Gapless topological states in bilayer graphene

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University of Antwerp

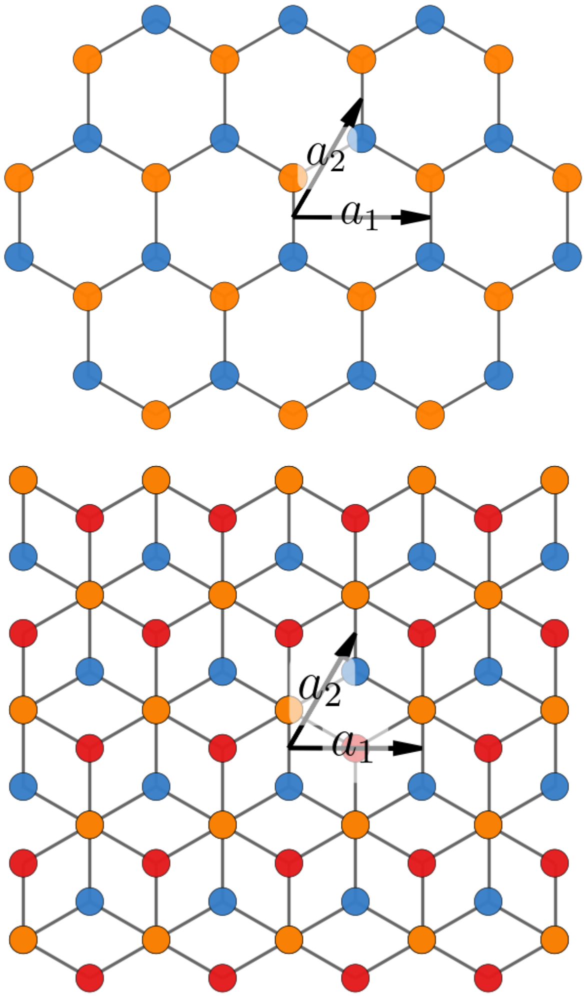
20th of February, 2018.

Introduction

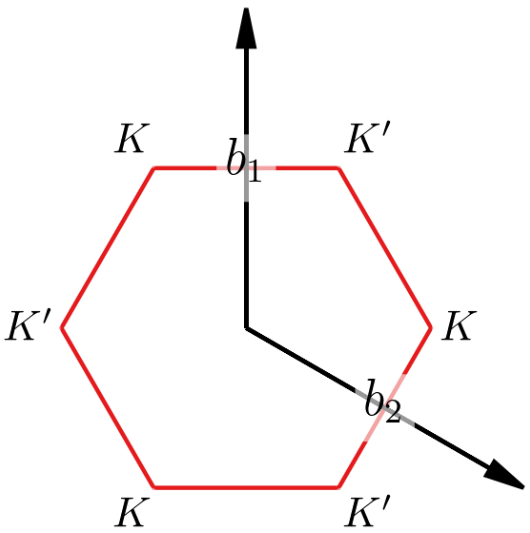
Theoretical description

Defining the system that allow appearance of in-gap states

Graphene, monolayer and bilayer

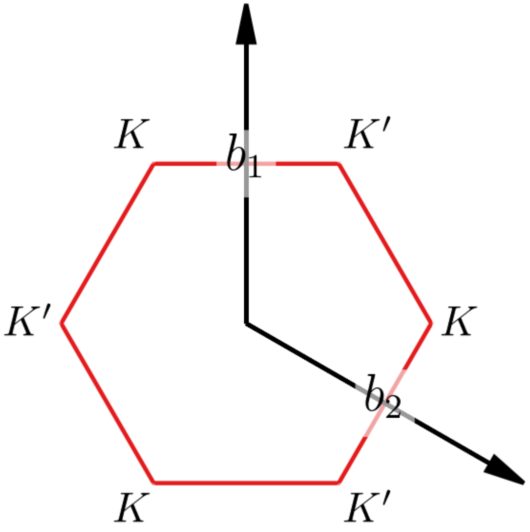


Monolayer and AB stacked bilayer system



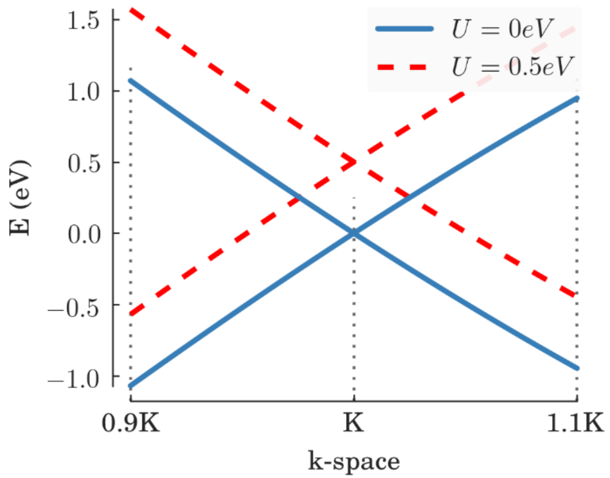
Brillouin zone

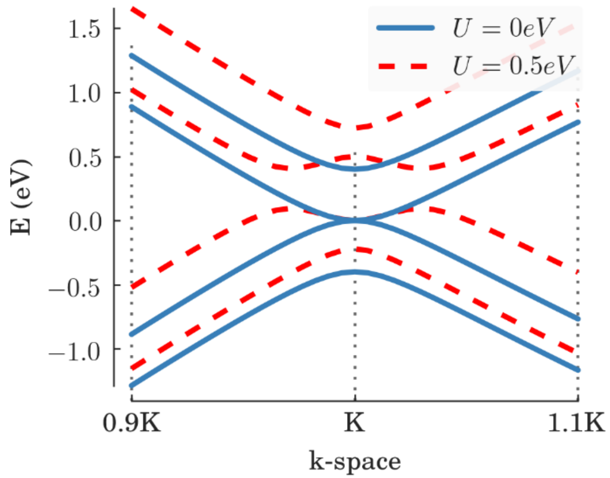
Graphene, monolayer and bilayer



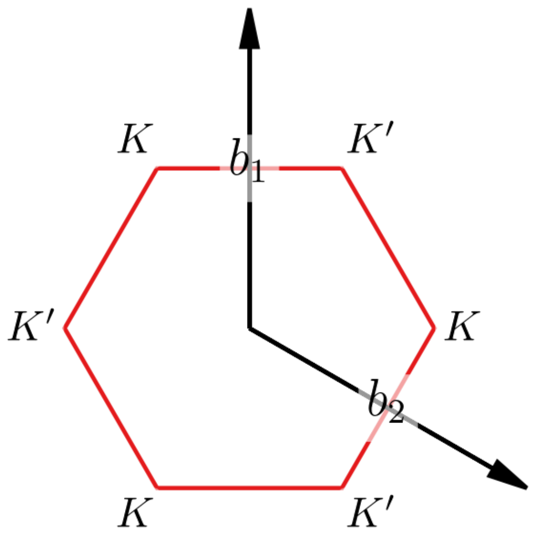
Brillouin zone

Graphene, monolayer and bilayer



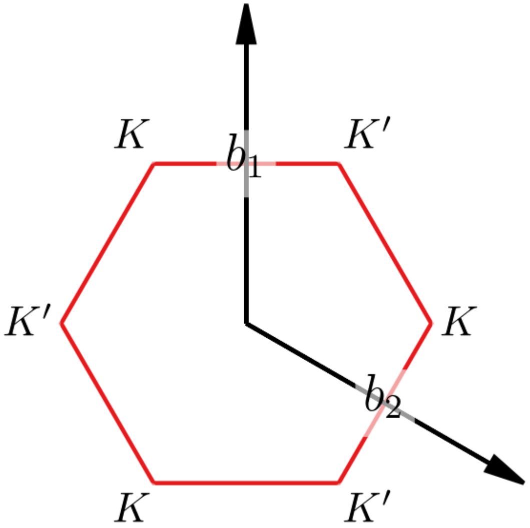


Band structure and electric field effect



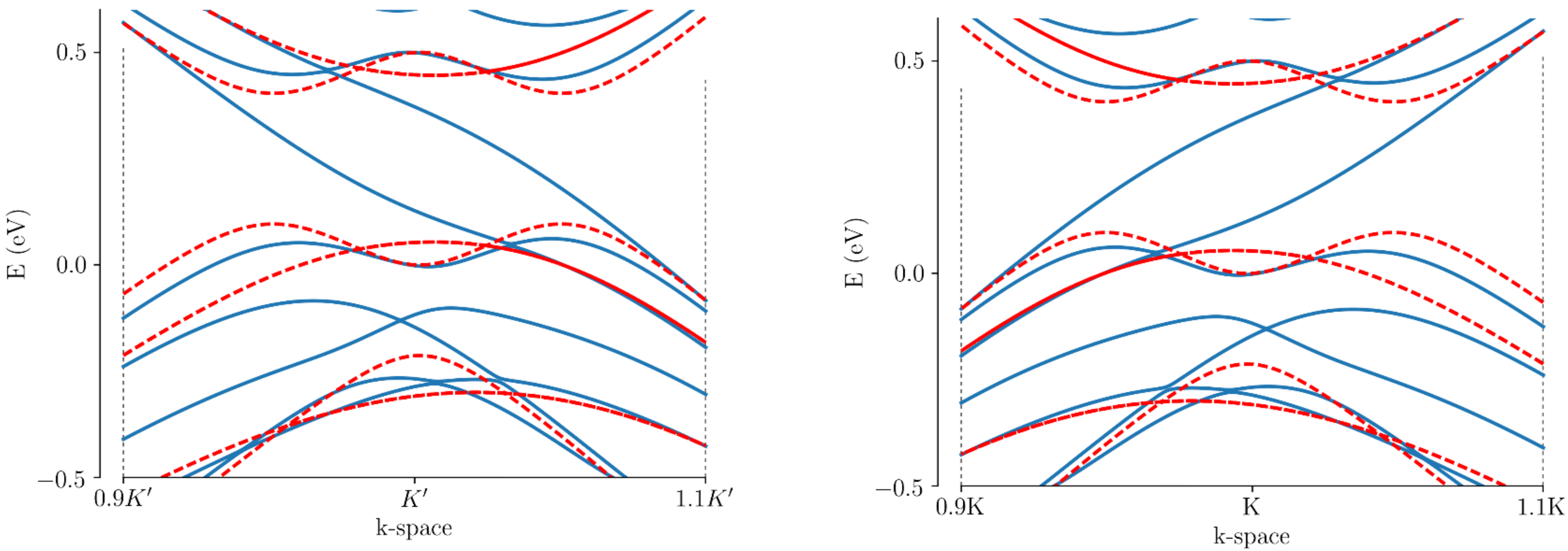
Brillouin zone

Graphene, monolayer and bilayer



Brillouin zone

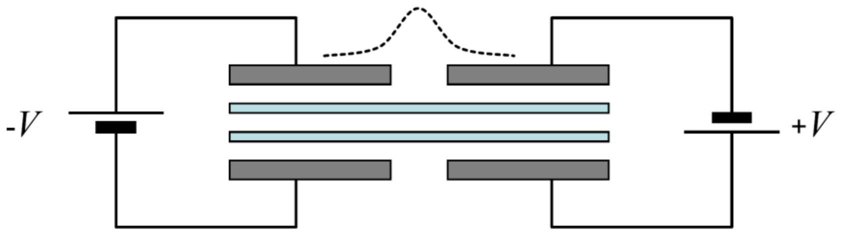
Graphene, monolayer and bilayer



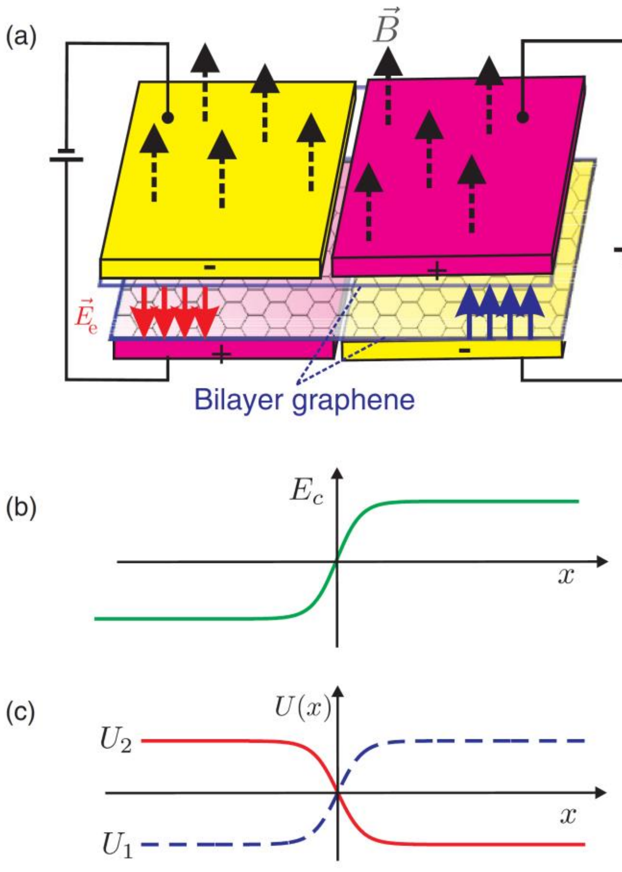
Valley polarized topological states in bilayer graphene AB/BA nanoribbon.

Appearance of in-gap states in bilayer graphene

Kink potential configuration



Martin et al., PRL **100**, 036804 (2008)

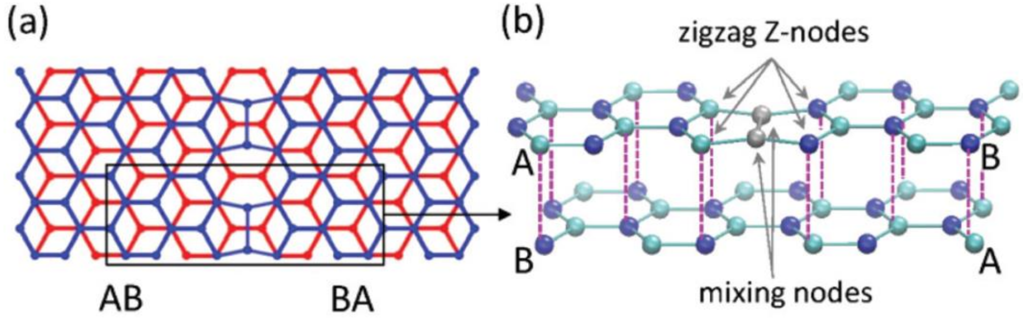


- chiral topological states,
- valley polarized unidirectional motion,
- additional non chiral bands due to kink flattening,
- weakly affected by the magnetic field.

Zarenia et al., PRB **84**, 125451 (2011)

Appearance of in-gap states

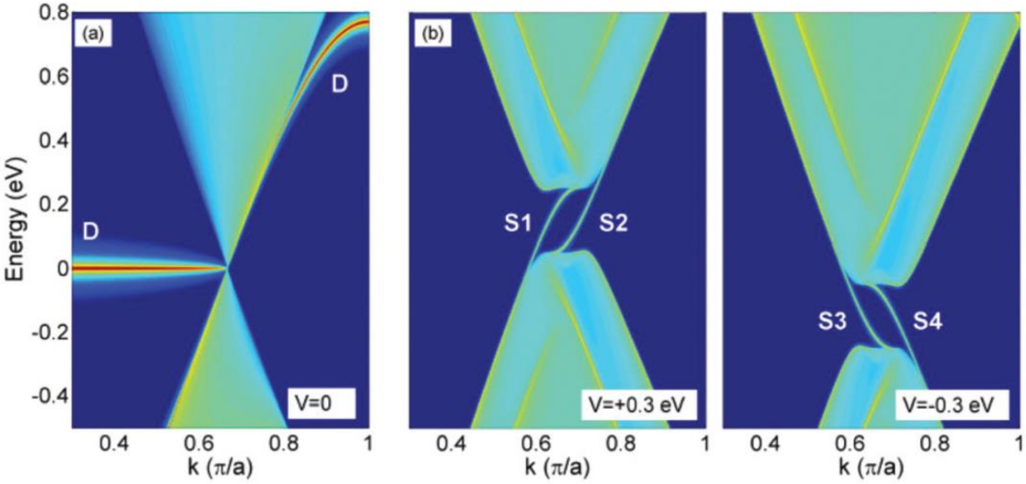
Defect line



AB/BA stacking bilayer graphene produced by a pentagon-octagon defect line
a) top view, b) bottom view.

Jaskólski et al., Nanoscale **8**, 6079-6084 (2016)

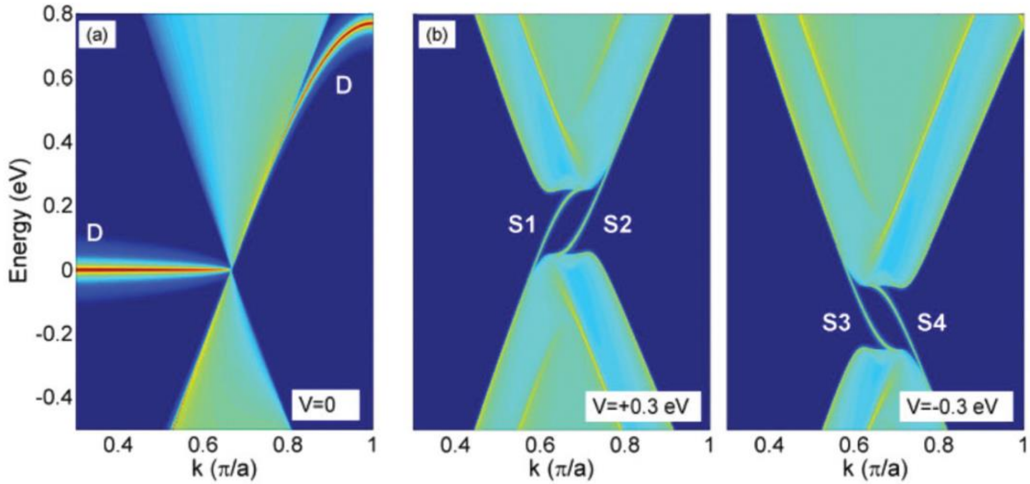
Appearance of in-gap states



LDOS(k) a) V=0V, with a system with a grain boundary, b), c) AB/BA bilayer graphene (corrugation) with positive and negative voltage applied to the bottom layer.

Jaskólski et al., Nanoscale **8**, 6079-6084 (2016)

Appearance of in-gap states



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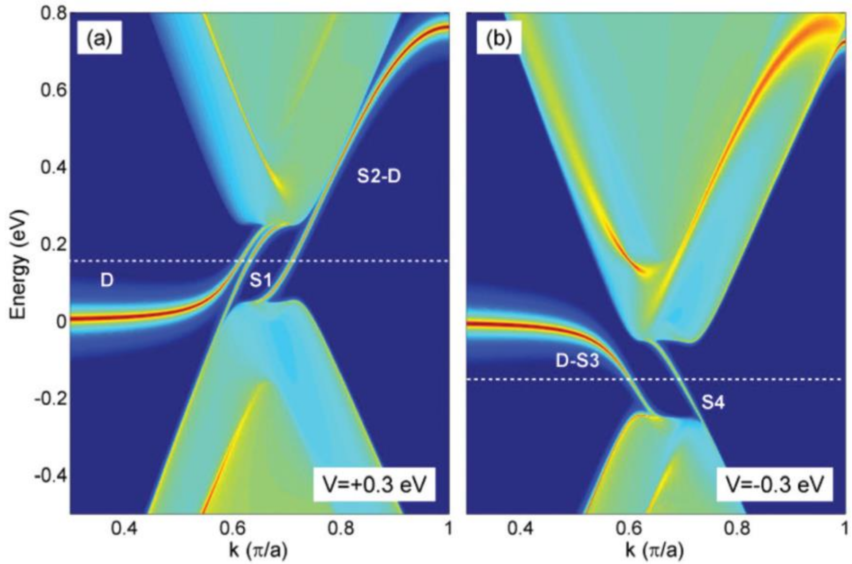


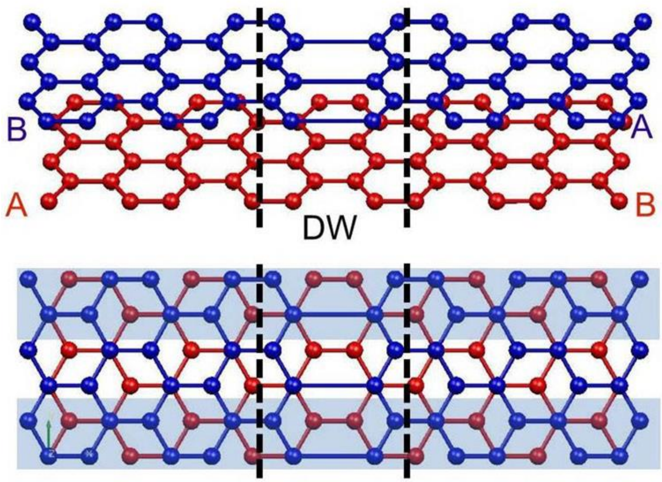
LDOS(k) AB/BA bilayer graphene induced by a octagon-pentagon grain boundary with a) positive and b) negative voltage applied to the bottom layer.

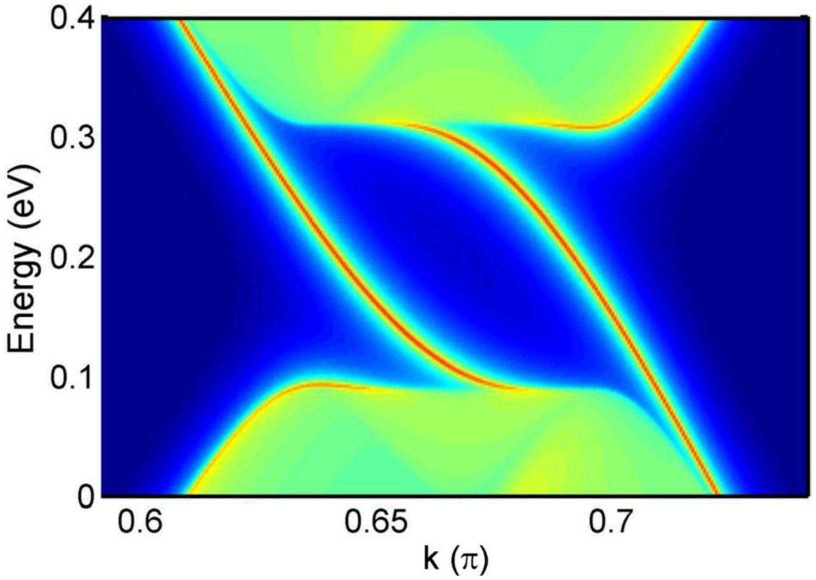
Jaskólski et al., Nanoscale **8**, 6079-6084 (2016)

Appearance of in-gap states

Domain wall

Tilt boundary (stacking change) + corrugation (delamination)





Vaezi *et al.,* PRX **3**, 021918 (2013)
Zhang *et al*., PNAS **110**, 10546–10551 (2013)
Pelc *et al*., PRB **92**, 085433 (2015)
Lane *et al.,* PRB **97**, 045301 (2018)
W Jaskólski *et al., 2D Mater.* **5** 025006 (2018)

Manipulation

Manipulation

Understanding the motion to be able to design the functionality

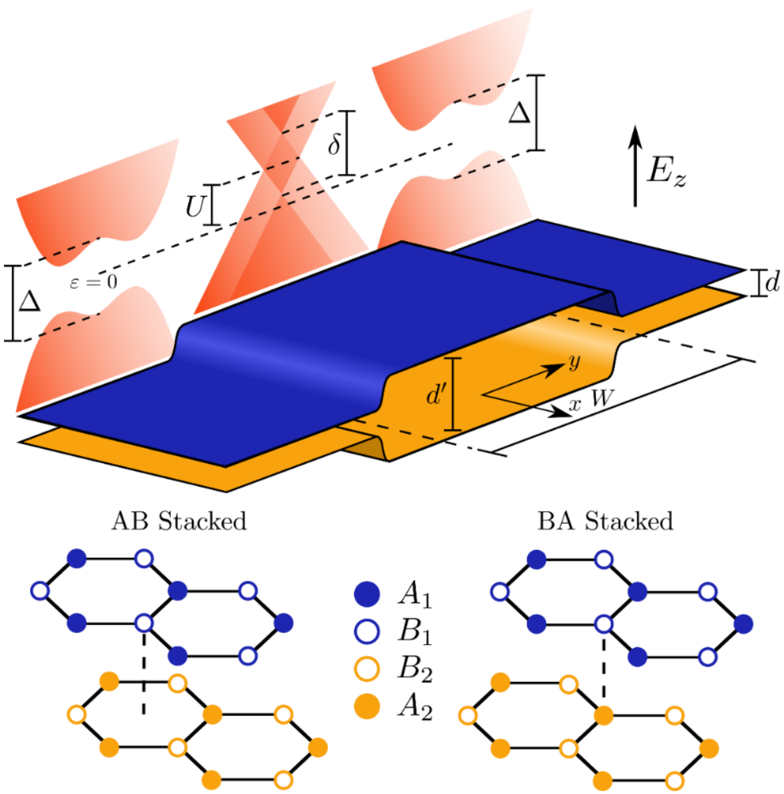
Delamination in bilayer graphene

$$H = -\sum_{l}\sum_{i,j}\gamma_0 e^{i2\pi\phi_{ij}/\phi_0} c_{l,i}^{\dagger} c_{l,j} - \sum_{i,j}\{[(\theta(y_i) + (\theta(y_i - W)]\gamma_1 c_{1,i}^{\dagger} c_{2,j} + H.C.\} + \sum_{i} V_{\pm} c_i^{\dagger} c_i$$

γ_0=3.1eV

γ_1=0.39eV

$$V_{\pm} = \Delta(y_i) + U(y_i) + \delta(y_i)$$



Lane *et al.*, PRB **97**, 045301 (2018)

Delamination in bilayer graphene

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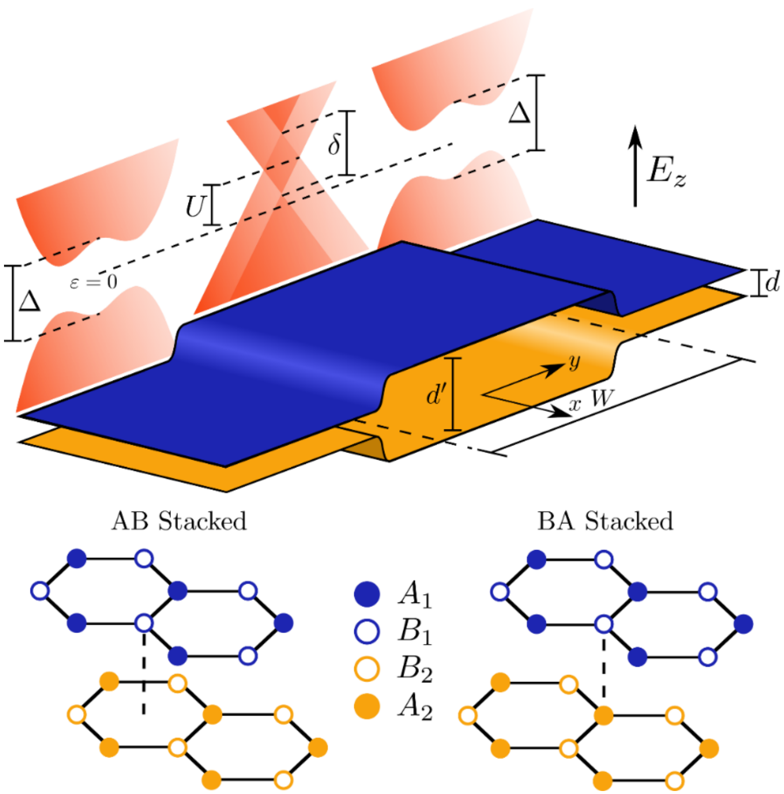
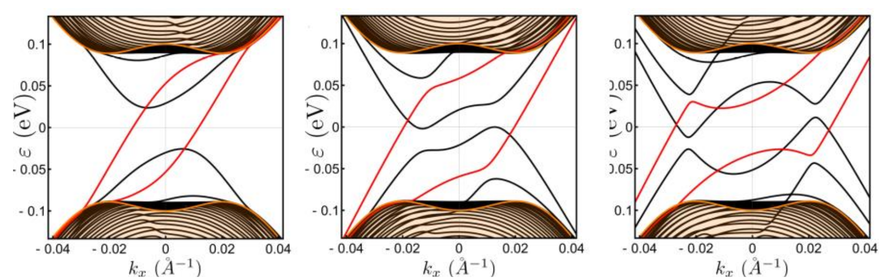


$U = 0eV$

$\Delta = 0.2eV$

$\delta = 0.2eV$ $\delta = 0.3eV$ $\delta = 0.4eV$



Lane *et al.*, PRB **97**, 045301 (2018)

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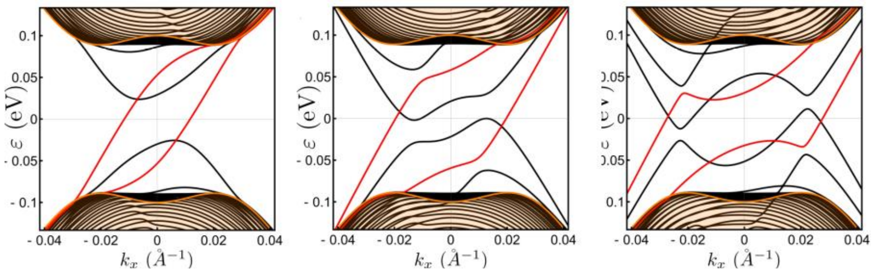
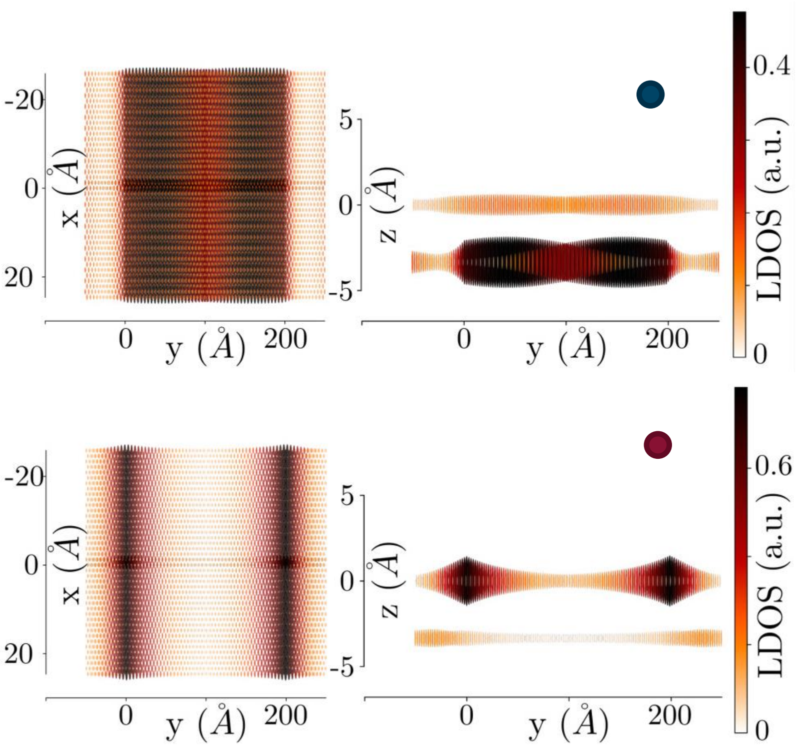


Lane *et al.,* PRB **97**, 045301 (2018)

Delamination in bilayer graphene



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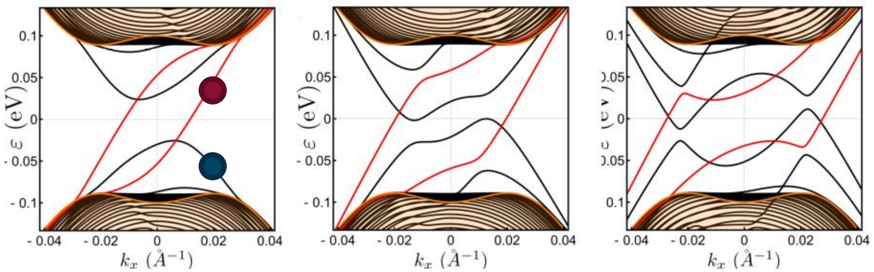
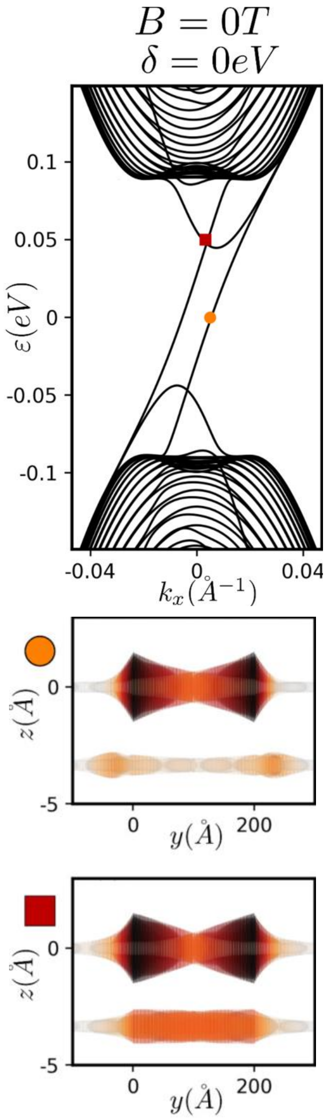


- localized along the edges,
- monolayer bouncing bands are distributed along delamination.

Lane *et al.,* PRB **97**, 045301 (2018)

Delamination in magnetic field

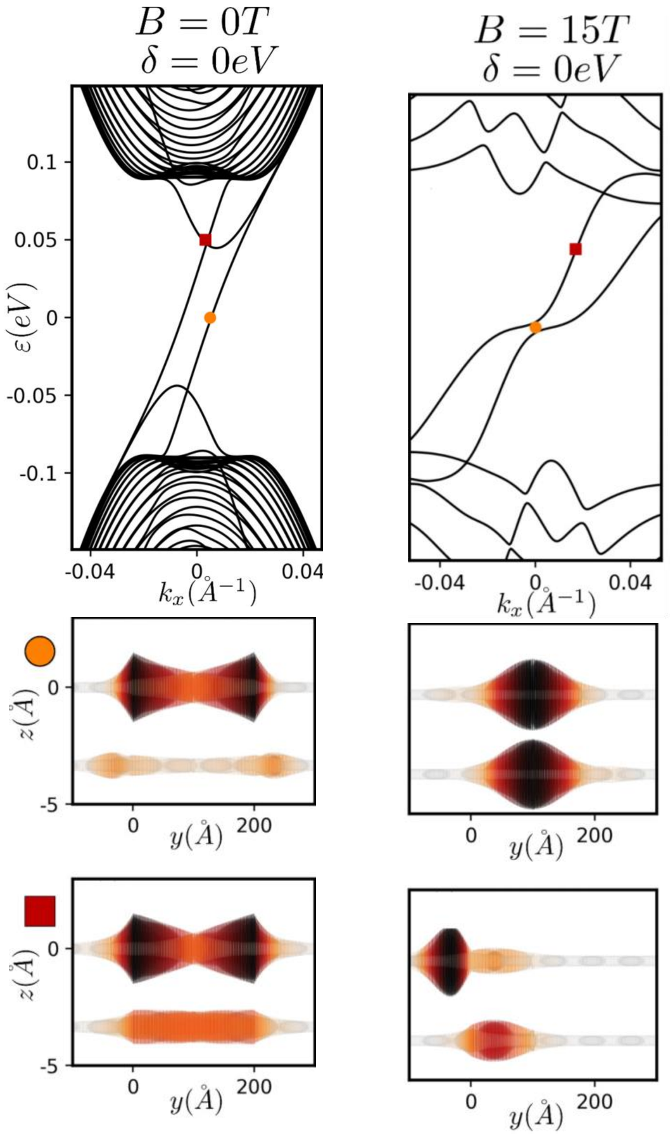


$r_0 \sim l_B = \sqrt{\hbar/eB} < W/2$

$\overrightarrow{F_L} = e\vec{v} \times \vec{B}$

Lane *et al.*, PRB **97**, 045301 (2018)

Delamination in magnetic field



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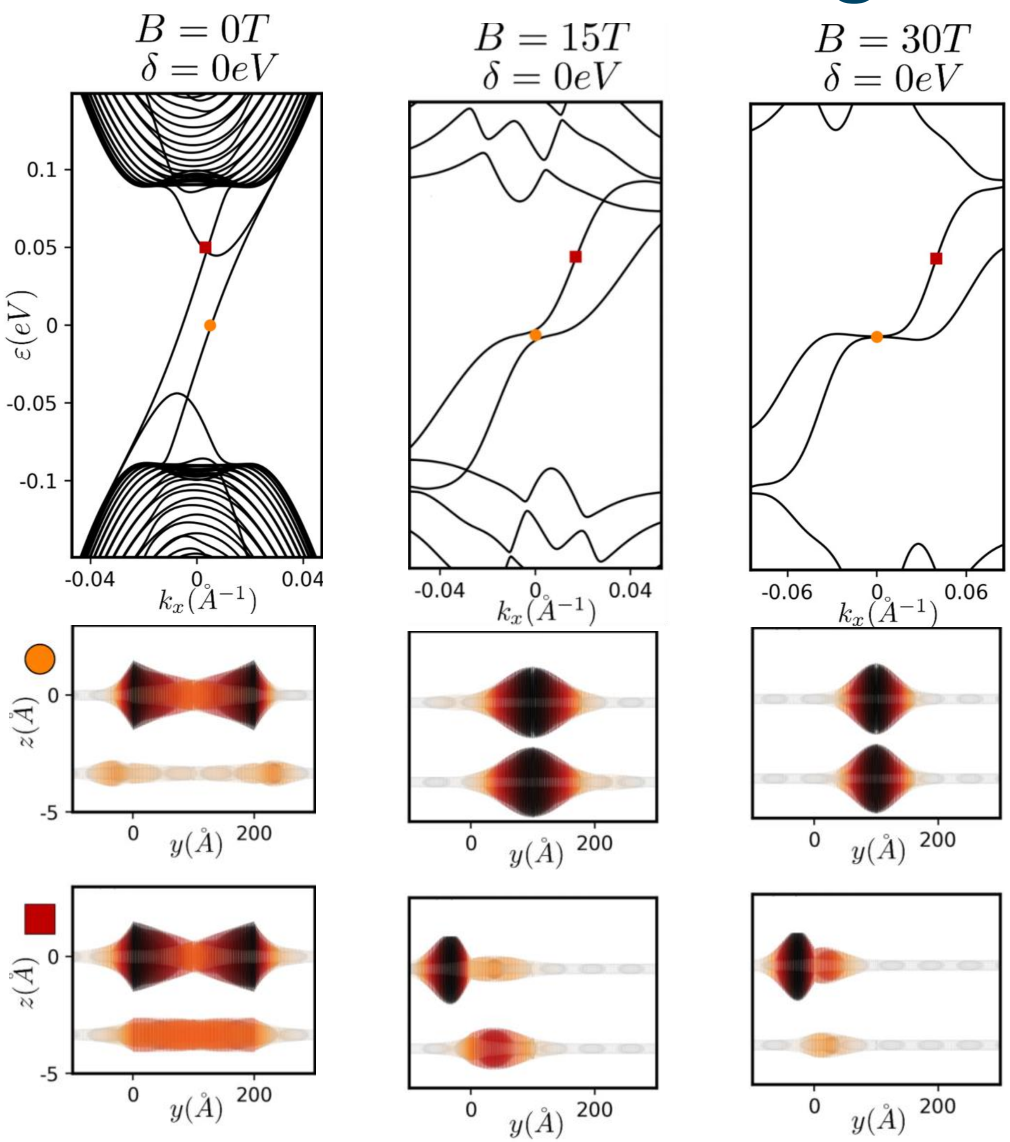

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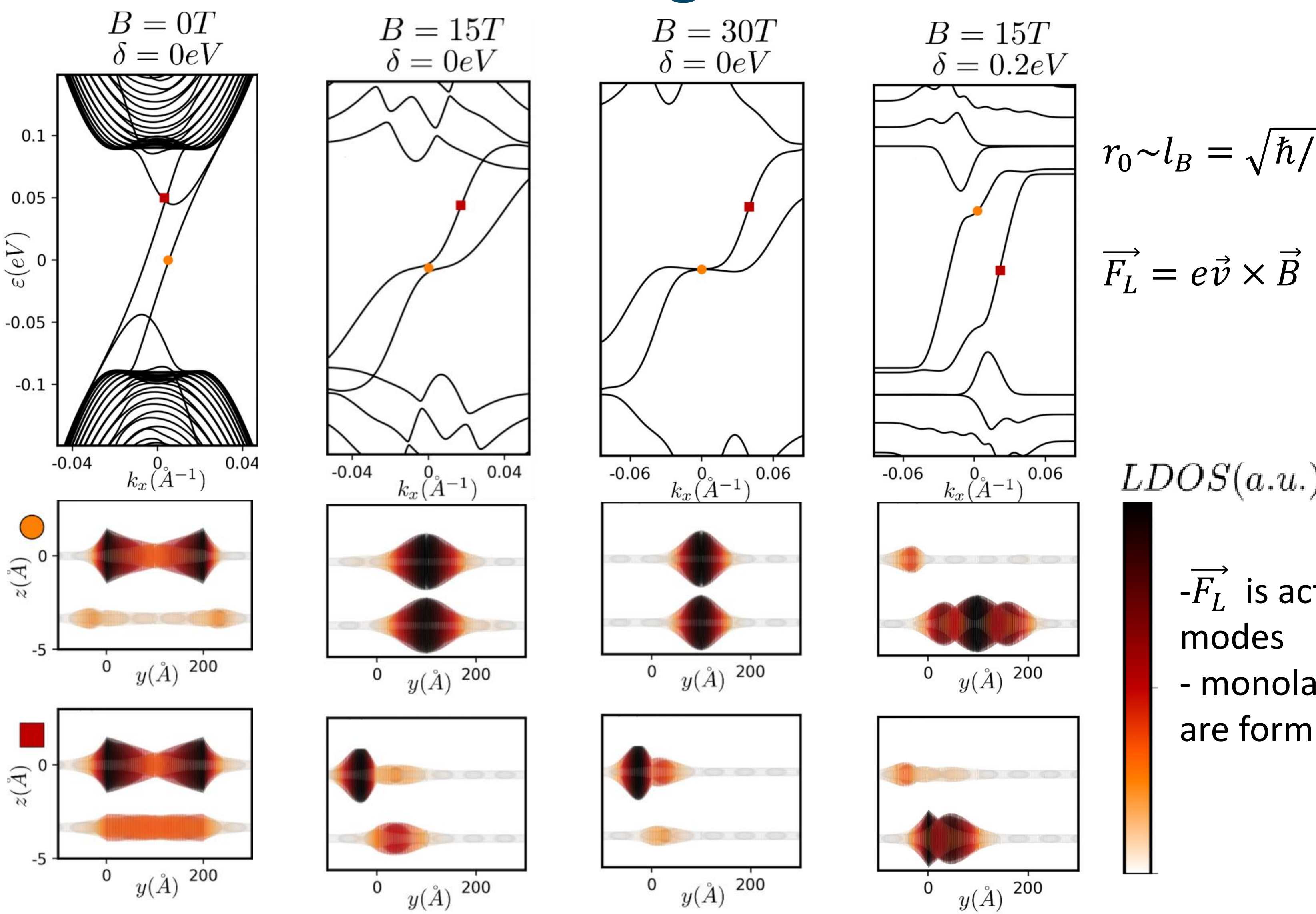


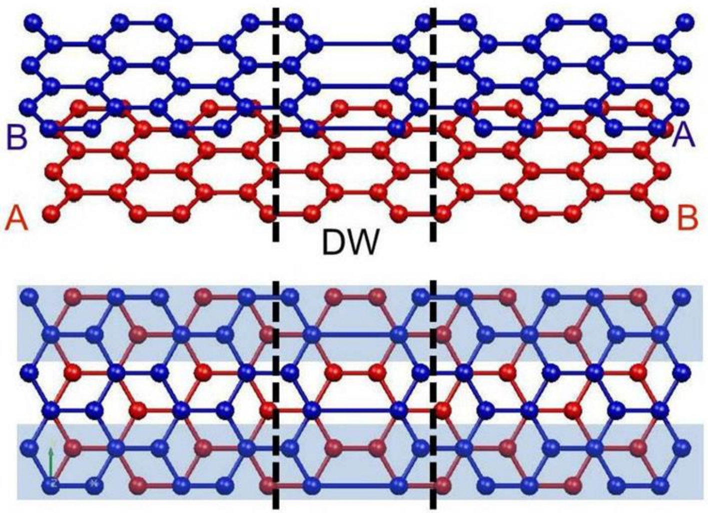
$r_0 \sim l_B = \sqrt{\hbar/eB} < W/2$

$\overrightarrow{F_L} = e\vec{v} \times \vec{B}$

- $\overrightarrow{F_L}$ is acting on the modes
- monolayer bands are forming LL.

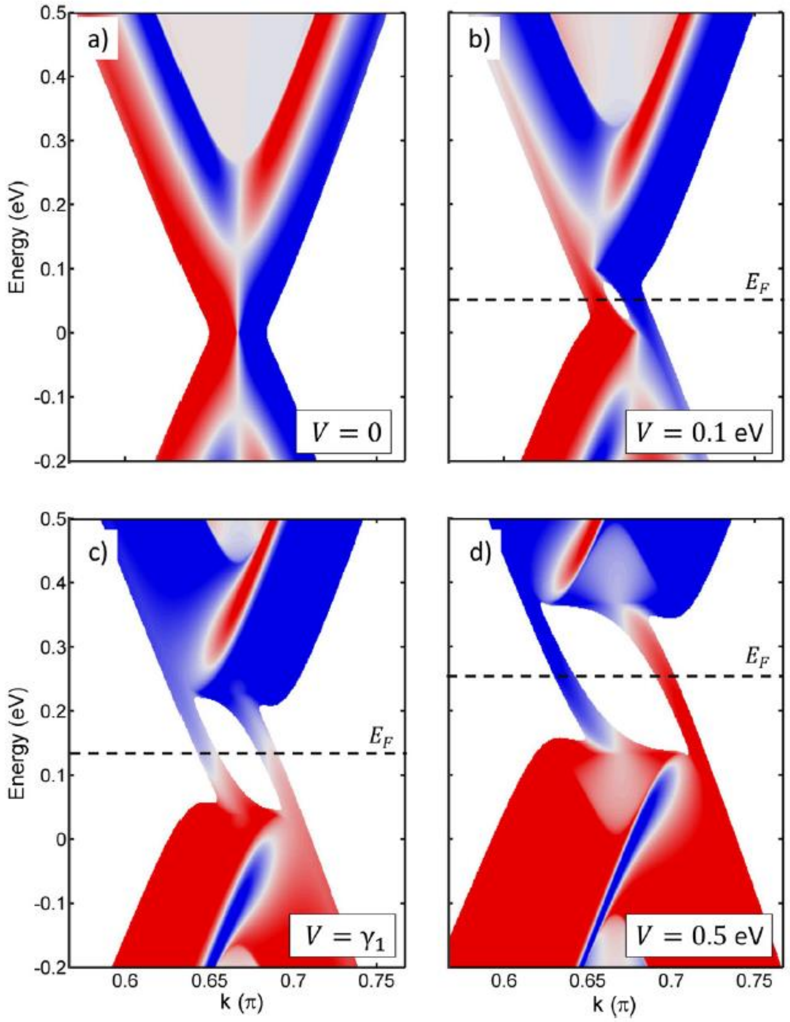
Lane *et al.*, PRB **97**, 045301 (2018)

Layer polarization



AB/domain wall/BA nanoribbon

- layer degree of freedom beside the valley and sublattice,
- tuned by doping and modified by electric field.



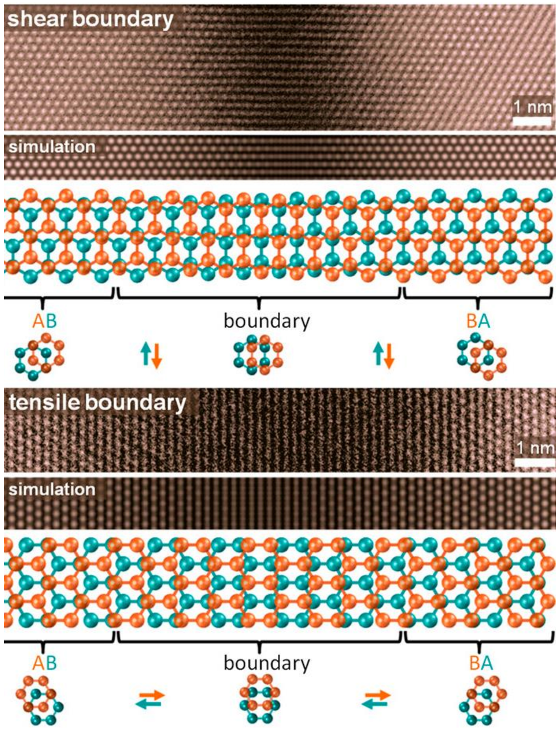
Layer dependent LDOS(k). Red and blue show localization in top and bottom layer respectively

W Jaskólski *et al., 2D Mater.* **5** 025006 (2018)

Gapless states in gated bilayer.
Is the gated bilayer really gapped?

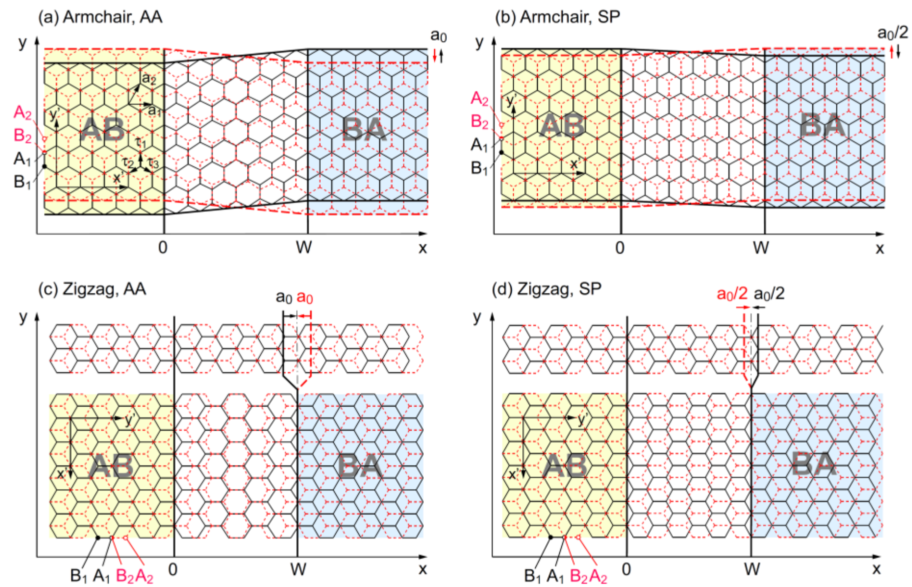
Oostinga *et al.*, Nature Materials **7**, 151–157 (2008) ~ bellow 50 meV
Zhang *et al.,* Nature (London) **459**, 820–823 (2009) ~ 250 meV

Domain walls, stacking solitons



STEM images and simulation of AB-BA domain boundary, shear + tensile strain soliton.

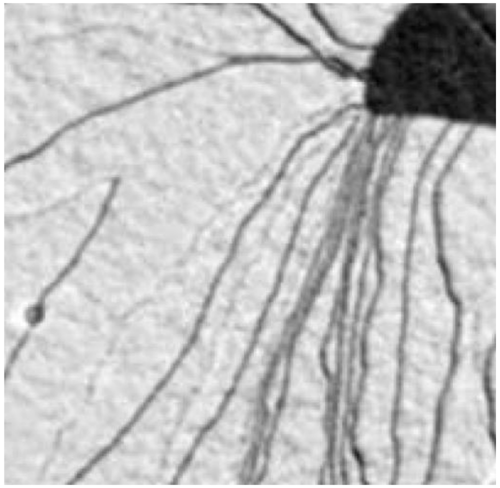
Obtaining different stacking through domain wall, strain soliton



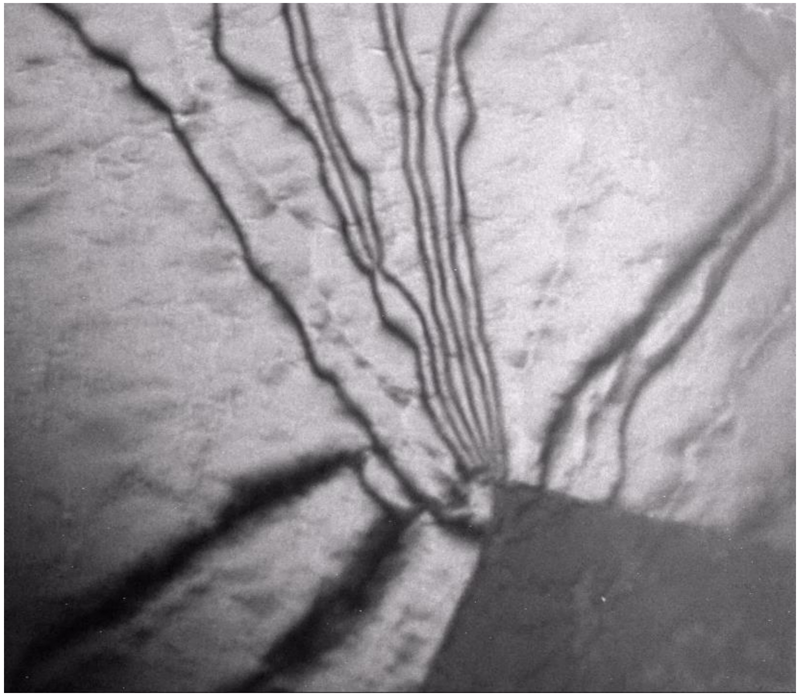
Koshino, PRB **11,** 115409 (2013)

Alden *et al.*, PNAS **110** (28)**,** 11256-11260 (2013)

Change of stacking

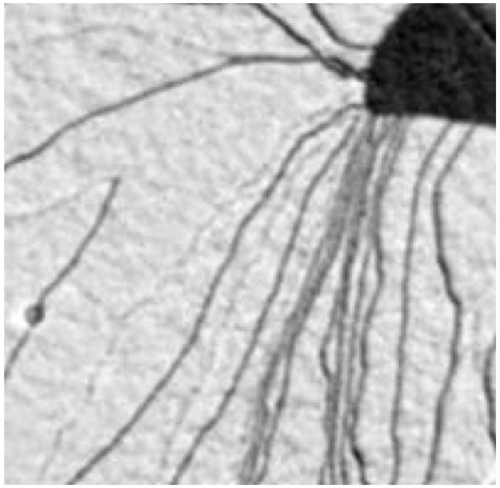


Dark-field TEM of a
large bilayer
graphene flake.



Lin *et al.,* Nano Lett. ***13*** (7)***,***
3262–3268 (2013)

Change of stacking



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Lin *et al.,* Nano Lett. ***13*** (7)***,*** 3262–3268 (2013)

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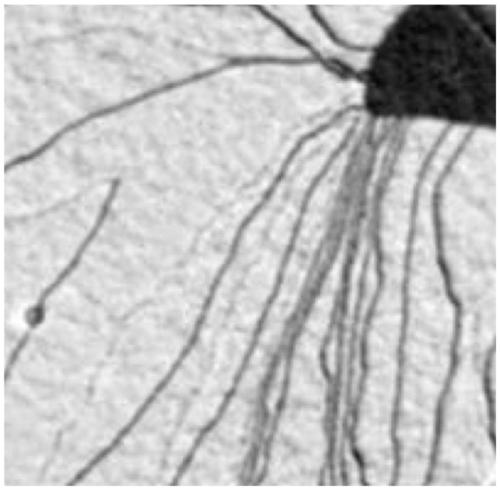

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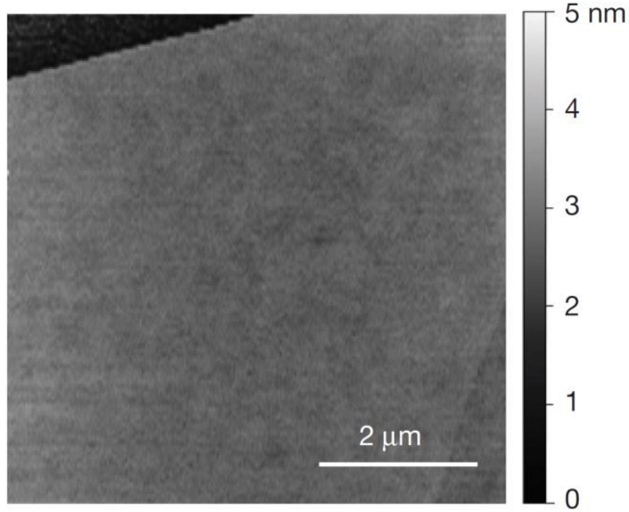
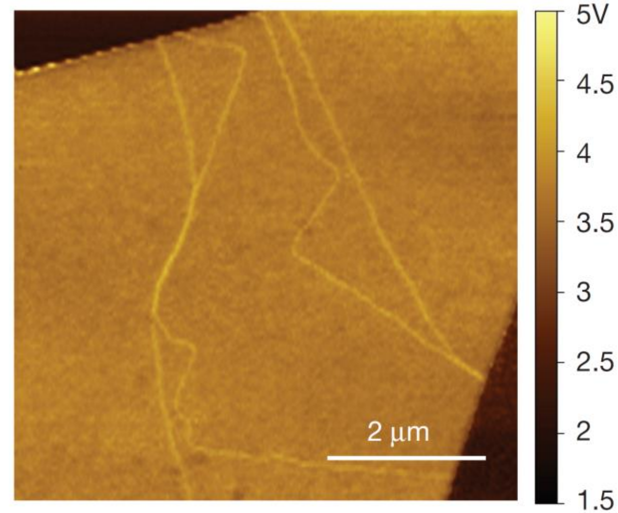


AFM topography map of bilayer graphene on SiO_2/Si + graphene monolayer bottom right.



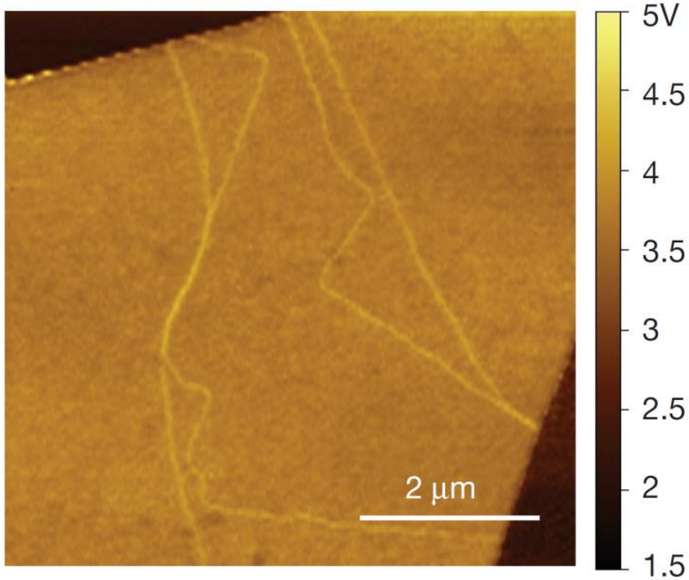
Near-field infrared nanoscopy of the same sample.

Lin *et al.,* Nano Lett. ***13*** (7)**,** 3262–3268 (2013)

Ju *et al.,* Nature **520** (7549), 650-655 (2015)

Experimental observation and realization possibilities

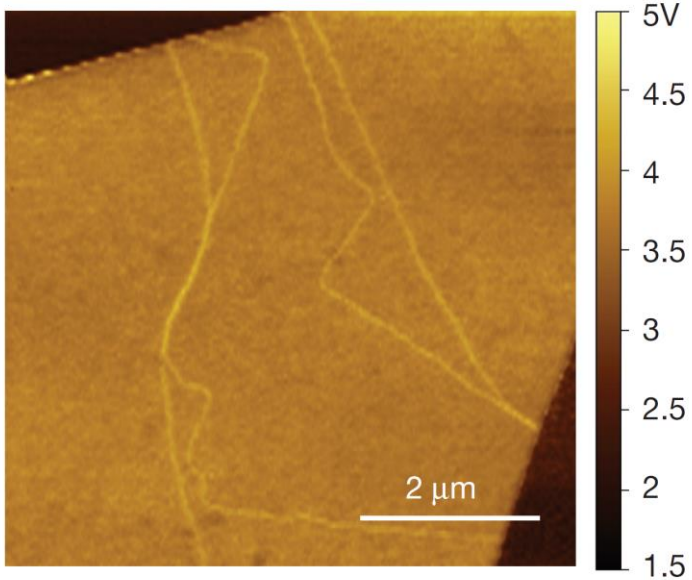
Topological transport at a domain wall



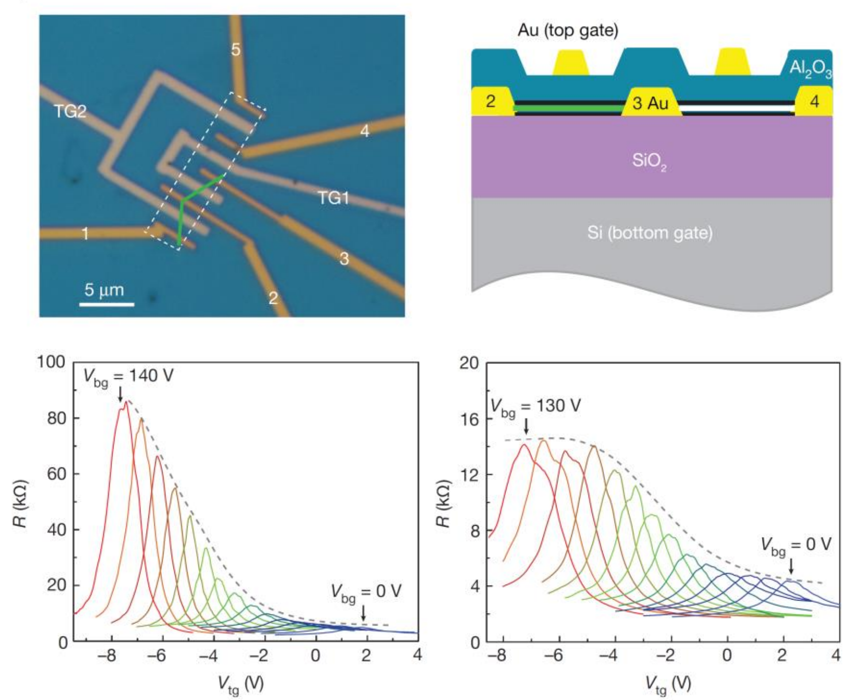
AB/BA domain walls in
exfoliated bilayer graphene

Ju *et al.*, *Nature* **520**, 650–655 (2015)

Topological transport at a domain wall



AB/BA domain walls in exfoliated bilayer graphene

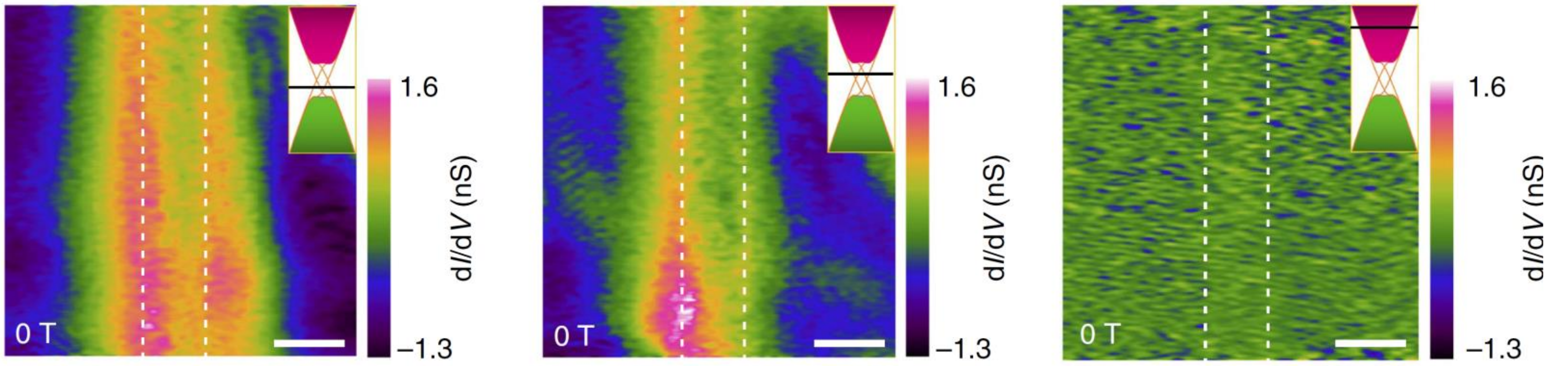


Gating a bilayer graphene flake, sample with and without a domain wall. Applied perpendicular electric field, appearance of boundary states.

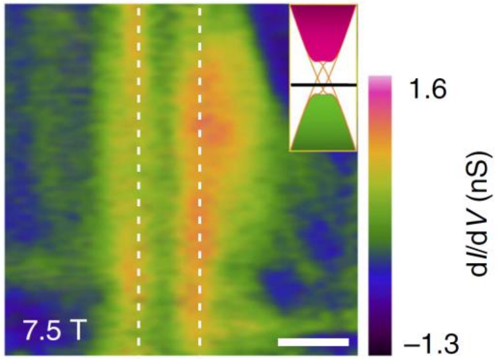
- conductance on the order of $\frac{2e^2}{h}$, smaller due to gate resistance, shorter chanells up to $\frac{4e^2}{h}$
- MFP up to 400 nm,
- limitation random appearance.

Ju *et al.*, *Nature* **520**, 650–655 (2015)

Imaging of topological states



STM image of the domain wall states. Dependence on the Fermi energy.

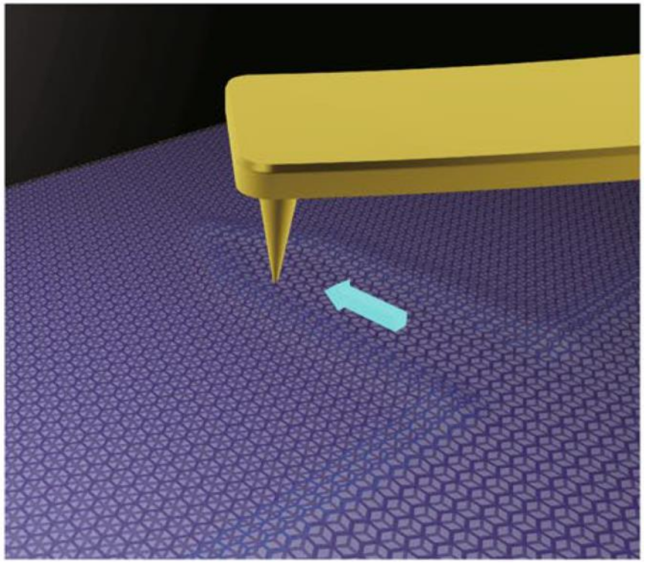


Imaging the domain wall states in the magnetic field.

Yin *et al.*, *Nat. Comm.* **7**, 11760 (2016)

Manipulation of domain walls

- move, erase, and split the domain walls with an AFM tip,
- most are stable at room temperature.



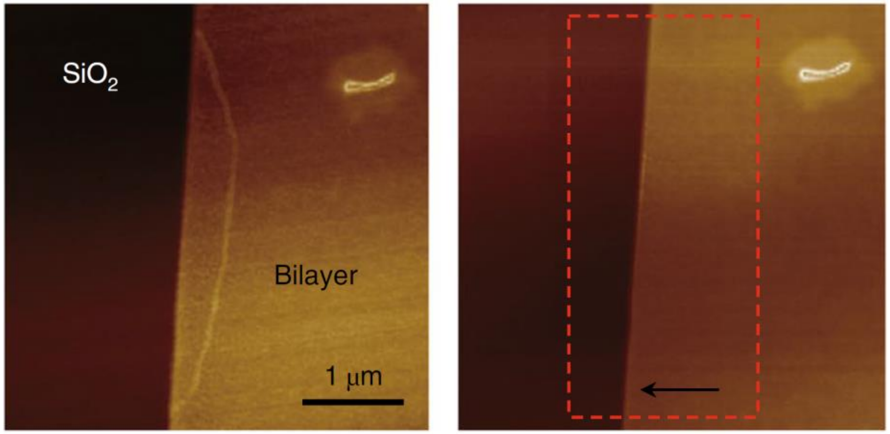
Jiang *et al.*, *Nat. Nano.* Letters (2018)

Manipulation of domain walls

Jiang *et al.*, *Nat. Nano.* Letters (2018)

Manipulation of domain walls

Erasing



Jiang *et al.*, *Nat. Nano.* Letters (2018)

Manipulation of domain walls

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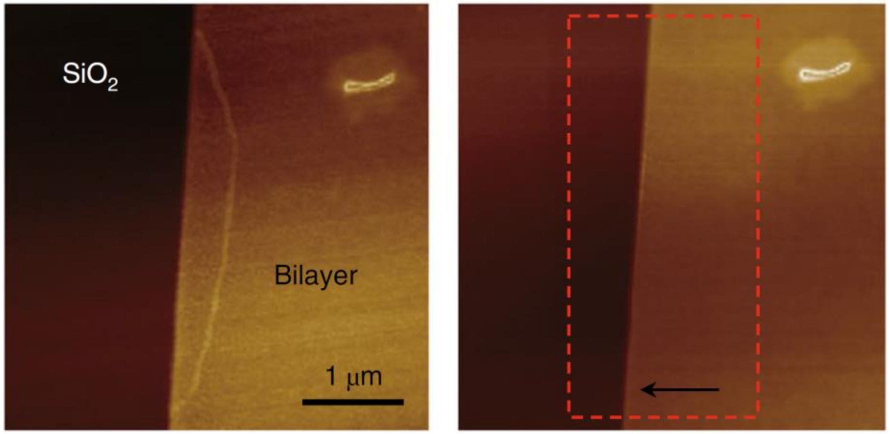
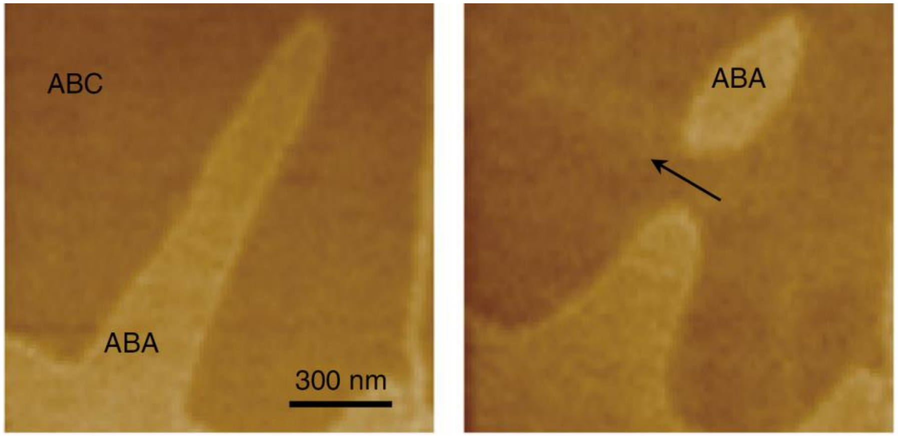


Splitting



Jiang *et al.*, *Nat. Nano.* Letters (2018)

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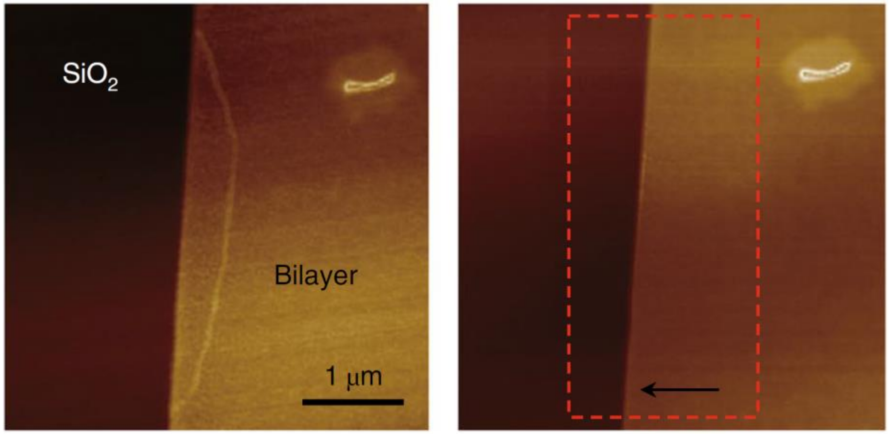

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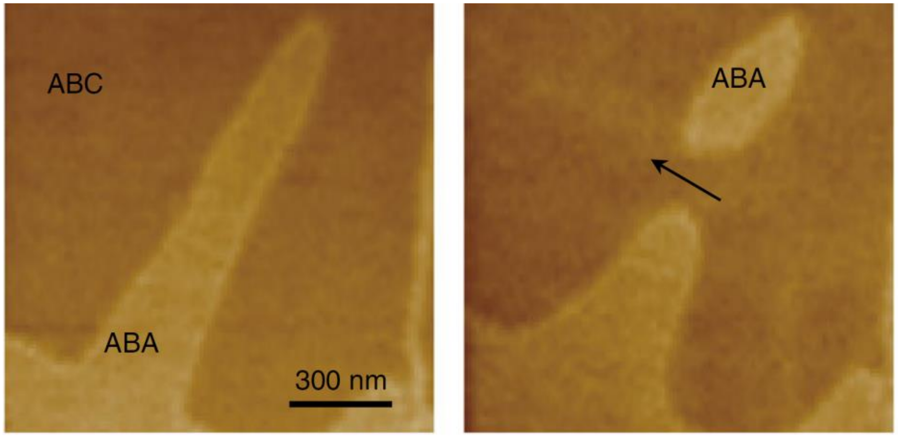
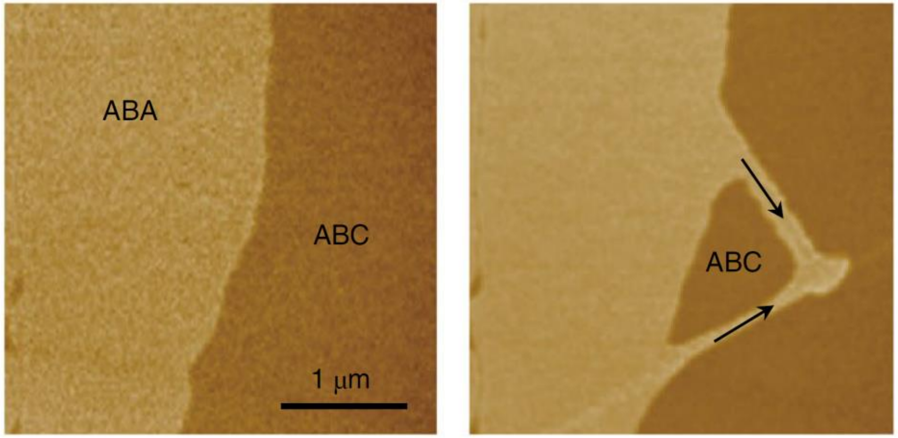


Moving

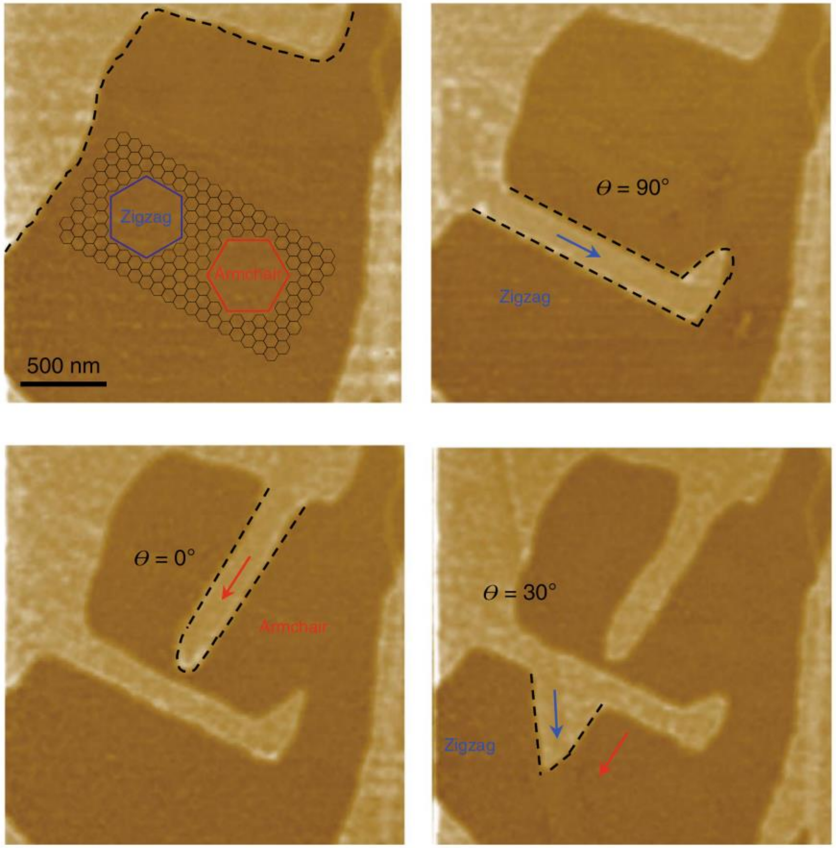


Near-field infrared nanoscopy images of treated samples of bilayer and trilayer graphene

Jiang *et al., Nat. Nano.* Letters (2018)

Manipulation of domain walls

Anisotropy in creation



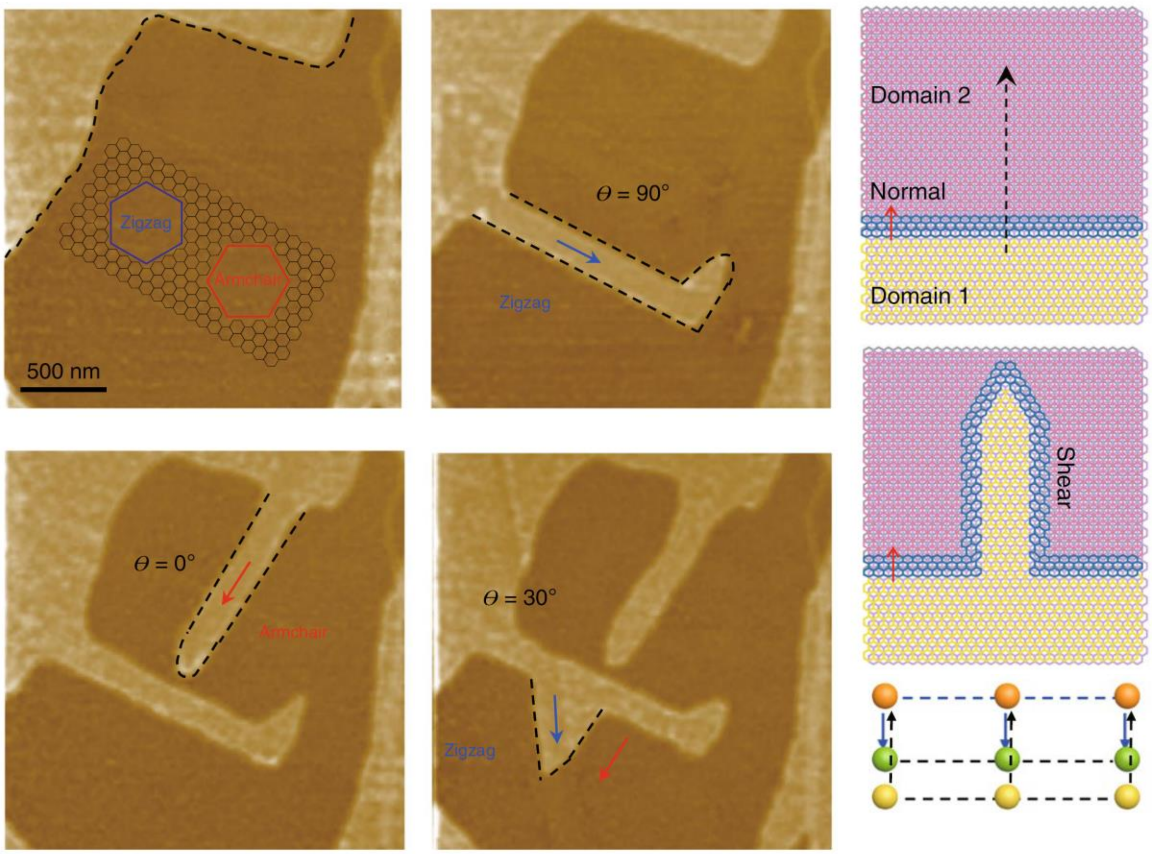
Creation of different shapes

Jiang *et al.*, *Nat. Nano.* Letters (2018)

Manipulation of domain walls

Anisotropy in creation

rounded
rectangular



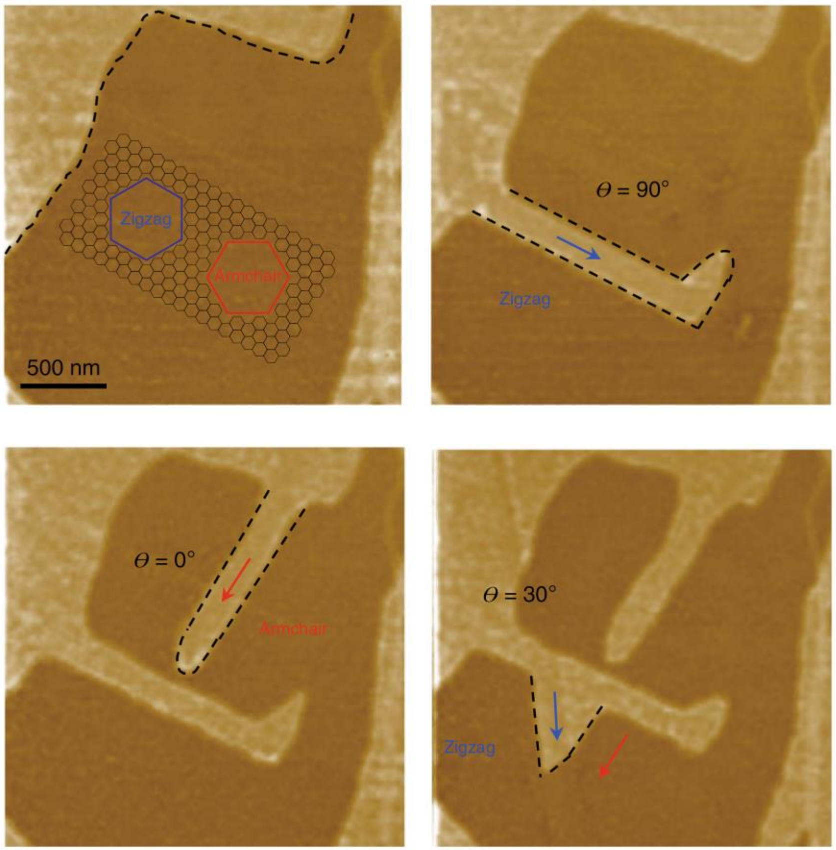
Creation of different shapes

Initial site   Non-equilibrium site   Bernal or rhombohedral stacking site

Jiang *et al., Nat. Nano.* Letters (2018)

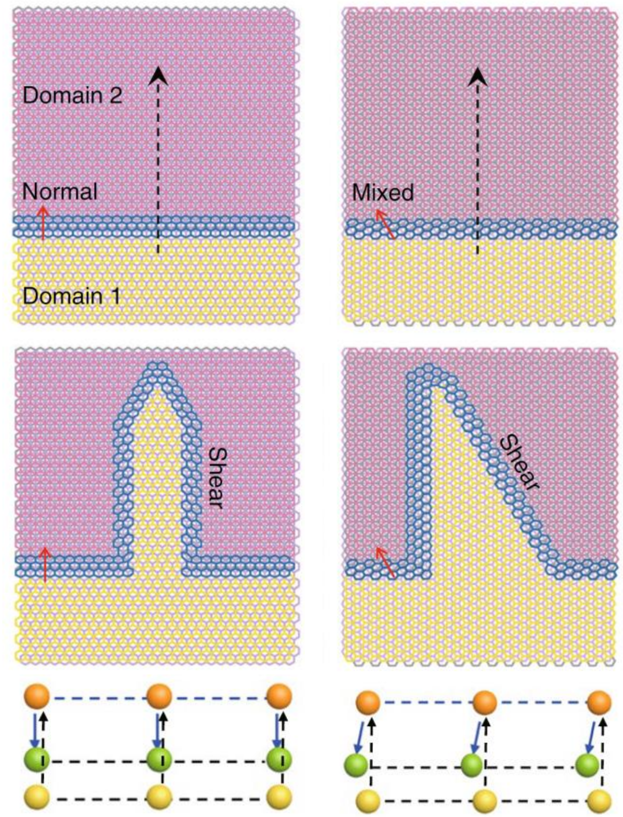
Manipulation of domain walls

Anisotropy in creation



rounded rectangular

triangular



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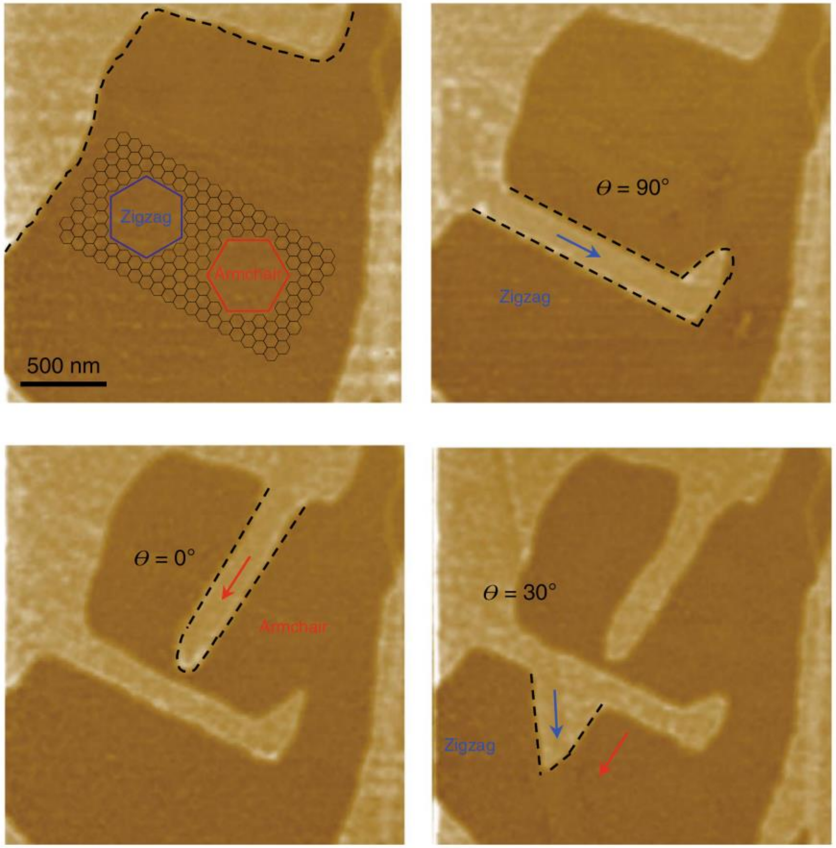
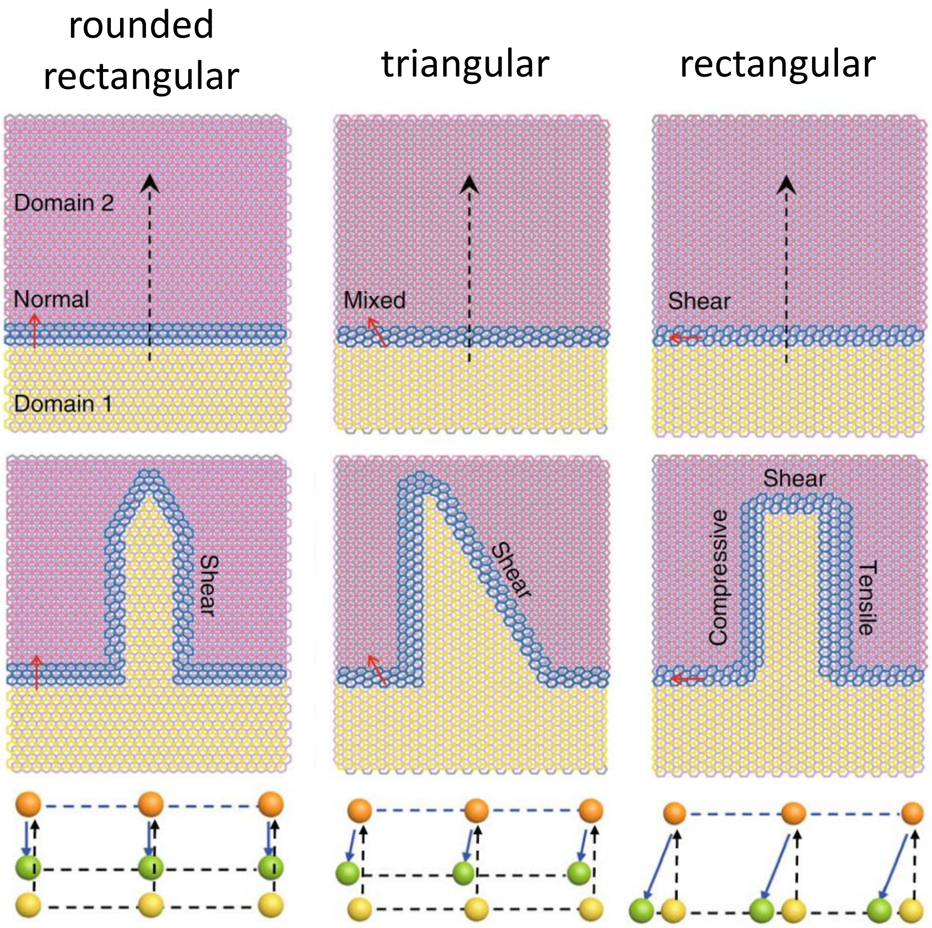
Jiang *et al., Nat. Nano.* Letters (2018)

Manipulation of domain walls

Anisotropy in creation



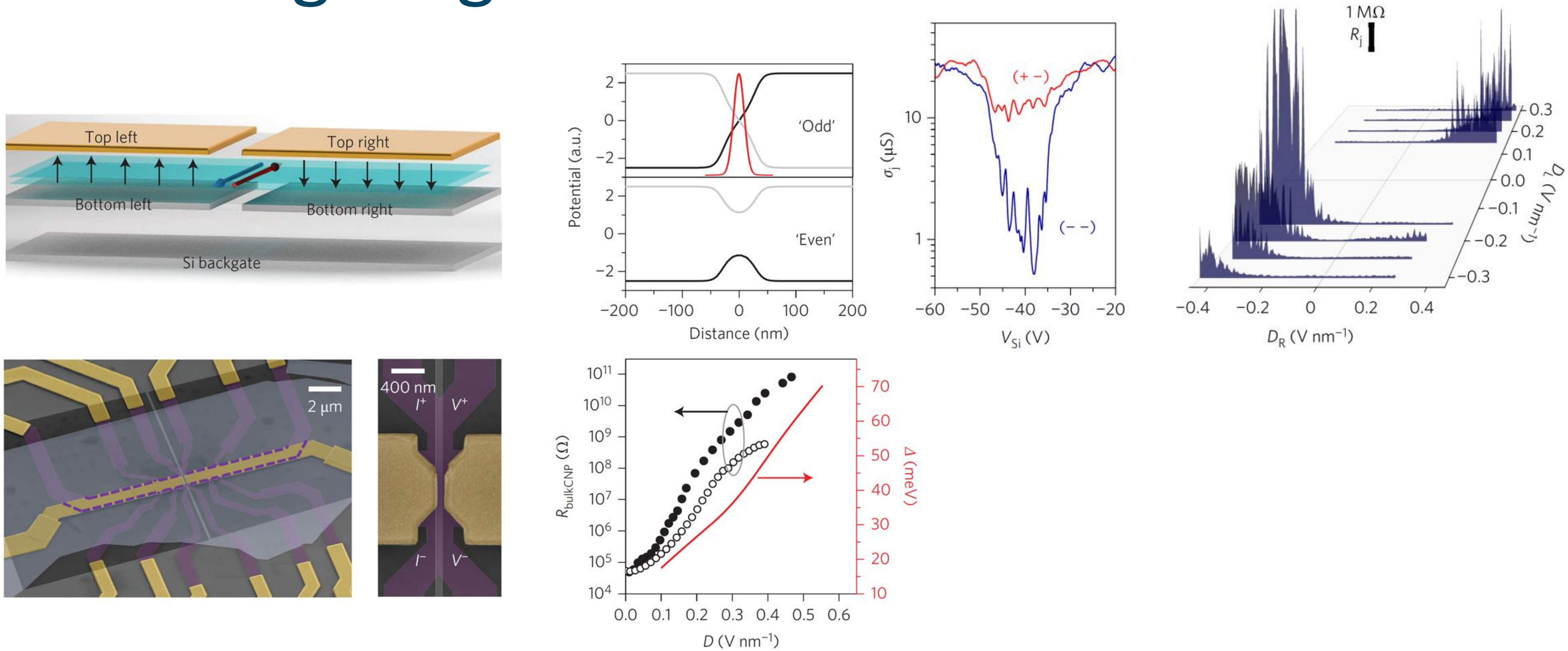


Creation of different shapes

Initial site   Non-equilibrium site   Bernal or rhombohedral stacking site

Jiang *et al.*, *Nat. Nano.* Letters (2018)

Double gating



Design of the double gate device and measurements

- lithography limitations,
- MFP up to 200 nm,
- resistance close to $\frac{h}{4e^2}$, larger,
- valley valve and beam splitter, 4 gate structure.

Li *et al.*, *Nat. Nano.* **11**, 1060–1065 (2016)
Jing *et al.*, arXiv (2018)

Conclusion

I Possibility to define ballistic transport channels could lead to **low power dissipation devices**.

II Prospective applications in fields of **valleytronics** and very recently suggested **layertronics**.

III Approach is **applicable to different materials** and structures.

Is there a **possibility to control spin** in similar manner in TMDC-s, with strong spin-orbit coupling?

Electronic transport in 2D Materials

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CMT
Condensed Matter Theory cmt.uantwerpen.be

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Bonus

docs.pybinding.site

pybinding
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- Material Repository
- API Reference
- Experimental

WRITE THE DOCS

Love Documentation? Write the Docs Prague is a 3-day docs event. Sept 10-12.

Docs » Tight-binding package for Python   Edit on GitHub

Pybinding is a scientific Python package for numerical tight-binding calculations in solid state physics. If you're just browsing, the Tutorial section is a good place to start. It gives a good overview of the most important features with lots of code examples.

As a very quick example, the following code creates a triangular quantum dot of bilayer graphene and then applies a custom asymmetric strain function:

```
import pybinding as pb
from pybinding.repository import graphene

def asymmetric_strain(c):
    @pb.site_position_modifier
    def displacement(x, y, z):
        ux = -c/2 * x**2 + c/3 * x + 0.1
        uy = -c*2 * x**2 + c/4 * x
        return x + ux, y + uy, z
    return displacement

model = pb.Model(
    graphene.bilayer(),
    pb.regular_polygon(num_sides=3, radius=1.1),
    asymmetric_strain(c=0.42)
)
model.plot()
```