

Física Experimental VI – 4300314

1º Semestre de 2017

Instituto de Física
Universidade de São Paulo

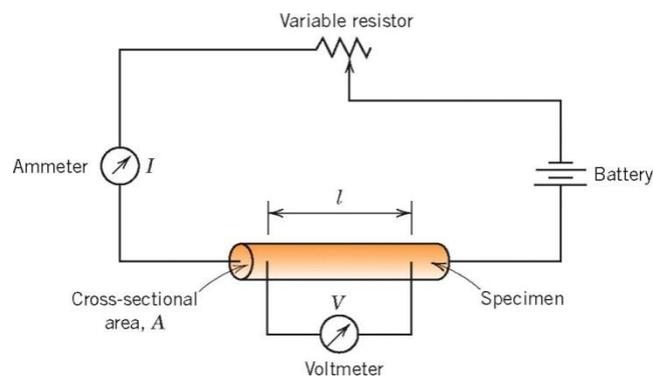
Professor: **Antonio Domingues dos Santos**

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Fone: 3091.6886

Propriedades Elétricas

$$V = RI$$



Condutividade

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

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

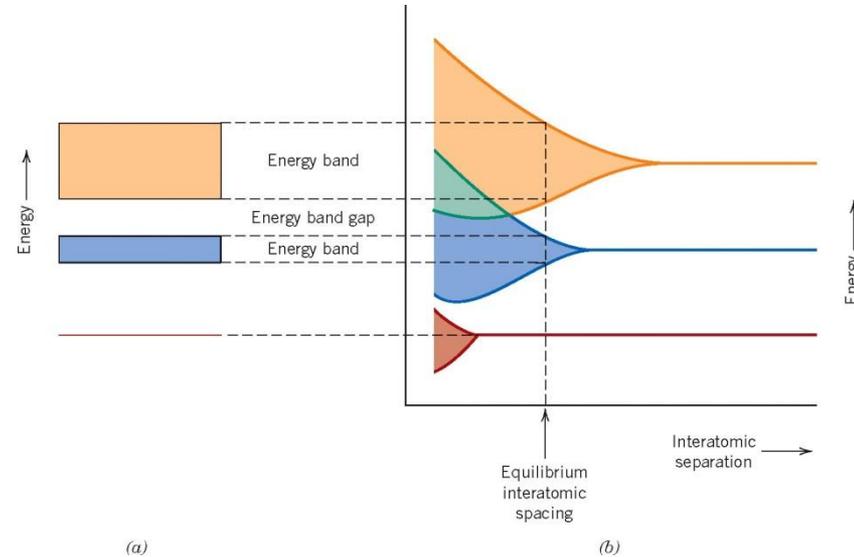
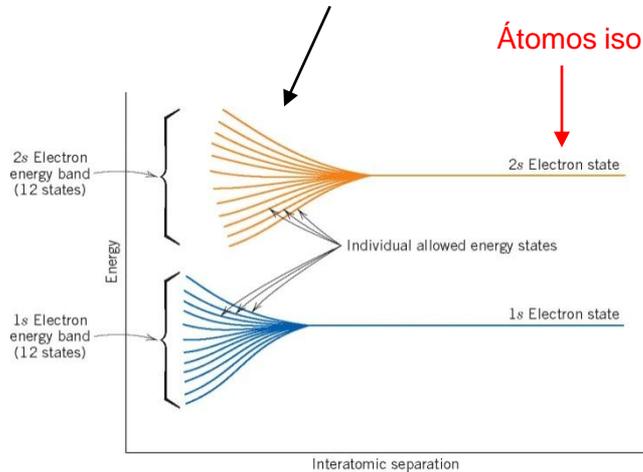
Isolantes = $10^{-10} \sim 10^{-20} (\Omega\text{m})^{-1}$

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

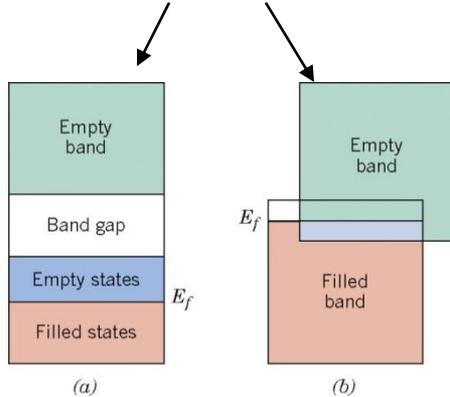
$$\rho = \frac{RA}{l} = \frac{VA}{Il}$$

Propriedades Elétricas

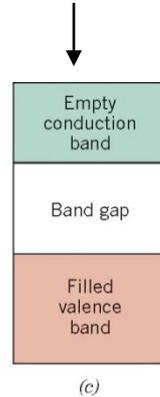
Estrutura de bandas em sólidos



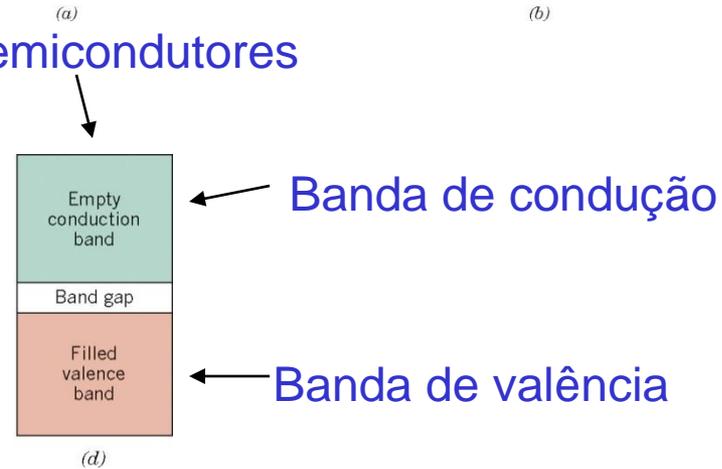
Metais



Isolantes

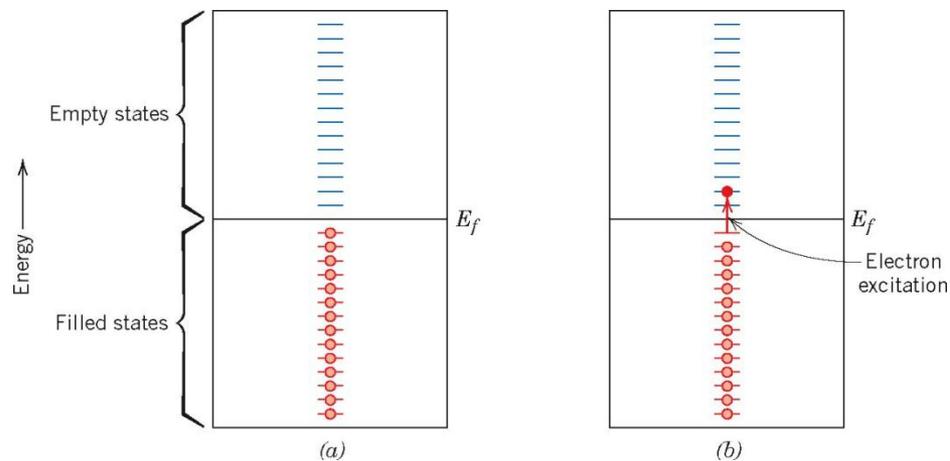


Semicondutores

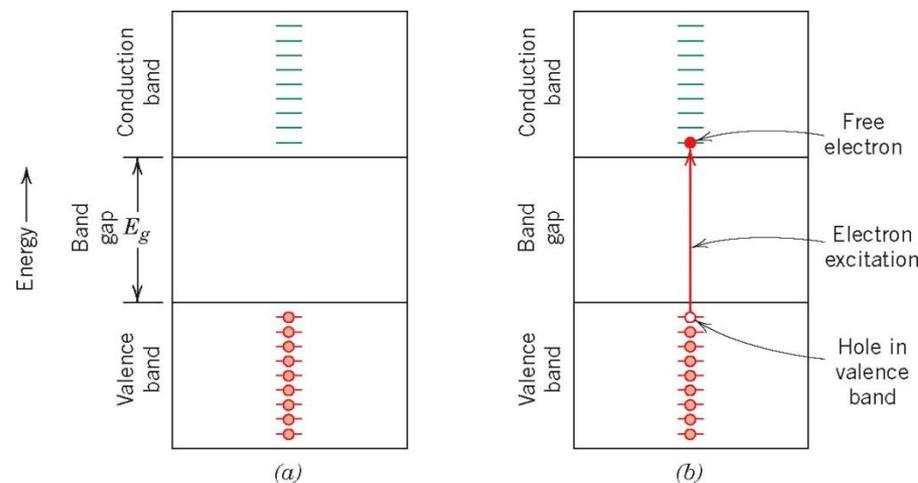


Propriedades Elétricas

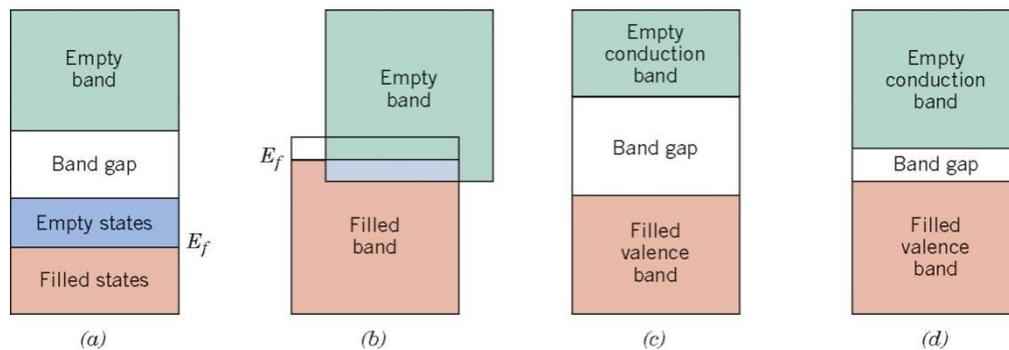
Metais



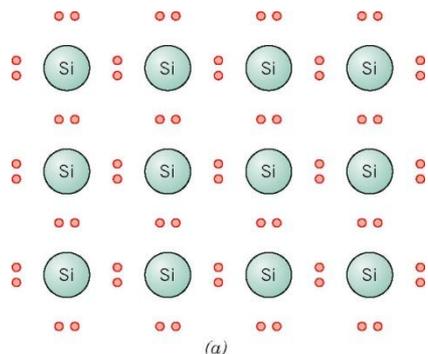
Isolantes e Semicondutores



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

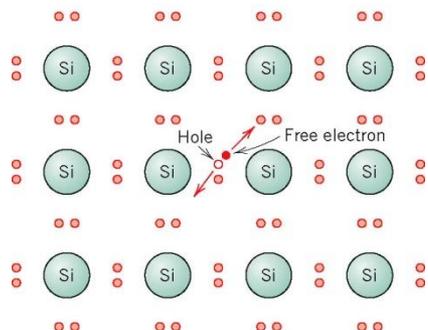


Semicondutores



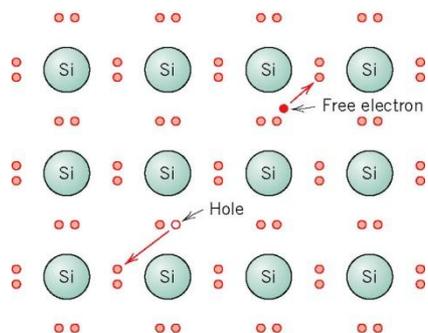
(a)

← Field

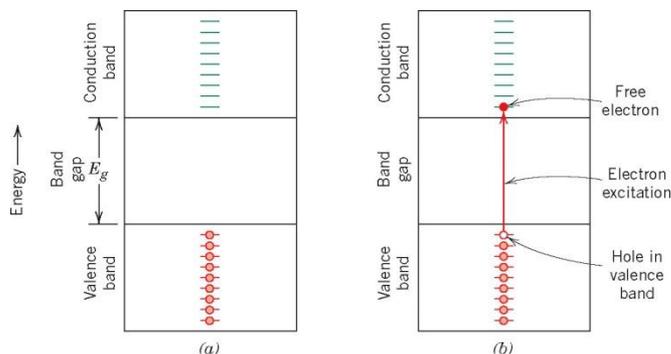


(b)

← 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 $(\text{m}^2/\text{V}\cdot\text{s})$
Elemental				
Si	1.11	4×10^{-4}	0.14	0.05
Ge	0.67	2.2	0.38	0.18
III-V Compounds				
GaP	2.25	—	0.03	0.015
GaAs	1.42	10^{-6}	0.85	0.04
InSb	0.17	2×10^4	7.7	0.07
II-VI Compounds				
CdS	2.40	—	0.03	—
ZnTe	2.26	—	0.03	0.01

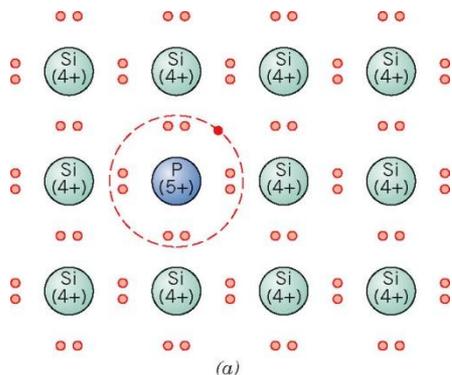
Semicondutores extrínsecos

Tipo n

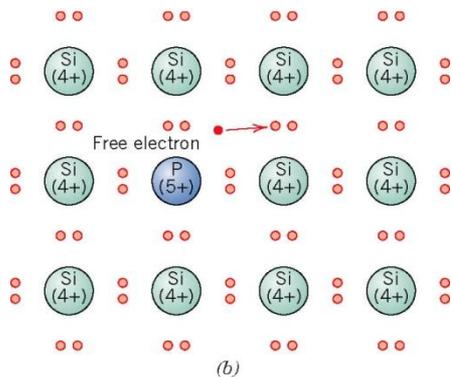
Condutividade

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

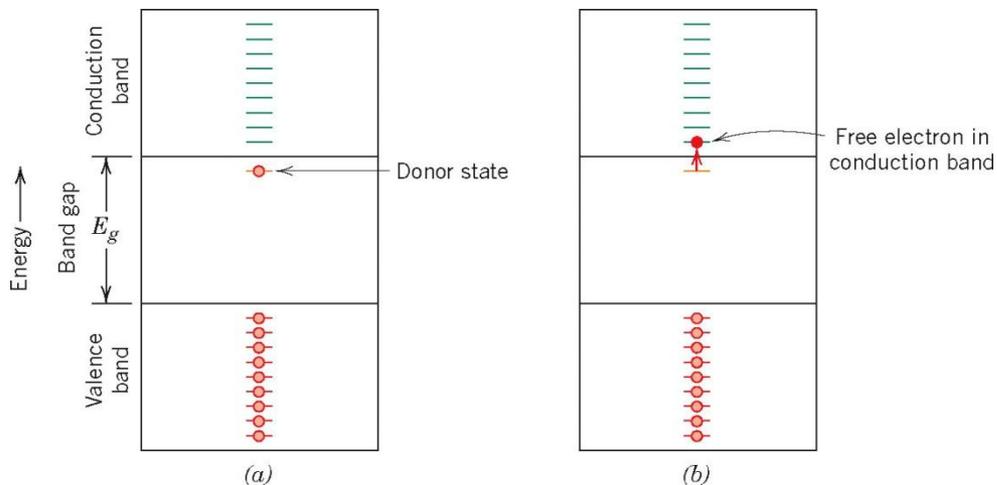
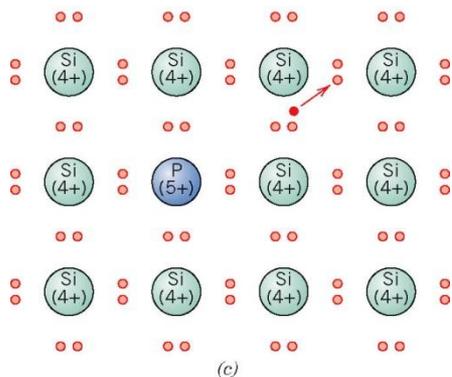
Por elétrons e buracos



Field ←



Field ←



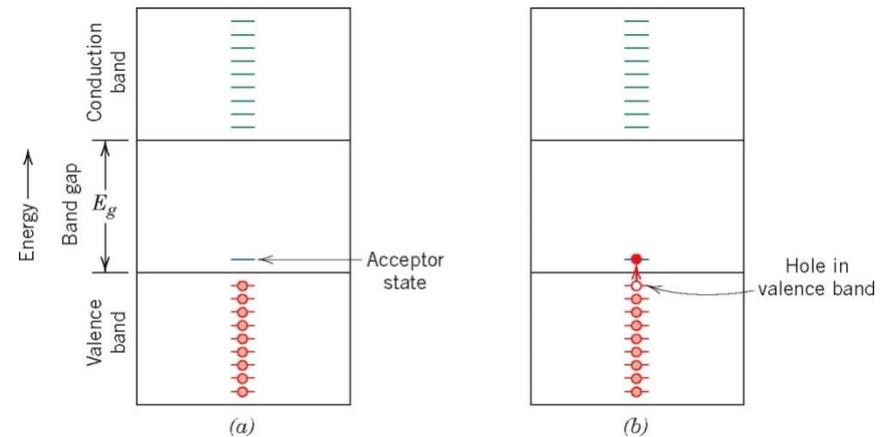
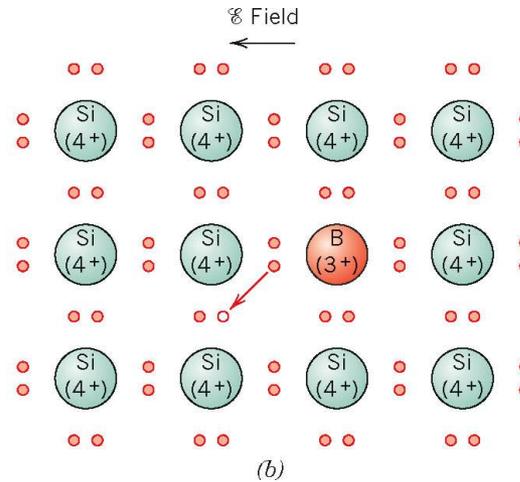
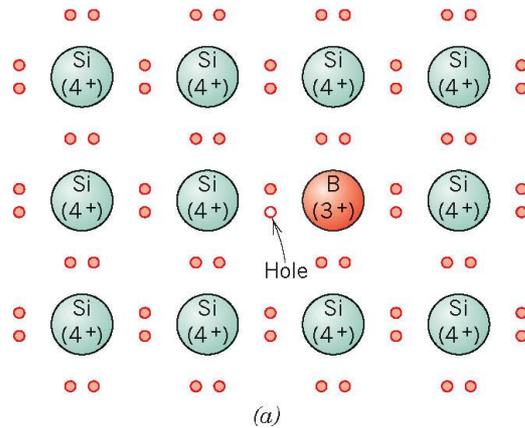
Semicondutores extrínsecos

Tipo p

Condutividade

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

Por elétrons e buracos



Dispositivos Semicondutores

Junção p-n

Diodos

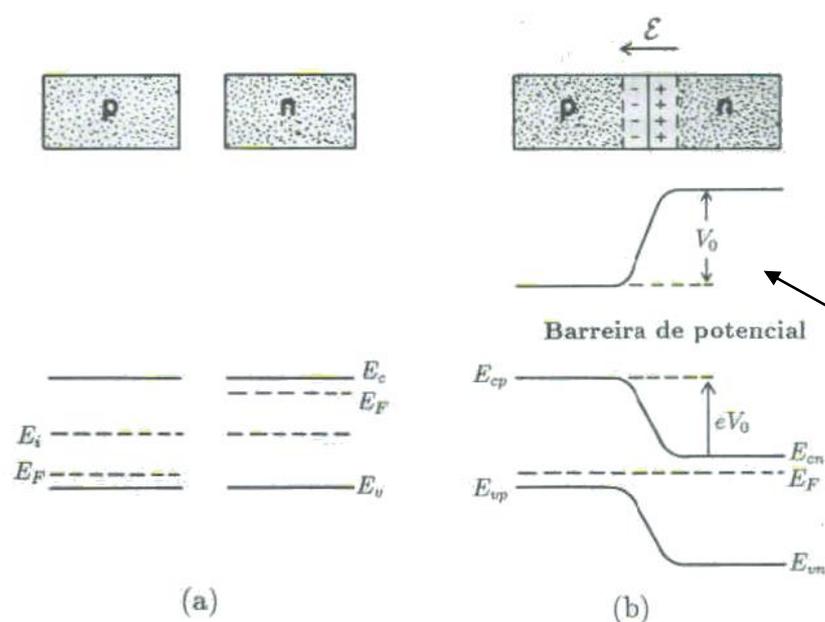


Figura 6.3: (a) Semicondutores *p* e *n* separados. (b) Carga, campo elétrico, potencial e níveis de energia na região de carga espacial de junção *p-n*.

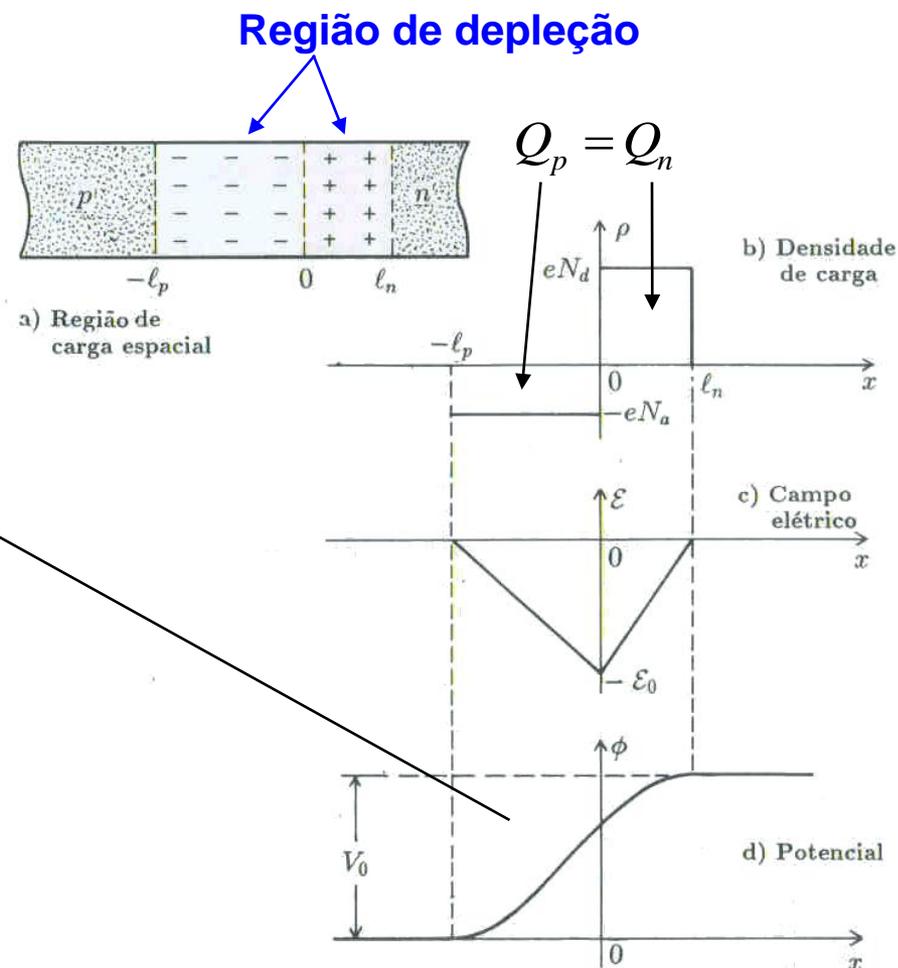


Figura 6.4: Variação da densidade de carga, campo elétrico e potencial eletrostático no modelo unidimensional da junção *p-n*.

Dispositivos Semicondutores

Junção p-n

Diodos

Região de depleção

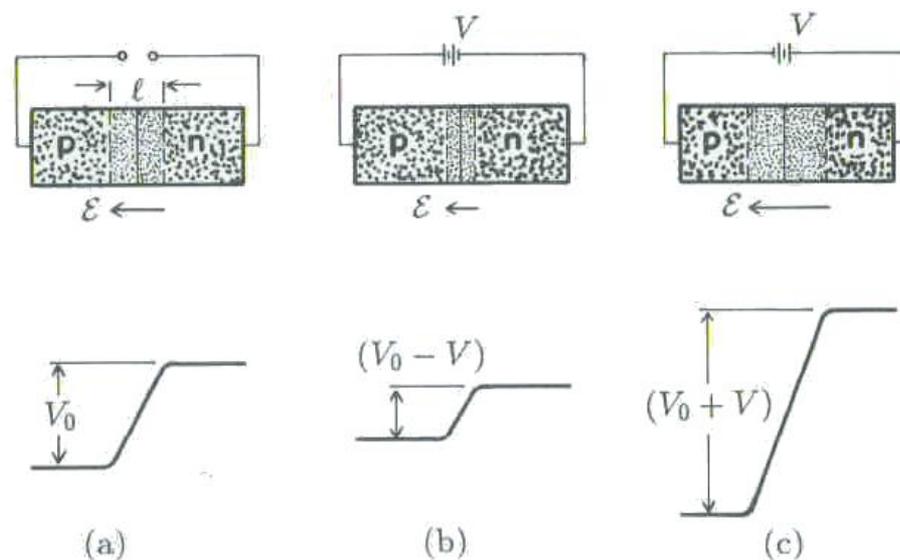


Figura 6.5: Efeito de tensão externa na espessura da região de carga espacial e na altura da barreira de potencial: (a) situação em equilíbrio; (b) polarização direta; (c) polarização reversa.

Corrente elétrica em um diodo

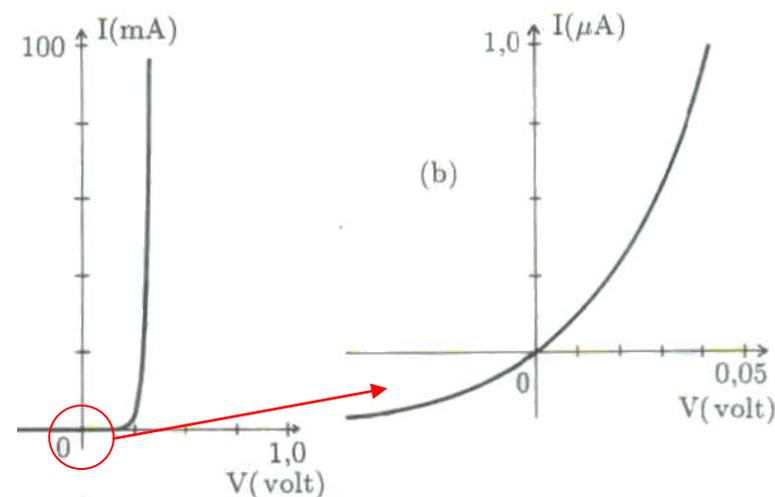


Figura 6.7: Característica I - V de junção p - n ideal dada pela equação do diodo com $I_s = 0,25 \mu A$, valor adequado para uma junção de germânio. A curva em (b) é a mesma que em (a), feita em escala ampliada para mostrar o comportamento em torno da origem.

Dispositivos Semicondutores

Transistor p-n-p

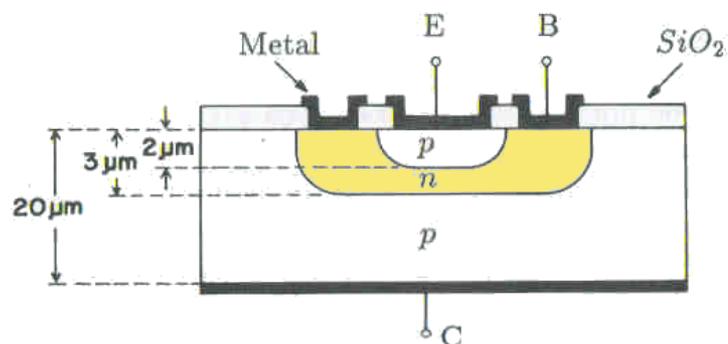


Figura 7.2: Estrutura planar do transistor bipolar de junção com algumas dimensões típicas. As letras E, B e C representam os terminais do emissor, da base e do coletor, respectivamente. As distâncias indicadas representam espessuras típicas.

Transistor bipolar

Corrente elétrica em um transistor

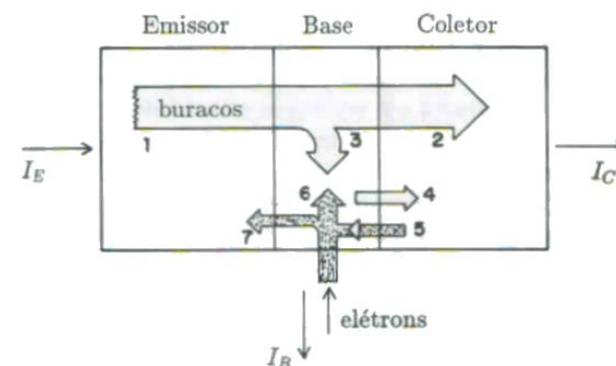
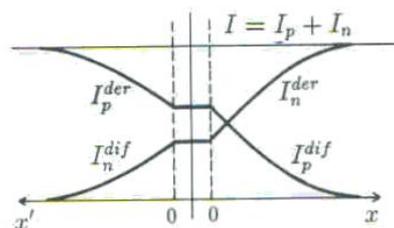
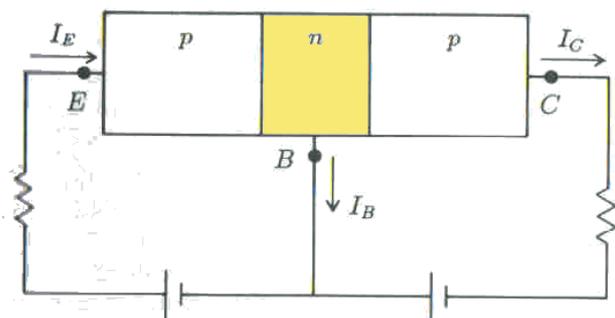
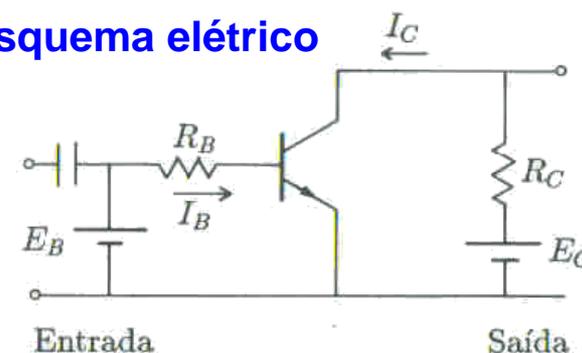


Figura 7.4: Ilustração do fluxo de elétrons e de buracos em transistor p-n-p: 1- Buracos em movimento de deriva no emissor; 2- Buracos que atingem o coletor em movimento de difusão; 3- Buracos que desaparecem na base por recombinação; 4 e 5- Buracos e elétrons gerados termicamente na base e que formam a corrente de saturação 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} .



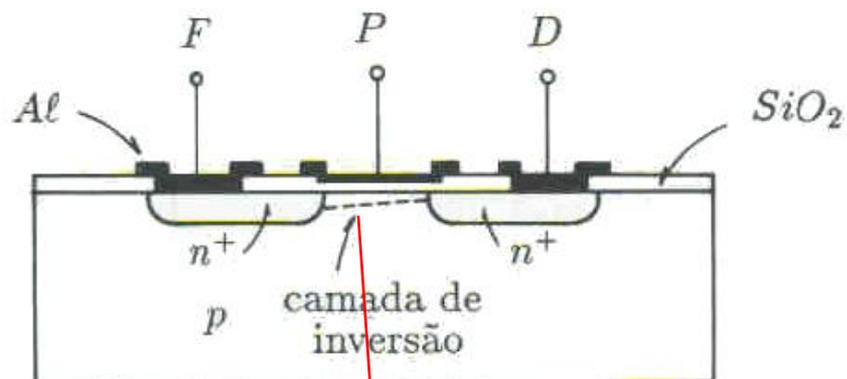
Correntes na região de depleção

Esquema elétrico

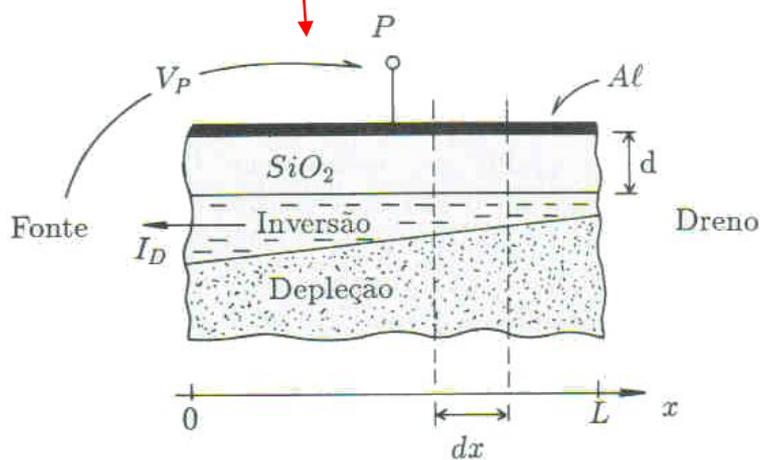


Dispositivos Semicondutores

Transistor MOS-FET



Estrutura planar de MOSFET de canal n .



Distribuição de carga no capacitor MOS

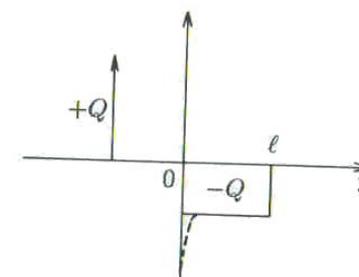
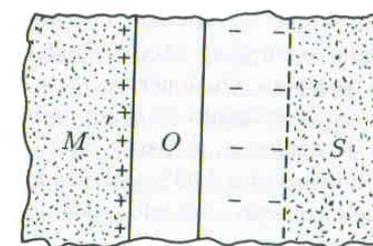


Figura 7.17: Distribuição de carga num capacitor MOS ideal com semiconductor tipo p (canal n), na aproximação de depleção. A linha tracejada indica a carga criada pela inversão quando $V > V_c$.

Circuitos integrados

Processo de Litografia

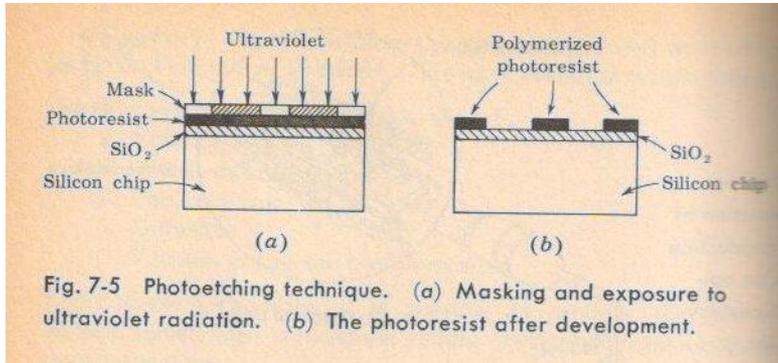


Fig. 7-5 Photoetching technique. (a) Masking and exposure to ultraviolet radiation. (b) The photoresist after development.

Transistores de efeito de campo

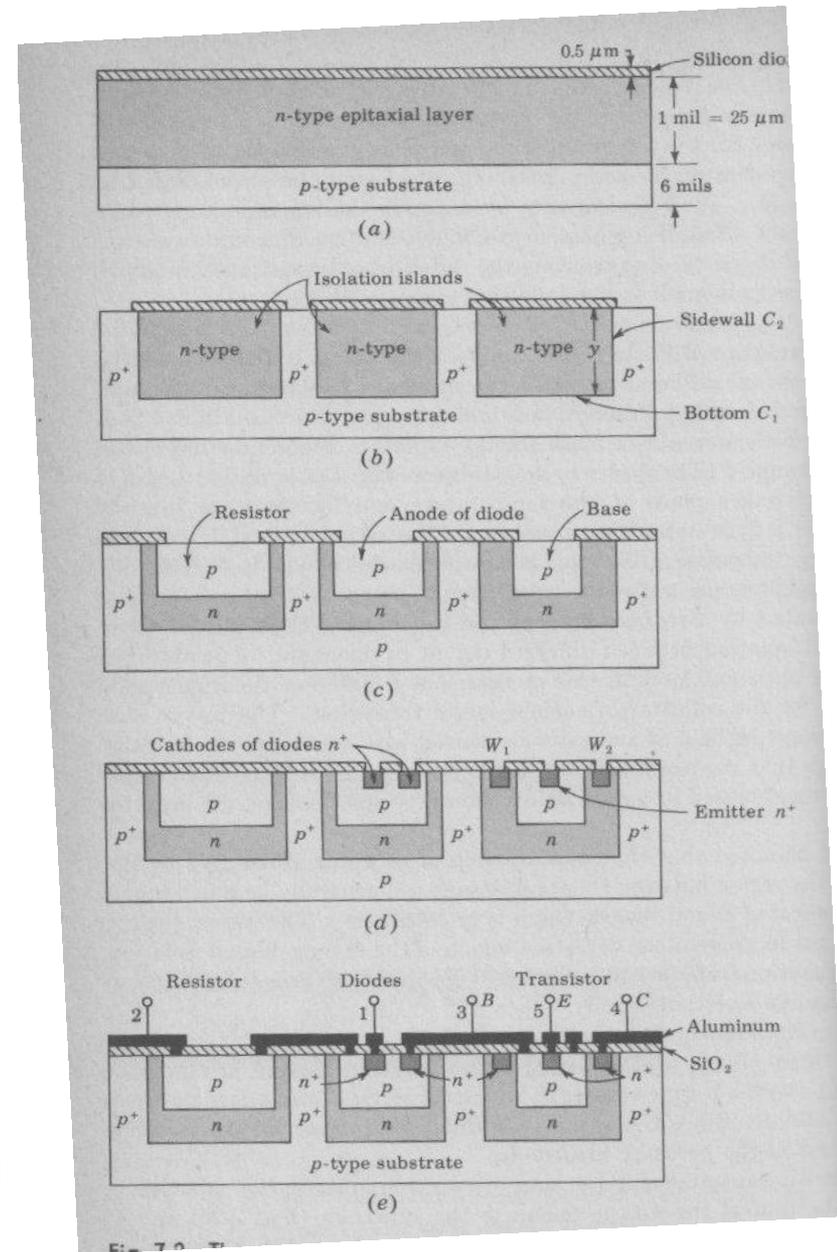
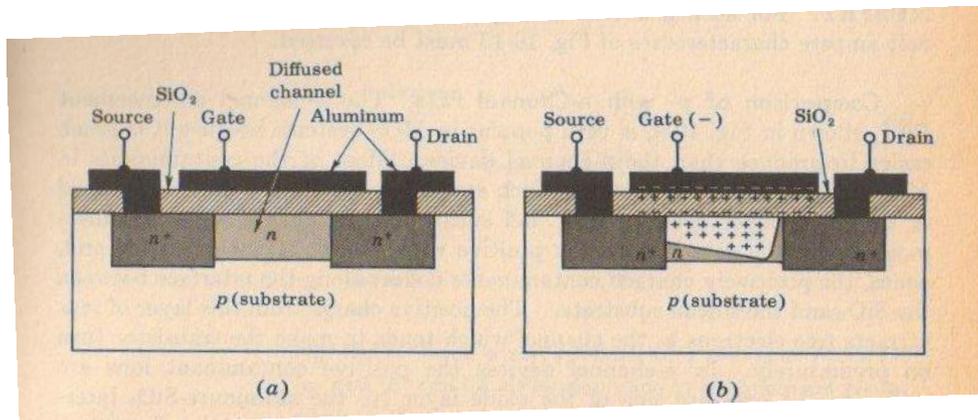
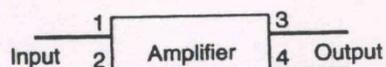


Fig. 7.9

Amplificadores Operacionais

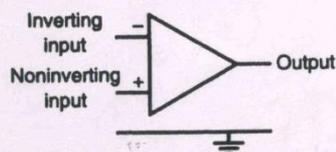
Amplificadores constituem-se nos mais importantes blocos usados em eletrônica analógica.



Malha aberta

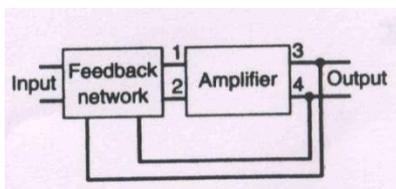
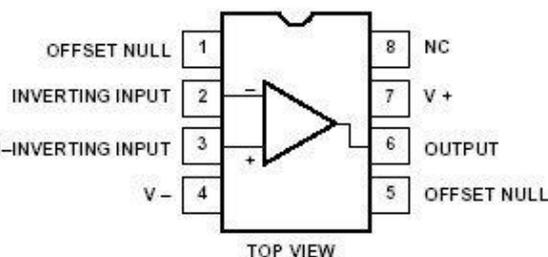
$$A = \frac{V_{out}}{V_{in}}$$

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



(a)

R 5



Malha fechada

Amp. Op. Modelo 741

Ganho $A \sim 10^5$ (ideal = ∞)

Impedância $2M\Omega$ (ideal = ∞)

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

V offset 2mV (ideal = 0)

Rampeamento $0,5V/\mu s$

Resposta em frequência

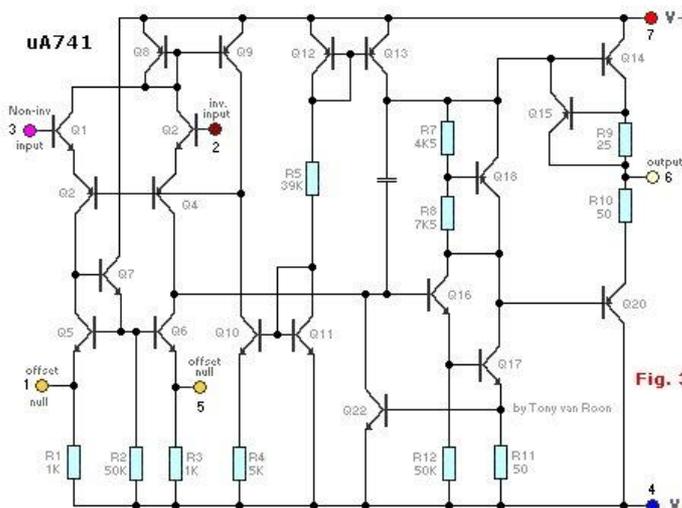
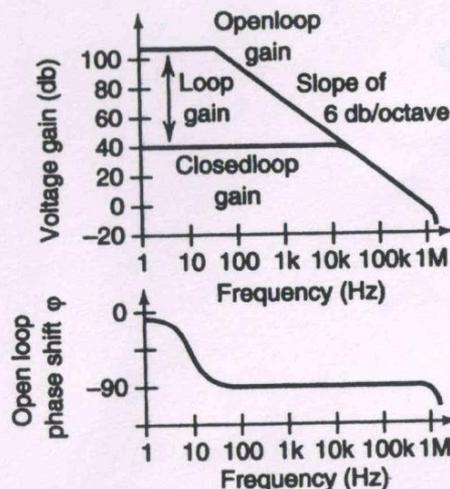


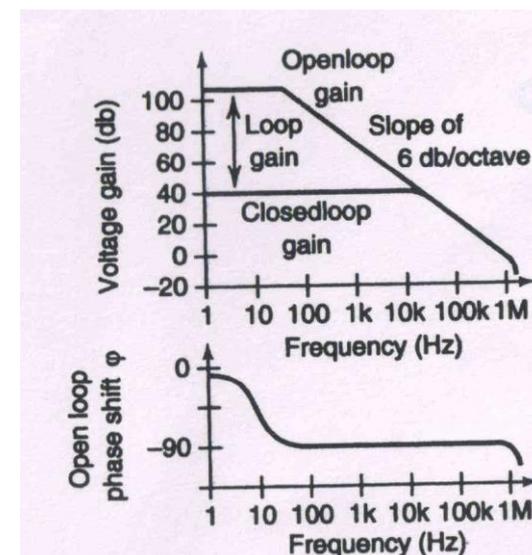
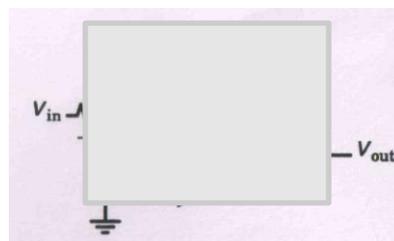
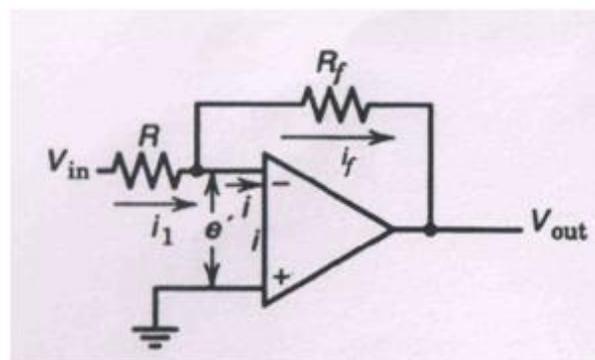
Fig. 3

=>



Uso de Amplificadores Operacionais

Amplificador inversor



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

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

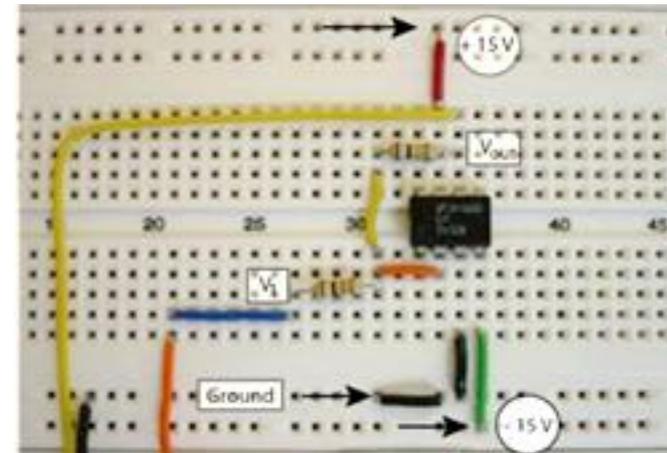
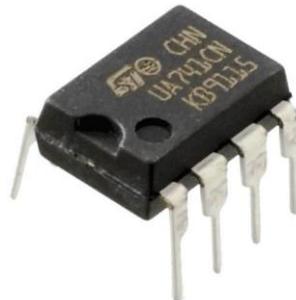
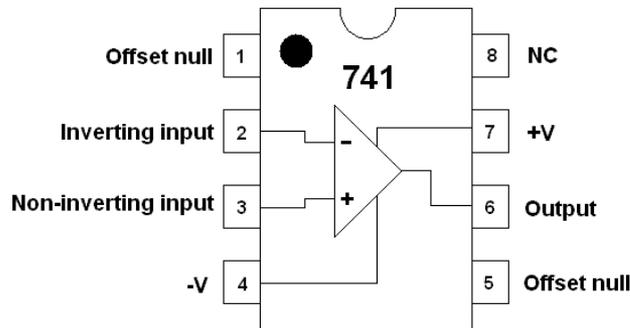
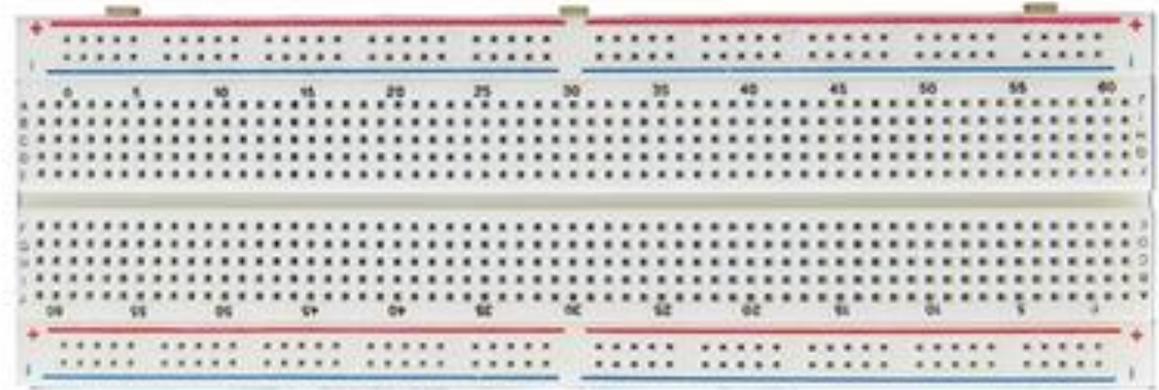
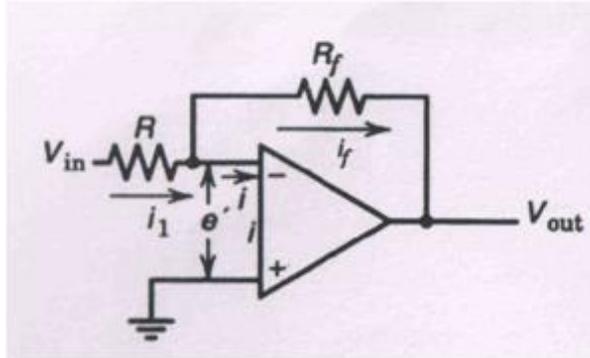
Idealmente: ($A = \infty$, $i_i = 0$)

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

Uso de Amplificadores Operacionais

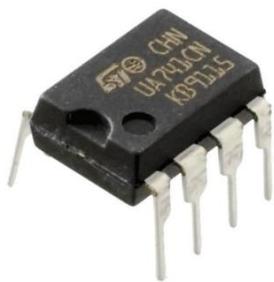
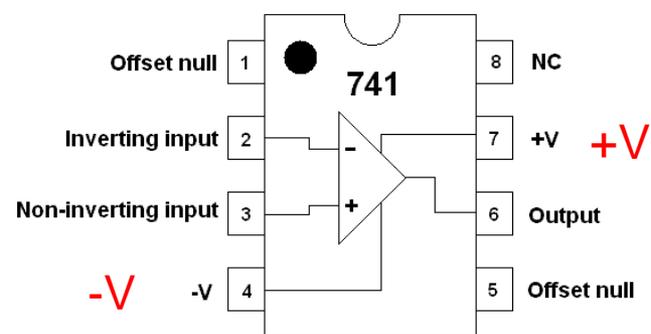
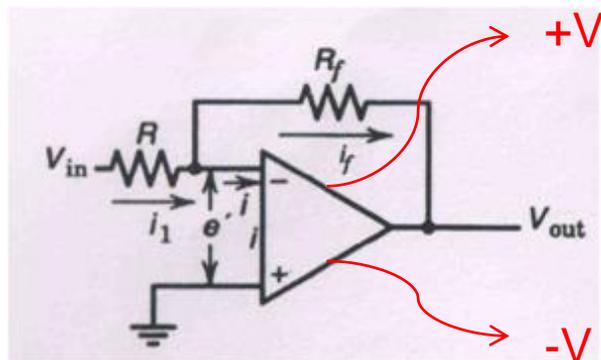
Protoboard

Amplificador inversor

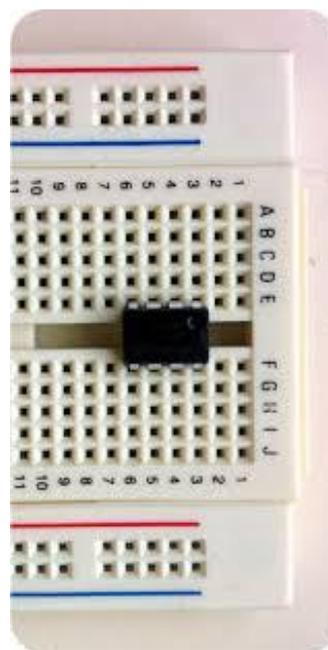
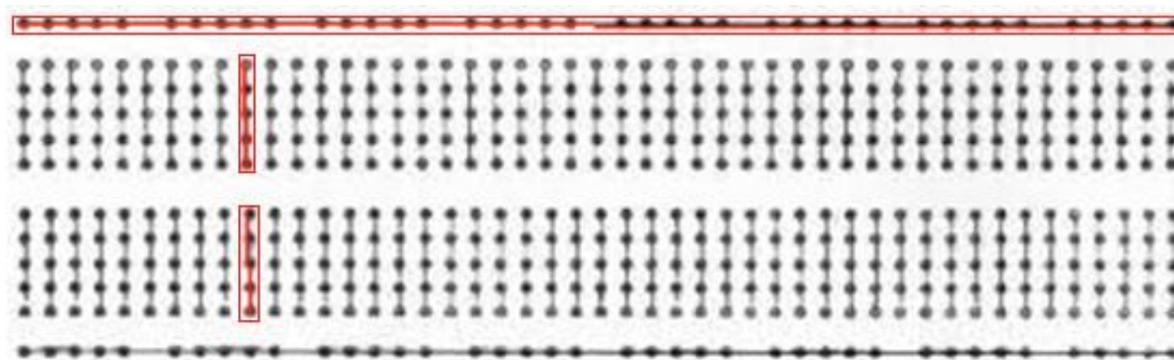


Uso de Amplificadores Operacionais

Montagem do Amplificador inversor



Protoboard

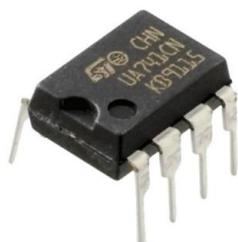
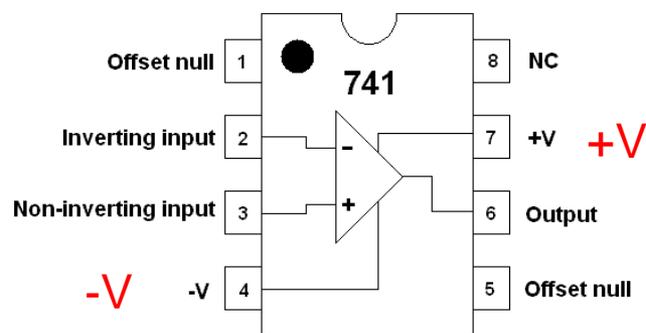
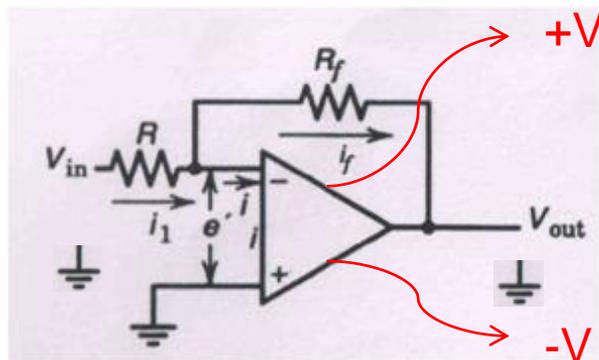


Primeiro passo:

- 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

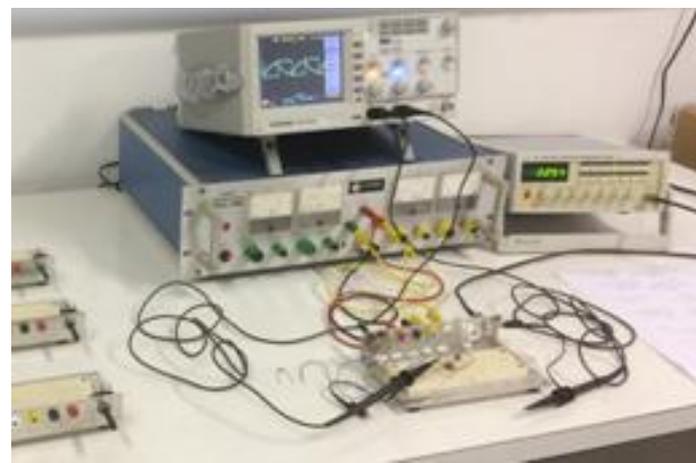


Segundo passo:

- 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.

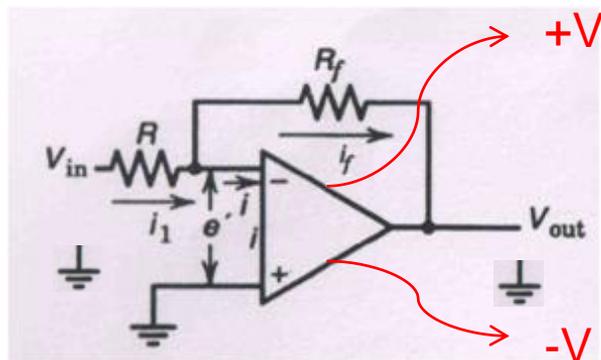
Terceiro passo:

- 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.



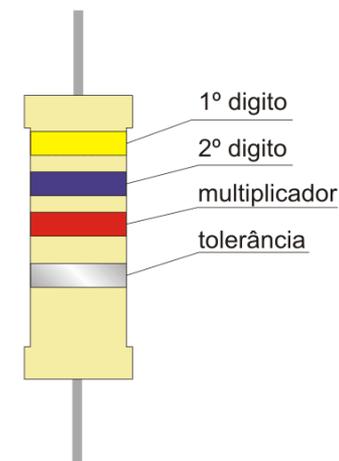
Uso de Amplificadores Operacionais

Montagem do Amplificador inversor



Código de cores para identificação de resistores:

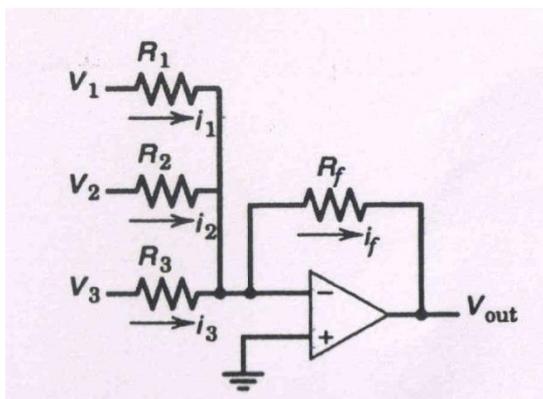
COR	1ºANEL	2ºANEL	3ºANEL	4ºANEL
Preto	-	0	x1	-
Marrom	1	1	x10	1%
Vermelho	2	2	x100	2%
Laranja	3	3	x1000	3%
Amarelo	4	4	x10000	4%
Verde	5	5	x100000	-
Azul	6	6	x1000000	-
Violeta	7	7	-	-
Cinza	8	8	-	-
Branco	9	9	-	-
Prata	-	-	x0,01	10%
Dourado	-	-	x0,1	5%



Alguns usos de Amplificadores Operacionais

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

Amplificador somador inversor



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

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

$$i_1 = i_i + i_f$$

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

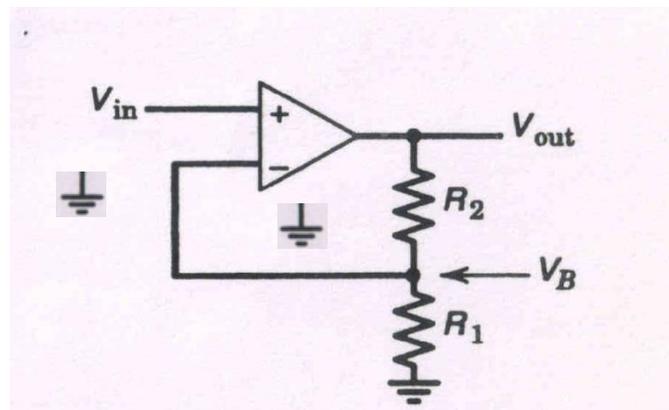
$$i_f = \frac{e' - V_{out}}{R_f}$$

$$i = i_1 + i_2 + i_3$$

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

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

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

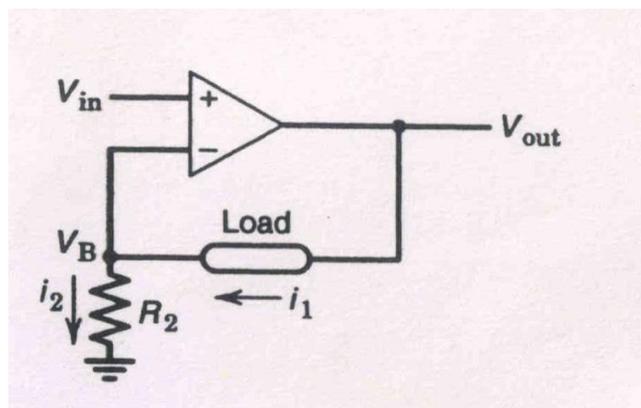
$$R_{in} \propto A$$

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

Alguns usos de Amplificadores Operacionais

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

Fonte de corrente constante

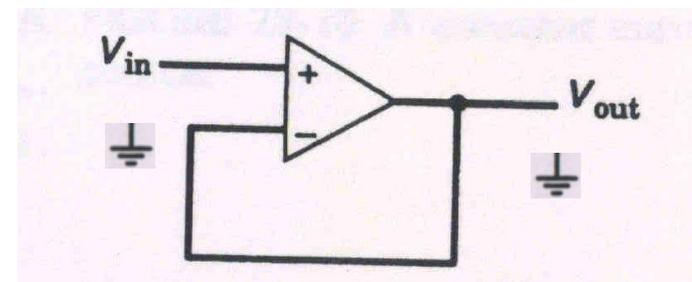


$$i_1 = i_2$$

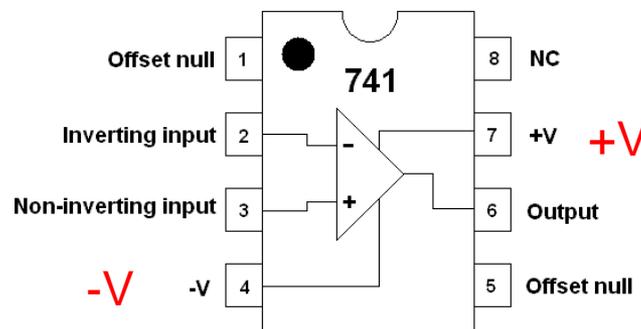
$$V_B = V_{in} = R_2 \cdot i_2$$

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

Seguidor de voltagem



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



com

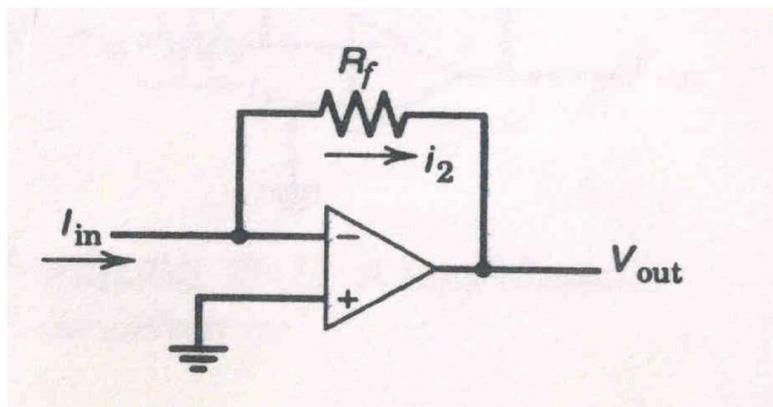
$$R_{in} \propto A$$

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

Alguns usos de Amplificadores Operacionais

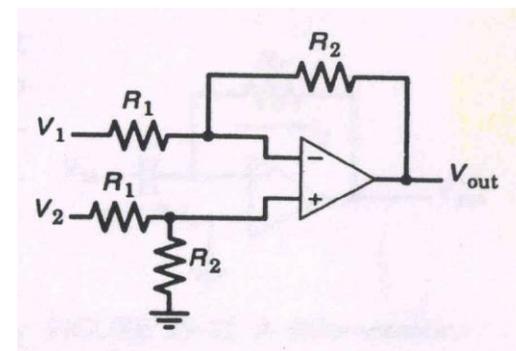
Idealmente: ($A = \infty$, $i_i = 0$)

Conversor corrente em voltagem



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

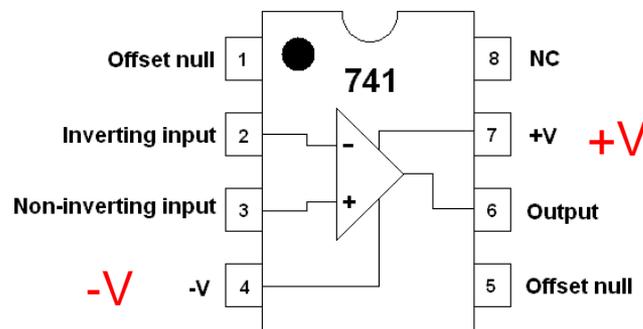
Amplificador de diferença
(Amplificador diferencial)



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

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

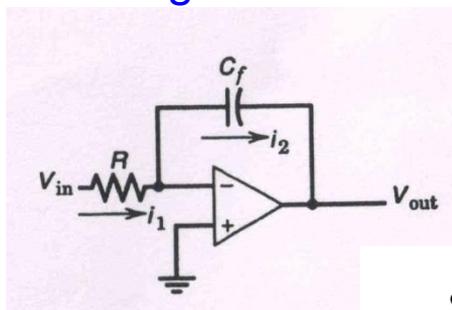
$$V_{out} = \frac{R_2}{R_1} (V_2 - V_1)$$



Alguns usos de Amplificadores Operacionais

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

integrador



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

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

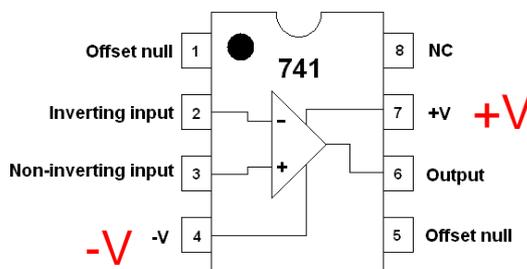
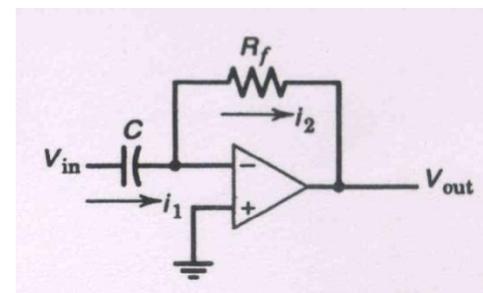
$$V_{out} = -\frac{1}{RC_f} \int_0^t V_{in} dt$$

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:

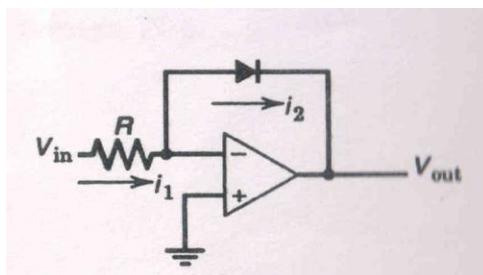
$$V_{out} \propto \omega RC_f V_{in}$$

Filtro passa-altas

Alguns usos de Amplificadores Operacionais

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

Amplificador não linear

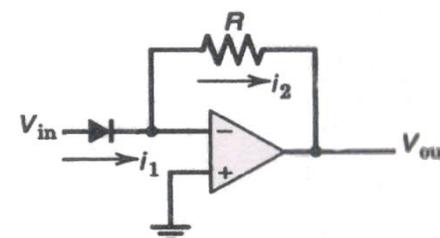
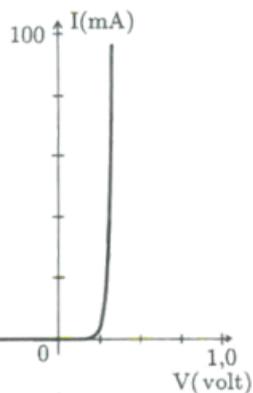


Para um diodo: $i_2 = B \exp\left(\frac{V_{out}}{\alpha}\right)$

$$i_1 = i_2$$

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

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



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

$$i_1 = i_2$$

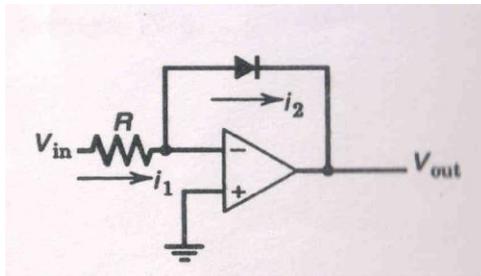
$$i_2 = \frac{V_{out}}{R}$$

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

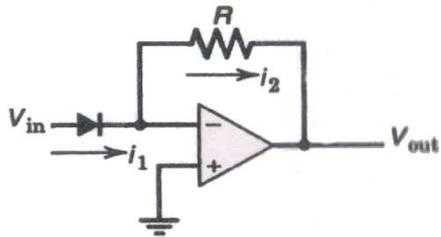
Alguns usos de Amplificadores Operacionais

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

Amplificador não linear

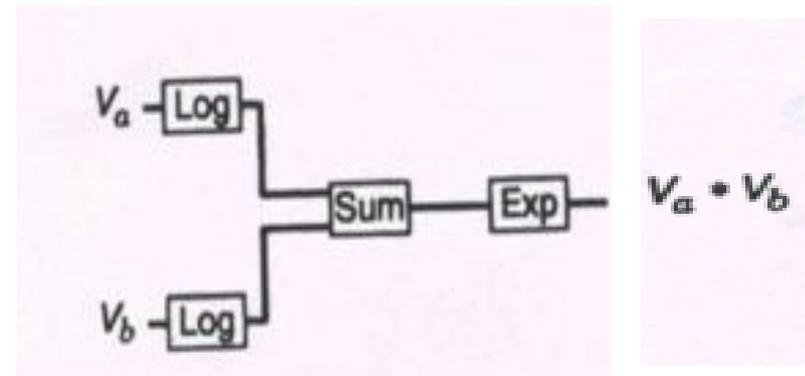


$$V_{out} = \alpha \ln\left(\frac{V_{in}}{RB}\right)$$



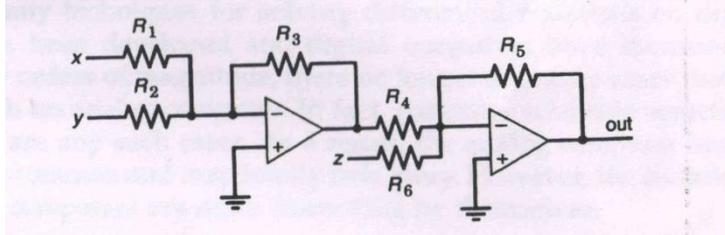
$$V_{out} = RB \exp\left(\frac{V_i}{\alpha}\right)$$

?



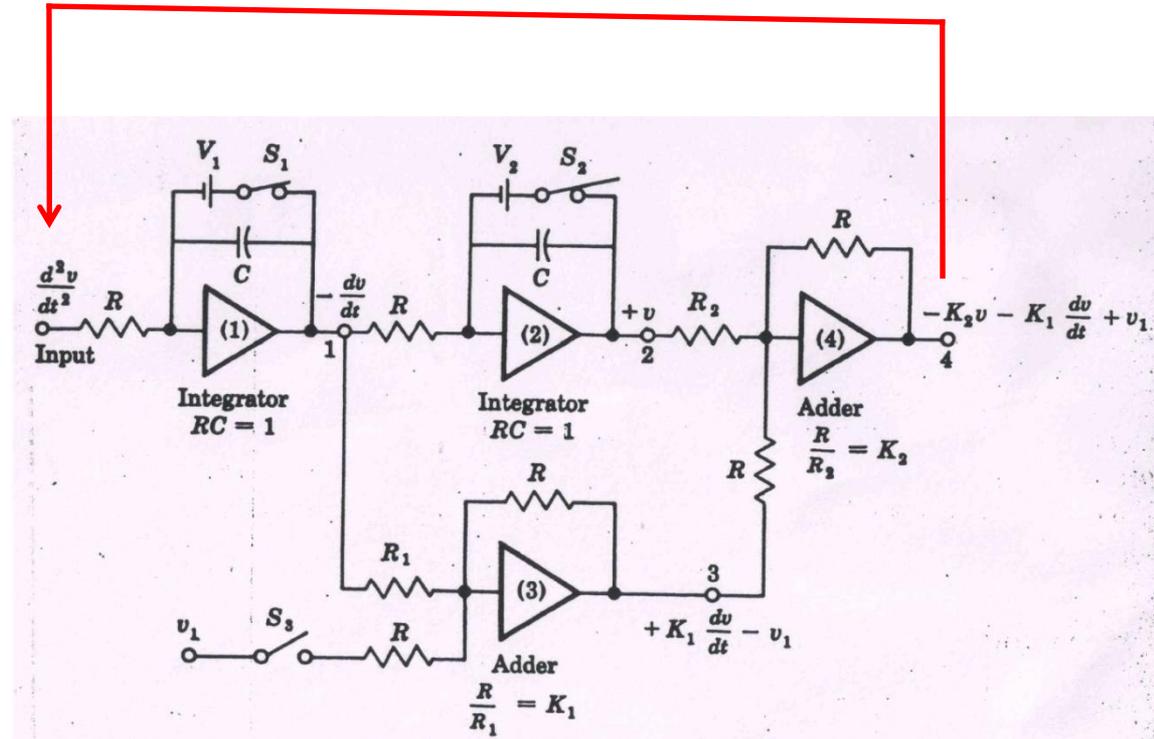
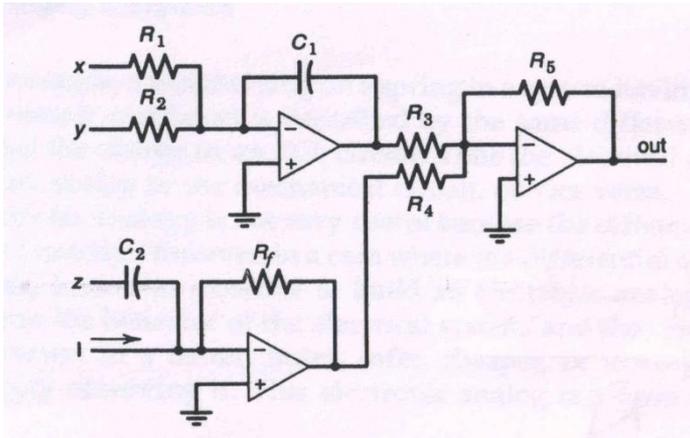
Multiplicador !!!

Alguns exemplos



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

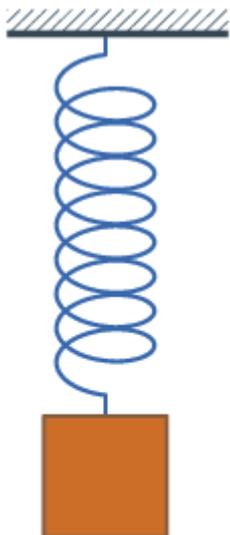
$$V_{out} = -\frac{R_5}{R_4} \cdot V_1 - \frac{R_5}{R_6} \cdot z$$



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

Computador analógico !!!

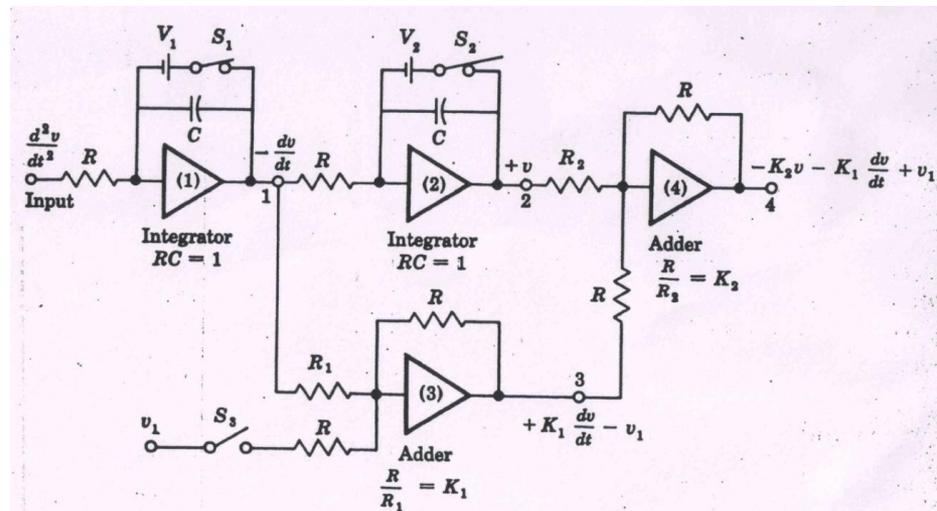
Um exemplo – Sistema massa-mola



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

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

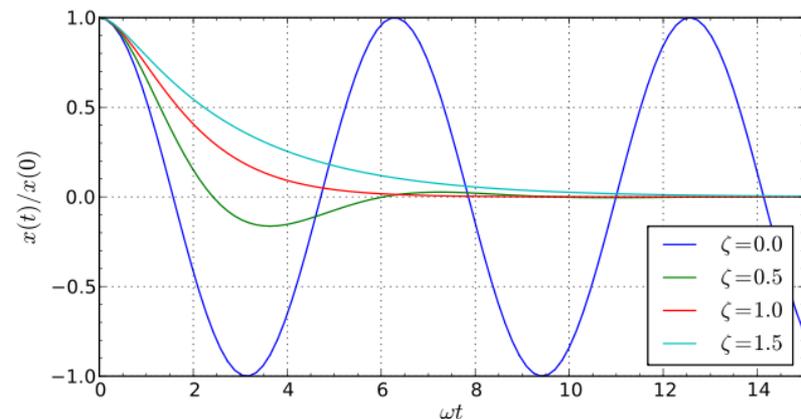
$$\frac{k}{m} = \omega_0^2$$



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

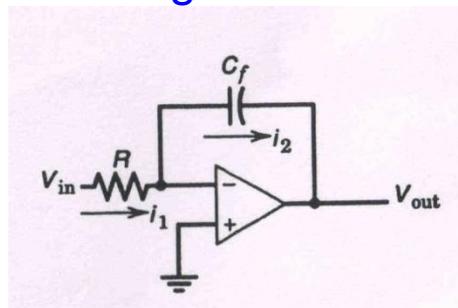
p/ $k = 5 \text{ N/m}$
 e $m = 200 \text{ g}$

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

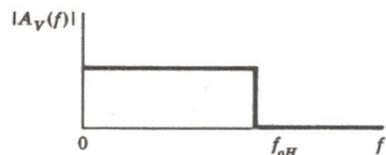
integrador



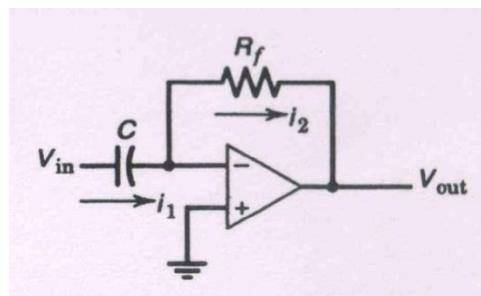
Para sinal senoidal:

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

Filtro passa-baixas



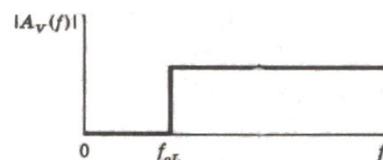
diferenciador



Para sinal senoidal:

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

Filtro passa-altas



Combinação de filtros

Filtro passa-banda

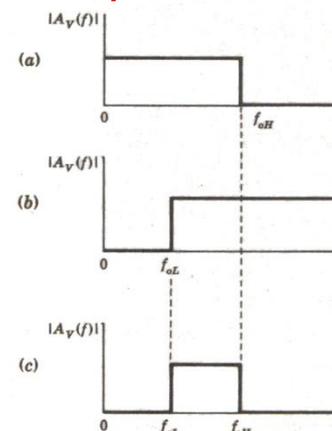


Fig. 16-15 Ideal filter characteristics. (a) Low-pass, (b) high-pass, and (c) bandpass.

Filtro rejeita-banda

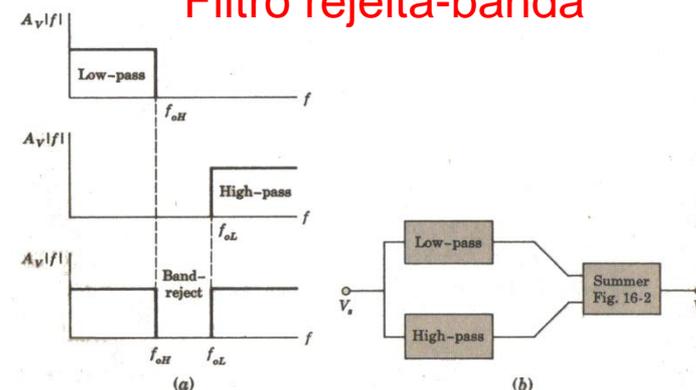
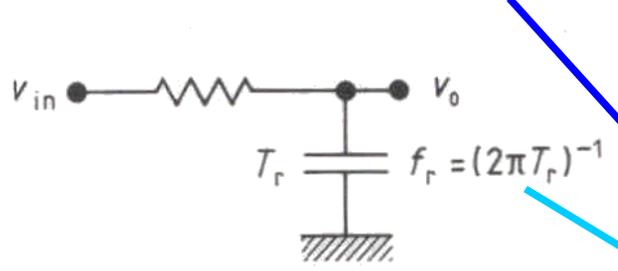


Fig. 16-20 (a) Ideal band-reject-filter frequency response. (b) Parallel combination of low-pass and high-pass filters results in a band-reject filter.

Resposta em frequência (vista espectral)

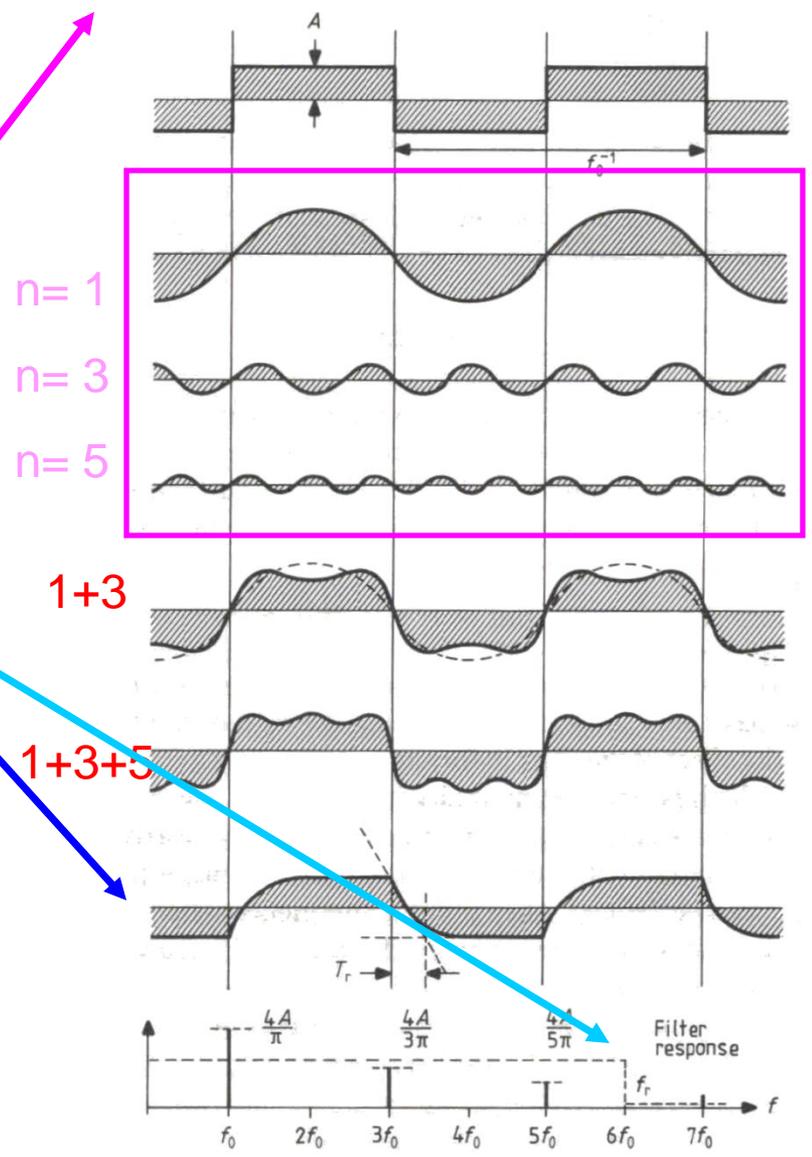
$$v = \frac{4A}{\pi} \sum_{n=\text{impar}} \frac{\sin(2\pi n f_0 t)}{n}$$

Filtro passa-baixas



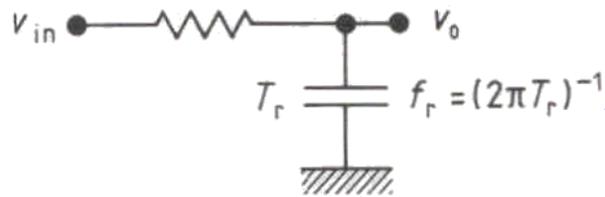
Para um sinal non-senoidal
de frequência f_0
(série de Fourier)

$$v = A_0 + \sum_{n=1}^{\infty} [A_n \cos(2\pi n f_0 t) + B_n \sin(2\pi n f_0 t)]$$



Resposta em frequência (vista espectral)

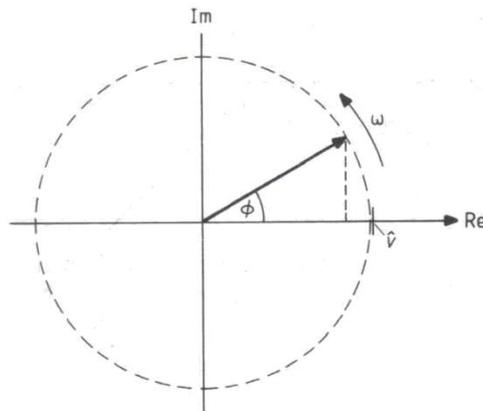
Filtro passa-baixas



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

$$= v_0 \cos(2\pi ft + \phi) + jv_0 \sin(2\pi ft + \phi)$$

Fasor



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

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

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

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

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

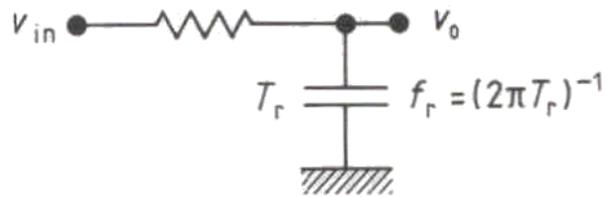
$$V_{out} = Z_c I$$

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

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

Resposta em frequência (vista espectral)

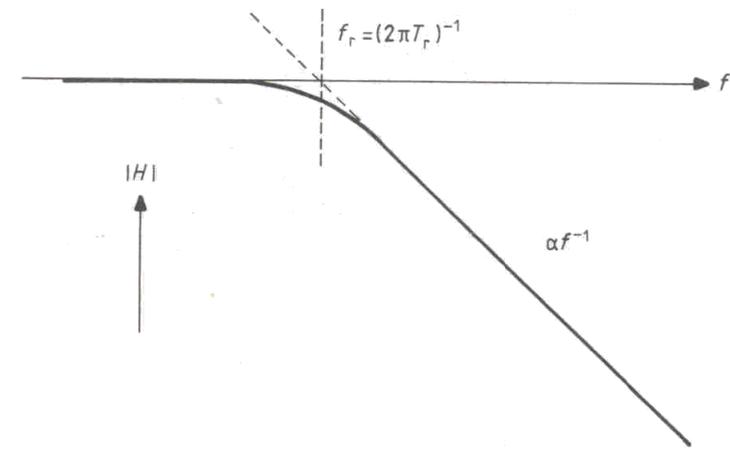
Filtro passa-baixas



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

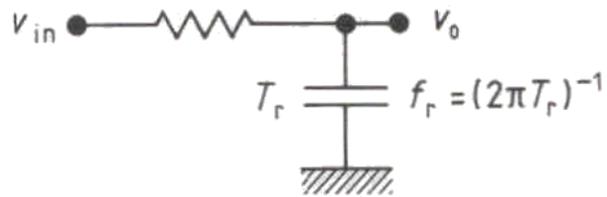
$$V_{out} = T_r^{-1} \int_{t-T_r}^t v_{in} \exp(j\omega t') dt'$$

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



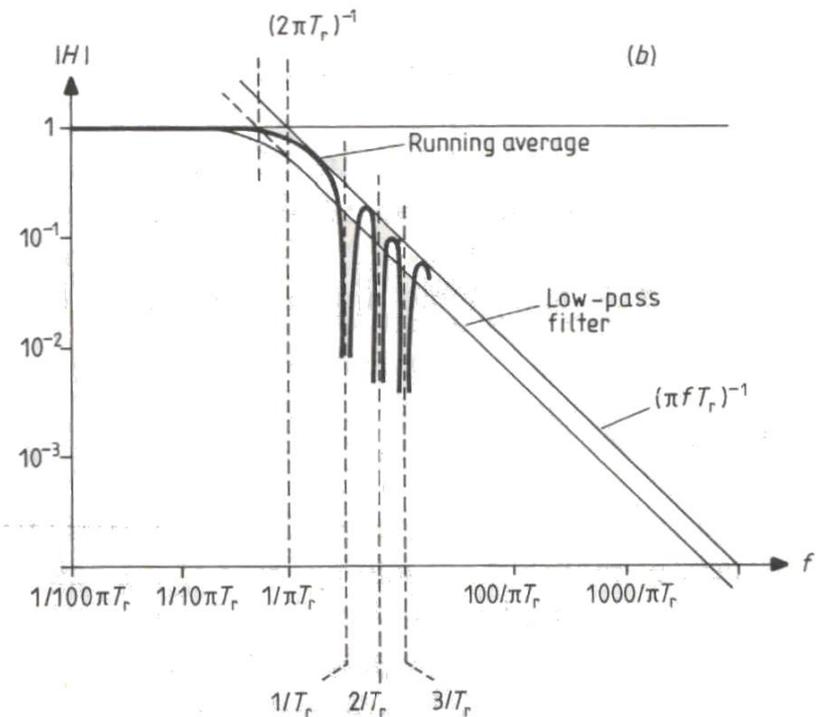
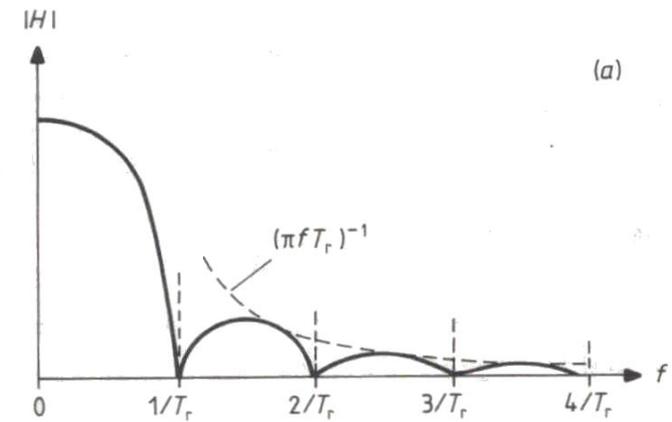
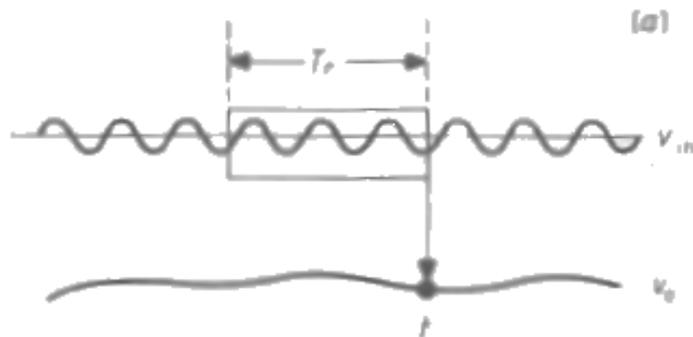
Resposta em frequência (vista espectral)

Filtro passa-baixas

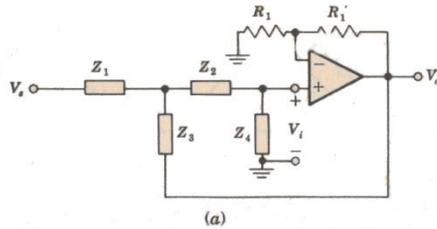


$$V_{out} = T_r^{-1} \int_{t-T_r}^t v_{in} \exp(j\omega t') dt'$$

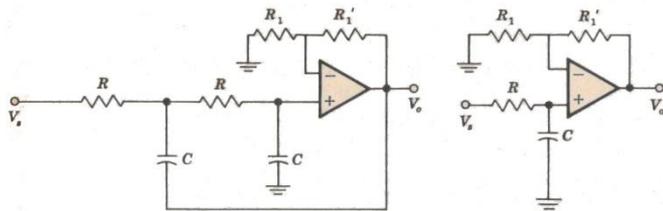
$$V_{out} = V_{in}(t) \exp(-j\omega T_r / 2) \frac{\sin(\omega T_r / 2)}{\omega T_r / 2}$$



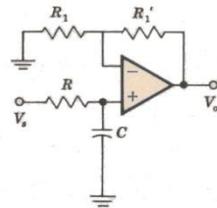
Eficiência dos Filtros



(a)

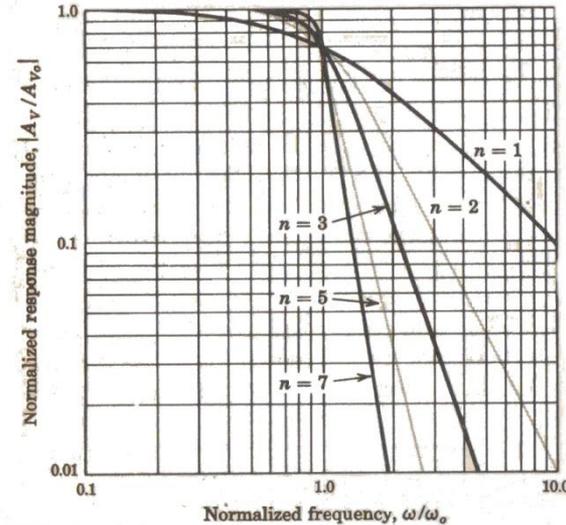


(b)



(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.

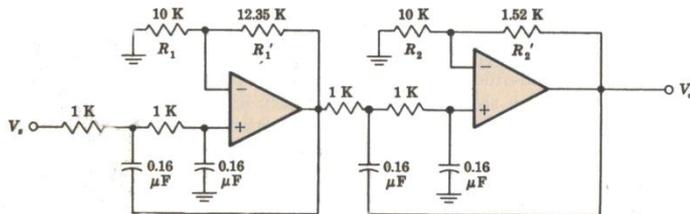


Fig. 16-19 Fourth-order Butterworth low-pass filter with $f_o = 1$ kHz.

Filtro Ressonante (passa-banda estreito)

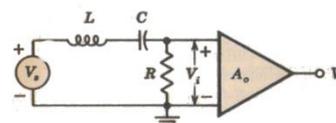
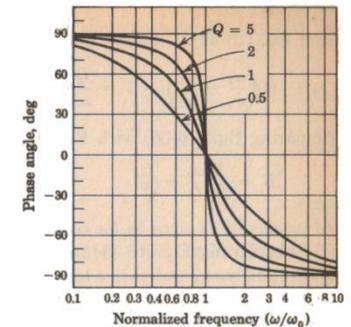
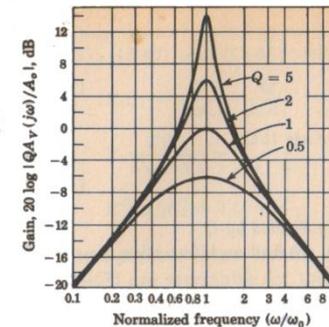
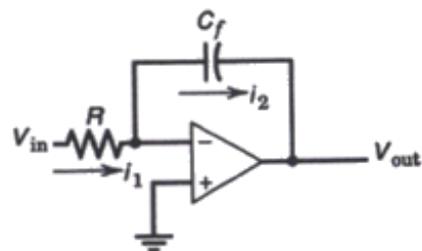


Fig. 16-21 A resonant circuit.



Filtros

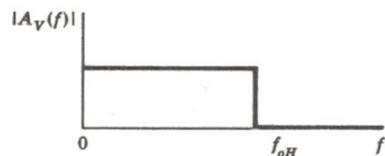
integrador



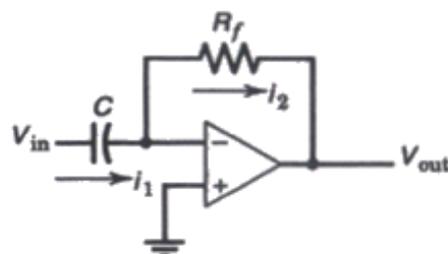
Para sinal senoidal:

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

Filtro passa-baixas



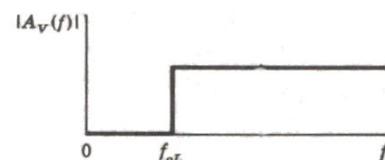
diferenciador



Para sinal senoidal:

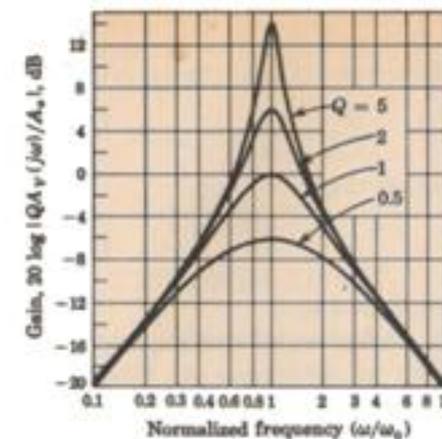
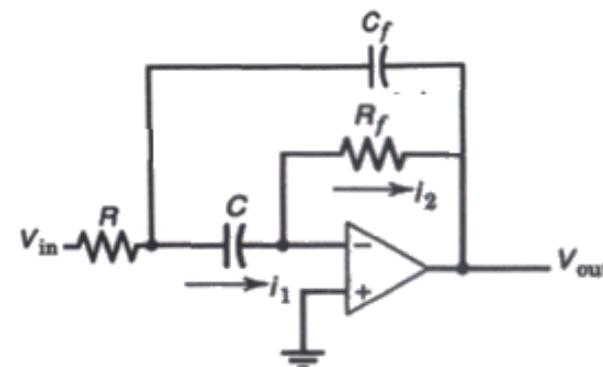
$$V_{out} \propto \omega RC_f V_{in}$$

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