

# Física Experimental VI – 4300314

1º Semestre de 2017

Instituto de Física  
Universidade de São Paulo

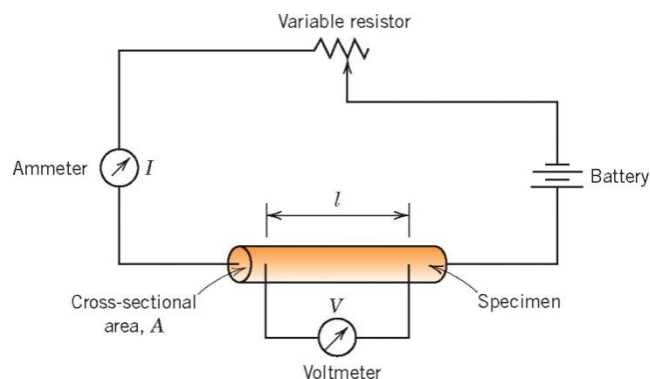
Professor: **Antonio Domingues dos Santos**

E-mail: [adsantos@if.usp.br](mailto:adsantos@if.usp.br)

Fone: **3091.6886**

# Propriedades Elétricas

$$V = RI$$



Condutividade

$$\sigma = \frac{1}{\rho} \quad J = \sigma E$$

Metais =  $\sim 10^7$   $(\Omega\text{m})^{-1}$

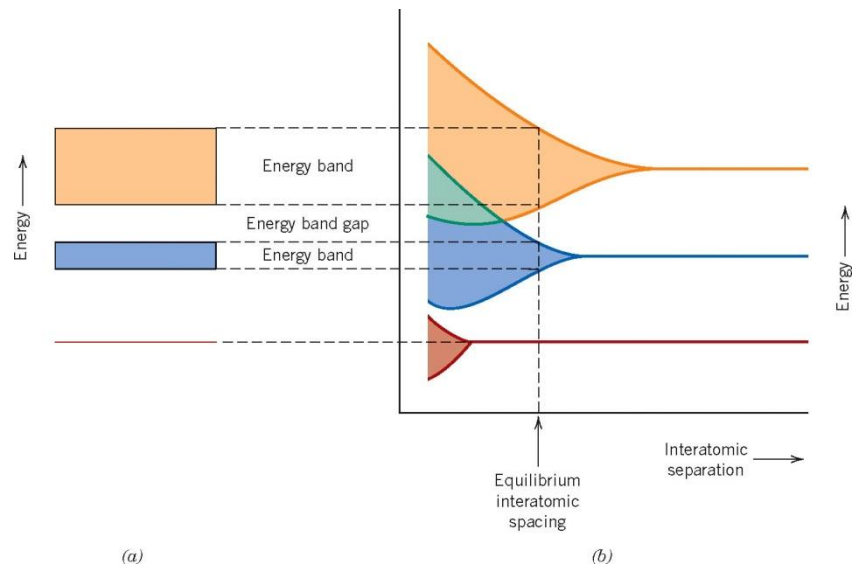
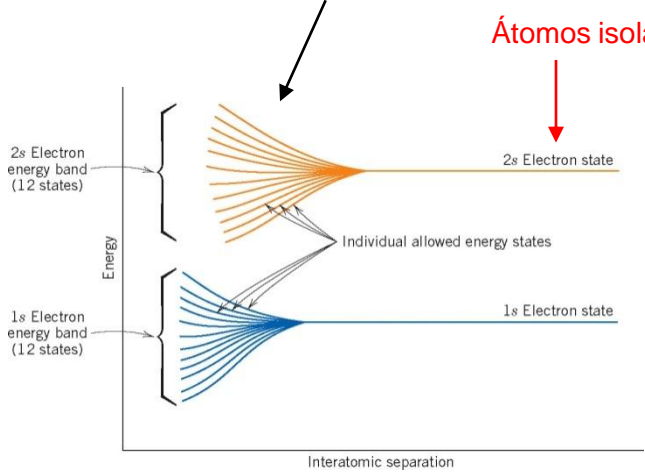
Isolantes =  $10^{-10} \sim 10^{-20}$   $(\Omega\text{m})^{-1}$

Semicondutores =  $10^{-6} \sim 10^4$   $(\Omega\text{m})^{-1}$

$$\rho = \frac{RA}{l} = \frac{VA}{Il}$$

# Propriedades Elétricas

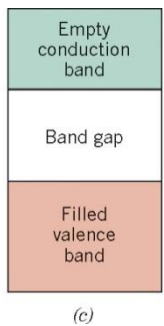
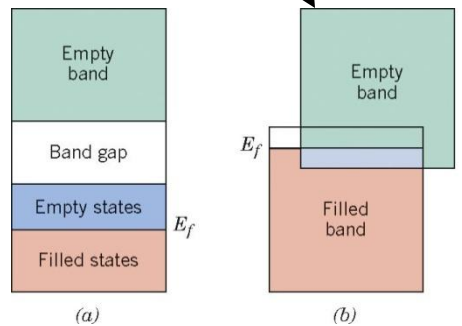
## Estrutura de bandas em sólidos



### Metais

### Isolantes

### Semicondutores



(a)

(b)

Banda de condução

Banda de valência

(a)

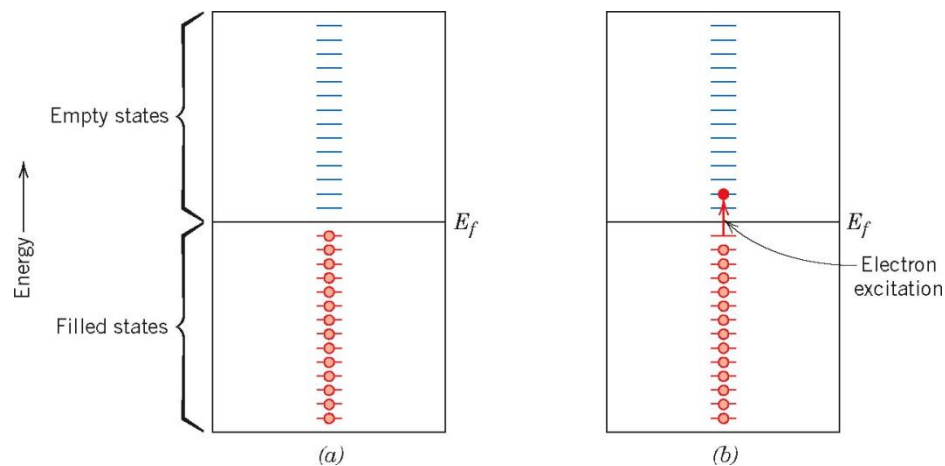
(b)

(c)

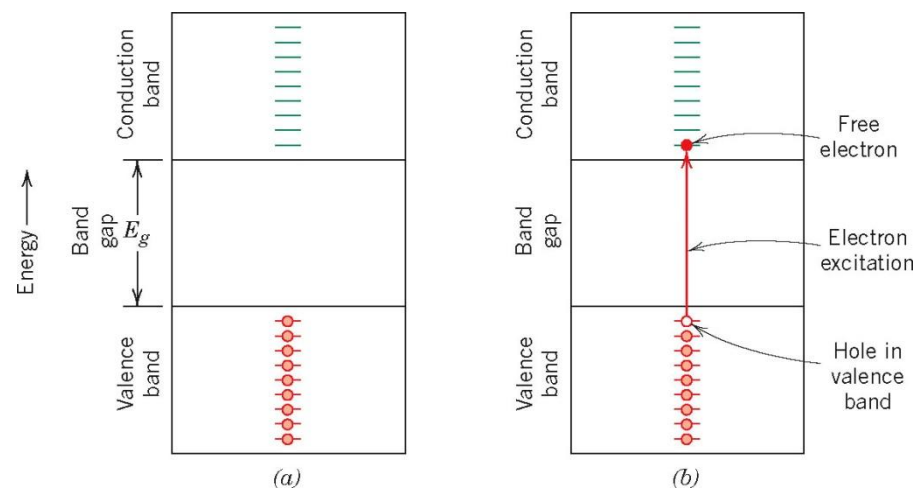
(d)

# Propriedades Elétricas

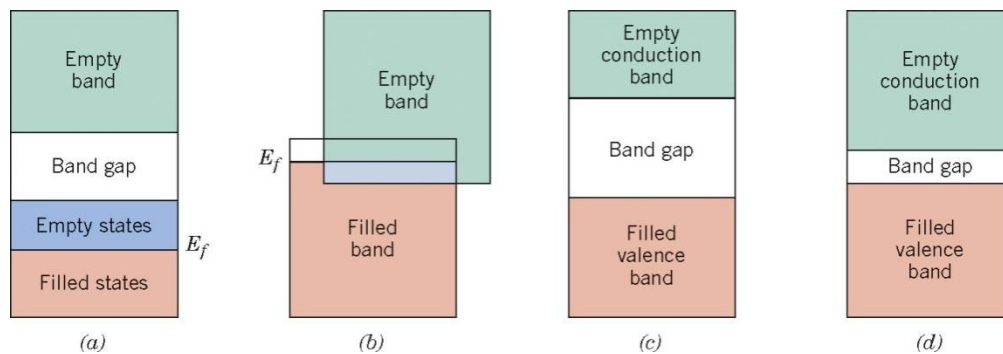
## Metais



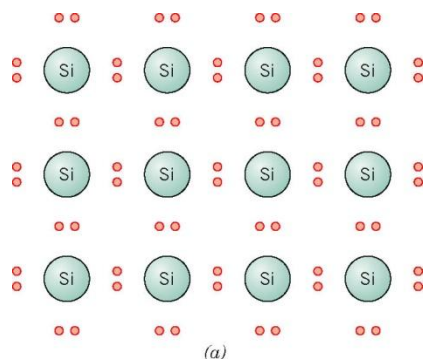
## Isolantes e Semicondutores



$$\sigma = n|e|\mu$$

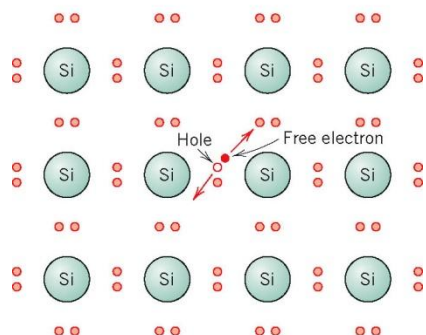


# Semicondutores



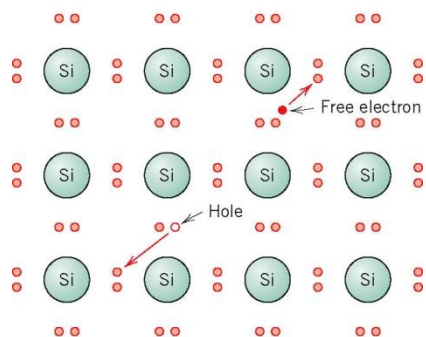
(a)

← Field

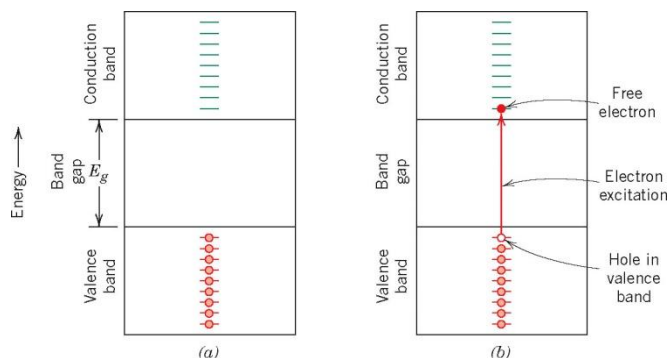


(b)

← Field



(c)



$$\sigma = n|e|\mu_e + p|e|\mu_b$$

$$\mu_e > \mu_b$$

**Table 18.3 Band Gap Energies, Electron and Hole Mobilities, and Intrinsic Electrical Conductivities at Room Temperature for Semiconducting Materials**

Material	Band Gap (eV)	Electrical Conductivity [ $(\Omega\text{-cm})^{-1}$ ]	Electron Mobility ( $\text{m}^2/\text{V}\cdot\text{s}$ )	Hole Mobility ( $\text{m}^2/\text{V}\cdot\text{s}$ )
<b>Elemental</b>				
Si	1.11	$4 \times 10^{-4}$	0.14	0.05
Ge	0.67	2.2	0.38	0.18
<b>III-V Compounds</b>				
GaP	2.25	—	0.03	0.015
GaAs	1.42	$10^{-6}$	0.85	0.04
InSb	0.17	$2 \times 10^4$	7.7	0.07
<b>II-VI Compounds</b>				
CdS	2.40	—	0.03	—
ZnTe	2.26	—	0.03	0.01

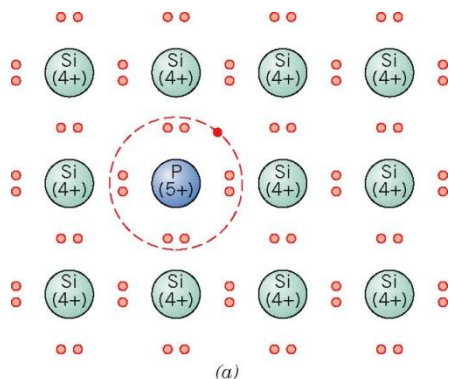
# Semicondutores extrínsecos

## Tipo n

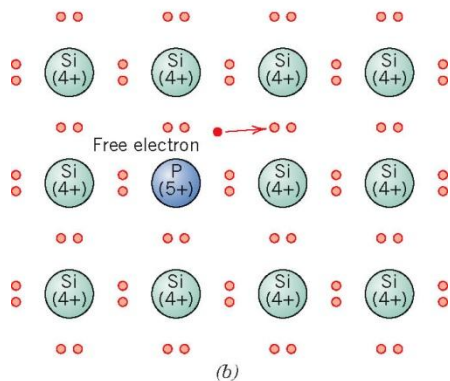
### Condutividade

$$\sigma = n|e|\mu_e + p|e|\mu_b$$

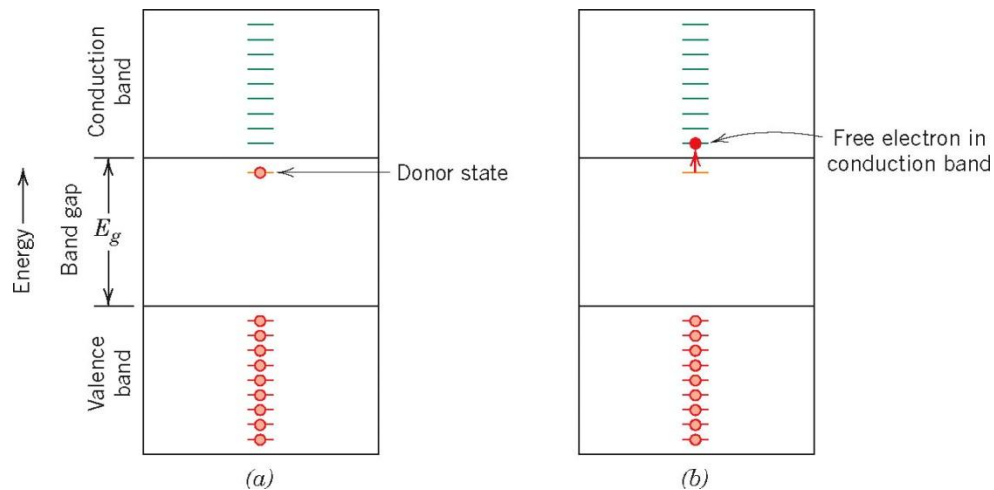
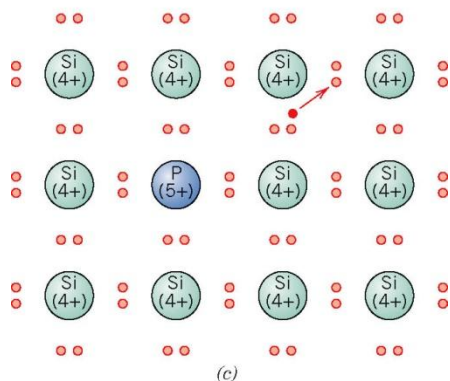
Por elétrons e buracos



← Field



← Field



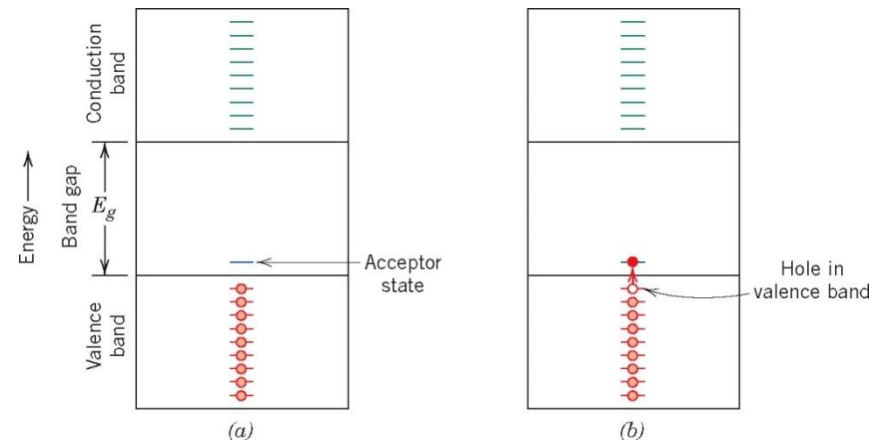
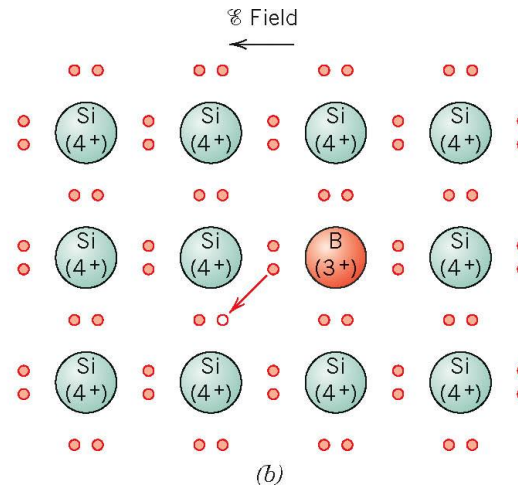
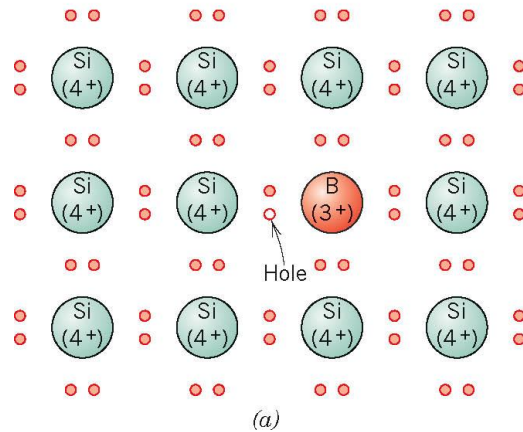
# Semicondutores extrínsecos

## Tipo p

Condutividade

$$\sigma = n|e|\mu_e + p|e|\mu_b$$

Por elétrons e buracos



# Dispositivos Semicondutores

## Junção p-n

### Diodos

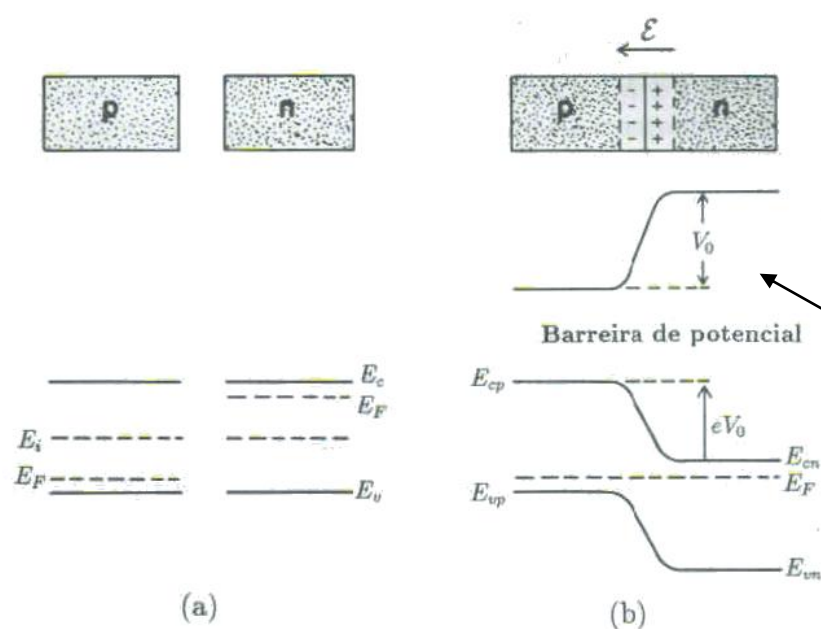


Figura 6.3: (a) Semicondutores *p* e *n* separados. (b) Carga, campo elétrico, potencial e níveis de energia na região de carga espacial de junção *p-n*.

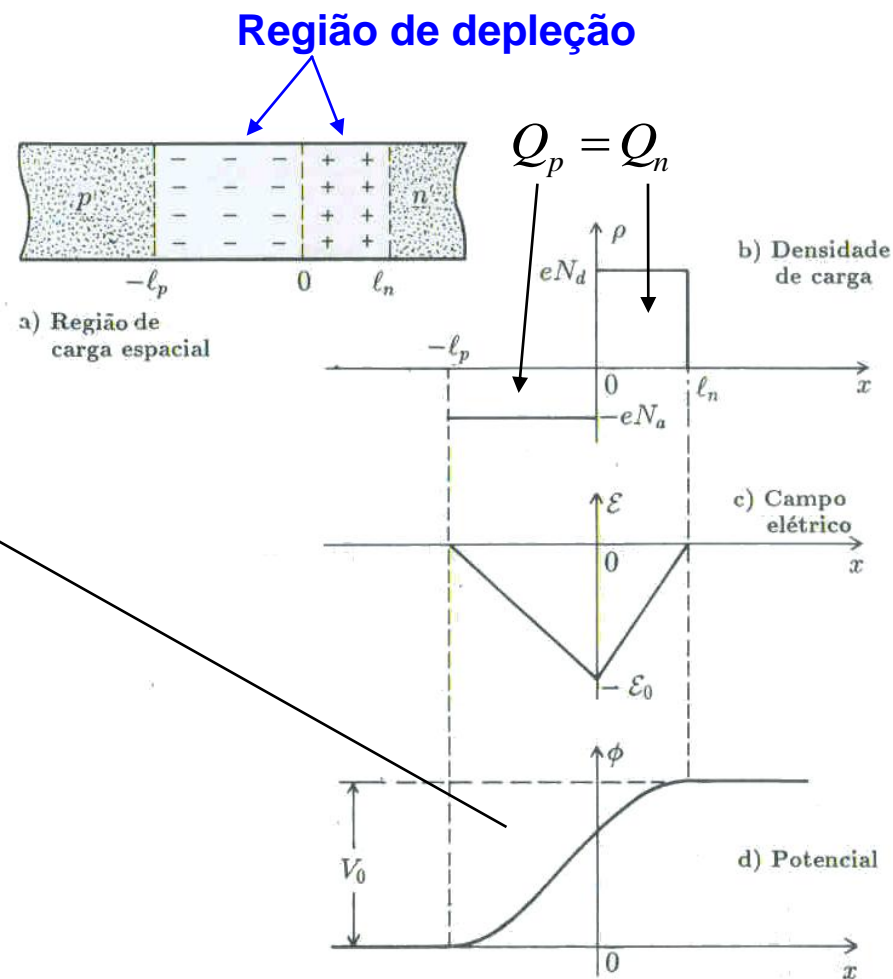


Figura 6.4: Variação da densidade de carga, campo elétrico e potencial eletrostático no modelo unidimensional da junção *p-n*.



# Dispositivos Semicondutores

## Junção p-n

### Diodos

#### Região de depleção

#### Corrente elétrica em um diodo

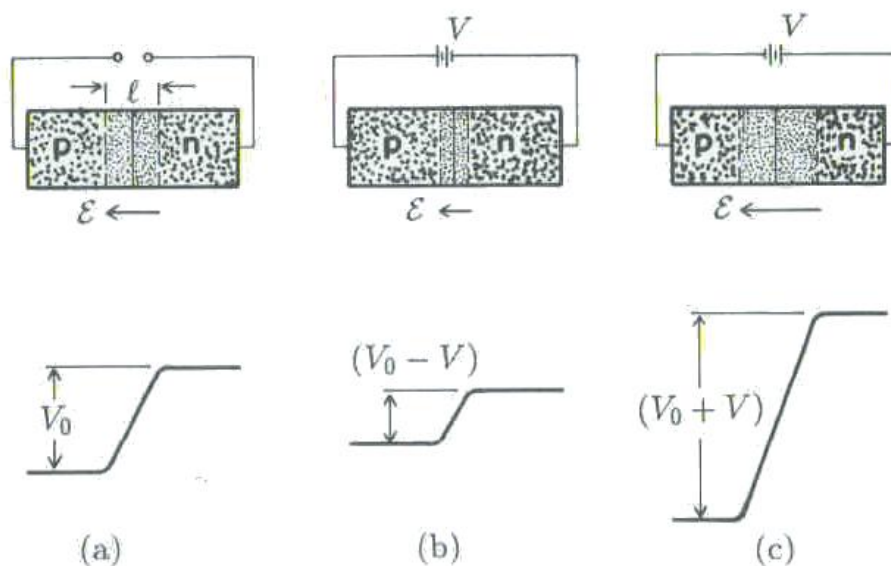


Figura 6.5: Efeito de tensão externa na espessura da região de carga espacial e na altura da barreira de potencial: (a) situação em equilíbrio; (b) polarização direta; (c) polarização reversa.

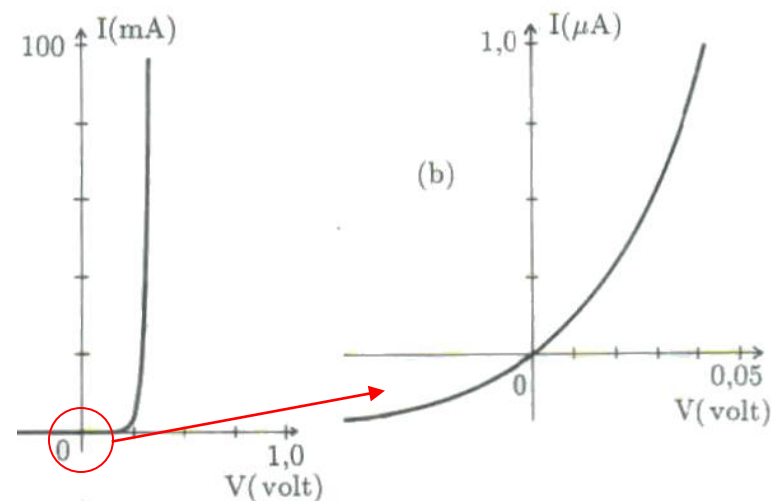


Figura 6.7: Característica  $I$ - $V$  de junção  $p$ - $n$  ideal dada pela equação do diodo com  $I_s = 0,25 \mu A$ , valor adequado para uma junção de germânio. A curva em (b) é a mesma que em (a), feita em escala ampliada para mostrar o comportamento em torno da origem.

# Dispositivos Semicondutores

## Transistor p-n-p

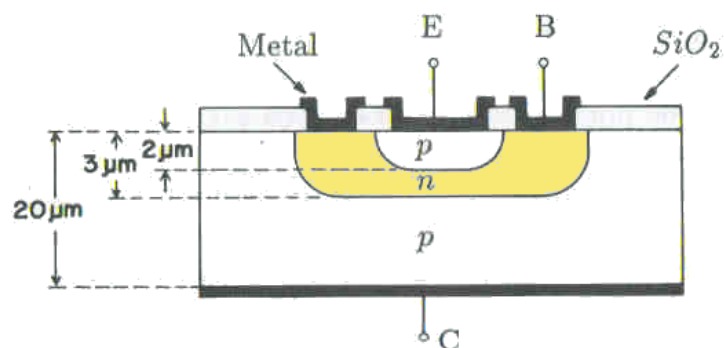


Figura 7.2: Estrutura planar do transistor bipolar de junção com algumas dimensões típicas. As letras E, B e C representam os terminais do emissor, da base e do coletor, respectivamente. As distâncias indicadas representam espessuras típicas.

## Transistor bipolar

### Corrente elétrica em um transistor

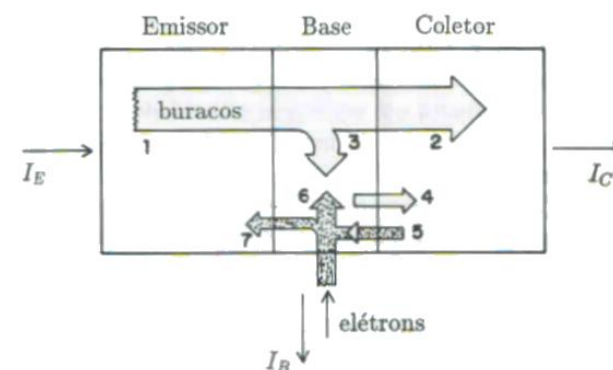
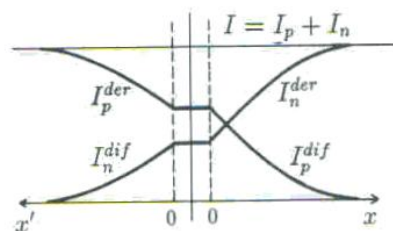
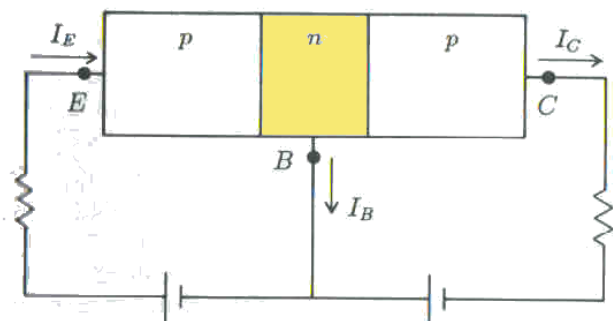
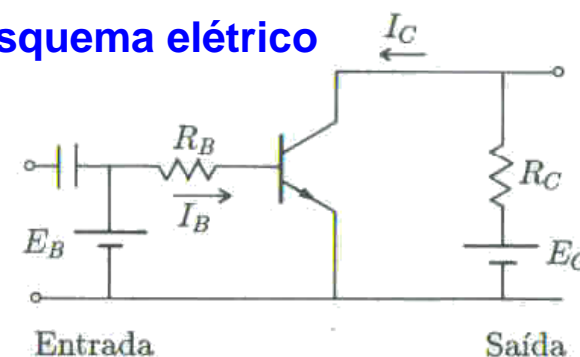


Figura 7.4: Ilustração do fluxo de elétrons e de buracos em transistor p-n-p: 1- Buracos em movimento de deriva no emissor; 2- Buracos que atingem o coletor em movimento de difusão; 3- Buracos que desaparecem na base por recombinação; 4 e 5- Buracos e elétrons gerados termicamente na base e que formam a corrente de saturação reversa da junção do coletor; 6- Elétrons que recombinaem com os buracos da componente 3; 7- Elétrons injetados da base para o emissor formando a corrente  $I_{E_n}$ .



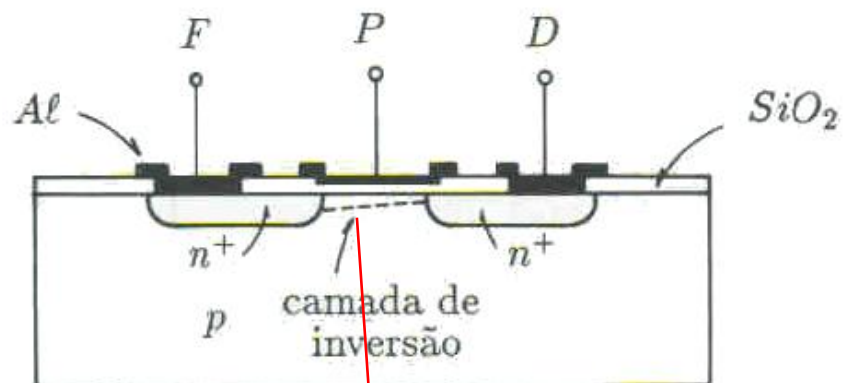
Correntes na região de depleção

### Esquema elétrico

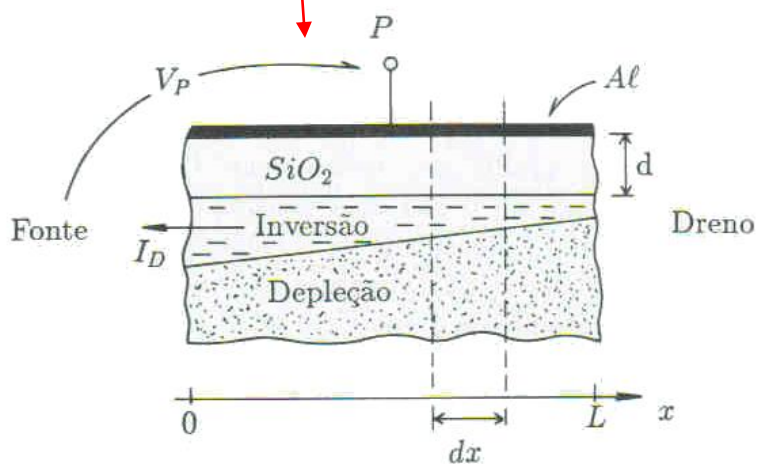


# Dispositivos Semicondutores

## Transistor MOS-FET



Estrutura planar de MOSFET de canal  $n$ .



### Distribuição de carga no capacitor MOS

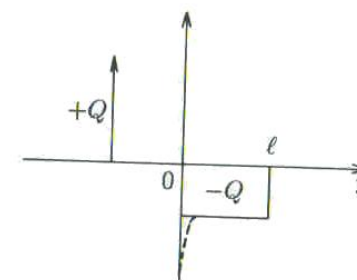
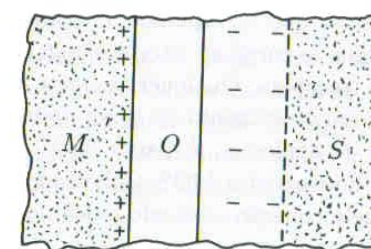


Figura 7.17: Distribuição de carga num capacitor MOS ideal com semiconductor tipo  $p$  (canal  $n$ ), na aproximação de depleção. A linha tracejada indica a carga criada pela inversão quando  $V > V_c$ .

# Circuitos integrados

## Processo de Litografia

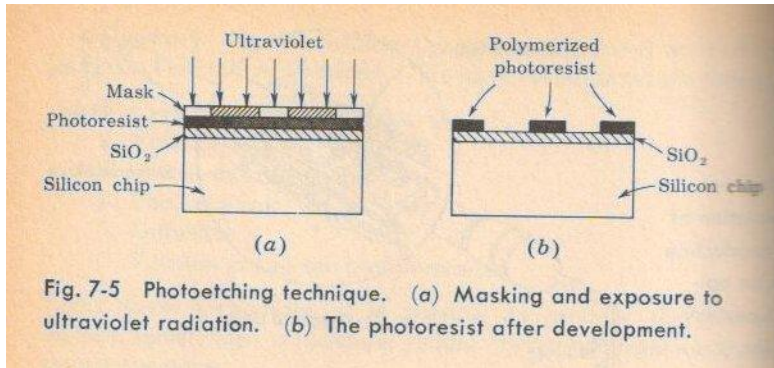


Fig. 7-5 Photoetching technique. (a) Masking and exposure to ultraviolet radiation. (b) The photoresist after development.

## Transistores de efeito de campo

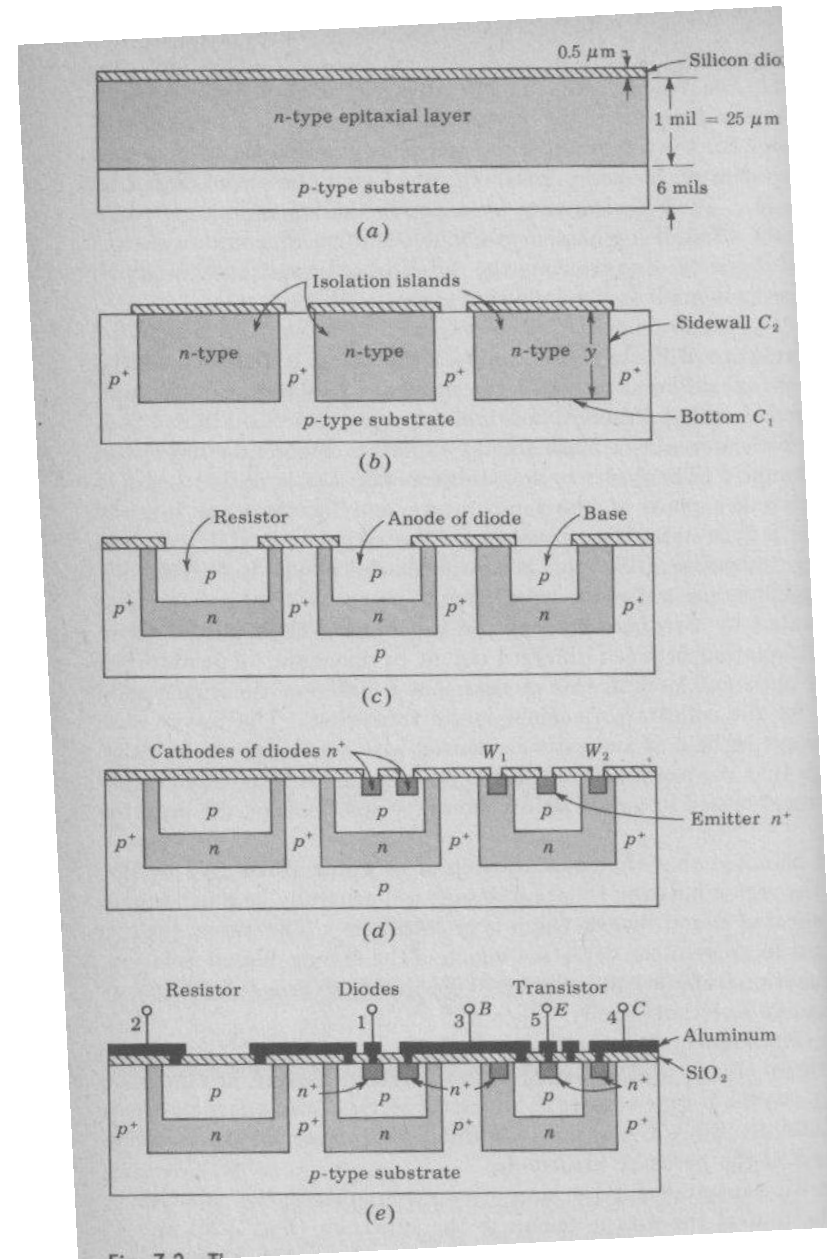
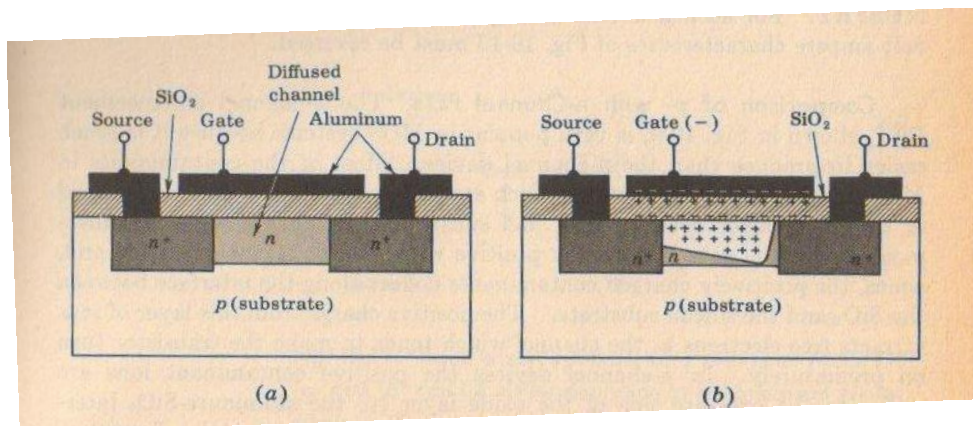
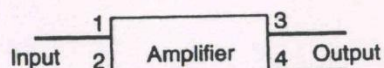


Fig. 7.9

# Amplificadores Operacionais

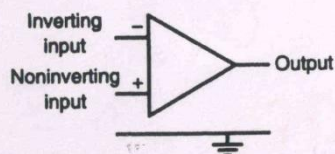
Amplificadores constituem-se nos mais importantes blocos usados em eletrônica analógica.



Malha aberta

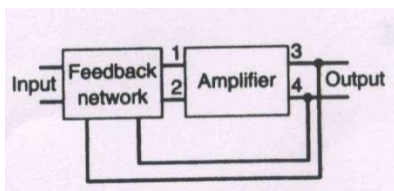
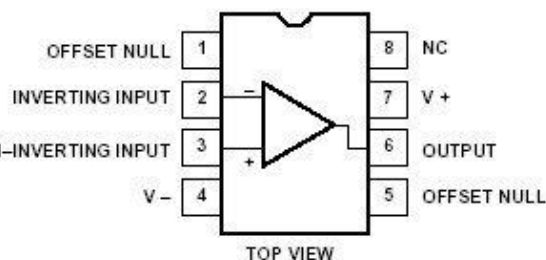
$$A = \frac{V_{out}}{V_{in}}$$

$$V_{out} = A \cdot (V_+ - V_-)$$



(a)

R 5



Malha fechada

## Amp. Op. Modelo 741

Ganho  $A \sim 10^5$  (ideal =  $\infty$ )

Impedância  $2M\Omega$  (ideal =  $\infty$ )

Corrente interna  $0,1\mu A$  (ideal = 0)

V offset 2mV (ideal = 0)

Rampeamento  $0,5V/\mu s$

Resposta em frequência

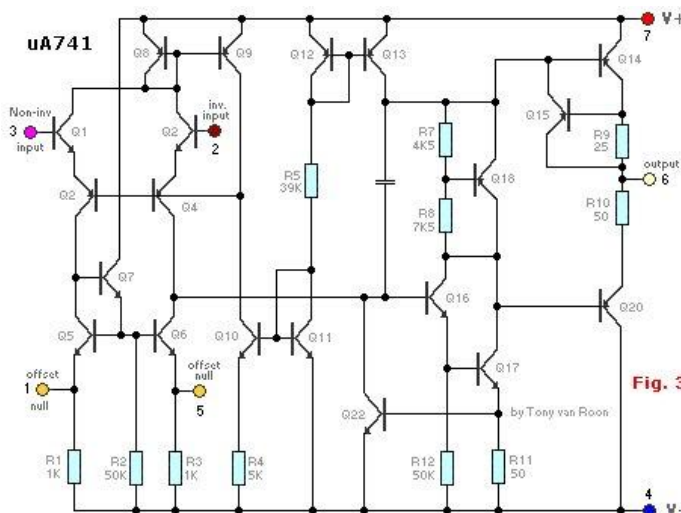
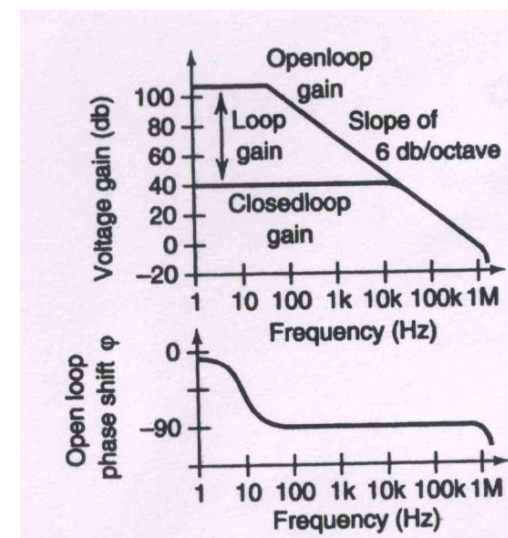


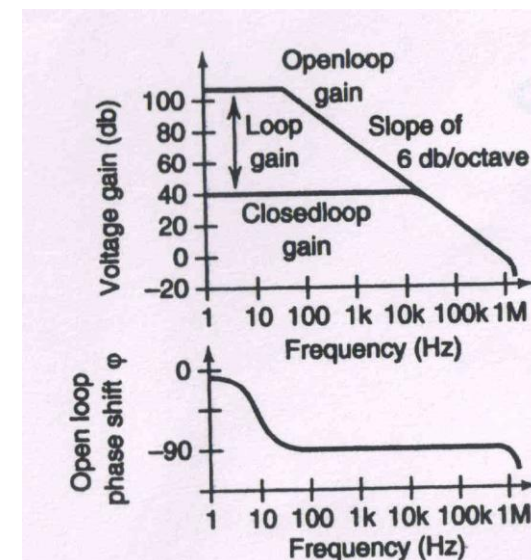
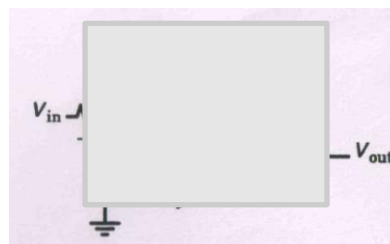
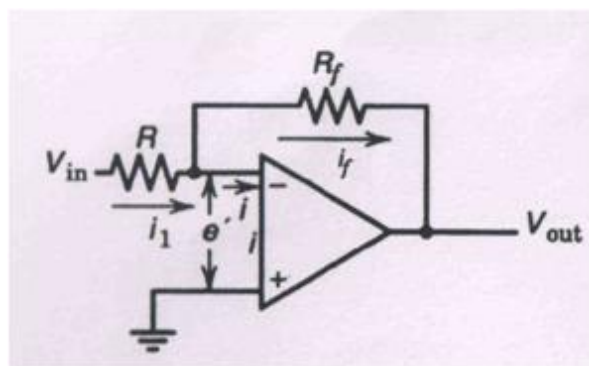
Fig. 3

=>



# Uso de Amplificadores Operacionais

## Amplificador inversor



$$\left. \begin{aligned} e' &= -(V_+ - V_-) \\ V_{out} &= -A \cdot e' \\ i_1 &= i_i + i_f \\ i_1 &= \frac{V_{in} - e'}{R} \\ i_f &= \frac{e' - V_{out}}{R_f} \end{aligned} \right\}$$

$$V_{out} = \frac{i_i}{1/R_f + 1/AR + 1/AR_f} - \frac{V_{in}/R}{1/R_f + 1/AR + 1/AR_f}$$

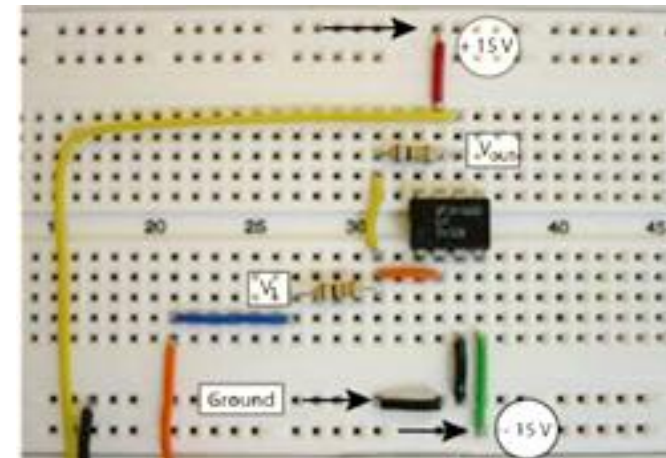
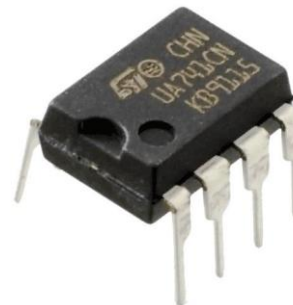
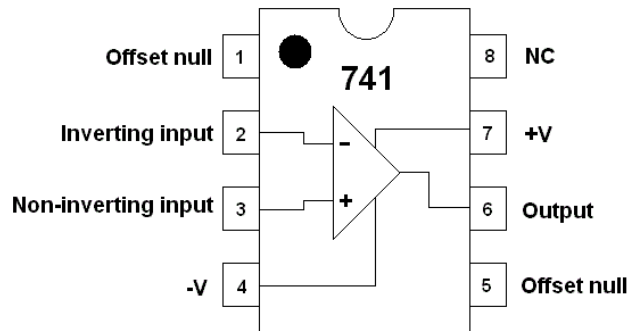
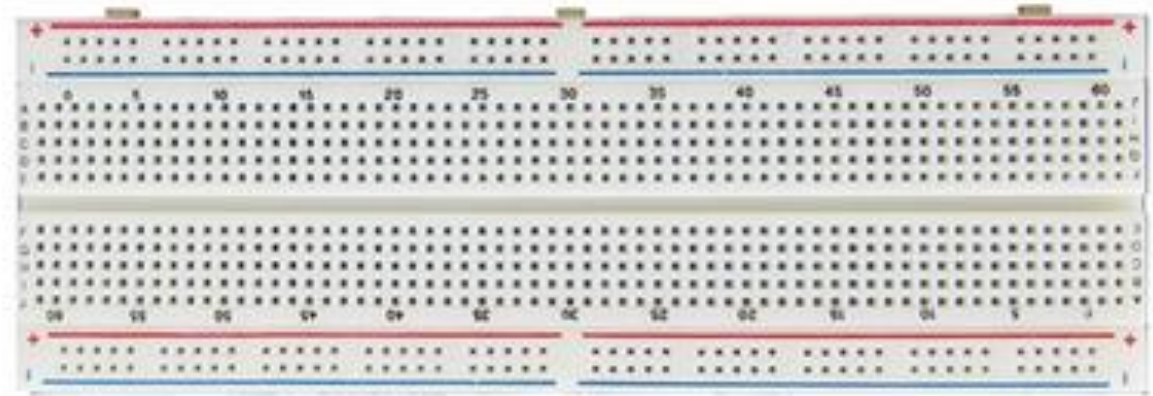
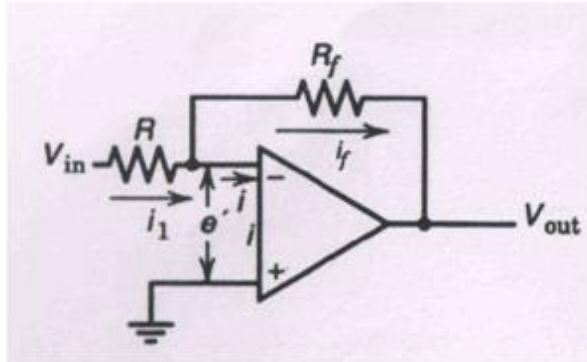
**Idealmente: ( $A = \infty$  ,  $i_i = 0$ )**

$$V_{out} = -\frac{R_f}{R} V_{in} \quad \Rightarrow \quad G_v = -\frac{R_f}{R}$$

# Uso de Amplificadores Operacionais

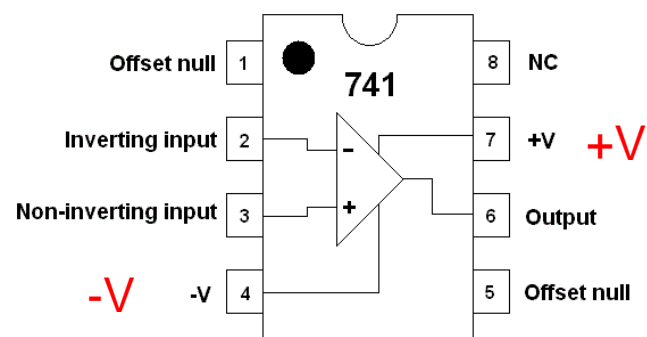
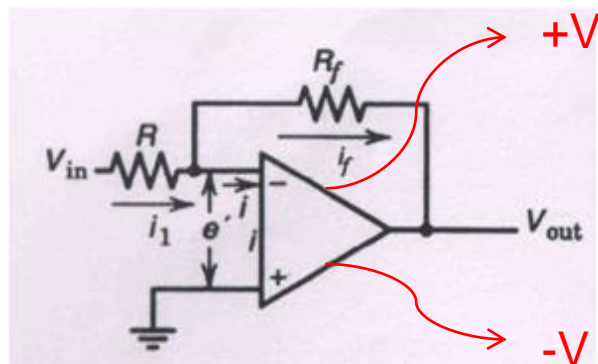
## Protoboard

### Amplificador inversor

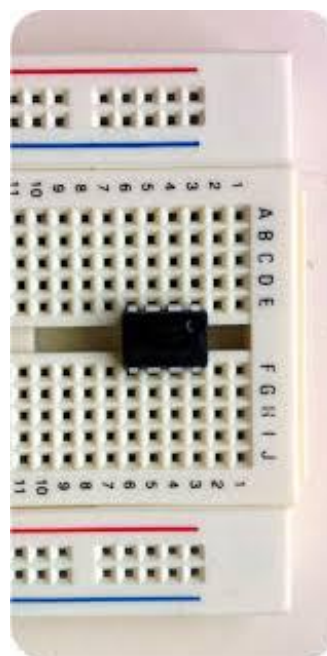
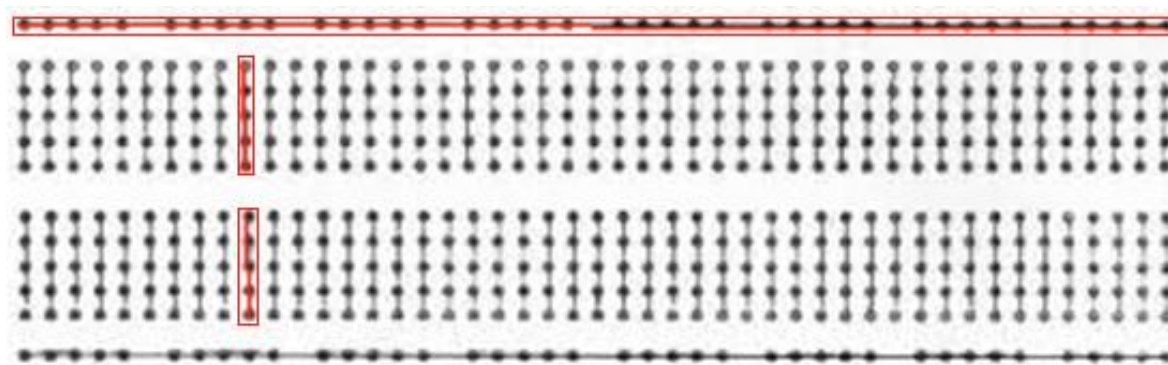


# Uso de Amplificadores Operacionais

## Montagem do Amplificador inversor



## Protoboard



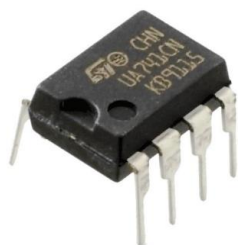
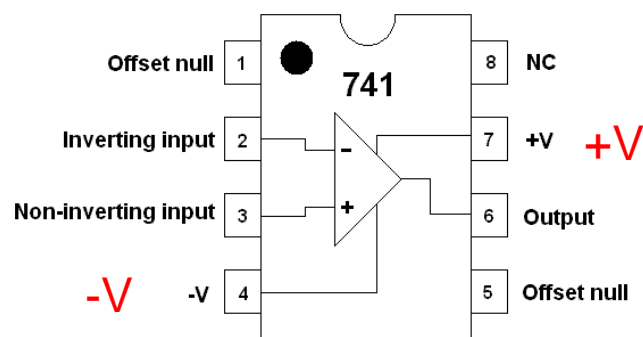
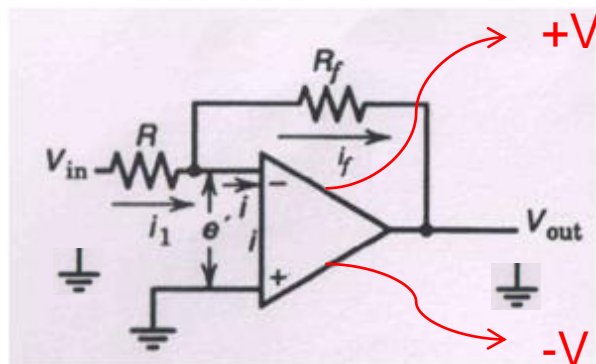
Primeiro passo:

- 1) Colocar o Amplificador Operacional no protoboard.
- 2) Ligar a sua alimentação, +V (pino 7) e -V (pino 4), na fonte de tensão.



# Uso de Amplificadores Operacionais

## Montagem do Amplificador inversor



## Segundo passo:

- 1) Colocar os resistores.
- 2) Definir o nível de referência de tensão (0V e Terra).
- 3) Conectar a entrada de sinal, do gerador de funções.

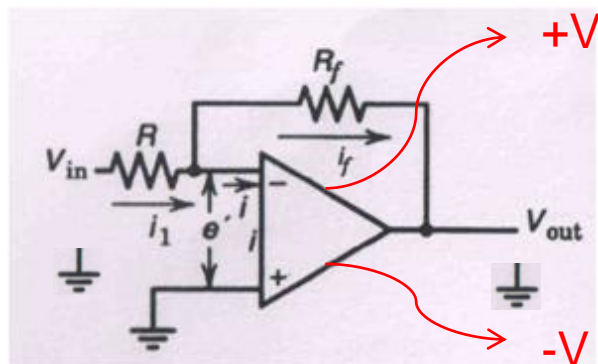
## Terceiro passo:

- 1) Ligar a fonte com +12V, 0V e -12V.
- 2) Ligar o gerador de funções em senoidal, ~500 Hz, Amplitude 1V.
- 3) Ligar o osciloscópio e monitorar o sinal do gerador de funções e da saída (pino 6) do Amplificador Operacional.



# Uso de Amplificadores Operacionais

## Montagem do Amplificador inversor



Código de cores para identificação de resistores:

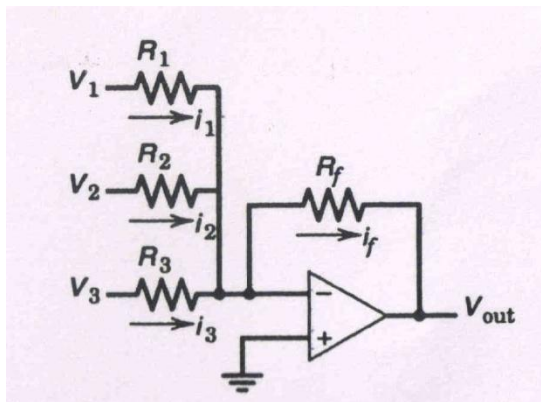
COR	1ºANEL	2ºANEL	3ºANEL	4ºANEL
Preto	-	0	x1	-
Marrom	1	1	x10	1%
Vermelho	2	2	x100	2%
Laranja	3	3	x1000	3%
Amarelo	4	4	x10000	4%
Verde	5	5	x100000	-
Azul	6	6	x1000000	-
Violeta	7	7	-	-
Cinza	8	8	-	-
Branco	9	9	-	-
Prata	-	-	x0,01	10%
Dourado	-	-	x0,1	5%



# Alguns usos de Amplificadores Operacionais

Idealmente: ( $A = \infty$  ,  $i_i = 0$ )

Amplificador somador inversor



$$e' = -(V_+ - V_-)$$

$$V_{out} = -A \cdot e'$$

$$i_1 = i_i + i_f$$

$$i_1 = \frac{V_{in} - e'}{R}$$

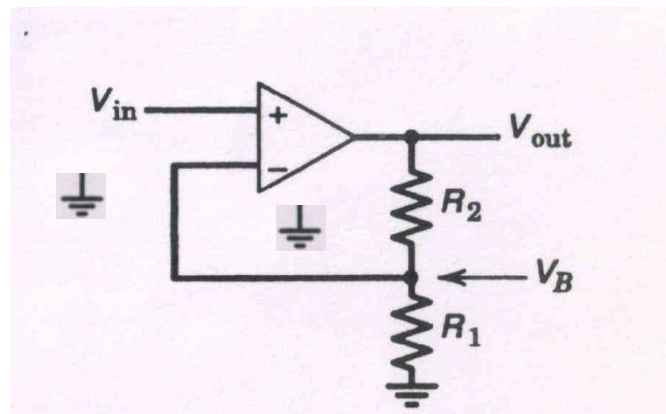
$$i_f = \frac{e' - V_{out}}{R_f}$$

$$i = i_1 + i_2 + i_3$$

$$i_1 = \frac{V_1}{R_1}, \dots$$

$$V_{out} = -\frac{R_f}{R_1} \cdot V_1 - \frac{R_f}{R_2} \cdot V_2 - \frac{R_f}{R_3} \cdot V_3$$

Amplificador não inversor



$$e' = -(V_+ - V_-) \sim 0$$

$$V_{in} = V_B$$

$$V_B = V_{out} \left(1 + \frac{R_2}{R_1}\right)$$

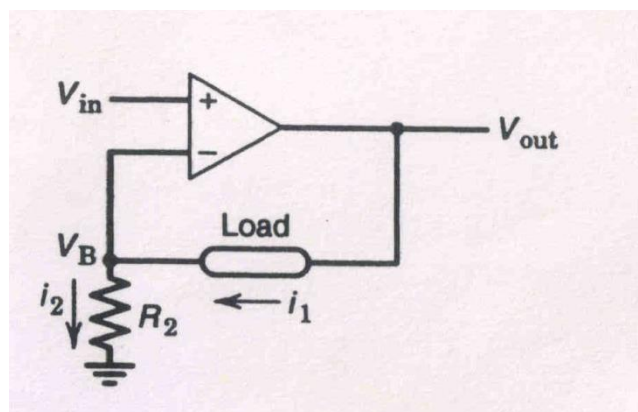
$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) \cdot V_{in}$$

com  $R_{in} \propto A$   
 $R_{out} \propto 1/A$

# Alguns usos de Amplificadores Operacionais

Idealmente: ( $A = \infty$  ,  $i_i = 0$ )

Fonte de corrente constante

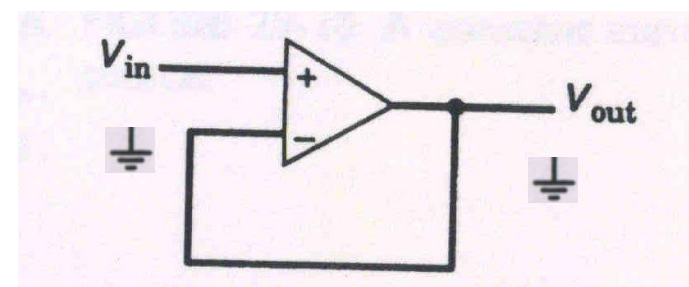


$$i_1 = i_2$$

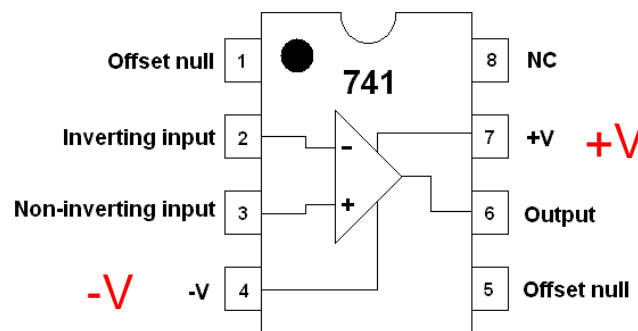
$$V_B = V_{in} = R_2 \cdot i_2$$

$$i_1 = \frac{V_{in}}{R_2}$$

Seguidor de voltagem



$$V_{out} = V_{in}$$



com

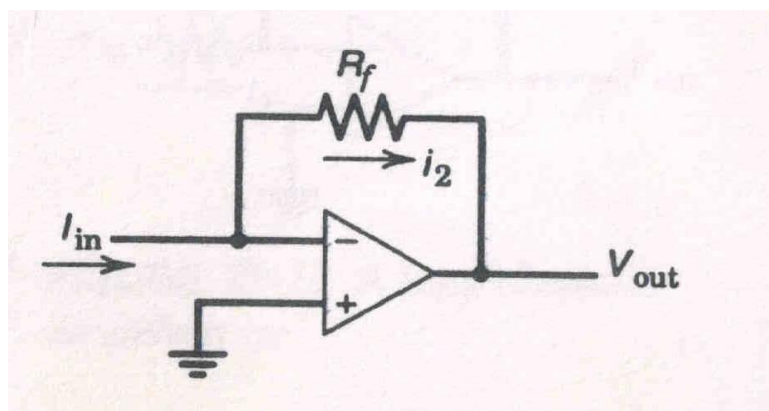
$$R_{in} \propto A$$

$$R_{out} \propto 1/A$$

## Alguns usos de Amplificadores Operacionais

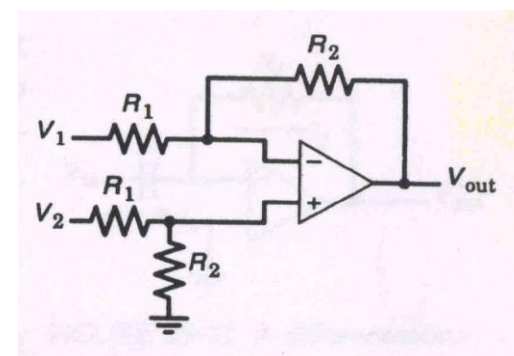
Idealmente: ( $A = \infty$  ,  $i_i = 0$ )

Conversor corrente em voltagem



$$V_{out} = -R_f \cdot I_{in}$$

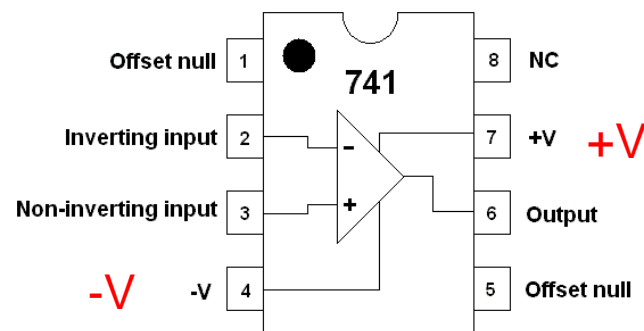
Amplificador de diferença  
(Amplificador diferencial)



$$V_+ = V_2 \frac{R_2}{R_1 + R_2} = V_-$$

$$\frac{V_1 - V_+}{R_1} = \frac{V_+ - V_{out}}{R_2}$$

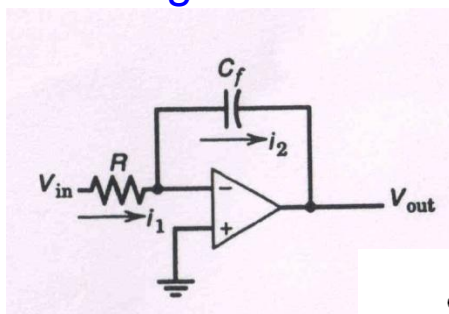
$$V_{out} = \frac{R_2}{R_1} (V_2 - V_1)$$



## Alguns usos de Amplificadores Operacionais

Idealmente: ( $A = \infty$  ,  $i_i = 0$ )

integrador



$$i_1 = \frac{V_{in}}{R} = i_2$$

$$V_{out} = -\frac{1}{C_f} \int_0^t i_2 dt$$

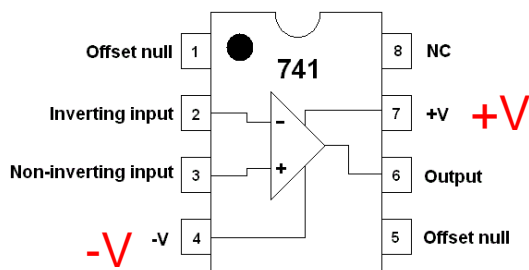
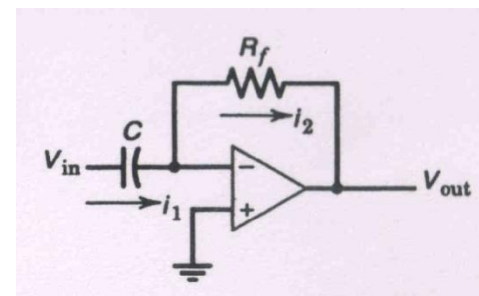
$$V_{out} = -\frac{1}{RC_f} \int_0^t V_{in} dt$$

Para sinal senoidal:

$$V_{out} \propto \frac{V_{in}}{\omega RC_f}$$

Filtro passa-baixas

diferenciador



$$V_{out} = -R_f C \frac{dV_{in}}{dt}$$

Para sinal senoidal:

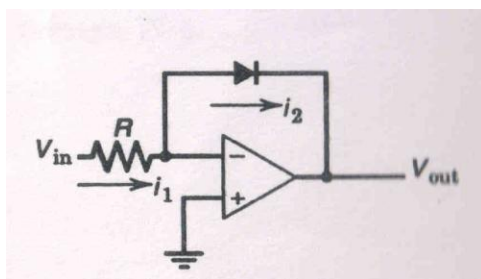
$$V_{out} \propto \omega RC_f V_{in}$$

Filtro passa-altas

## Alguns usos de Amplificadores Operacionais

Idealmente: ( $A = \infty$  ,  $i_i = 0$ )

Amplificador não linear

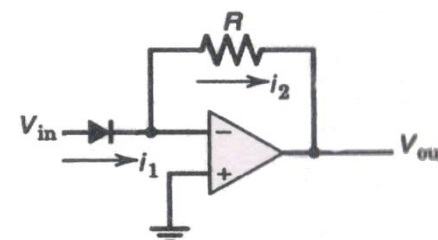
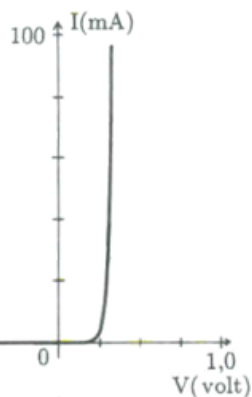


Para um diodo:  $i_2 = B \exp\left(\frac{V_{out}}{\alpha}\right)$

$$i_1 = i_2$$

$$\frac{V_{in}}{R} = B \exp\left(\frac{V_{out}}{\alpha}\right)$$

$$V_{out} = \alpha \ln\left(\frac{V_{in}}{RB}\right)$$



Para um diodo:  $i_1 = B \exp\left(\frac{V_i}{\alpha}\right)$

$$i_1 = i_2$$

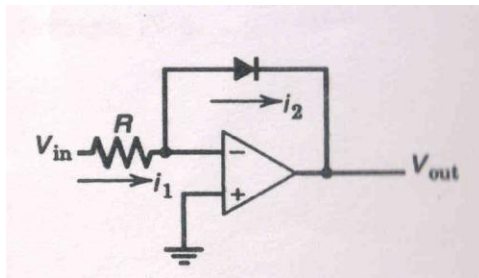
$$i_2 = \frac{V_{out}}{R}$$

$$V_{out} = RB \exp\left(\frac{V_i}{\alpha}\right)$$

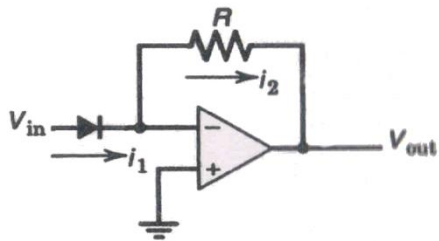
## Alguns usos de Amplificadores Operacionais

Idealmente: ( $A = \infty$  ,  $i_i = 0$ )

Amplificador não linear

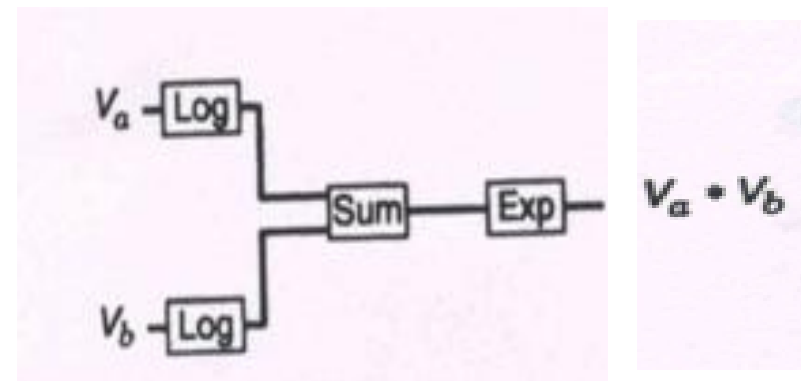


$$V_{out} = \alpha \ln\left(\frac{V_{in}}{RB}\right)$$



$$V_{out} = RB \exp\left(\frac{V_i}{\alpha}\right)$$

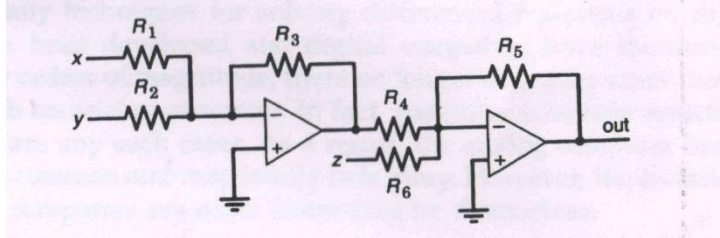
?



Multiplicador !!!

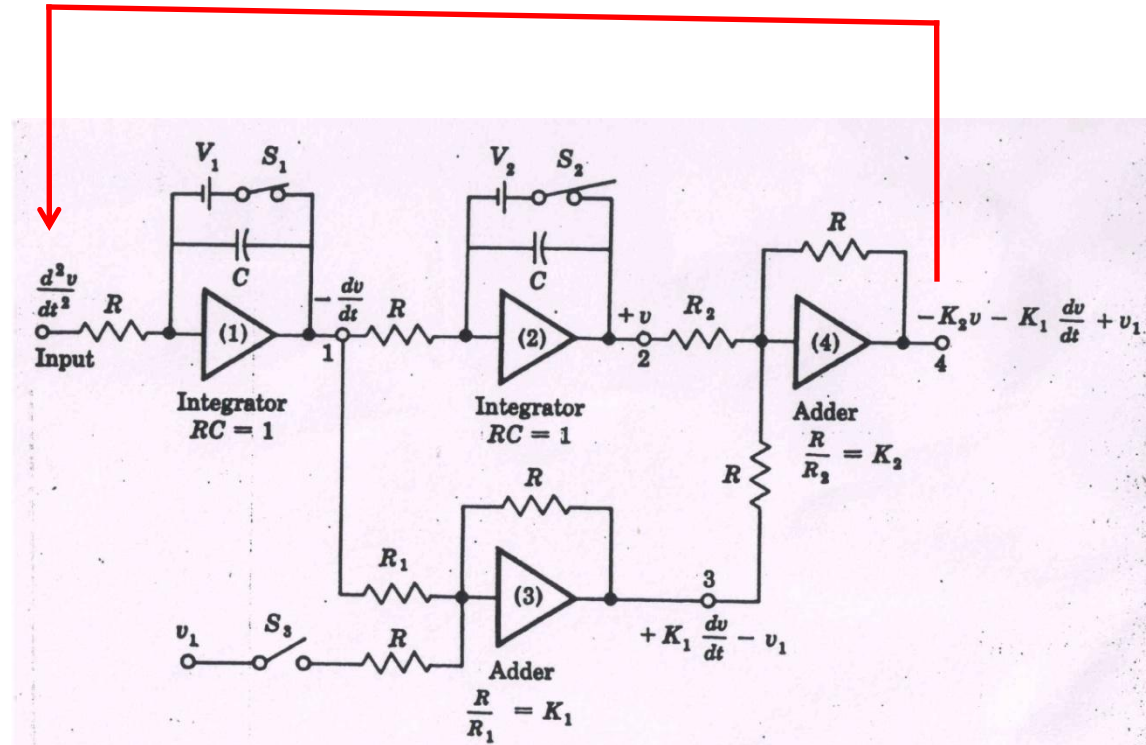
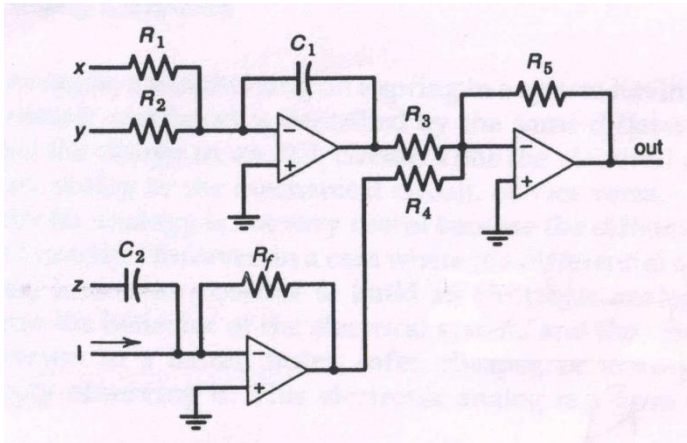


## Alguns exemplos



$$V_1 = -\frac{R_3}{R_1} \cdot x - \frac{R_3}{R_2} \cdot y$$

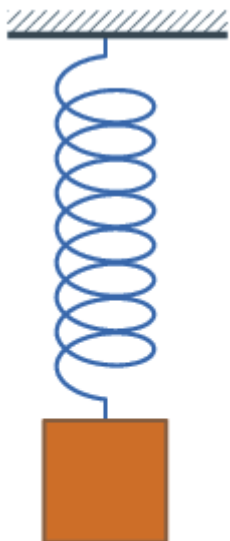
$$V_{out} = -\frac{R_5}{R_4} \cdot V_1 - \frac{R_5}{R_6} \cdot z$$



$$\frac{d^2v}{dt^2} + K_1 \frac{dv}{dt} + K_2v - v_1 = 0$$

Computador analógico !!!

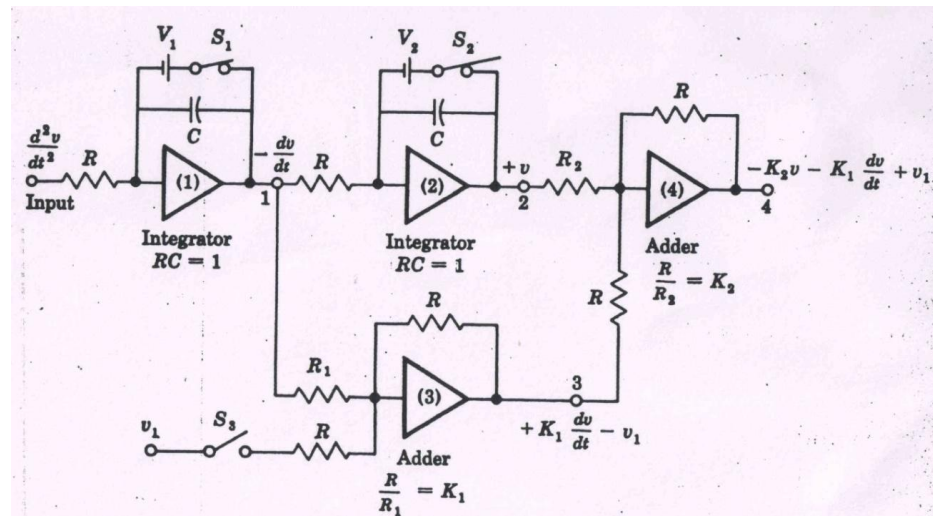
# Um exemplo – Sistema massa-mola



$$\frac{d^2 x}{dt^2} + \frac{b}{m} \frac{dx}{dt} + \frac{k}{m} x = \frac{F(t)}{m}$$

$$\frac{b}{m} = 2\zeta\omega_0$$

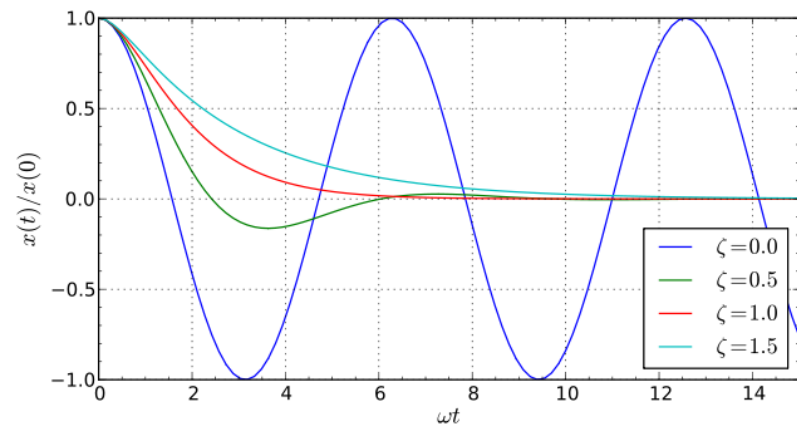
$$\frac{k}{m} = \omega_0^2$$



$$\frac{d^2 v}{dt^2} + K_1 \frac{dv}{dt} + K_2 v - v_1 = 0$$

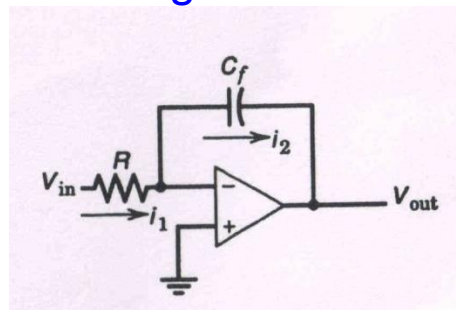
p/  $k = 5 \text{ N/m}$   
 e  $m = 200 \text{ g}$

Se  $\zeta = 1$ ,  
 $k/m = 25$  ( $K_2 = 25$ ),  
 $\omega_0 = 5 \text{ rad/s}$  ( $f = 0,8 \text{ Hz}$ ),  
 $b/m = 10$  ( $K_1 = 10$ )



# Filtros

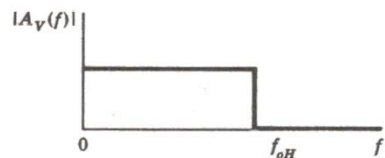
## integrador



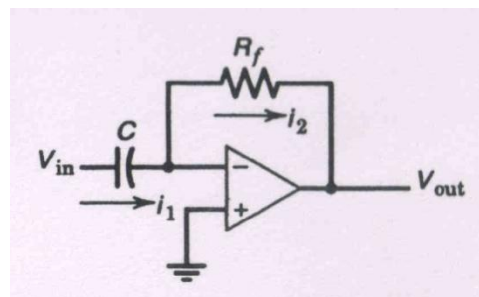
Para sinal senoidal:

$$V_{out} \propto \frac{V_{in}}{\omega RC_f}$$

Filtro passa-baixas



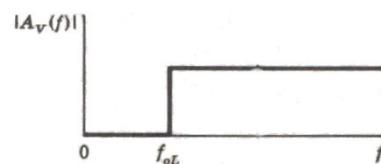
## diferenciador



Para sinal senoidal:

$$V_{out} \propto \omega RC_f V_{in}$$

Filtro passa-altas



## Combinação de filtros

### Filtro passa-banda

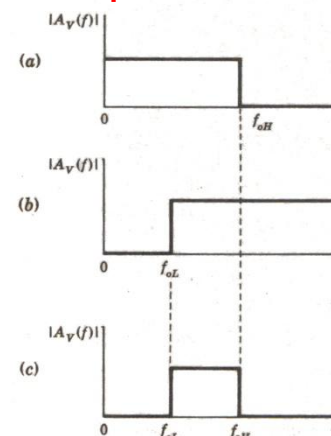


Fig. 16-15 Ideal filter characteristics. (a) Low-pass, (b) high-pass, and (c) bandpass.

### Filtro rejeita-banda

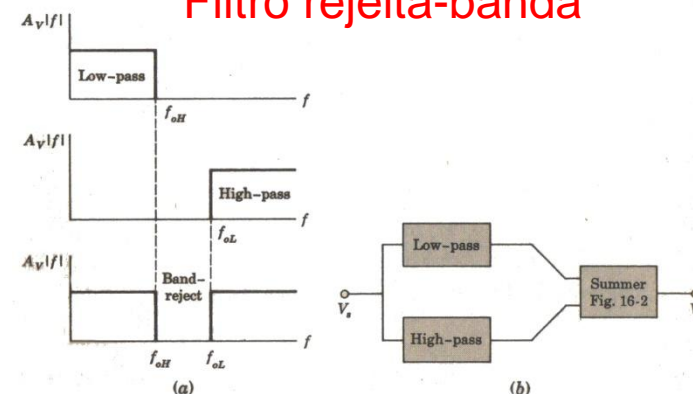
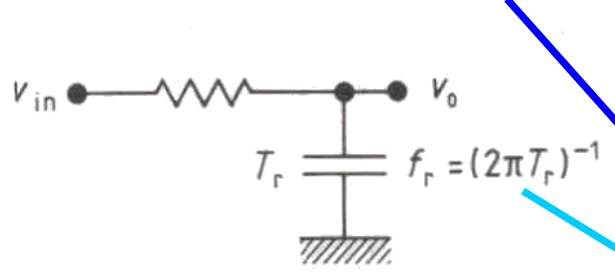


Fig. 16-20 (a) Ideal band-reject-filter frequency response. (b) Parallel combination of low-pass and high-pass filters results in a band-reject filter.

# Resposta em frequência (vista espectral)

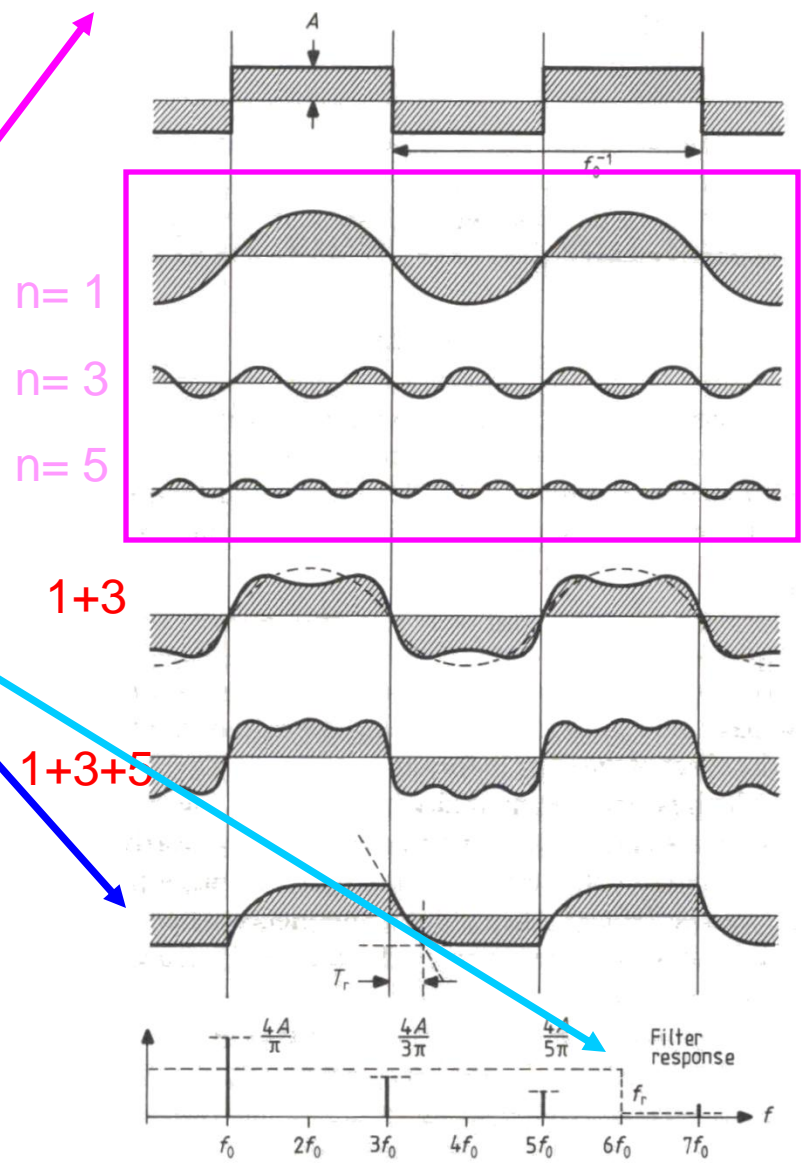
$$v = \frac{4A}{\pi} \sum_{n=\text{impar}} \frac{\sin(2\pi n f_o t)}{n}$$

Filtro passa-baixas



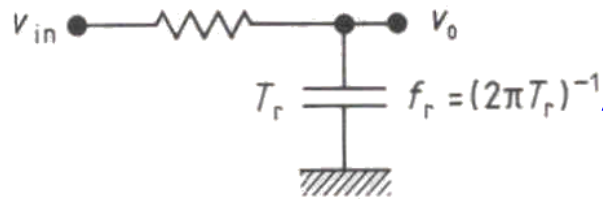
Para um sinal non-senoidal  
de frequência  $f_o$   
(série de Fourier)

$$v = A_0 + \sum_{n=1}^{\infty} [A_n \cos(2\pi n f_o t) + B_n \sin(2\pi n f_o t)]$$



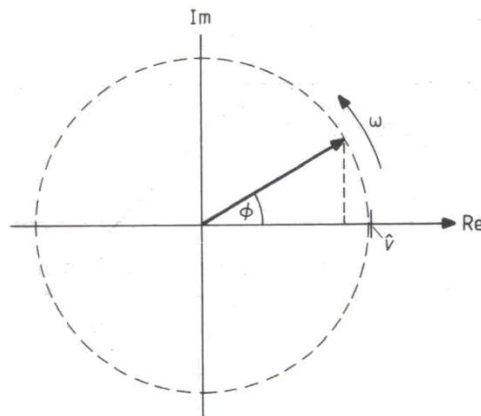
## Resposta em frequência (vista espectral)

Filtro passa-baixas



$$V = v_0 \exp[j(2\pi ft + \phi)] = \\ = v_0 \cos(2\pi ft + \phi) + jv_0 \sin(2\pi ft + \phi)$$

Fasor



Phasor representation of  $V = \hat{v} \exp[j(\omega t + \phi)]$

$$V_c = v_{0c} \exp[j(2\pi ft + \phi_c)]$$

$$I_c = C \frac{dV_c}{dt} = j2\pi fCV_c$$

$$\therefore Z_c = \frac{V_c}{I_c} = \frac{1}{j2\pi fC} = \frac{1}{j\omega C}$$

$$V_{in} = (R + Z_c)I$$

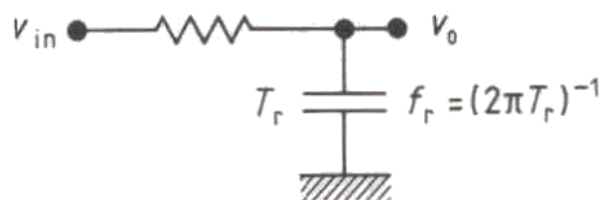
$$V_{out} = Z_c I$$

$$\therefore V_{out} = \frac{Z_c}{R + Z_c} V_{in}$$

$$V_{out} = \frac{1}{1 + j\omega/\omega_r} V_{in}$$

## Resposta em frequência (vista espectral)

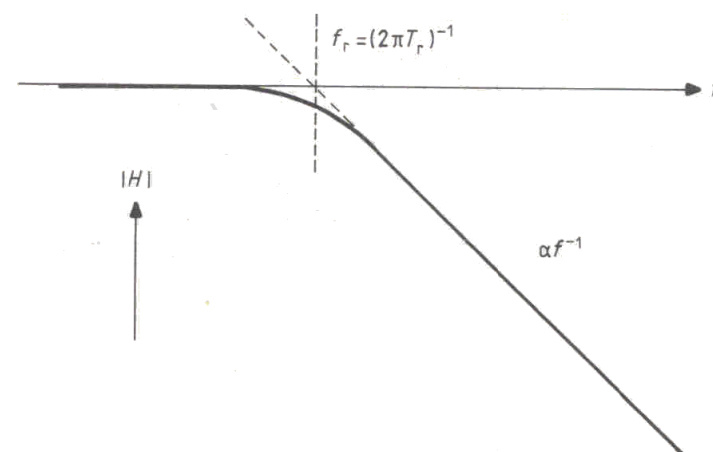
Filtro passa-baixas



$$V_{out} = \frac{1}{1 + j\omega / \omega_r} V_{in}$$

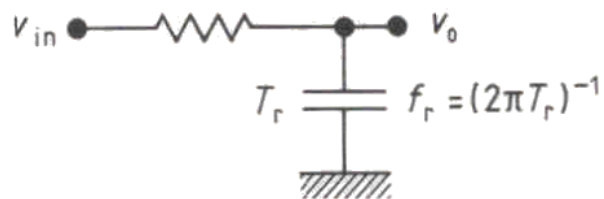
$$V_{out} = T_r^{-1} \int_{t-T_r}^t v_{in} \exp(j\omega t') dt'$$

$$V_{out} = V_{in}(t) \exp(-j\omega T_r / 2) \frac{\sin(\omega T_r / 2)}{\omega T_r / 2}$$



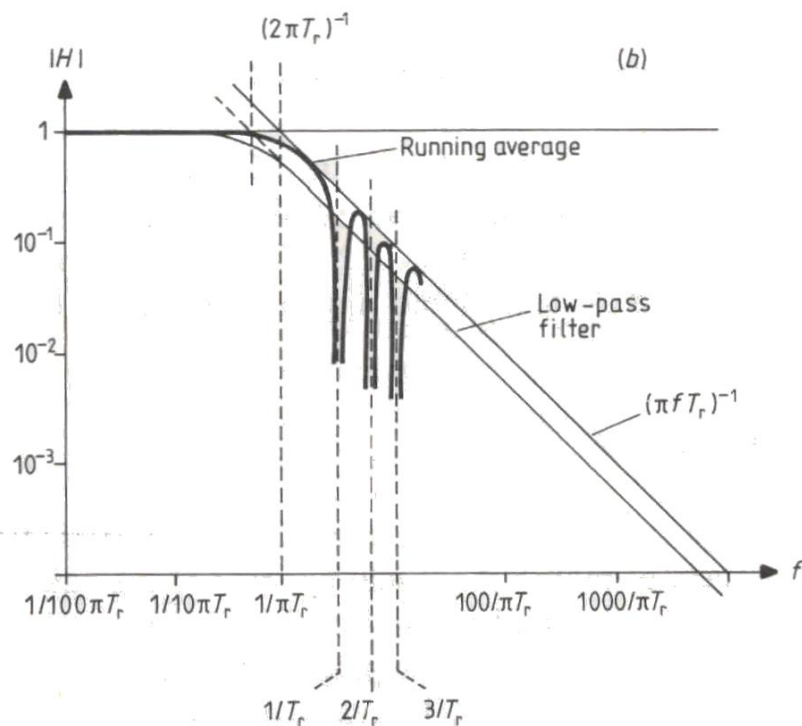
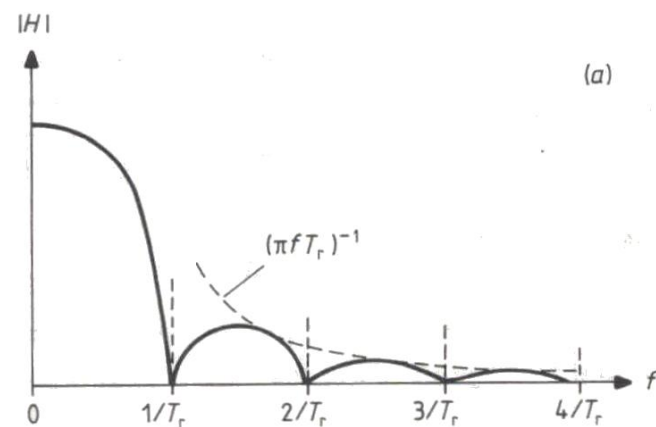
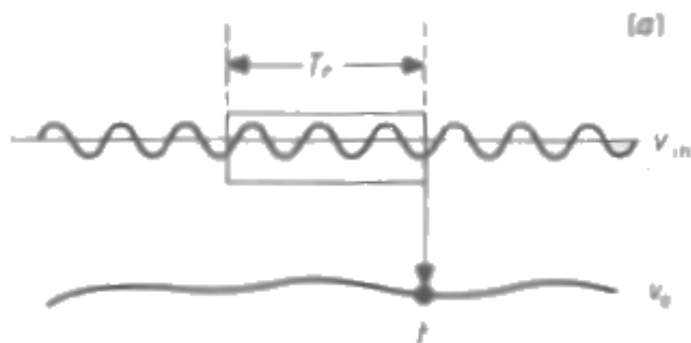
## Resposta em frequência (vista espectral)

Filtro passa-baixas

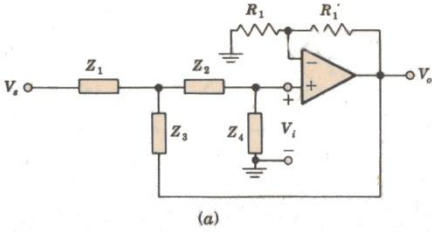


$$V_{out} = T_r^{-1} \int_{t-T_r}^t v_{in} \exp(j\omega t') dt'$$

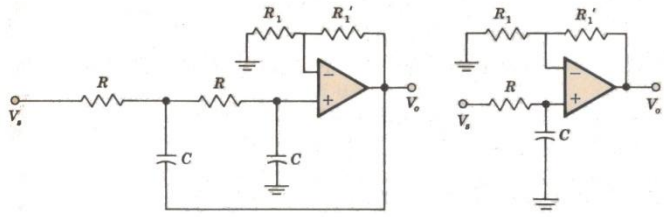
$$V_{out} = V_{in}(t) \exp(-j\omega T_r / 2) \frac{\sin(\omega T_r / 2)}{\omega T_r / 2}$$



# Eficiência dos Filtros



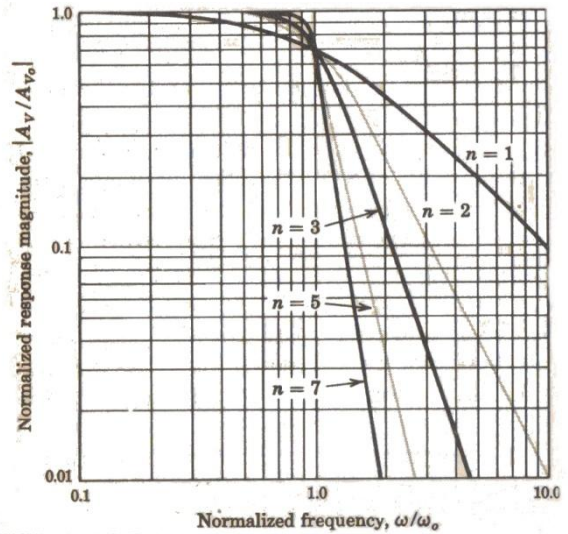
(a)



(b)

(c)

Fig. 16-18 (a) Generalized active-filter prototype. (b) Second-order low-pass section. (c) First-order low-pass section.



Butterworth low-pass filter frequency response.

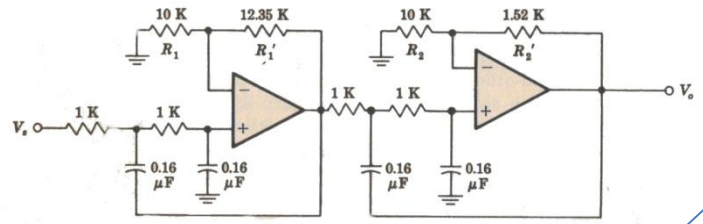


Fig. 16-19 Fourth-order Butterworth low-pass filter with  $f_o = 1$  kHz.

## Filtro Ressonante (passa-banda estreito)

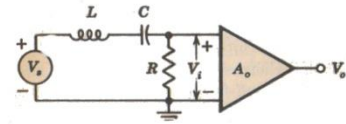
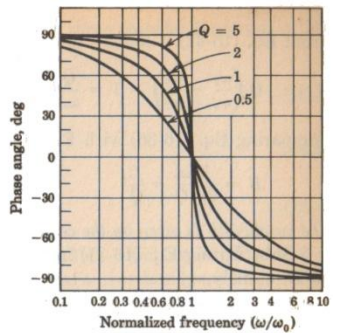
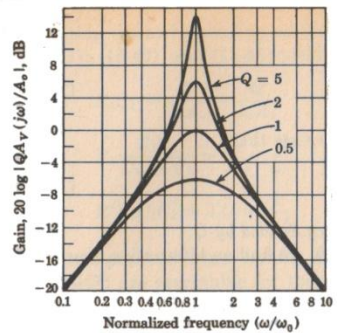


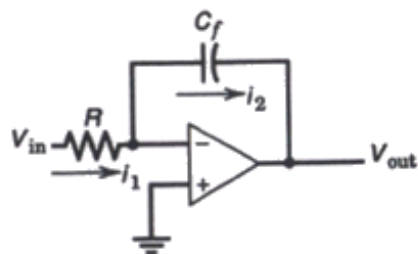
Fig. 16-21 A resonant circuit.





# Filtros

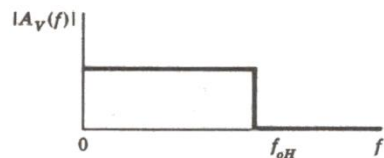
integrador



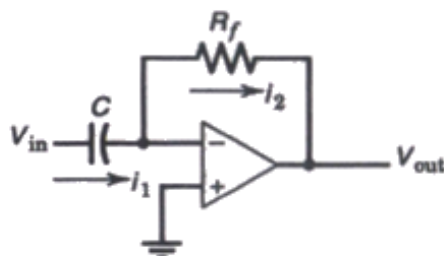
Para sinal senoidal:

$$V_{out} \propto \frac{V_{in}}{\omega RC_f}$$

Filtro passa-baixas



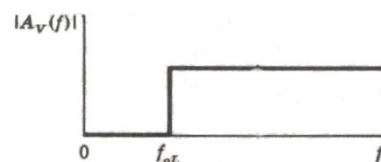
diferenciador



Para sinal senoidal:

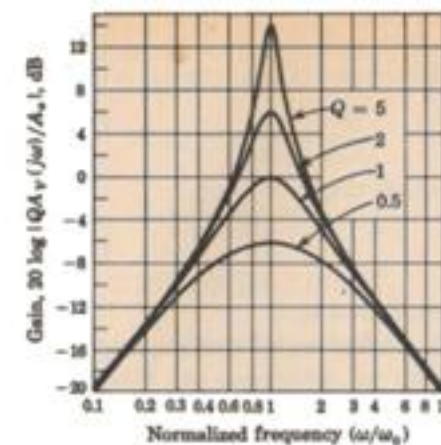
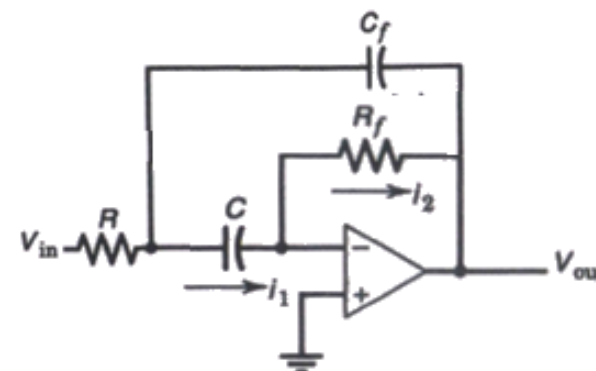
$$V_{out} \propto \omega RC_f V_{in}$$

Filtro passa-altas



Combinação de filtros

Filtro passa-banda



## 2) Projetos de Experimentos

- Laboratórios didáticos

experimentos com Lock-in (foto-elétrico, Franck-Hertz, Lei de Malus, efeito Hall e resistividade, efeito Faraday/Kerr, curva I-V de diodo, efeito magnetoótico, ...)

experimentos com controladores de processos PID

- Espaço InovaLab

- Experimentos Clássicos

### 3) Elaboração dos Projetos

- Título e Proponentes
- Resumo
- Introdução e motivação  
(relevância e estado da arte no tema, vantagens/desvantagens, ...  
( O que fazer? Porquê fazer? Como fazer? ) )
- Justificativa tecnico-científica  
(facilidade de operação, melhores resultados, flexibilidade, ...)
- Detalhamento do projeto
- Orçamento