Introdução à Mecânica Quântica

Aplicações

Bandas em cristais
Ocupação das bandas
Aplicações - Sistemas semicondutores

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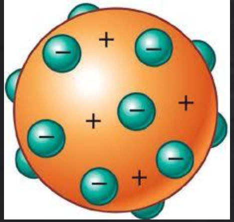
Graduação/mestrado – USP-São Carlos
Doutorado – Univ. California San Diego

Mecânica Quântica ←→ Modelos atômicos

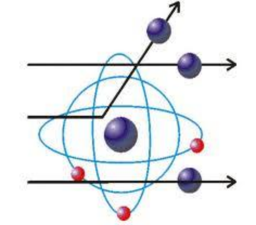
1808

Dalton



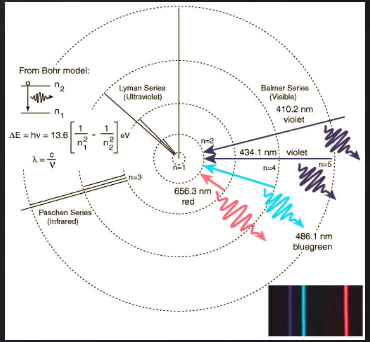
1887

Thomson



1911

Rutherford

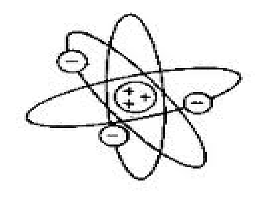


1920

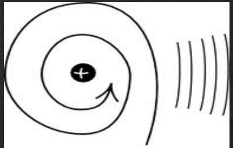
Bohr

Surgimento da
Mecânica Quântica

Precisava reconciliar:



+



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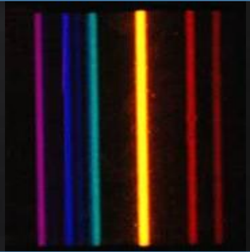


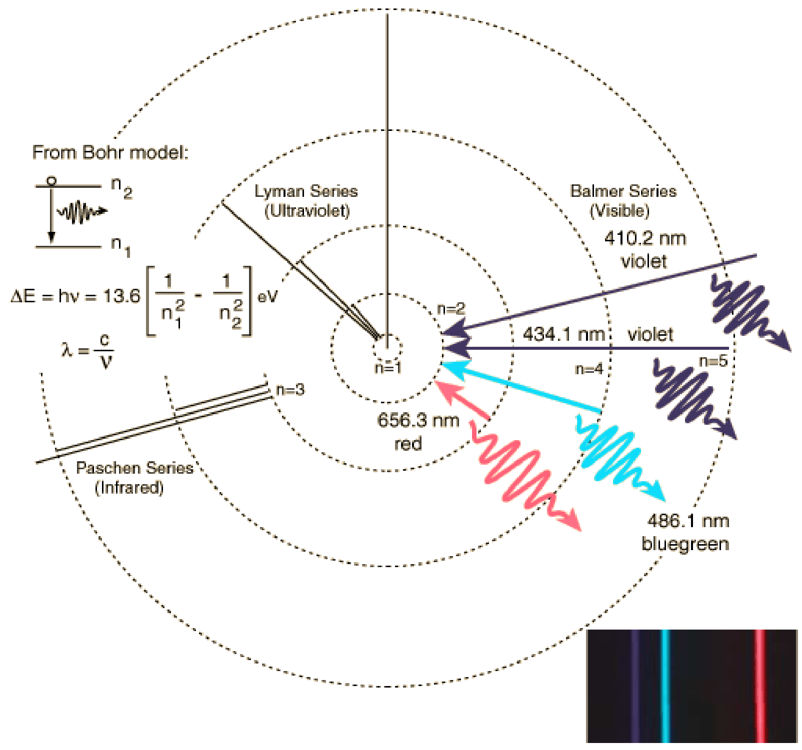
Niels Bohr

(1885 -1962, Nobel.1922)

Novo Modelo Atômico (1913)

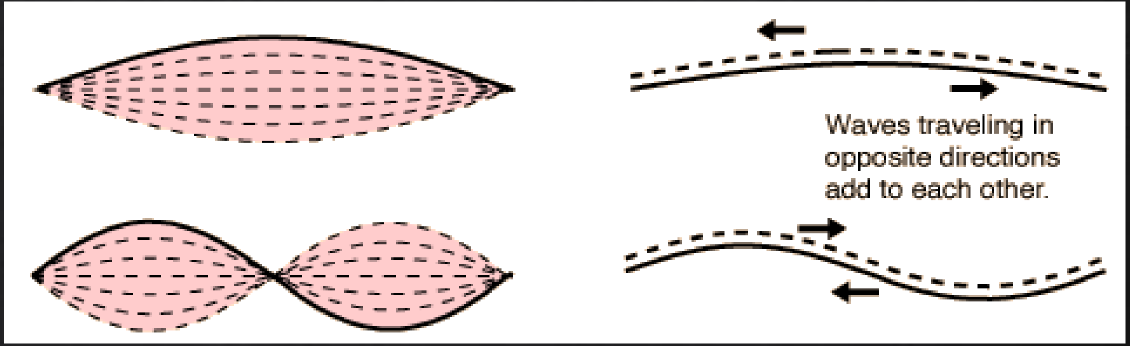
Estados ESTACIONÁRIOS

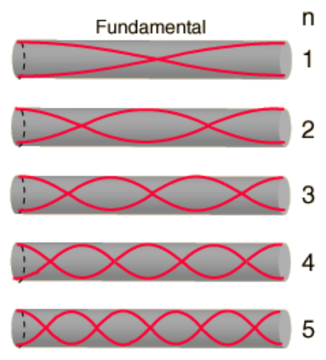
Energias DISCRETAS

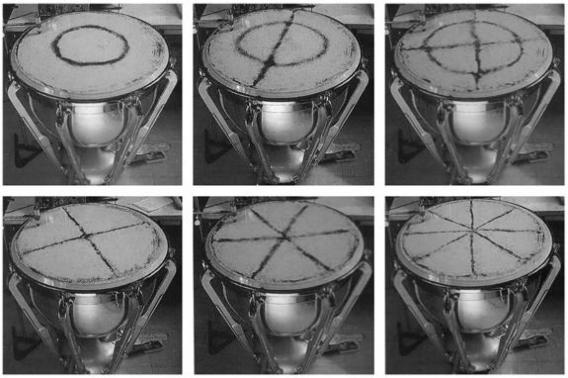


Ondas estacionárias

-- Frequências discretas (harmônicos)

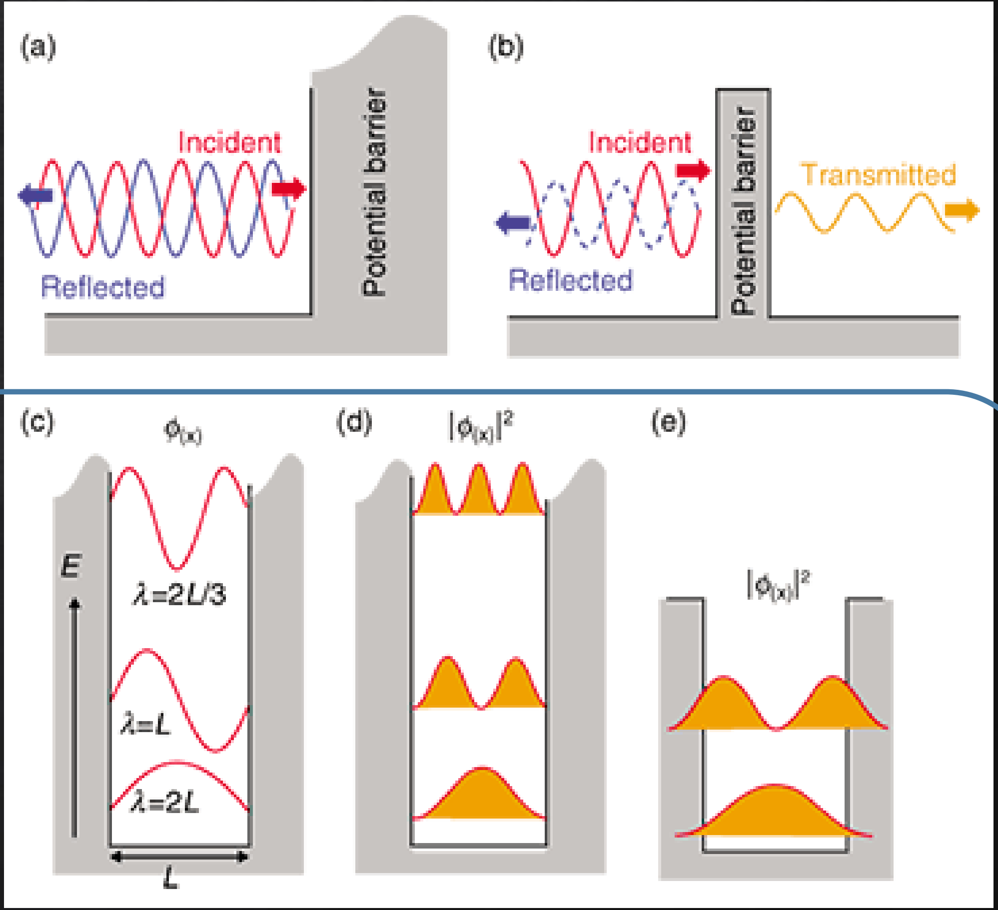

Waves traveling in opposite directions add to each other.





Natureza Ondulatória do elétron

Reflete / refrata (tunelamento)



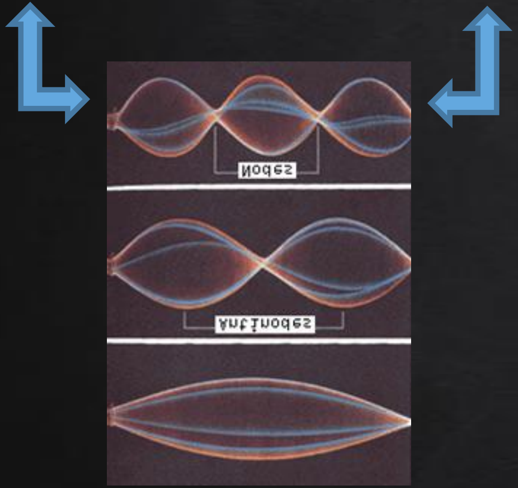
Confinamento

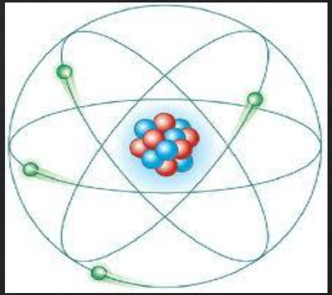
→ Níveis discretos

→ Ondas estacionárias

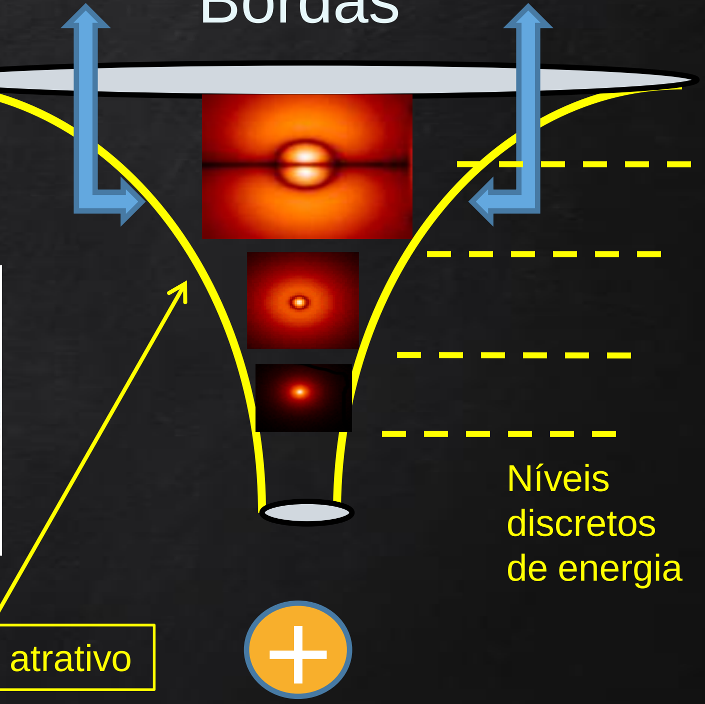
Elétron num átomo (Orbitais)

Bordas FIXAS





“Bordas”



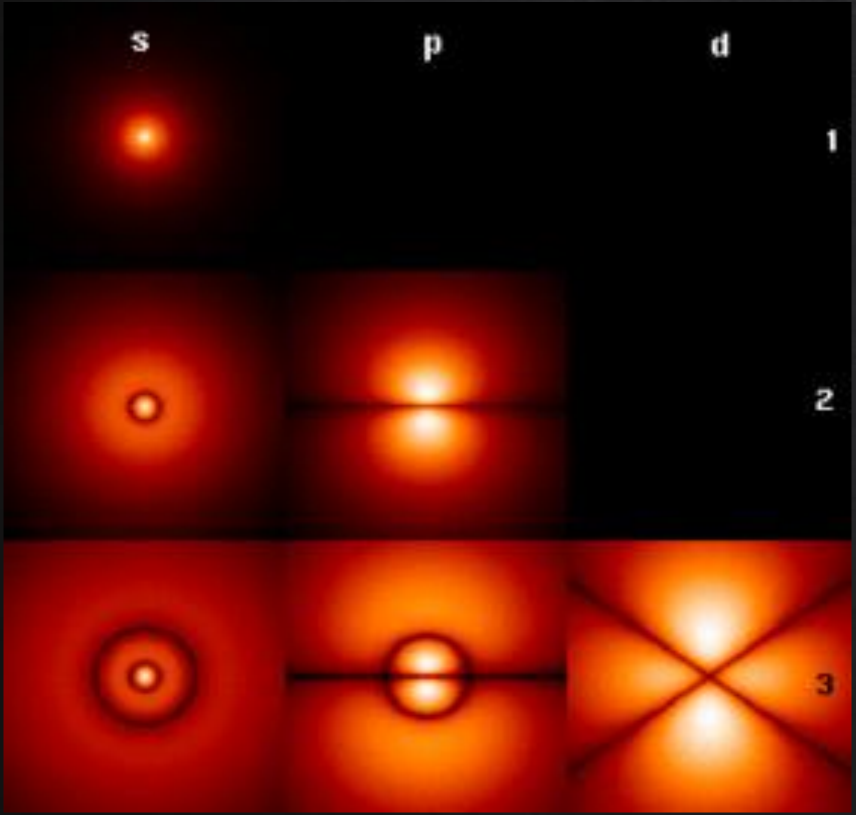
Potencial atrativo

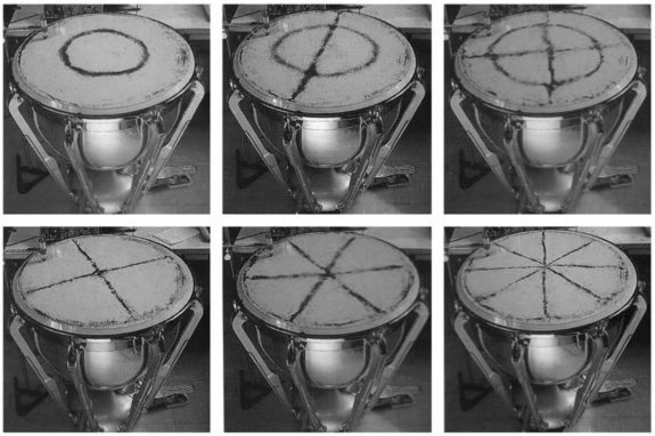
Níveis discretos de energia

Núcleo

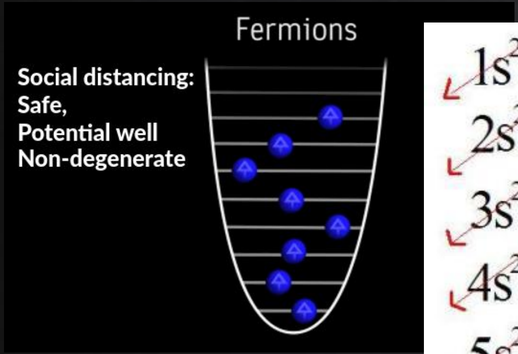
Elétron num átomo

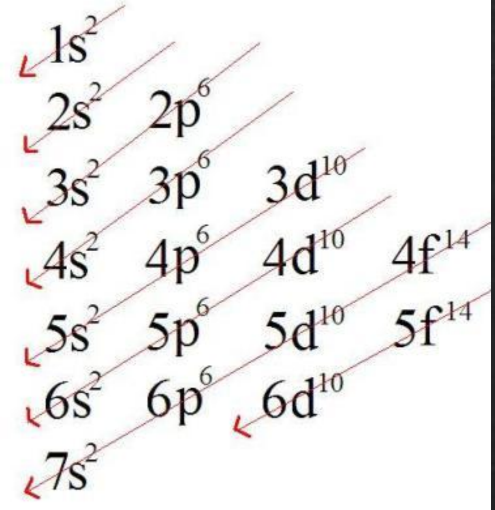
Orbitais <-> ondas estacionárias em 3D

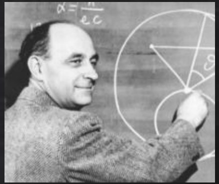


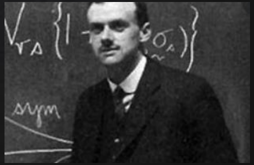


Preenchimento dos níveis:FÉRMIONs - Estatísticas de Fermi-Dirac

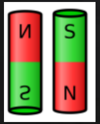


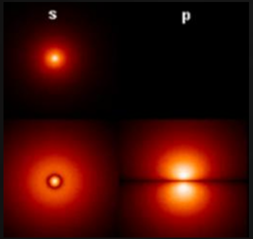

$1s^2$
$2s^2$ $2p^6$
$3s^2$ $3p^6$ $3d^{10}$
$4s^2$ $4p^6$ $4d^{10}$ $4f^{14}$
$5s^2$ $5p^6$ $5d^{10}$ $5f^{14}$
$6s^2$ $6p^6$ $6d^{10}$
$7s^2$

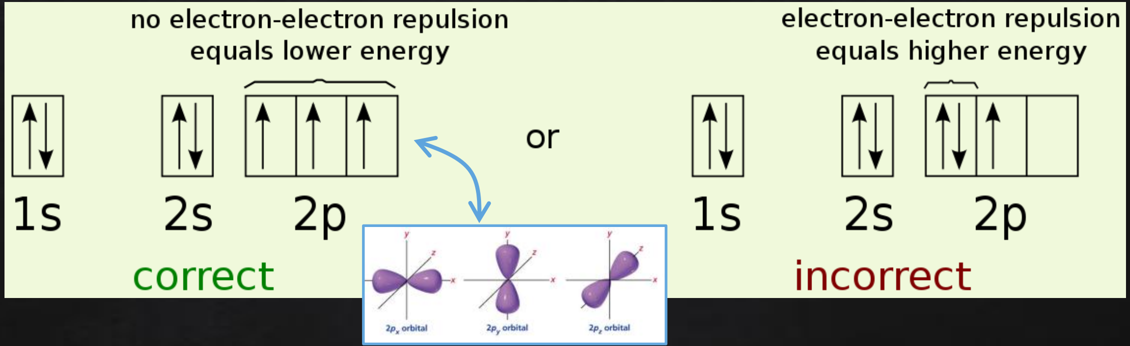




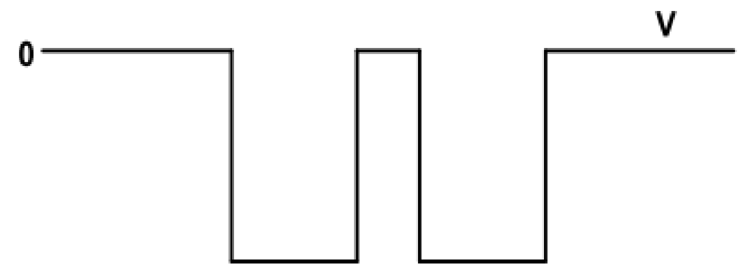
Lei de Hund do preenchimento eletrônico dos níveis atômicos

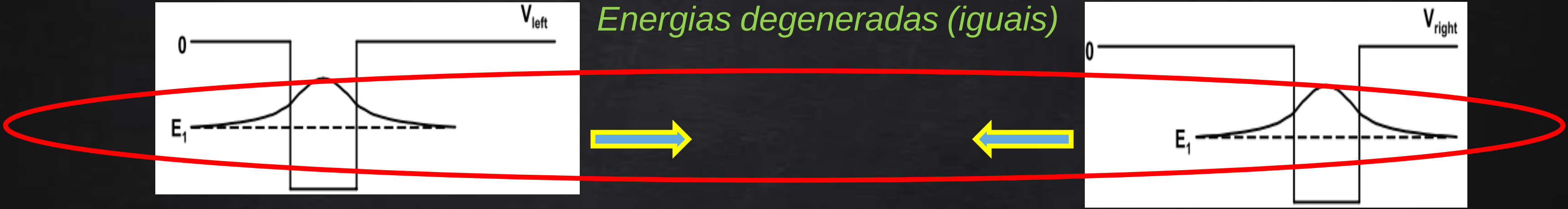






Poço-duplo

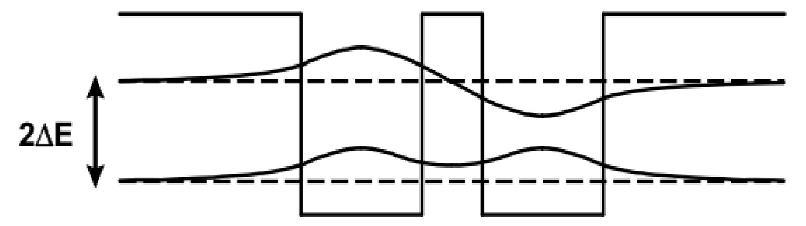




Energias degeneradas (iguais)

Splitting energético

Dubleto



Solução ASSIMÉTRICA (anti-ligante)

ungerade

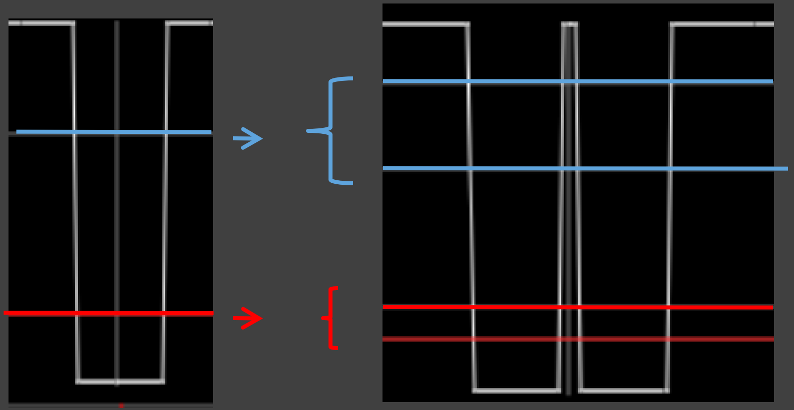
gerade

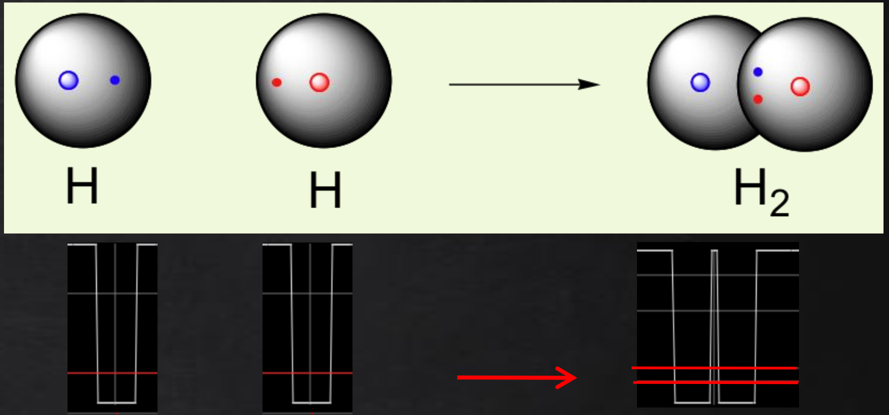
Solução SIMÉTRICA (ligante)

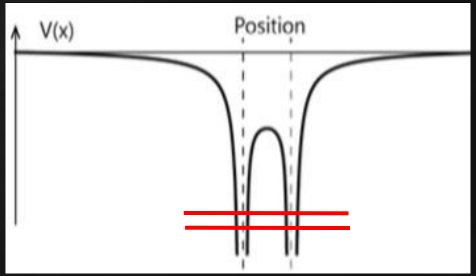
Molécula de hidrogênio H_2

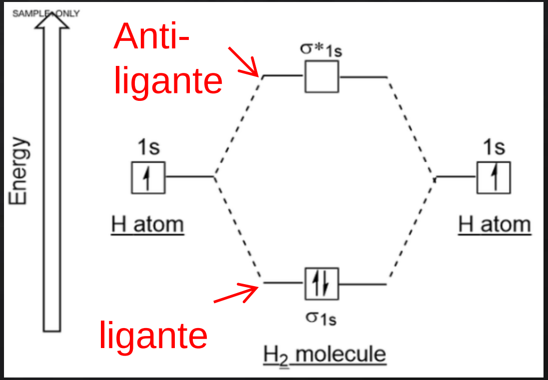
1 poço
singletos

2 poços
dubletos







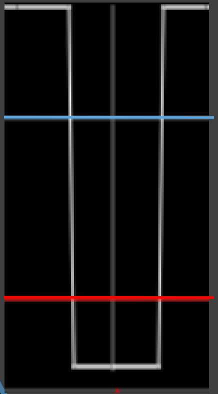


Anti-
ligante

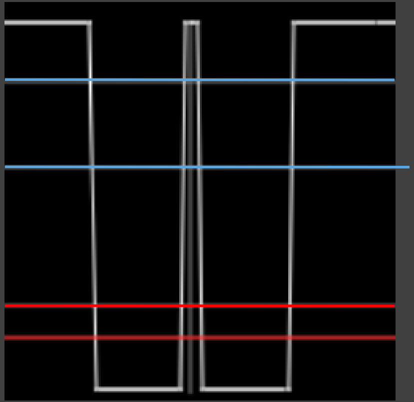
ligante

Múltiplos poços (super-redes)

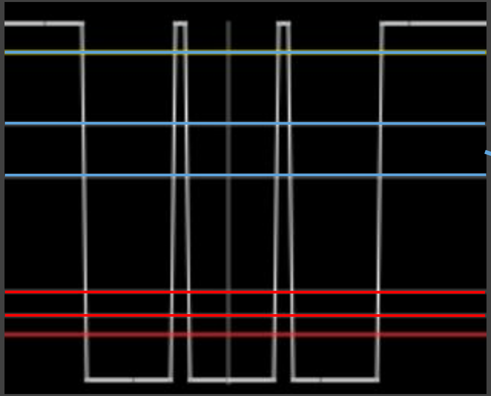
1 poço
singletos



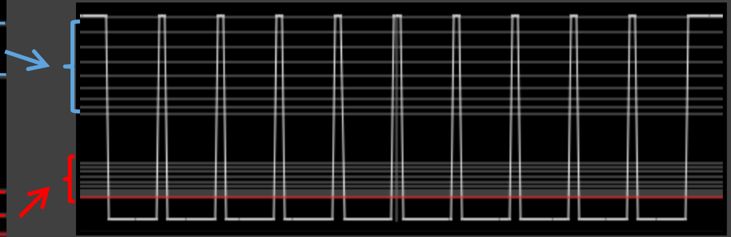
2 poços
dubletos



3 poços
tripletos



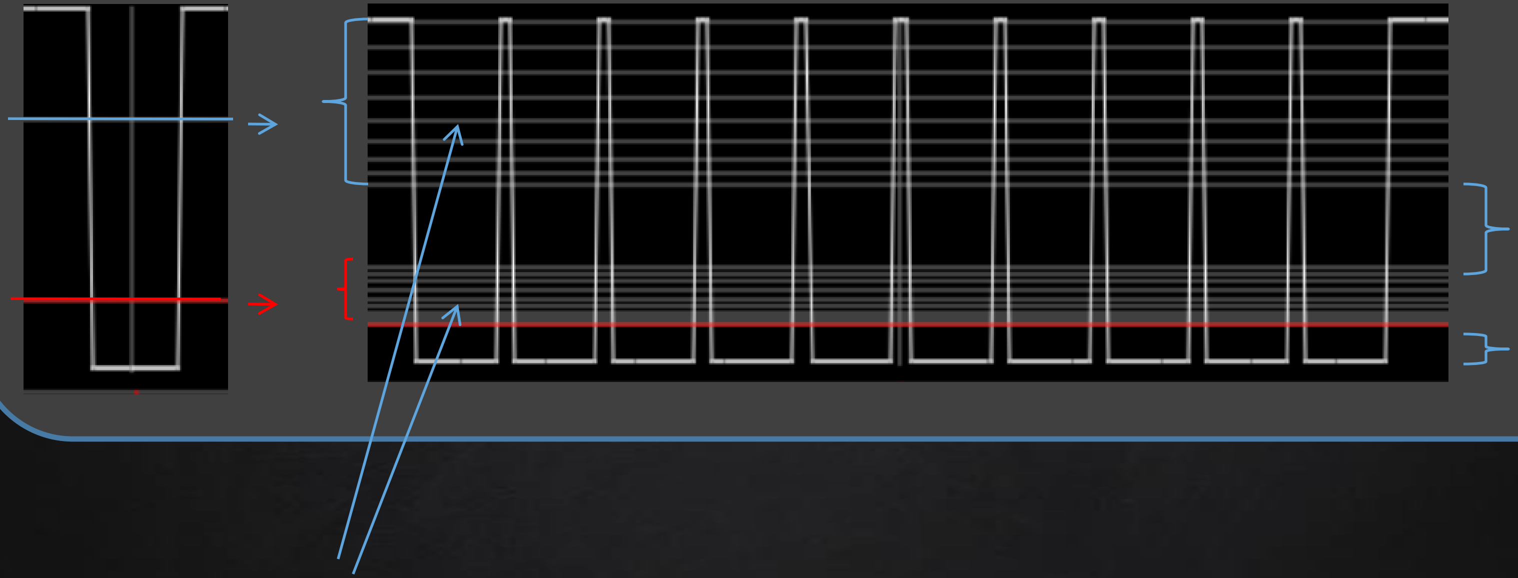
Múltiplos poços
Multipletos



Múltiplos poços (super-redes)

1 poço
singletos

Múltiplos poços
Multipletos



Gaps de energias
(energias não permitidas)

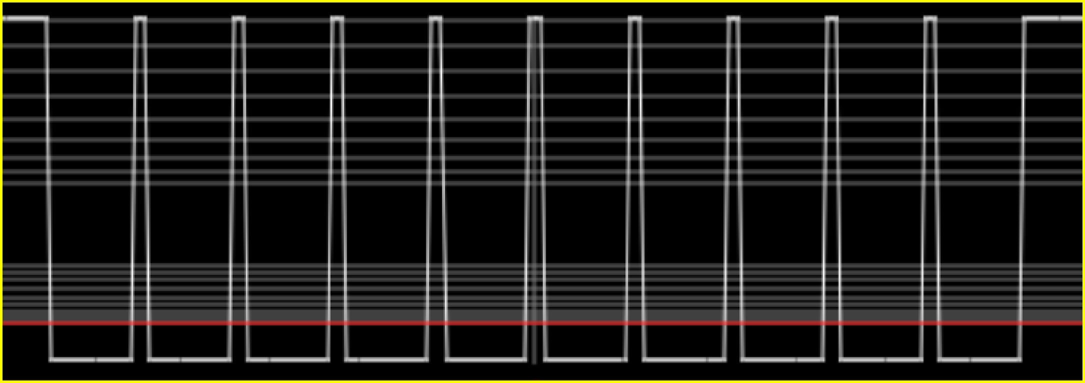
Bandas de energias

Formam um contínuo de energias permitidas

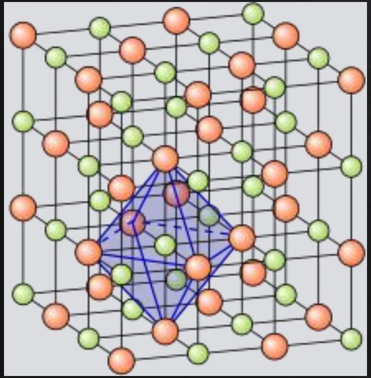
- Estados deslocalizados – “em todos os poços”

https://www.falstad.com/qm1d/

Múltiplos poços (super-redes)

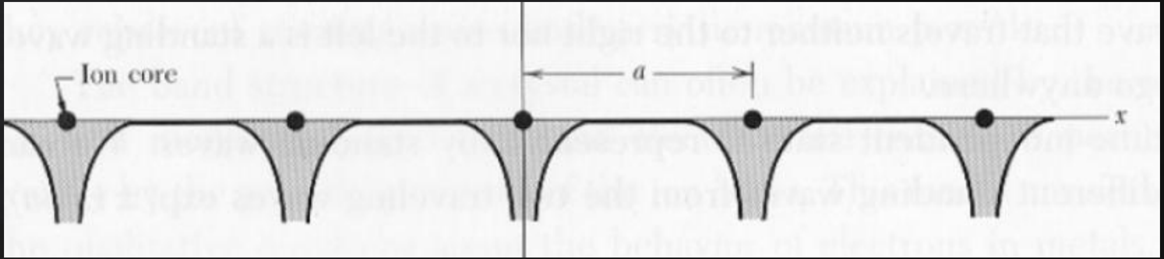


Rede cristalina (elétron num sólido)



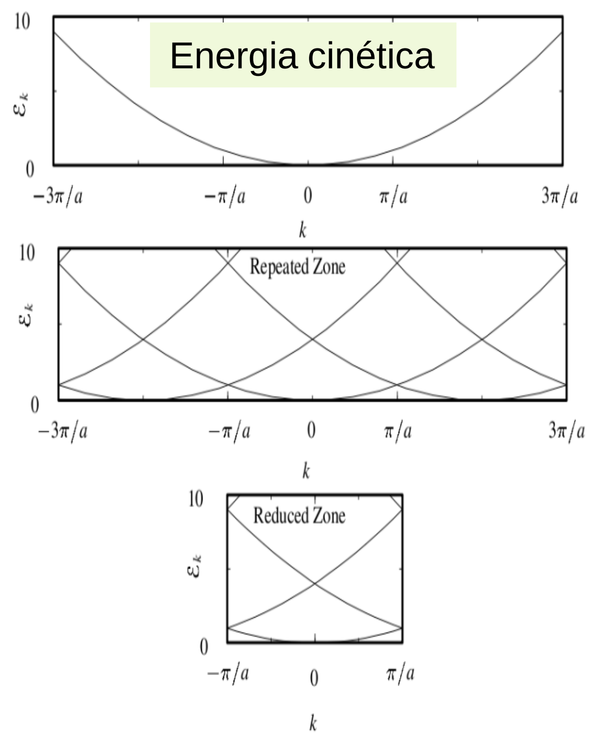
Exemplo unidimensional (1D)

$$V(x+a) = V(x)$$

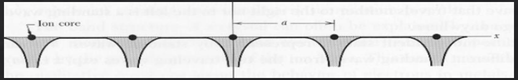


Rede cristalina

1D

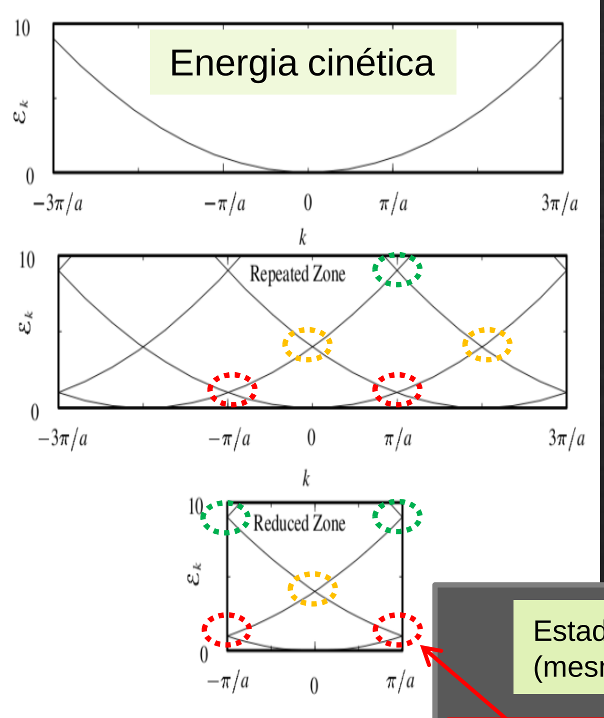


Efeito do potencial periódico

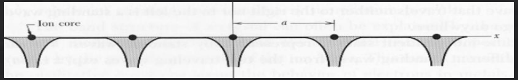


Rede cristalina

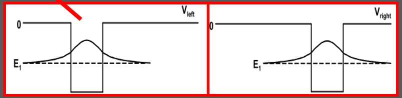
1D

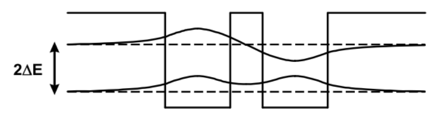

Energia cinética

Efeito do potencial periódico



Estados degenerados (mesma energia)

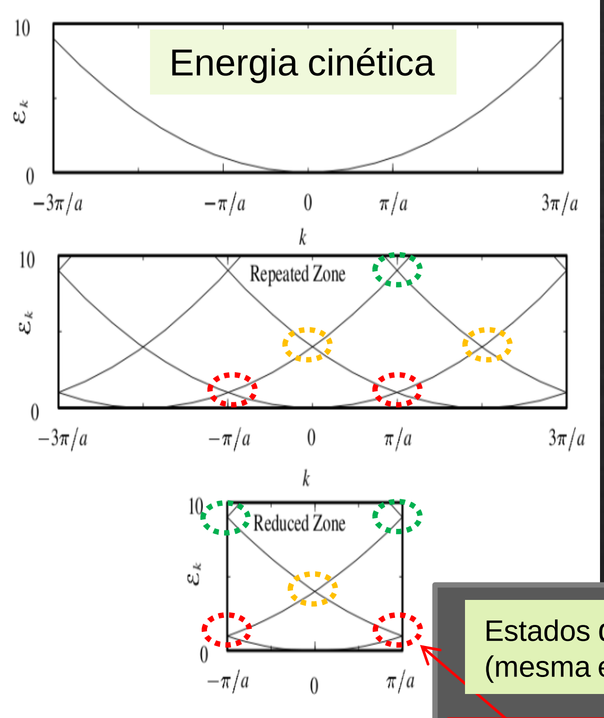




Abertura de dubletos

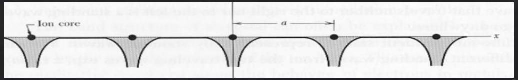
Rede cristalina

1D

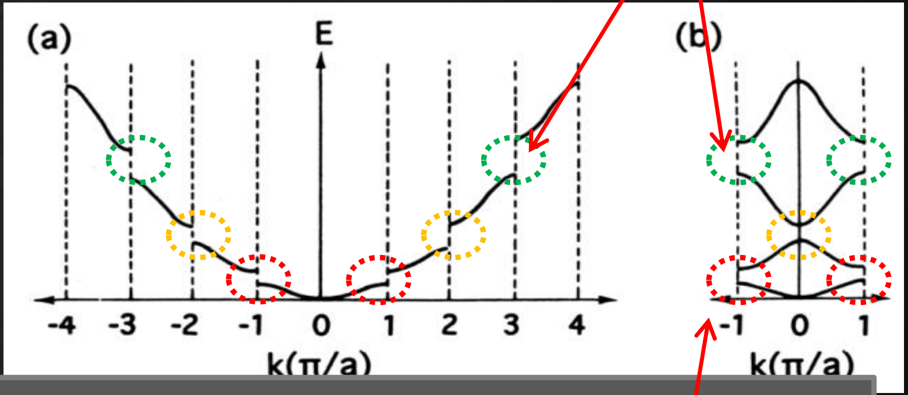


Energia cinética

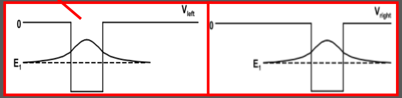
Efeito do potencial periódico

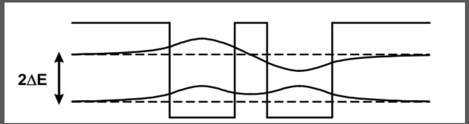


Abertura de gaps de energia
(energias não permitidas)



Estados degenerados
(mesma energia)



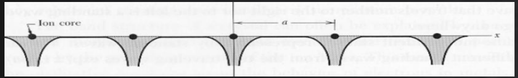


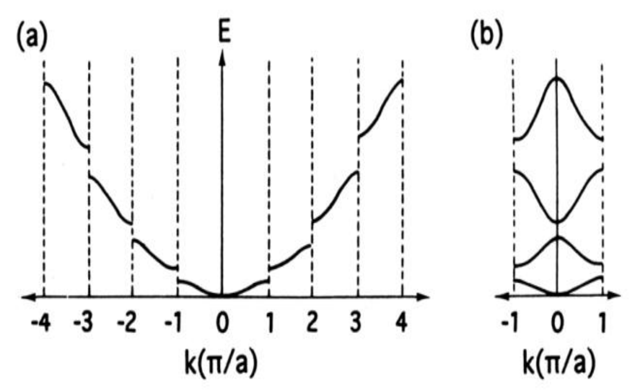
Abertura de dubletos

Rede cristalina

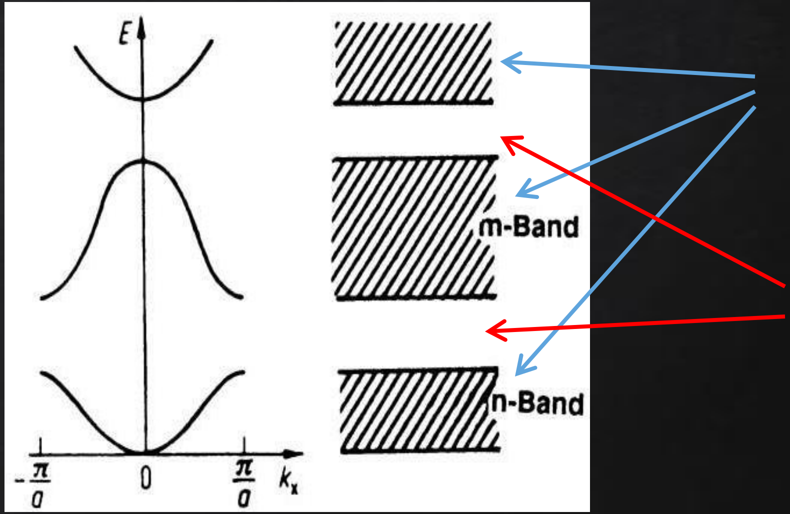
1D

Efeito do potencial periódico





Estrutura de
bandas eletrônicas do cristal



Bandas

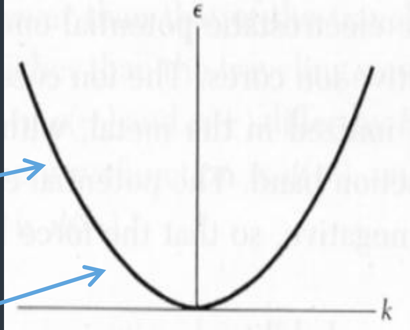
Gaps
(energias não permitidas)

Rede cristalina

Partícula livre

Dispersão parabólica

$E(k) \sim k^2$

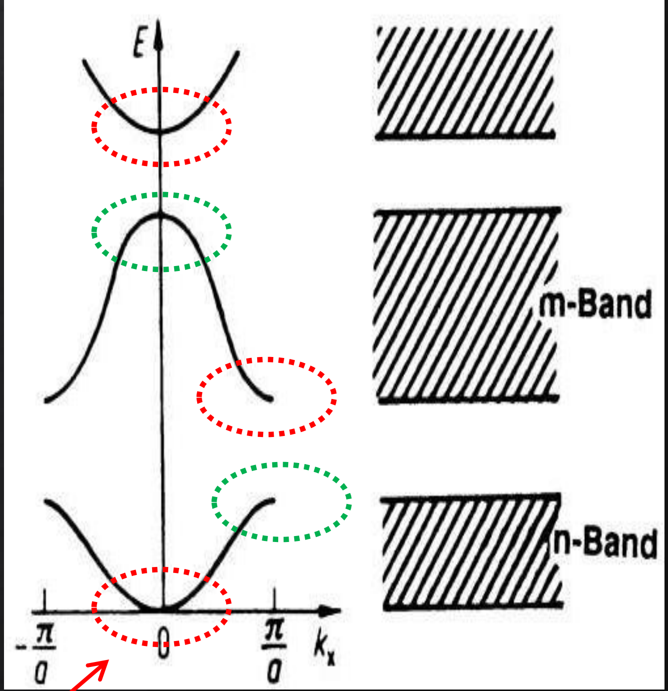


Concavidade ~1 / massa

$$\frac{\partial^2 E(k)}{\partial k^2} = \frac{\hbar^2}{m}$$

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

Estrutura de bandas eletrônicas do cristal



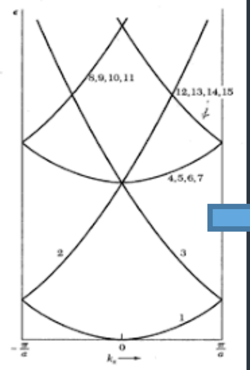
Regiões onde a dispersão é aproxima/e parabólica $E(k) \sim k^2$

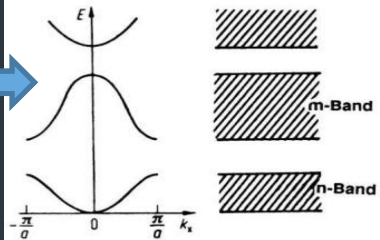
Pedemos definir uma “massa efetiva” (+ / -)

$$\frac{\partial^2 E(k)}{\partial k^2} = \frac{\hbar^2}{m}$$

Rede cristalina

1D



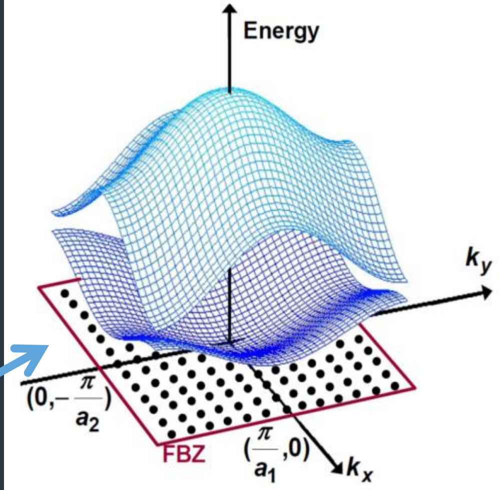


2D

Exemplo

Rede cúbica

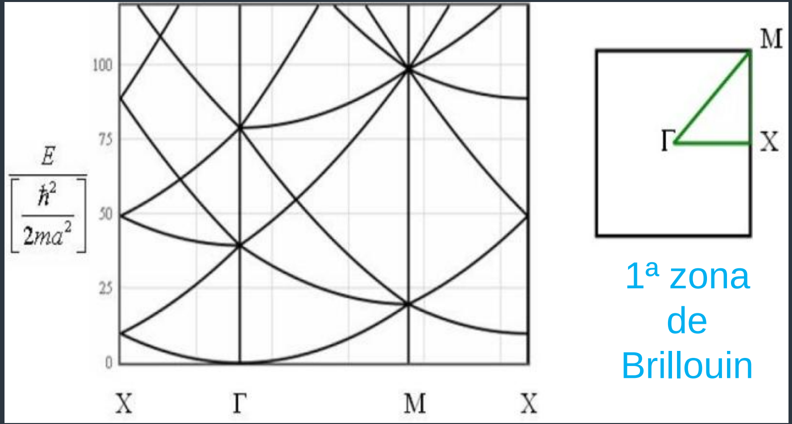
Espaço real



Rede cúbica

Espaço

Recíproco (k’s)



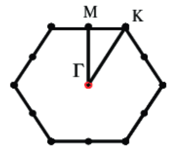
1ª zona de Brillouin

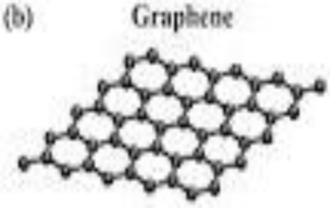
Rede cristalina

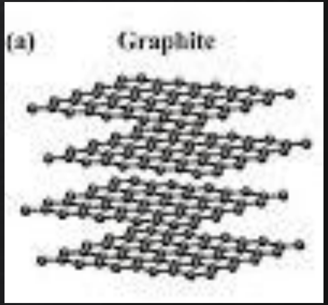
2D

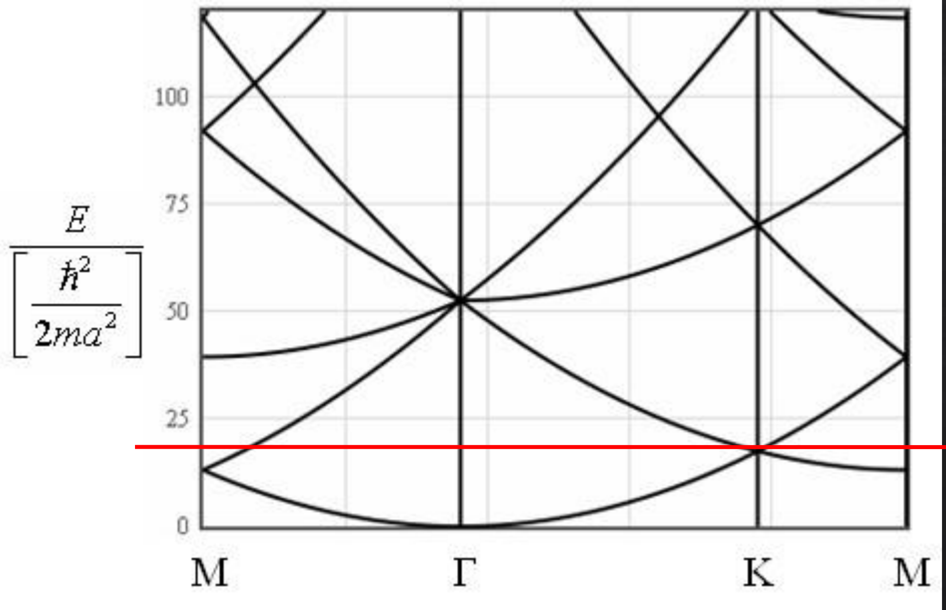
Exemplo

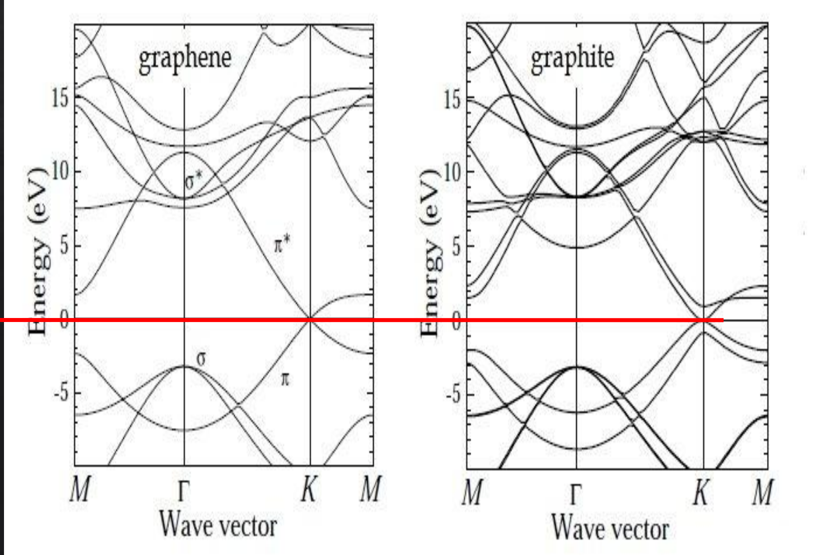
Rede HEXAGONAL







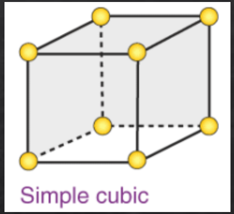


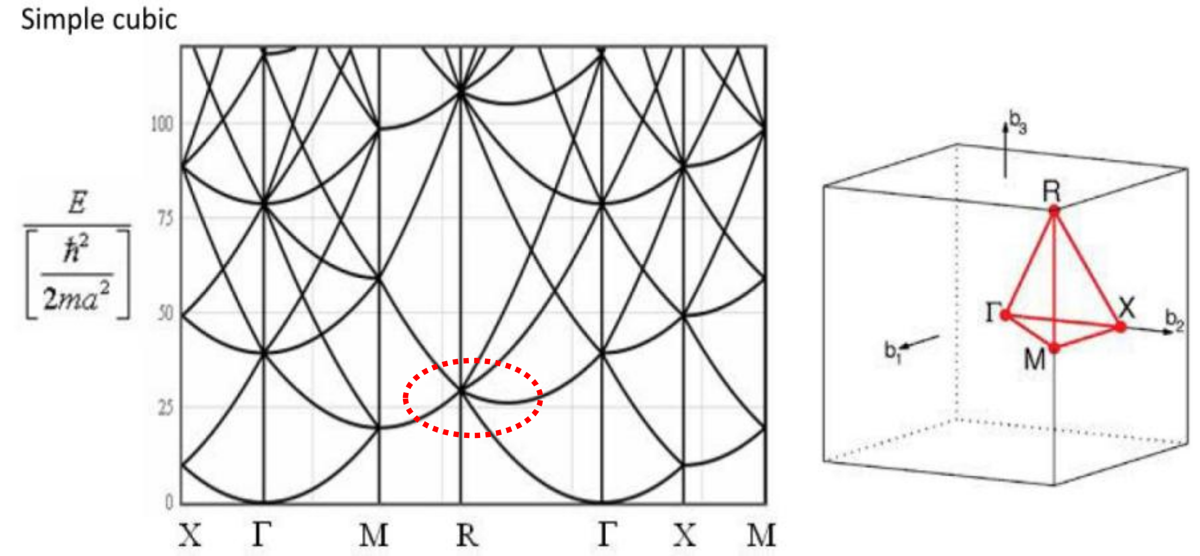


Rede cristalina

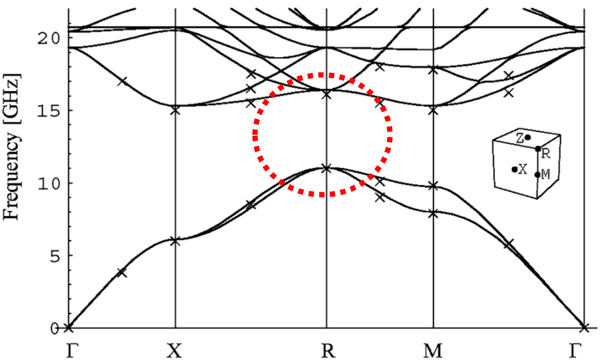
3D

Exemplo
Rede CÚBICA Simples





Bandas com os gaps

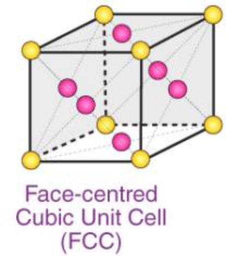


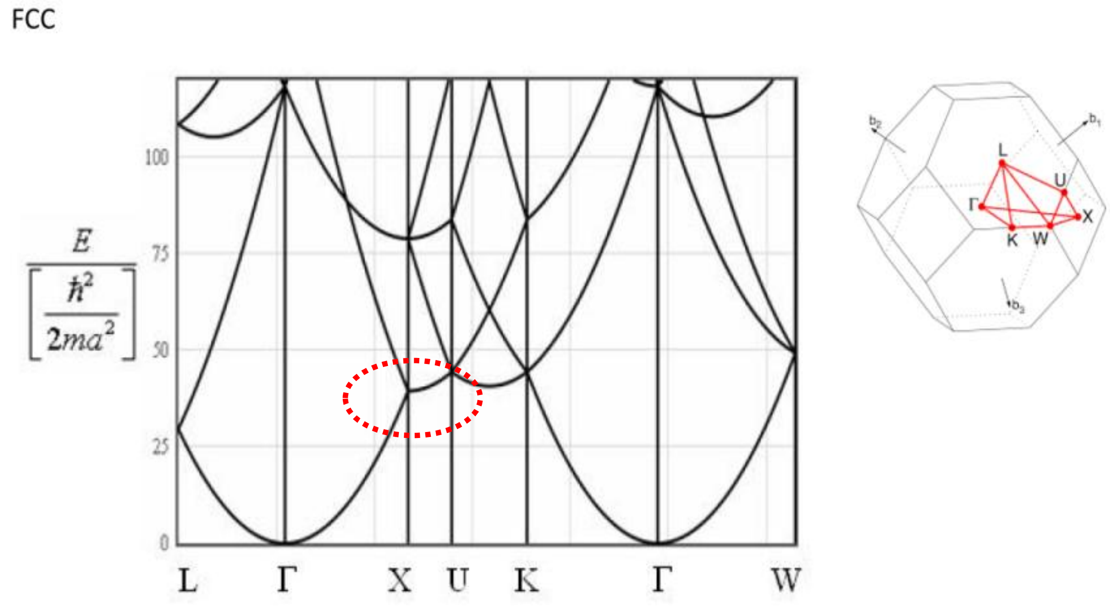
Rede cristalina

3D

Exemplo

Rede FCC

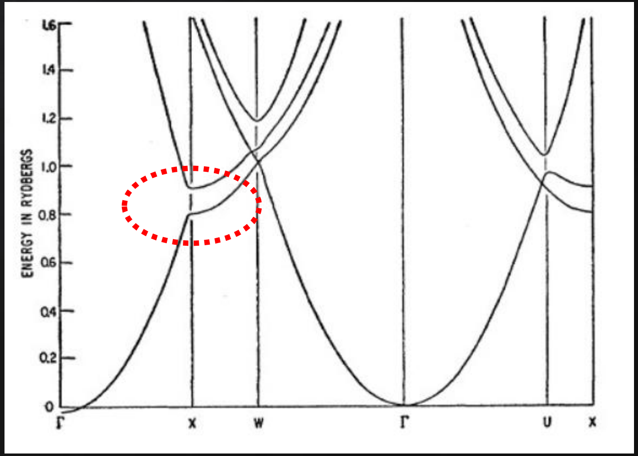




Alumínio metal

Rede fcc

Bandas com os gaps

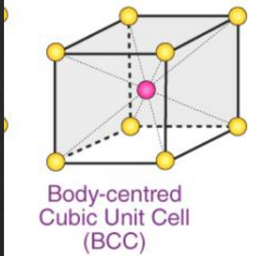


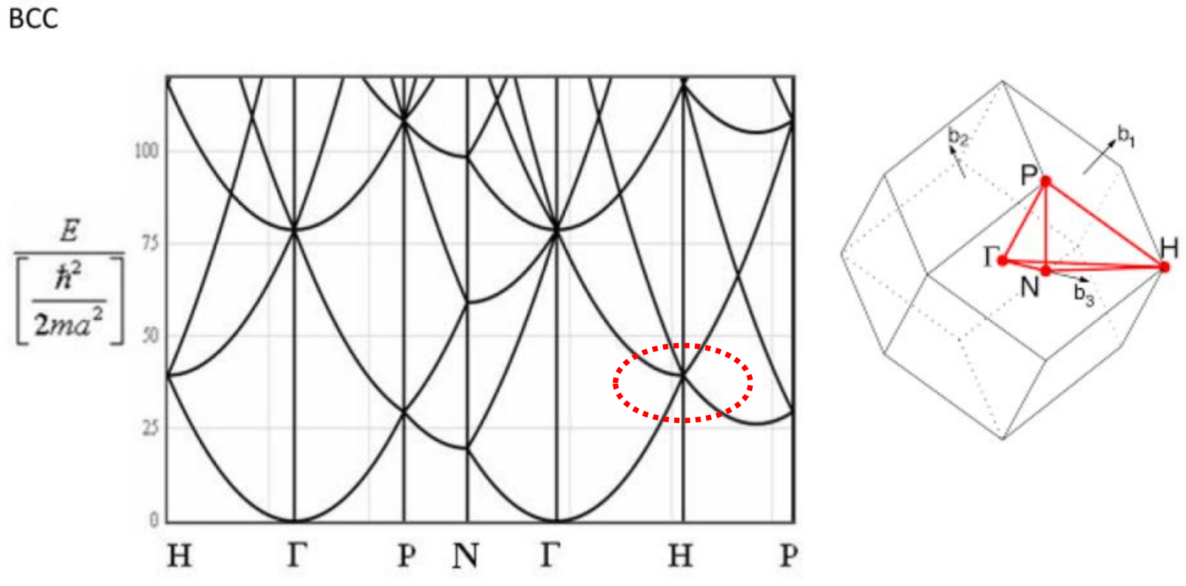
Rede cristalina

3D

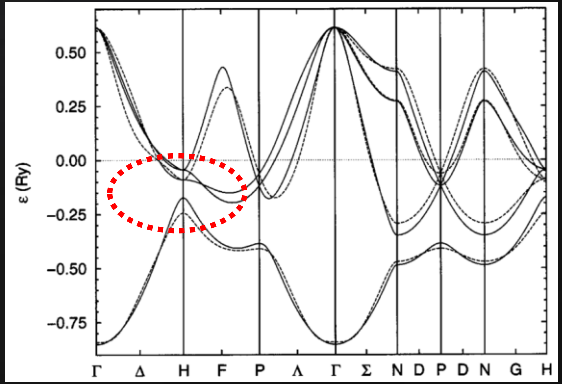
Exemplo

Rede BCC

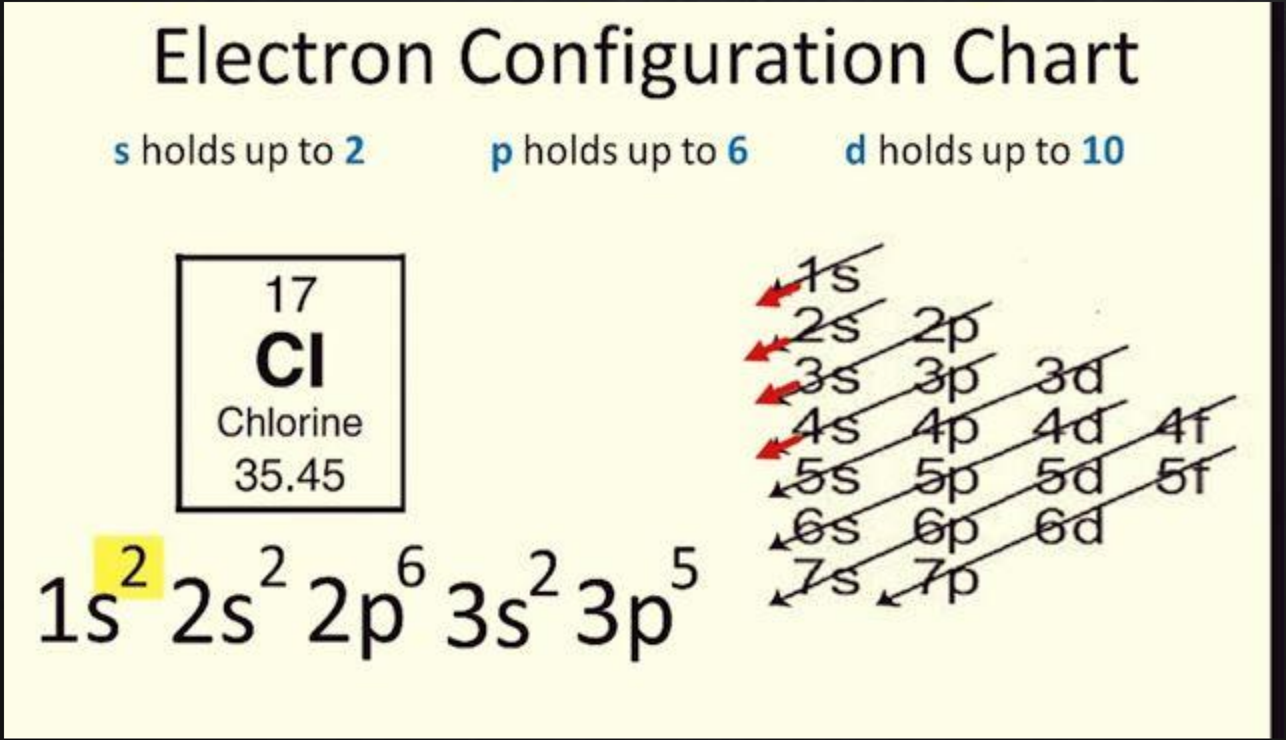




Bandas com os gaps



Estatísticas de ocupação de estados



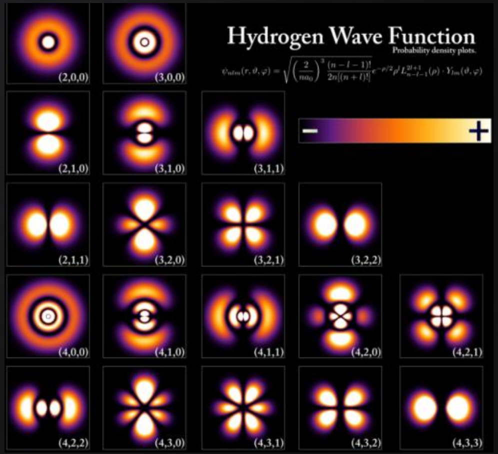
Electron Configuration Chart

s holds up to **2** **p** holds up to **6** **d** holds up to **10**

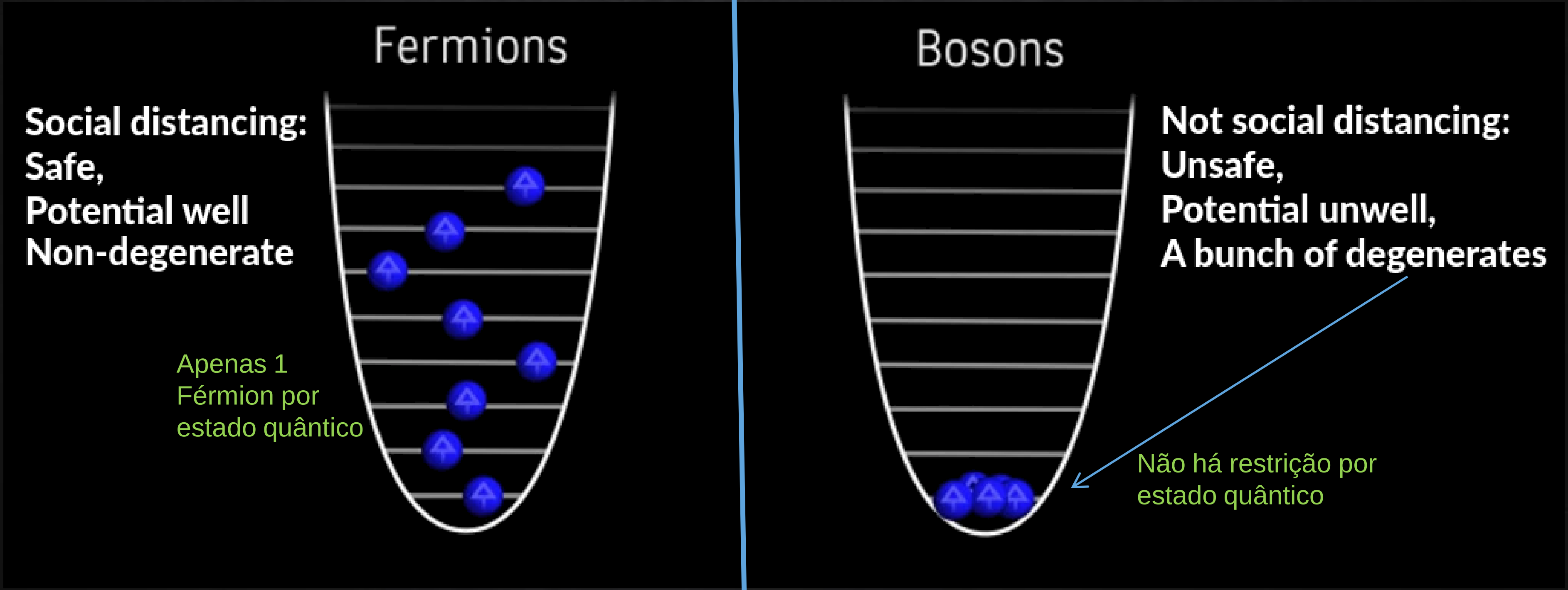
17
Cl
Chlorine
35.45

$1s^2 2s^2 2p^6 3s^2 3p^5$

Lei de Hund



Estatísticas de ocupação de estados



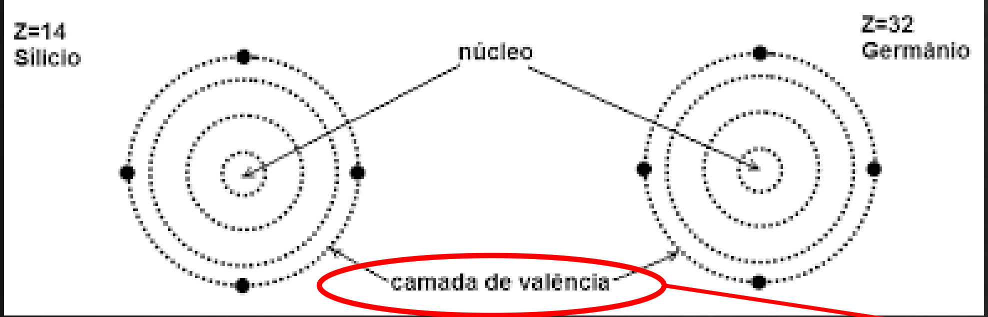
Apenas 1
Férmion por
estado quântico

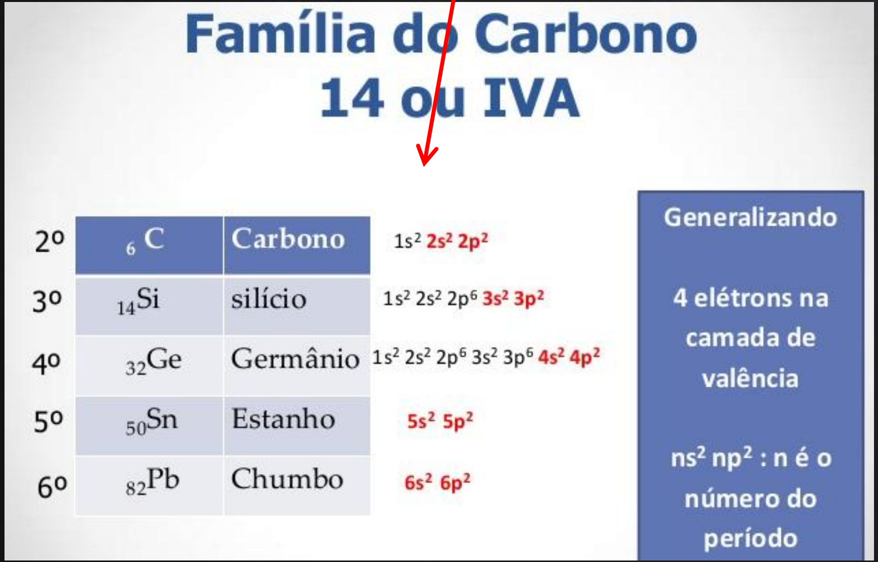
Não há restrição por
estado quântico

FÉRMIONs -
partículas com spin semi-inteiro N / 2
(p.ex. ½, 3/2 , 5/2 ....)

BÓSONs -
partículas com spin Inteiro N
(p.ex. 1, 2, 3 ....)

Elétrons - **Férmions** - Estatística de Fermi-Dirac





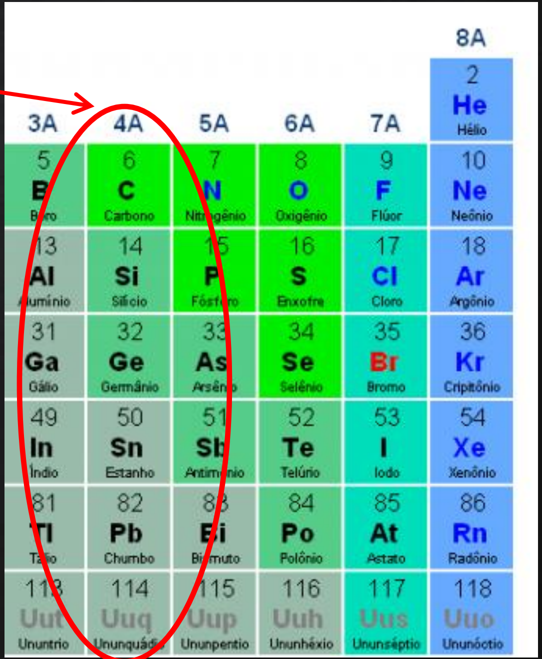
Família do Carbono
14 ou IVA

2º	$_{6}$C	Carbono	$1s^2\ 2s^2\ 2p^2$
3º	$_{14}$Si	silício	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$
4º	$_{32}$Ge	Germânio	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 4p^2$
5º	$_{50}$Sn	Estanho	$5s^2\ 5p^2$
6º	$_{82}$Pb	Chumbo	$6s^2\ 6p^2$

Generalizando

4 elétrons na camada de valência

$ns^2\ np^2$: n é o número do período



3A	4A	5A	6A	7A	8A
					2 He Hélio
5 B Boro	6 C Carbono	7 N Nitrogênio	8 O Oxigênio	9 F Flúor	10 Ne Neônio
13 Al Alumínio	14 Si Silício	15 P Fósforo	16 S Enxofre	17 Cl Cloro	18 Ar Argônio
31 Ga Gálio	32 Ge Germânio	33 As Arsênio	34 Se Selênio	35 Br Bromo	36 Kr Criptônio
49 In Índio	50 Sn Estanho	51 Sb Antimônio	52 Te Telúrio	53 I Iodo	54 Xe Xenônio
81 Tl Tálio	82 Pb Chumbo	83 Bi Bismuto	84 Po Polônio	85 At Astato	86 Rn Radônio
113 Uut Ununtrio	114 Uuq Ununquádio	115 Uup Ununpentio	116 Uuh Ununhéxio	117 Uus Ununséptio	118 Uuo Ununóctio

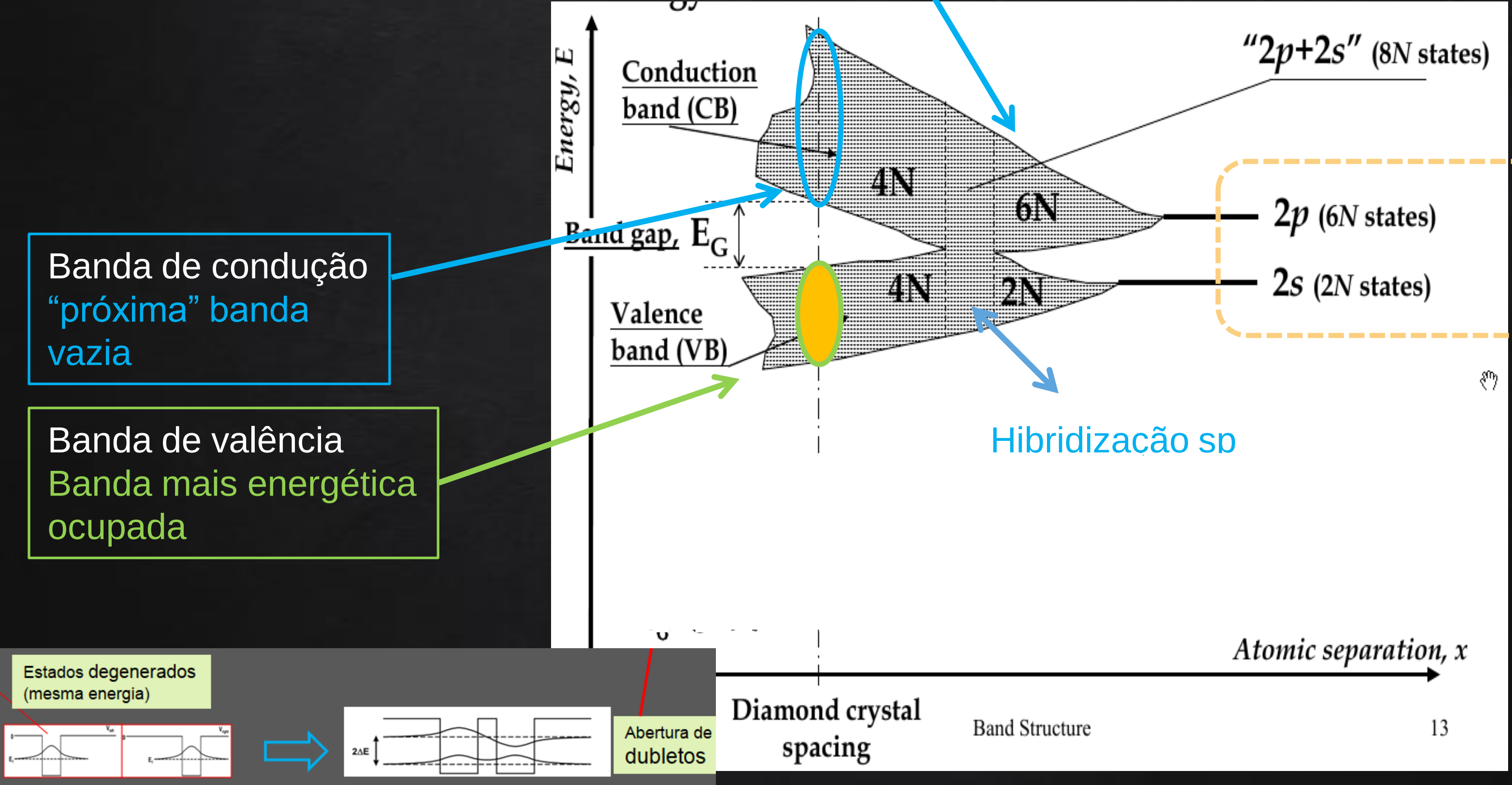
Elétrons - **Férmions**

Formação de bandas

$_6$C	Carbono	$1s^2\ 2s^2\ 2p^2$

4 elétrons

8 estados
S=2
P=6



Banda de condução
"próxima" banda vazia

Banda de valência
Banda mais energética ocupada

Hibridização sp

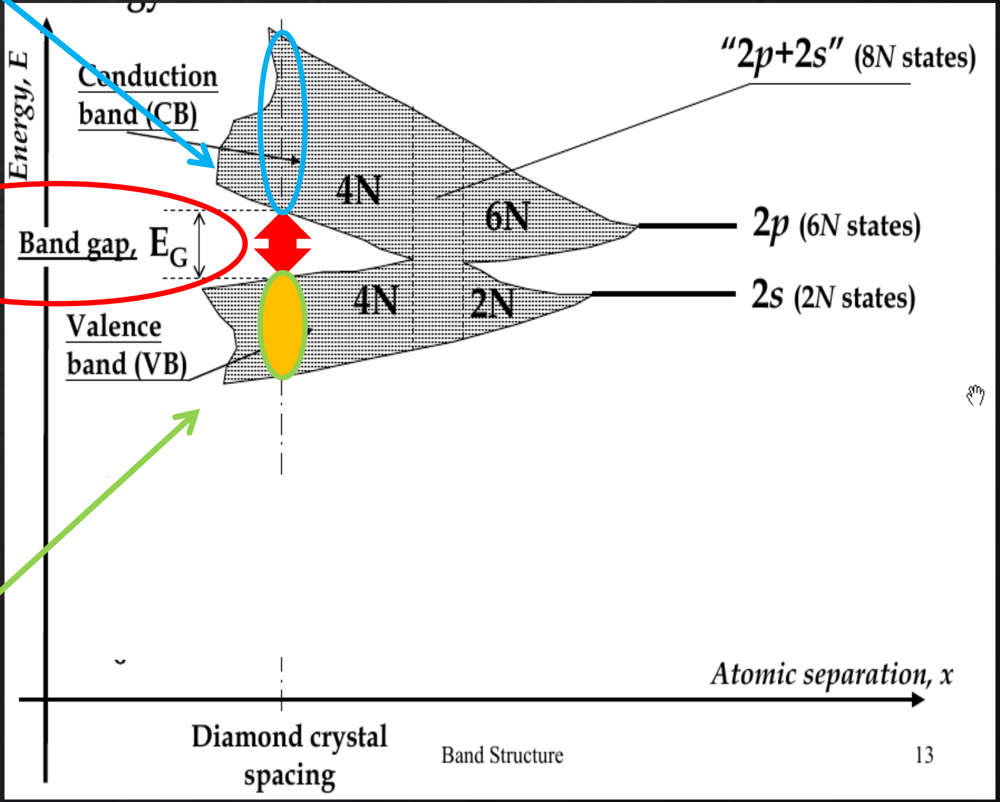
Estados degenerados (mesma energia)

Abertura de dubletos

Elétrons - Férmions

Banda de condução
“próxima” banda vazia

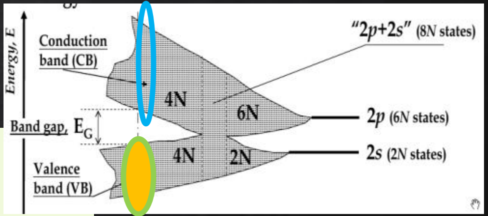
Formação de bandas

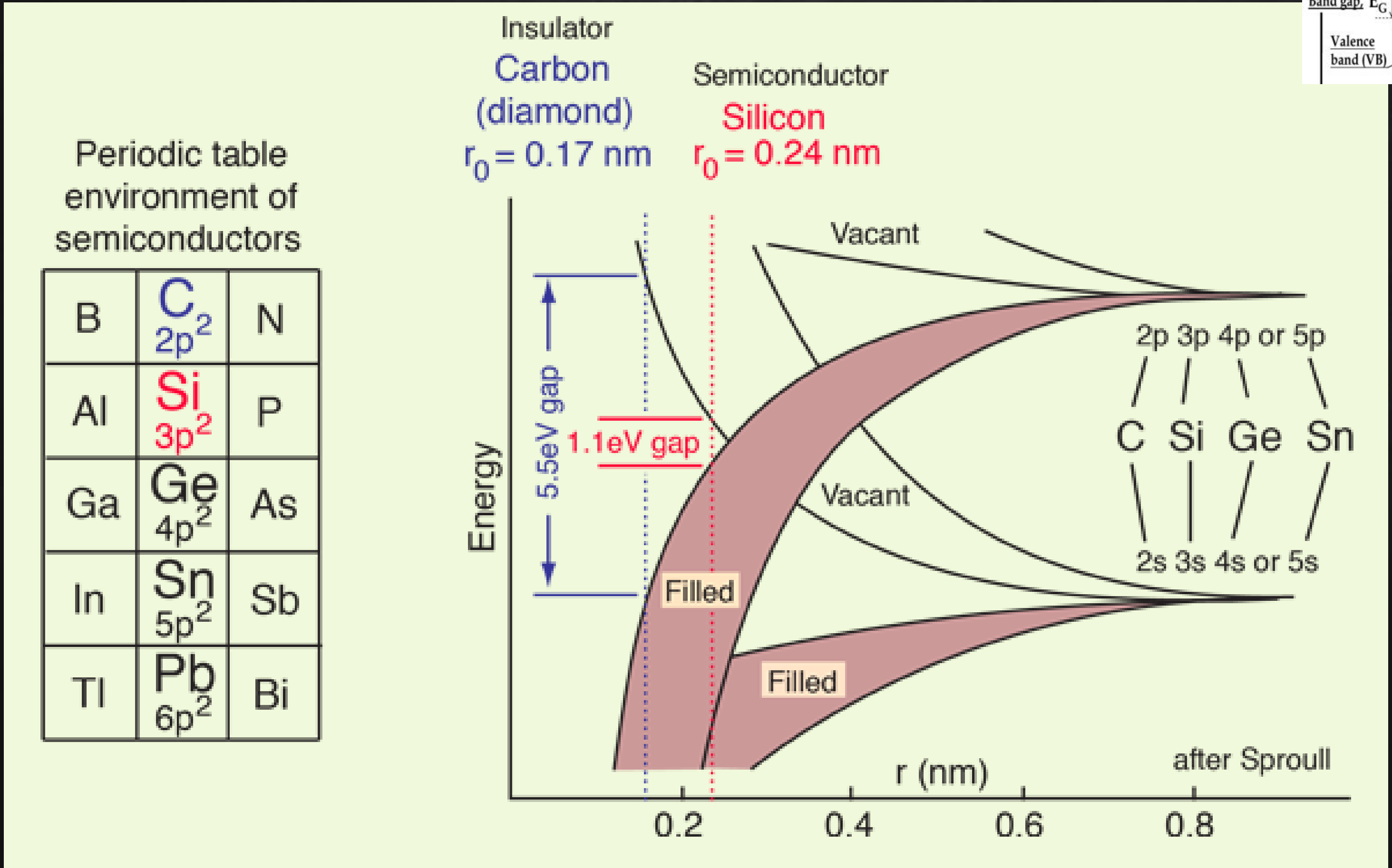


Gap de energia
Distância energética entre BV e BC

Banda de valência
Banda mais energética ocupada

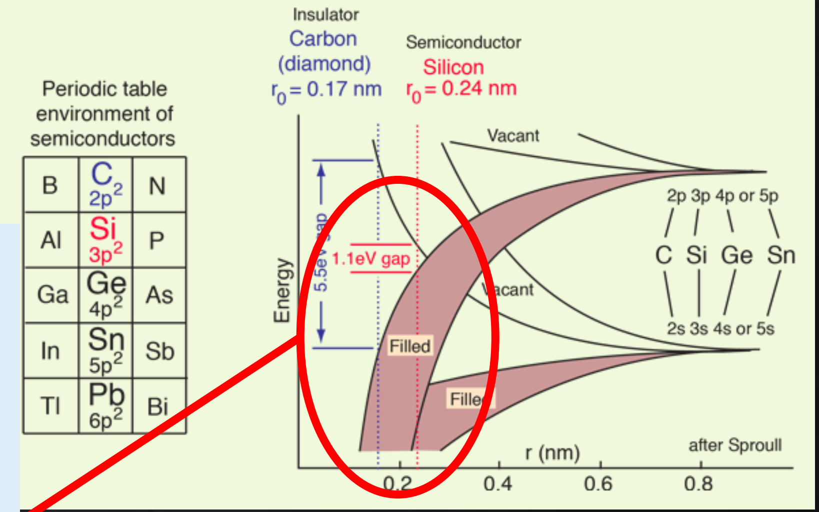
Elétrons - **Férmions**



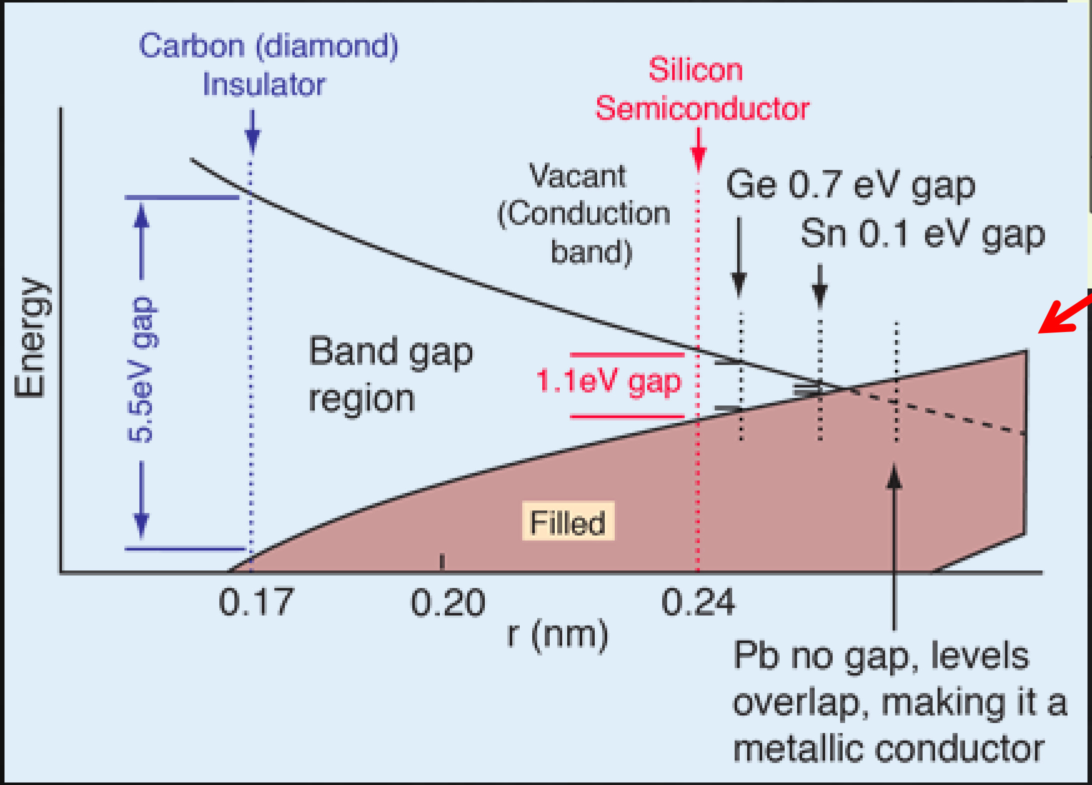


B	C $2p^2$	N
Al	Si $3p^2$	P
Ga	Ge $4p^2$	As
In	Sn $5p^2$	Sb
Tl	Pb $6p^2$	Bi

Elétrons - **Férmions**

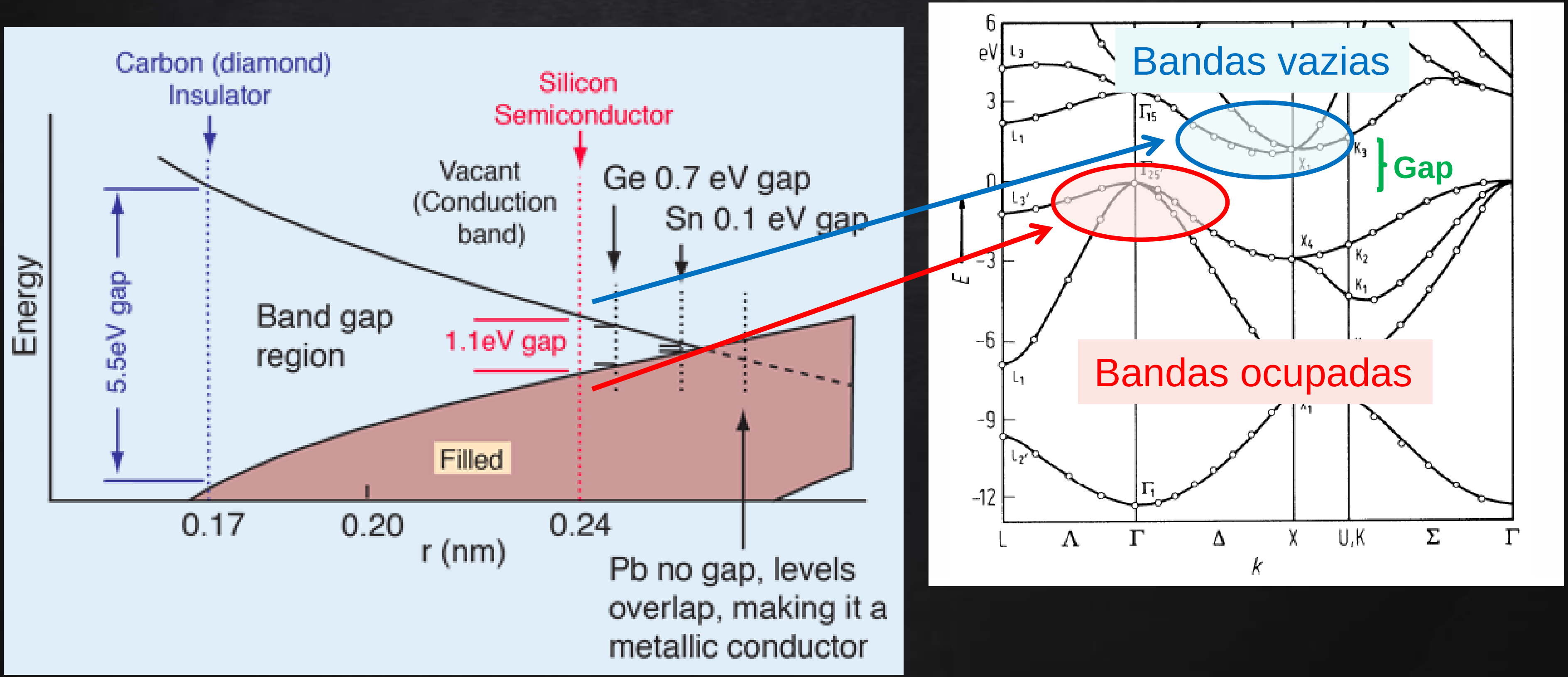

Periodic table environment of semiconductors

B	C_2 $2p^2$	N
Al	Si $3p^2$	P
Ga	Ge $4p^2$	As
In	Sn $5p^2$	Sb
Tl	Pb $6p^2$	Bi

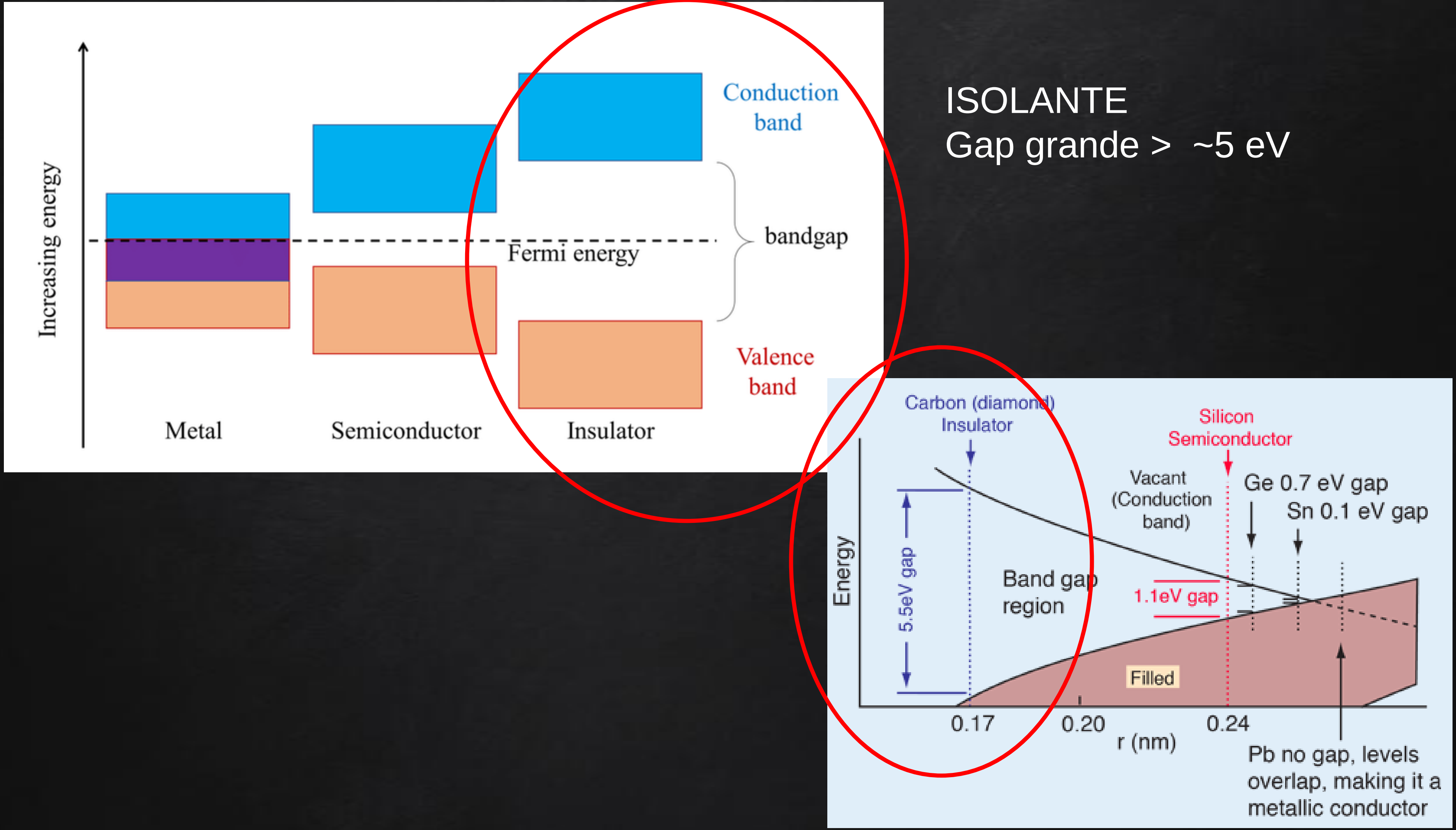


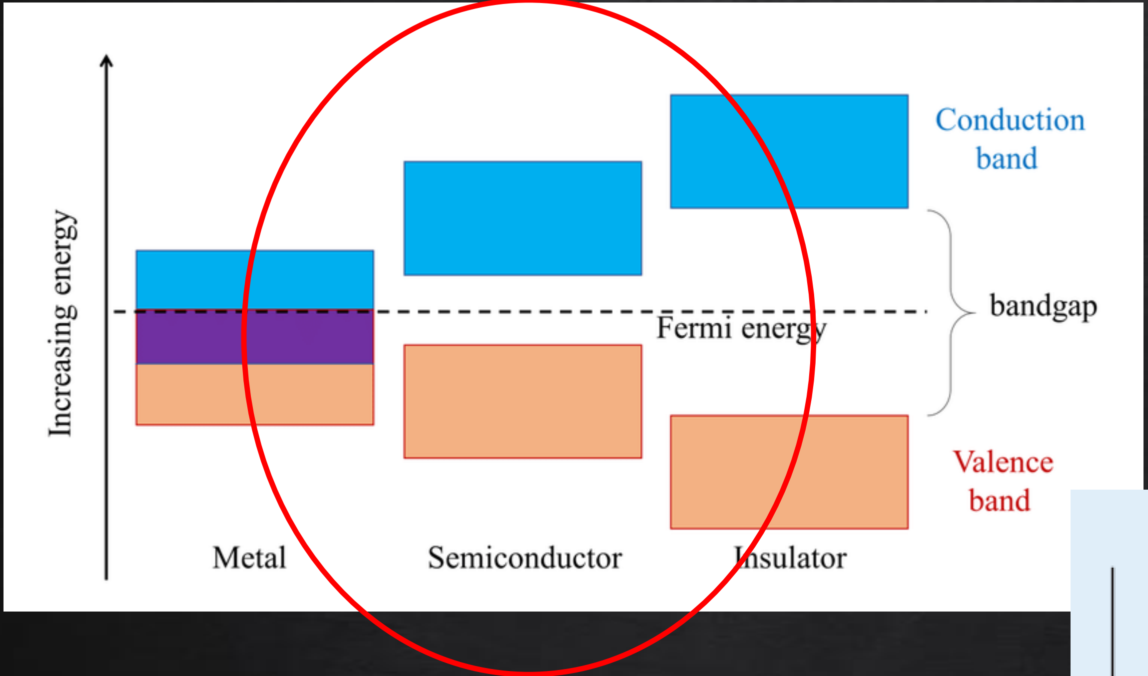
Elétrons - **Férmions**

Silício

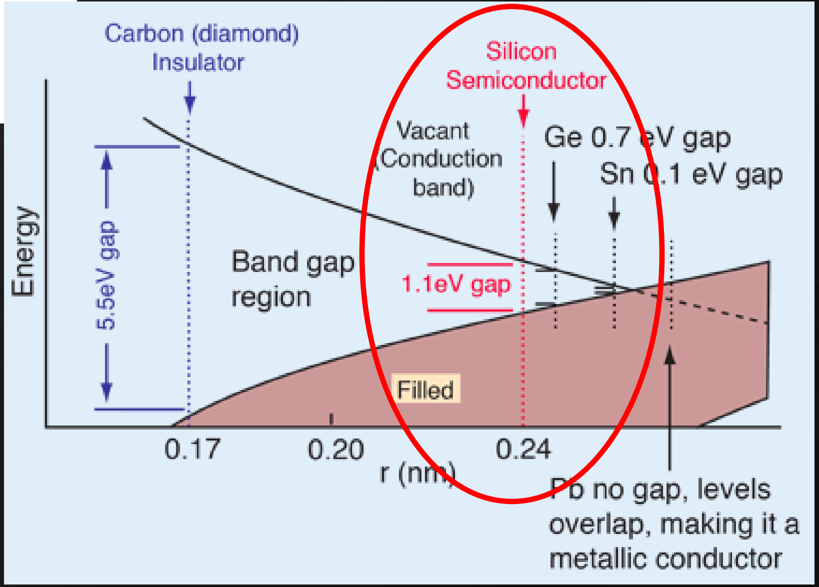


ISOLANTE
Gap grande > ~5 eV

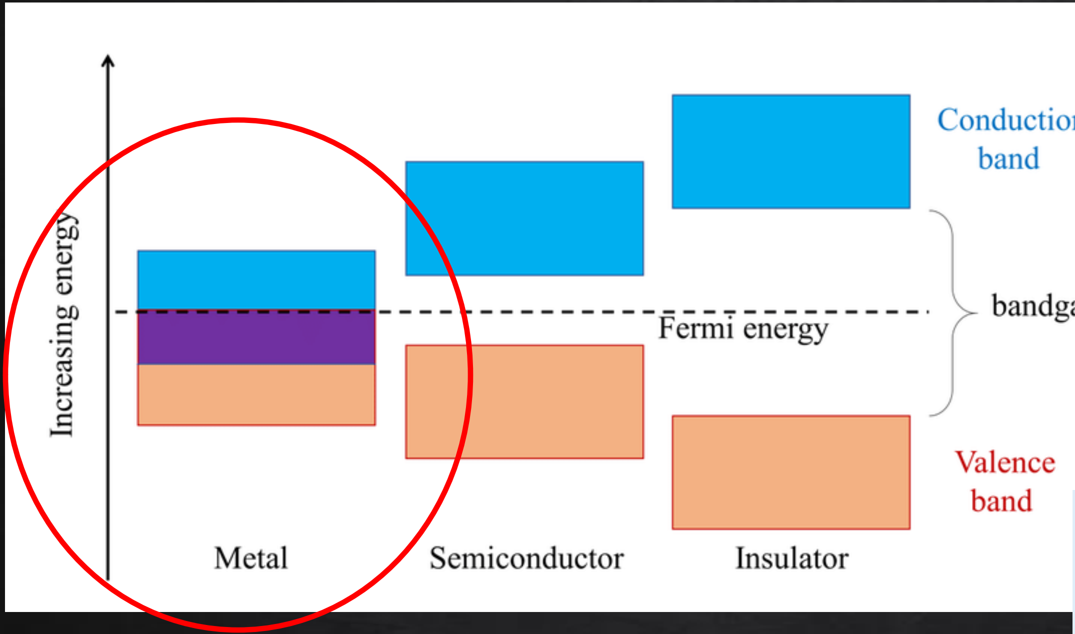


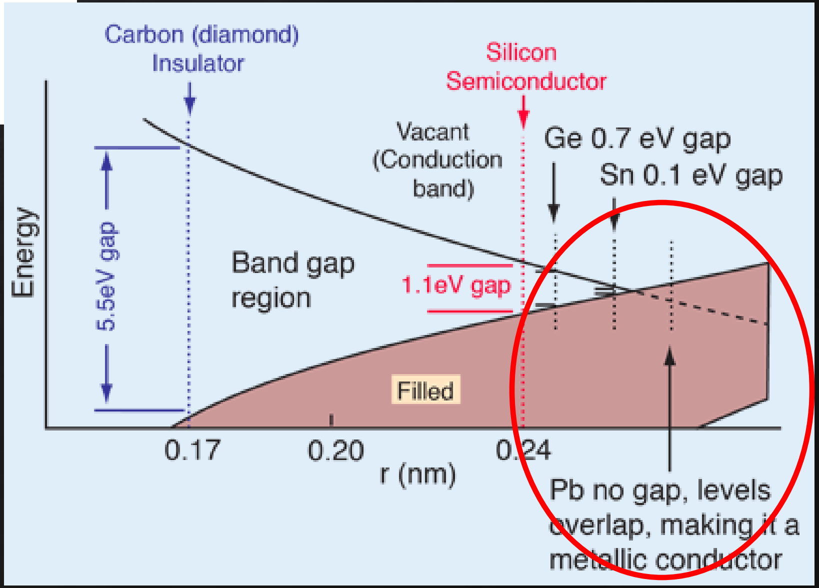


SEMICONDUTOR
Gap médio ~ 1 -- 5 eV



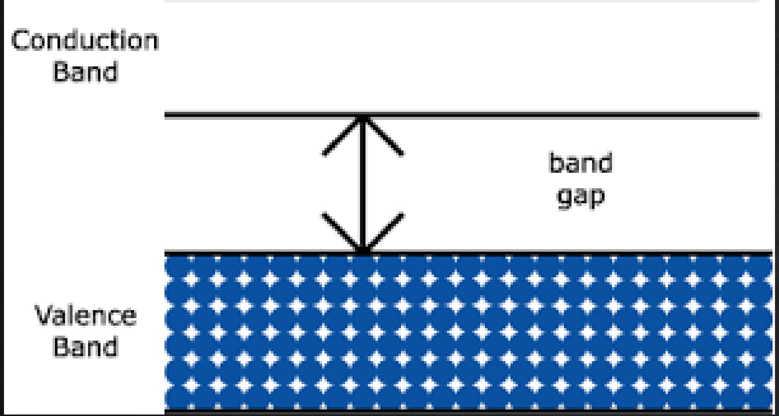
CONDUTOR (metal)
Sem gap





Isolantes

Banda vazias (BC)

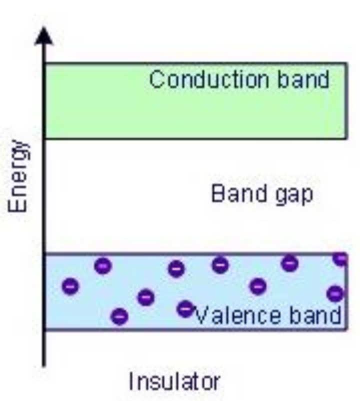


Banda ocupadas (BV)

Se o gap for grande (isolante) não conseguem “saltar”´para os estados vazios da BC

Elétrons são férmions

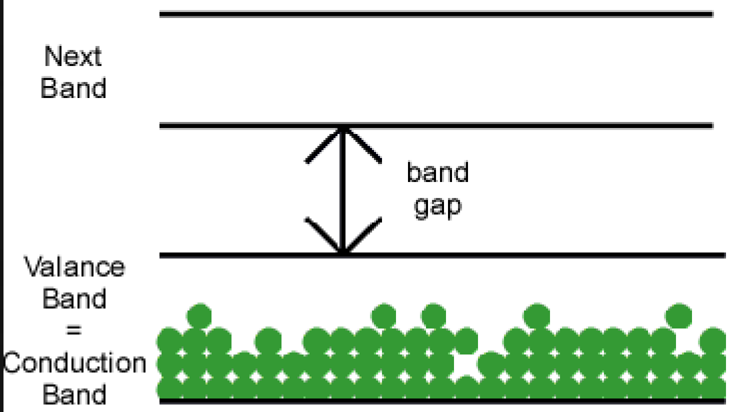
Não conseguem ganhar energia pois todos os estados estão ocupados na BV



Isolante
Não há condução de corrente elétrica

Condutores

Banda vazias

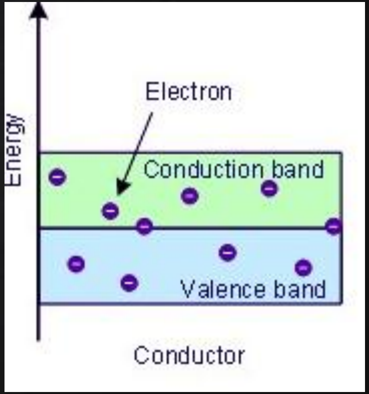


Banda de condução
Semi-ocupadas

Elétrons são férmions

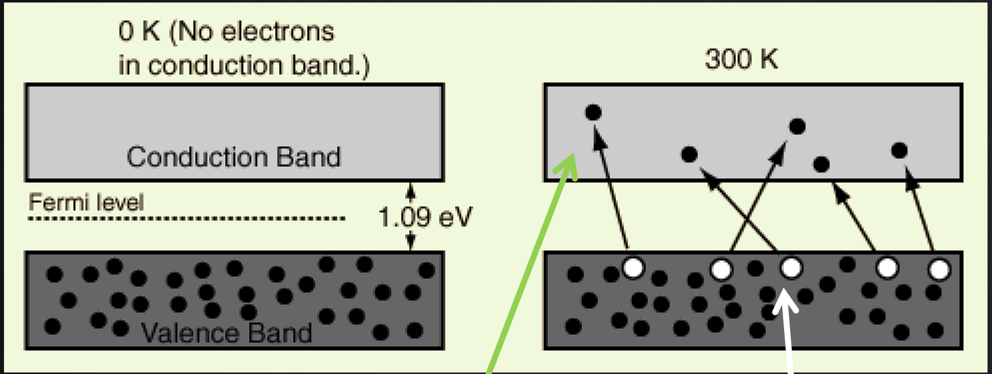
Conseguem ganhar energia ocupando estados +energéticos que estão vazios na BC

Elétrons livres
ou
Elétrons de condução



Condutor
Há condução de corrente elétrica

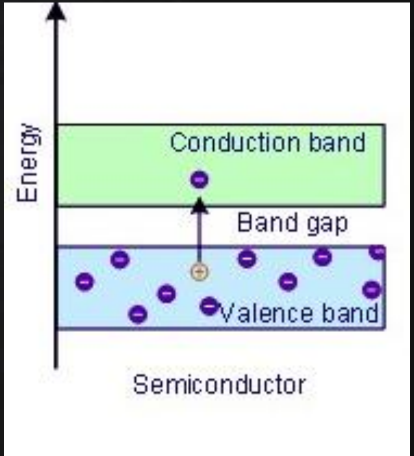
Semicondutores



Excitação térmica consegue transferir elétrons para a BC (gap pequeno)

Elétrons de condução

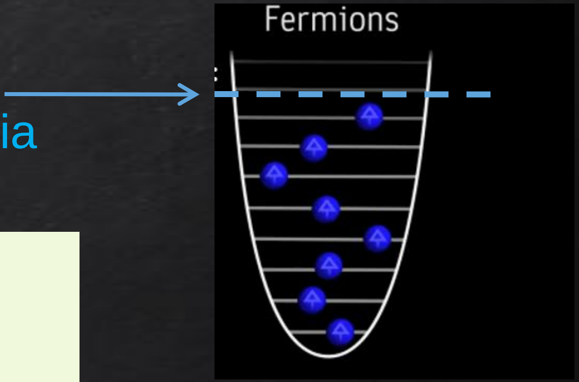
Ausência de elétrons “buracos”
Se comportam como partícula de carga positiva

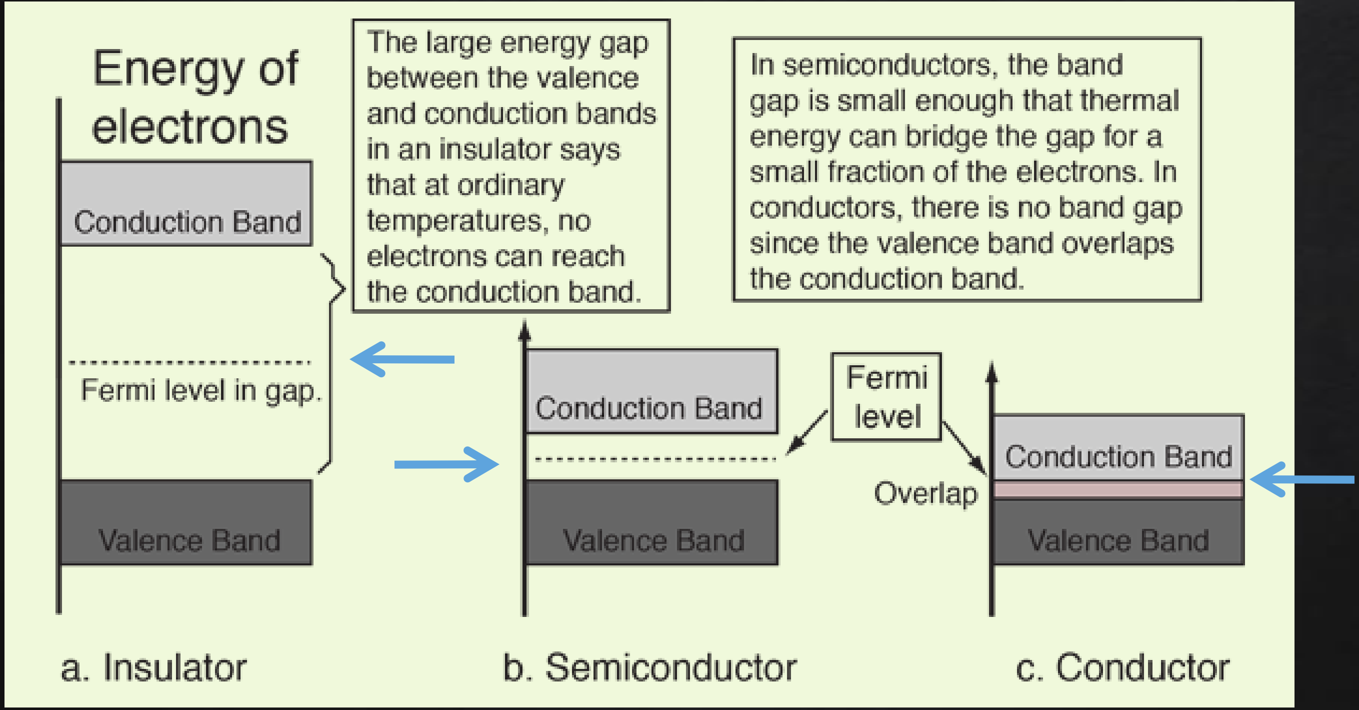


SEMIcondutor
Há condução de corrente elétrica por POUCOS elétrons/buracos

Nível de Fermi
Energia de Fermi

Nível/Energia do estado
Ocupado de maior energia





The large energy gap between the valence and conduction bands in an insulator says that at ordinary temperatures, no electrons can reach the conduction band.

In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.

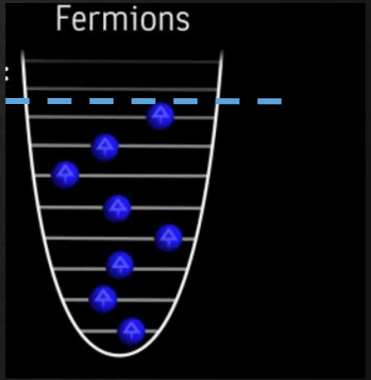
a. Insulator

b. Semiconductor

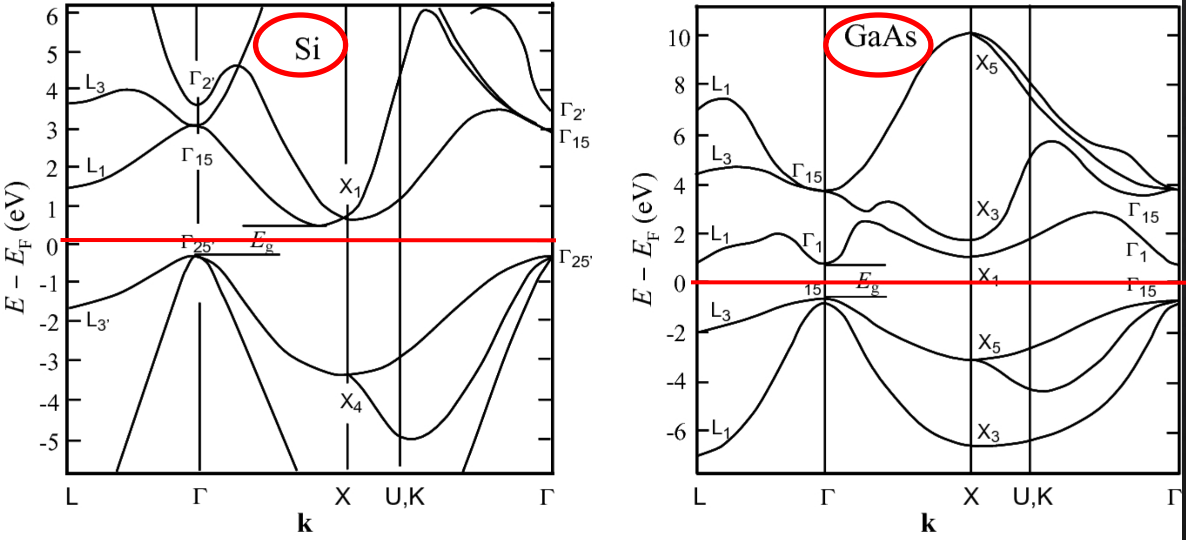
c. Conductor

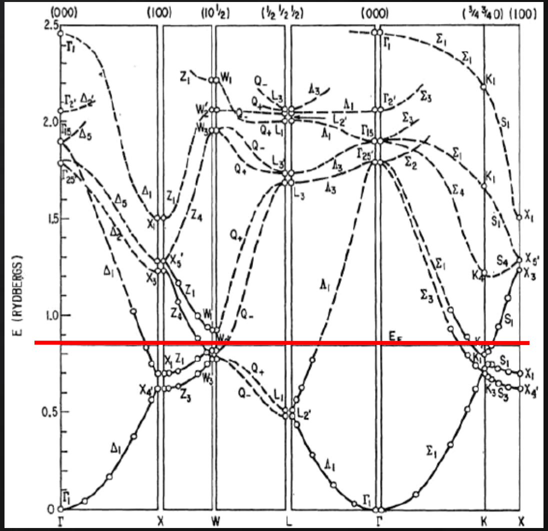
Nível de Fermi
Energia de Fermi

Nível/Energia do estado
Ocupado de maior energia



Semicondutores (Nível de Fermi no meio do gap)

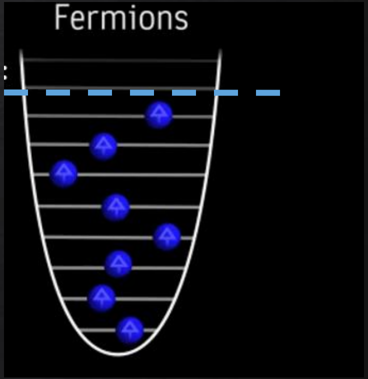




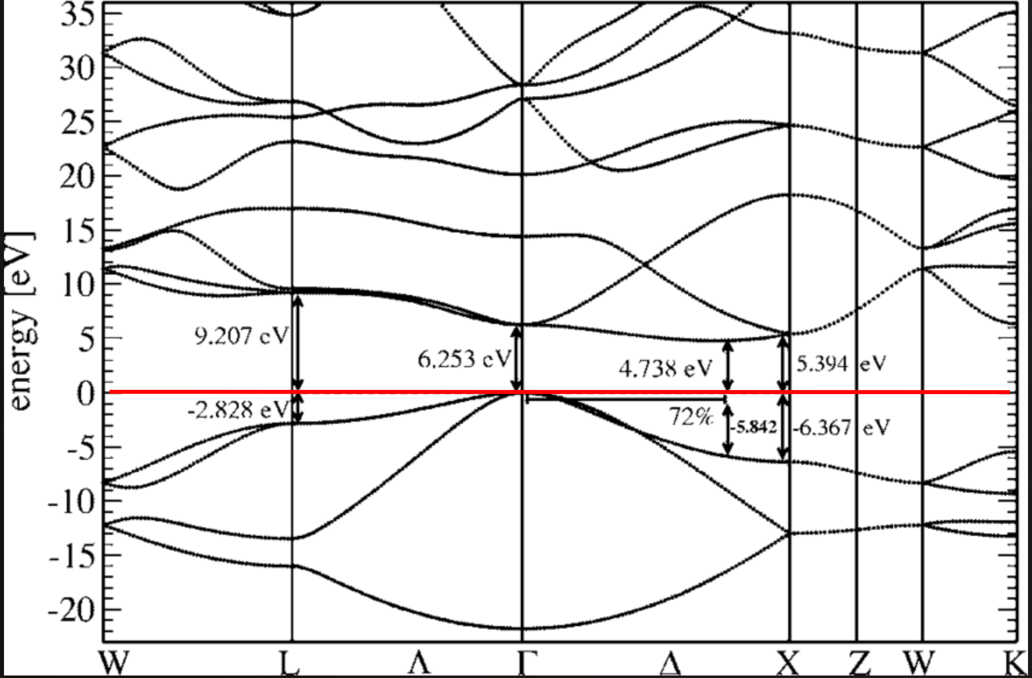
Alumínio condutor

Nível de Fermi
Energia de Fermi

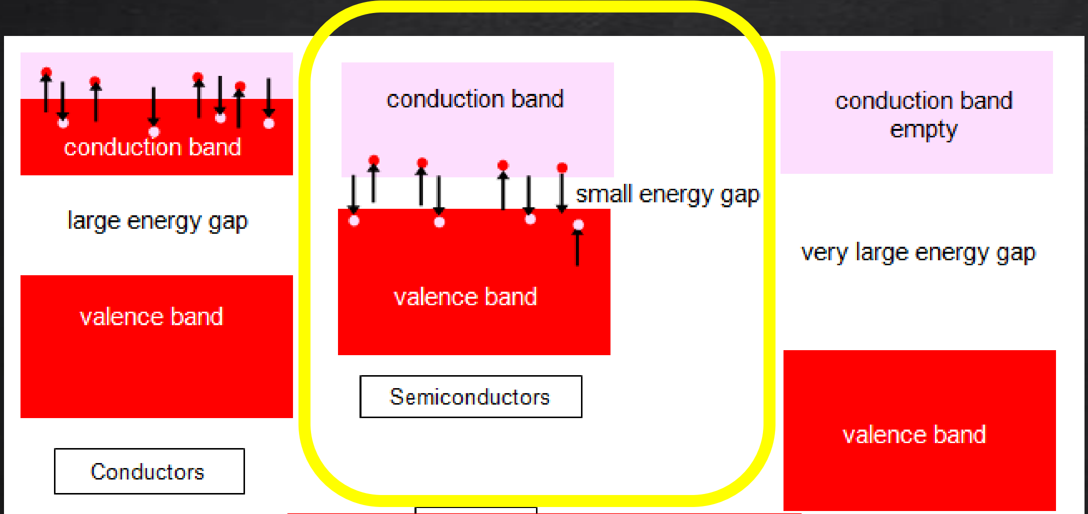
Nível/Energia do estado
Ocupado de maior energia

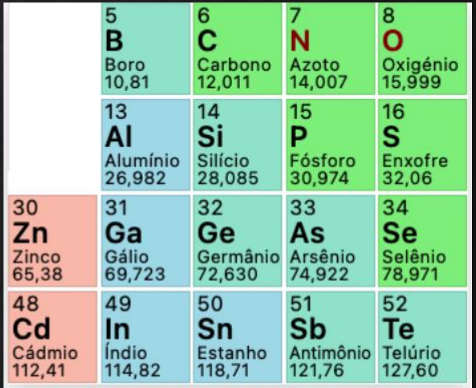


Diamante (isolante ~semicondutor) (Nível de Fermi no topo da BV)

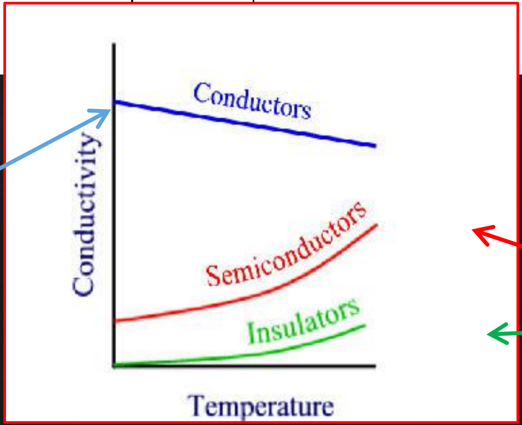


Semicondutores





	5 **B** Boro 10,81	6 **C** Carbono 12,011	7 **N** Azoto 14,007	8 **O** Oxigénio 15,999
	13 **Al** Alumínio 26,982	14 **Si** Silício 28,085	15 **P** Fósforo 30,974	16 **S** Enxofre 32,06
30 **Zn** Zinco 65,38	31 **Ga** Gálio 69,723	32 **Ge** Germânio 72,630	33 **As** Arsênio 74,922	34 **Se** Selênio 78,971
48 **Cd** Cádmio 112,41	49 **In** Índio 114,82	50 **Sn** Estanho 118,71	51 **Sb** Antimônio 121,76	52 **Te** Telúrio 127,60



Maior condutividade
- Maior densidade de elétrons livre

$$\sigma_{Drude} = \frac{n e^2 \tau}{m}.$$

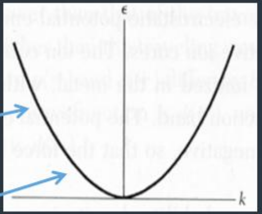
Menor condutividade
- Menor densidade de elétrons livre
- aumenta com a temperatura

Semicondutores - Massa Efetiva

Rede cristalina

Partícula livre

Dispersão parabólica $E(k) \sim k^2$

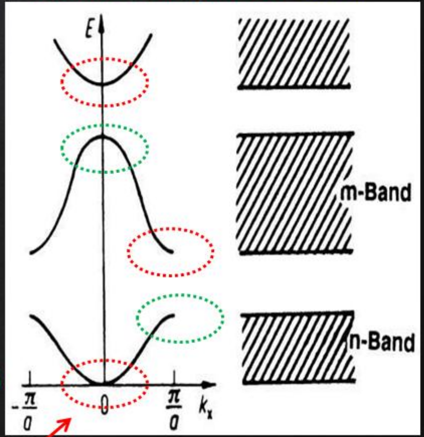


Concavidade ~1 / massa

$$\frac{\partial^2 E(k)}{\partial k^2} = \frac{\hbar^2}{m}$$

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

Estrutura de bandas eletrônicas do cristal



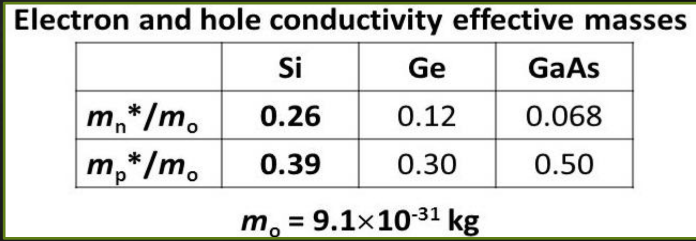
Regiões onde a dispersão é aproxima/e parabólica $E(k) \sim k^2$

Pedemos definir uma "massa efetiva" (+ / -)

$$\frac{\partial^2 E(k)}{\partial k^2} = \frac{\hbar^2}{m}$$

$$\sigma_{Drude} = \frac{n e^2 \tau}{m}.$$

Menor massa
-Maior mobilidade elétrica



Electron and hole conductivity effective masses

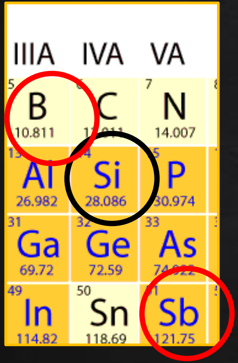
	Si	Ge	GaAs
m_n^*/m_o	**0.26**	0.12	0.068
m_p^*/m_o	**0.39**	0.30	0.50

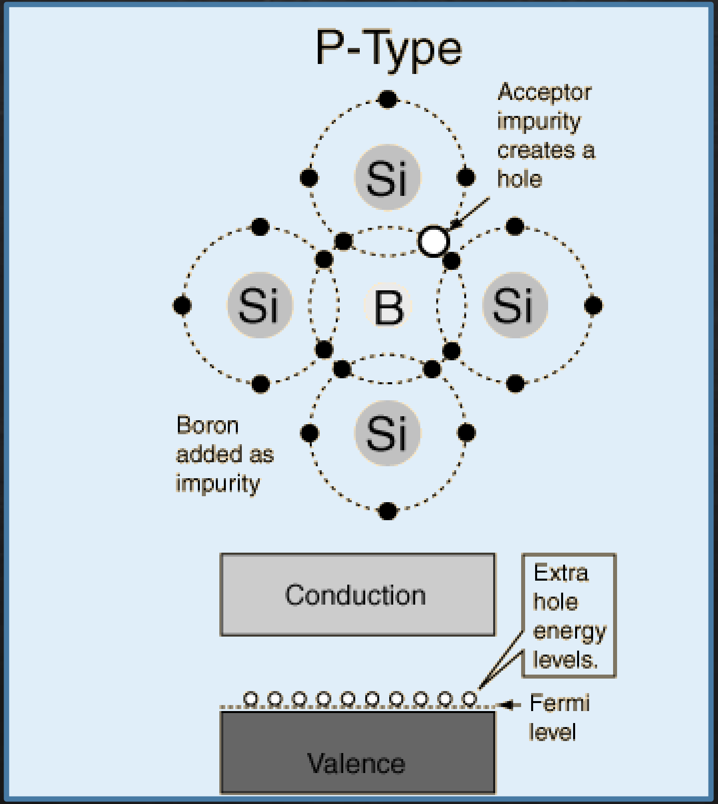
$m_o = 9.1 \times 10^{-31}$ kg

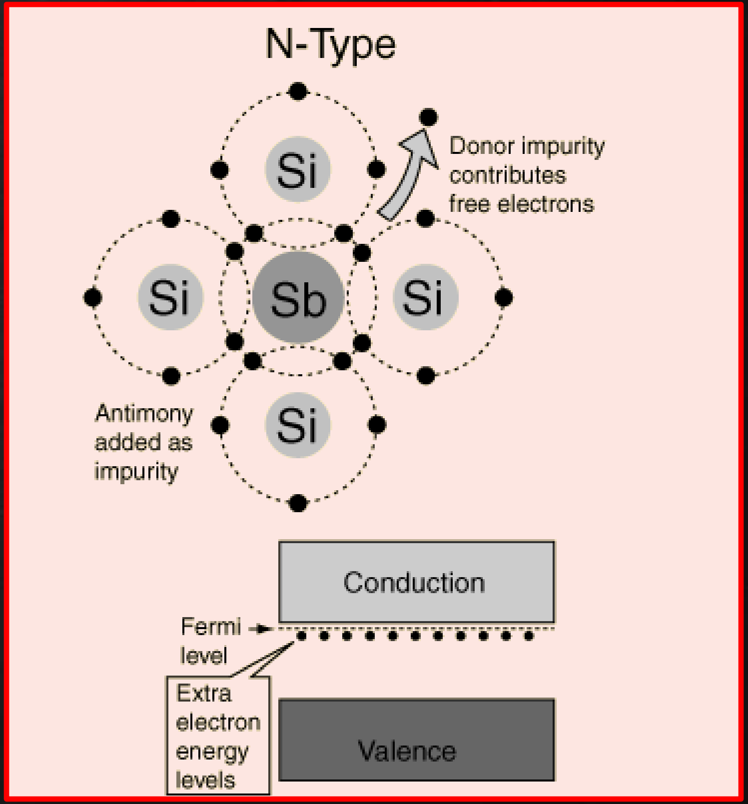
SEMICONDUTORES DOPADOS

Proporciona portadores de carga → aumenta a densidade de carga condutora

$$\sigma_{Drude} = \frac{n\,e^2\,\tau}{m}.$$



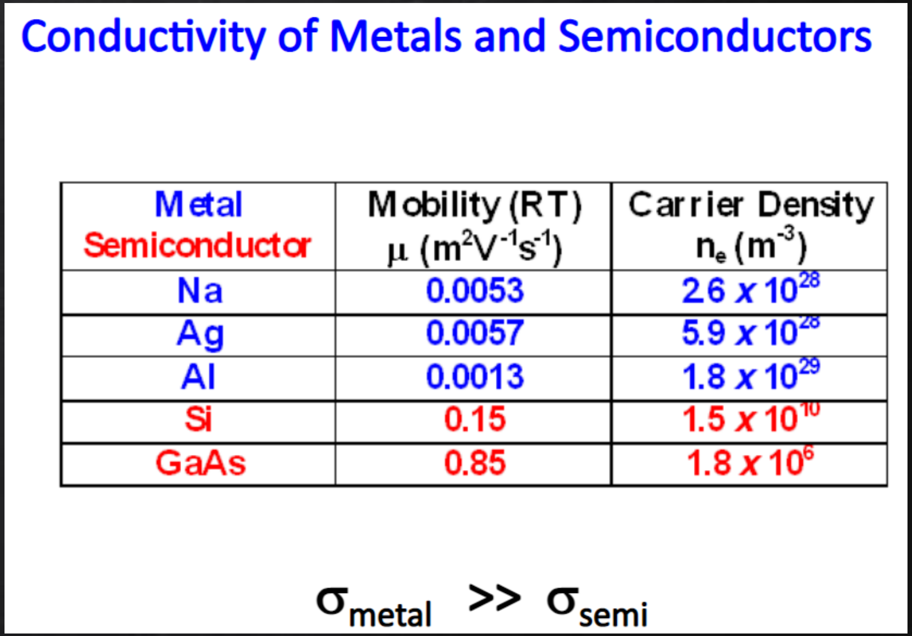




DISPOSITIVOS SEMICONDUTORES

Vantagens do Semicondutor

- Mobilidade de cargas muita alta –
  baixa resistência (cristal perfeito)
- Controle da dopagem
- Heterojunções
  - Crescimento controlado
  - Baixa dimensionalidade

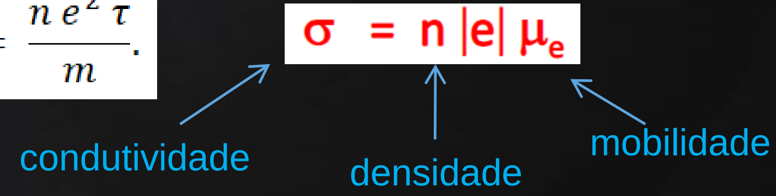


Conductivity of Metals and Semiconductors

Metal Semiconductor	Mobility (RT) μ ($m^2V^{-1}s^{-1}$)	Carrier Density n_e (m^{-3})
Na	0.0053	2.6×10^{28}
Ag	0.0057	5.9×10^{28}
Al	0.0013	1.8×10^{29}
Si	0.15	1.5×10^{10}
GaAs	0.85	1.8×10^{6}

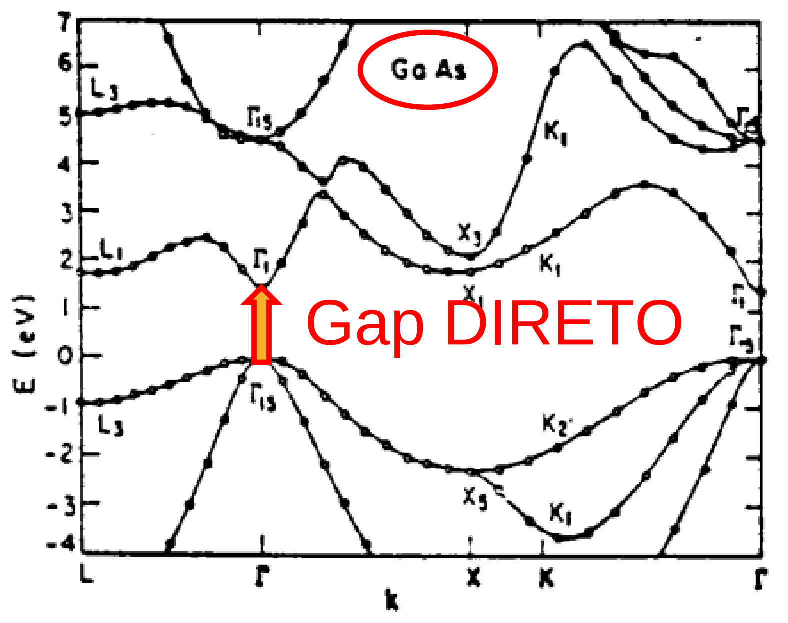
$$\sigma_{metal} \gg \sigma_{semi}$$

$$\sigma_{Drude} = \frac{n\, e^2\, \tau}{m}.$$



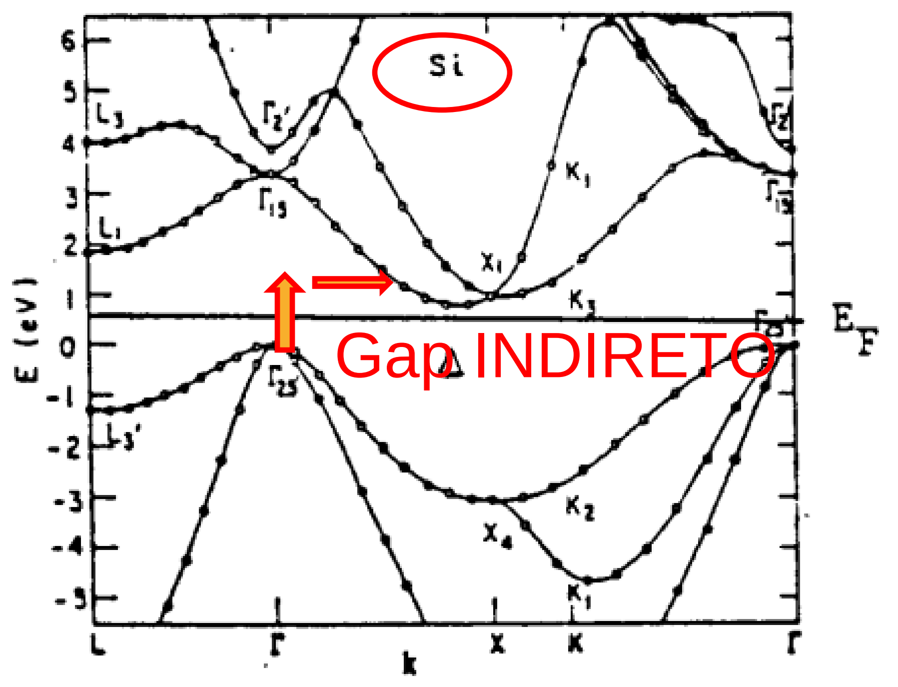
$$\sigma = n\,|e|\,\mu_e$$

Semicondutores - Propriedades Ópticas



Gap DIRETO

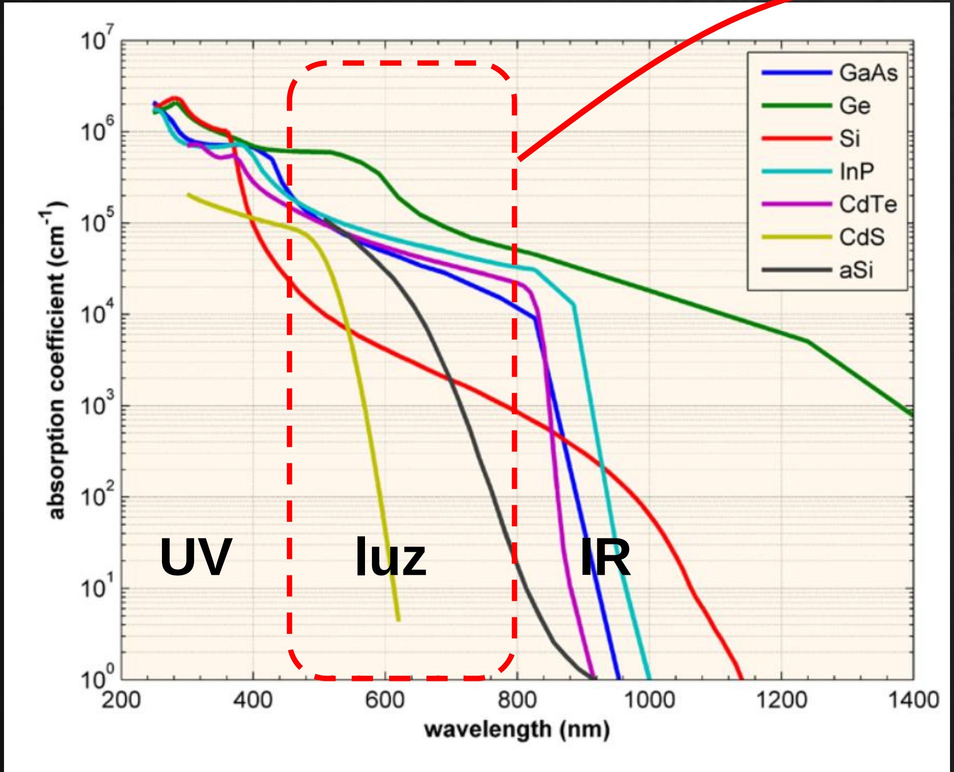
Forte acoplamento com a luz



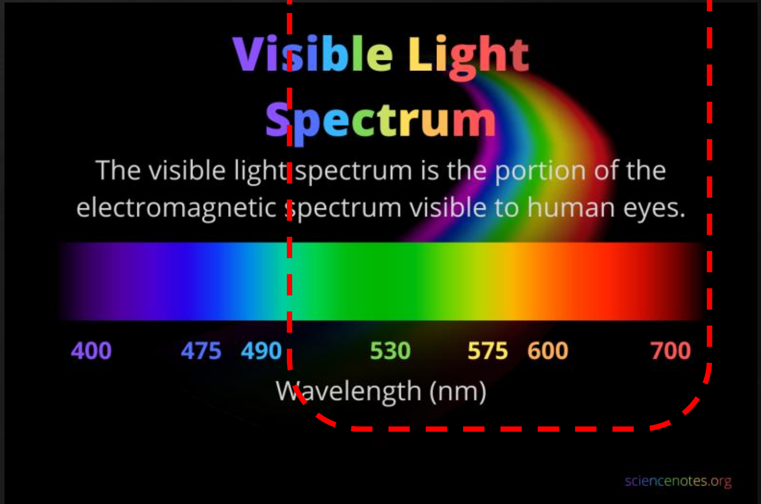
Gap INDIRETO

Fraco acoplamento com a luz

Semicondutores - Propriedades Ópticas



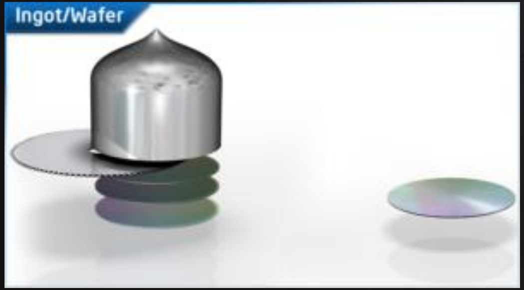
he absorption coefficient, α, in a variety of semiconductor materials at 300K as a function of the acuum wavelength of light

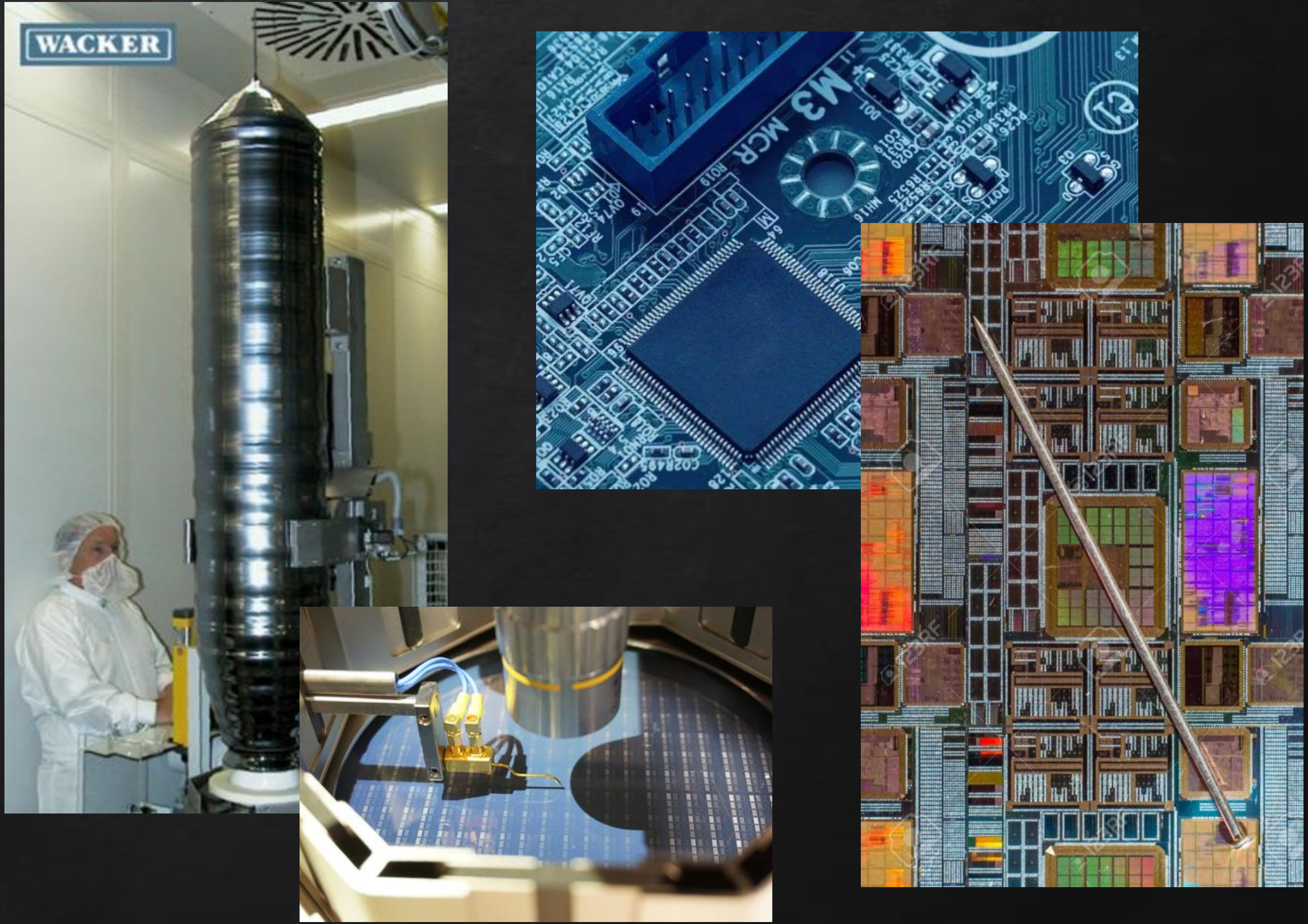


Visible Light Spectrum

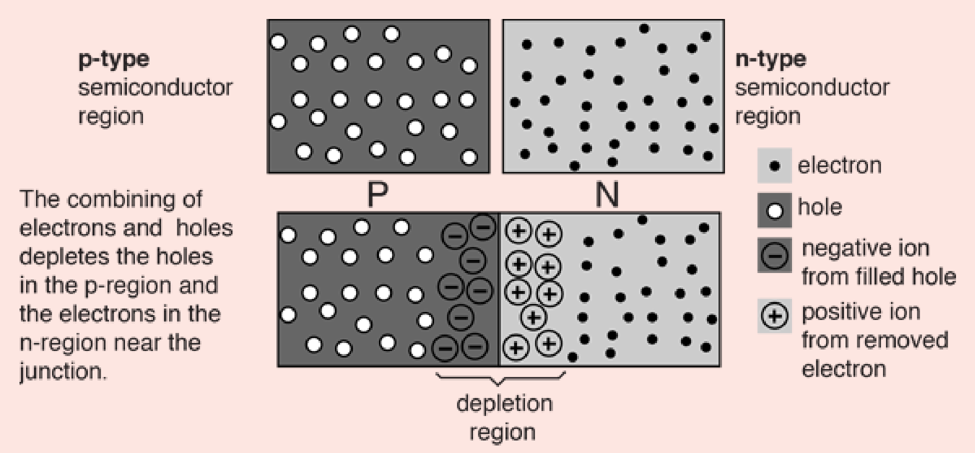
The visible light spectrum is the portion of the electromagnetic spectrum visible to human eyes.

Dispositivos semicondutores

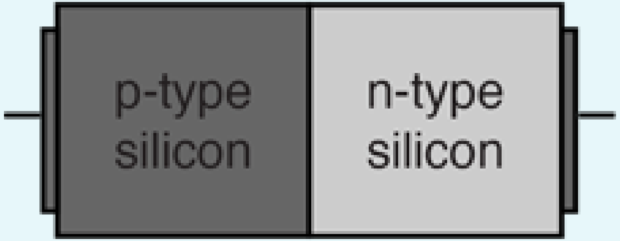




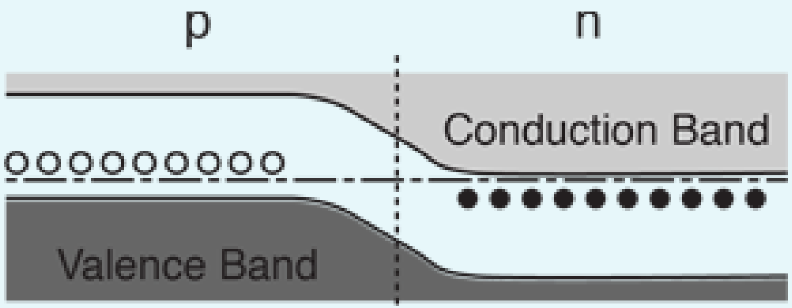
DIODOs SEMICONDUTORES



The combining of electrons and holes depletes the holes in the p-region and the electrons in the n-region near the junction.

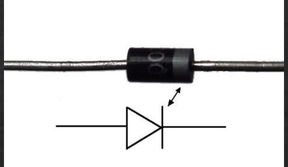


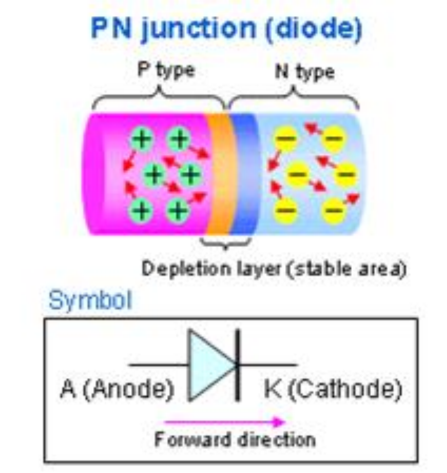
p-n junction



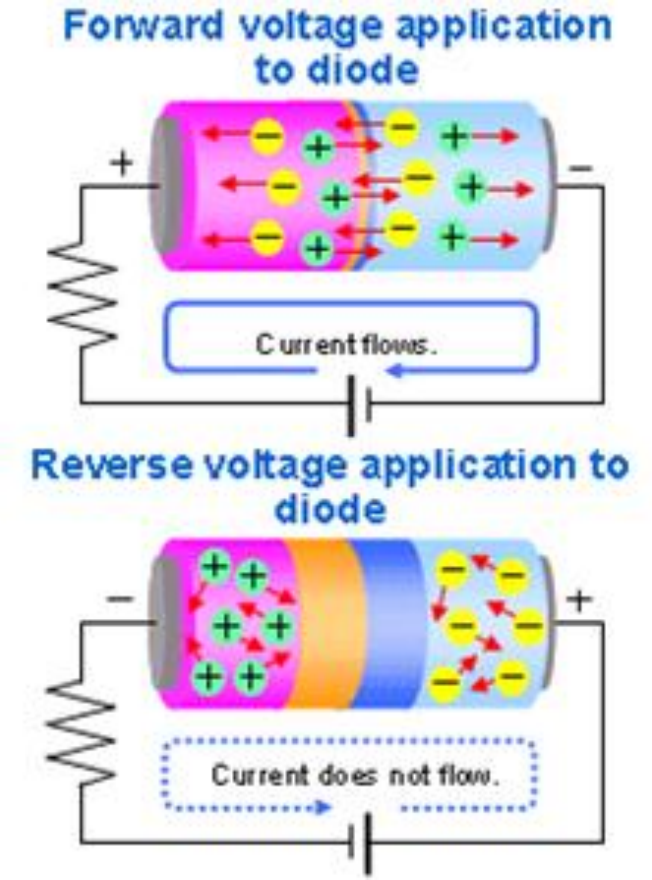
Energy bands at equilibrium

DIODOs SEMICONDUTORES





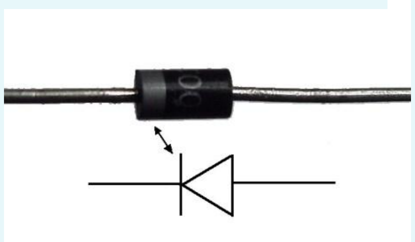
Chave direcional
de
corrente elétrica

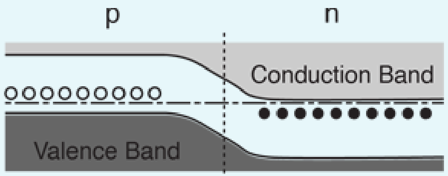


DIODOs SEMICONDUTORES

Diodo convencional

Gap INDIRETO

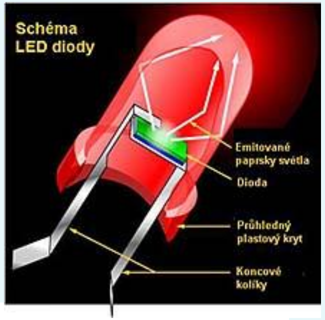


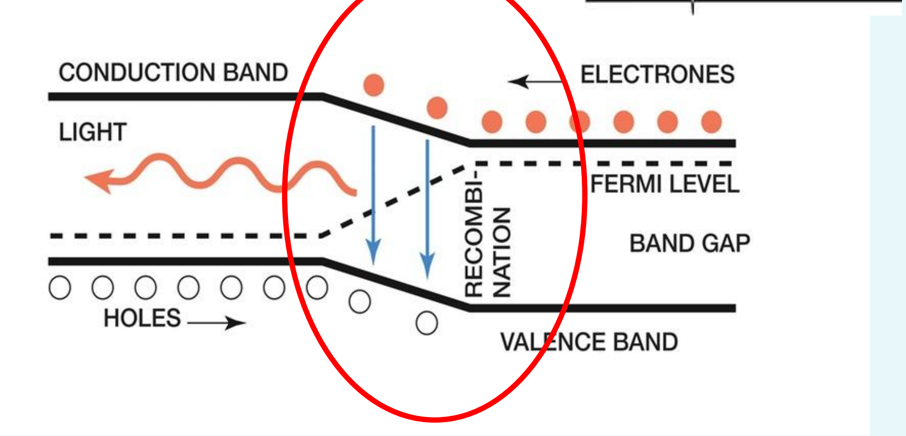


Energy bands at equilibrium

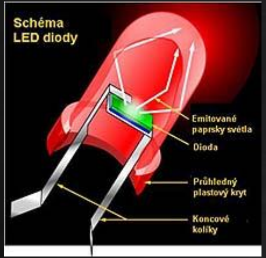
LED – *light emitting diode*

Gap DIRETO

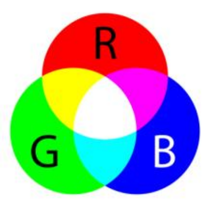


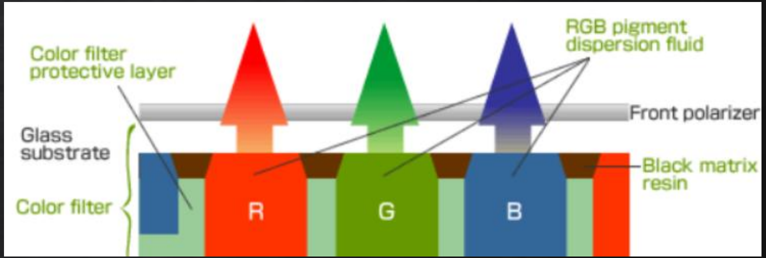


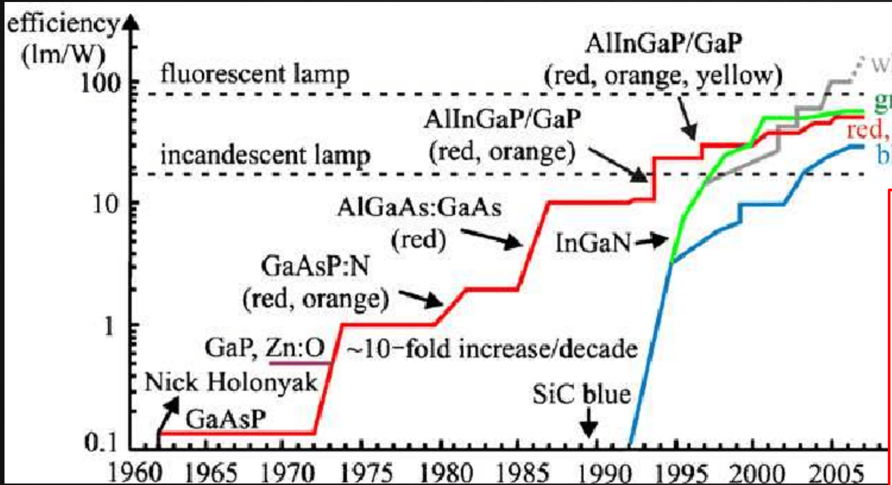
LED – *light emitting diode*

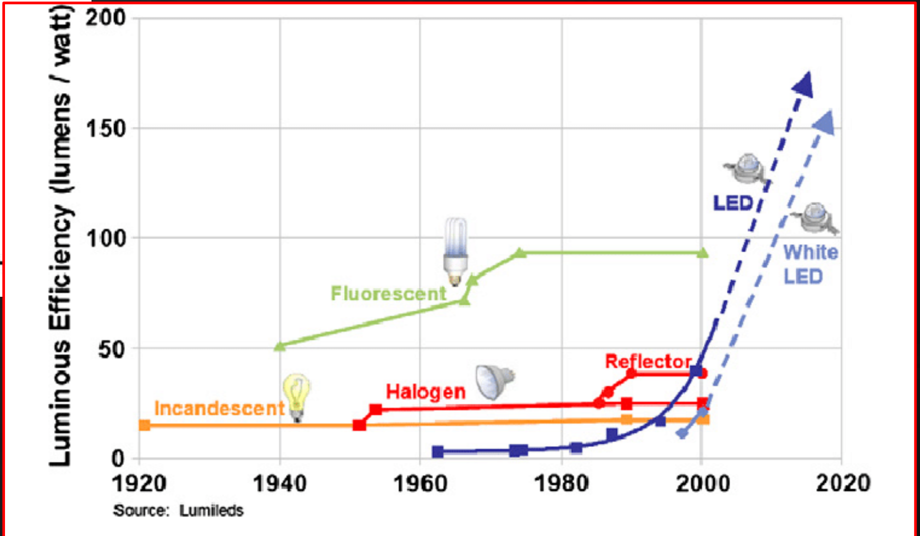


Evolução dos LEDs



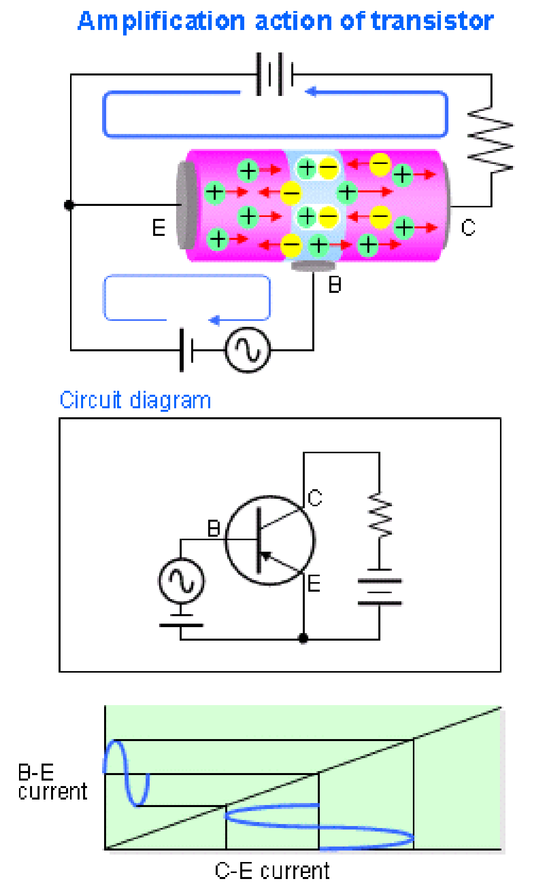


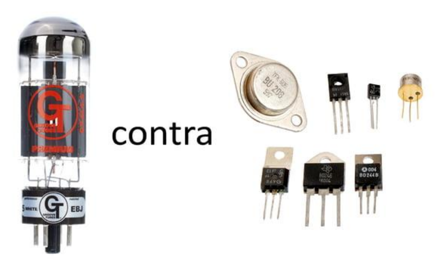


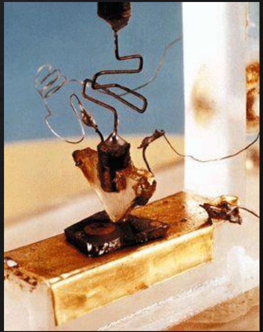


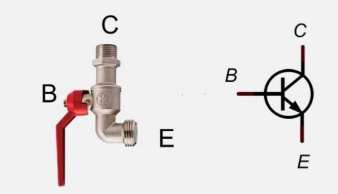
Source: Lumileds

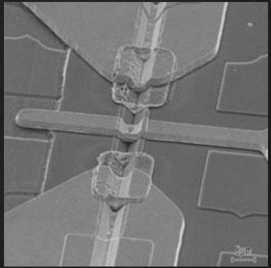
Transitores

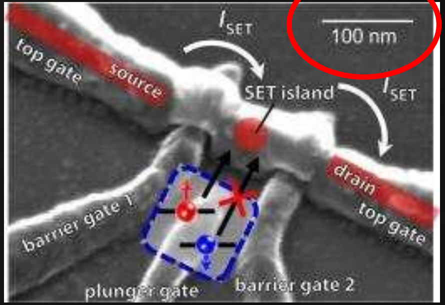












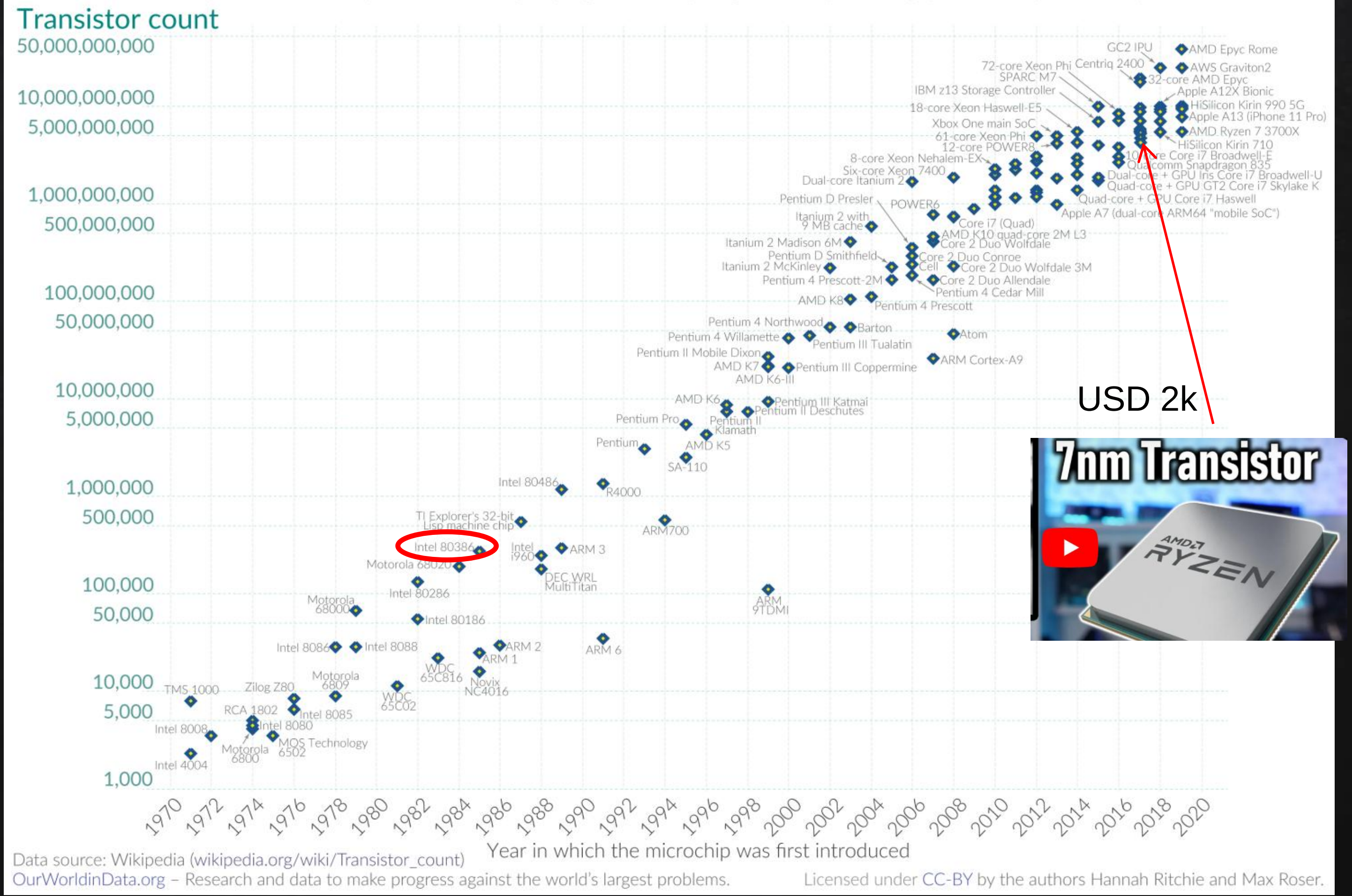
-Principais funções

-- Chaveamento (on/off)

-- Amplificação

Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.



USD 2k

Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

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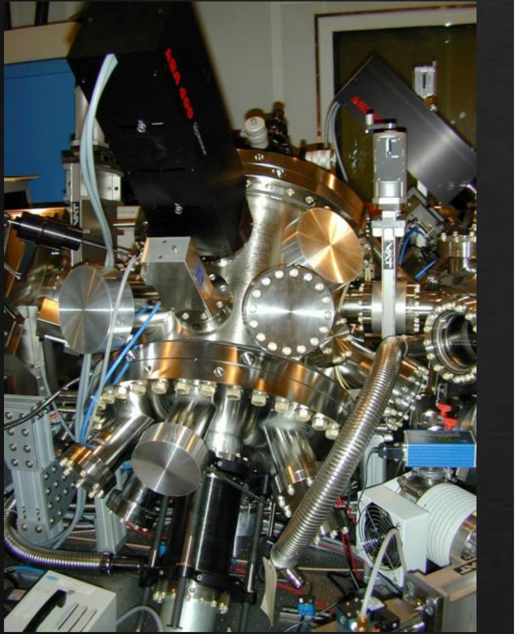
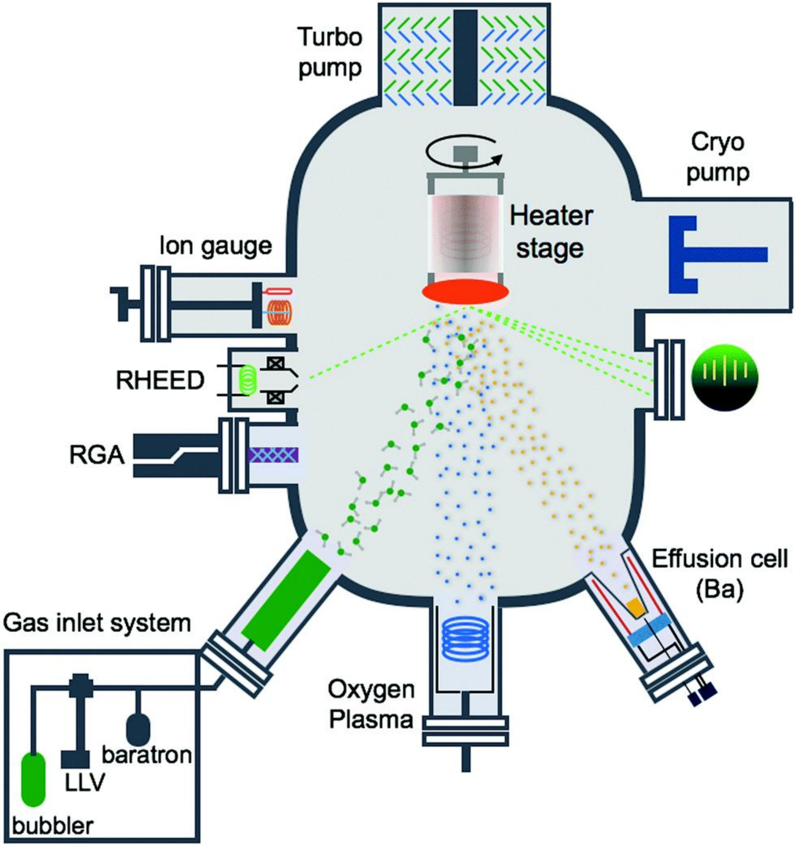
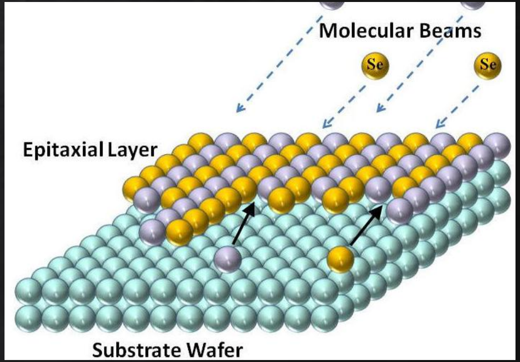
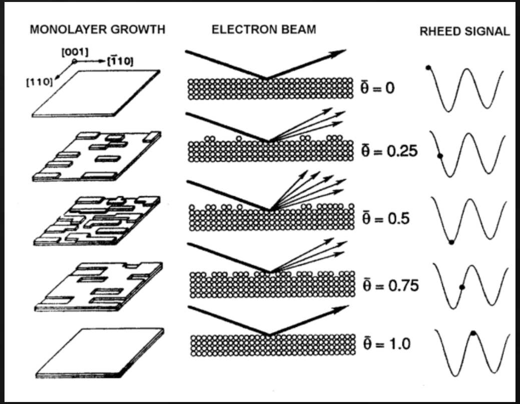
Crescimento por camadas

MBE- molecular beam epitaxy

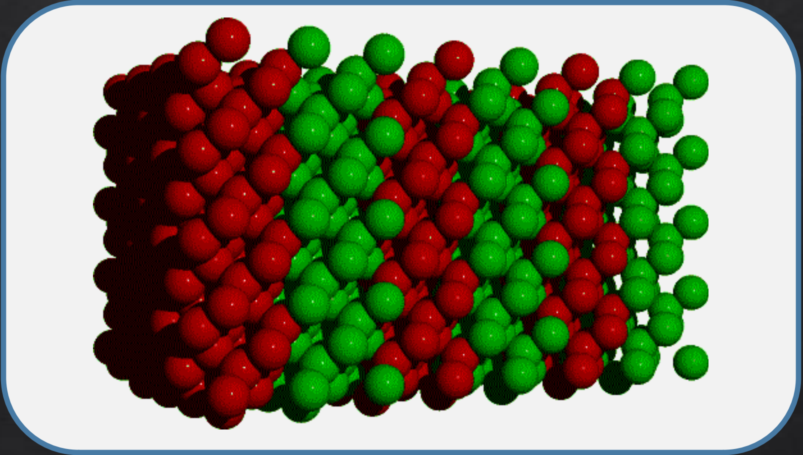








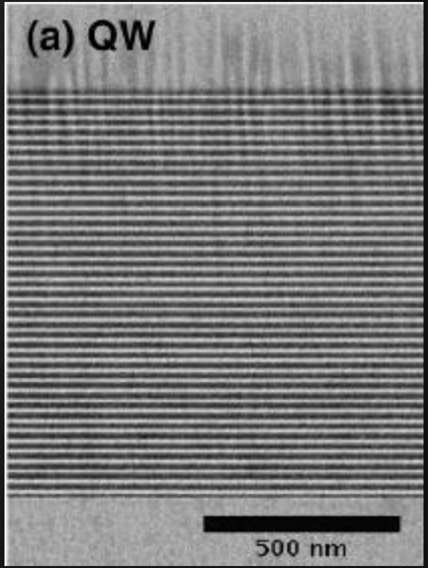
Heteroestruturas semicondutoras baixa dimensionalidade



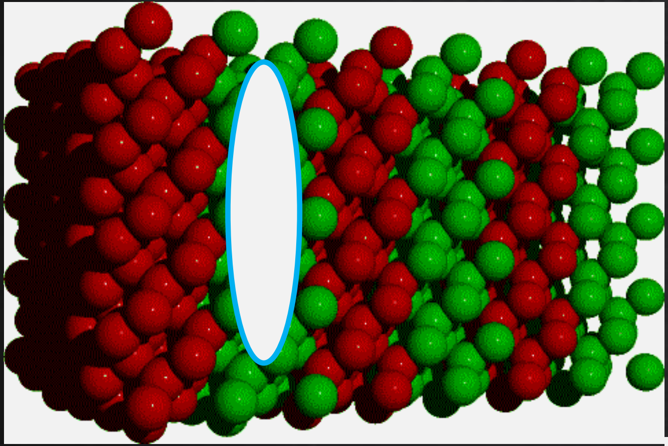
Engenharia
de gap

g
a
p

Poço quântico (*quantum well QW*)

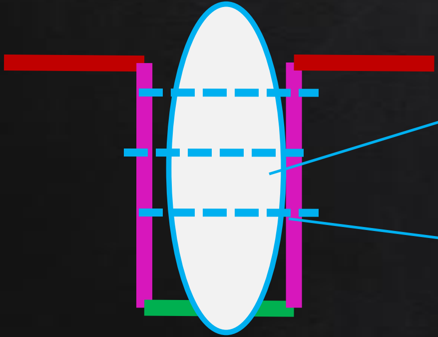


Heteroestruturas semicondutoras baixa dimensionalidade



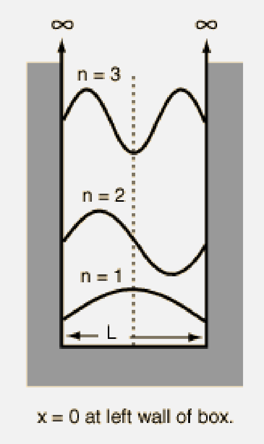
Dopagem seletiva (fora do poço)
- maior mobilidade

Poço Quântico

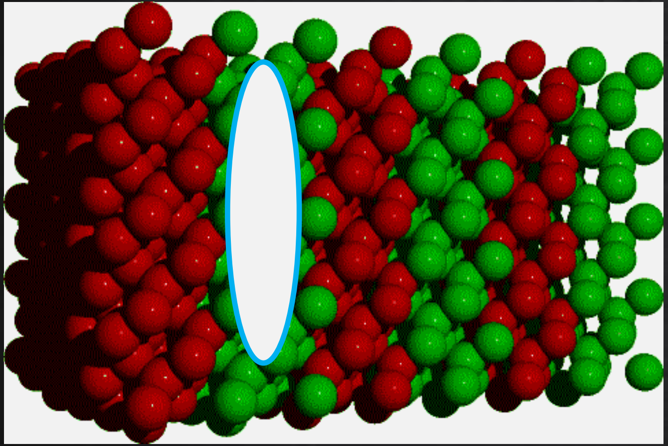


Camada 2D de elétrons

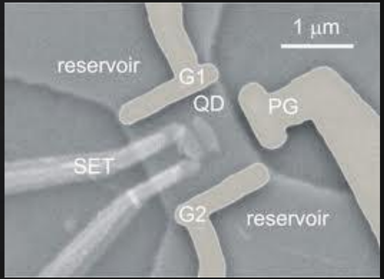
Níveis discretos de energias

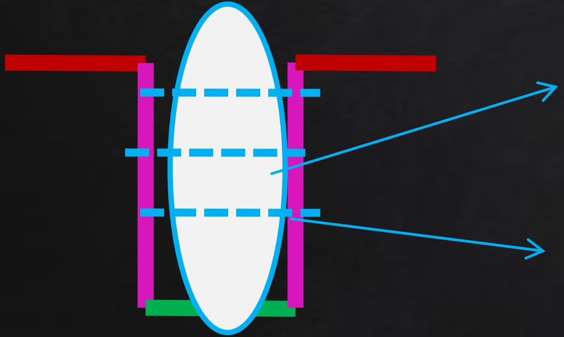


Heteroestruturas semicondutoras baixa dimensionalidade



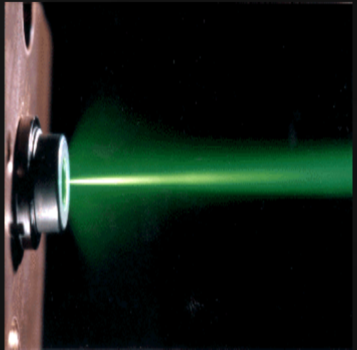
Camada 2D de elétrons
→ ótimo condutor
→ Chips rápidos



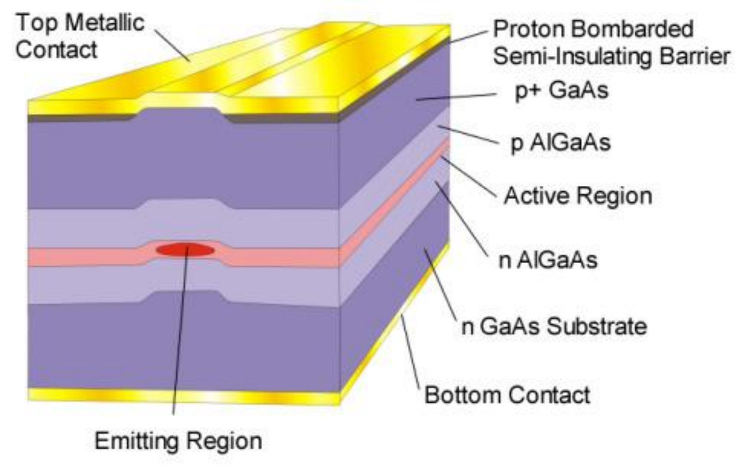


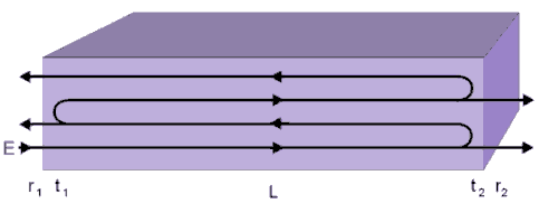
Níveis discretos de energias

→Absorção/emissão de luz
de freq. determinada
→ DETETORES / LASERs

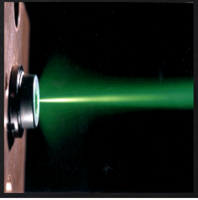


Heteroestruturas semicondutoras baixa dimensionalidade

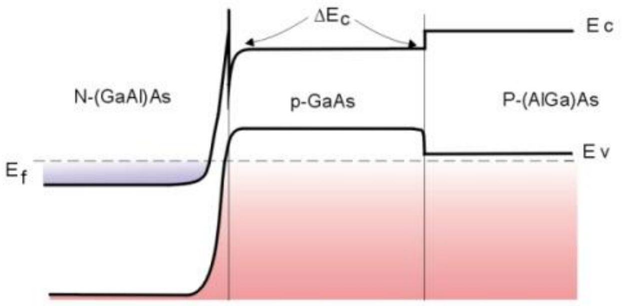




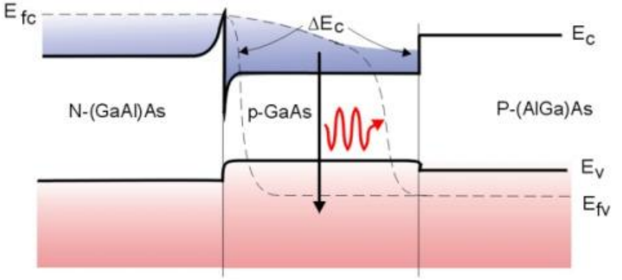
LASERS



(a) Equilibrium bandstructure

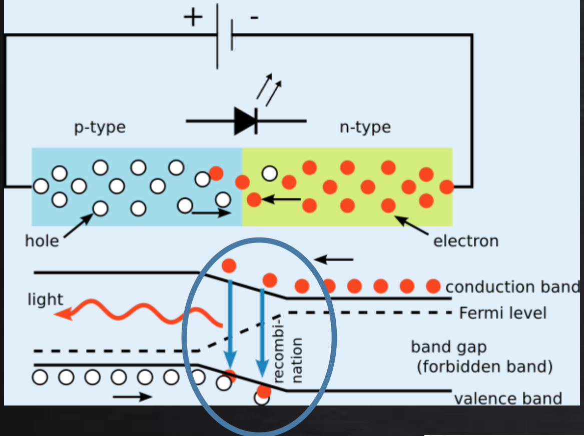


(b) Forward biased

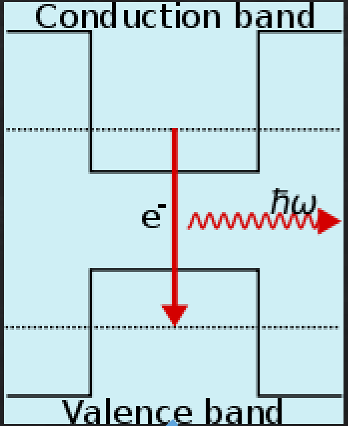


Laser de poço quântico

LED – junção PN

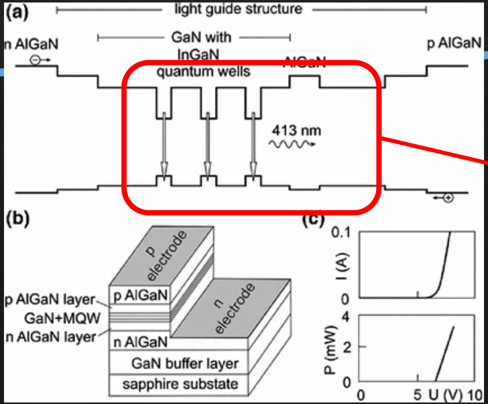


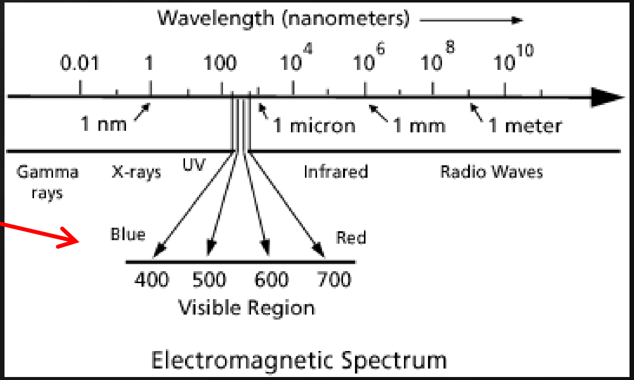
Emissão num poço quântico



Luz com frequência muito bem definida (laser)

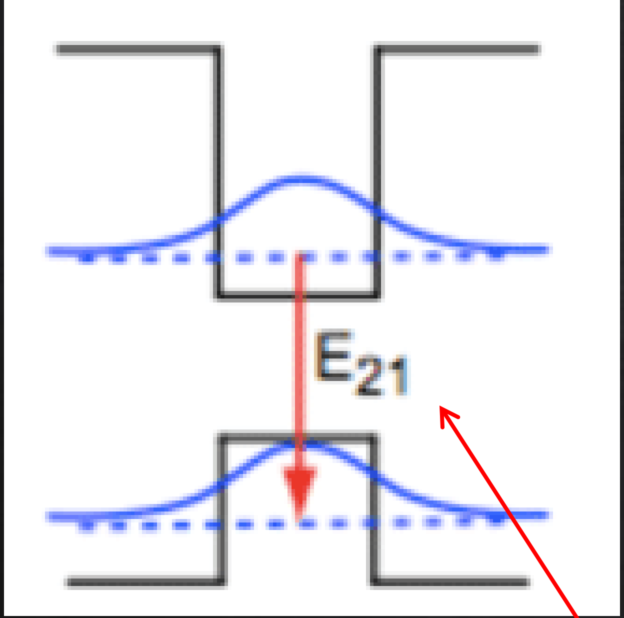
Energia alta – luz visível





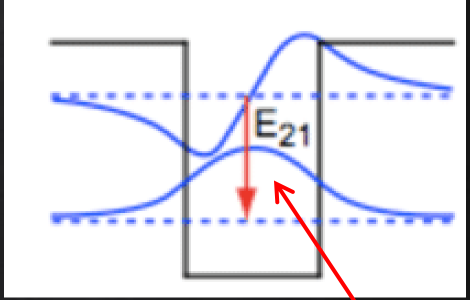
Laser de poço quântico

Emissão INTERBanda

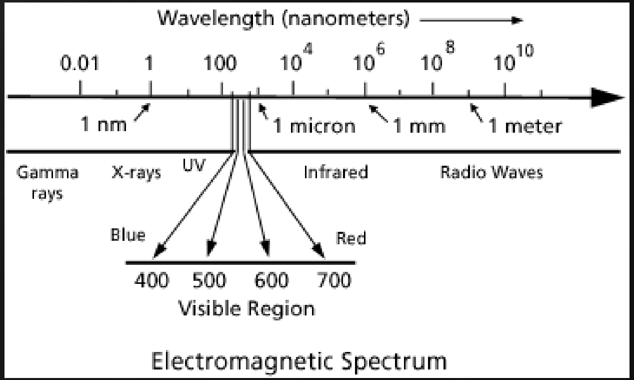


Alta energia
vísivel

Emissão INTRABanda



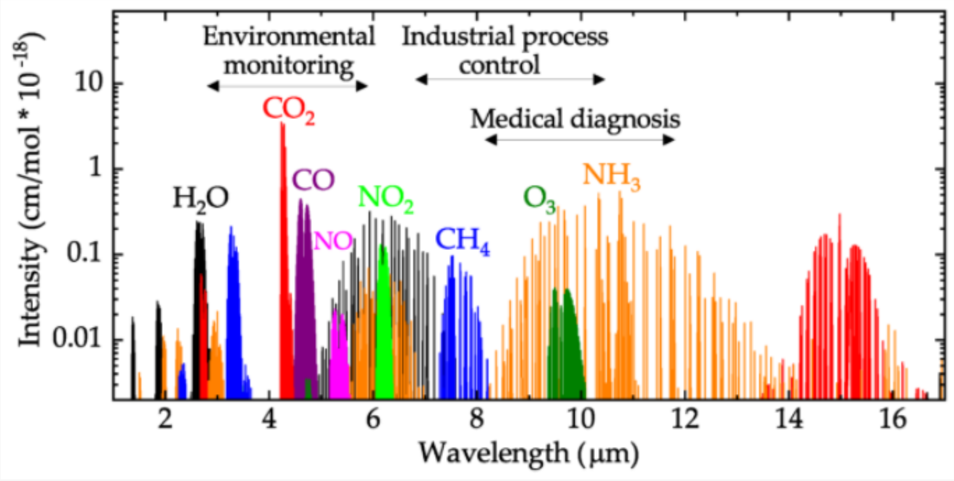
Baixa energia
Infravermelho

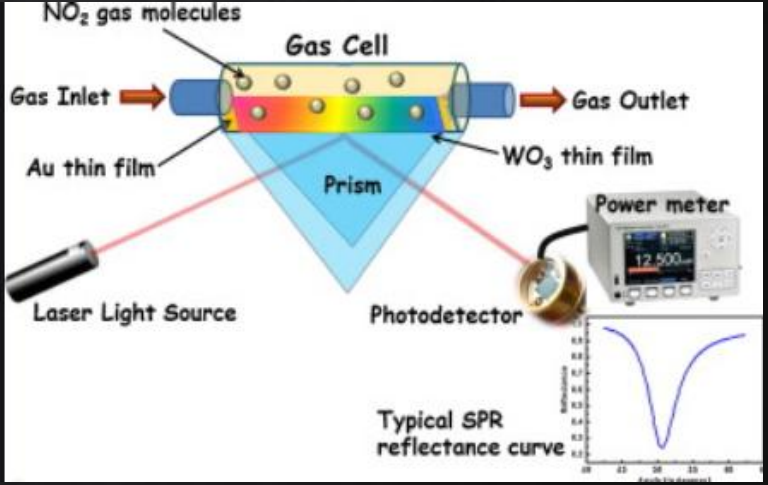


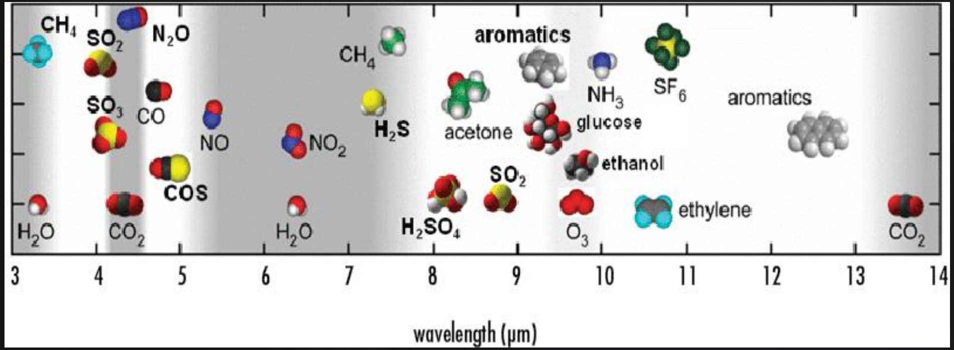
Espectroscopia no infravermelho (IR)

Sensores IR

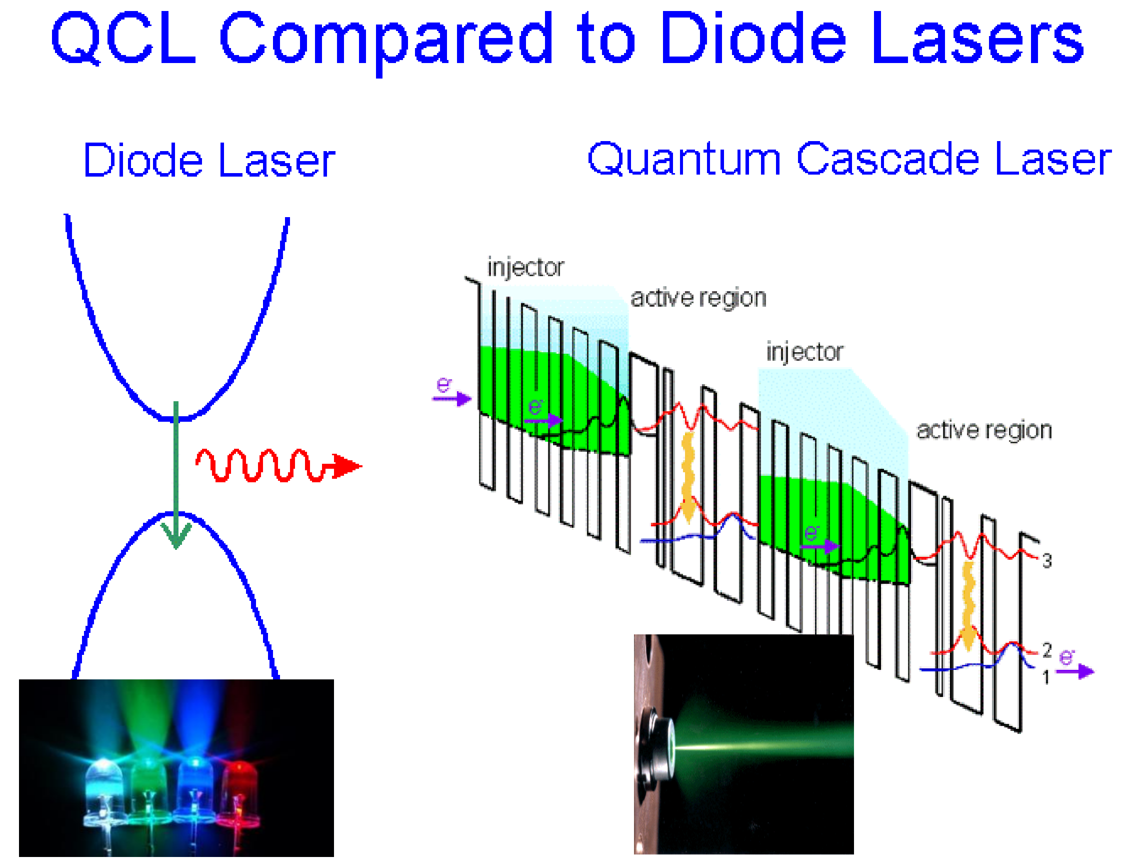
Figure 1. Mid-infrared absorption spectra of selected molecules with their relative intensities. H_2O: water; CO_2: carbon dioxide; CO: carbon monoxide; NO: nitric oxide; NO_2; nitrogen dioxide; CH_4: methane; O_3: oxygen; NH_3: ammonia. Source: HITRAN [10].







Heteroestruturas semicondutoras baixa dimensionalidade



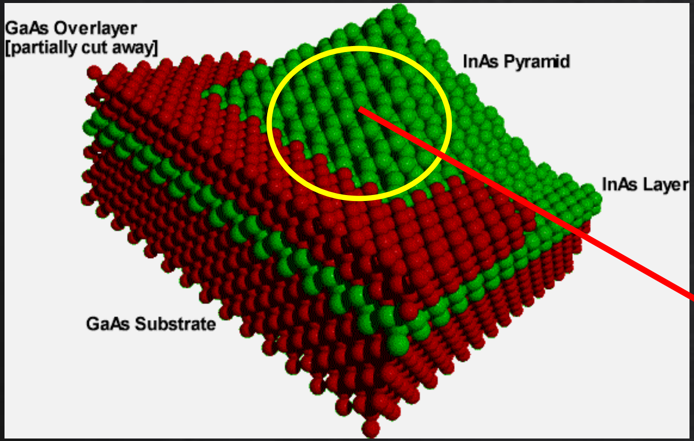
QCL Compared to Diode Lasers

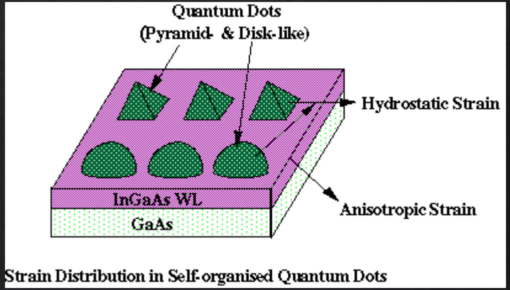
Diode Laser

Quantum Cascade Laser

Heteroestruturas semicondutoras baixa dimensionalidade

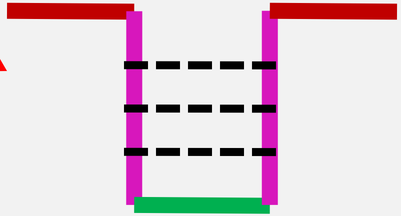
Pontos quânticos (*quantum dots QD*)

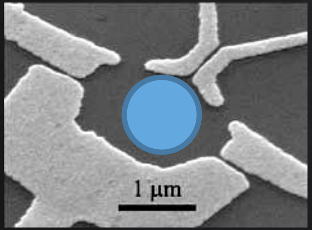




Strain Distribution in Self-organised Quantum Dots

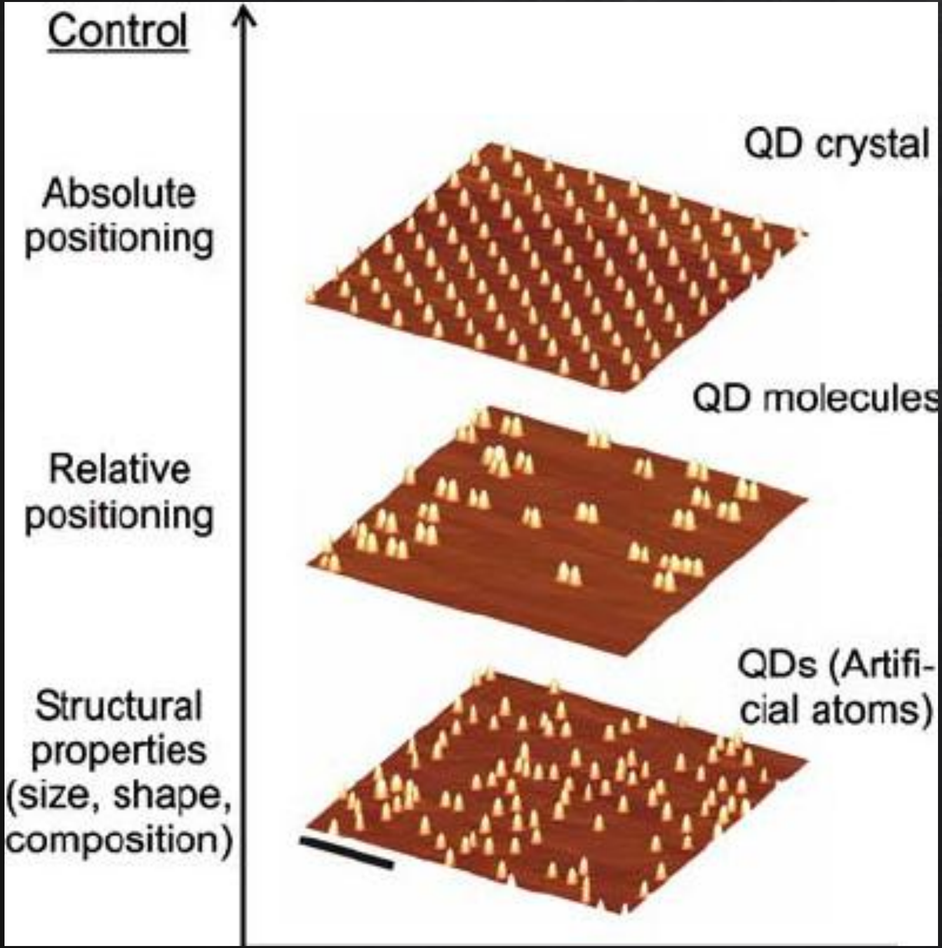
Átomos artificiais

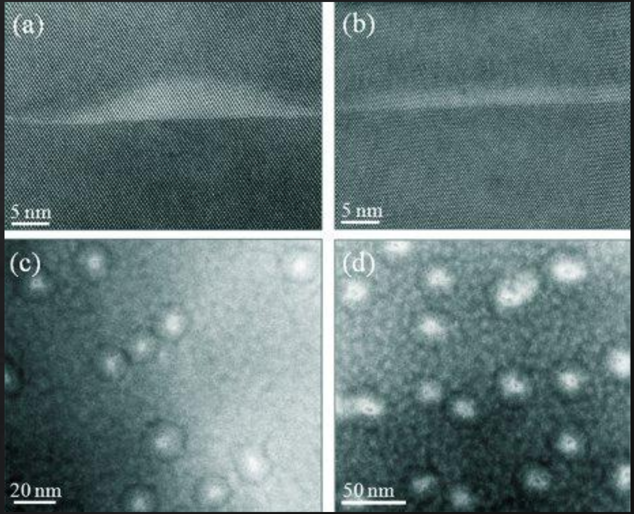




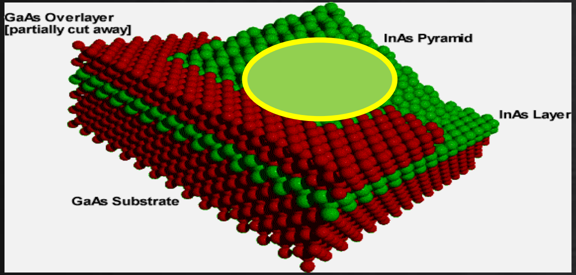
Níveis discretos de energias
→Absorção/emissão de luz
De freq. determinada
→ DETETORES / LASERs

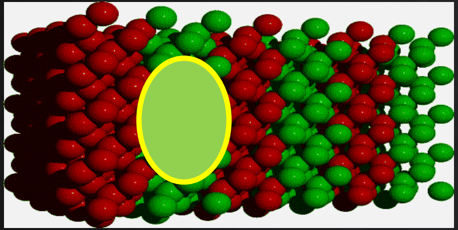
Heteroestruturas semicondutoras baixa dimensionalidade

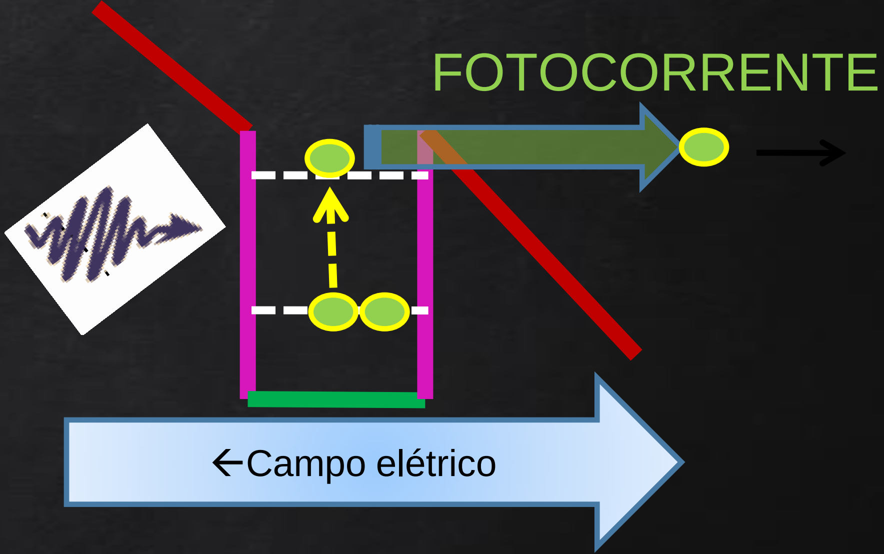




Detetor Infravermelho

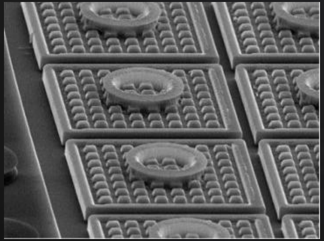






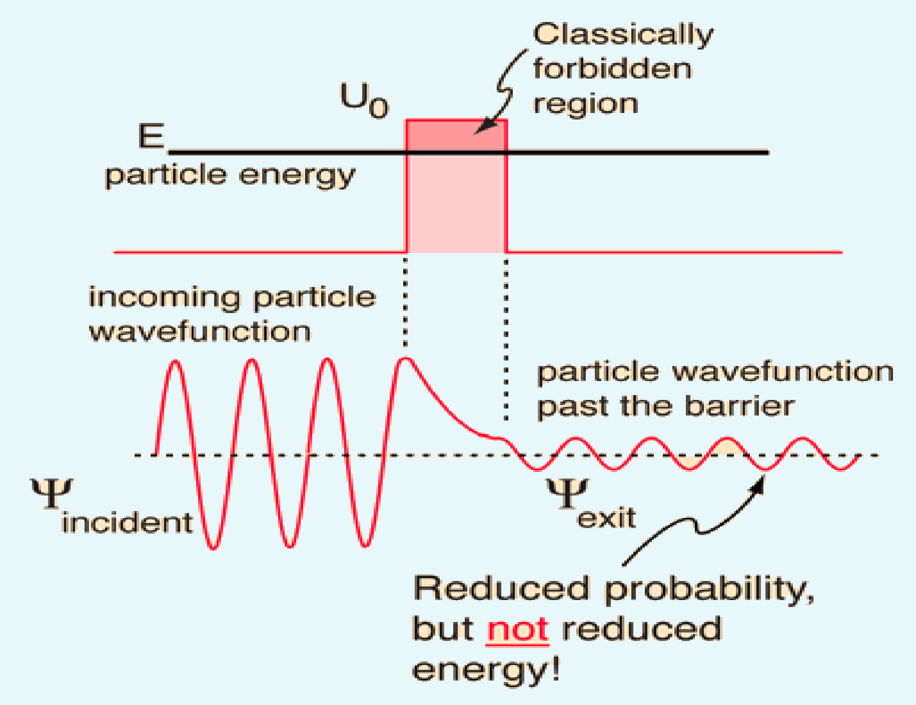
FOTOCORRENTE

←Campo elétrico

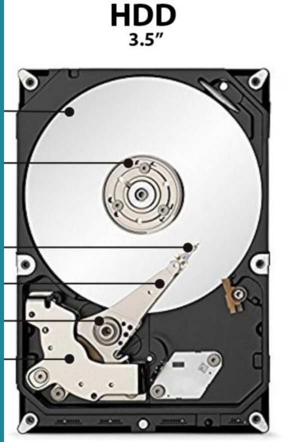


Pode ser também o princípio de funcionamento das células fotovoltaicas

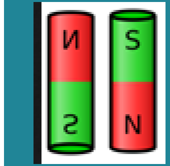
Tunelamento quântico

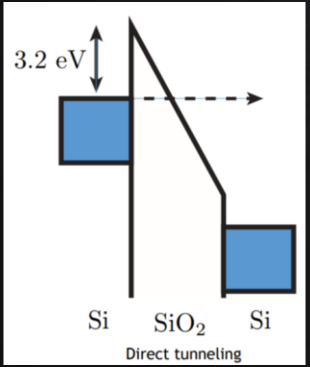


Algumas aplicações do tunelamento quântico: Memória Flash (SSD)

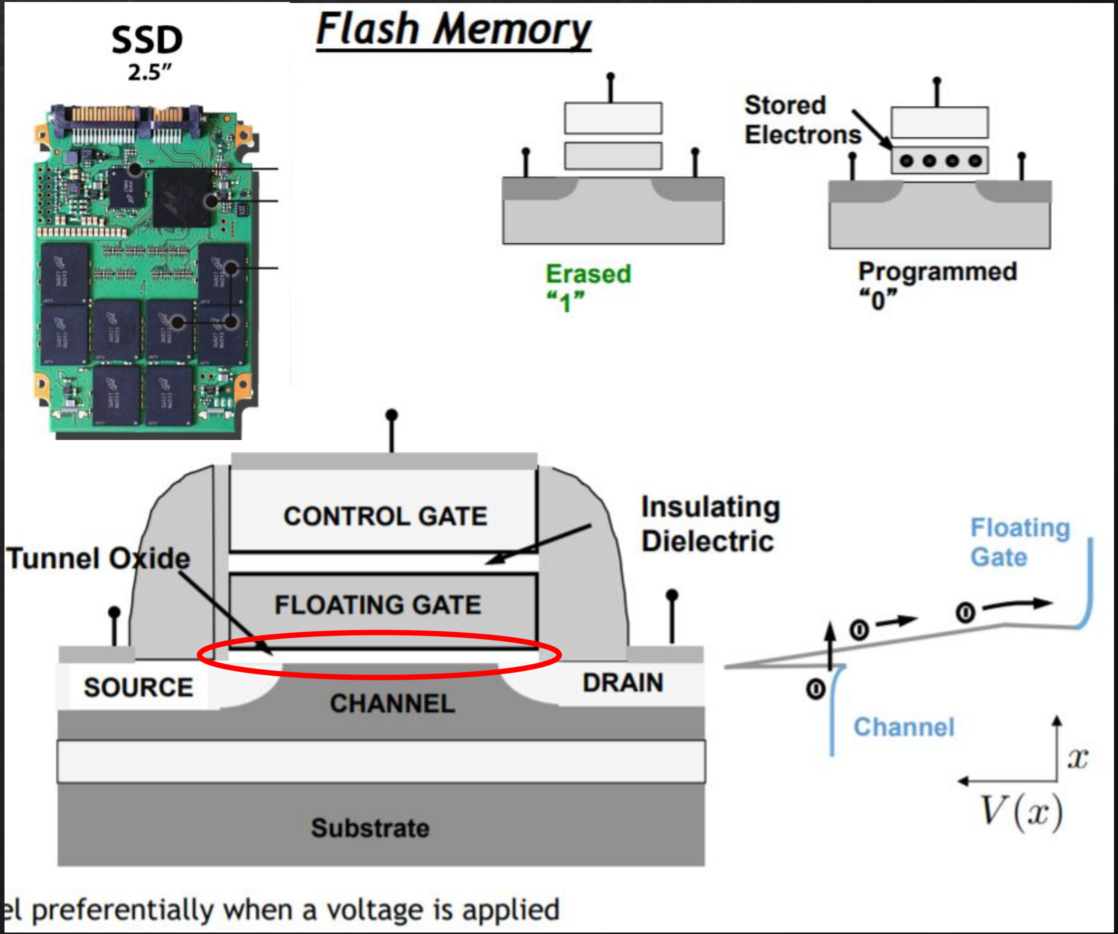


HD magnético





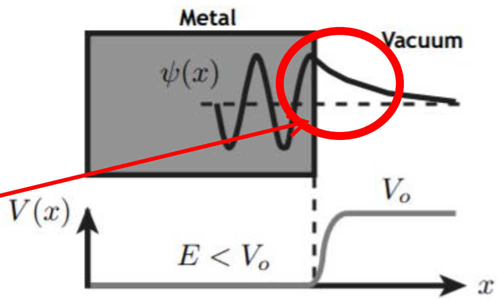
Barreira isolante

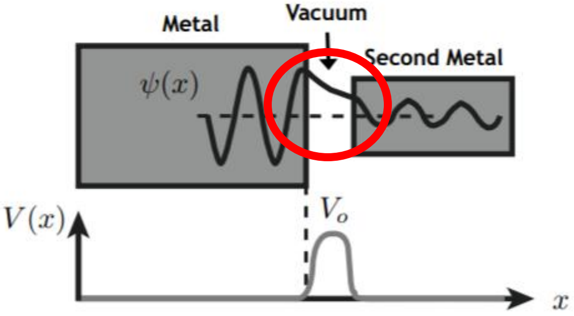


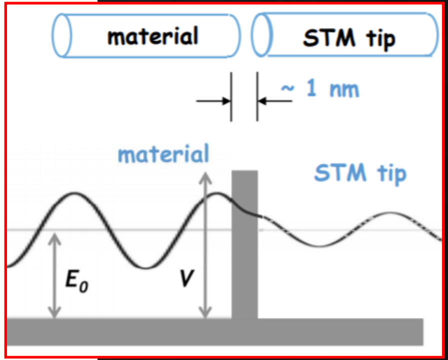
el preferentially when a voltage is applied

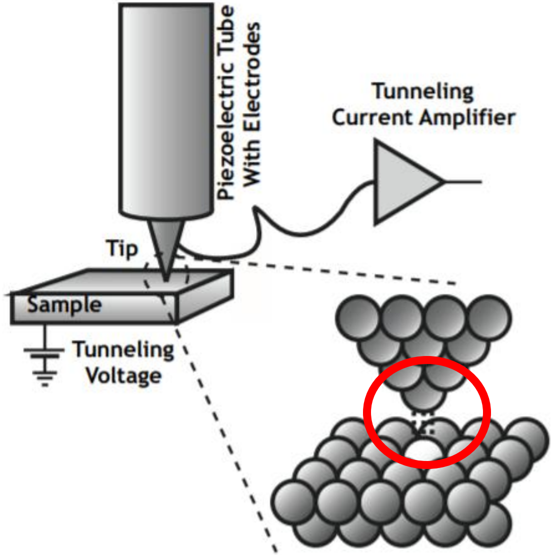
Algumas aplicações do tunelamento quântico: STM – Scanning Tunneling Microscopy

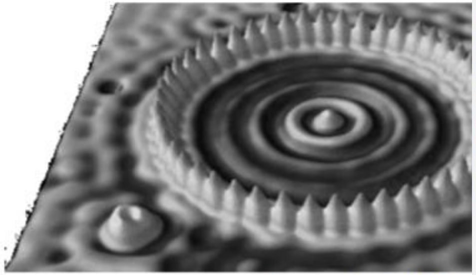
≈ 0.3 nm











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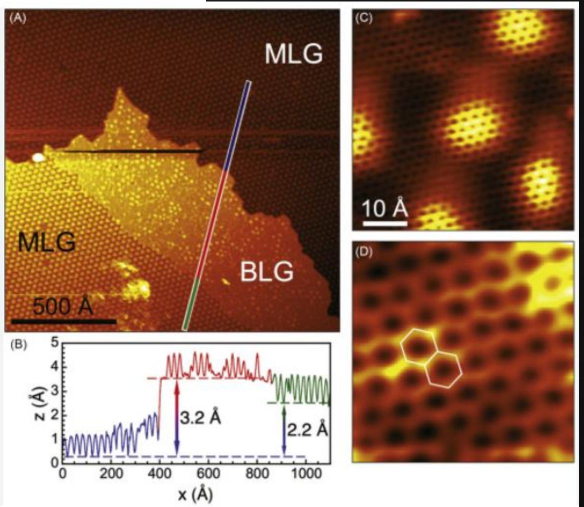
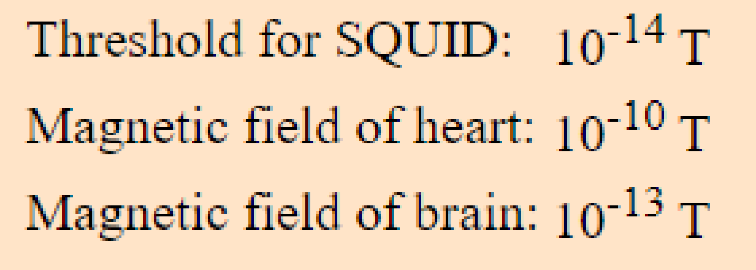


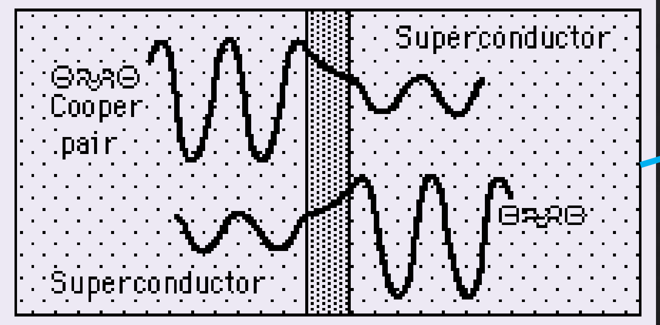
Algumas aplicações do tunelamento quântico:

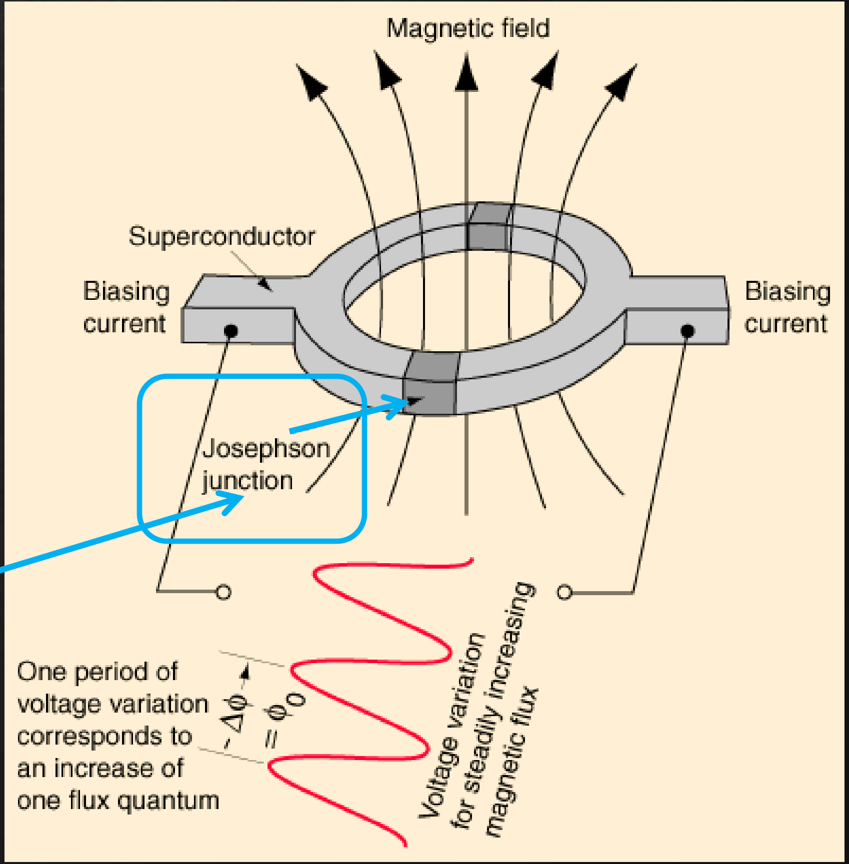
SQUID (Superconducting Quantum Interference Device) – Mede campo magnético



Threshold for SQUID:	10^{-14} T
Magnetic field of heart:	10^{-10} T
Magnetic field of brain:	10^{-13} T

Junção Josephson (S-N-S)

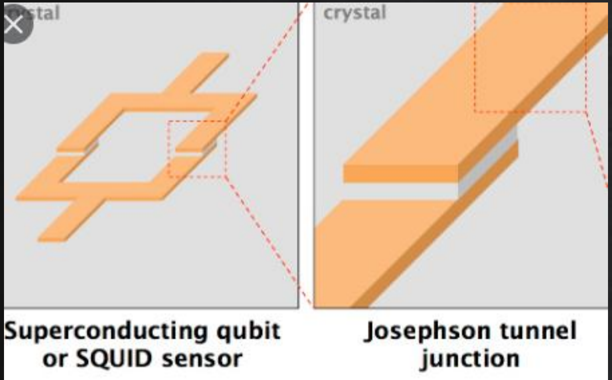


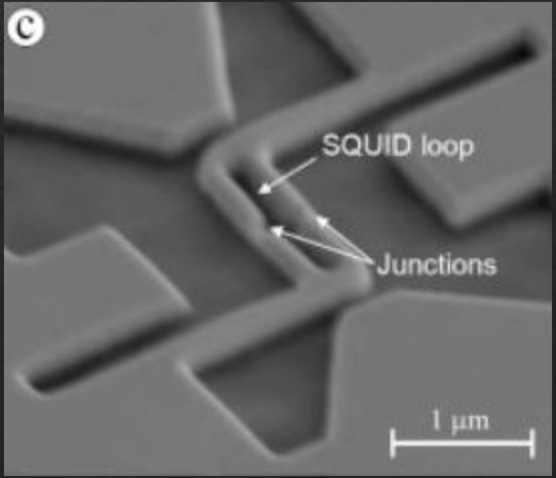


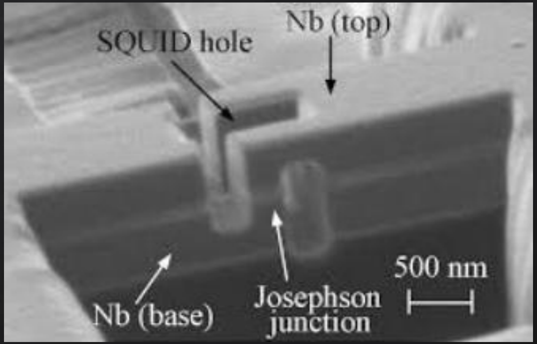
One period of voltage variation corresponds to an increase of one flux quantum

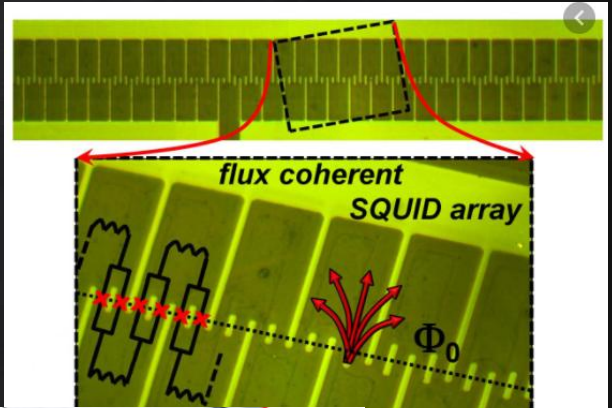
Algumas aplicações do tunelamento quântico:

SQUID (Superconducting Quantum Interference Device) – Mede campo magnético



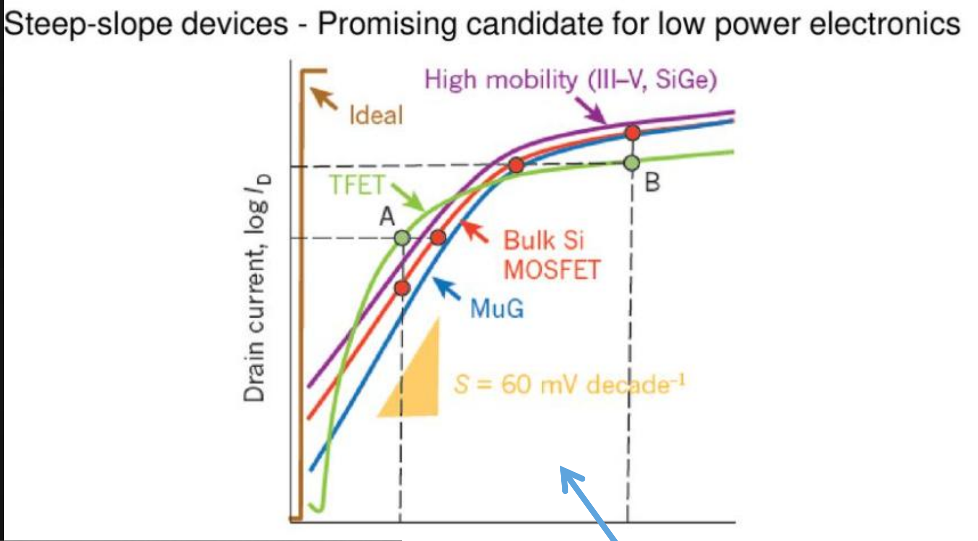


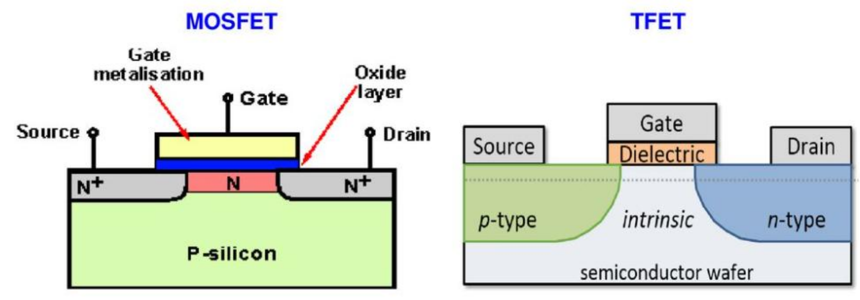


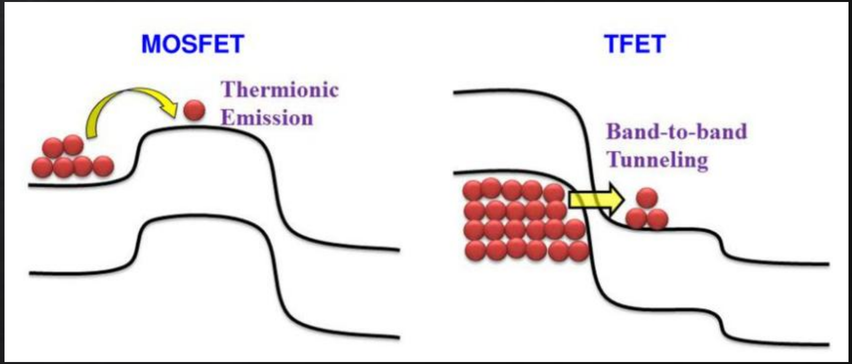


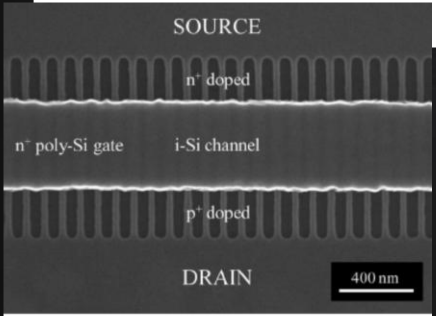
Algumas aplicações do tunelamento quântico:

Tunnel field-effect transistor







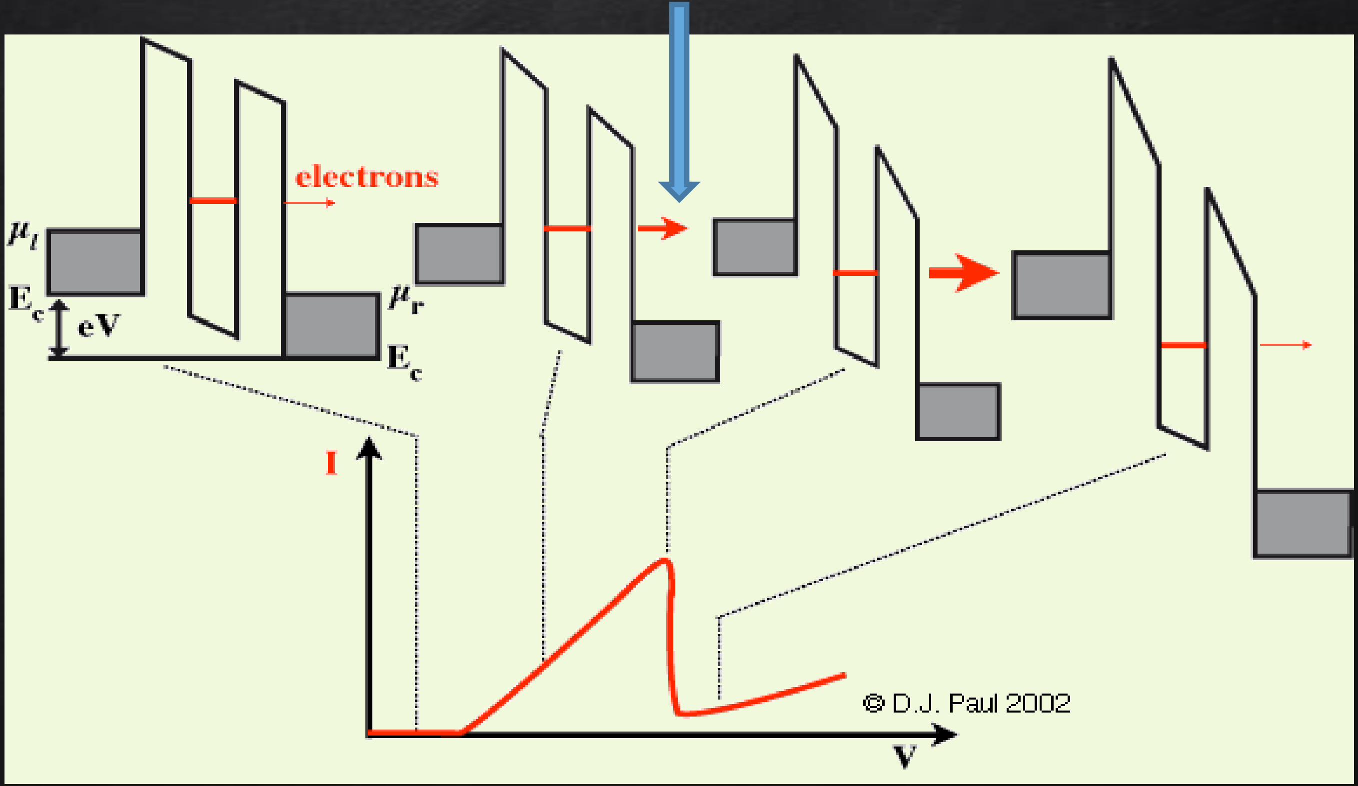


canning electron microscope image of a NW-TFET array with a nominal wire pitch of 100 nm and wire width of 20 nm. An intrinsic Si channel region is preserved under the 500-nm-wide poly-Si gate and n + - and p + - egions were formed through ion implantation and RTA, ELA, and LT-RTA

Maior eficiência energética (não há barreira)

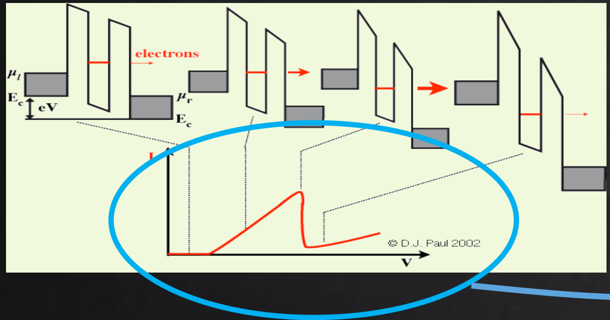
Tunelamento ressonante - Uso

“abaixa” o drain (voltagem)



Curva Corrente-Voltagem

Tunelamento ressonante - Uso



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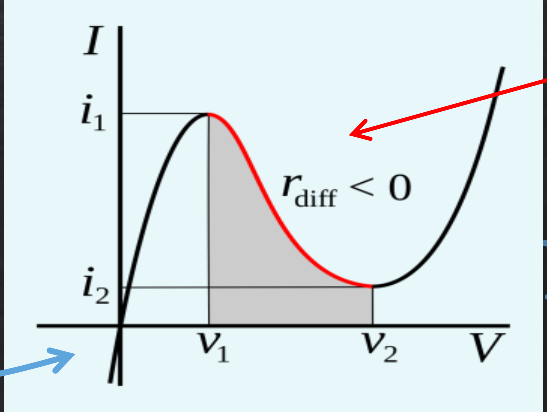
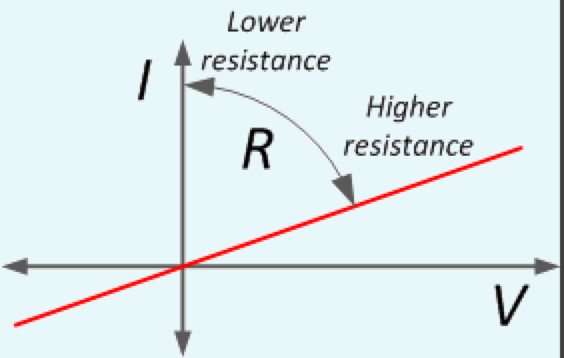


Região de “resistência diferencial negativa”

V aumenta – *I* diminui



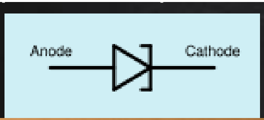
Lei de Ohm – R=V/I

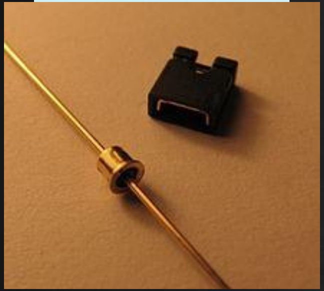
V aumenta – *I* Aumenta

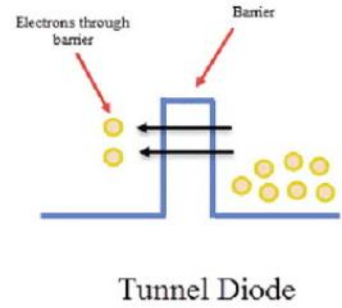
Tunelamento ressonante - Uso

"diodo túnel" (não ressonante)

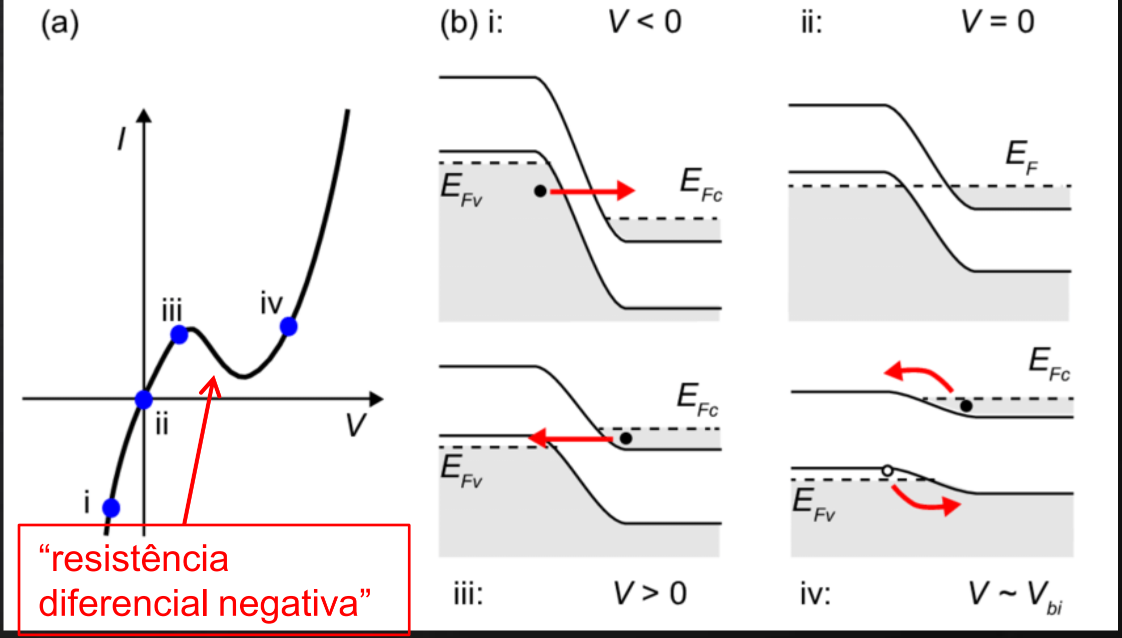
https://en.wikipedia.org/wiki/Tunnel_diode





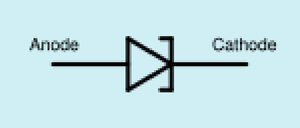


Tunelamento através do gap valência-condução

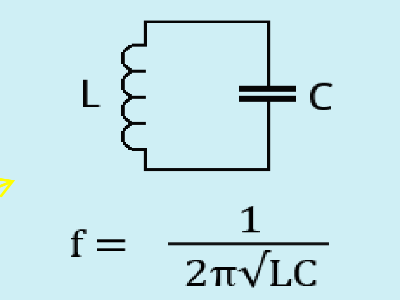


"resistência diferencial negativa"

Diodos Túnel (ressonante ou não) em uso

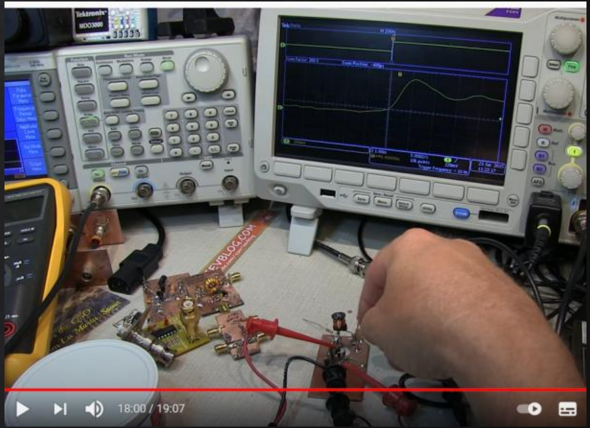


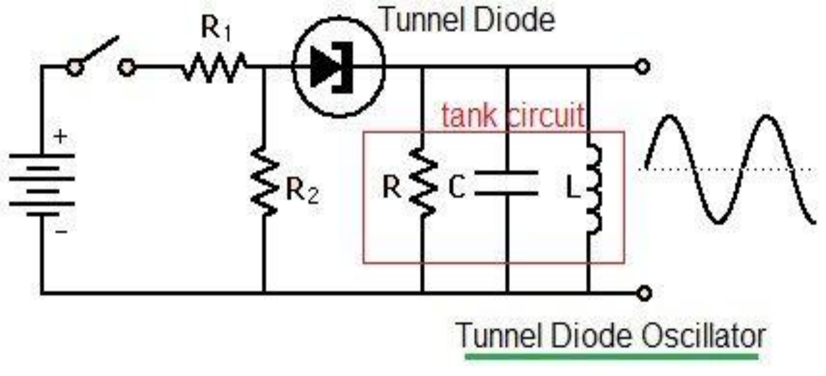
Alimentação de um Oscilador LC
(tank circuit)



$$f = \frac{1}{2\pi\sqrt{LC}}$$

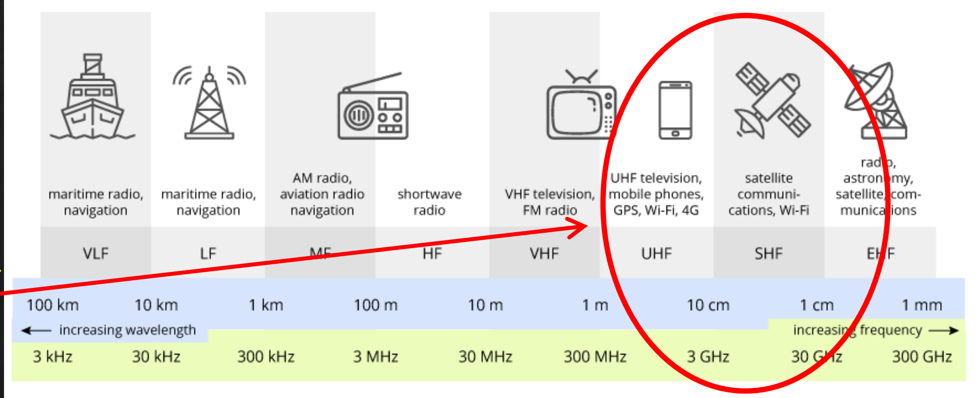
https://www.youtube.com/watch?v=PuG8CCUbg58





Tunnel Diode Oscillator

Obs.: Diodo tuunel funciona em altíssima frequência
(acima de GHz)



maritime radio, navigation	maritime radio, navigation	AM radio, aviation radio navigation	shortwave radio	VHF television, FM radio	UHF television, mobile phones, GPS, Wi-Fi, 4G	satellite communi- cations, Wi-Fi	radio, astronomy, satellite com- munications
VLF	LF	MF	HF	VHF	UHF	SHF	EHF

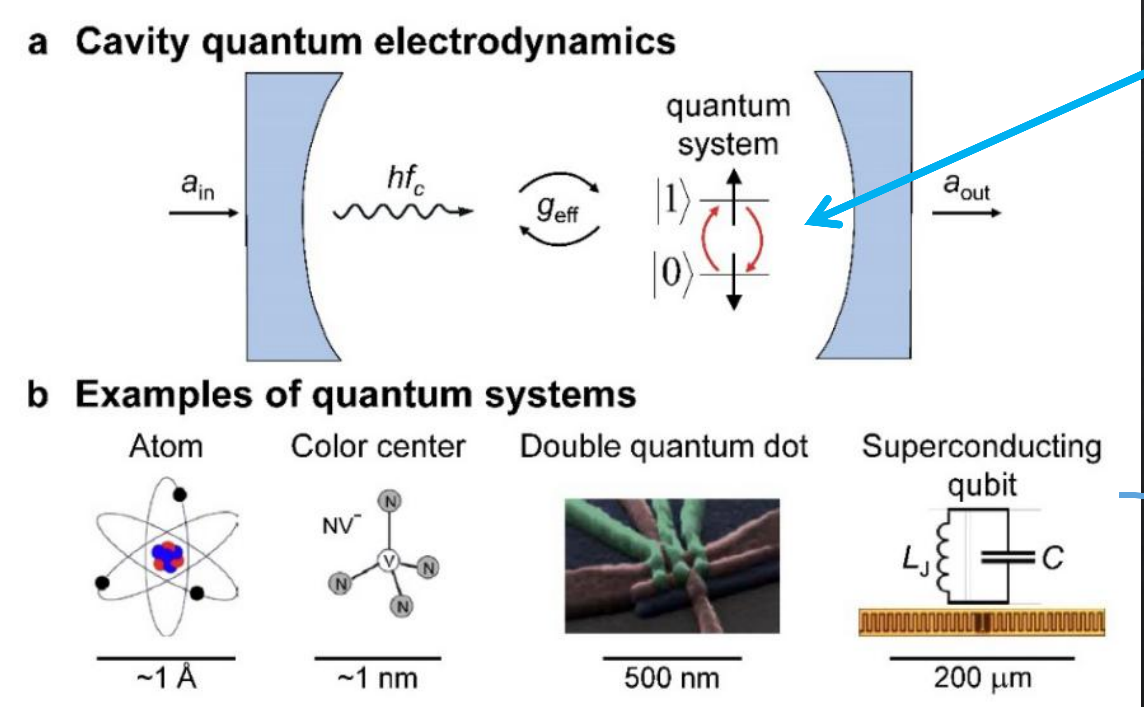
100 km 10 km 1 km 100 m 10 m 1 m 10 cm 1 cm 1 mm

← increasing wavelength

increasing frequency →

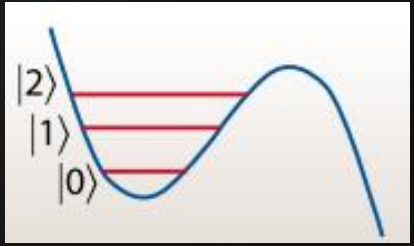
3 kHz 30 kHz 300 kHz 3 MHz 30 MHz 300 MHz 3 GHz 30 GHz 300 GHz

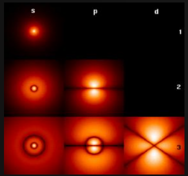
Computação Quântica - Plataformas

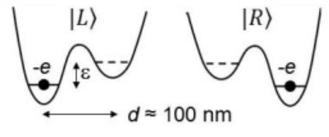


Bit quântico
“qubit”

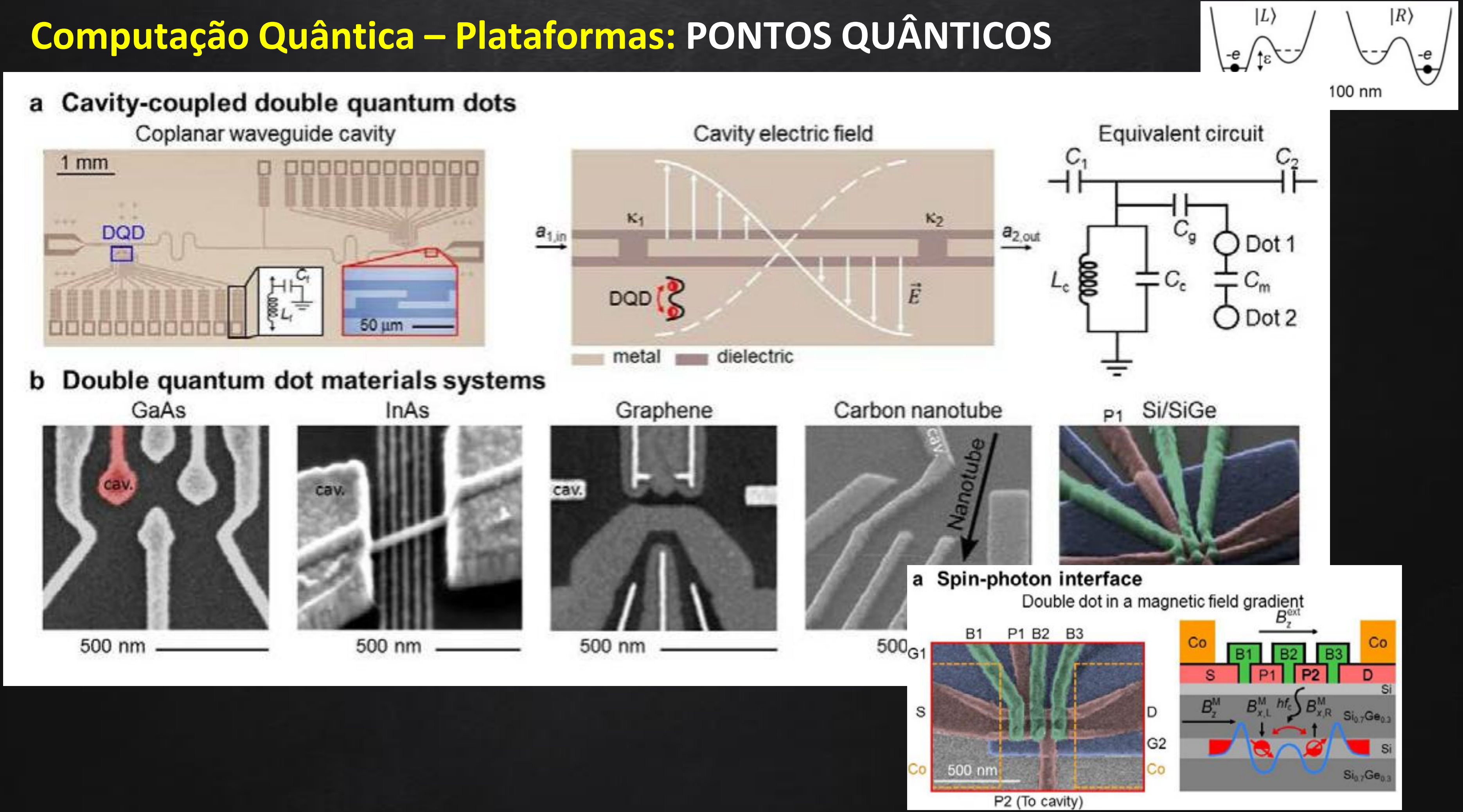
Algumas plataformas





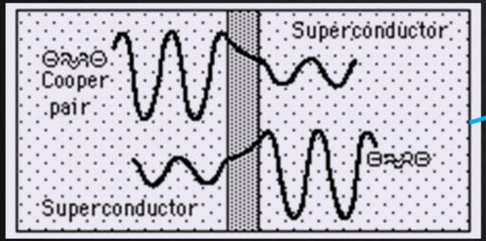


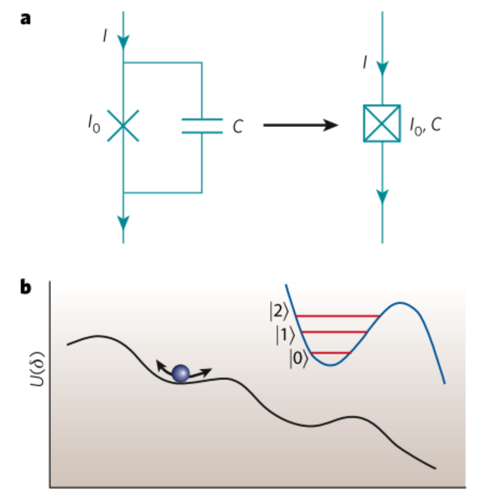
Computação Quântica – Plataformas: PONTOS QUÂNTICOS



Computação Quântica – Plataformas: QUBIT SUPERCONDUTOR

Junção Josephson (S-N-S)





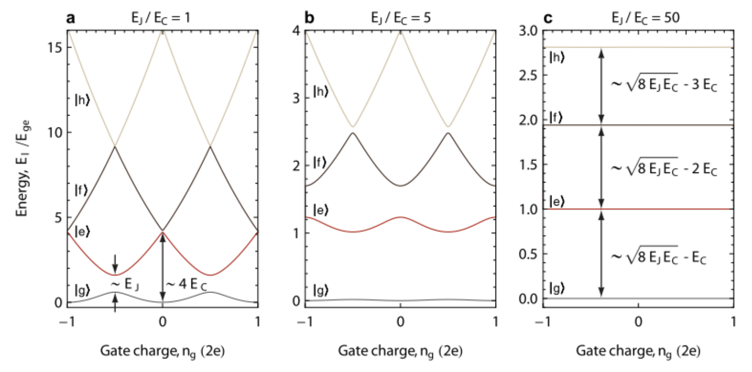
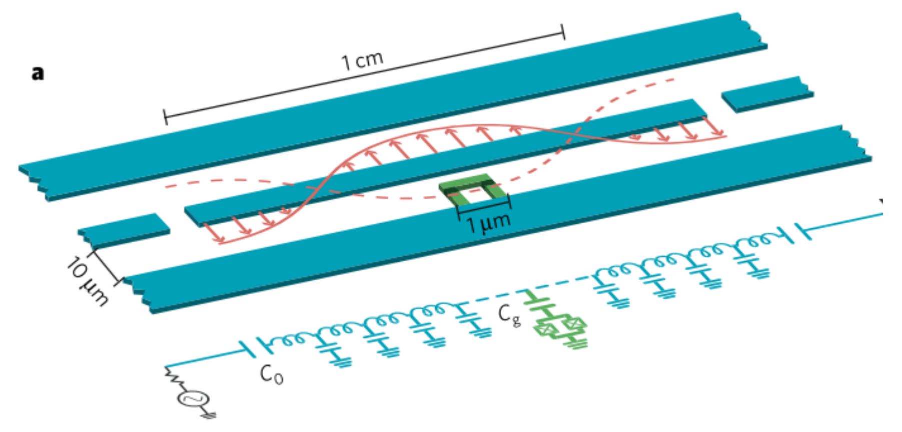


Figure 2.5: **Energy level diagram of the Cooper pair box and the transmon.** Calculated eigenenergies E_l of



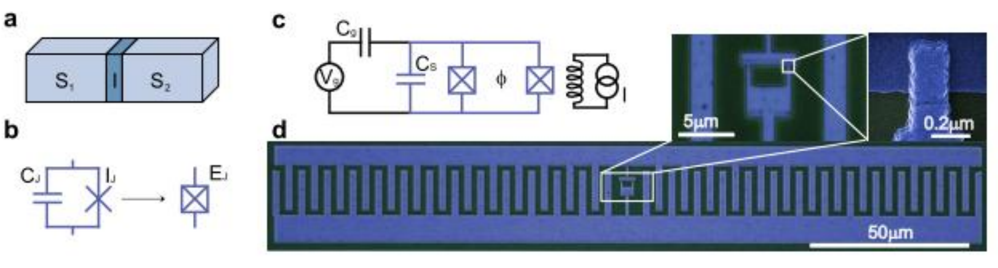
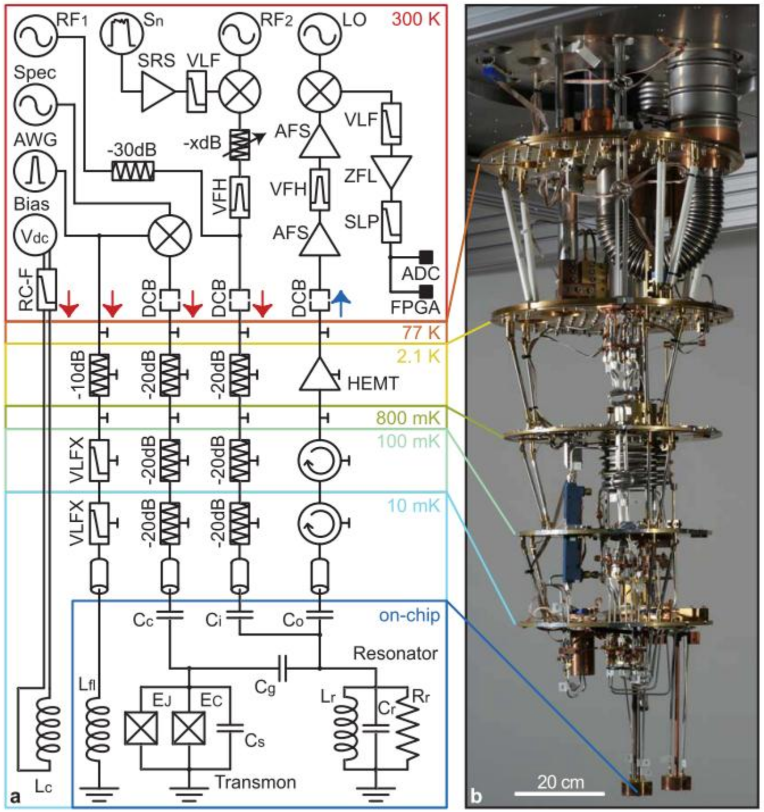


Figure 2.4: **Josephson junction and transmon charge qubit. a,** A Josephson tunnel junction consisting of

Computação Quântica – Plataformas: QUBIT SUPERCONDUTOR



gure 4.1: **Exemplary measurement & control circuit (a) and cryogenic part of the setup (b).** **a**, Th
ansmon (bottom, middle) is controlled via a superconducting coil L_c, an on-chip flux bias line with larg