Many Body Effects on Optical Properties of Graphene

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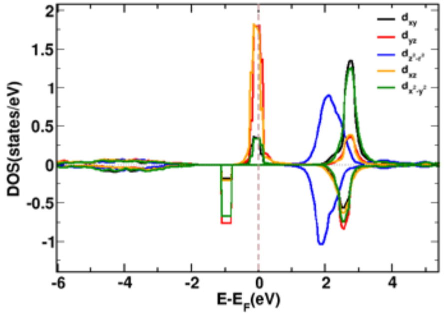
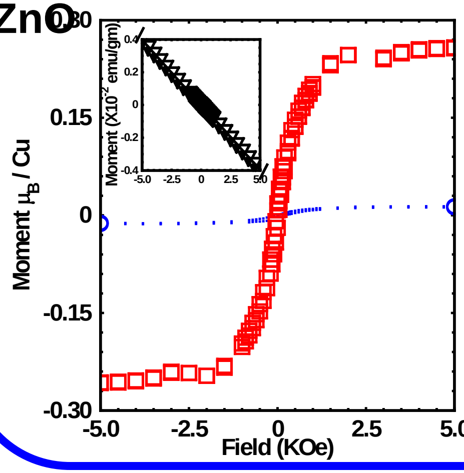
Research Activities

ZnO

1. Ferroelectricity and half metallic state in doped ZnO

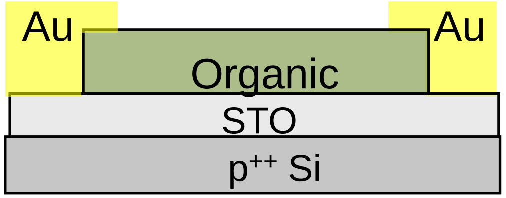


2. Ferromagnetsim in non magnetic ion doped ZnO



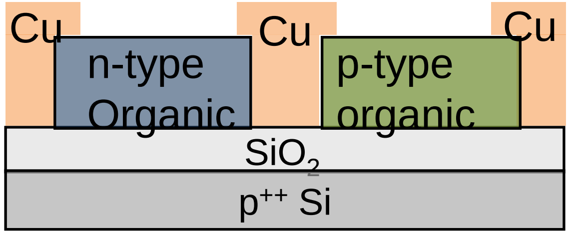
Organic Electronics

1.Low voltage Field Effect Transistor



2. Microscopic Mechanism of charge transport

3.Organic Inverter

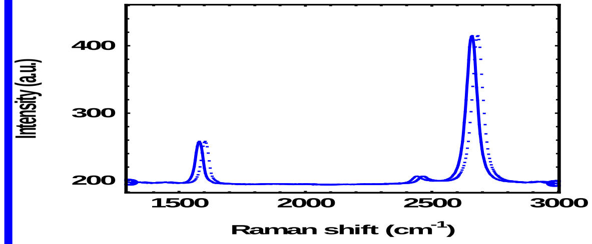


4.Transparent-Flexible OTFT

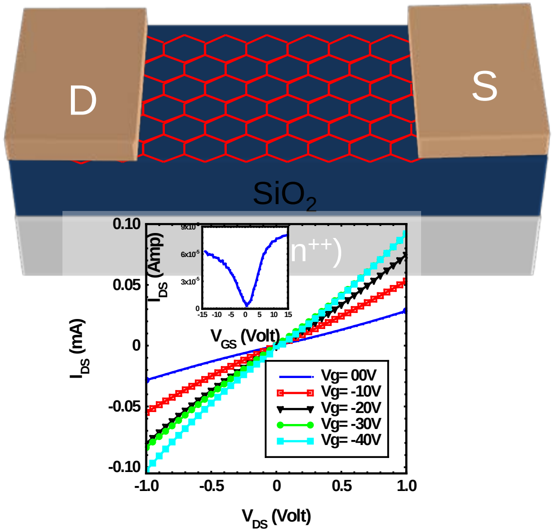
Dirac Materials

(Graphene & MoS$_2$)

1.Growth of Graphene & MoS$_2$



2.High Mobility Transistor



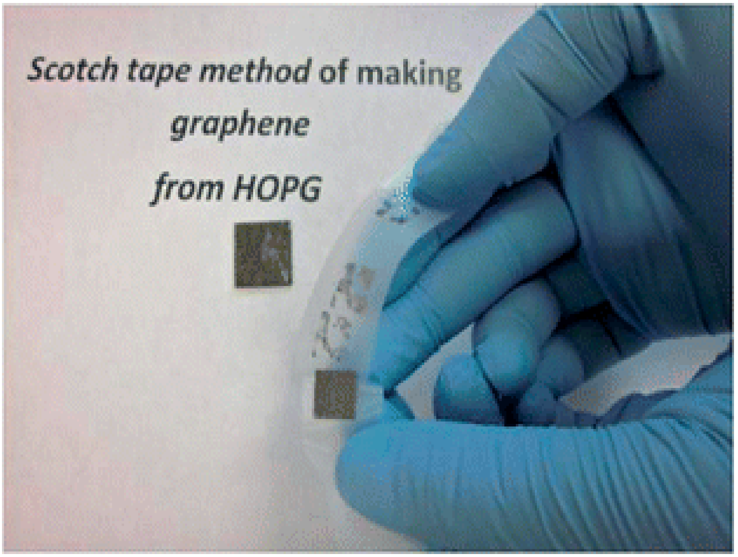
3. Many Body Effects

Plan of this talk

- Introduction to graphene bandstructure and “chirality”.
- Growth and characterization of graphene.
- Robustness of universality under interlayer coupling and many body interactions.
- **<u>Doping of graphene</u>** to modulate the e-e interaction on universality
- How to break this universality ?

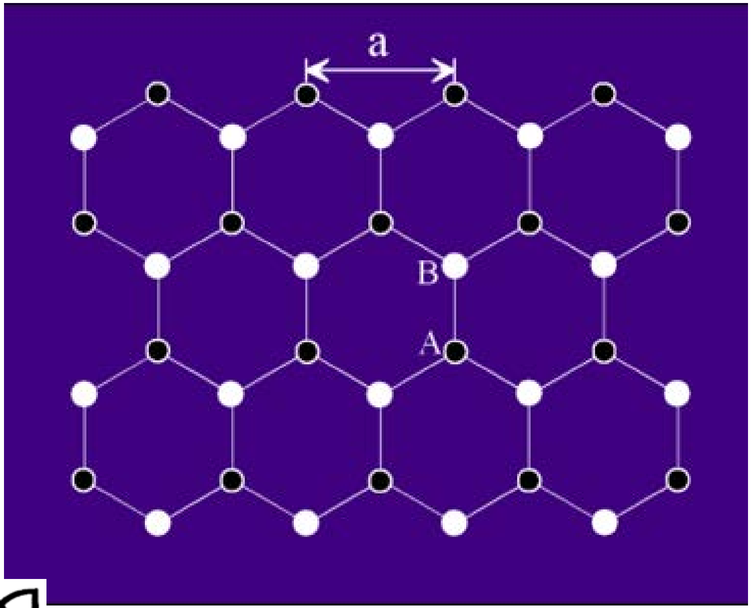
What is graphene?

In 2004, graphene was discovered by Andre Geim and Kostya Novoselov (Univ. of Manchester).



Science 306, 666 (2004)

2010 Nobel Prize in Physics



Q1. How thick is it? million times thinner than paper
(The interlayer spacing : 0.33~0.36 nm)

Q2. How strong is it? stronger than diamond
(Maximum Young's modulus : ~1.3 TPa)

Q3. How conductive is it? better than copper
(The resistivity : 10^{-6} Ω·cm)
(Mobility: 200,000 cm^2 V^{-1} s^{-1})

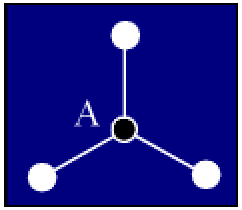
Novel Phenomena in Graphene

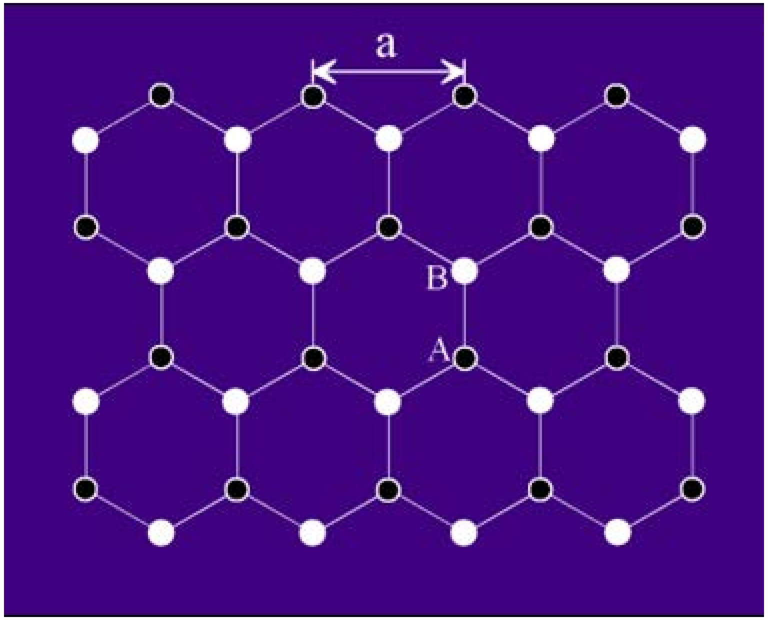
- **Quantun Hall effect**
- **Fractional QHE**
- **Berry’s phase**
- **Klein tunneling**
- **Kondo Effect**
- **Majorana Fermion**

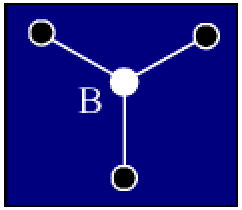
Potential Applications of Graphene

- **Membranes for ultra filtration**
- **Composites and coating**
- **Energy storage**
- **Biomedical**
- **Sensors**
- **Fast Electronic devices**

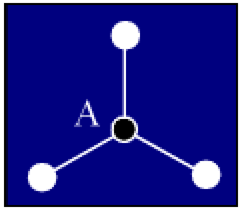
2 different ways of orienting bonds means there are 2 different types of atomic sites



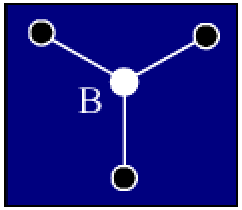




Sublattice ≡ Pseudospin



$\equiv \left| A \right\rangle$ or spin up (↑)



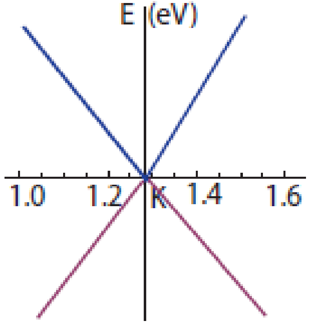
$\equiv \left| B \right\rangle$ or spin down (↓)

Bandstructure of Monolayer Graphene

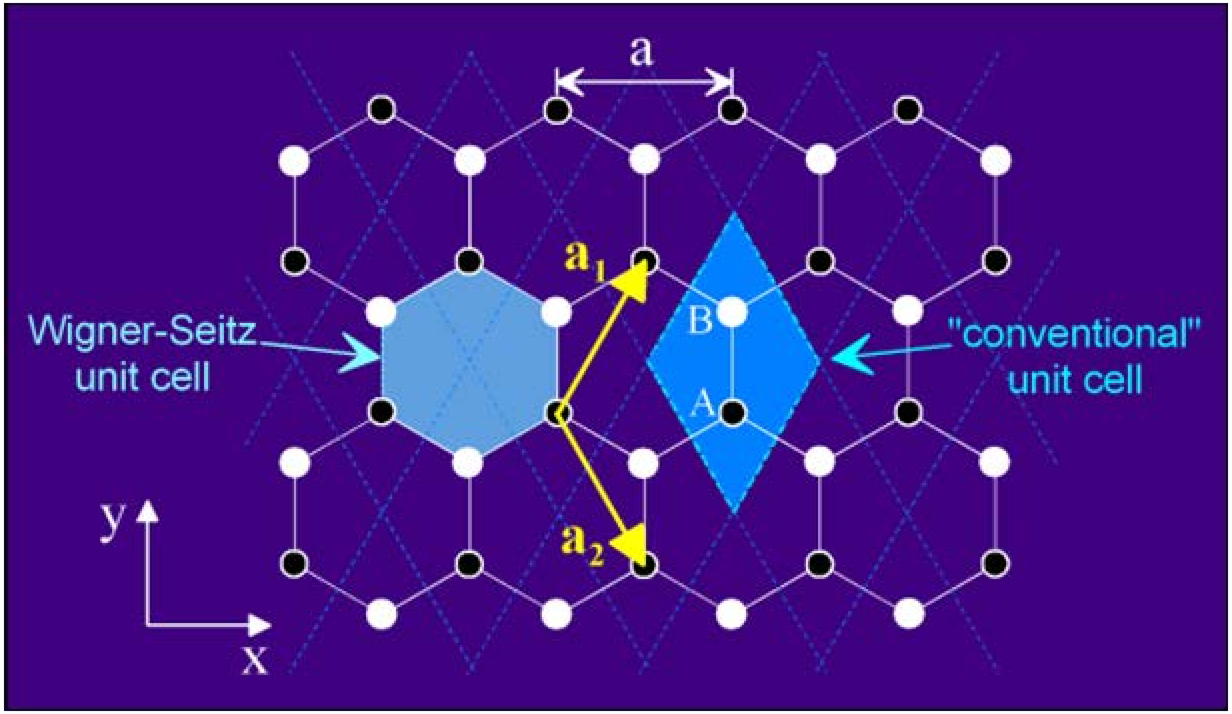
Define Unit Cell

Tight Binding Model

Energy Dispersion Relation (E vs k plot)



Unit Cell



Two atoms per unit cell

Triangular/rhombic/hexagonal unit cell – hexagonal Brillouin zone

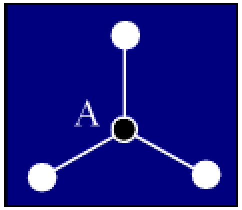
Tight binding model of monolayer graphene

Bloch functions

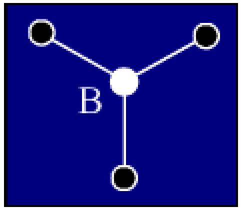
$$\Phi_j\left(\vec{k},\vec{r}\right)=\frac{1}{\sqrt{N}}\sum_{\vec{R}_j}^{N} e^{i\vec{k}.\vec{R}_j}\varphi_j\left(\vec{r}-\vec{R}_j\right)$$

sum over all type j(i) atomic sites in N unit cells

atomic wavefunction



***j=1* (A sites)**



***j=2* (B sites)**

$$H_{ij}=\left\langle \Phi_i \middle| H \middle| \Phi_j \right\rangle; \qquad S_{ij}=\left\langle \Phi_i \middle| \Phi_j \right\rangle$$

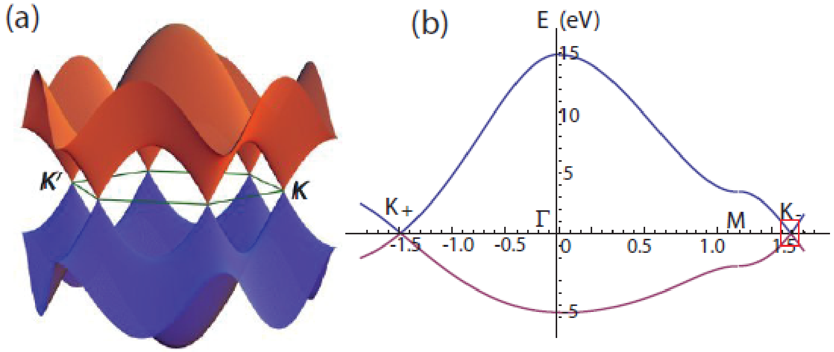
$$H=\begin{pmatrix} \varepsilon_0 & -\gamma_0 f\left(\vec{k}\right) \\ -\gamma_0 f^*\left(\vec{k}\right) & \varepsilon_0 \end{pmatrix}; \quad S=\begin{pmatrix} 1 & sf\left(\vec{k}\right) \\ sf^*\left(\vec{k}\right) & 1 \end{pmatrix}$$

$$f\left(\vec{k}\right)=\sum_{\vec{\delta}_j=1}^{3} e^{i\vec{k}.\vec{\delta}_j}=e^{ik_y a/\sqrt{3}}+2e^{-ik_y a/2\sqrt{3}}\cos\left(\frac{k_x a}{2}\right)$$

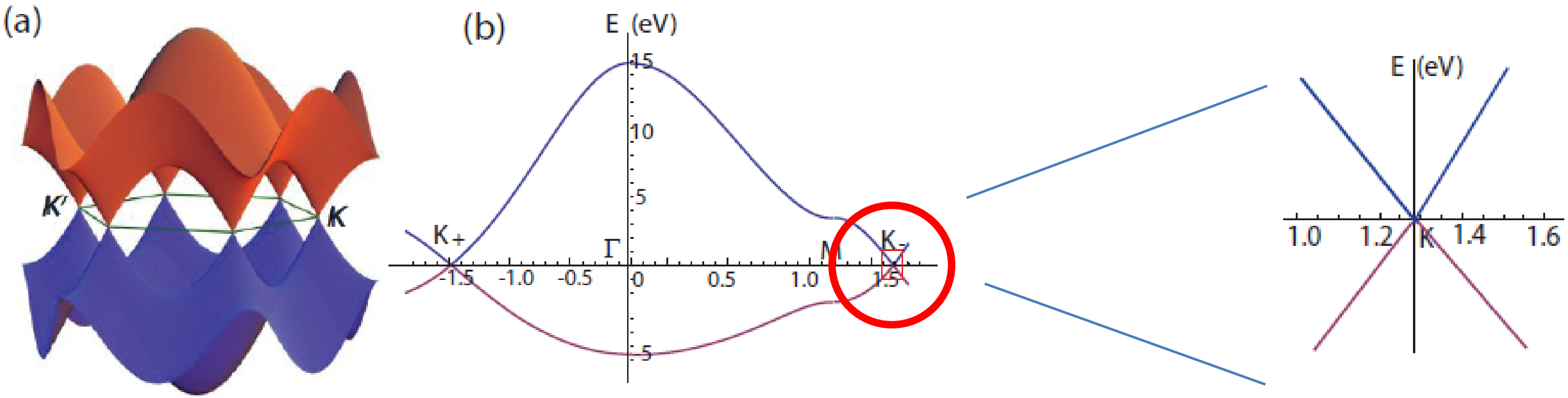
$$\det(H-ES)=0$$

$$\det\begin{pmatrix} \varepsilon_0-E & -(\gamma_0+Es)f\left(\vec{k}\right) \\ -(\gamma_0+Es)f^*\left(\vec{k}\right) & \varepsilon_0-E \end{pmatrix}=0$$

$$E=\frac{\varepsilon_0\pm\gamma_0\left|f\left(\vec{k}\right)\right|}{1\mp s\left|f\left(\vec{k}\right)\right|}$$



Low Energy Properties



Expansion around K-points:

$$f\left(\vec{k}\right)=\sum_{\vec{\delta}_j=1}^{3} e^{i\vec{k}.\vec{\delta}_j}=e^{ik_y a/\sqrt{3}}+2e^{-ik_y a/2\sqrt{3}}\cos\left(\frac{k_x a}{2}\right)=-\frac{\sqrt{3}a}{2\hbar}\left(p_x-ip_y\right)+O\left(pa/\hbar\right)^2$$

$$H=\begin{pmatrix} 0 & -\gamma_0 f\left(\vec{k}\right) \\ -\gamma_0 f^*\left(\vec{k}\right) & 0 \end{pmatrix}\approx v\begin{pmatrix} 0 & p_x-ip_y \\ p_x+ip_y & 0 \end{pmatrix}$$

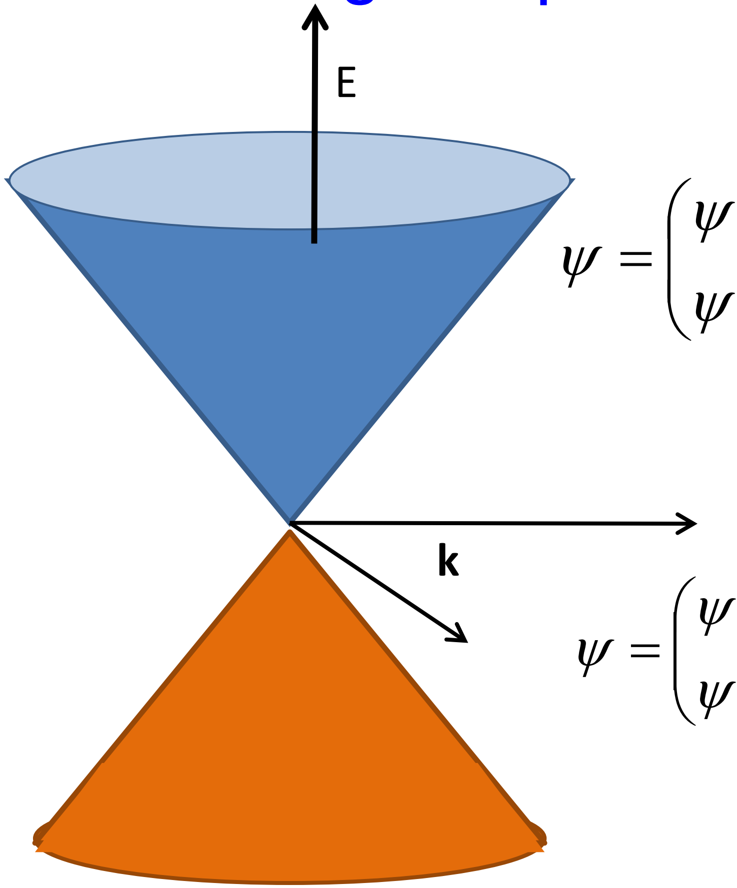
$$S=\begin{pmatrix} 1 & sf\left(\vec{k}\right) \\ sf^*\left(\vec{k}\right) & 1 \end{pmatrix}\approx\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}+O\left(\frac{spa}{\hbar}\right)$$

$$H=v\begin{pmatrix} 0 & p_x-ip_y \\ p_x+ip_y & 0 \end{pmatrix}=v\begin{pmatrix} 0 & \pi^+ \\ \pi & 0 \end{pmatrix}=v\left(\sigma_x p_x+\sigma_y p_y\right)=v\vec{\sigma}.\vec{p}$$

$$v\begin{pmatrix} 0 & p_x-ip_y \\ p_x+ip_y & 0 \end{pmatrix}\begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}=E\begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}$$

$$v=\frac{\sqrt{3}a\gamma_0}{2\hbar}\approx 10^6 m/s$$

Schrodinger equation to Dirac equation at low energy



$$\psi = \begin{pmatrix} \psi_{+A} \\ \psi_{+B} \end{pmatrix}$$

$$\psi = \begin{pmatrix} \psi_{-A} \\ \psi_{-B} \end{pmatrix}$$

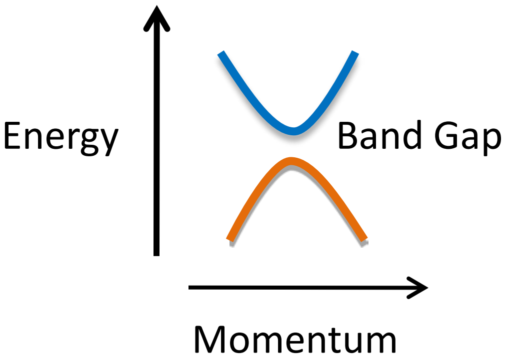
$$\psi = \begin{pmatrix} \psi_{+A} \\ \psi_{+B} \\ \psi_{-A} \\ \psi_{-B} \end{pmatrix}$$

+, - valley index

A,B sublattice (pseudospin) index

$$H = v \begin{pmatrix} 0 & p_x - ip_y & 0 & 0 \\ p_x + ip_y & 0 & 0 & 0 \\ 0 & 0 & 0 & -p_x - ip_y \\ 0 & 0 & -p_x + ip_y & 0 \end{pmatrix}$$

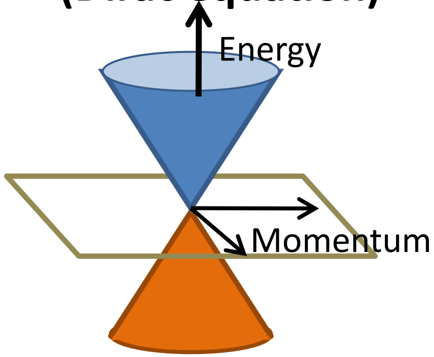
Electrons in usual solids (Schrodinger equation)



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

Electrons and holes in condensed matter physics are normally described by separate Schrödinger equations, which are not in any way connected (**Seitz sum rule**)).

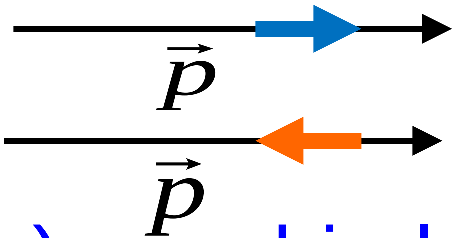
Electrons in graphene (Dirac equation)



$$E = \hbar k v_F$$

In contrast, electron and hole states in graphene are interconnected, analogous to the charge-conjugation symmetry in QED. This allows one to introduce **chirality** – formally a projection of pseudospin on the direction of motion – which is positive and negative for electrons and holes, respectively.

$$H = v\begin{pmatrix} 0 & \pi^+ \\ \pi & 0 \end{pmatrix} = v\vec{\sigma}\cdot\vec{p} = vp\ \vec{\sigma}\cdot\vec{n}$$



$$\vec{\sigma}\cdot\vec{n} = 1$$

$$\vec{\sigma}\cdot\vec{n} = -1$$

Electrons(holes) are chiral.

Electrons in conduction band and holes in valence band are entangled.

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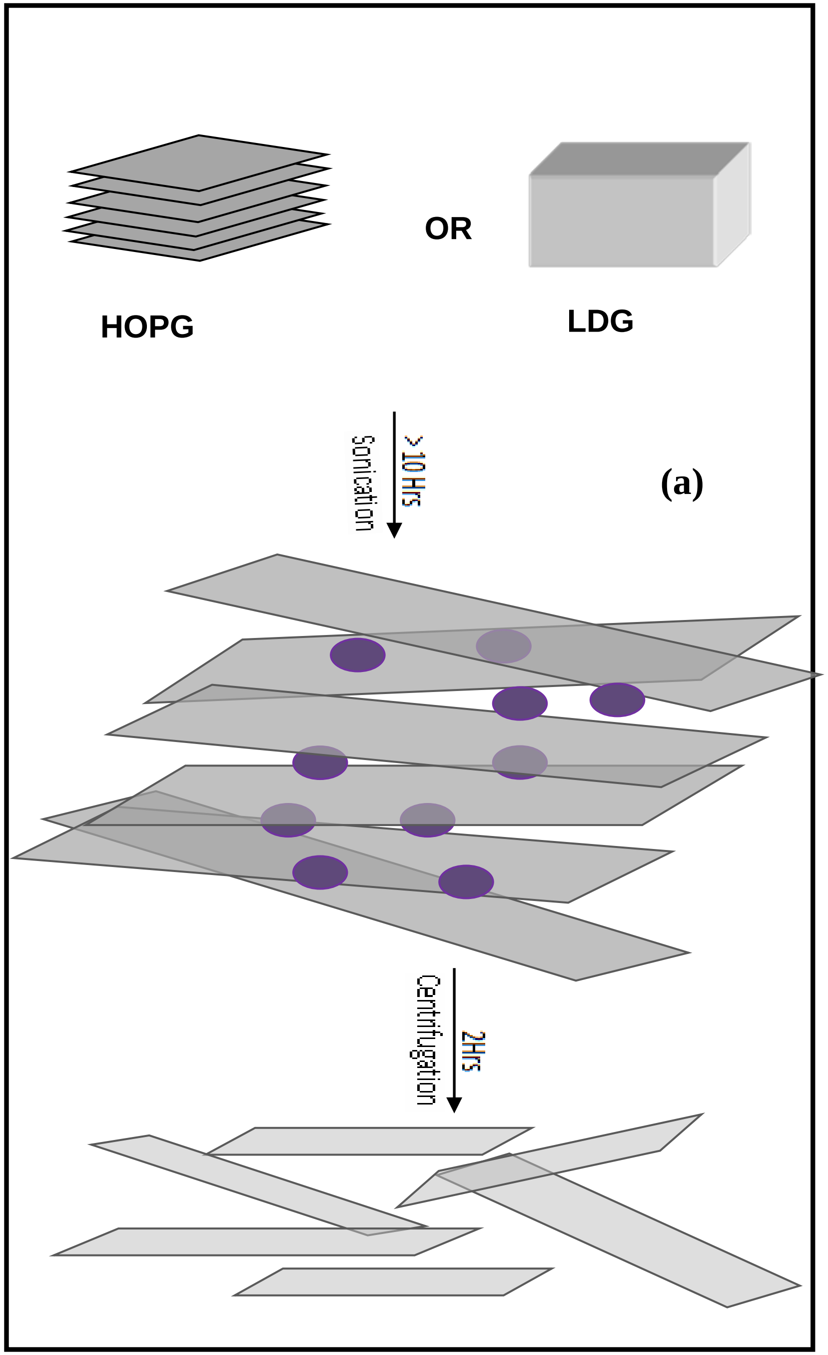
Growth and Characterization Graphene

How we grow graphene monolayer

- Mechanical Exfoliation
- Chemical Exfoliation
- Chemical Vapor Deposition

A New (?) Method for Growth of High Quality Monolayer, Bilayer and Multilayer Graphene

Controllability & Reproducibility

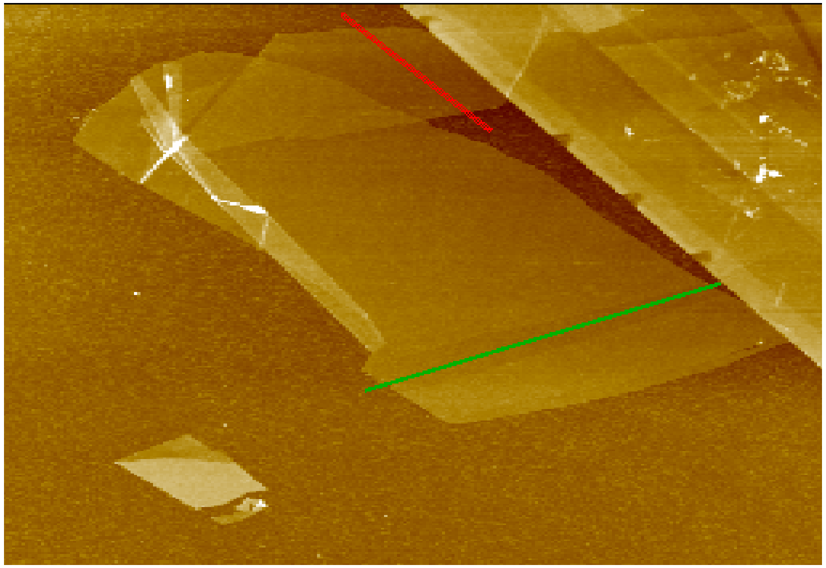


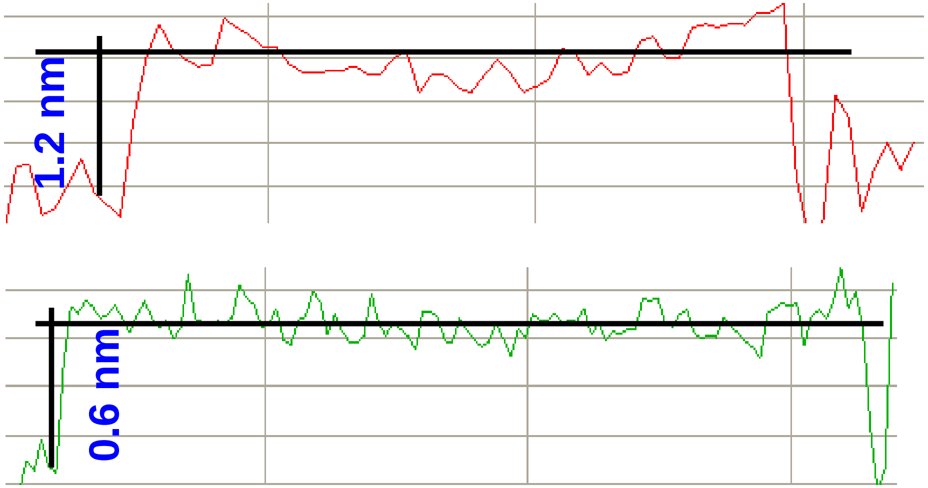
● → **Organic Molecules**

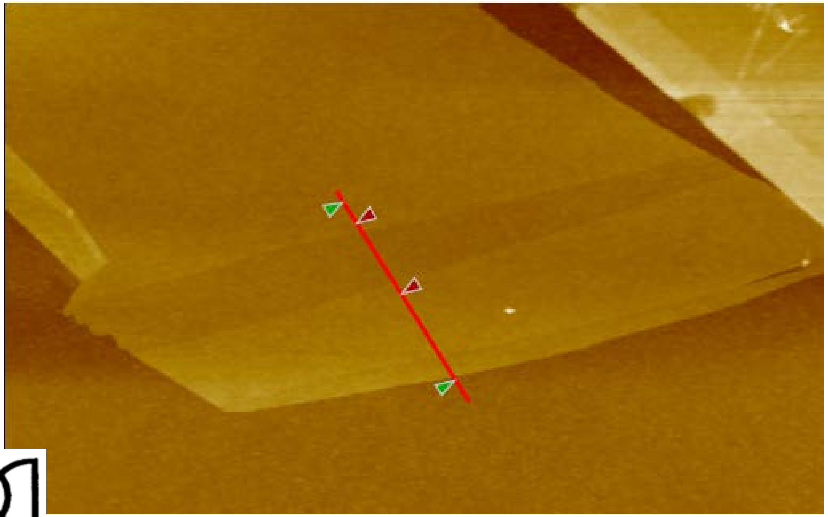
Also with water

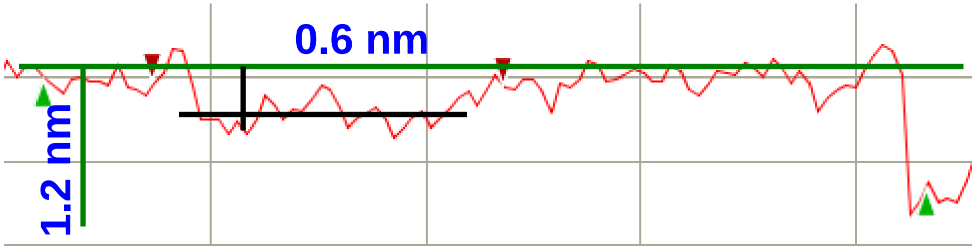
Atomic Force Microscopy

(Graphene sheet synthesized in Propylene carbonate)

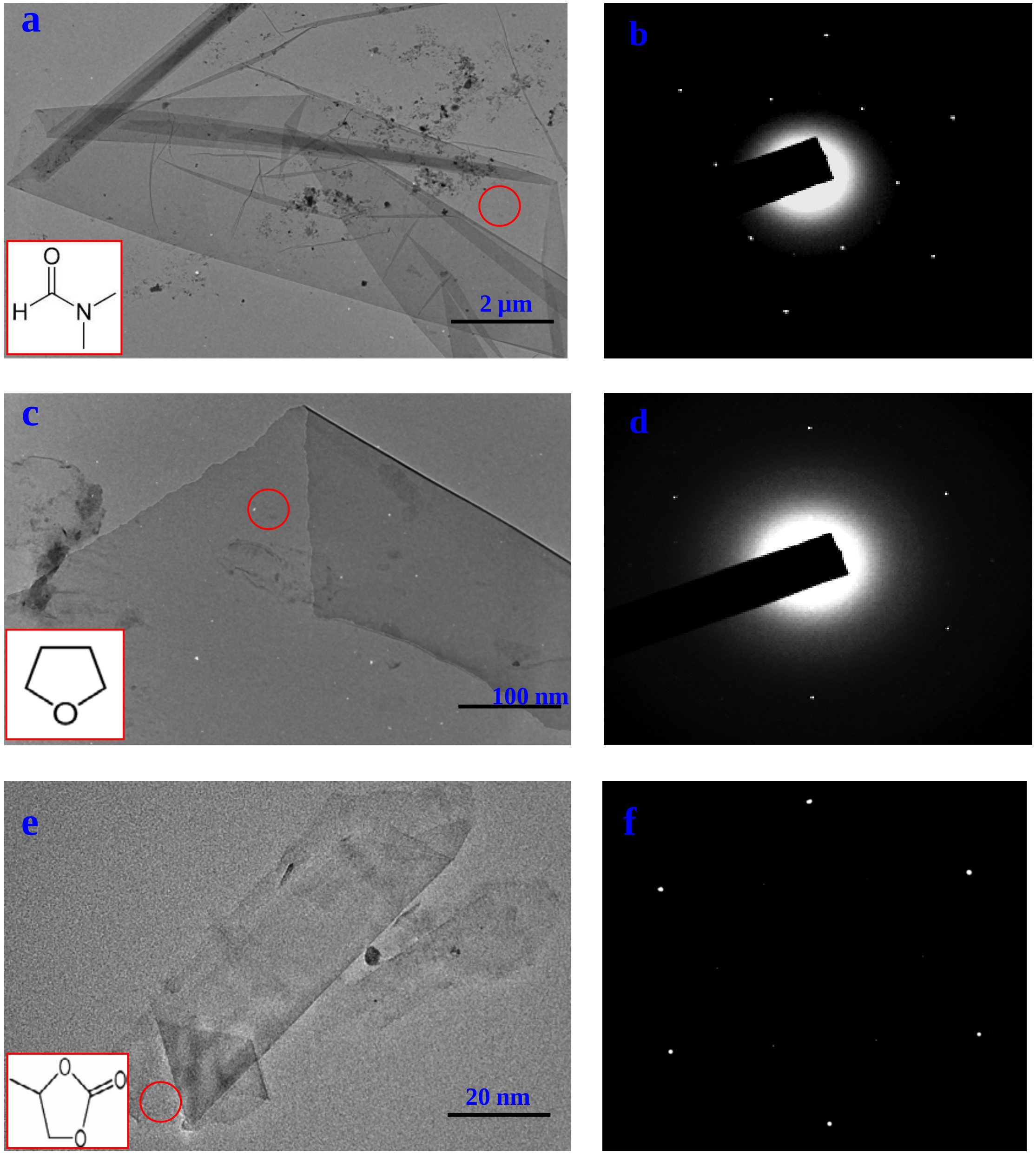




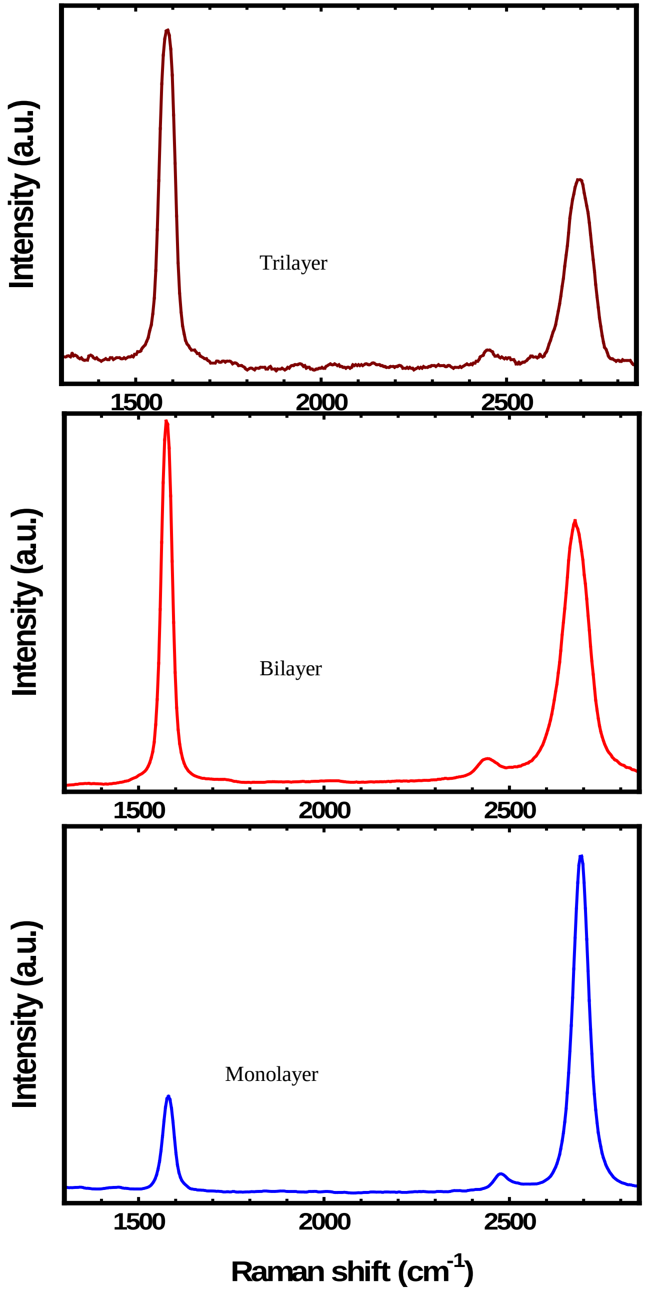




Transnission electron microscopy



Excellent Control of No of Layers



Plan of this talk

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- **Doping of graphene** to modulate the e-e interaction on universality
- How to break this universality ?

Fine Structure Constant Defines Visual Transparency of Graphene

R. R. Nair,[1] P. Blake,[1] A. N. Grigorenko,[1] K. S. Novoselov,[1] T. J. Booth,[1] T. Stauber,[2]
N. M. R. Peres,[2] A. K. Geim[1]*

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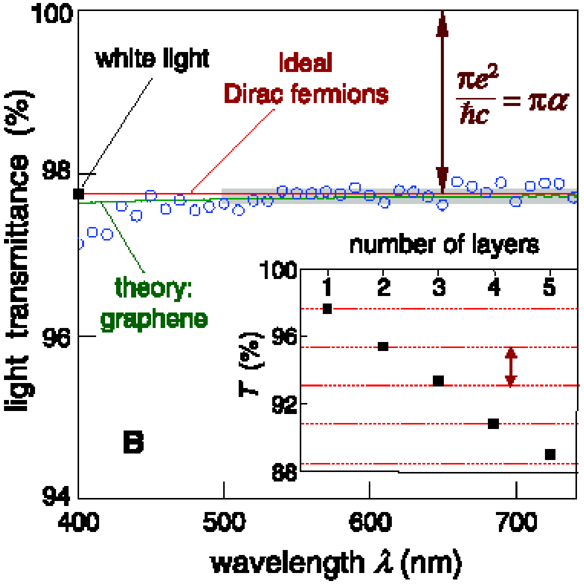
$$T = \left(1 - \pi\alpha\right)$$

$$\alpha = \frac{1}{137}$$

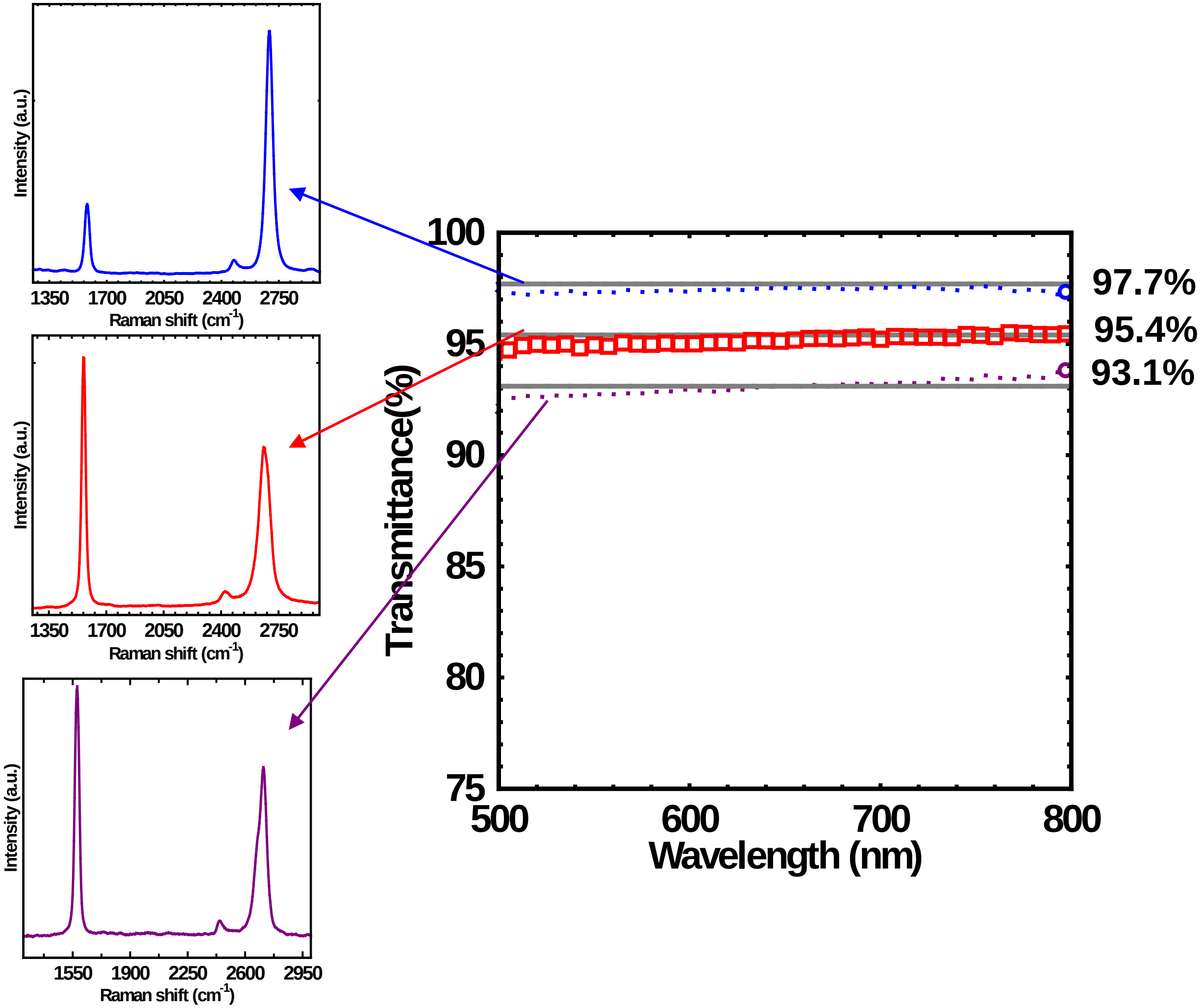


97.7%

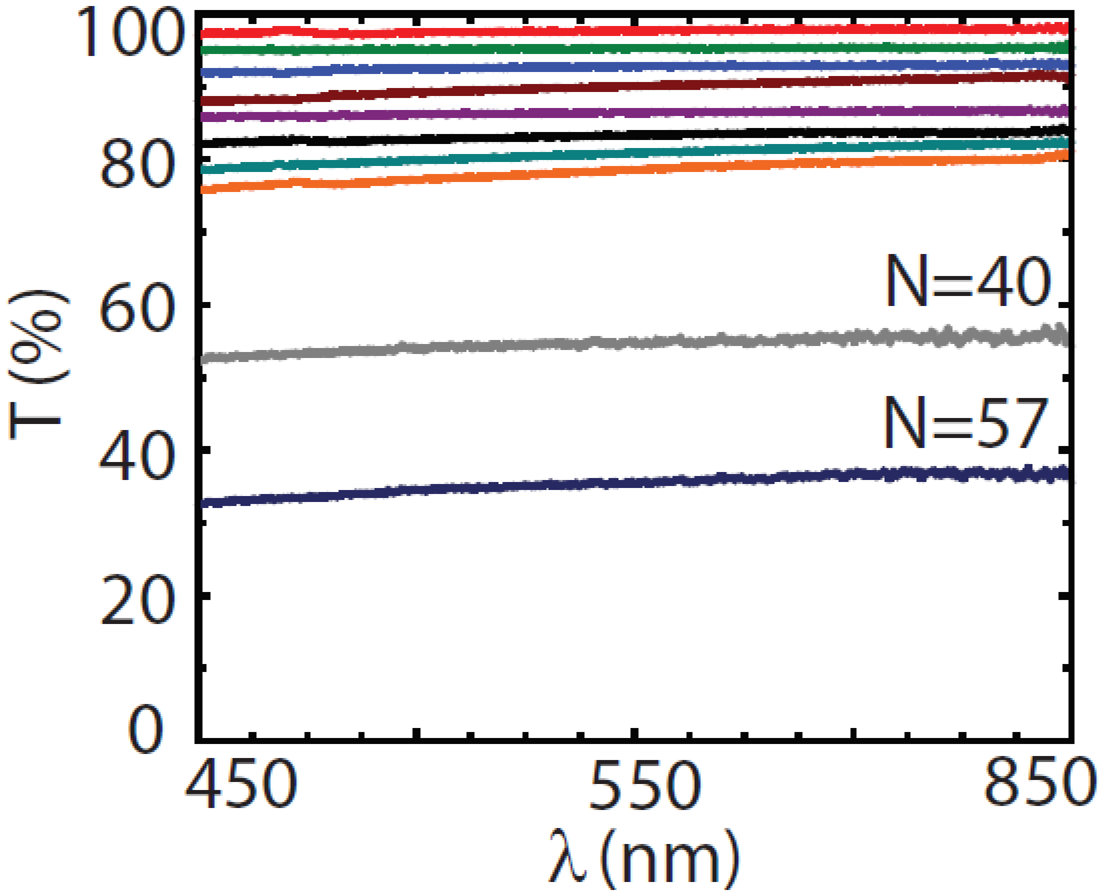
Origin: Dirac cone (linear dispersion) and optical properties are dictated by QED

What about bilayer, trilayer…….multilayer ?

Does it depend on inter layer coupling ?



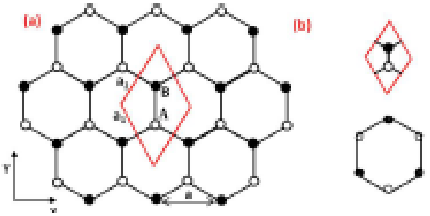
$$T = \left(1 - N\pi\alpha\right)$$



Universal in monolayer to multilayer graphene.

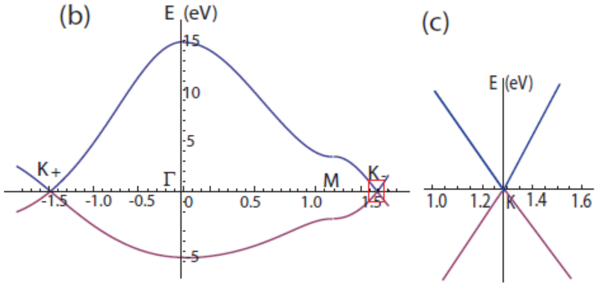
No effect of interlayer coupling.

Monolayer

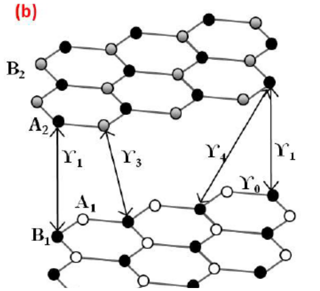


$$\mathbf{H}_1 = \begin{bmatrix} \varepsilon_A & -\gamma_0 f(\mathbf{k}) \\ -\gamma_0 f^*(\mathbf{k}) & \varepsilon_B \end{bmatrix} \qquad \mathbf{S}_1 = \begin{bmatrix} 1 & s_0 f(\mathbf{k}) \\ s_0 f^*(\mathbf{k}) & 1 \end{bmatrix}$$

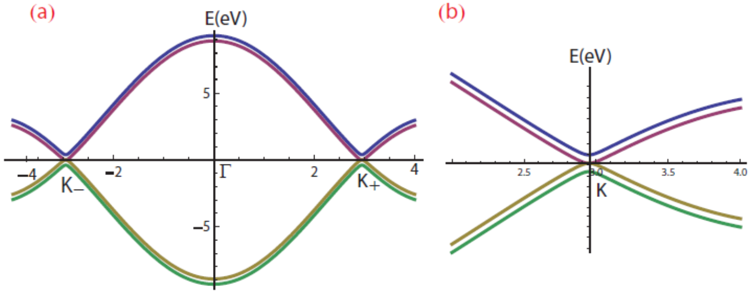
$$\det\left(\mathbf{H}_1 - E_i \mathbf{S}_1\right) = 0 \qquad E_\pm = \frac{\varepsilon_{2p} \pm \gamma_0 |f(\mathbf{k})|}{1 \mp s_0 |f(\mathbf{k})|}$$



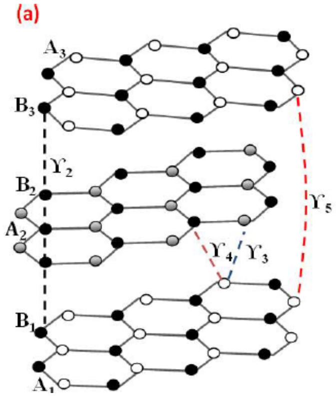
Bilayer



$$\mathbf{H}_2 = \begin{array}{c} \\ A_1 \\ B_1 \\ A_2 \\ B_2 \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & B_1 & A_2 & B_2 \end{array} \\ \begin{pmatrix} \varepsilon_{A_1} & -\gamma_0 f(\mathbf{k}) & \gamma_4 f(\mathbf{k}) & -\gamma_3 f^*(\mathbf{k}) \\ -\gamma_0 f^*(\mathbf{k}) & \varepsilon_{B_1} & \gamma_1 & \gamma_4 f(\mathbf{k}) \\ \gamma_4 f^*(\mathbf{k}) & \gamma_1 & \varepsilon_{A_2} & -\gamma_0 f(\mathbf{k}) \\ -\gamma_3 f(\mathbf{k}) & \gamma_4 f^*(\mathbf{k}) & -\gamma_0 f^*(\mathbf{k}) & \varepsilon_{B_2} \end{pmatrix} \end{array}$$



Trilayer



$$\mathbf{H}_3 = \begin{array}{c} \\ A_1 \\ B_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \end{array} \begin{array}{c} \begin{array}{cccccc} A_1 & B_1 & A_2 & B_2 & A_3 & B_3 \end{array} \\ \begin{pmatrix} \varepsilon_{A_1} & -\gamma_0 f(\mathbf{k}) & \gamma_4 f(\mathbf{k}) & -\gamma_3 f^*(\mathbf{k}) & \gamma_2 & 0 \\ -\gamma_0 f^*(\mathbf{k}) & \varepsilon_{B_1} & \gamma_1 & \gamma_4 f(\mathbf{k}) & 0 & \gamma_5 \\ \gamma_4 f^*(\mathbf{k}) & \gamma_1 & \varepsilon_{A_2} & -\gamma_0 f(\mathbf{k}) & \gamma_4 f^*(k) & \gamma_1 \\ -\gamma_3 f(k) & \gamma_4 f^*(\mathbf{k}) & -\gamma_0 f^*(\mathbf{k}) & \varepsilon_{B_2} & -\gamma_3 f(\mathbf{k}) & \gamma_4 f^*(\mathbf{k}) \\ \gamma_2 & 0 & \gamma_4 f(k) & -\gamma_3 f^*(\mathbf{k}) & \varepsilon_{A_3} & -\gamma_0 f(k) \\ 0 & \gamma_5 & \gamma_1 & \gamma_4 f(\mathbf{k}) & -\gamma_0 f^*(\mathbf{k}) & \varepsilon_{B_3} \end{pmatrix} \end{array} \tag{2.38}$$

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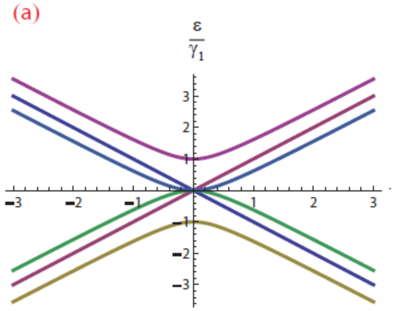
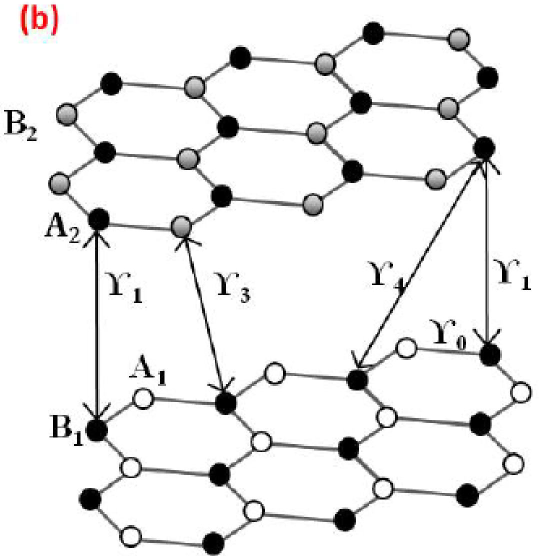


Bilayer Graphene : 4 atoms per unit cell



$$\mathrm{H}_2 = \begin{array}{c|cccc} & A_1 & B_1 & A_2 & B_2 \\ \hline A_1 & \varepsilon_{A_1} & v\pi^\dagger & -v_4\pi^\dagger & v_3\pi \\ B_1 & v\pi & \varepsilon_{B_1} & \gamma_1 & -v_4\pi^\dagger \\ A_2 & -v_4\pi & \gamma_1 & \varepsilon_{A_2} & v\pi^\dagger \\ B_2 & v_3\pi^\dagger & -v_4\pi & v\pi & \varepsilon_{B_2} \end{array}$$

$$\mathbf{H}_2 = \begin{bmatrix} h_\theta & u \\ u^\dagger & h_\chi \end{bmatrix}$$

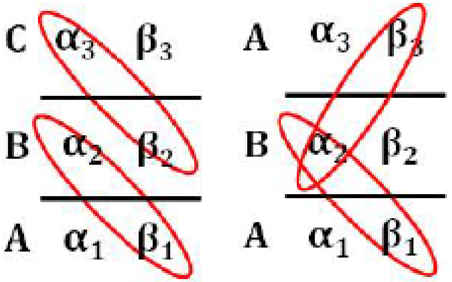
$$h_\theta = \begin{array}{c|cc} & A_2 & B_1 \\ \hline A_2 & \varepsilon_{A_1} & v_3\pi \\ B_1 & v_3\pi^\dagger & \varepsilon_{B_2} \end{array} \quad h_\chi = \begin{array}{c|cc} & A_2 & B_1 \\ \hline A_2 & \varepsilon_{A_2} & \gamma_1 \\ B_1 & \gamma_1 & \varepsilon_{B_1} \end{array} \quad u = \begin{array}{c|cc} & A_1 & B_2 \\ \hline A_1 & -v_4\pi^\dagger & v\pi^\dagger \\ B_2 & v\pi & -v_4\pi \end{array} \quad u^\dagger = \begin{array}{c|cc} & A_1 & B_2 \\ \hline A_1 & -v_4\pi & v\pi^\dagger \\ B_2 & v\pi & -v_4\pi^\dagger \end{array}$$

$$\mathrm{H}_2 = \frac{1}{2m} \begin{bmatrix} 0 & (\pi^\dagger)^2 \\ (\pi)^2 & 0 \end{bmatrix}$$

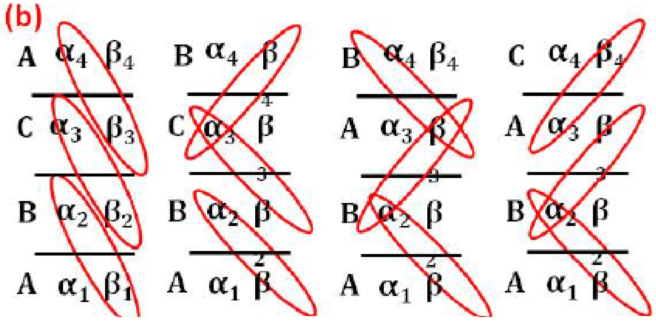
H. Min and A. H. MacDonald, Phys. Rev. Lett. 103, 067402 (2009).

H. Min and A. H. MacDonald, Phys. Rev. Lett. 103, 067402 (2009).

$$\mathbf{H_3} = \begin{bmatrix} h_\theta & u \\ u^\dagger & h_\chi \end{bmatrix}$$



$$\mathbf{H_4} = \begin{bmatrix} h_\theta & u \\ u^\dagger & h_\chi \end{bmatrix}$$



$$\mathbf{H}_J = g_J \begin{bmatrix} 0 & (\pi^\dagger)^J \\ (\pi)^J & 0 \end{bmatrix} = \gamma_1 \left(\frac{v}{\gamma_1} \right)^J \begin{bmatrix} 0 & (\pi^\dagger)^J \\ (\pi)^J & 0 \end{bmatrix}$$

$$H_N^{eff} = H_{J_1} \otimes H_{J_2} \otimes H_{J_3} \otimes H_{J_4} \ldots\ldots\ldots\ldots\ldots\ldots H_{J_N}$$

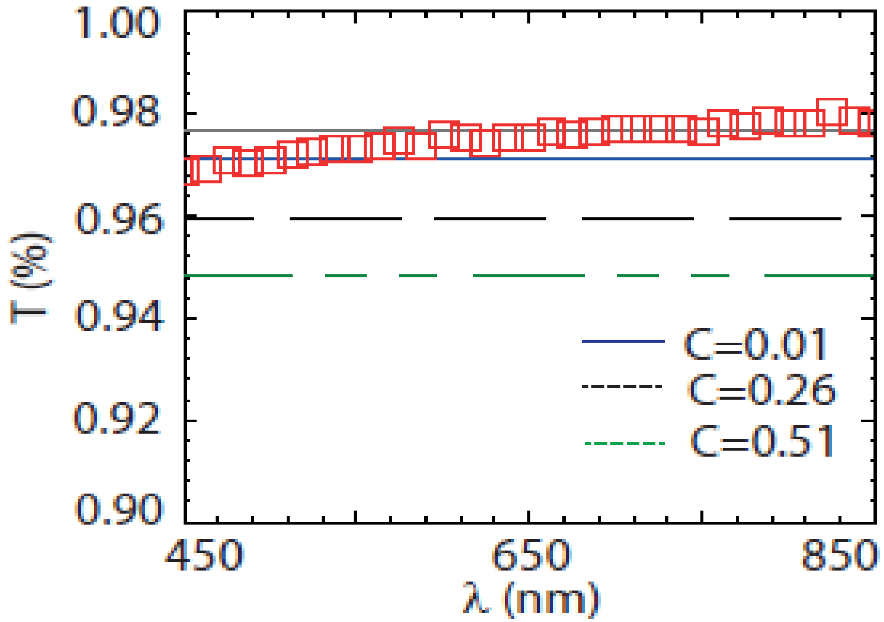
**Inspite of inter layer coupling ,
chirality is protected in
bilayer…….multilayer ……..and graphite.**

**Hence it appears that chirality
and not linear dispersion is responsible
for optical transmittance universality.**

Plan of this talk

- Introduction to graphene bandstructure and “chirality”.
- Growth and characterization of graphene.
- Robustness of universality under interlayer coupling and many body interactions.
- **Doping of graphene** to modulate the e-e interaction on universality
- How to break this universality ?

What is the effect of e-e interaction on this universality ?



$$\sigma(\omega)=\sigma(0)\left[1+\frac{c\ \alpha}{\left(1+\frac{\alpha}{4}\log\left(D/\omega\right)\right)}\right]$$

Europhys. Lett. 83, 17005 (2008) (c=0.01)

Phys. Rev. B 80, 193411 (2009) (c=0.51)

Phys. Rev. B 86, 115408 (2012). (c=0.12)

Phys. Rev. Lett. 114, 246801 (2015) (c=0.26)

Schrodinger Materials
(V<<c)

Galilean invariance

$$E_C = \frac{e^2}{\varepsilon\langle r\rangle}$$

$$E_{KG} = \frac{p^2}{2m}$$

$$\alpha_G = \frac{E_C}{E_{KG}} = \frac{n_0}{n^{1/2}}$$

Dependent on carrier density

Dirac Materials
(V ≤ c)

Lorentzian invariance

$$E_C = \frac{e^2}{\varepsilon\langle r\rangle}$$

$$E_{KL} = \hbar v_F \sqrt{\pi n}$$

$$\alpha_L = \frac{E_C}{E_{KL}} = \frac{e^2}{\varepsilon\hbar v_F}$$

Independent on carrier density

How to dope graphene ?

Various routes to dope Graphene

Metal contacts

Phys. Rev. Lett.
101, 026803 (2008)
Phys. Rev. Lett.
104, 076807 (2010)

Substitutional

Nat. Commun. 6:7123
doi: 10.1038/ncomms8123 (2015)
Nat. Commun. 6:8098
doi: 10.1038/ncomms9098 (2015)

Covalent functionalization

Chem. Rev. **112**, 6156-6214
(2012)
J. Am. Chem. Soc. **135**, 8981-8988
(2013)

Substrate modification

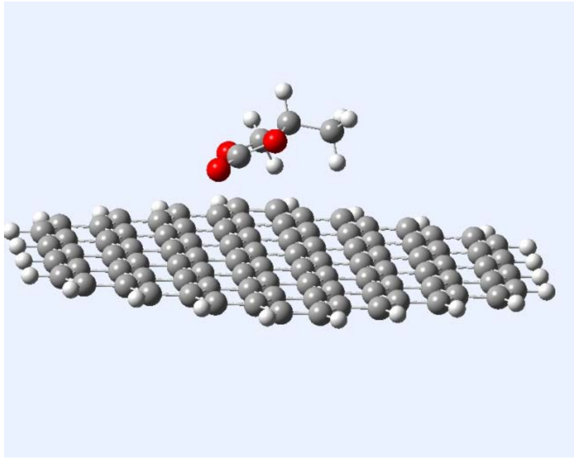
Adv. Mat. **26**, 8141-8146, (2014)

Sci. Rep. **6**, 21070, (2016)

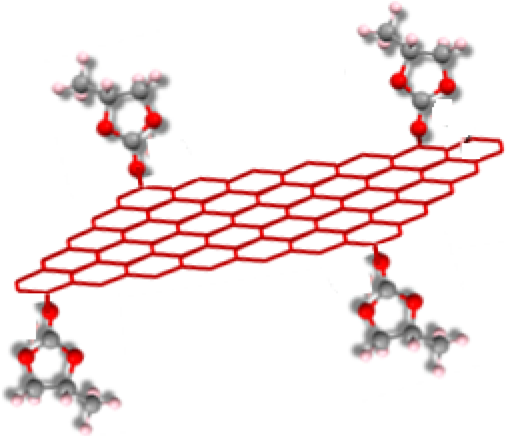
- graphene becomes disordered after doping
- difficult to dope both types(p and n)
- poor controllability
- low mobility

Doping
By
Functionalization

- Weak (supramolecular)
- Medium
- Covalent

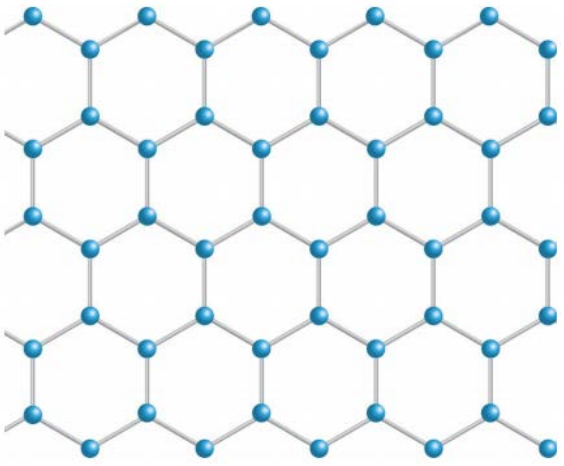


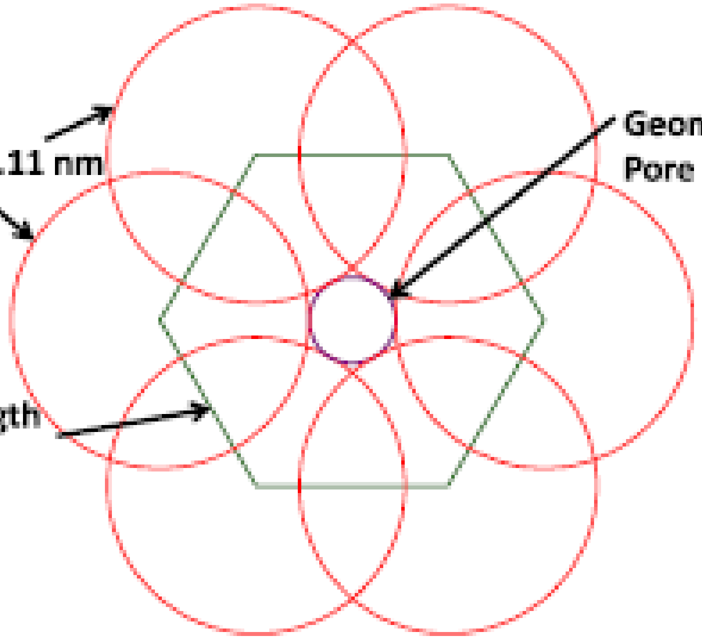
-high mobility
-no disorder



-low mobility
-disorder

Impermeability of Graphene





Carbon atoms
vdw radius = 0.11 nm

Geometric
Pore = 0.064 nm

C-C bond length
= 0.142 nm

NANO
LETTERS

2008
Vol. 8, No. 8
2458-2462

Impermeable Atomic Membranes from Graphene Sheets

J. Scott Bunch, Scott S. Verbridge, Jonathan S. Alden, Arend M. van der Zande,
Jeevak M. Parpia, Harold G. Craighead, and Paul L. McEuen*

Cornell Center for Materials Research, Cornell University, Ithaca, New York 14853

Received May 21, 2008; Revised Manuscript Received June 12, 2008

ABSTRACT

We demonstrate that a monolayer graphene membrane is impermeable to standard gases including helium. By applying a pressure difference across the membrane, we measure both the elastic constants and the mass of a single layer of graphene. This pressurized graphene membrane is the world's thinnest balloon and provides a unique separation barrier between 2 distinct regions that is only one atom thick.

nature
COMMUNICATIONS

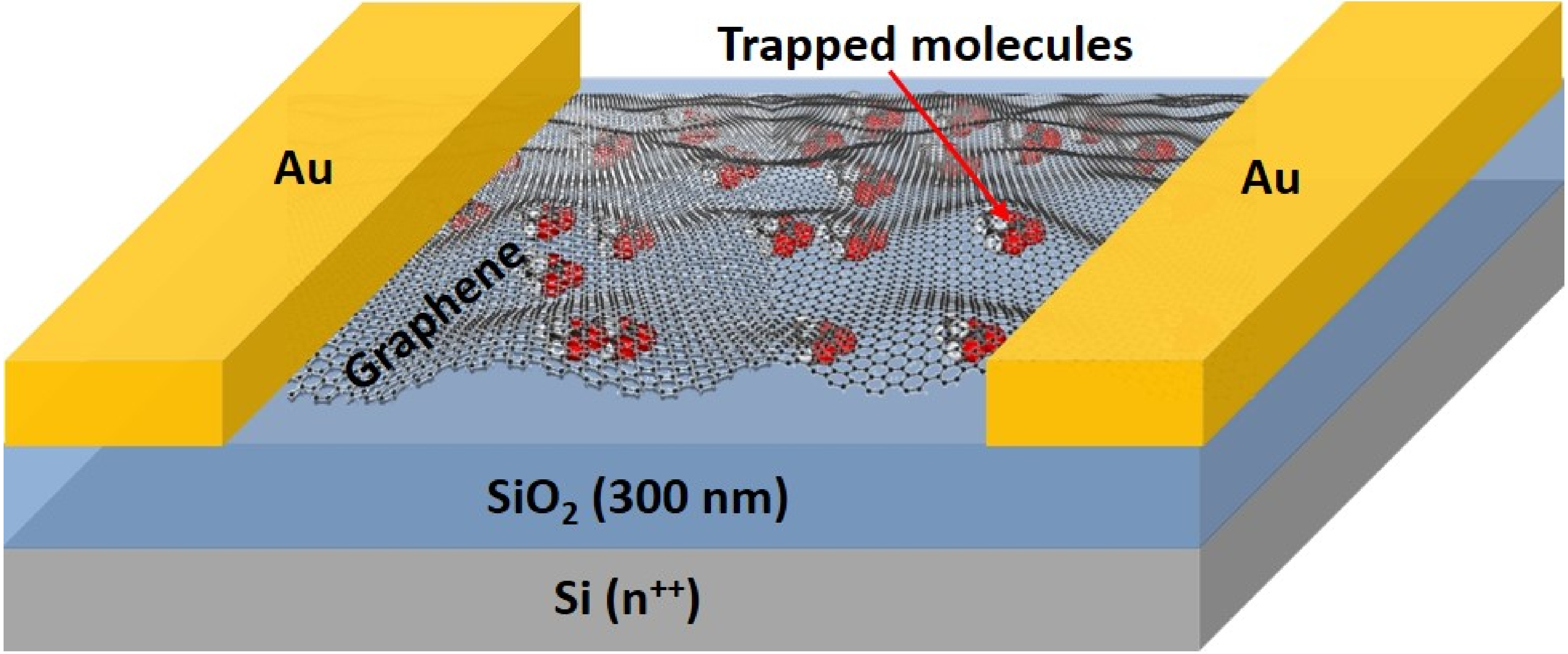
ARTICLE

Received 24 Apr 2014 | Accepted 29 Jul 2014 | Published 11 Sep 2014

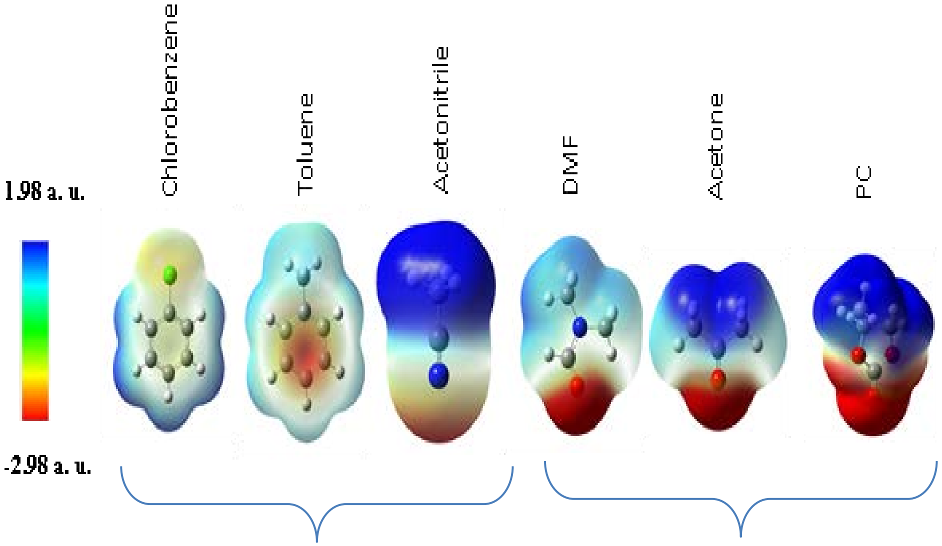
DOI: 10.1038/ncomms5843

Impermeable barrier films and protective coatings based on reduced graphene oxide

Y. Su[1], V.G. Kravets[1], S.L. Wong[1], J. Waters[2], A.K. Geim[1] & R.R. Nair[1]


Trapped molecules
Au
Au
Graphene
SiO$_2$ (300 nm)
Si (n^{++})

Doping tunability: Donor and acceptor nature of trapped molecules

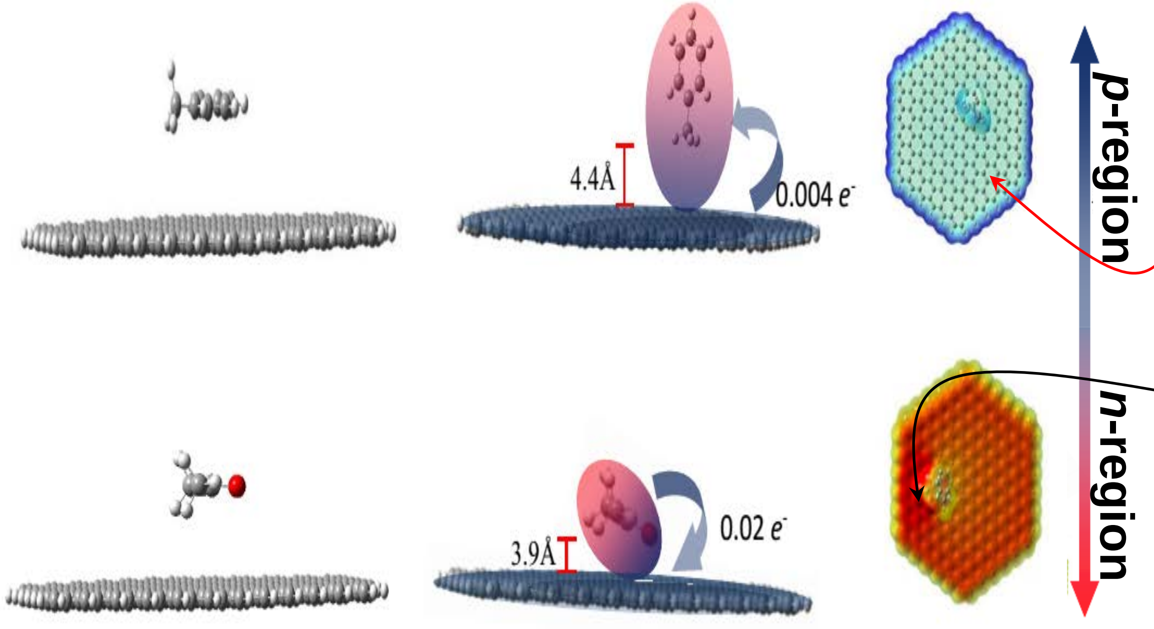


Electrophilic molecules (Acceptor)

Nucleophilic molecules (Donor)

DFT calculations

DFT calculations using Gaussian 9.0. using Lee-Yang-Parr correlation functional (B3LYP) with 631G-basis set



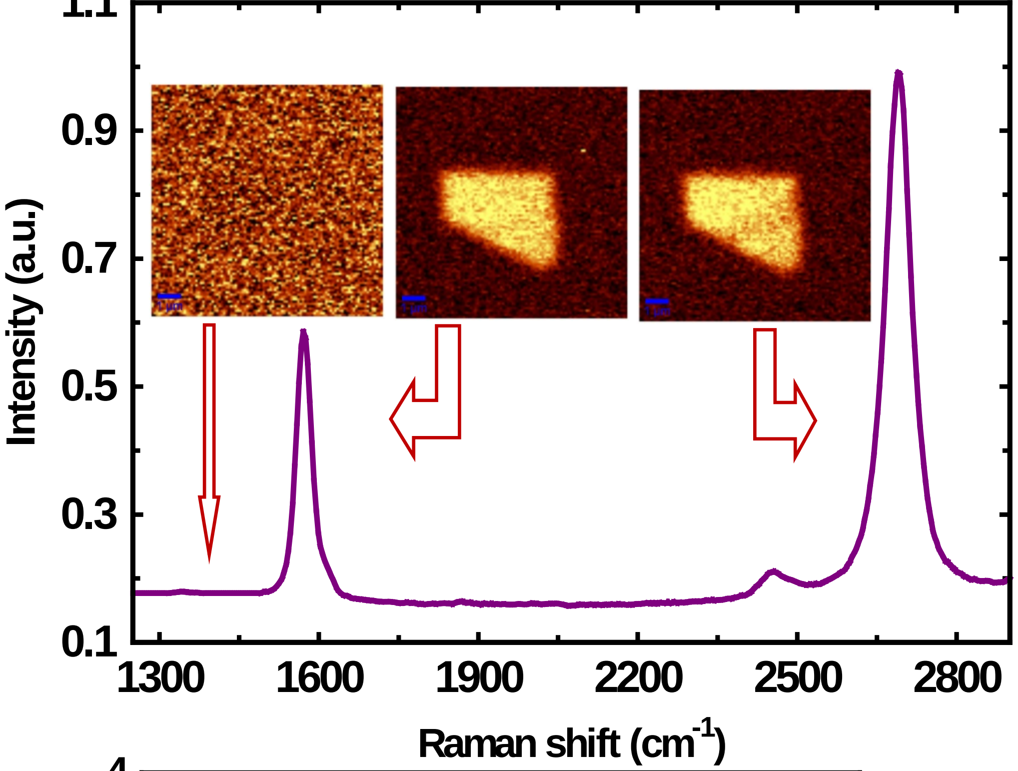
Electron deficit regions

Electron rich regions

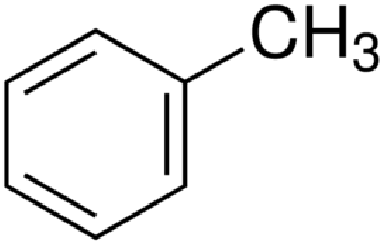
Trial geometry

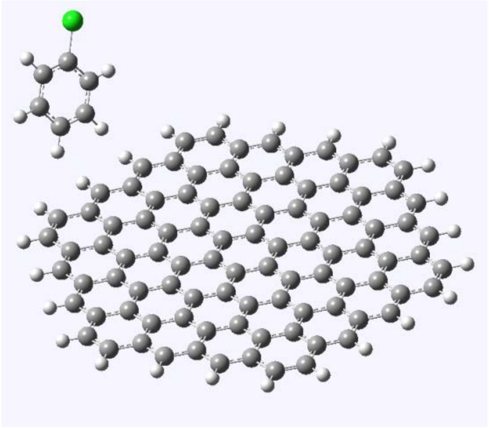
Optimized geometry

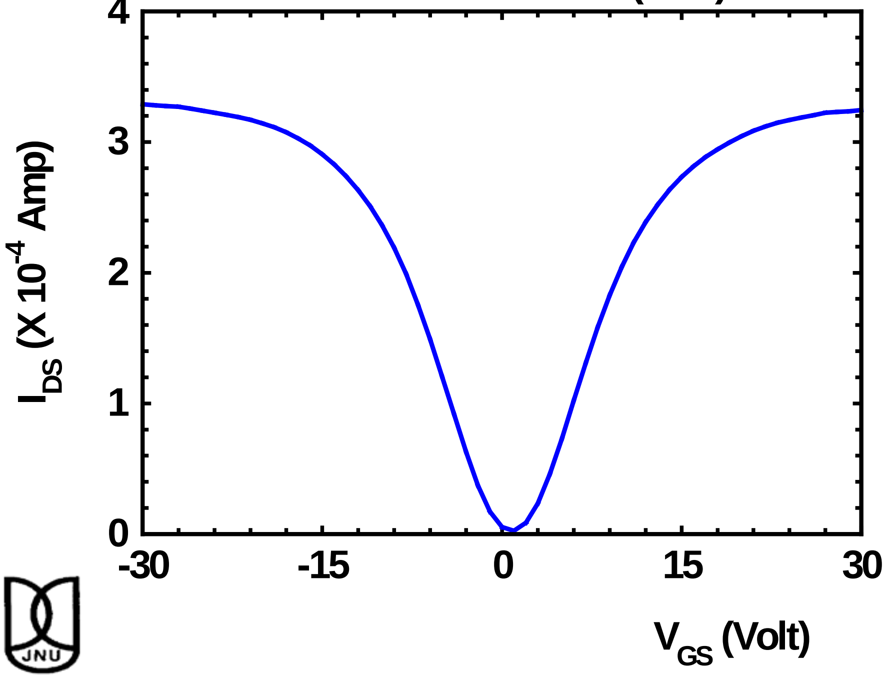
Charge density map

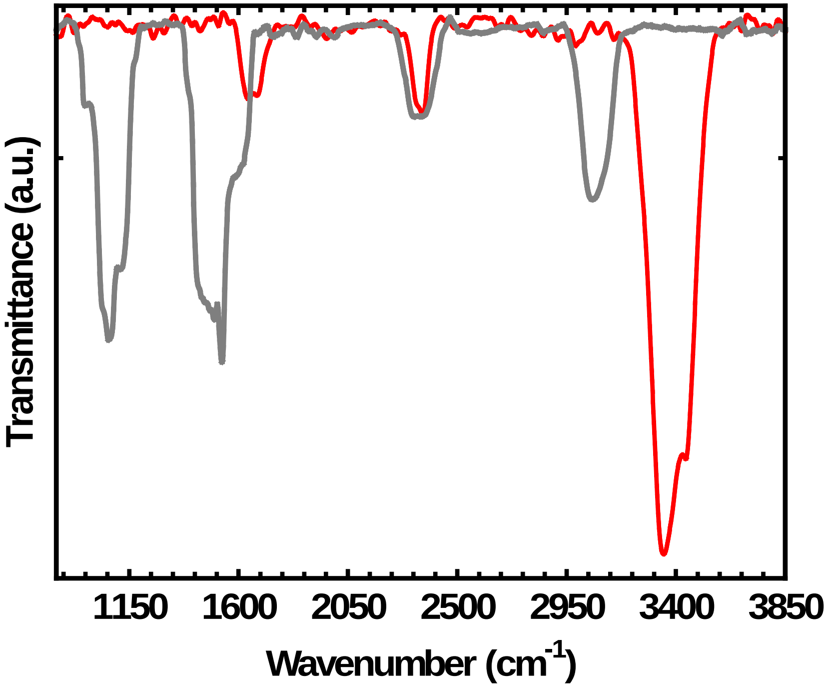

1.1
0.9
0.7
0.5
0.3
0.1
Intensity (a.u.)
1300
1600
1900
2200
2500
2800
Raman shift (cm^{-1})

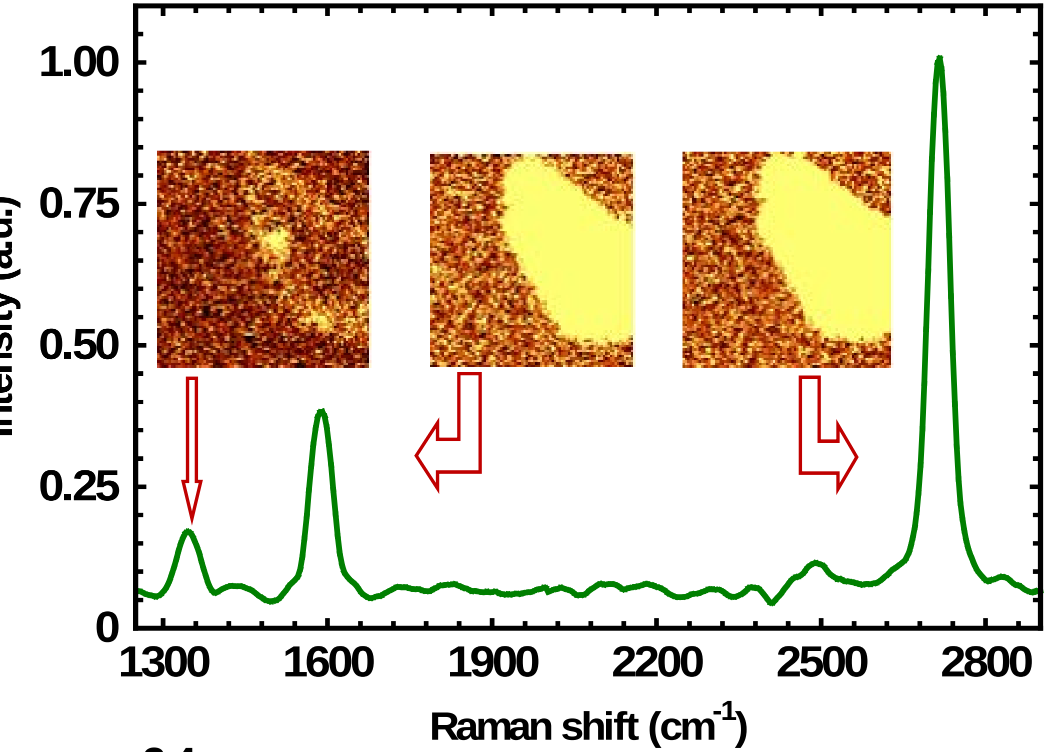
Toluene


CH_3

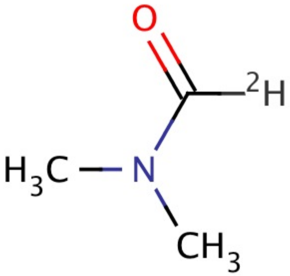


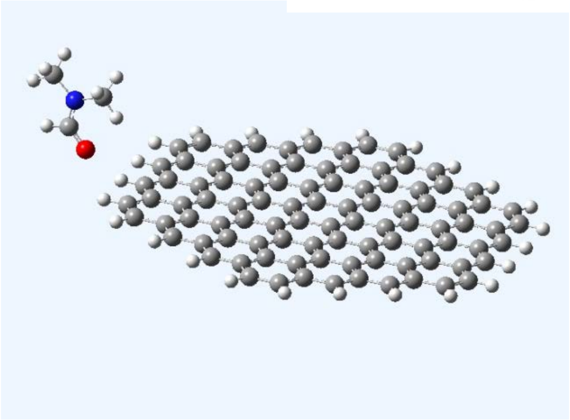

4
3
2
1
0
I_{DS} (X 10^{-4} Amp)
-30
-15
0
15
30
V_{GS} (Volt)

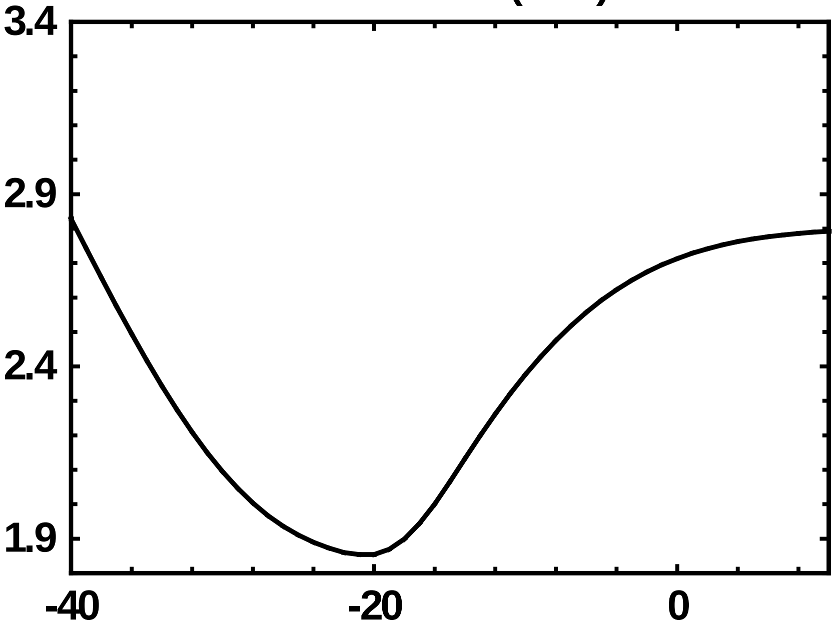

Transmittance (a.u.)
1150
1600
2050
2500
2950
3400
3850
Wavenumber (cm^{-1})

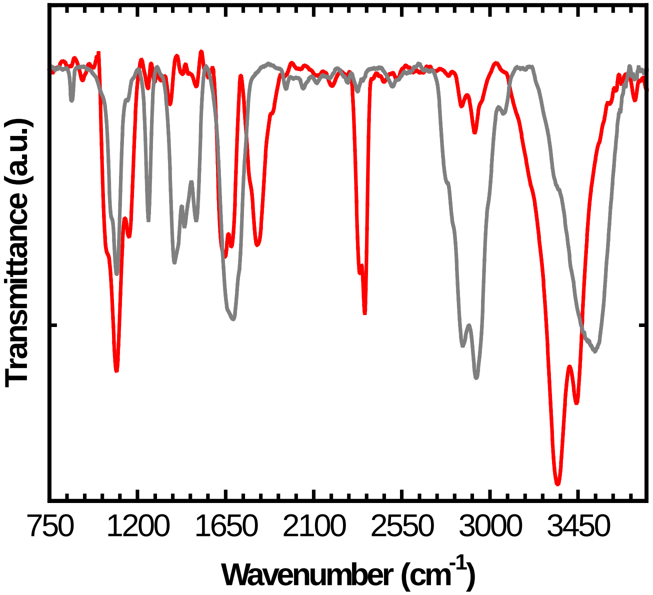

Intensity (a.u.)
1.00
0.75
0.50
0.25
0
1300
1600
1900
2200
2500
2800
Raman shift (cm^{-1})

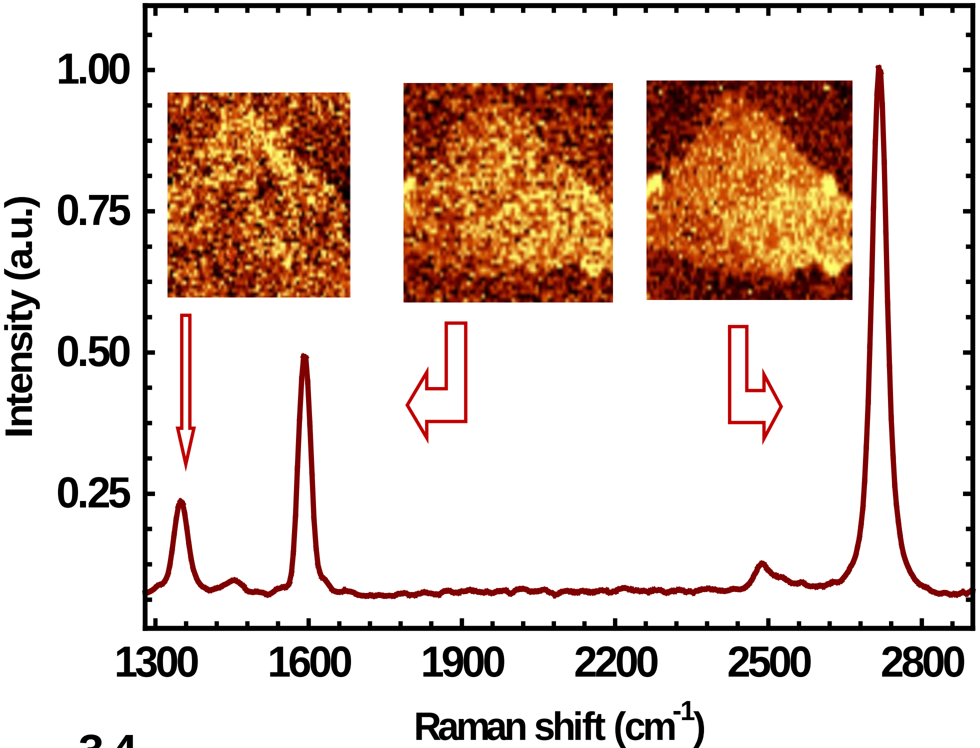
DMF


O
^{2}H
H_3C
N
CH_3



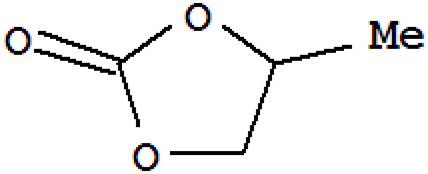

3.4
2.9
2.4
1.9
-40
-20
0


Transmittance (a.u.)
750
1200
1650
2100
2550
3000
3450
Wavenumber (cm^{-1})

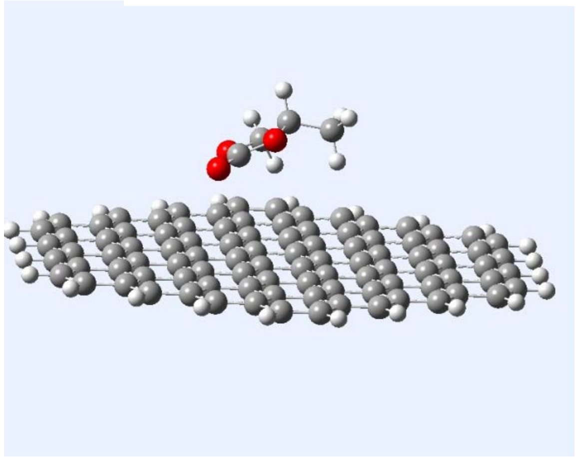


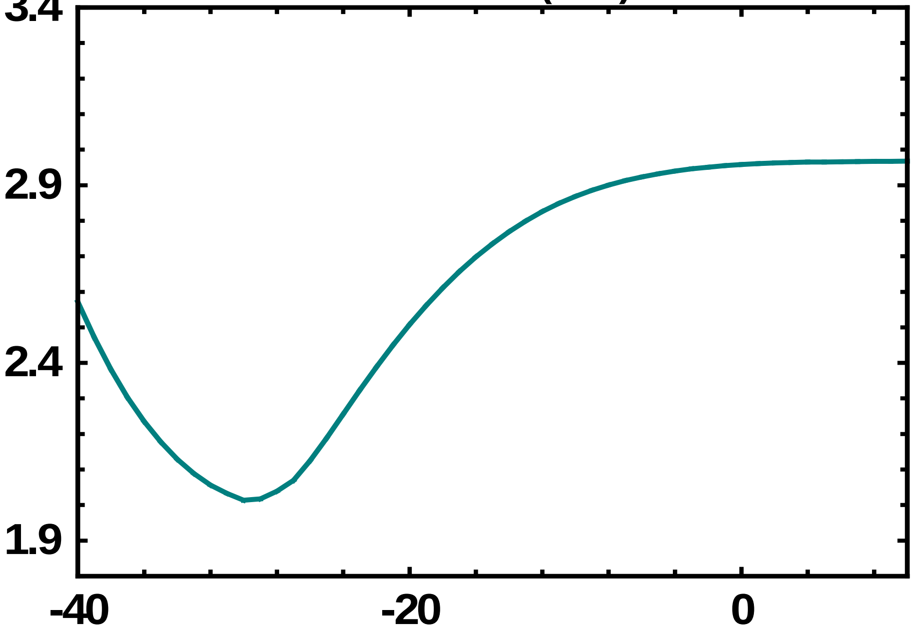
Intensity (a.u.)
1.00
0.75
0.50
0.25
1300
1600
1900
2200
2500
2800
Raman shift (cm^{-1})

PC

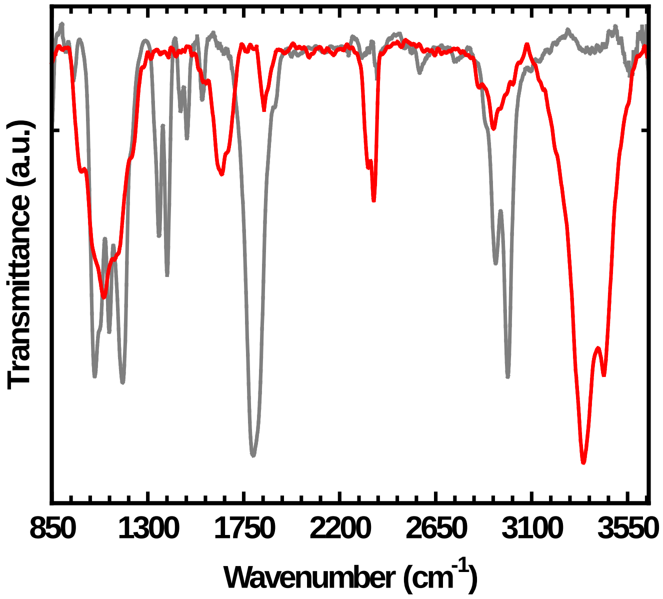


O
O
Me
O

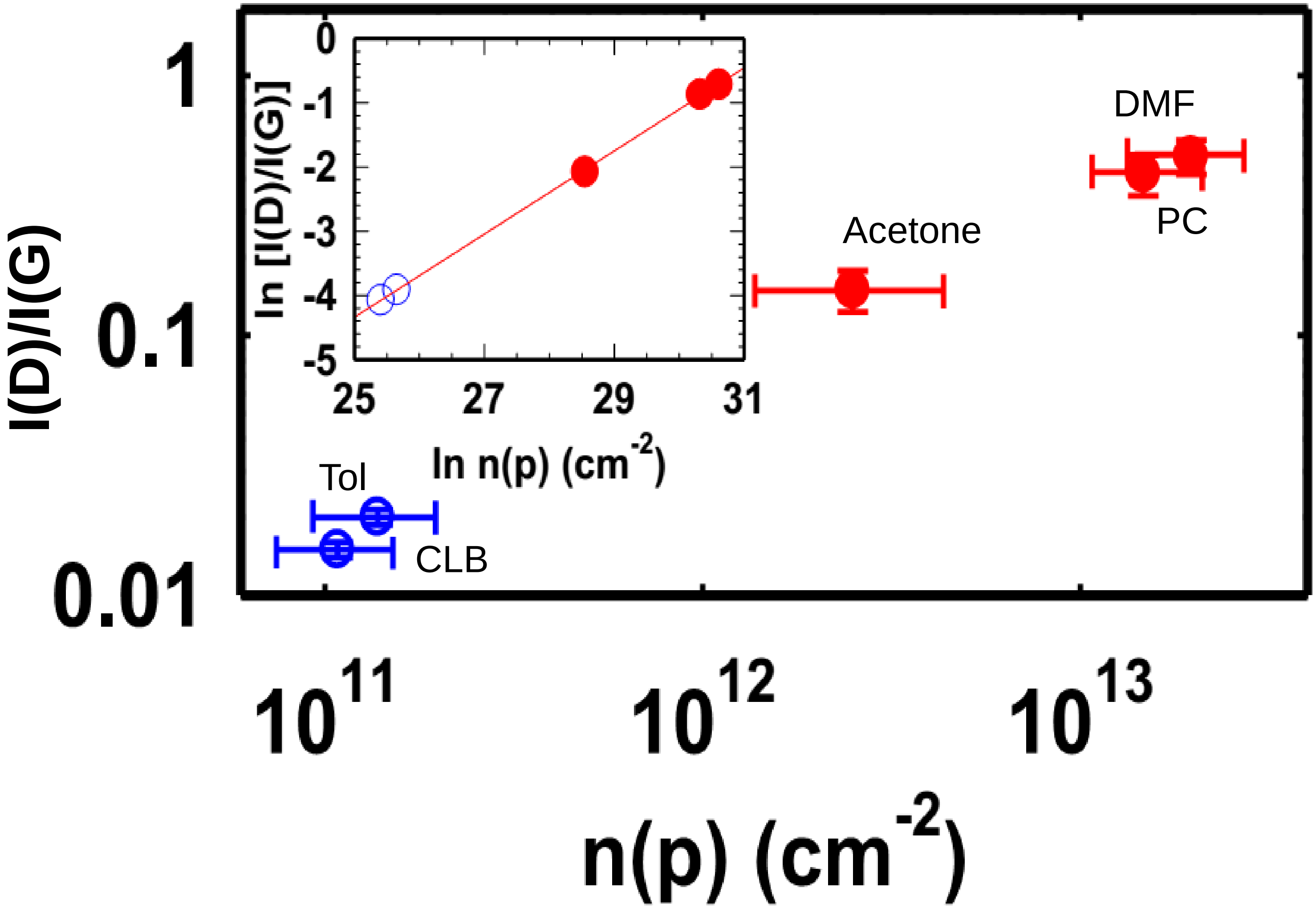




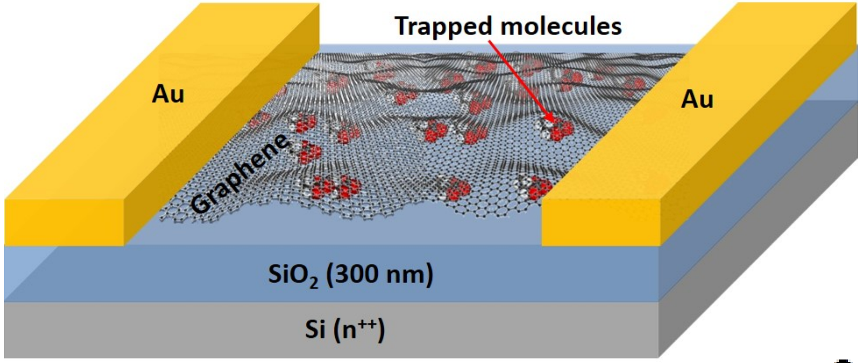
3.4
2.9
2.4
1.9
-40
-20
0

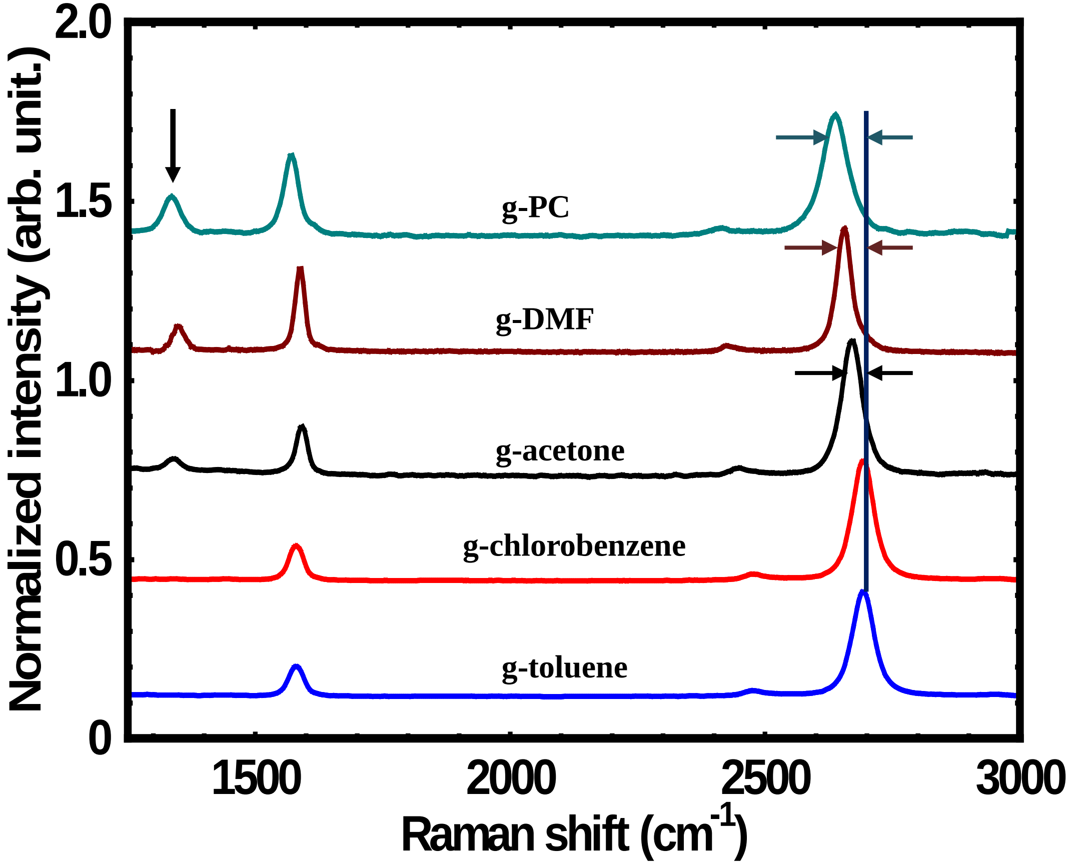


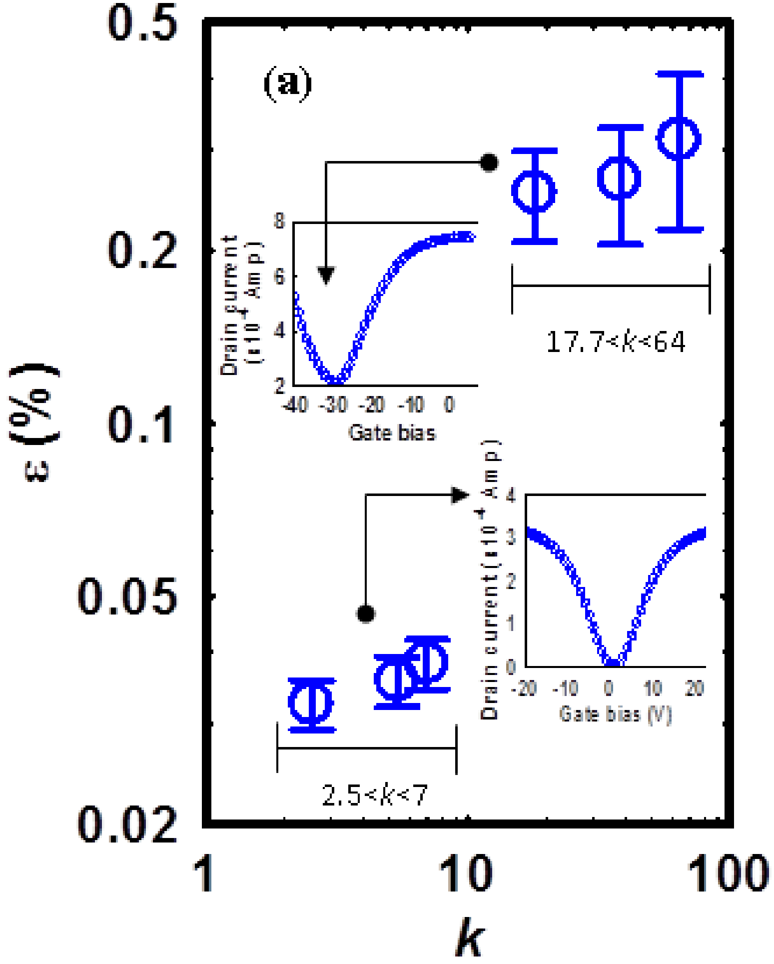
Transmittance (a.u.)
850
1300
1750
2200
2650
3100
3550
Wavenumber (cm^{-1})



I(D)/I(G)
1
0.1
0.01
n(p) (cm^{-2})
10^{11}
10^{12}
10^{13}
DMF
PC
Acetone
Tol
CLB
ln [I(D)/I(G)]
0
-1
-2
-3
-4
-5
25
27
29
31
ln n(p) (cm^{-2})

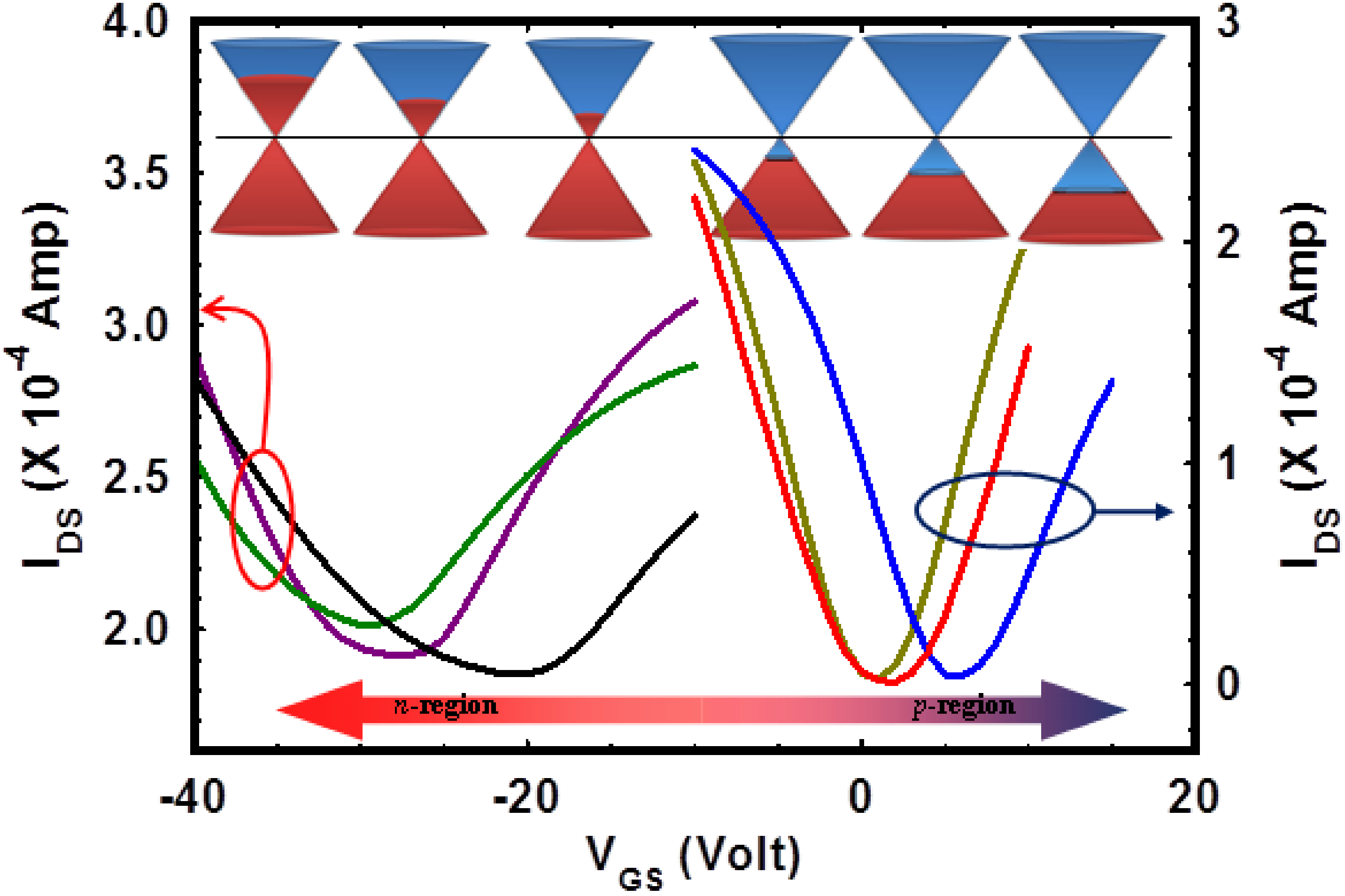

Trapped molecules
Au
Au
Graphene
SiO$_2$ (300 nm)
Si (n^{++})

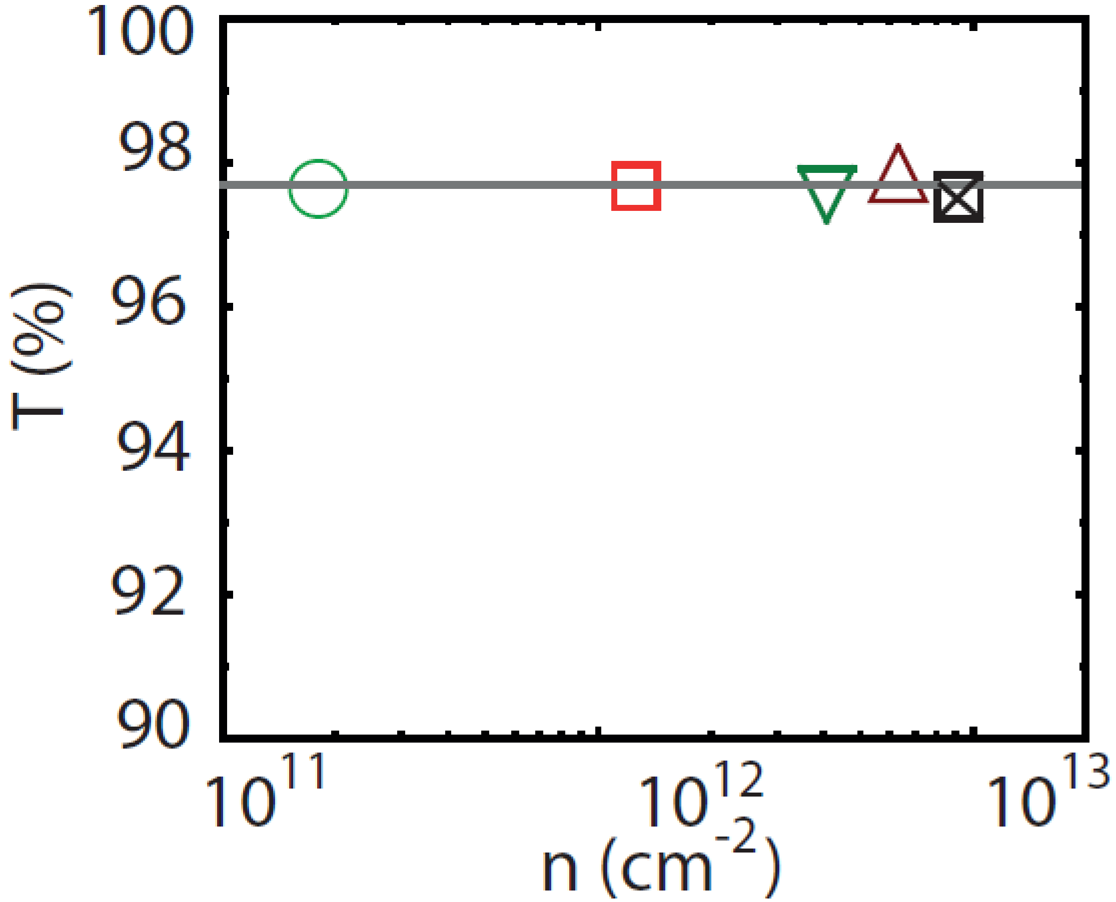

Normalized intensity (arb. unit.)
2.0
1.5
1.0
0.5
0
g-PC
g-DMF
g-acetone
g-chlorobenzene
g-toluene
1500
2000
2500
3000
Raman shift (cm^{-1})

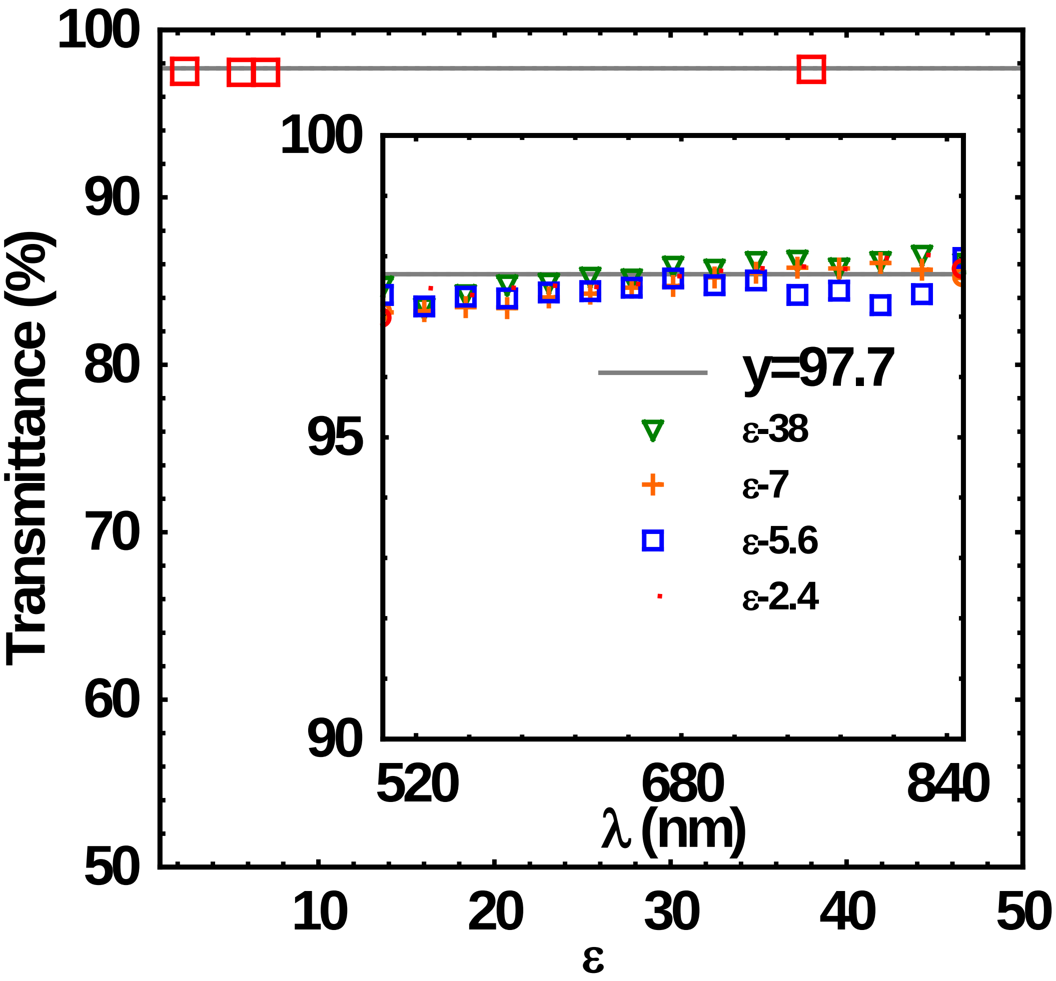

ε (%)
0.5
0.2
0.1
0.05
0.02
1
10
100
k
(a)
Drain current (x10^{-4} Amp)
8
6
4
2
-40
-30
-20
-10
0
Gate bias
17.7<k<64
Drain current (x10^{-4} Amp)
4
3
2
1
0
-20
-10
0
10
20
Gate bias (V)
2.5<k<7

DFT Results

Solvents Used	**Dielectric Constant**	**Adsorption Energy (eV)**	**Distance b/n Graphene & Molecule (A^0)**	**Charge Transfer (e)**	**Dirac Point (FET) (Volts)**	**Mobility (cm^2/Vs)**
THF	7.5	-0.078694	3.81	0.021	~10	7632
Chlorobenzene	5.6	0.064171	4.0	0.014	~1	11650
DMF	37.5	-1.49501	3.44	-0.025	~25-27	5598
PC(propylene carbonate)	64	-2.48779	3.47	-0.035	~25-30	5530


4.0
3.5
3.0
2.5
2.0
I_{DS} (X 10^{-4} Amp)
3
2
1
0
I_{DS} (X 10^{-4} Amp)
-40
-20
0
20
V_{GS} (Volt)
n-region
p-region


100
98
96
94
92
90
T (%)
10^{11}
10^{12}
10^{13}
n (cm^{-2})


Transmittance (%)
100
90
80
70
60
50
10
20
30
40
50
ε
100
95
90
520
680
840
λ (nm)
y=97.7
ε-38
ε-7
ε-5.6
ε-2.4

Plan of this talk

- Introduction to graphene bandstructure and "chirality".
- Growth and characterization of graphene.
- Robustness of universality under interlayer coupling and many body interactions.
- **Doping of graphene** to modulate the e-e interaction on universality
- How to break this universality ?

How to break universality ?

By breaking chiral symmetry?

Phys. Rev. Lett **99, 226803, 2007**

Phys. Rev. Lett **102, 026802 (2009)**

Phys. Rev. Lett. **107**, **016602 (2011)**

Phys. Rev. Lett. **114**, **246801 (2015)**

Phys. Rev. Lett. **115**, **186602 (2015)**

How to break CHIRAL SYMMETRY in GRAPHENE ?

1. By electron-hole interaction (Exciton)

The attractive force that should be enough to create the electron – hole pairs that would break the chiral symmetry spontaneously. Excitonic condensate indicates opposite charges on sublattices

$$\left\langle \bar{\psi}^{a} \psi^{a} \right\rangle > 0$$

This would make quasiparticle massive and the phase insulating.

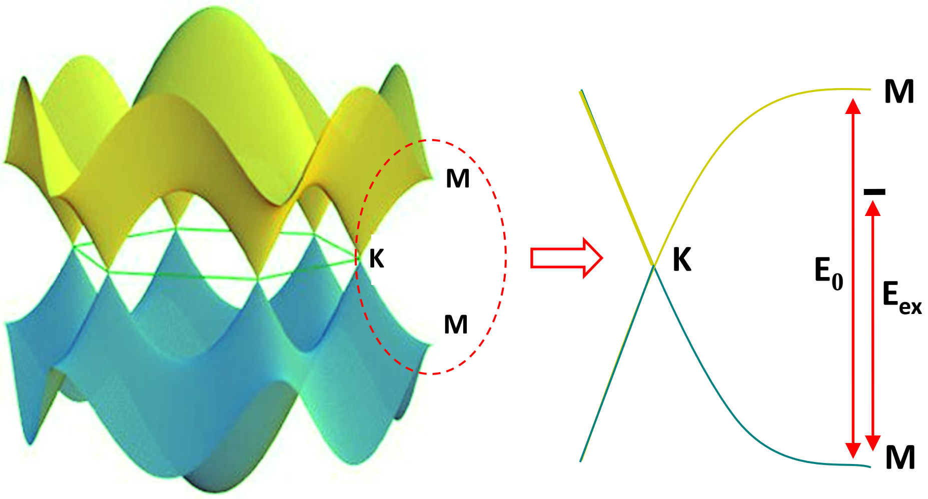
2. By antiferromagnetic ordering

Antiferromagnetic ordering of spins corresponds to opposite spin of electrons on different sublattices

$$\left\langle \bar{\psi}^{a} \sigma_{ab} \psi^{b} \right\rangle > 0$$

This also would make quasiparticle massive and should lead to metal-insulator transistion.

Exciton in Graphene



Electron-hole bound state ≡ Exciton

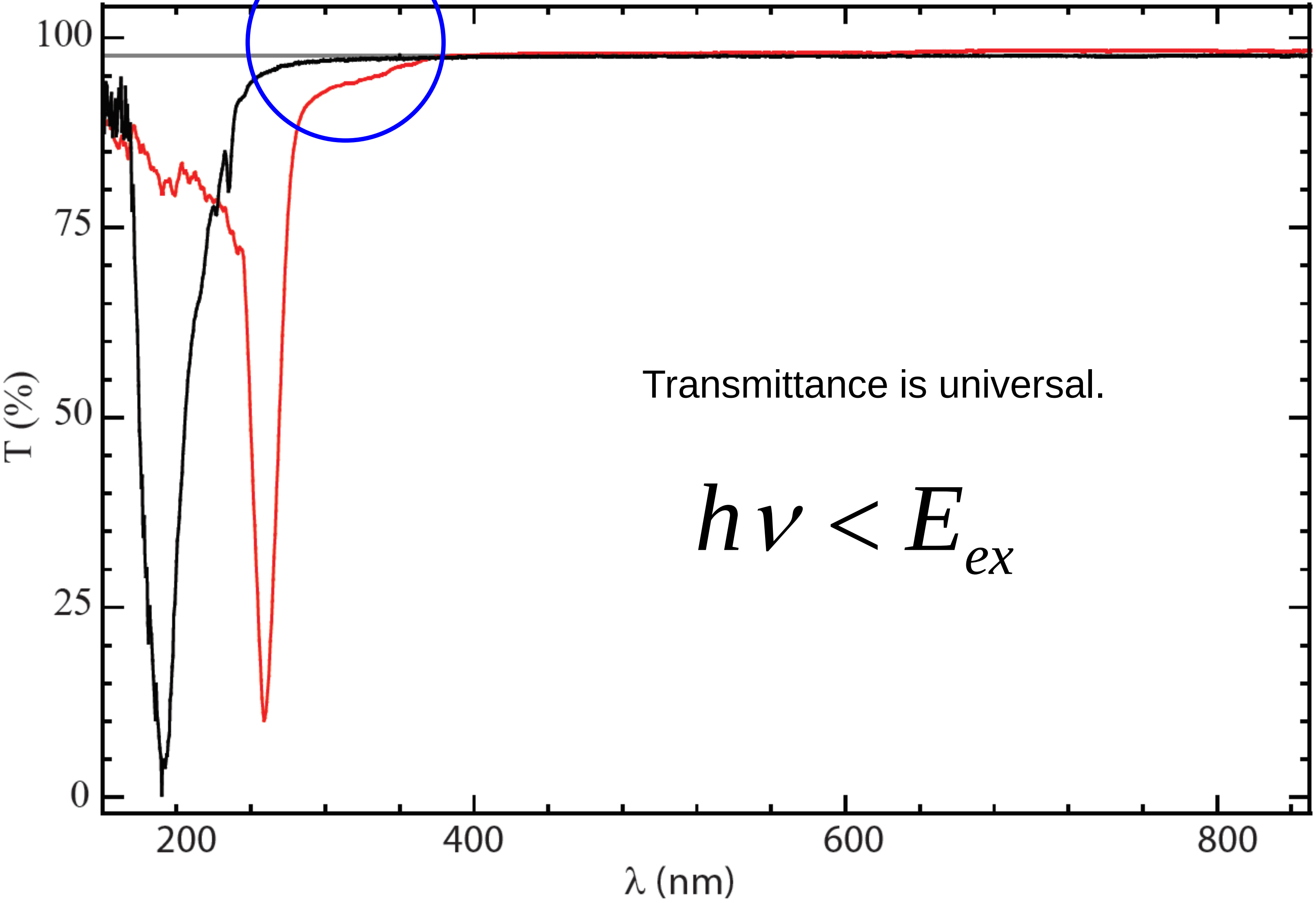
$$H \neq v\vec{\sigma}\cdot\vec{p}$$

Chirality is not conserved if electron-hole bound state exists

$$h\nu > E_{ex}$$

Universality is broken.

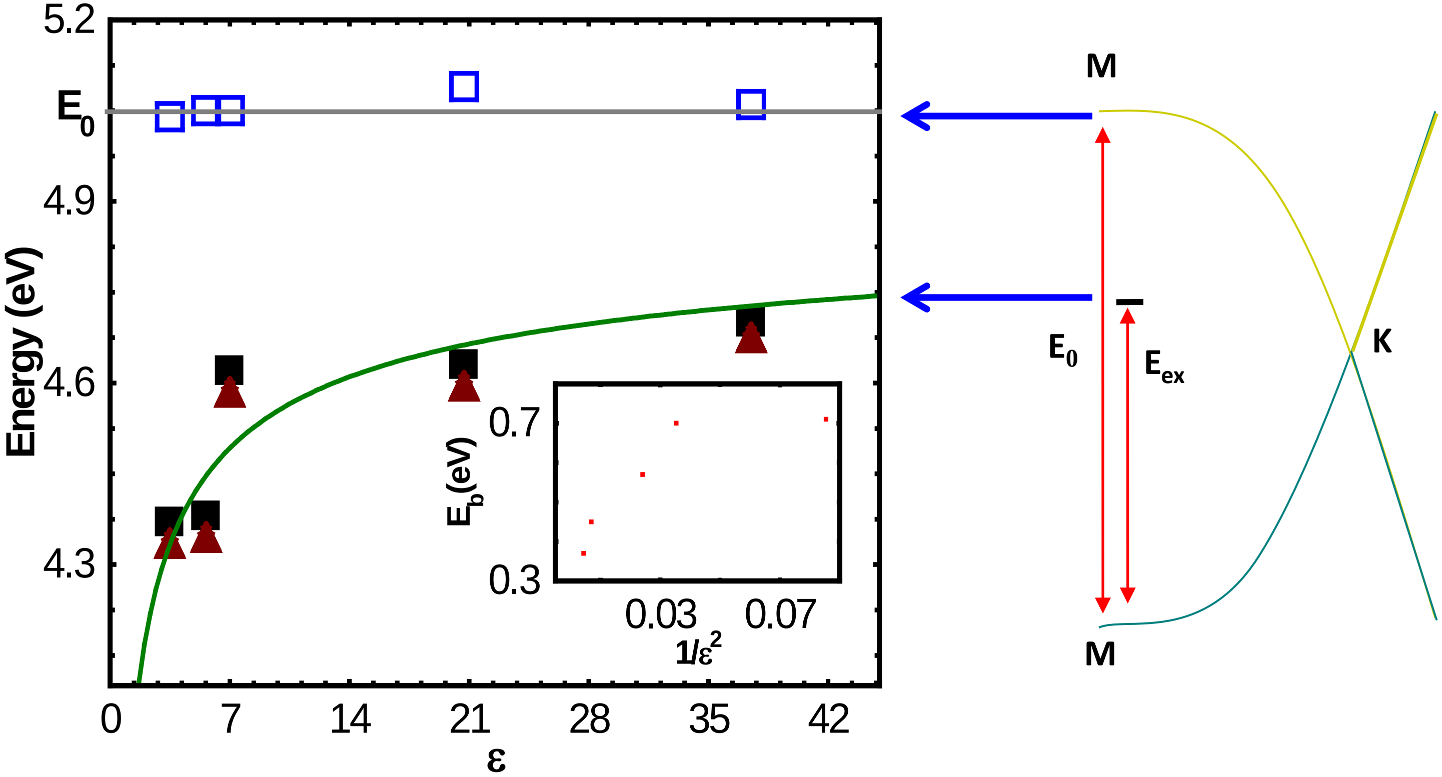
$$h\nu > E_{ex}$$



Transmittance is universal.

$$h\nu < E_{ex}$$

Strong Effect of e-e Interaction



Conclusions

✓Universality is not affected by long range interactions.

✓Chiral symmetry is responsible for optical transmittance universality.

✓Strong many body interaction when $h\nu > E_{ex}$

✓ Phase transition due to breaking of Chirality is not yet observed.

Thank You