BILAYER GRAPHENE FIELD EFFECT TRANSISTORS

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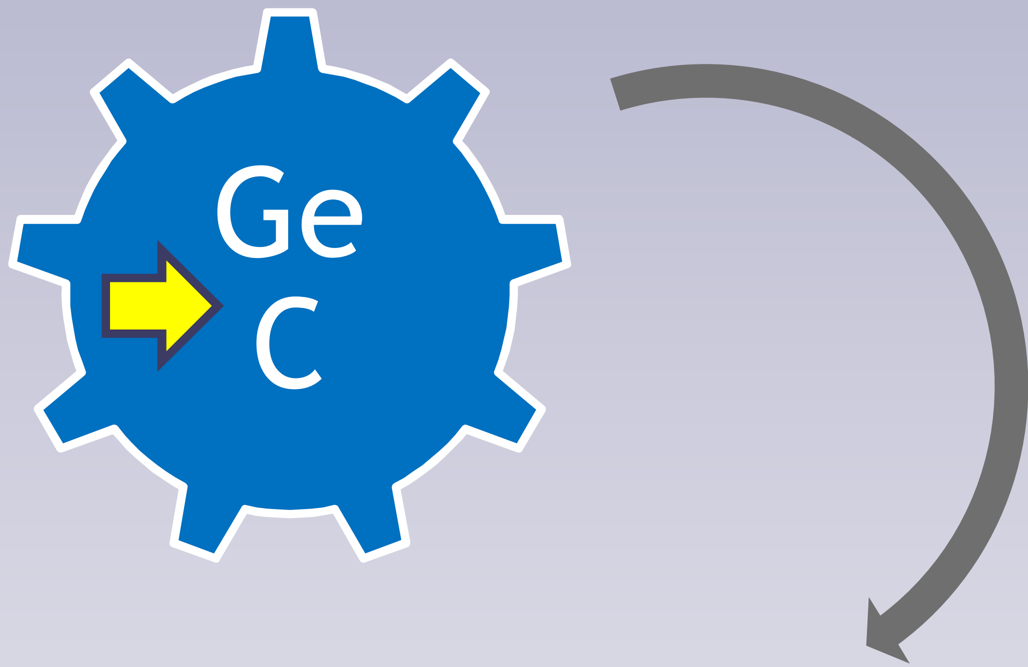
OUTLINE

Intro.
- Transistors (From Ge to C)
- Importance of Graphene

Model
- monolayer Graphene
- Bilayer Graphene

conclusion
- Bilayer: a good condidate for FET

INTORDUCTION



SI & GE TRANSISTORS

Small size

+

High mobility

→

2 important Properties that a transistors must have

Si & Ge

Properties	Si	Ge	GaAs
Atoms/cm^3	5.02 x 10^{22}	4.42 x 10^{22}	4.42 x 10^{22}
Effective mass electrons (m/m_0)	0.26	0.082	0.067
Effective mass holes (m/m_0)	0.69	0.28	0.57
Electron affinity (V)	4.05	4.0	4.07
Energy gap (eV)	1.12	0.67	1.42
Mobility electrons ($cm^2/V\ s$)	1500	3900	8500
Mobility holes ($cm^2/V\ s$)	450	1900	450

C

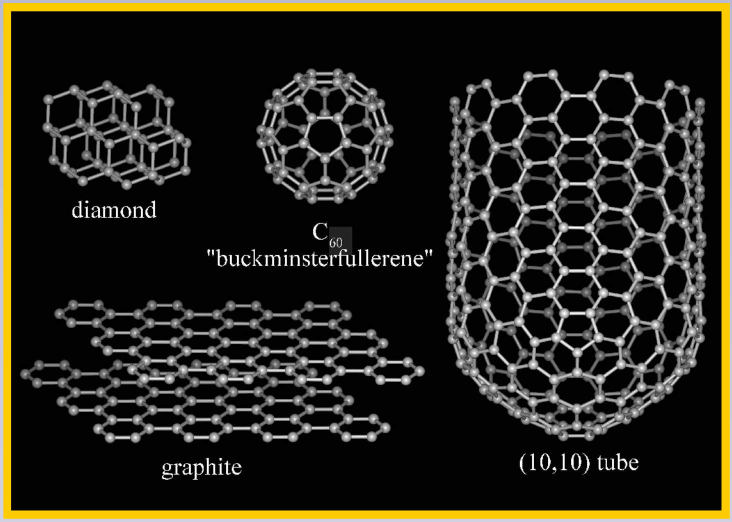
Si

Ge

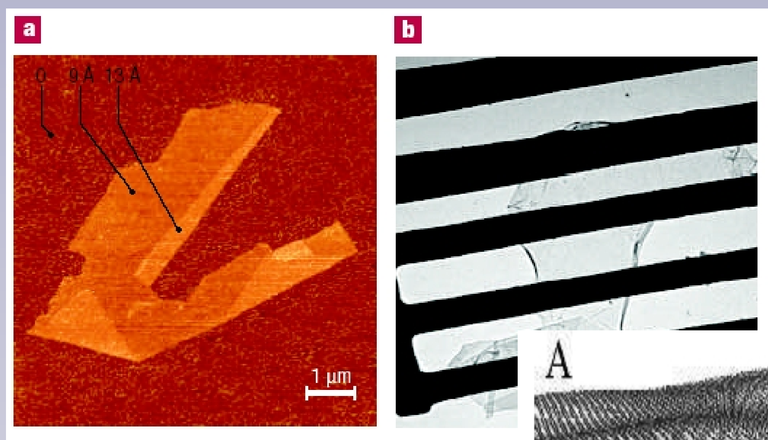
Sn

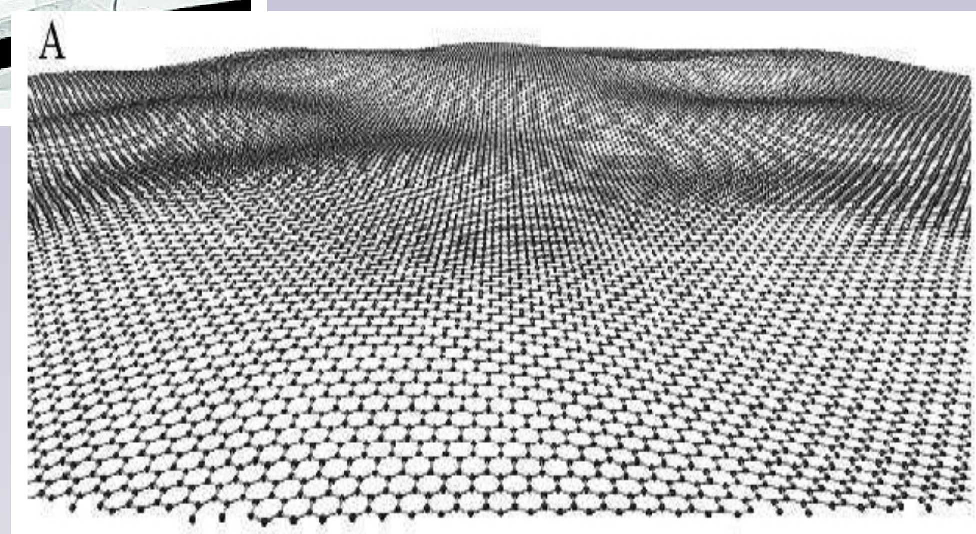
Pb

CARBON ALOTROPES



SINGLE LAYER OF CARBON ATOMS





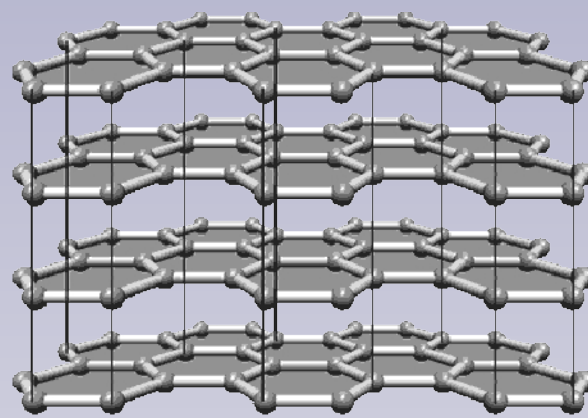
Wallace Phys. Rev. 104, 666

Geim et. al. Nat. Mat. 6, 183

GRAPHENE

- Carbon: smallest atom in group 4

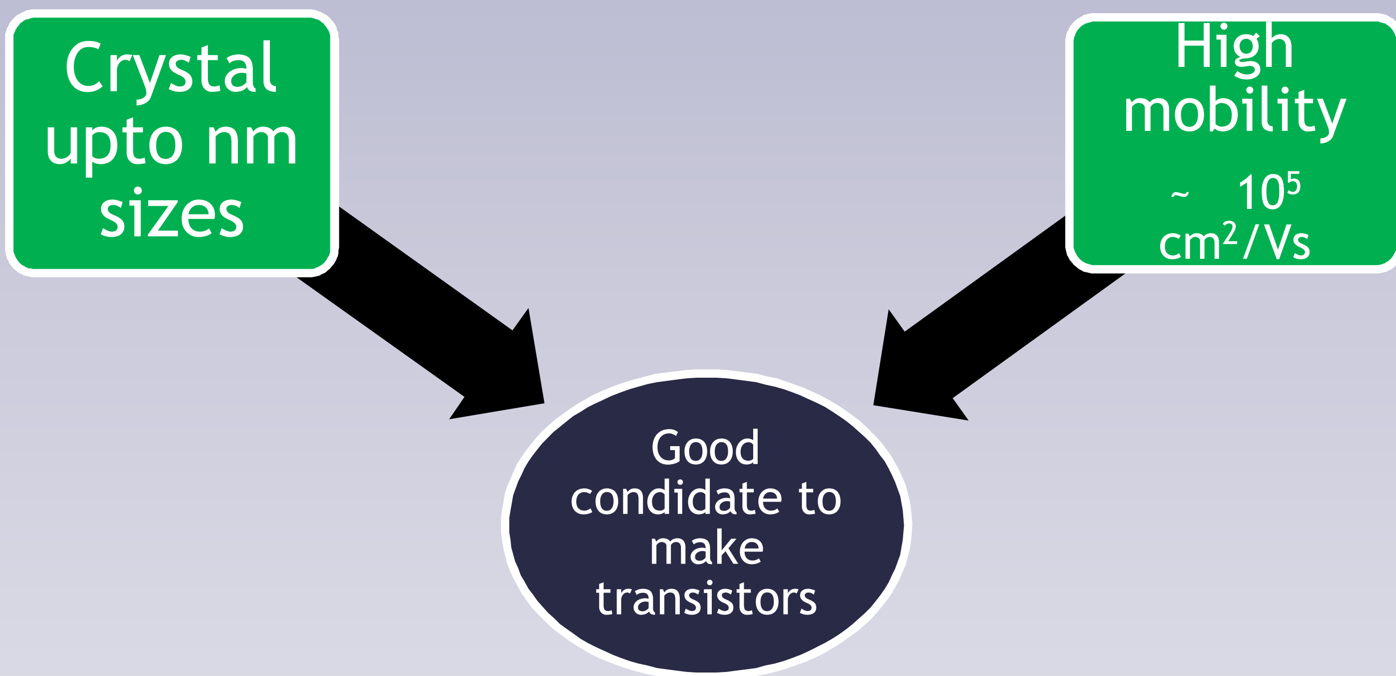
$$C:1S^2 2S^2 2P^2$$



sp2 orbitals which makes σ-bond

p_z Orbital which makes π-bond

GRAPHENE


Crystal upto nm sizes
High mobility
~ 10^5 cm^2/Vs
Good condidate to make transistors

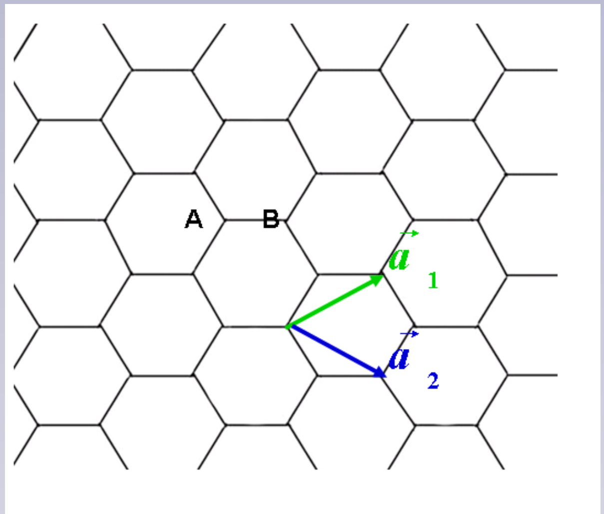
MODEL I

GRAPHENE: HONEYCOMB LATTICE

- Honeycomb lattice is not a Bravious Lattice

- Hoping of P_Z Orbitals

$$H = \sum_{<ij>} t_{ij} C^{\dagger}{}_i C_j + H.C.$$



GRAPHENE: TB MODEL

- Taking Fourier Transform:

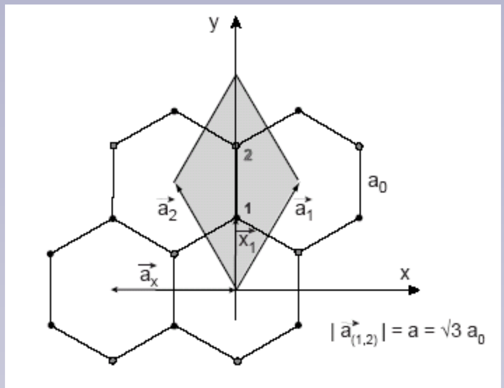
$$c_\alpha(k) = \sum_i c_{\alpha,i} e^{ik.r_i}$$

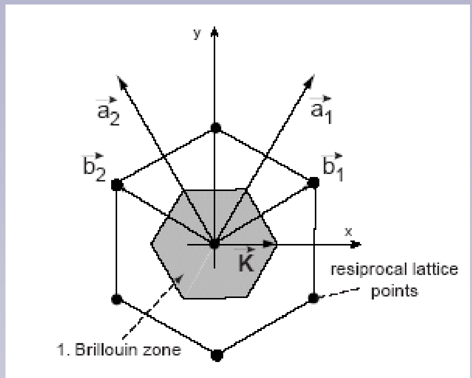
$$H\begin{pmatrix}\psi_A \\ \psi_B\end{pmatrix} = \begin{pmatrix} E_p & f(\vec{k}) \\ f^*(\vec{k}), & E_p \end{pmatrix}\begin{pmatrix}\psi_A \\ \psi_B\end{pmatrix}$$

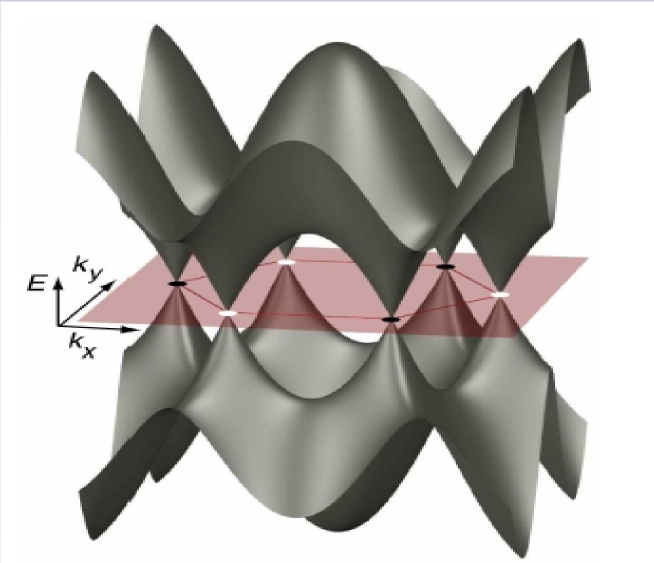
$$f(\vec{k}) = \gamma[1 + e^{i\vec{k}\cdot\vec{a}_1} + e^{i\vec{k}\cdot\vec{a}_2}]$$

$$E(k) = E_p \pm \sqrt{3 + 2\cos\vec{k}\cdot\vec{a}_1 + 2\cos\vec{k}\cdot\vec{a}_2 + 2\cos\vec{k}(\vec{a}_2 - \vec{a}_1)}$$

GRAPHENE: B.Z.







Two independent K-Point

GRAPHENE: LOW ENERGY LIMIT

$H =$

- Expanding the function f(k):

$$f(k) = v_F(k_x \pm ik_y)\begin{cases} K \\ K' \end{cases}$$

$$\Rightarrow \quad H = \sum_{\vec{k}} \hat{\sigma}.\vec{k}$$

- massless Dirac Fermions $E(k) = v_F k$

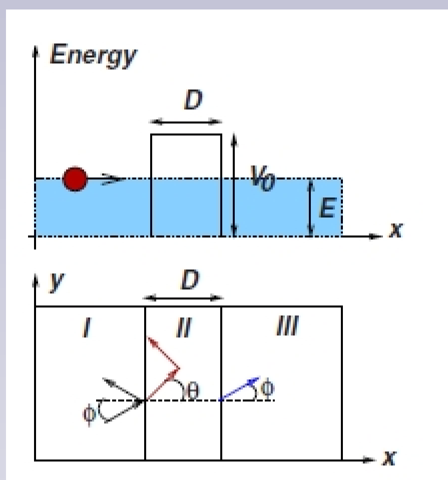
$$v_F \sim 10^6 m/s \sim c/300$$

- Where $\hat{\sigma}$ is the Pauli matrix for pseudospins

GRAPHENE: CHIRALITY

$$H = \sum_{\vec{k}} \hat{\sigma}.\vec{k}$$

- Absence of e-backscattering:



$$\psi_I(r) = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ se^{i\varphi}\end{pmatrix}e^{i(k_x x + k_y y)} + \frac{r}{\sqrt{2}}\begin{pmatrix}1\\ se^{i(\pi-\varphi)}\end{pmatrix}e^{i(-k_x x + k_y y)}$$

$$\psi_{II}(r) = \frac{a}{\sqrt{2}}\begin{pmatrix}1\\ s'e^{i\theta}\end{pmatrix}e^{i(q_x x + k_y y)} + \frac{b}{\sqrt{2}}\begin{pmatrix}1\\ s'e^{i(\pi-\theta)}\end{pmatrix}e^{i(-q_x x + k_y y)}$$

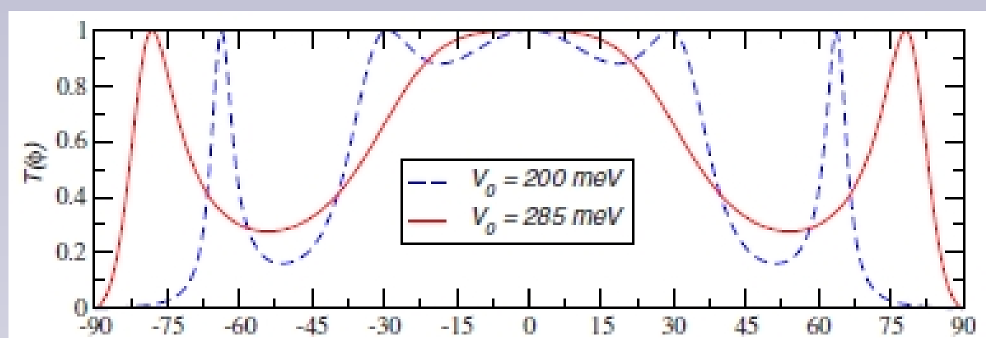
$$\psi_{III}(r) = \frac{t}{\sqrt{2}}\begin{pmatrix}1\\ se^{i\varphi}\end{pmatrix}e^{i(k_x x + k_y y)}$$

$$s = \mathrm{sgn}(E), s' = \mathrm{sgn}(E - V_0), \theta = \tan^{-1}(k_y / q_x)$$

Castro Neto et. Al. Rev. Mod. Phys. 81,109

GRAPHENE: KLEIN PARADOX

$$T(\phi) = \frac{\cos^2\theta \cos^2\phi}{[\cos(Dq_x)\cos\phi\cos\theta]^2 + \sin^2(Dq_x)(1 - ss'\sin\phi\sin\theta)^2}.$$



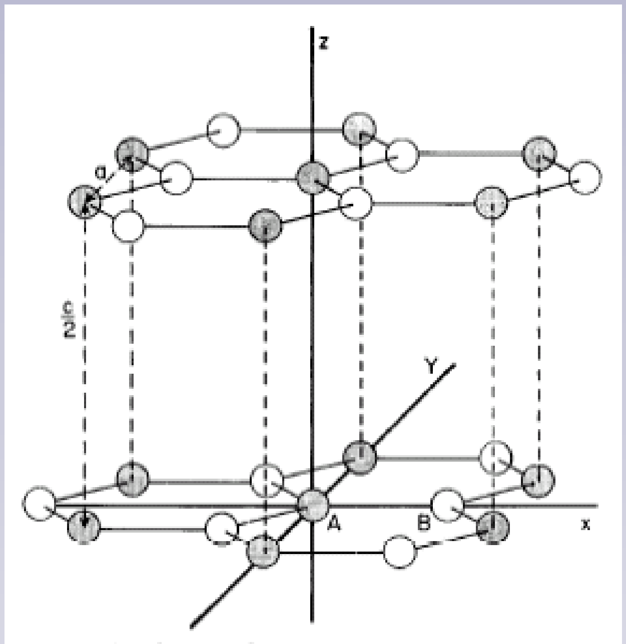
- Quasi particles can not be trapped

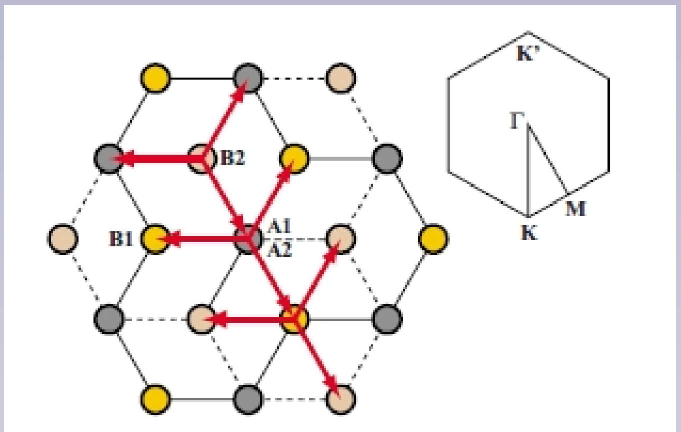
your PC will not turn off

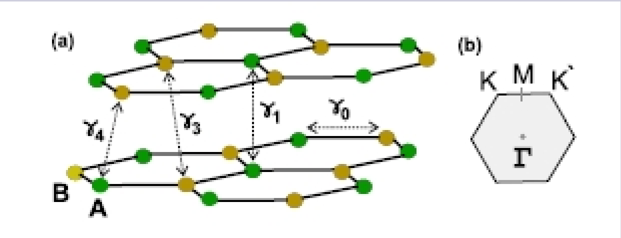
MODEL II

BLG: Bernal Stacking

- Most possible config.





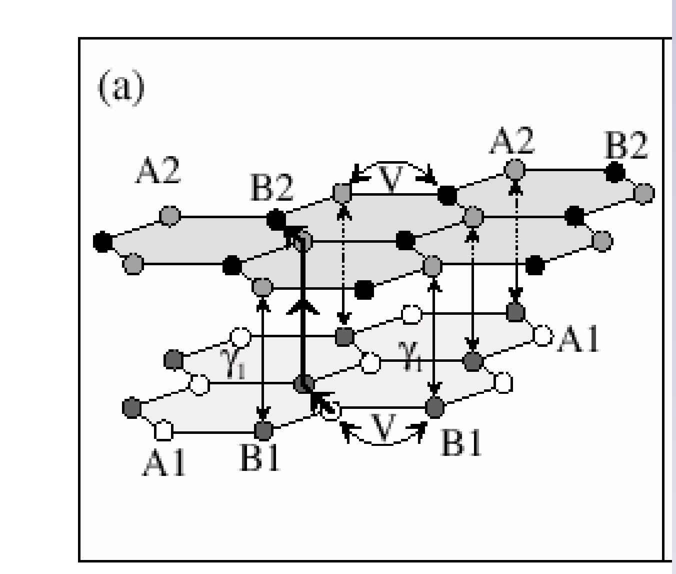


TIGHT BINDING MODEL

$$H = -t \sum_{<ij>m\sigma} (a^{\dagger}_{m,i,\sigma} b_{m,j,\sigma} + H.C.) - t_{\perp} \sum_{j\sigma} (a^{\dagger}_{1,j,\sigma} a_{2,j,\sigma} + H.C.)$$

$$-tv_4 \sum_{<ij>m\sigma} (a^{\dagger}_{1,i,\sigma} b_{2,j,\sigma} + H.C.) - tv_4 \sum_{<ij>m\sigma} (a^{\dagger}_{2,i,\sigma} b_{1,j,\sigma} + H.C.)$$

$$-tv_3 \sum_{<ij>m\sigma} (b^{\dagger}_{1,i,\sigma} b_{2,j,\sigma} + H.C.)$$



HOPING COEFFICIENT

	$t \equiv \gamma$	γ_1	γ_3	γ_4	Δ
Kuzmenko [147] (IR spec.)		0.378 (0.005)			0.015 (0.005)
Kuzmenko [164] (IR spec.)	3.16 (0.03)	0.381 (0.003)	0.38 (0.06)	0.14 (0.03)	0.022 (0.003)
Zhang [165] (IR spec.)	3.0	0.40	0.3	0.15	0.018
Malard [166] (Raman)	2.9	0.30	0.10	0.12	
Malard [167] (Raman)	3.0	0.35	0.13	0.13	
Min [168] (ab init.)	2.6	≈ 0.34	0.3		
Gava [169] (ab init.)	−3.4013	0.3963	0.3301	0.1671	

Table 1. Tight-binding parameters for bilayer graphene, given in eV. Methods of determination of the parameters include infra-red spectroscopy (IR spec.), Raman spectroscopy (Raman), and ab initio density functional theory calculations (ab init.). Note that Min et al. claim that γ_1 varies slightly with the interlayer potential U. Bracketed values are stated uncertainties.

T.Chakraborty et. Al. advance in phys. April 2010

BLG: MODEL

Fourier transform:

$$H = \sum_k \Psi^\dagger(k) \begin{pmatrix} \Delta & f(k) & t_\perp & v_4 f^*(k) \\ f^*(k) & \Delta & v_4 f^*(k) & v_3 f(k) \\ t_\perp & v_4 f(k) & -\Delta & f^*(k) \\ v_4 f(k) & v_3 f^*(k) & f(k) & -\Delta \end{pmatrix} \Psi(k)$$

$$\Psi^\dagger(k) = (a^\dagger{}_{1,k,\sigma}, b^\dagger{}_{1,k,\sigma}, a^\dagger{}_{2,k,\sigma}, b^\dagger{}_{2,k,\sigma})$$

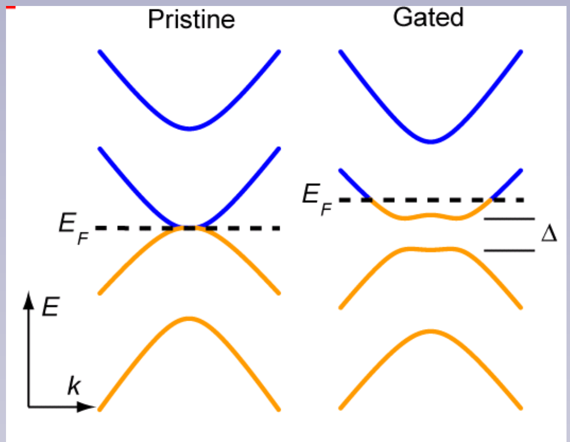
$$f(k) = t\sum_{i=1}^{3} e^{ik.d_i} \simeq v_F q \Phi(q)$$

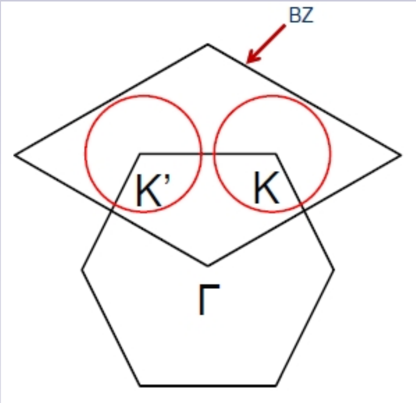
BLG: MODEL

- Dispersion Relation:

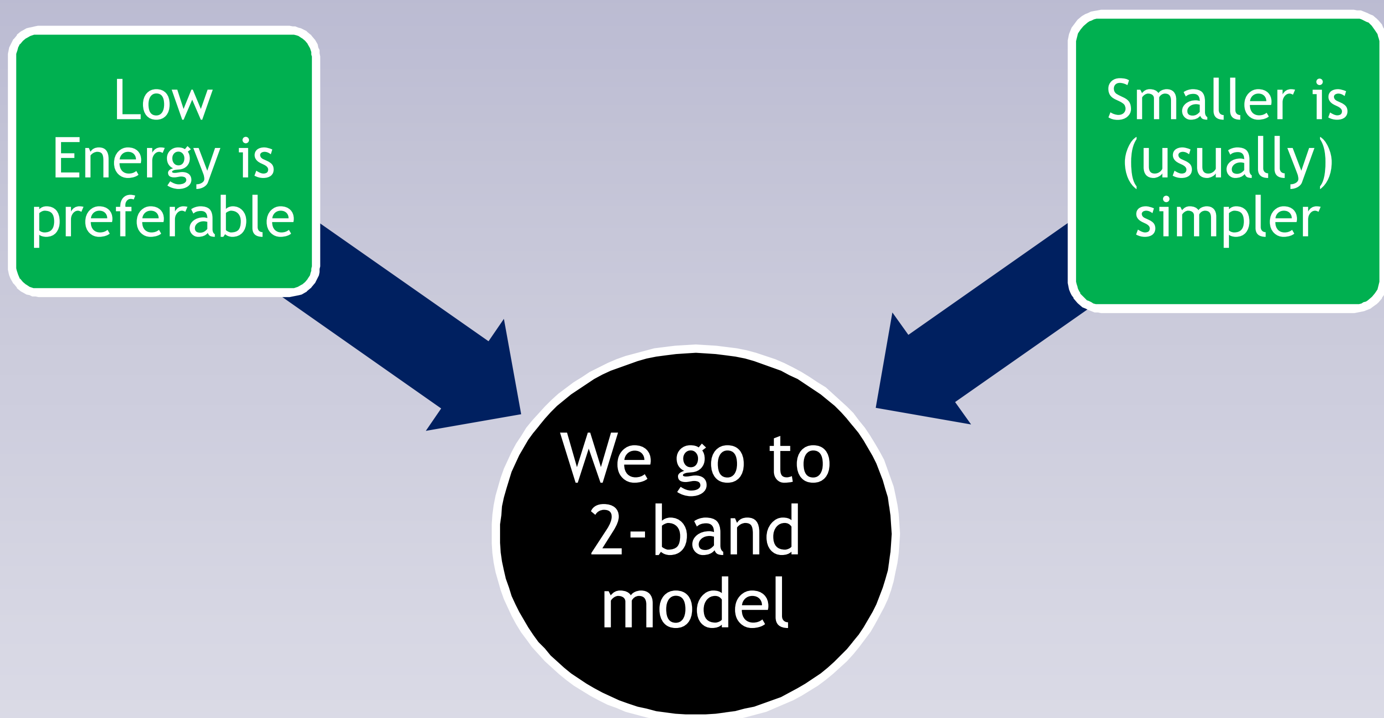
$$\varepsilon^2 = v^2 p^2 + \frac{t_\perp^{\ 2}}{2} + \frac{V^2}{4} - \sqrt{v^2 p^2 (V^2 + t_\perp^{\ 2}) + t_\perp^{\ 4}/4}$$

- Independent of $\Phi(k)$





BLG LOW ENERGY MODEL



2-BAND LOW ENERGY MODEL

In low energy limit ($\varepsilon << t_\perp$):

$$H = K_0 + K_1 + K_2$$

$$K_0 = \begin{pmatrix} V/2 & 0 & t_\perp & 0 \\ 0 & V/2 & 0 & 0 \\ t_\perp & 0 & -V/2 & 0 \\ 0 & 0 & 0 & -V/2 \end{pmatrix}$$

$$K_1 = \begin{pmatrix} 0 & pe^{i\phi} & 0 & v_4 pe^{-i\phi} \\ f^*(k) & 0 & v_4 pe^{-i\phi} & 0 \\ 0 & v_4 pe^{i\phi} & 0 & pe^{-i\phi} \\ v_4 pe^{i\phi} & 0 & pe^{i\phi} & 0 \end{pmatrix}$$

$$K_{2=} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & v_3 pe^{i\phi} \\ 0 & 0 & 0 & 0 \\ 0 & v_3 pe^{-i\phi} & 0 & 0 \end{pmatrix}$$

LOW ENERGY 2-BAND MODEL

using degenerate 2nd order perturbation:

$$\langle l | P_0 H P_0 | l' \rangle = \langle l | P_0 [K_0 + \lambda K_2] P_0 | l' \rangle + \lambda^2 \left\langle l \middle| P_0 K_1 P_1 \frac{1}{E - K_0} P_1 K_1 P_0 \middle| l' \right\rangle$$

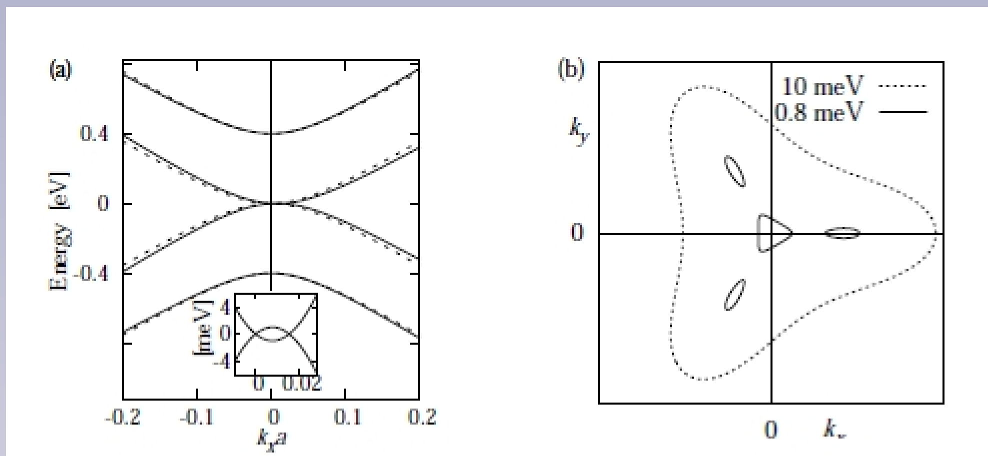
⇨

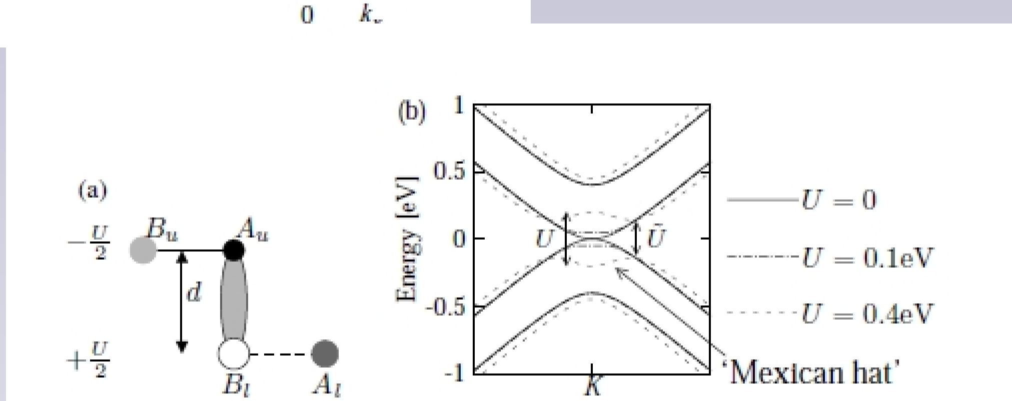
$$H_{low} = \frac{-1}{2m} \begin{pmatrix} 0 & (\pi^\dagger)^2 \\ (\pi)^2 & 0 \end{pmatrix} + v_3 \begin{pmatrix} 0 & \pi^\dagger \\ \pi & 0 \end{pmatrix} + \frac{V}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

McCann et. al. PRL 96, 086805

Nilsson et. al. PRB 78, 045405

BAND DISPERSION:TRIGONAL WARPING

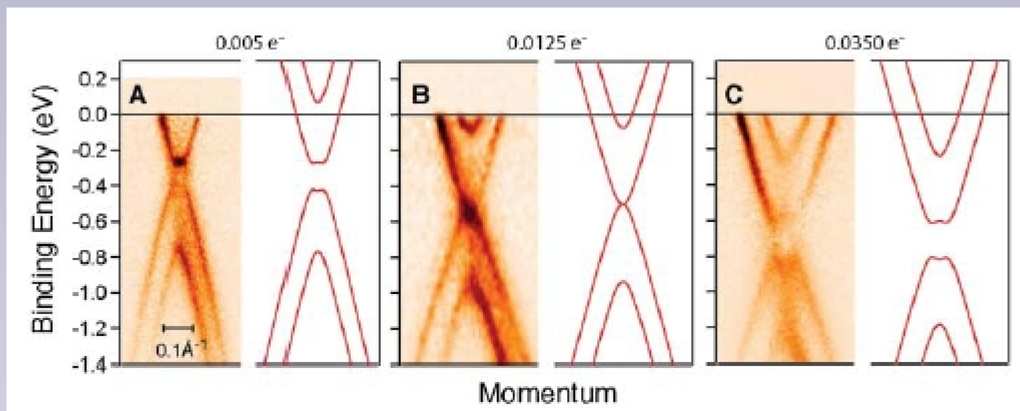




T.Chakraborty et. Al. advance in phys. April 2010

BLG: BAND GAP

Experimental evidence of the gap:



Ohta et. al. Science 313, 951

MAGNITUDE OF THE GAP

- Low energy band with the gap:

$$\varepsilon^2 = v^2 p^2 + \frac{t_\perp{}^2}{2} + \frac{V^2}{4} - \sqrt{v^2 p^2 (V^2 + t_\perp{}^2) + t_\perp{}^4 / 4}$$

$$\tilde{U} = \frac{t_\perp V}{\sqrt{V^2 + t_\perp{}^2}}$$

at momentum:

$$p^2 = \frac{V^2}{4v^2} \frac{V^2 + 2t_\perp{}^2}{V^2 + t_\perp{}^2}$$

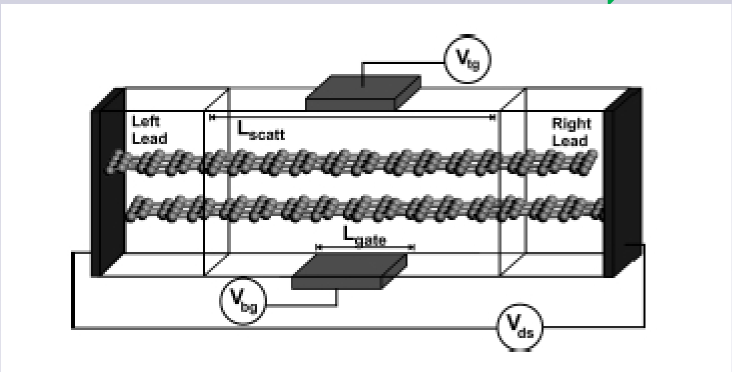
$$V \sim .2eV$$

BIASED BLG

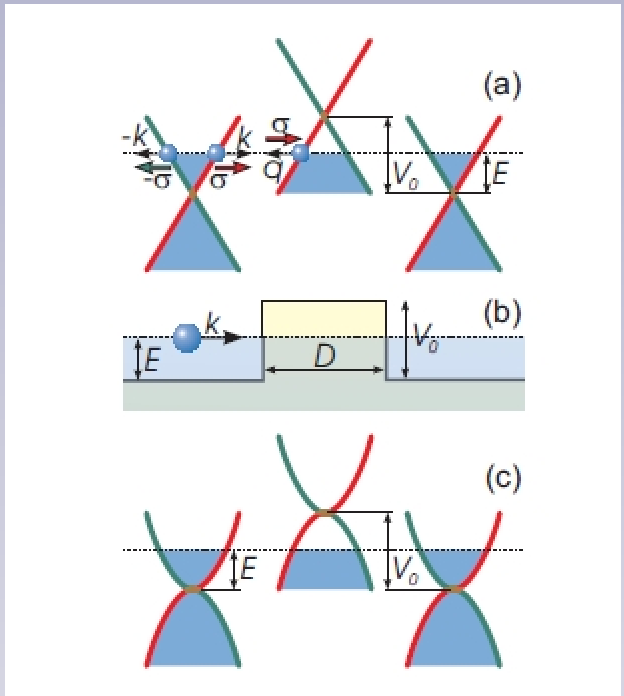
Gate Voltage Change the Fermi energy.

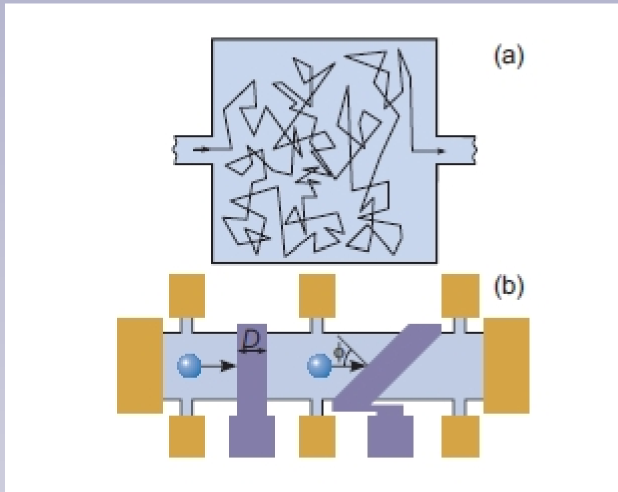
Using Dual gated BLG:

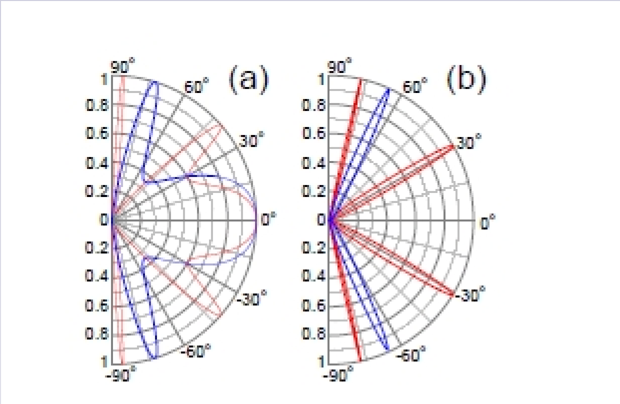
2 tuning parameter



KLEIN TUNELLING IN BLG







CONCLUSION

BILAYER APPLICATIONS

- Digital Electronics
- Pseudospintronics
- Terahertz Technology
- Infrared nanophotonics

GAPLESS MONOLAYER

SLG is Gapless

On/off ratio ~ 5

We need Gap

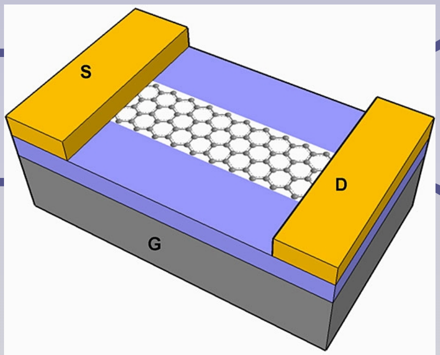
SUGGESTION TO PRODUCE GAP

- Uniaxial Strain
- Substrate Interaction
- Lateral Confinement
- Biased BLG

GRAPHENE NANORIBBON

Advantages

- Gap~Hundereds of meV
- High On/Off ratio



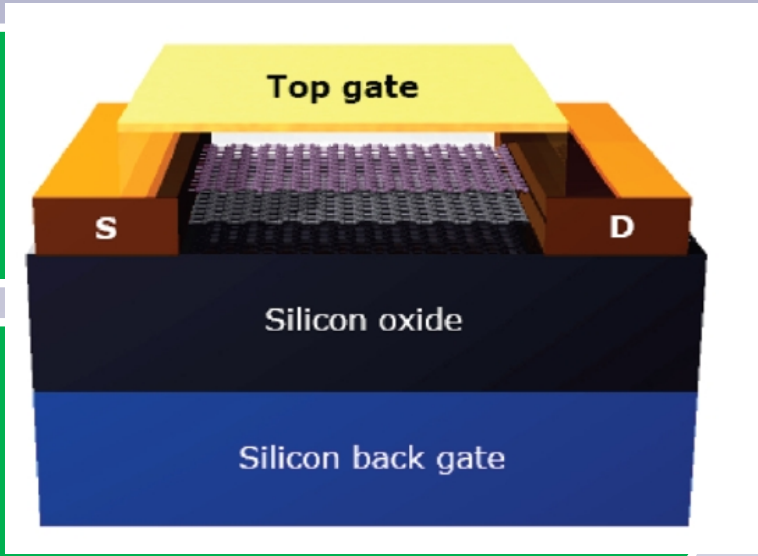
Disadvantages

- Low mobility
- Undesirable shape

BLG FET

Gap upto .3eV

On/off ratio: (100-2000)



Nano lett. 2010,10,715


Thanks for your attention