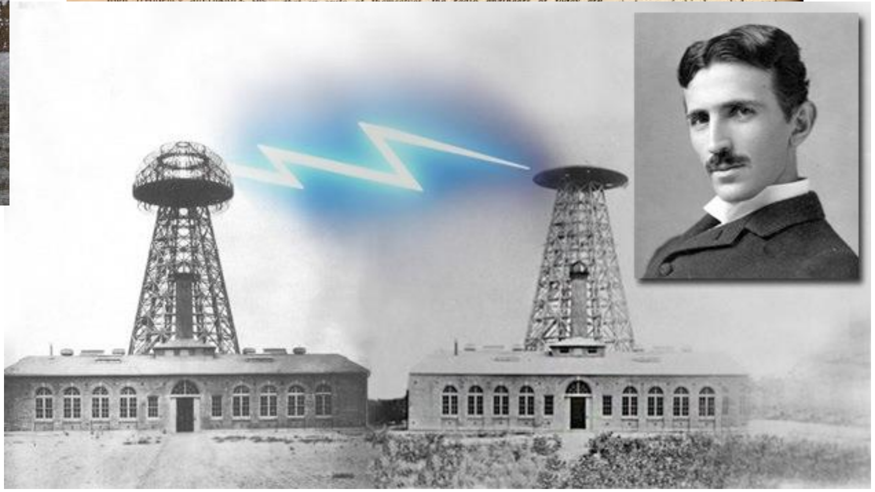
application of these radiations for the purpose was quite obvious. When Dr. Hertz was asked whether such a system would be of practical value, he did not think so, and he was correct in his forecast. The best that might have been expected was a method of communication similar to the

Electric Transmission Thru Two Wires and Hydraulic Analog. Fig. 3.

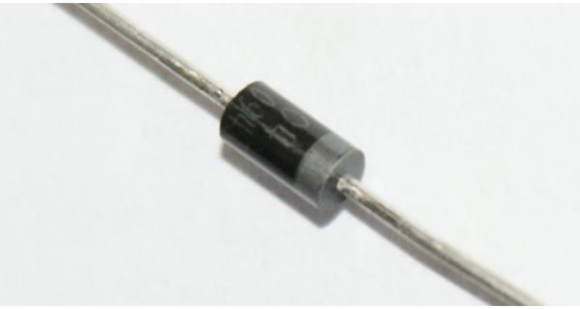
heliographic and subject to the same or even greater limitations.

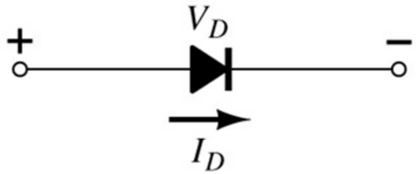
In the spring of 1891 I gave my demonstrations with a high frequency machine before the American Institute of Electrical Engineers at Columbia College, which laid the foundation to a new and far more promising departure. Altho the laws of electrical resonance were well known at that time and my lamented friend, Dr. John Hopkinson, had even indicated their specific application to an alternator in the Proceedings of the Institute of Electrical Engineers, London, Nov. 13, 1889, nothing had been done towards the prac-

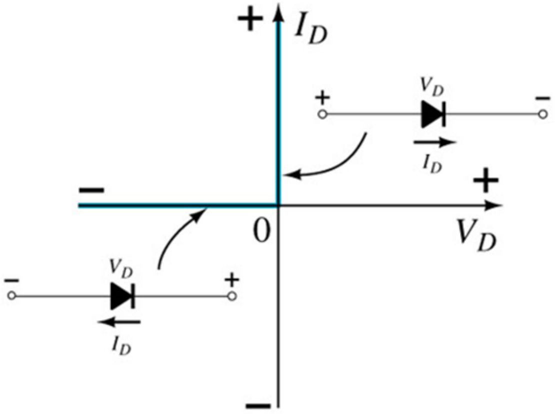
IN this remarkable and complete story of his discovery of the "True Wireless" and the principles upon which transmission and reception, even in the present day systems, are based, Dr. Nikola Tesla shows us that he is indeed the "Father of the Wireless." To him the Hertz wave theory is a delusion; it looks sound from certain angles, but the facts tend to prove that it is hollow and empty. He convinces us that the real Hertz waves are blotted out after they have traveled but a short distance from the sender. It follows, therefore, that the measured antenna current is no indication of the effect, because only a small part of it is effective at a distance. The limited activity of pure Hertz wave transmission and reception is here clearly explained, besides showing definitely



O diodo ideal

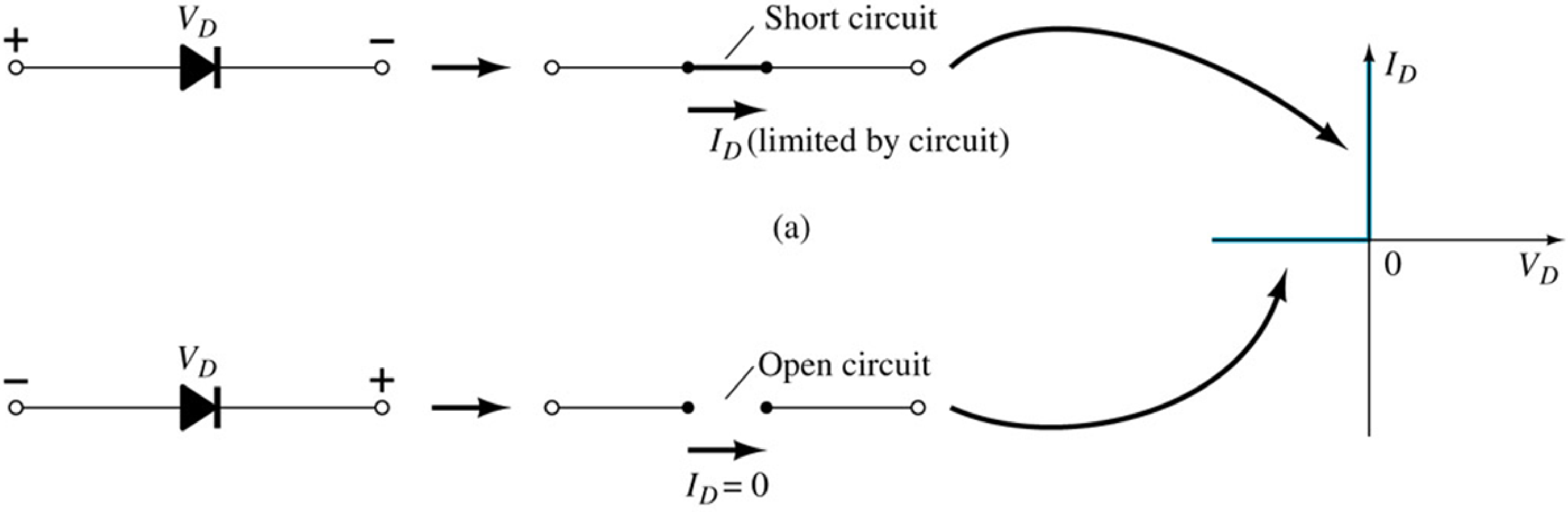






- Analogia:

- Polarização
- **Dispositivos de estado sólido**

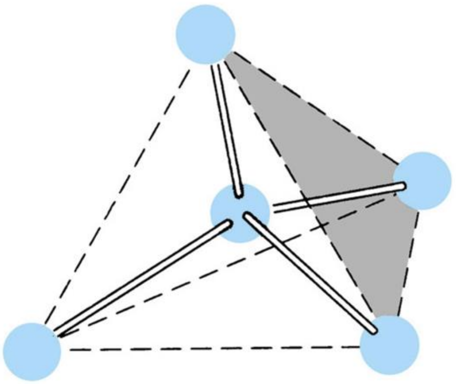


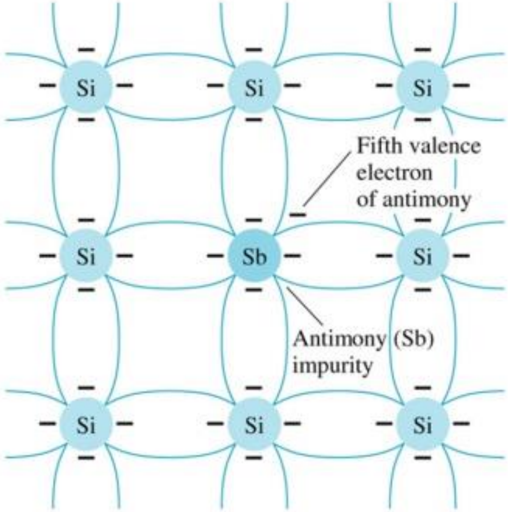
Física dos semicondutores

- Resistividade dos materiais

Conductor	*Semiconductor*	*Insulator*
$\rho \cong 10^{-6}\ \Omega$-cm (copper)	$\rho \cong 50\ \Omega$-cm (germanium) $\rho \cong 50 \times 10^{3}\ \Omega$-cm (silicon)	$\rho \cong 10^{12}\ \Omega$-cm (mica)

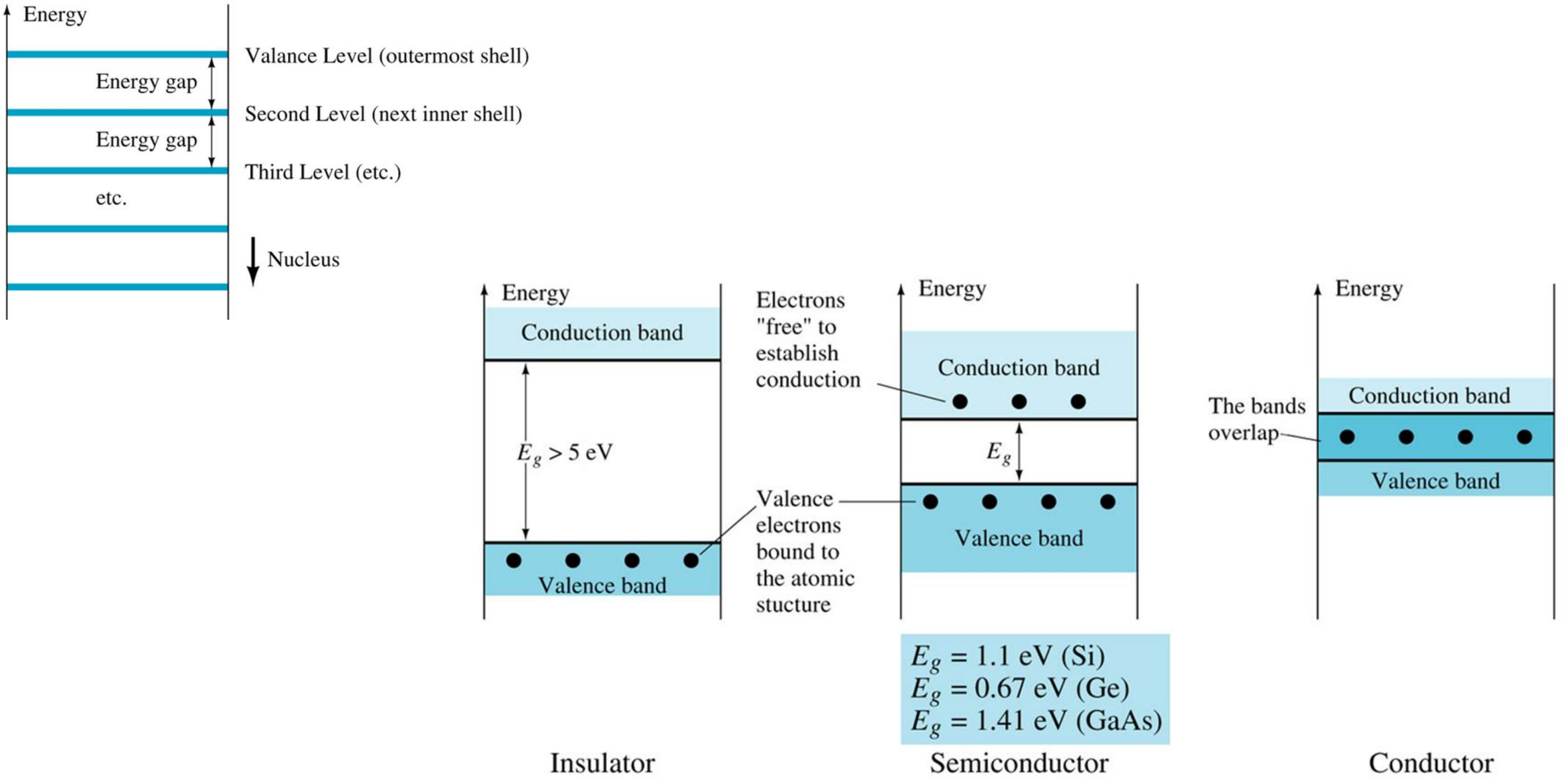
- Átomos tetravalentes





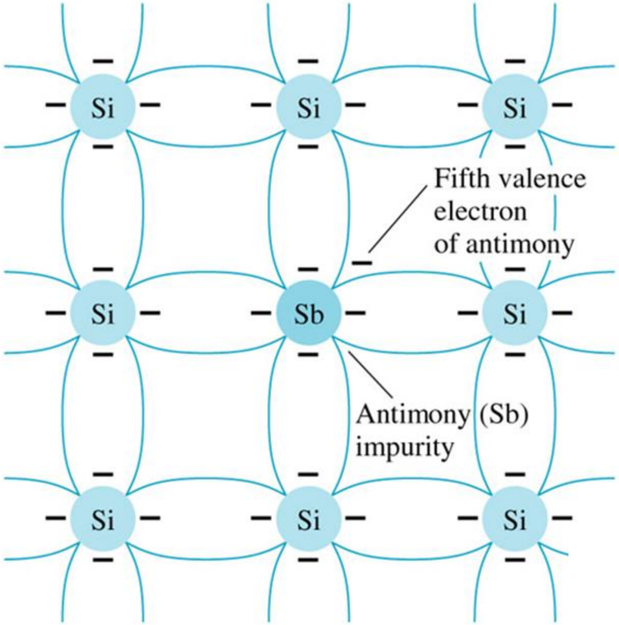
  - Portadores intrínsecos (Ge=2.5x10^{13}e)

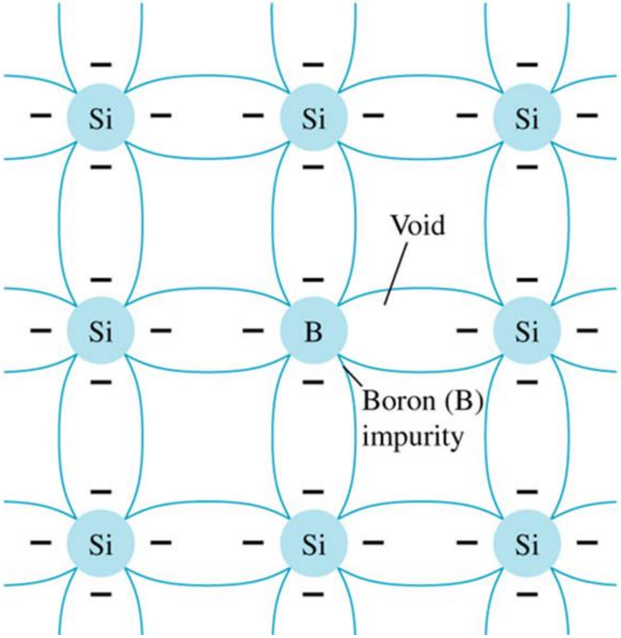
- Níveis de energia discretos

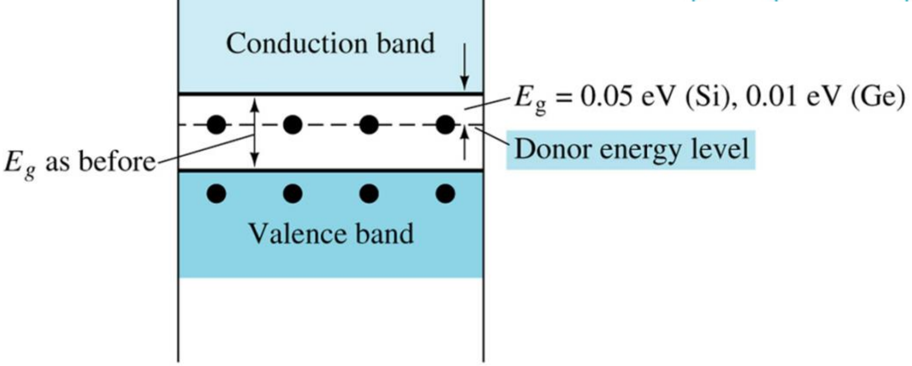


Sendo que: 1 eV = 1,6 x 10^{-19}J

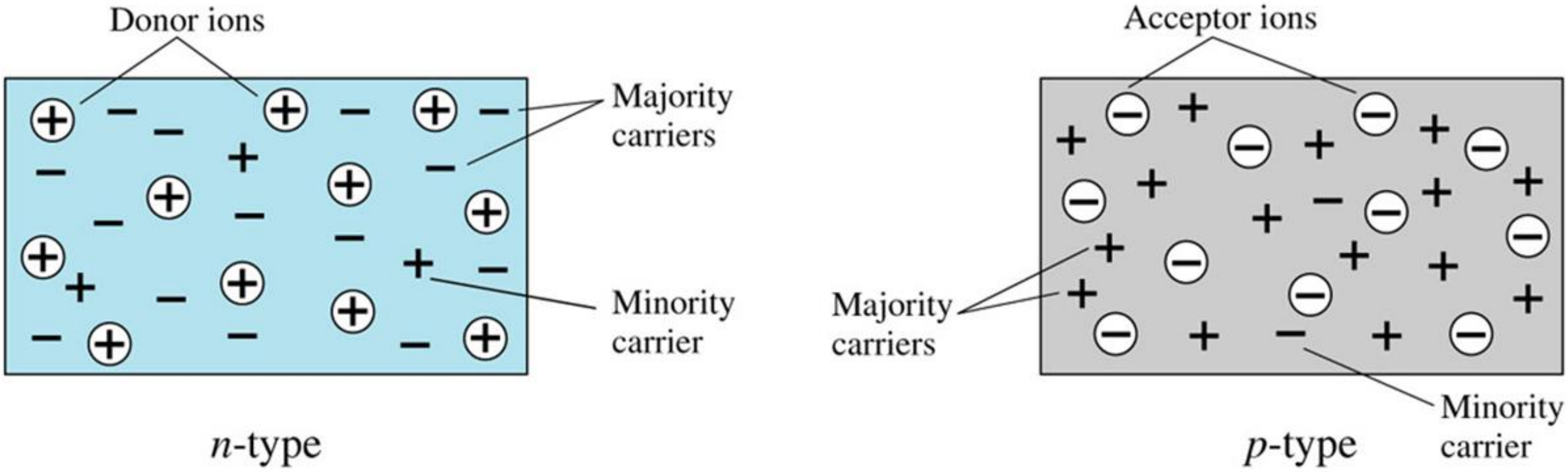
- Materiais extrínsecos
  - Dopagem ***n*** e ***p***
  - Fluxo de lacunas x elétrons



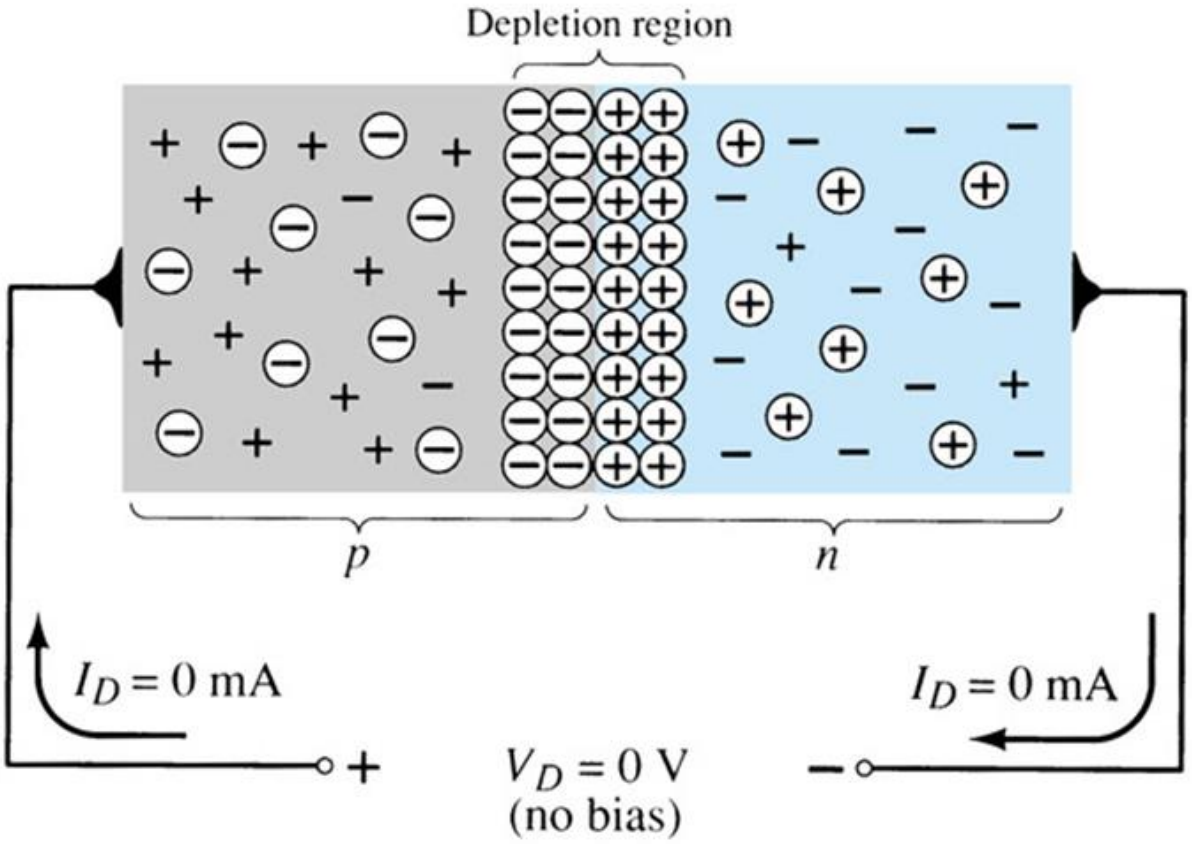




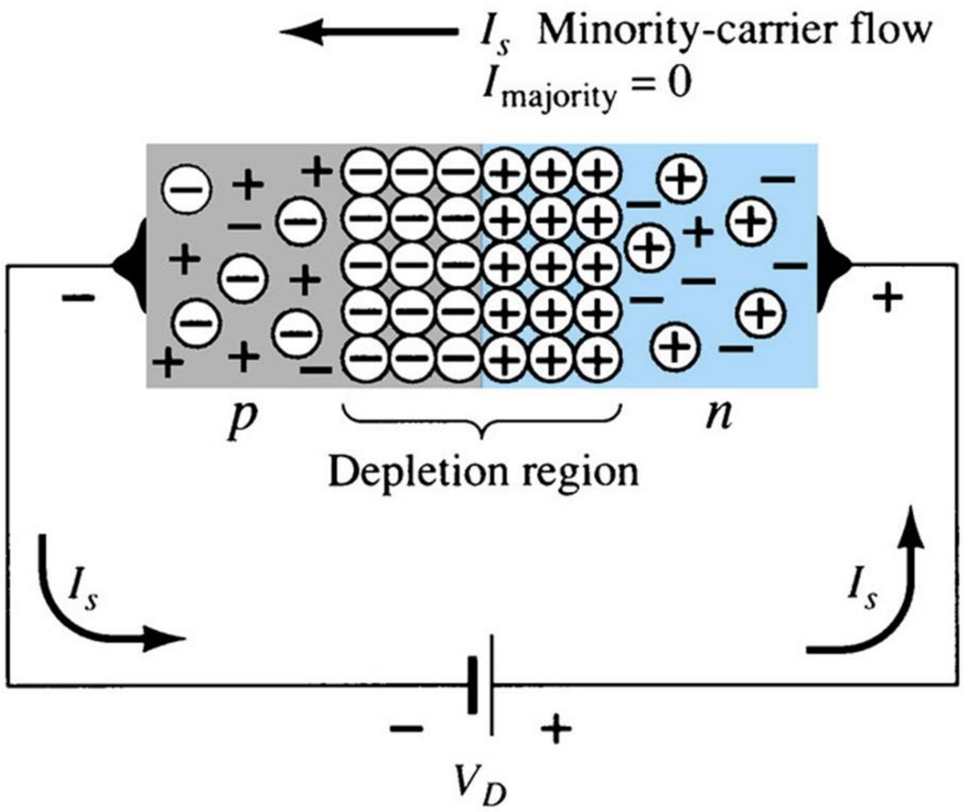
- Portadores majoritários e minoritários

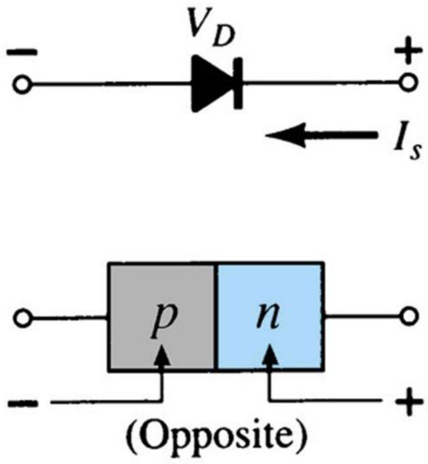


- O diodo como semicondutor
  - **Caso A**: sem polarização



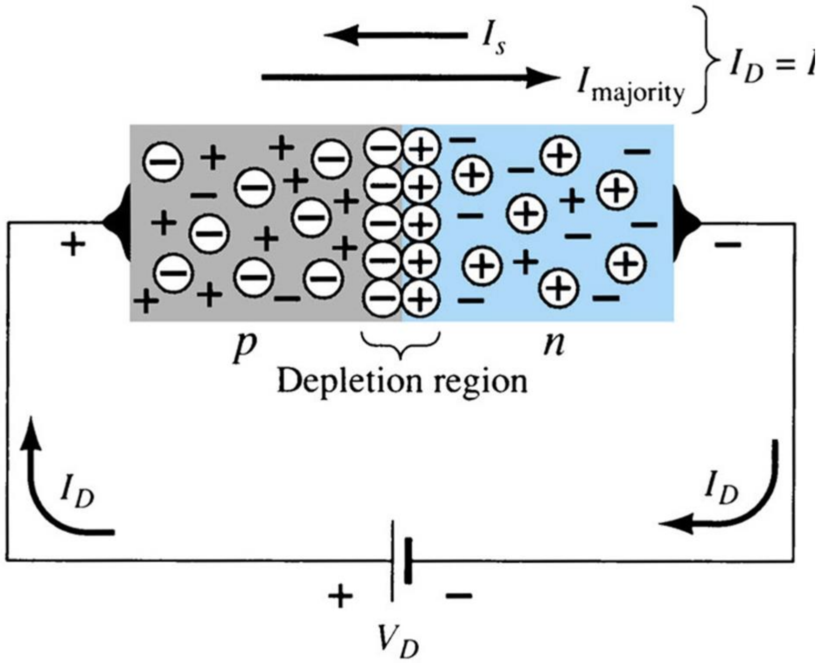
- **Caso B**: polarização reversa ($V_d < 0V$)
  - Aumento da região depleção
  - Surgimento de uma "**corrente de saturação reversa**" ***I_s*** (***fuga***)
    - Baixíssimo valor (≤ µA)
    - Independe da intensidade de polarização

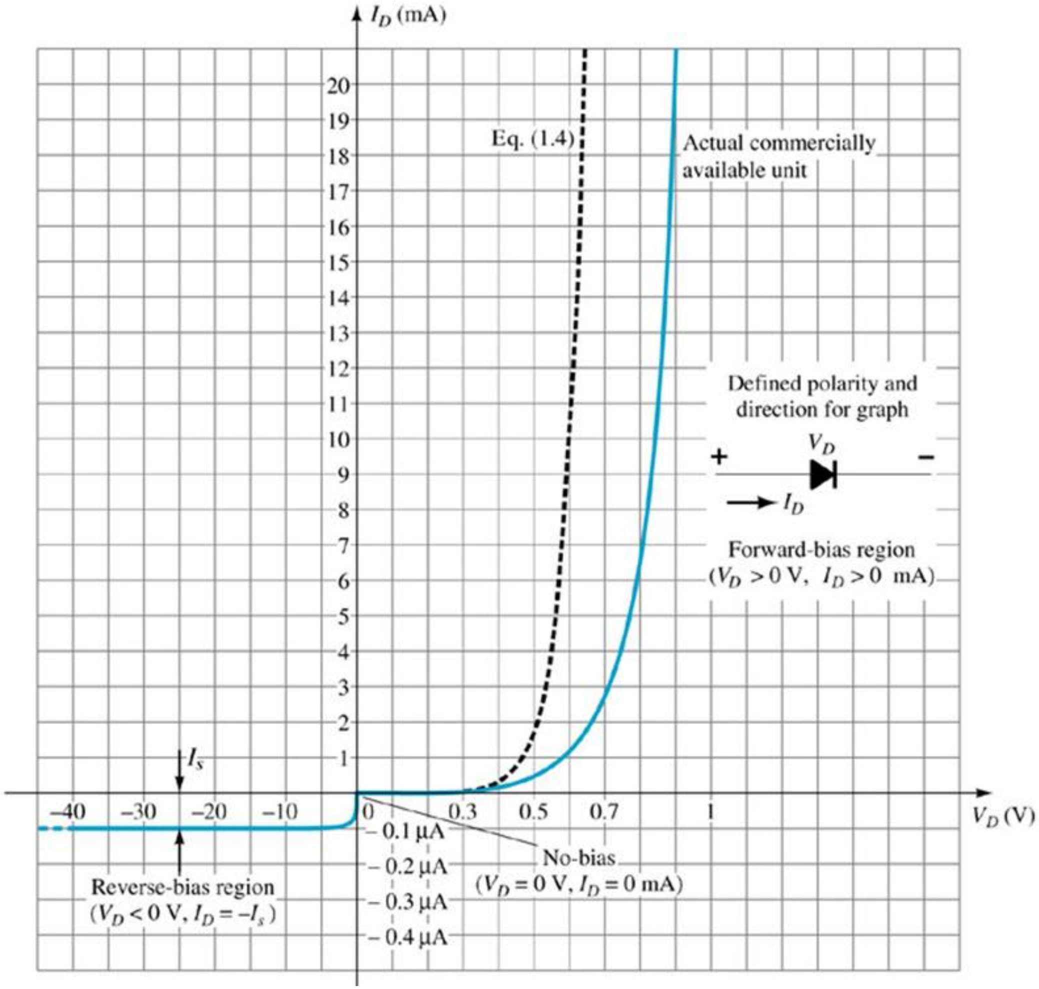




– **Caso C**: polarização direta ($V_d > 0V$)

- Pólos forçam portadores majoritários a se recombinarem com os íons da fronteira reduzindo a depleção





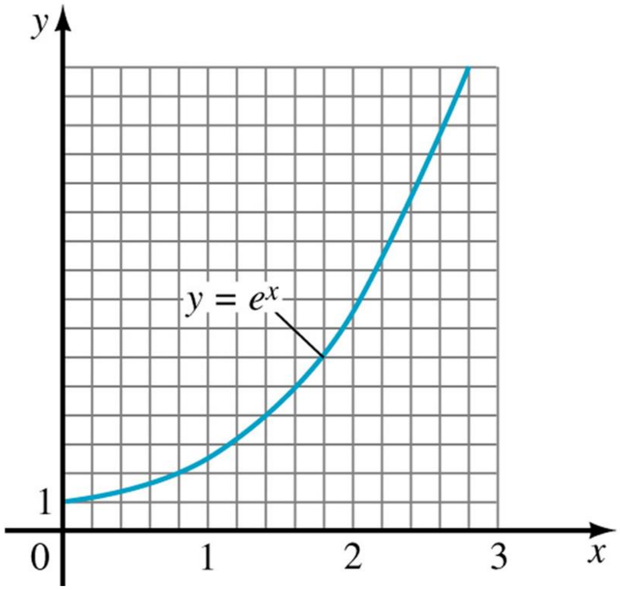
- Equação geral do diodo semicondutor:

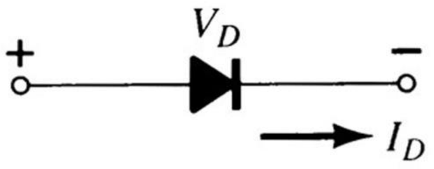
$$I_D = I_S(e^{kV_D/T_K} - 1)$$

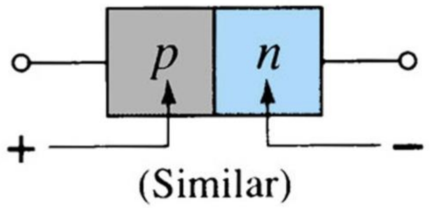
"d'onde":

- Is = corrente de saturação reversa
- k = 11600/η

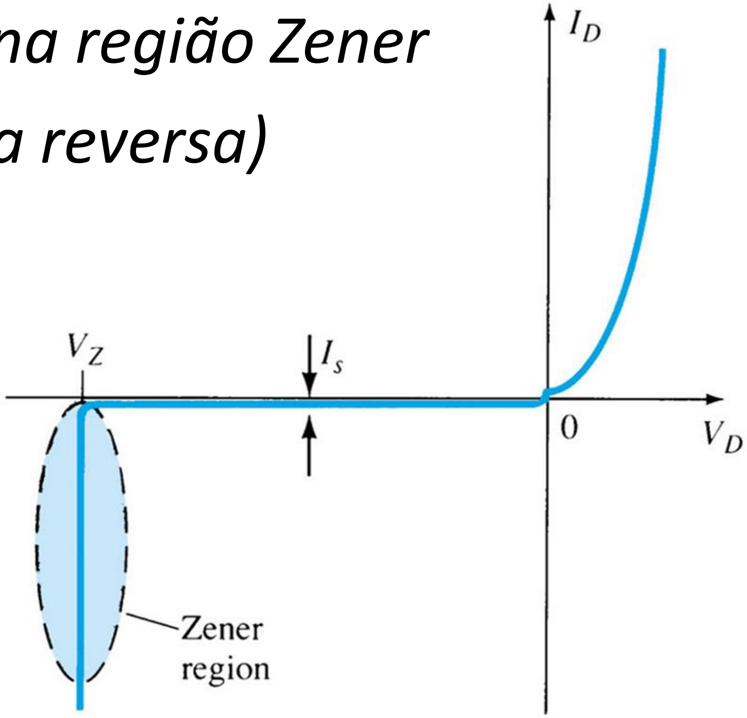
  com η=2 para G_e e η=1 para S_i
- $T_k = T_c + 273º$



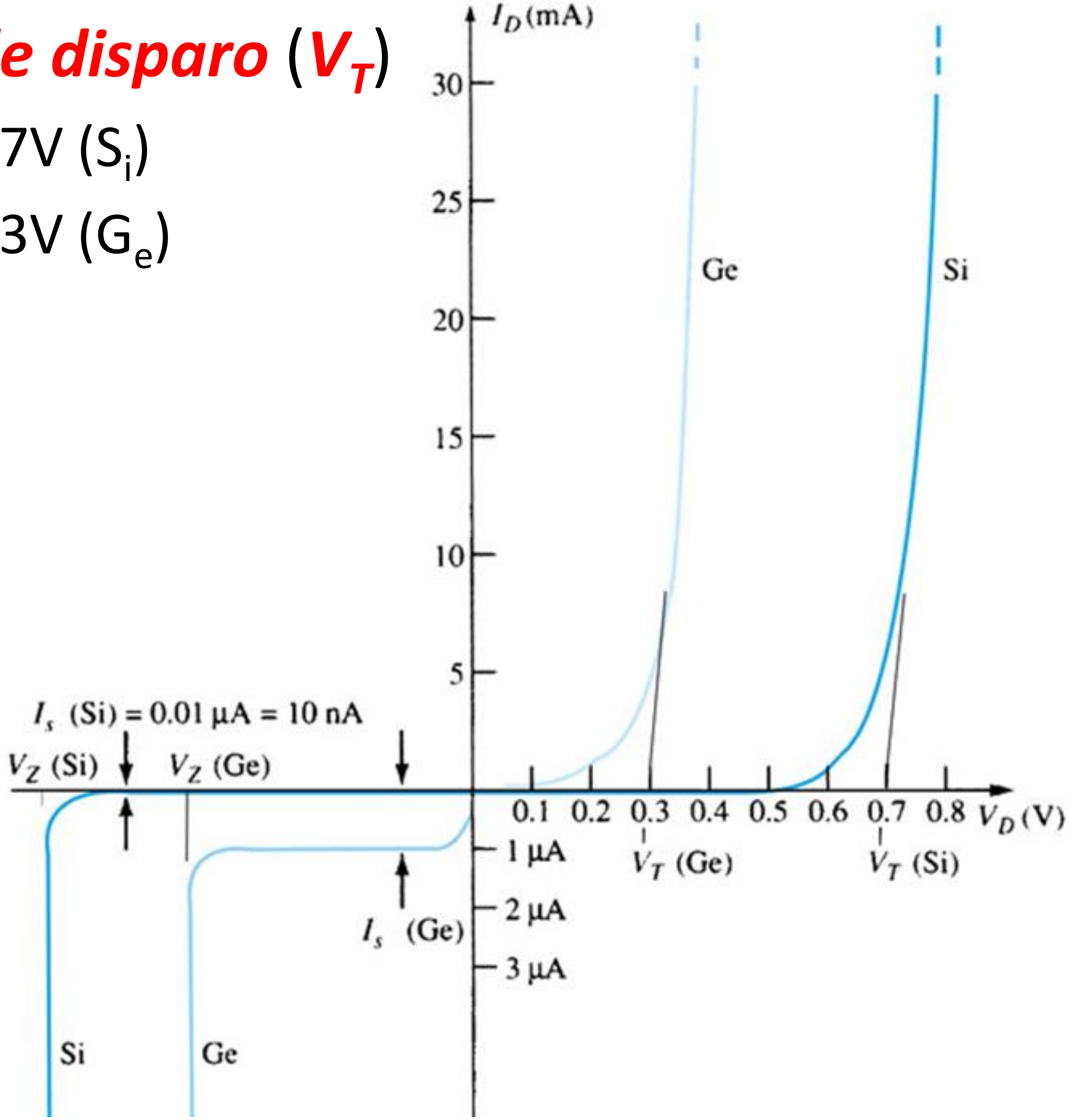




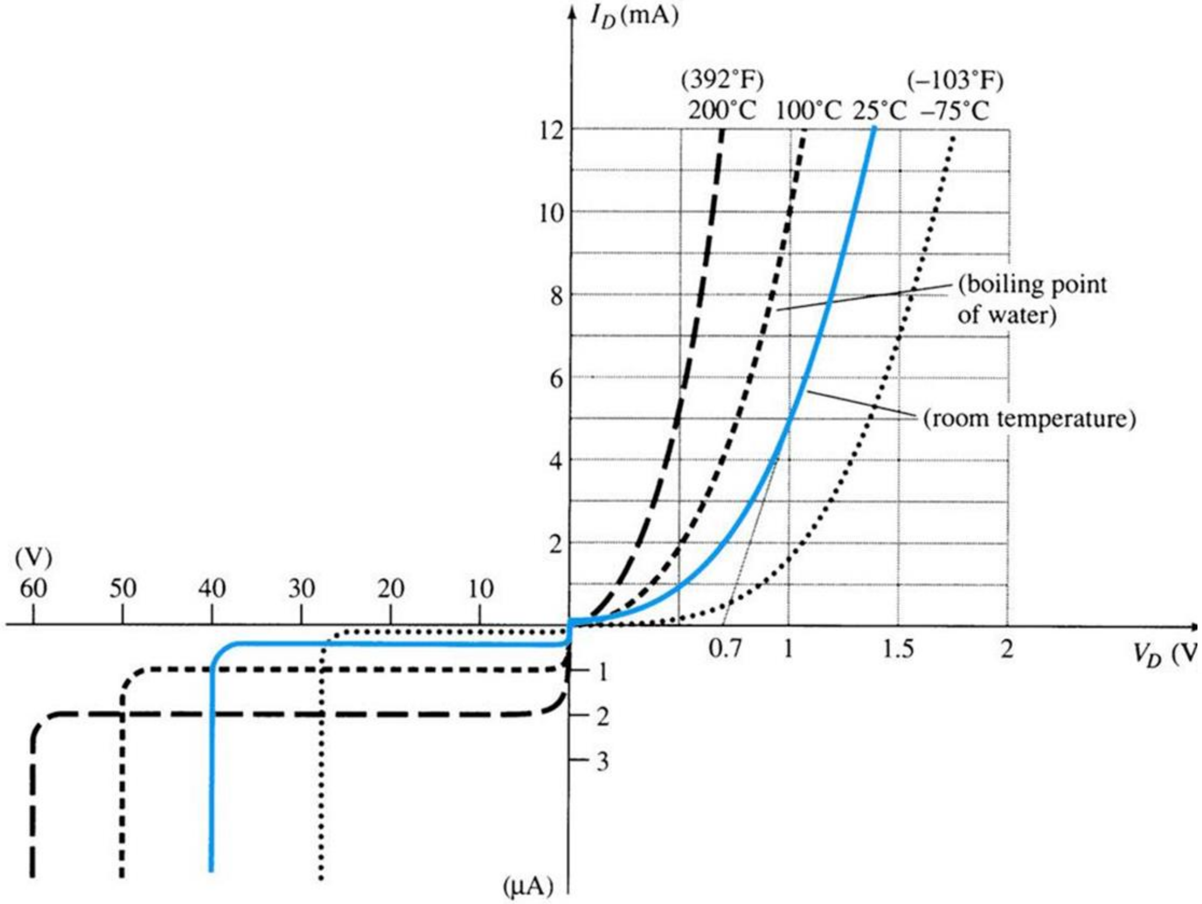
- Região Zener
  - Aumento velocidade portadores minoritários
    - liberação outros portadores por colisões (ionização);
    - “Corrente de avalanche”;
  - *Diodos de Zener*
  - ***Tensão pico inversa*** (V_z , V_{PIV} , V_{PRV}) = *máximo potencial inverso antes diodo entrar na região Zener*
  - V_R *ou* V_{BR}*(tensão de ruptura reversa)*

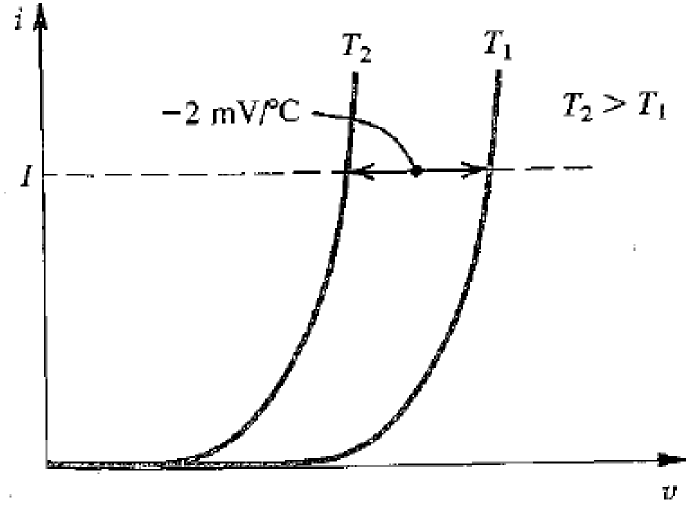


- S_i *versus* G_e
  - **Limiar de disparo** (V_T)
    - $V_T \approx 0{,}7V$ (S_i)
    - $V_T \approx 0{,}3V$ (G_e)

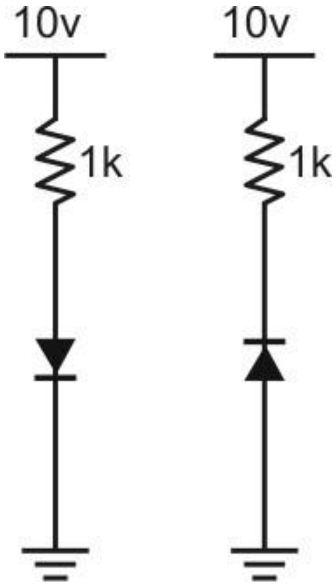


- Efeitos da temperatura
  - I_S praticamente dobra para cada aumento de 10ºC



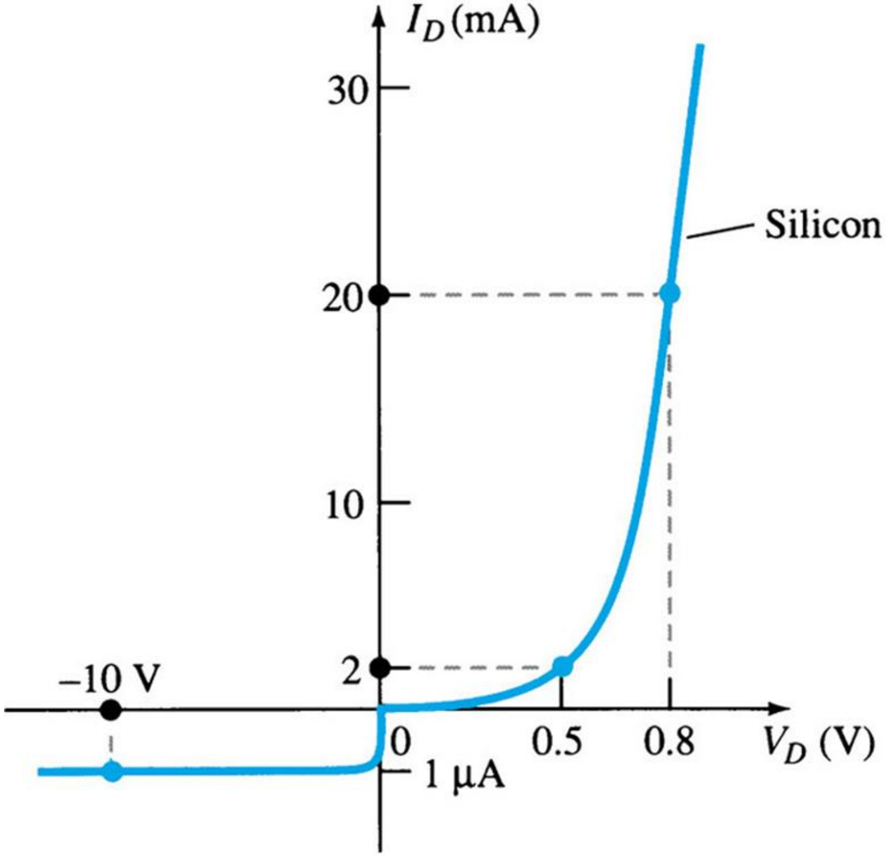


Exemplo 1: n*as duas versões abaixo de circuitos, determine a tensão sobre o diodo*

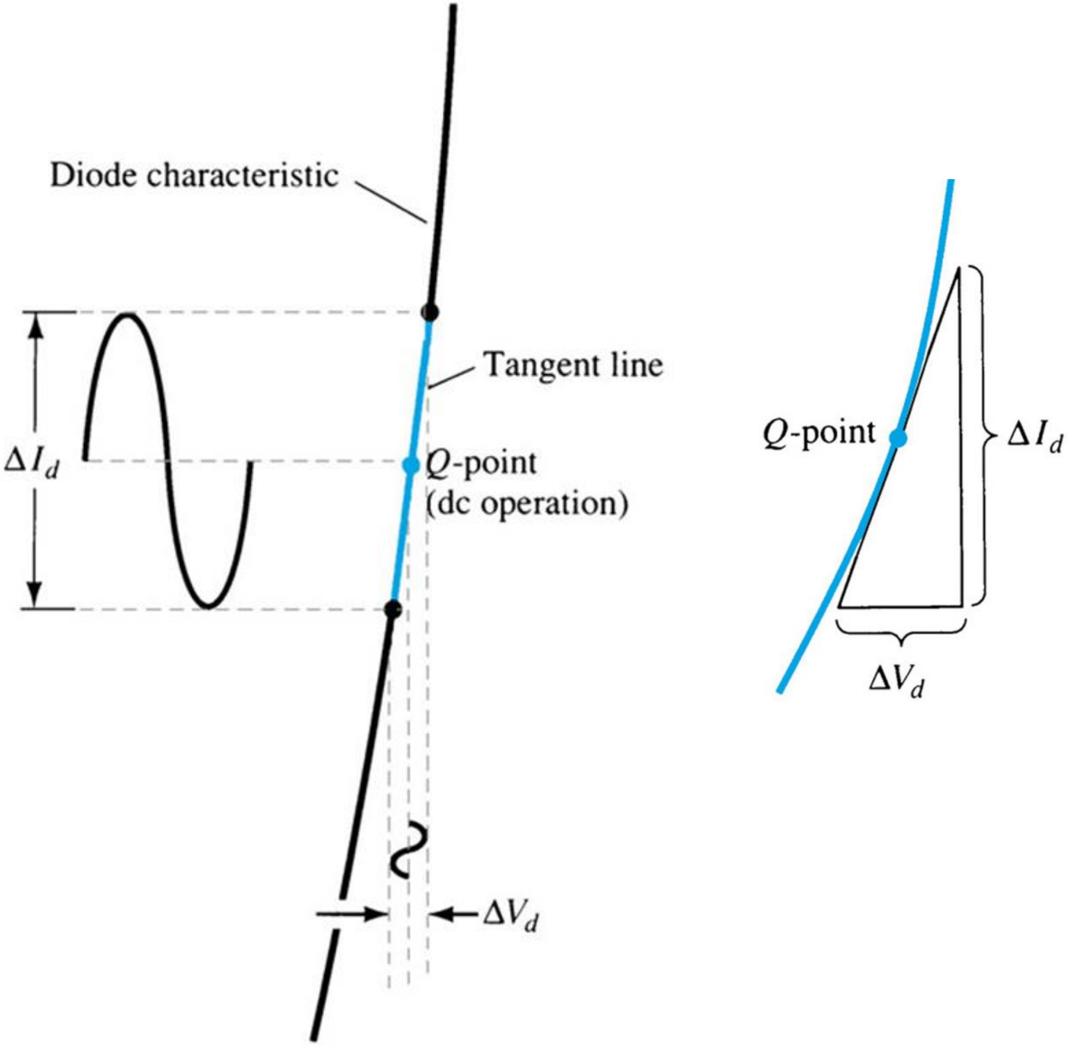


Valores de resistência e modelos equivalentes do diodo

- TIPO 1: resistência CC (ou estática)
  - Exemplo:

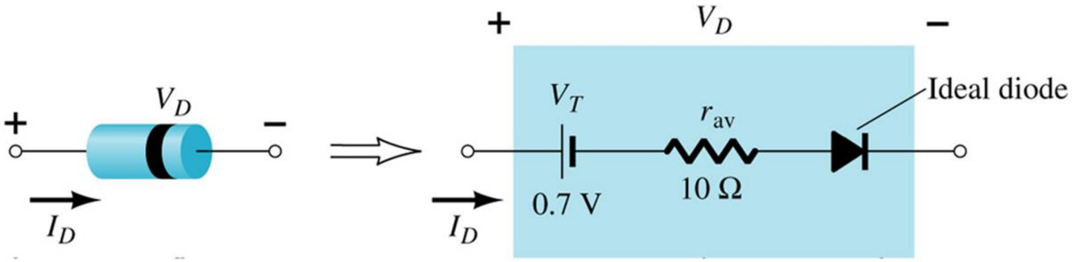


- TIPO 2: resistência CA (ou dinâmica)
  - Ponto quiescente (*Q*)
  - $$r_d = \frac{\Delta V_d}{\Delta I_d} \approx \frac{25{,}6\text{mV}}{I_D}$$

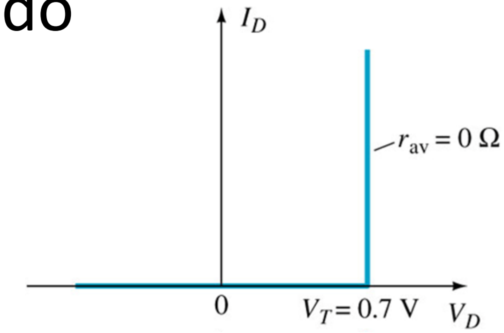


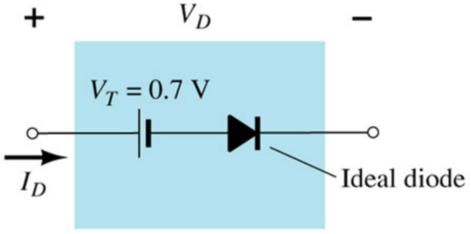
  - Resistência de corpo (r_B) ou de conexão metálica: 0,1 a 2 Ω

- Circuitos equivalentes
  - TIPO 1: linear

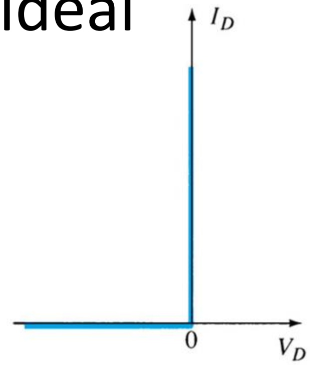


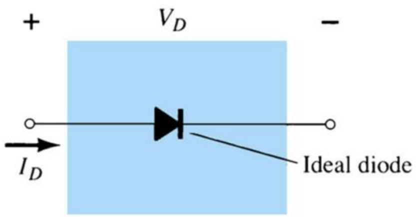
  - TIPO 2: Simplificado



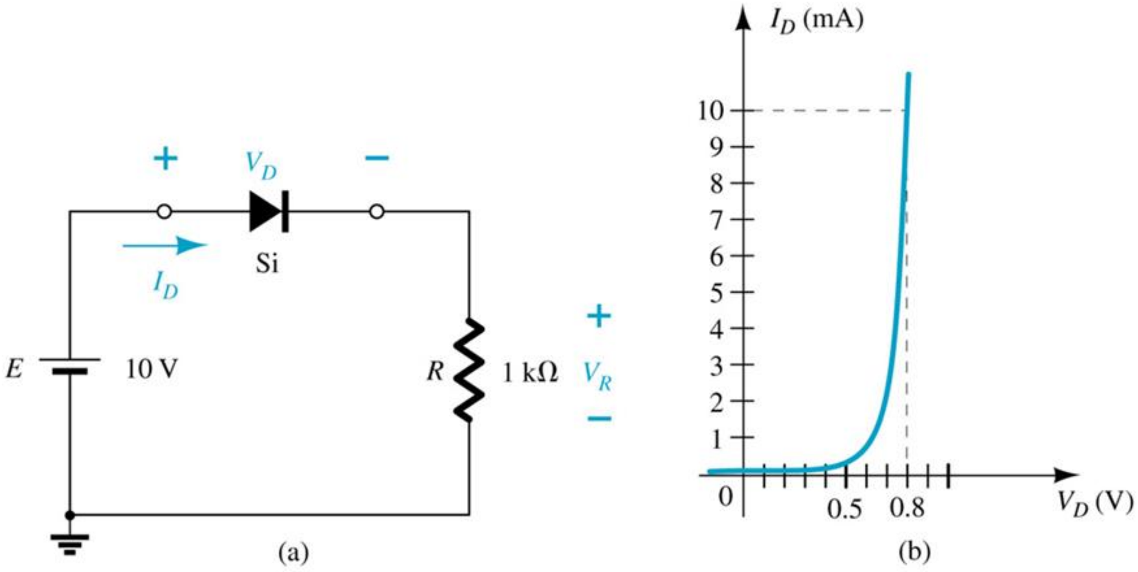


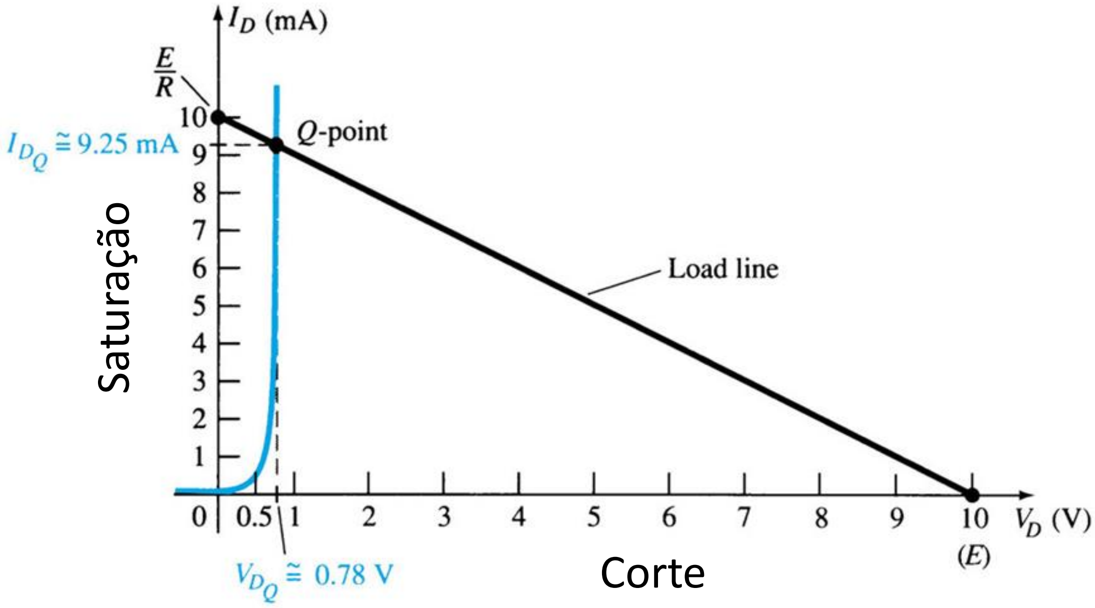
  - TIPO 3: ideal





- Reta de carga



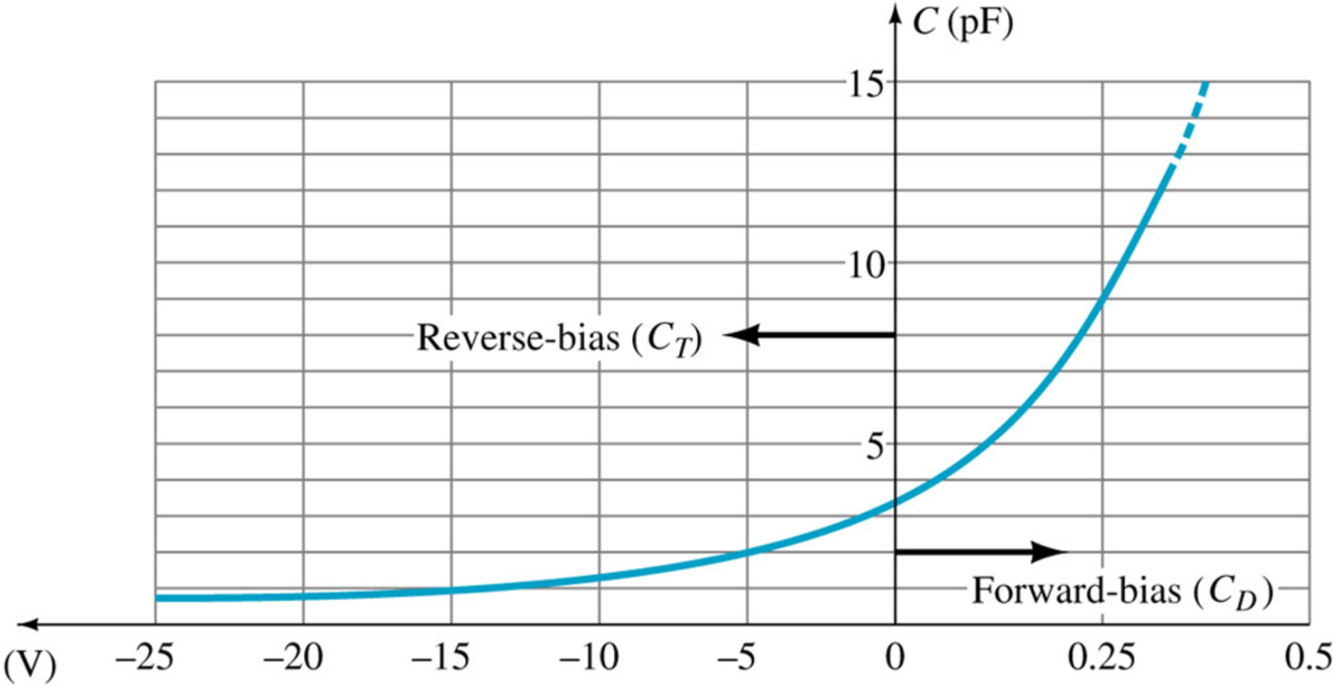


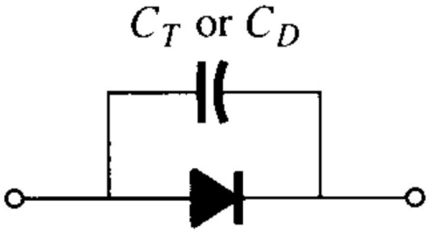
Saturação

Corte

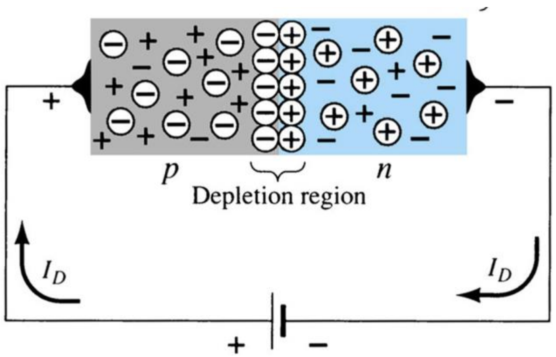
Capacitância e tempos do diodo

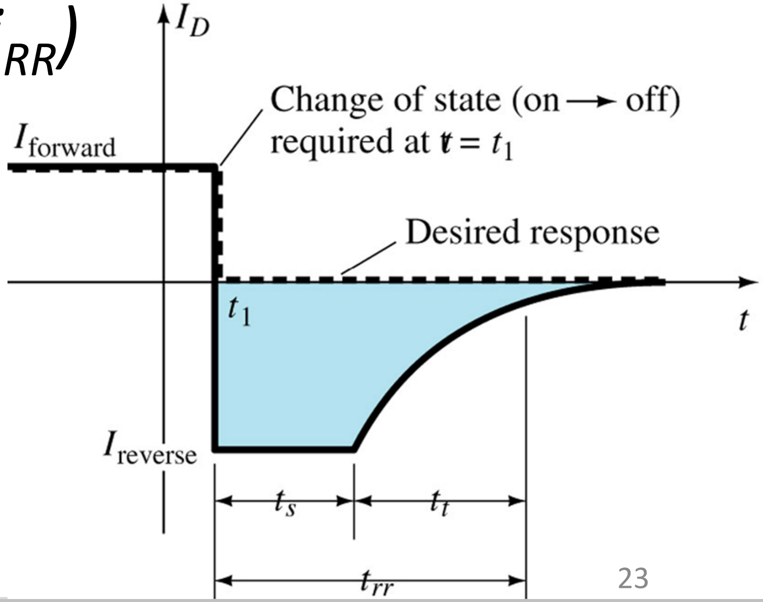
- Capacitância
  - Depleção como meio isolante
  - Capacitância depende do potencial de polarização





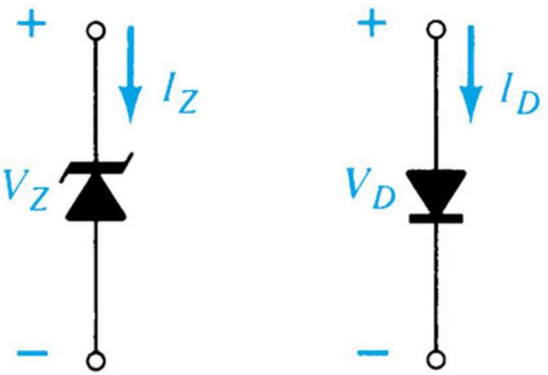
- Tempo de recuperação reversa
  - t_s (tempo armazenamento)
    - Portadores minoritários voltarem ao material oposto
  - t_t (tempo transição)
  - $t_{rr} = t_s + t_t$
    - Varia de 1 μs a poucos *os*
  - *Corrente recuperação inversa (i_{RR})*





Diodo de Zener

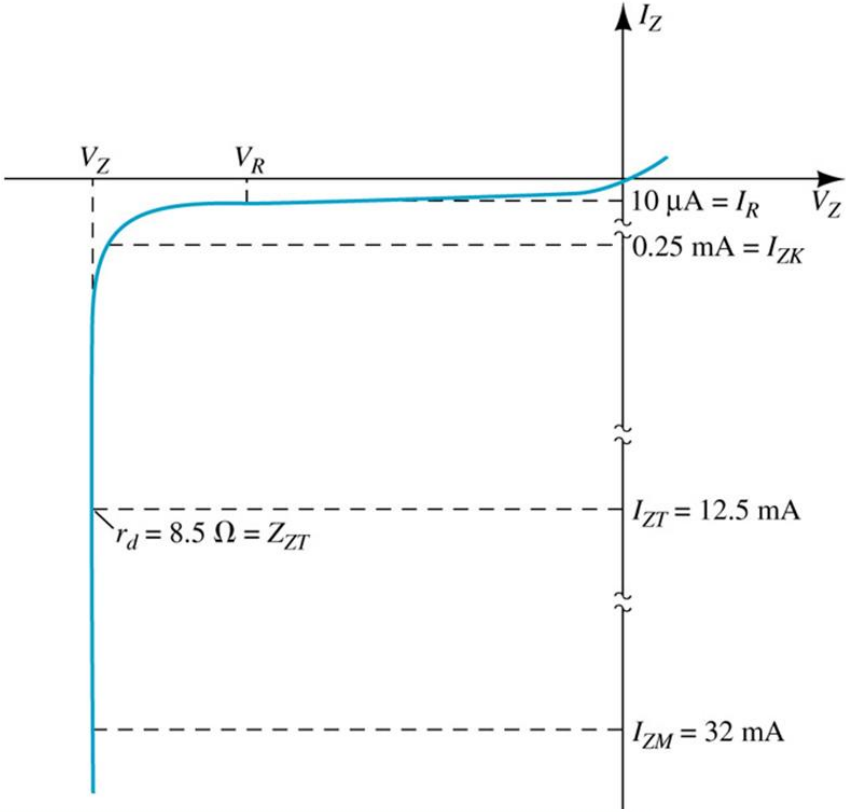
- Principal característica: $V_D \leq V_Z$
- Controla-se a região de Zener variando-se nível dopagem



- Características elétricas

Zener Voltage Nominal, V_Z (V)	Test Current, I_{ZT} (mA)	Max Dynamic Impedance, Z_{ZT} at I_{ZT} (Ω)	Maximum Knee Impedance, Z_{ZK} at I_{ZK} (Ω)	(mA)	Maximum Reverse Current, I_R at V_R (μA)	Test Voltage, V_R (V)	Maximum Regulator Current, I_{ZM} (mA)	Typical Temperature Coefficient (%/°C)
10	12.5	8.5	700	0.25	10	7.2	32	+0.072

Observação: V_Z é nominal e pode ter variação de até 20%

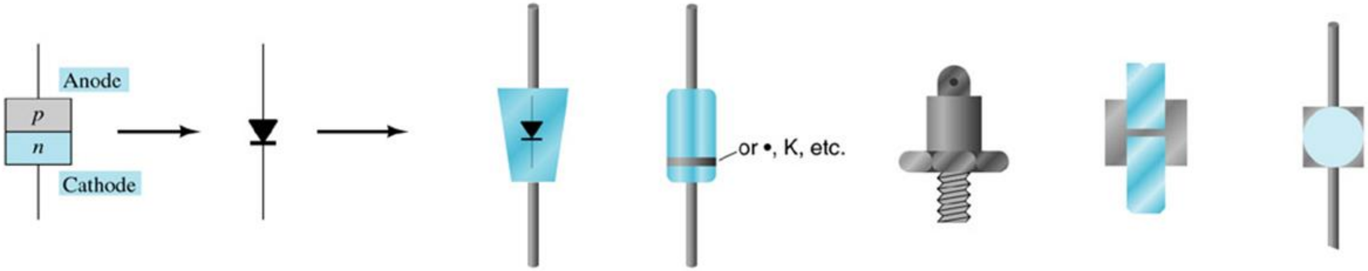


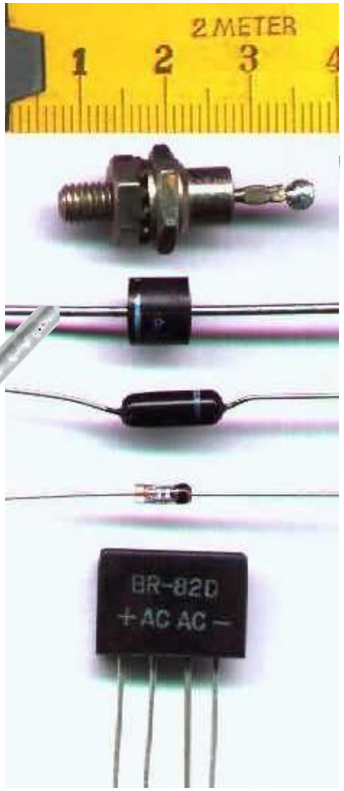
Interpretação de folha de dados (data sheets)

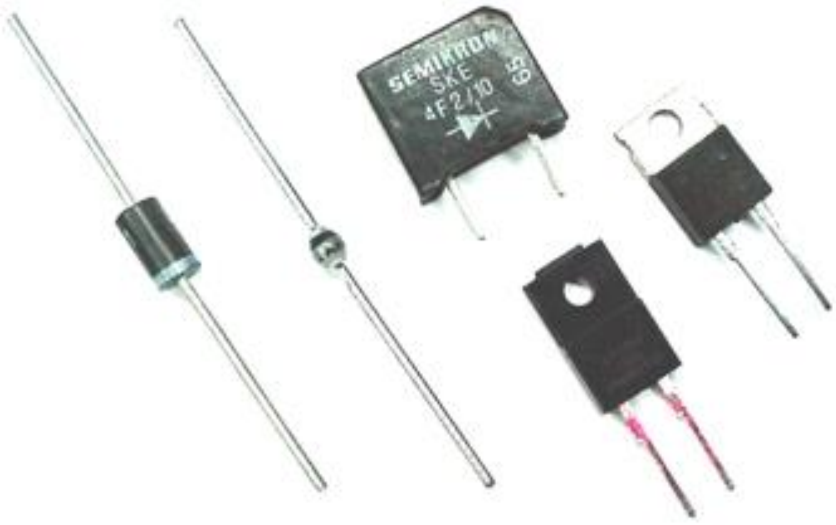
- Principais parâmetros:
  - Tensão direta V_F
  - Corrente direta máxima I_F
  - Corrente saturação reversa I_R
  - Tensão reversa nominal ou de ruptura (V_{PIV}, V_{PRV}, V_{BR})
  - Valor máximo de potência
  - Tempo de recuperação reversa t_{rr}
  - Faixa de temperatura de operação

Modelos e testes com diodos

- Notação:







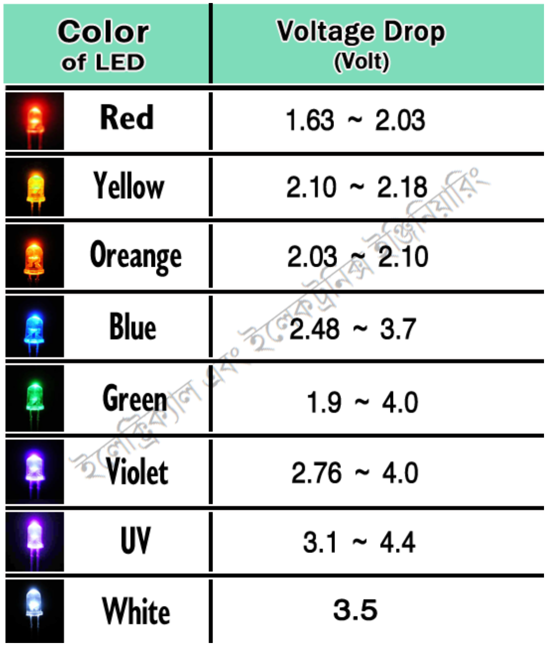
- Classes básicas:
  - 1N4148 (diodos de pequeno sinal)
  - Família 1N400X (diodos retificadores)
  - Família BZX61 (diodos Zener)

- Alguns exemplos de diodos comerciais

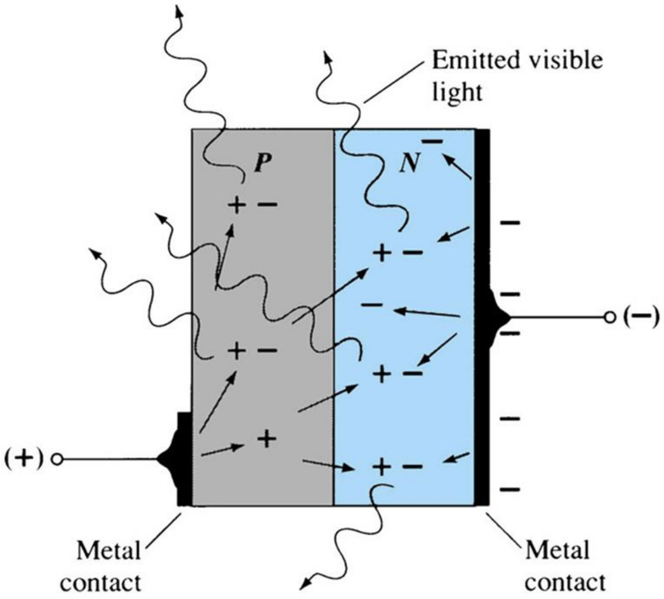
Tipo	**Uso**	**Corrente**	**$V_{ruptura}$**
1N914	alta velocidade	75 mA	75
1N4148	alta velocidade	200 mA	75
BB119	Varicap	-	-
BB809	varicap usado em VHF	-	-
1N4001	retificador	1A	50
1N4002	retificador	1A	100
1N4003	retificador	1A	200
1N4004	retificador	1A	400
1N4005	retificador	1A	600
1N4006	retificador	1A	800
1N4007	retificador	1A	1000

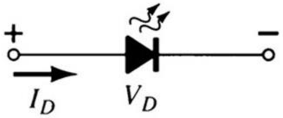
Tipos especiais de diodos

- A) Diodo emissor de luz (LED)
  - Recombinação de lacunas e elétrons = calor e fótons
  - $1,7 < V_T < 3,3V$

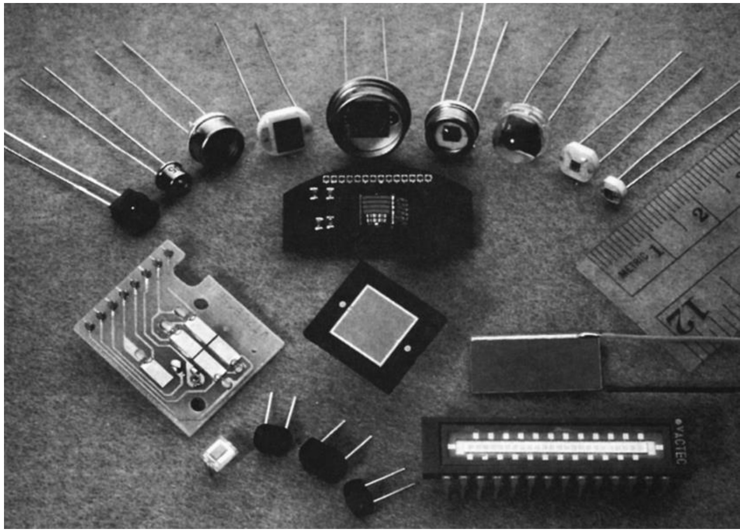


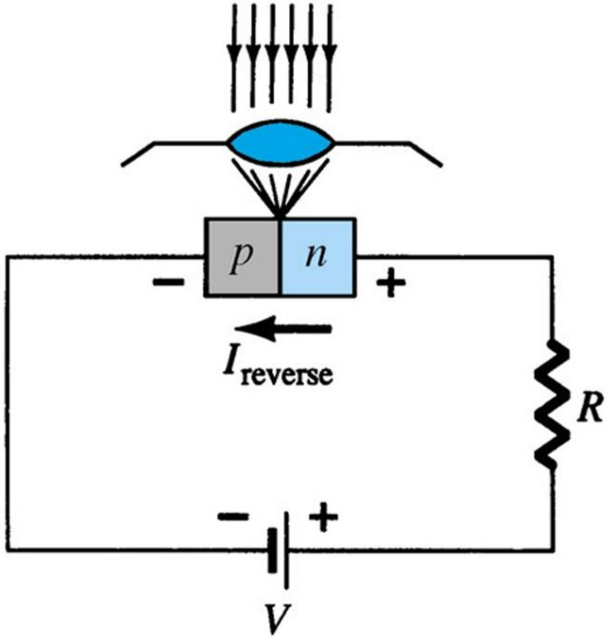
Color of LED	Voltage Drop (Volt)
Red	1.63 ~ 2.03
Yellow	2.10 ~ 2.18
Oreange	2.03 ~ 2.10
Blue	2.48 ~ 3.7
Green	1.9 ~ 4.0
Violet	2.76 ~ 4.0
UV	3.1 ~ 4.4
White	3.5

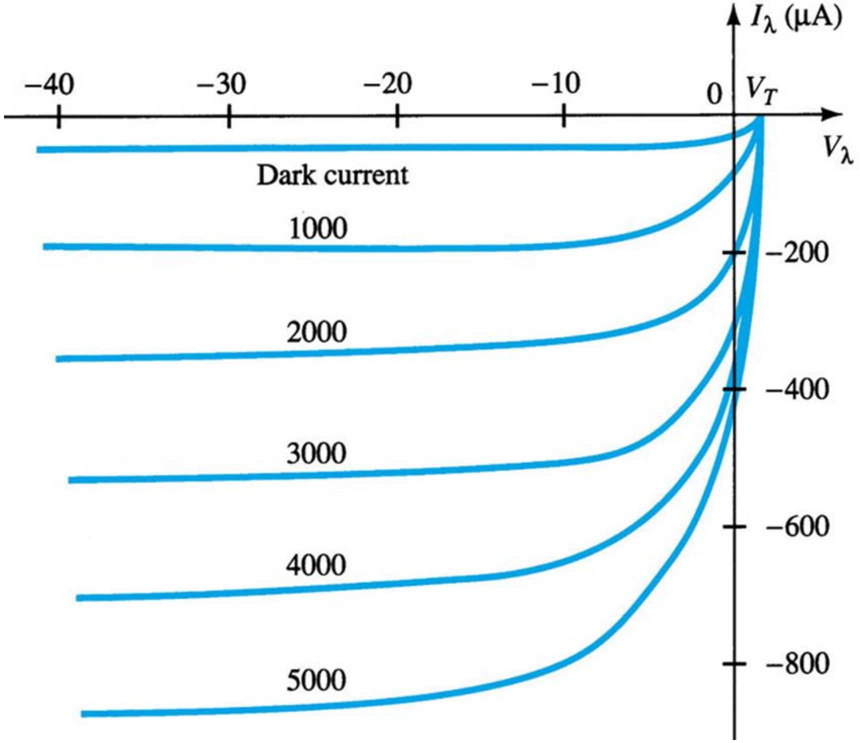




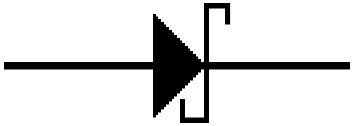
- B) Fotodiodo
  - Somente corrente reversa
  - Luz desloca elétrons de valência





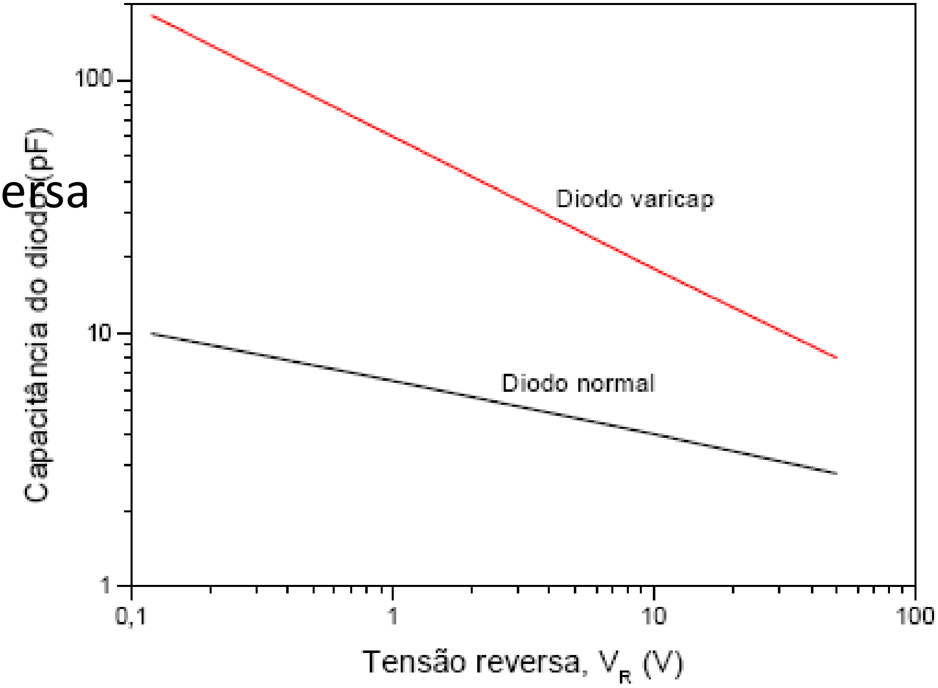


- C) Diodo de Schottky

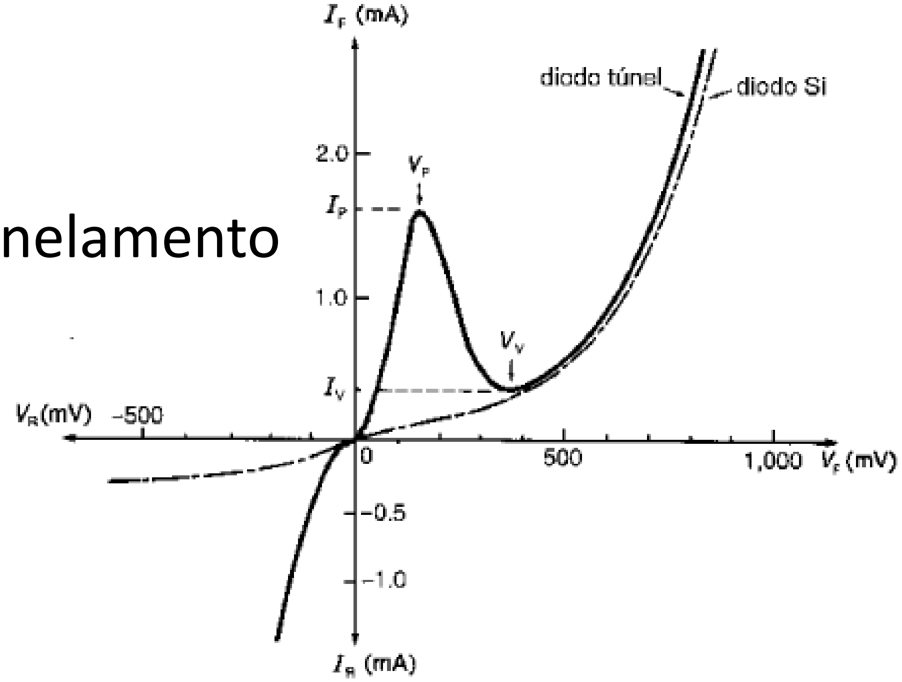


  - Barreira metálica substituindo material p
    - sem injeção e armazenamento de portadores minoritários
    - ausência recuperação reversa
    - V_T=0,25 V

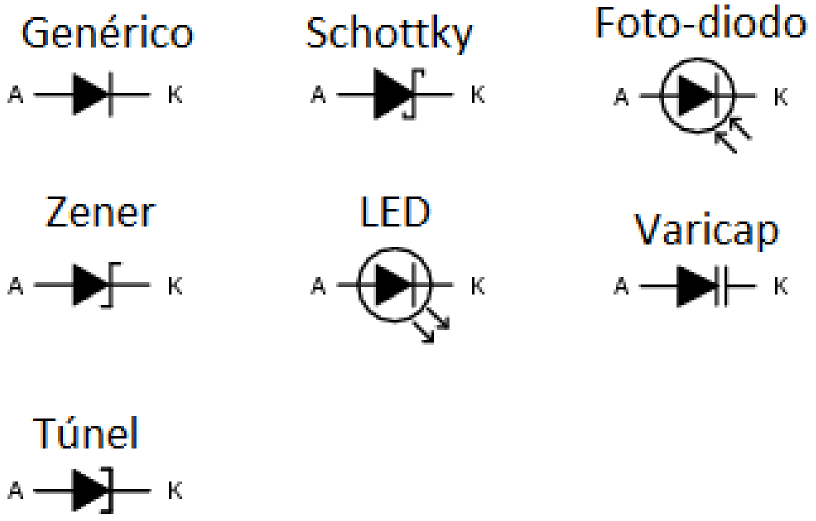
- D) Varactores/Varicap
  - Controle na junção pn
  - Capacitância varia com a tensão reversa



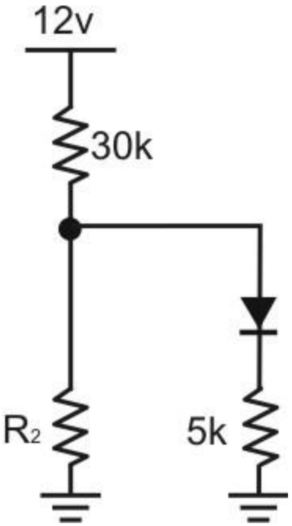
- E) Diodo de tunel
  - Excesso de impurezas
  - Fenômeno quântico de tunelamento



- Simbologia

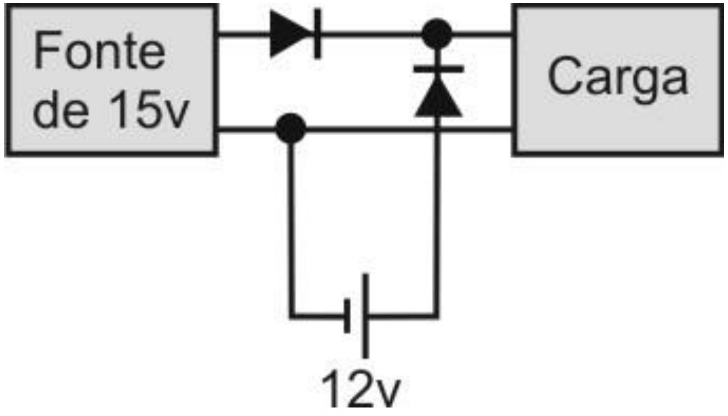


Exercícios e exemplos



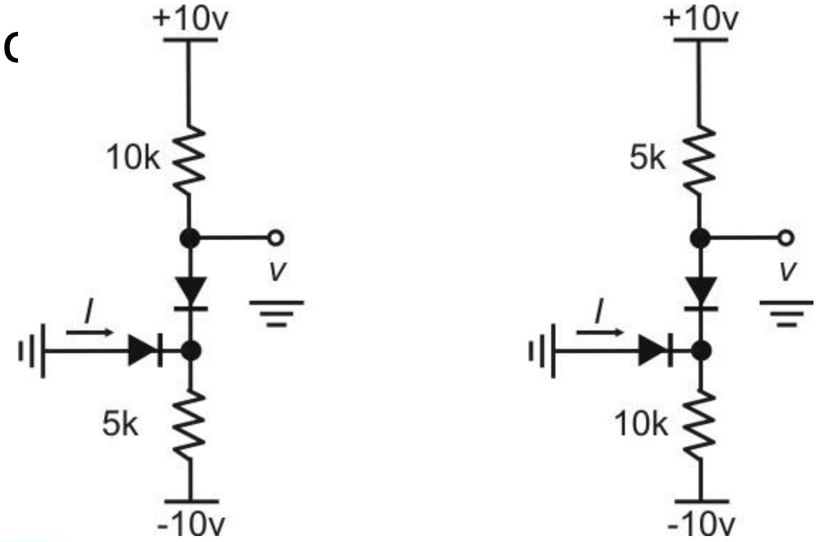
Exemplo 2: Que valor deve ter R2 na figura abaixo para que a corrente no diodo seja de 0,25mA?

Exemplo 3: Alguns sistemas, como os alarmes, usam uma bateria de emergência para o caso de uma eventual queda da tensão da rede. Descreva como o circuito da figura abaixo funciona



Exemplo 4: A figura abaixo mostra um circuito alimentando por uma onda senoidal de 24v de pico. Determine a (i) forma de onda de condução do diodo, (ii) o valor de pico da corrente no diodo e (iii) a tensão de polarização inversa máxima sobre o diodo

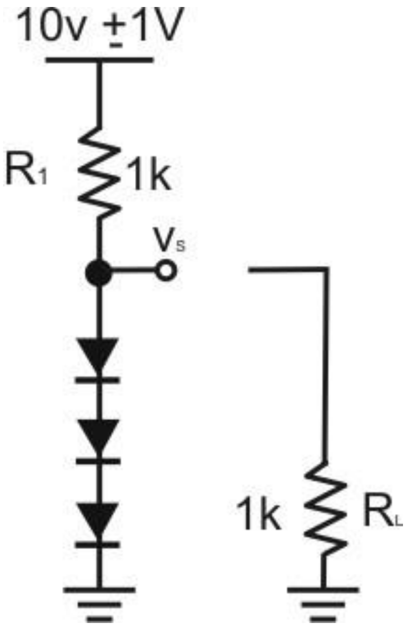
Exemplo 5: Considerando diodos ideais, calcule os valores de I e V nos circuitos abaixo. Considere diod



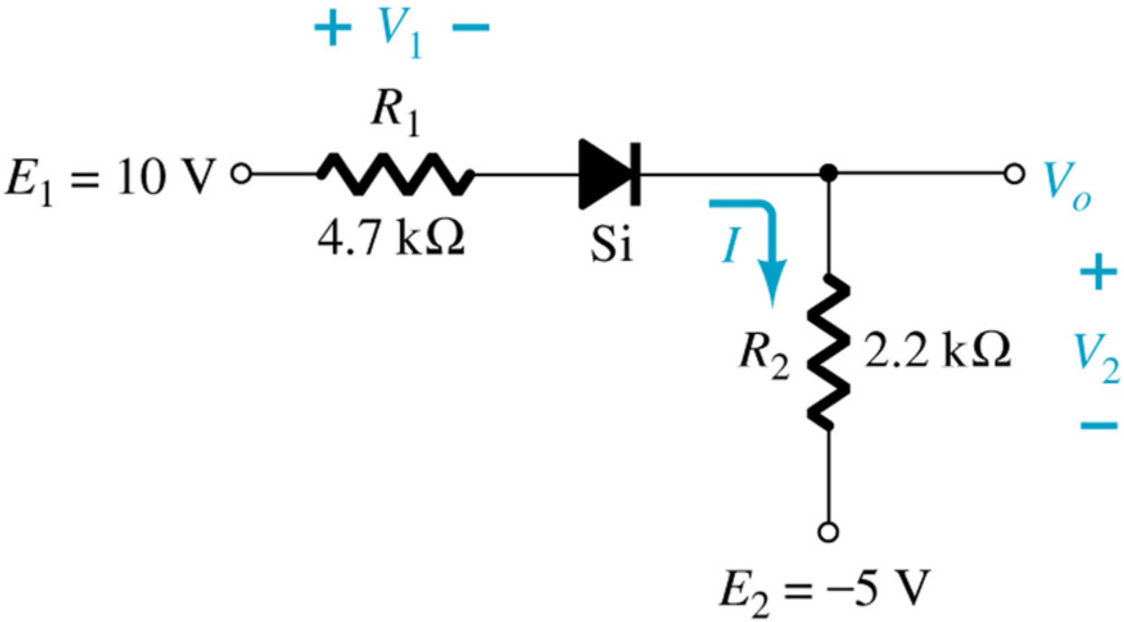
Exemplo 6: baseando-se na figura abaixo, responda:

a) Considerando uma alimentação fixa de 10v, três diodos são usados para conseguir uma saída Vs fixa de 2,4V. Considere que os diodos tenham uma queda de 0,7V de queda com corrente de 1mA e que ΔV=0,1V/década de variação de corrente, estipule um valor para R_1.

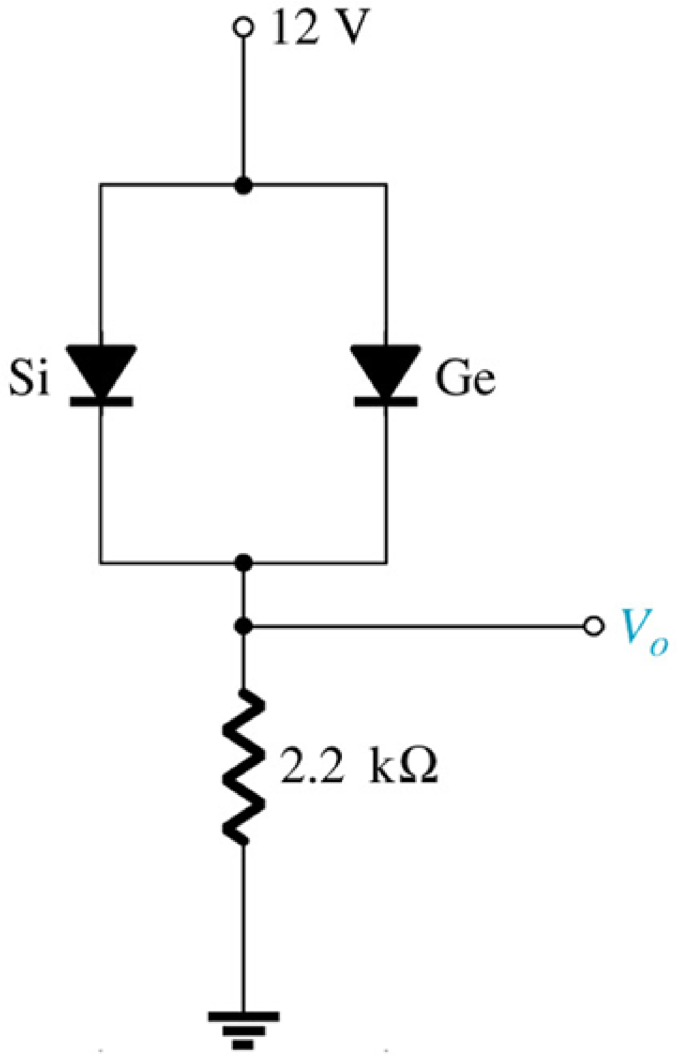
b) Três diodos são usados para uma saída de 2,1V. Deseja-se calcular a variação de saída provocada por (i) uma variação de ±1V na fonte e (ii) a ligação de uma resistência de carga de 1kohm



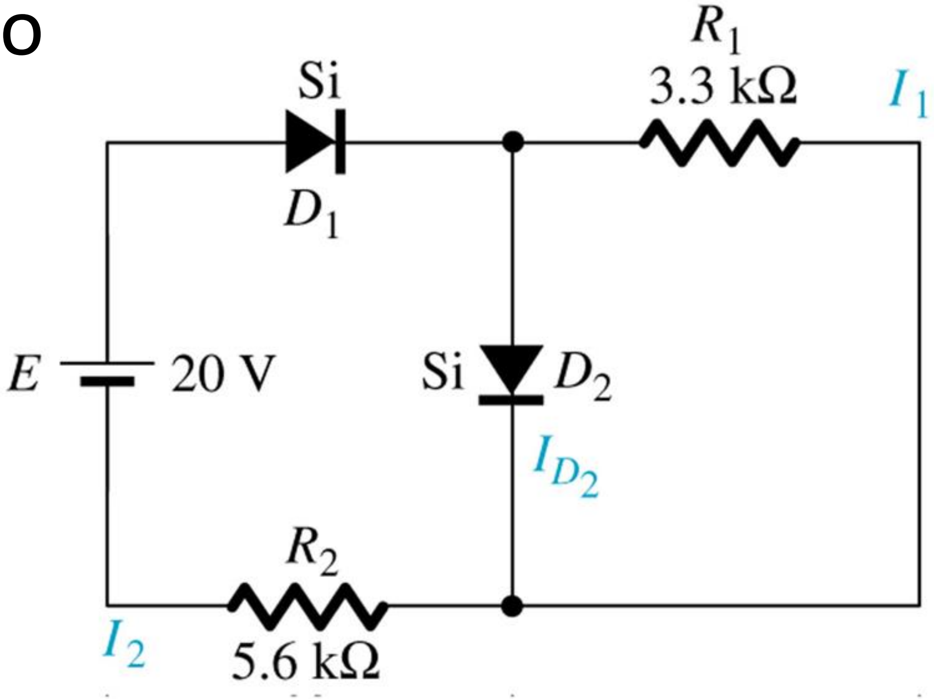
Exemplo 7: Determine I, V_1, V_2, V_0 da figura abaixo.



Exemplo 8: Calcule V_O para a figura abaixo



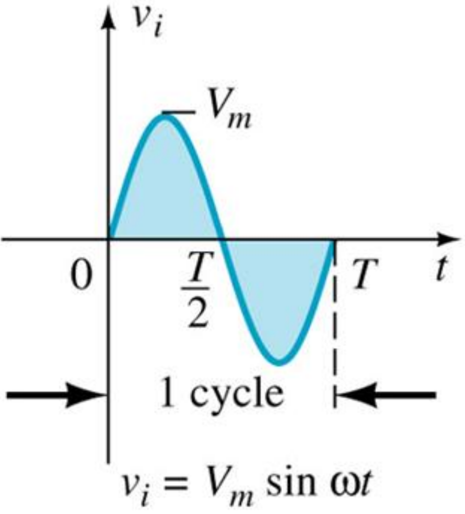
Exemplo 9: determine as correntes I_1, I_2 e I_D na figura abaixo

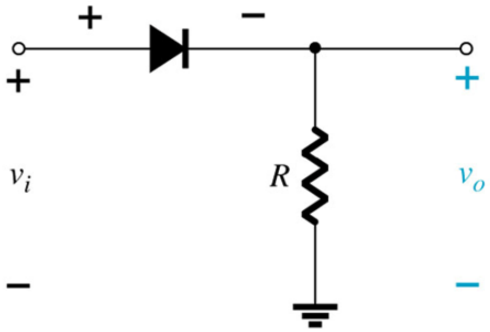


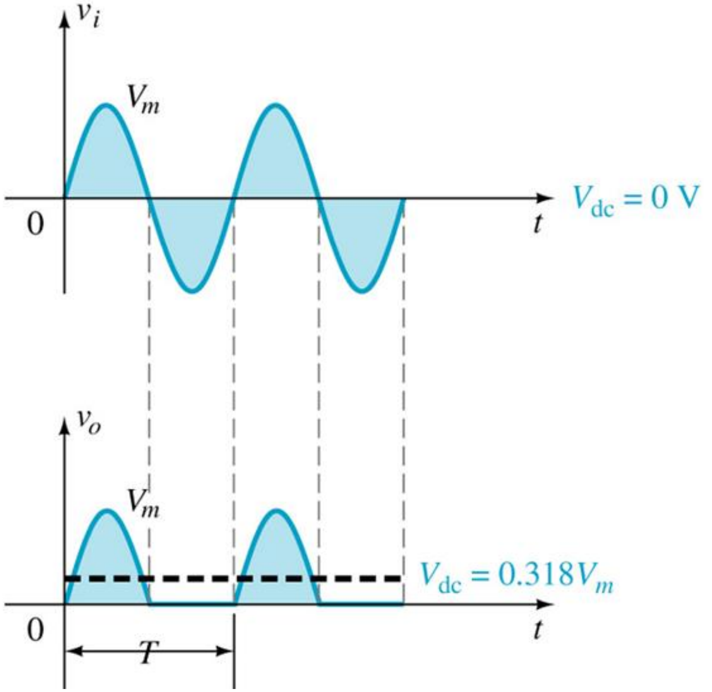
Parte 2:

Circuitos com diodos – aplicações

- A) Retificador de meia onda:
  - $V_{rms} = 0{,}318\,(V_m - V_T)$ onde $V_T = 0{,}7$v

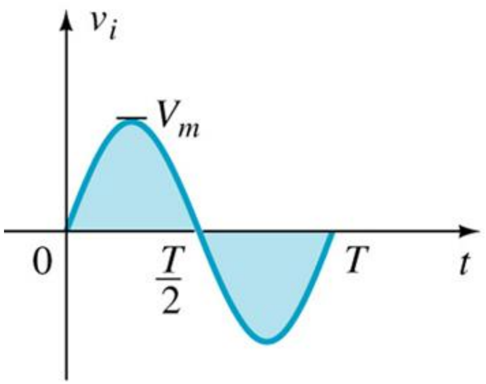


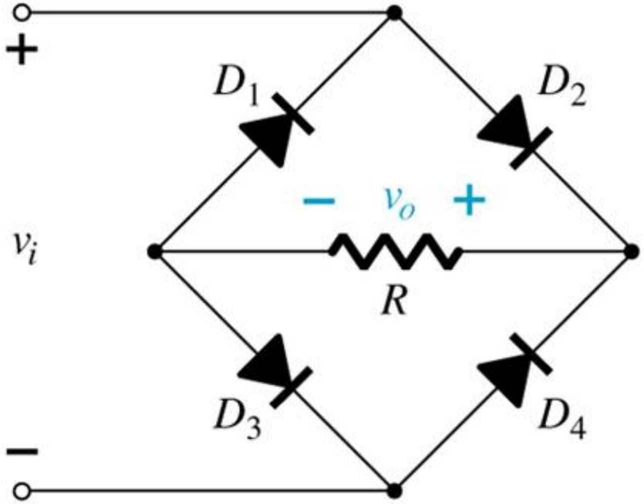


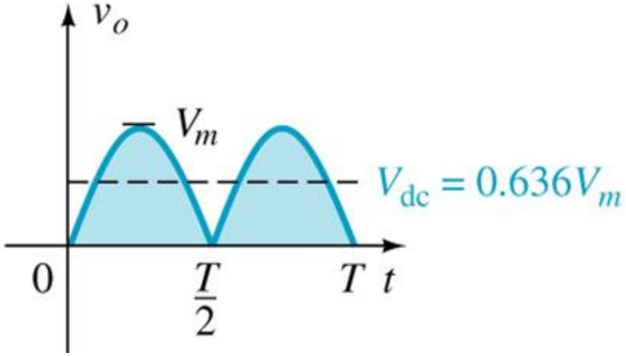


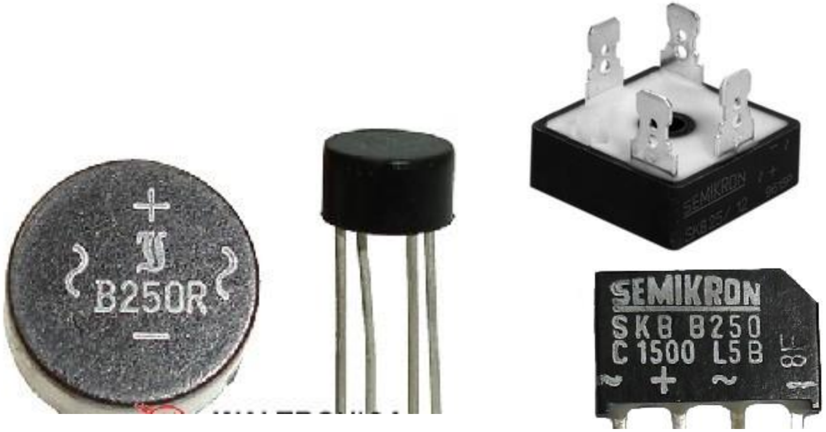
  - Tensão pico inversa (PIV)/tensão de pico reversa (PRV):
    - PIV ≥ V_m

- B) Retificador de onda completa em ponte



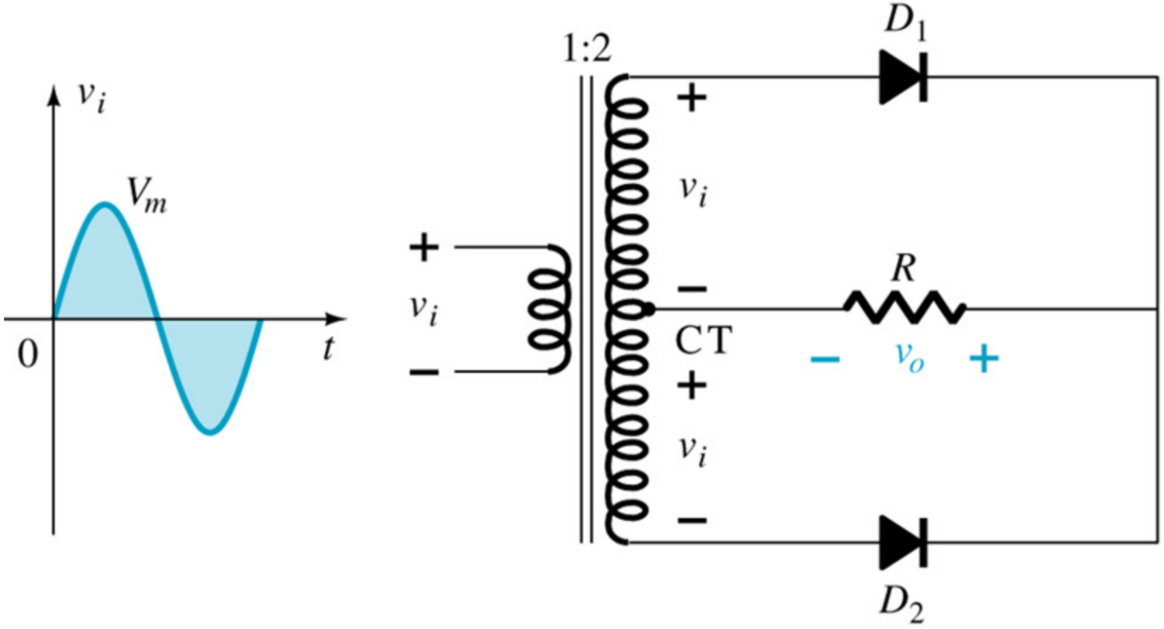






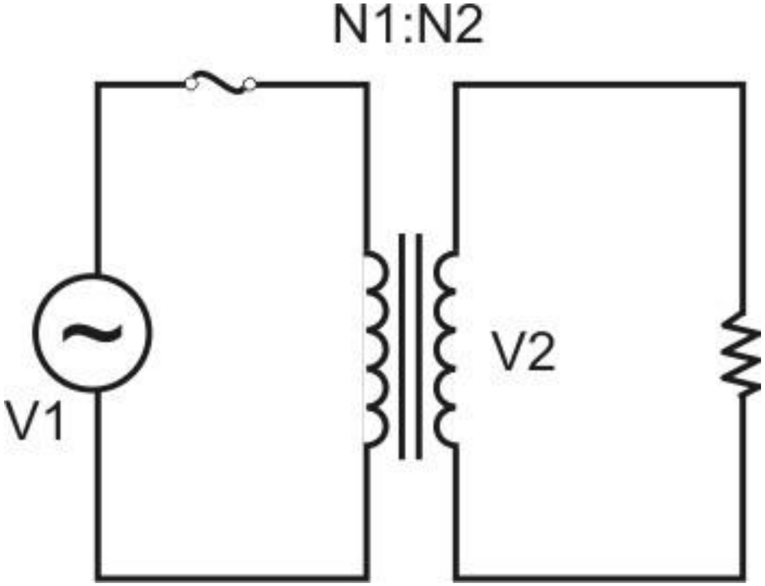
  - $V_{rms} = 0,636\ (V_m - 2V_T)$
  - PIV $\geq V_m$
- – CI’s de ponte retificadora: 1B4B42 e SKB1,2/08 B250R

- C) Retificador de onda completa com transformador com derivação (tap) central



- $V_{rms} = 0,636\ (V_m - V_T)$
- $PIV \geq 2\ V_m$

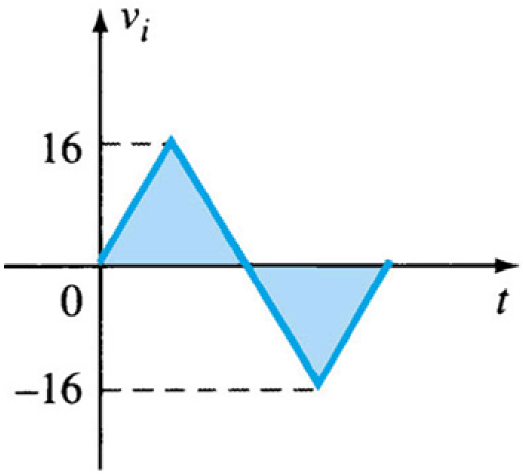
- Equações básicas do transformador:

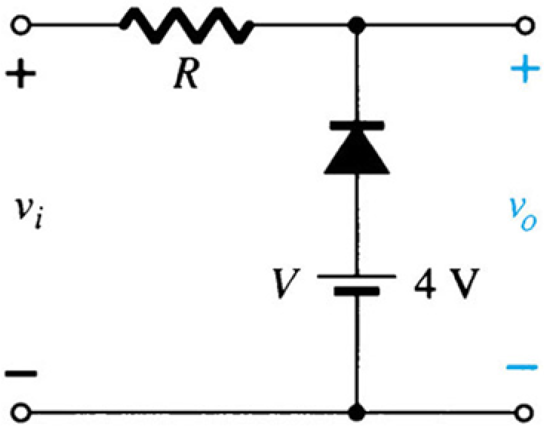


  - $V_2=(N_2/N_1)V_1$
  - P1=P2 ou $V_2I_2=V_1I_1$

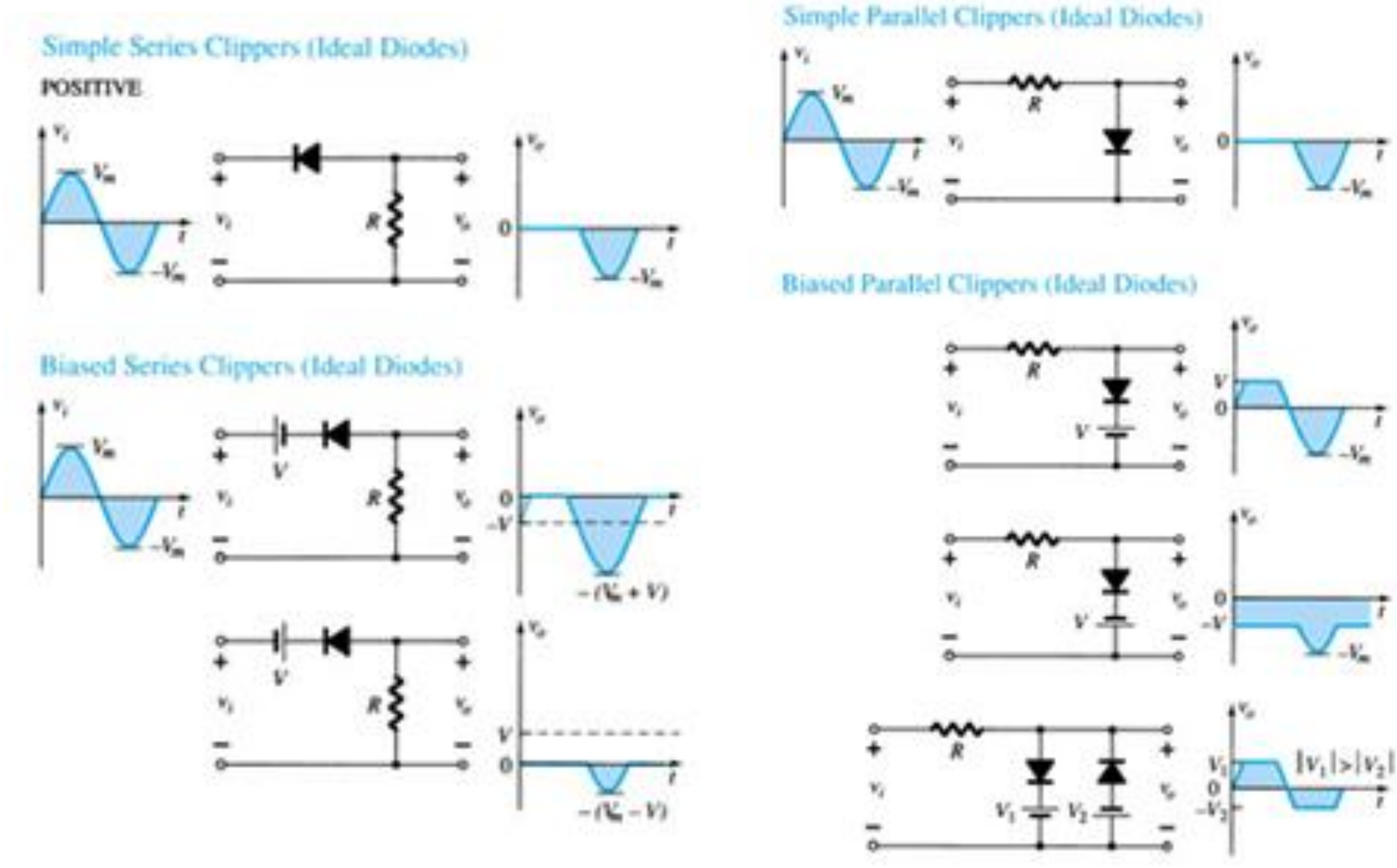
Ceifadores

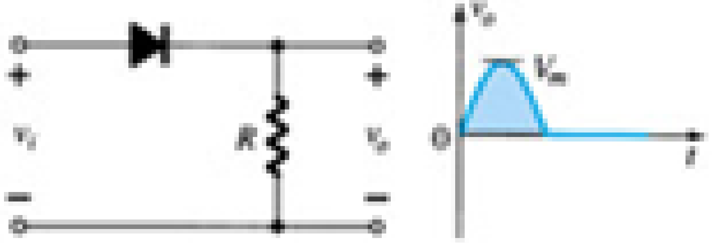
- Ceifar parte da onda sem distorcer o restante da onda
- Exemplo 10: Determine a saída do circuito abaixo.

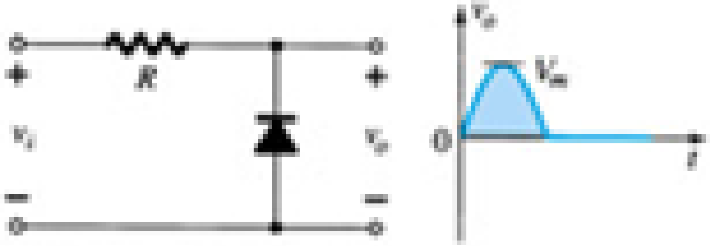


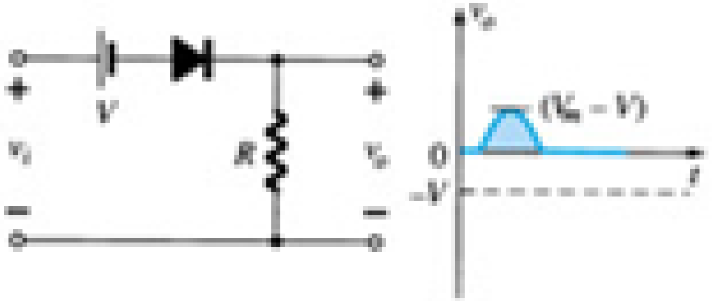


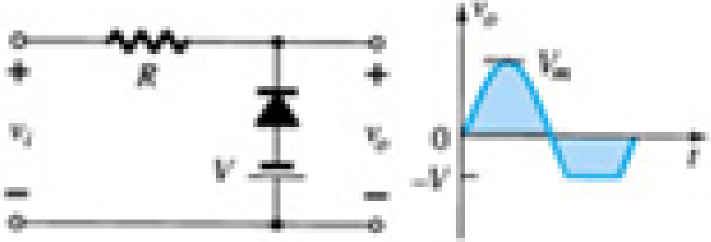
- Exemplos diversos de modelos de ceifadores

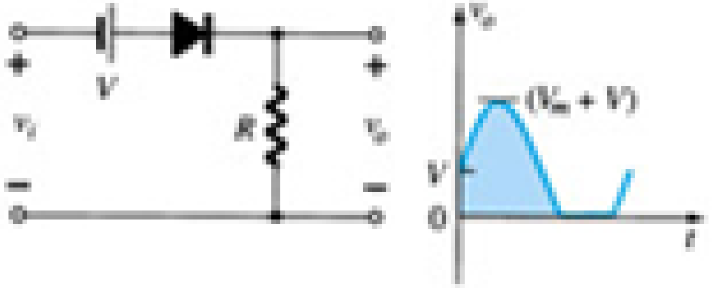


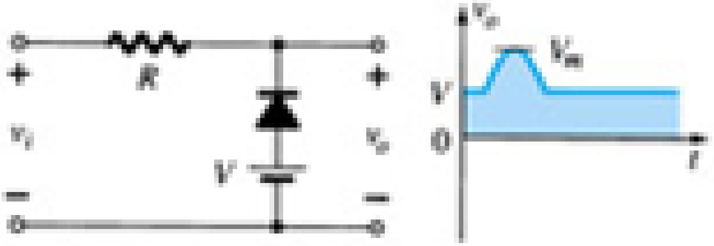

+
v_i
−
R
+
v_o
−
v_o
V_m
0
t


+
v_i
−
R
+
v_o
−
v_o
V_m
0
t


+
V
v_i
−
R
+
v_o
−
v_o
$(V_m - V)$
0
$-V$
t

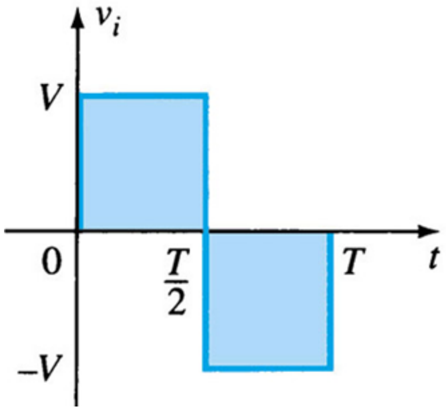

+
v_i
−
R
V
+
v_o
−
v_o
V_m
0
$-V$
t

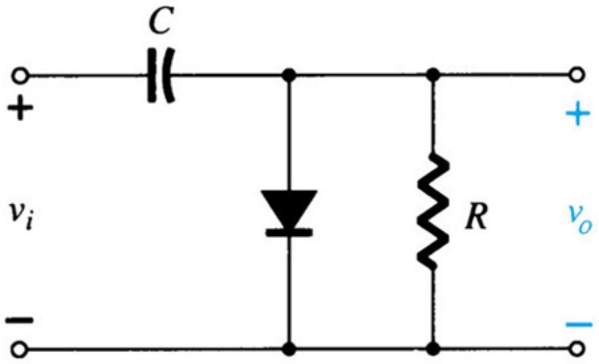

+
V
v_i
−
R
+
v_o
−
v_o
$(V_m + V)$
V
0
t

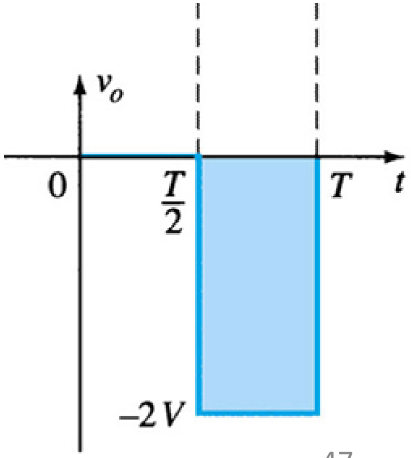

+
v_i
−
R
V
+
v_o
−
v_o
V_m
V
0
t

Grampeadores de tensão

- Geralmente usa capacitor ou fonte para *adicionar nível CC ao sinal*
  - – *CONVENÇÃO:* RC deve ser elevada para assegurar que tensão no capacitor não descarregue significativamente
- Exemplo 11:







- Regras para análise:

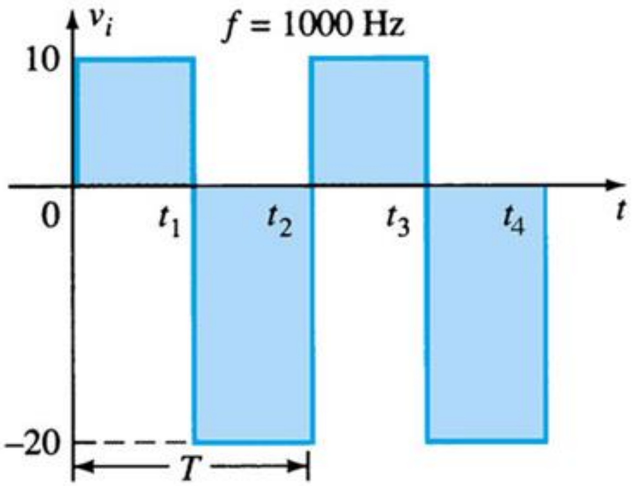
  1) Comece a análise começando pela parte do sinal de entrada que polarizara diretamente o diodo ;

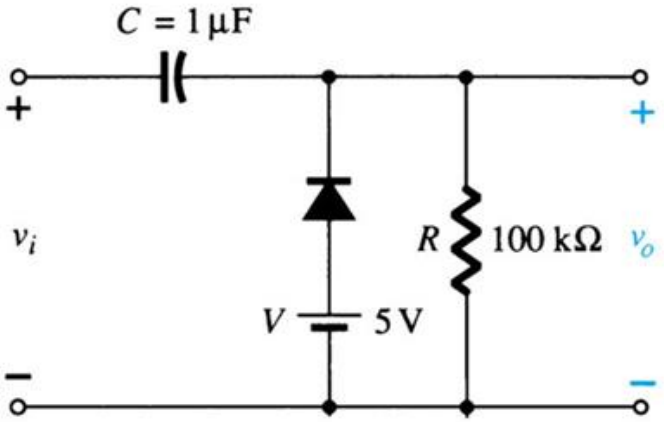
  2) Durante o período ligado do diodo, presuma que o capacitor carrega-se instantaneamente;

  3) Convencione que, durante o período em que o diodo está desligado, o capacitor se mantém no valor estabelecido (RC alto em relação T_{IN});

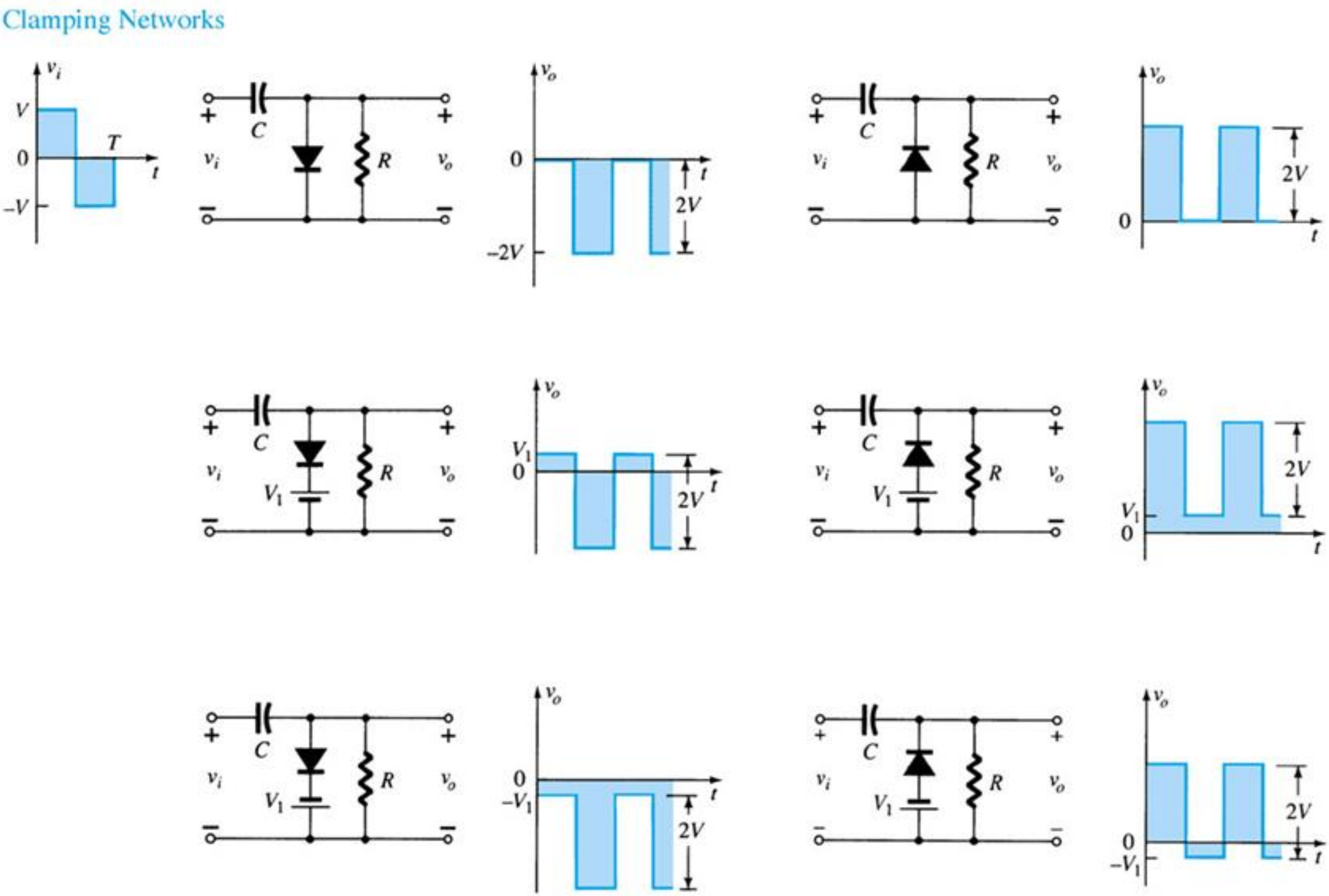
  4) ....o resto “Deus” ajuda

- **Exemplo 12**: determine a forma de onda para v_0 para a entrada indicada abaixo



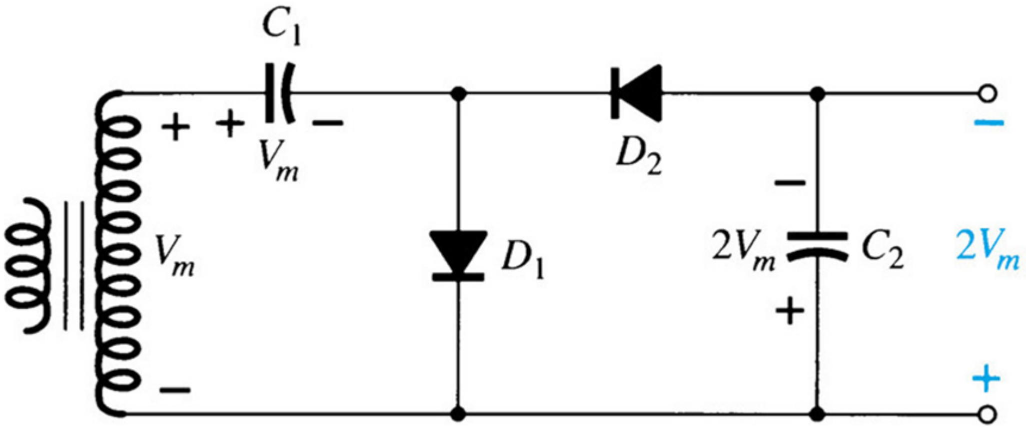


- Modelos diversos:

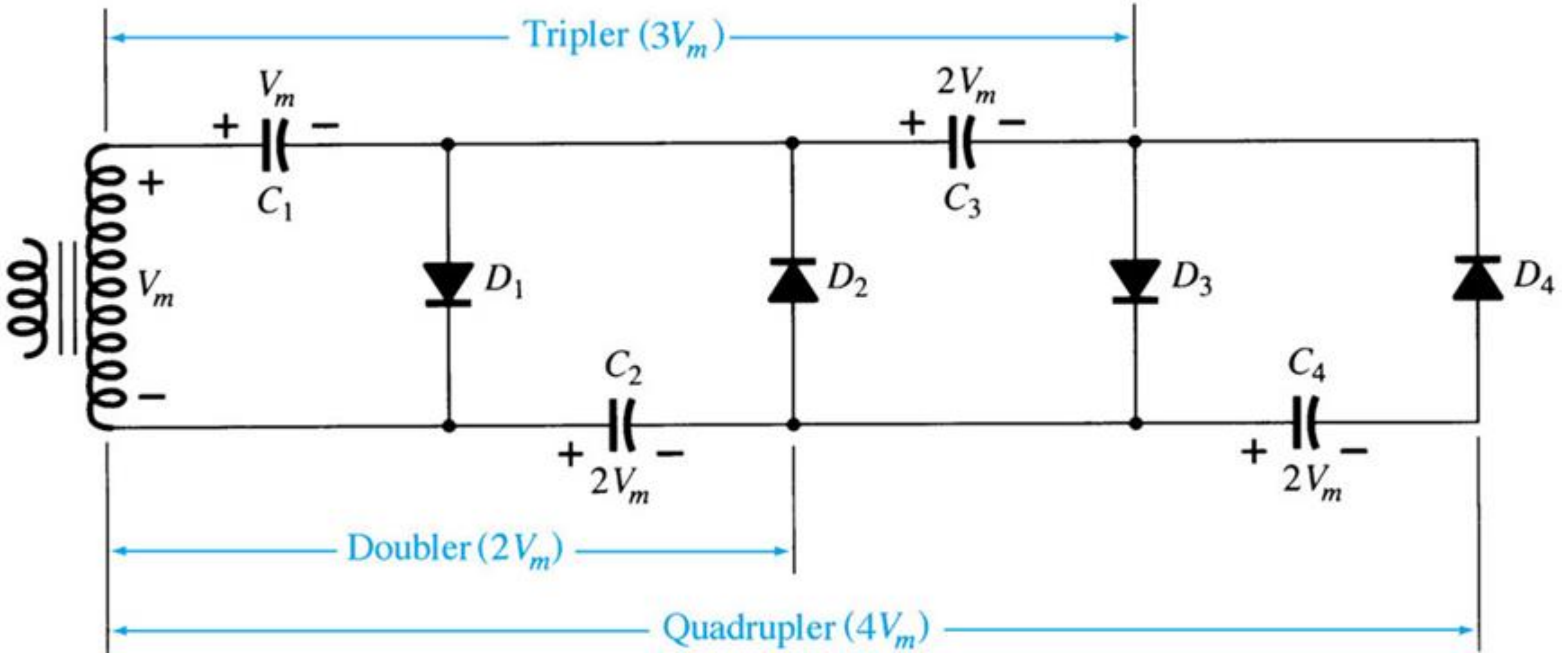


Multiplicadores de tensão

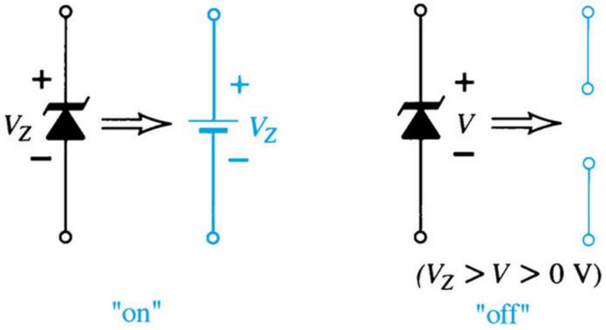
- Dobrador de tensão



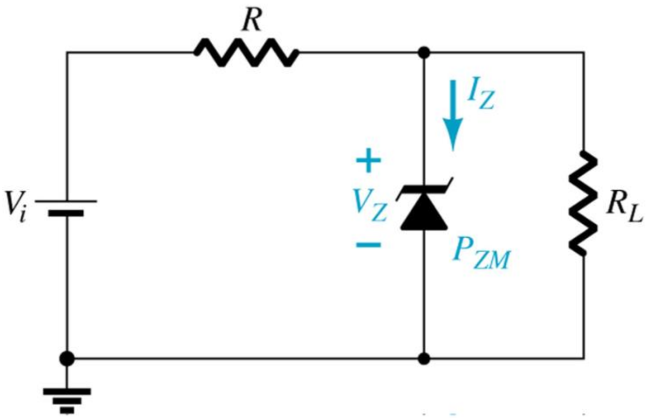
- Triplicador e quadruplicador de tensão

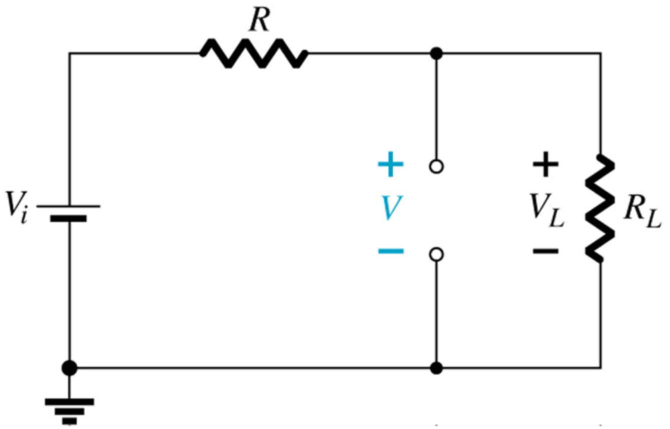


Diodo Zener: projeto



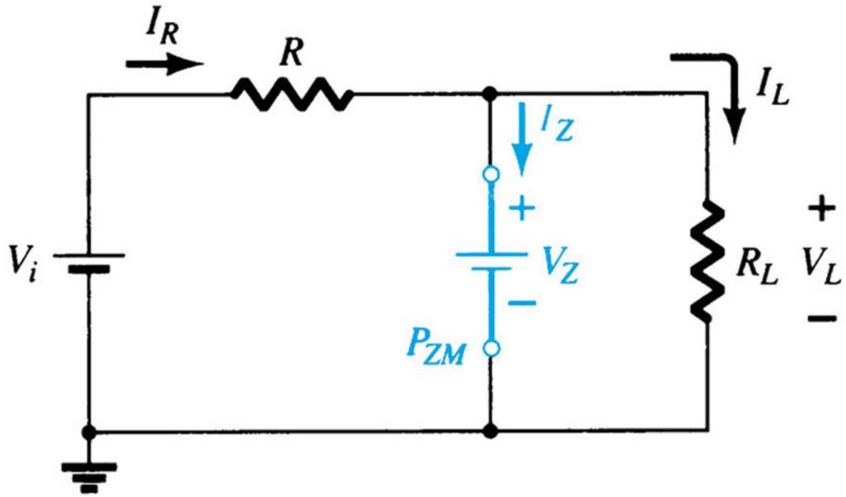
- **Passo 1:** determine o estado do Zener removendo-o do circuito e calculando a tensão do circuito aberto resultante





$$V_L = \frac{R_L V_I}{R + R_L}$$

Passo 2: substitua o circuito equivalente apropriado e determine as variáveis desejadas

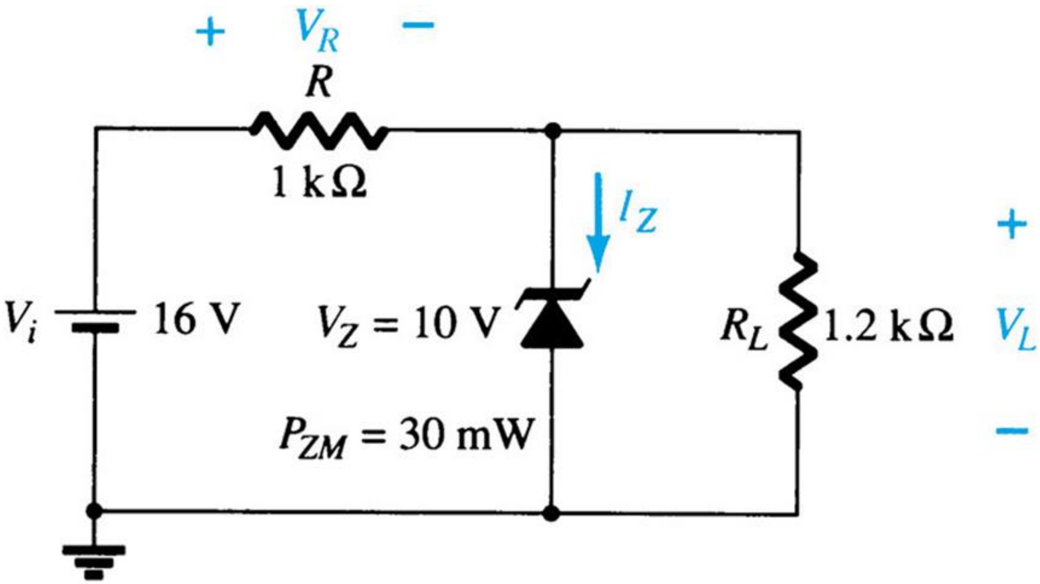


- Determine a corrente Iz no Zener: Iz = $I_R - I_L$
- Determine a potência no Zener: $P_Z = V_Z I_Z$

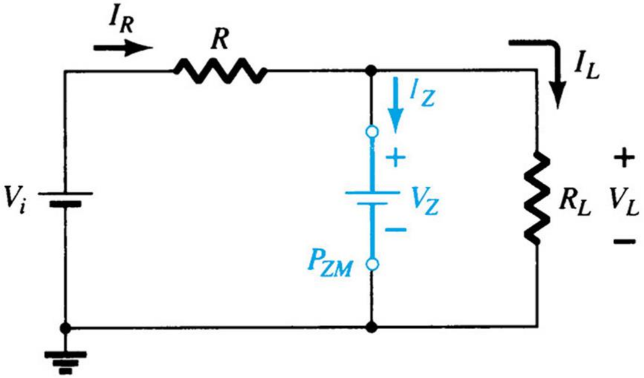
- Exemplo 13: para o circuito abaixo determine:

a) V_L, V_{R}, I_Z e P_Z

b) Repita os cálculos para R_L = 3K ohms



- Há uma faixa específica de valores de V_i e R_L que garantirá que o Zener esteja ativo. Logo:



Observe que:

- I_R é fixo
- I_Z é limitado a I_{ZM} (dado *datasheet*)

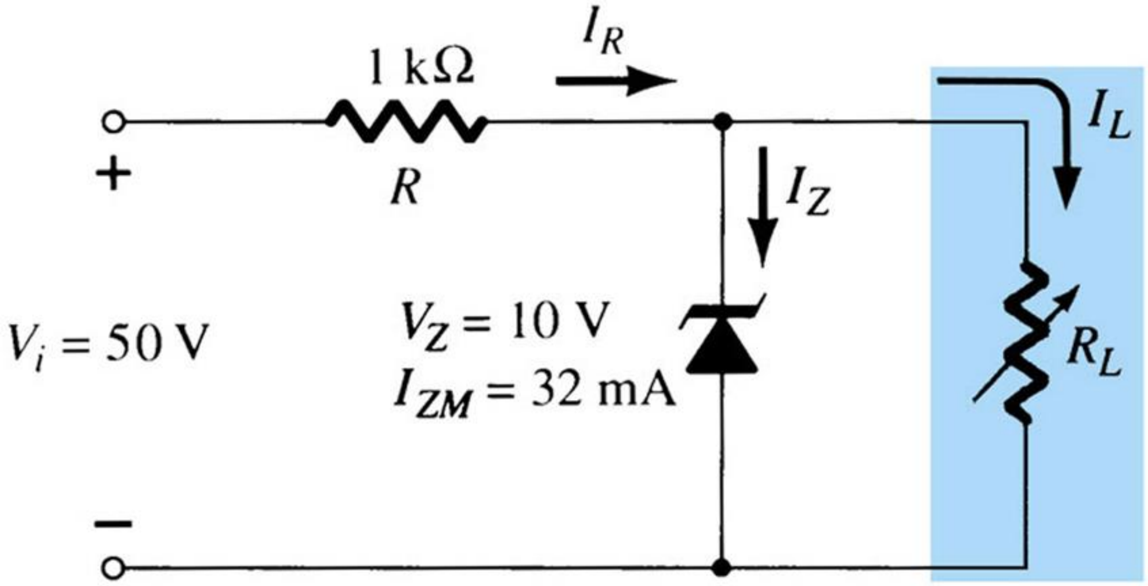
  - **CASO A** (V_i fixo e R_L variável): Carga mínima para ativar o Zener

$$R_{L\min} = \frac{RV_z}{V_i - V_Z}$$

  - **CASO B** (V_i fixo e R_L variável): Carga máxima para ativar o Zener

$$R_{Lmáx} = \frac{V_z}{I_{L\min}}$$

- Exemplo 14: Determine a faixa de valores de R_L e I_L que manterá o diodo na região Zener



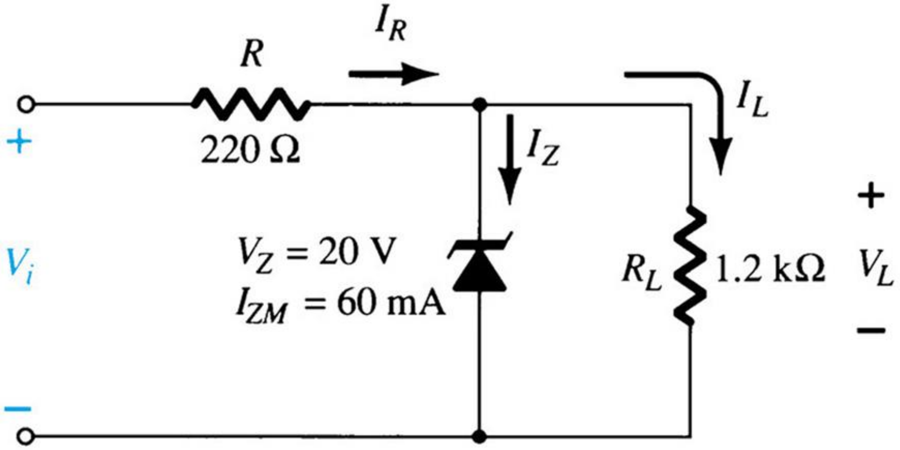
- **CASO C** (V_i variável e R_L fixo): V_i mínima para ativer Zener.

$$V_{i\_mim} = \frac{(R_L + R)V_z}{R_L}$$

- **CASO D** (V_i variável e R_L fixo): V_i máxima para ativer Zener.

$$V_{i\_máx} = I_{Rmáx} R + V_Z$$

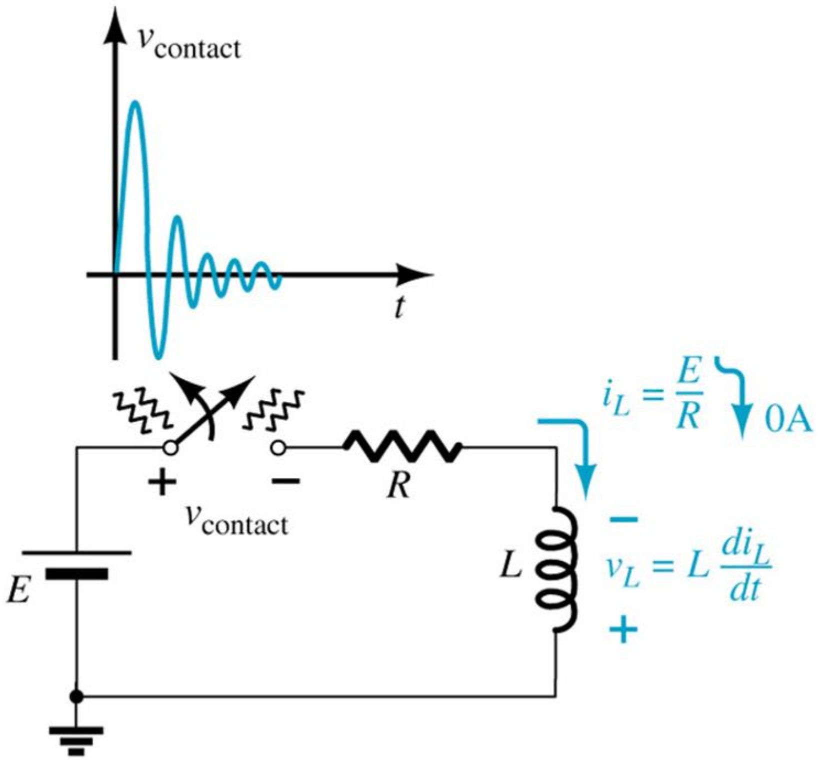
Exemplo 15: Determine a faixa de valores de alimentação que manterão o diodo na região Zener

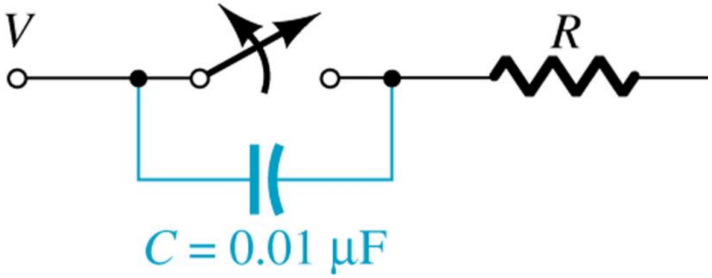


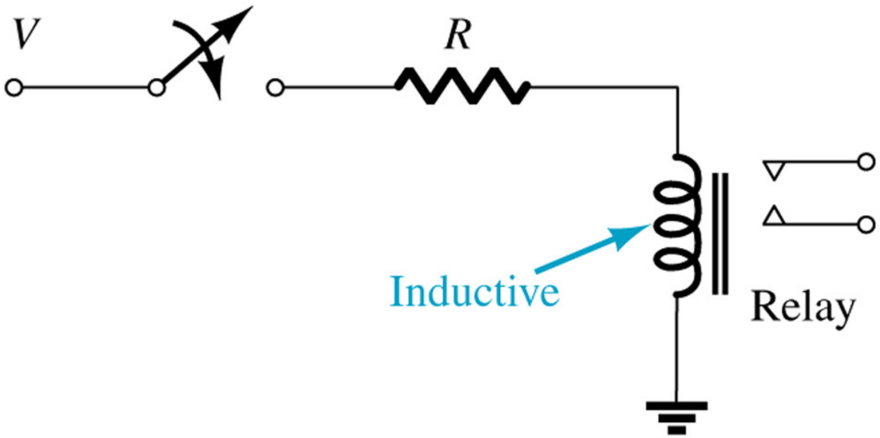
Outras aplicações

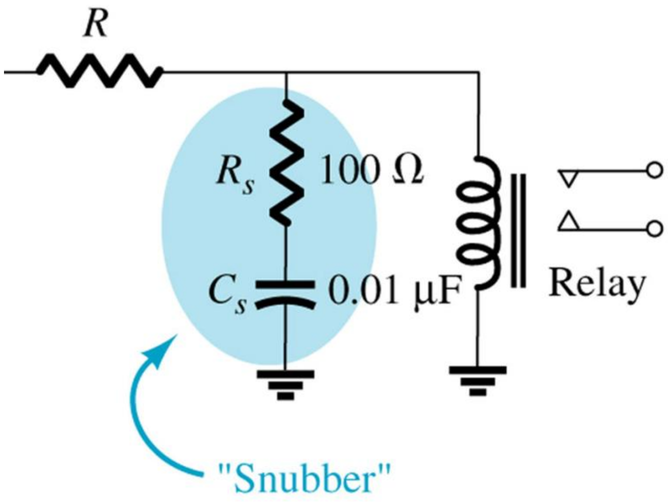
- Configurações de proteção

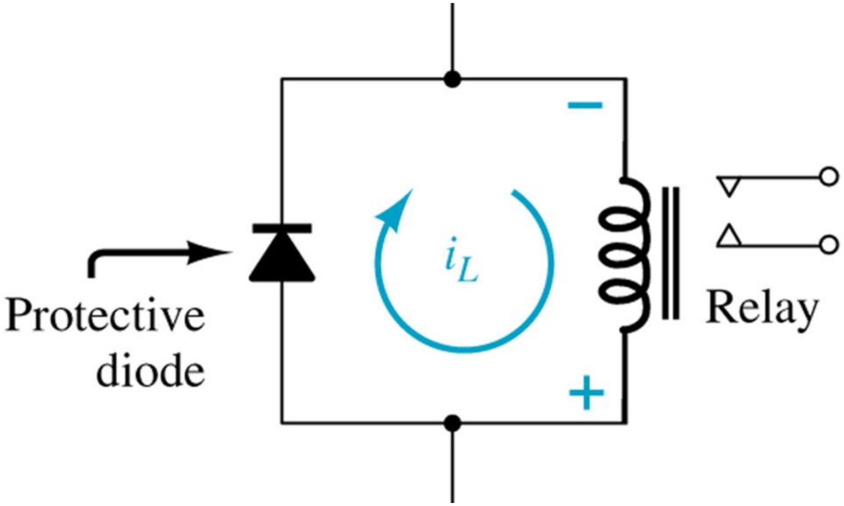
  Golpe indutivo

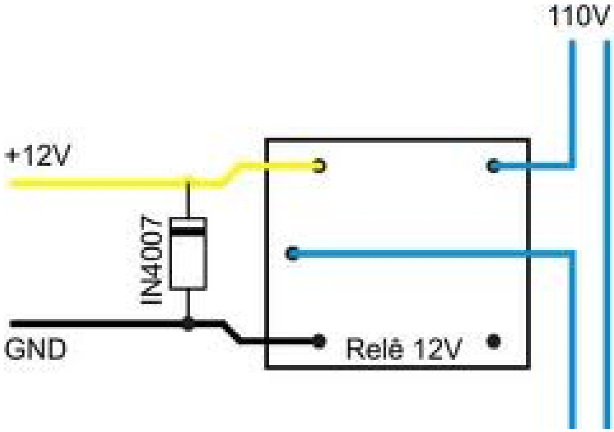


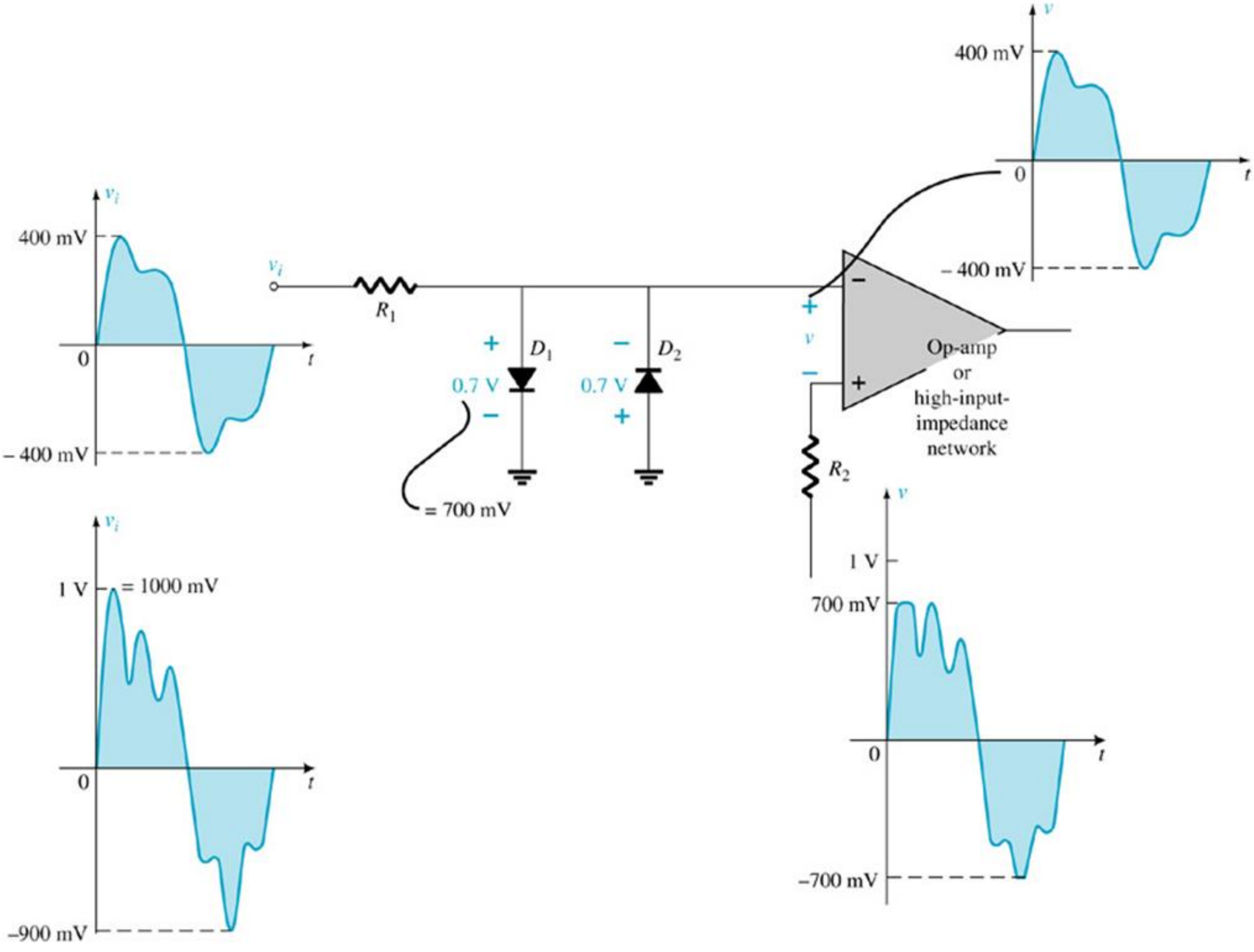



V
R
Inductive
Relay

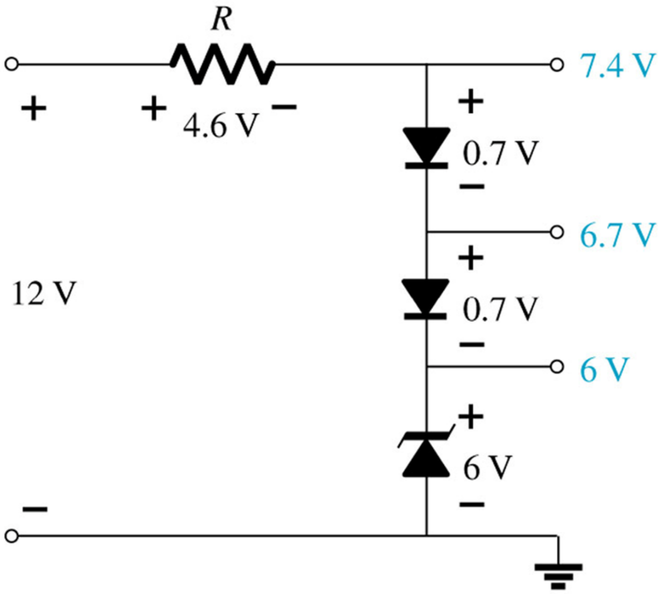

R
R_s
100 Ω
C_s
0.01 μF
Relay
"Snubber"


Protective
diode
i_L
−
+
Relay

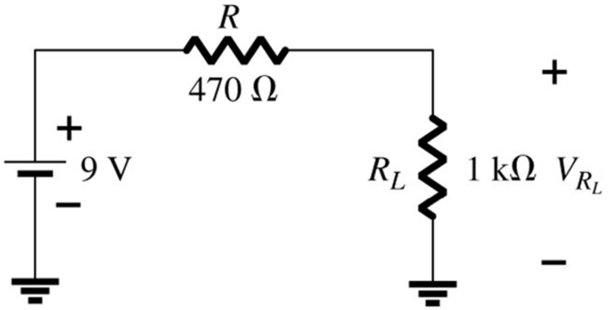

110V
+12V
IN4007
GND
Relê 12V

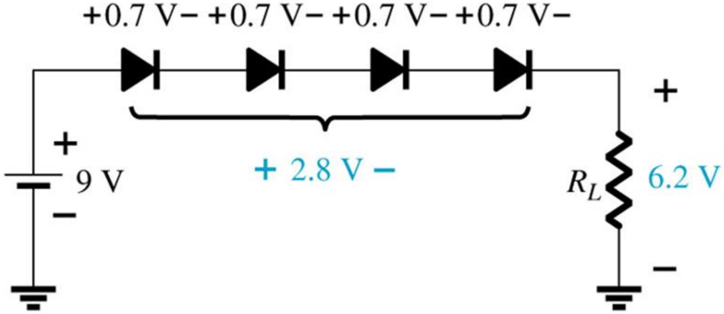

v_i
400 mV
0
t
– 400 mV
v_i
1 V
= 1000 mV
0
t
–900 mV
v_i
R_1
+
D_1
0.7 V
–
= 700 mV
–
D_2
0.7 V
+
+
v
–
–
+
Op-amp
or
high-input-
impedance
network
R_2
v
400 mV
0
t
– 400 mV
v
1 V
700 mV
0
t
–700 mV

- Estabelecimento de níveis de referência de tensão



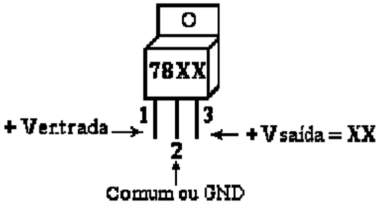
  - Referência por divisor *resistivo x diodo*

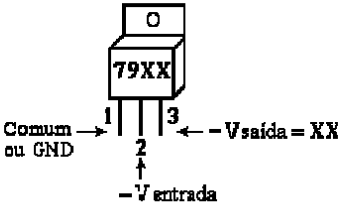




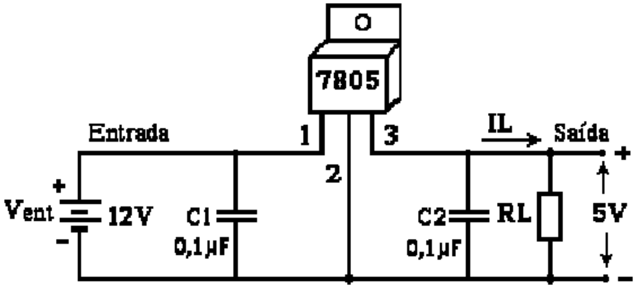
– Reguladores de tensão:

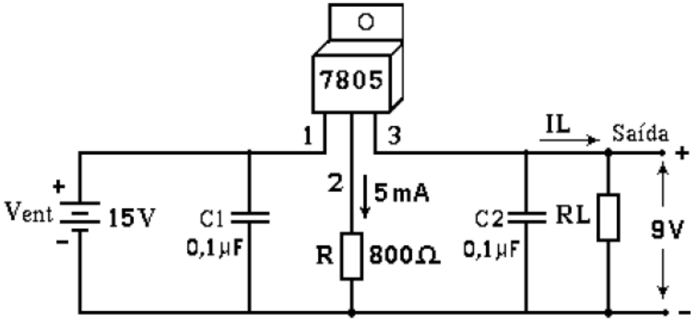
Reguladores de tensão 78XX – 79XX				
Código		Tensão máxima a aplicar na entrada (E)	Tensão de saída (S) regulada	Corrente máxima na saída
Positivo	Negativo			
7805	7905	35V	5V	1A
7806	7906	35V	6V	1A
7810	7910	35V	10V	1A
7812	7912	35V	12V	1A
7815	7915	35V	15V	1A
7818	7918	35V	18V	1A
7824	7924	40V	24V	1A





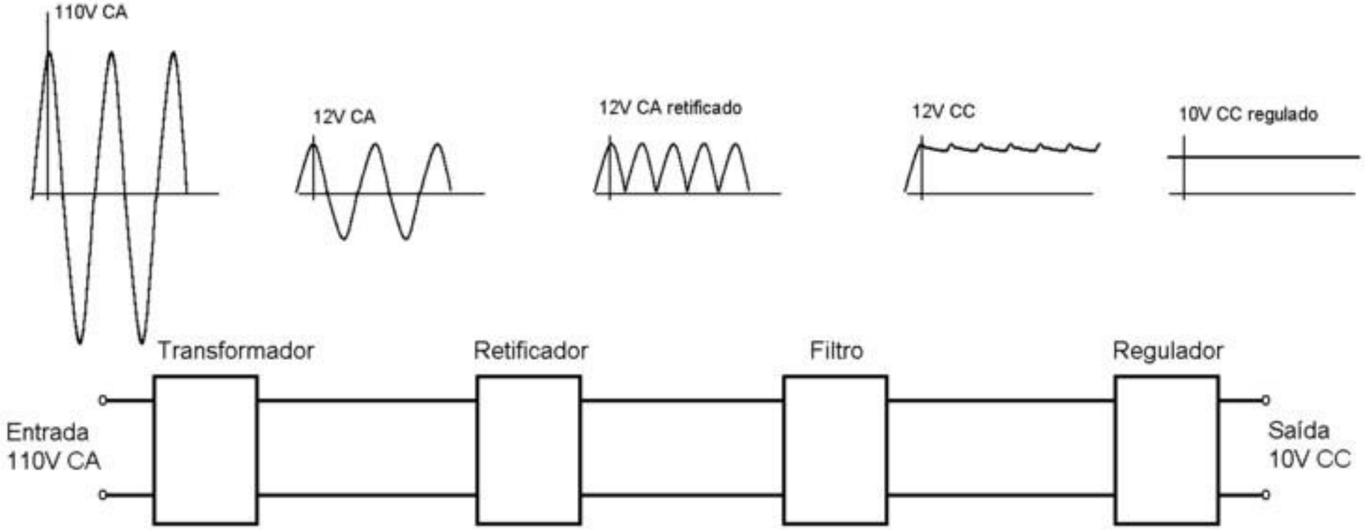
- Máxima potência: 15W (P = $[V_{in}-V_{out}].I_L$)
- Exemplos de ligação:



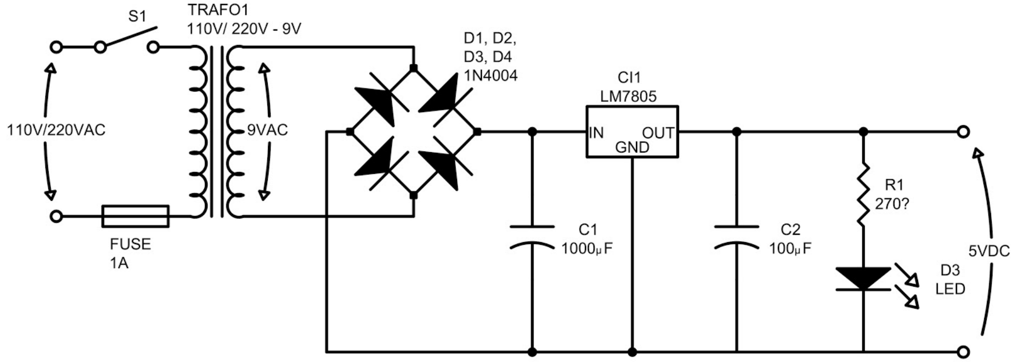


Projeto básico fontes de alimentação

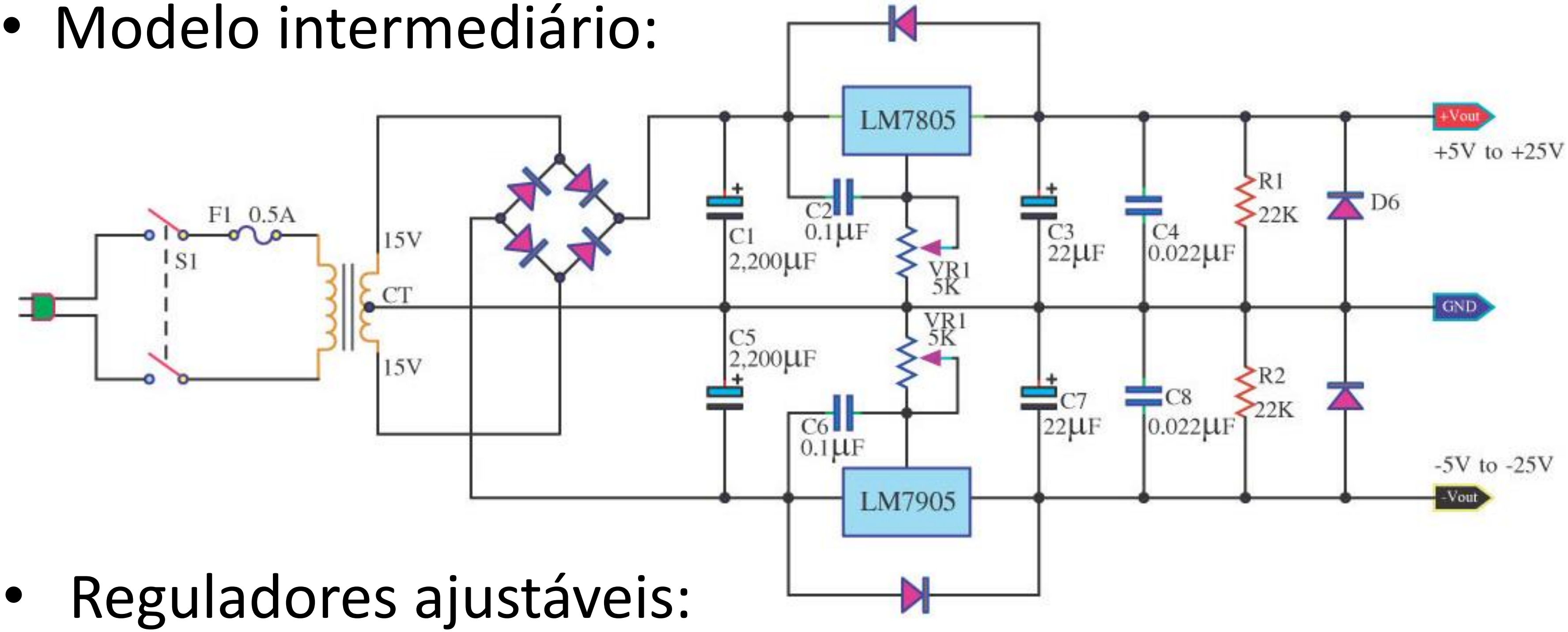
- Visão geral:



- Modelo básico:

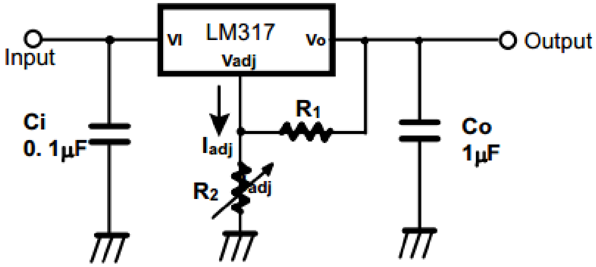


- Modelo intermediário:



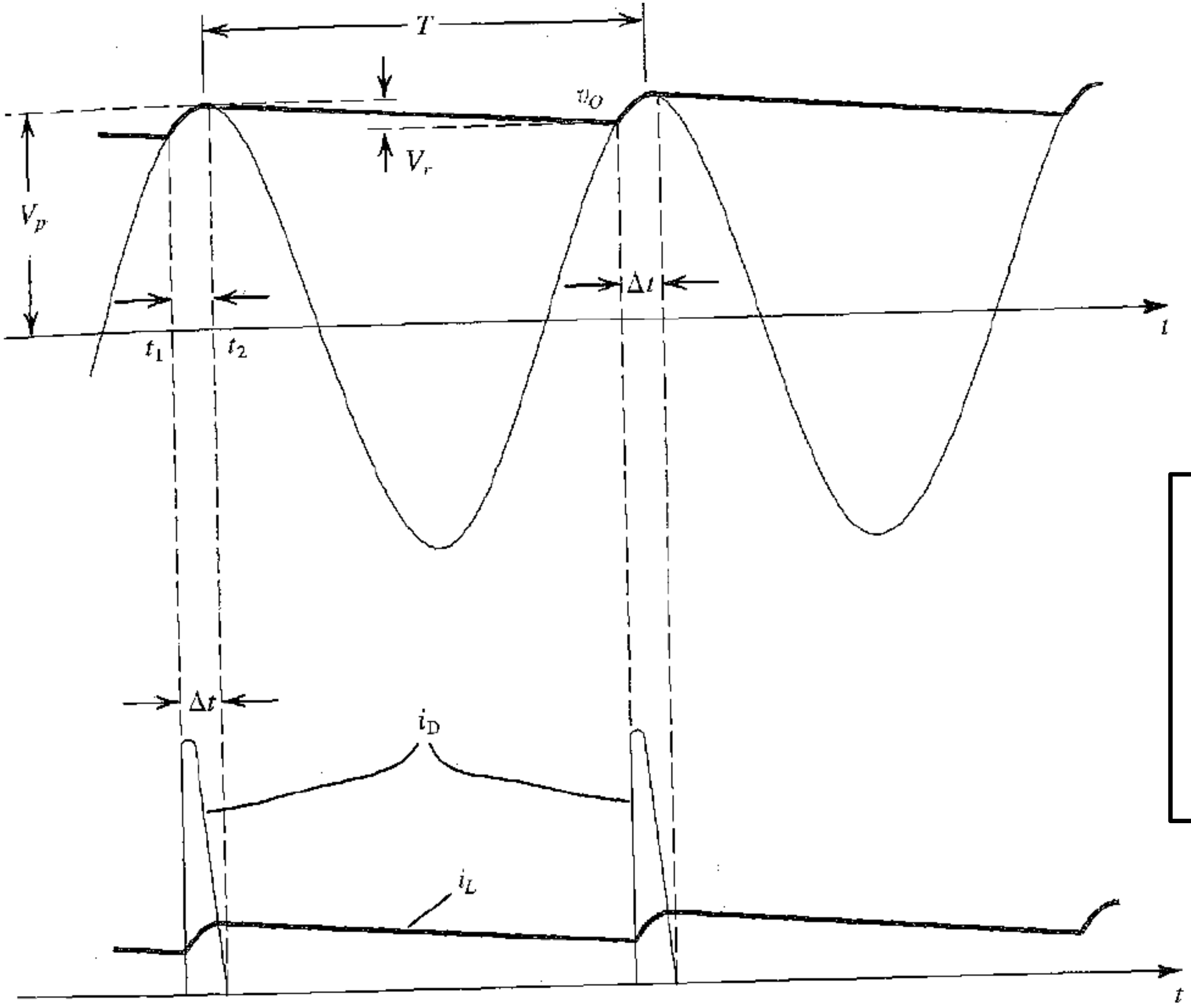
- Reguladores ajustáveis:

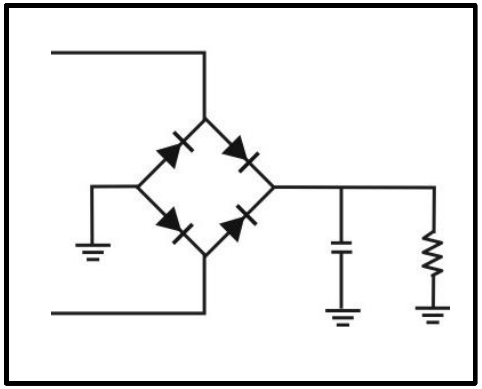
Chip	LM317T	LM350T	LM338T
Output Voltage	1.2...37 V	1.2...33 V	1.2...33 V
Max. Output Current	1.5 A	3 A	5 A
Max. Input Voltage	40 V	35 V	35 V
Max. power dissipation	15-20 W *	25-50 W *	25-50 W *
Temperature Range	0° - 125°C	0° - 125°C	0° - 125°C
Package	TO-220	TO-220	TO-220



$V_O = 1.25V\,(1 + R_2/R_1) + I_{adj} R_2$

- Formas de onda da condução





- Para calcular o *ripple* (V_r):

$$V_P - V_r \cong V_P e^{-T/CR}$$

Onde T (=1/60Hz) é o período da onda da rede elétrica. Considerando que C.R >> T, (tempo descarga muito maior que período oscilação da rede) podemos usar a aproximação:

$$e^{-T/CR} = 1 - T/CR$$

Logo:

$$V_r \cong V_P \frac{T}{CR}$$

Considerando uma frequência de ondulação 2x maior (retificador completo), basta substituir T=T/2. Assim:

$$V_r \cong V_P \frac{T}{2CR} \longrightarrow V_r \cong \frac{I_L}{2fC}$$