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Exceptional service in the national interest

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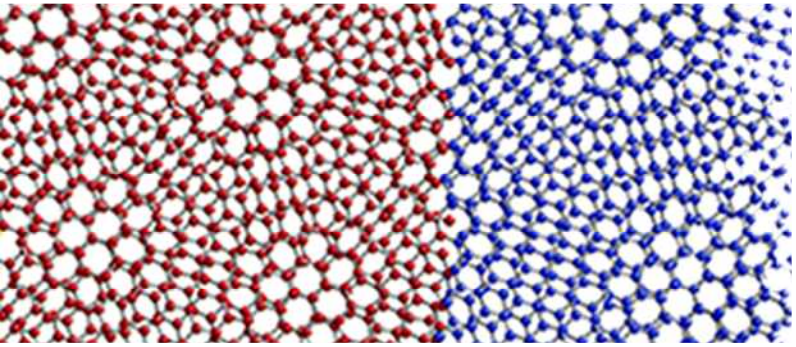
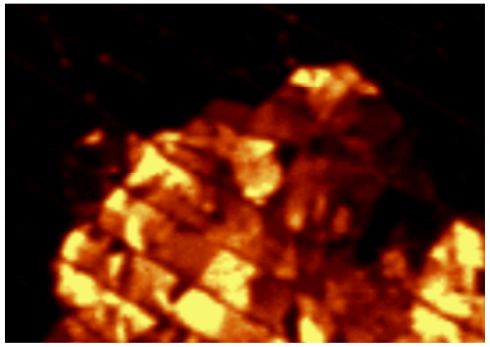
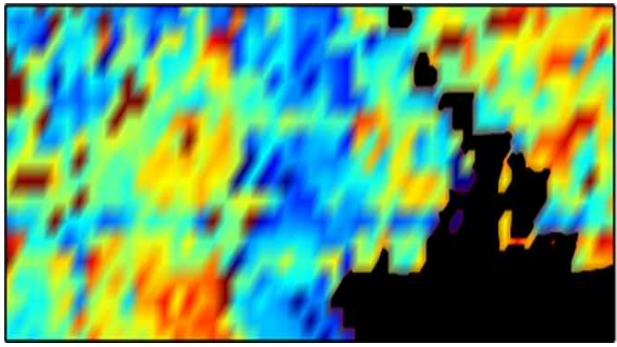

Twist & Stack:

Rotational Disorder in Twisted Bilayer Graphene (TBG) and its Implications for Hybrid 2D-Solids

Thomas Beechem

U.S. DEPARTMENT OF ENERGY | NNSA Nuclear National Security Administration

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Stacking Atomic Legos

Sandia National Laboratories

LETTER

doi:10.1038/nature11408

Graphene and boron nitride lateral heterostructures for atomically thin circuitry

Mark P. Levendorf[1]*, Cheol-Joo Kim[1]*, Lola Brown[1], Pinshane Y. Huang[2], Robin W. Havener[2], David A. Muller[2,3] & Jiwoong Park[1,3]

ARTICLE

Nonvolatile Memory Cells Based on MoS_2/Graphene Heterostructures

Simone Bertolazzi, Daria Krasnozhon, and Andras Kis*

Electrical Engineering Institute, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

ARTICLES
PUBLISHED ONLINE: 16 DECEMBER 2012 | DOI: 10.1038/NMAT3518

nature materials

Vertically stacked multi-heterostructures of layered materials for logic transistors and complementary inverters

Woo Jong Yu[1], Zheng Li[1], Hailong Zhou[1], Yu Chen[2], Yang Wang[2], Yu Huang[2,3] and Xiangfeng Duan[1,3]*

ARTICLE

Electronic Hybridization of Large-Area Stacked Graphene Films

Jeremy T. Robinson,[†,*] Scott W. Schmucker,[†] C. Bogdan Diaconescu,[‡] James P. Long,[†] James C. Culbertson,[†] Taisuke Ohta,[‡] Adam L. Friedman,[†] and Thomas E. Beechem[‡]

[†]Naval Research Laboratory, Washington, D.C. 20007, United States and [‡]Sandia National Laboratories, Albuquerque, New Mexico 87185, United States

VOL. 7 ▪ NO. 1 ▪ 637–644 ▪ 2013 ACSNANO www.acsnano.org

nature nanotechnology

LETTERS
PUBLISHED ONLINE: 23 DECEMBER 2012 | DOI: 10.1038/NNANO.2012.224

Vertical field-effect transistor based on graphene–WS_2 heterostructures for flexible and transparent electronics

Thanasis Georgiou[1], Rashid Jalil[2], Branson D. Belle[2], Liam Britnell[1], Roman V. Gorbachev[2], Sergey V. Morozov[3], Yong-Jin Kim[1,4], Ali Gholinia[5], Sarah J. Haigh[5], Oleg Makarovsky[6], Laurence Eaves[1,6], Leonid A. Ponomarenko[1], Andre K. Geim[2], Kostya S. Novoselov[1] and Artem Mishchenko[1]*

Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures

L. Britnell,[1] R. V. Gorbachev,[2] R. Jalil,[2] B. D. Belle,[2] F. Schedin,[2] A. Mishchenko,[1] T. Georgiou,[1] M. I. Katsnelson,[3] L. Eaves,[4] S. V. Morozov,[5] N. M. R. Peres,[6,7] J. Leist,[8] A. K. Geim,[1,2]* K. S. Novoselov,[1]* L. A. Ponomarenko[1]*

www.sciencemag.org SCIENCE VOL 335 24 FEBRUARY 2012

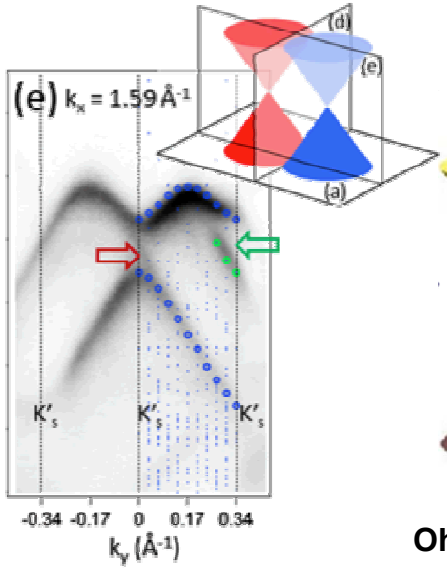
nature materials

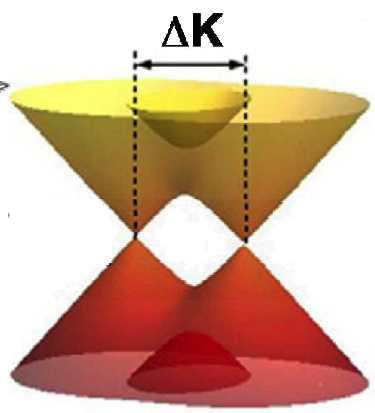
LETTERS
PUBLISHED ONLINE: 29 JULY 2012 | DOI: 10.1038/NMAT3386

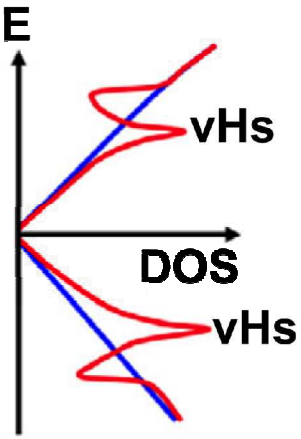
Cross-sectional imaging of individual layers and buried interfaces of graphene-based heterostructures and superlattices

S. J. Haigh[1]*, A. Gholinia[1], R. Jalil[2], S. Romani[3], L. Britnell[2], D. C. Elias[2], K. S. Novoselov[2], L. A. Ponomarenko[2], A. K. Geim[2] and R. Gorbachev[2]*

Hybrid 2D-Solids: A+B≠A+B



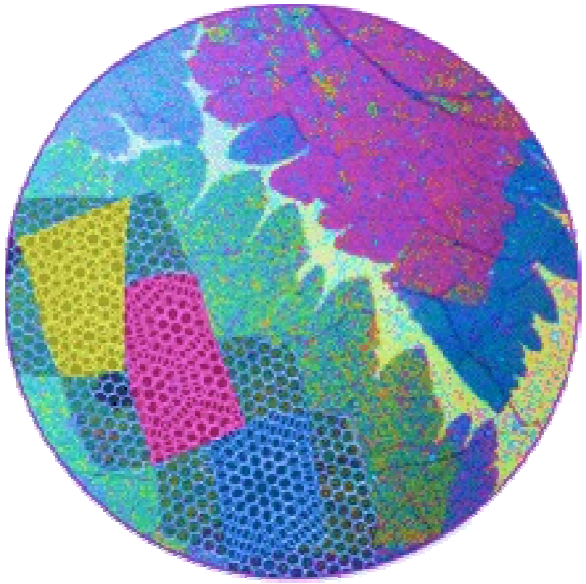




Layer interaction changes bands

Ohta, Robinson, Feibelman, Bostwick, Rotenberg, Beechem, Phys. Rev. Let. (109) 186807, 2012.

Provides "knob" to create new materials



Robinson, Schmucker, Diaconescu, Long, Culbertson, Ohta, Friedman, Beechem. ACS Nano (7) 637 2013.

Interlayer Interaction: Gimme Moiré

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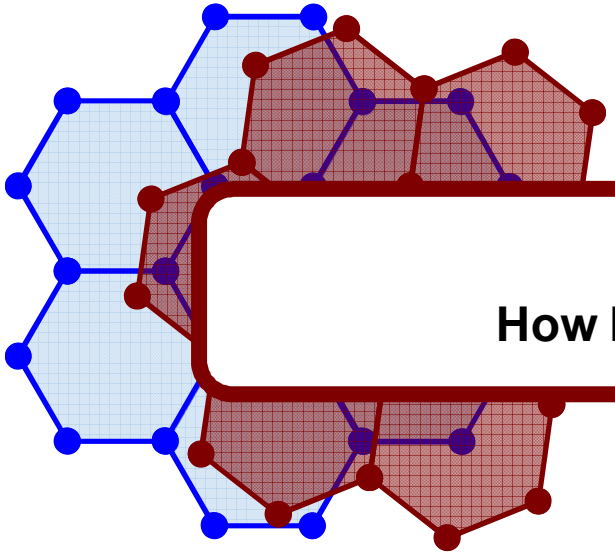
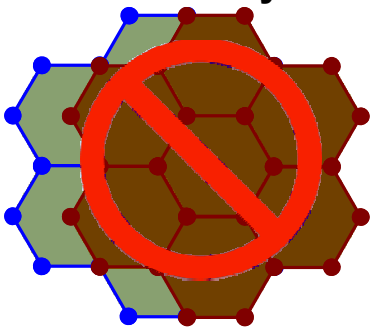
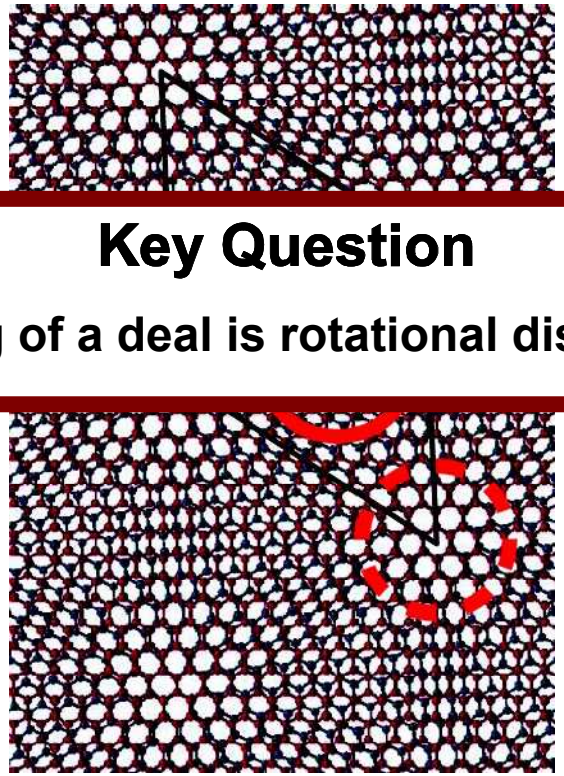
Twisted Bilayer Graphene



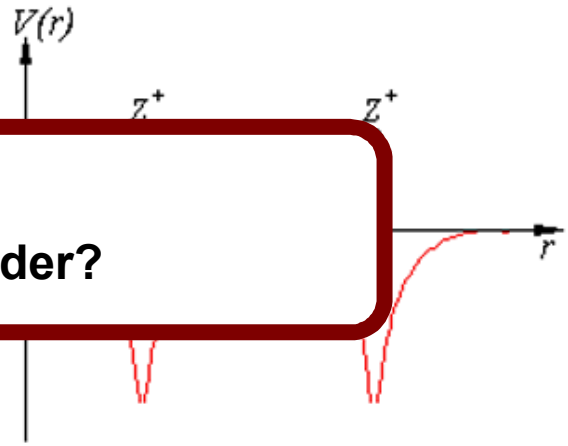
Bernal Bilayer



Moiré Superlattice



Periodic Potential



Key Question

How big of a deal is rotational disorder?

Non-Uniform Response in TBG

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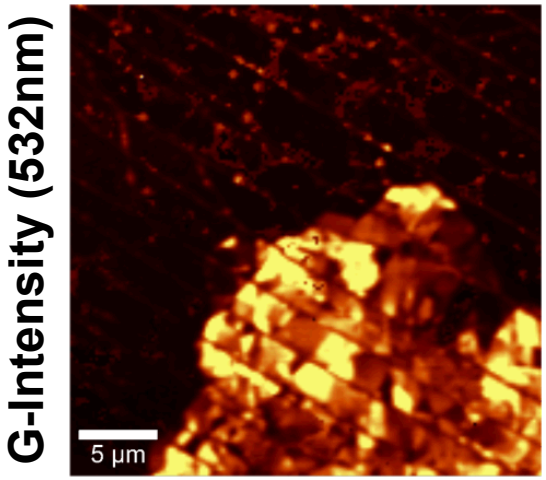

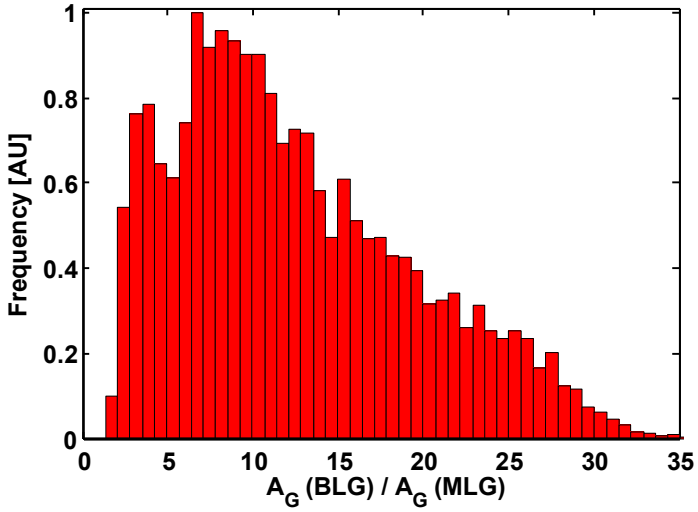

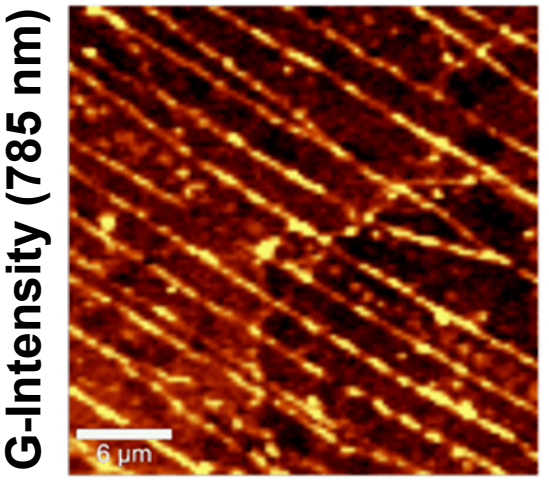

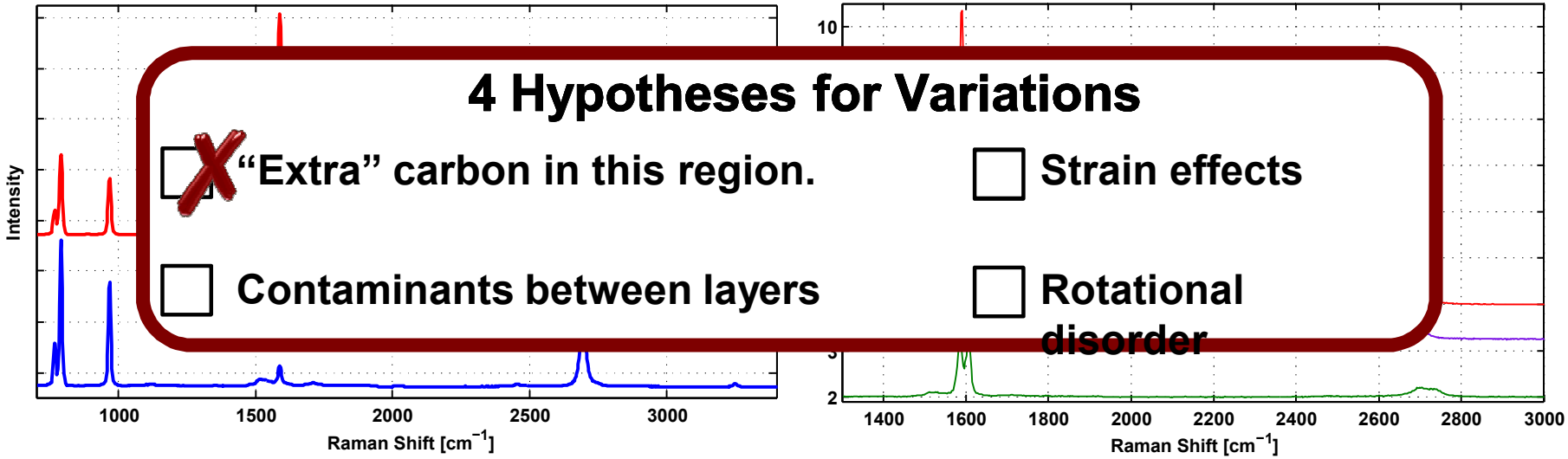

4 Hypotheses for Variations

- ☒ "Extra" carbon in this region.
- ☐ Strain effects
- ☐ Contaminants between layers
- ☐ Rotational disorder

Special thanks to Jianyong Yang of WiTec (Tennessee) Instruments for aide in these measurements

Interlayer Contaminants?

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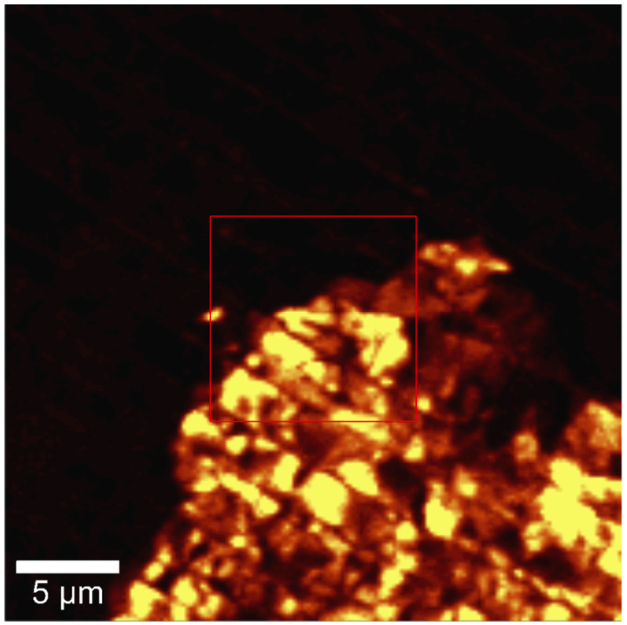
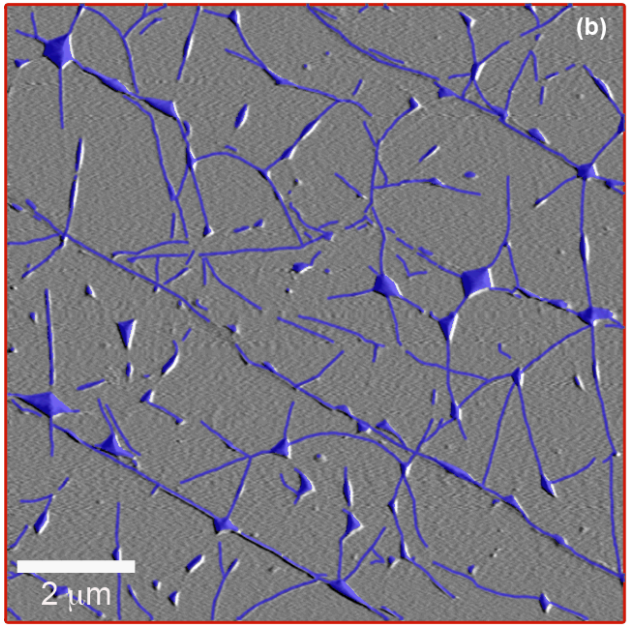
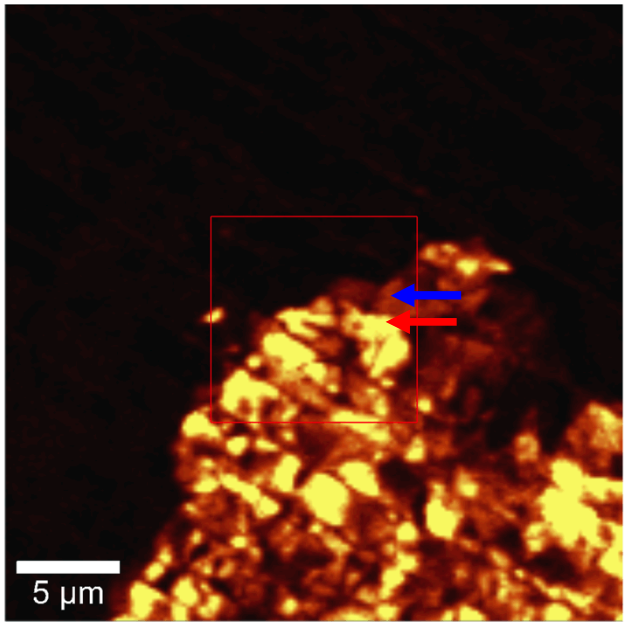




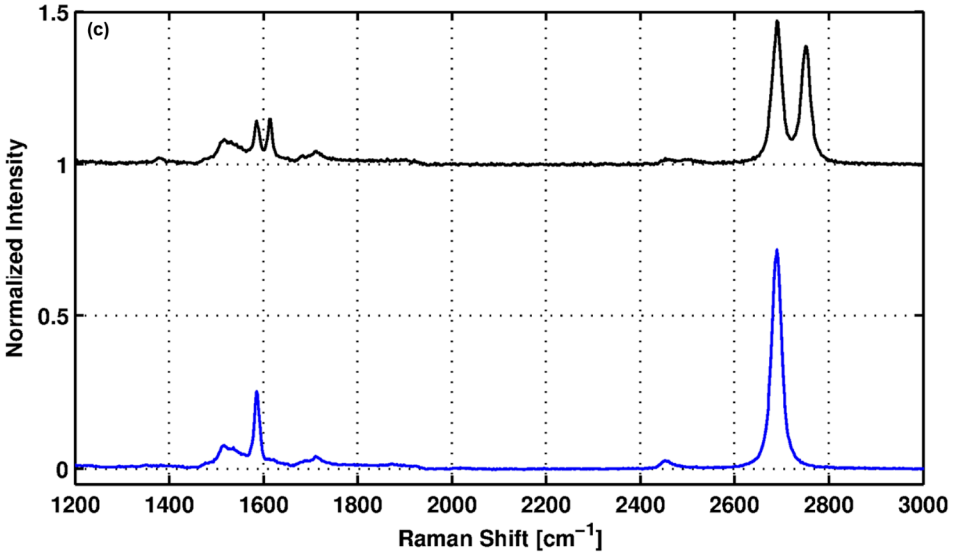


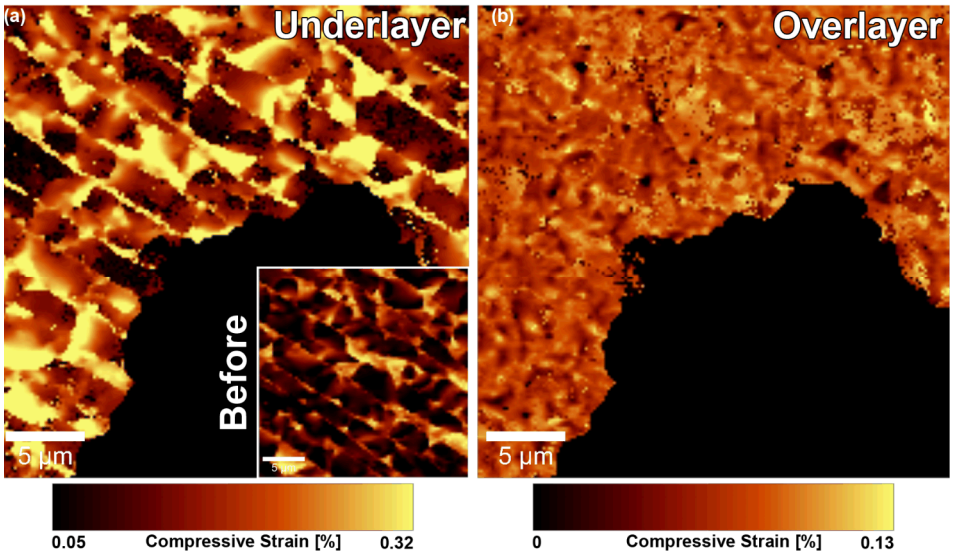
4 Hypotheses for Variations

- [x] "Extra" carbon in this region.
- [ ] Strain effects
- [x] Contaminants between layers
- [ ] Rotational disorder

Special thanks to Jianyong Yang of WiTec (Tennessee) Instruments for aide in these measurements

Strain?

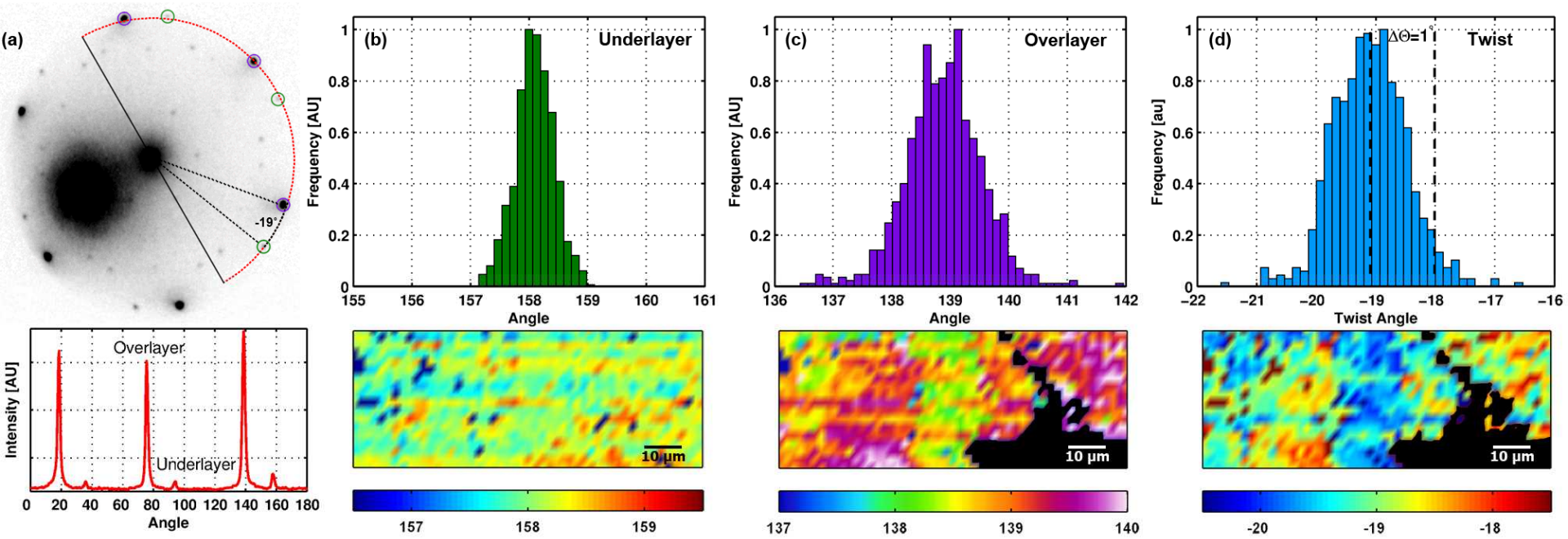




4 Hypotheses for Variations

- ☒ "Extra" carbon in this region.
- ☒ Strain effects
- ☒ Contaminants between layers
- ☐ Rotational disorder

Measuring Rotation: LEED



Key Question

Does this rotational disorder correlate with Raman results?

Acknowledgements: Bogdan Diaconescu (SNL) for performing LEED experiments & analysis

Comparing Raman & LEED

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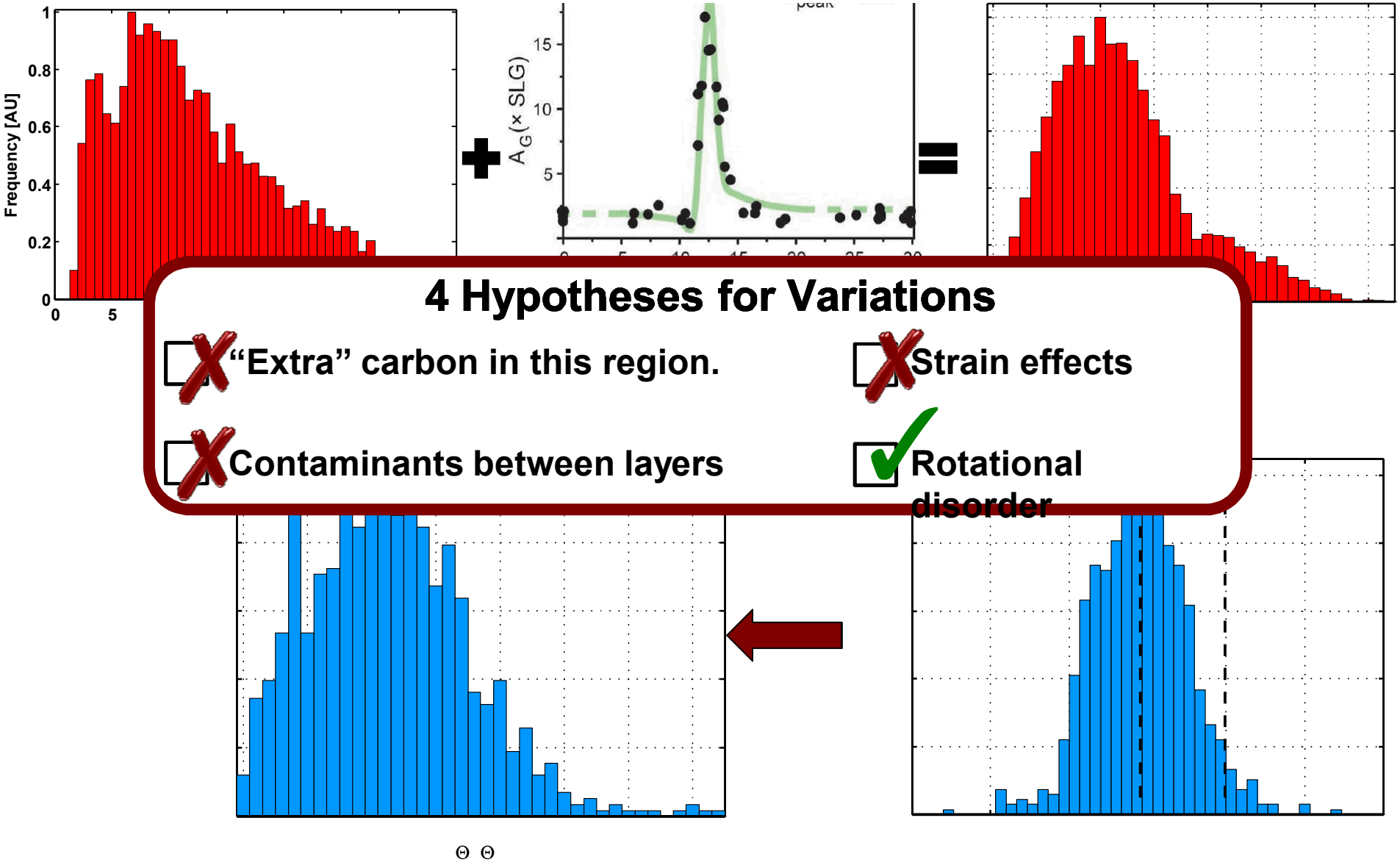

4 Hypotheses for Variations

- ☒ "Extra" carbon in this region.
- ☒ Strain effects
- ☒ Contaminants between layers
- ☑ Rotational disorder

Is All Lost?...the Good News

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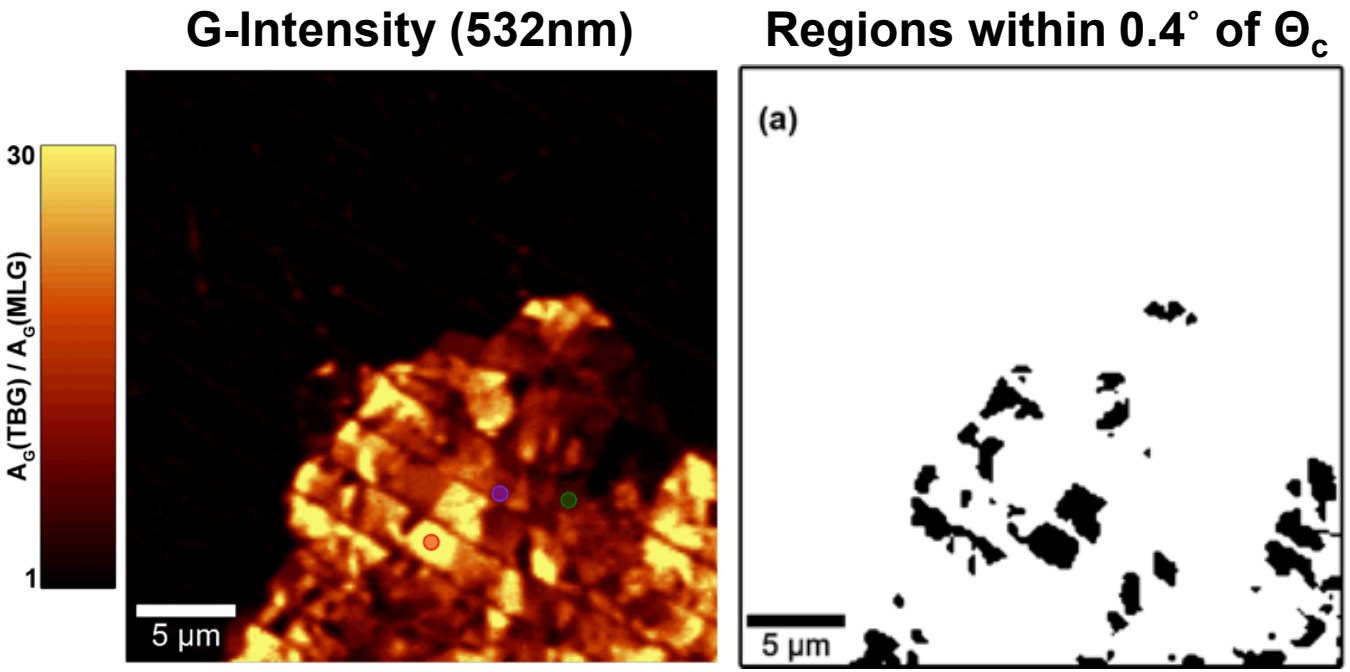

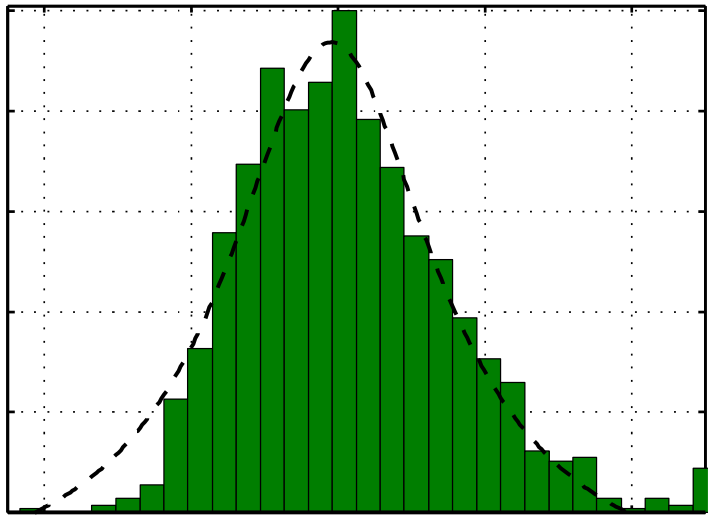

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Take Home Message

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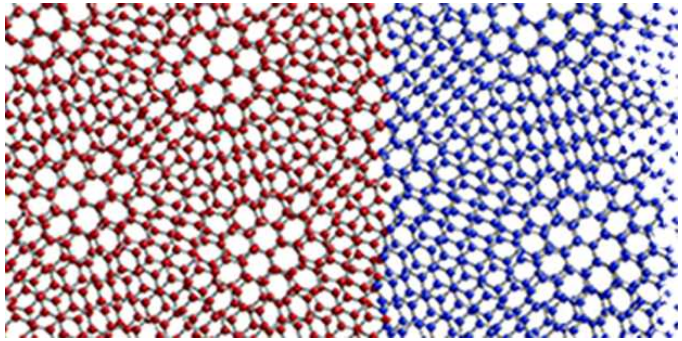
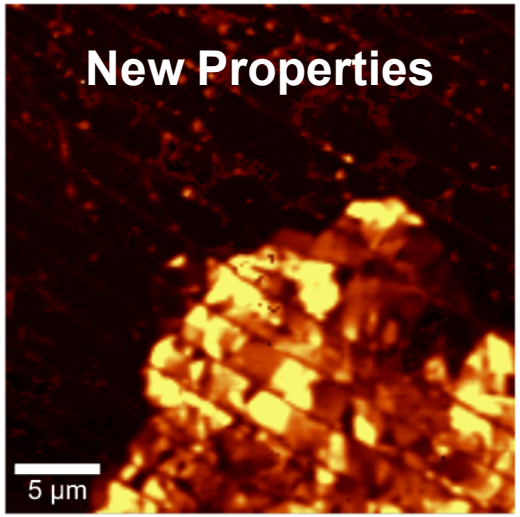
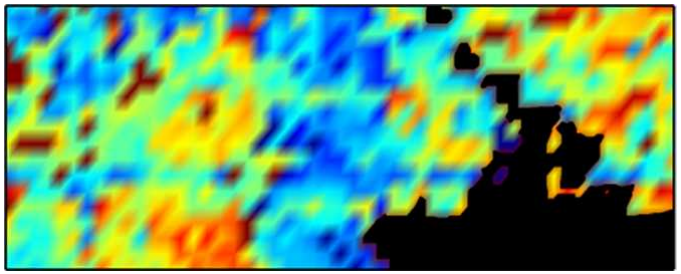
2D-Solids





Rotational Disorder



Bottom Line

1. New materials: 2D-Solids
1. New Properties from Moiré
3. Rotational disorder exists
4. This must be minimized

Acknowledgements

TEAM:

- SNL: Taisuke Ohta, Bogdan Diaconescu, Anthony McDonald
- NRL: Jeremy Robinson

DO YOU WANT TO WORK WITH ME?

I am looking for passionate, talented, and independent undergraduate and graduate student interns for both experimental and computational work.

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tebeech@sandia.gov

505-284-3503

What about the splitting?

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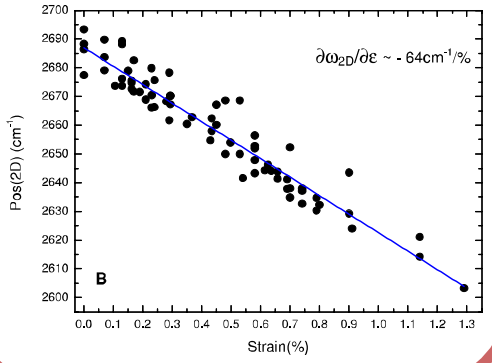
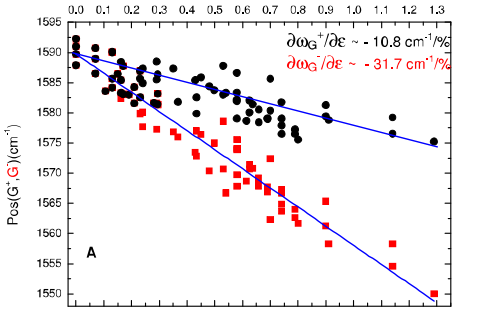
2D-Mode

G-Mode

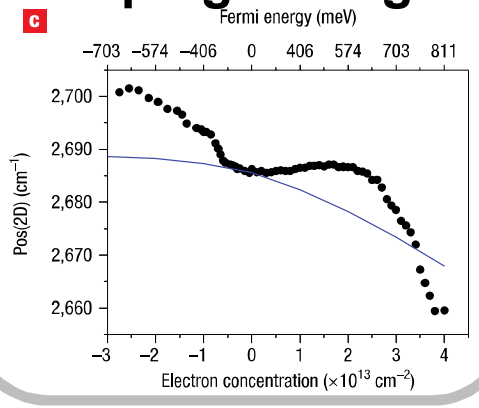
Strain Change

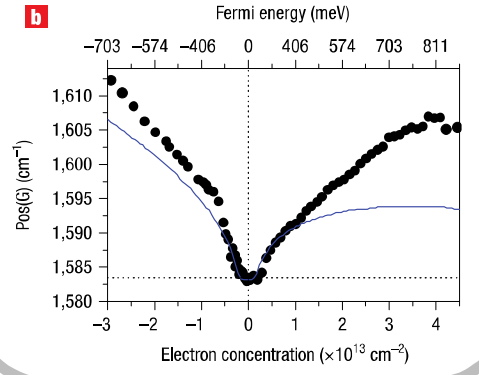




Mohiuddin et al. PRB (79) 205433 2009

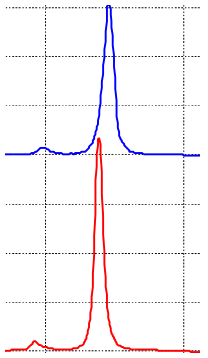
Doping Change

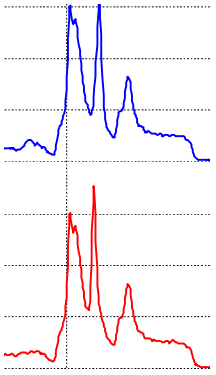




Das et al. Nat. Mtl. (3) 210. 2008

Total Change



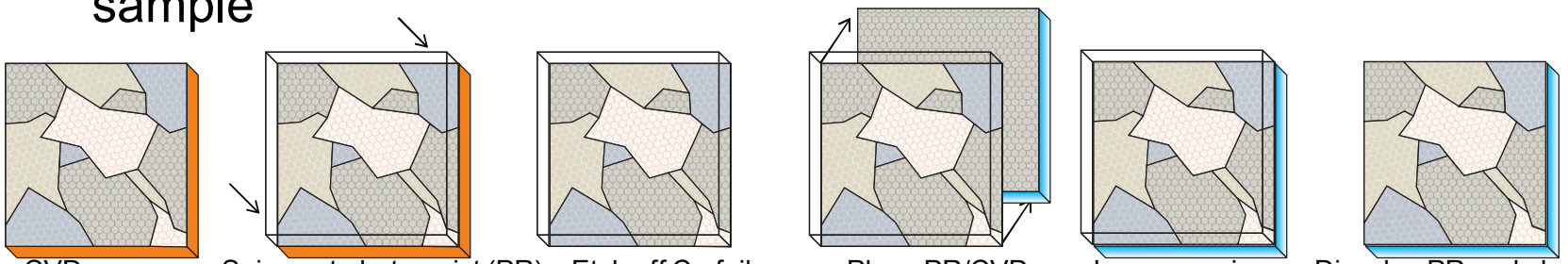


Producing TBG

Sandia National Laboratories

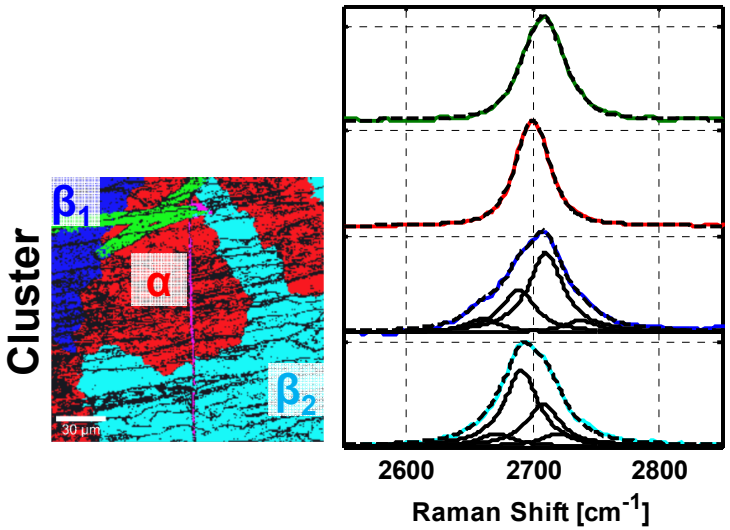
[+]Ohta et al. PRB (85) 075415 2012.

- **METHOD:** Transfer ("stamp") CVD graphene onto epitaxial graphene.[*]
  - Large TBG domains (>100um-size) with various twist angles on a sample



[*]In collaboration with J. Robinson (NRL)

- **Result:** Change in angle affects electronic dispersion.



- **Result:** vHs are observed at usable energies.