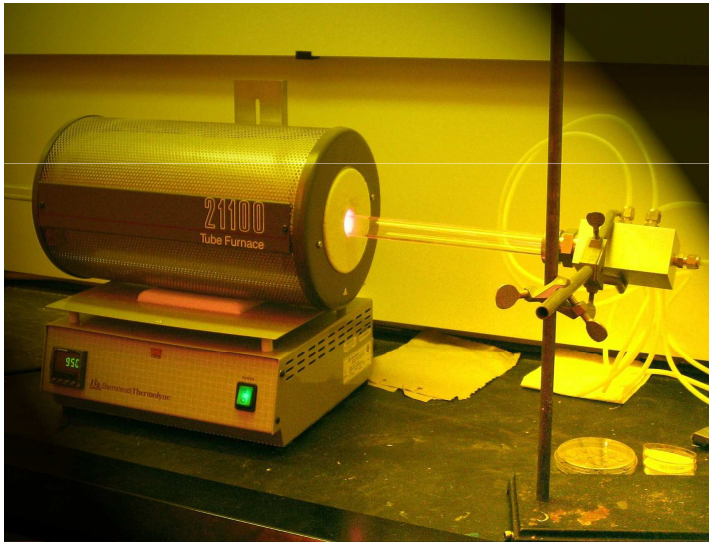
Random Telegraph Signal in Carbon Nanotube Device

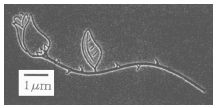


Tsz Wah Chan

Feb 28, 2008

Introduction

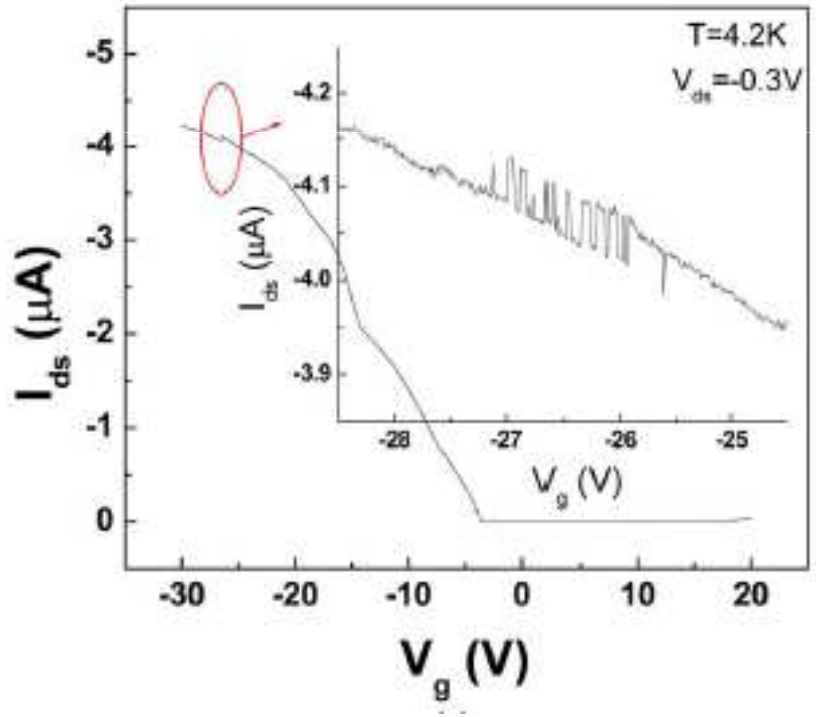
1. Structure of Single-walled Carbon Nanotube (SWCNT)
2. Electronic properties of SWCNT
3. Sample preparation: Catalytic synthesis of SWCNT, Fabrication.
4. Electronic transport: carbon nanotube field effect transistor (CNT-FET), ideal IV curves.
5. RTS basics, Other groups' data, our data
6. Future work
7. Group and Collaboration



Motivation:

1. Interaction between single molecular defects and 1D conduction channel in nano scale

2. Potential sensing technology in nano scale



F. Liu, K. L. Wang, C. Li, and C. Zhou, IEEE Transaction on Nanotechnology, **5**, 411 (2006)

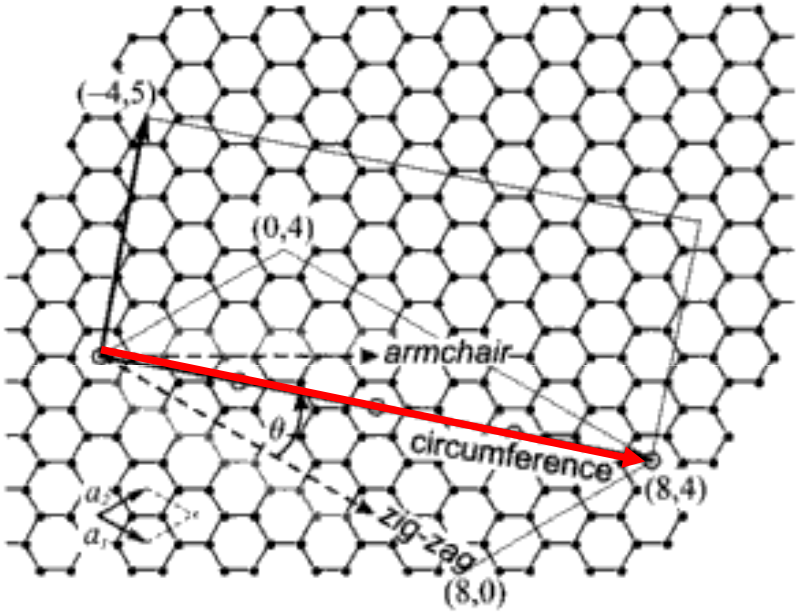
1. Structure of Single-walled carbon nanotube (SWCNT).

•Graphene sheet rolled up into a hollow cylinder

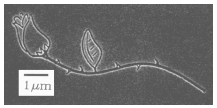
•Graphene is rolled along Chiral vector into cylinder

•Chiral Vector $\mathbf{C} = n\mathbf{a}_1 + m\mathbf{a}_2$

• Chirality indices (n, m) uniquely define a tube



•Dresselhaus et al., Physics World 1998



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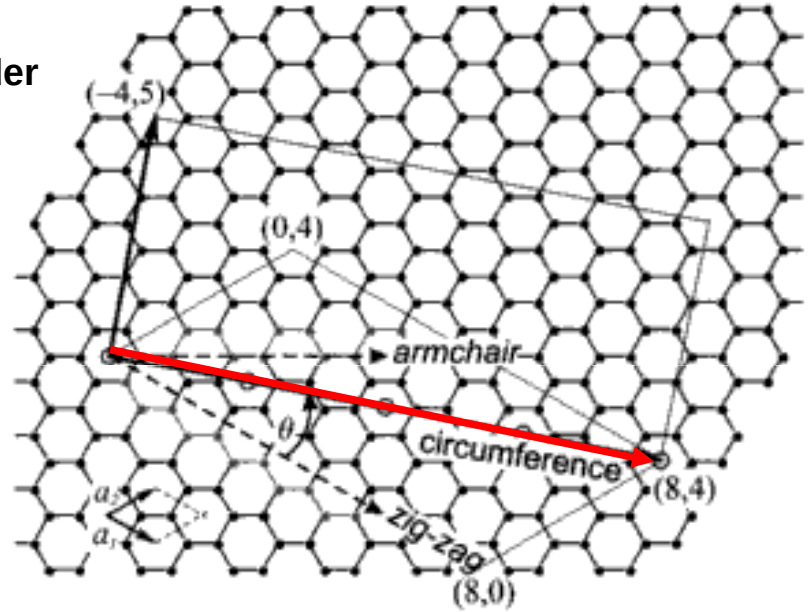

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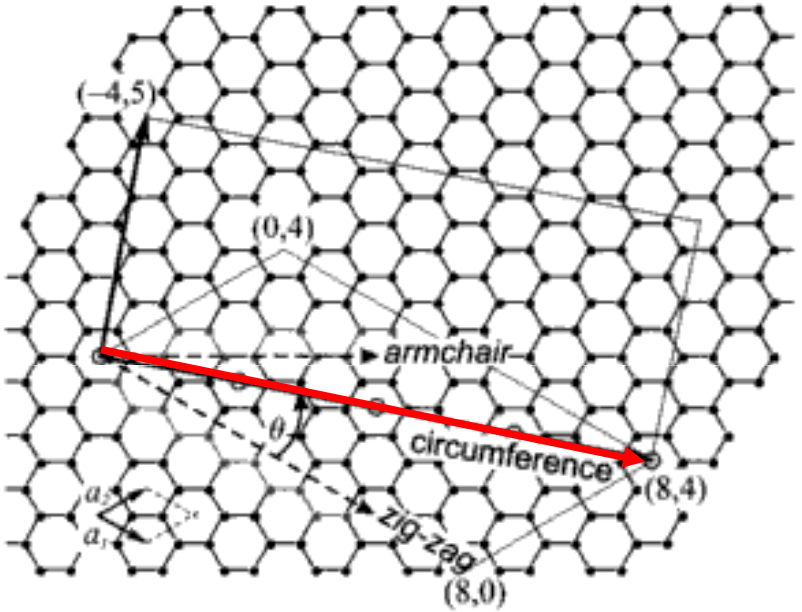

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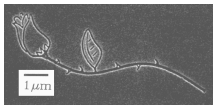

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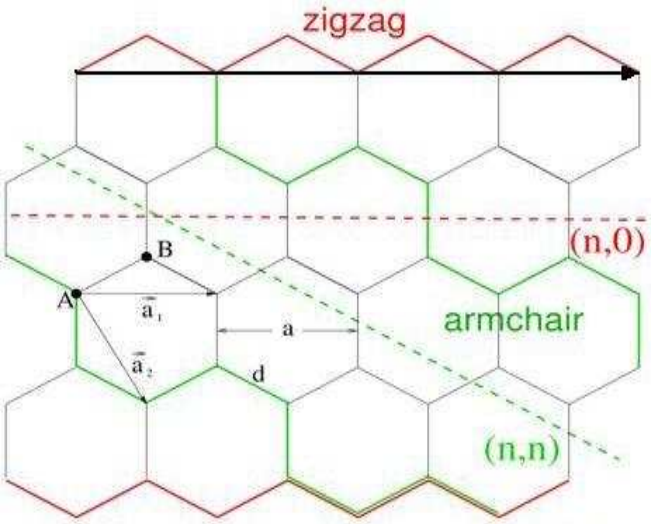

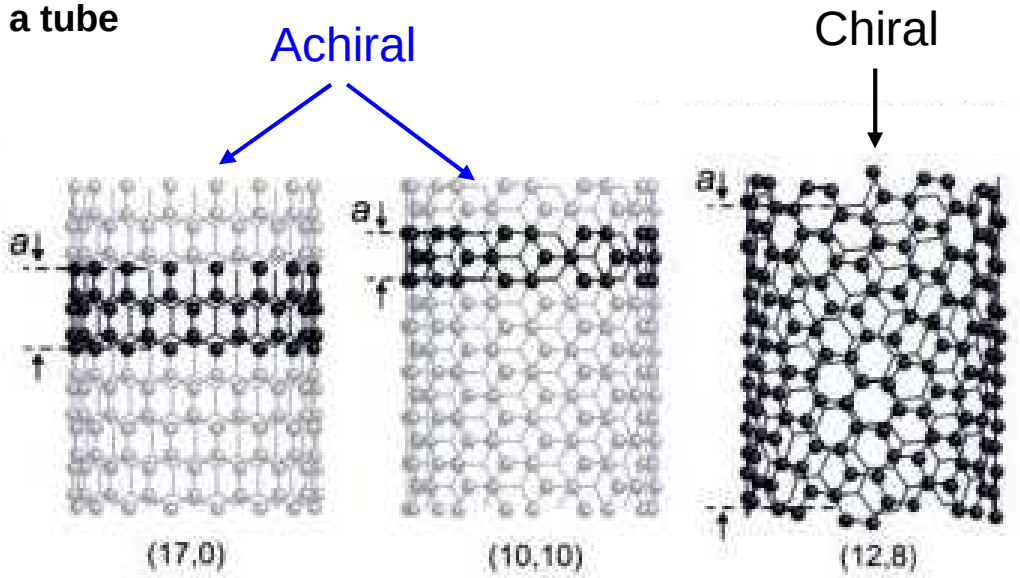

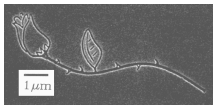

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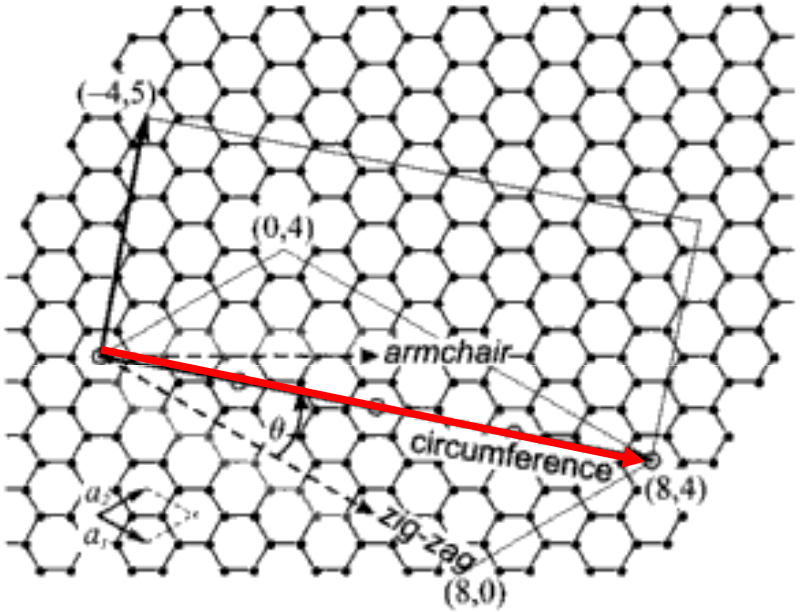
1. Structure of Single-walled carbon nanotube (SWCNT).

•**Diameter** $d = \frac{|C|}{\pi} = \frac{a_0}{\pi}\sqrt{(n^2 + nm + m^2)}$

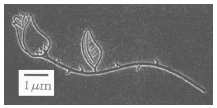
•**Metallic if** $|n-m| = 3q$, q=1,2,3…

•**Semiconducting if** $|n-m| = 3q \pm 1$



$$a_0 = 1.42 \times \sqrt{3} = 2.46\,\mathring{A}$$

•Dresselhaus et al., Physics World 1998



2. Electronic properties

•Bonding in graphene

•Tight Binding Description of graphene

•Dispersion of graphene

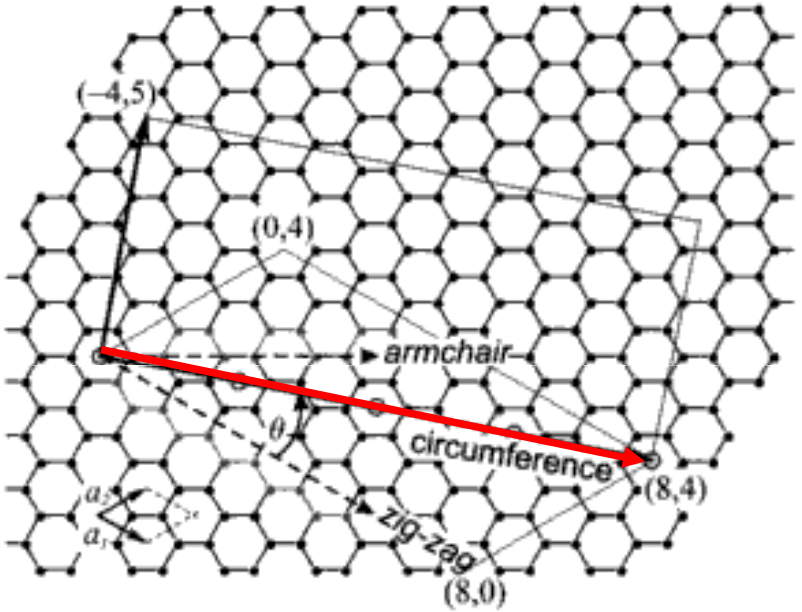
•Zone-folding Approximation

•1D electronic density of states

- Many CNT properties derived from Graphene

- Origin of conductivity in Graphene

- Zone folding approximation: graphene to CNT



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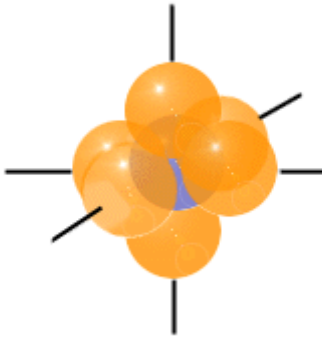
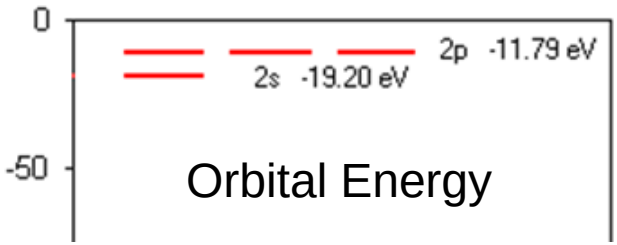




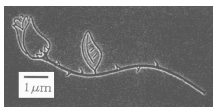
Orange: $2p_x$, $2p_y$, $2p_z$,
Blue: 2s

Origin of conductivity in Graphene

- 4 outer most shell electrons

- energies are so close together, new orbtials formed by mixing orbitals

World of Carbon, invsee.asu.edu/nmodules/**Carbon**mod/bonding.html



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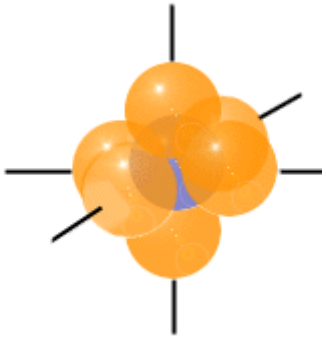
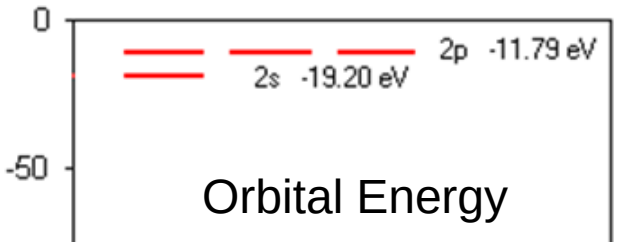


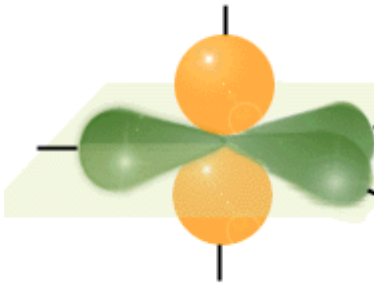


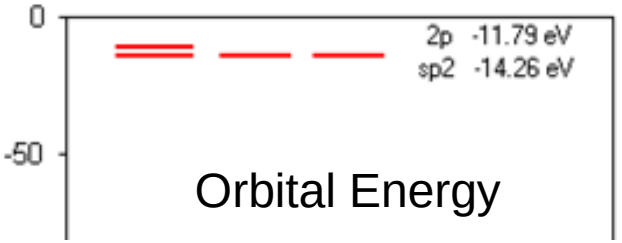
Orange: $2p_x$, $2p_y$, $2p_z$,
Blue: 2s

Sp_2 hybridization

- **Sp_2 orbitals are trigonal planar**
- **$2p_z$ orbital is not hybridized**

Sp_2 hybridization





Orange: $2p_z$,
Green: sp_2

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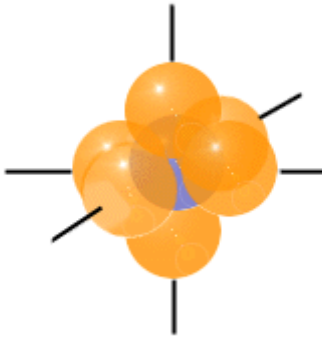
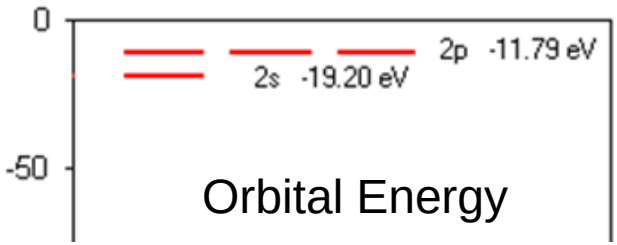




Orange: $2p_x$, $2p_y$, $2p_z$,
Blue: 2s

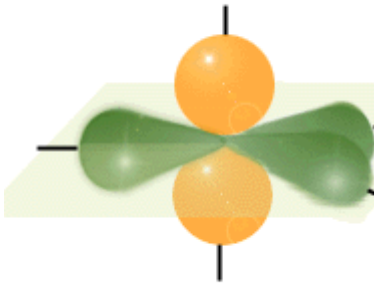
Sigma bond:

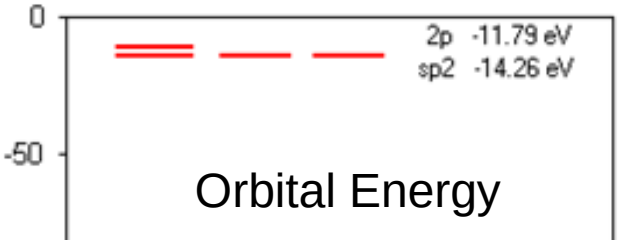
- overlapping between sp_2 orbitals

- responsible for hexagonal network

- no energy band close to Fermi level, doesn't contribute to conductivity

Sp_2 hybridization





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- **Bonding in graphene**
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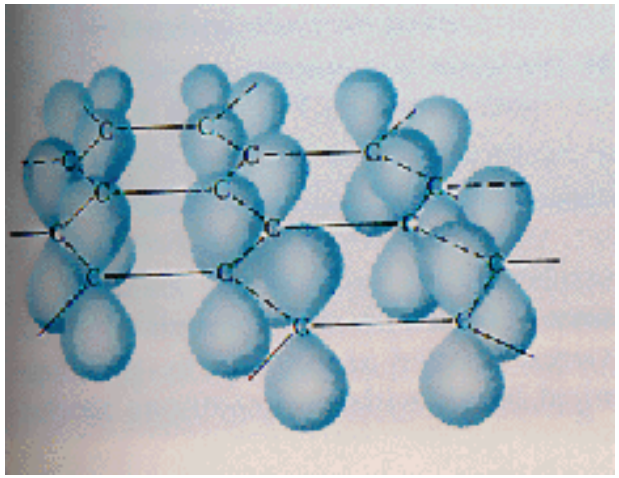
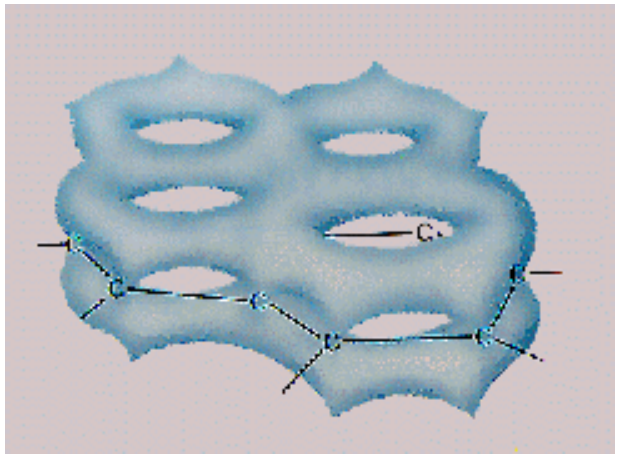


Pi bond:

- overlapping between $2p_z$ orbitals in side way manner

- responsible for electrical conduction



2. Electronic properties

•Bonding in graphene
•Dispersion of graphene
•Zone-folding Approximation
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- Dispersion obtained by tight binding approximation

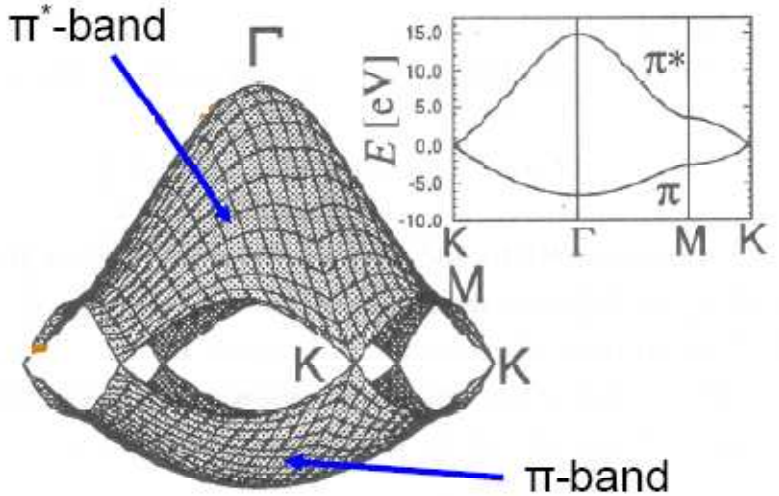
$$E^{\pm}(\boldsymbol{k}) = \frac{\varepsilon_{2p} \mp \gamma_0 \sqrt{f(\boldsymbol{k})}}{1 \mp s_0 \sqrt{f(\boldsymbol{k})}}.$$

3 empirical parameters:

$\varepsilon_{2p} \sim -0.28eV$

$\gamma_0 \sim -2.97eV$

$s_0 \sim 0.073eV$



S. REICH, J. MAULTZSCH, C. THOMSEN, AND P. ORDEJON
PHYSICAL REVIEW B **66**, 035412 ~2002!

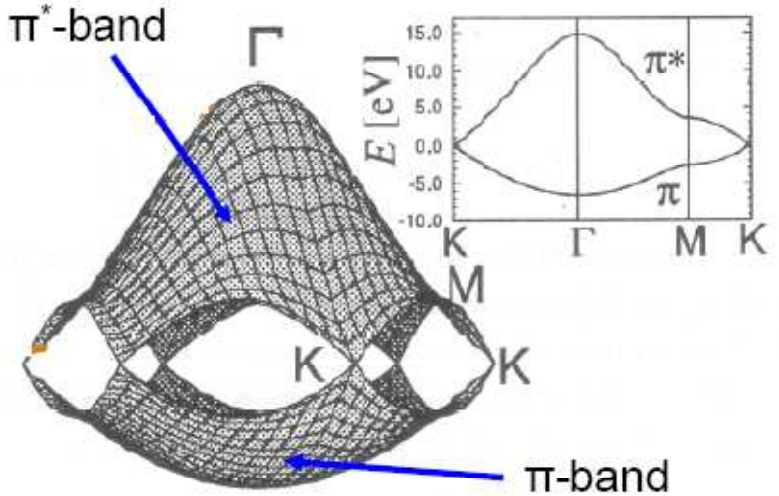
2. Electronic properties

•Bonding in graphene
•Dispersion of graphene
•Zone-folding Approximation
•1D electronic density of states

Upper band: anti-pi bond,
conduction band

-Lower band: pi valence band

-Meet at K point,
metallic behavior in Graphene



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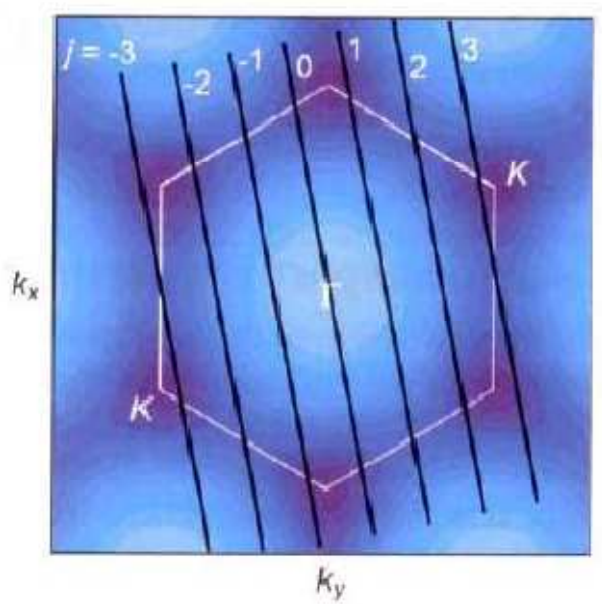

Dispersion of a (4,2) Chiral tube**

$\overrightarrow{k_z}$ continuous along the tube

$\overrightarrow{k_{\perp q}}$ Quantized along Circumference:

- Only certain k vector is allowed along Circumference

$\overrightarrow{k_{\perp q}} \cdot \vec{C} = 2\pi q$,q=integer

- one line in Brillouin zone for each q

- allowed k-vectors on these lines.

**R. Saito, et. al, *Physical Properties of Carbon Nanotubes*, Imperial College Press,1998.

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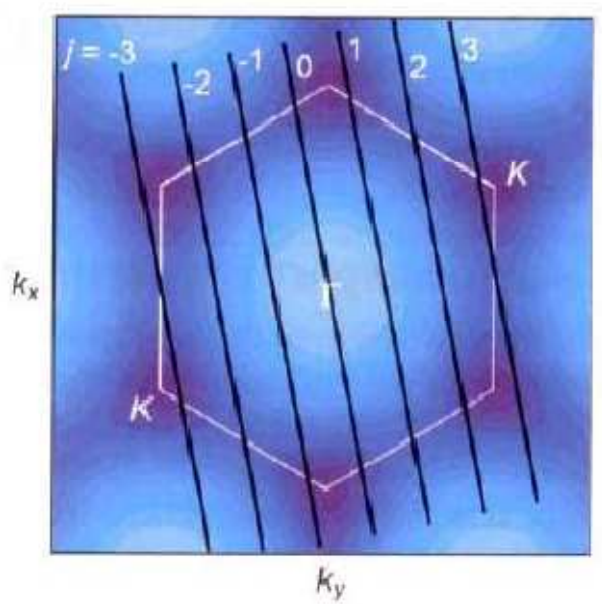

Dispersion of a (4,2) Chiral tube**

-Only K point has energy band crossing Fermi level

- Metallic if K point $(\frac{1}{3}\vec{k}_1 - \frac{1}{3}\vec{k}_2)$ is allowed:

$$\vec{K}\cdot\vec{C} = (\frac{1}{3}\vec{k}_1 - \frac{1}{3}\vec{k}_2)\cdot(n\vec{a}_1 + m\vec{a}_2) = \frac{2\pi}{3}(n-m) = 2\pi q$$

=> $n - m = 3q$ where $\vec{a}_1\cdot\vec{b}_1 = \vec{a}_2\cdot\vec{b}_2 = 2\pi$

- (4,2) is a semi-conducting tube

**R. Saito, et. al, *Physical Properties of Carbon Nanotubes*, Imperial College Press,1998.

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- Bonding in graphene
- Dispersion of graphene
- **Zone-folding Approximation**
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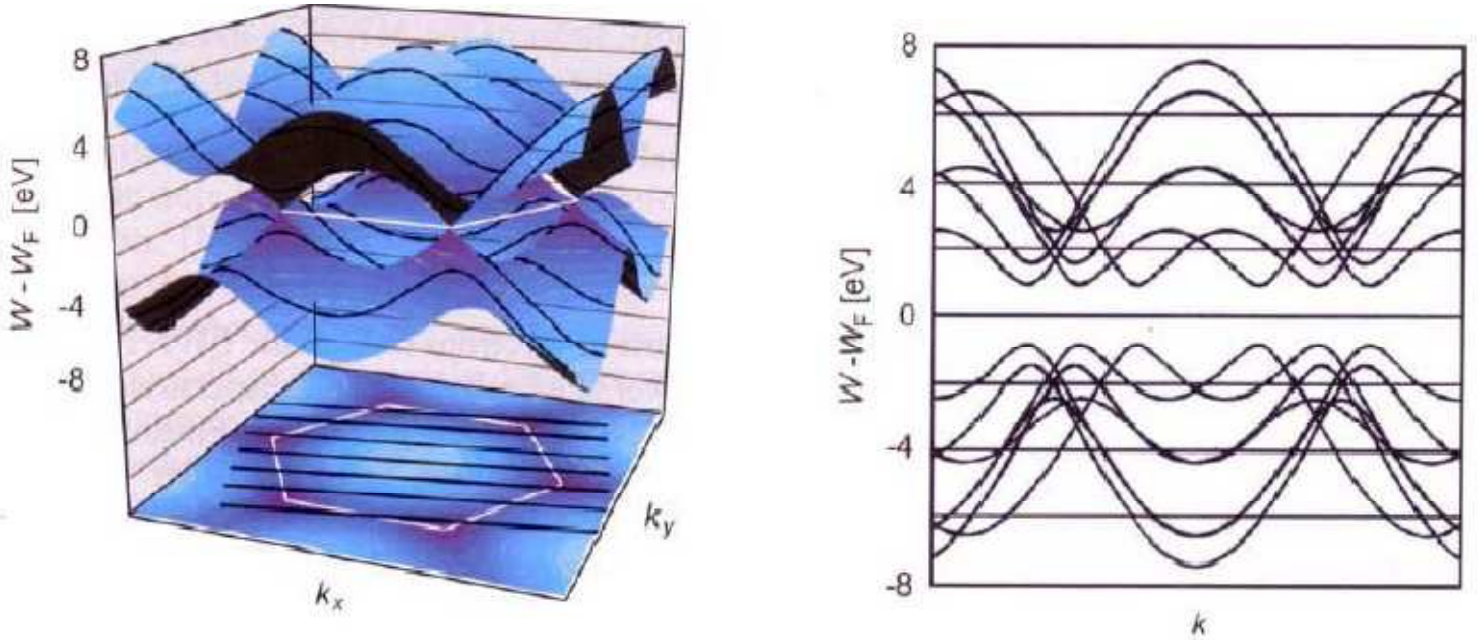

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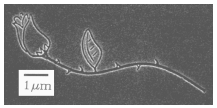
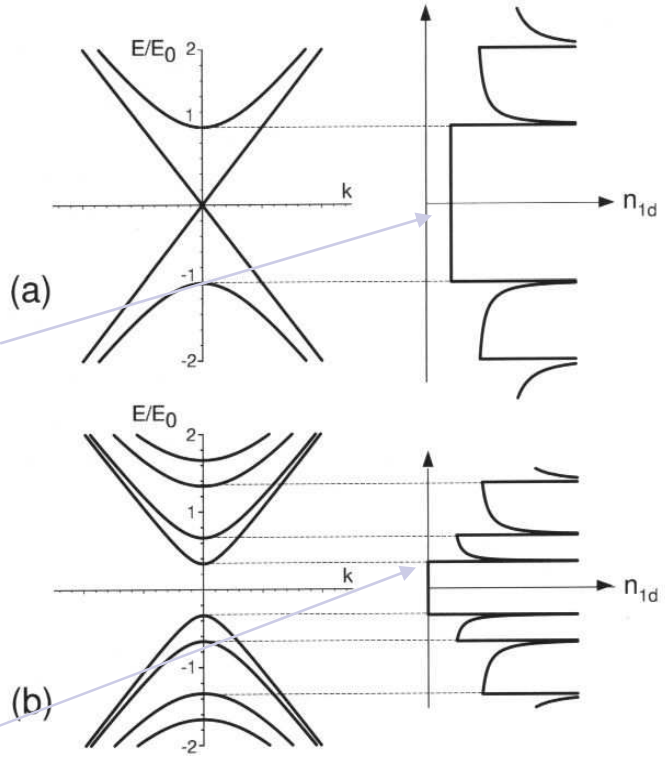


2. Electronic properties

- Bonding in graphene
- Dispersion of graphene
- Zone-folding Approximation
- **1D electronic density of states**

Different between CNT and graphene:

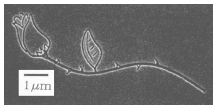
- Highly peaked DOS in 1D system



Metallic

Semiconducting

[2] Raman resonance: Rao, Richter, Bandow, Chase, Eklund, Williams, Fang, Subbaswamy, Menon, Thess, Smalley, Dresselhaus, Dresselhaus

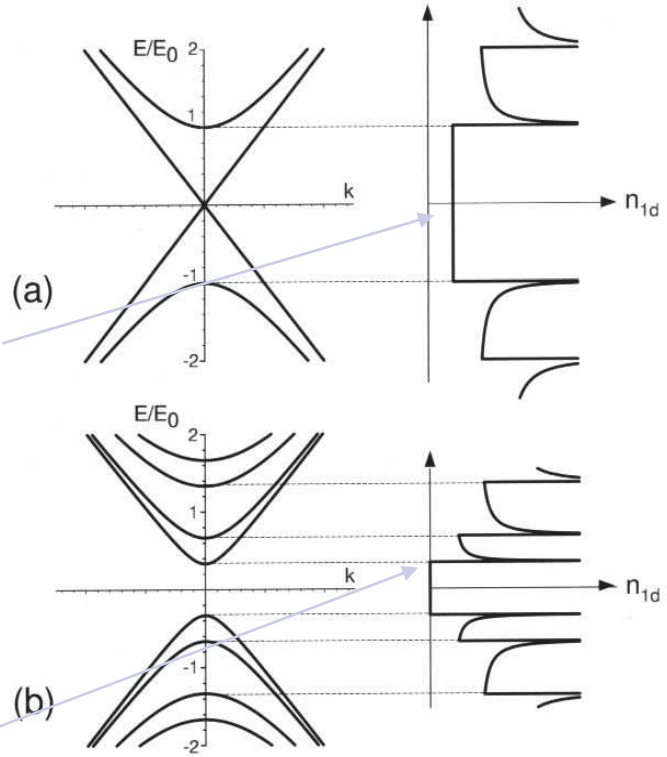


2. Electronic properties

- Bonding in graphene
- Dispersion of graphene
- Zone-folding Approximation
- **1D electronic density of states**

Metallic: DOS is constant around Fermi level

Metallic



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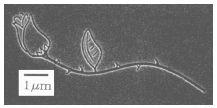

2. Electronic properties

- Bonding in graphene
- Dispersion of graphene
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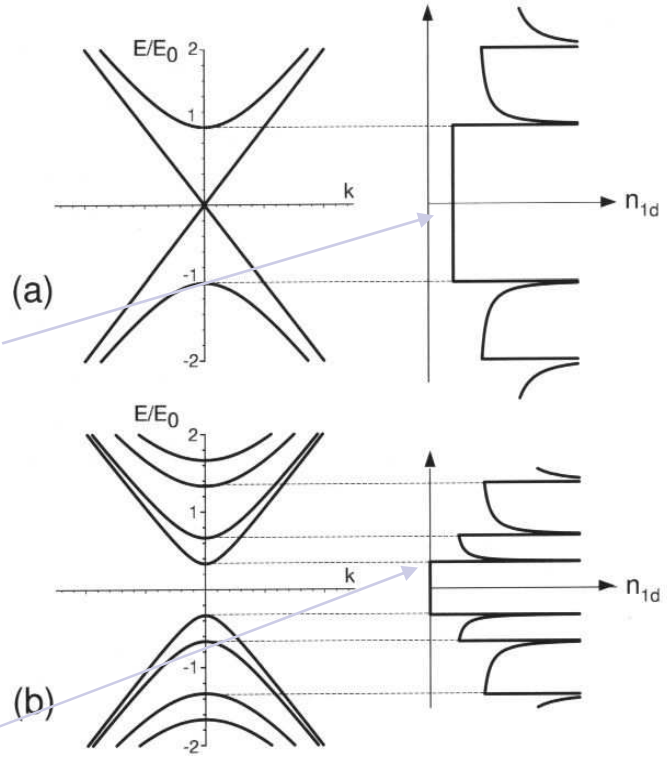
- **1D electronic density of states**

Metallic:
DOS is non-zero around Fermi level

Metallic



Important in optical spectroscopy!

Semiconducting:
DOS is zero around Fermi level

Semiconducting

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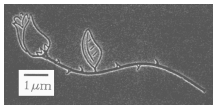
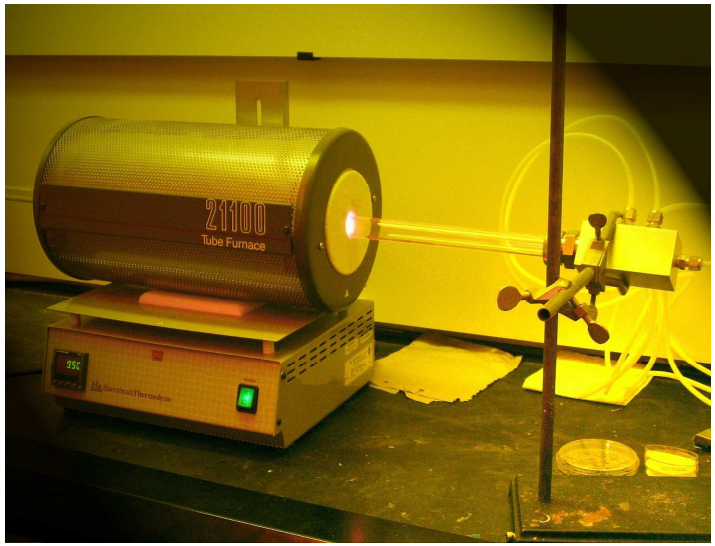


3. Device

- **Catalytic synthesis of SWCNT**
- Field effect transistor



CVD tubes:

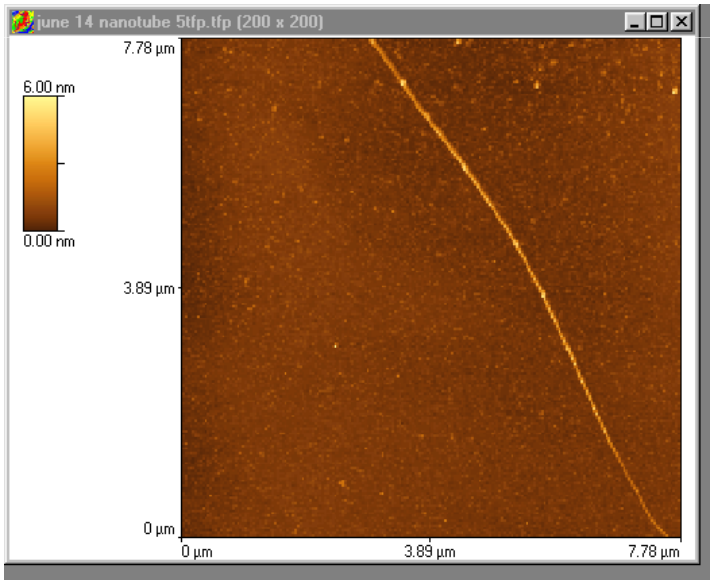
-Mostly single-walled, 1-3nm

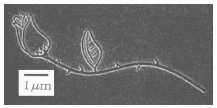
-tens of micron in length

-long, straight, in designated area

-cannot control chirality

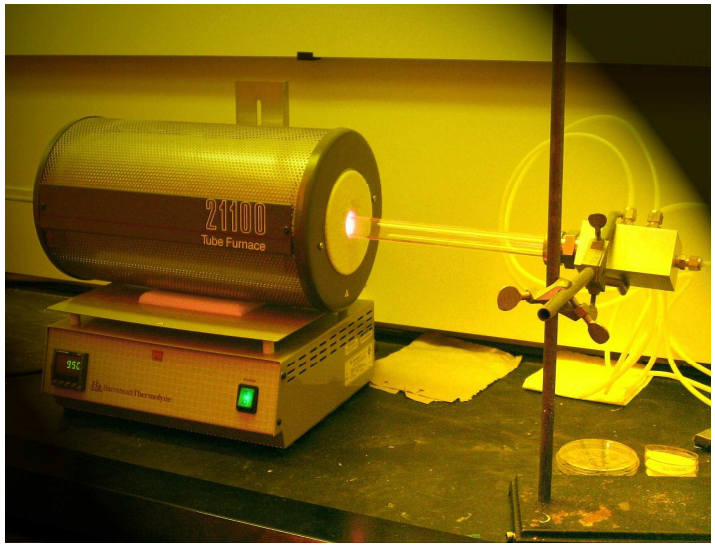
-random orientation





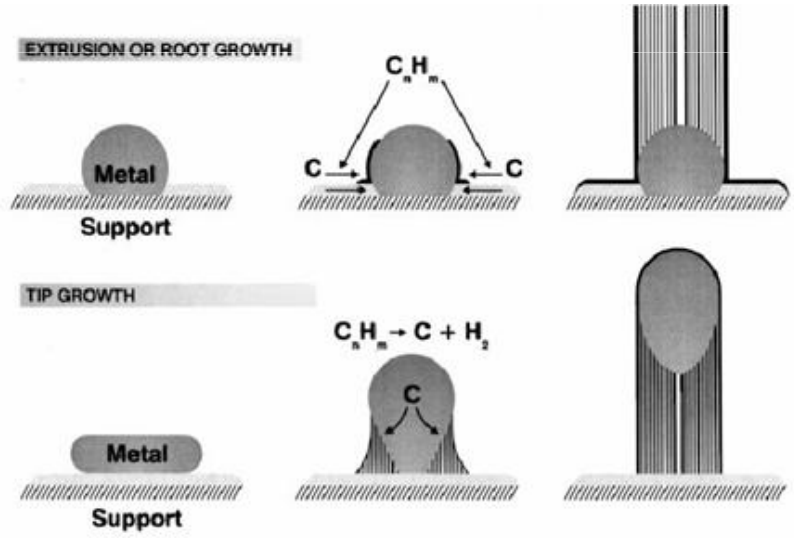
3. Device

- **Catalytic synthesis of SWCNT**
- Field effect transistor

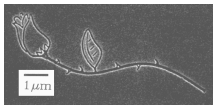


Growth Mechanism

- Present of catalyst metal (Fe, Mb, Al)
- ++Mutual dissolution of carbon and metal at ~1000°C
- Decompose and Defuse
- Root growth: favor single walled CNT
- Tip growth: favor multi-walled CNT



Kong. J., Soh. H.T., Cassell. A.M., Quate. C.J., Nature, **395, 878.(1998)**
Qian D,Dickey E.C.,Andrews R,Jacques D
,Center for applied energy research, Univ. of Kentucky



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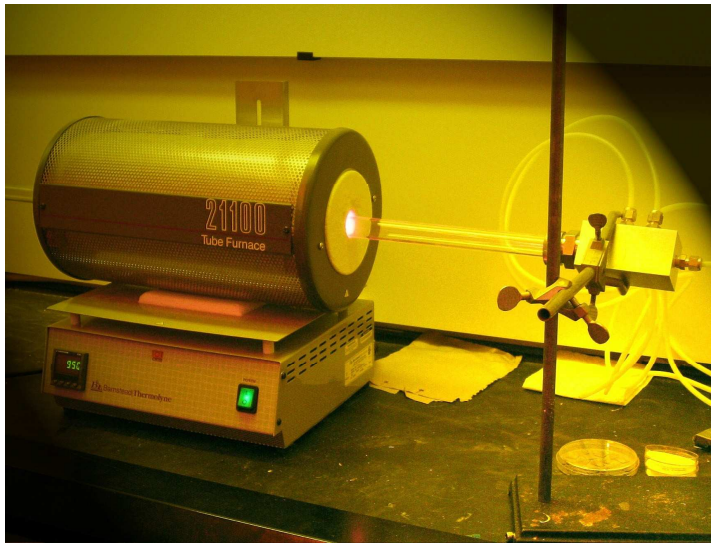
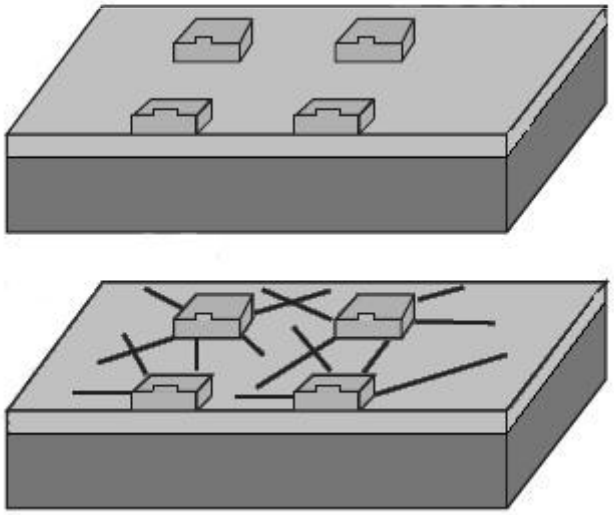


Growth process:

1. Furnace
2. Catalysts (Fe, Mb, Al)
3. Methane as carbon feedstock



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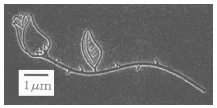

3. Device

•Catalytic synthesis of SWCNT

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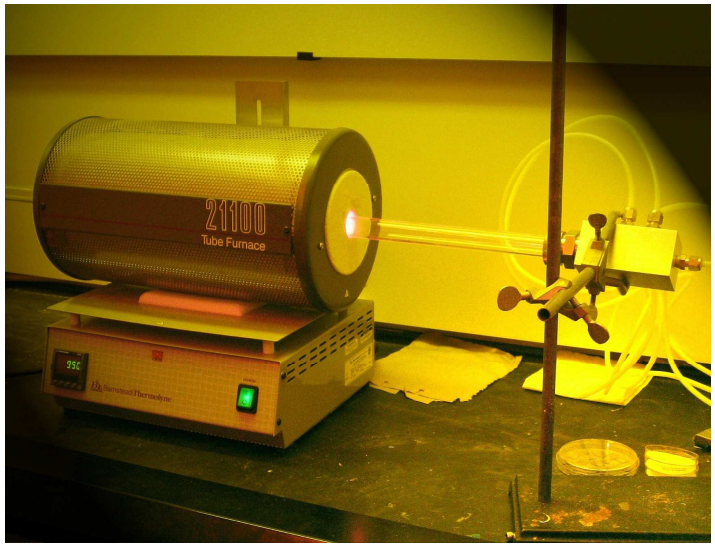
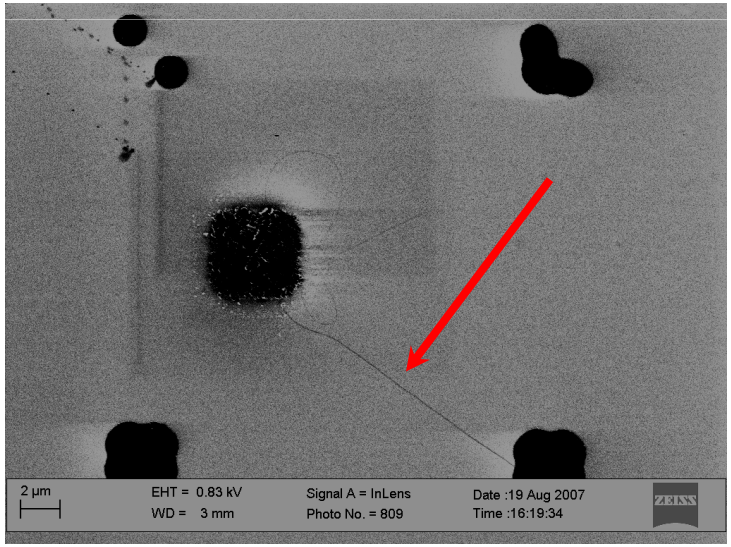


Device preparation:

-CNT growth on catalysts site

-Fabricate markers

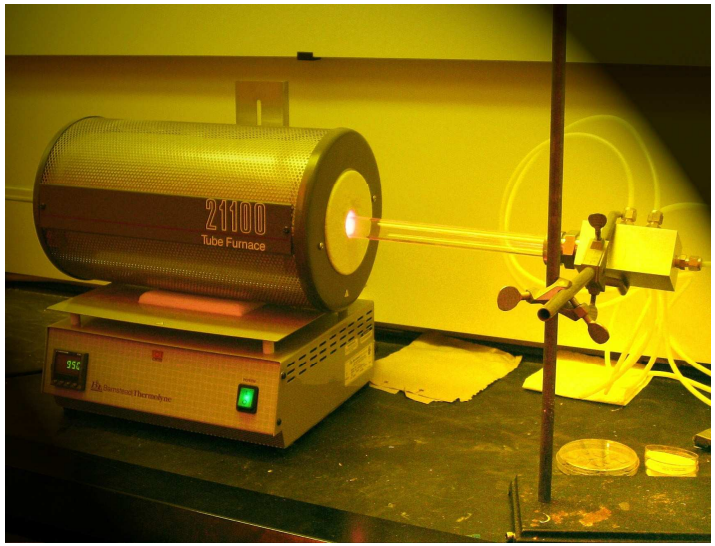
-Identify the location by markers



3. Device

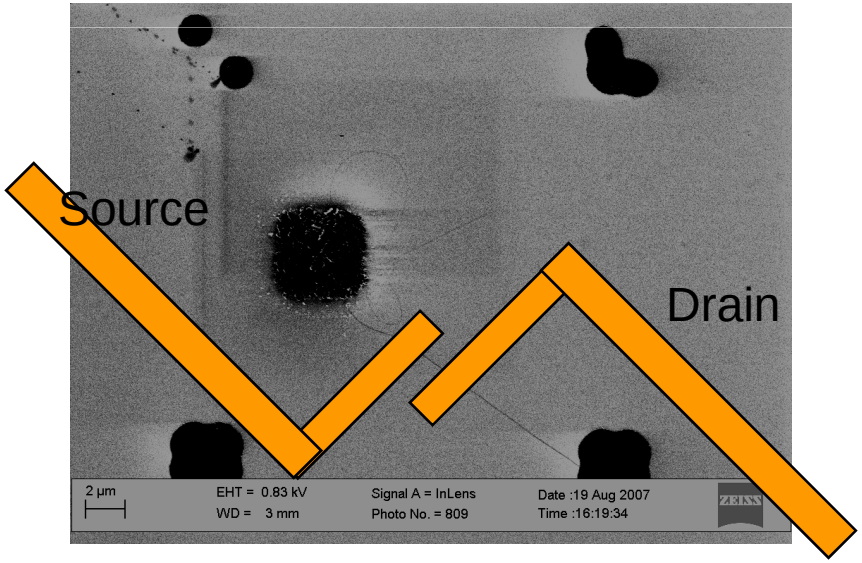
•Catalytic synthesis of SWCNT

•Field effect transistor



Device preparation:

-contact electrodes by photolithography
by picking the right electrodes



3. Device

•Catalytic synthesis of SWCNT

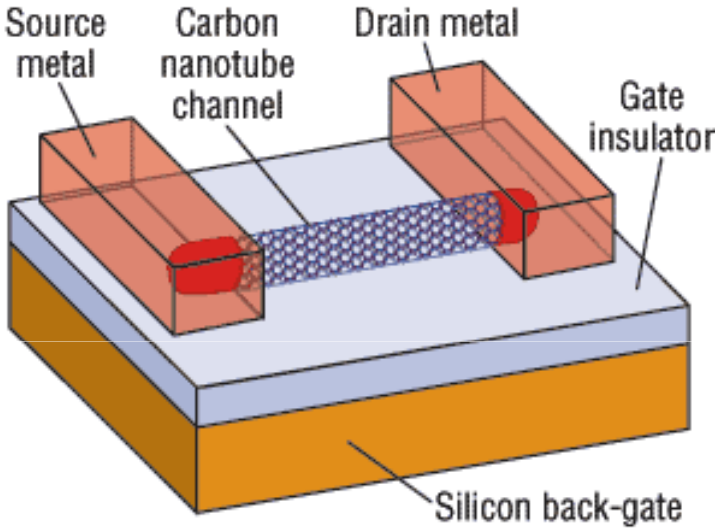
•Field effect transistor

Device structure:

-CNT Field effect transistor

-control the electric field at the CNT by back-gate

-channel insulated with the back gate



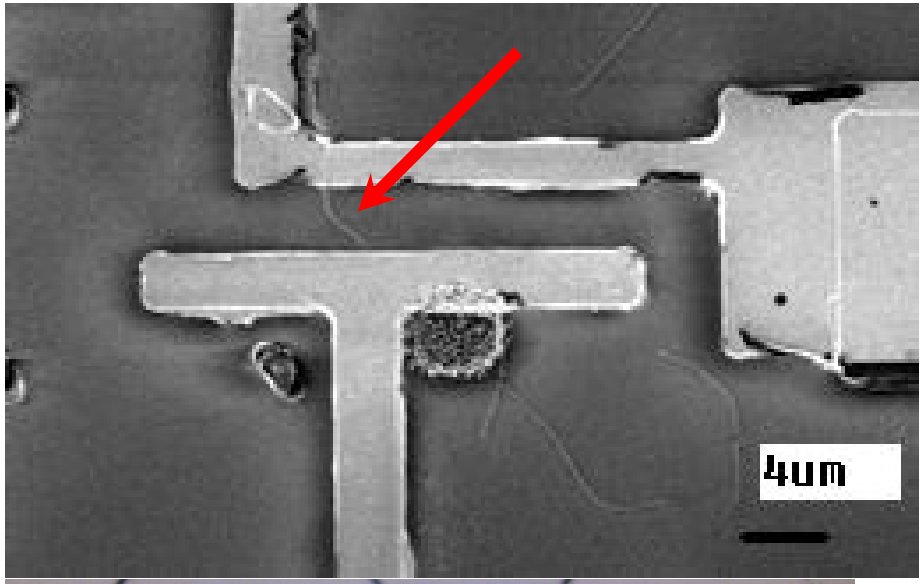
3. Device

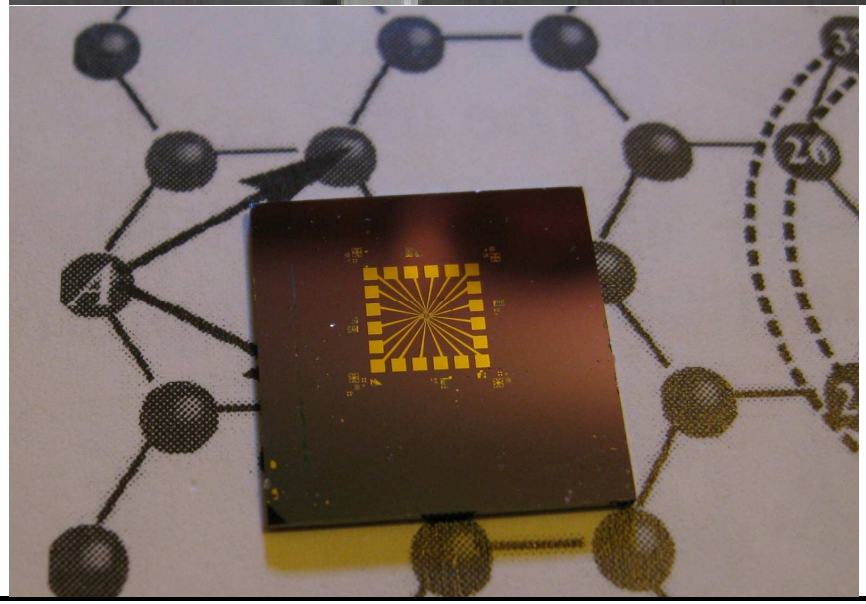
•Catalytic synthesis of SWCNT

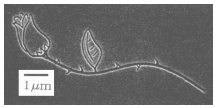
•Field effect transistor

Device preparation:

-successful device image



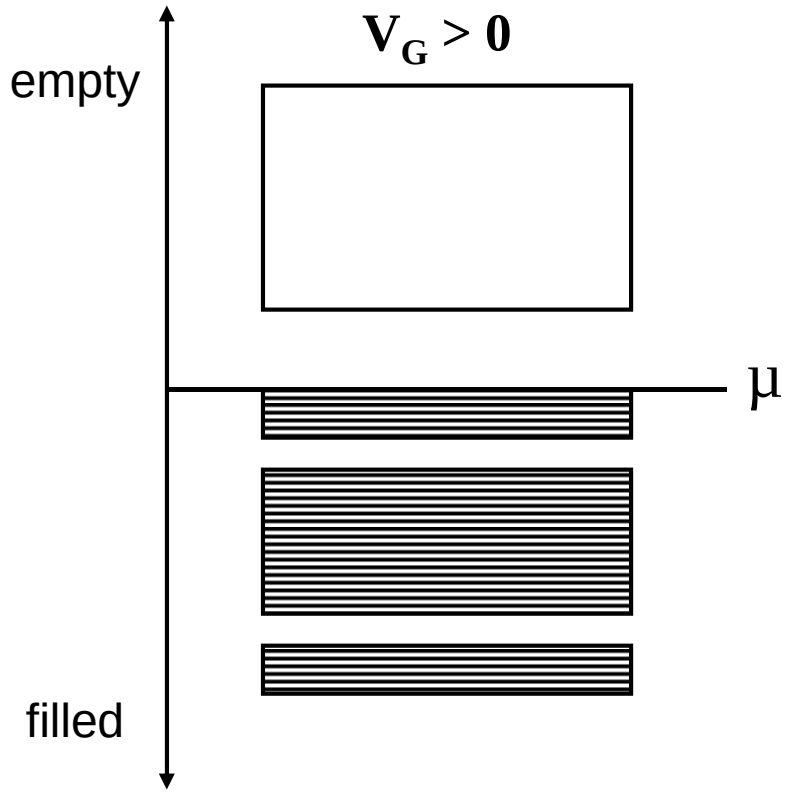




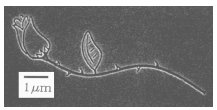
4. Electronic transport

- **Basic transport theory**
- Transport of Ideal CNT
- Metallic versus semi-conducting
- Schottky barrier transistor
- Coulomb Blockade

Conduction channel modulated by gate V_G



+Slides prepared by
Brian Burke



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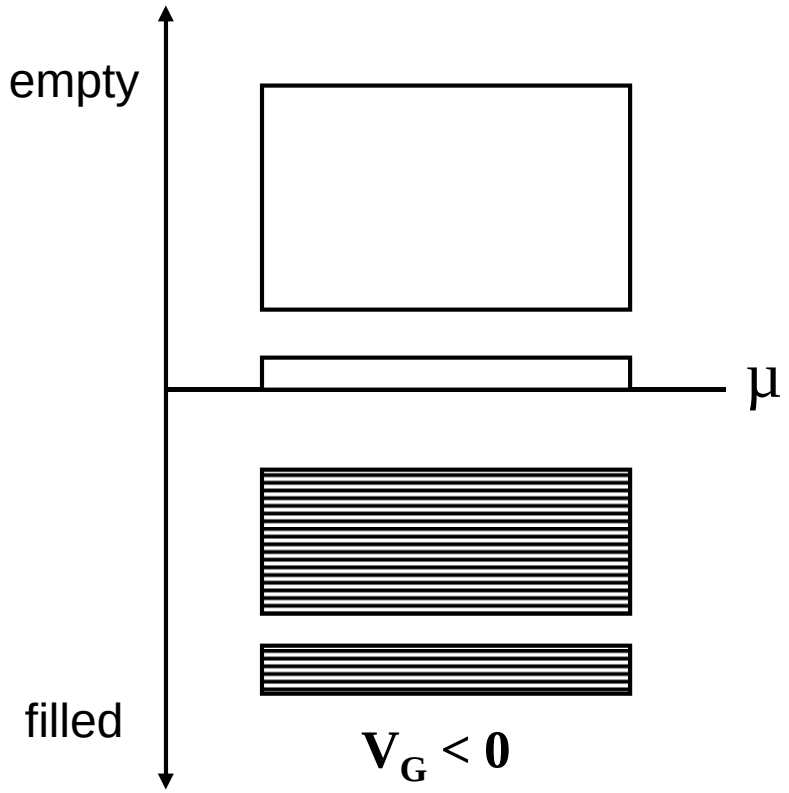

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4. Electronic transport

- **Basic transport theory**
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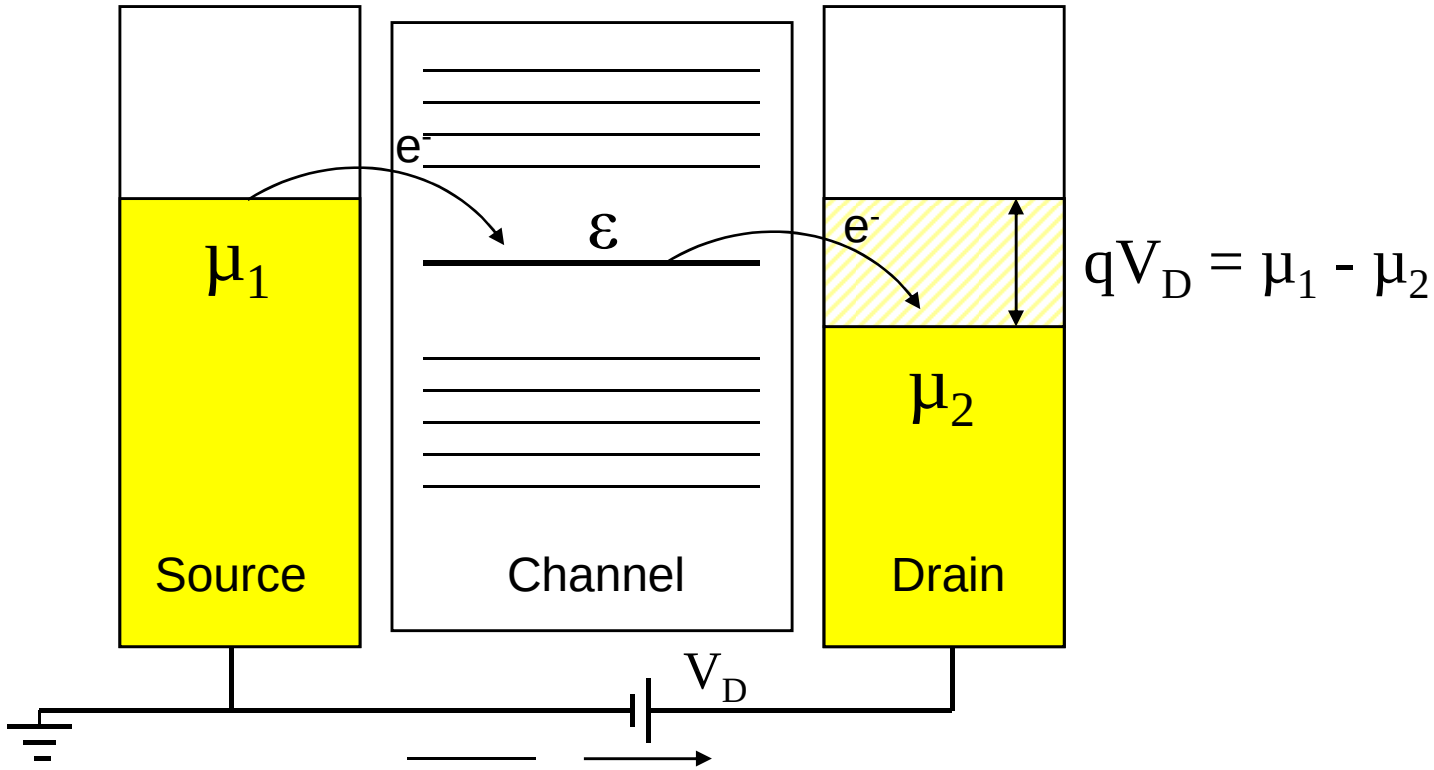
Level between source and drain is needed for conduction



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4. Electronic transport

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- **Metallic versus semi-conducting**
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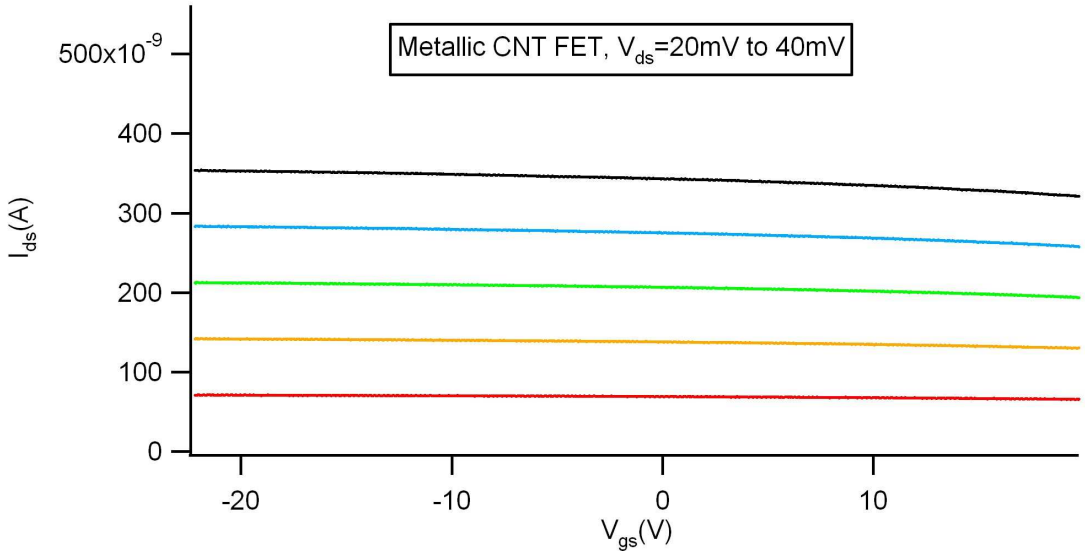
Metallic



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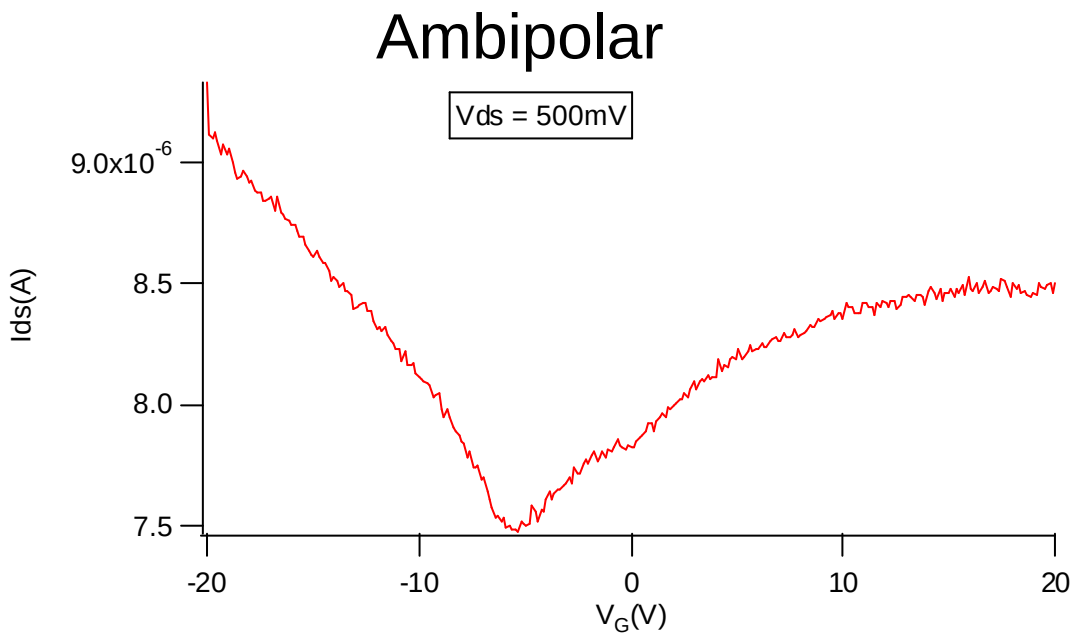

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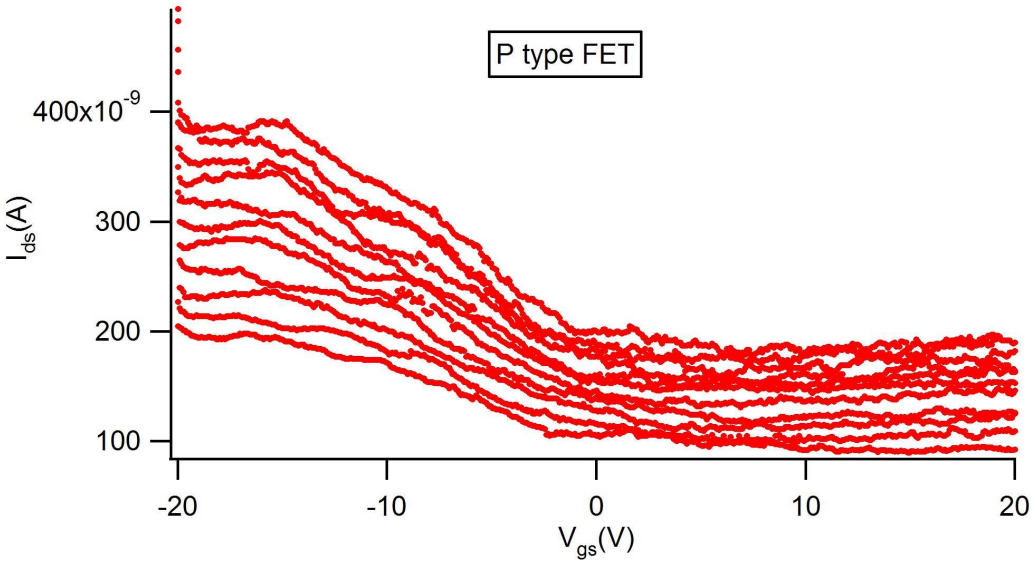


5. Random Telegraph Signal

- **Basic theory**
- Other group's data
- Our data

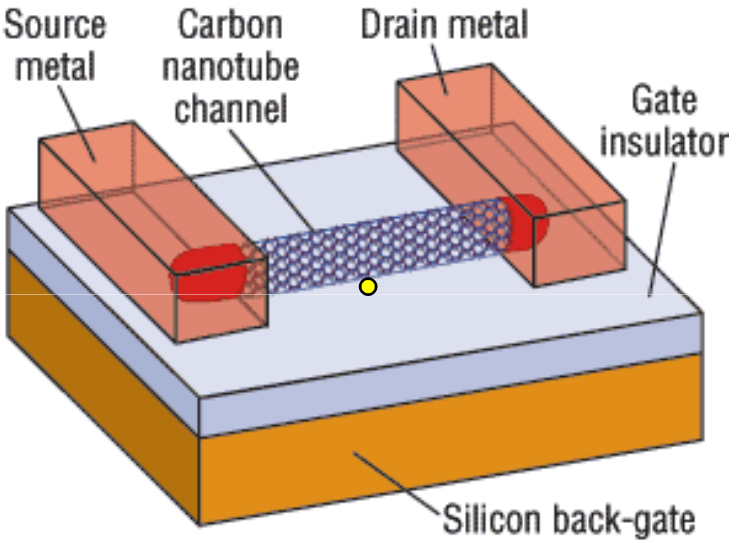
- RTS origin

  - Charge trap defects inside SiO_2 or SiO_2/CNT interface

  - defect filled: local electric field affect conductivity

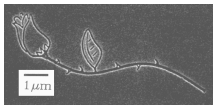
  - trapped defect center => coulomb scattering center

  - charge trapping and detrapping of the defect change the current level



Modeling electrostatic and quantum detection of molecules
S. Vasudevan1, K. Walczak1, N. Kapur2, M. Neurock2, A.W. Ghosh1, in press

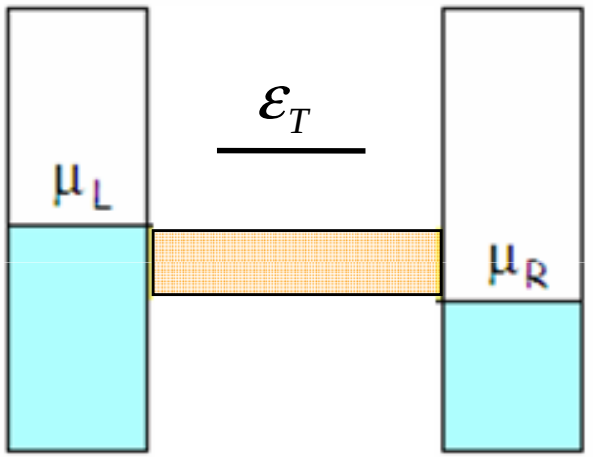
S. Heinze, J. Tersoff, R Martel, V. Derycke, J. Appenzeller, Ph. Avouris Phys Rev Let., **89, 106801 (2002)**



5. Random Telegraph Signal

- **Basic theory**
- Other group's data
- Our data

- RTS origin
  - defects level ε_T
  - control defect level by V_G
  - emptied when above both fermi levels
  - filled if below both fermi levels
  - finite probability filled or empited



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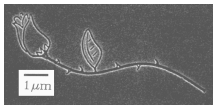

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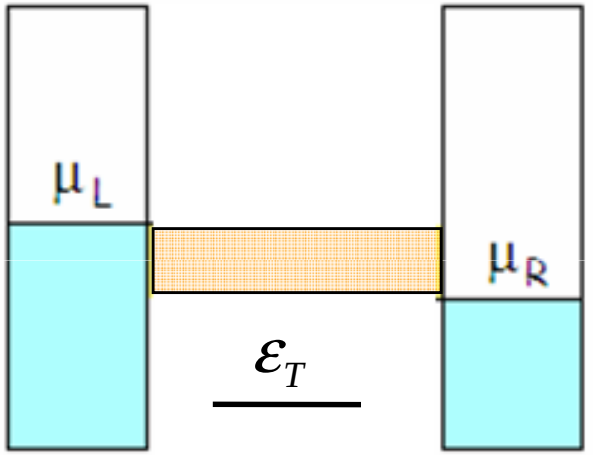

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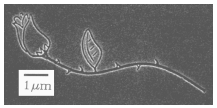

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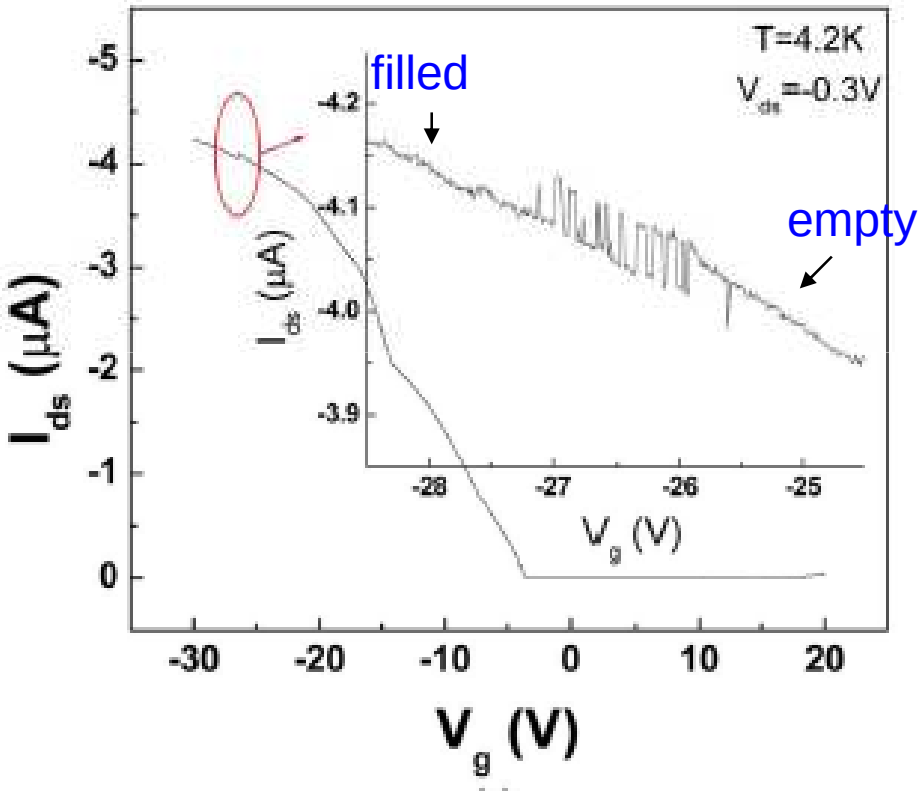

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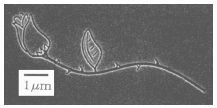


5. Random Telegraph Signal

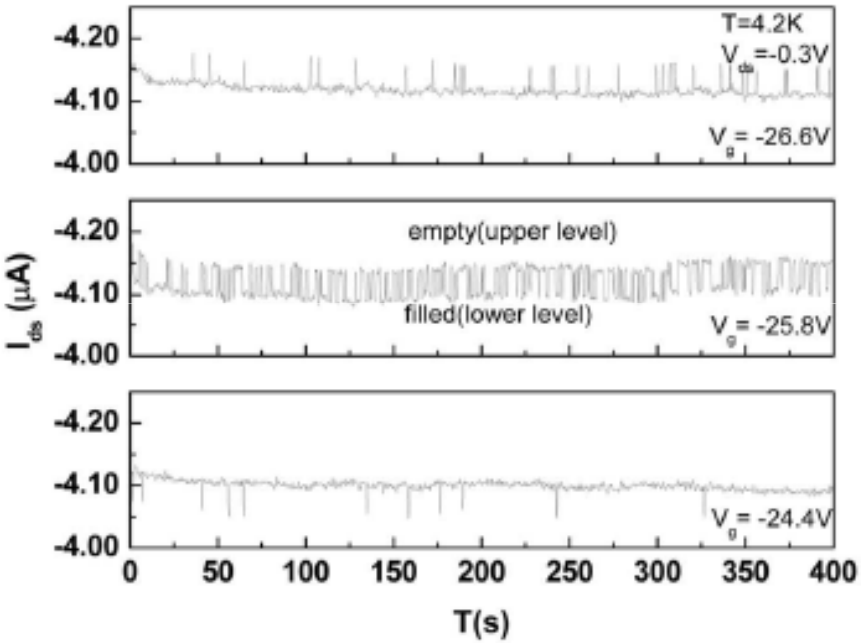
•Basic theory
•Other group's data
•Our data

- RTS origin
  - capture time τ_c and emission time τ_e
  - detailed balance equation

$$\frac{\tau_c}{\tau_e} = 2\exp[\frac{\varepsilon_T - \varepsilon_F - \kappa e V_G}{k_B T}]$$

- switching frequently between discrete level if

$$\tau_c \sim \tau_e \quad \text{so,} \quad \varepsilon_T \approx \varepsilon_F - \kappa e V_G$$



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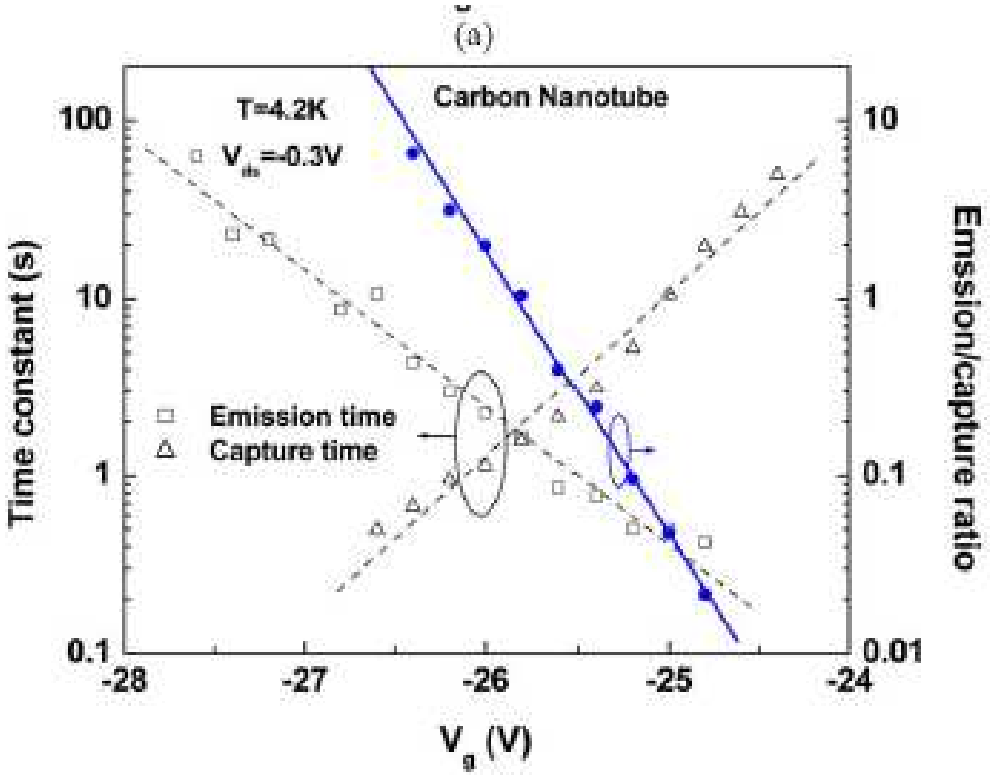
5. Random Telegraph Signal

•Basic theory
•Other group's data
•Our data

- RTS origin

$$\frac{\tau_c}{\tau_e} = 2\exp[\frac{\varepsilon_T - \varepsilon_F - \kappa e V_G}{k_B T}]$$

$$\log\frac{\tau_c}{\tau_e} \propto V_G$$



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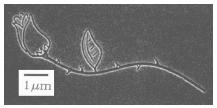
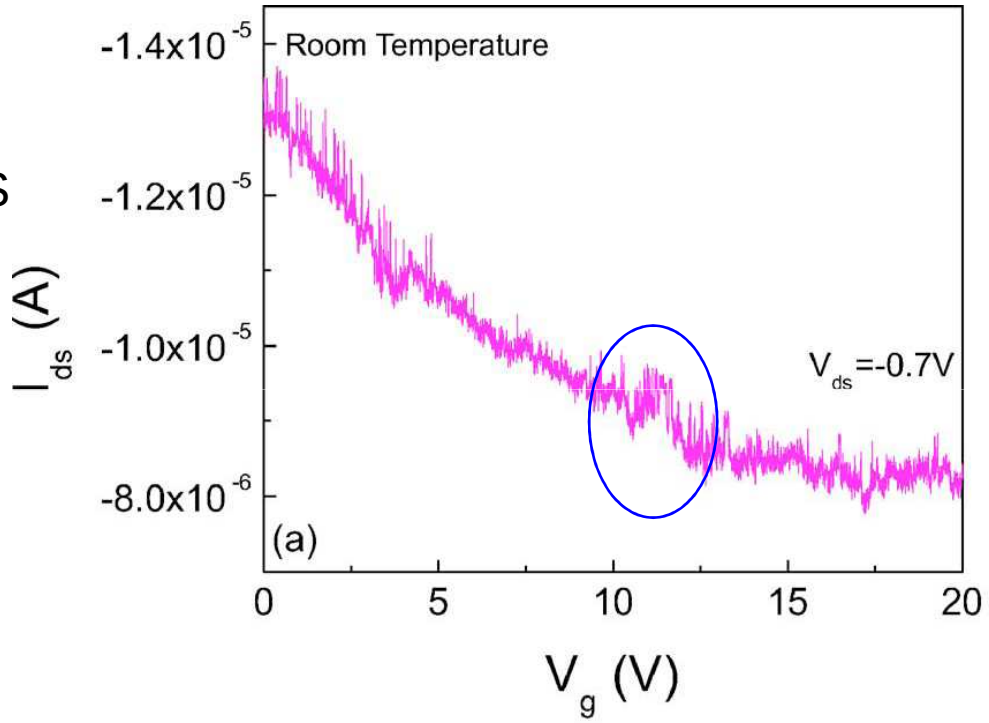


5. Random Telegraph Signal

- Basic theory
- **Other group's data**
- Our data

- claimed room temperature RTS
- never been analysed



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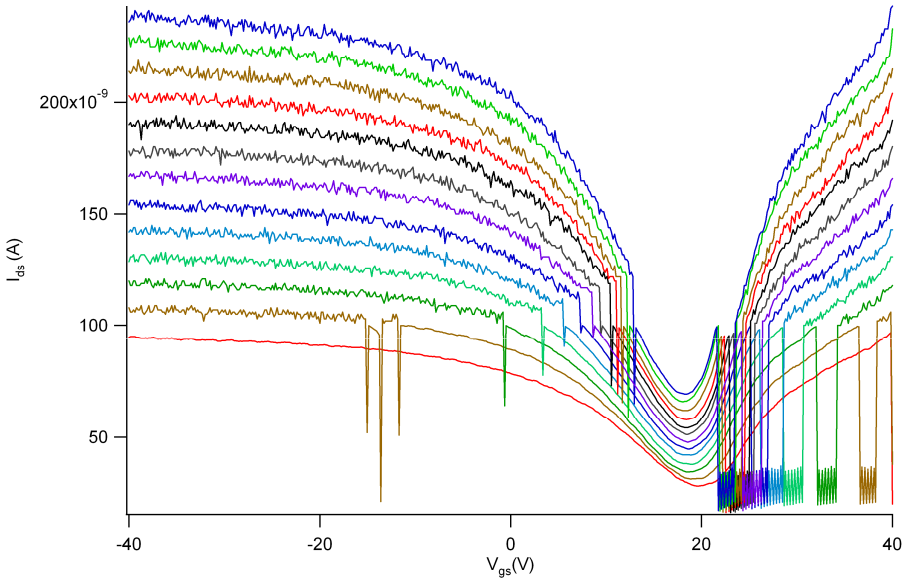
5. Random Telegraph Signal

- Basic theory
- Other group's data
- **Our data**

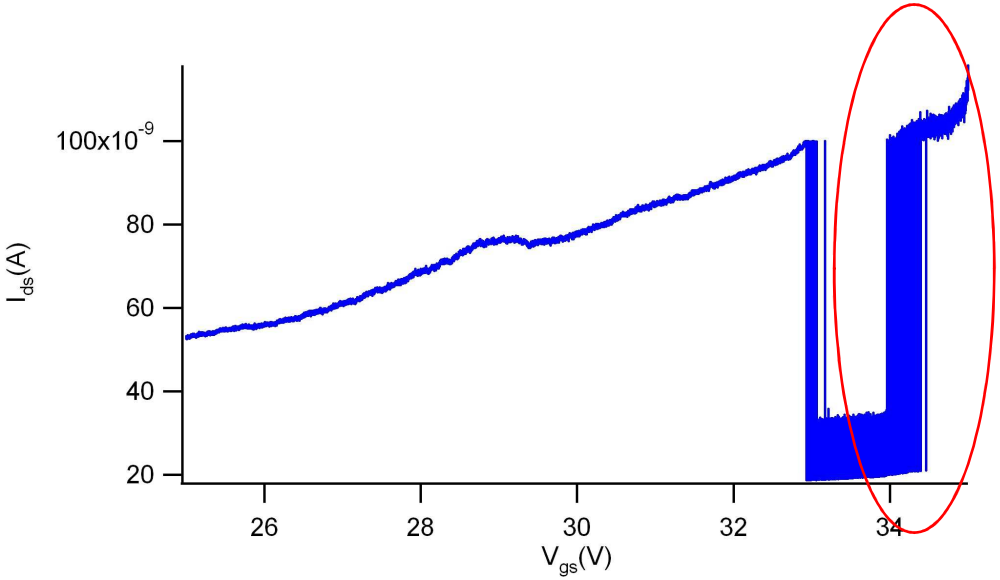
- Well defined in Room temperature
- discrete current jumping in both sides
- Unexpected RTS "windows"

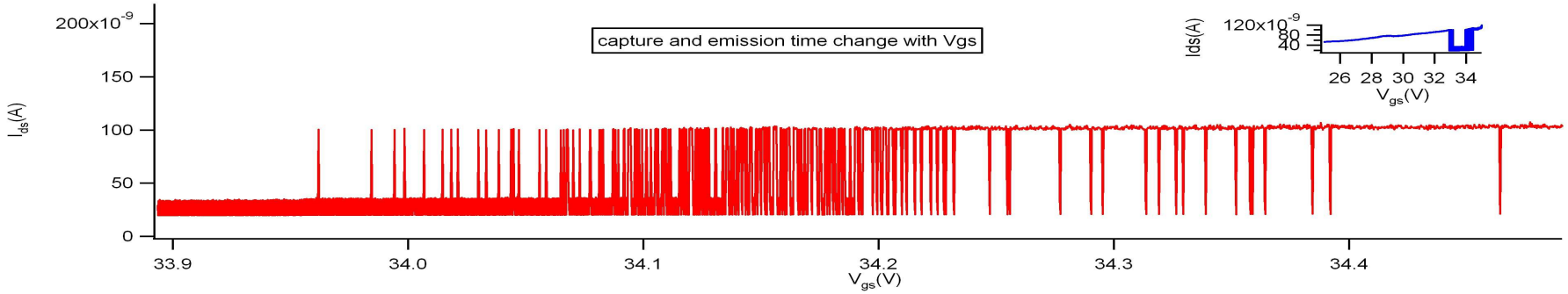


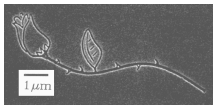
5. Random Telegraph Signal

- Basic theory
- Other group's data
- **Our data**

- See discrete jumping in both side of RTS windows
- τ_c and τ_e changing with V_G







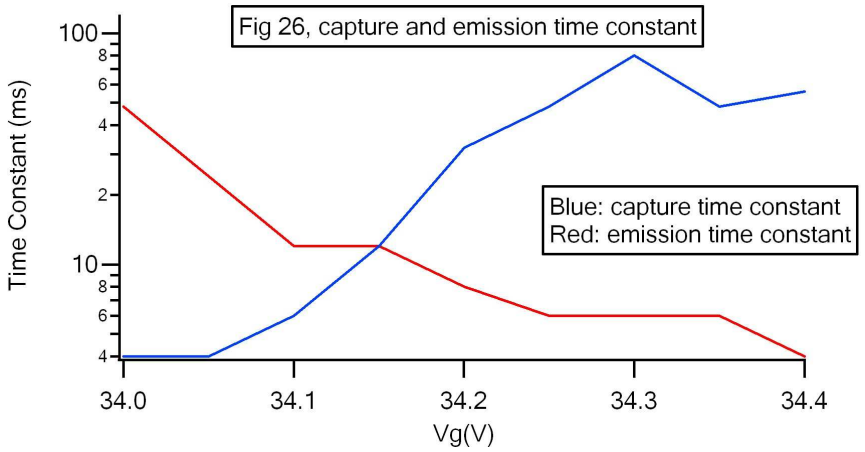
5. Random Telegraph Signal

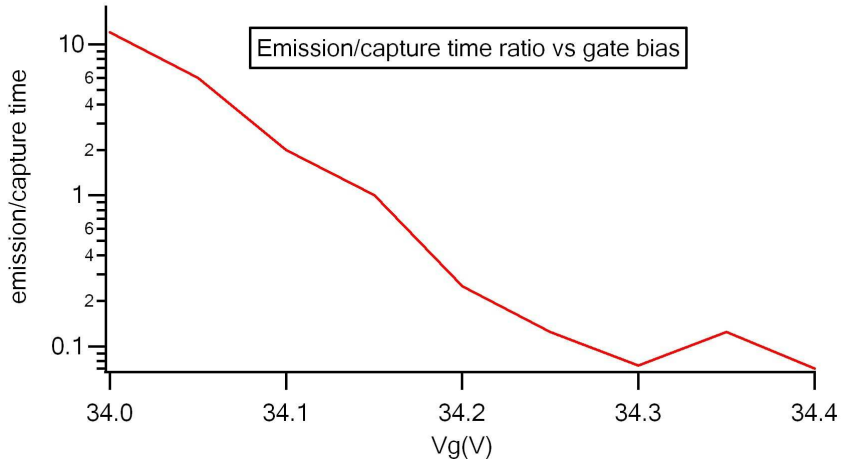
- Basic theory
- Other group's data
- **Our data**

- Agreed with principle of detailed balance

$$\frac{\tau_c}{\tau_e} = 2\exp[\frac{\varepsilon_T - \varepsilon_F - \kappa e V_G}{k_B T}]$$

$$\log\frac{\tau_c}{\tau_e} \alpha V_G$$

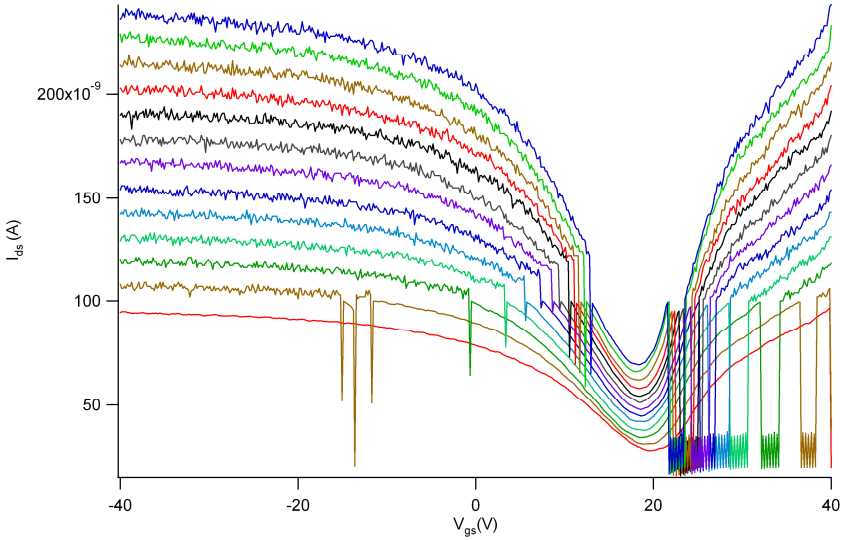


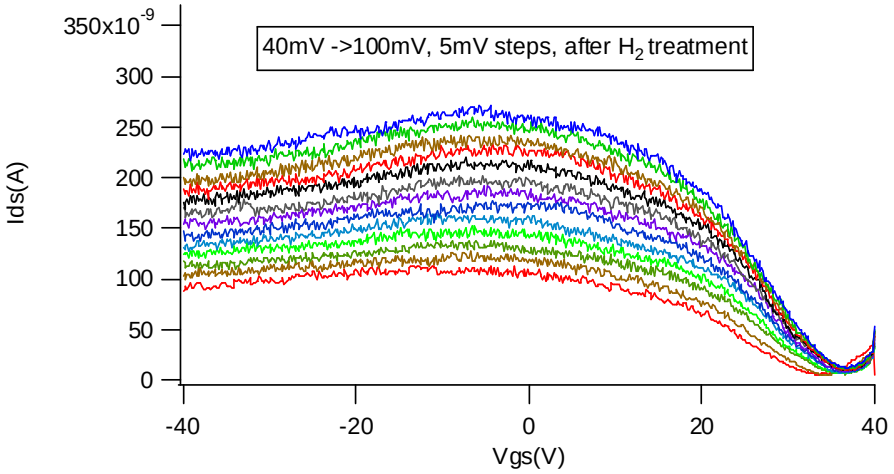


5. Random Telegraph Signal

- Basic theory
- Other group's data
- **Our data**

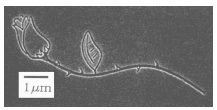
- Hysteresis effect due of water molecules on oxides surface
- Annealing in H_2 removed RTS
- Hysteresis effect enhanced after annealing
- No confident explanation on the data yet





6. Future works

- Explain our data, further characterization
- Decorate molecular defect on CNT FET, O_2, N_2
- Identify corresponding RTS signature



7. Group, Collaborations:

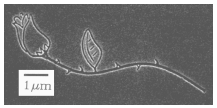
Advisor: Prof. Keith Williams
Graduate student: Brian Burke, Jack Chan.
Undergraduate student: Kenneth Evans, Andrew Spisak.
Collaborator:

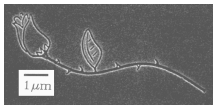
Prof. Avik Ghosh, Kamil Walczak, Smitha Vasudevan. (theoretical)
NSF award for Novel Transistor Research at the Nanoscale

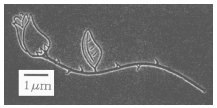
Prof. Joe Campbell Group (experimental).

Future collaborator: CNMS in ORNL.

End

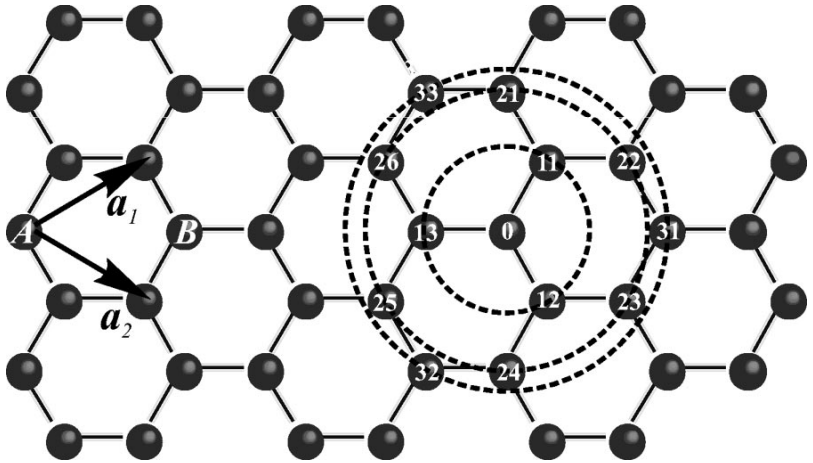



1 μm


1 μm

3. Electronic properties

- Bonding in graphene
- **Tight Binding Description of graphene**
- Dispersion of graphene
- Zone-folding Approximation
- 1D electronic density of states



- Ready to get $E(k)$ and $\begin{pmatrix} C_A \\ C_B \end{pmatrix}$

$$\begin{vmatrix} H_{AA}(\boldsymbol{k})-E(\boldsymbol{k})S_{AA}(\boldsymbol{k}) & H_{AB}(\boldsymbol{k})-E(\boldsymbol{k})S_{AB}(\boldsymbol{k}) \\ H^*_{AB}(\boldsymbol{k})-E(\boldsymbol{k})S^*_{AB}(\boldsymbol{k}) & H_{AA}(\boldsymbol{k})-E(\boldsymbol{k})S_{AA}(\boldsymbol{k}) \end{vmatrix} = 0,$$

$$E(\boldsymbol{k})^{\pm} = \frac{-(-2E_0+E_1) \pm \sqrt{(-2E_0+E_1)^2-4E_2E_3}}{2E_3},$$

with

$$E_0 = H_{AA}S_{AA}, \quad E_1 = S_{AB}H^*_{AB} + H_{AB}S^*_{AB}$$

$$E_2 = H^2_{AA} - H_{AB}H^*_{AB} \quad E_3 = S^2_{AA} - S_{AB}S^*_{AB}.$$

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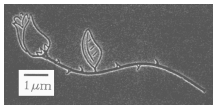

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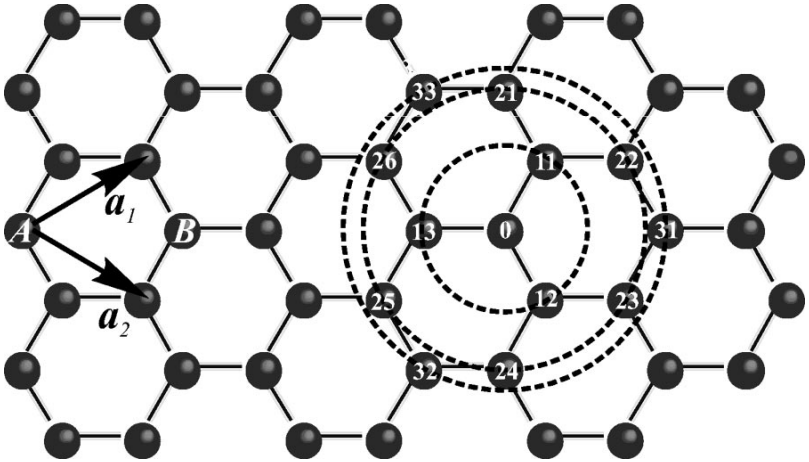

$$H_{AA}=\frac{1}{N}\sum_{R_A}\sum_{R_{A'}} e^{ik(R_{A'}-R_A)}\langle\varphi_A(r-R_A)|H|\varphi_A(r-R_{A'})\rangle$$

$$=\frac{1}{N}\sum_{R_A}\langle\varphi_A(r-R_A)|H|\varphi_A(r-R_A)\rangle=\varepsilon_{2p},$$

$$H_{AB}=\frac{1}{N}\sum_{R_A}\sum_{R_B} e^{ik(R_B-R_A)}\langle\varphi_A(r-R_A)|H|\varphi_B(r-R_B)\rangle$$

$$=\gamma_0(e^{ikR_{11}}+e^{ikR_{12}}+e^{ikR_{13}})$$

with

$$\gamma_0=\langle\varphi_A(r-R_A)|H|\varphi_B(r-R_A-R_{1i})\rangle \quad (i=1,2,3),$$

$$S_{AB}=s_0(e^{ikR_{11}}+e^{ikR_{12}}+e^{ikR_{13}})$$

with

$$s_0=\langle\varphi_A(r-R_A)|\varphi_B(r-R_A-R_{1i})\rangle \quad (i=1,2,3),$$

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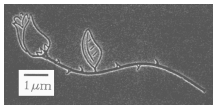


2. Structure of Single-walled carbon nanotube (SWCNT).

a) Rolled up of a graphene sheet, graphene is a layer of graphite.

b) Chirality vector: $\mathbf{C}=n\mathbf{a}_1+m\mathbf{a}_2$, graphene is rolled along **C** into cylinder.

c) Chirality indices (n, m) determines electronic band structure.

d) diameter: C/pi=…….

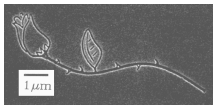
e) Metallic if n-m=3q, semiconducting otherwise.

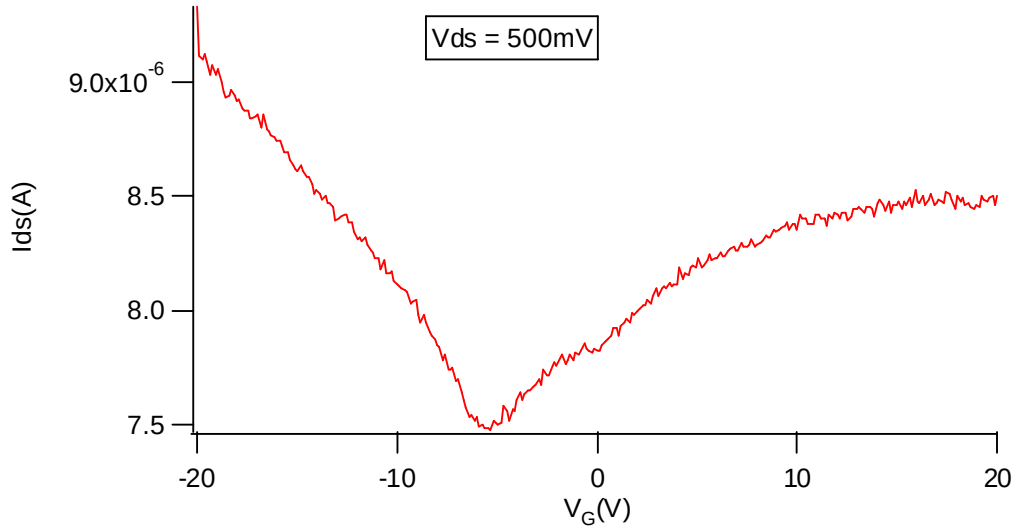
f) talk about Brillouin zone?

g) Physical properties:

Electrically conductive
High current carrying capacity
Can be functionalized (doped).
High Length/Diameter aspect ratio
Extra ordinary mechanical properties, eg. Young Modulus>1T Pascal.

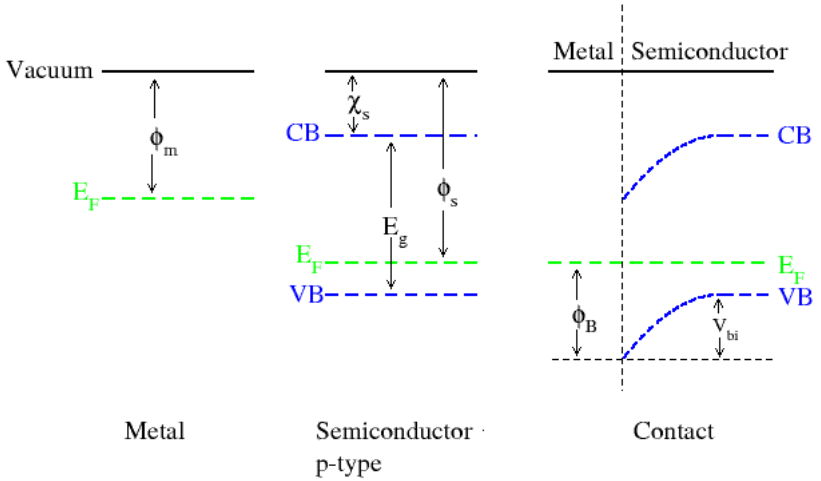
●Dresselhaus et al., Physics World 1998




Vds = 500mV
9.0x10-6
8.5
8.0
7.5
Ids(A)
-20
-10
0
10
20
VG(V)

5. Electronic transport

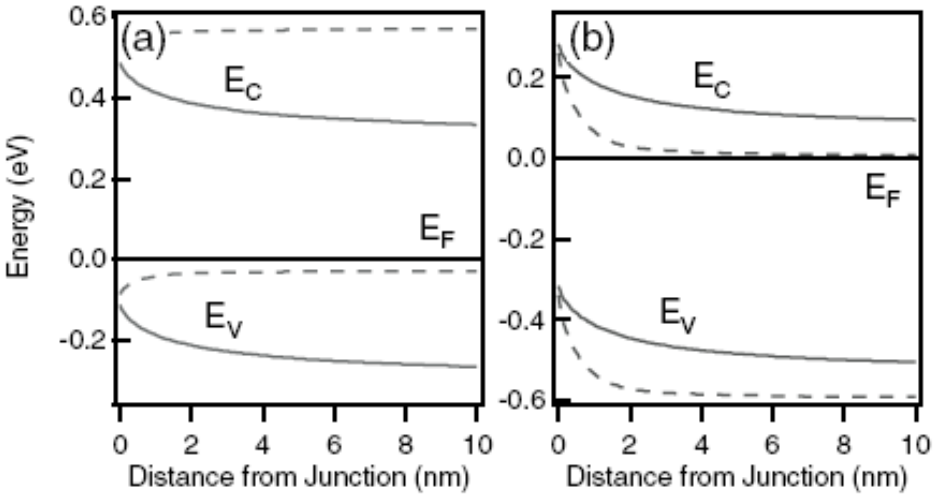
- Basic transport theory
- Transport of Ideal CNT
- **Schottky barrier (SB) transistor**
- Coulomb Blockade



- SB
  - formed between metal and semi-cond
  -

- IV_G changes with dopant level:
  - Whole curve shifted
  - Shape doesn't change

- SB device IV_G:
  - change with work function, i.e. metal
  - formed between semi-cond and metal
  - minimum current range almost unchange
  - curve change shape



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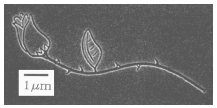

5. Electronic transport

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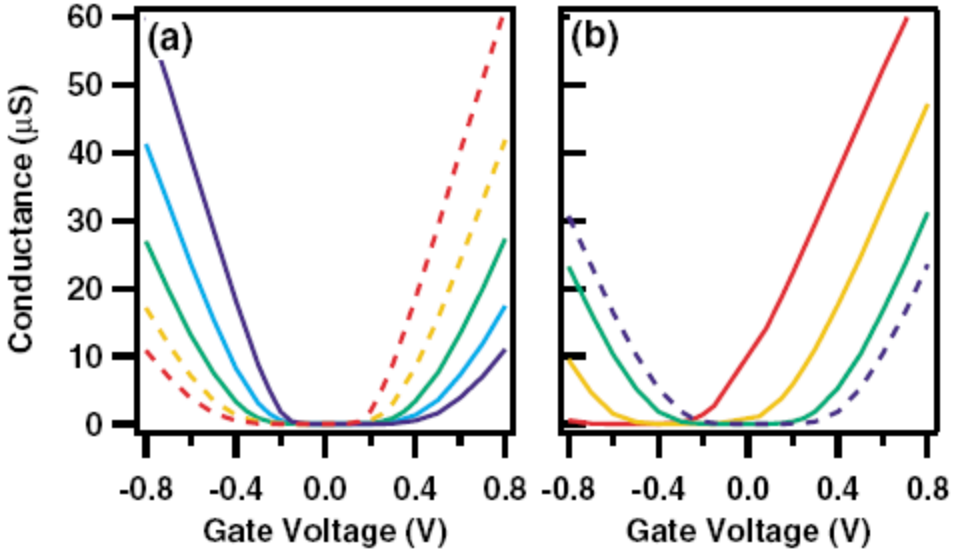
- SB
  - formed between metal and semi-cond
  - matching fermi level by electron flowing
  - build in voltage developed



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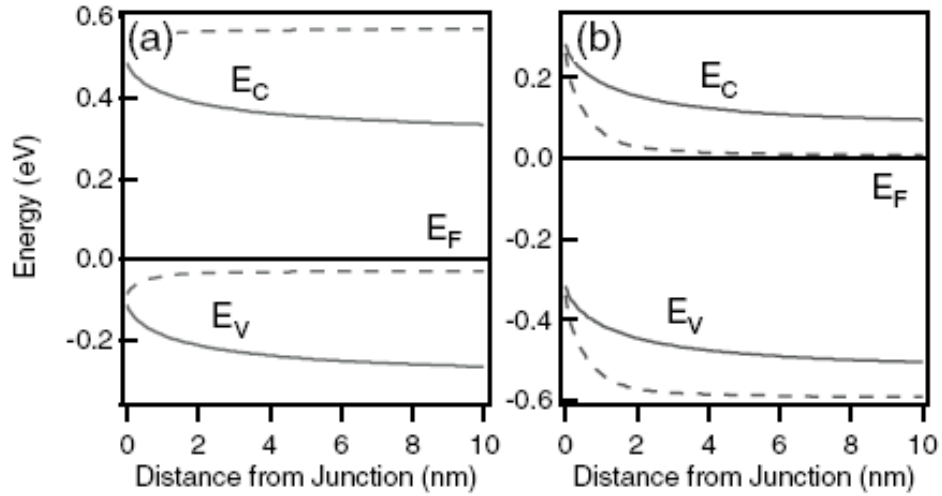

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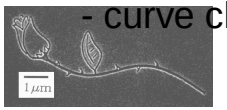

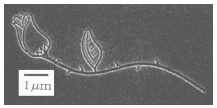
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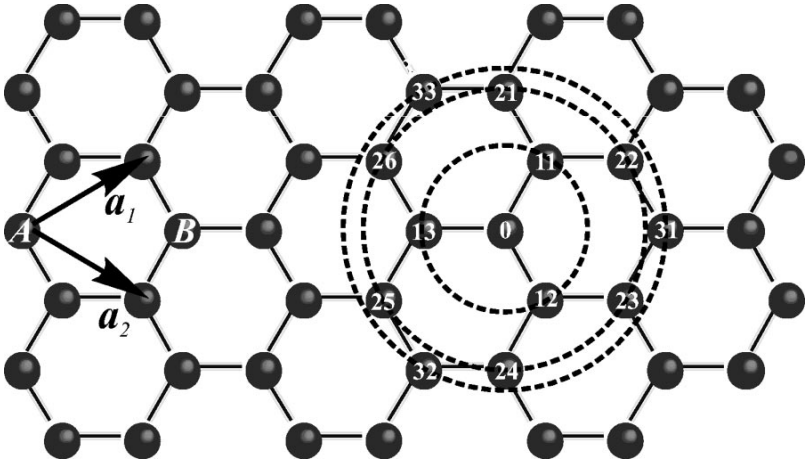

Ingredients:

- Schrodinger's equation $H\psi(k) = E\psi(k)$
- Normalized $2p_z$ orbitals of C atom $\varphi(r)$
- 2 atoms in graphene unit cell
- Bloch function of graphene sublattice

$$\Phi_A = \frac{1}{\sqrt{N}} \sum_{R_A} e^{ik \cdot R_A} \varphi(r - R_A)$$

$$\Phi_B = \frac{1}{\sqrt{N}} \sum_{R_B} e^{ik \cdot R_B} \varphi(r - R_B)$$

- Eigenfunctions $\psi(k) = C_A \Phi_A(k) + C_B \Phi_B(k)$

- Approximation:
  - -Only nearest neighbor
  - -Overlapping integral So is non-zero

- Ready to get $E(k)$ and $\begin{pmatrix} C_A \\ C_B \end{pmatrix}$

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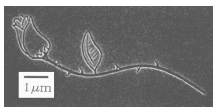

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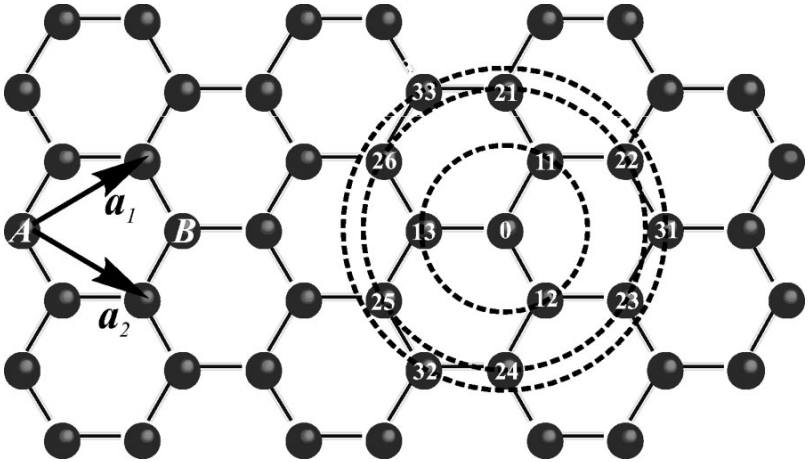
$$E^{\pm}(k)=\frac{\varepsilon_{2p}\mp\gamma_0\sqrt{f(k)}}{1\mp s_0\sqrt{f(k)}}.$$



where

$$f(k)=3+u(k)$$
$$=3+2\cos k\cdot a_1+2\cos k\cdot a_2+2\cos k\cdot(a_1-a_2)$$
$$=3+2\cos 2\pi a k_1+2\cos 2\pi a k_2+2\cos 2\pi a(k_1-k_2),$$

$$\gamma_0=\langle\varphi_A(r-R_A)|H|\varphi_B(r-R_A-R_{1i})\rangle \quad (i=1,2,3),$$

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