Scanning tunneling spectroscopy of graphene on BN

Brian LeRoy

January 14, 2012

Outline

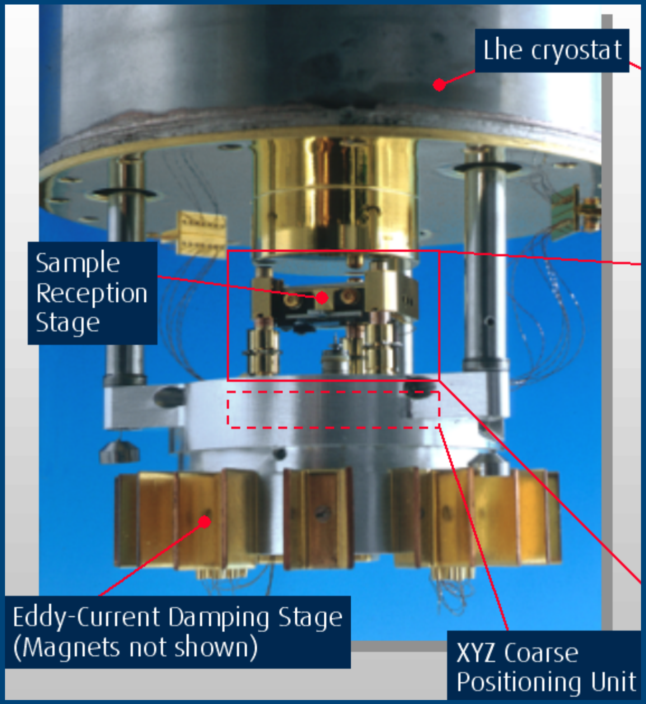
Scanning tunneling microscopy

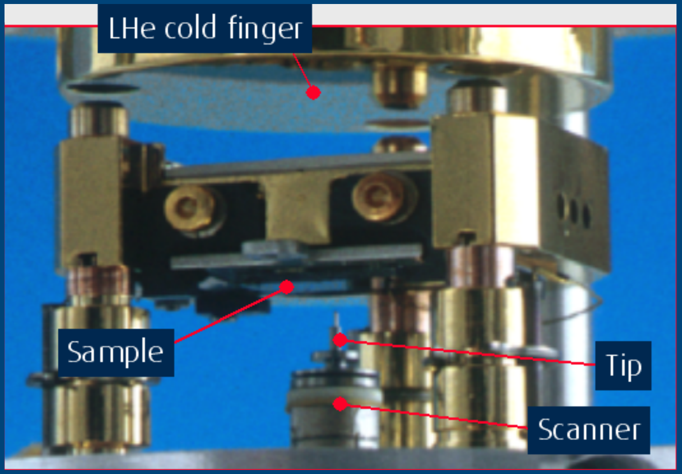
Topography
- Moiré patterns

Spectroscopy
- Charged impurities
- Scattering from edges
- Periodic potentials

Conclusions

Scanning Tunneling Microscope





Spatial Resolution 1 Å

Pressure < 3 x 10^{-11} mbar

Temperature 4.5 K

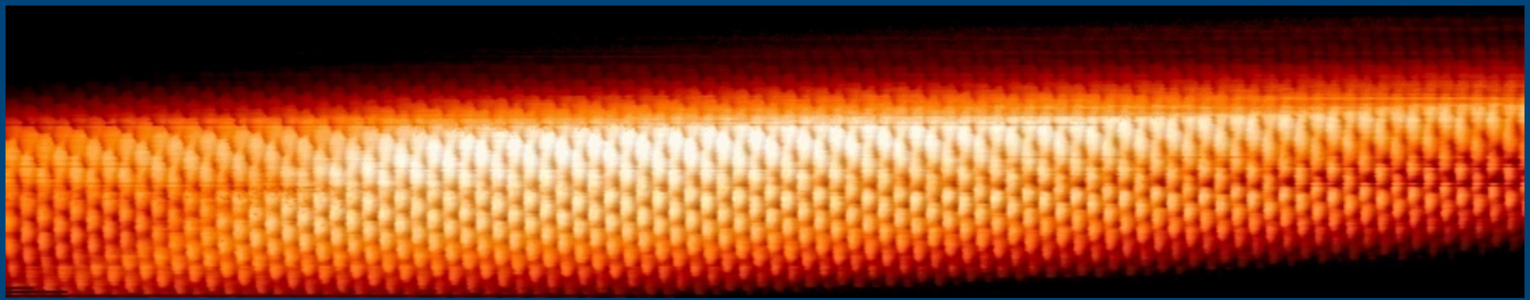
Scanning Tunneling Microscopy

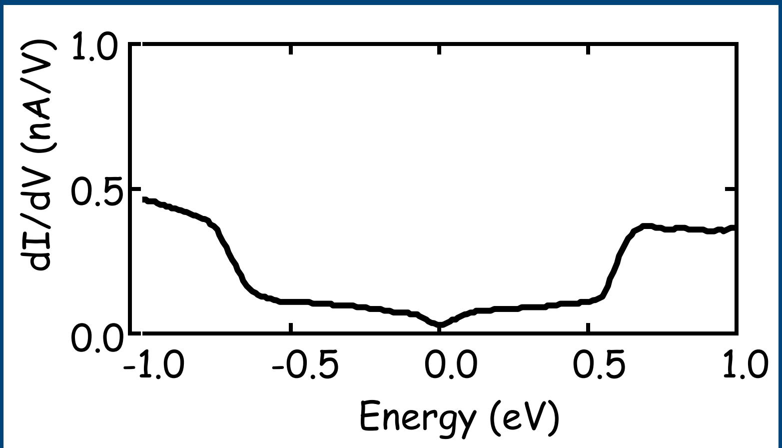
Topography

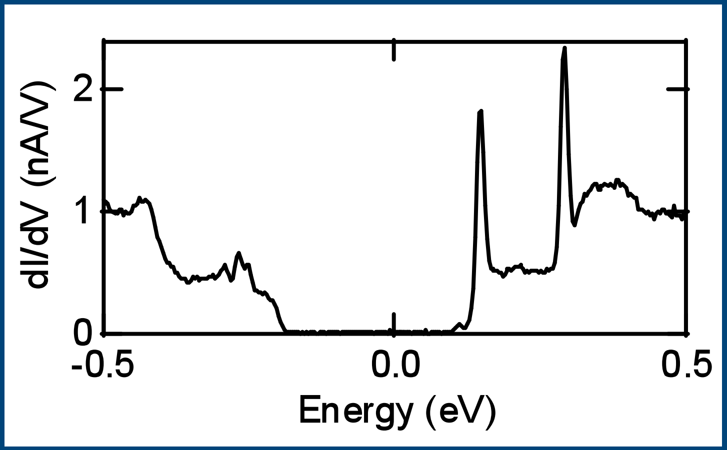
$$I \propto e^{-Z/Z_0} \int_0^{eV} dE\, LDOS(E,r)$$

Spectroscopy

$$\partial I / \partial V \;\propto\; LDOS(eV, r)$$







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Why use hBN?

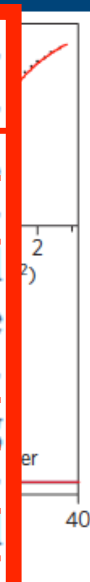
h-BN: hexagonal lattice, with ~same lattice constant as graphene (1.8% mismatch)
atomically smooth surface
no dangling bonds / charge traps
insulator, with bandgap ~6eV

Boron nitride substrates for high-quality graphene electronics

C. R. Dean[1,2]*, A. F. Young[3], I. Meric[1], C. Lee[4,5], L. Wang[2], S. Sorgenfrei[1], K. Watanabe[6], T. Taniguchi[6], P. Kim[3], K. L. Shepard[1] and J. Hone[2]*

Dean et al, Nature Nano **5**, 722 (2010)

It has been proposed that a bandgap would be induced in graphene aligned to an h-BN substrate[20]. In our experiment the graphene had a random crystallographic orientation to the substrate, and thus we did not expect the necessary sublattice symmetry breaking to occur. Indeed, the temperature dependence of σ_{min} observed here does not follow the simply activated behaviour that would be indicative of an energy gap. Although we cannot rule out the possibility of locally gapped regions resulting from symmetry breaking over finite length scales, we see no evidence from transport measurements that an appreciable gap is present in this randomly stacked graphene on h-BN.



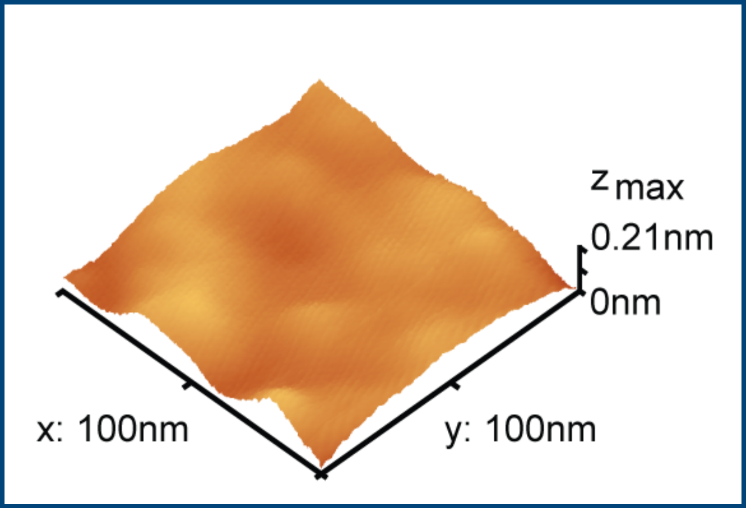
AFM topography, h(r)

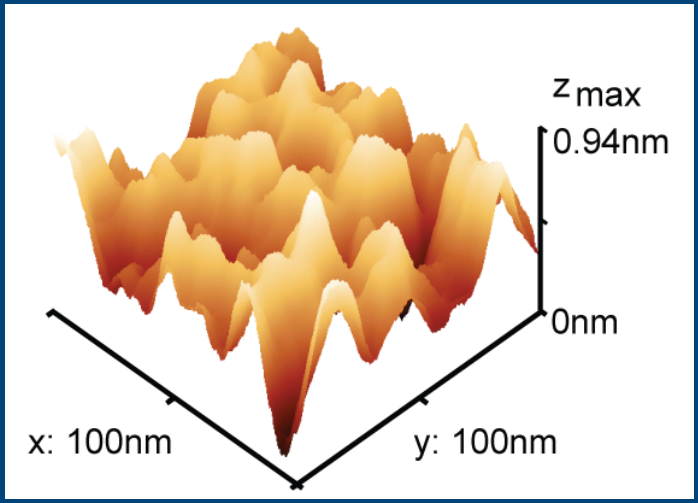
Weakly shifted away from V_g=0

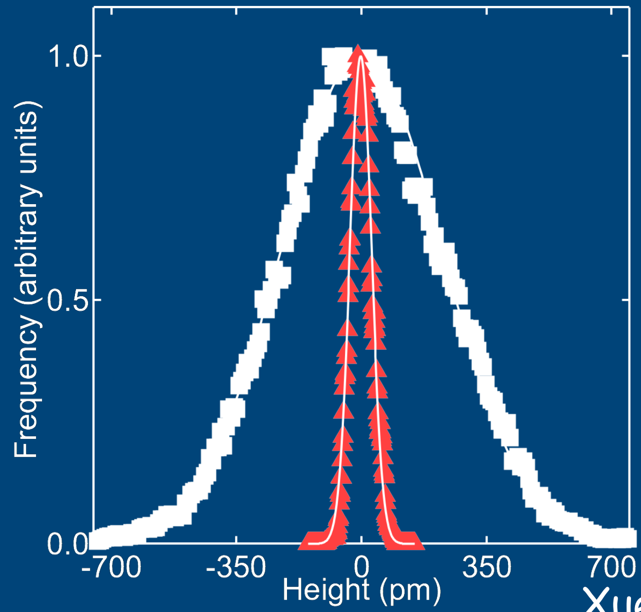
Topography Measurements

hBN

SiO_2







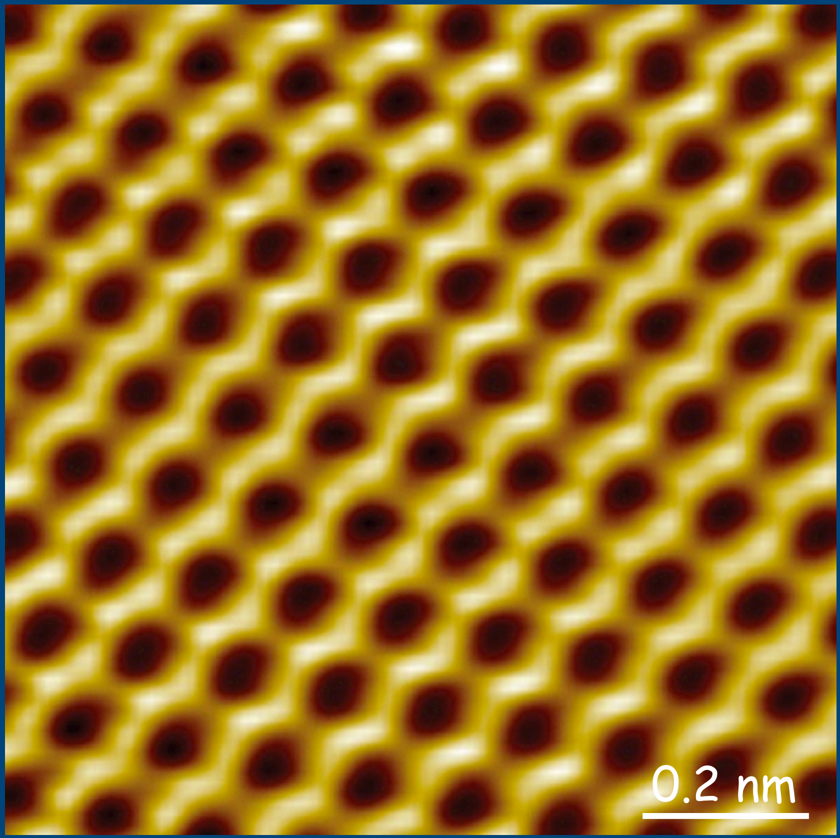
Standard deviations are:

SiO_2: 224.5±0.9 pm

BN: 30.2 ± 0.2 pm

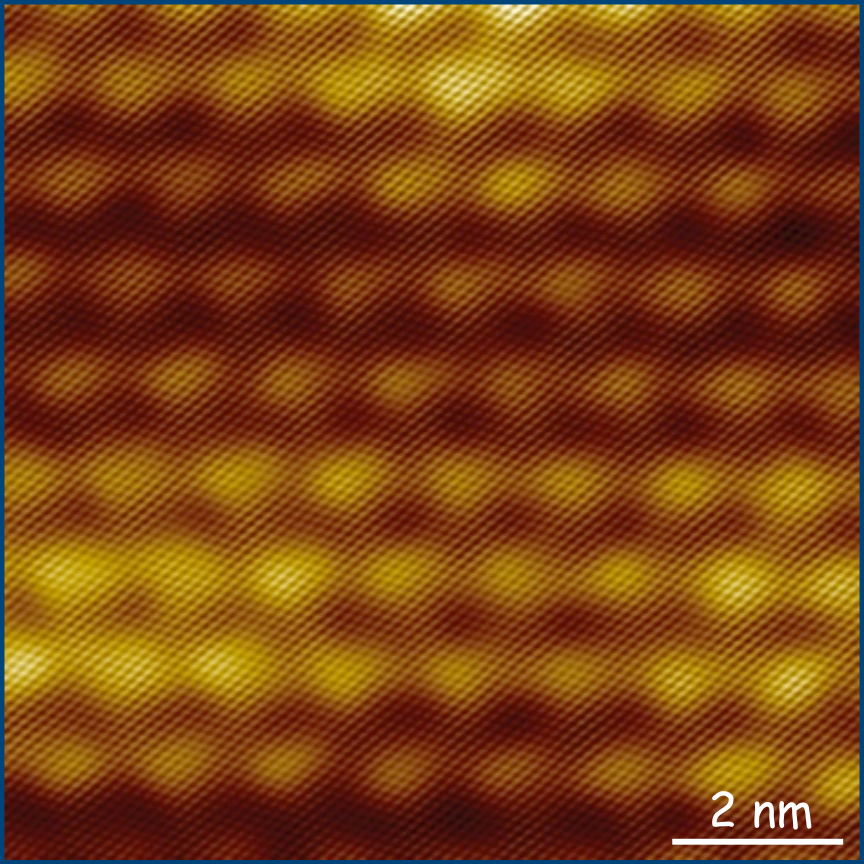
Xue et al., Nat. Mater. **10**, 282 (2011)

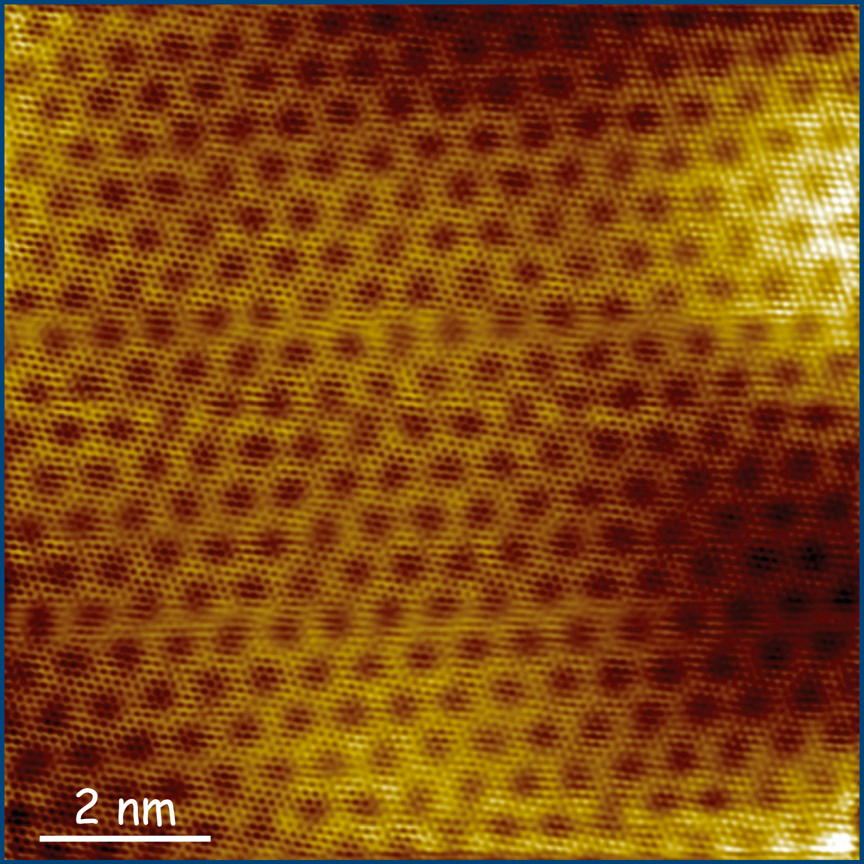
Atomic Resolution



Atomic resolution image shows hexagonal lattice

Topography Measurements

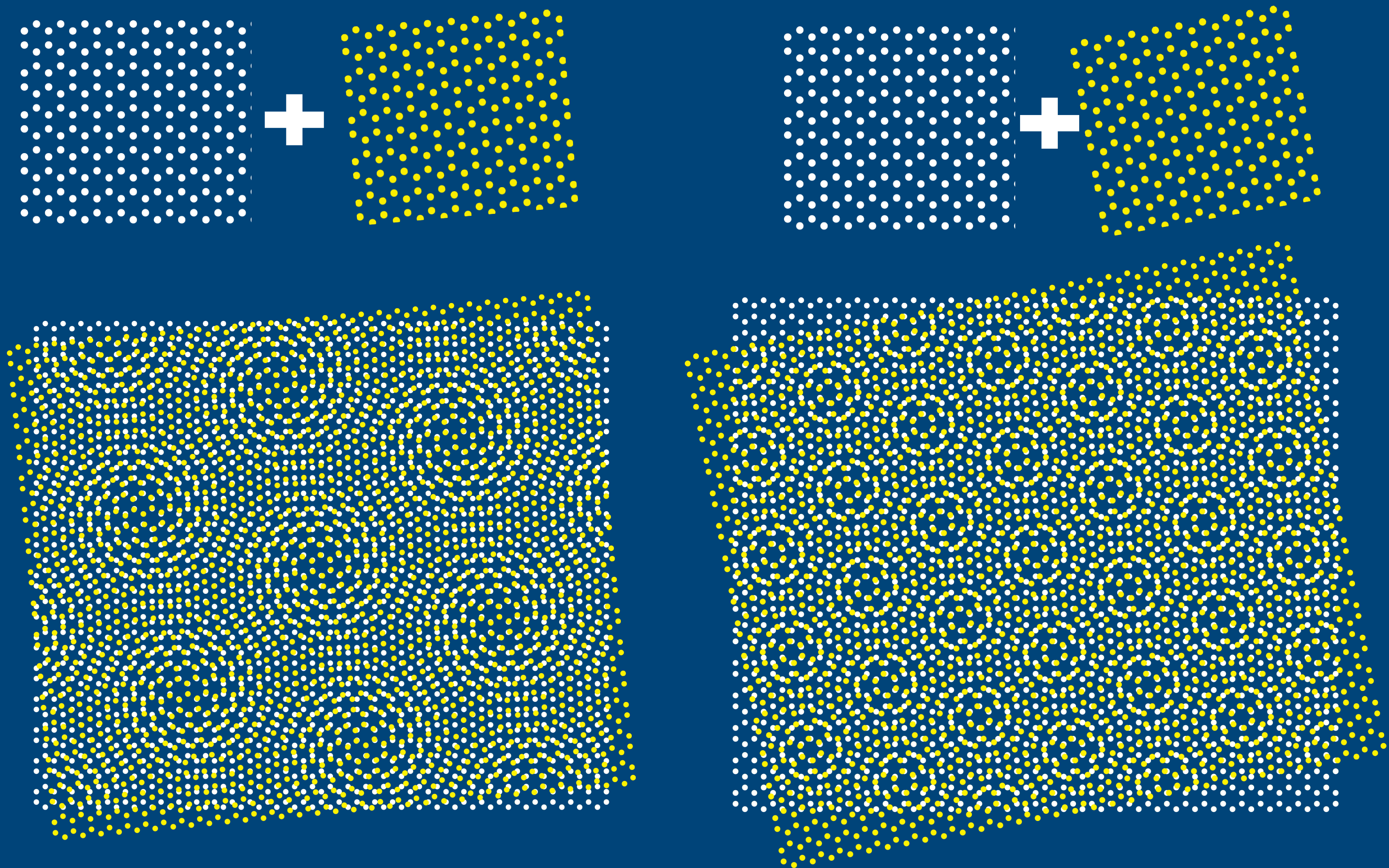




Large scale images show moiré pattern

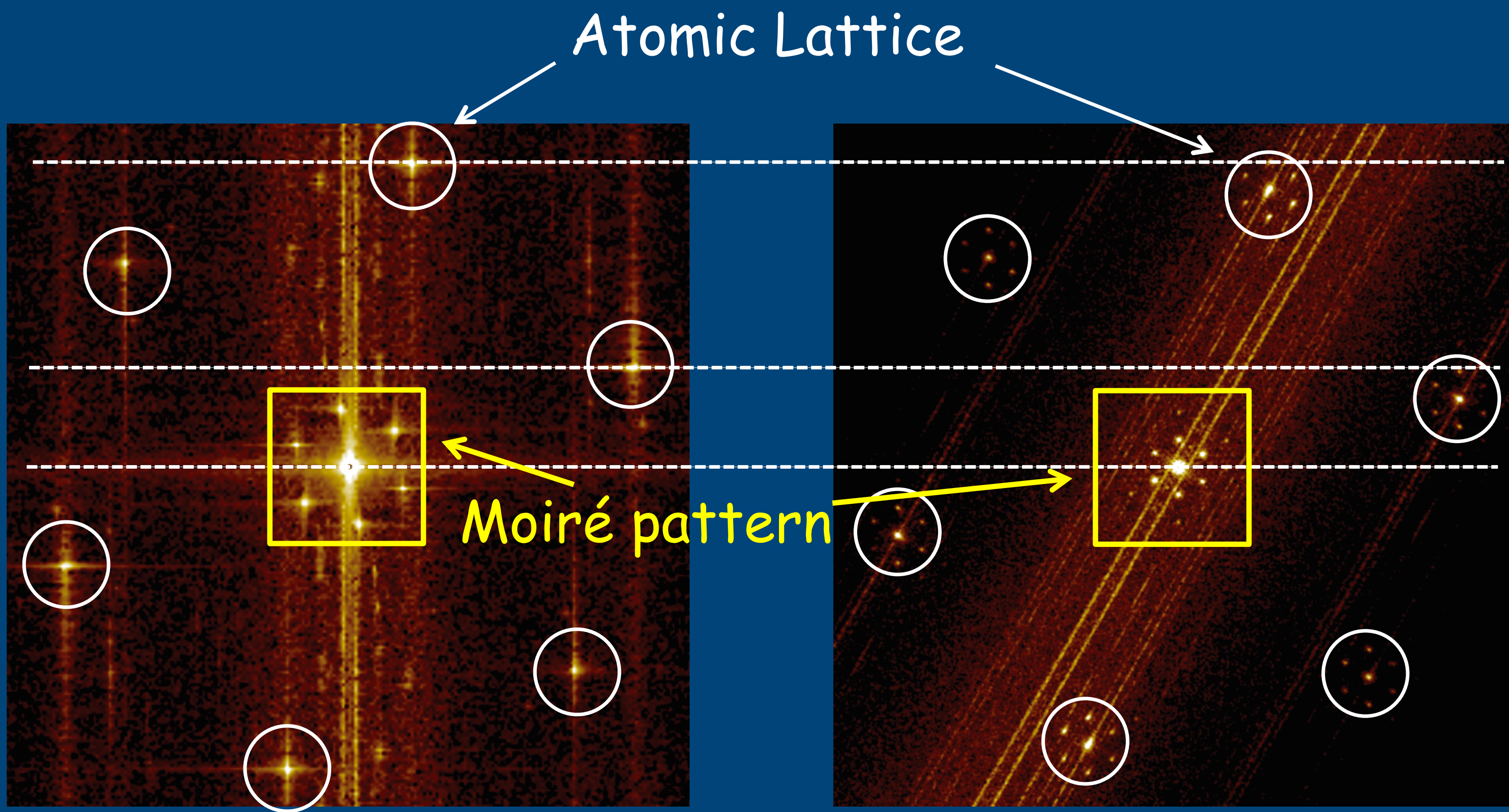
Different areas of the same graphene flake

Moiré Patterns



Moiré patterns arise from rotation between graphene and hBN

Fourier Transforms



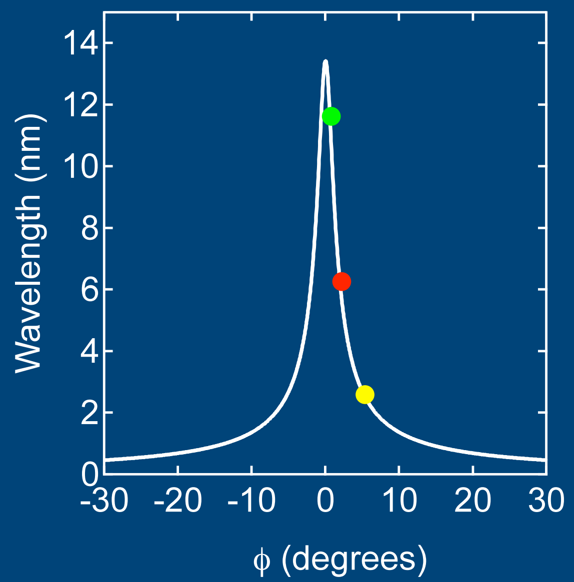
Different size moiré patterns

Graphene lattice rotated between two images

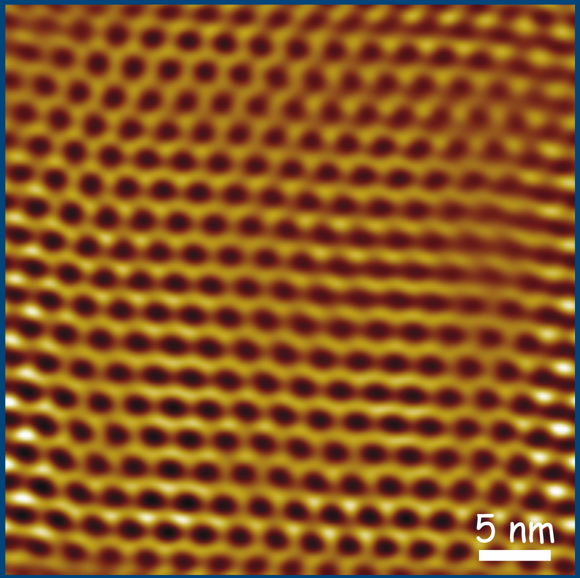
Moiré Wavelength

$$\lambda = \frac{(1+\delta)a}{\sqrt{2(1+\delta)(1-\cos\phi)+\delta^2}}$$

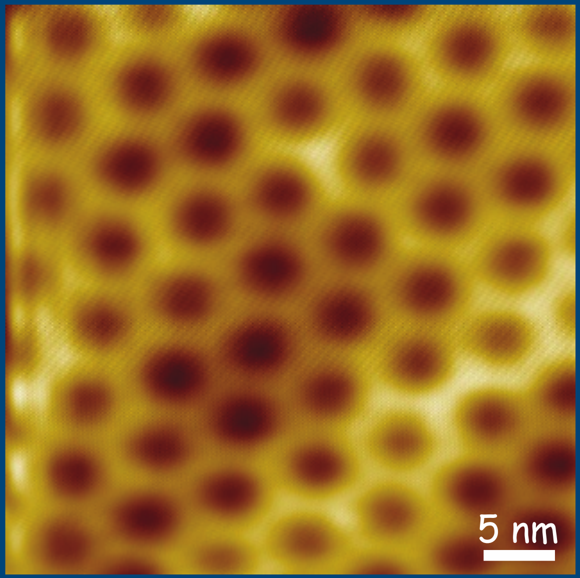
a: graphene lattice constant
δ: mismatch of h-BN
φ: Angle between lattices



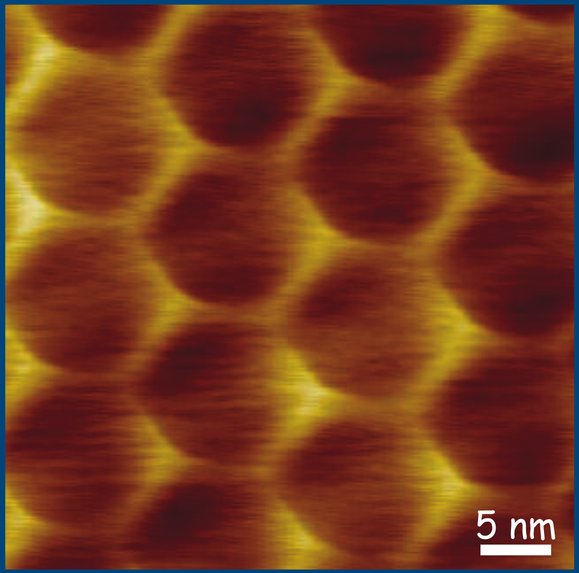
2.4 nm



6.0 nm



11.5 nm



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Consequence of moiré pattern: No energy gap

<u>Previous theoretical prediction</u>[1]

No moiré pattern.

Broken symmetry of A-B carbon atoms.

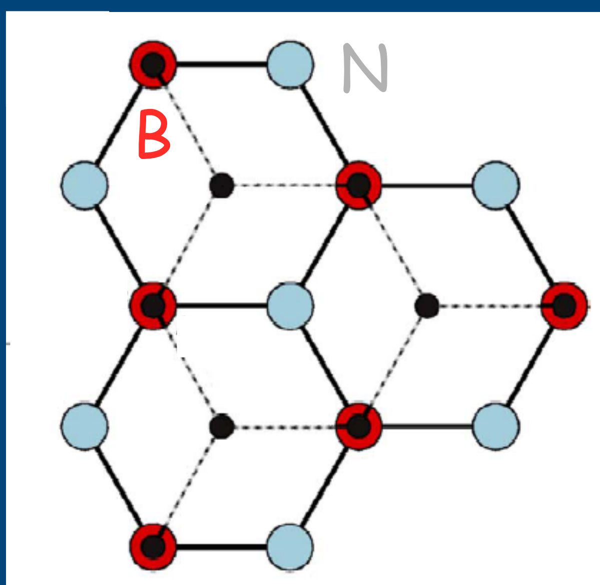
50 meV energy gap.

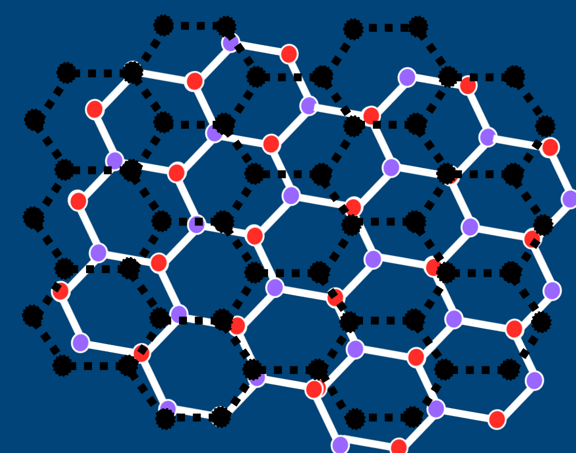
<u>Experimental observation:</u>

Has moiré pattern.

Symmetry of A-B carbon atoms is restored.

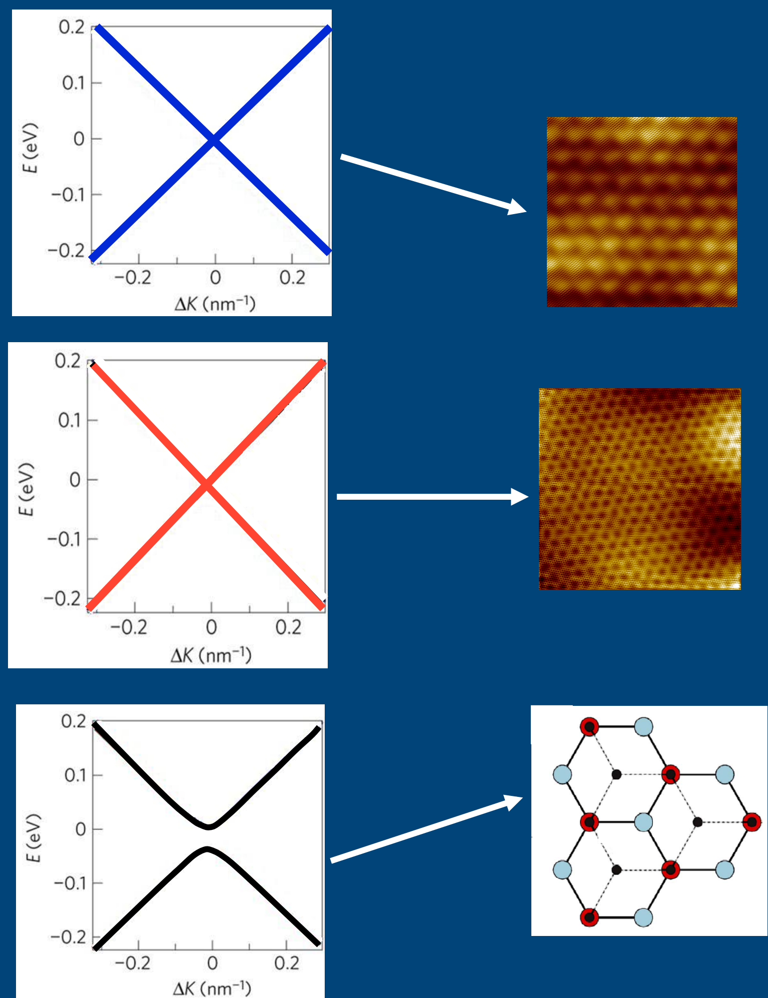
No energy gap.



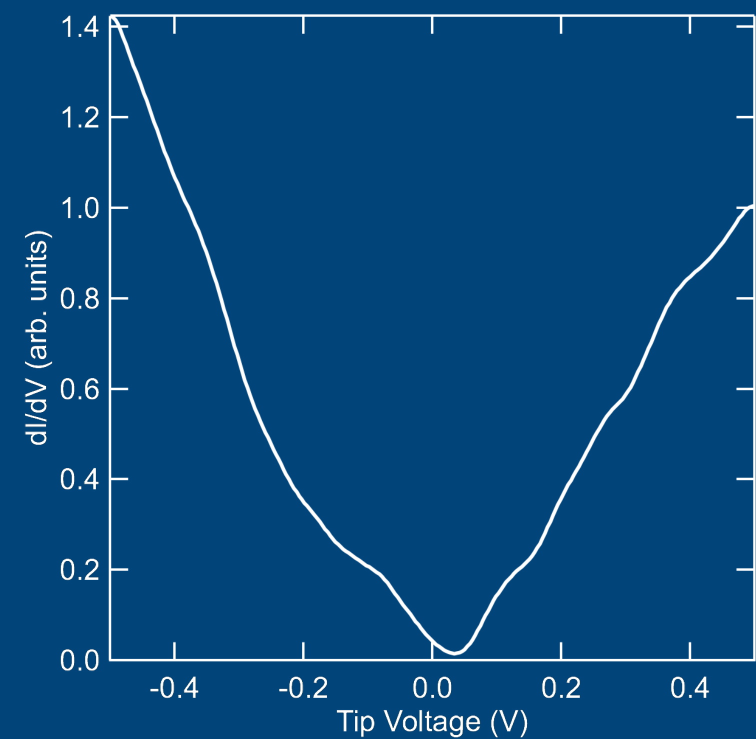


1: G. Giovannetti *et al.*, *PRB* (2007)

Spectroscopy Measurements



Calculated dispersion relations for three different configurations.

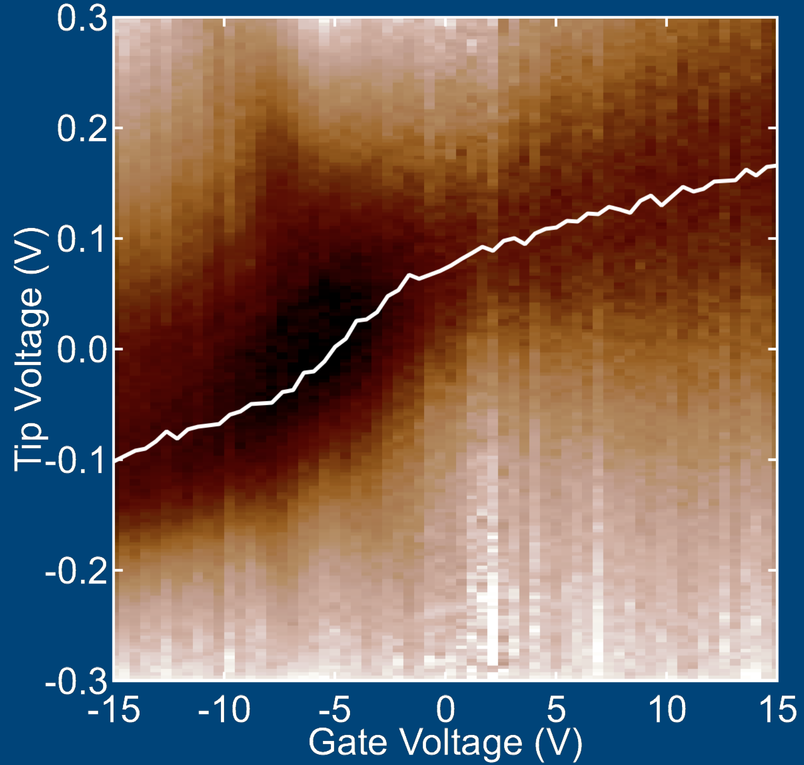


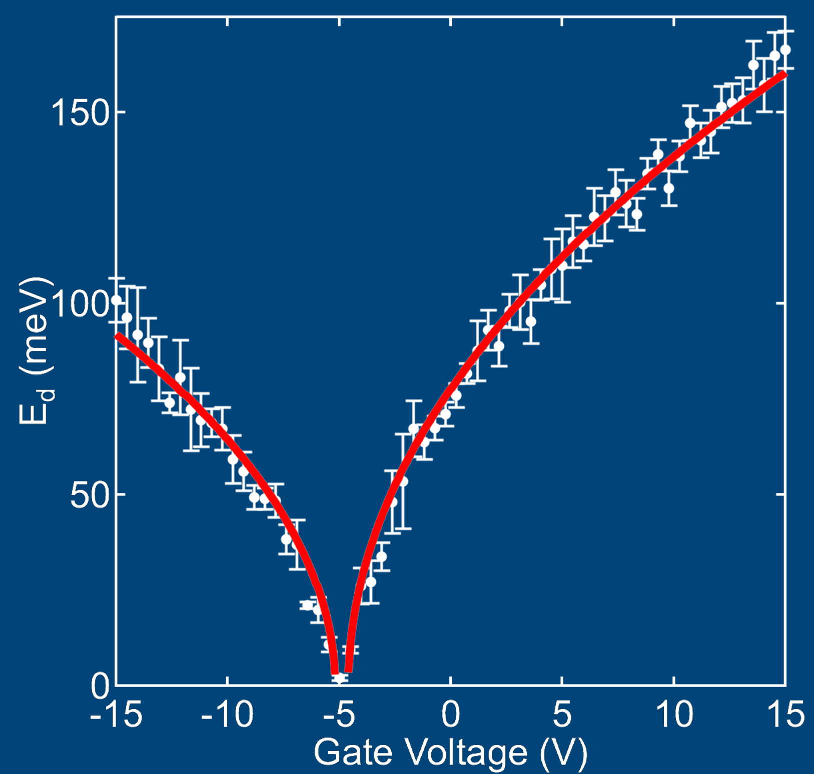
Spectroscopy measured by STM

No energy gap.

Gate Dependence

dI/dV curves

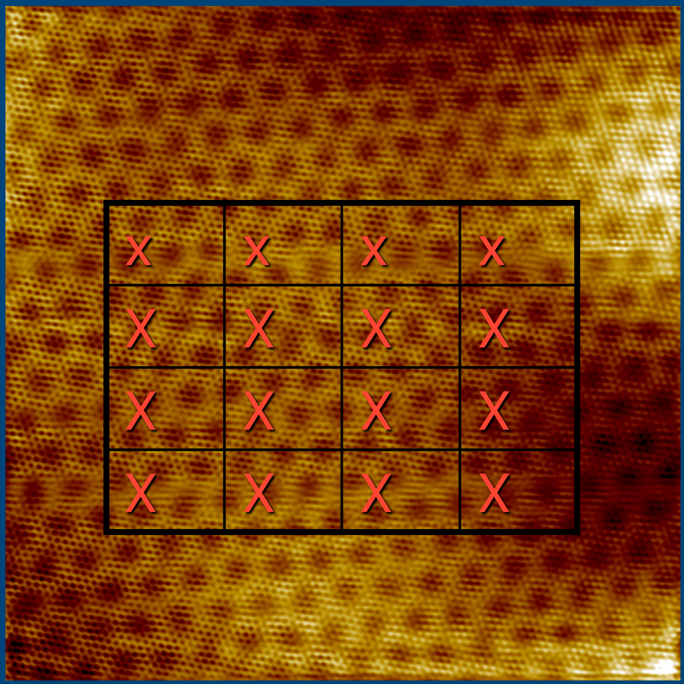


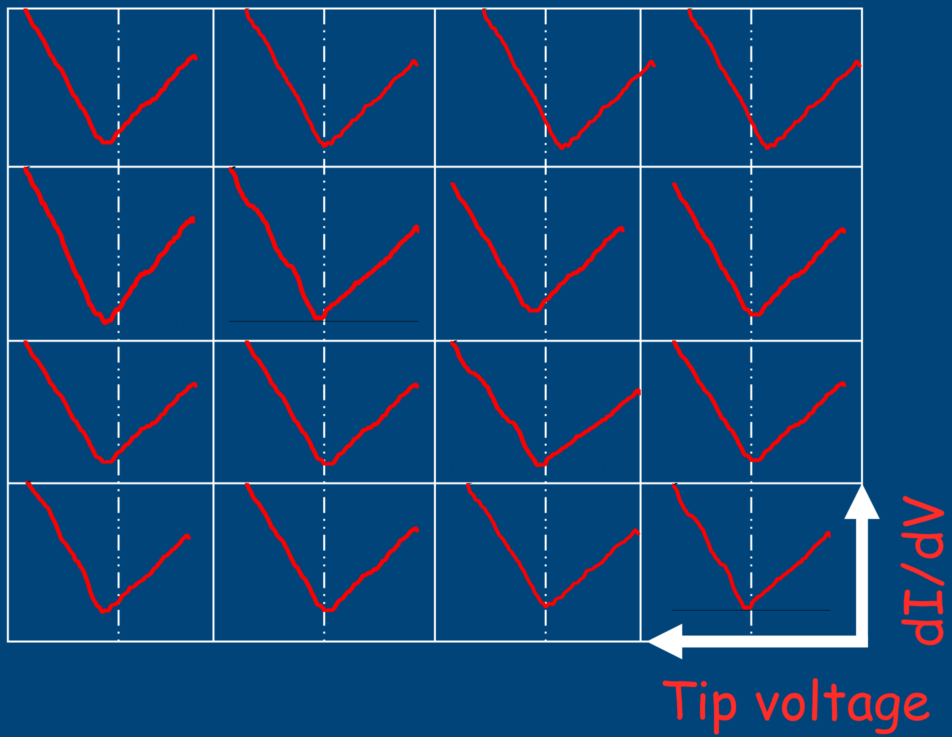


Dirac point follows expected energy for linear dispersion

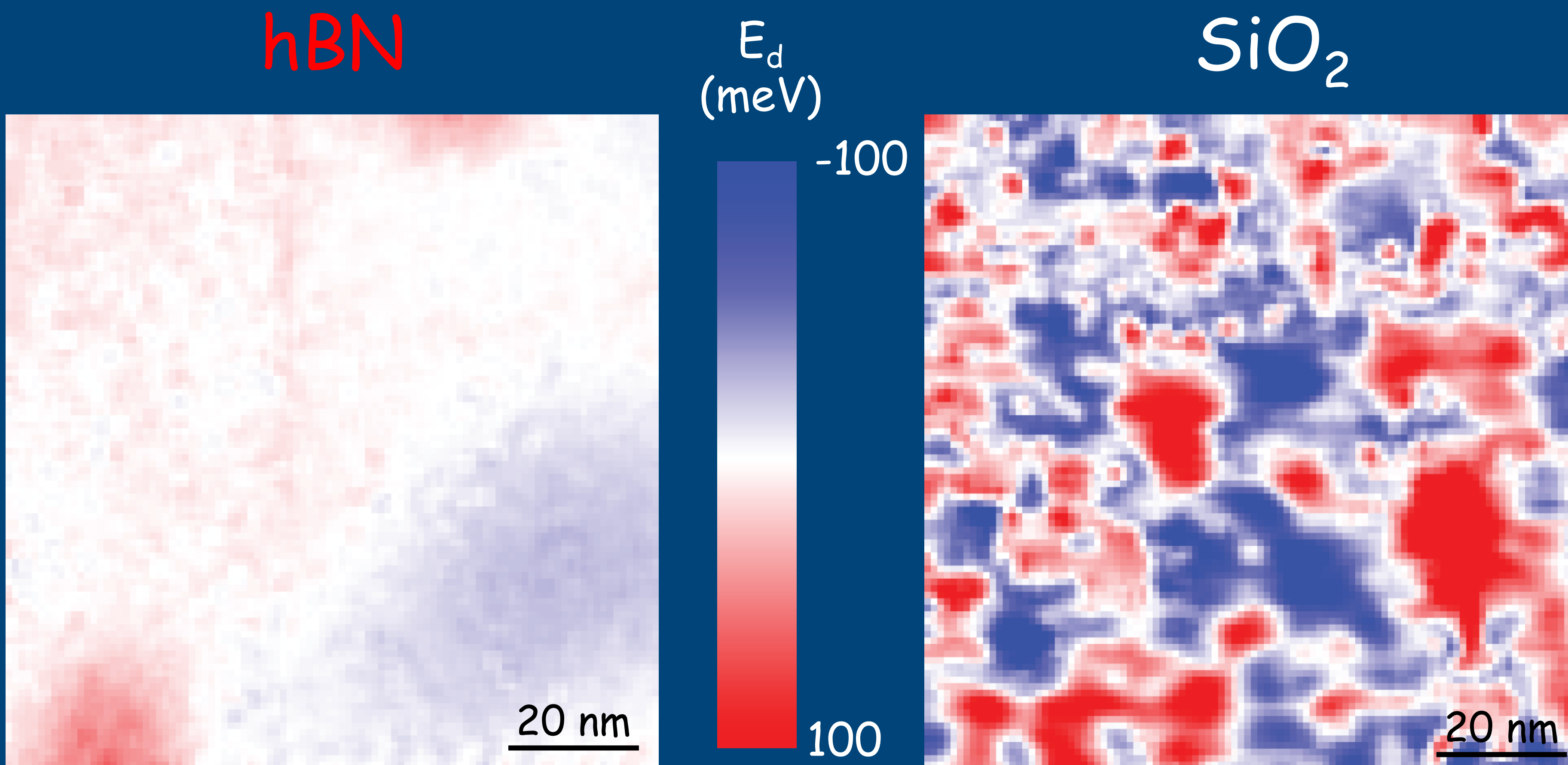
Spectroscopy Map

- Spectroscopy performed on a 1 nm x 1 nm grid
- Measure tip voltage corresponding to Dirac point



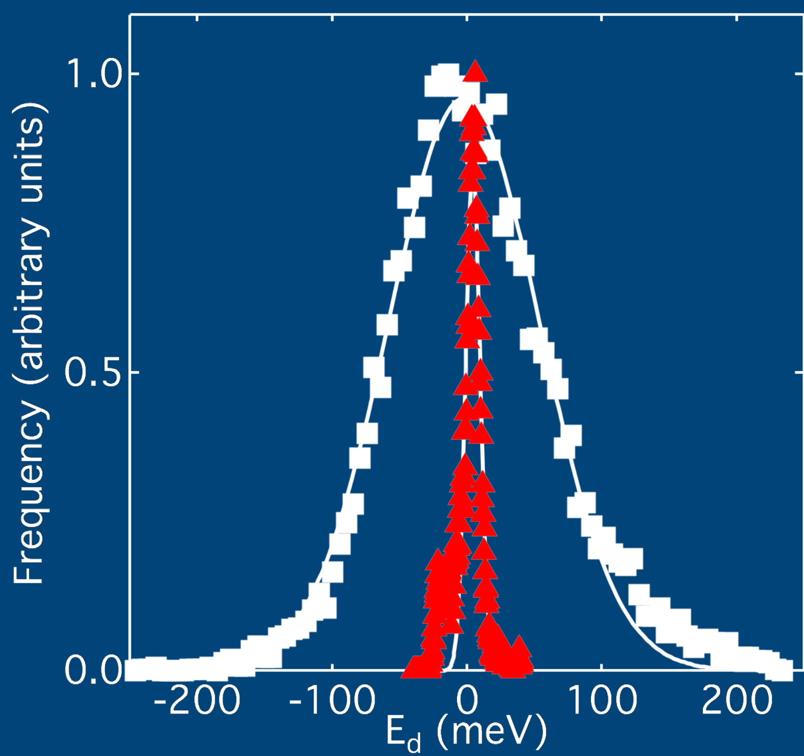


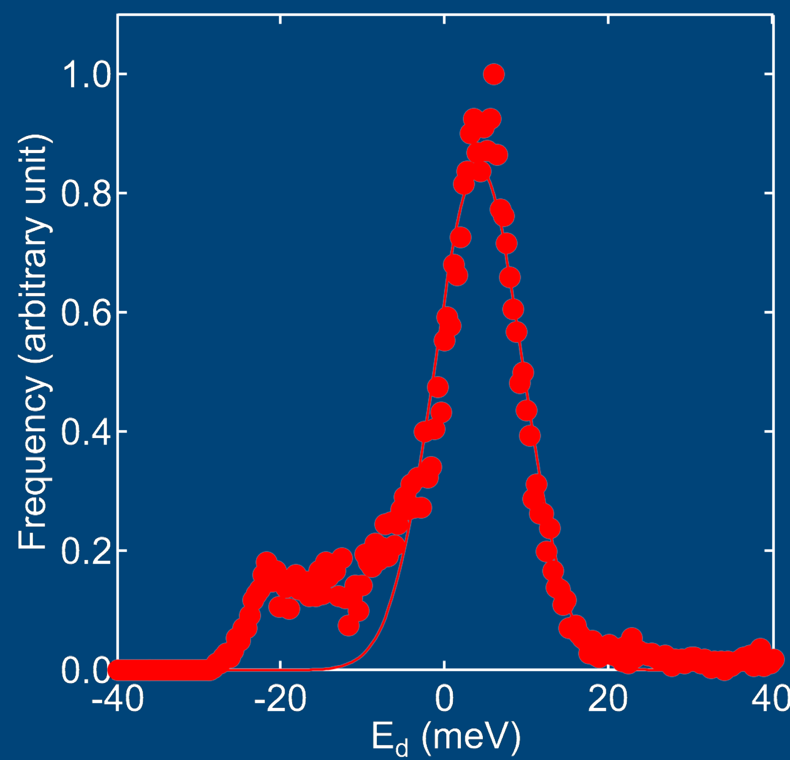
Spectroscopy Map



Potential fluctuations much smaller on hBN
Spatial extent of puddles is larger on hBN

Spectroscopy Comparison





SiO_2: 55.6 ± 0.7 meV

BN: 5.4±0.1 meV

Distribution on hBN is 10 times narrower

Extra bump in distribution observed in most samples

Xue et al., Nat. Mater. **10**, 282 (2011)

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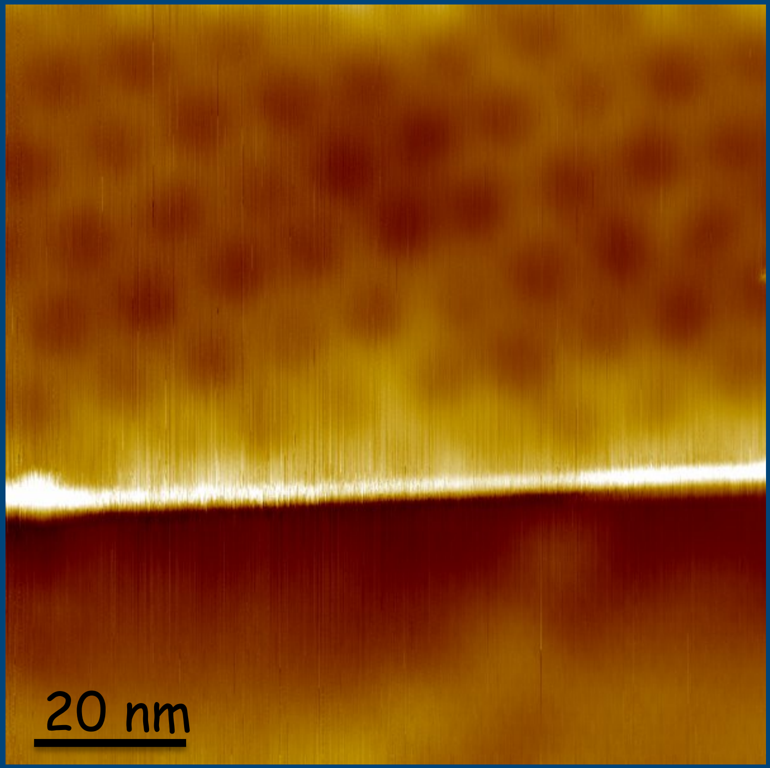
Topography of step edge



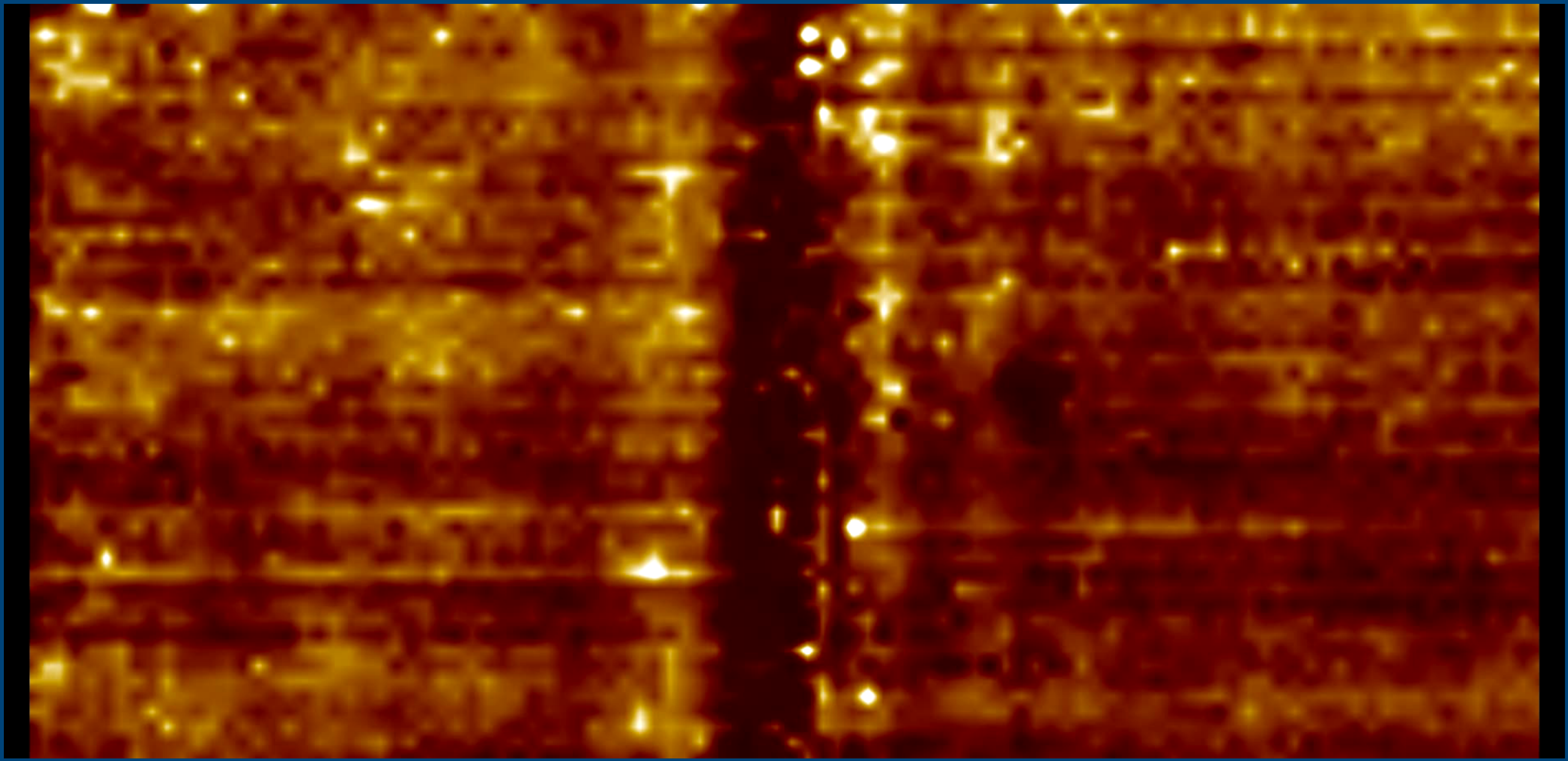
Step is about 0.6 nm high

Graphene lattice has the same orientation above and below the step

Density of States Versus Energy

Step edge running vertically through images

Series of gap voltages (energies)



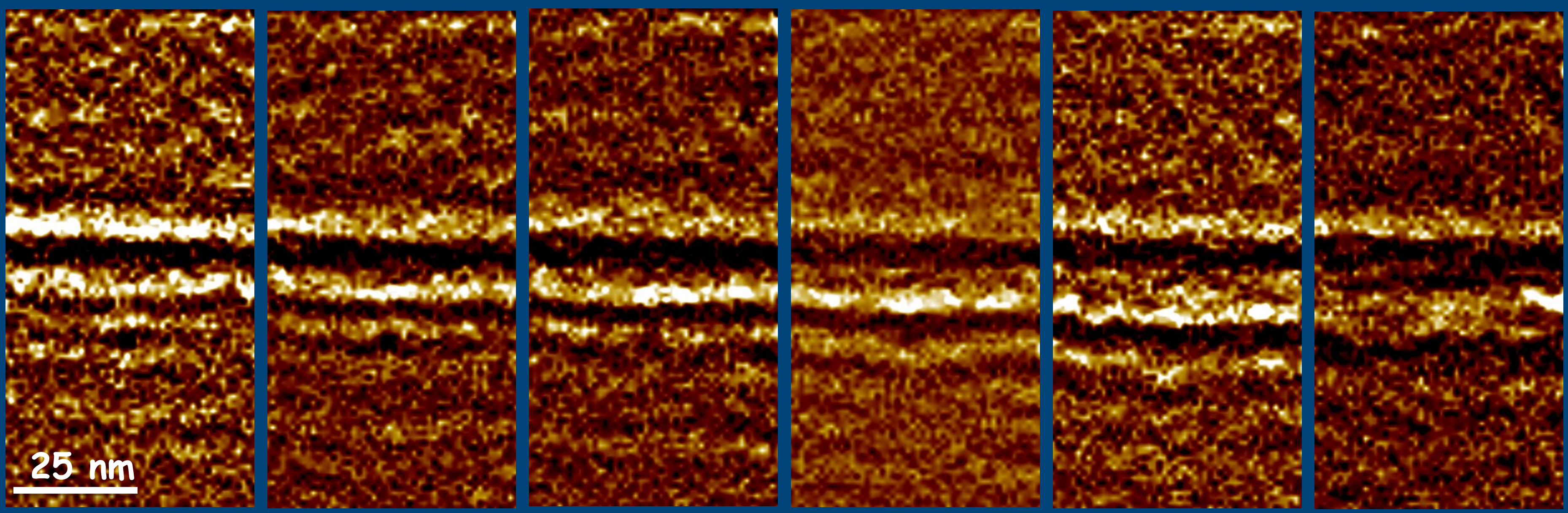
Xue et al., PRL **108**, 016801 (2012)

Density of States Images

Step edge running horizontally through images

Series of gap voltages (energies)

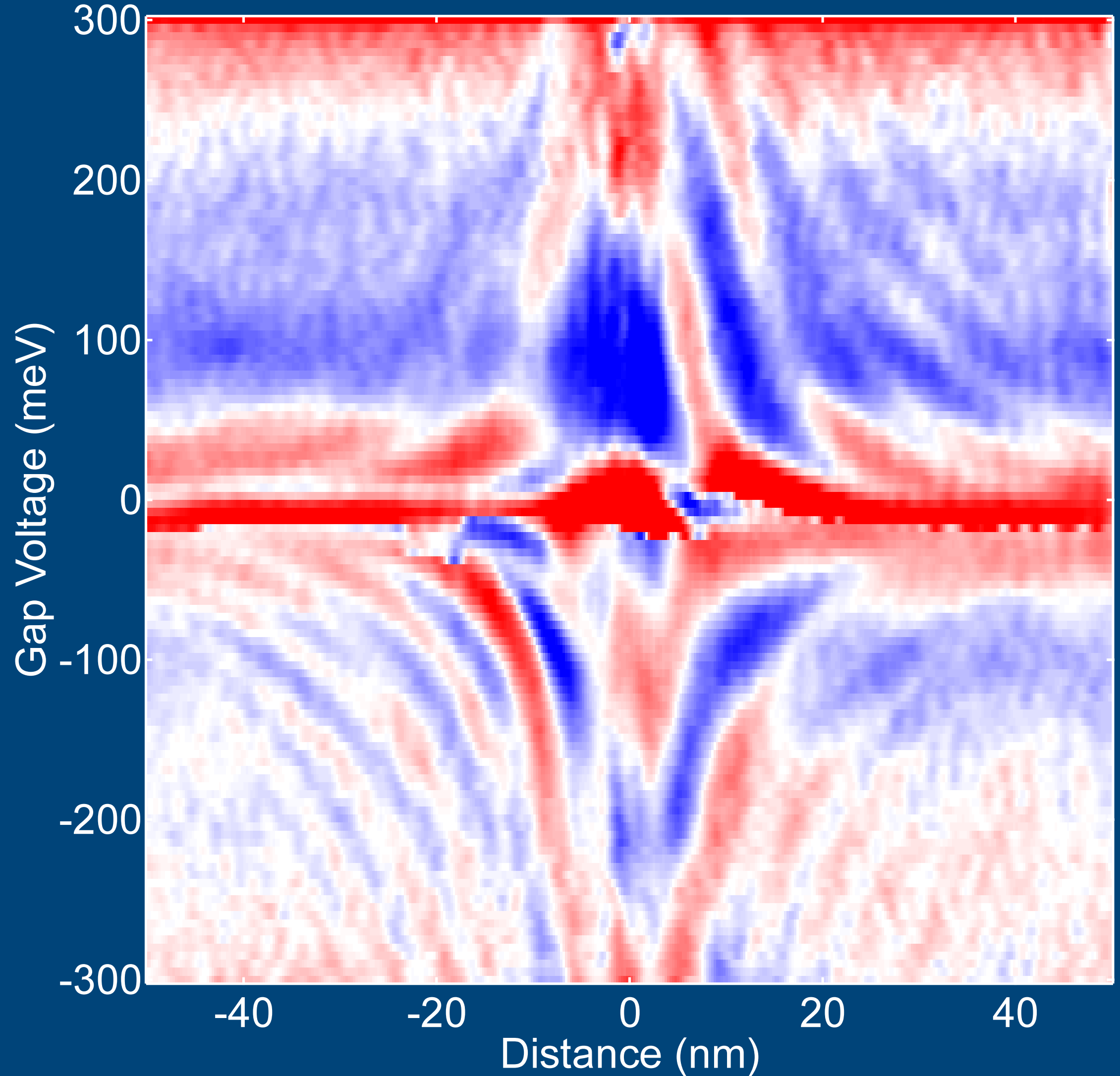
-138 meV -118 meV -98 meV -78 meV -58 meV -38 meV



Wavelength increases with decreasing energy

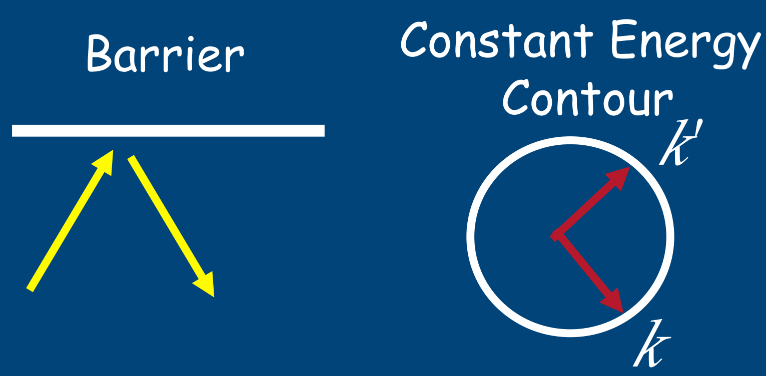
Density of States Images

All data in x-direction (along step edge) averaged



Color scale is change in density of states

Distance Dependence



Assume barrier along x-axis

$$k_x = k'_x \qquad k_y = -k'_y$$

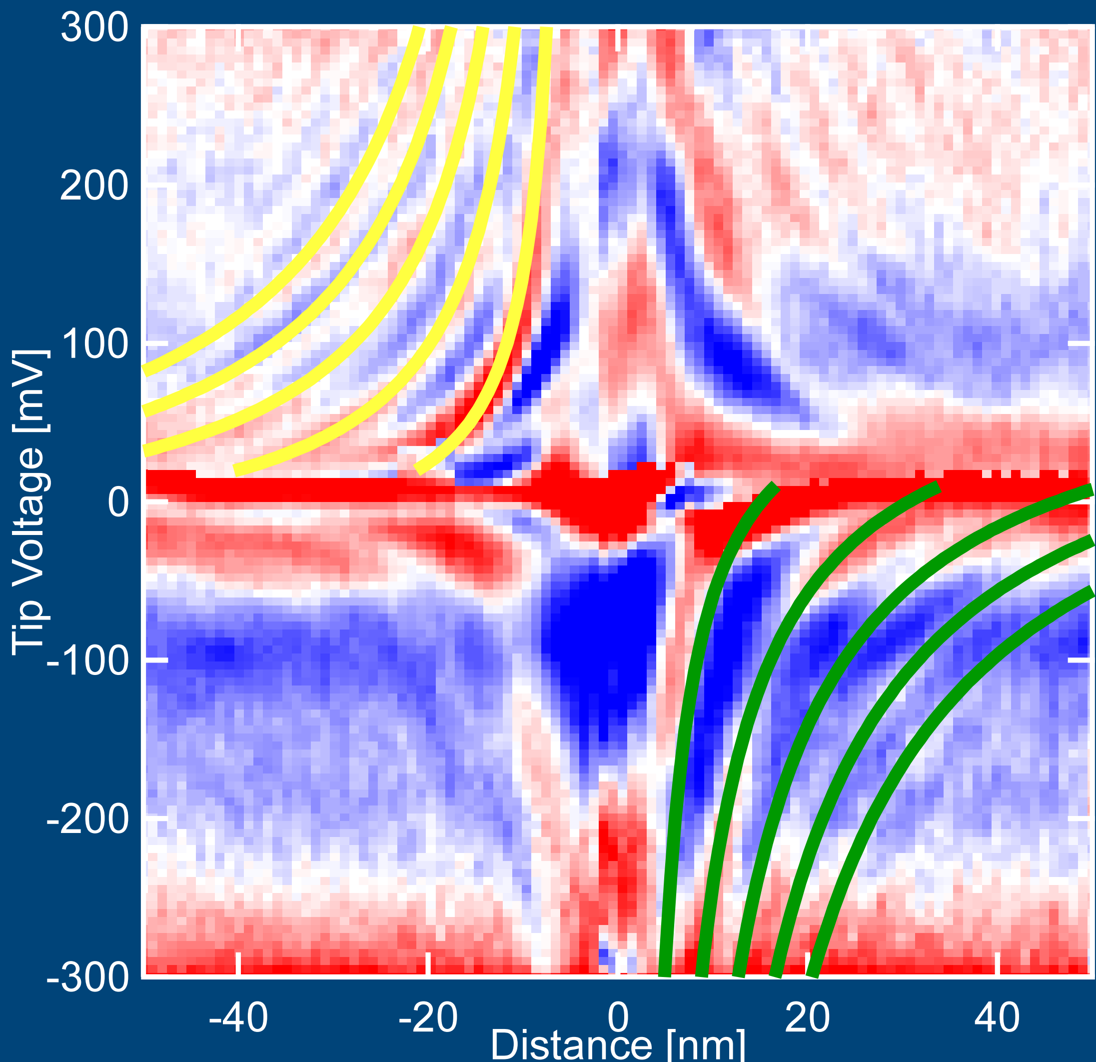
$$\rho(E,y) \propto \oint_{CEC} \left| \psi(k_x,k_y) + r\,\psi(k_x,-k_y) \right|^2 dk$$

$$\delta\rho(E,y) \propto \oint_{CEC} \cos(2k_y y)\sin\theta_k\, dk \qquad \tan\theta_k = \frac{k_x}{k_y}$$

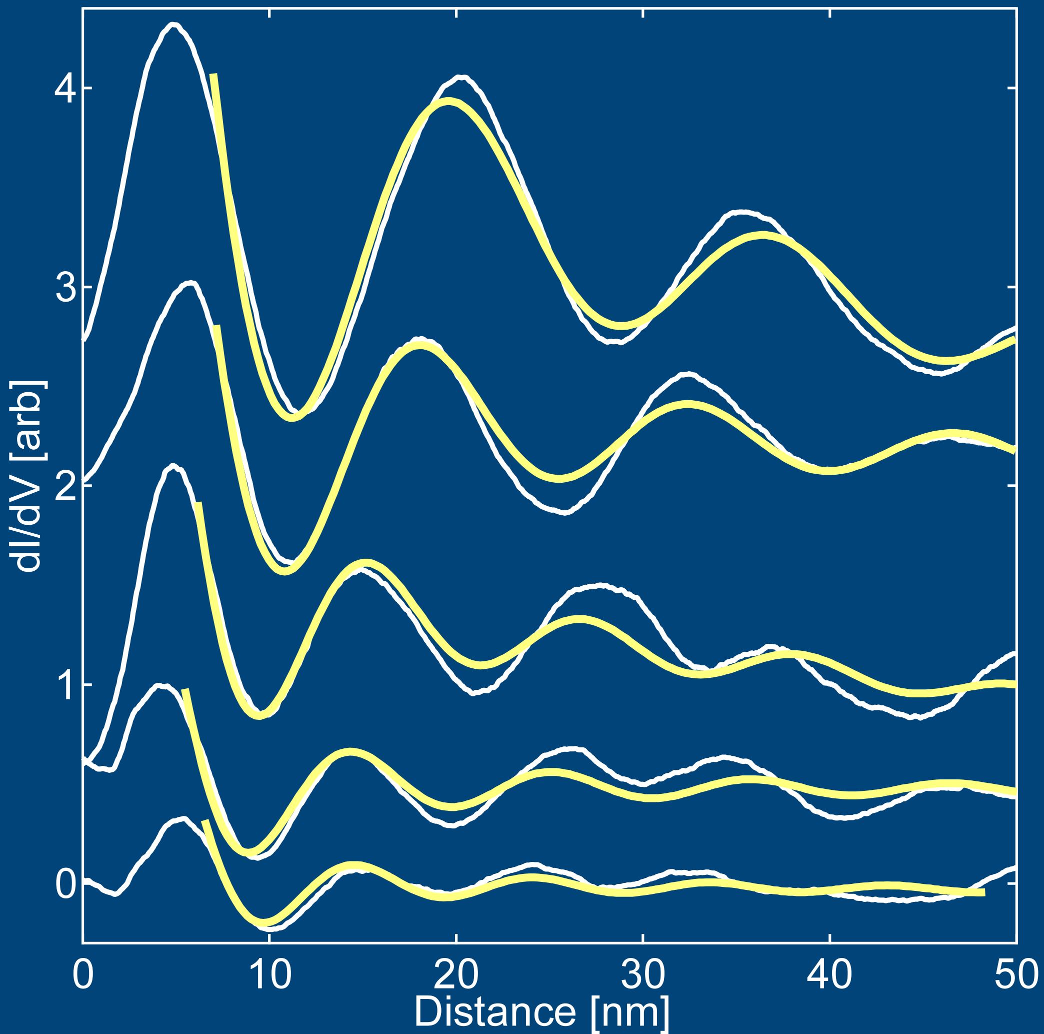
$$\delta\rho(E,y) \propto \frac{\cos(2ky - 3\pi/4)}{(ky)^{3/2}}$$

Faster decay than normal metal

Energy Dependence



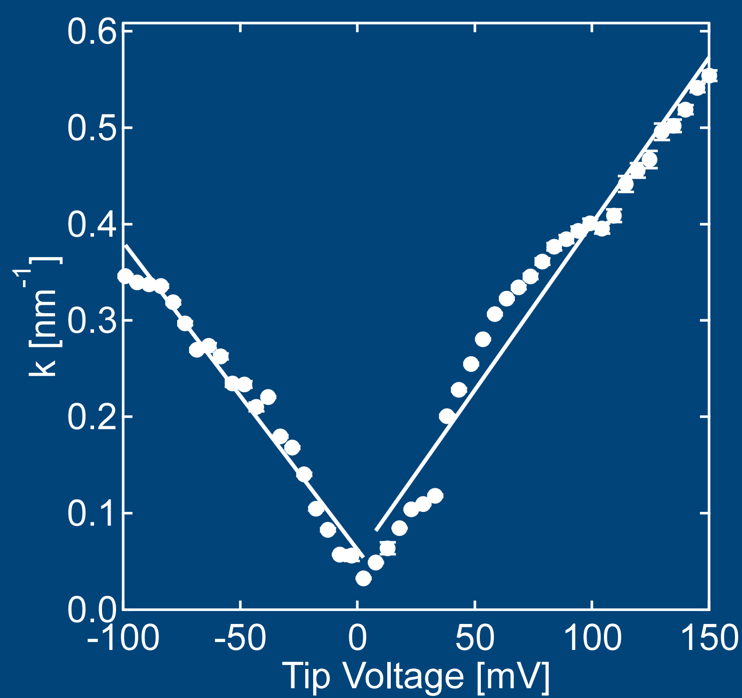
Distance Dependence



$$\delta\rho(E,y) \propto \frac{\cos(2ky - 3\pi/4)}{(ky)^{3/2}}$$

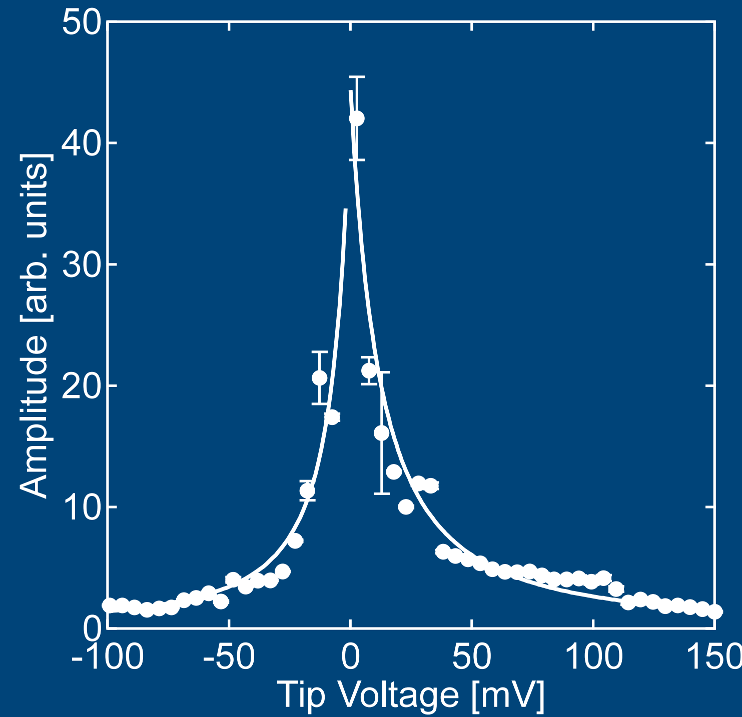
Analysis

Dispersion Relation



$v_F = 0.50 \pm 0.05 \times 10^6$ m/s

Amplitude of oscillations



Xue et al., PRL **108**, 016801 (2012)

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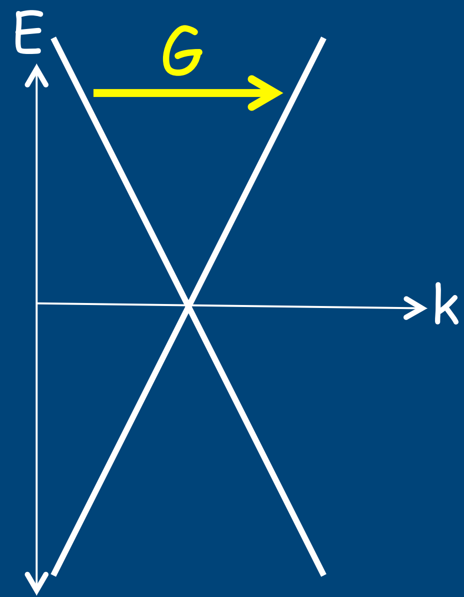
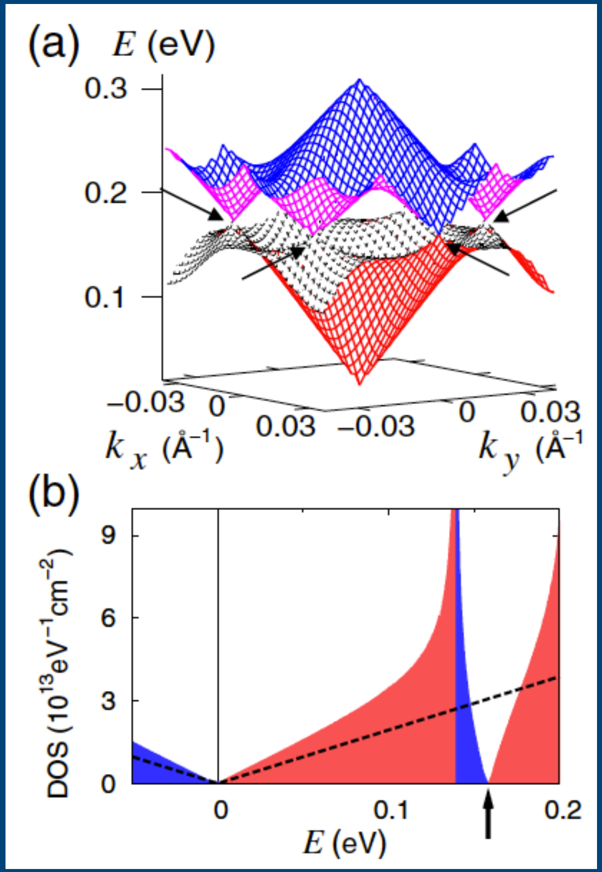
Graphene in Periodic Potential





<u>Schrödinger</u>

Band gap opens

<u>Dirac</u>

New superlattice Dirac point

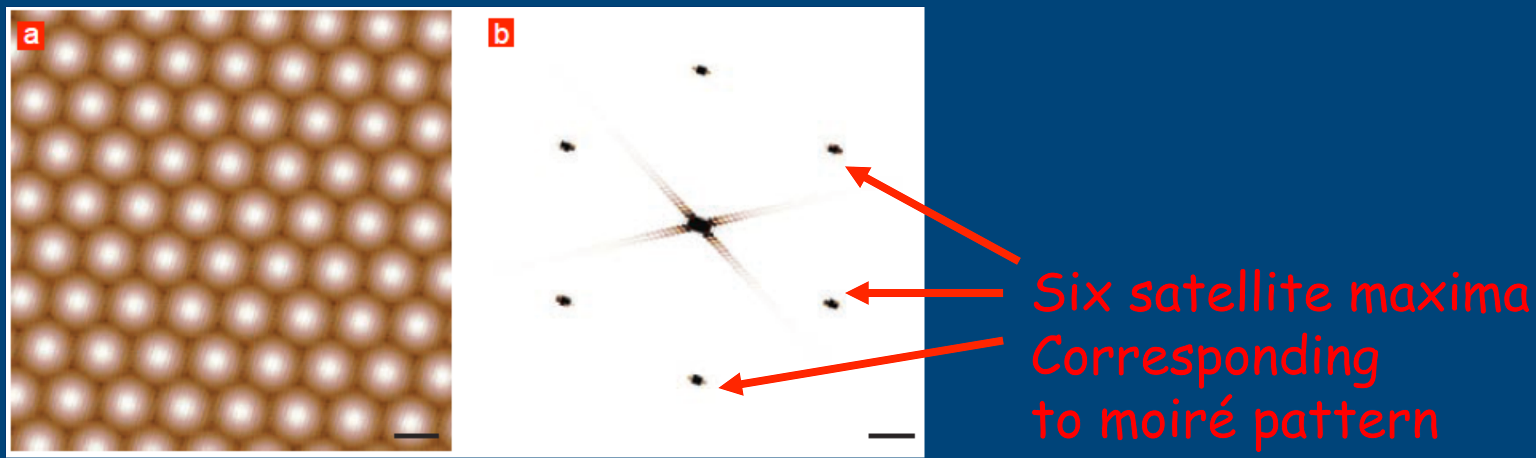
$$E = \hbar v_F G / 2$$

Park et al., *Nat. Phys.* **4**, 213 (2008); *PRL* **101**, 126804 (2008); Barbier et al., *PRB* **77**, 115446 (2008)
Brey and Fertig, *PRL* **103**, 046809 (2009); Barbier et al., *PRB* **80**, 205415 (2009);
Sun et al., *PRL* **105**, 156801 (2010); Burset et al., *PRB* **83**, 195434 (2011);
Ortix et al., arXiv:1111:0399 (2011)

Graphene on hBN

- Calculate interlayer hopping from μ=A,B carbon sites to ν=Boron, Nitrogen sites
- Keep nearest neighbors and next n.n. -> four different hoppings

$$V_{\mu\nu}(m,n) = \gamma_\perp \exp[-|\mathbf{r}_{1\mu}(m,n) - \mathbf{r}_{2\nu}(m',n')|/\xi]$$

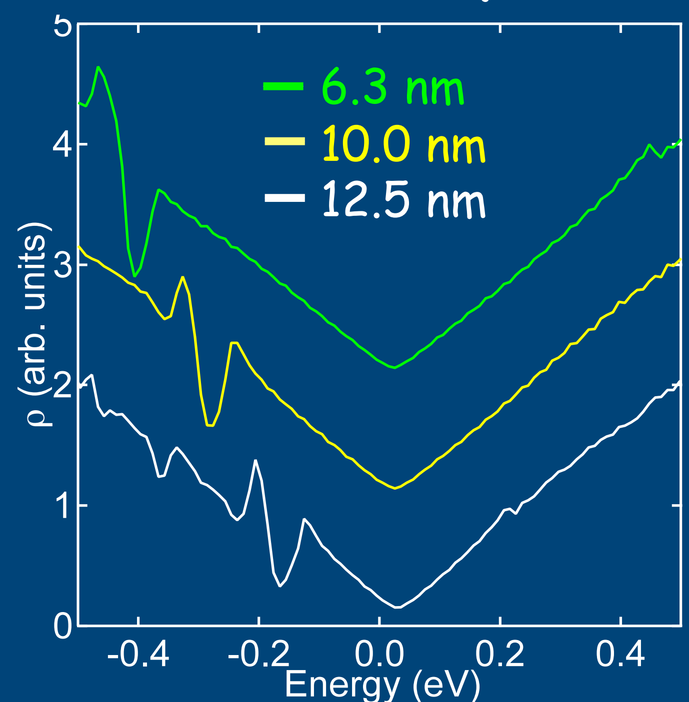


$V_{AA}(m,n)$ $V_{AA}(k_x,k_y)$

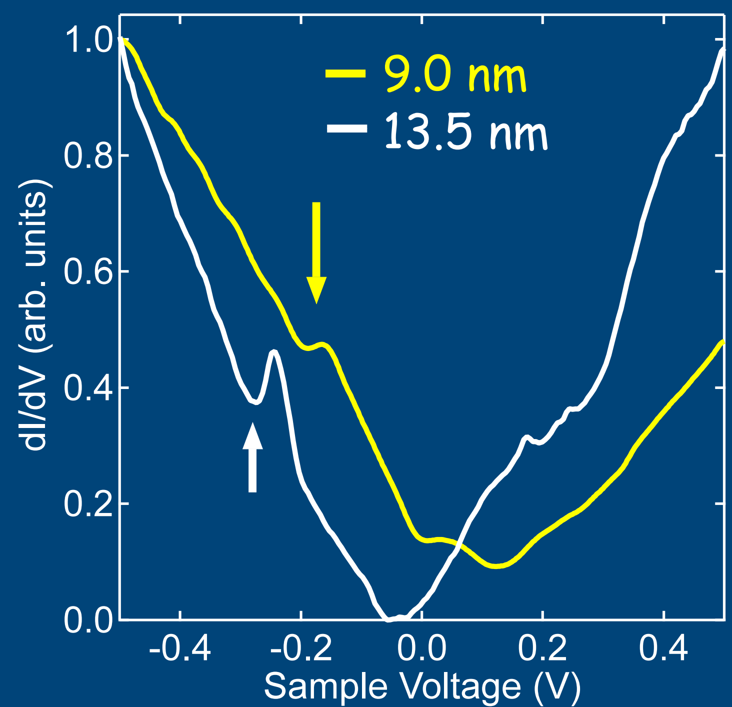
Graphene experiences periodic potential given by moiré pattern

Spectroscopy

Theory



Experiment

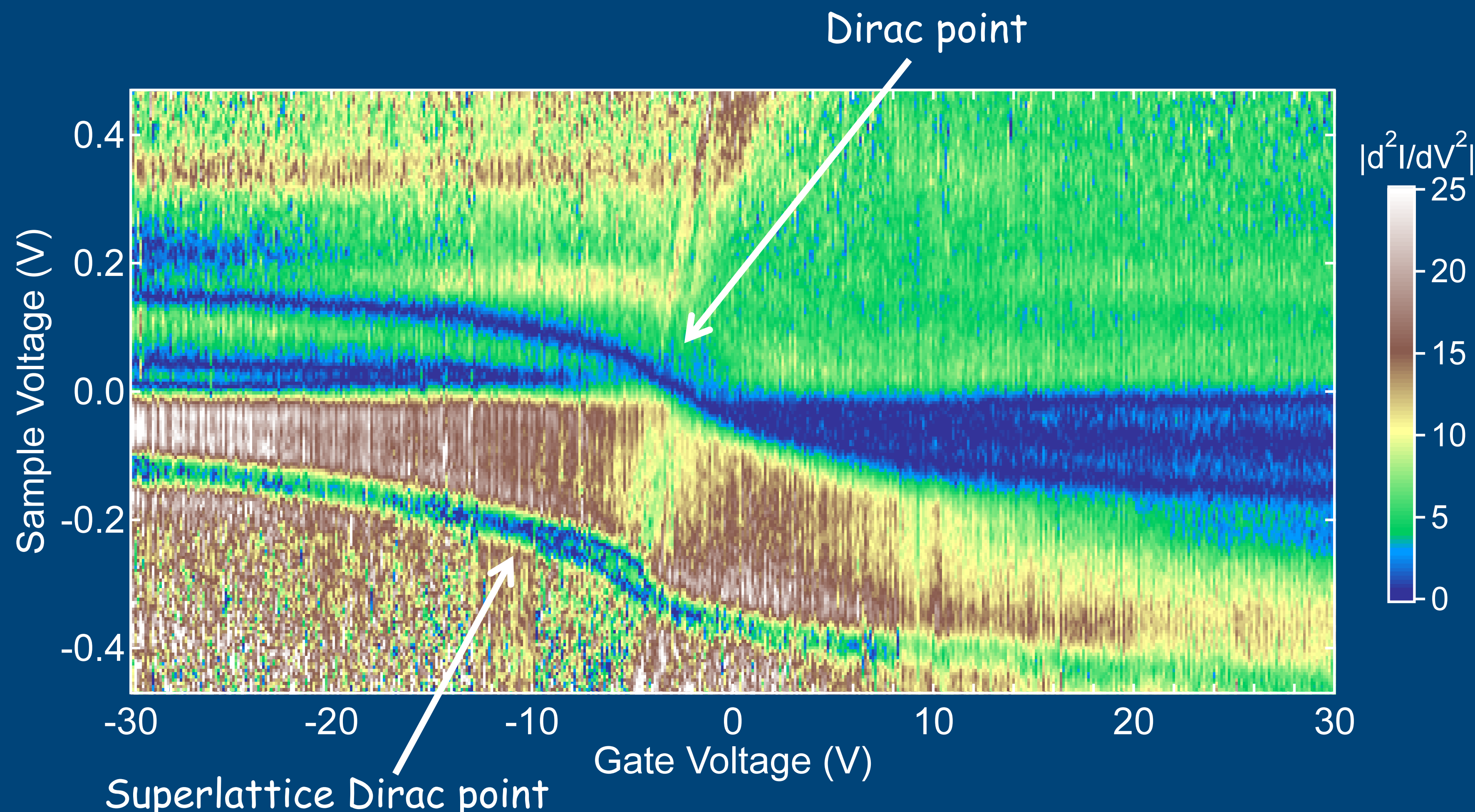


Dips in density of states due to superlattice potential

Yankowitz et al., submitted

Gate Dependence

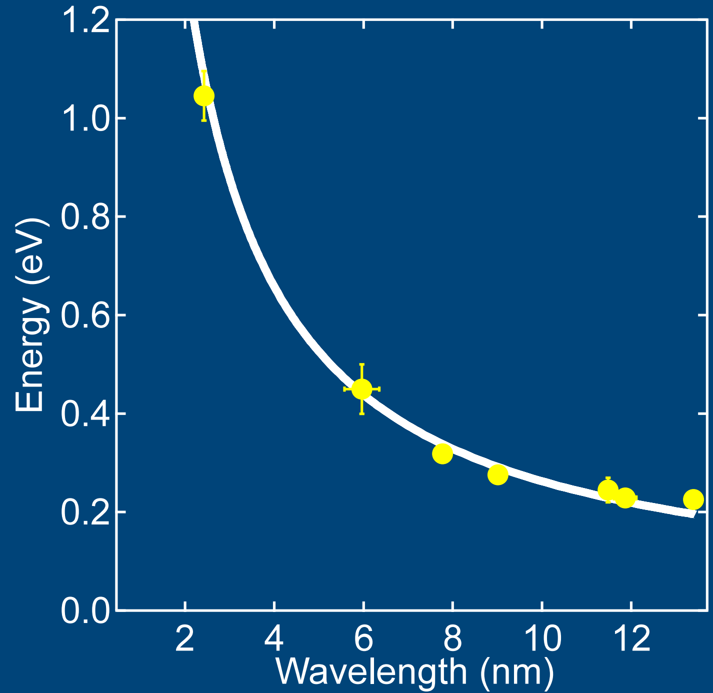
9.0 nm moiré



Dips move together with Fermi energy

Yankowitz et al., submitted

Superlattice Dirac Point



Energy of superlattice Dirac points determined by wavelength of potential

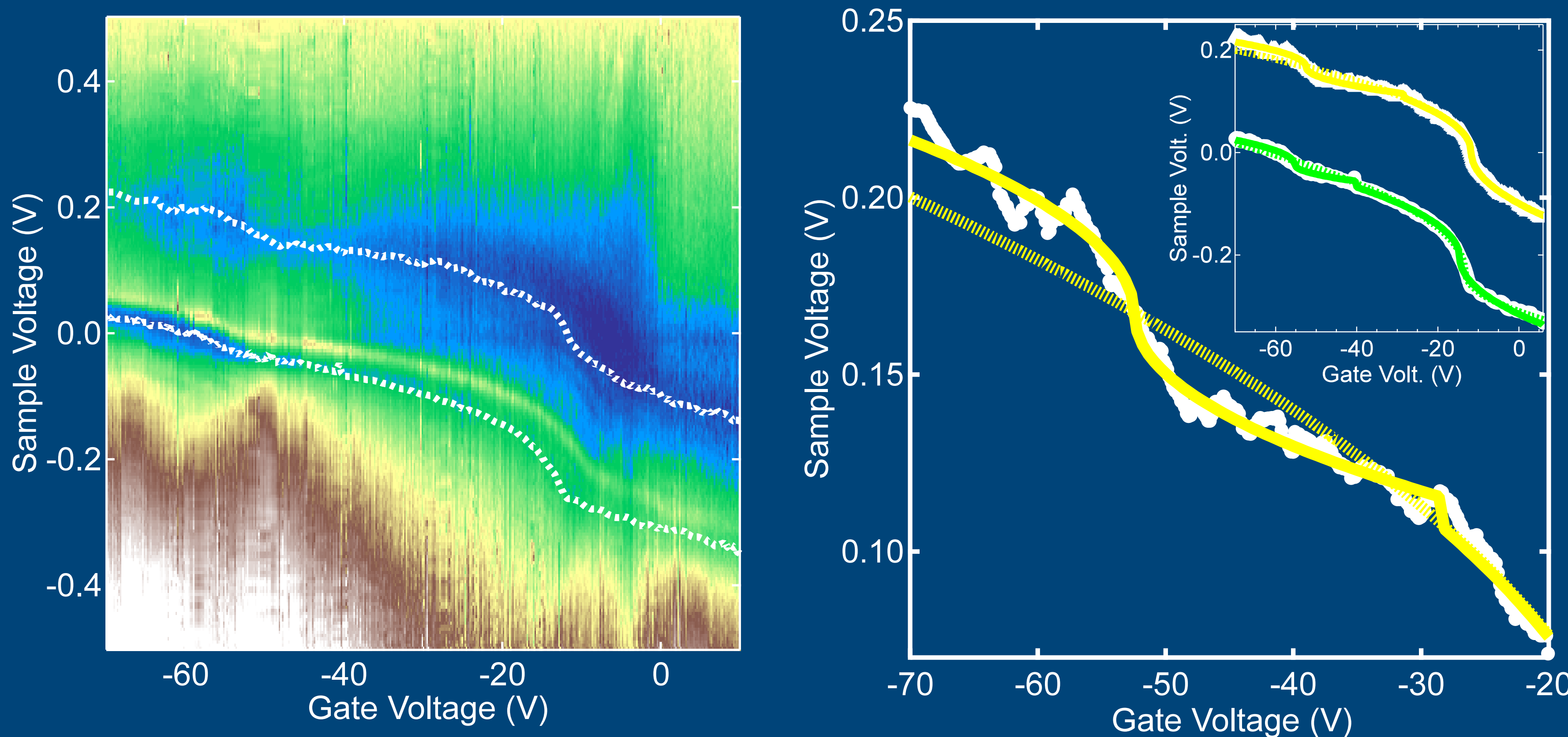
$$E = \hbar v_F G / 2 = 2\pi\hbar v_F / \sqrt{3}\lambda$$

$$v_F = 1.1 \times 10^6 \, \mathrm{m/s}$$

Yankowitz et al., submitted

Superlattice Dirac Point

13.5 nm moiré



Superlattice Dirac point has reduced Fermi velocity

$$v_F^* / v_F = 0.5 - 0.7$$

Yankowitz et al., submitted

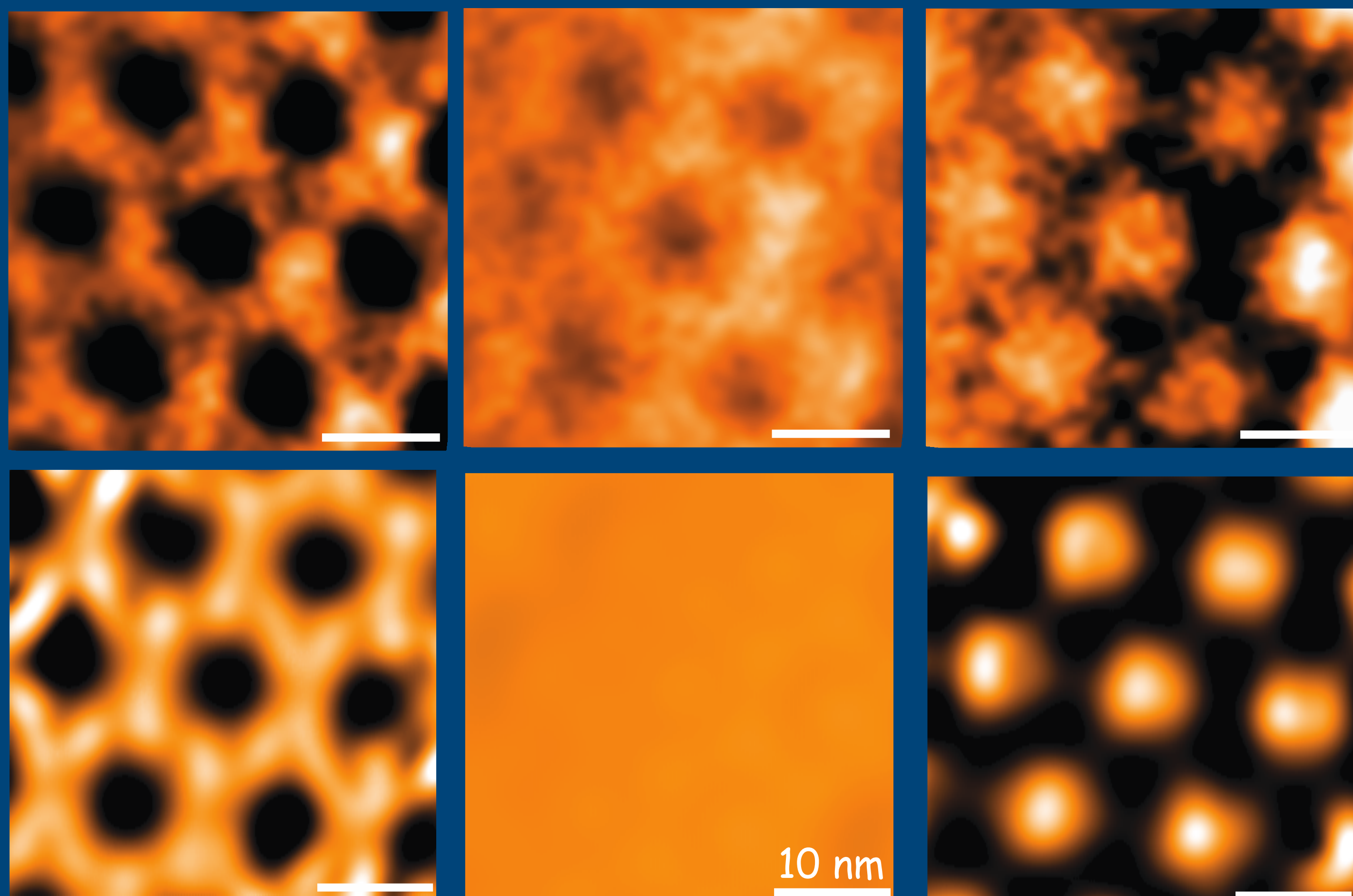
LDOS Maps

13.5 nm moiré

-0.3 eV | E_d | +0.3 eV

Expt.

Theory

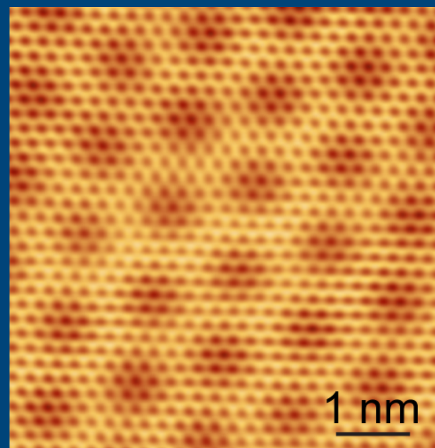


Spatial variation of images → v_F varies

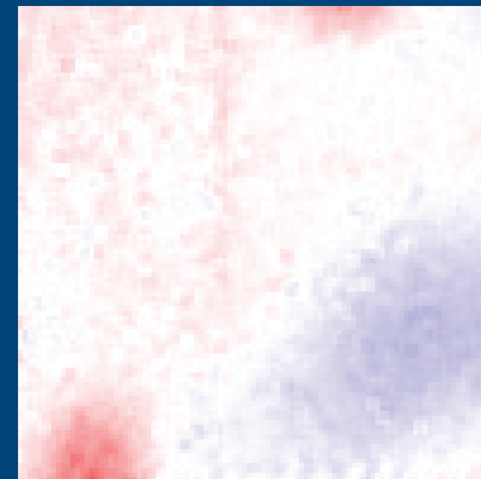
Yankowitz et al., submitted

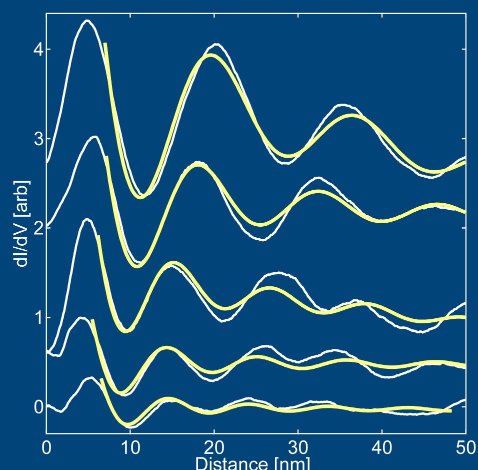
Conclusions

Moiré pattern observed for graphene on hBN

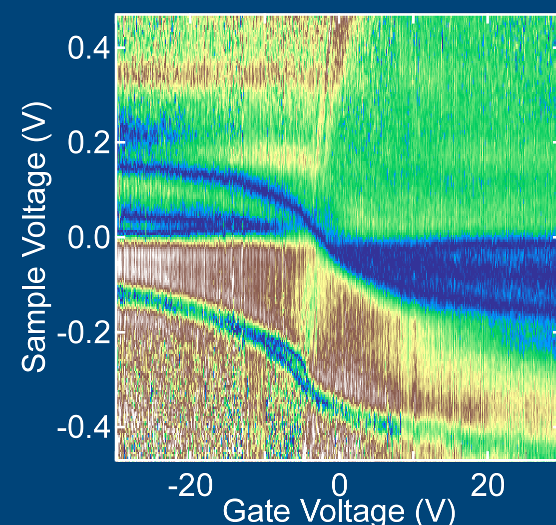


Electron and hole puddles reduced on hBN





LDOS oscillations near step edges



Superlattice Dirac point due to periodic potential

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LeRoy group

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Sam Silva (Undergrad)
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Reilly Bello (High School Student)
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Javier Sanchez-Yamagishi
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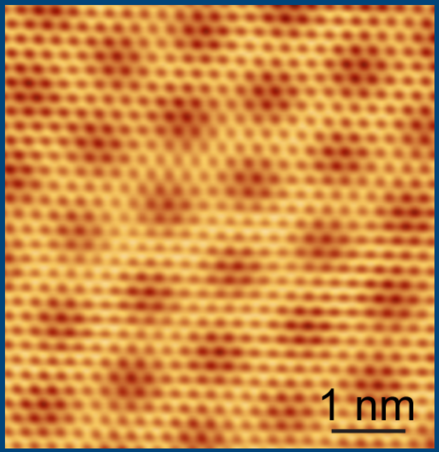
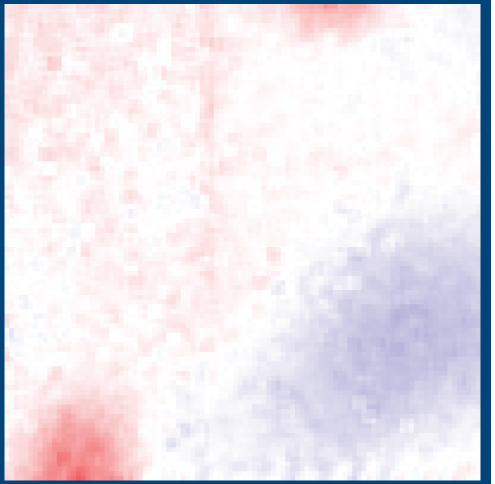
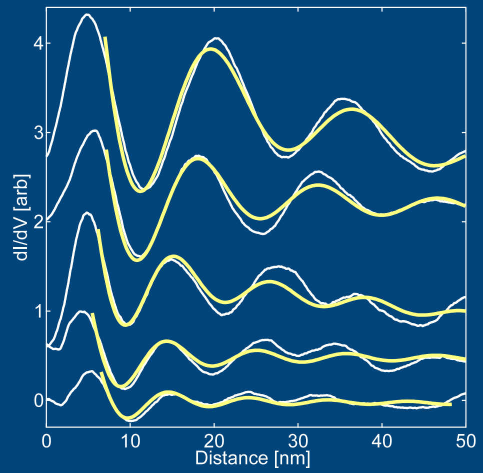
Conclusions

Moiré pattern observed for graphene on hBN

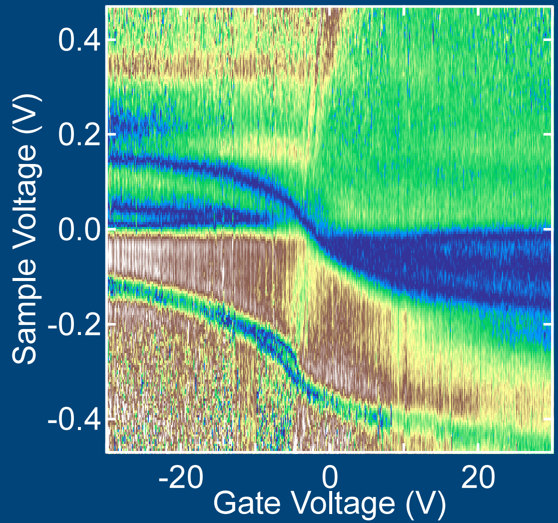


Electron and hole puddles reduced on hBN





LDOS oscillations near step edges



Superlattice Dirac point due to periodic potential

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