

Universidade de São Paulo
Programa de Pós-Graduação em Física
Disciplina: Teoria Quântica de Muitos Corpos na Matéria
Condensada

Efeito Kondo em Nanotubos de Carbono

Eduardo Santos Carvalho

Sumário

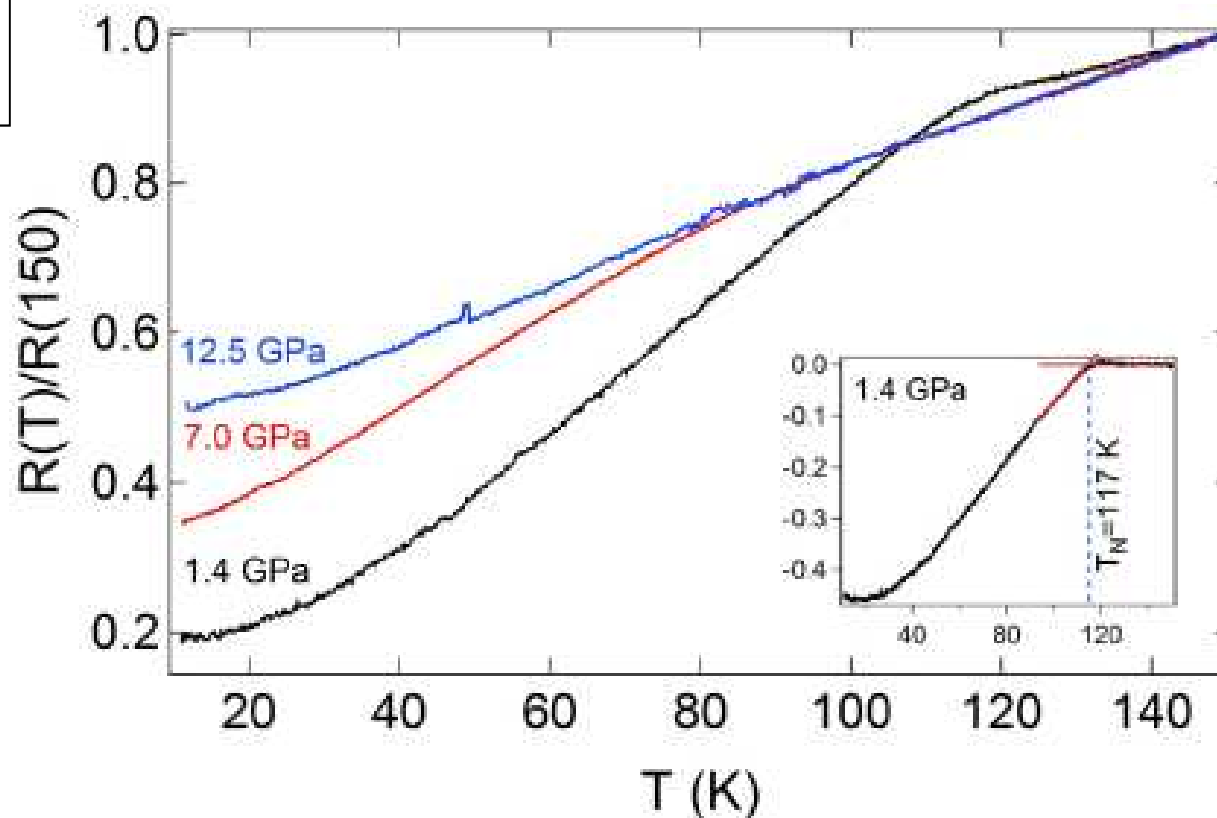
- Efeito Kondo
 - O Mínimo de Resistência
 - Impurezas Magnéticas e o Modelo de Anderson
- Pontos Quânticos
- Nanotubos de Carbono
- Efeito Kondo em Nanotubos de Carbono

Variação da Resistividade Elétrica com a temperatura: Curva Típica

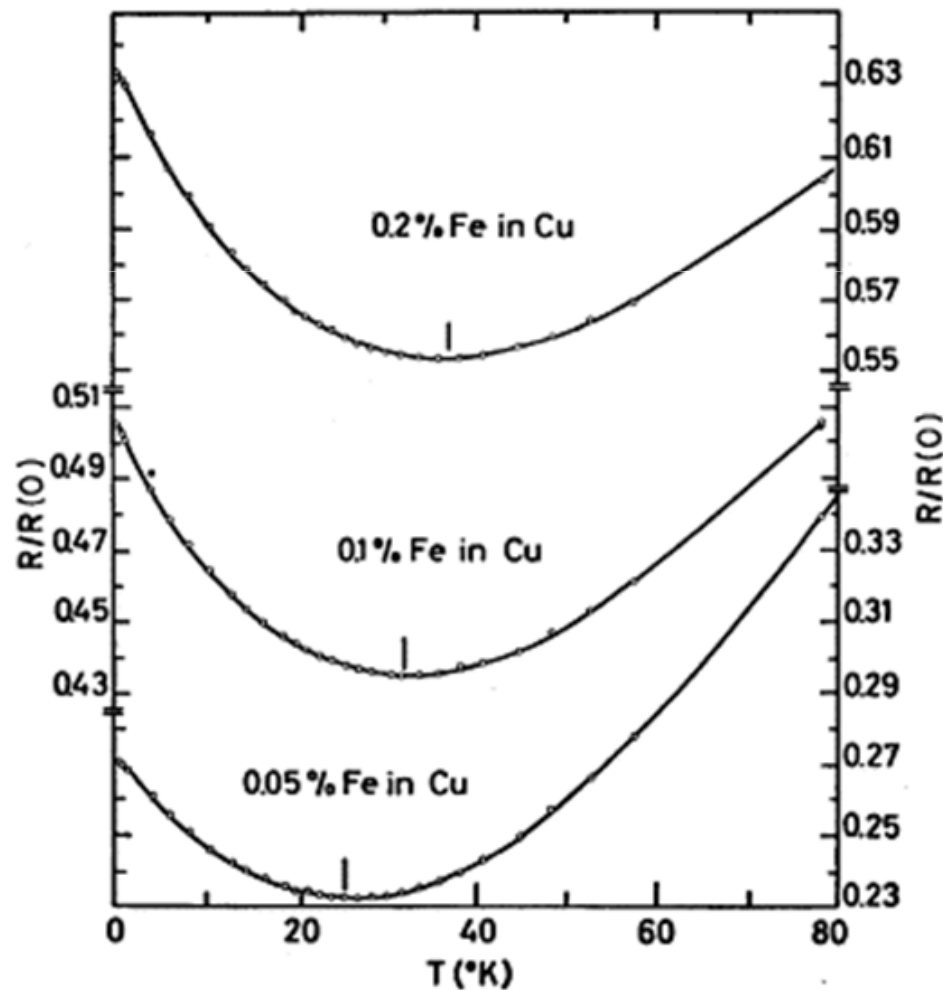
Contribuições para a resistividade:

- Defeitos da Rede
- Elétrons
- Vibrações da rede

$$\rho = \rho_0 + aT^2 + bT^5$$



Mínimo de Resistividade: Impurezas magnéticas em metais e o Efeito Kondo



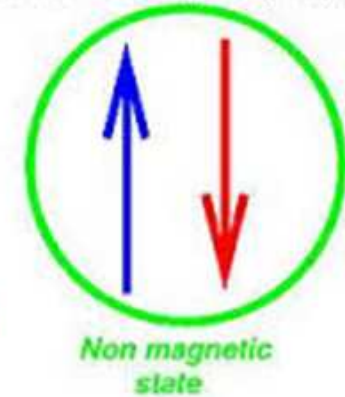
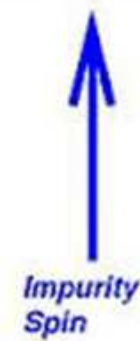
$$\rho = \rho_0 + aT^2 + bT^5 + c \ln \frac{\mu}{T}$$

Efeito Kondo e a Correlação Eletrônica



High T – weak coupling

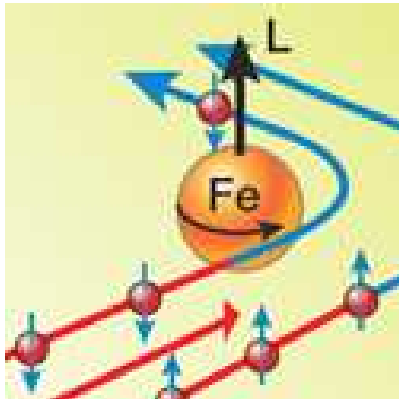
Low T – strong coupling



Modelo de Anderson

$$H^A = \sum_{k\sigma} \epsilon_k a_{k\sigma}^\dagger a_{k\sigma} + \sum_{\sigma} \epsilon_d n_{d\sigma} + \sum_{k\sigma} V_{kd} (a_{k\sigma}^\dagger a_{d\sigma} + a_{d\sigma}^\dagger a_{k\sigma}) + U n_{d\uparrow} n_{d\downarrow}$$

Interação entre elétrons no mesmo orbital favorece estados com elétrons desemparelhados e conseqüentemente com um dado momento magnético.



Hamiltoniana de Kondo

$$H^A = \sum_{k\sigma} \varepsilon_k a_{k\sigma}^\dagger a_{k\sigma} + \sum_{kk'} \frac{J_{kk'}}{\hbar^2} (\Psi_{k'}^\dagger S \Psi_k) \cdot (\Psi_d^\dagger S \Psi_d)$$

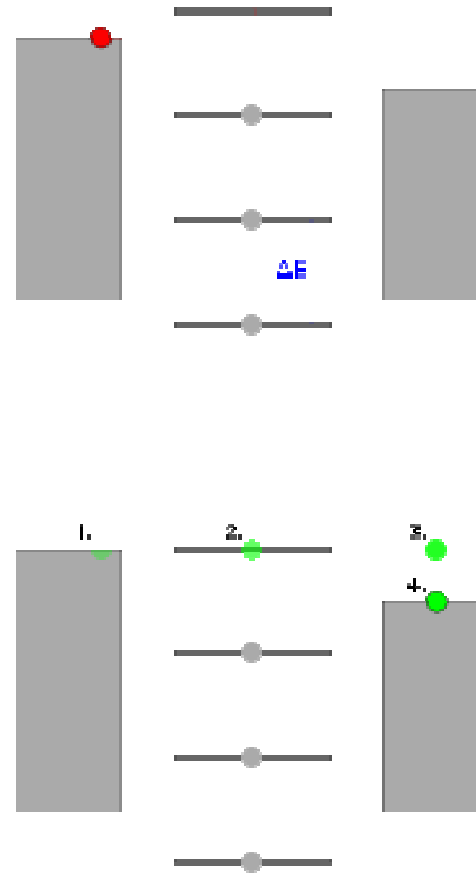
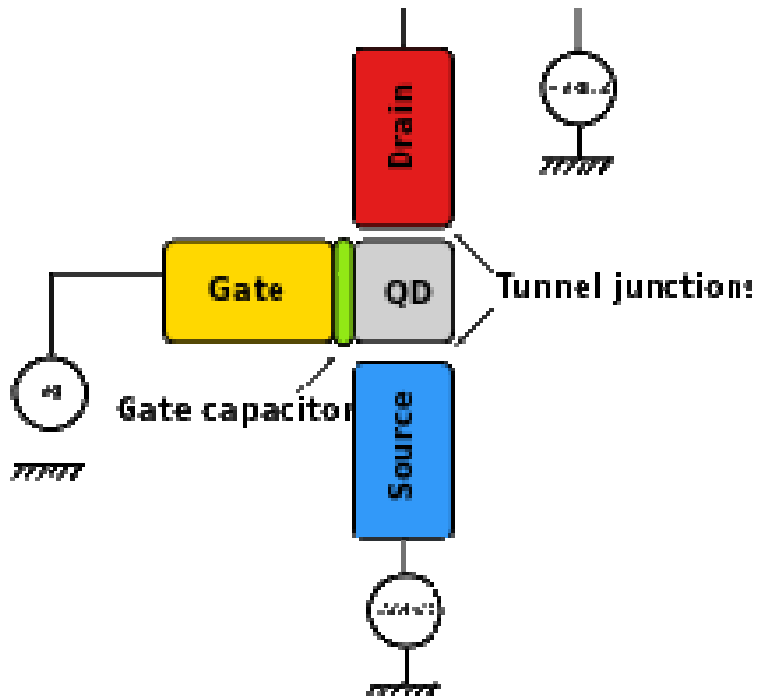
$$\Psi_k = \begin{pmatrix} a_{k\uparrow} \\ a_{k\downarrow} \end{pmatrix} \quad \Psi_d = \begin{pmatrix} a_{d\uparrow} \\ a_{d\downarrow} \end{pmatrix}$$

$$S = \frac{\hbar}{2} \sigma$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Processos de ordem maior que envolvem espalhamento com transição de spin contribuem para a divergência logarítmica da resistividade.

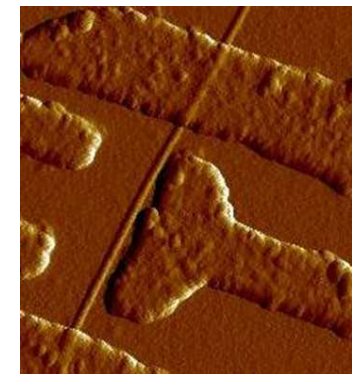
Ponto Quântico



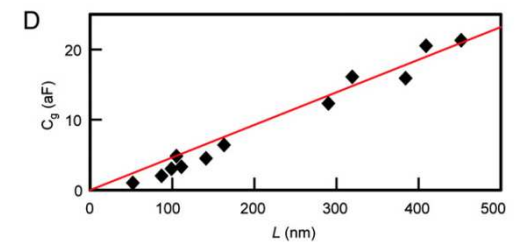
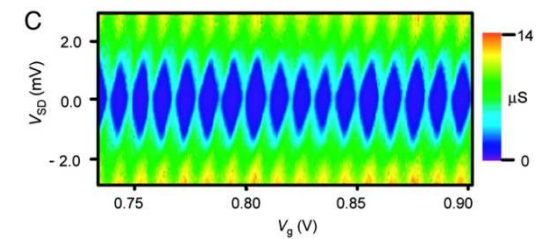
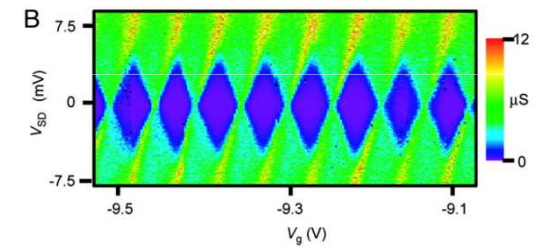
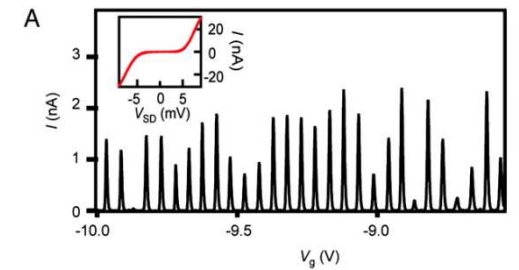
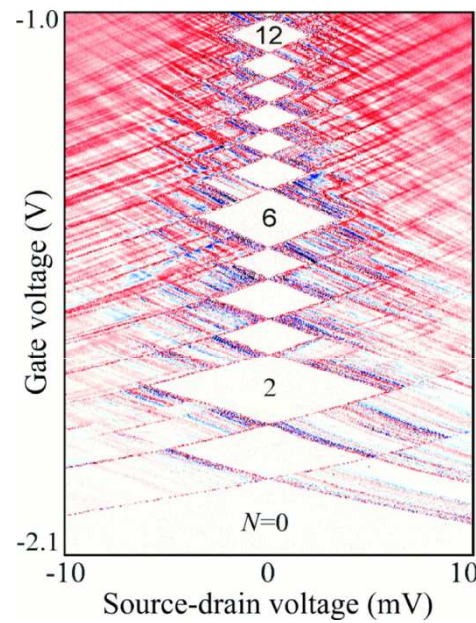
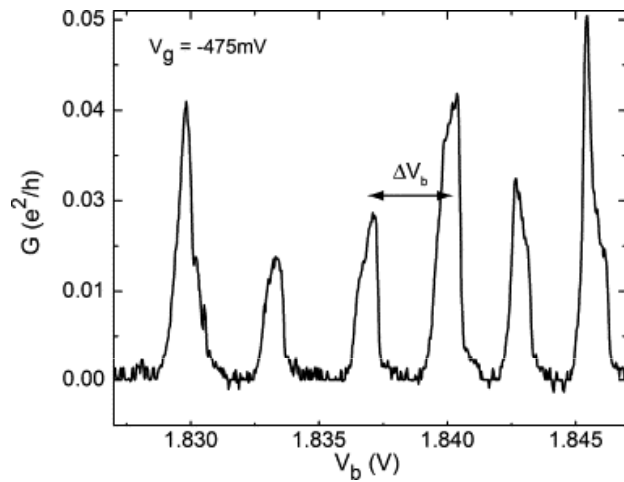
$$\Delta E$$

$$C_d = \frac{e}{\Delta E}$$

$$E_c = \frac{e^2}{C_d}$$

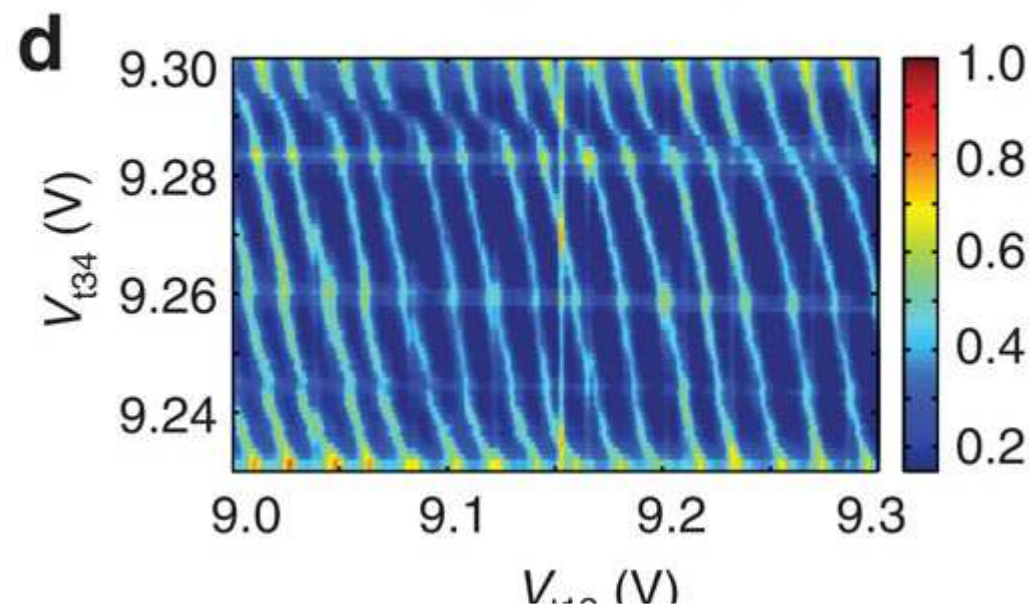
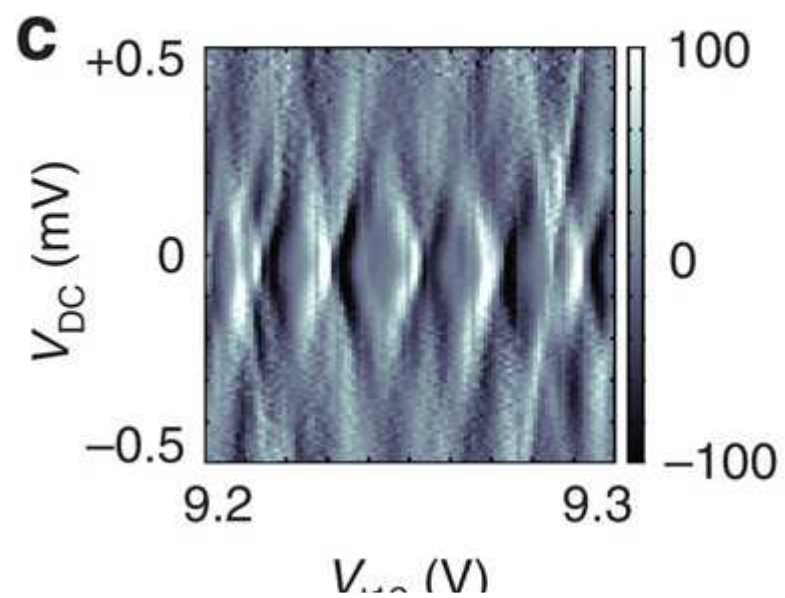
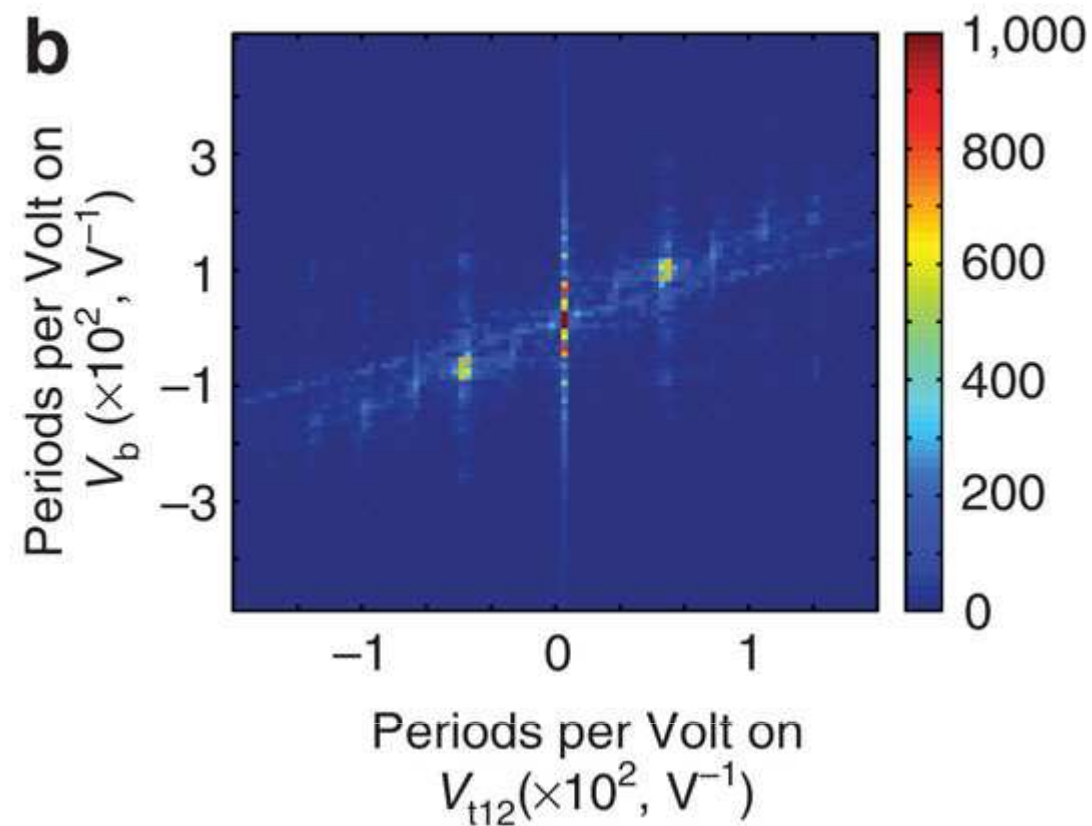
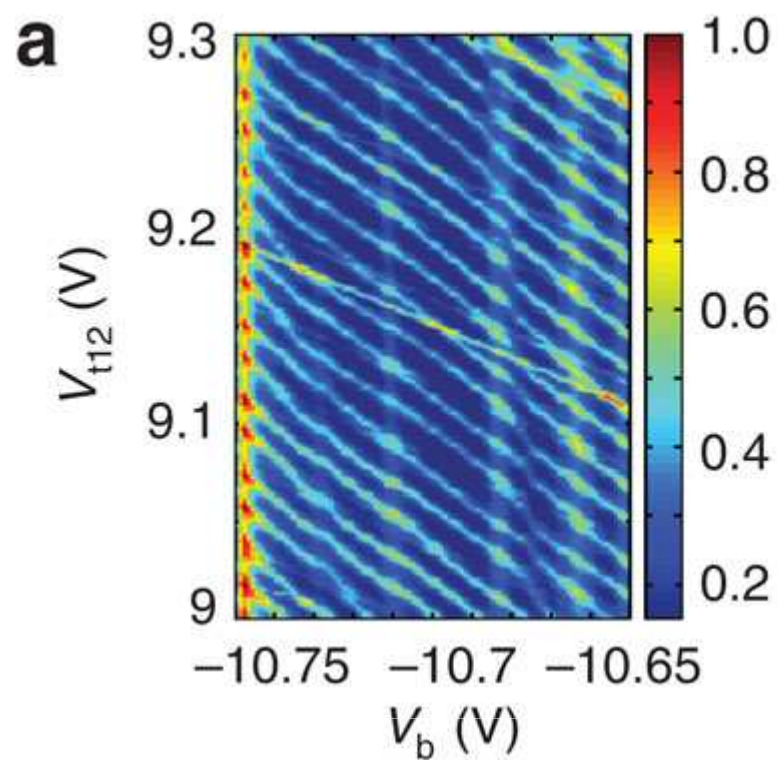


Bloqueio de Coulomb



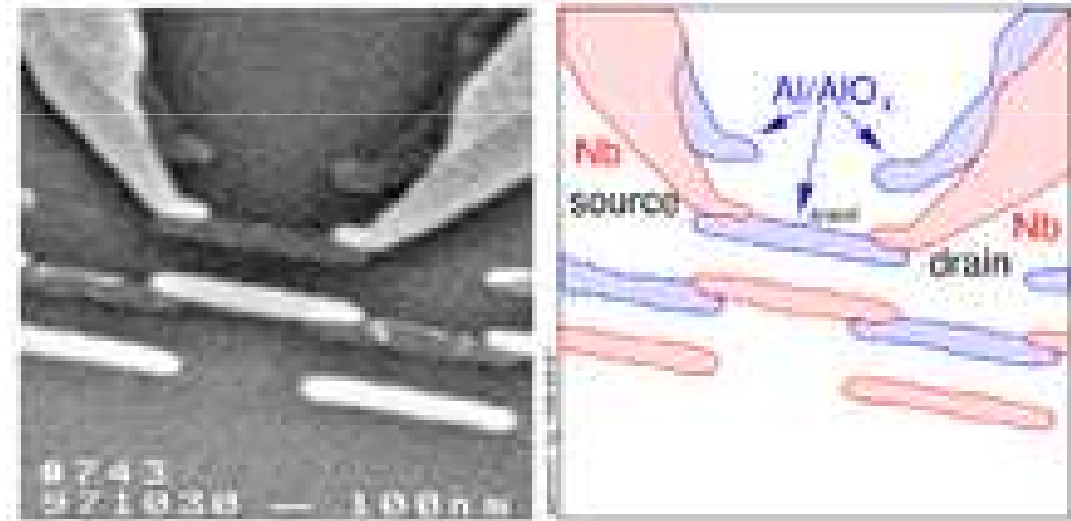
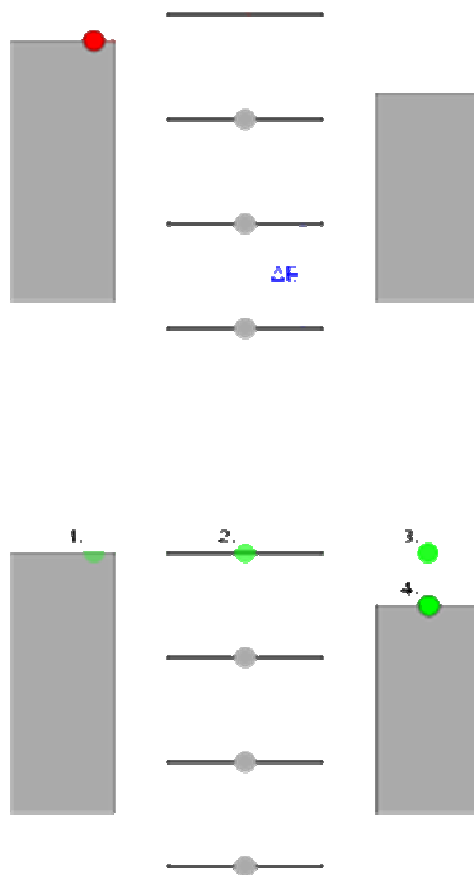
$$V_{bias} < \frac{e}{C_d}$$

$$k_B T < \frac{e}{C_d}$$

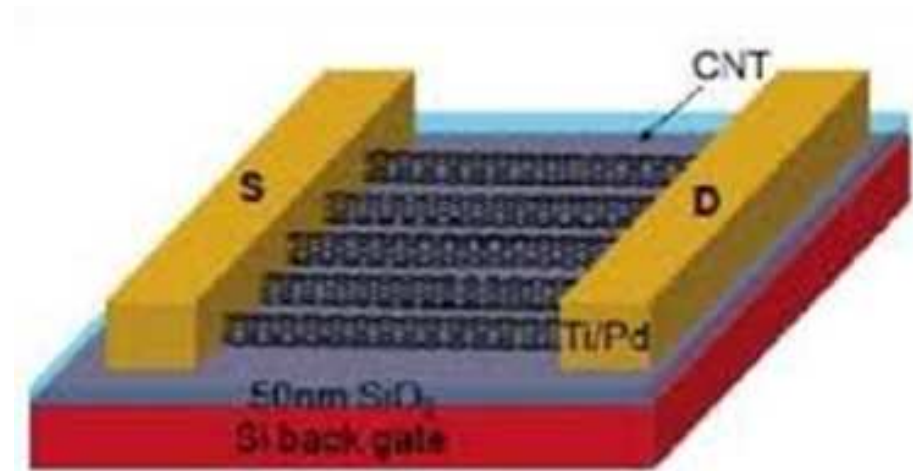
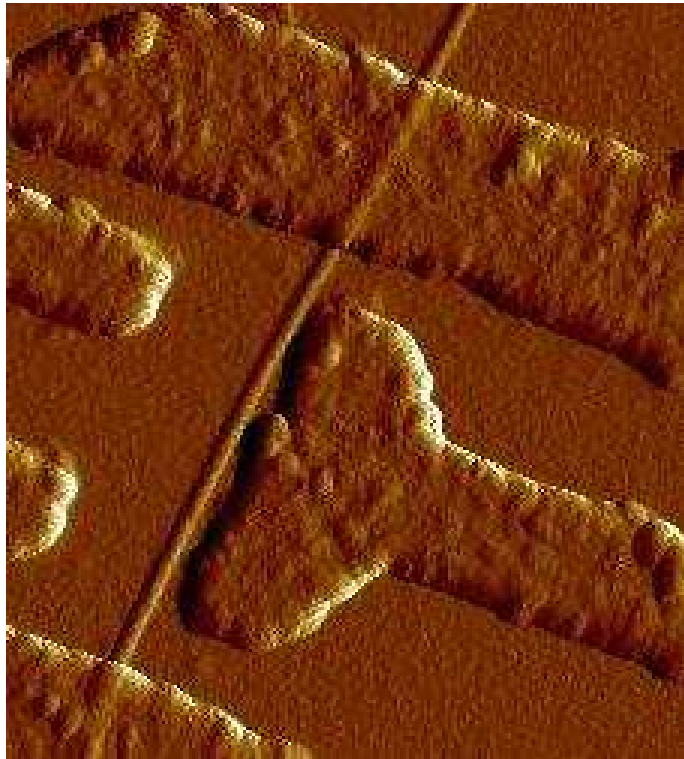


Transistor de Elétron Único

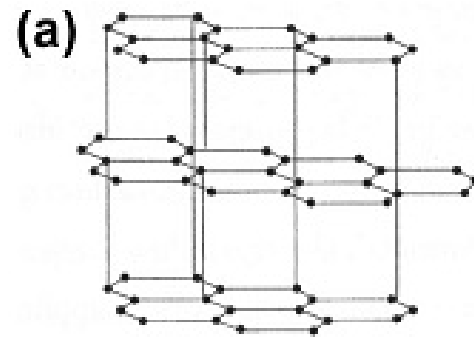
O campo elétrico pode controlar o gap entre os estados, permitindo ou não a passagem de elétrons.



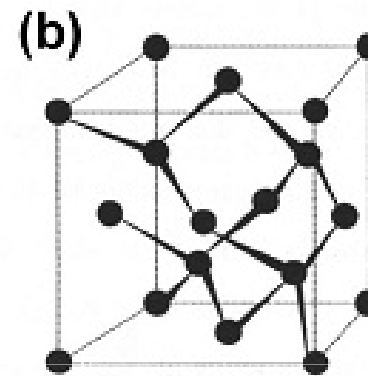
Nanotubos de Carbono como Pontos Quânticos



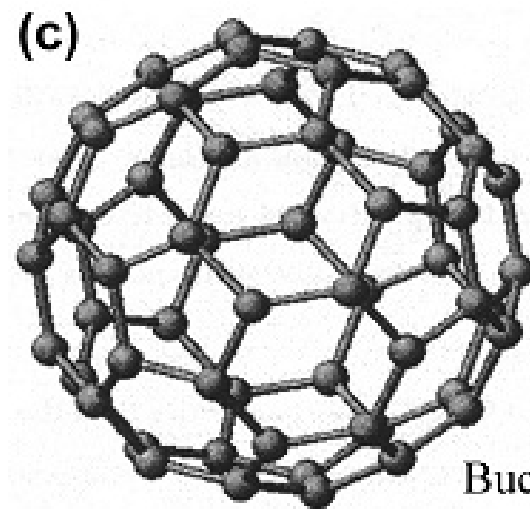
Carbono: Formas Alotrópicas



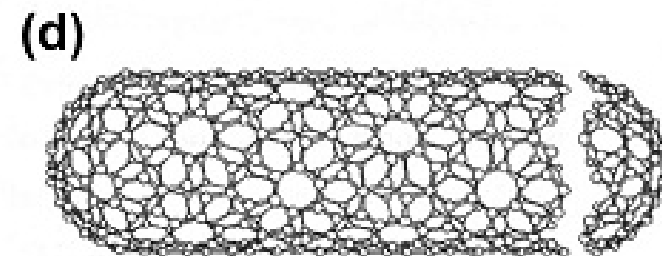
Graphite



Diamond

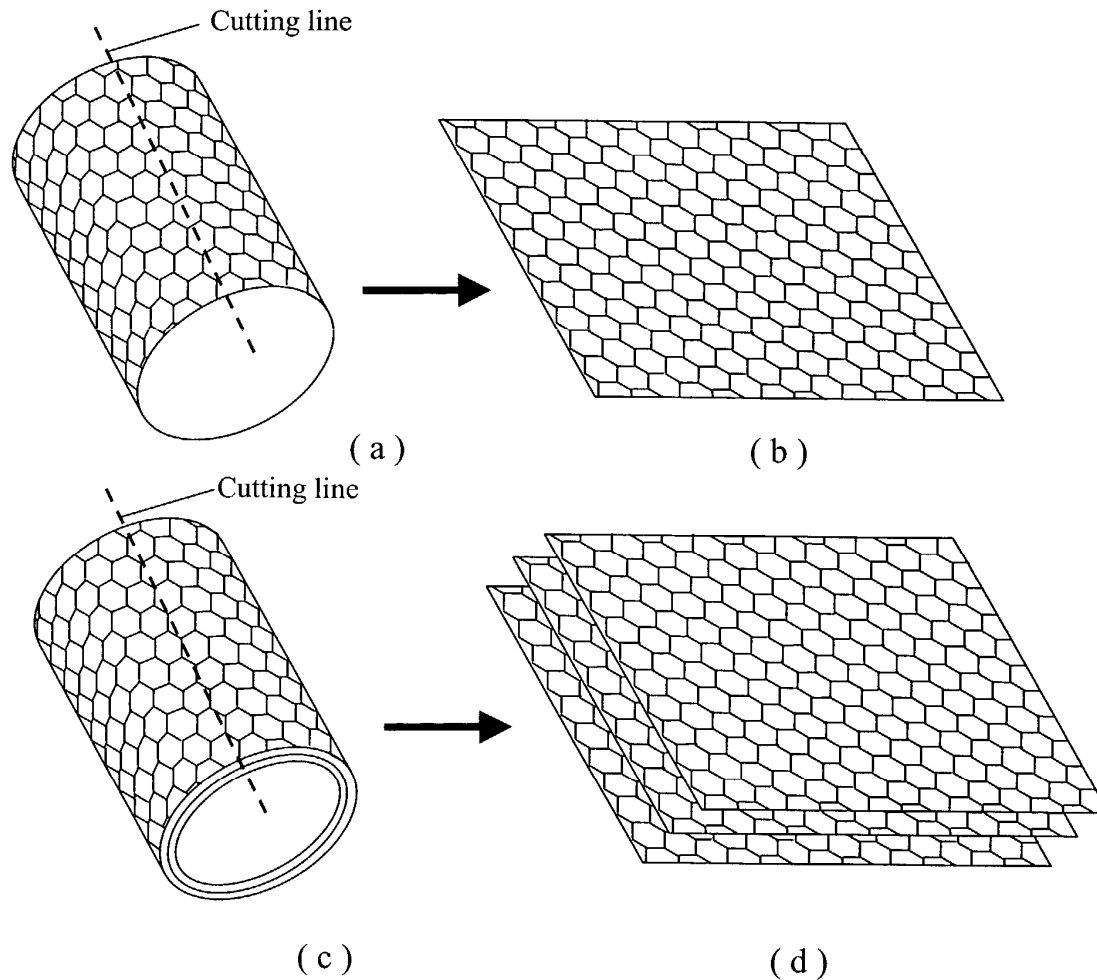


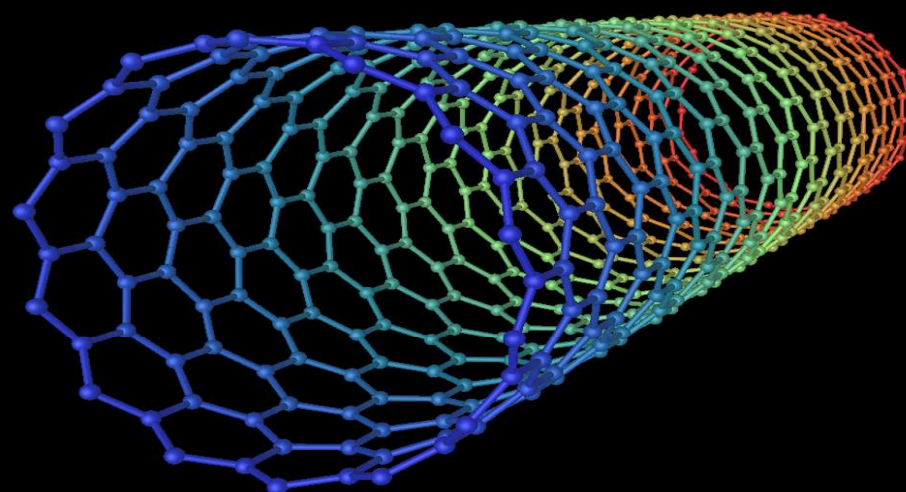
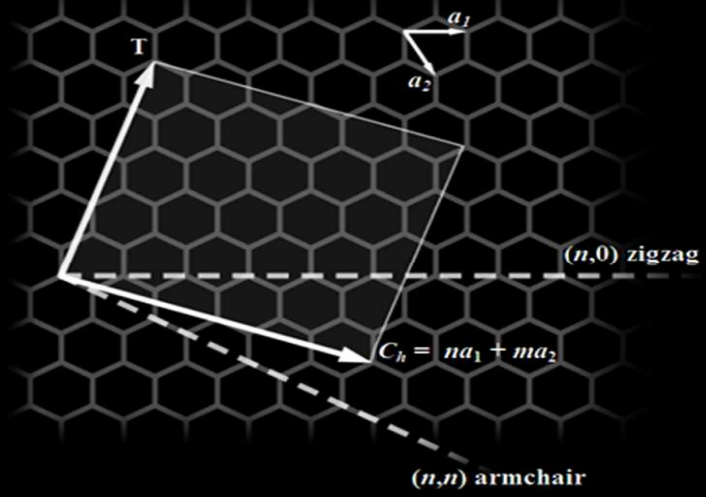
Bucky ball



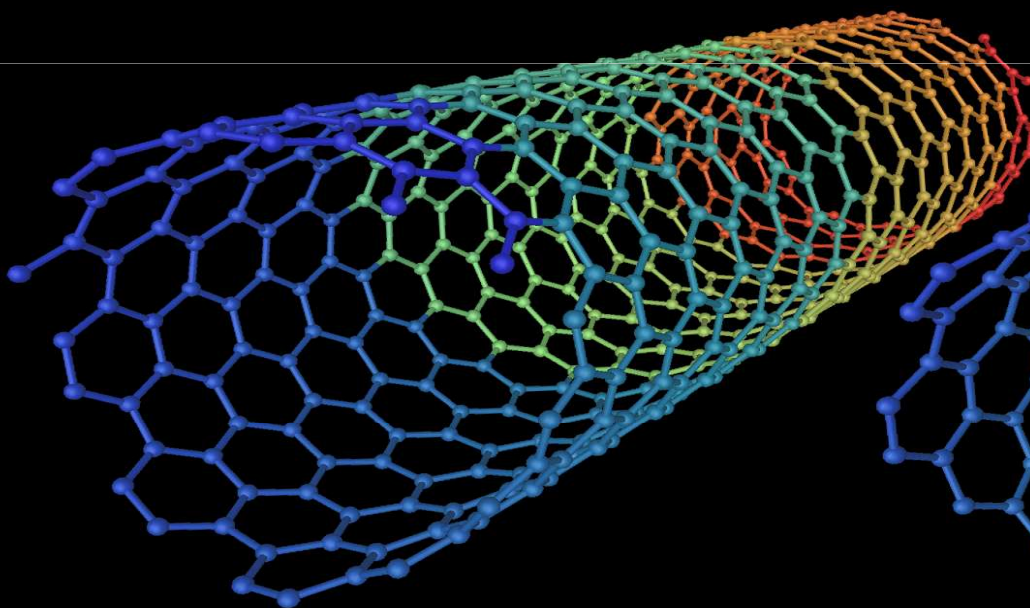
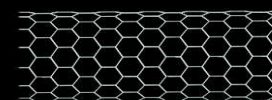
Nanotube

A Folha de Grafeno e o Nanotubo de Carbono

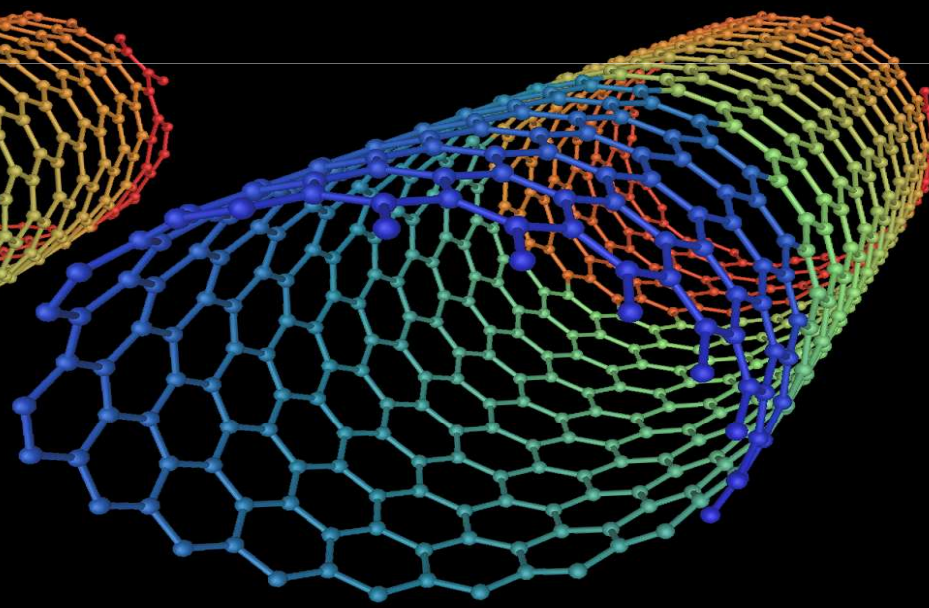
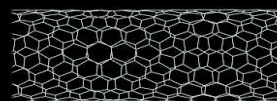




(0,10) nanotube
(zig-zag)



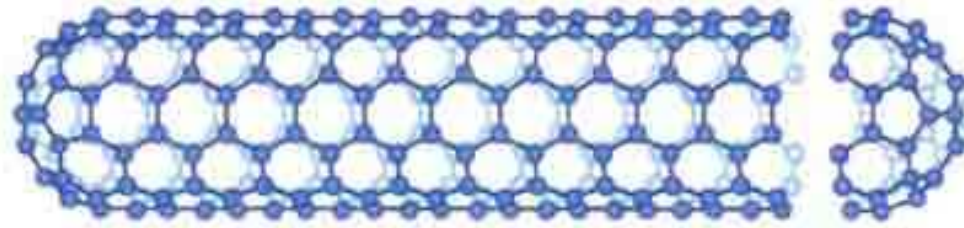
(7,10) nanotube
(chiral)



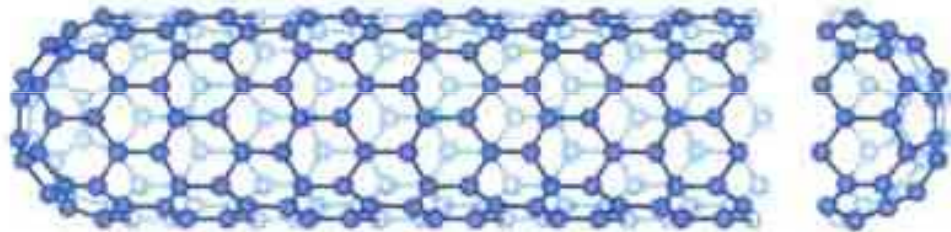
(10,10) nanotube
(armchair)



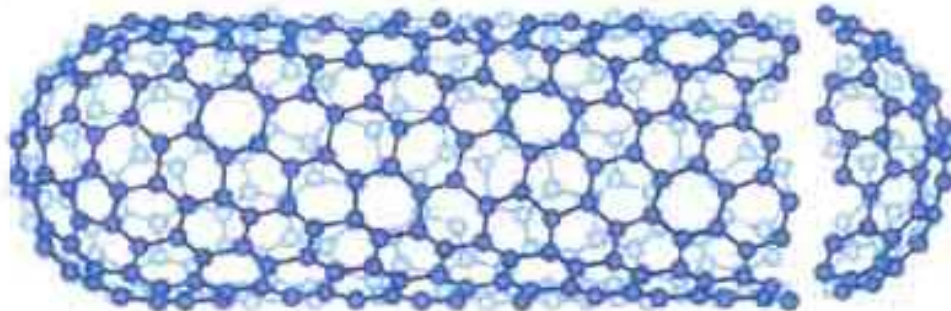
Tipos de Nanotubo



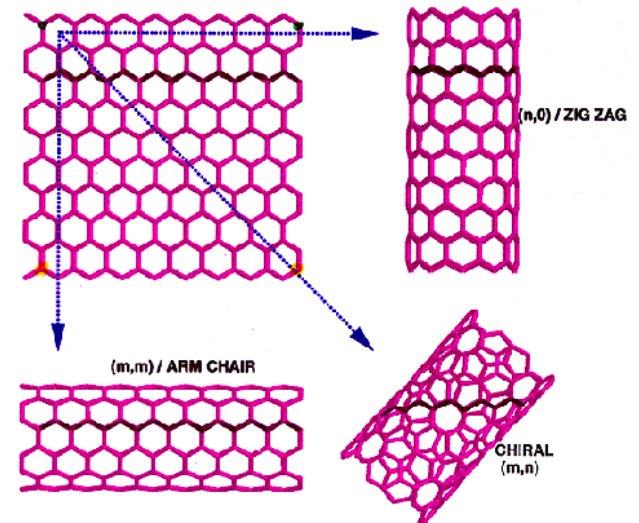
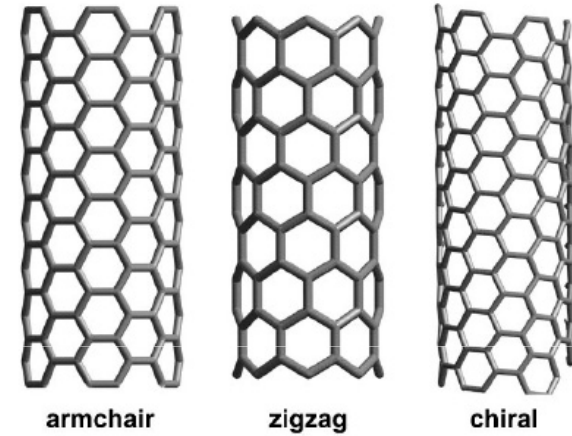
$(n,m) = (5,5)$



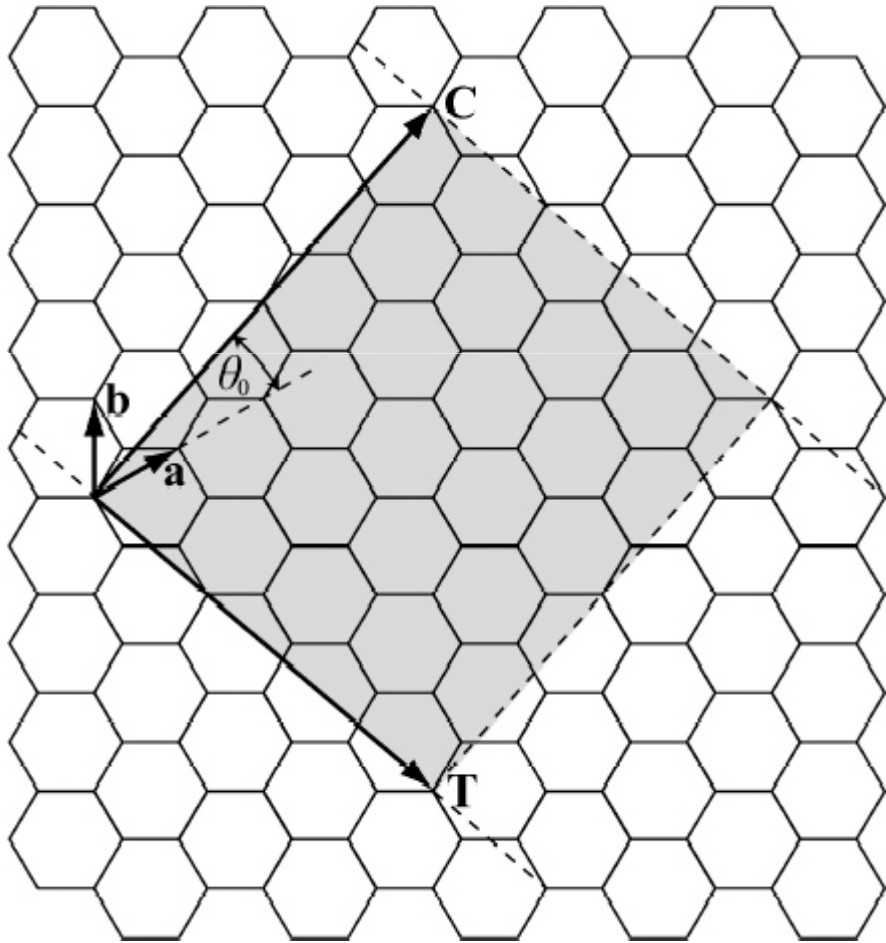
$(n,m) = (9,0)$



$(n,m) = (10,5)$



Algumas Relações Importantes



$$\vec{C}_h = n \vec{a}_1 + m \vec{a}_2$$

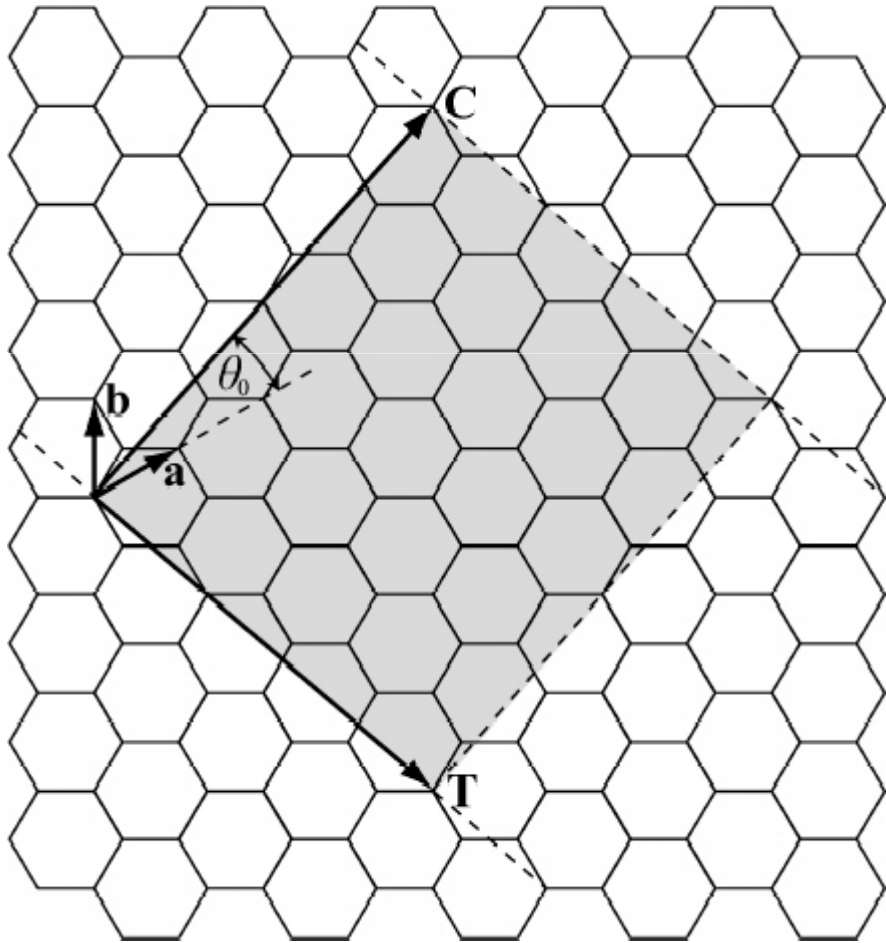
$$\vec{T} = t_1 \vec{a}_1 + t_2 \vec{a}_2$$

$$t_1 = \frac{2m + n}{N}$$

$$t_2 = -\frac{2n + m}{N}$$

$$\vec{C}_h \cdot \vec{T} = 0$$

Algumas Relações Importantes



$$R = \frac{|\vec{C}_h|}{2\pi} = \frac{a\sqrt{n^2 + m^2 + nm}}{2\pi}$$

$$\cos \theta = \frac{\vec{C}_h \cdot \vec{a}_1}{|\vec{C}_h| |\vec{a}_1|} = \frac{2n + m}{2\sqrt{n^2 + m^2 + nm}}; \quad 0^\circ \leq \theta \leq 30^\circ$$

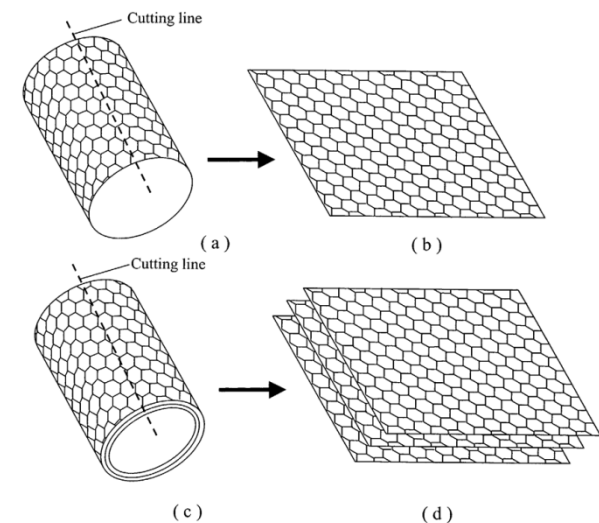
armchair :
 $(n = m \neq 0)$
 $\cos \theta = \frac{3n}{2n\sqrt{3}} = \frac{\sqrt{3}}{2}; \quad \theta = 30^\circ$

zigzag :
 $(n \neq 0 \text{ e } m = 0)$
 $\cos \theta = \frac{2n}{2n} = 1; \quad \theta = 0$

Critérios para o Caráter Metálico

- Em um nanotubo metálico a circunferência do tubo deve conter um número inteiro de comprimentos de onda do elétron.
- Com isso, dos vários estados metálicos presente no grafeno, apenas alguns poucos permanecerão no nanotubo.

$$2n + m = 3p$$



Critérios para o Caráter Metálico

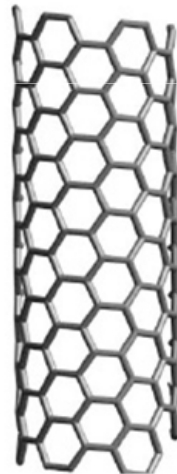
$$2n + m = 3p$$



armchair



zigzag



chiral

armchair :

$$(n = m \neq 0)$$

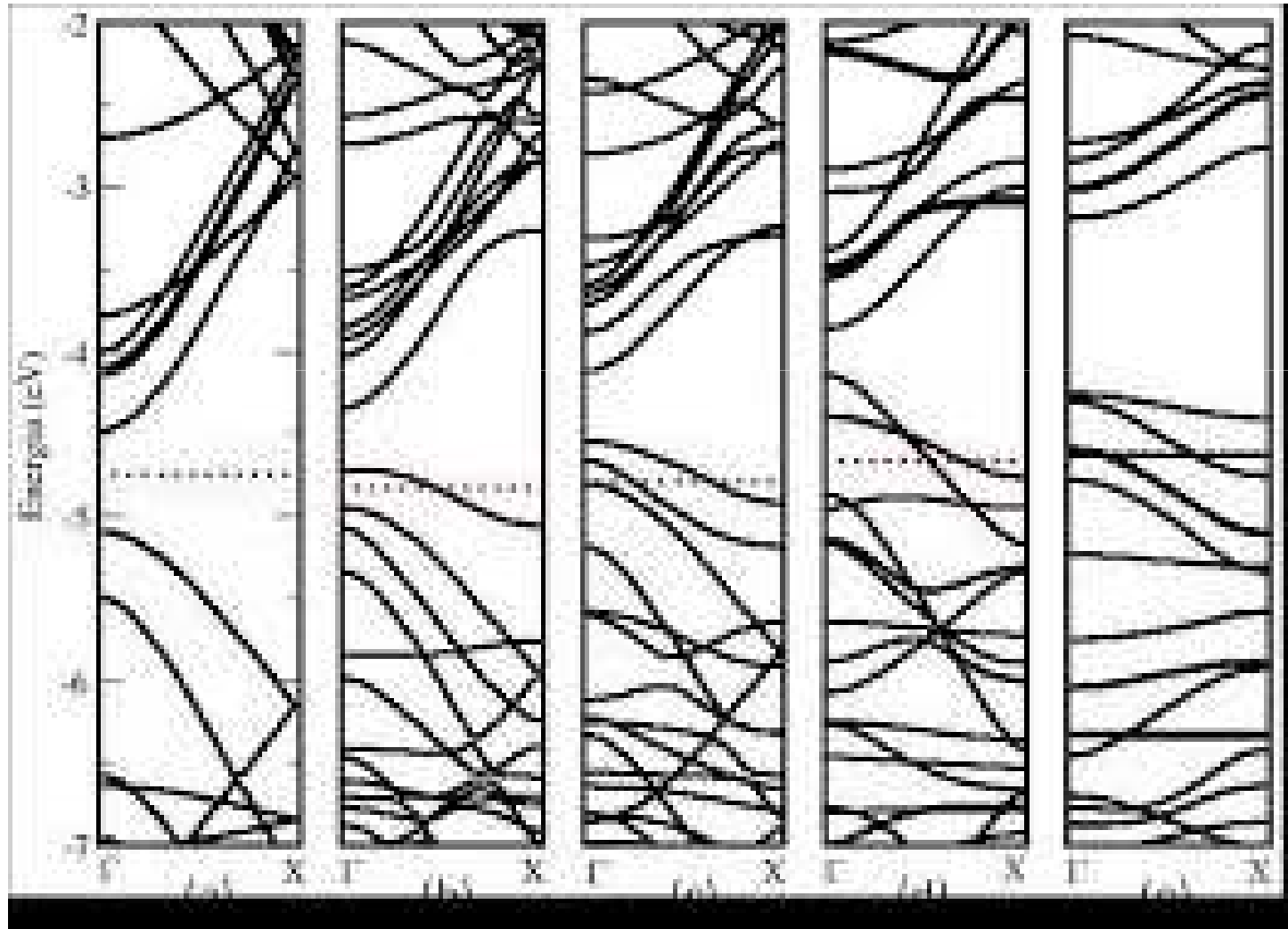
metálico

zigzag :

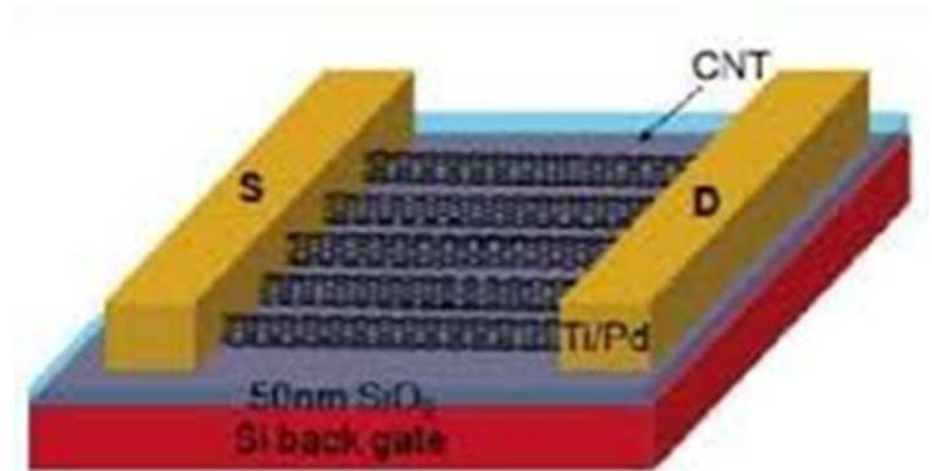
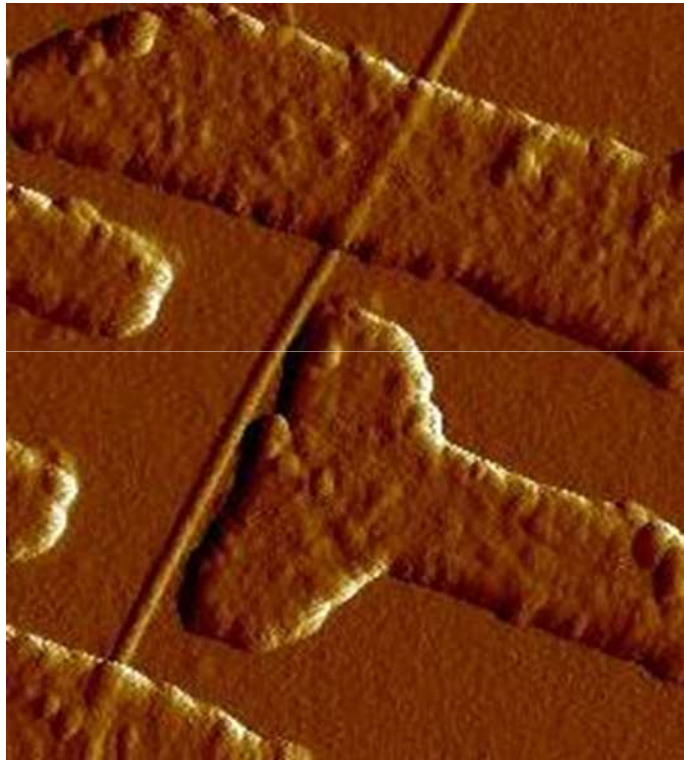
$$(n \neq 0 \text{ e } m = 0)$$

metálico para n múltiplo de 3,
do contrário semicondutor

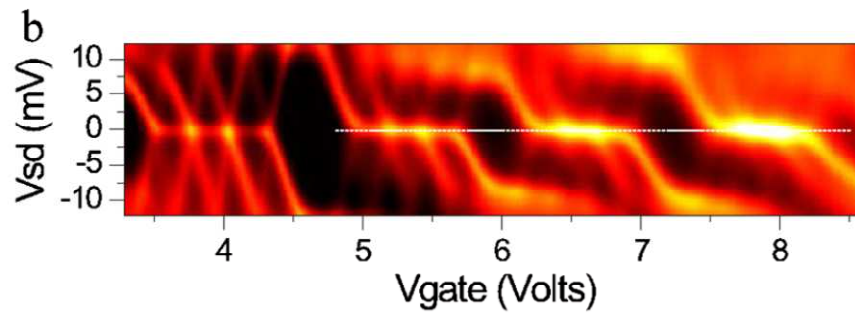
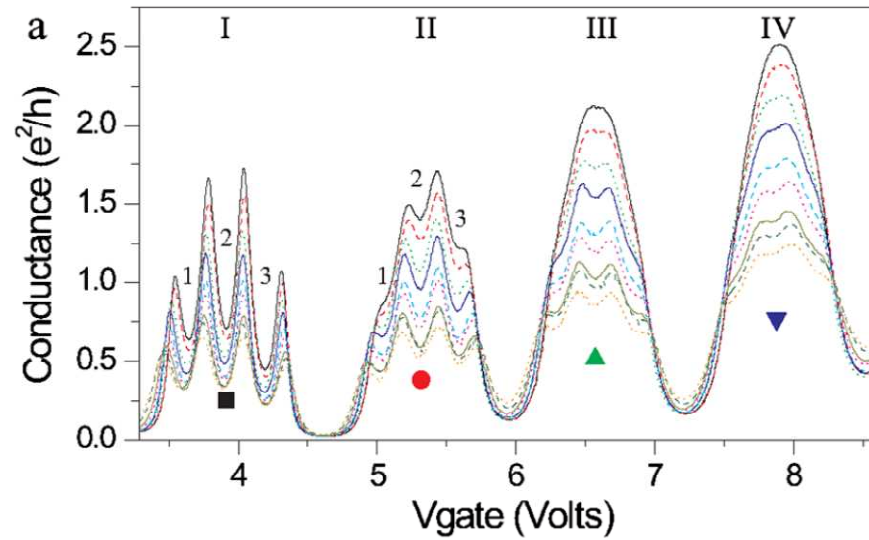
Nanotubo Semicondutor



Efeito Kondo em Nanotubos



Ressonâncias



$$\Gamma_S \gg \Gamma_D \quad [h]$$

