Materiais Elétricos e Magnéticos para Engenharia

Prof. Marcus V. Batistuta

batistuta@unb.br

Aula-1

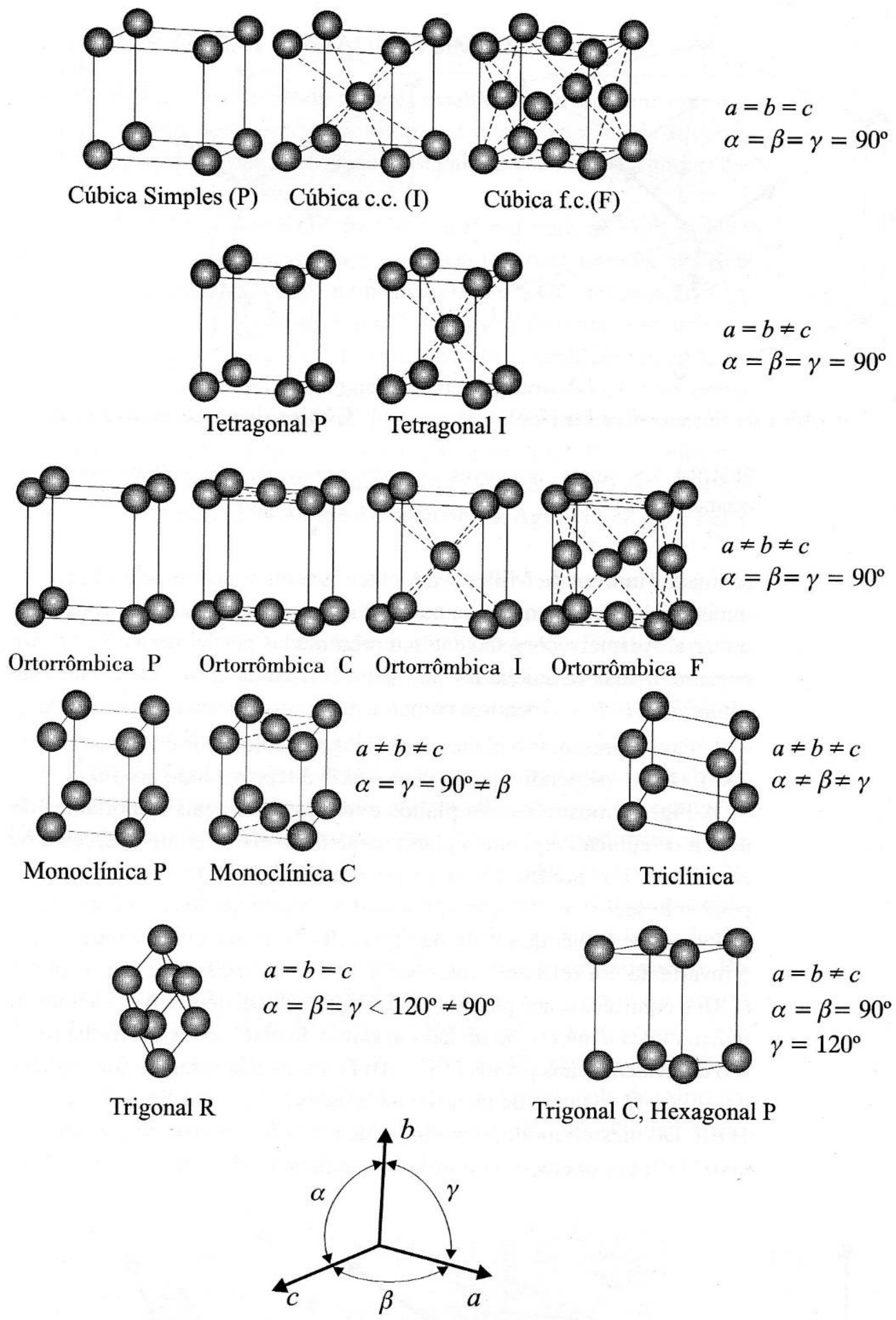
Ondas e Partículas na Matéria

1º Semestre de 2018

FGA - Universidade de Brasília

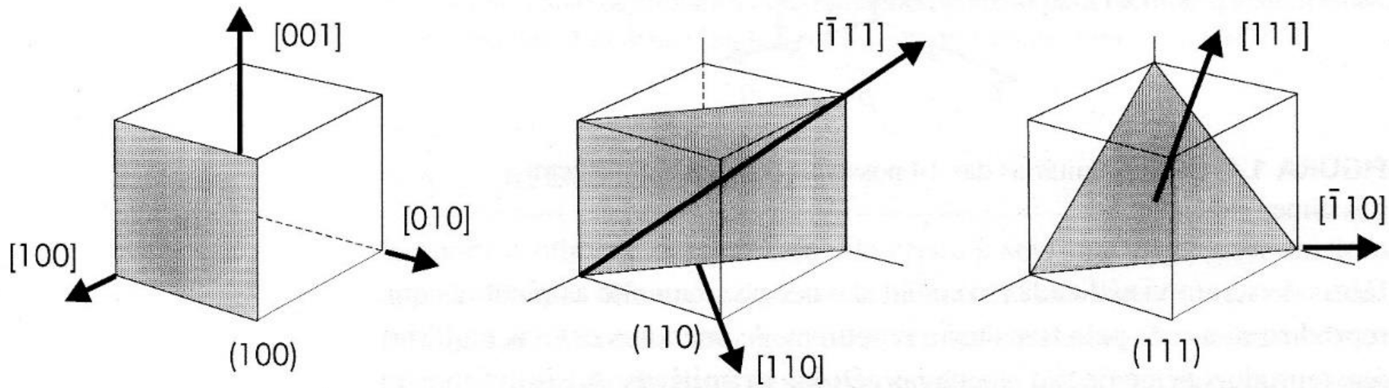
14 Tipos Básicos de Redes Cristalinas de Bravais

Auguste Bravais (1850)

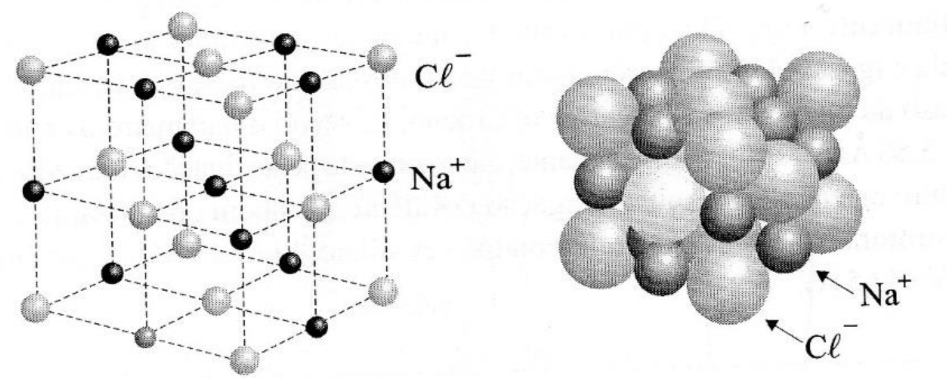


Pirita (FeS_2)

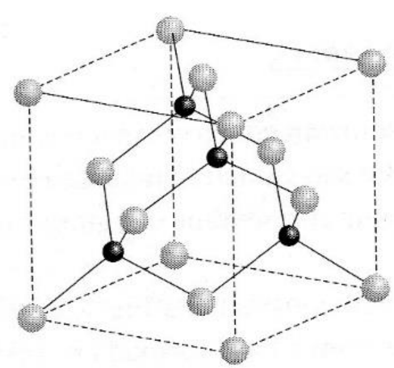
Cúbico



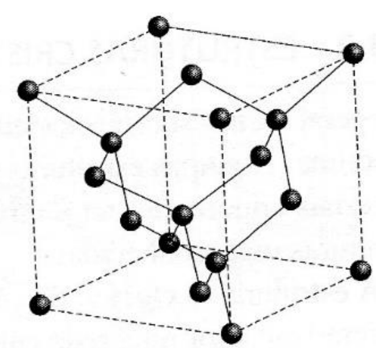
Índices de Miller (Rede Cúbica)



NaCl

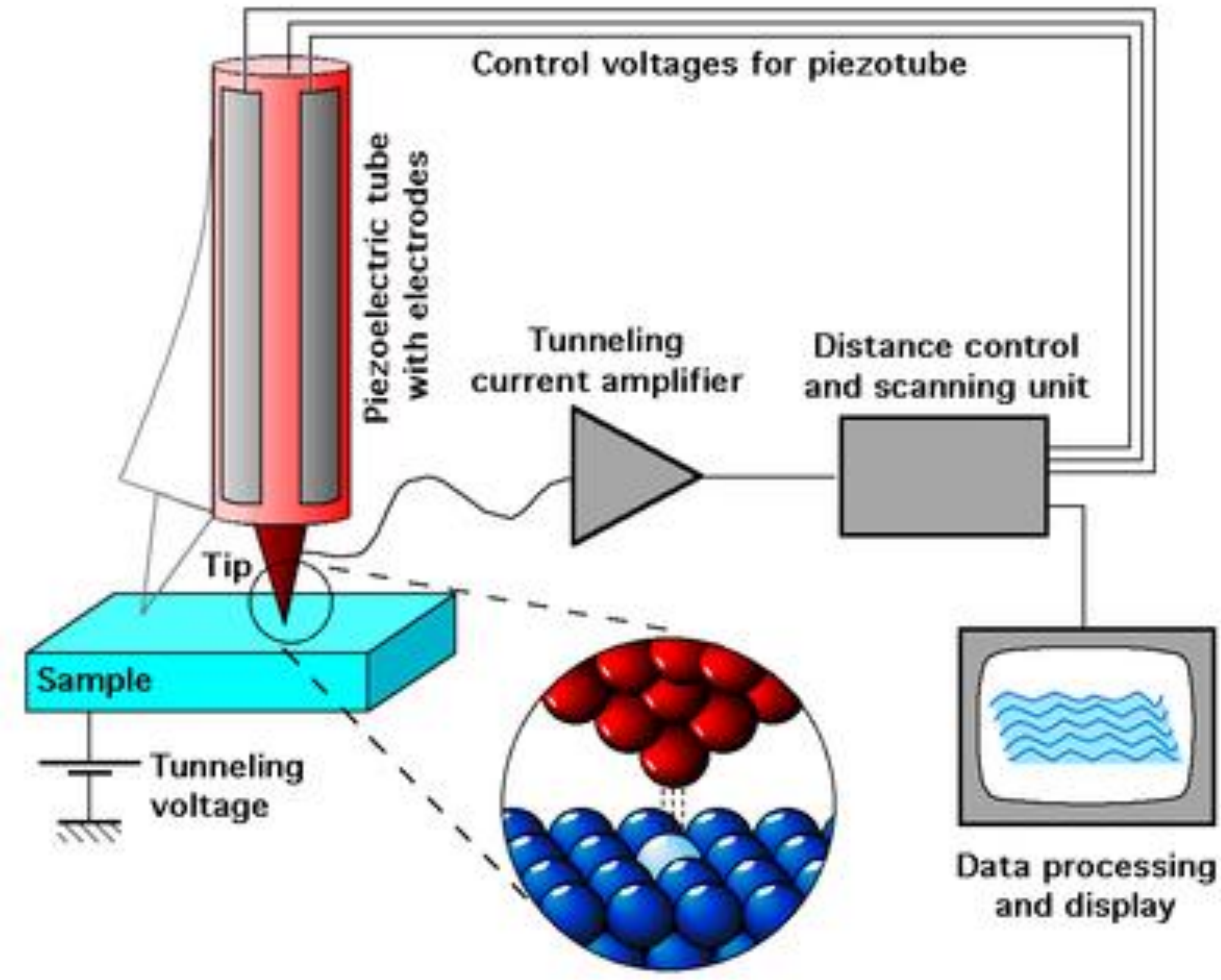


ZnS, GaAs

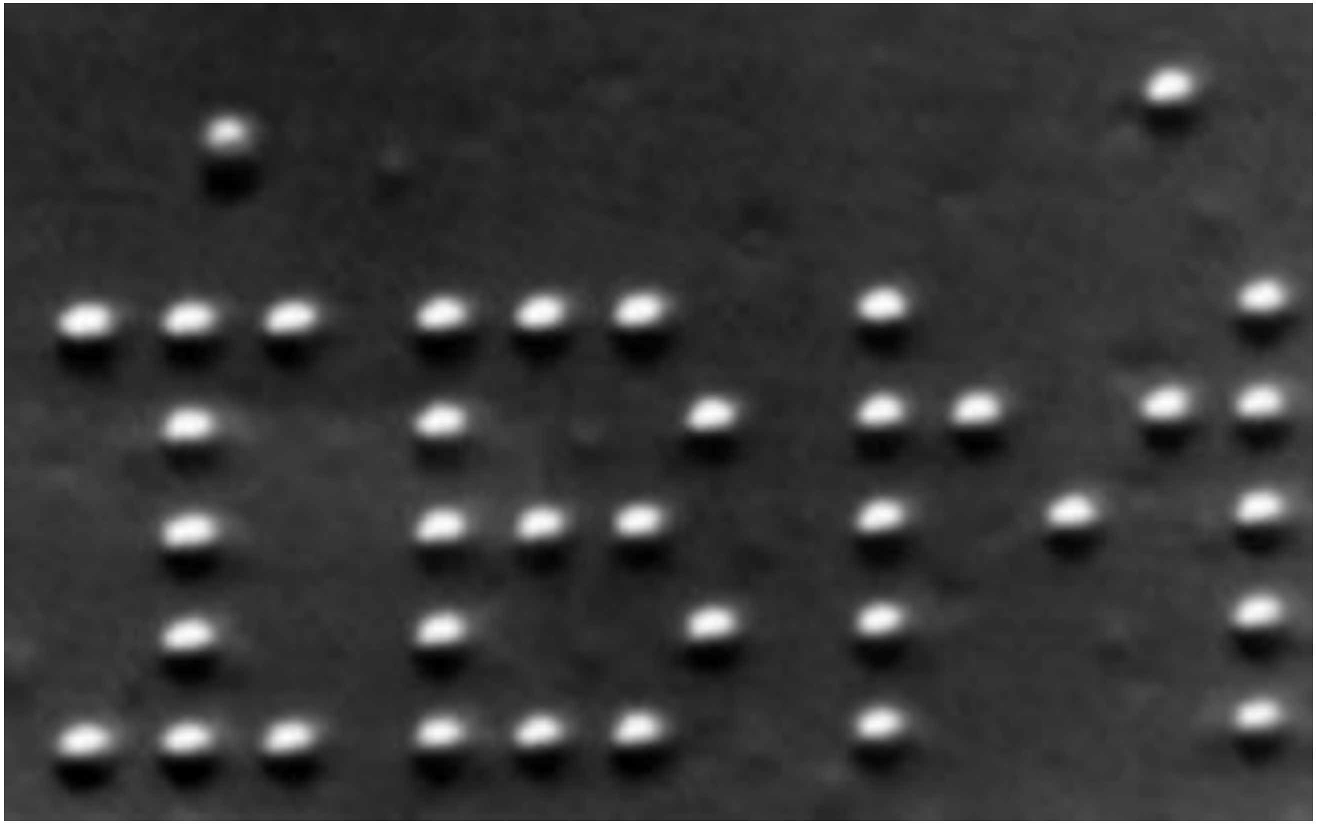


Si, Ge

Scanning Tunneling Microscope (STM)



Scanning Tunneling Microscope (STM)

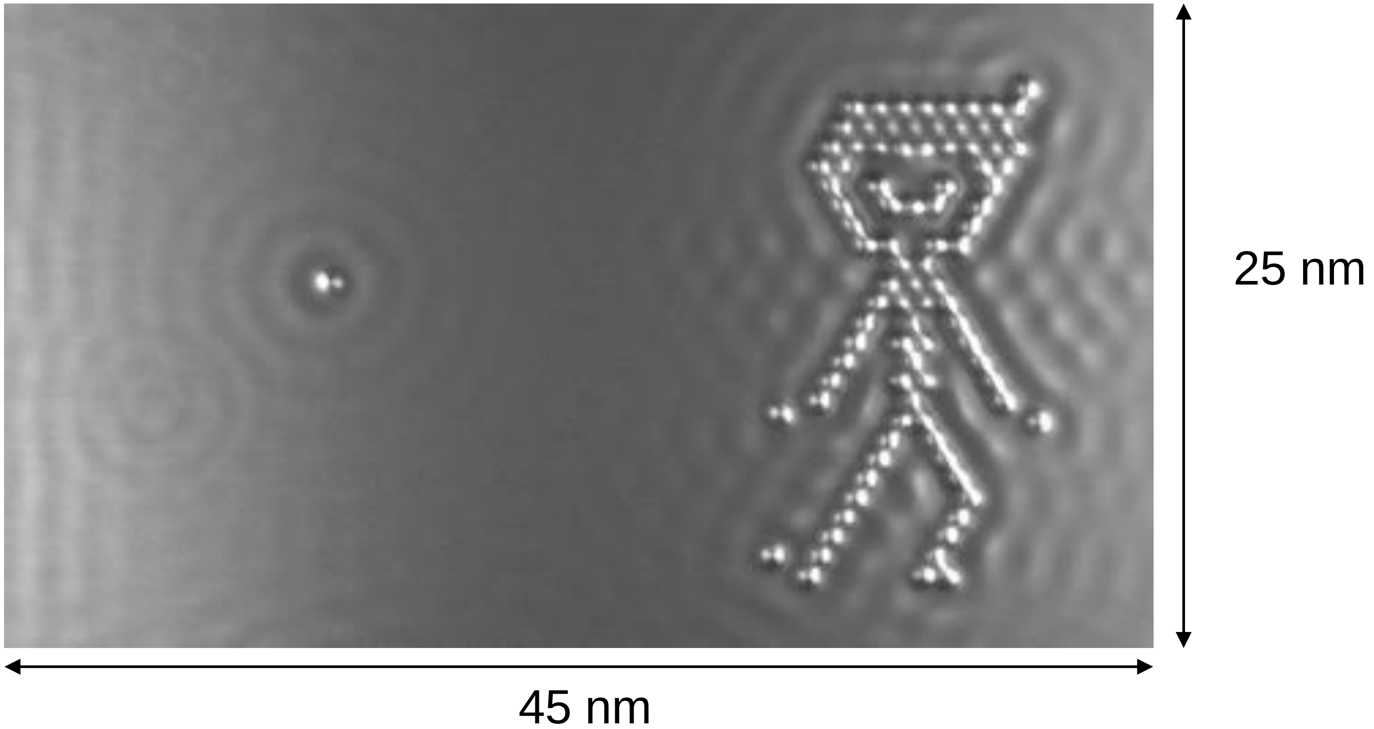


Átomos de Xenônio sobre Níquel

Donald Eigler and Erhard Schweizer of the IBM Almaden Research Center in San Jose, California, 1989.

STM: Animação com Átomos

A Boy and His Atom (2013)



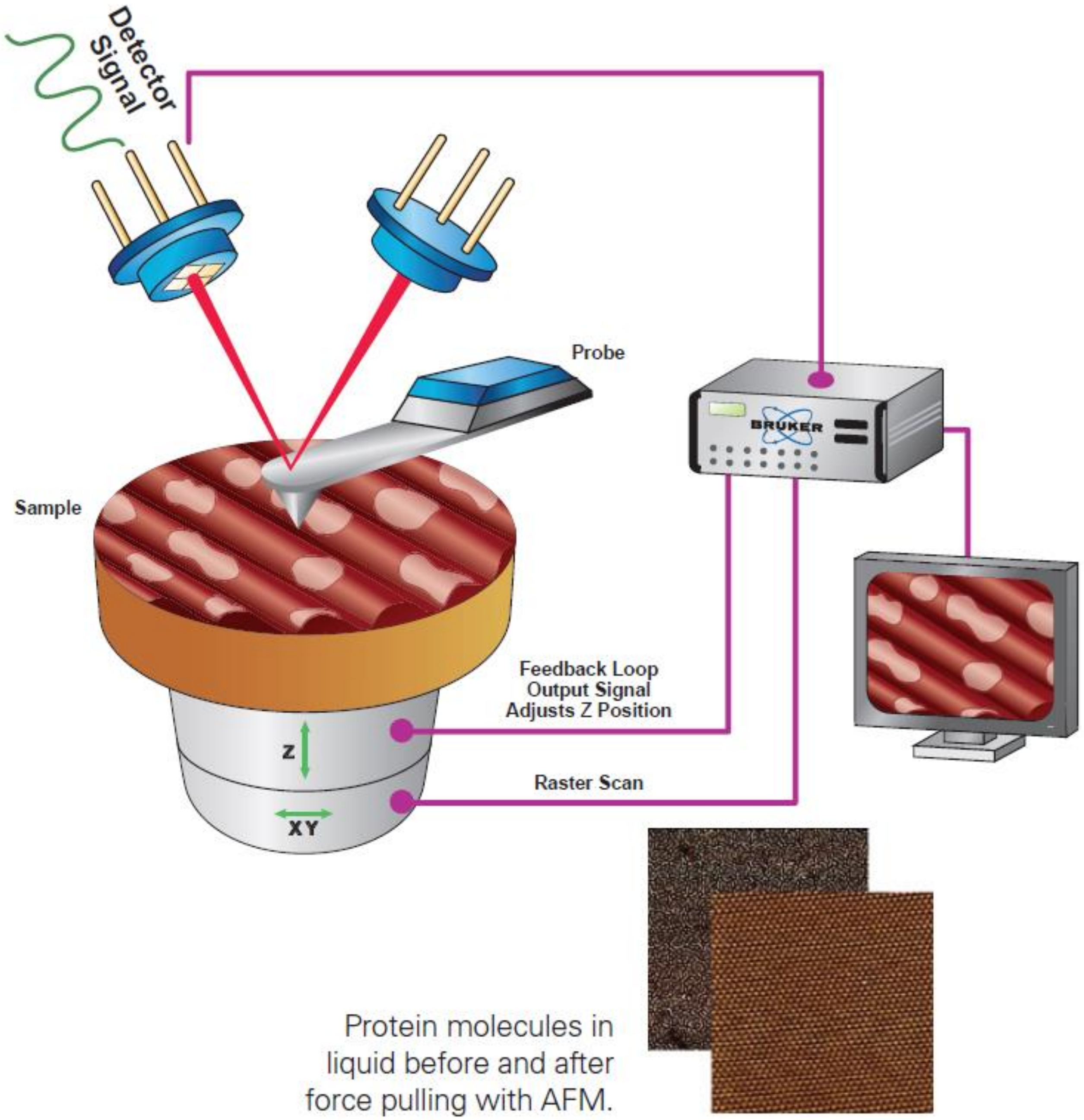
Técnica: Stop-motion com átomos de monóxido de carbono sobre cobre.
(242 imagens com 65 moléculas de dioxide de cabono)

Duração: 2 semanas (dias de 18 horas) **Magnificação: x10^8**

Temperatura: 5 K **Distância de Manipulação: 1 nm**

https://www.youtube.com/watch?v=oSCX78-8-q0

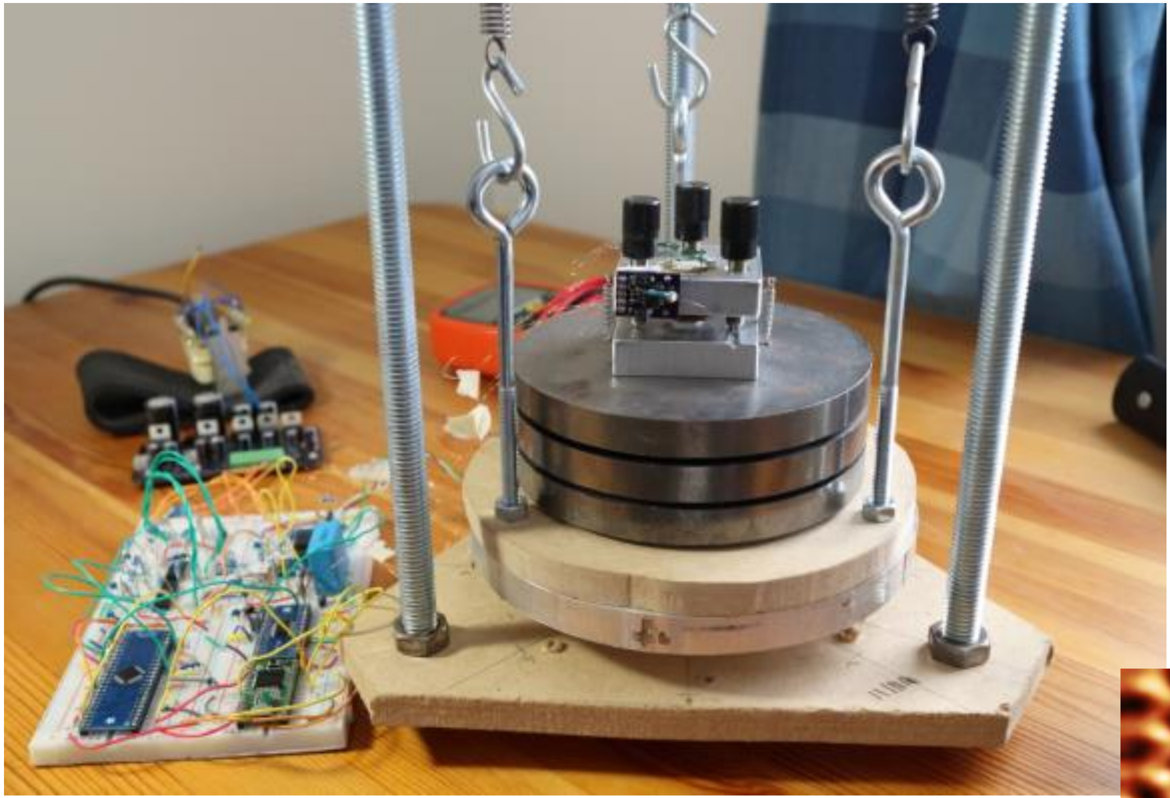
Atomic Force Microscope (AFM)

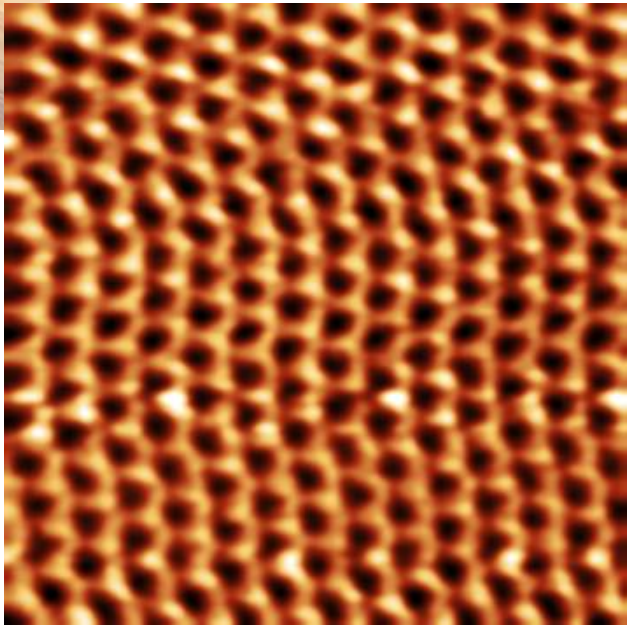


Protein molecules in
liquid before and after
force pulling with AFM.

http://www.nanosurf.com

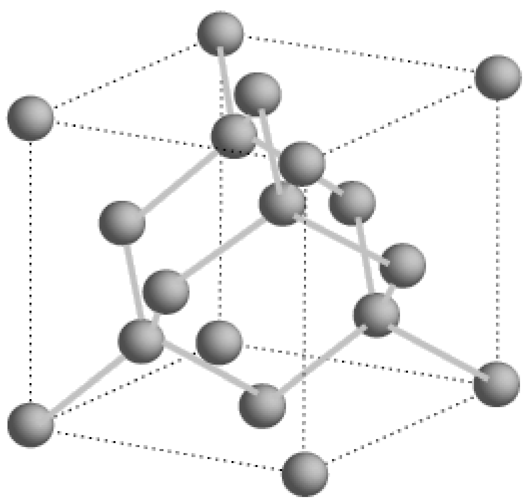
https://dberard.com/home-built-stm/



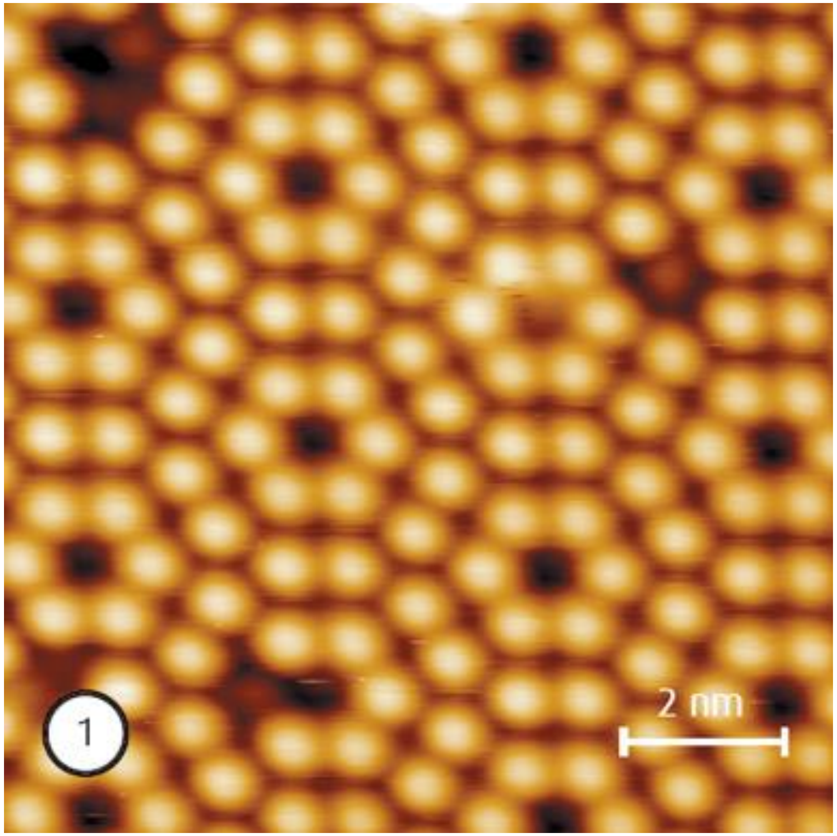


Propriedades da Matéria

- Propagação de Calor (Condução)
- Capacidade Calorífica
- Propagação de Ondas Eletromagnéticas
- Propagação de Ondas Mecânicas
- Transporte de Cargas (Corrente Elétrica)
- Emissividade (Elétrons e Fótons)

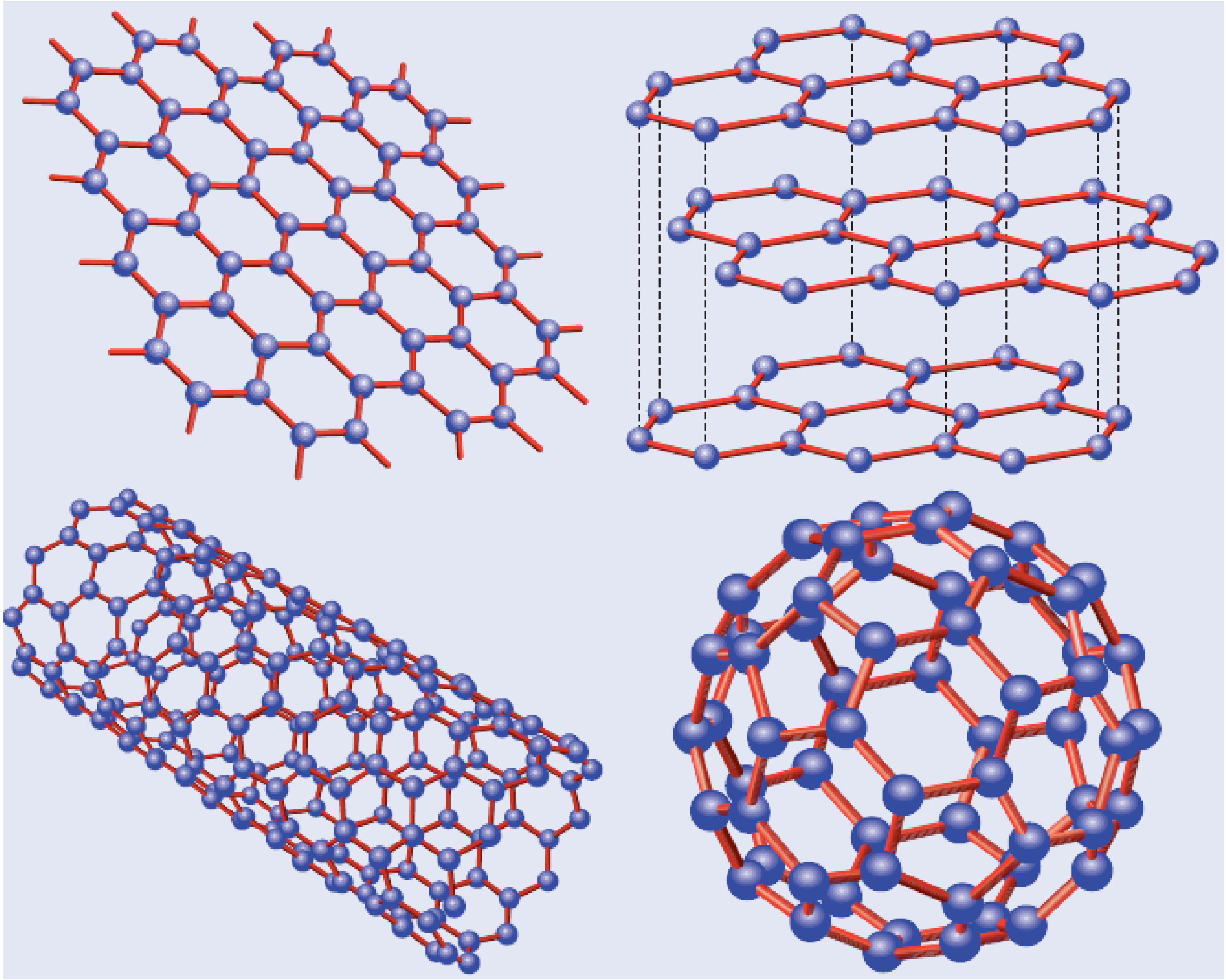


Silício
a = 5,430 angstroms
d = 2,340 angstroms



Si(111) por STM

Organização de Átomos de Carbono



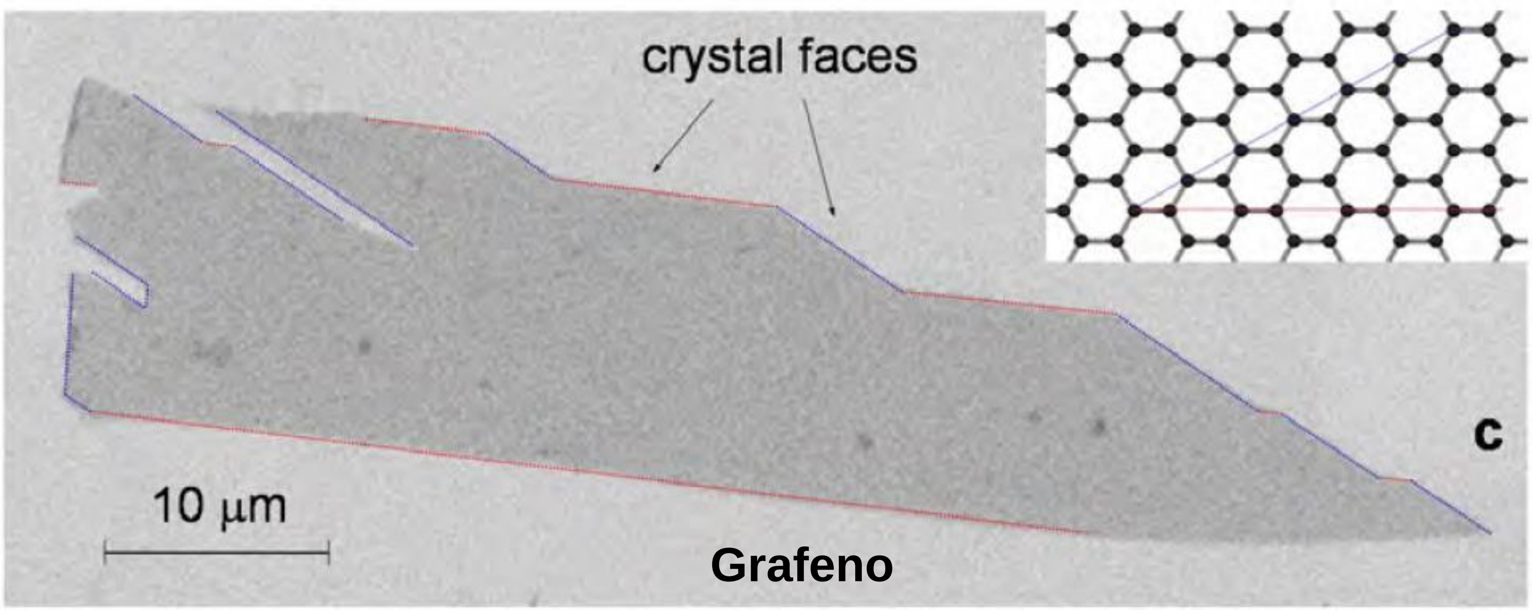
Prêmio Nobel de Física - 2010

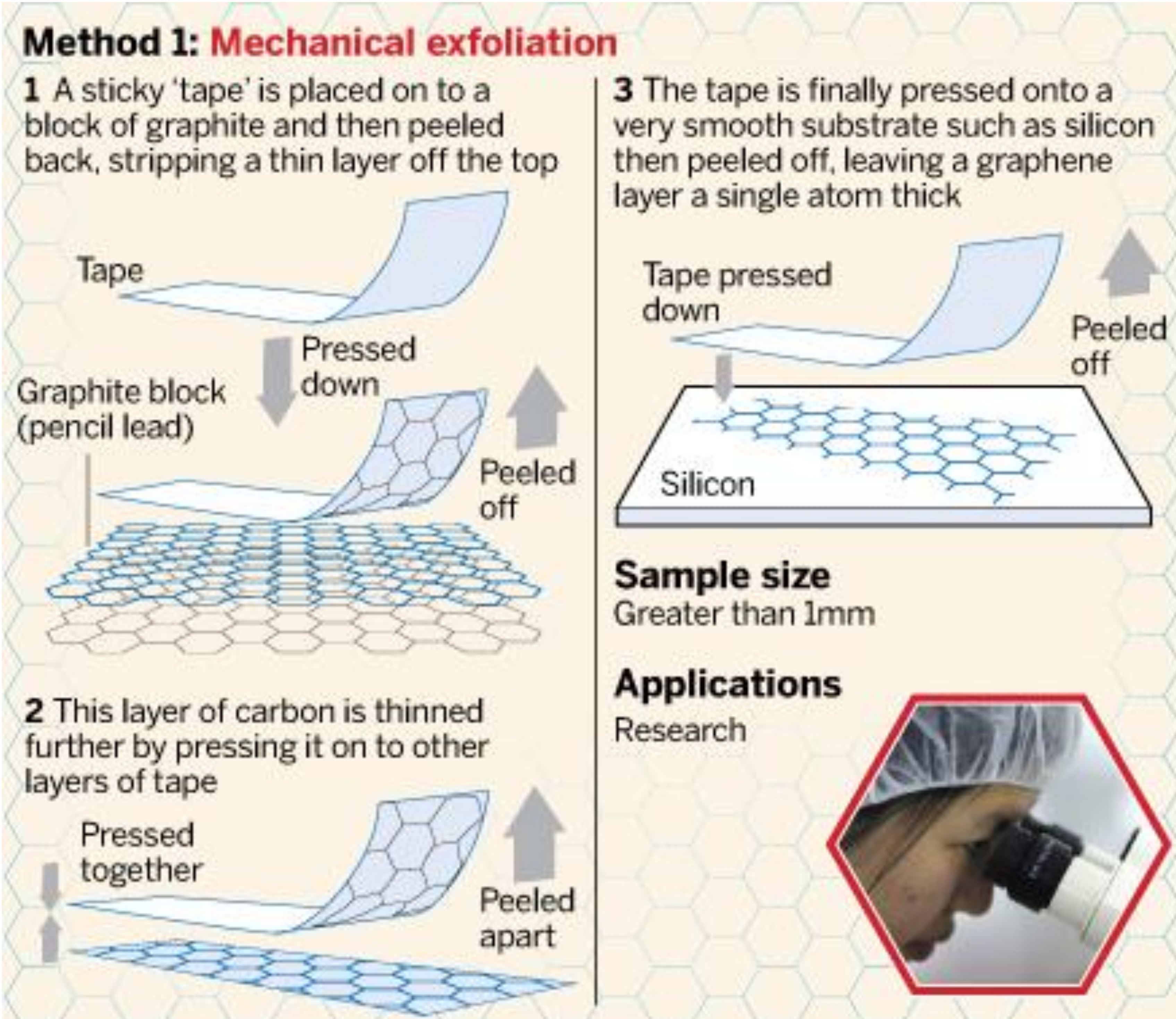
Photo: Sergeom, Wikimedia Commons

Andre Geim

Photo: University of Manchester, UK

Konstantin Novoselov




Method 1: Mechanical exfoliation
1 A sticky 'tape' is placed on to a block of graphite and then peeled back, stripping a thin layer off the top
Tape
Pressed down
Graphite block (pencil lead)
Peeled off
2 This layer of carbon is thinned further by pressing it on to other layers of tape
Pressed together
Peeled apart
3 The tape is finally pressed onto a very smooth substrate such as silicon then peeled off, leaving a graphene layer a single atom thick
Tape pressed down
Peeled off
Silicon
Sample size
Greater than 1mm
Applications
Research

Silicene: Compelling Experimental Evidence for Graphenelike Two-Dimensional Silicon

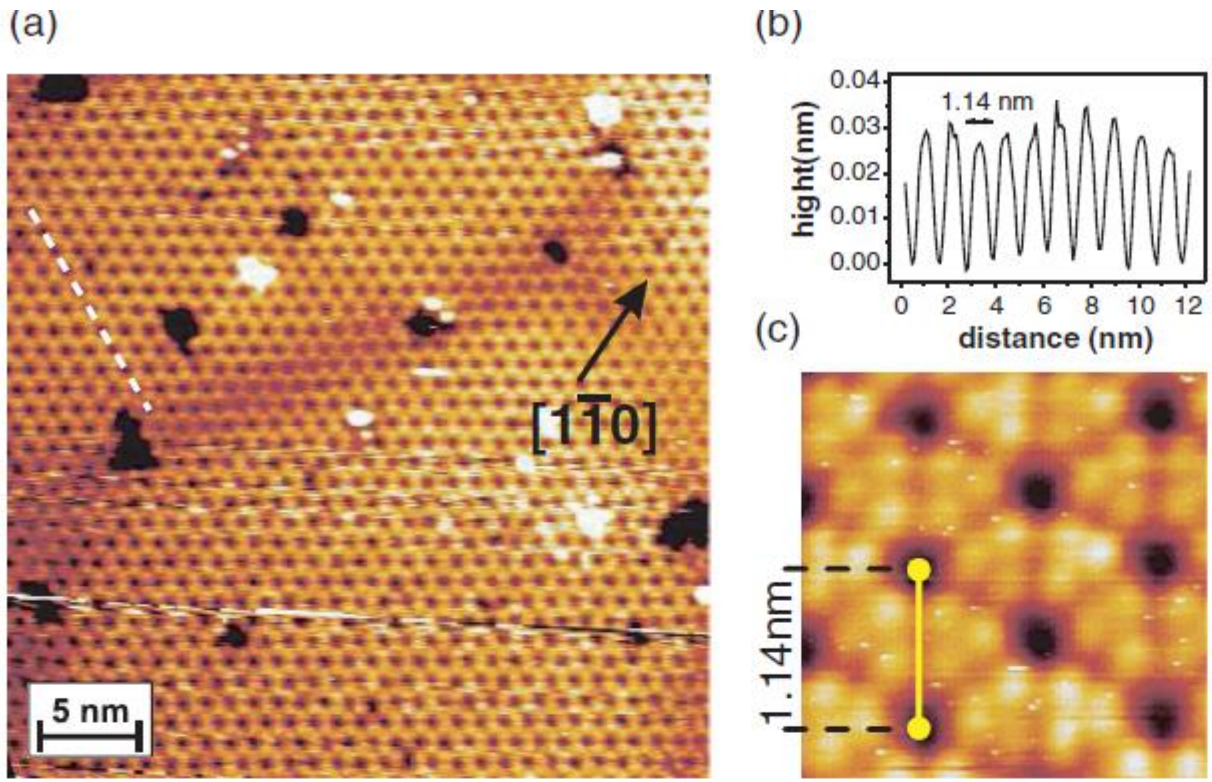


FIG. 2 (color). (a) Filled-states STM image of the 2D Si layer on Ag(111)-(1 × 1) ($U_{\text{bias}} = -1.3$ V, $I = 0.35$ nA). Clearly visible is the honeycomblike structure. (b) Line profile along the dashed white line indicated in (a). The dark centers in the STM micrograph are separated by 1.14 nm, corresponding to 4 times the Ag(111) lattice constant, in agreement with the (4 × 4) symmetry. (c) High-resolution STM topograph (3 × 3 nm, $U_{\text{bias}} = -1.3$ V, $I = 0.35$ nA) of the Si adlayer.

Equações de Maxwell – Eletromagnetismo Clássico

Gauss: $\begin{cases} \nabla.\vec{D} &= \rho \\ \nabla.\vec{B} &= 0 \end{cases}$

Faraday: $\nabla \times \vec{\mathcal{E}} = -\dfrac{\partial \vec{B}}{\partial t}$

Ampère: $\nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t}$

Corrente de Condução + Convecção

Corrente de Deslocamento

$\vec{D} = \epsilon \vec{\mathcal{E}}$ $\qquad$ $\vec{B} = \mu \vec{H}$

Equações de Onda

Aproximação sem cargas livres: $\rho = 0$ **e** $J = 0$

Vetor Campo Elétrico

$$\nabla^2 \vec{\mathcal{E}}(\vec{r},t) - \mu\epsilon \frac{\partial^2 \vec{\mathcal{E}}(\vec{r},t)}{\partial t^2} = 0$$

Vetor Campo Magnético

$$\nabla^2 \vec{H}(\vec{r},t) - \mu\epsilon \frac{\partial^2 \vec{H}(\vec{r},t)}{\partial t^2} = 0$$

$$\boxed{v = 1/\sqrt{\mu\epsilon}}$$

$$\frac{\partial^2 \vec{\mathcal{E}}(x,t)}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 \vec{\mathcal{E}}(x,t)}{\partial t^2}$$

$$\frac{\partial^2 \vec{H}(x,t)}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 \vec{H}(x,t)}{\partial t^2}$$

$$\vec{\mathcal{E}}(x,t) = \vec{\mathcal{E}}_0 \cos(kx - \omega t)$$

$$\vec{H}(x,t) = \vec{H}_0 \cos(kx - \omega t)$$

$$\boxed{\omega = vk}$$

$$\mathcal{E}_0 = \sqrt{\mu/\epsilon}\, H_0 \qquad \omega = 2\pi\nu \qquad \nu = 1/T$$

Letras Gregas

maiúsculas		
Alfa: A	Iota: I	Rô: P
Beta: B	Kapa: K	Sigma: Σ
Gama: Γ	Lâmbda: Λ	Tau: T
Delta: Δ	Mi: M	Upsilon: Y
Epsilon: E	Ni: N	Fi: Φ
Zeta: Z	Csi: Ξ	Qui: X
Eta: H	Ômicron: O	Psi: Ψ
Theta: Θ	Pi: Π	Ômega: Ω

minúsculas		
Alfa: α	Iota: ι	Rô: ρ
Beta: β	Kapa: κ	Sigma: σ
Gama: γ	Lâmbda: λ	Tau: τ
Delta: δ	Mi: μ	Upsilon: υ
Epsilon: ε	Ni: ν	Fi: ϕ (ou φ)
Zeta: ζ	Csi: ξ	Qui: χ
Eta: η	Ômicron: o	Psi: ψ
Theta: θ	Pi: π	Ômega: ω

Propagação de Onda Eletromagnética

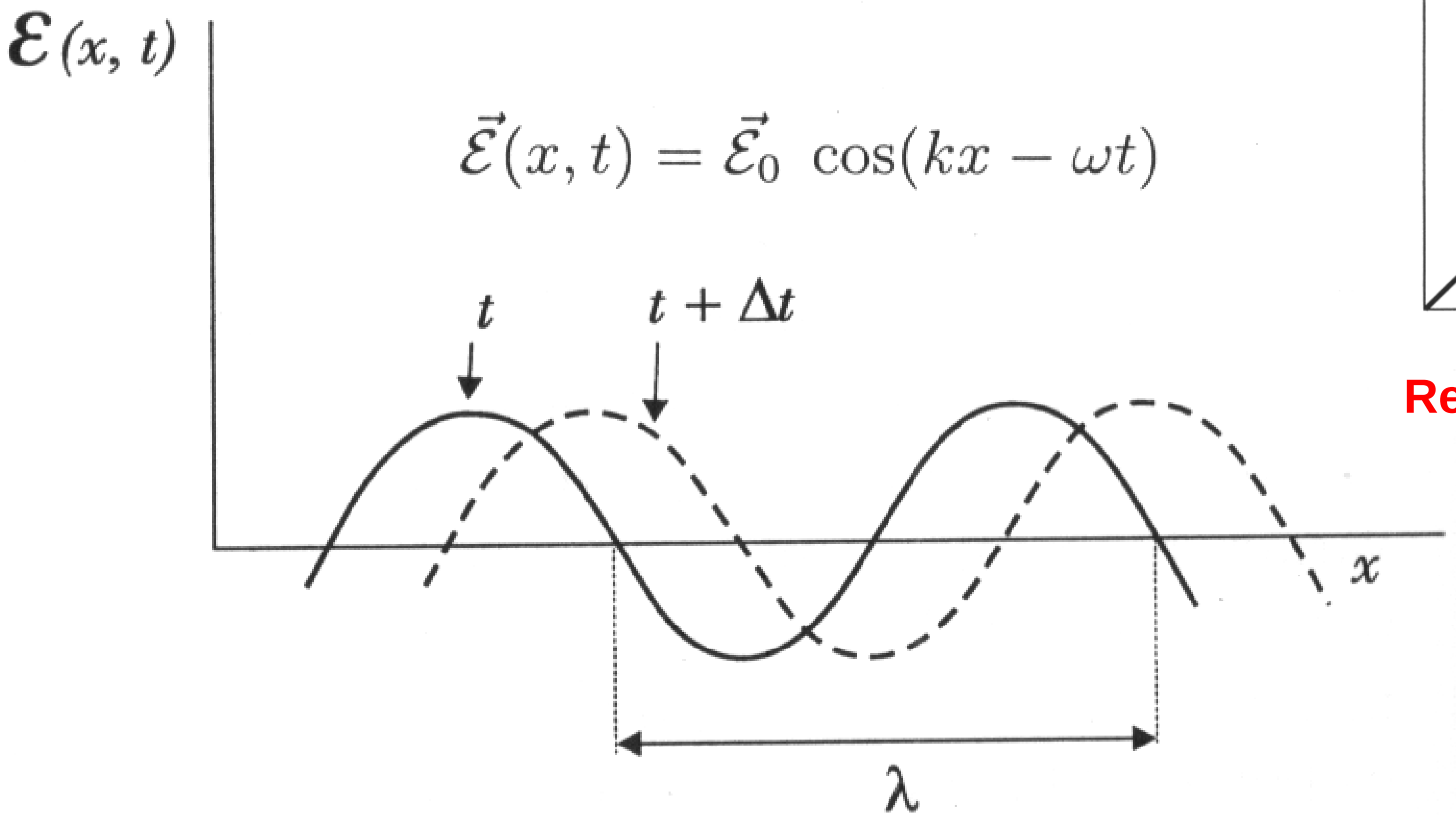
$$v_f = \frac{\omega}{k} = \frac{c}{n}$$

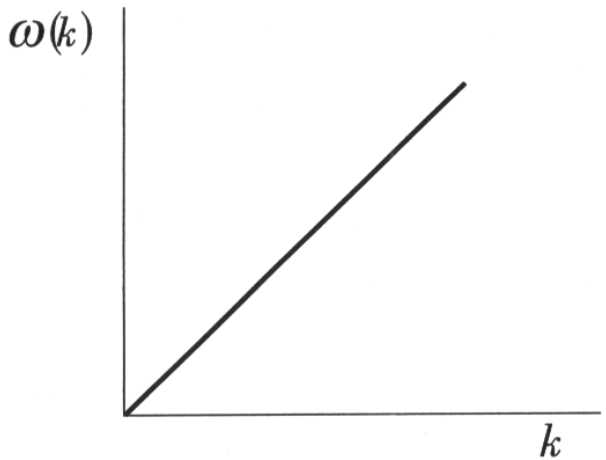
Dispersão Linear

$$v_g = \frac{c}{n} = \frac{\partial \omega}{\partial k}$$

$$n = (\mu\epsilon/\mu_0\epsilon_0)^{1/2} \qquad \lambda = \frac{2\pi}{k} \qquad c = 1/\sqrt{\mu_0\epsilon_0}$$

$$\vec{\mathcal{E}}(x,t) = \vec{\mathcal{E}}_0 \cos(kx - \omega t)$$





Relação de Dispersão Linear

Propagação de Onda Eletromagnética

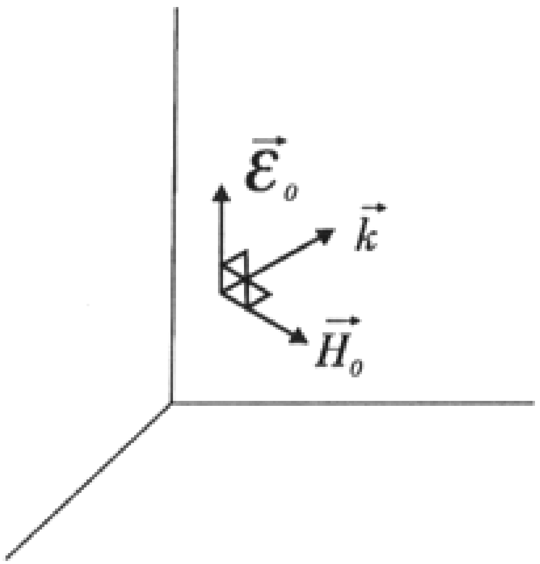
$$\vec{\mathcal{E}}(\vec{r},t) = \vec{\mathcal{E}}_0 \cos(\vec{k}.\vec{r} - \omega t + \phi) \qquad \vec{H}(\vec{r},t) = \vec{H}_0 \cos(\vec{k}.\vec{r} - \omega t + \phi)$$

$$\vec{H}_0 = \frac{\sqrt{\epsilon/\mu}}{k}\, \vec{k} \times \vec{\mathcal{E}}_0$$

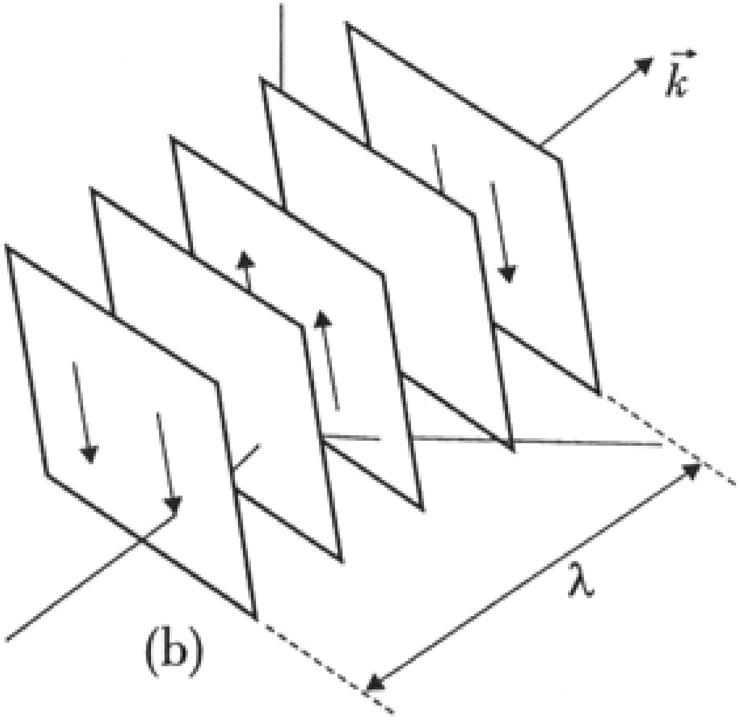
Euler: $\mathrm{e}^{i\theta} = \cos\theta + i\mathrm{sen}\theta$

$$\vec{\mathcal{E}}(\vec{r},t) = Re\,\left[\vec{\mathcal{E}}_0\, \mathrm{e}^{i(\vec{k}.\vec{r}-\omega t+\phi)}\right] \qquad \vec{H}(\vec{r},t) = Re\,\left[\vec{H}_0 \mathrm{e}^{i(\vec{k}.\vec{r}-\omega t+\phi)}\right]$$

Propagação de Onda Eletromagnética



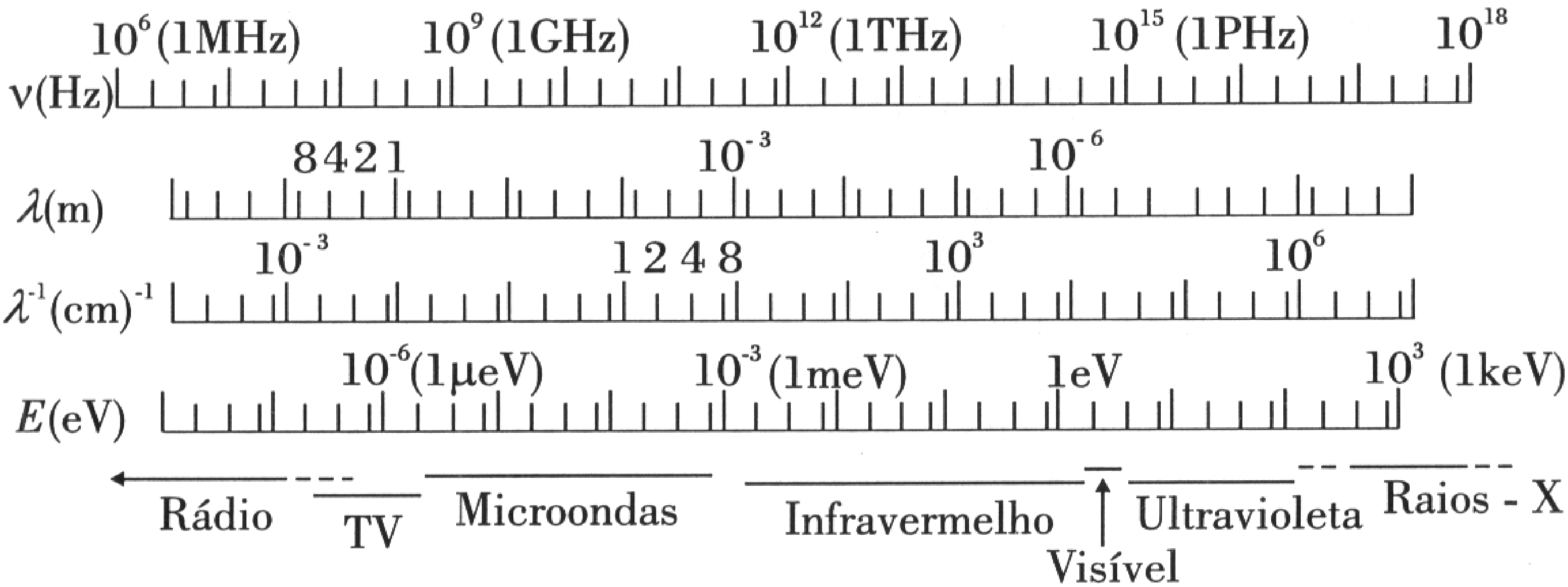
(a)



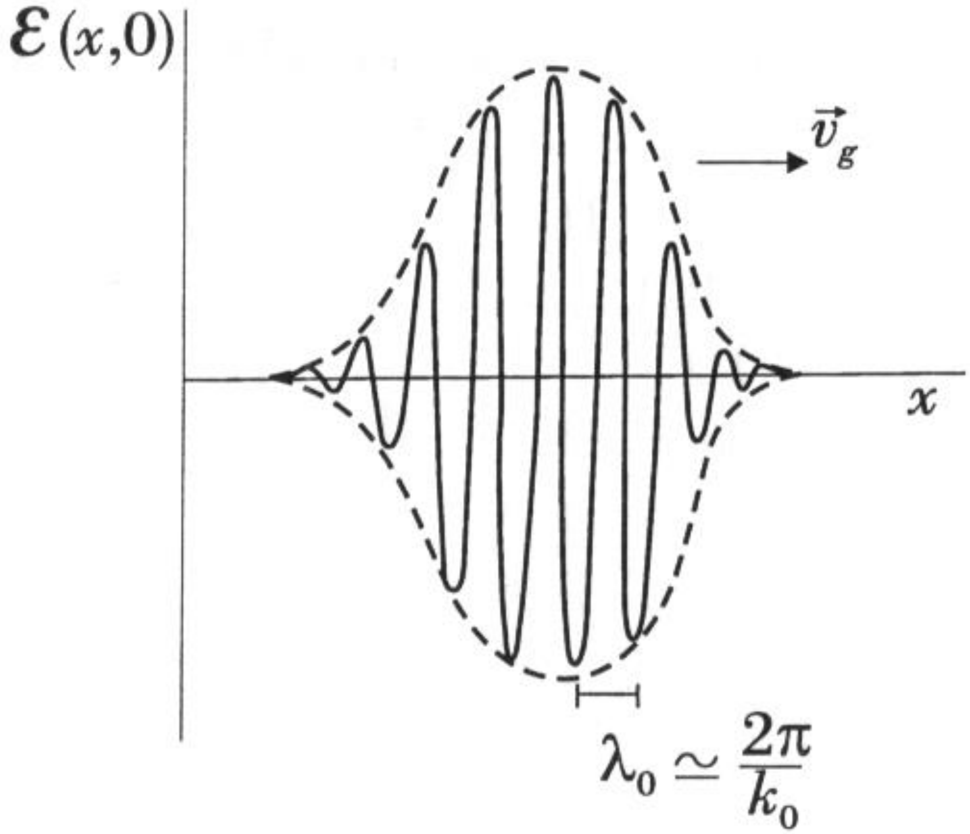
(b)

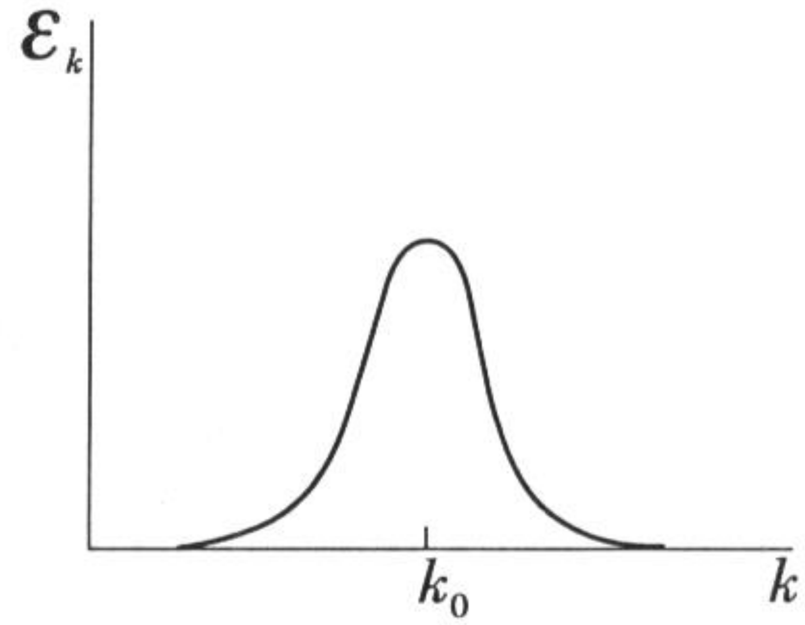
$$v_f = \omega/k \qquad \omega(k) = ck/n$$

Espectro Eletromagnético



Grupo de Ondas Planas

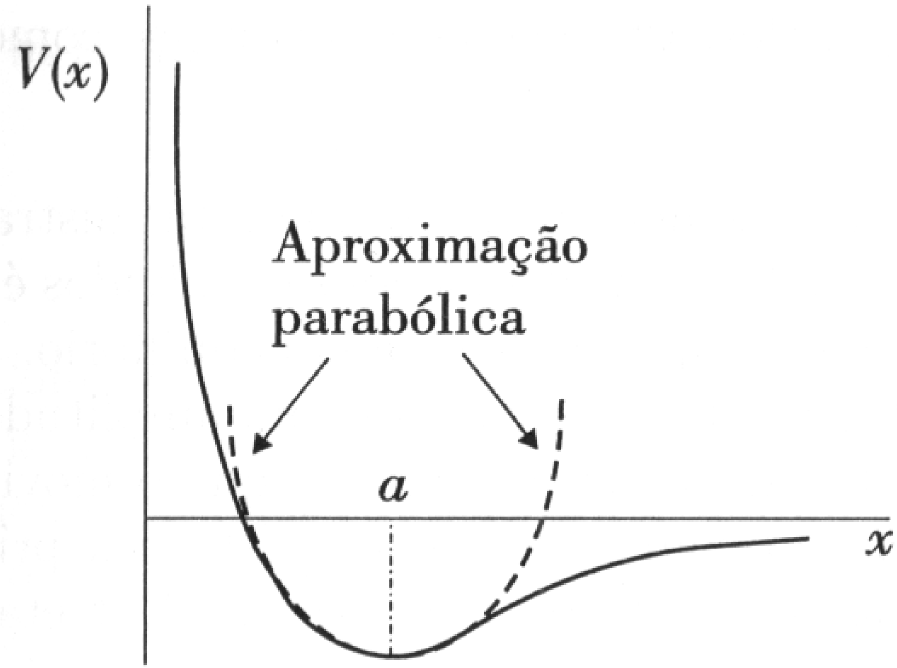




$$\vec{\mathcal{E}}_k = \frac{1}{2\pi}\int_{-\infty}^{\infty} \vec{\mathcal{E}}(x,0)\, \mathrm{e}^{-ikx} dx \qquad \vec{\mathcal{E}}(x,0) = \int_{-\infty}^{\infty} \vec{\mathcal{E}}_k\, \mathrm{e}^{ikx} dk$$

$$\boxed{v_g = \left.\frac{\partial \omega}{\partial k}\right|_{k_0}}$$

Ondas Elásticas em Sólidos



$(dV/du)_0 = 0$

$u = x - a$

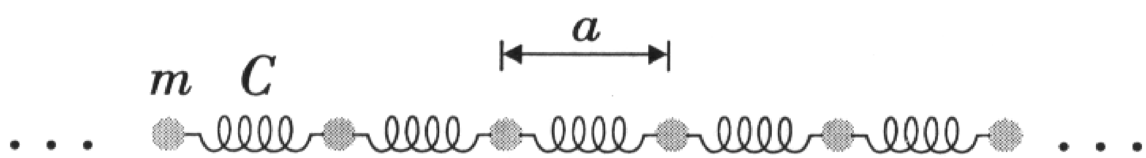
Série de Taylor: $V(u) = V(0) + \left(\frac{dV}{du}\right)_0 u + \frac{1}{2}\left(\frac{d^2V}{du^2}\right)_0 u^2 + \cdots$

$$V(u) \simeq V(0) + \frac{1}{2}Cu^2 \qquad C = (d^2V/du^2)_0$$

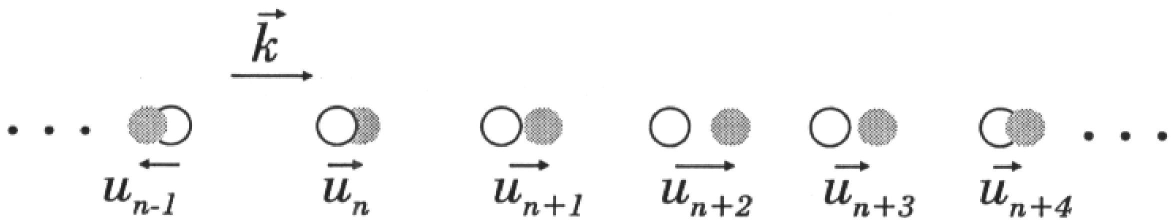
Oscilador Harmônico Simples: $F(u) = -\frac{dV}{du} = -Cu$

Propagação de Ondas Elásticas em Sólidos

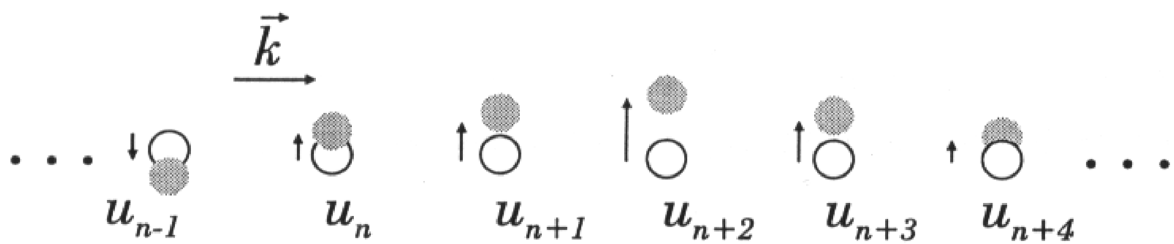
$$F_n = C\{(u_{n+1} - u_n) - (u_n - u_{n-1})\} = C(u_{n+1} - 2u_n + u_{n-1})$$



Cadeia Monoatômica



Onda Longitudinal



Onda Transversal

$$m\frac{d^2u_n}{dt^2} \equiv m\,\ddot{u}_n = C(u_{n+1} - 2u_n + u_{n-1})$$

$$u_n(x,t) = u_k(t)\,\mathrm{e}^{ikna}$$

$$x = na$$

$$m\,\ddot{u}_k \;=\; Cu_k\,(\mathrm{e}^{ika} - 2 + \mathrm{e}^{-ika}) \;=\; 2\,Cu_k\,(\cos ka - 1)$$

$$u_k(t) = A\mathrm{e}^{-i\omega_k t}$$

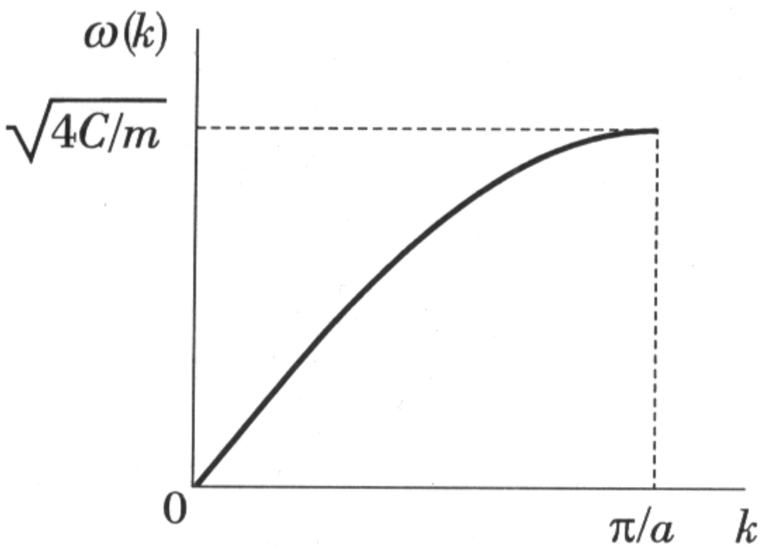
$$\omega(k) = \left(\frac{2C}{m}\right)^{1/2}(1-\cos ka)^{1/2}$$

$$\lambda \gg a$$

$$\cos ka \simeq 1 - (ka)^2/2$$

$$\omega(k) = \sqrt{C/m} \quad ka$$

$$v = \sqrt{C/m}\, a \quad \sim 10^4 \text{ m/s}$$



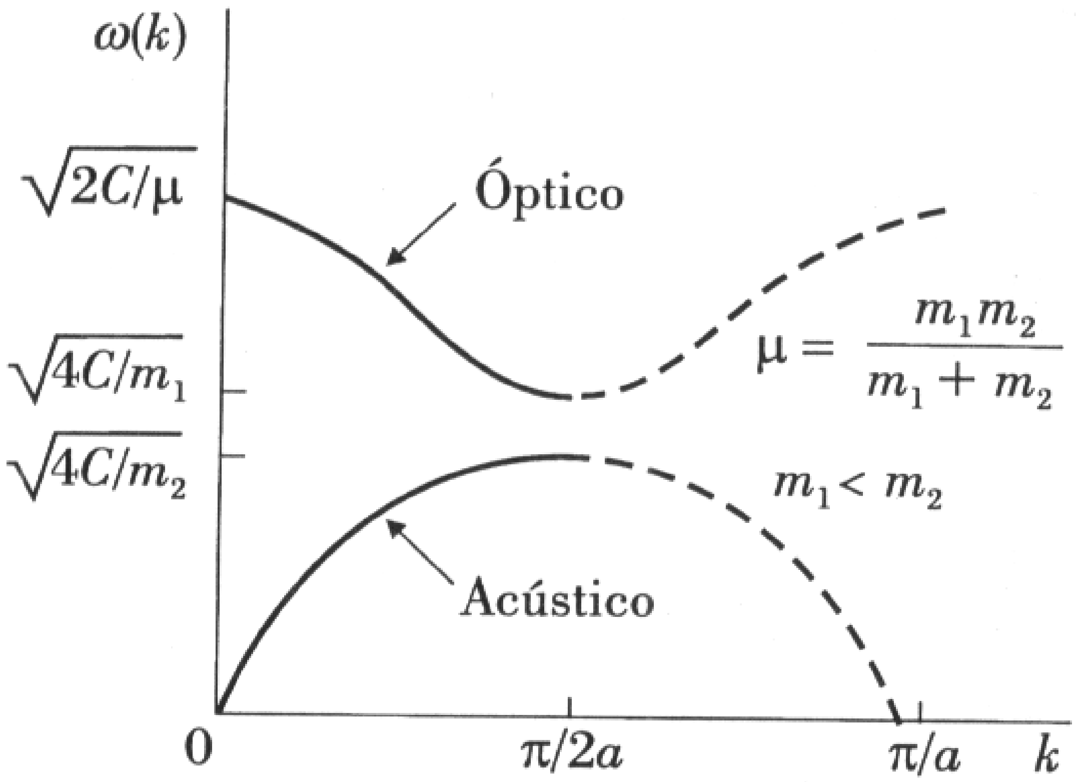
Relação de Dispersão

Primeira Zona de Brillouin: $-\pi/a < k < \pi/a$

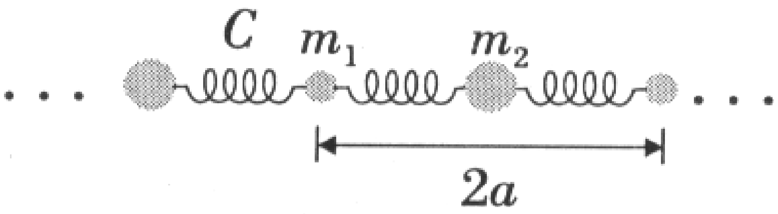
$$\lambda = 2a \qquad ka = \pi \quad \Longrightarrow \quad \omega_{\max} = \sqrt{4C/m}$$

ω_{max} ~ 1 a 10 THz   1 THz = 1×10^{12} Hz

Cadeia Diatômica



Relação de Dispersão



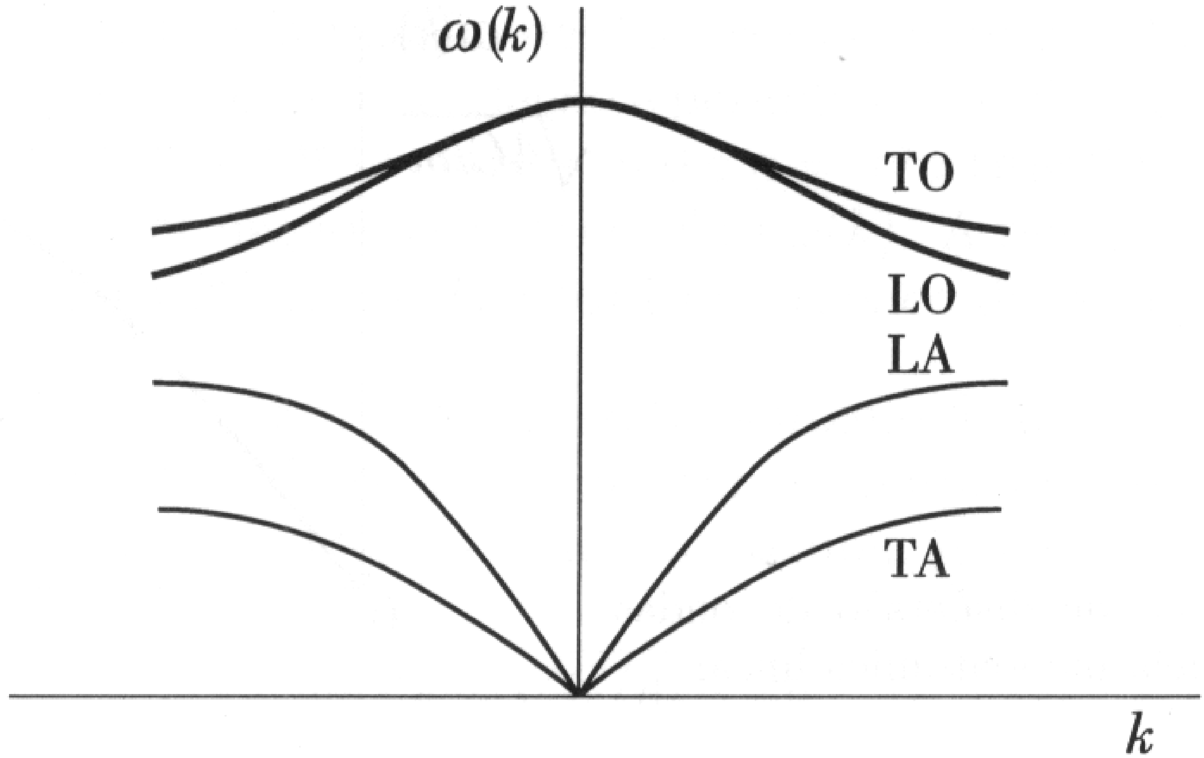
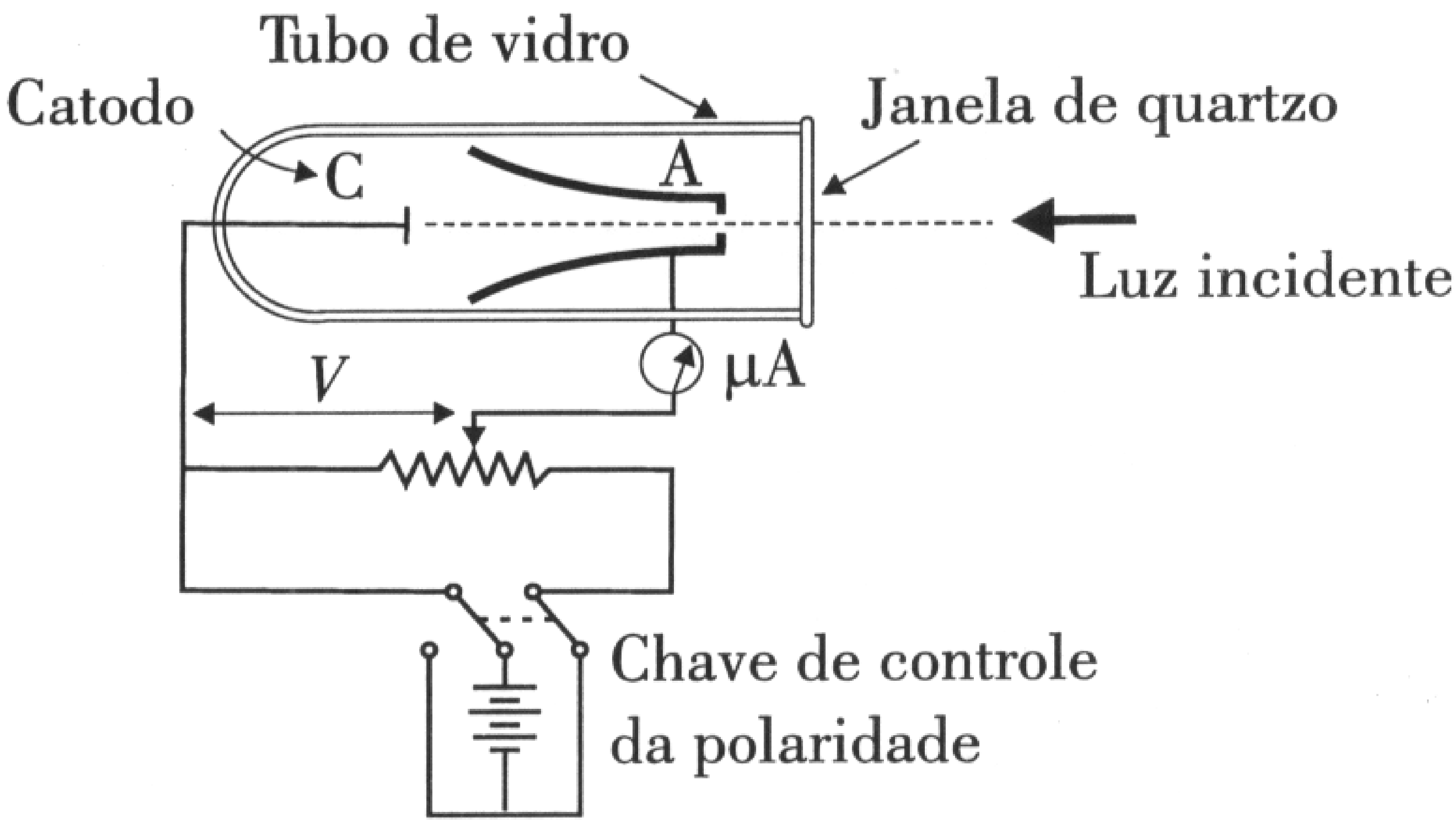


Figura 2.10: Curvas de dispersão de ondas elásticas em um cristal cúbico diatômico, com o vetor de onda na direção de um eixo principal (L = longitudinal, T = transversal, O = óptico e A = acústico).

$$\vec{R}_\lambda(\vec{r}, t) = Re\ \left[A_k\ \mathrm{e}^{i(\vec{k}.\vec{r} - \omega_\lambda t)}\right]$$

Efeito Fotoelétrico



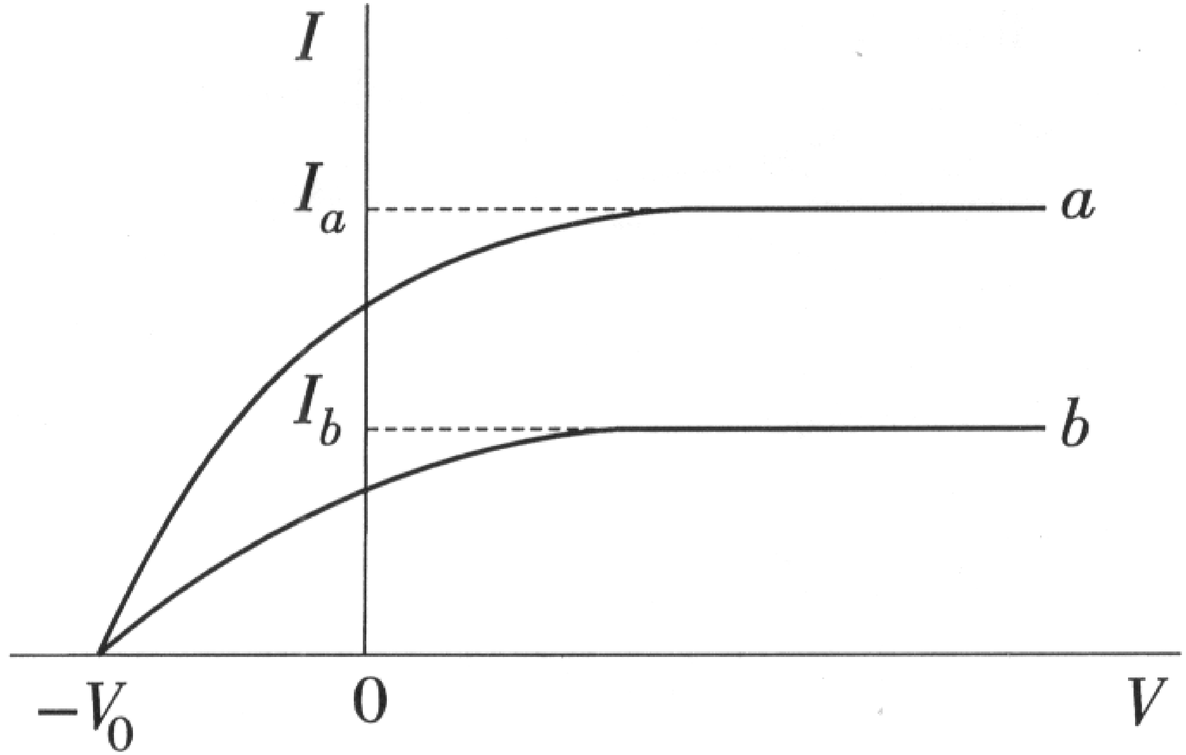
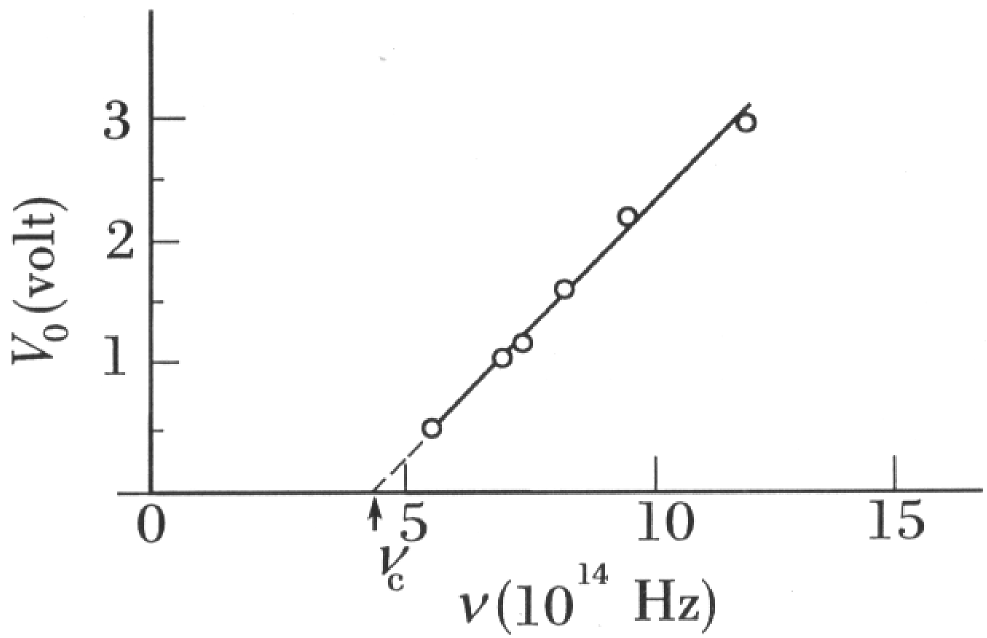


Figura 2.12: Variação da corrente fotoelétrica com a tensão aplicada, para dois valores de intensidade da luz incidente. A tensão V_0 é independente da intensidade de luz, mas a corrente de saturação é diretamente proporcional à mesma.

Energia Cinética Máxima: $T_{max} = e\,V_0$



$$\text{sódio } \nu_c = 4,39 \times 10^{14} \text{ Hz}$$

$$\lambda \simeq 683 \text{ nm}$$

$$h = 6,6262 \times 10^{-34} \text{ J.s}$$

$$E = h\nu = \hbar\omega$$

$$\hbar = h/2\pi$$

Einstein (Nobel -1921)

$$p = \frac{E}{c}$$

$$\vec{p} = \hbar\vec{k}$$

$$T = h\nu - W$$

$$T_{max} = h\nu - W_0$$

$$h\nu_c = W_0$$

$$e\mathrm{V}_0 = h\nu - W_0$$

$$V_0 = \frac{h}{e}\,(\nu - \nu_c)$$

Exemplo 2.1: Numa experiência de efeito fotoelétrico, o material do fotocatodo é o lítio, cuja função trabalho é 2,3 eV, e o comprimento de onda da luz usada para iluminar o fotocatodo é 300 nm. Determine: a) A freqüência de corte do lítio; b) O potencial de retardo.

a) A relação entre a função trabalho e a freqüência de corte é dada pela Eq. (2.36). Então,

$$\begin{aligned}\nu_c &= \frac{W_0}{h} \simeq \frac{2,3 \text{ eV} \times 1,6 \times 10^{-19} \text{ coulomb}}{6,63 \times 10^{-34} \text{ joule-seg}} \\ &\simeq 5,5 \times 10^{14} \text{ Hz}\end{aligned}$$

b) O potencial de retardo é relacionado com a freqüência de corte e a freqüência da luz pela Eq.(2.38). A freqüência da luz é,

$$\nu = \frac{c}{\lambda} = \frac{3,0 \times 10^8 \text{ m/s}}{300 \times 10^{-9} \text{ m}} = 10,0 \times 10^{14} \text{ Hz} .$$

Assim,

$$\begin{aligned}V_0 &= \frac{h}{e}(\nu - \nu_c) = \frac{6,63 \times 10^{-34} \text{ joule-seg}}{1,6 \times 10^{-19} \text{ coulomb}} \times 4,5 \times 10^{14}\text{Hz} \\ &= 1,86 \text{ V}\end{aligned}$$

Dualidade Onda - Partícula

Louis de Broglie (Tese -1924, Nobel -1929)

$$E = h\nu \qquad\qquad p = h/\lambda$$

$$k = 2\pi/\lambda$$

$$p = \hbar k$$

$$\boxed{\left.\begin{array}{l} v = 100\ \mathrm{m/s} \\ m = 1{,}0\ \mathrm{kg} \end{array}\right\} \Longrightarrow \lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6,6 \times 10^{-34}}{100} = 6,6 \times 10^{-36}\ \mathrm{m}}$$

Não trata de fenômeno físico!

$$T = 100\ \mathrm{eV} \Longrightarrow \lambda = \frac{h}{p} = \frac{h}{\sqrt{2mT}} \simeq 1,2 \times 10^{-10}\ \mathrm{m} = 1,2\ \text{Å}$$

Exemplo 2.2: Calcule as energias e as velocidades de um feixe de elétrons e outro de nêutrons, para que ambos tenham comprimento de onda de 2 Å.

A relação entre energia e comprimento de onda é dada pela Eq. (2.43). Então, $T = h^2/2m\lambda^2$. Para o feixe de elétrons $m = 9,1 \times 10^{-31}$ kg, logo,

$$\begin{aligned} T &= \frac{6,63^2 \times 10^{-68}}{2 \times 9,1 \times 10^{-31} \times 2^2 \times 10^{-20}} = 6,0 \times 10^{-18}\ \mathrm{J} \\ &= \frac{6,0 \times 10^{-18}}{1,6 \times 10^{-19}}\ \mathrm{eV} = 37,5\ \mathrm{eV} \end{aligned}$$

A velocidade é relacionada com a energia cinética por $T = mv^2/2$. Portanto, a velocidade dos elétrons é,

$$v = (2T/m)^{1/2} = \left(\frac{2 \times 6,0 \times 10^{-18}}{9,1 \times 10^{-31}}\right)^{1/2} = 3,6 \times 10^6\ \mathrm{m/s}$$

No caso do feixe de nêutrons, $m = 1,67 \times 10^{-27}$ kg. Então,

$$\begin{aligned} T &= \frac{6,63^2 \times 10^{-68}}{2 \times 1,67 \times 10^{-27} \times 2^2 \times 10^{-20}} = 3,3 \times 10^{-21}\,\mathrm{J} \\ v &= \left(\frac{2 \times 3,3 \times 10^{-21}}{1,67 \times 10^{-27}}\right)^{1/2} = 2,0 \times 10^3\ \mathrm{m/s} \end{aligned}$$