Pseudospintronics: a new electronic device scheme in graphene systems
– 연필심 위의 물리학

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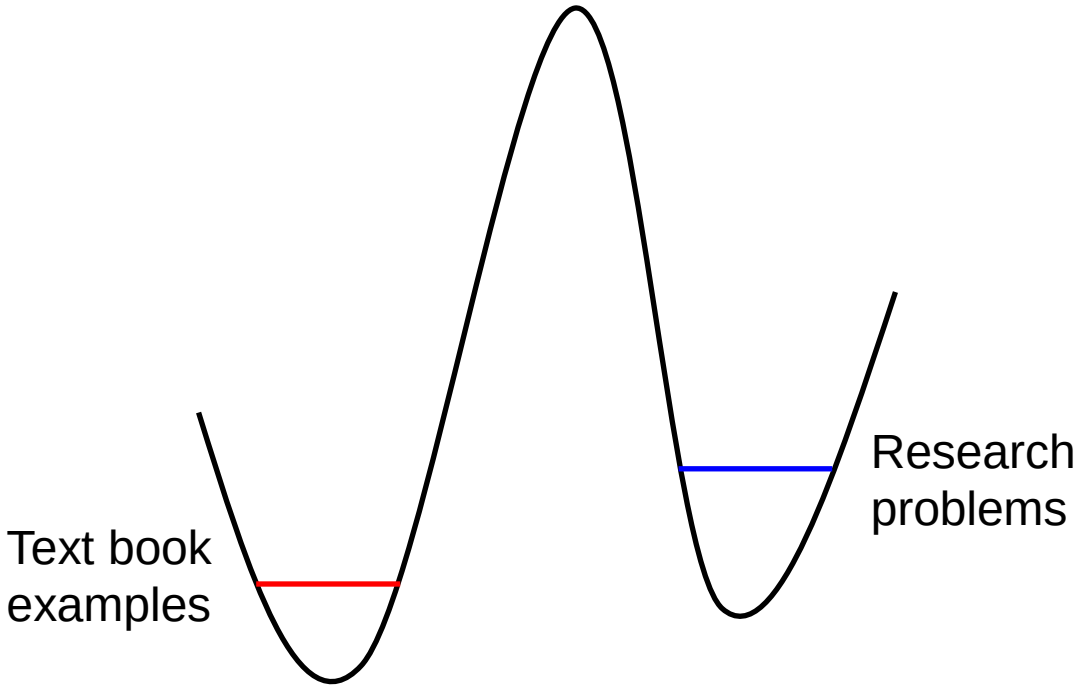
Seoul National University, May 16, 2012

DEPARTMENT OF
PHYSICS & ASTRONOMY

Motivation

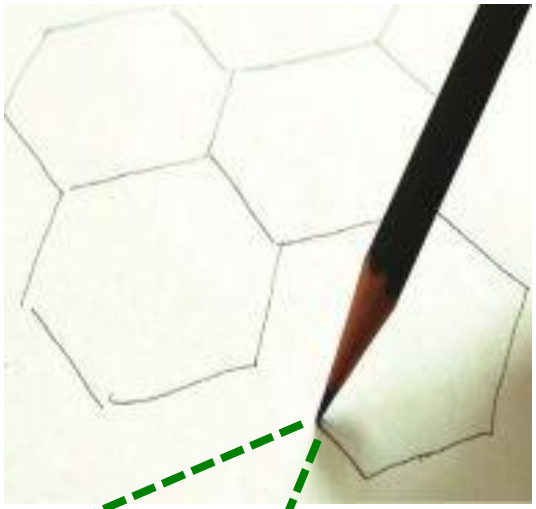
Text book examples *vs* research problems



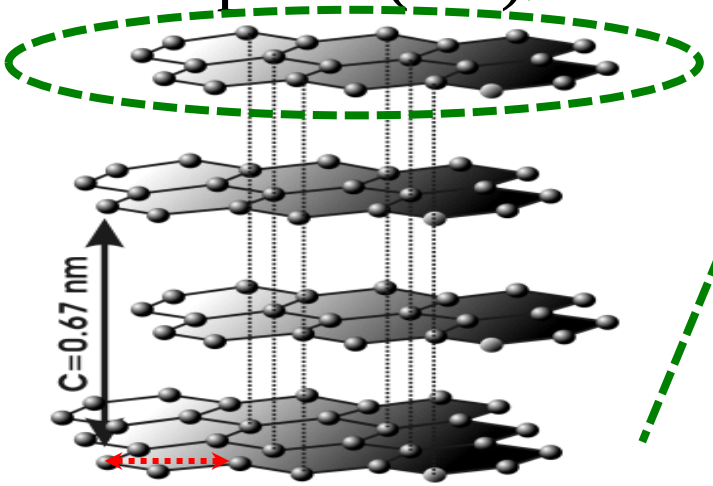
- How can we overcome the barrier efficiently between the text book and real research problems?

What is graphene?

Graphene is 2D honeycomb lattice of carbon atoms

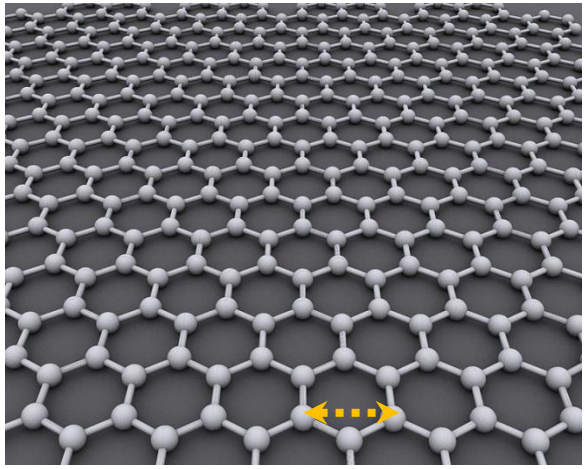


Graphite (3D)



$a = 0.246$ nm

Graphene (2D)

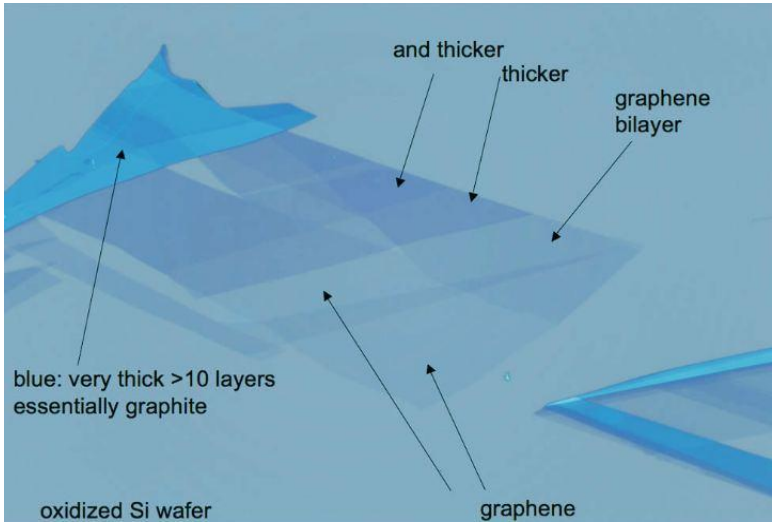


$a = 0.246$ nm

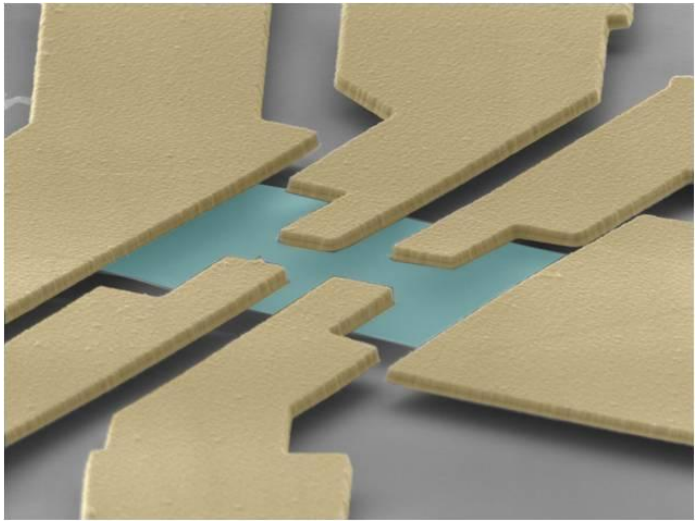
Adapted from *Wikipedia*

How to make graphene?

Scotch tape method



Adapted from *Scientific American*

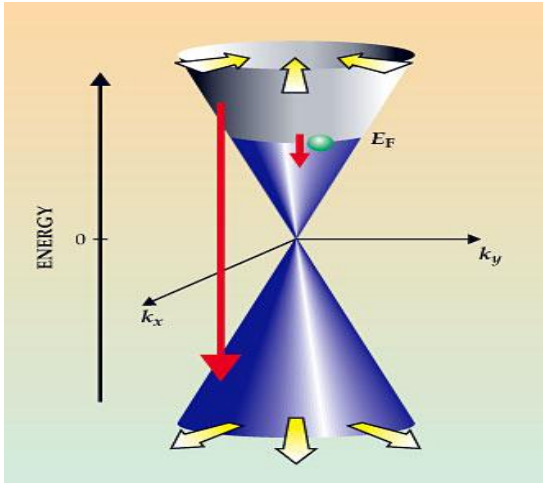


Adapted from *NIST*

Other methods: epitaxial growth, chemical vapor deposition, …

Why graphene?

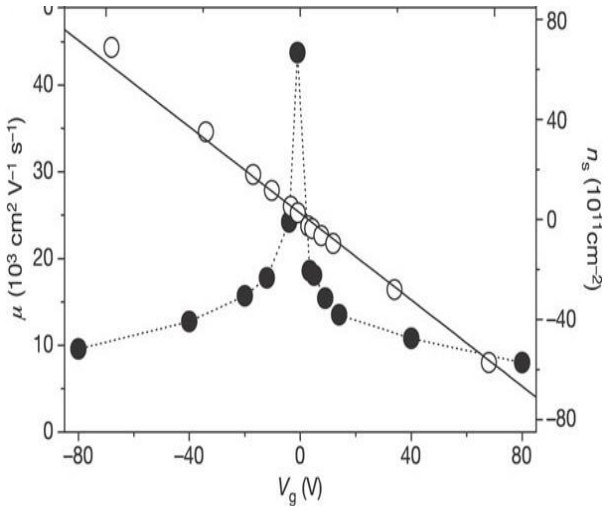
Graphene is described by relativistic wavefunction



Relativistic wavefunction
in a low energy system

P. R. Wallace,
Phys. Rev. **71**, 622 (1947)

Graphene has high electron mobility

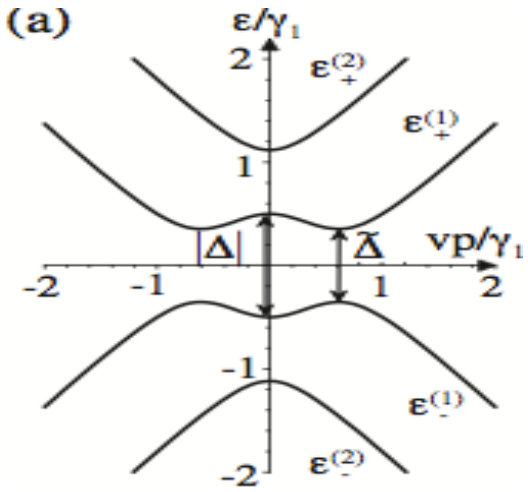


100 times faster than
conventional semiconductors
at room temperature

Y. Zhang *et al*,
Nature **438**, 201 (2005)

Why graphene?

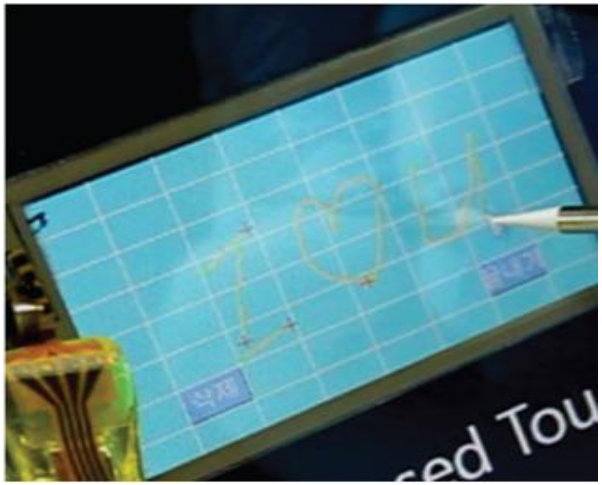
Bilayer graphene is a band gap tunable semiconductor



Band gap opening
by an external electric field

E. McCann,
Phys. Rev. B **74**, 161403 (2006)

Graphene can be used as touch screen and flexible display

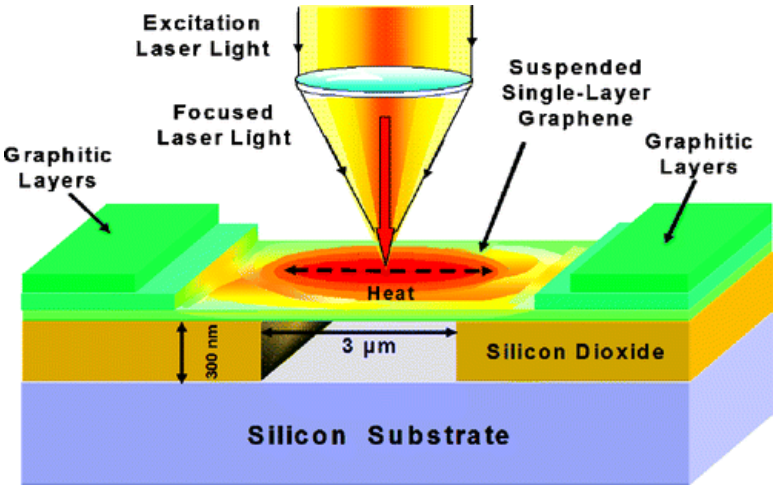


Atomically thin and conducting

S. Bae *et al*,
Nat. Nanotech. 5, 574 (2010)

Why graphene?

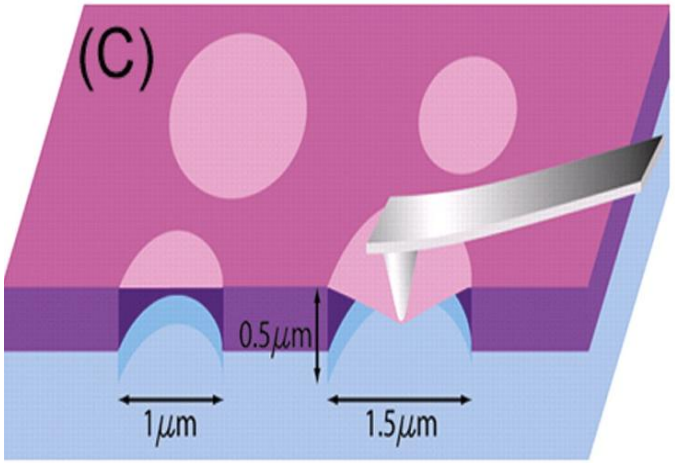
Graphene is an excellent thermal conductor



Heat spreader

A. Balandin et al,
Nano Lett. **8**, 902 (2008)

Graphene is 200 times stronger than steel



NEMS application

C. Lee *et al*,
Science 321, 385 (2008)

Outline

1. Electronic structure
   — Tight-binding model

2. Transport and optical properties
   — Boltzmann transport theory

3. Electron-electron interactions
   — Mean-field theory

4. Conclusion and future work
   — New electronic device scheme

Electronic structure
– Tight-binding model

- What is the model Hamiltonian for graphene?
- What is the effective theory near the Fermi energy?
- What is the effect of stacking sequence?

Hamiltonian

Time independent Schrödinger equation

$$H(\mathbf{k})\left|\Psi_n(\mathbf{k})\right\rangle = E_n(\mathbf{k})\left|\Psi_n(\mathbf{k})\right\rangle$$

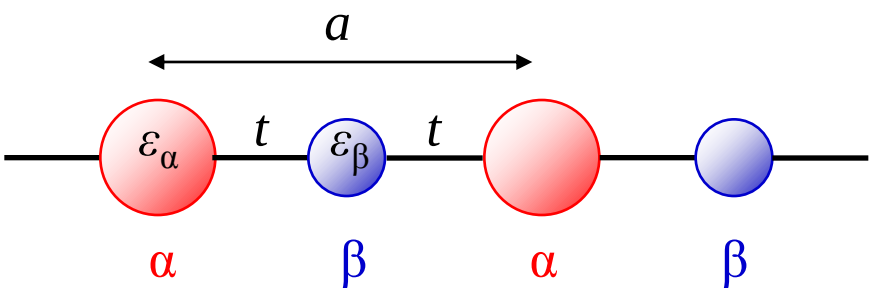
$\mathbf{k}$ = wave vector

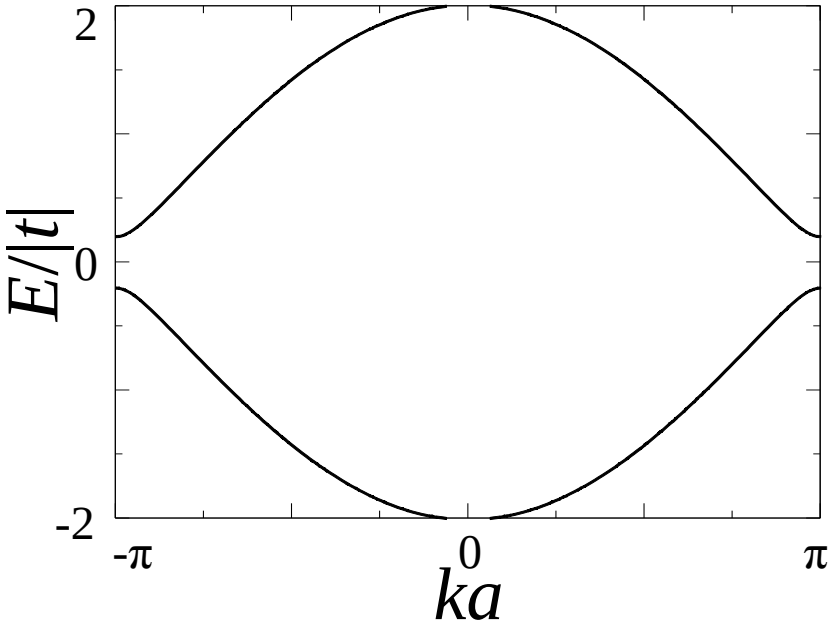
E_n = energy band

n = band index

Tight-binding model

Example: 1D chain composed of two kinds of atoms





$$H = \begin{bmatrix} \varepsilon_\alpha & f(\mathbf{k}) \\ f^*(\mathbf{k}) & \varepsilon_\beta \end{bmatrix} \quad \alpha \quad \beta$$

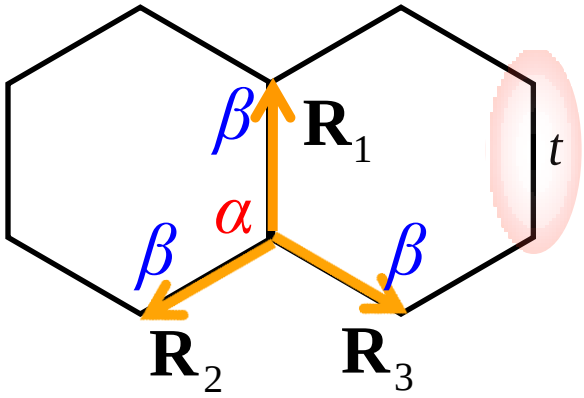
$$\varepsilon_\alpha = -\varepsilon_\beta = 0.2\,|t|$$

$$f(\mathbf{k}) = t\left[e^{ik(a/2)} + e^{-ik(a/2)}\right] = 2t\cos\left(\frac{ka}{2}\right)$$

Monolayer graphene

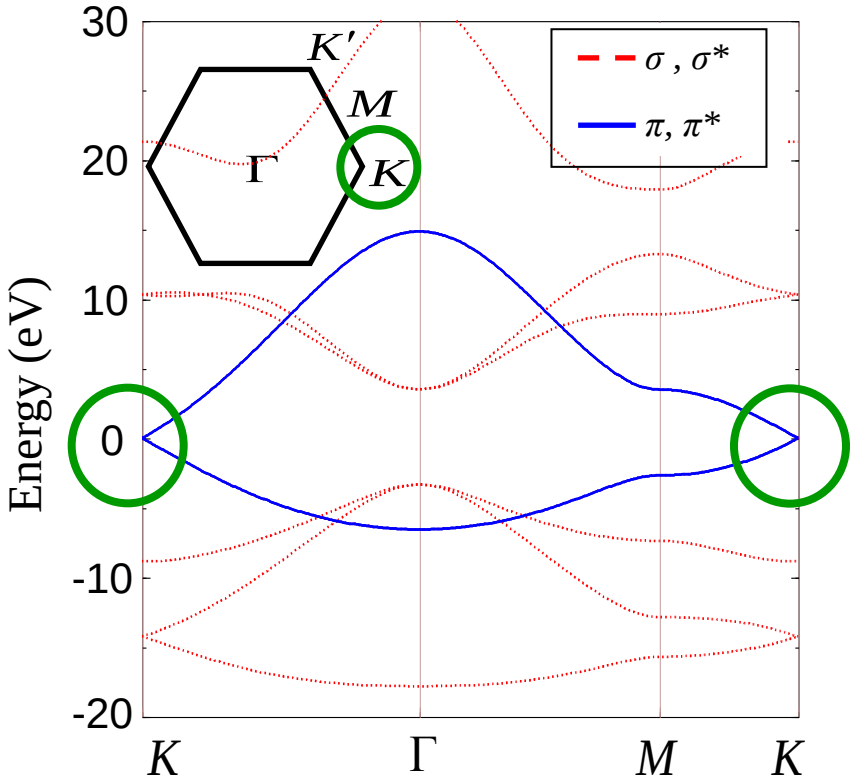
$^6C=1s^22s^22p^2$

Tight-binding model



σ,σ^*: sp^2 π,π^*: p_z

$$H=\begin{bmatrix} \alpha & \beta \\ 0 & f(\mathbf{k}) \\ f^*(\mathbf{k}) & 0 \end{bmatrix}$$



$$f(\mathbf{k})=t\left[e^{i\mathbf{k}\cdot\mathbf{R}_1}+e^{i\mathbf{k}\cdot\mathbf{R}_2}+e^{i\mathbf{k}\cdot\mathbf{R}_3}\right]\rightarrow\hbar v_0(k_x-ik_y)$$

Expand around K

Monolayer graphene

Monolayer graphene has a linear dispersion at low energies

Effective theory around K

$$H = v_0 \begin{pmatrix} 0 & \pi^* \\ \pi & 0 \end{pmatrix} = v_0 \mathbf{p} \cdot \boldsymbol{\sigma}$$

(α β)

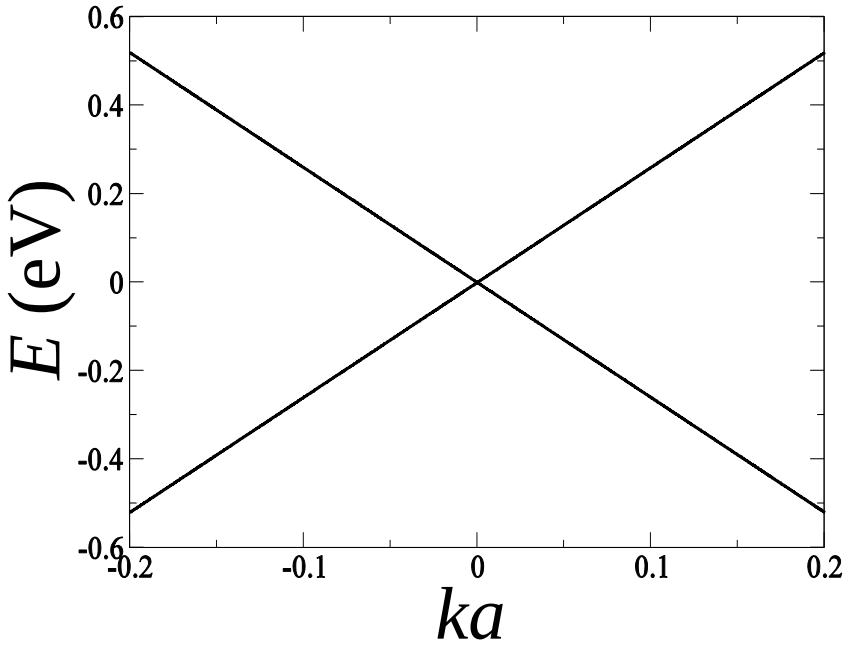
$$\pi = p_x + i p_y$$

$v_0 =$ in-plane velocity

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

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

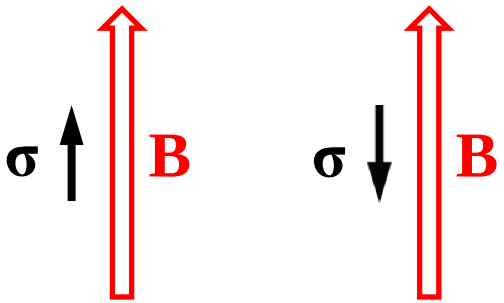
$$E(\mathbf{p}) = \pm v_0 p$$



Monolayer graphene

Pseudospin, chirality and Berry phase

$$H = \mathbf{B}\cdot\boldsymbol{\sigma}$$



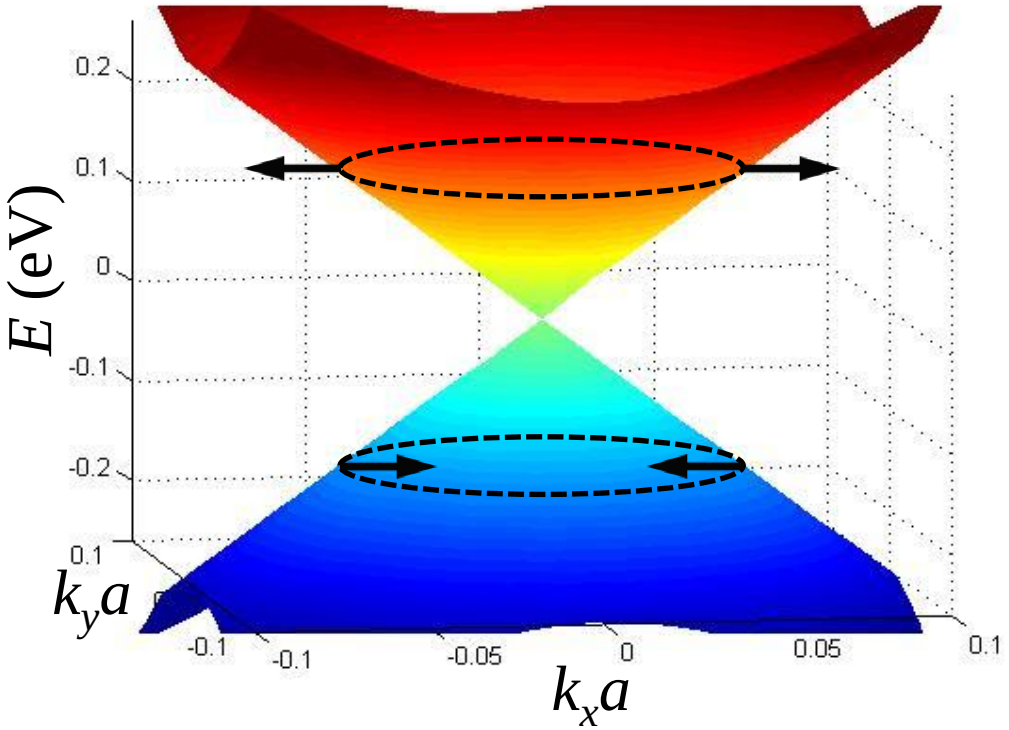
$$E = +|\mathbf{B}| \qquad E = -|\mathbf{B}|$$

$\alpha \quad \beta \leftarrow$ pseudospin

$$H = v_0 \begin{pmatrix} 0 & \pi^* \\ \pi & 0 \end{pmatrix} = v_0 \mathbf{p}\cdot\boldsymbol{\sigma}$$

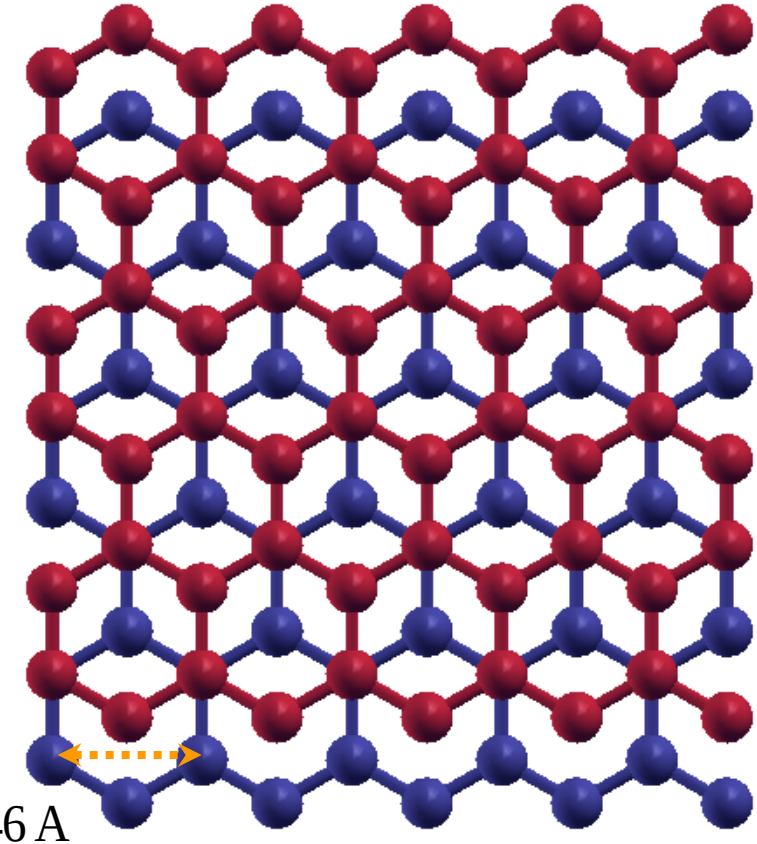
chirality

$$\mathbf{B} = v_0 \mathbf{p}$$

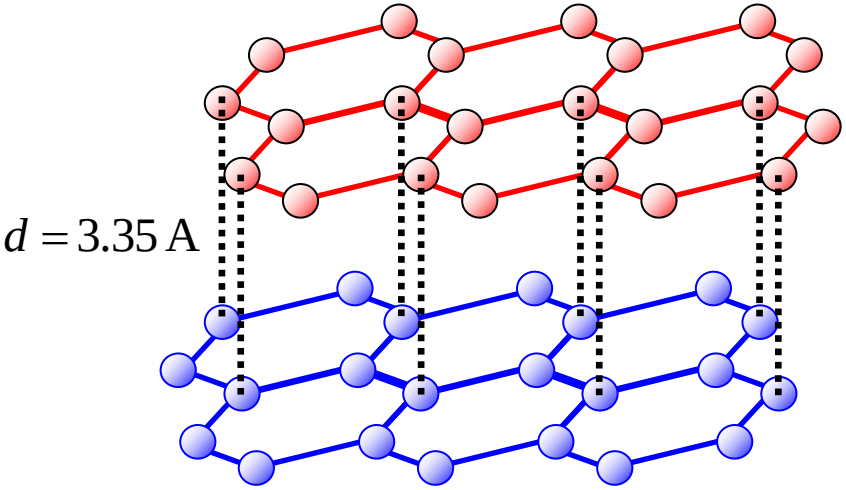


Bilayer graphene

Bilayer graphene is composed of a pair of coupled graphene



$a = 2.46\,\text{A}$



$d = 3.35\,\text{A}$

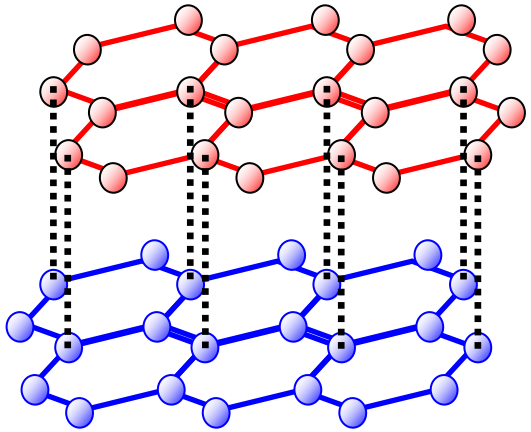
Electronic structure of bilayer graphene

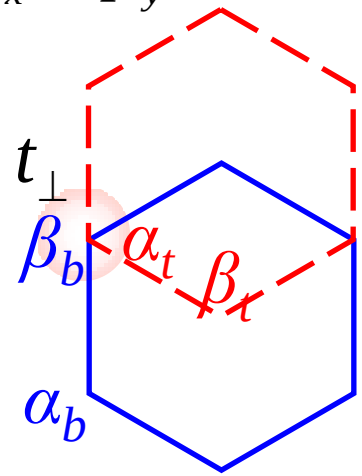
Bilayer graphene is composed of a pair of coupled graphene

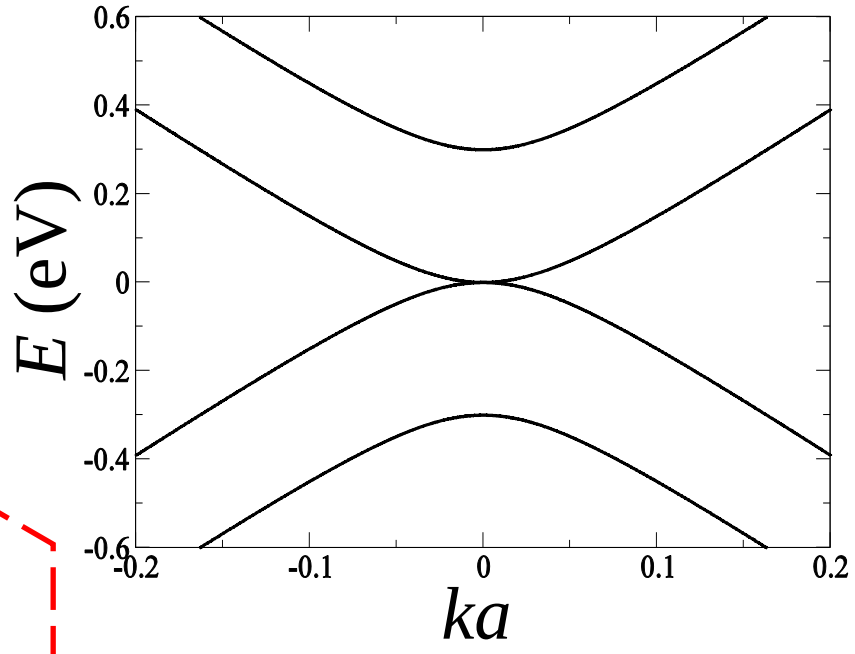
4-band model around K

$$H = \begin{array}{c} \begin{matrix} \alpha_b & \beta_b & \alpha_t & \beta_t \end{matrix} \\ \left(\begin{array}{cc:cc} 0 & v_0\pi^* & 0 & 0 \\ v_0\pi & 0 & t_\perp & 0 \\ \hdashline 0 & t_\perp & 0 & v_0\pi^* \\ 0 & 0 & v_0\pi & 0 \end{array} \right) \end{array}$$

$$\pi = p_x + ip_y$$







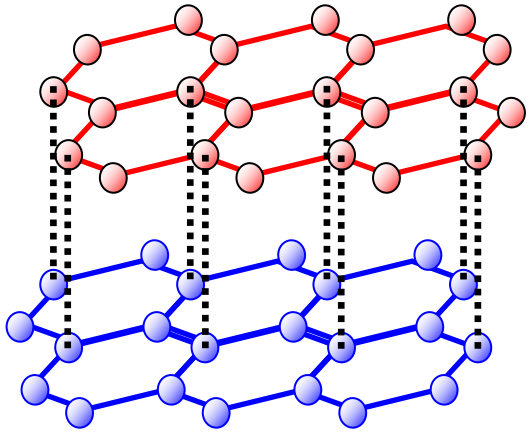
Band gap opening in bilayer graphene

Band structure control by an external electric field

4-band model around K

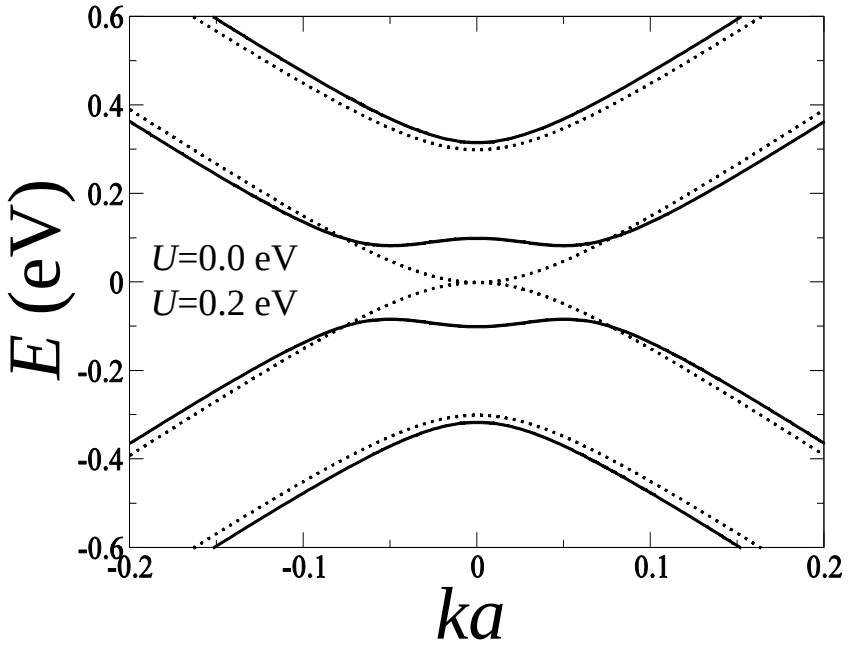
$$H = \begin{array}{c} \begin{array}{cccc} \alpha_b & \beta_b & \alpha_t & \beta_t \end{array} \\ \left(\begin{array}{cc:cc} -U/2 & v_0\pi^* & 0 & 0 \\ v_0\pi & -U/2 & t_\perp & 0 \\ \hdashline 0 & t_\perp & +U/2 & v_0\pi^* \\ 0 & 0 & v_0\pi & +U/2 \end{array} \right) \end{array}$$

$$\pi = p_x + ip_y$$



+U/2

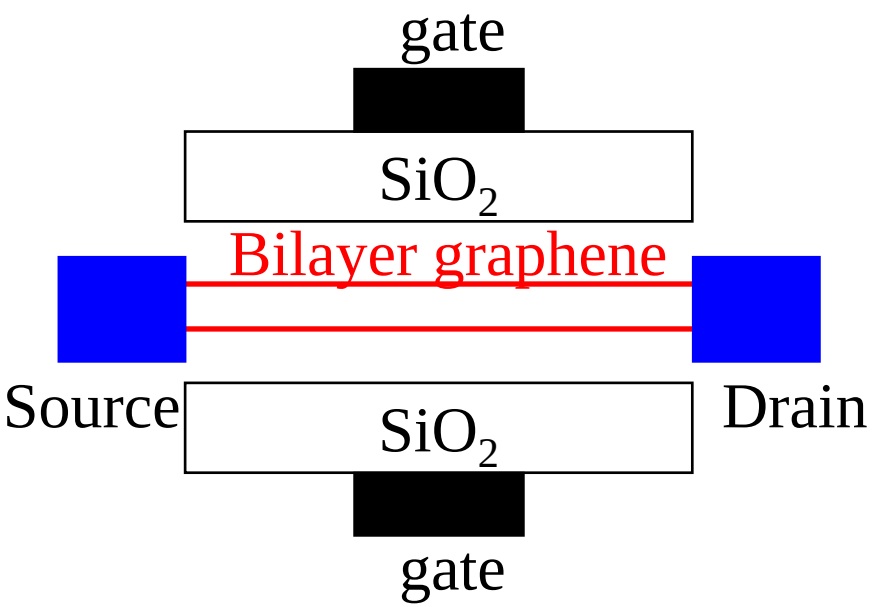
−U/2

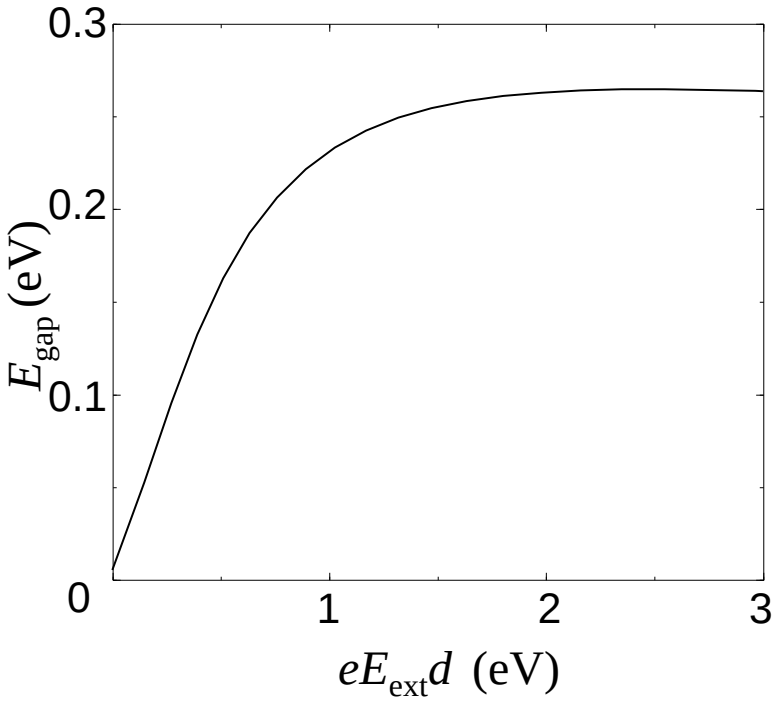


Band gap opening in bilayer graphene

Band structure control by an external electric field

$\Rightarrow$ Tunable energy gap semiconductor
Possible application to a switch device





Min, Sahu, Banerjee, and MacDonald, Phys. Rev. B **75**, 155115 (2007)

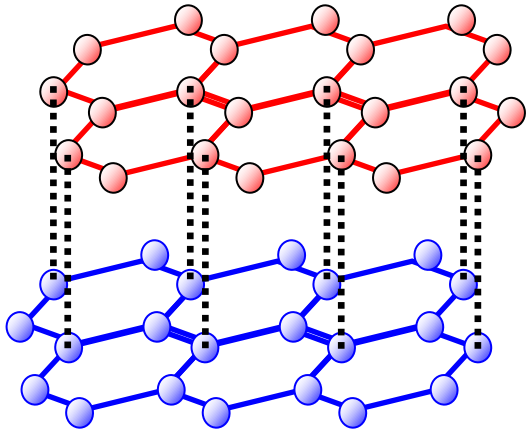
Effective theory of bilayer graphene

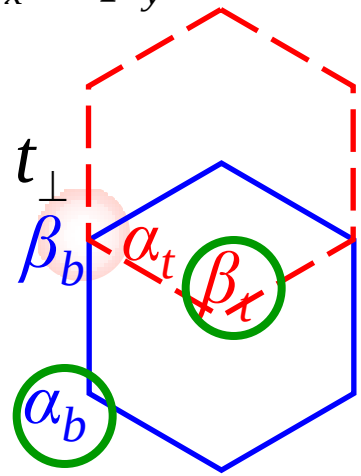
Bilayer graphene is composed of a pair of coupled graphene

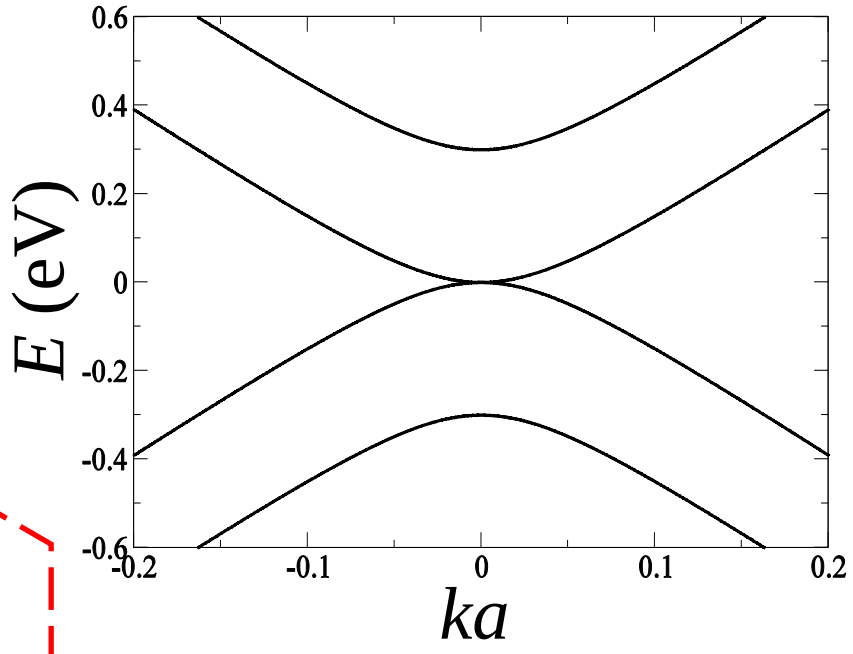
4-band model around K

$$H = \begin{array}{c} \begin{matrix} \alpha_b & \beta_b & \alpha_t & \beta_t \end{matrix} \\ \left(\begin{array}{cc:cc} 0 & v_0\pi^* & 0 & 0 \\ v_0\pi & 0 & t_\perp & 0 \\ \hdashline 0 & t_\perp & 0 & v_0\pi^* \\ 0 & 0 & v_0\pi & 0 \end{array} \right) \end{array}$$

$$\pi = p_x + ip_y$$







Effective theory of bilayer graphene

Bilayer graphene has a parabolic dispersion at low energies

Effective theory around K

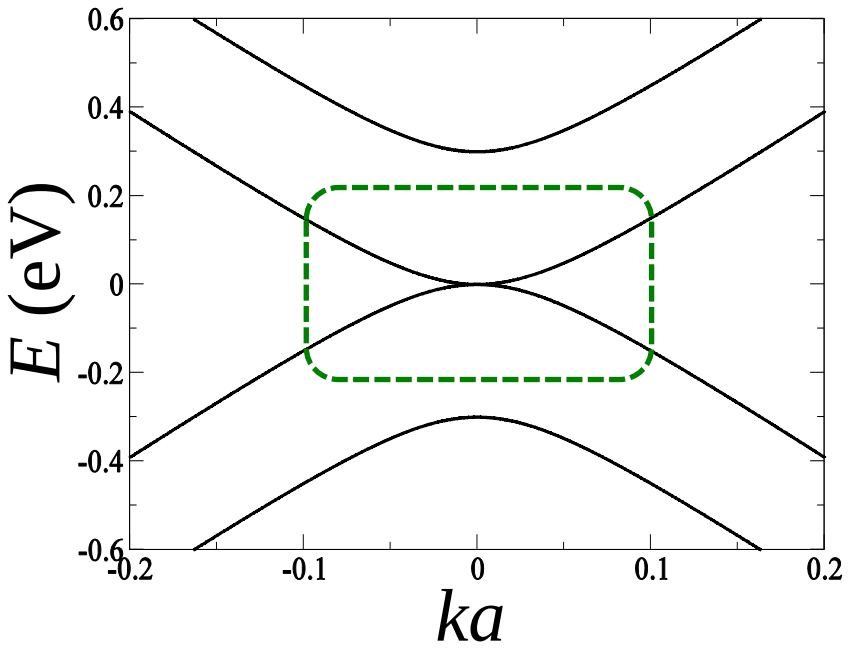
α_b β_t

$$H = -\frac{1}{2m}\begin{pmatrix} 0 & \pi^{*2} \\ \pi^2 & 0 \end{pmatrix} = -\frac{p^2}{2m}\mathbf{n}_2(\phi_\mathbf{p})\cdot\boldsymbol{\sigma}$$

$$\mathbf{n}_2(\phi_\mathbf{p}) = (\cos 2\phi_\mathbf{p}, \sin 2\phi_\mathbf{p})$$

$$\pi = p_x + ip_y$$
$$\phi_\mathbf{p} = \tan^{-1}(p_y / p_x)$$
$$m = t_\perp / 2v_0^2$$

$$E(\mathbf{p}) = \pm\frac{p^2}{2m}$$



Effective theory of bilayer graphene

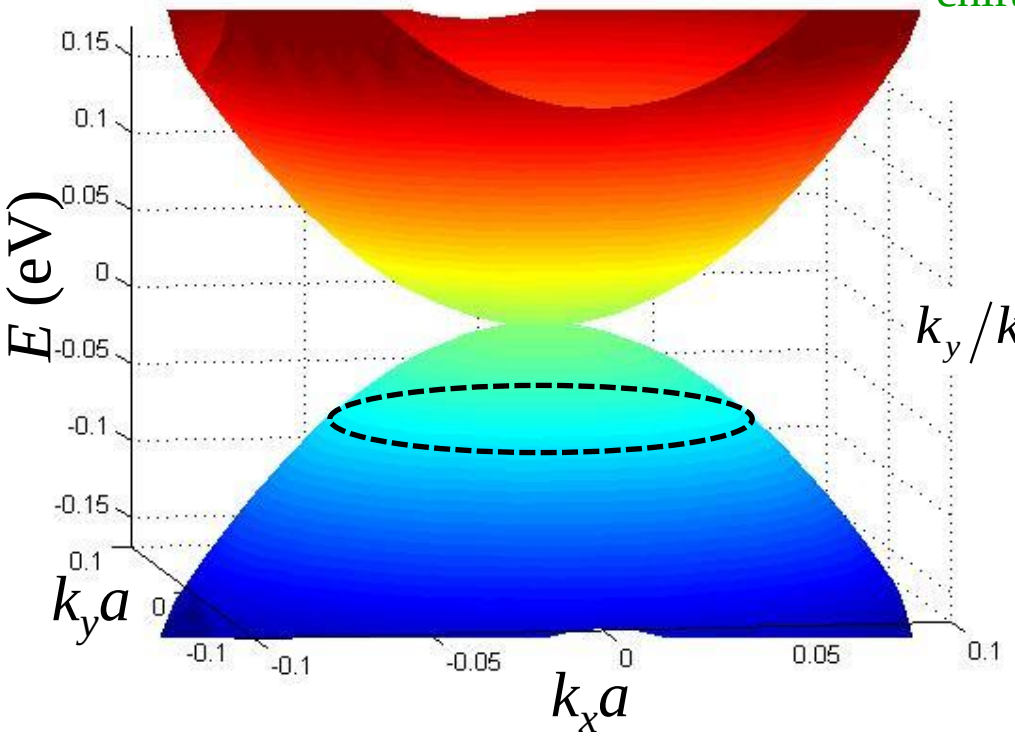
Pseudospin, chirality and Berry phase

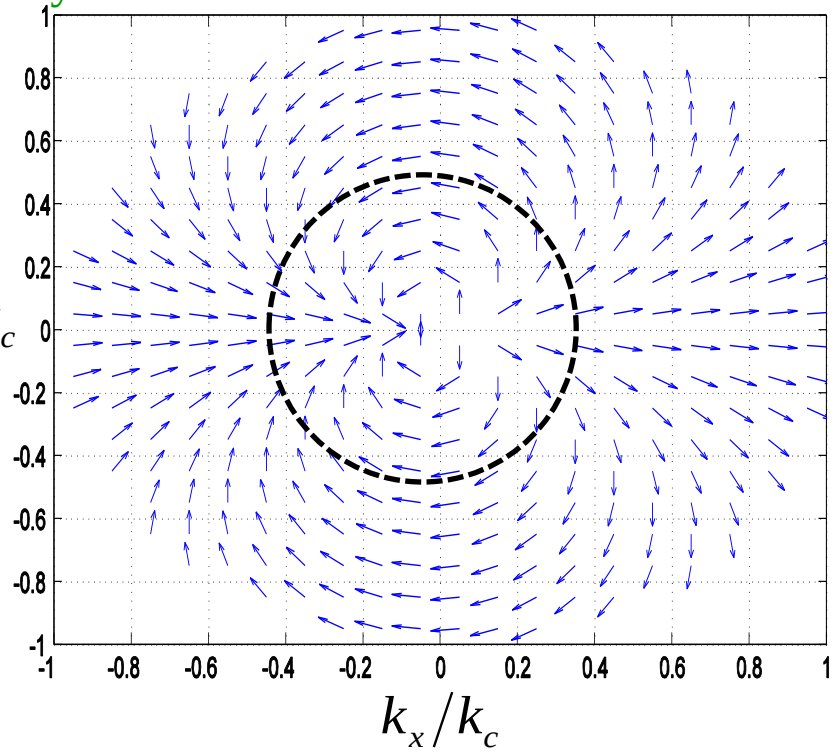
α_b β_t ← pseudospin

$$H = -\frac{1}{2m}\begin{pmatrix} 0 & \pi^{*2} \\ \pi^2 & 0 \end{pmatrix} = -\frac{p^2}{2m}\mathbf{n}_2(\phi_\mathbf{p})\cdot\boldsymbol{\sigma}$$

chirality

$$\mathbf{n}_2(\phi_\mathbf{p}) = (\cos 2\phi_\mathbf{p}, \sin 2\phi_\mathbf{p})$$



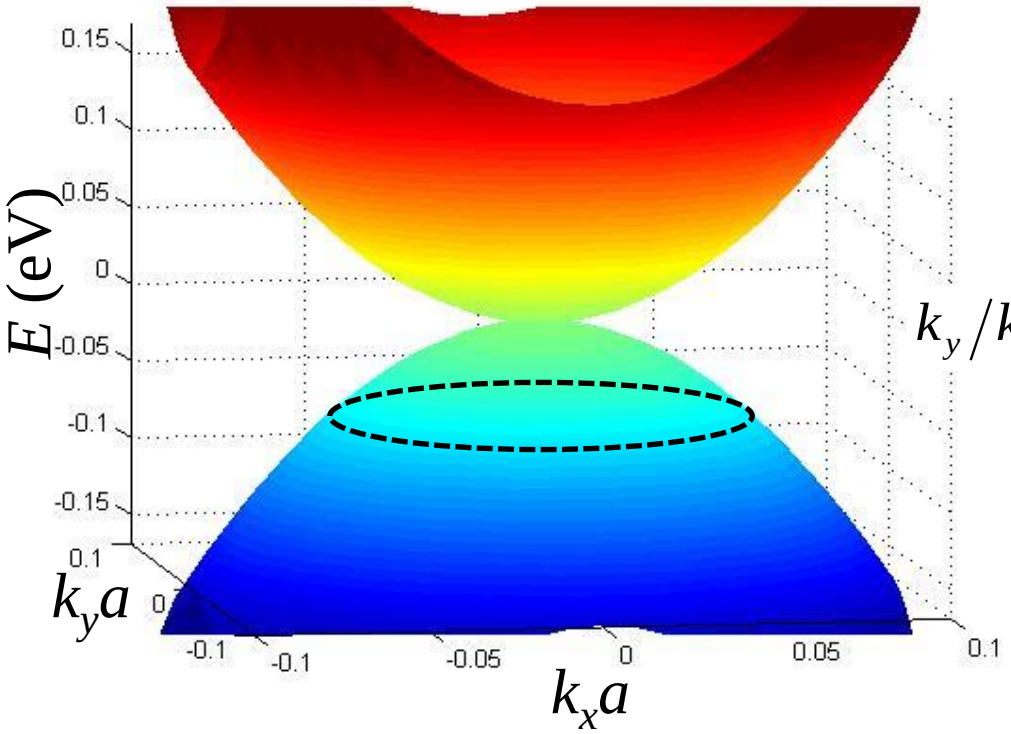


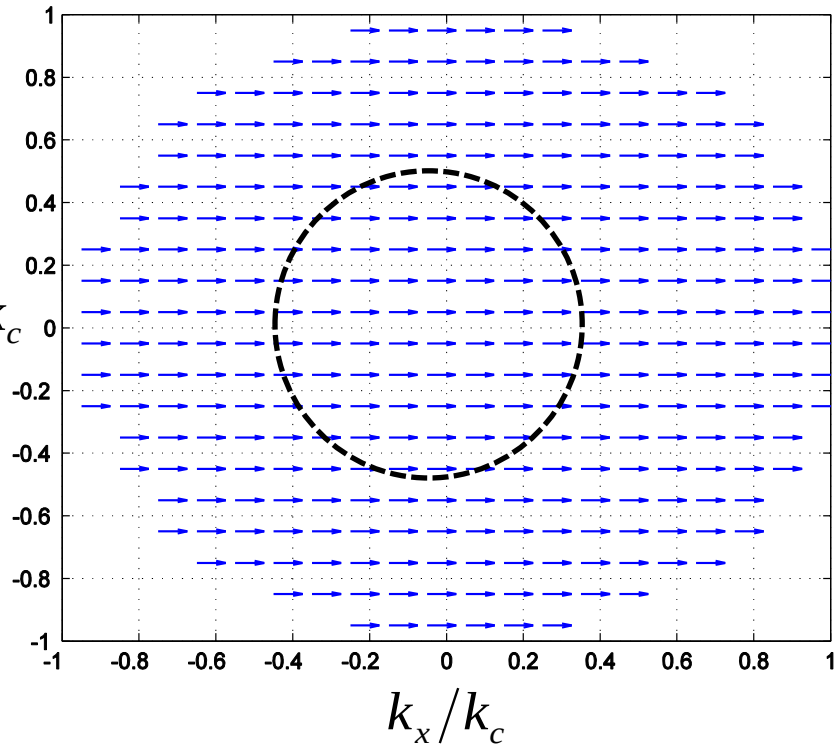
Effective theory of bilayer graphene

Pseudospin, chirality and Berry phase

$$H = -\frac{1}{2m}\begin{pmatrix} 0 & p^2 \\ p^2 & 0 \end{pmatrix} = -\frac{p^2}{2m}\sigma_x$$

$$E(\mathbf{p}) = \pm\frac{p^2}{2m}$$





Pseudospin and Chirality

Effective theory of a general chiral system

“↑” “↓”

$$H_J = \varepsilon_0 \begin{pmatrix} 0 & \pi^{*J} \\ \pi^J & 0 \end{pmatrix} = \varepsilon_0 p^J \left(\boldsymbol{\sigma} \cdot \mathbf{n}_J(\phi_{\mathbf{p}}) \right)$$

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

$$\mathbf{n}_J(\phi_{\mathbf{p}}) = (\cos J\phi_{\mathbf{p}}, \sin J\phi_{\mathbf{p}})$$

$$\pi = p_x + ip_y$$
$$\phi_{\mathbf{p}} = \tan^{-1}(p_y / p_x)$$

$$E_J(\mathbf{p}) = \pm \varepsilon_0 p^J$$

McCann & Fal’ko , Phys. Rev. Lett. **96**, 086805 (2006)
Min & MacDonald, Phys. Rev. B **77**, 155416 (2008)

Pseudospin: Two-valued quantum degrees of freedom

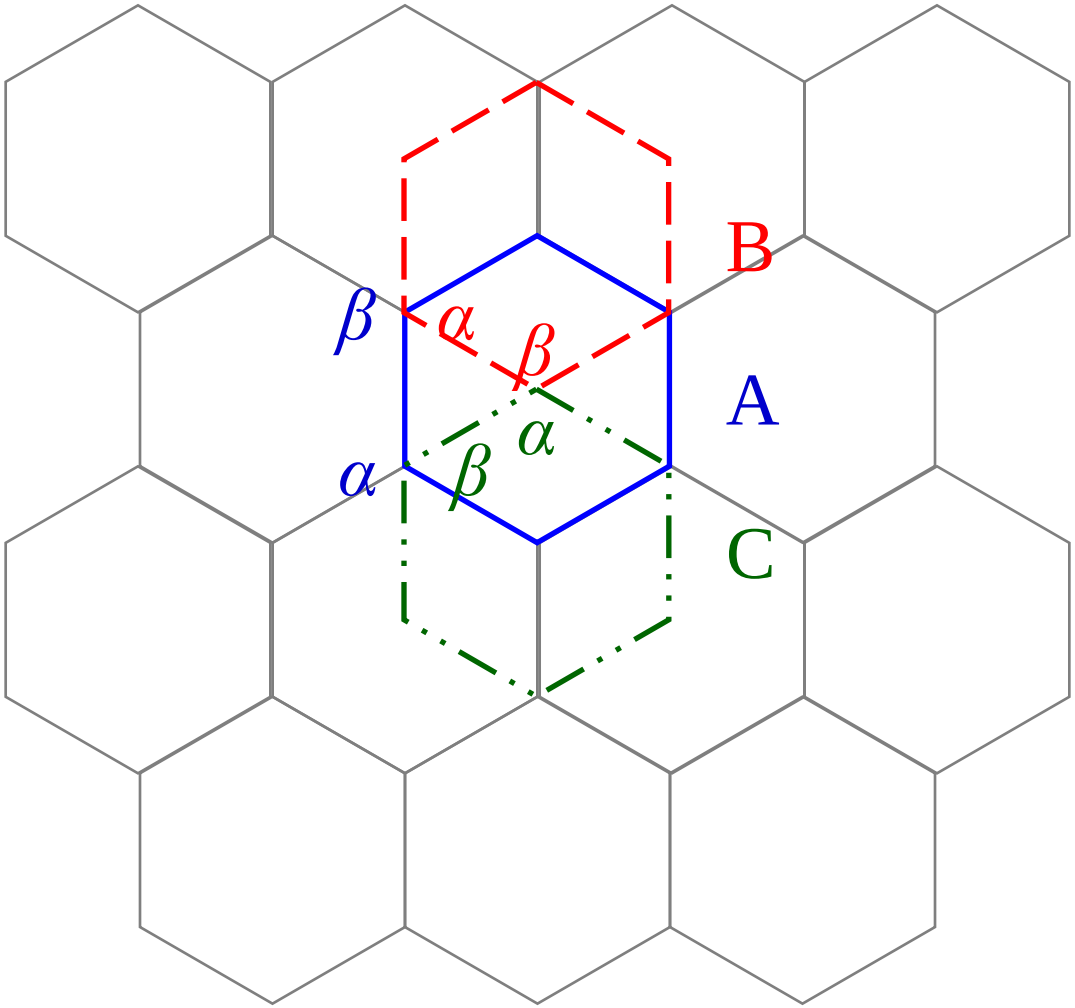
Example: sublattice, layer

Chirality: Projection of pseudospin to momentum direction

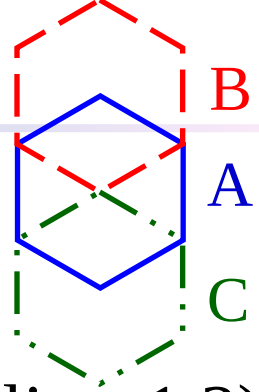
Monolayer graphene : 2D chiral system with chirality J=1
Bilayer graphene : 2D chiral system with chirality J=2

Multilayer stacking

Three distinct stacking arrangements, labeled A,B,C



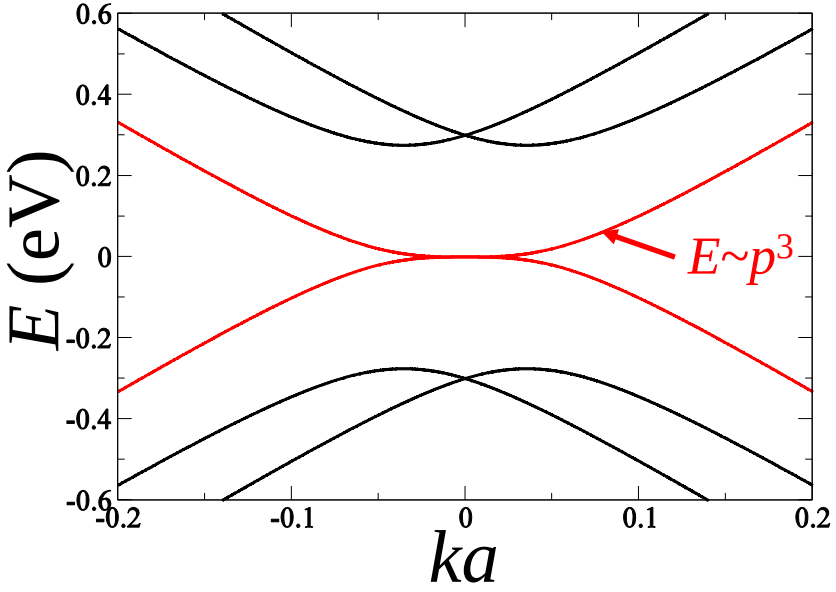
Electronic structure of multilayer



Stacking sequence and energy band structure

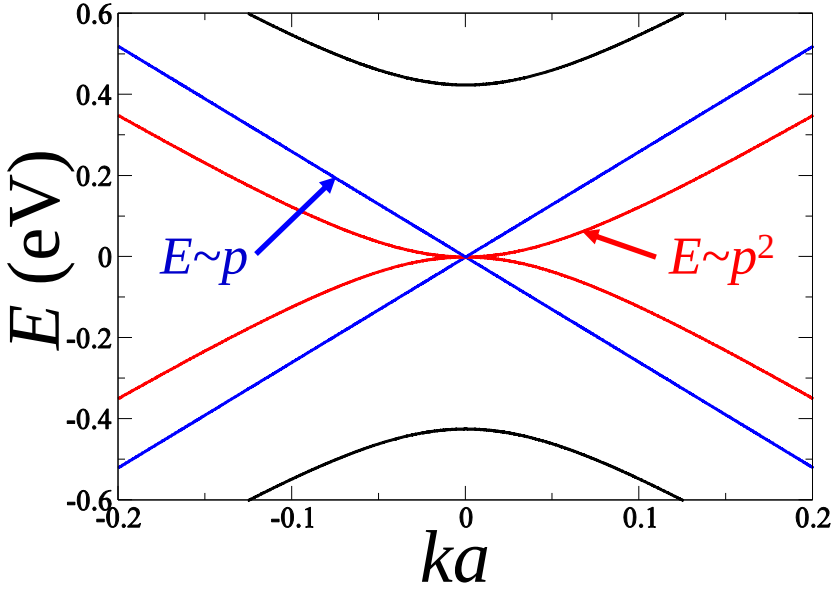
Min and MacDonald, Phys. Rev. B **77**, 155416 (2008)

ABC trilayer (chirality=3)



$$H_{eff} \sim \begin{pmatrix} 0 & \pi^{*3} \\ \pi^{3} & 0 \end{pmatrix}$$

ABA trilayer (chirality=1,2)



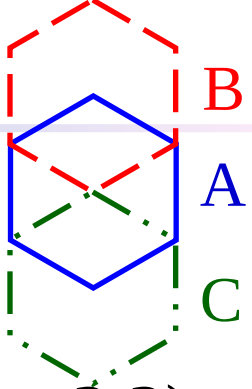
$$H_{eff} \sim \begin{pmatrix} 0 & \pi^{*} \\ \pi & 0 \end{pmatrix} \oplus \begin{pmatrix} 0 & \pi^{*2} \\ \pi^{2} & 0 \end{pmatrix}$$

$$\pi = p_x + ip_y = pe^{i\phi_{\mathbf{p}}}$$

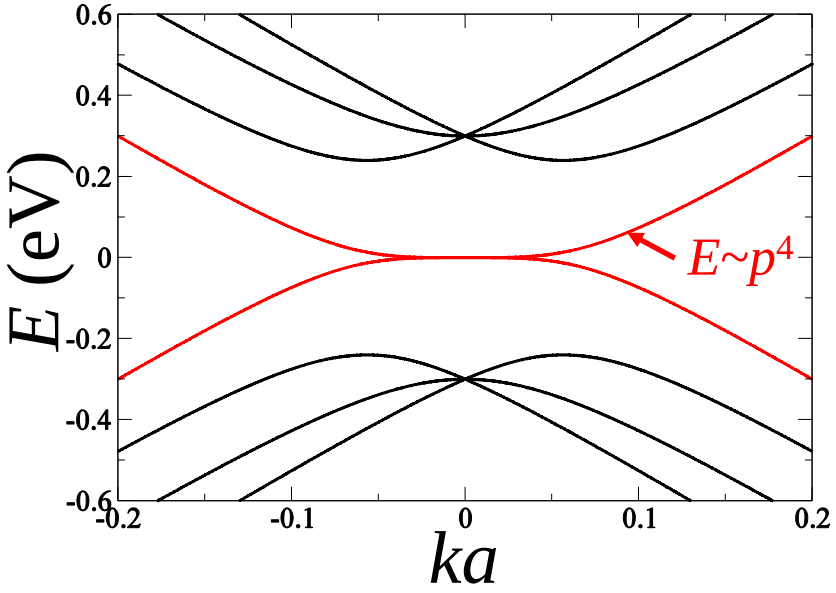
Electronic structure of multilayer

Stacking sequence and energy band structure

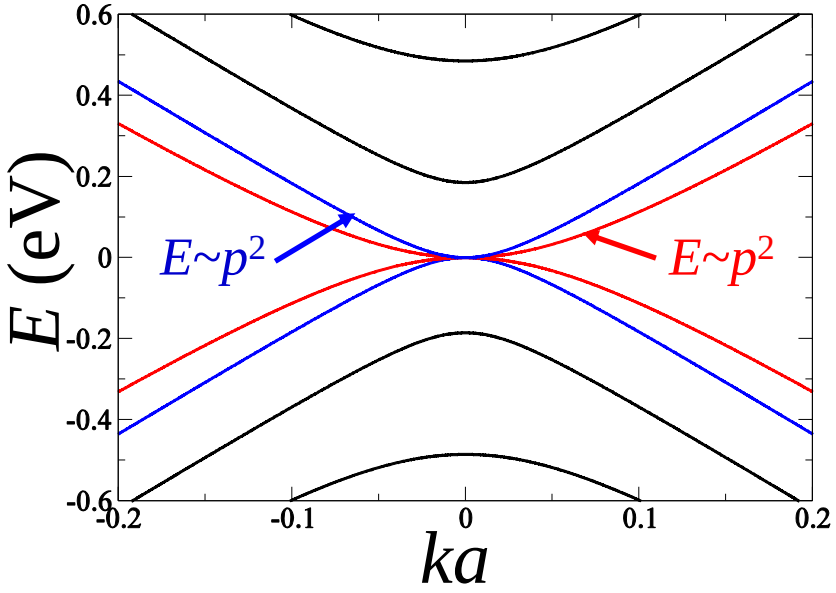
Min and MacDonald, Phys. Rev. B **77**, 155416 (2008)



ABCA (chirality=4)



ABAB (chirality=2,2)



$$H_{eff} \sim \begin{pmatrix} 0 & \pi^{*4} \\ \pi^{4} & 0 \end{pmatrix}$$

$$H_{eff} \sim \begin{pmatrix} 0 & \pi^{*2} \\ \pi^{2} & 0 \end{pmatrix} \oplus \begin{pmatrix} 0 & \pi^{*2} \\ \pi^{2} & 0 \end{pmatrix}$$

$$\pi = p_x + ip_y = pe^{i\phi_{\mathbf{p}}}$$

Electronic structure

Important lessons

Min and MacDonald, Phys. Rev. B **77**, 155416 (2008)

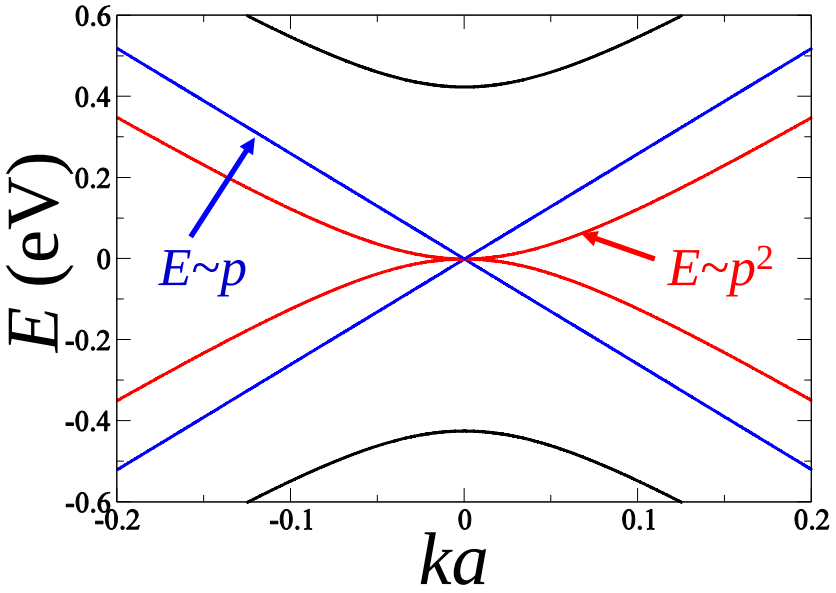
Electronic structure strongly depends on the stacking sequences.

$\Rightarrow$ Electronic structure engineering by stacking sequences

Low-energy band structure is described by a set of chiral systems.

Ex: ABA trilayer (J=1,2)

$$H_{eff} \sim \begin{pmatrix} 0 & \pi^{*} \\ \pi & 0 \end{pmatrix} \oplus \begin{pmatrix} 0 & \pi^{*2} \\ \pi^{2} & 0 \end{pmatrix}$$



High-energy band structure follows that of monolayer graphene.

Transport and optical properties – Boltzmann transport theory

- What is the effect of impurities?
- What is the response to light?
- How can we identify the stacking sequence?

Model

Boltzmann transport theory

- Non-equilibrium distribution function

$$dn = \frac{d\mathbf{k}}{(2\pi)^d} f(\mathbf{k},t)$$

$$\mathbf{J} = (-e)\int \frac{d\mathbf{k}}{(2\pi)^d} f(\mathbf{k},t)\mathbf{v}(\mathbf{k})$$

electrical conductivity

- Relaxation time approximation

$$\frac{df(\mathbf{k},t)}{dt} = \frac{\partial f(\mathbf{k},t)}{\partial \mathbf{k}} \cdot \frac{d\mathbf{k}}{dt} + \frac{\partial f(\mathbf{k},t)}{\partial t}$$

$$\approx -\frac{f(\mathbf{k},t) - f_0(\mathbf{k})}{\tau_{\mathbf{k}}}$$

$$\hbar \frac{d\mathbf{k}}{dt} = (-e)\mathbf{E}$$

$f_0(\mathbf{k}) =$ equilibrium distribution function

$\tau_{\mathbf{k}} =$ relaxation time

Model

Boltzmann transport theory

- Relaxation time

$$\frac{1}{\tau_F} = \frac{2\pi}{\hbar} n_{imp} V_{imp}^2 \nu(\varepsilon_F)$$

DOS

Fermi's Golden rule

- Electrical conductivity $\mathbf{J} = (-e)\int \frac{d\mathbf{k}}{(2\pi)^d} f(\mathbf{k},t)\mathbf{v}(\mathbf{k}) = \sigma\mathbf{E}$

$$\sigma = e^2 \left[g_s g_v \nu(\varepsilon_F) \right] \left[\frac{1}{2} \mathrm{v}_F^2 \tau_F \right]$$

DOS Diffusion constant in 2D

$$\mathrm{v}_F = \frac{1}{\hbar} \frac{\partial \varepsilon}{\partial k}\bigg|_{\varepsilon=\varepsilon_F}$$

Fermi velocity

$$\Rightarrow \quad \sigma \propto \frac{\mathrm{v}_F^2}{n_{imp} V_{imp}^2}$$

Density dependence of conductivity

Short-range scatterers

Min *et al*. Phys. Rev. B **83**, 195117 (2011)

$$\sigma \sim \frac{v_F^2}{n_{imp} V_{imp}^2}$$

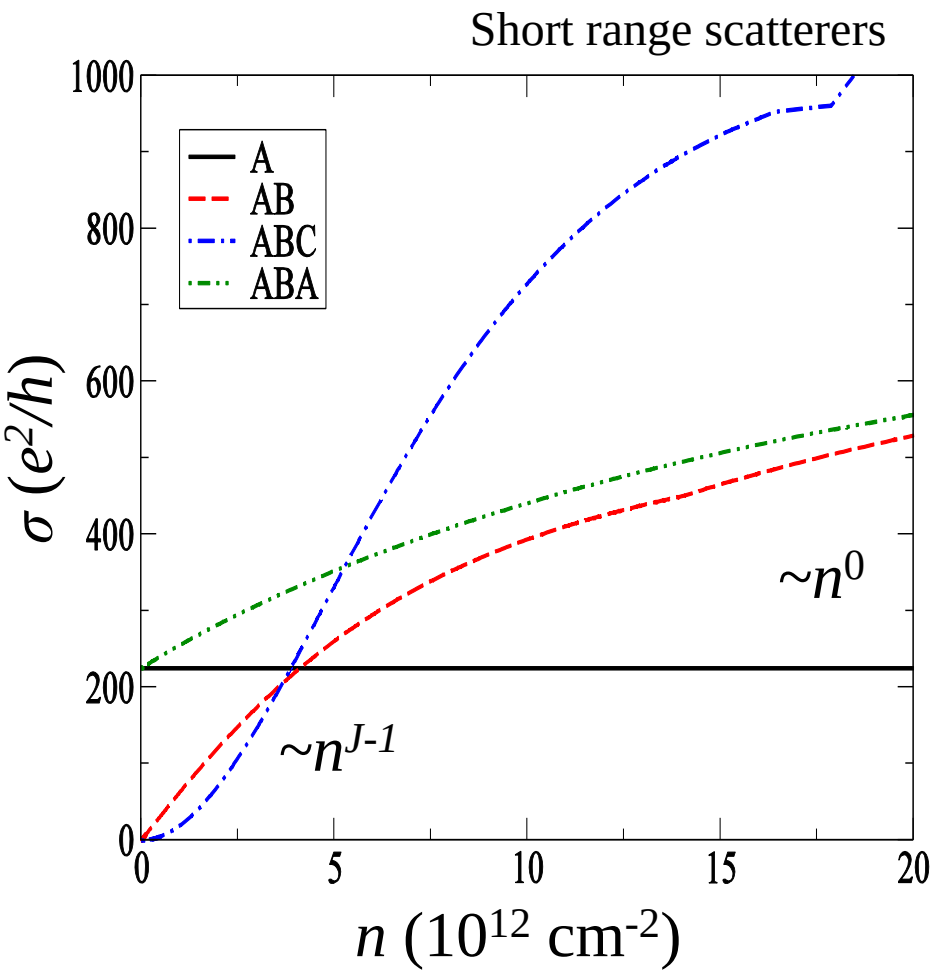
$V_{imp} \sim$ constant

For J-chiral system

$$\sigma \sim \frac{n^{J-1}}{n_{imp}} \qquad v_F \sim k_F^{J-1}$$

$$n \sim k_F^2$$

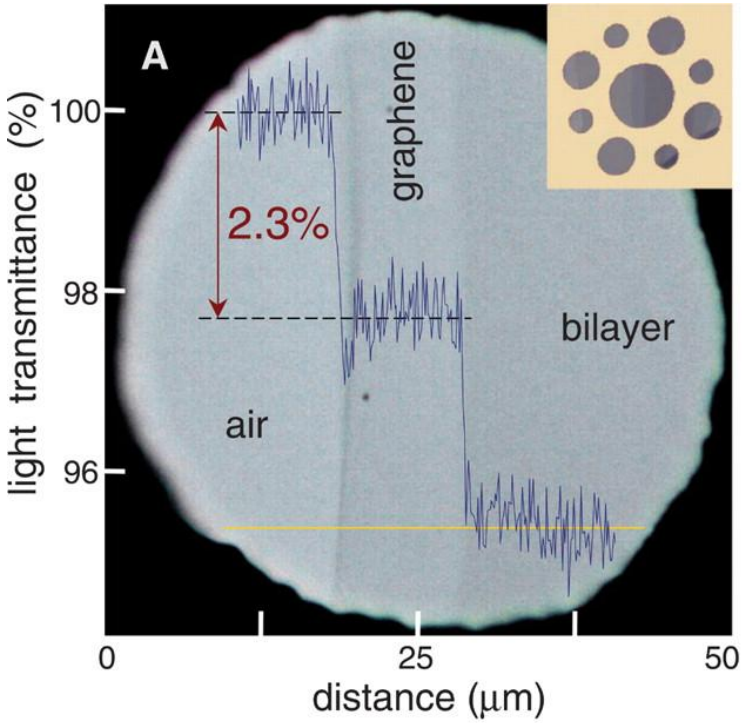
$$\xrightarrow[J \sim 1]{} \sigma \sim \frac{n^0}{n_{imp}} \quad \text{at high } n$$



A→J=1, AB→J=2, ABC→J=3, ABA→J=1,2

Optical conductivity measurements

Transmittance of graphene



$$T(\omega) = \left(1 + \frac{2\pi}{c}\sigma(\omega)\right)^{-2}$$

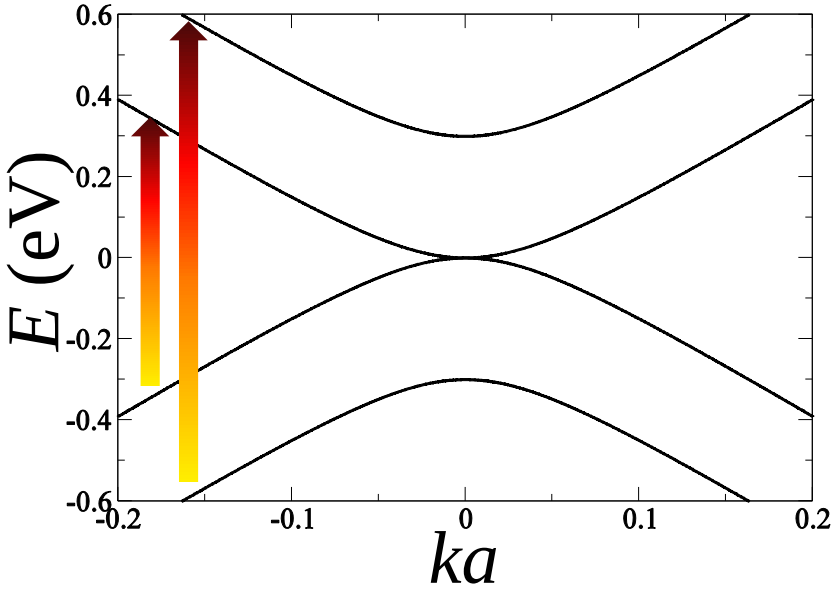
$$R(\omega) = 1 - T(\omega)$$

Nair et al, Science **320**, 1308 (2008)

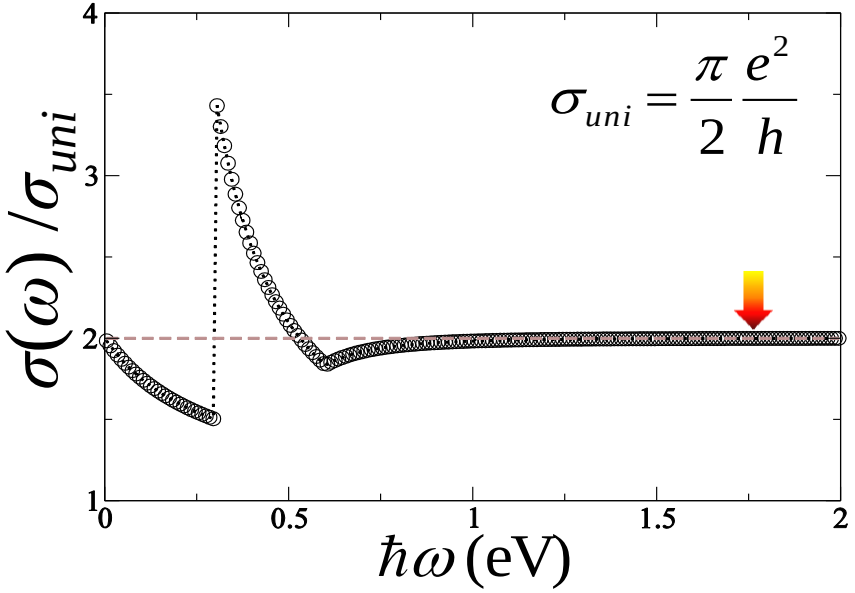
Optical conductivity of bilayer graphene

High frequency limit

Bilayer graphene



Optical conductivity

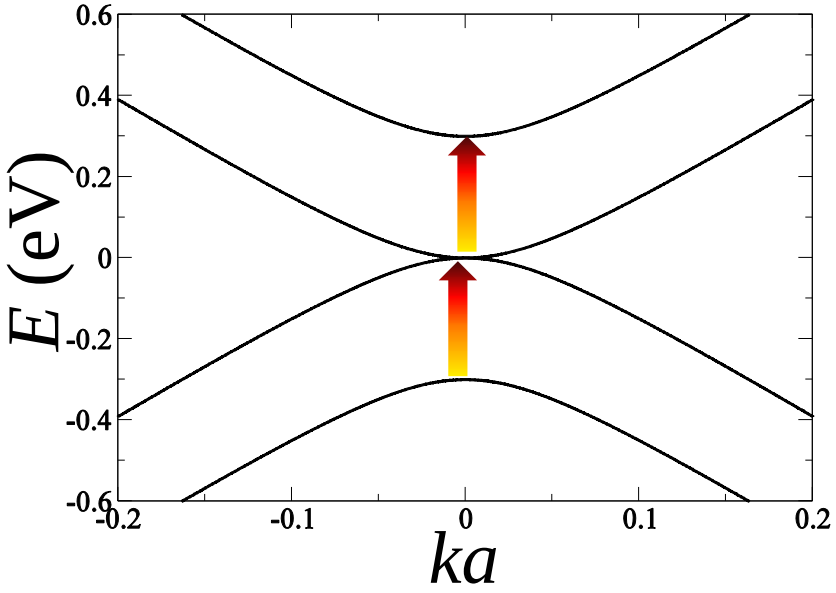


At high frequencies, each decoupled layer gives σ_{uni}, thus optical conductivity approaches to $N\sigma_{uni}$.

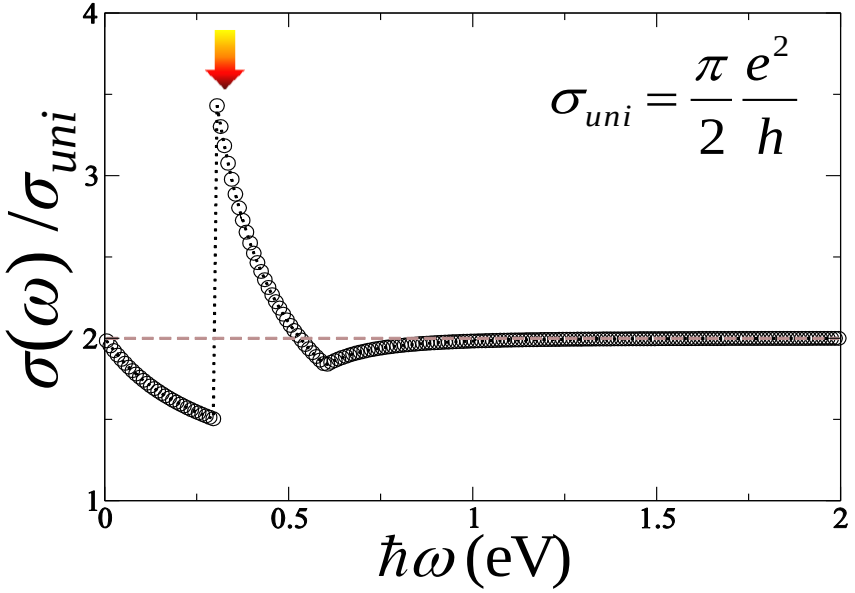
Optical conductivity of bilayer graphene

Intermediate frequency regime ($t_\perp$=0.3~0.4 eV)

Bilayer graphene



Optical conductivity

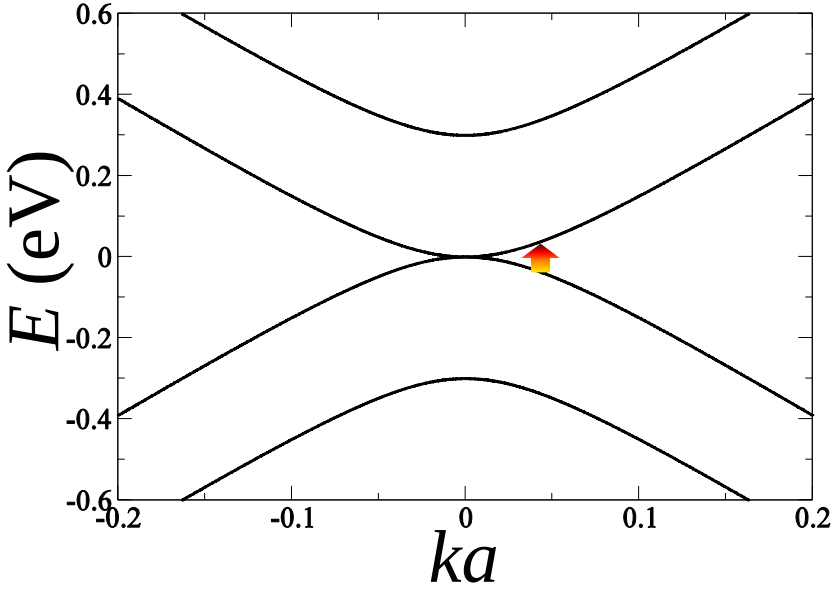


At intermediate frequencies, optical conductivity shows characteristic peaks depending on the stacking sequence.

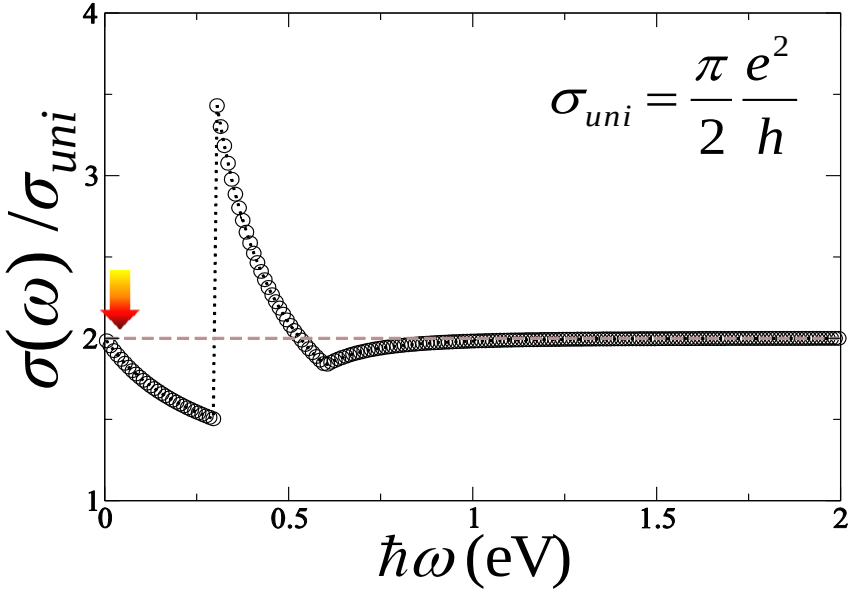
Optical conductivity of bilayer graphene

Low frequency limit

Bilayer graphene



Optical conductivity



At low frequencies, optical conductivity approaches to $N\sigma_{uni}$.

Optical conductivity of graphene multilayers

Low frequency limit

- Monolayer graphene (J=1)

$$\sigma_{uni} = \frac{\pi}{2}\frac{e^2}{h}$$

- J-chiral system

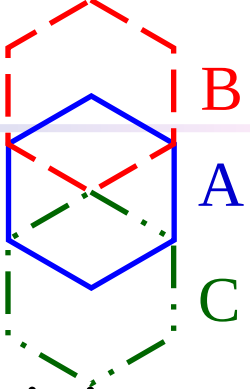
$$\sigma_J = J\sigma_{uni}$$

- Chirality sum is the number of layers

$$\sigma = \sum_i \sigma_{J_i} = N\sigma_{uni}$$

At low frequencies, optical conductivity approaches to $N\sigma_{uni}$.

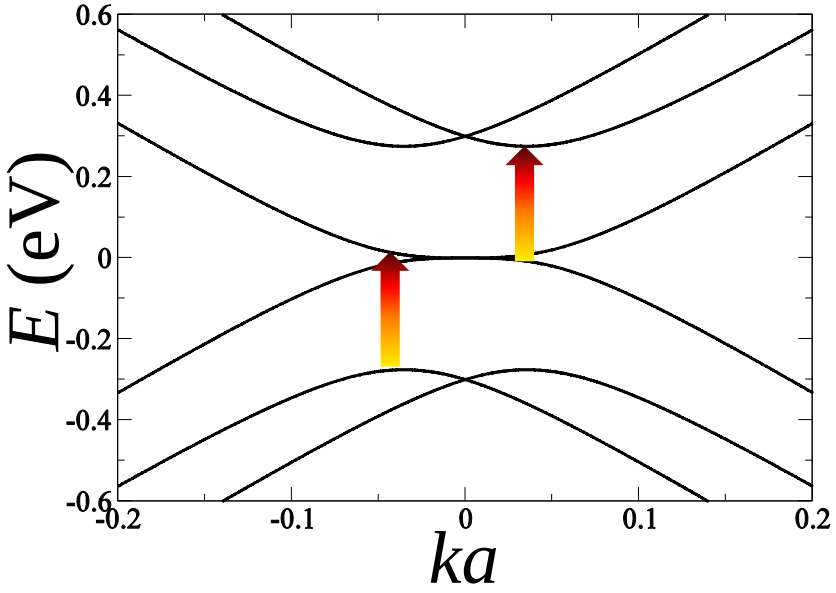
Optical conductivity of ABC trilayer



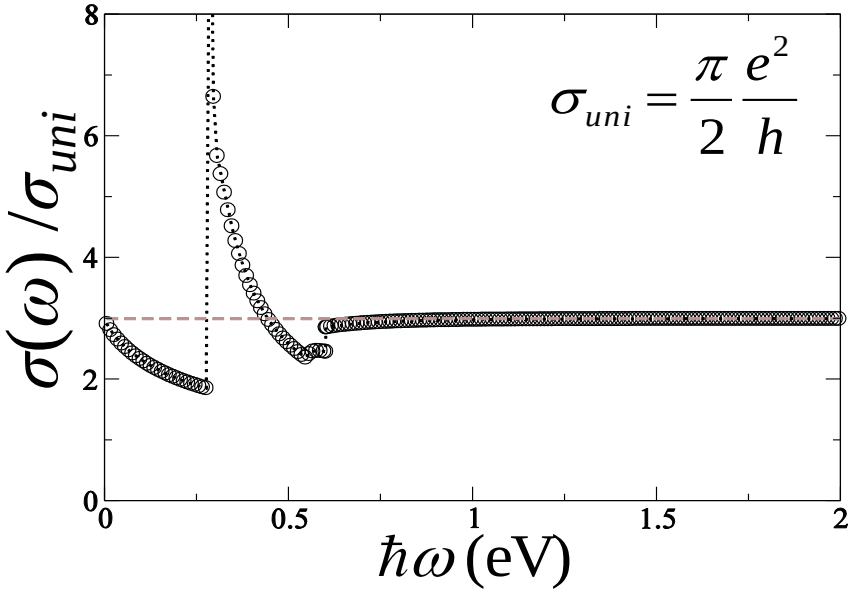
Optical conductivity and stacking sequence

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

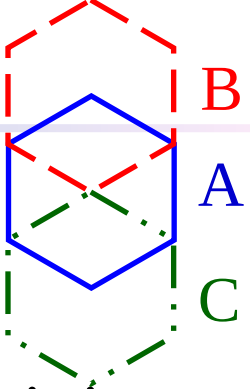
ABC trilayer



Optical conductivity



Optical conductivity of ABA trilayer



Optical conductivity and stacking sequence

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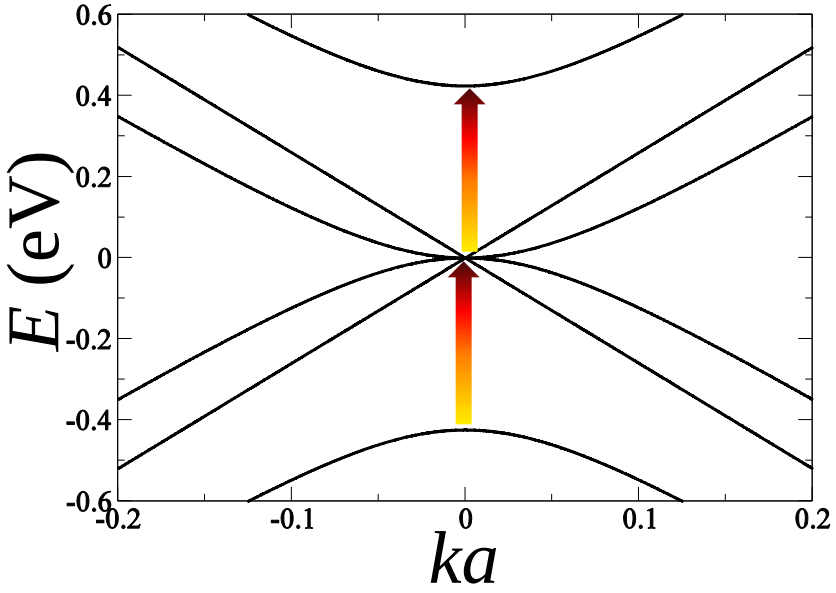
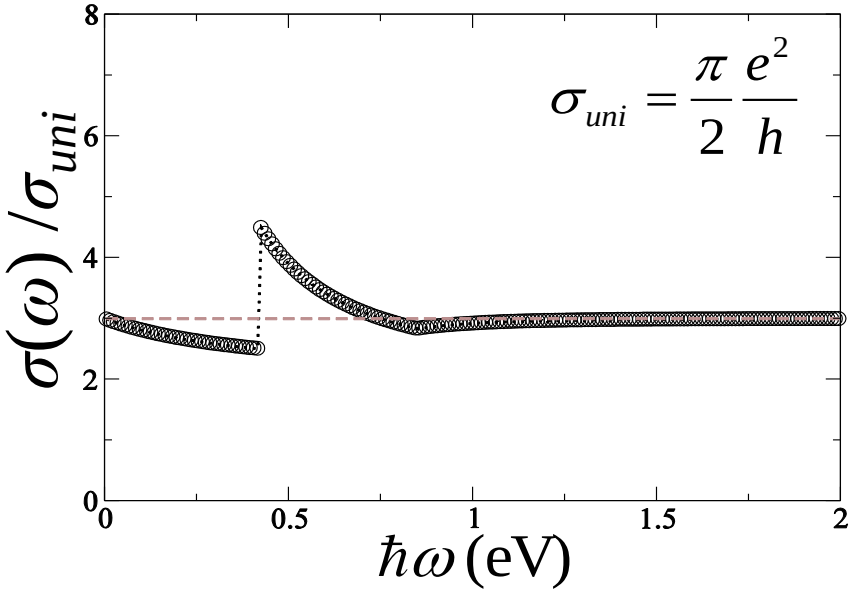
ABA trilayer



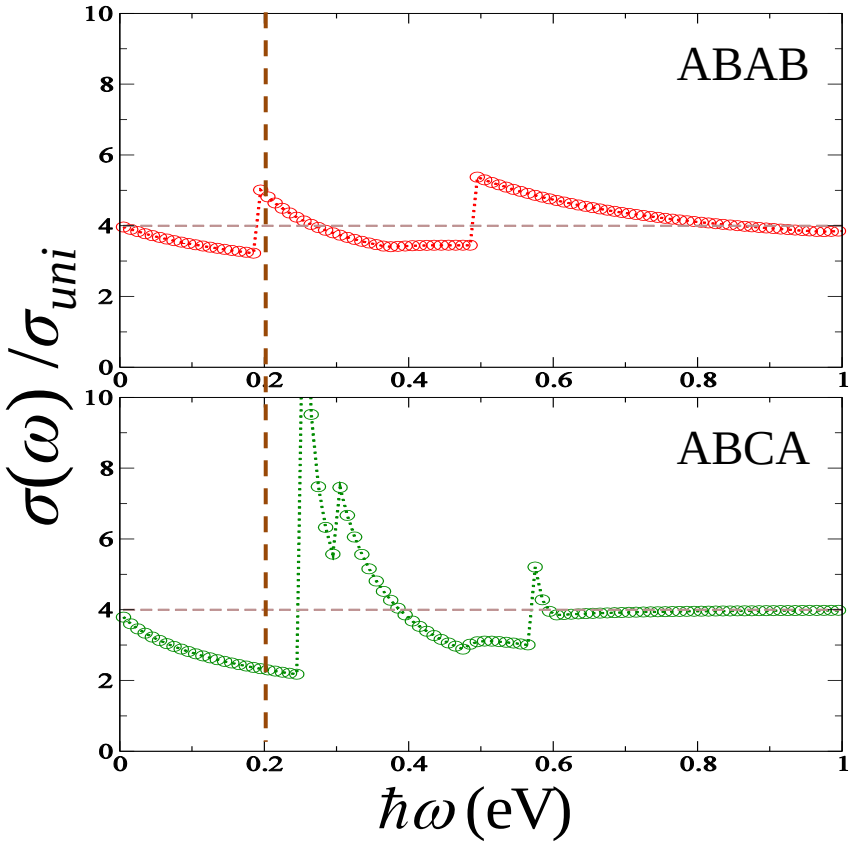
Optical conductivity

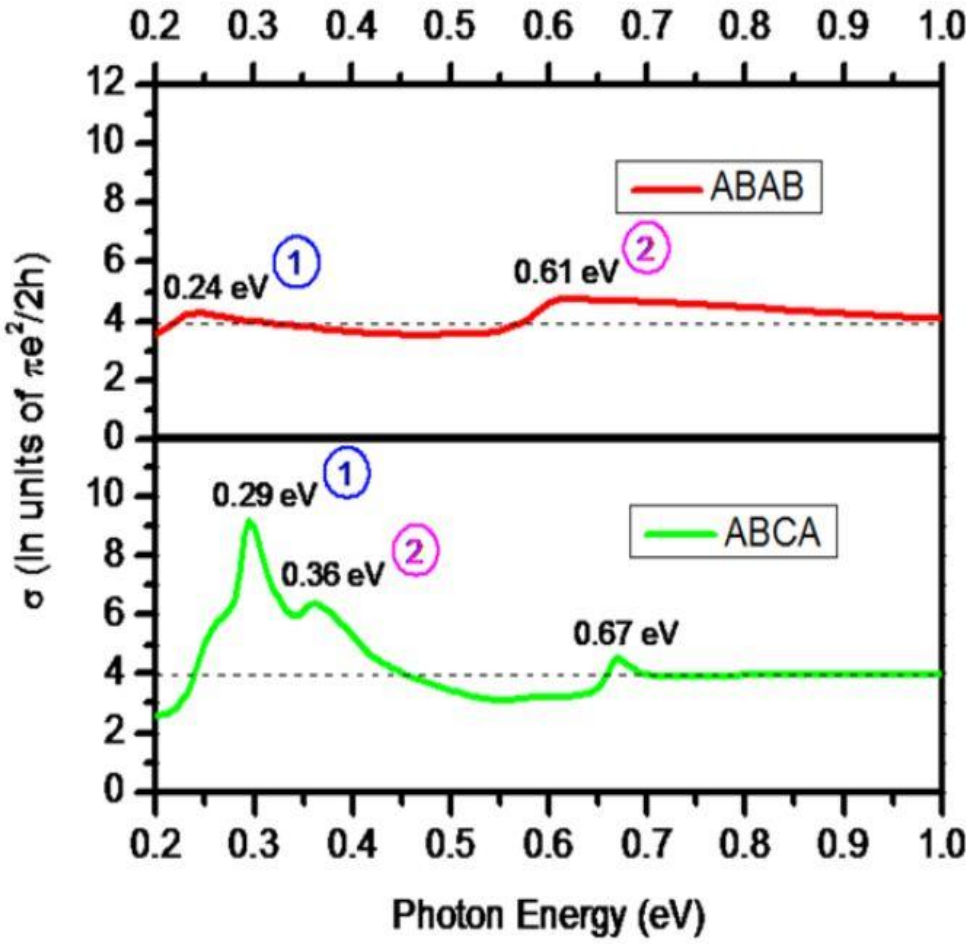


Optical conductivity measurements provide a useful way to identify the number of layers and stacking sequences.

Comparison with experiments

Optical conductivity and stacking sequence





Min and MacDonald, PRL **103**, 067402 (2009)

Mak *et al*, PRL **104**, 176404 (2010)

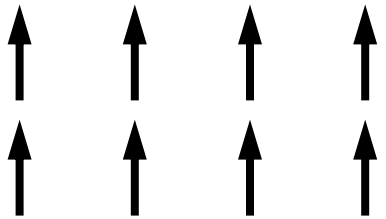
Electron-electron interactions – Mean-field theory

- What is the effect of electron-electron interaction?
- How can we treat the electron-electron interaction?
- Is there a pseudospin version of ferromagnetism?

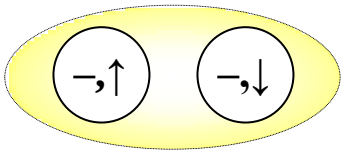
Electron-electron interaction

Interaction-induced ordered states

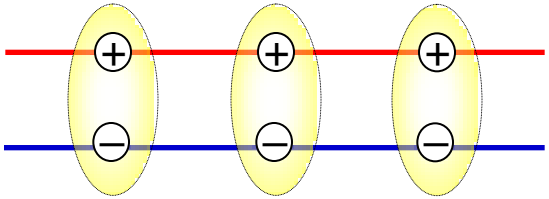
- Magnetism



- Superconductivity



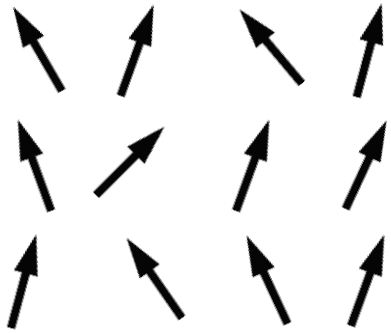
- Exciton-condensation



...

Mean-field theory

Weiss molecular-field approximation



$$H = -\frac{1}{2}\sum_{<i,j>} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$

$$\mathbf{S}_i = \langle \mathbf{S}_i \rangle + \delta\mathbf{S}_i$$

$$\mathbf{S}_i \cdot \mathbf{S}_j = \left(\langle \mathbf{S}_i \rangle + \delta\mathbf{S}_i\right)\cdot\left(\langle \mathbf{S}_j \rangle + \delta\mathbf{S}_j\right)$$

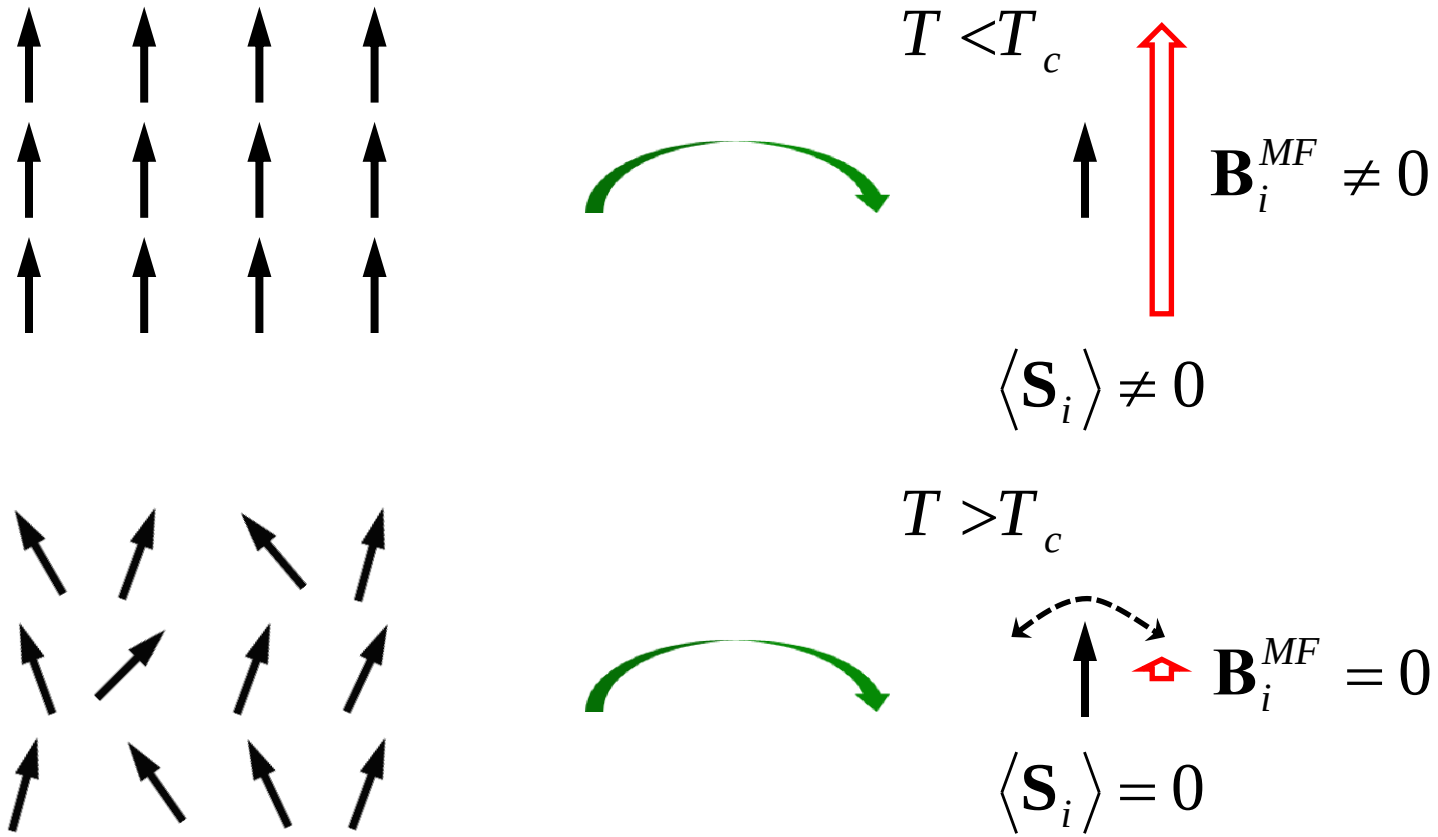
$$= \langle \mathbf{S}_i \rangle \cdot \langle \mathbf{S}_j \rangle + \delta\mathbf{S}_i \cdot \langle \mathbf{S}_j \rangle + \langle \mathbf{S}_i \rangle \cdot \delta\mathbf{S}_j + \cancel{\delta\mathbf{S}_i \cdot \delta\mathbf{S}_j}$$

$$\approx \langle \mathbf{S}_i \rangle \cdot \mathbf{S}_j + \langle \mathbf{S}_j \rangle \cdot \mathbf{S}_i - \langle \mathbf{S}_i \rangle \cdot \langle \mathbf{S}_j \rangle$$

$$H^{MF} \approx -\sum_i \mathbf{B}_i^{MF} \cdot \mathbf{S}_i \qquad \mathbf{B}_i^{MF} = \sum_j J_{ij} \langle \mathbf{S}_j \rangle$$

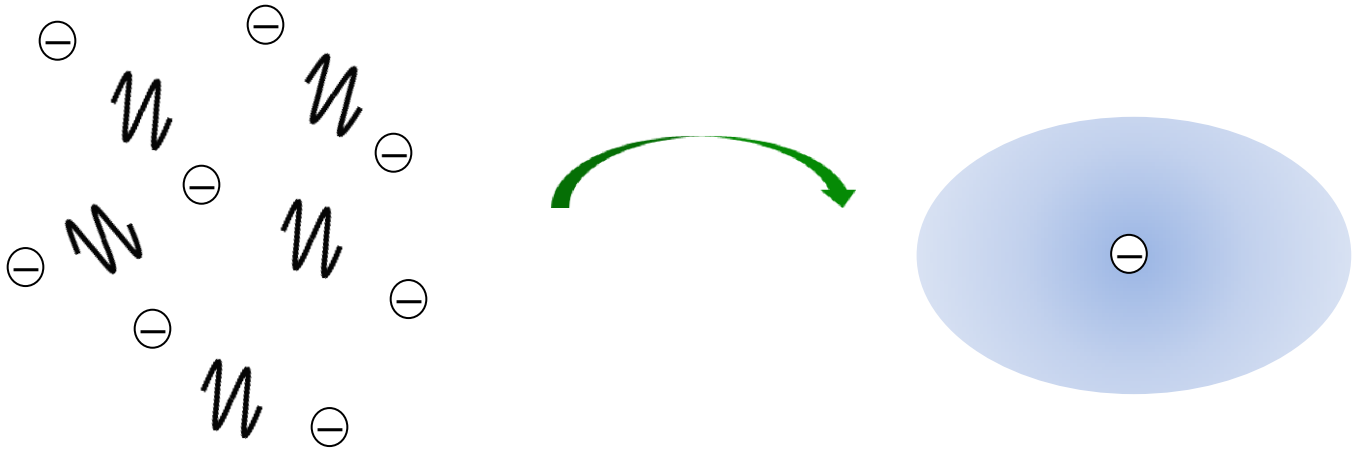
Mean-field theory

Weiss molecular-field approximation



Mean-field theory

Hartree-Fock approximation



Interacting electrons

Non-interacting electrons
in an effective potential

Pseudospin magnetism

Pseudospin $\Rightarrow$ Two-valued quantum degrees of freedom

Bilayer graphene (chirality J=2)

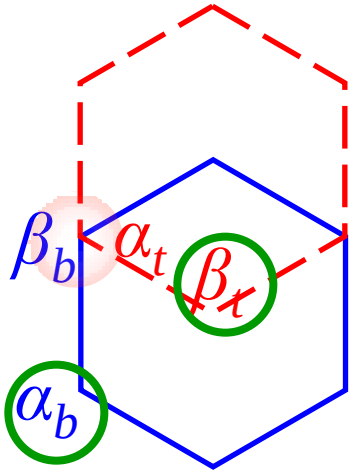
"↑"=α_b "↓"=β_t

$$H = -\frac{1}{2m}\begin{pmatrix} 0 & \pi^{*2} \\ \pi^2 & 0 \end{pmatrix} = -\frac{p^2}{2m}\boldsymbol{\sigma}\cdot\mathbf{n}_2(\phi_{\mathbf{p}})$$

$$\mathbf{n}_2(\phi_{\mathbf{p}}) = (\cos 2\phi_{\mathbf{p}}, \sin 2\phi_{\mathbf{p}})$$

$$\pi = p_x + ip_y$$

$$\phi_{\mathbf{p}} = \tan^{-1}(p_y / p_x)$$



Ferromagnetism means spontaneous spin polarization.

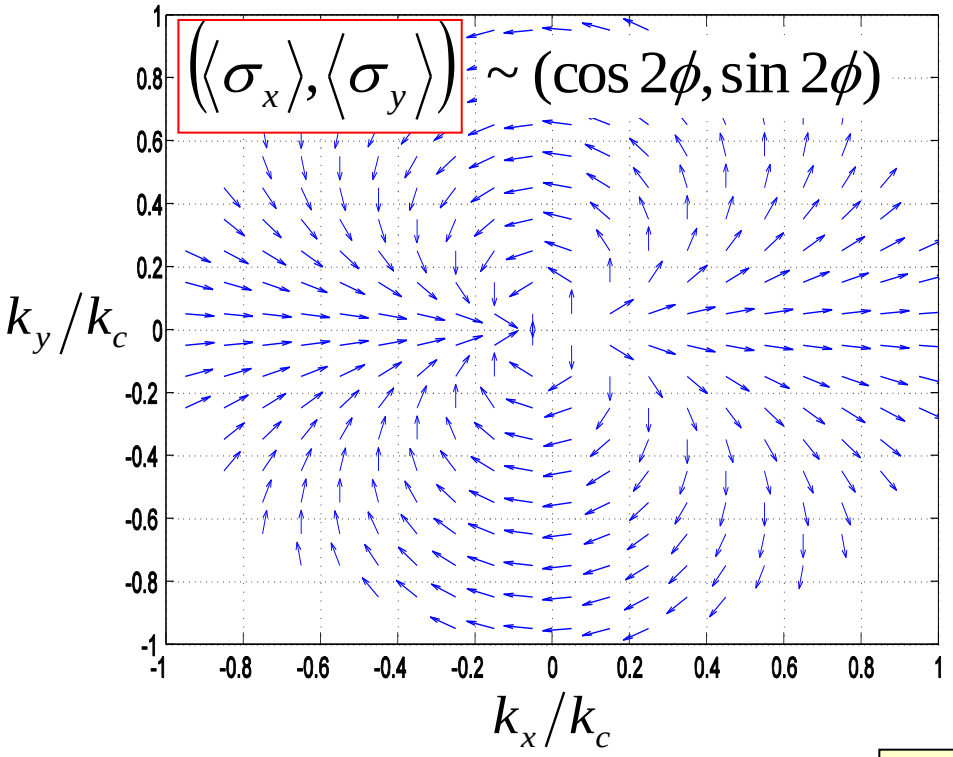
Is there spontaneous charge polarization in the presence of electron-electron interactions?

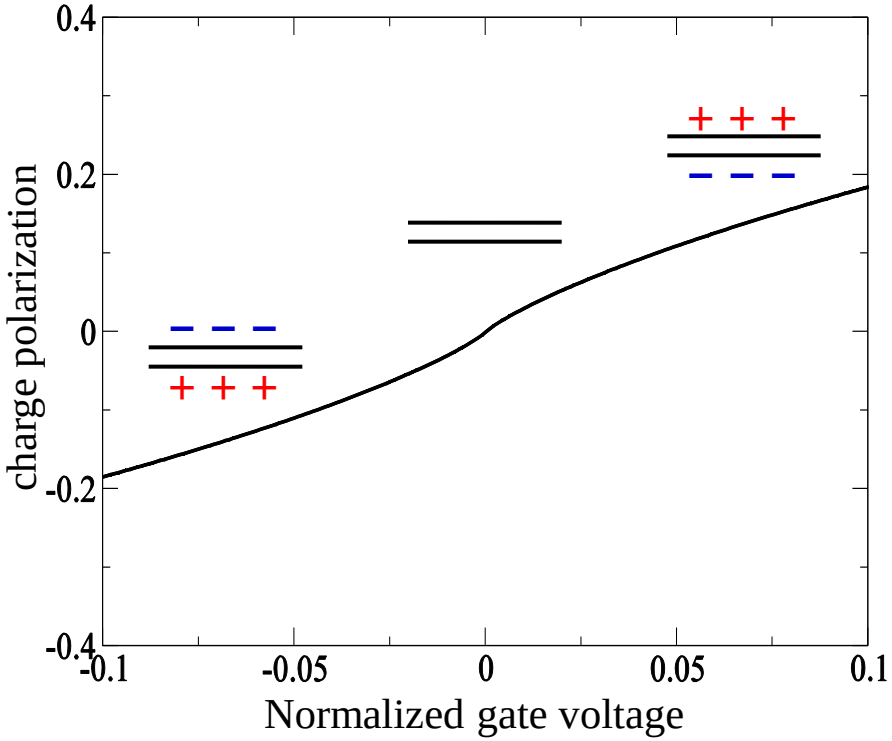
$\Rightarrow$ Pseudospin magnetism

Pseudospin magnetism in bilayer graphene

In-plane pseudospin direction

Min *et al*. Phys. Rev. B **77**, 041407(R) (2008)





$$H_0 = -\mathbf{B}_0(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

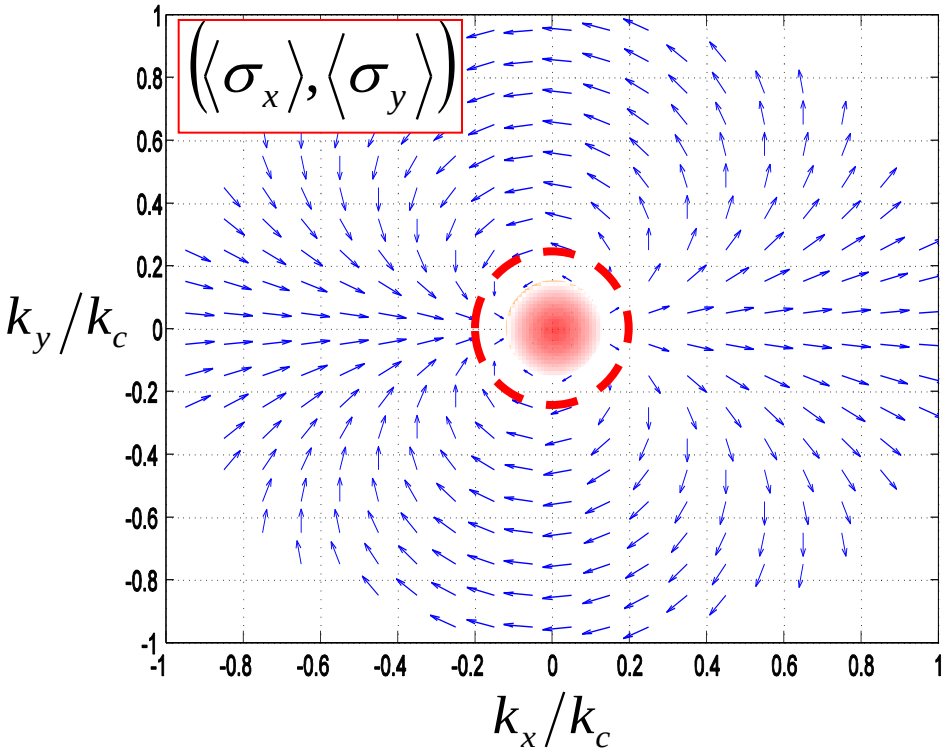
$$\mathbf{B}_0(\mathbf{k}) = \frac{\hbar^2 k^2}{2m}(\cos 2\phi_{\mathbf{k}}, \sin 2\phi_{\mathbf{k}}, 0)$$

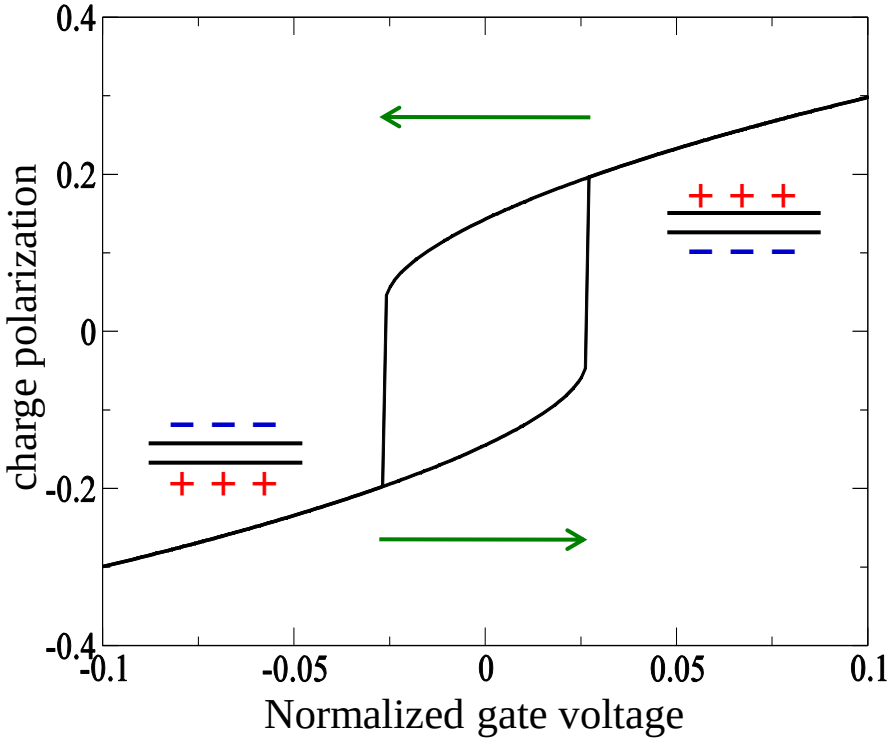
No electron-electron interaction

Pseudospin magnetism in bilayer graphene

In-plane pseudospin direction

Min *et al*. Phys. Rev. B **77**, 041407(R) (2008)





$$H_{\mathrm{MF}} = -\mathbf{B}_{\mathrm{eff}}(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

$$\mathbf{B}_{\mathrm{eff}}(\mathbf{k}) = (B_{\perp}\cos 2\phi_{\mathbf{k}}, B_{\perp}\sin 2\phi_{\mathbf{k}}, B_z)$$

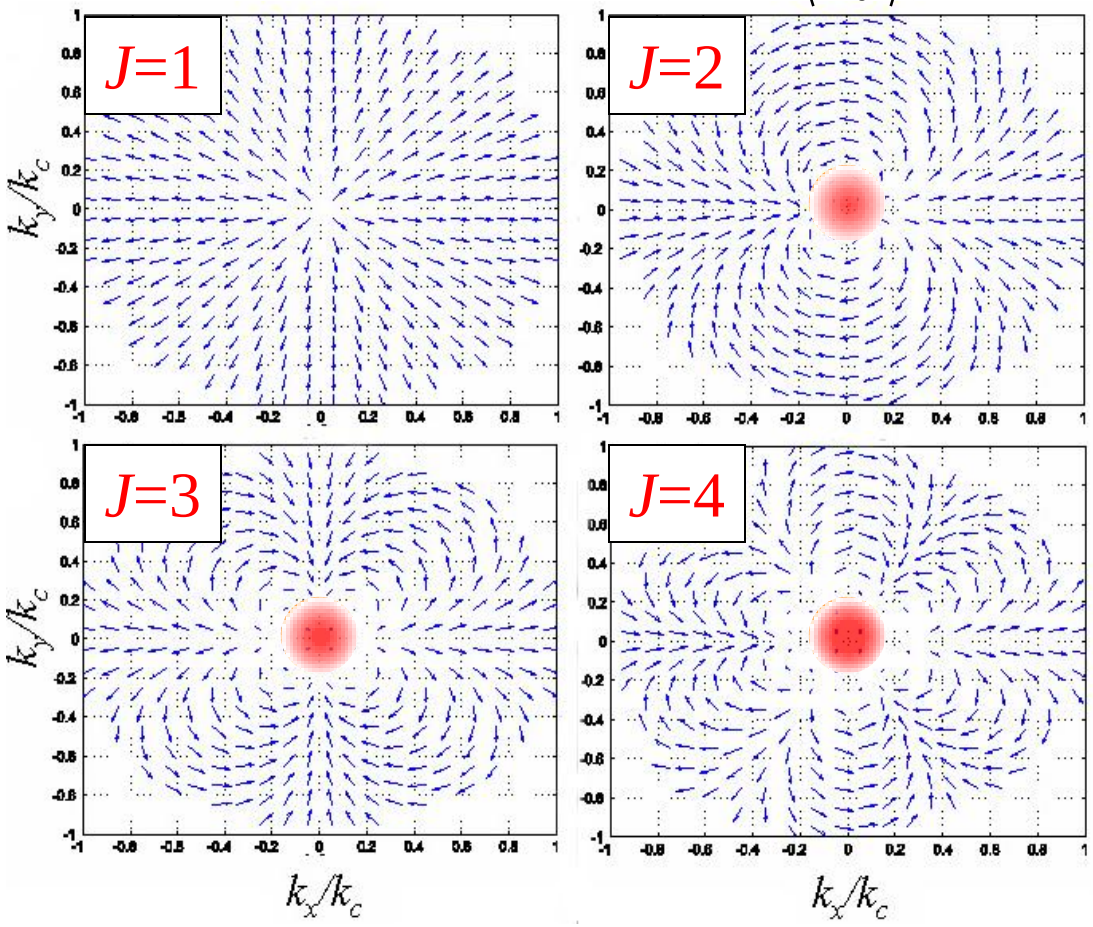
$\Rightarrow$ Vortex formation in momentum space

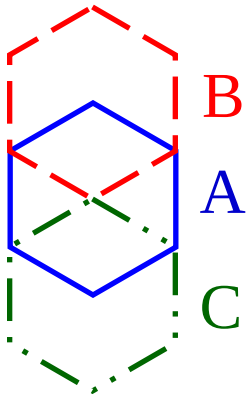
Electron-electron interactions are turned on

Spontaneous charge transfer between the two layers

Pseudospin magnetism in multilayer graphene

In-plane pseudospin direction $\left(\langle\sigma_x\rangle, \langle\sigma_y\rangle\right) \sim (\cos J\phi, \sin J\phi)$





Pseudospin magnetism is more stable for larger chirality.

$\Rightarrow$ ABC stacked multilayers are excellent candidates.

Ex) AB, ABC, ABCA, ABCAB,…

Conclusion and future work
– New electronic device scheme

- How can we use the ordered states in devices?
- Are there other interaction-induced ordered states?
- Ongoing work

Search for ordered states in graphene systems

Interplay between chirality, e-e interaction and disorder

Dirac-like chiral wavefunction

\+ Electron-electron interaction

– Disorder

$\Rightarrow$ New ordered states in graphene systems

Energy band structure and stacking sequences

Pseudospin magnetism in coupled graphene bilayers

High-quality sample with low disorder

Prospects

Current electronic device scheme

⇒ Future electronic device scheme

Single particle behavior

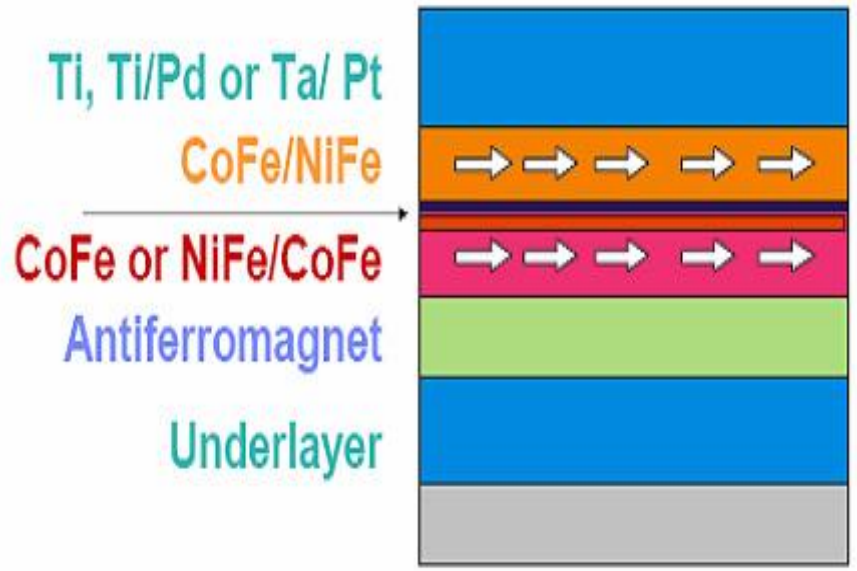
⇒ Collective behavior of many particles

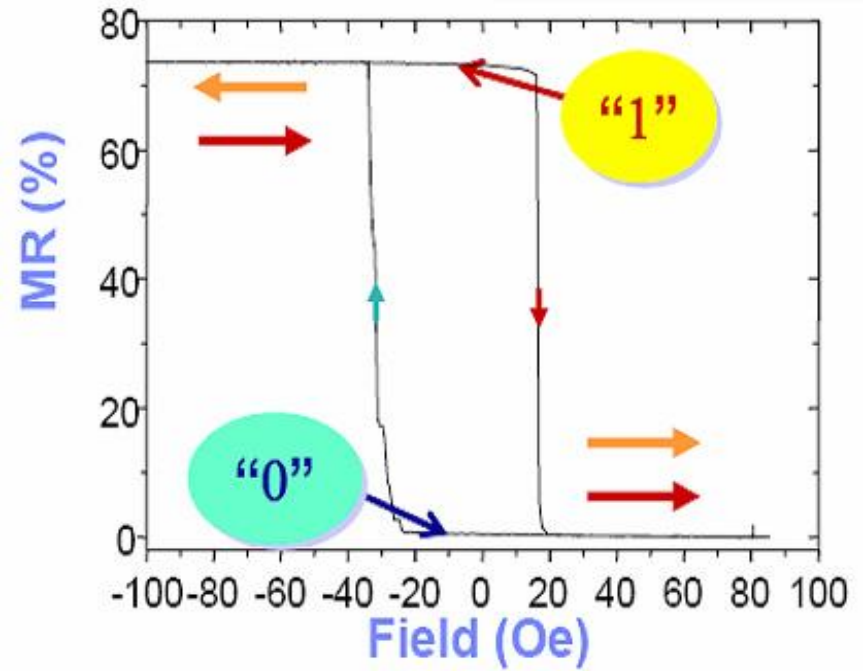
Classical/semi-classical phenomena

⇒ Quantum phenomena in macroscopic scale

Collective electron device scheme

Example: Giant magnetoresistance (GMR)





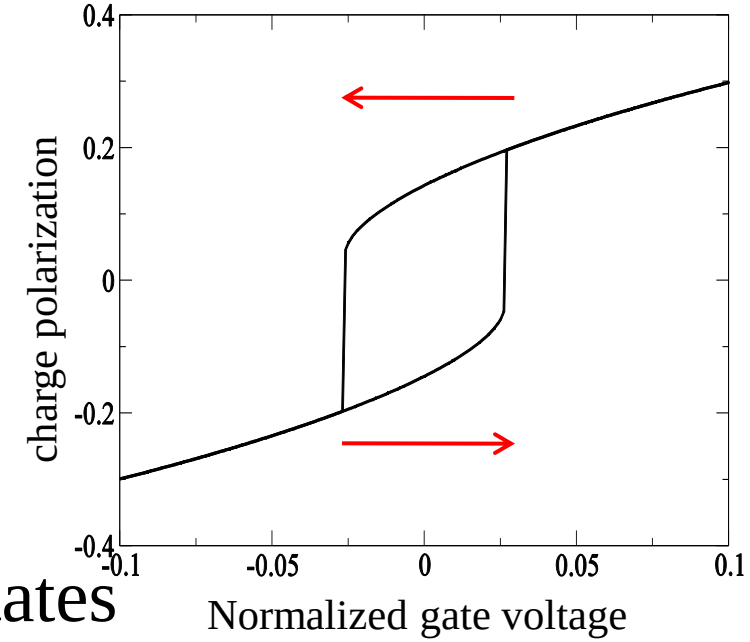
$\Rightarrow$ Collective behavior of many electrons

Magnetic field control of ordered states

Collective electron device scheme

Example: Pseudospin magnetism

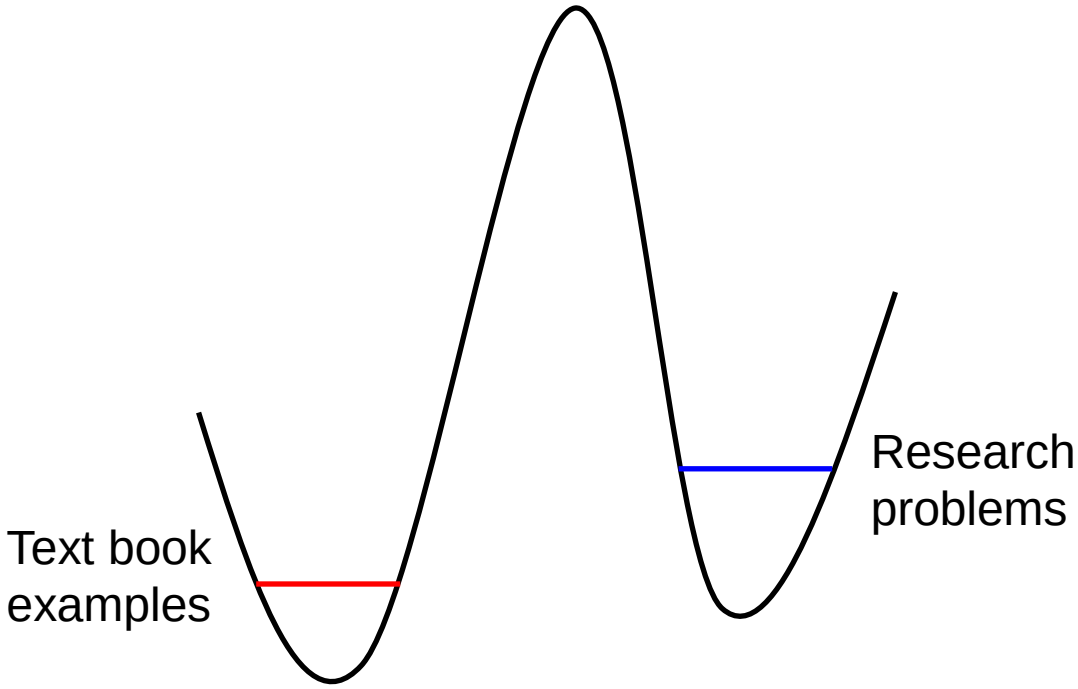
- Collective behavior of many electrons
- Can be switched with a small gate voltage change using much less power
- Electrical control of ordered states
- Can exhibit a pseudospin version of GMR and spin-transfer torque



Pseudospintronics!

Conclusion

Text book examples *vs* research problems



- Ask : Questions
- Seek : Motivation
- Knock : Doors