Chun Ning Lau
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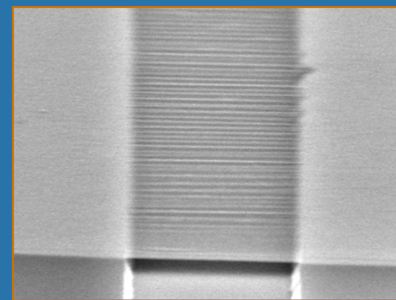
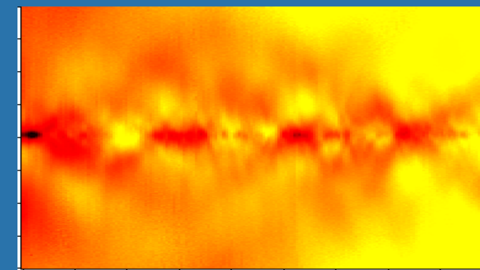
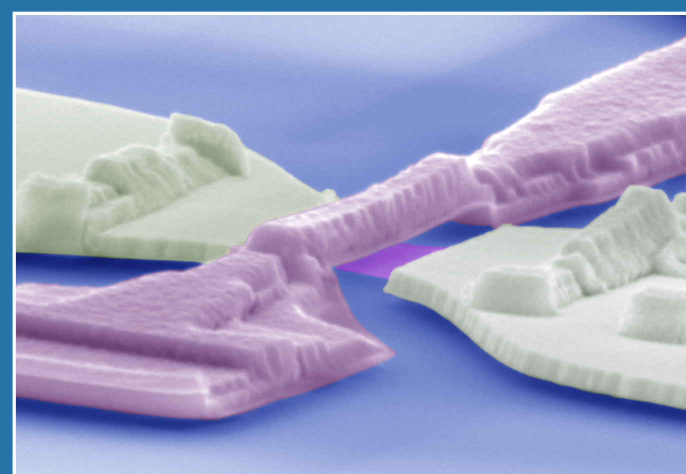




1, 2, 3…
Ripples, Gaps and Transport in Few-layer Graphene Membranes



Acknowledgments

Graduate Students

Yongjin Lee

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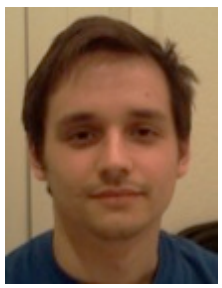
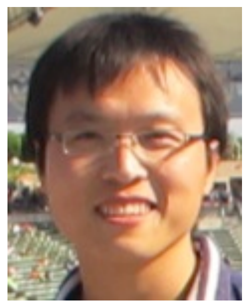


Nathaniel Gilgren



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DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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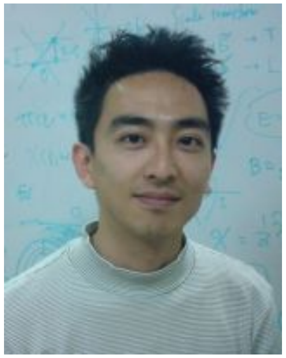


UT Austin
Allan MacDonald
Fan Zhang,Jeil Jung

USC
Steve Cronin

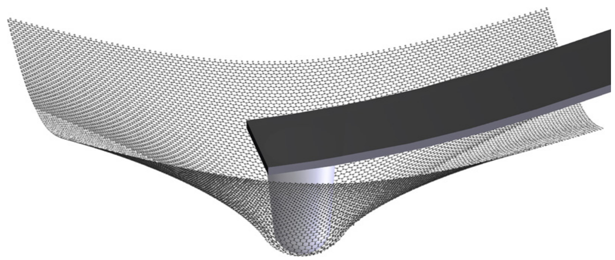
Outline

- Suspending Graphene Membranes
- Bilayer Graphene
  - Tunable gap (single particle)
  - Tunable gap (many body interactions)
  - Collective, symmtry-broken states in bilayer graphene
- Trilayer graphene
  - ABA and ABC stacking
  - Tunable interaction-induced gap in ABC-stacked trilayer

Outline

- Suspending Graphene Membranes
  -- free of substrate interference
  – intrinsic optical, mechanical, thermal and electrical properties
- Bilayer Graphene
  - Tunable gap (single particle)
  - Tunable gap (many body interactions)
  - Collective, symmtry-broken states in bilayer graphene
- Trilayer graphene
  - ABA and ABC stacking
  - Tunable interaction-induced gap in ABC-stacked trilayer

Strange Graphene Mechanics



Source: Columbia Univ.

Graphene is very strong and tough

Breaking strength is ~ 200 times of steel

Graphene is very elastic

can be stretched by 25% and return to its original shape
(most materials can only be stretched by one-tenth of 1 percent)

Graphene is very soft

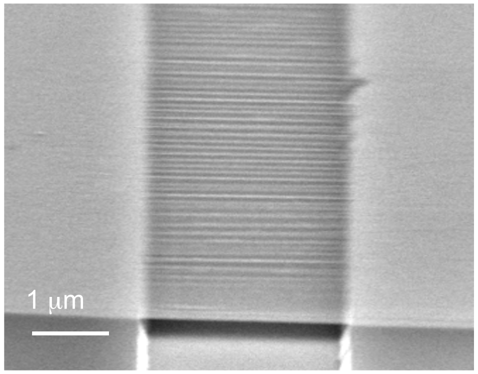
Single atomic layer, bends or
buckles very easily

Mechanical Properties: Periodic Ripple Formation

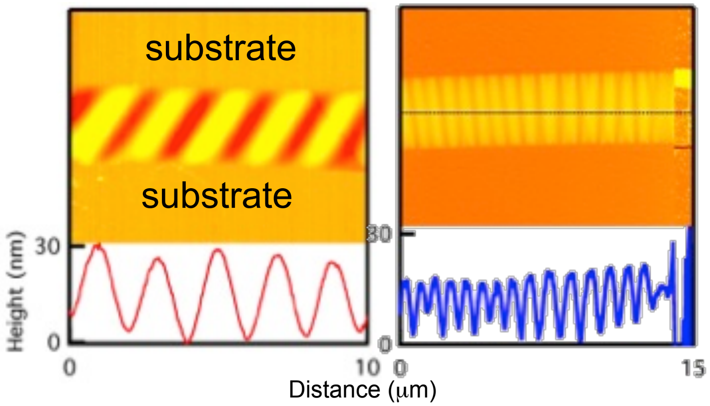
Directly exfoliate graphene sheets across pre-defined trenches

- Many graphene sheets are not flat, but spontaneously form ripples
- Almost perfectly sinusoidal profile
  - ♦ thickness: 0.3 nm (single layer) -- 16 nm
  - ♦ amplitude: 0.7 to 30 nm
  - ♦ wavelength: 370 nm – 5 μm

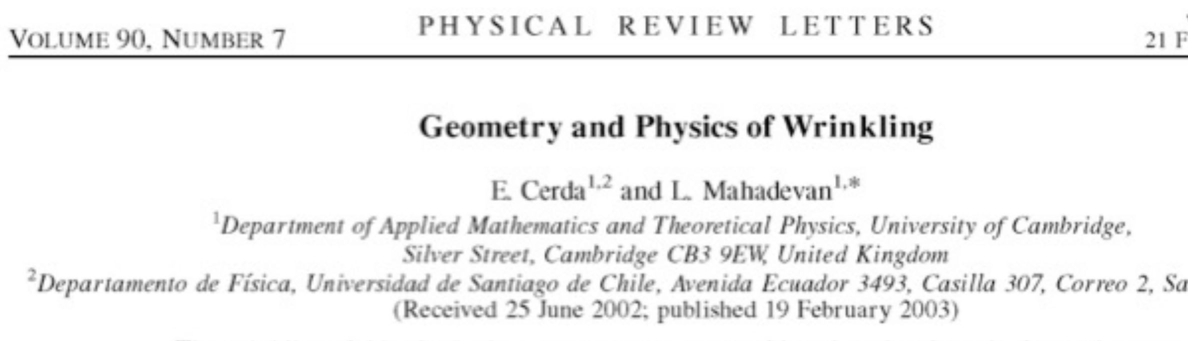
SEM



AFM



Graphene as an Elastic Membrane


VOLUME 90, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 21 FEBRUARY 2003

Geometry and Physics of Wrinkling

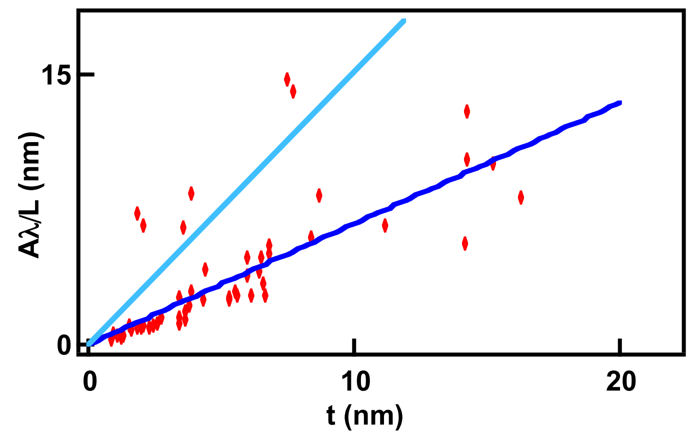
E. Cerda[1,2] and L. Mahadevan[1,*]
[1]*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, United Kingdom*
[2]*Departamento de Física, Universidad de Santiago de Chile, Avenida Ecuador 3493, Casilla 307, Correo 2, San*
(Received 25 June 2002; published 19 February 2003)

- competition between bending and stretching
- ripples induced by longitudinal strains or shears

$$\frac{A\lambda}{L} = \sqrt{\frac{8\nu}{3(1-\nu^2)}}\,t$$ in-plane shear

$$\frac{A\lambda}{L} = \sqrt{\frac{8}{3(1+\nu)}}\,t$$ in-plane strain

Data from 51 samples



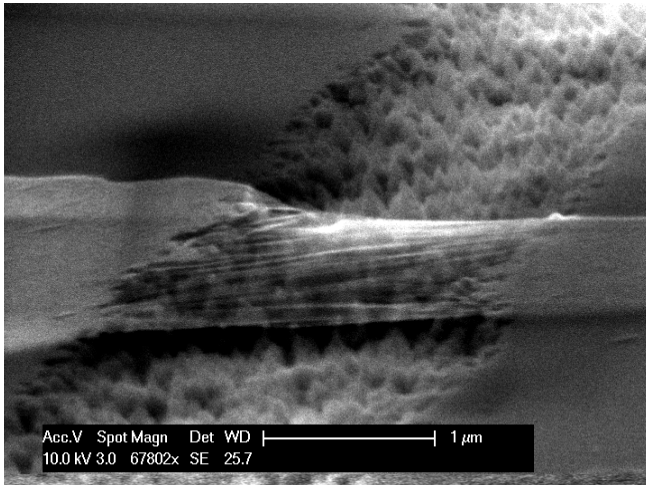
A=amplitude, *L*=length, λ=wavelength,
t=thickness, ν=Poisson ratio~0.165

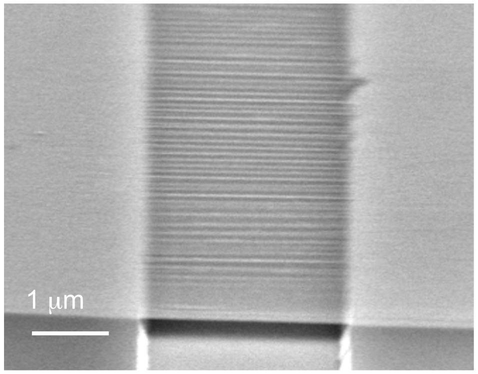
W. Bao, F. Miao, Z. Chen, H. Zhang, W. Jang, C. Dames, and C. N. Lau, Nature Nanotechnology, 4, 562 (2009).

Graphene as the World's thinnest Saran Wrap

macroscopic

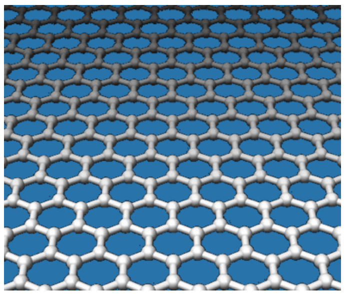
mesoscopic

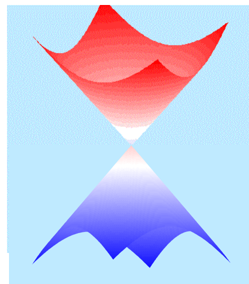




Graphene's Double Identity

Extraordinary Conductor

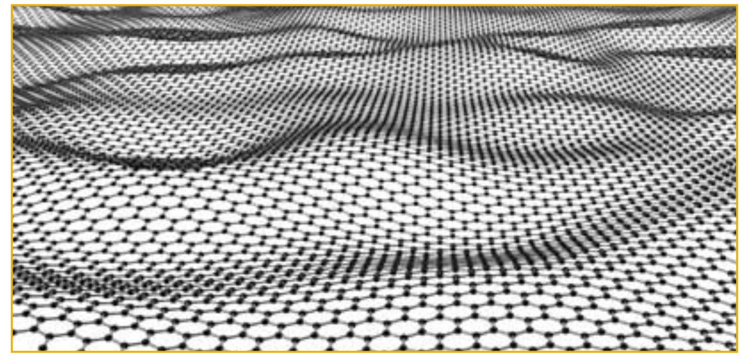




New model system for condensed matter research and electronic materials

Linear dispersion, tunable carrier, surface 2DEG, high thermal and electrical conductivity
….

2D Elastic Membrane



Thinnest isolated membrane with exceptional mechanical properties

Castro Neto, Guinea, Katsnelson, Brey, Louie, etc

Exploit Electrical Properties of Rippled Graphene?

superlattices, strain-based engineering…

Engineering Based on Strain and Ripples

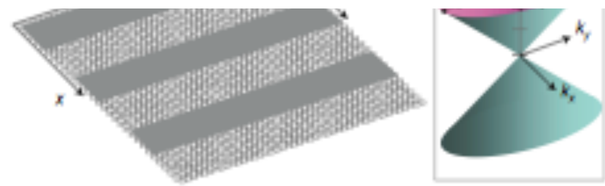
All-graphene integrated circuits via strain engineering

Vitor M. Pereira, Antonio H. Castro Neto

(Submitted on 27 Oct 2008 (v1), last revised 19 Feb 2009 (this version, v3))

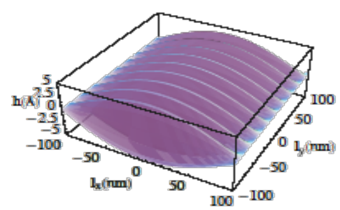
We propose a route to all-graphene integrated electronic devices by exploring the influence of strain on the electronic structure of graphene. We show that strain can be easily tailored to generate electron beam collimation, 1D channels, surface states and confinement, the basic elements for all-graphene electronics. In addition this proposal has the advantage that patterning can be made on substrates rather than on the graphene sheet, thereby protecting the integrity of the latter.

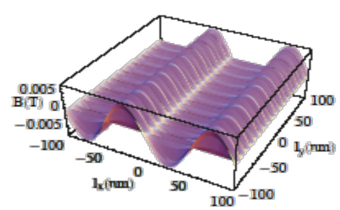
Novikov & Levitov, PRL (2006)
Brey & Fertig, arxiv (2009).



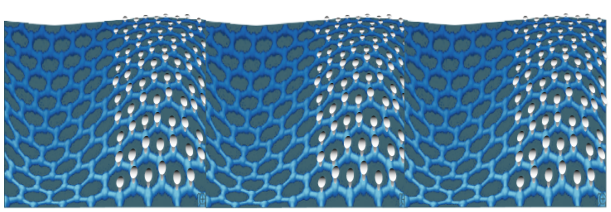
Park, Yang, Son, Cohen, Louie, *Nature Physics* (2008)

- Modified band structure
- Anisotropic transport
- Supercollimation
- Inducing effective magnetic field
- Selective sp^2-sp^3 modification





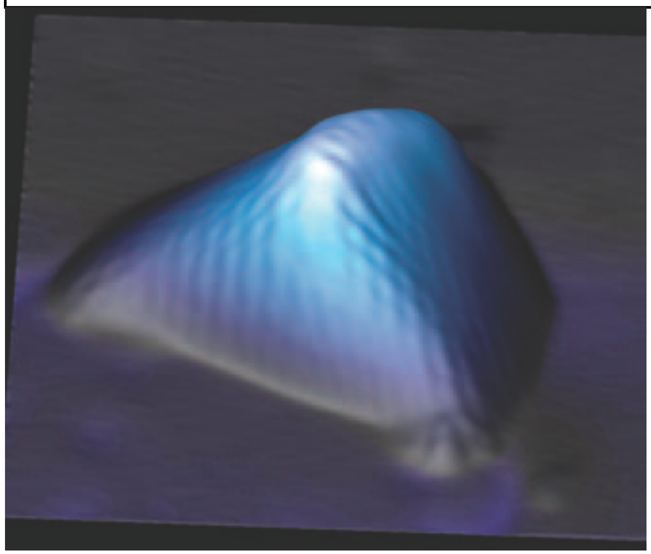
Paco Guinea, Katsnelson and co.



Engineering Based on Strain and Ripples

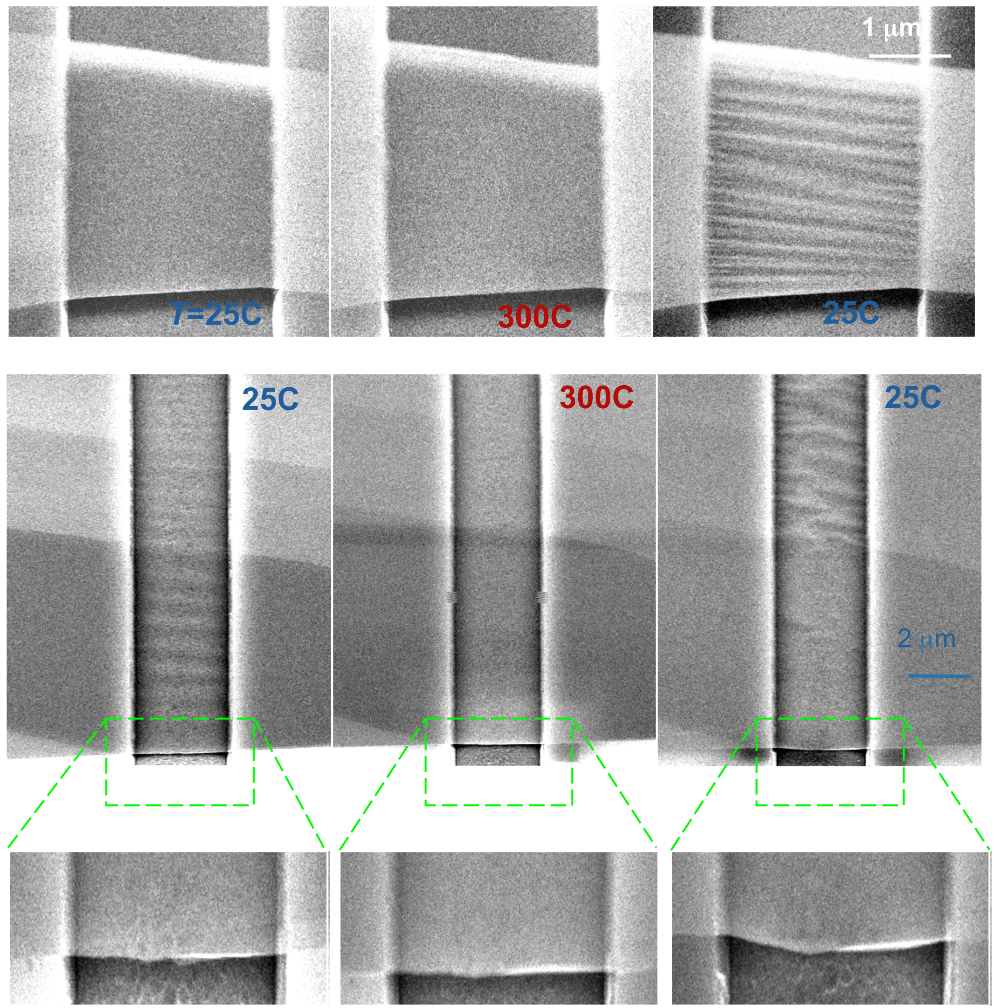
Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

N. Levy,[1,2]*† S. A. Burke,[1]*‡ K. L. Meaker,[1] M. Panlasigui,[1] A. Zettl,[1,2] F. Guinea,[3] A. H. Castro Neto,[4] M. F. Crommie[1,2]§



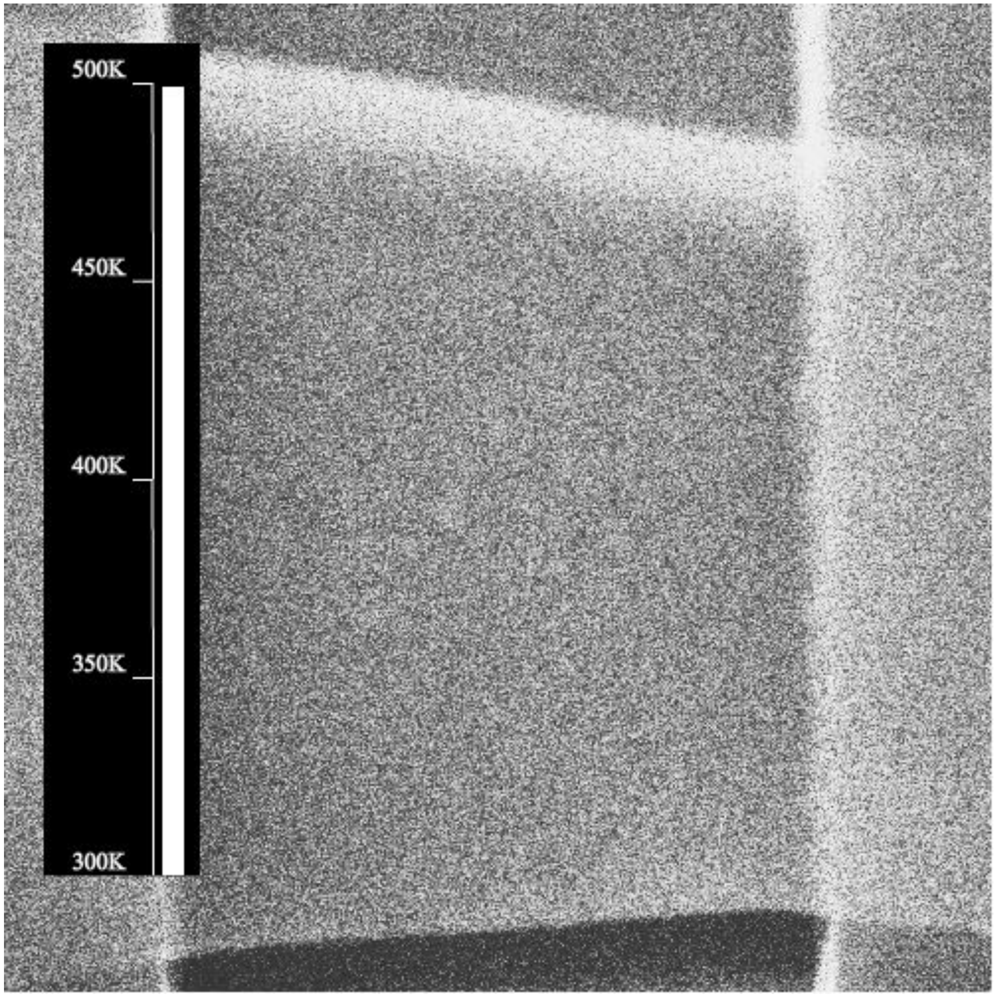
Highest steady magnetic field on earth:
= 45T
in National High Magnetic Field Lab,
Tallahassee, FL.

In Situ SEM imaging of annealing effect

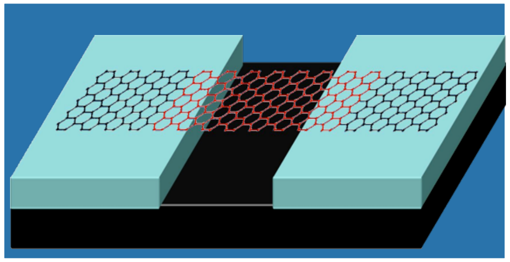


- Ripples have larger wavelengths and amplitudes
- Membranes buckles upward or towards the bottom of the trench

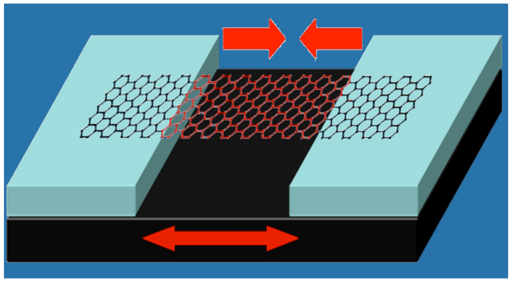
Movie of ripple formation



Mechanism of ripple formation

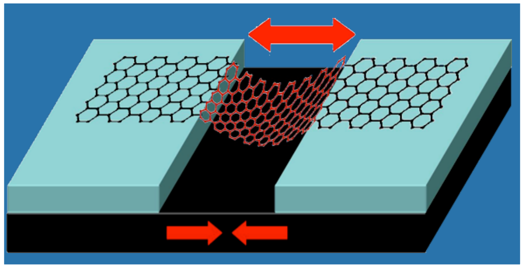


Graphene has a *negative* thermal expansion coefficient



Heating

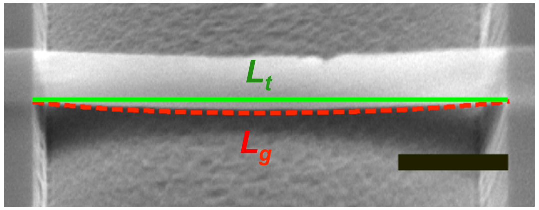
graphene contracts, substrate expands
→ erasing pre-existing ripples



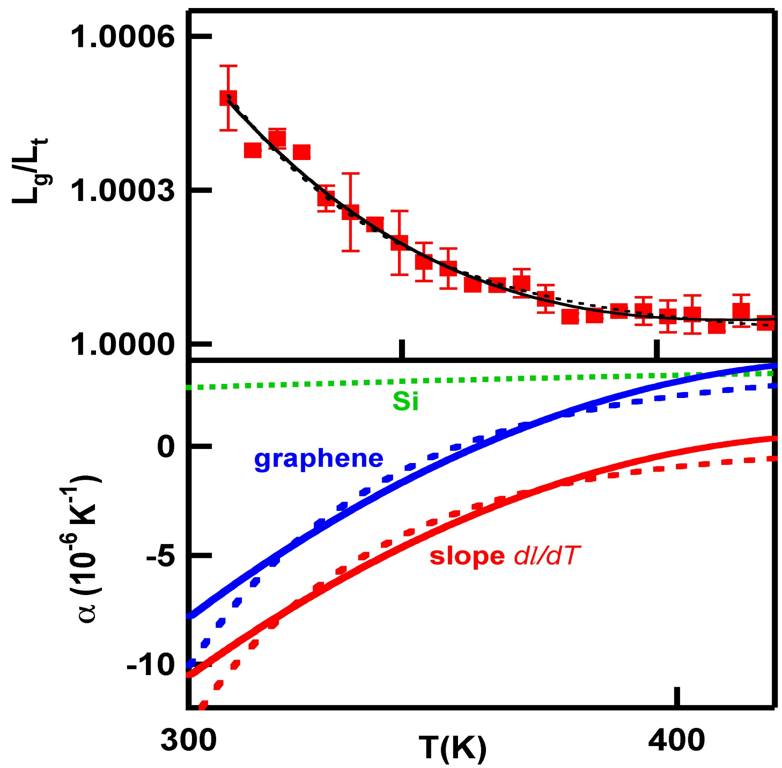
Cooling

• graphene expands, substrate contracts
• bending is easier than sliding
→ edges remain pinned by the trench edges
→ ripples (transverse)
slacks (longitudinal)

Measurement of Thermal Expansion Coefficient



- Single layer graphene heated to 500 K and cools down slowly
- Compute $l(T)=L_g(T)/L_t(T)$ at different temperatures
- Slope $b = \frac{dl}{dT} \approx \alpha - \alpha_{Si}$
- Important for graphene synthesis and thermal management of graphene electronics

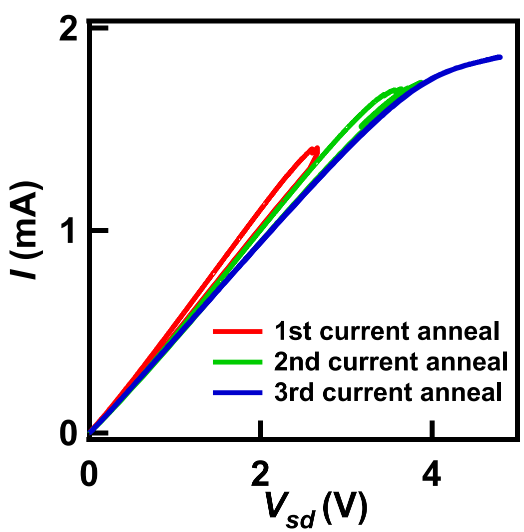


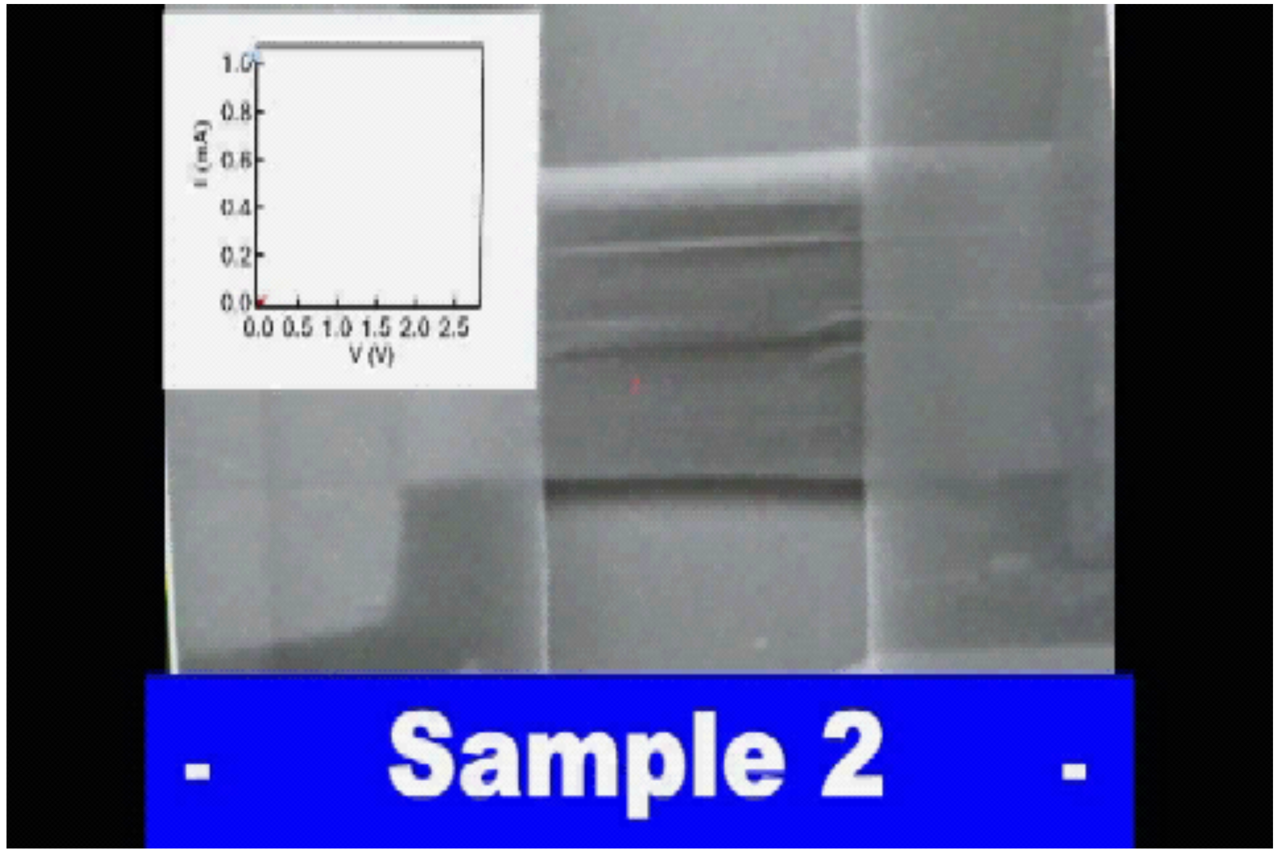
W. Bao, F. Miao, Z. Chen, H. Zhang, W. Jang, C. Dames, and C. N. Lau, Nature Nanotechnology, 4, 562 (2009).

Current Annealing

Moser et al, APL.

- Current annealing performed at 4K
- Optimal when current saturates, ~0.2mA/layer/μm

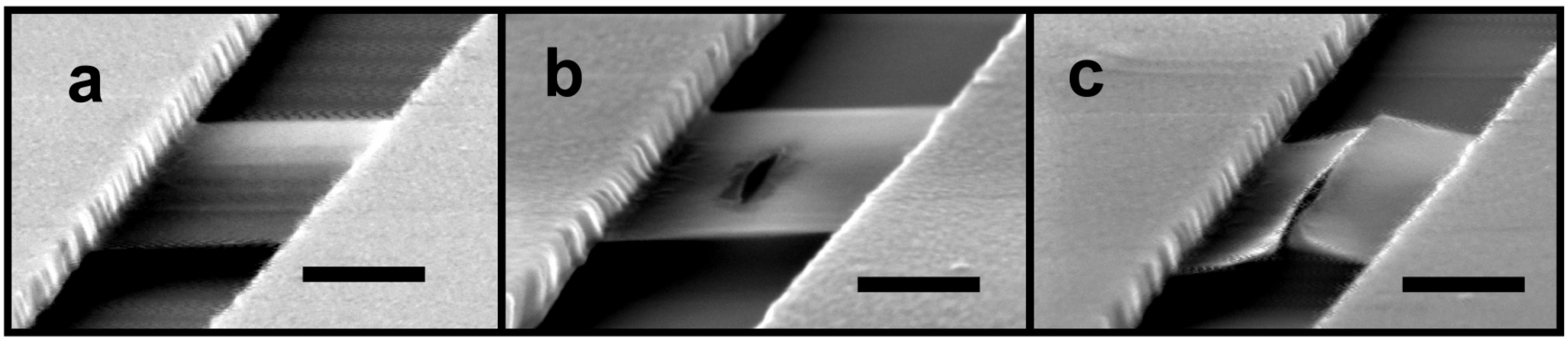




H. Zhang, W. Bao, Z. Zhao, J.-W. Huang, B. Standley, G. Liu, F. Wang, P. Kratz, L. Jing, M. Bockrath, C. N. Lau, Nano Lett., 12, 1772 (2012)

In situ Imaging of Annealing and Electromigration

Further annealing
→Ripple starts to form due to negative thermal expansion of graphene
→abrupt changes in I-V curves
→Electromigration occurs



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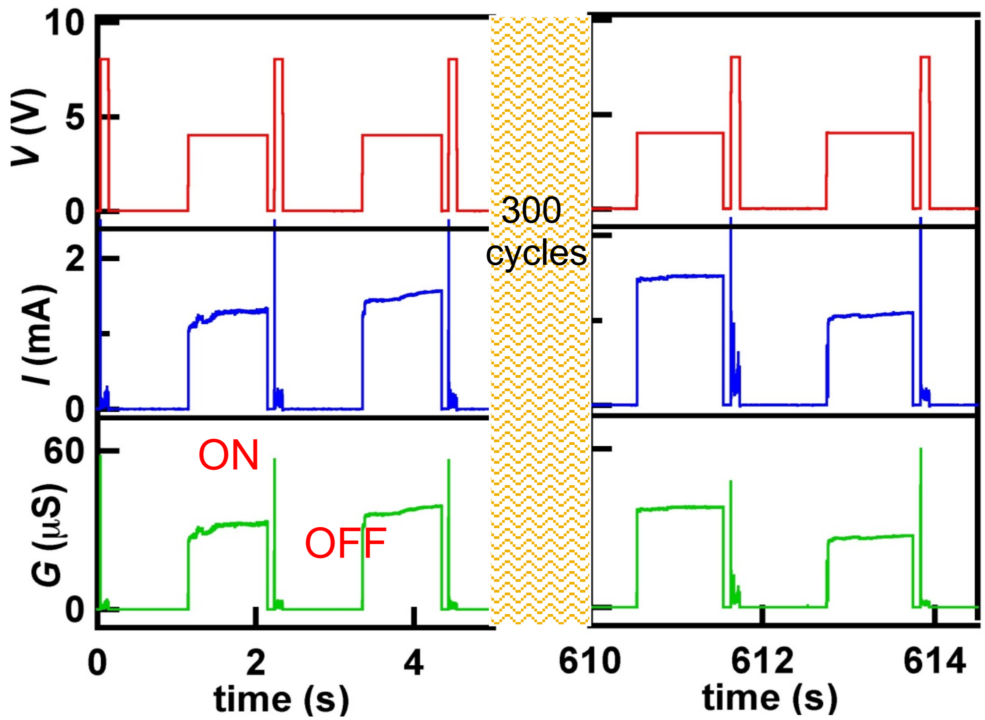
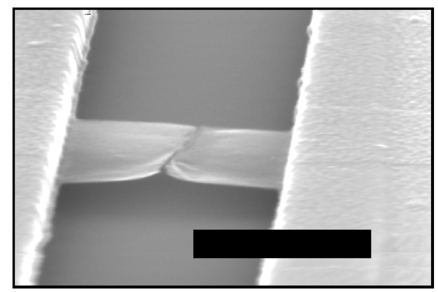
Atomic Switches in Suspended Graphene

- After electromigration → atomic switches
- Reversible, cyclable switching
- Proposed mechanism: formation and dissolution of carbon chains





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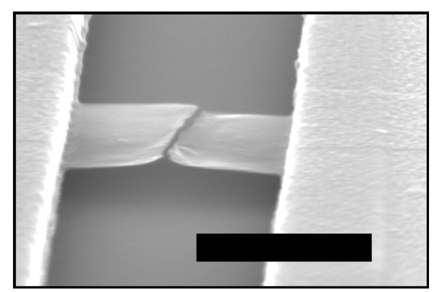


OFF

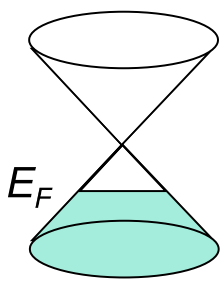
H. Zhang, W. Bao, Z. Zhao, J.-W. Huang, B. Standley, G. Liu, F. Wang, P. Kratz, L. Jing, M. Bockrath, C. N. Lau, Nano Lett., 12, 1772 (2012)

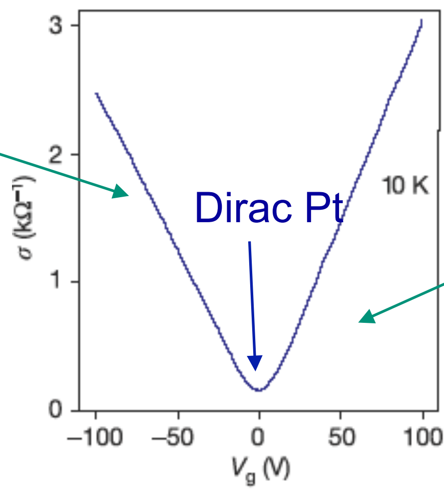
Outline

- Suspending Graphene Membranes
- Band gap engineering in Bilayer Graphene
  - Tunable gap (single particle)
  - Tunable gap (many body interactions)
  - Collective, symmtry-broken states in bilayer graphene
- Trilayer graphene
  - ABA and ABC stacking
  - Tunable interaction-induced gap in ABC-stacked trilayer

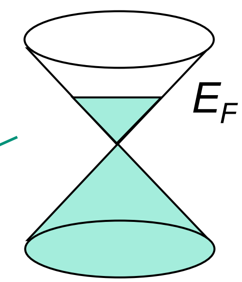
Graphene Bipolar FET

Hole doped



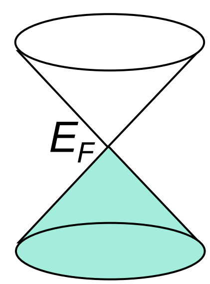


Electron doped



Novoselov et al, *Science*, 2004.

Miao et al, *Science*, 2007.



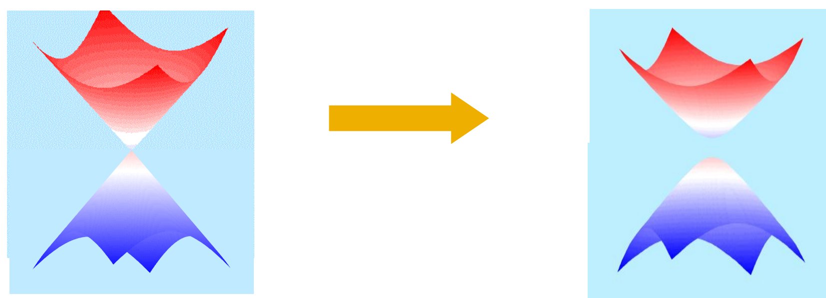
- Conductivity increases (more or less) linearly with charge density *n* $\sigma \propto V_g \propto n$
- σ remains finite at Dirac point → σ_{min}

  (Novoselov *et al*, *Nature*, 2005, Zhang et al, *Nature* 2005, Lau group, *Science* 2007; Kim group, Fuhrer group, Das Sarma group, Ando, Castro Neto, Katsnelson, Beenakker, Guinea, Lee, Peres…)
- mobility up to 10^6 cm^2/Vs; High current density (10^8 -10^9 mA/μm, or μA/atomic row)

Band Gap Engineering

- What makes graphene such a wonderful conductor also gives rise to its critical weakness
- Gapless: not useful for digital electronics

→ Band gap engineering



- Many proposals
  - Nanoribbons
  - Chemical modification
  - Strain-based engineering
  - Bilayer and trilayer

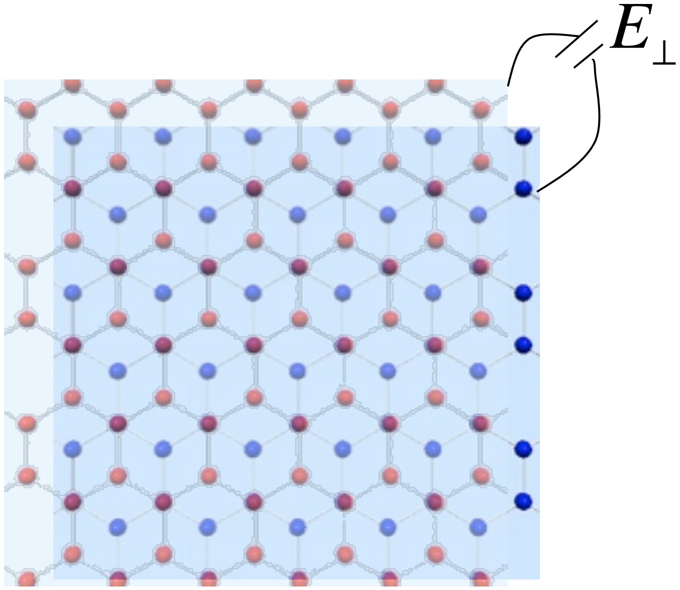
most cases: transport gap induced by disordered edges, not true band gap (Nanoribbons, Chemical modification)

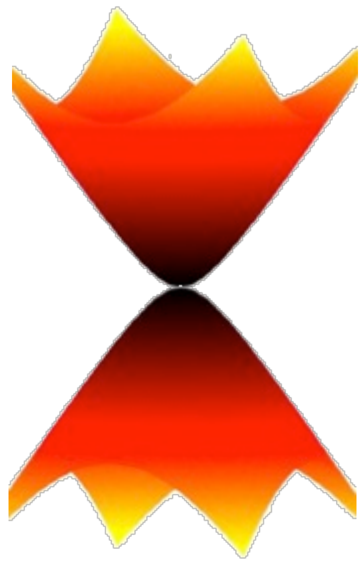
→ requires very large strain (Strain-based engineering)

Bilayer and Trilayer

- ✓Truly 2D material
- ✓Quadratic and cubic Dispersion Relations: massive Dirac fermions
- ✓Surface 2DEG with tunable charge density and type
  - ✓Optical, STM and mechanical measurements
  - ✓Easily coupled to special electrodes (superconductors, ferromagnets)
- ✓the ultimate elastic membrane
  - ✓Morphology ⇔ electronic properties
- ✓High Mobility (up to $10^5 – 10^6$ cm^2/Vs)
- ✓High thermal conductivity
- ✓Chemically inert and stable
- ✓Tunable band gaps (both single-particle and interaction-induced)
- ✓Interaction-induced collective states

Bilayer Graphene (BLG) – Single Particle Picture



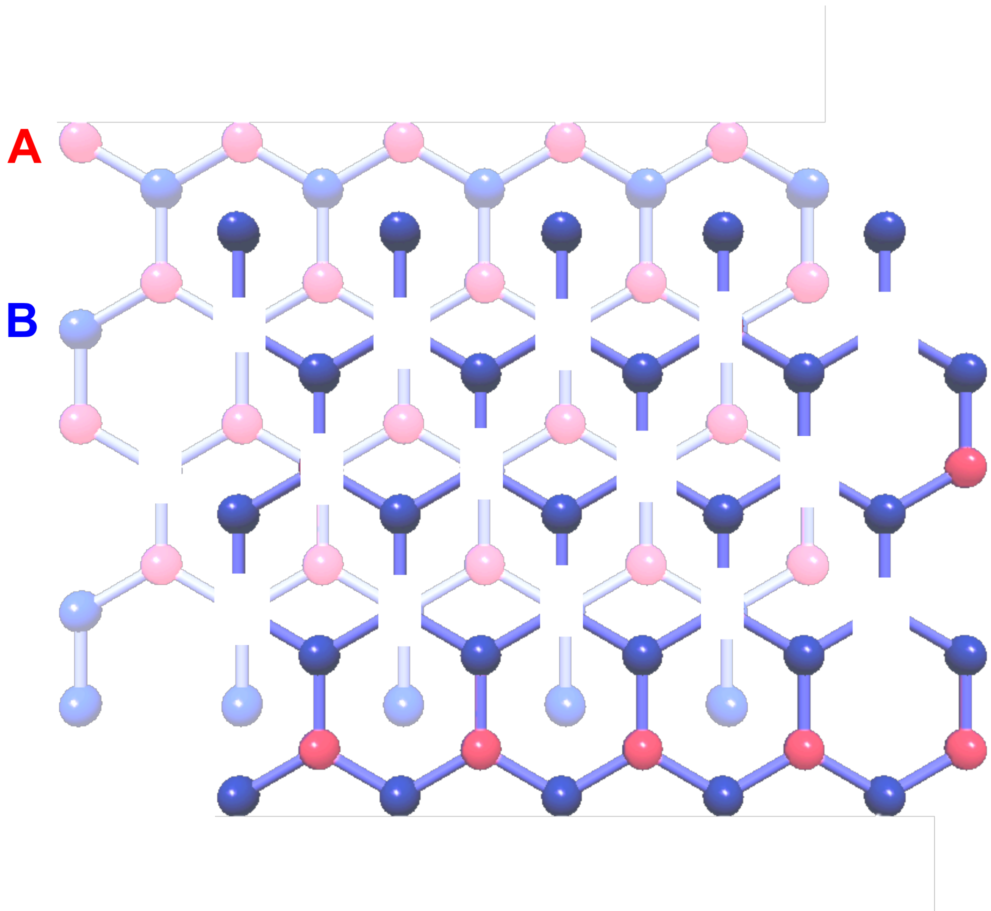


- Quadratic dispersion with zero band gap

McCann PRB 2006; McCann & Fal' ko PRL 2006;Castro *et al* PRL 2007; Castro Neto *et al* PRB

Morpurgo group, Nature Materials 2008; Avouris group, Nano Lett., 2010; Szafranek *et al*, APL 2010; Wang group, Nature 2009; Zhu group, PRB 2010; Fuhrer group, Nano Lett. 2010; Jarillo-Herrero group, PRL 2010; Lau group, Nano Lett. 2010.

Bilayer Graphene – Single particle gap

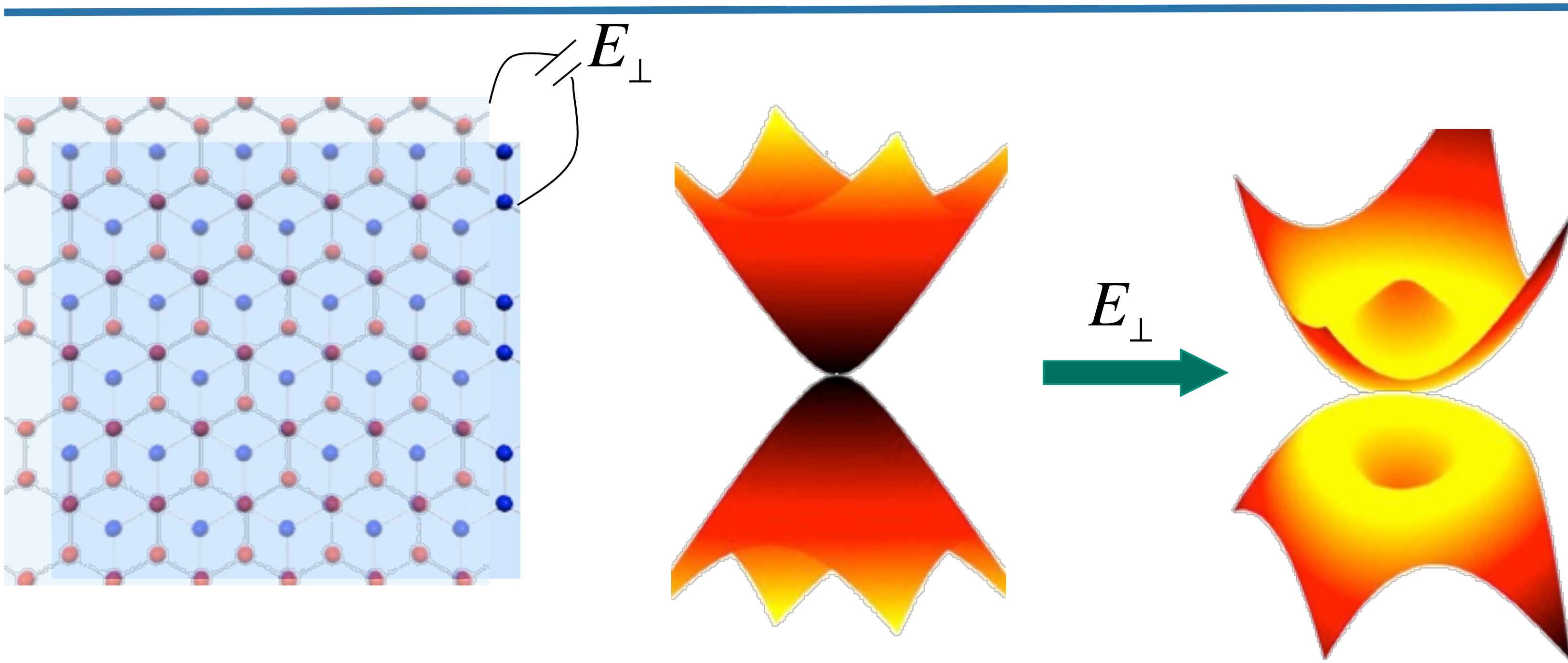


- Stacked atoms hybridize to form higher energy bands
- Left with A sub-lattice from top layer and B sub-lattice from bottom layer
- A-B symmetry <-> layer symmetry
- Out-of-plane electric field breaks A-B symmetry → generate a gap

Lui et al Nano Lett. 2010

Aoki *et al, Solid state commun.* 2007; McCann PRB 2009; Guinea et al PRB 2006

Bilayer Graphene (BLG) – Single Particle Picture

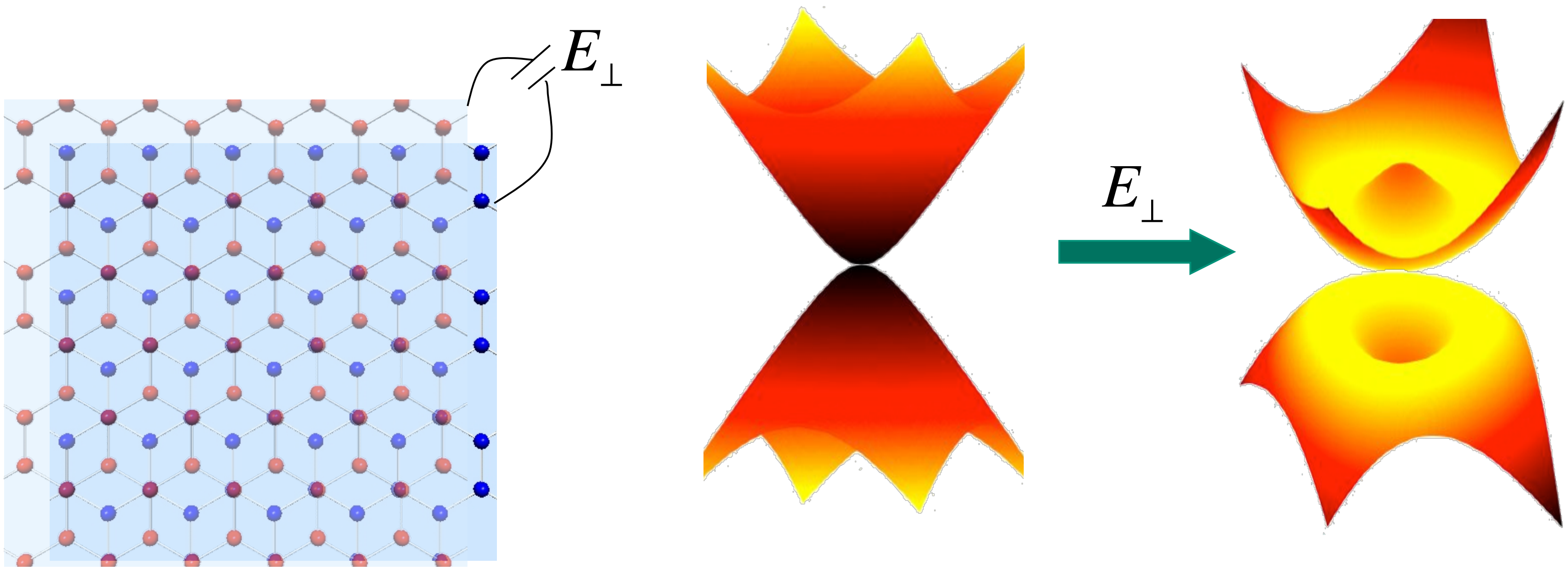


- Quadratic dispersion with zero band gap
- Perpendicular electric field induces band gap

McCann PRB 2006; McCann & Fal'ko PRL 2006;Castro *et al* PRL 2007; Castro Neto *et al* PRB

Morpurgo group, Nature Materials 2008; Avouris group, Nano Lett., 2010; Szafranek *et al*, APL 2010; Wang group, Nature 2009; Zhu group, PRB 2010; Fuhrer group, Nano Lett. 2010; Jarillo-Herrero group, PRL 2010; Lau group, Nano Lett. 2010.

Bilayer Graphene (BLG) – Band Structure



McCann PRB 2006; McCann & Fal'ko PRL 2006;Castro *et al* PRL 2007; Castro Neto *et al* PRB

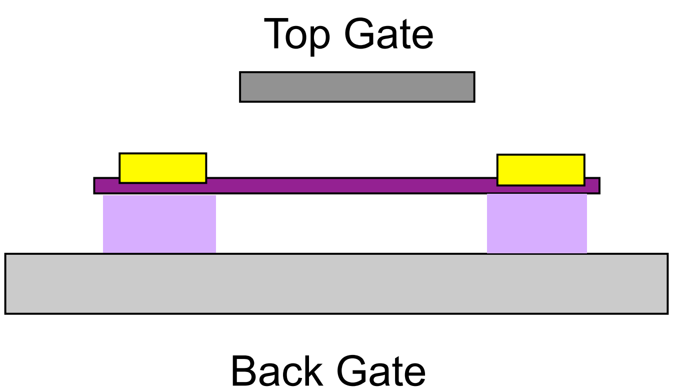
- Quadratic dispersion with zero band gap
- Perpendicular electric field $E_\perp$ breaks sublattice and inversion symmetry

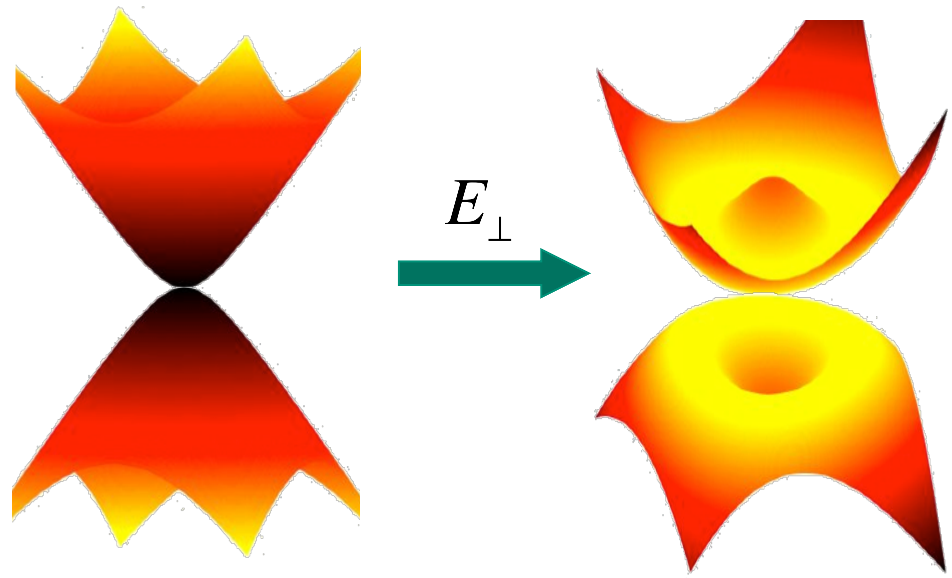
→ opens band gap

- Tunable Band gap ($\propto$ electric field)

Morpurgo group, Nature Materials 2008; Avouris group, Nano Lett., 2010; Szafranek *et al*, APL 2010; Wang group, Nature 2009; Zhu group, PRB 2010; Fuhrer group, Nano Lett. 2010; Jarillo-Herrero group, PRL 2010; Lau group, Nano Lett. 2010.

Necessity for Dual Gates





McCann PRB 2006; McCann & Fal' ko PRL 2006;Castro *et al* PRL 2007; Castro Neto *et al* PRB

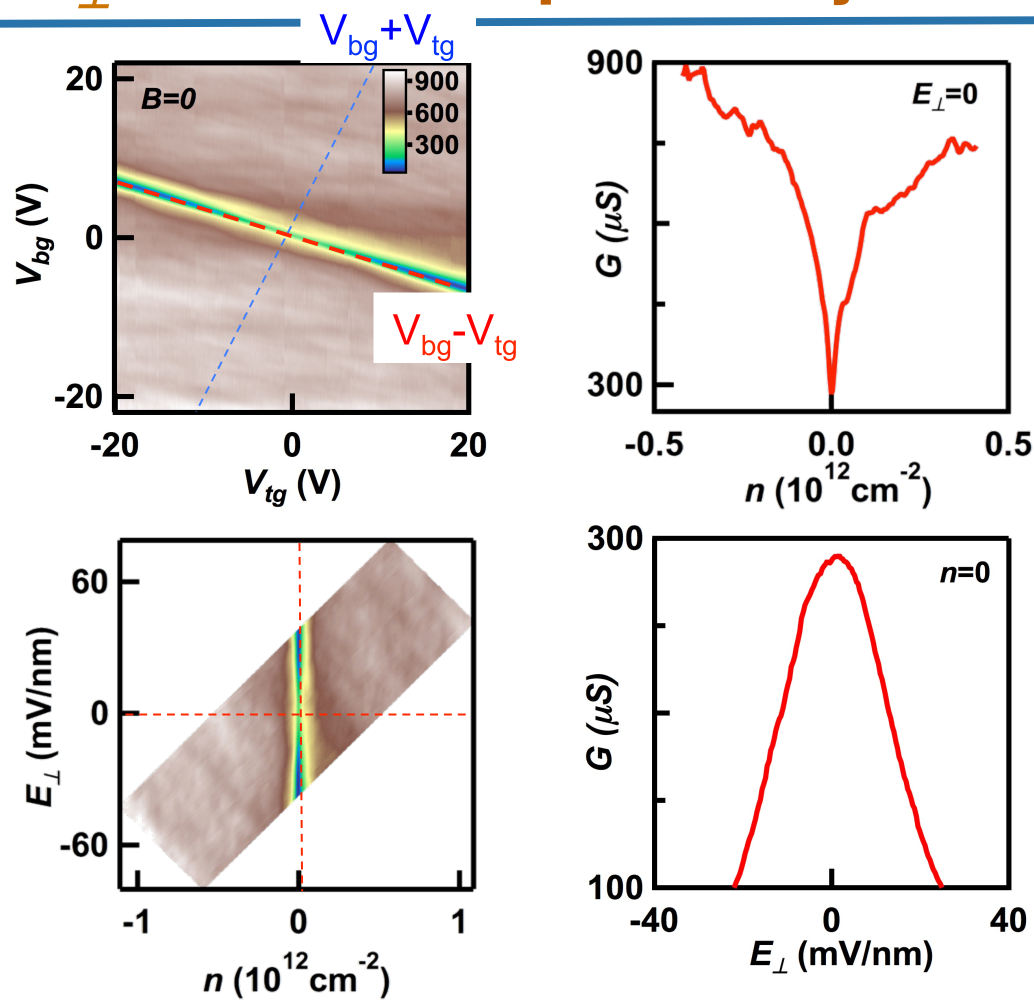
- In single-gated devices, $E_\perp$ scales with charge density *n*
- Dual-gated devices:

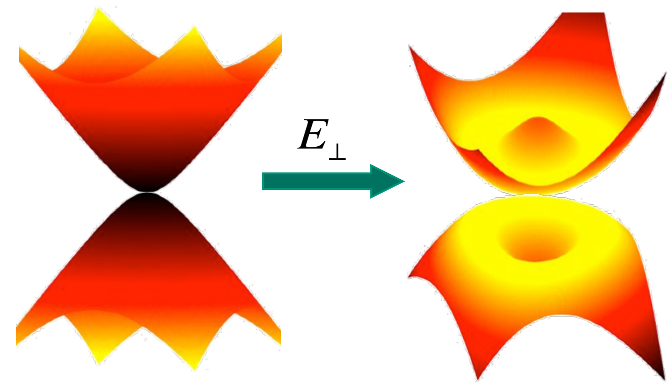
$$n \propto V_{bg} + V_{tg}$$

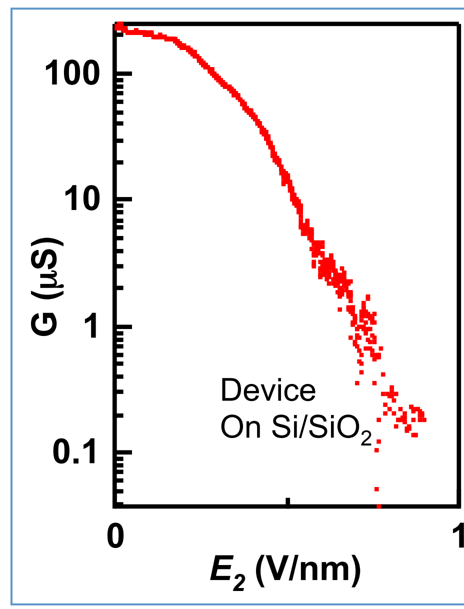
$$E_\perp \propto V_{bg} - V_{tg}$$

Lau group, APL 2007, New J. Phys. 2008; Savchenko group, Nano Lett. 2007; Marcus group, Science 2007; Goldhaber-Gordon group, PRL 2007.

$E_\perp$-induced Gap of Bilayer Graphene



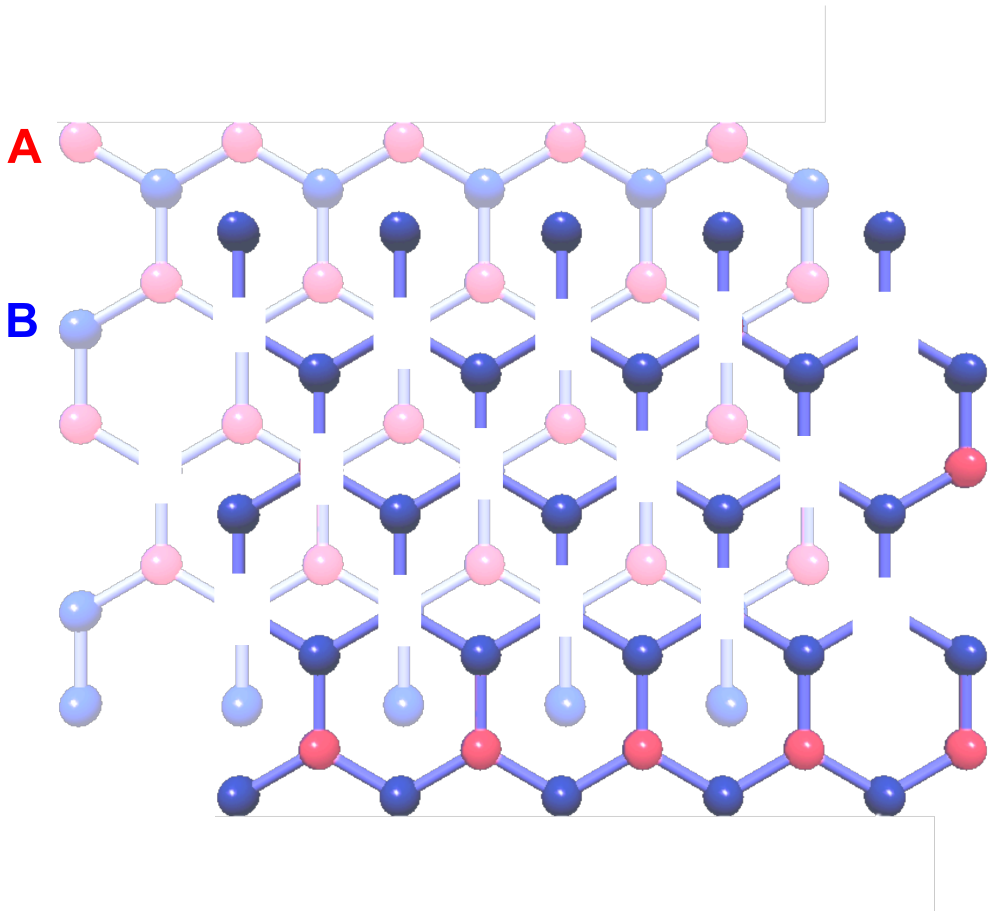




McCann &
astro *et al*
eto *et al* PRB

- Device mobility ~ 10,000 cm^2/Vs
- Tunable Band gap ($\propto$ electric field), G~exp($-E_\perp$)
- *needs very large voltages*

Bilayer Graphene – Interaction-induced gap



- Stacked atoms hybridize to form higher energy bands
- Left with A sub-lattice from top layer and B sub-lattice from bottom layer
- A-B symmetry <-> layer symmetry

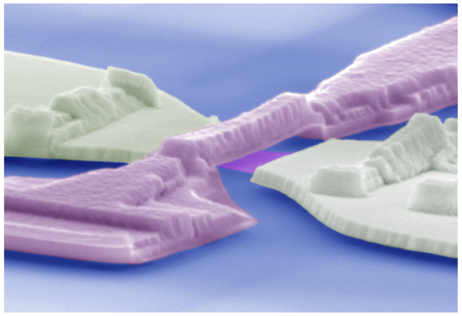
electronic interactions spontaneously

- ~~Out-of-plane electric field~~ breaks A-B symmetry → generate a gap

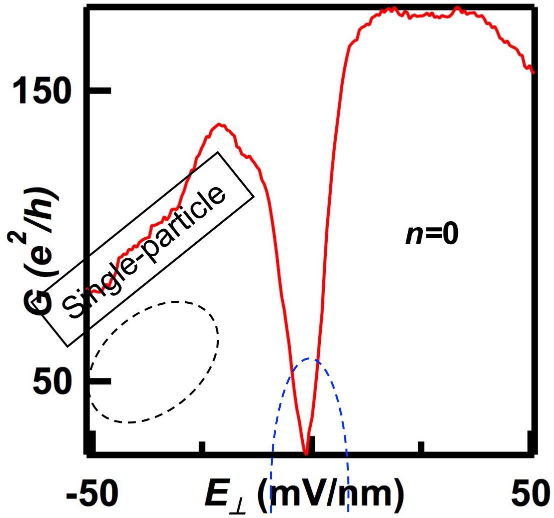
Lui et al Nano Lett. 2010

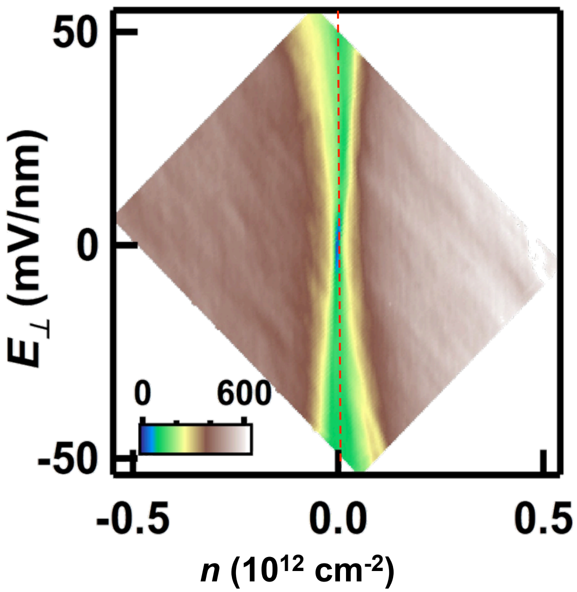
Aoki *et al, Solid state commun.* 2007; McCann PRB 2009; Guinea et al PRB 2006

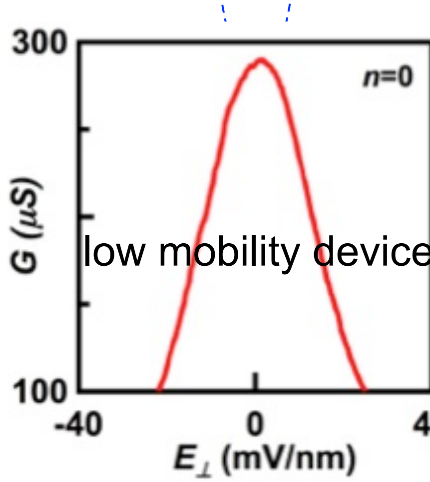
High Mobility Bilayer Devices

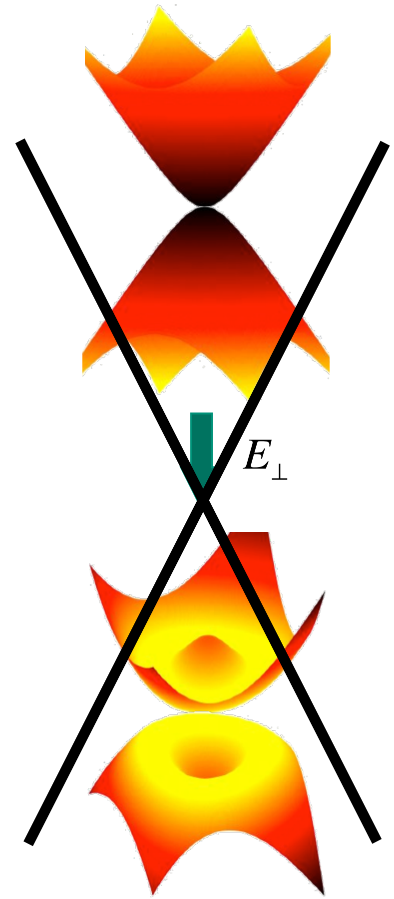


Device mobility ~ 80,000 cm^2/Vs









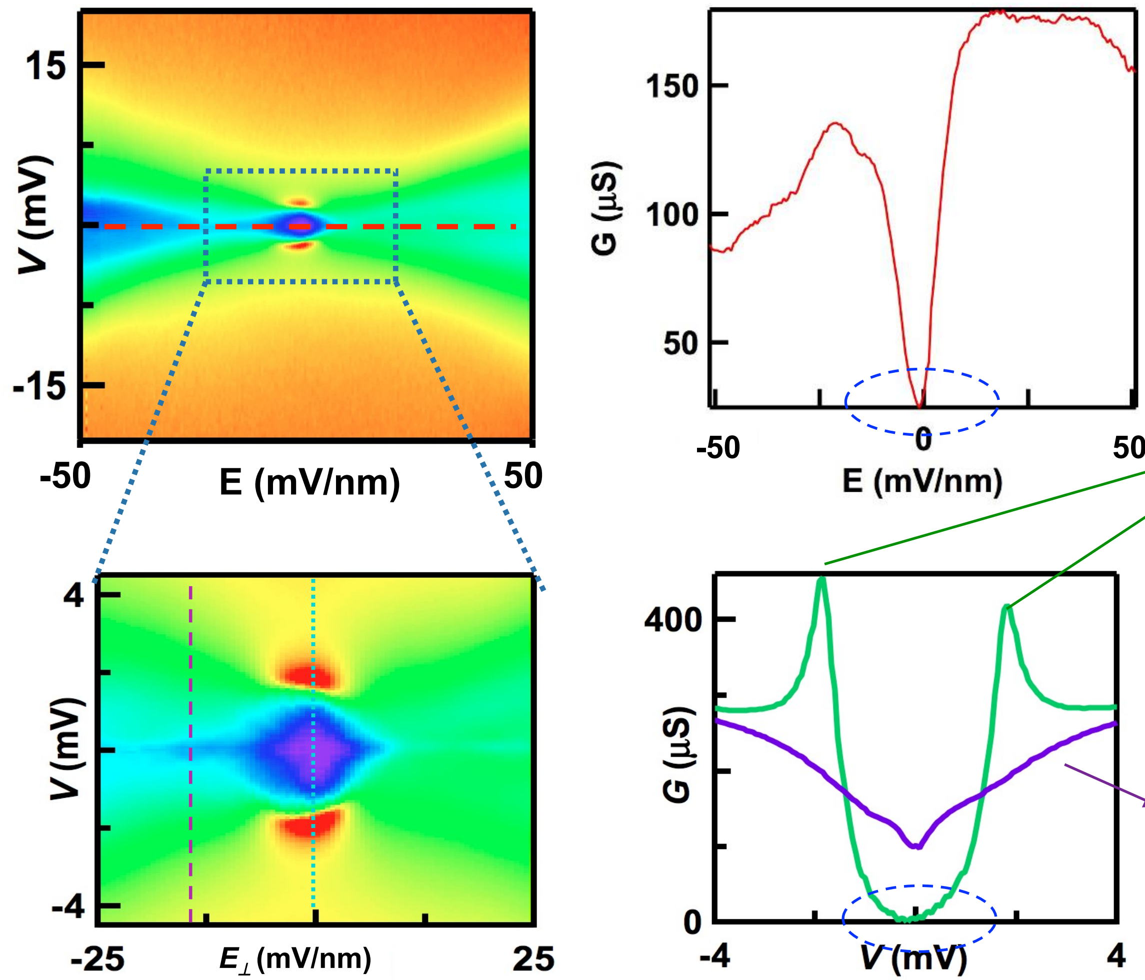
Lowest conductance (insulating) at *n=E=0.*

- contradicts single particle picture

See also R. T. Weitz, M. T. Allen, B. E. Feldman, J. Martin, A. Yacoby, Science, 330, 812 (2010).

Insulating State and Intrinsic Gap

dI/dV vs. Electric field and source-drain bias at charge neutrality point



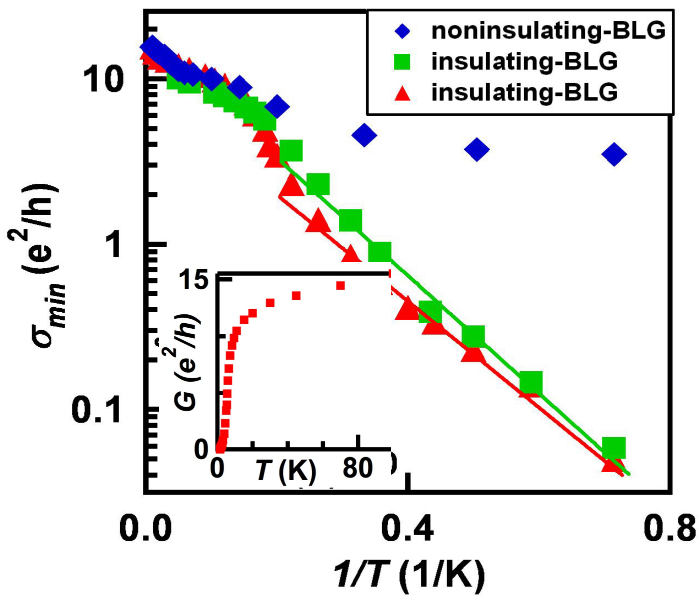
Insulating at V=n=E=0 (R~ MΩ)

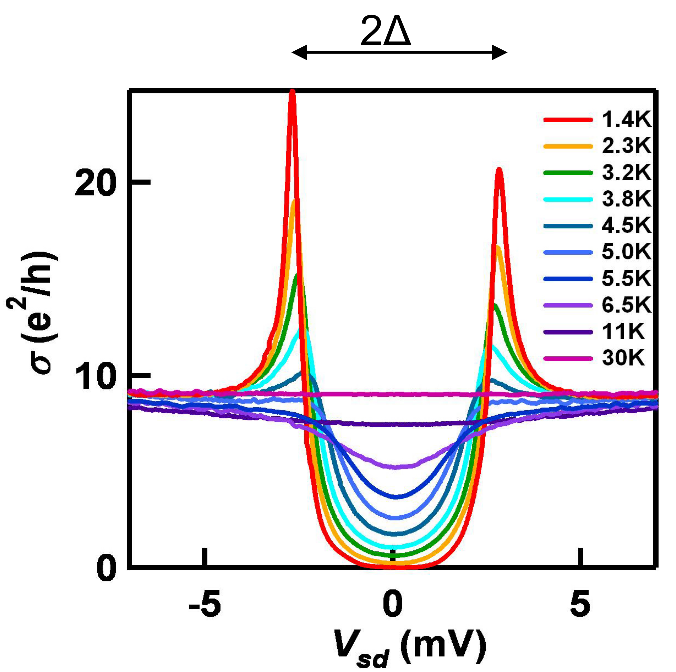
dI/dV resembles the density of states of a gapped state
→ an **intrinsic gapped** ground state ~ 2meV

- Gap can be closed by electric field of either polarity ~ 12 meV/nm.

J. Velasco Jr., L. Jing, W. Bao, Y. Lee, P. Kratz, V. Aji, M. Bockrath, C.N. Lau, C. Varma, R. Stillwell, D. Smirnov, Fan Zhang, J. Jung, A.H. MacDonald, Nature Nanotechnol., 7, 156 (2012).

Temperature Dependence





- Consistent $\sigma_{min}(T)$ dependence among different devices for 5<T<130K
- At 5K
  - abrupt change in slope of $\sigma_{min}(T)$
  - deviation between insulating and non-insulating devices
  - *dI/dV* side peaks disappear

➔Transition from insulating to conductive states, T_c ~ 5K, activation gap ~ 1.8 meV

W. Bao, J. Velasco Jr, F. Zhang, L. Jing, B. Standley, D. Smirnov, M. Bockrath, A. MacDonald, C.N. Lau, PNAS, 109, 10802 (2012).

Collective State(s) at the Dirac Point in BLG

- Strong interaction at the Dirac point → broken symmetry states

Experimental Work

- R. T. Weitz, M. T. Allen, B. E. Feldman, J. Martin, A. Yacoby, Science, 330, 812 (2010).
- J. Martin, B. E. Feldman, R. T. Weitz, M. T. Allen, A. Yacoby, Phys. Rev. Lett. 105, 256806 (2010).
- A. S. Mayorov, D. C. Elias, M. Mucha-Kruczynski, R. V. Gorbachev, T. Tudorovskiy, A. Zhukov, S. V. Morozov, M. I. Katsnelson, V. I. Fal'ko, A. K. Geim, K. S. Novoselov, Science, 333, 860 (2011).
- J. Velasco Jr., L. Jing, W. Bao, Y. Lee, P. Kratz, V. Aji, M. Bockrath, C.N. Lau, C. Varma, R. Stillwell, D. Smirnov, Fan Zhang, J. Jung, A.H. MacDonald, Nature Nanotechnol., 7, 156 (2012).
- F. Freitag, J. Trbovic, M. Weiss, C. Schönenberger, Phys. Rev. Lett., 108,076602 (2012).
- W. Bao, J. Velasco Jr, F. Zhang, L. Jing, B. Standley, D. Smirnov, M. Bockrath, A. MacDonald, C.N. Lau, Proc. Nat. Acad. Sci., to appear (2012).
- A. Veligura, H. J. van Elferen, N. Tombros, J. C. Maan, U. Zeitler, B. J. van Wee, PRB, 2012

Partial list of theoretical work

- H. Min, G. Borghi, M. Polini, and A. H. MacDonald, Phys. Rev. B 77, 041407(R) (2008).
- Johan Nilsson, A. H. Castro Neto, N. M. R. Peres, and F. Guinea, Phys. Rev. B 73, 214418 (2006).
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- F. Zhang, H. Min, M. Polini, and A. H. MacDonald, Phys. Rev. B, 81, 041402(R) (2010).
- O. Vafek and K. Yang, Phys. Rev. B 81, 041401(R) (2010).
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- R. Nandkishore and L. Levitov, Phys. Rev. Lett. 104, 156803 (2010).
- R. Nandkishore and L. Levitov, Phys. Rev. B 82, 115431 (2010).
- O. Vafek, Phys. Rev. B 82, 205106 (2010).
- Y. Lemonik, I. L. Aleiner, C. Toke, and V. I. Fal'ko, Phys. Rev. B 82, 201408(R) (2010).
- F. Zhang, J. Jung, G. A. Fiete, Q. Niu, and A. H. MacDonald, e-print arXiv:1010.4003.
- F. Zhang, A. H. MacDonald, preprint, arXiv:1107.4727v1 (2011).
- M. Kharitonov, preprint, arXiv: 1105.5386v1 (2011); 1109.1553v1 (2011).
- L. Zhu, V. Aji and C. Varma, arXiv:1202.0821v1 (2012).
- Michael M. Scherer, Stefan Uebelacker, Carsten Honerkamp, arXiv:1112.5038 (2012)

An analogy…

Singe Particle Picture

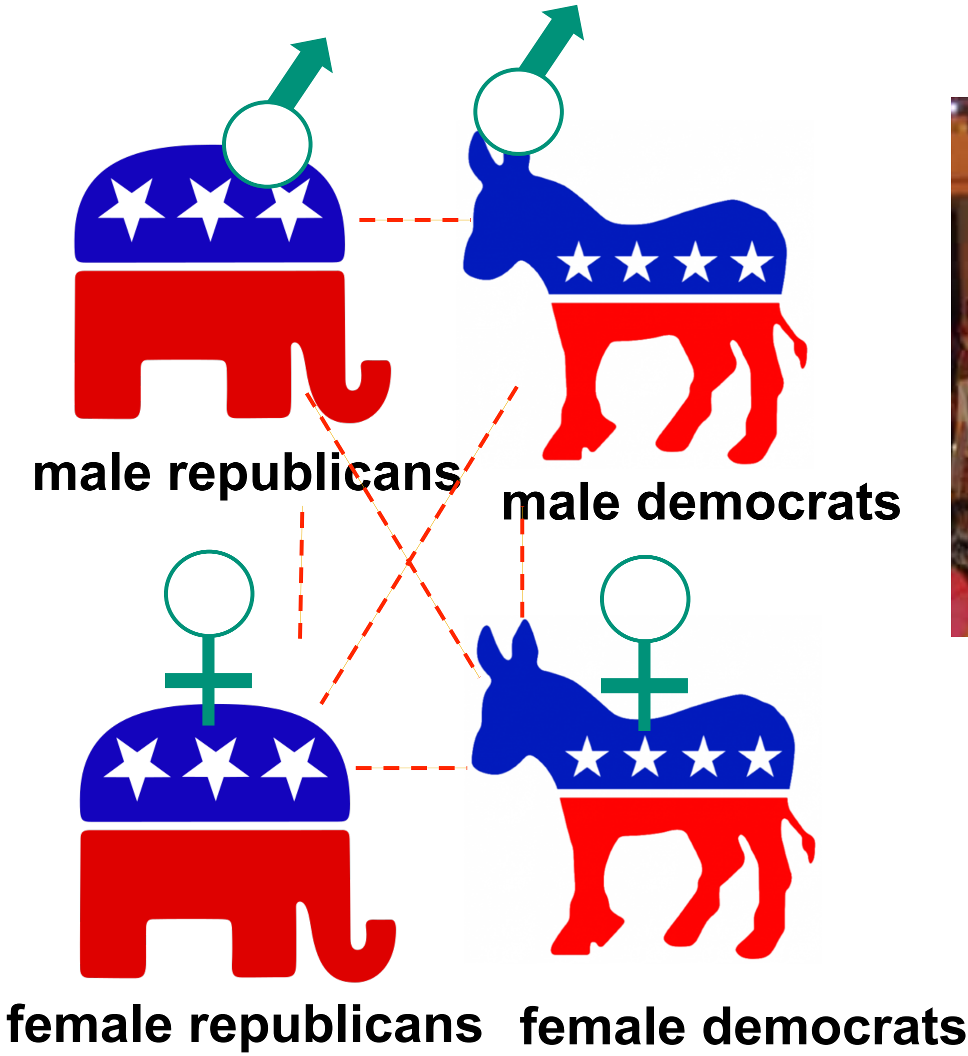
8 million strangers…

Electronic Interactions

dinner party with assigned seating

→ correlated phases such as superconductors, magnets, Mott insulators, etc…

An analogy…



Electronic Interactions

dinner party with assigned seating

Electrons can
- have spin up or down
- K and K' valleys

Collective States at the Dirac Point in BLG

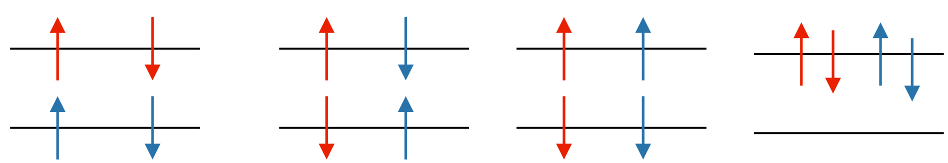
- Strong interaction at the Dirac point → broken symmetry states
- Nature of the states under intense efforts.

Popular Candidates

Protected edge states (Anomalous Hall, Quantum Spin Hall)

Bulk gap (Anomalous Hall, Quantum Spin Hall, Layer Antiferromagnet, QVH)

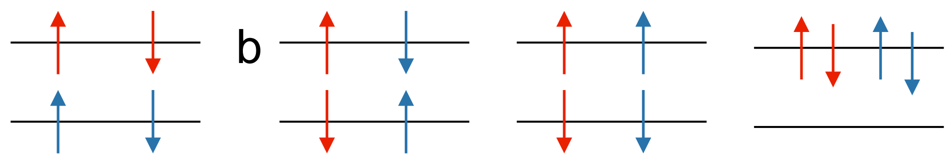
	Nematic Order	Anomalous Hall	Quantum Spin Hall	Layer Antiferromagnet	QVH
Gapped?	No	Yes	Yes	Yes	Yes
2- terminal σ_{min}	finite	$4e^2/h$	$4e^2/h$	0	0
Symmetry Broken	rotation	time reversal; Ising Valley	spin rotational; Ising Valley	time reversal; spin rotation	inversion



red: K electrons
blue: K' electrons

Possible Collective States

	Nematic Order	Anomalous Hall	Quantum Spin Hall	Layer Antiferromagnet	QVH
Gapped?	No	Yes	Yes	Yes	Yes
2- terminal σ_{min}	finite	$4e^2/h$	$4e^2/h$	0	0
Symmetry Broken	rotation	time reversal; Ising Valley	spin rotational; Ising Valley	time reversal; spin rotation	inversion

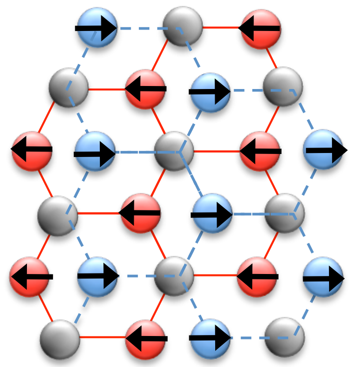


red: K electrons
blue: K' electrons

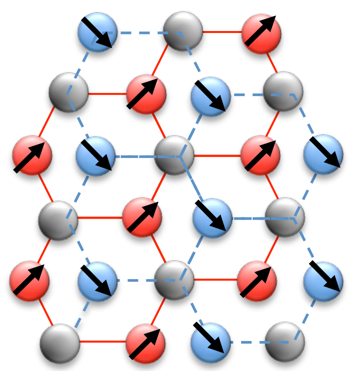
- Electronic interactions gives rise to a intrinsic gapped, insulating collective state in charge neutral graphene
- Gap can be closed by electric field of either polarity

Most likely candidate

B=0
Antiferromagnet



B≠0
Canted
Antiferromagnet



Layer Antiferromagnet
Gapped
Insulating
Breaks time reversal & spin rotation symmetry

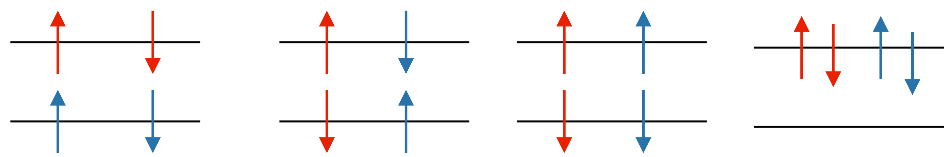
- Electronic interactions gives rise to a intrinsic gapped, insulating collective state in charge neutral graphene
- Gap can be closed by electric field of either polarity

Collective States

Protected edge states ~ topological insulators

Bulk gap

	Nematic Order	Anomalous Hall	Quantum Spin Hall	Layer Antiferromagnet	QVH
Gapped?	No	Yes	Yes	Yes	Yes
2- terminal σ_{min}	finite	$4e^2/h$	$4e^2/h$	0	0
Symmetry Broken	rotation	time reversal; Ising Valley	spin rotational; Ising Valley	time reversal; spin rotation	inversion



red: K electrons
blue: K' electrons

Outstanding Questions

- Is the insulating state antiferromagnetic?
- Is it the ground state?
- Can we engineer BLG to other ordered, collective states, e.g. with protected edge states, dissipationless transport?

(tentative yes)

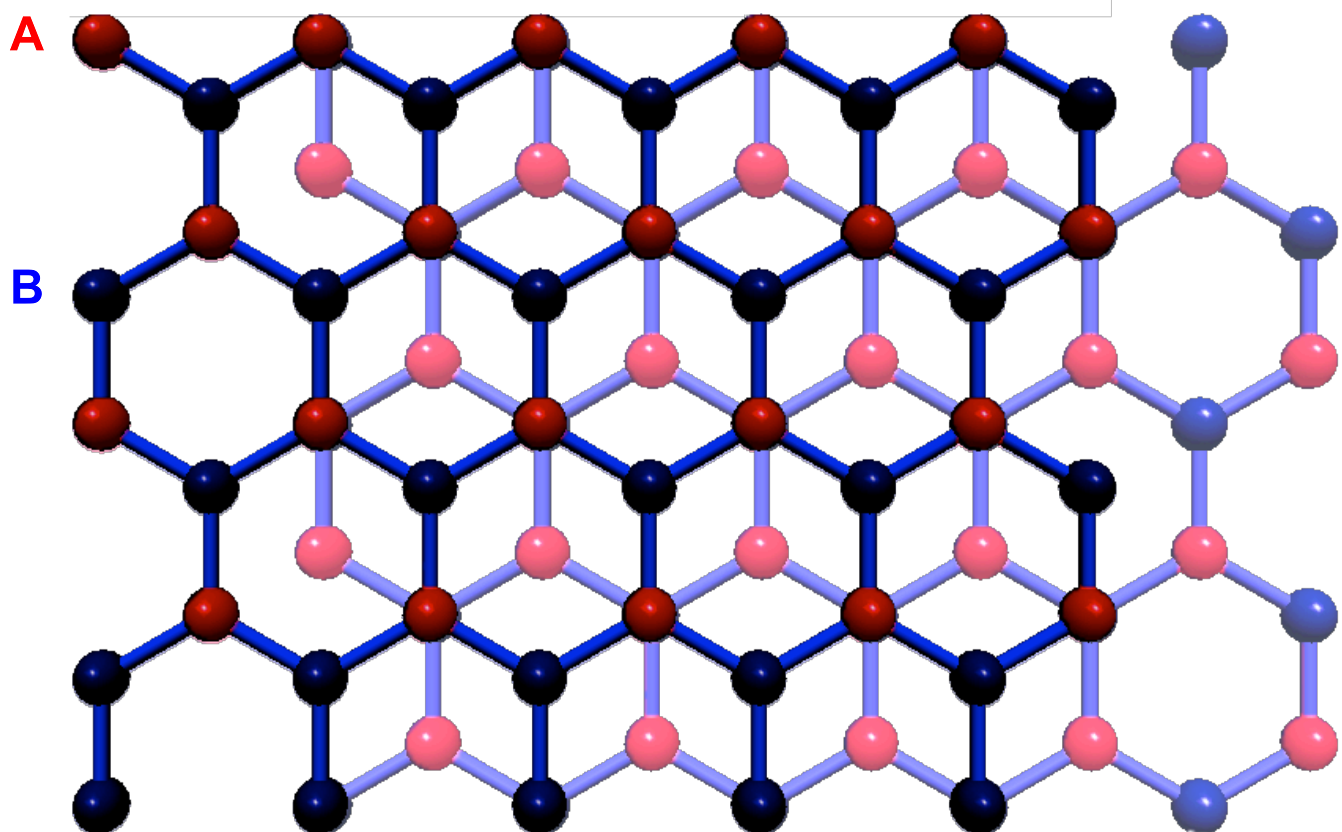
Conclusion

- Insulating state with an intrinsic gap ~ 2-3 meV in bilayer graphene
- Gap can be tuned by temperature, disorder, electric field and density
- Can we realize transition among various collective states?
- Source-drain bias spectroscopy to resolve symmetry-broken Landau level gaps, which are strongly electric field dependent

Why stop at 2?

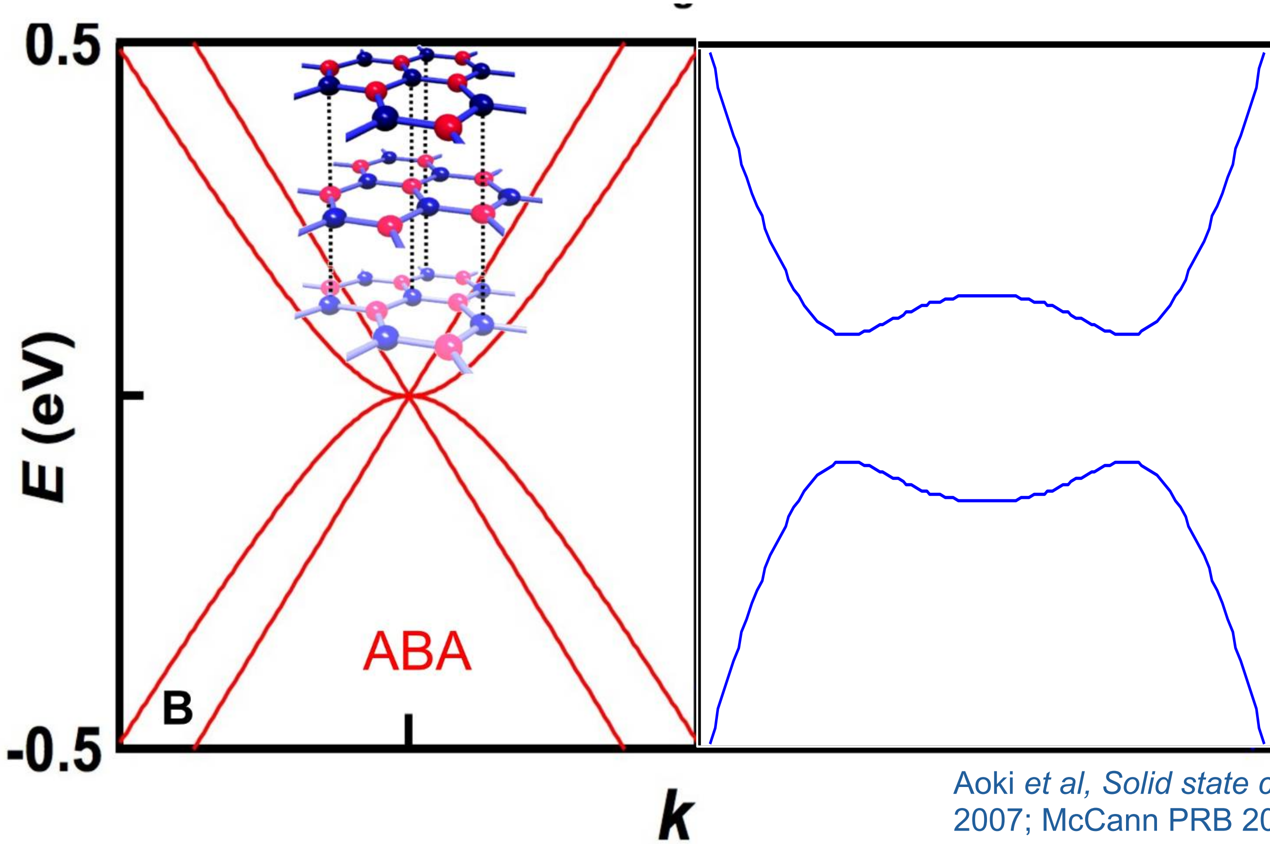
Trilayer Graphene

- ABA (Bernal) stacking
- ABC (rhombohedral) stacking
- can be distinguished using Raman spectroscopy



Aoki *et al, Solid state commun.* 2007; McCann PRB 2009; Guinea et al PRB 2006

Trilayer graphene – Single Particle Picture



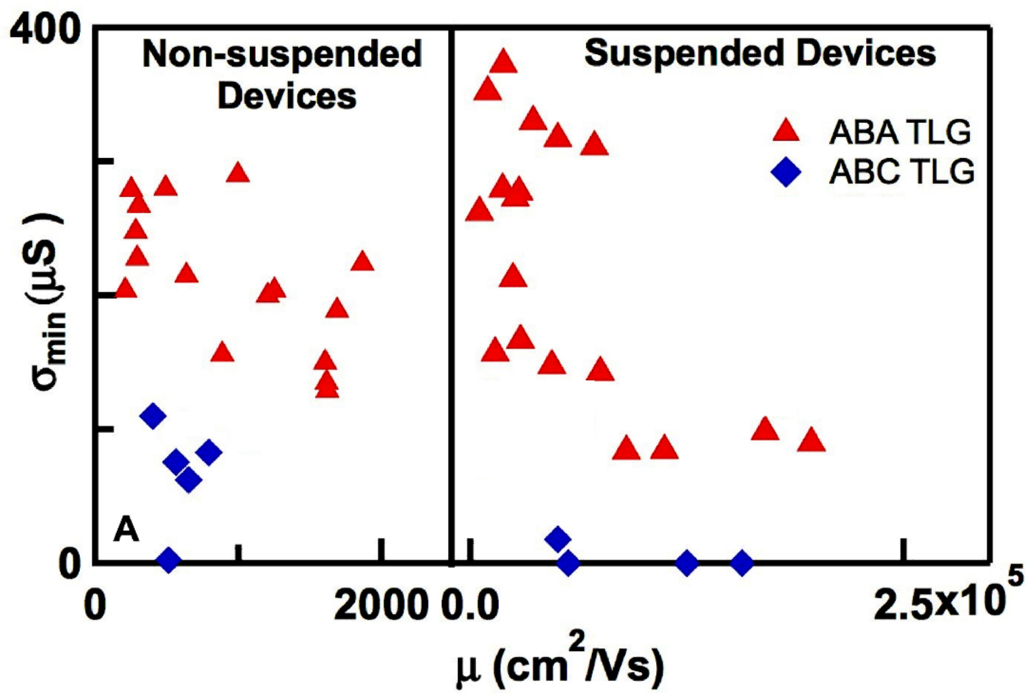
Aoki *et al, Solid state commun.* 2007; McCann PRB 2009; Guinea et al PRB 2006

$E_{\perp} = 0$ | *E* ~ monolayer band + bilayer band | $E \sim \hbar^3 k^3$

$E_{\perp} \neq 0$ | Tunable Band Overlap | Tunable Band Gap

Craciun *et al, Nature Nanotech.* 2009; Lui *et al Nature Phys.* 2011; Bao *et al Nature Phys.* 2011, Taychatanapat *et al Nature Phys.* 2011; Henriksen *et al PRX* 2012; Zhang *et al Nature Phys.* 2011; Zhu group Nano Lett. 2013.

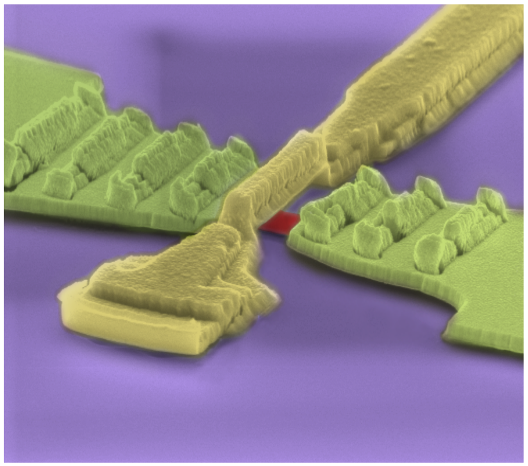
Minimum conductivity (σ_{min})

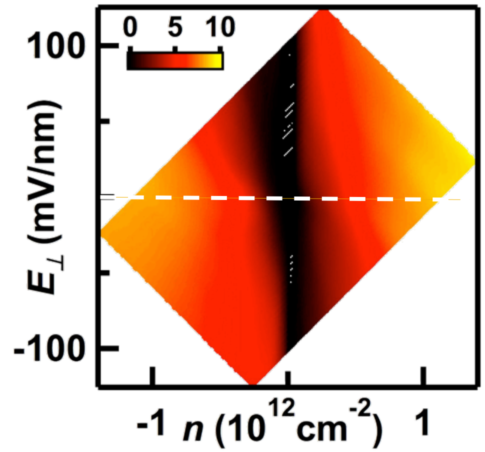


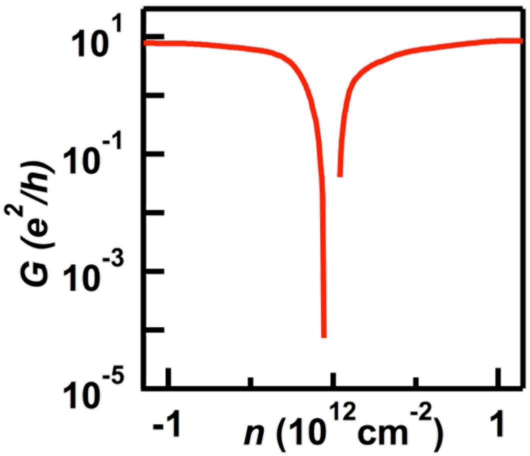
- Stacking orders identified by Raman spectroscopy
- ***σ_{min}*** ABA-stacked trilayer remains finite >100 μS.
- ***σ_{min}*** of ABC-stacked trilayer is significantly smaller, ~0 for suspended devices.

W. Bao, L. Jing, J. Velasco Jr., Y. Lee, G. Liu, D. Tran, B. Standley, M. Aykol, S. B. Cronin, D. Smirnov, M. Koshino, E. McCann, M. Bockrath, and C.N. Lau, Nature Phys. (2011)

Dual-Gated Suspended ABC Trilayer Devices

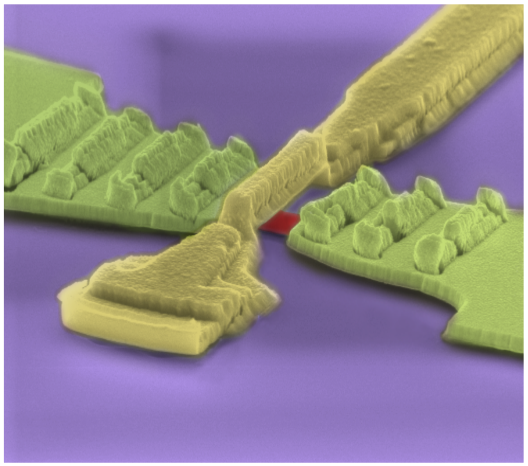


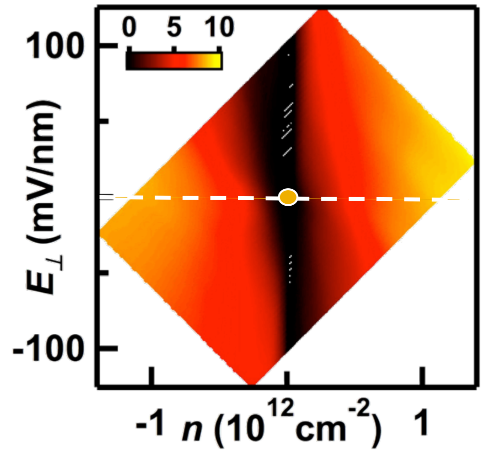


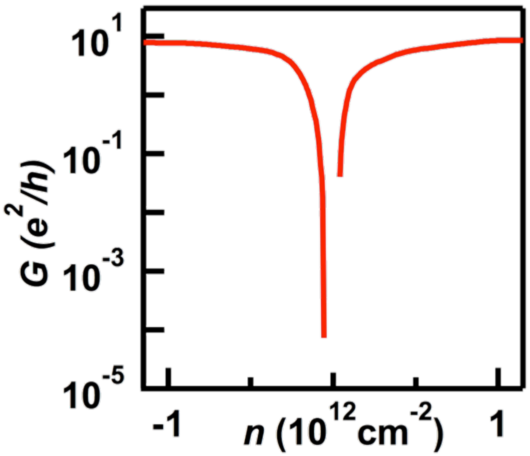


- mobility 20,000 – 90,000 cm^2/Vs
- Device is insulating at $n = E_\perp = 0$
- Insulating state persists for large range of $E_\perp$
- Failure of single particle picture

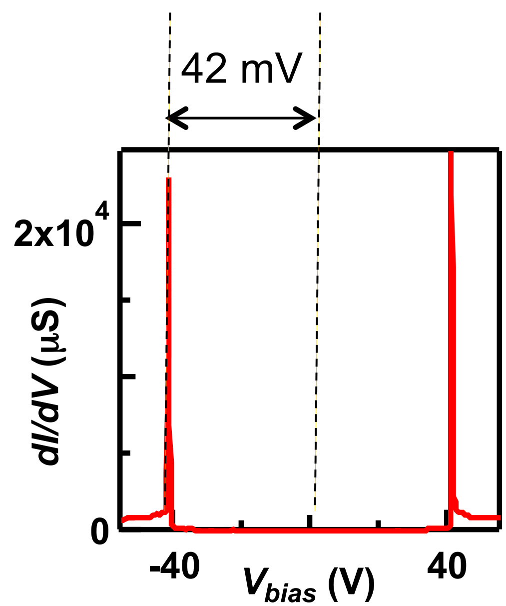
Intrinsic Insulating state





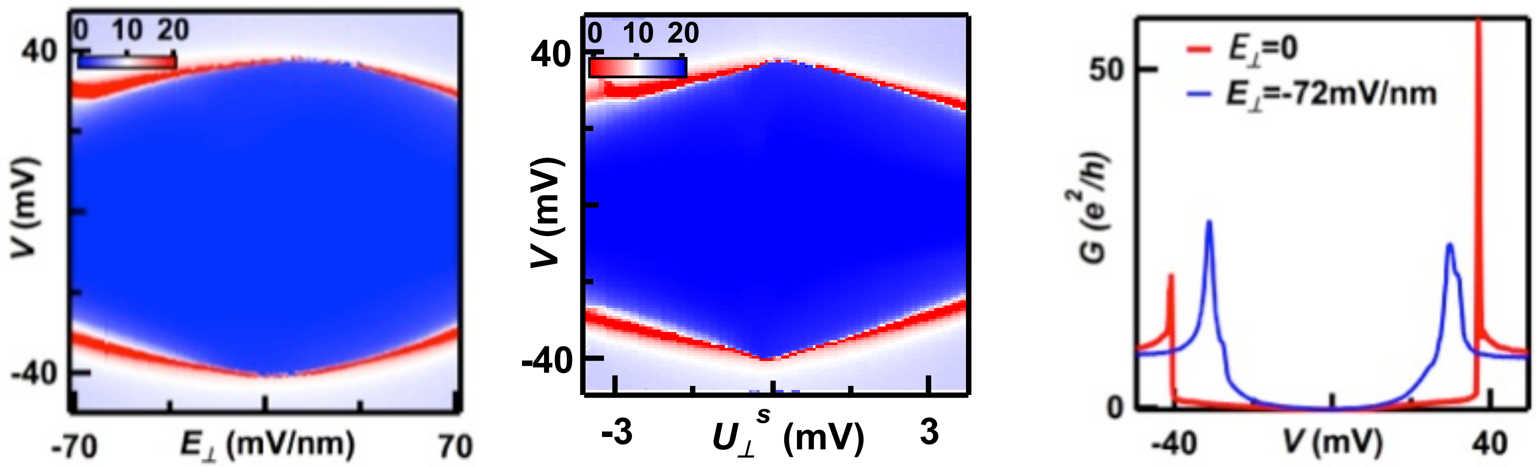


- mobility 20,000 – 90,000 cm^2/Vs
- Device is insulating at $n= E_{\perp}=0$
- Insulating state persists for large range of $E_{\perp}$
- Failure of single particle picture
- $\Delta \sim 42$ meV



Effect of electric field

Differential conductance *G* vs source drain bias *V* at *n=0*



Lee et al, submitted.

- intrinsically insulating at $n=E_\perp=0$, a gap ~42 meV
- gap closes symmetrically with applied $E_\perp$ (linearly after corrected for screening)
- gap not completely closed at largest $|E_\perp|$

→ not a single particle gap

→ arises from electronic interactions

Recent theoreis: MacDonald, Vafek, Xie, Honerkamp, Vozmediano, Barlas

Interaction Parameter

$$\alpha \sim \frac{\text{Coulomb Energy}}{\text{Fermi Energy} \sim k^{p}}$$

$$\sim \kappa^{-1} n^{-\frac{p-1}{2}}$$

n=charge density (10^{10} cm^{-2})
κ=dielectric constant

	Dispersion	α (κ=1)	Interaction-induced Gap
GaAs/AlGaAs	$E \sim k^2$	(10-50)/√n	
Single Layer Graphene	$E \sim k$	2.2	<0.2 meV
Bilayer Graphene	$E \sim k^2$	70/√n	2-3 meV
ABC-stacked Trilayer	$E \sim k^3$	1500/n	42 meV
ABC-stacked N-layer	$E \sim k^N$	gigantic	300 meV?

Interaction-induced gap in tetra-layer?

Conclusion

Challenges and Opportunities

- Large scale growth with controlled stacking order
- Controlling impurities and substrate