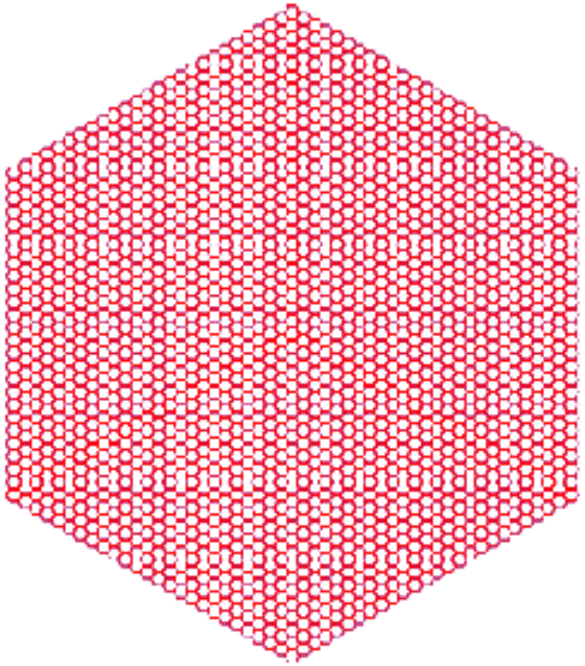


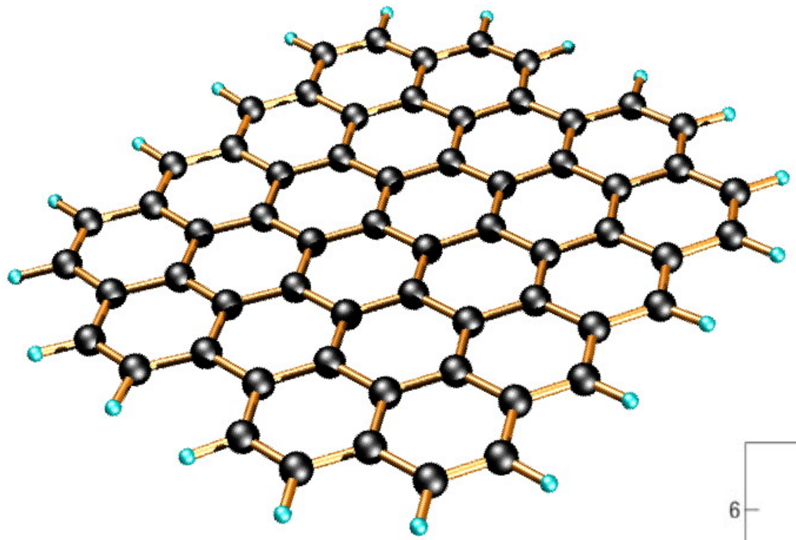
On demand angle control in van der Waals heterostructures

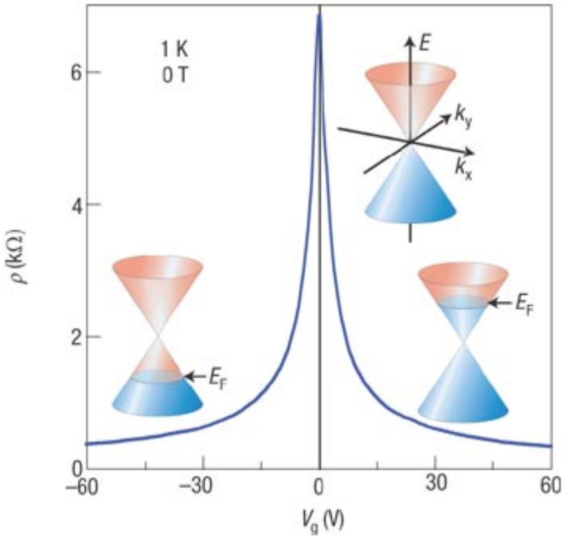
<u>R. Ribeiro-Palau</u>*, T. Chari**, K. DeLello*, K. Shepard** and C.R. Dean*

**Physics and **Electrical Engineering Department*

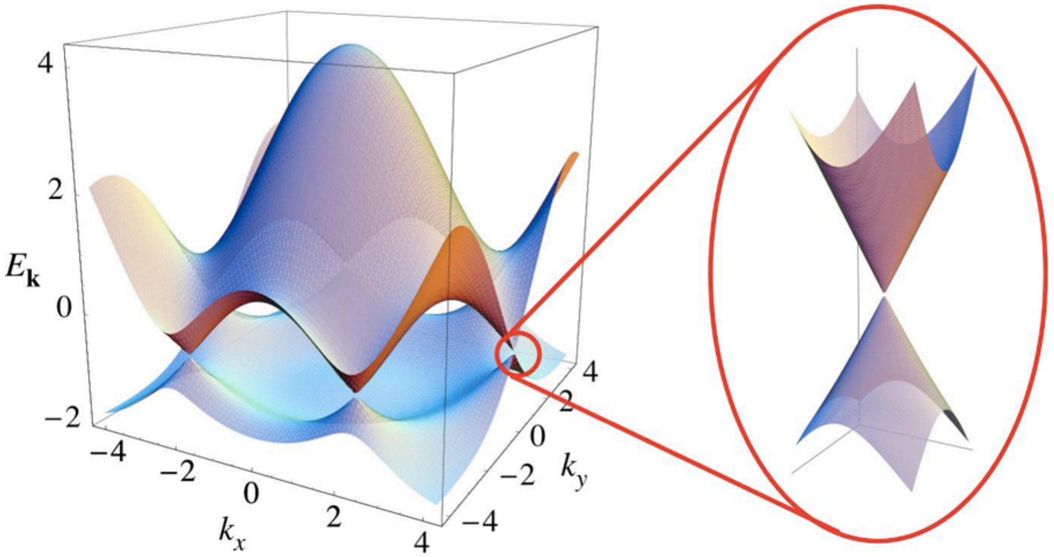
Columbia University

Graphene





Geim and Novoselov, Nature Materials (2009)



Castro-Neto *et al.*, Rev. Mod Phys. (2009)

Graphene and its new family

A. K. Geim and I. V. Grigorieva Nature (2013)

Graphene and its new family

Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide

A. K. Geim and I. V. Grigorieva Nature (2013)

Graphene and its new family

<table>
<tr><td>Graphene family</td><td>Graphene</td><td colspan="2">hBN
'white graphene'</td><td>BCN</td><td>Fluorographene</td><td>Graphene oxide</td></tr>
<tr><td rowspan="2">2D chalcogenides</td><td rowspan="2" colspan="2">MoS_2, WS_2, $MoSe_2$, WSe_2</td><td rowspan="2" colspan="2">Semiconducting dichalcogenides:
$MoTe_2$, WTe_2,
ZrS_2, $ZrSe_2$ and so on</td><td colspan="2">Metallic dichalcogenides:
$NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on</td></tr>
<tr><td colspan="2">Layered semiconductors:
GaSe, GaTe, InSe, Bi_2Se_3 and so on</td></tr>
</table>

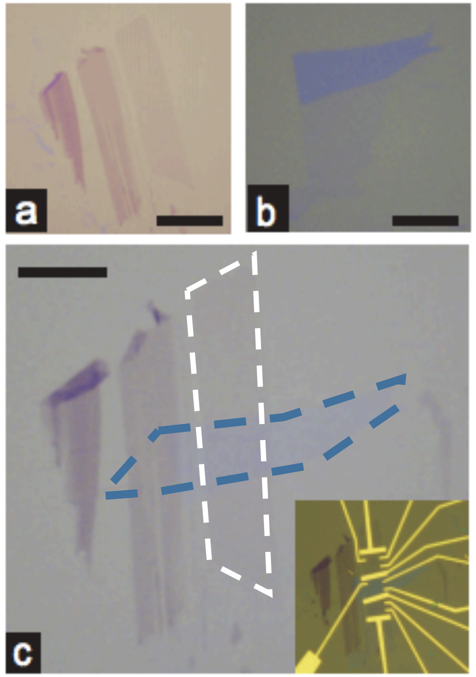
A. K. Geim and I. V. Grigorieva Nature (2013)

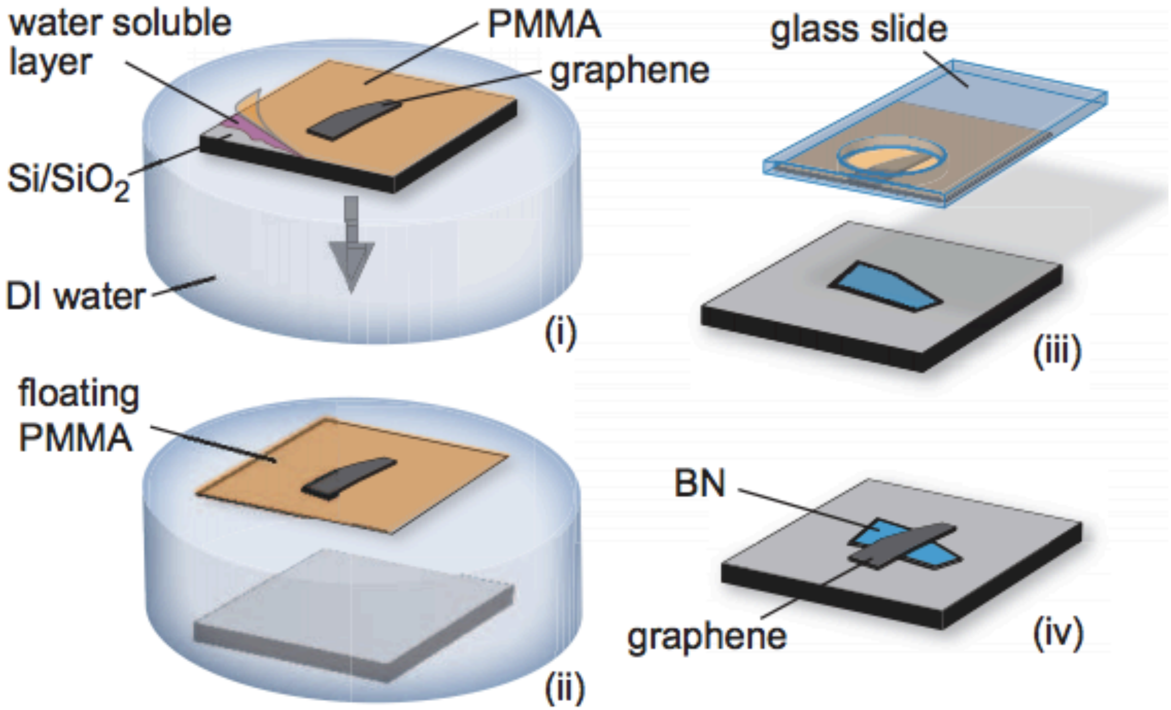
Graphene and its new family

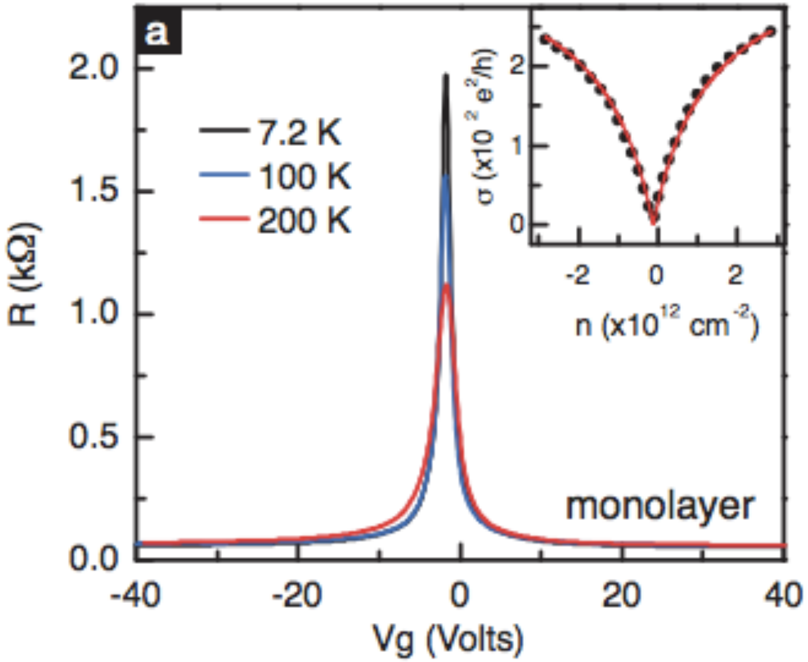
Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2	Semiconducting dichalcogenides: $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$ and so on	Metallic dichalcogenides: $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on		
			Layered semiconductors: GaSe, GaTe, InSe, Bi_2Se_3 and so on		
2D oxides	Micas, BSCCO	MoO_3, WO_3	Perovskite-type: $LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on	Hydroxides: $Ni(OH)_2$, $Eu(OH)_2$ and so on	
	Layered Cu oxides	TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2 and so on		Others	

A. K. Geim and I. V. Grigorieva Nature (2013)

New van der Waals heterostructures





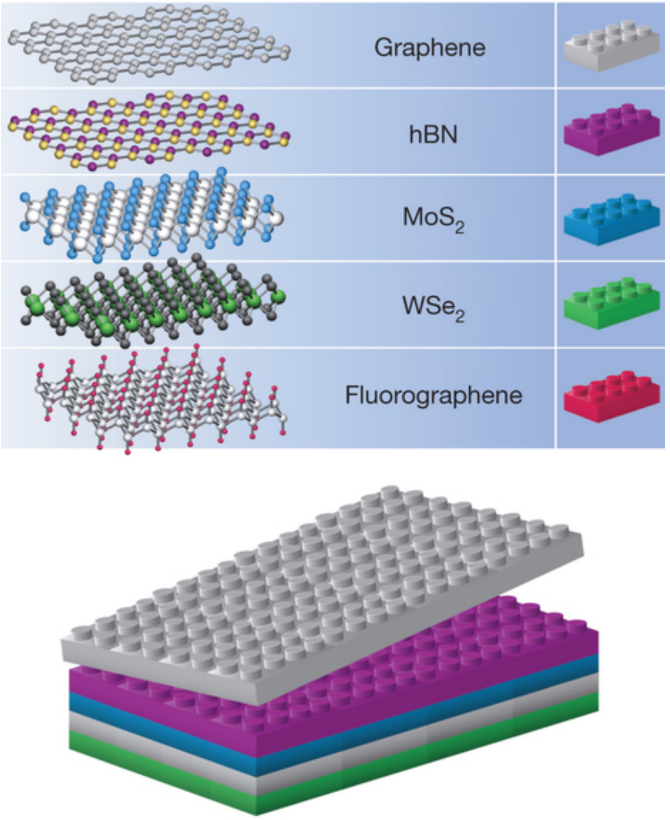


Improvement of graphene's quality

C.R. Dean *et al.*, Nature Nanotech. (2010)

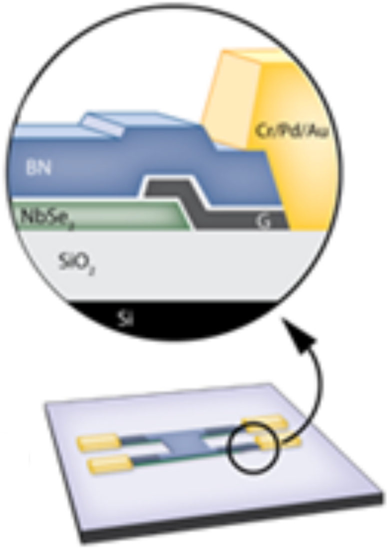
New degrees of freedom and limits

Mix of materials
(as many as we want)



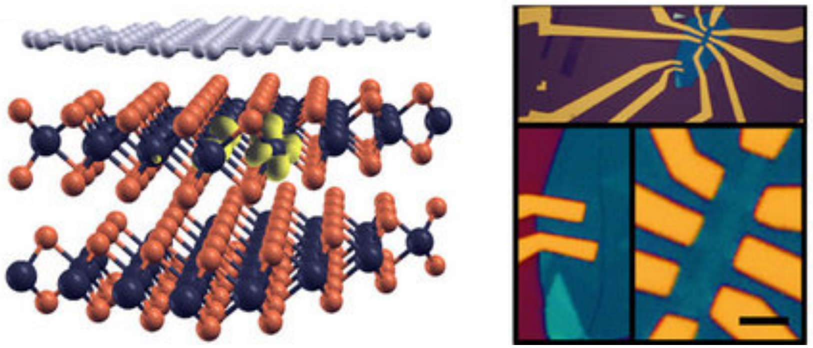
A. K. Geim and I. V. Grigorieva Nature (2013)

BN/Graphene/$NbSe_2$



A.W. Tsen *et al.*, Nature Physics (2016)

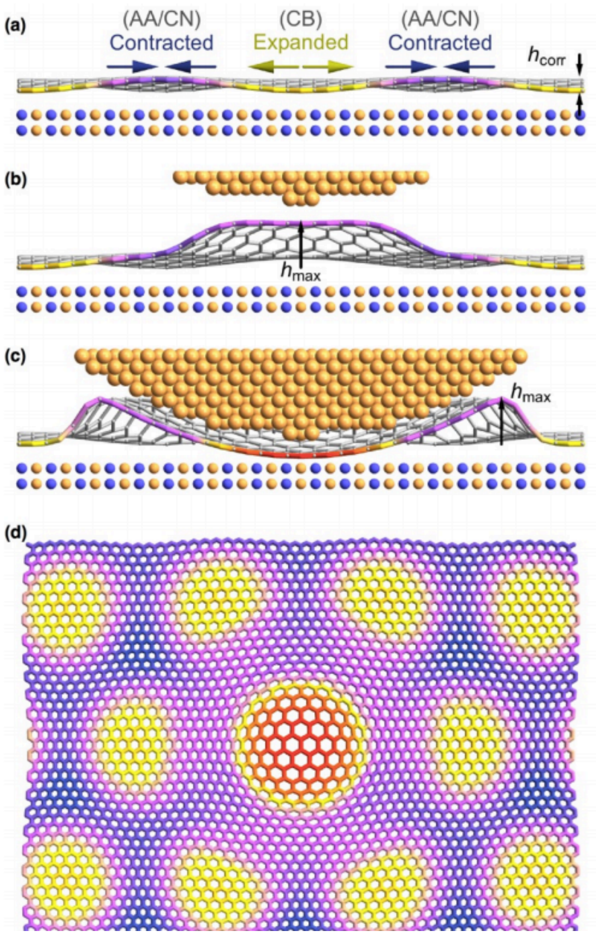
Graphene/WS_2



Avsar *et al.*, Nature Comms. (2015)

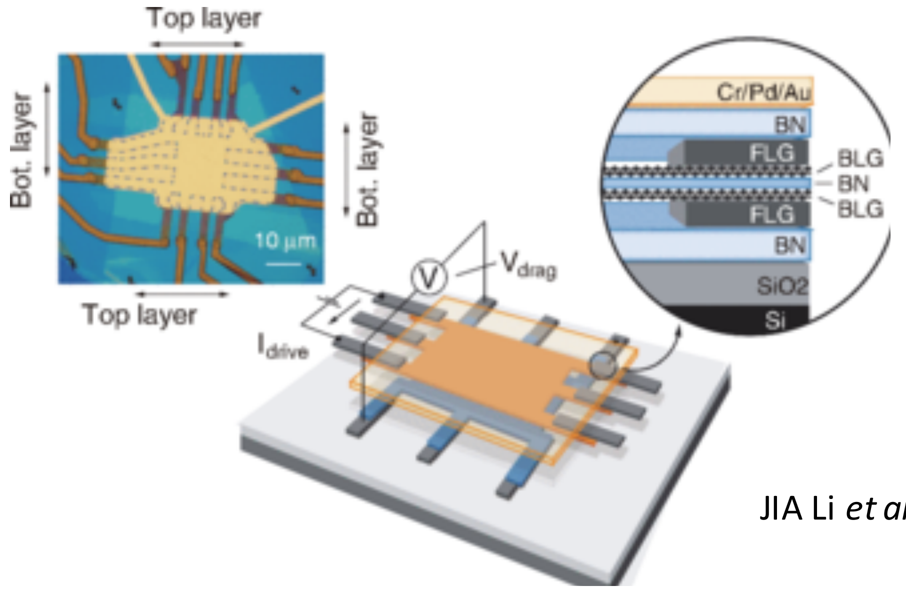
New degrees of freedom and limits

Interlayer spacing



M. Yankowitz *et al.*, *arXiv:1603.03244* (2015)

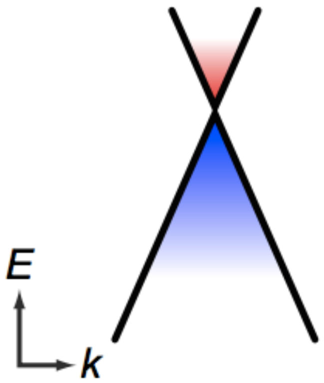
Layer spacing – Coulomb drag measurements

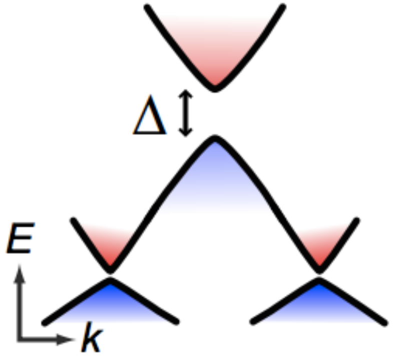


JIA Li *et al.* PRL (2016)

New degrees of freedom and limits

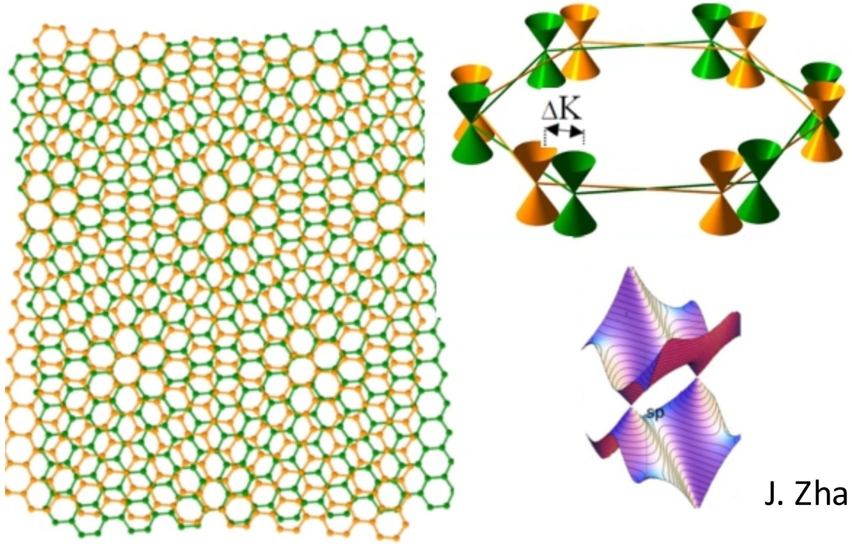
Crystallographic orientation
(to modify electronic properties)





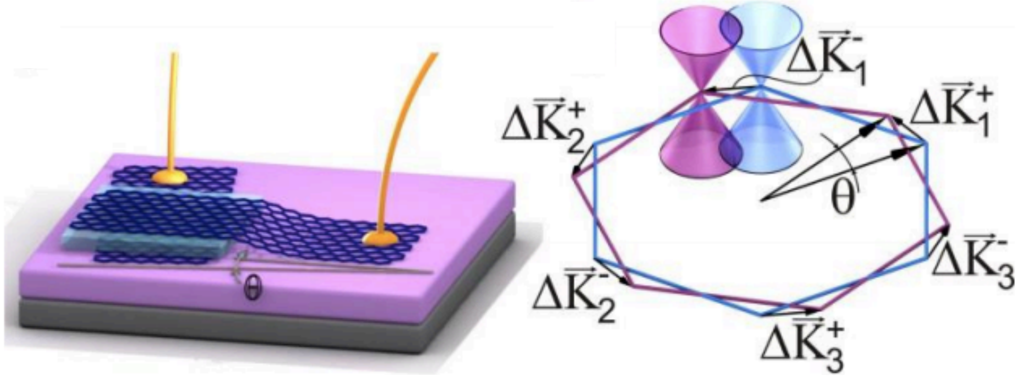
B. Hunt *et al.*, Science (2013)

Twisted bilayer graphene



J. Zhang *et al.*, PRL (2014)

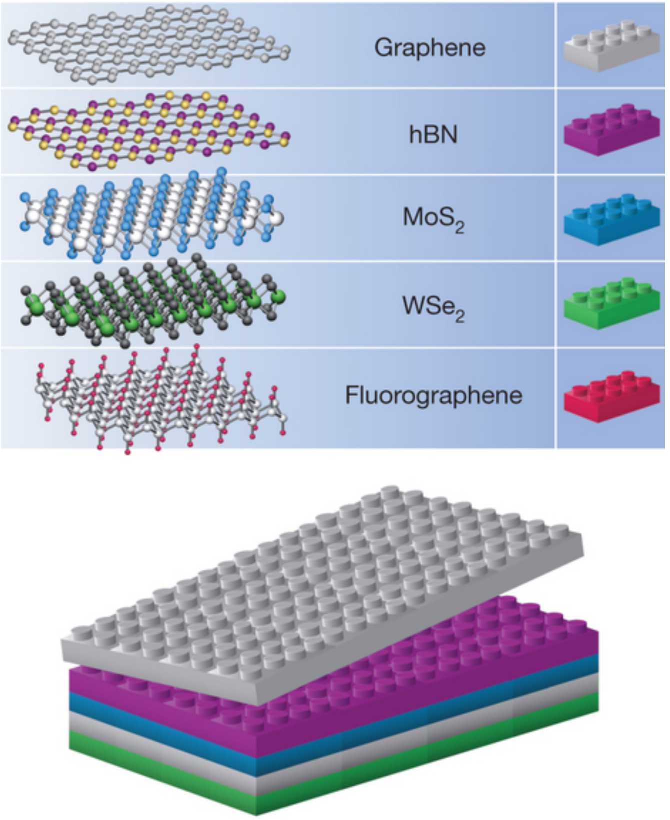
Layer spacing – Resonant tunnelling



A. Mishchenko *et al.* Nature Nanotech (2014)

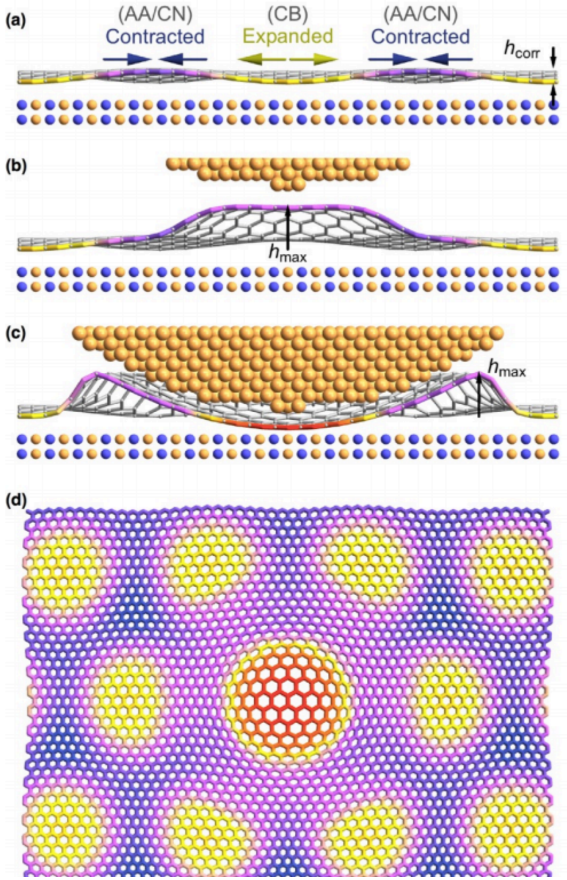
New degrees of freedom and limits

Mix of materials



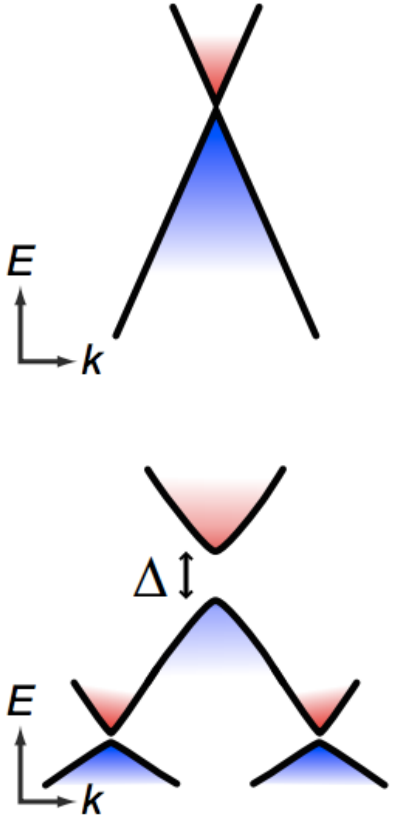
A. K. Geim and I. V. Grigorieva Nature (2013)

Interlayer spacing



M. Yankowitz *et al.*, arXiv:1603.03244 (2015)

Crystallographic orientation



B. Hunt *et al.*, Science (2013)

Some vocabulary

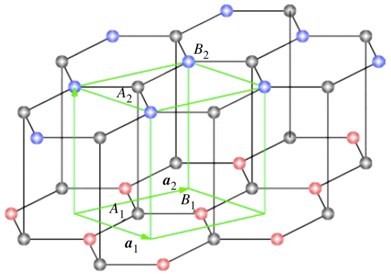
Aligned crystals: When two or more layers have the same crystal orientation (e.g. zigzag, armchair).

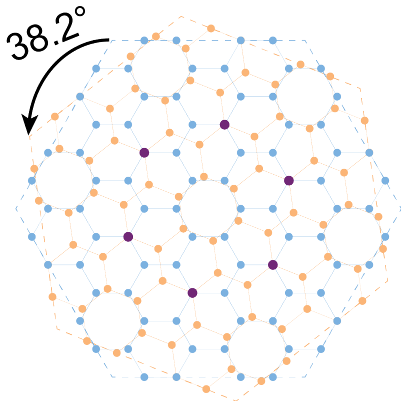
Commensurate state: When the orientation between layer give rise to a new lattice constant.

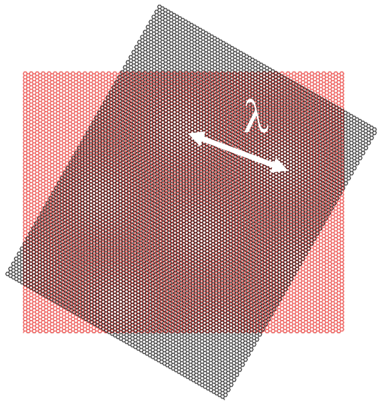
Uncommensurate state: when the layers are not aligned nor in a commensurate state.

Moiré pattern: periodic potential develop by two layers, with the same lattice structure, when these are close to alignment.

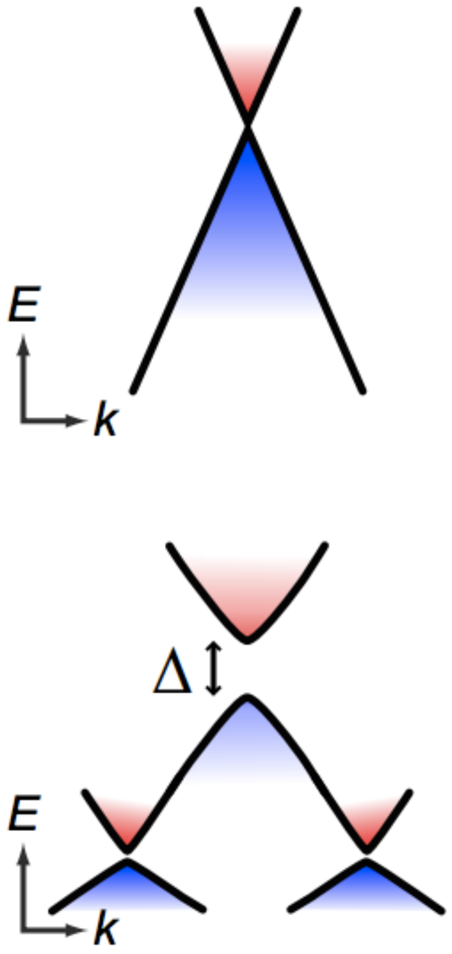
Twistronics: fancy name that appeared in Arxiv few months ago (arXiv:1611.00649v2).

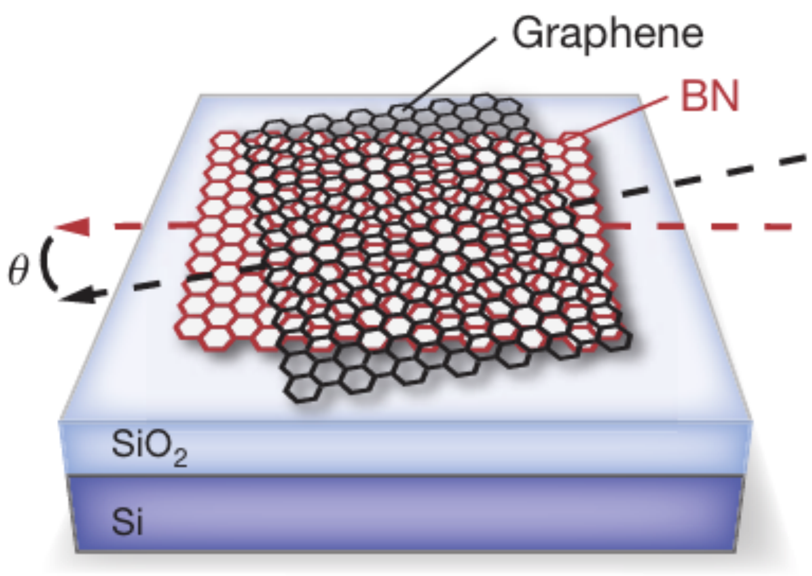


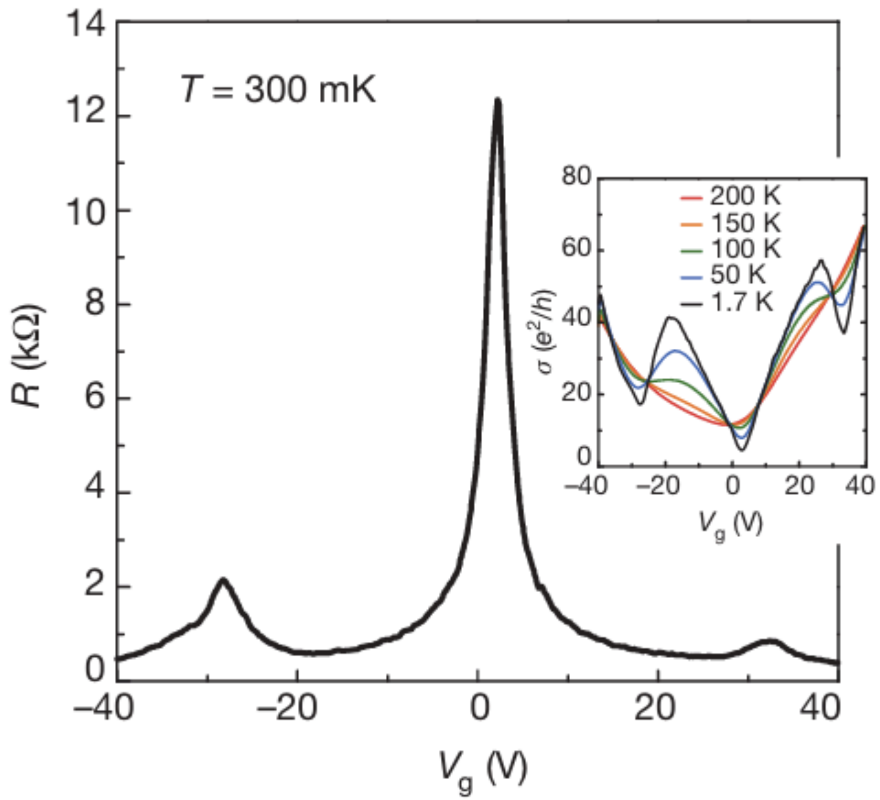




Crystallographic orientation (Moiré superlattice)

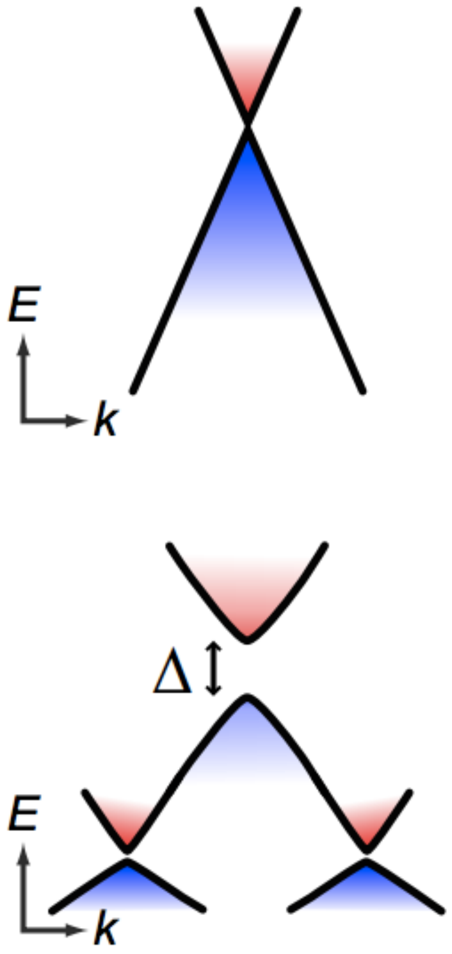


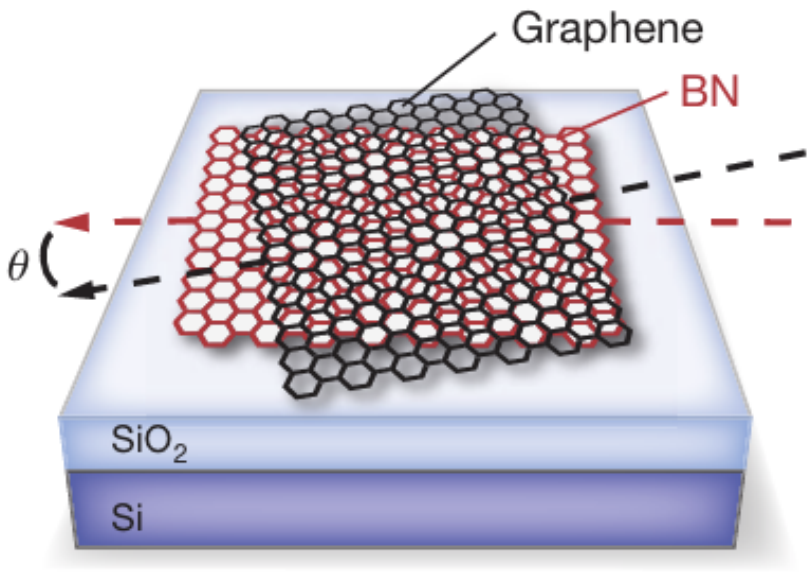


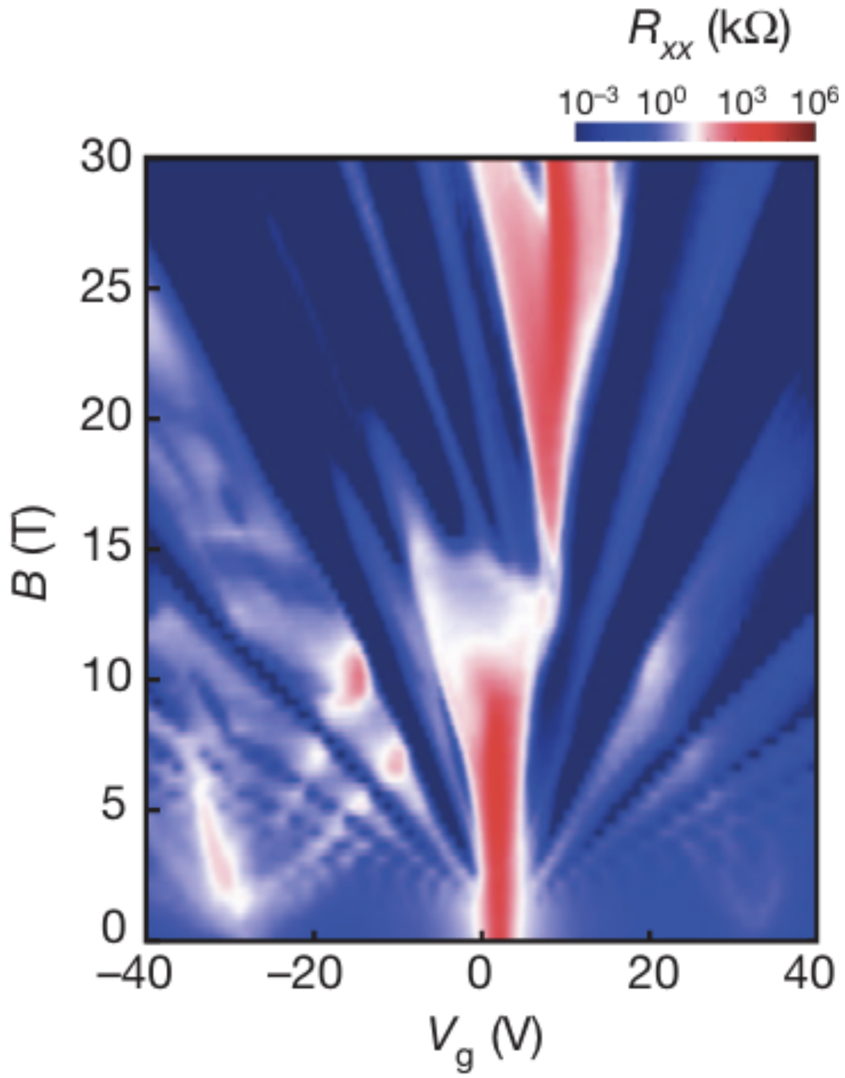


C.R. Dean *et al.*, Nature (2013); B. Hunt *et al.*, Science (2013); L. Ponomarenko *et al.*, Nature (2013)

Crystallographic orientation (Moiré superlattice)

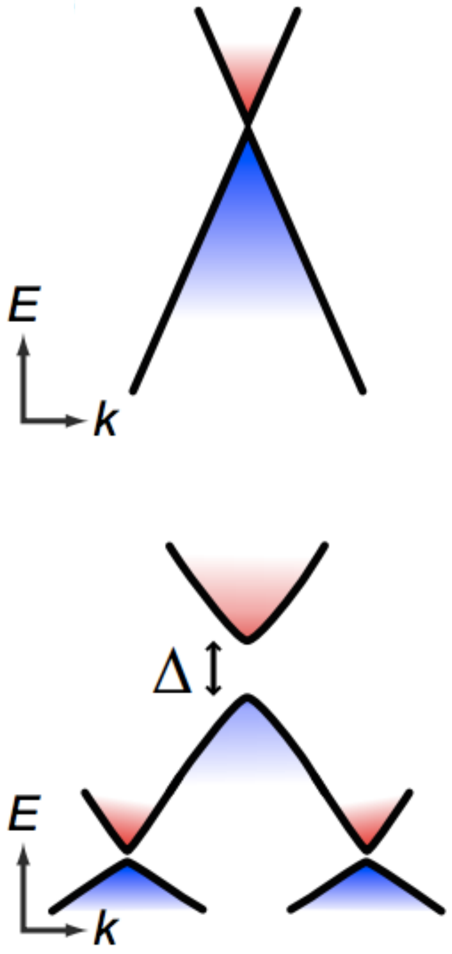




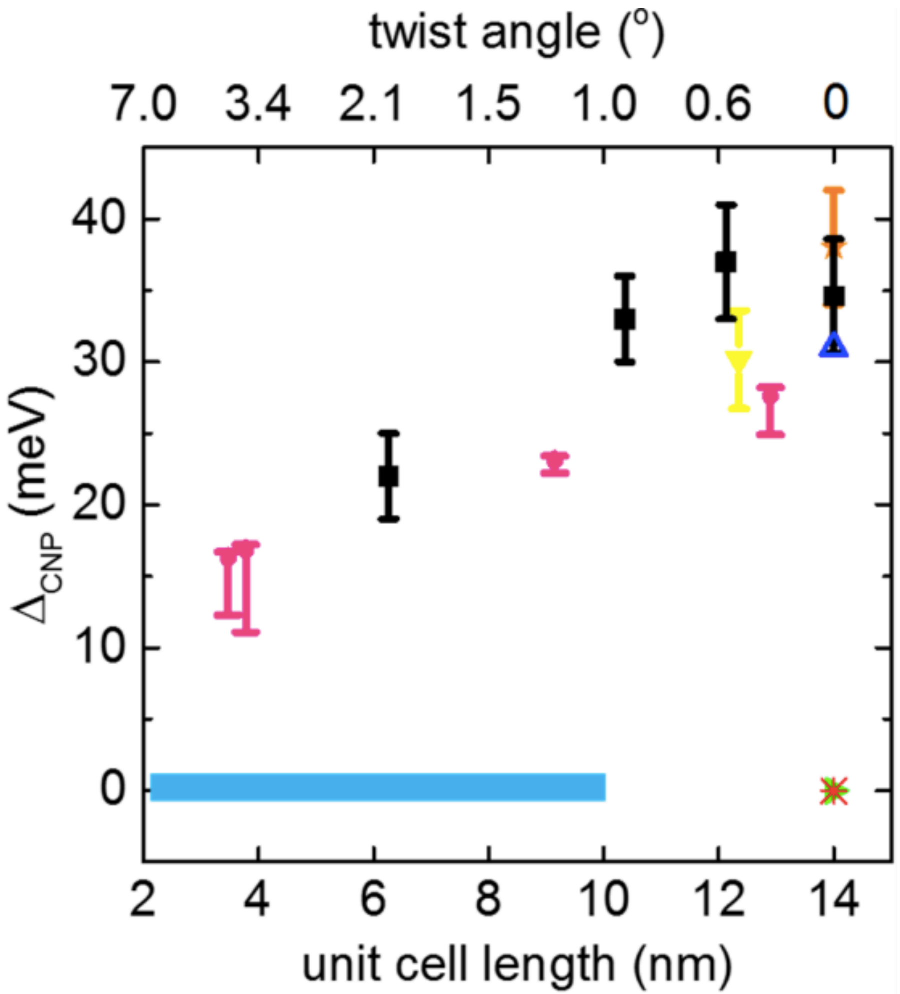


C.R. Dean *et al.*, Nature (2013); B. Hunt *et al.*, Science (2013); L. Ponomarenko *et al.*, Nature (2013)

Crystallographic orientation (Moiré remaining questions)



B. Hunt *et al.*, Science (2013)



- Origin of the energy gap
- Encapsulated devices do not show gap?
- Gapped devices without satellite peaks?

L. Wang et al., science (2015) – encapsulated

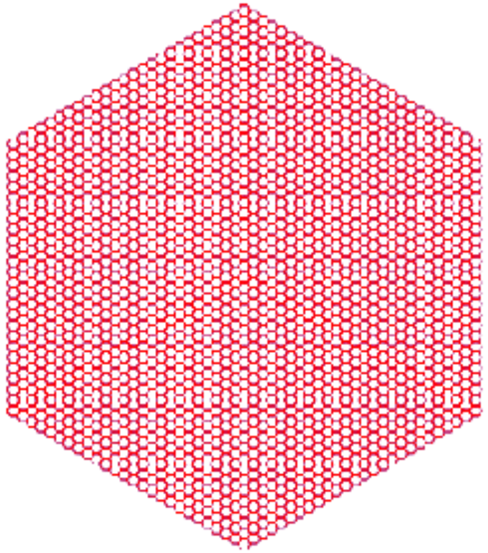
B. Hunt et al., Science (2013)

L. Ponomarenko et al., Nature (2013) - encapsulated

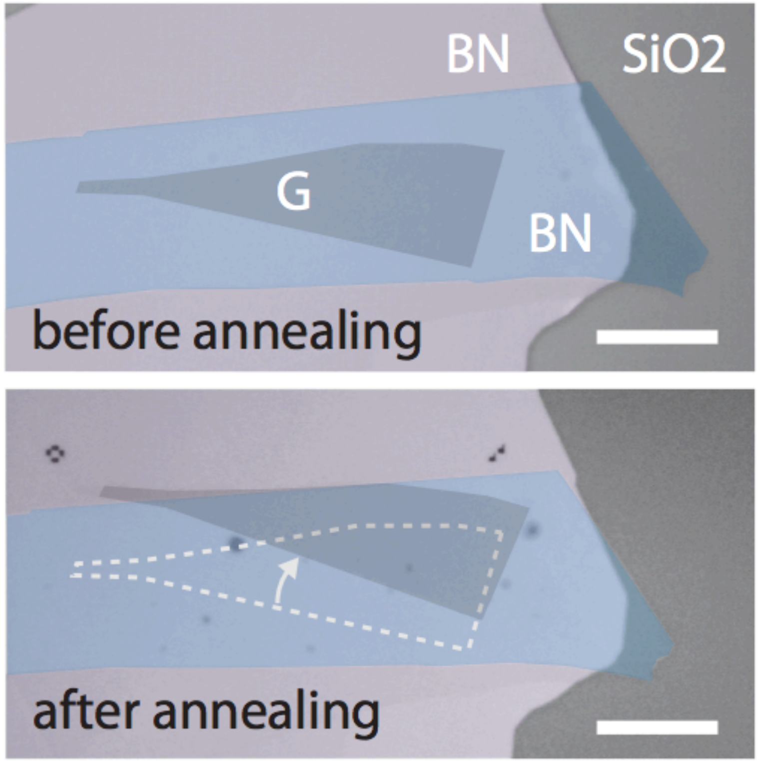
C.R. Woods et al., Nature Phys. (2014) - encapsulated

Layer alignment in fabrication (multiple devices)

Edge aligment

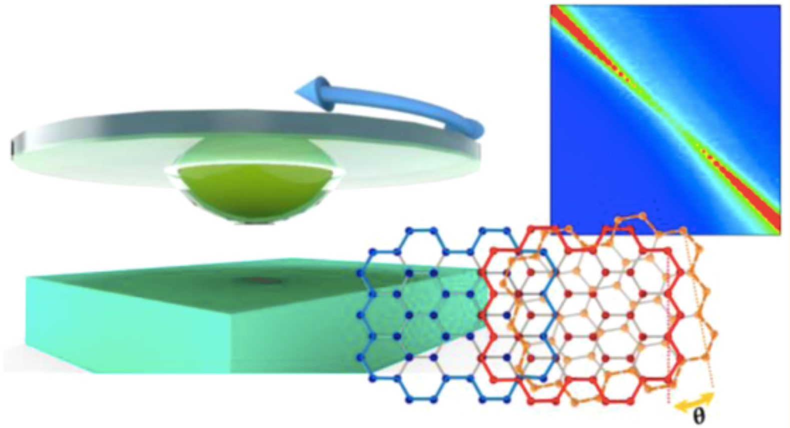


Thermal self-alignment



L. Wang *et al.*, Science (2015)

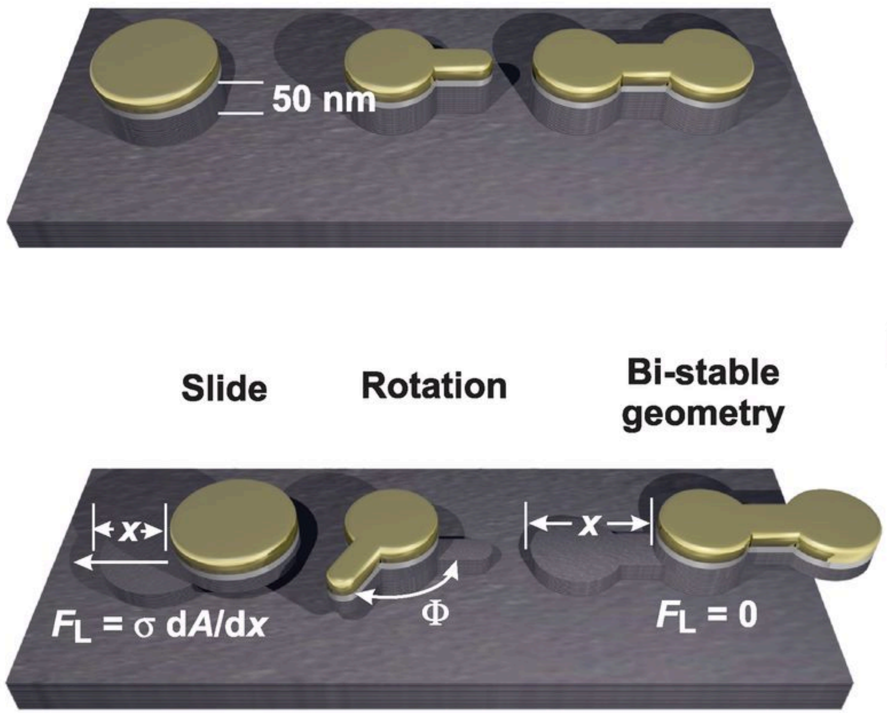
Rotational alignmet

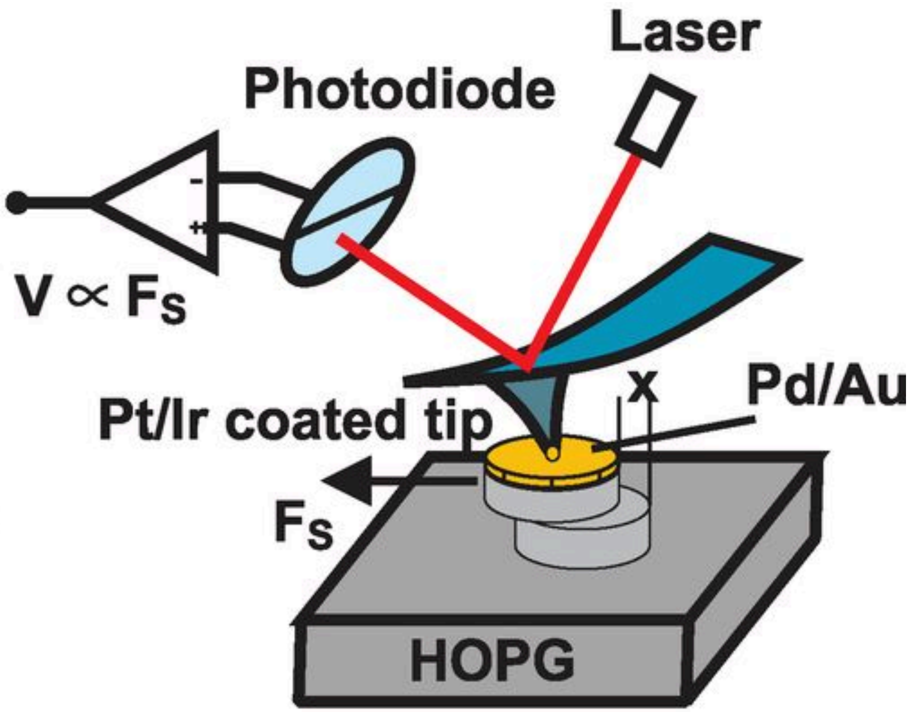


K. Kim *et al.* Nano Letters (2016)

NO Precise angle control impossible to measure more than one angle per sample

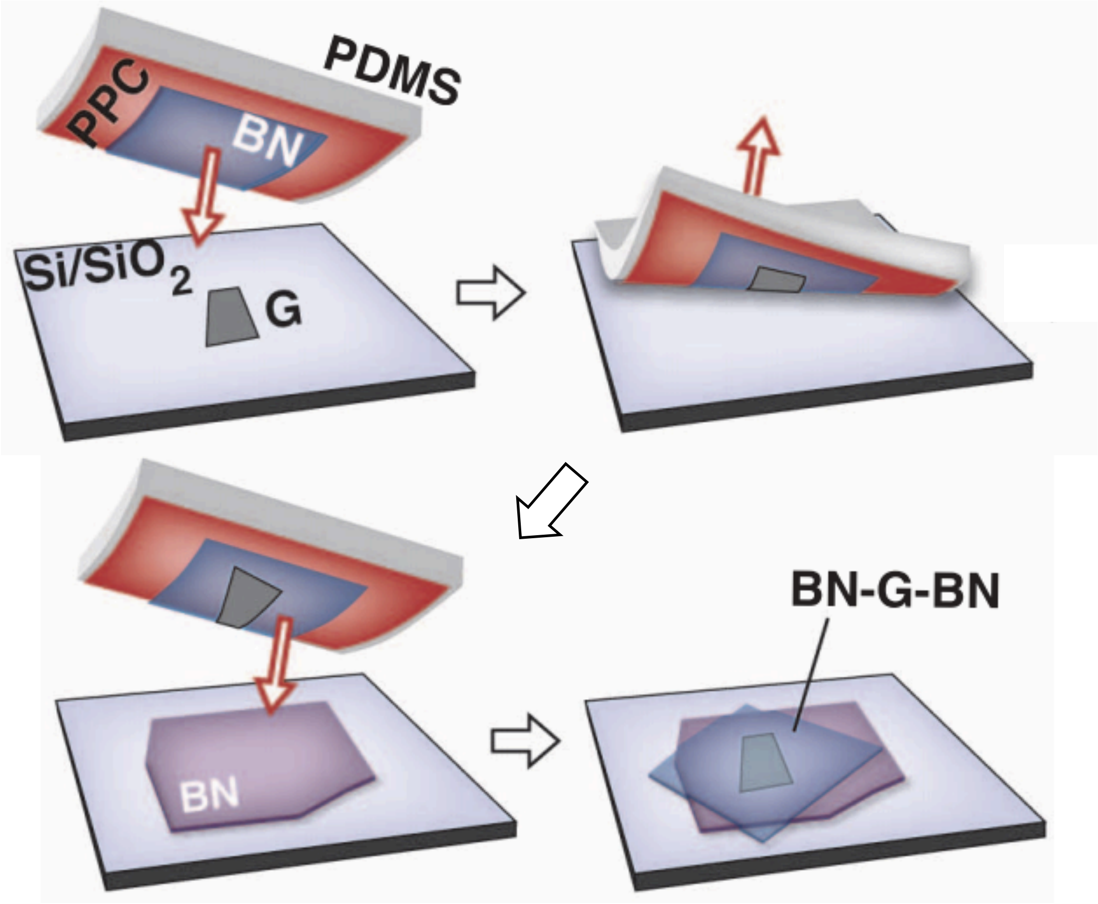
Inspiration



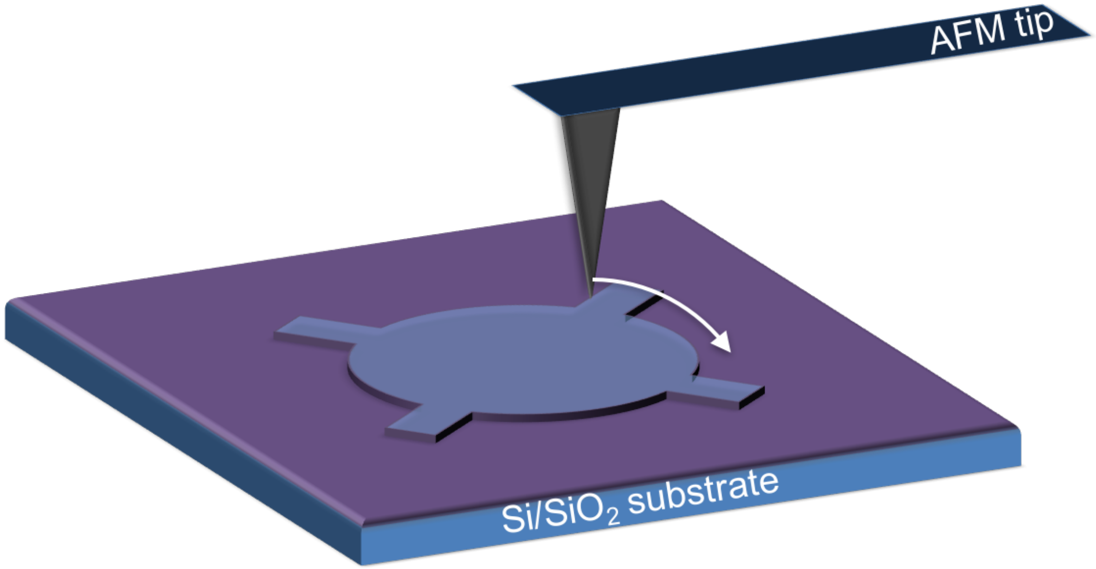


E. Koren *et al.*, Science (2015)

Van der Waals heterostructures + AFM manipulation

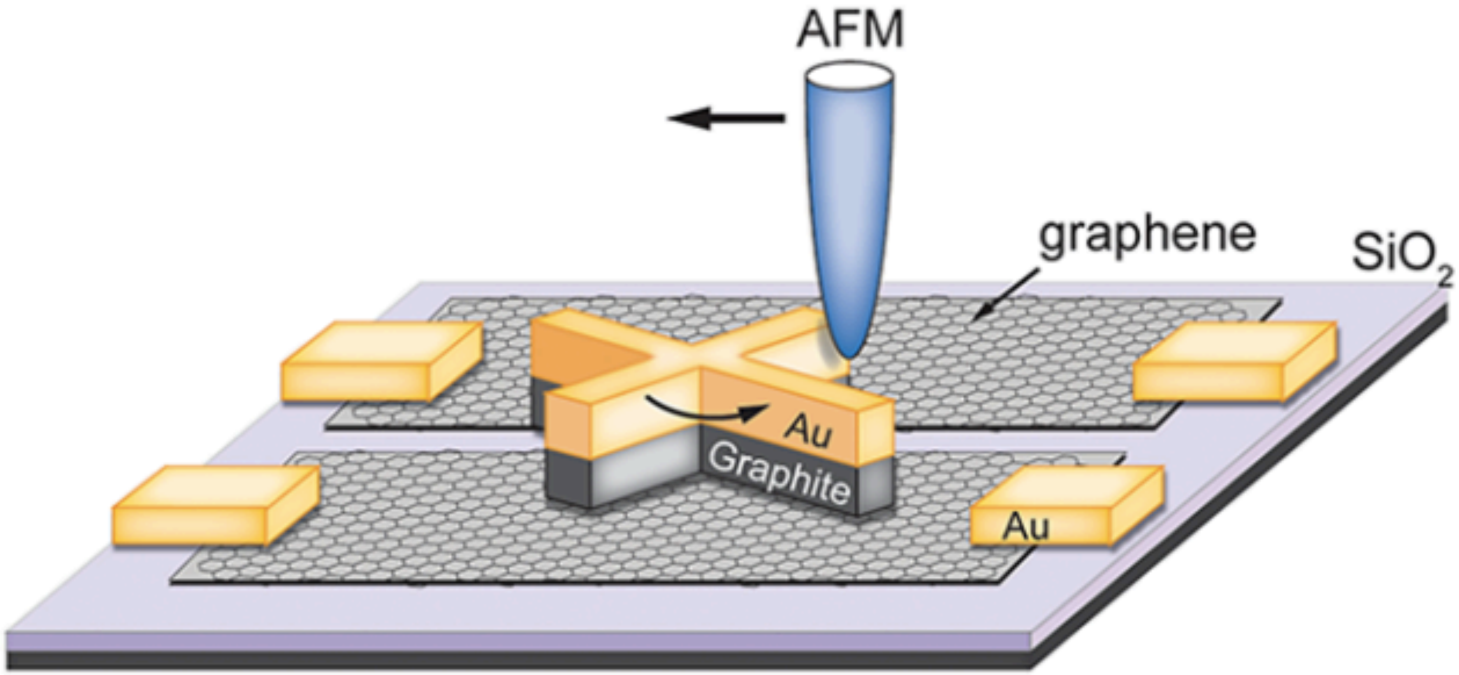


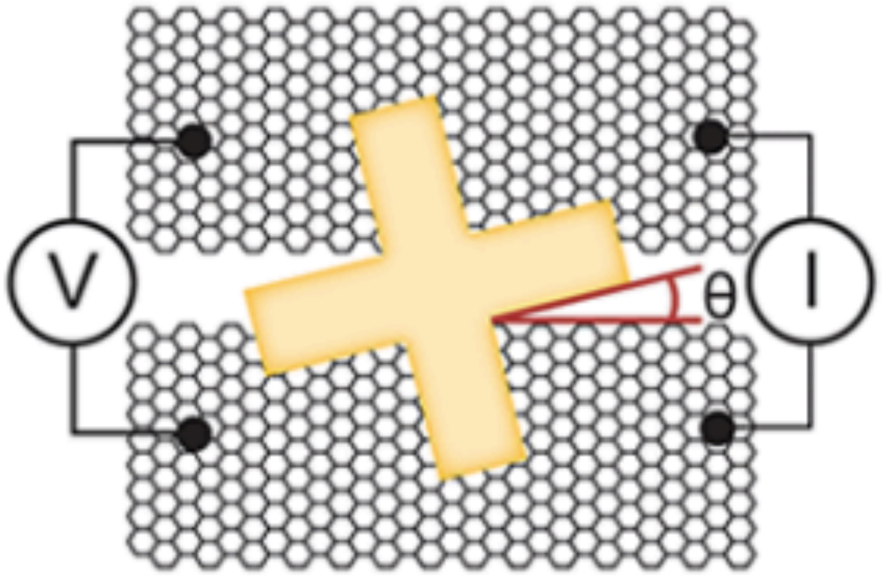
+



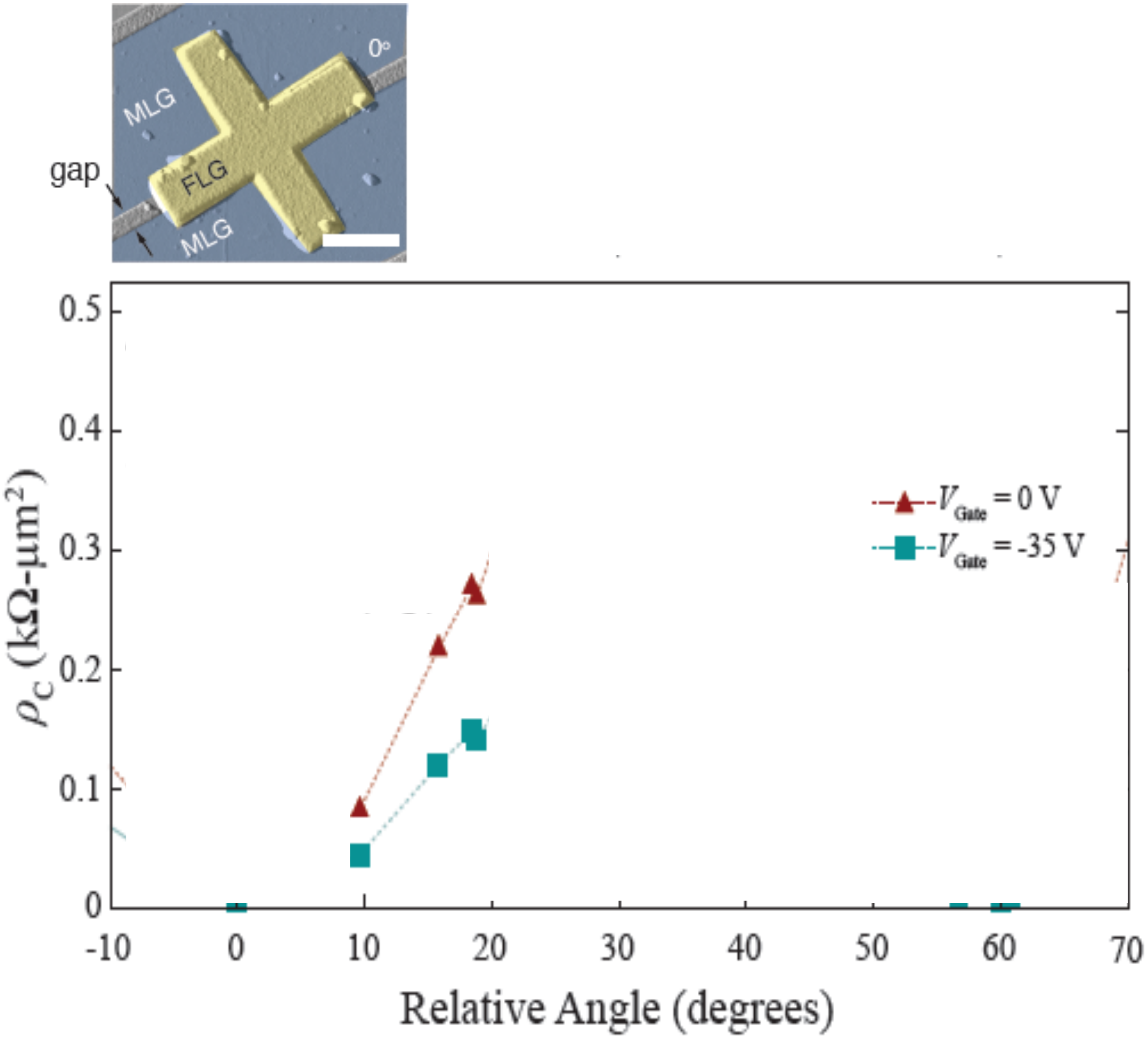
L. Wang *et al.*, Science (2013)

Graphite on graphene (device)



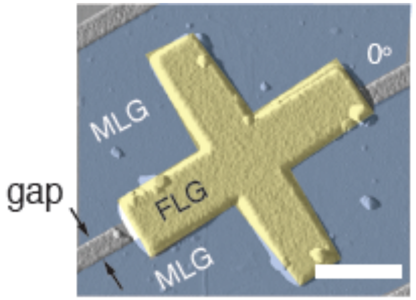


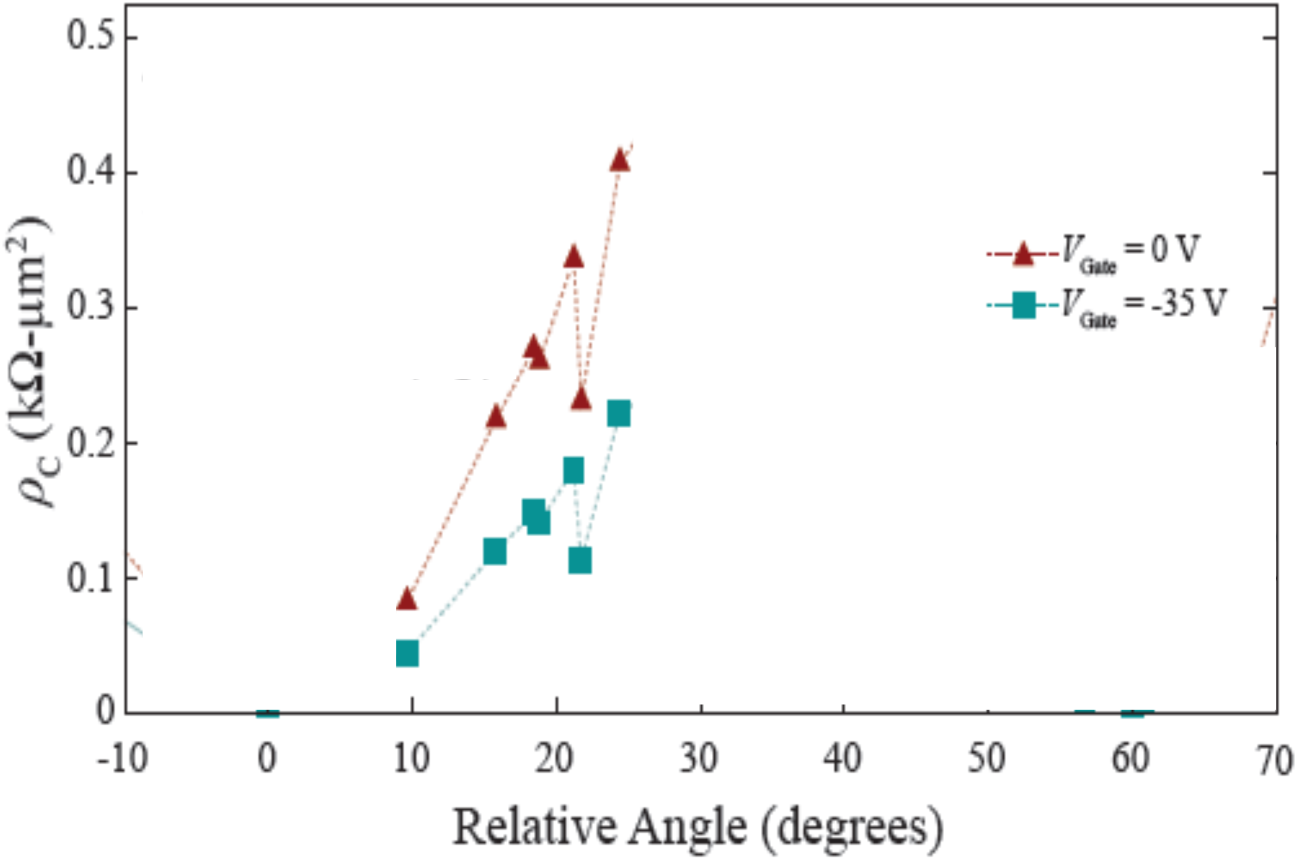
Graphite on graphene (as a function of the angle)



T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

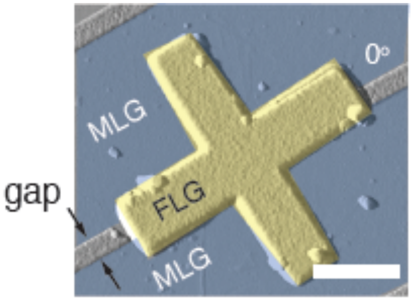
Graphite on graphene (as a function of the angle)

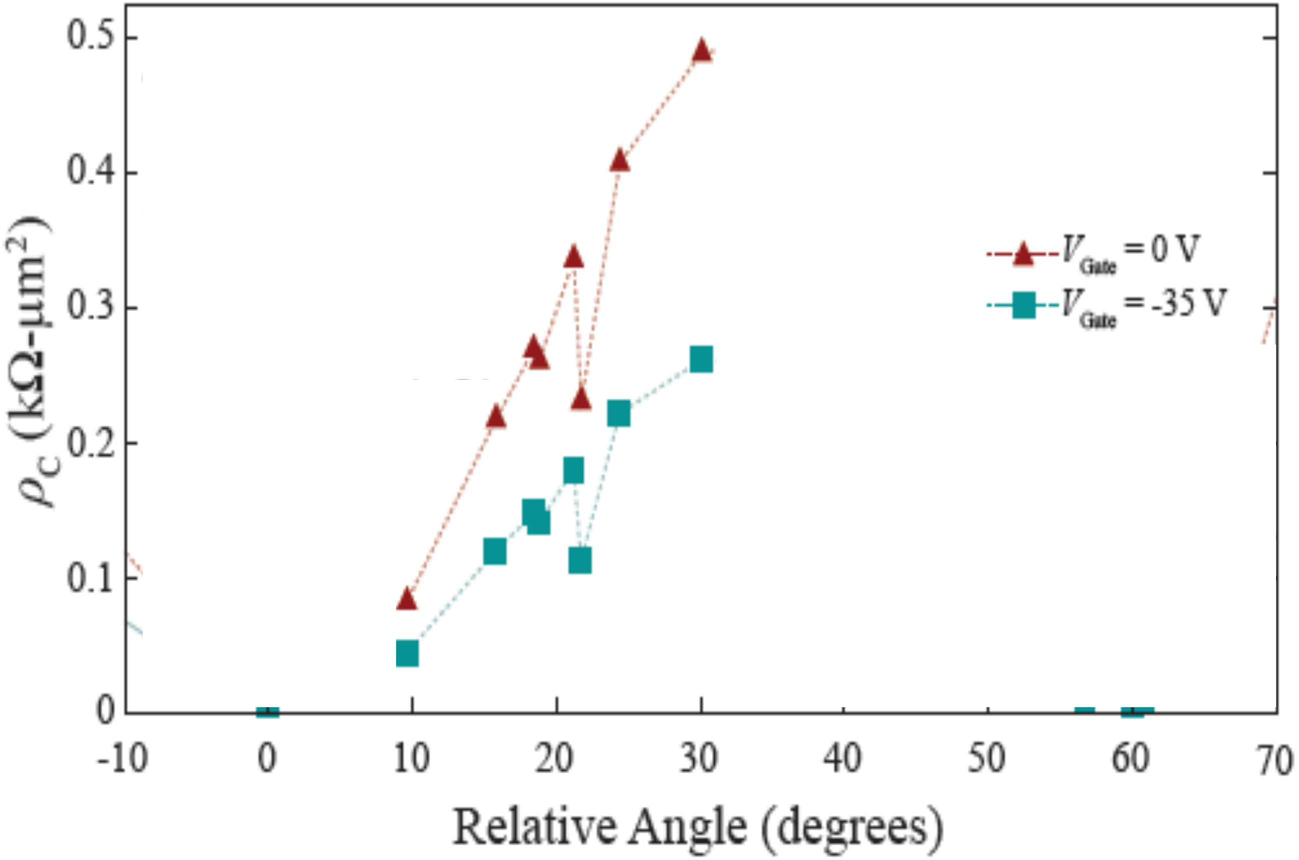




T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

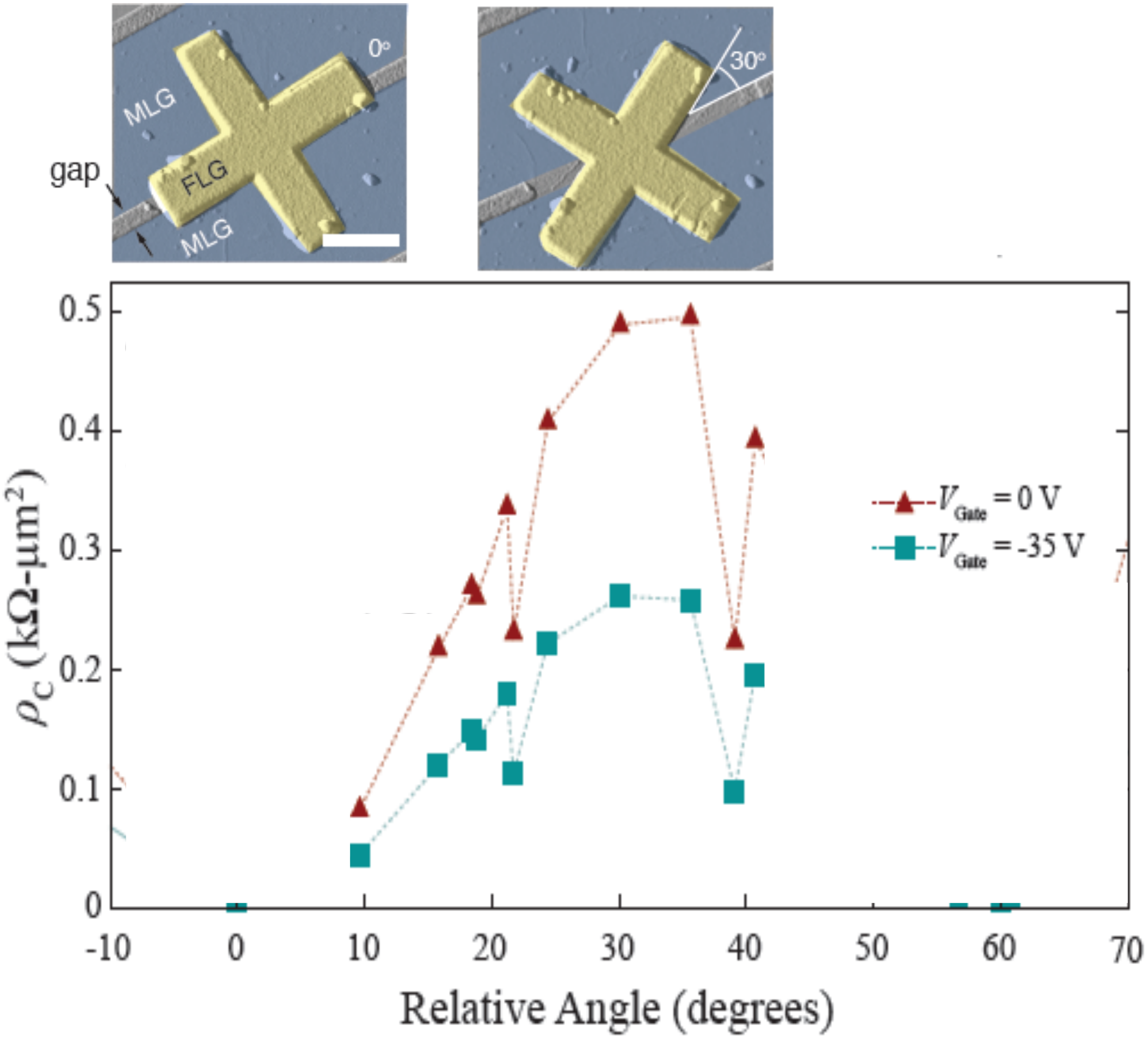
Graphite on graphene (as a function of the angle)





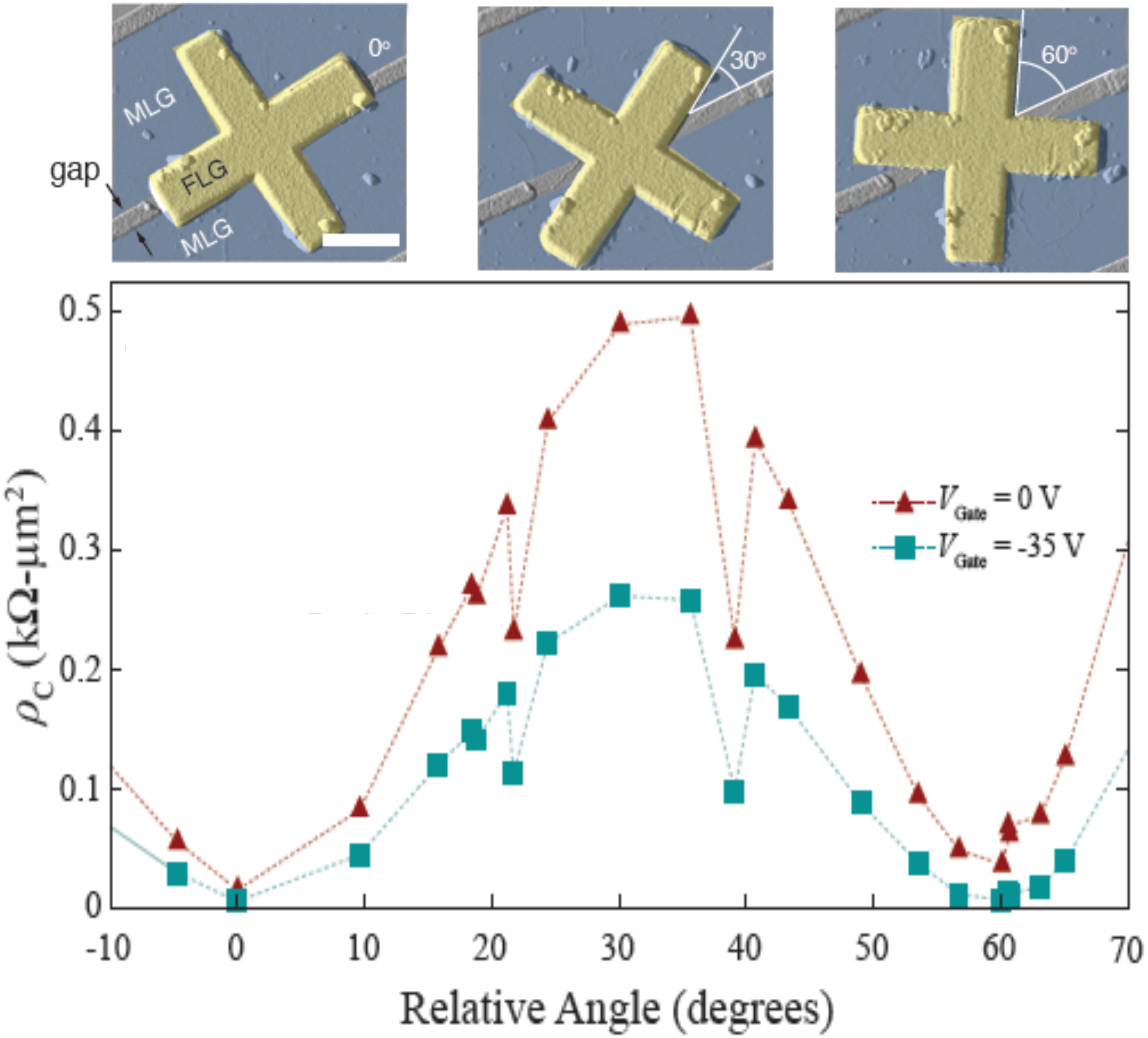
T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

Graphite on graphene (as a function of the angle)



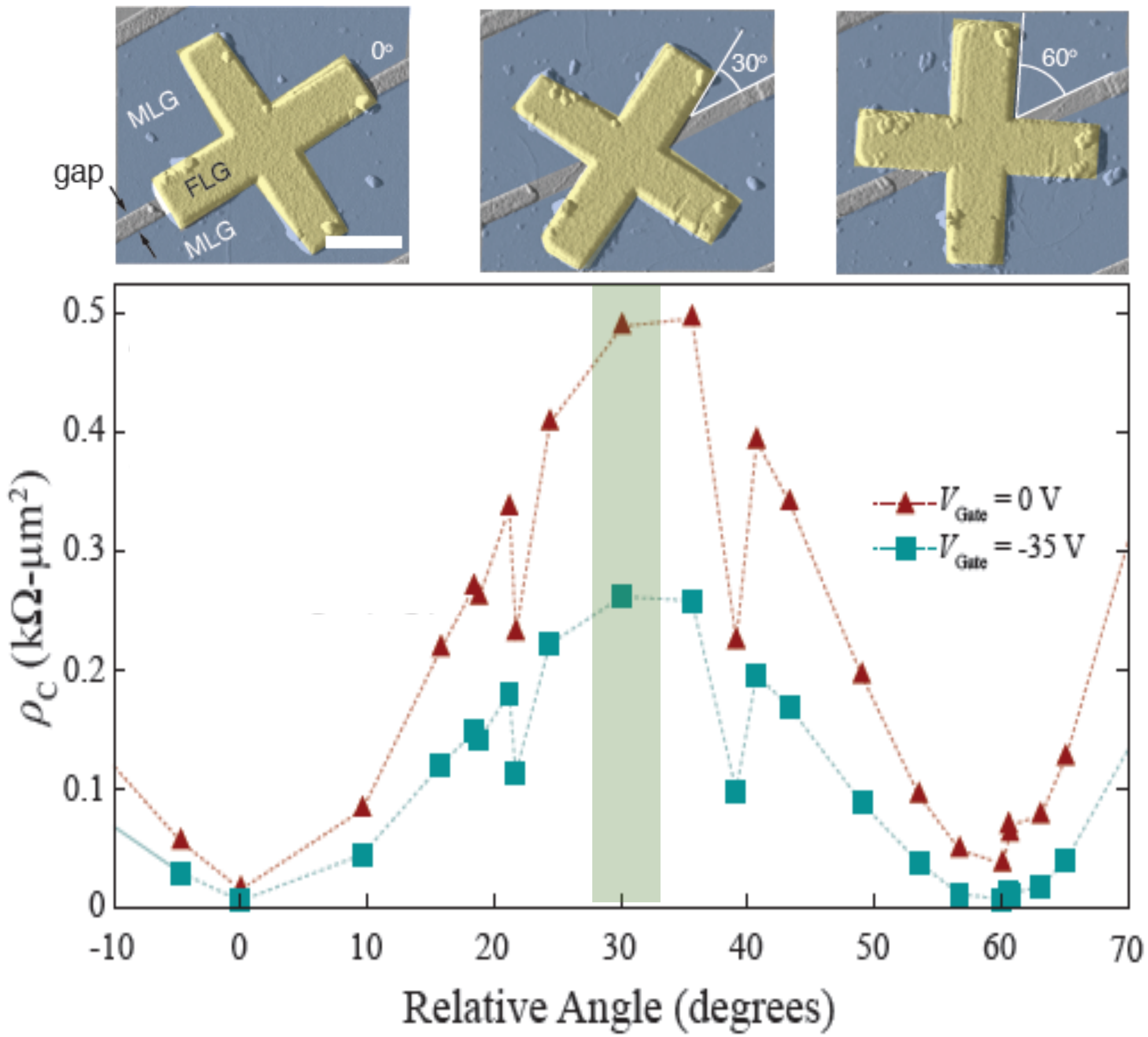
T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

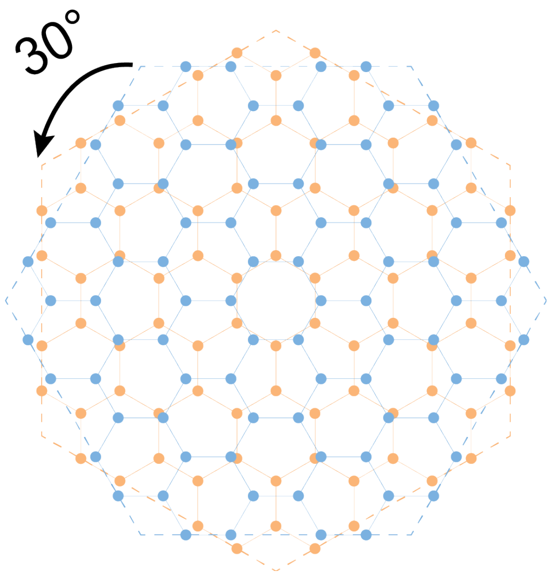
Graphite on graphene (as a function of the angle)



T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

Graphite on graphene (as a function of the angle)

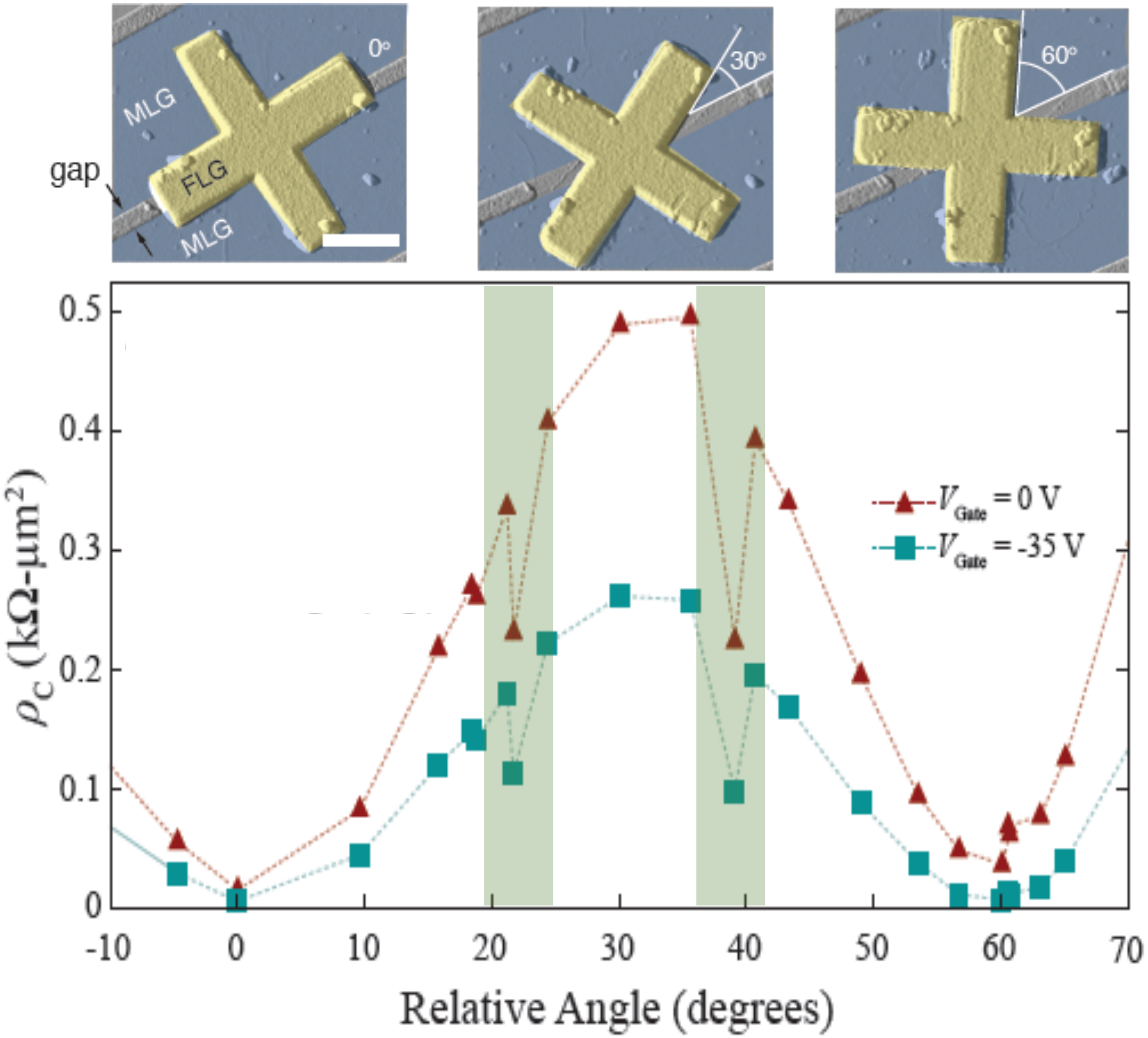




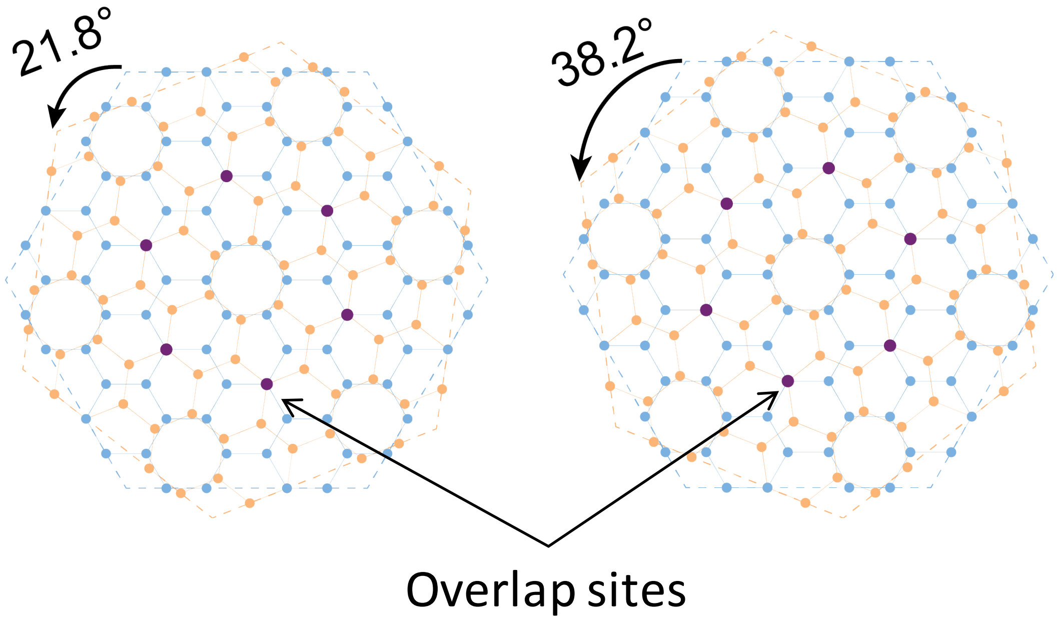
Fully momentum mismatch

T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

Graphite on graphene (as a function of the angle)

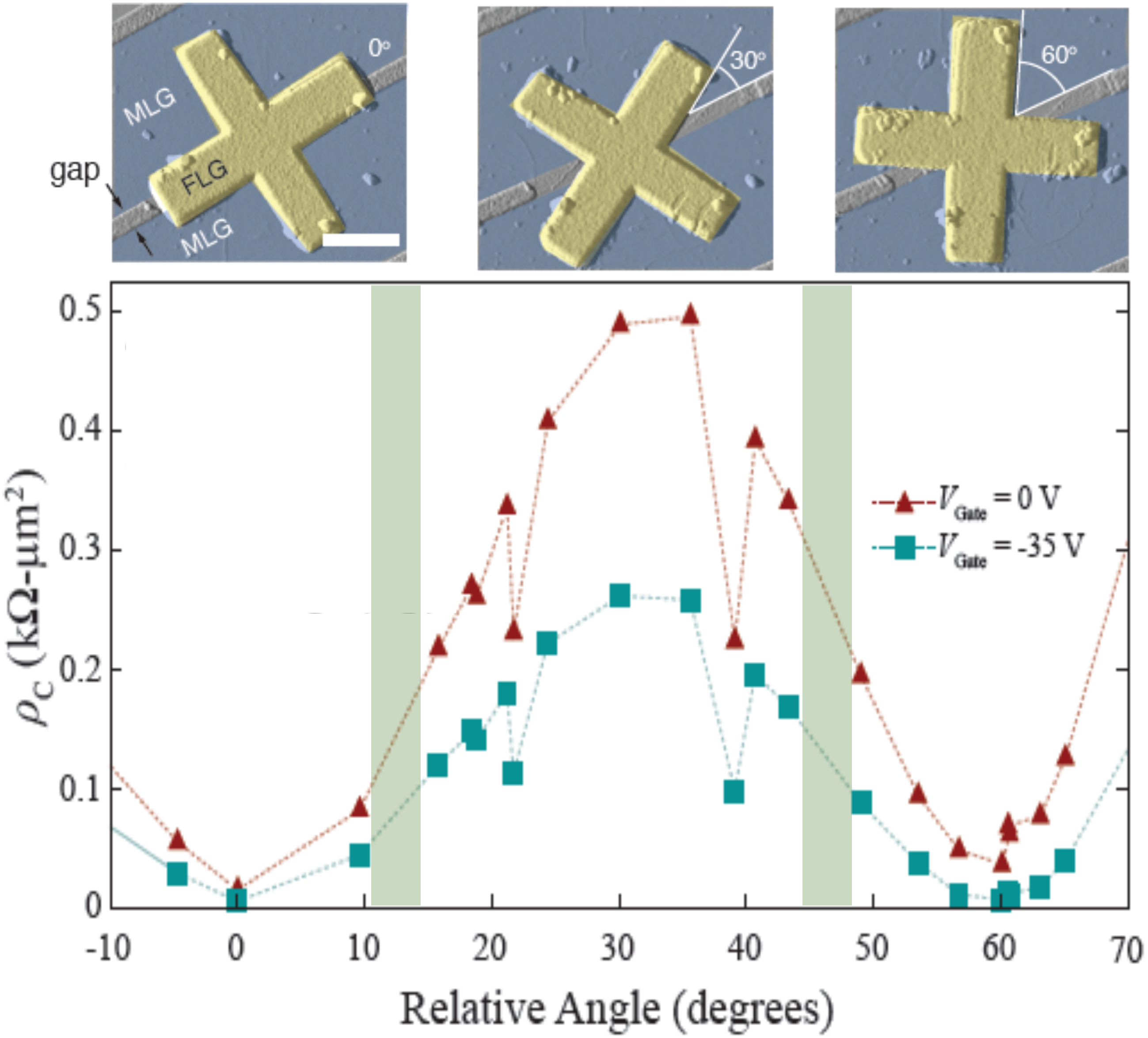


Commensurate angles

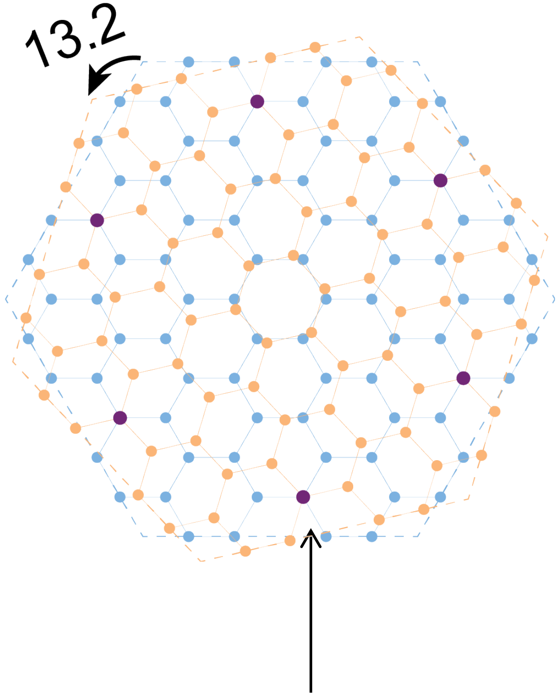


T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

Graphite on graphene (as a function of the angle)



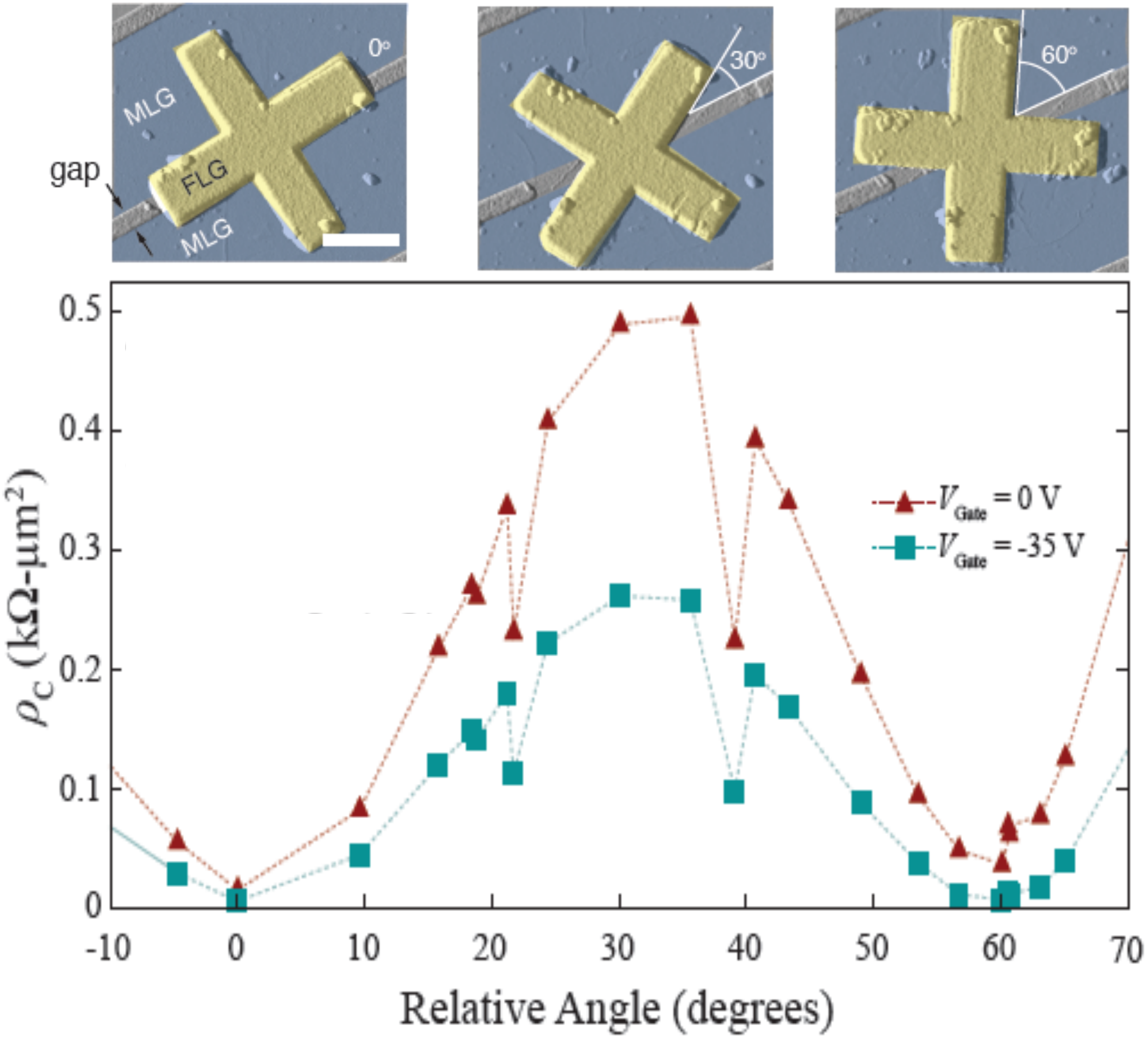
Commensurate angles



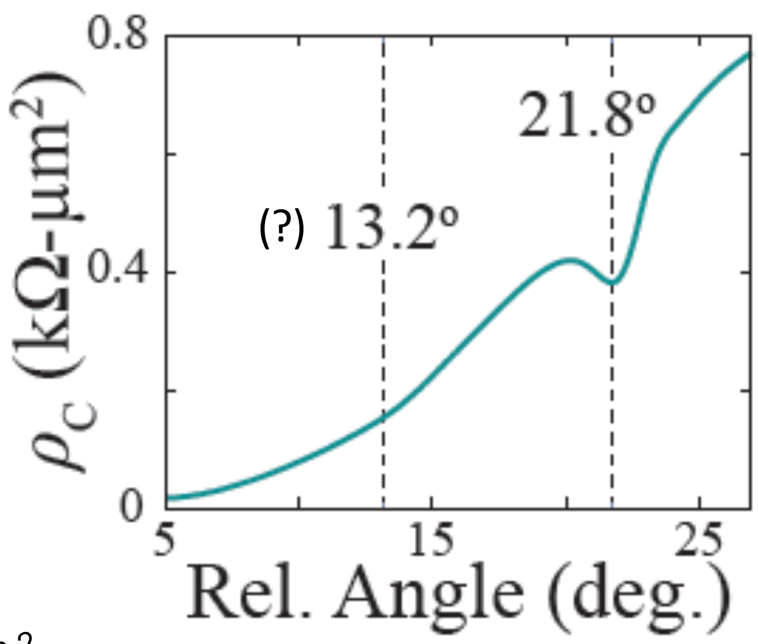
Overlap sites

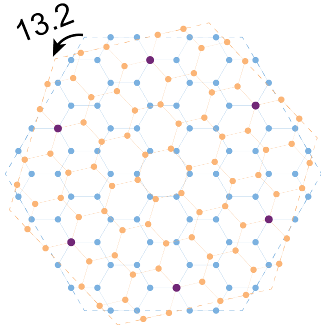
T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

Graphite on graphene (as a function of the angle)



Dynamical measurement
(different sample)

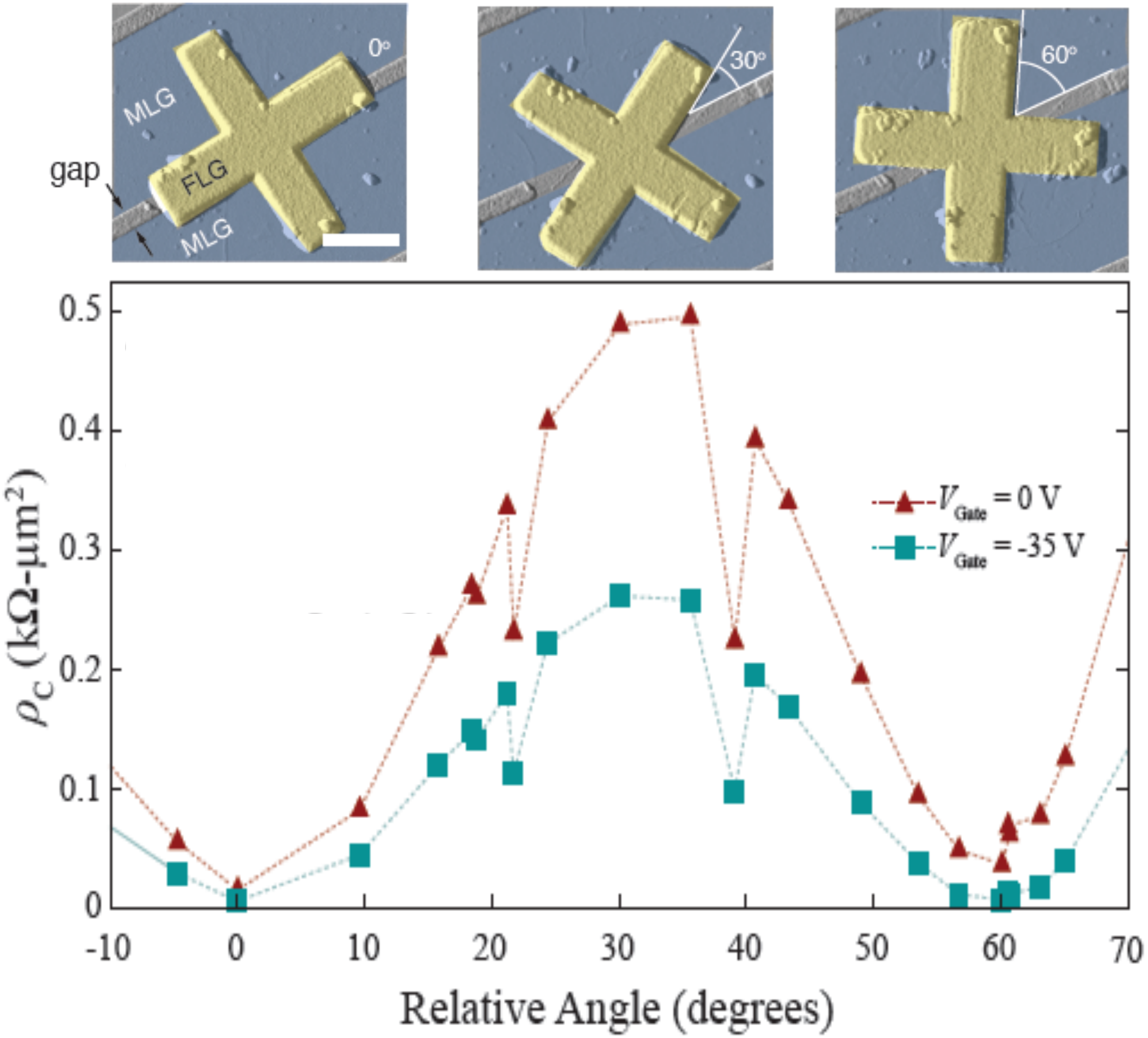




Where is 13.2° (46.8°)?

T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

Graphite on graphene (as a function of the angle)

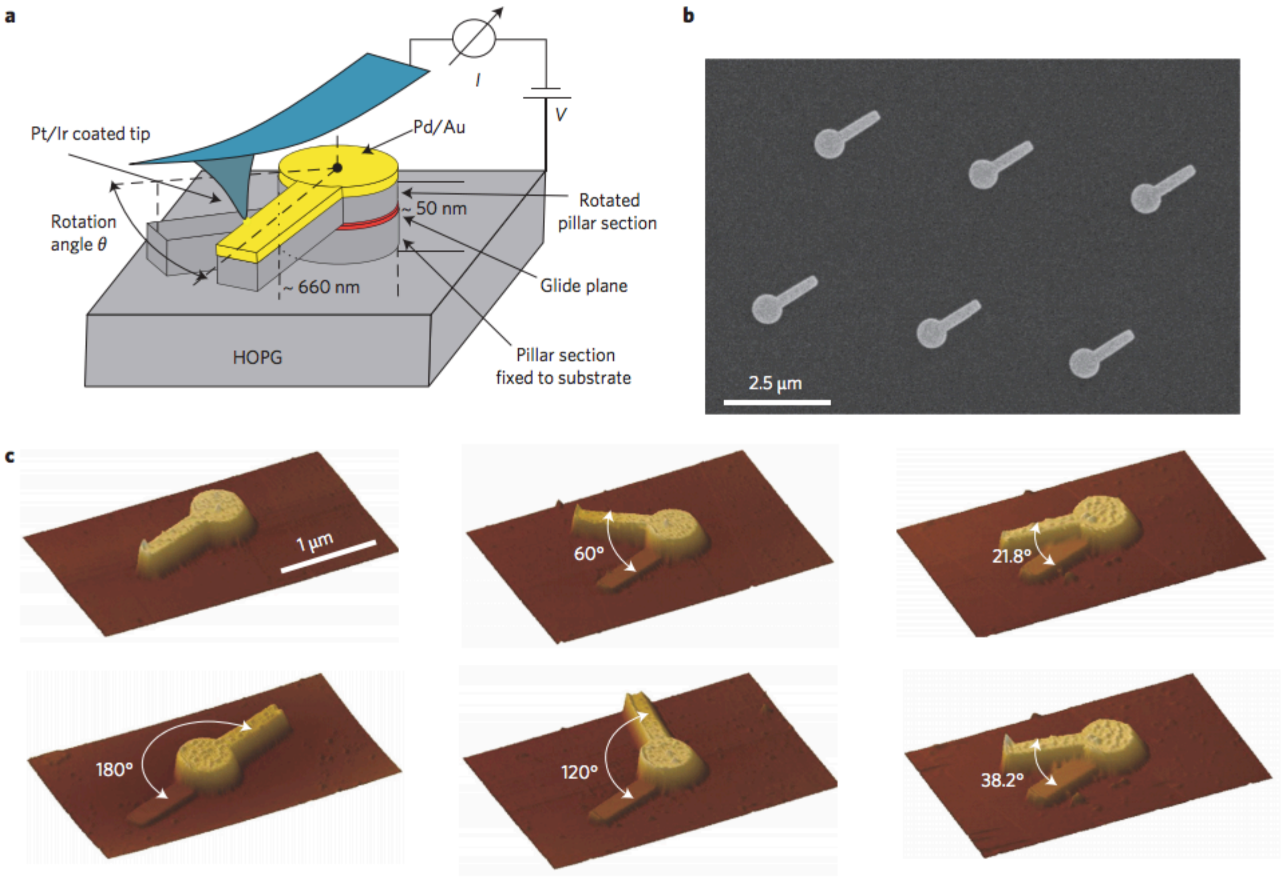


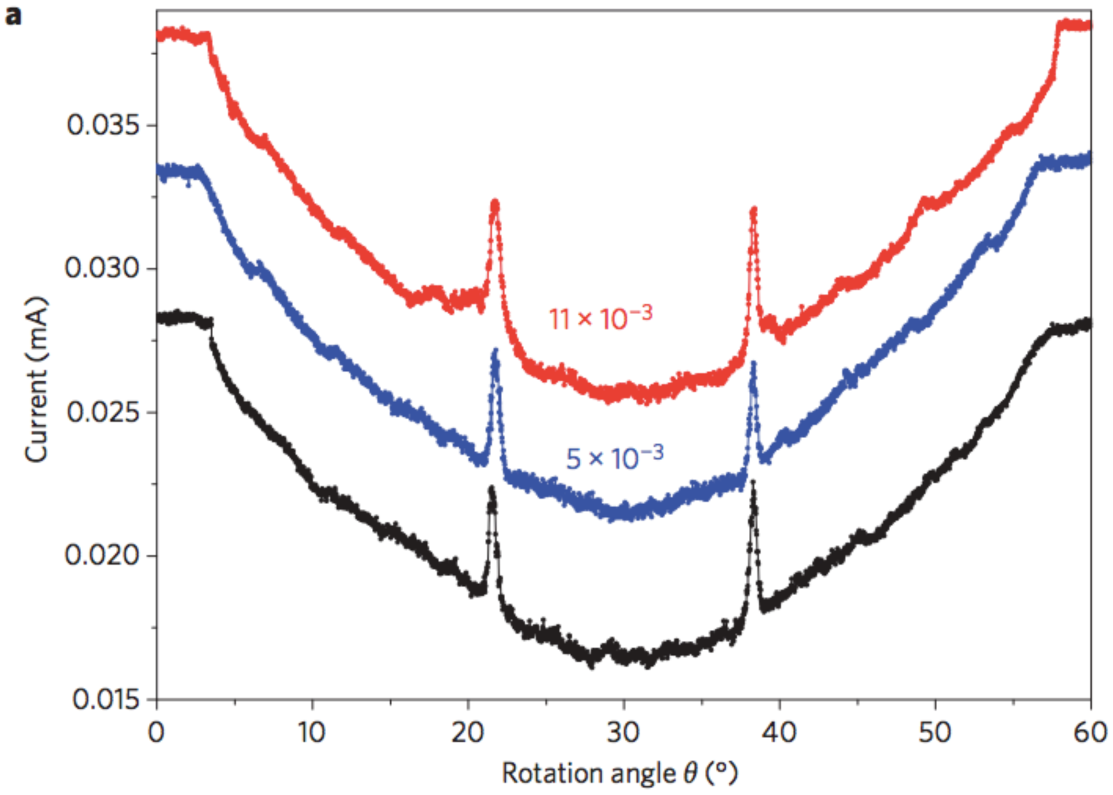
<u>New physics to study</u>:

- Monolayer – bilayer transition
- Weakly couple bilayer
- Aligned transparent contacts to 2D materials

T. Chari, R. Ribeiro-Palau *et al.*, Nano Letters (2016)

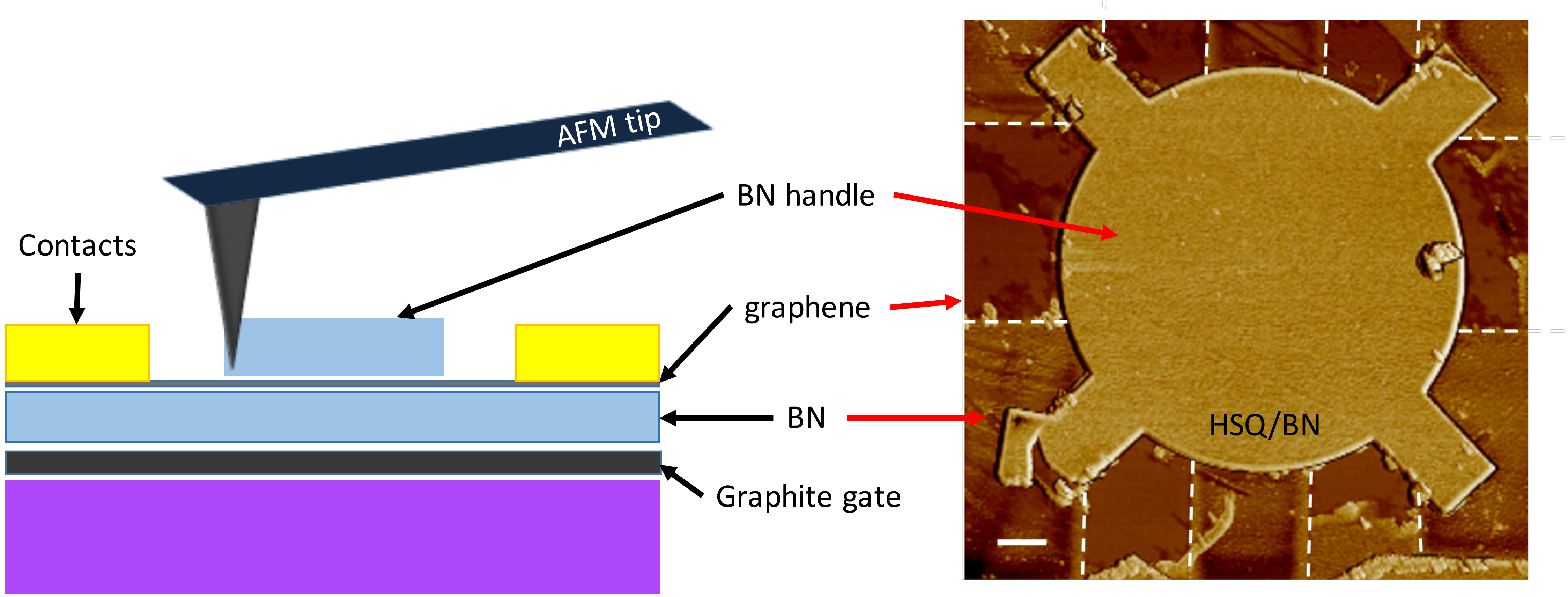
Graphite on graphite (at the same time in IBM)





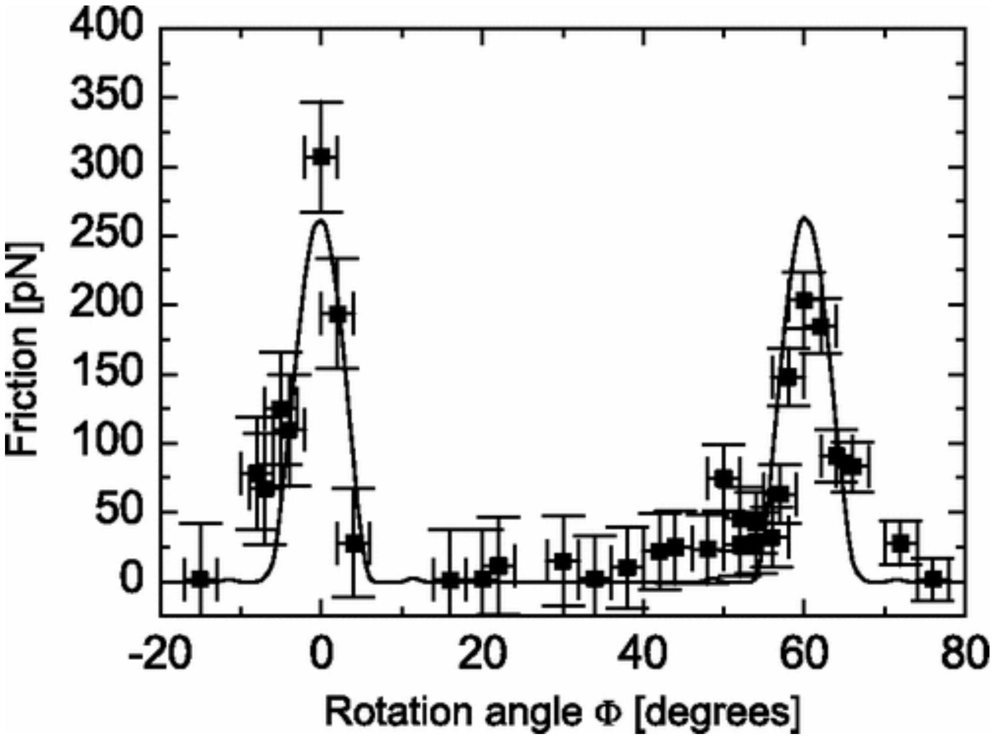
E. Koren *et al.*, Nature Nanotech (2016)

BN on graphene (band structure manipulation)

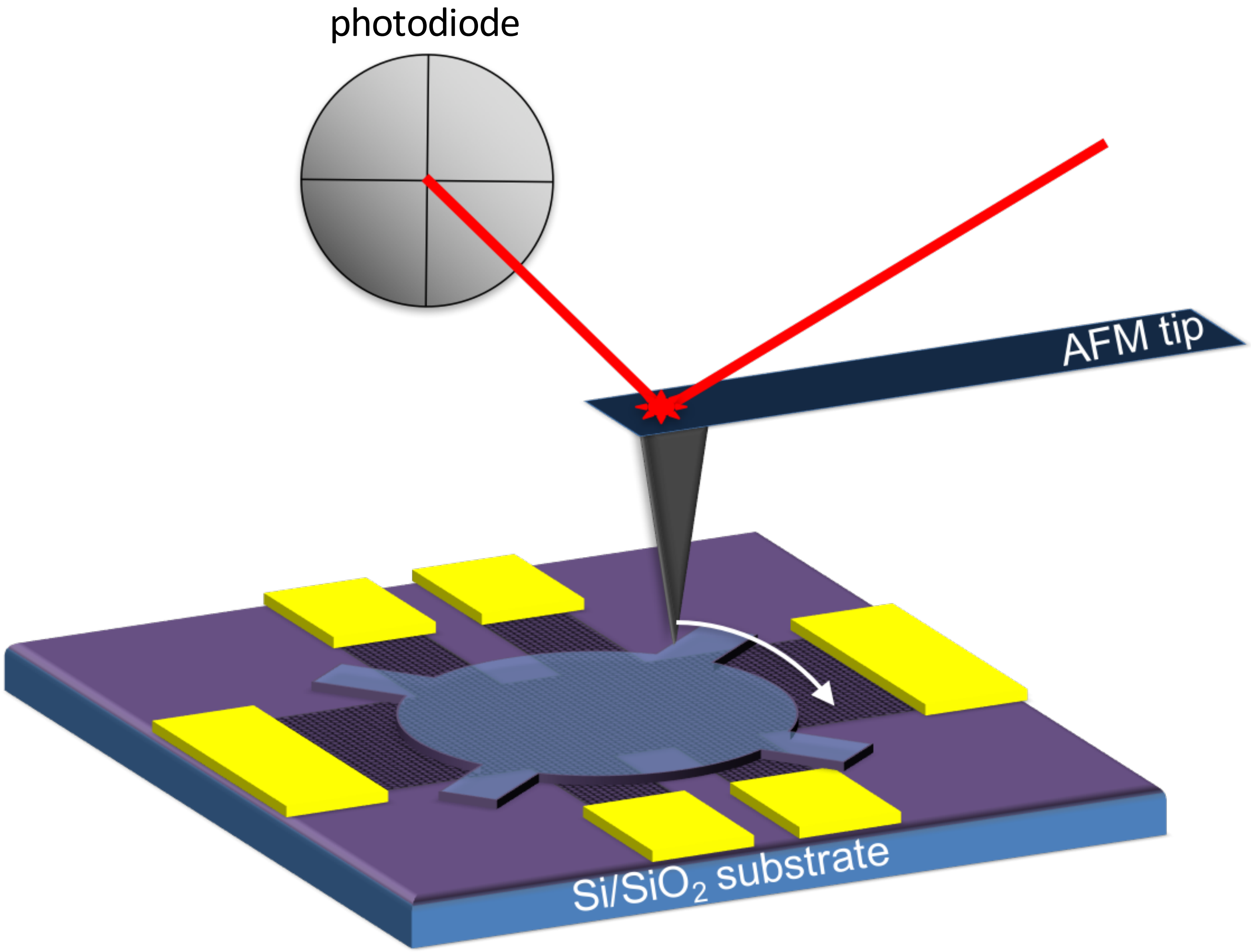


BN on graphene (friction)

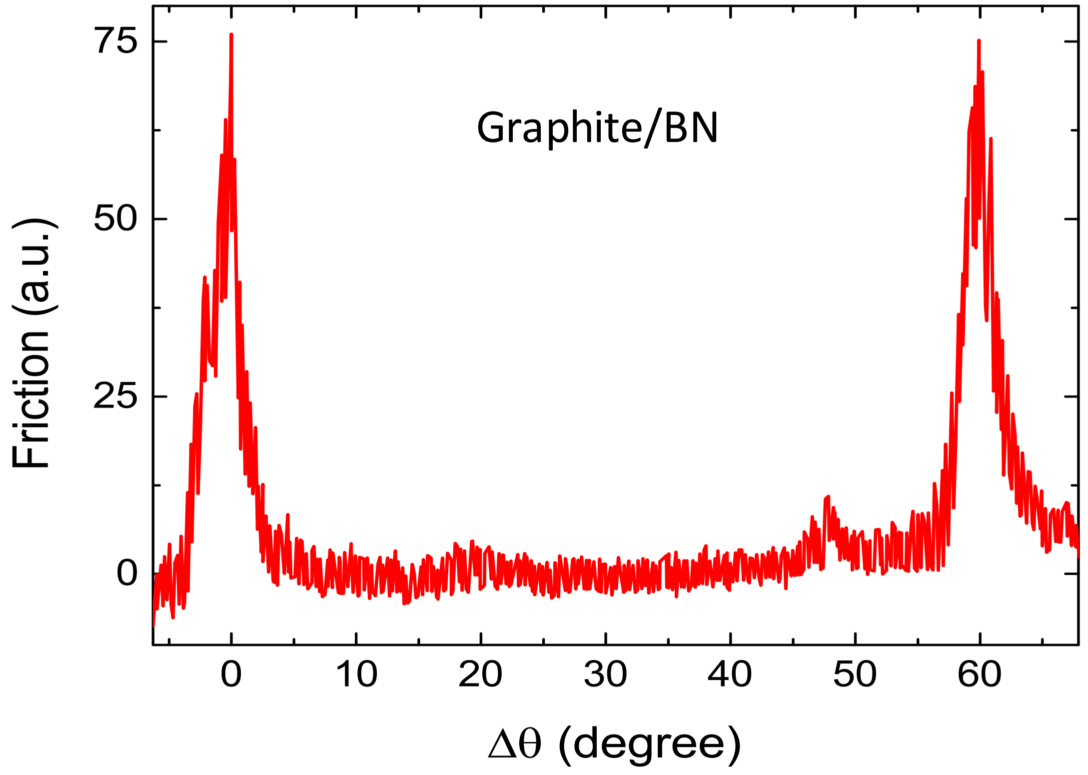
Superlubricity in graphene

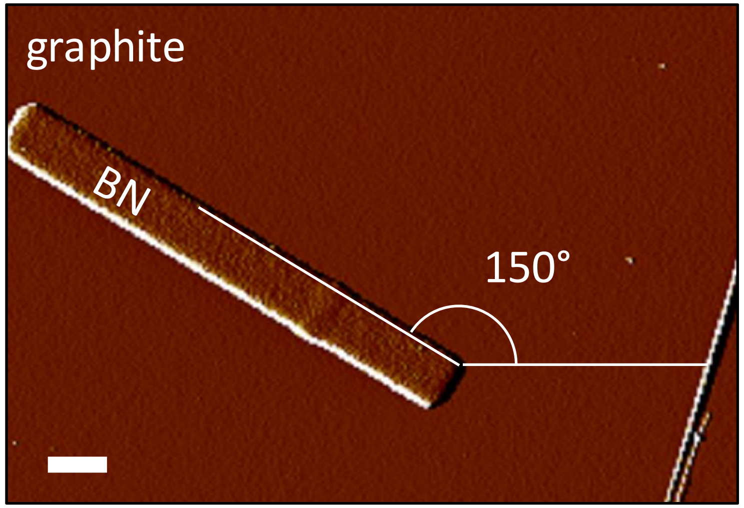


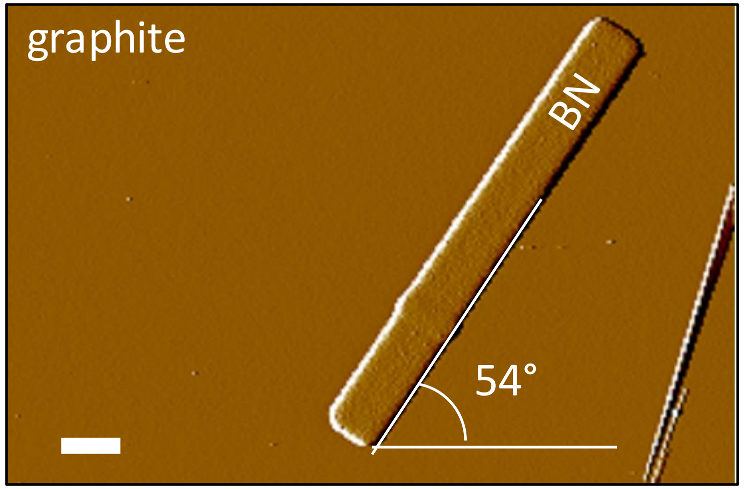
M. Dienwiebel *et al.*, PRL (2004)



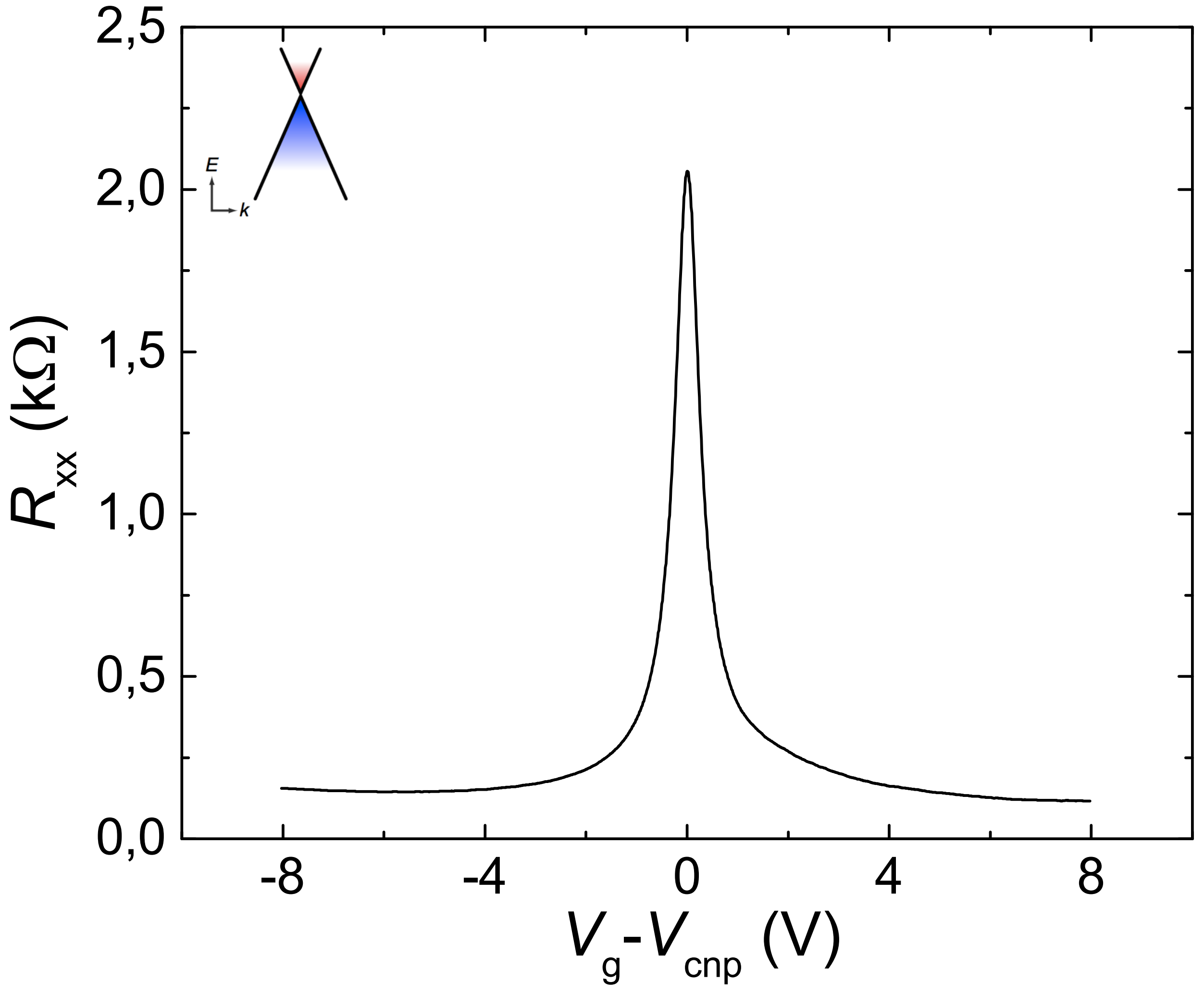
BN on graphene (friction)



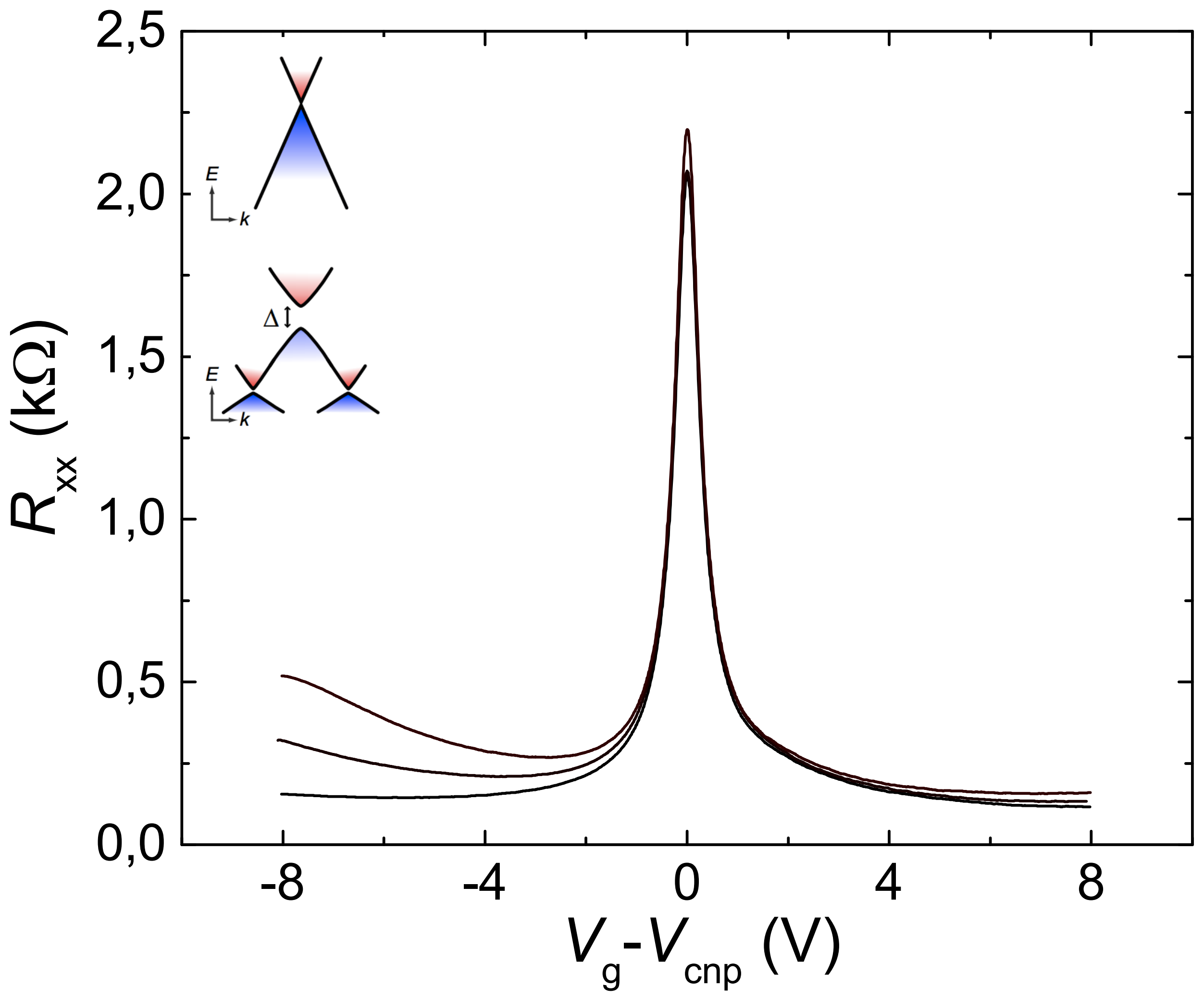




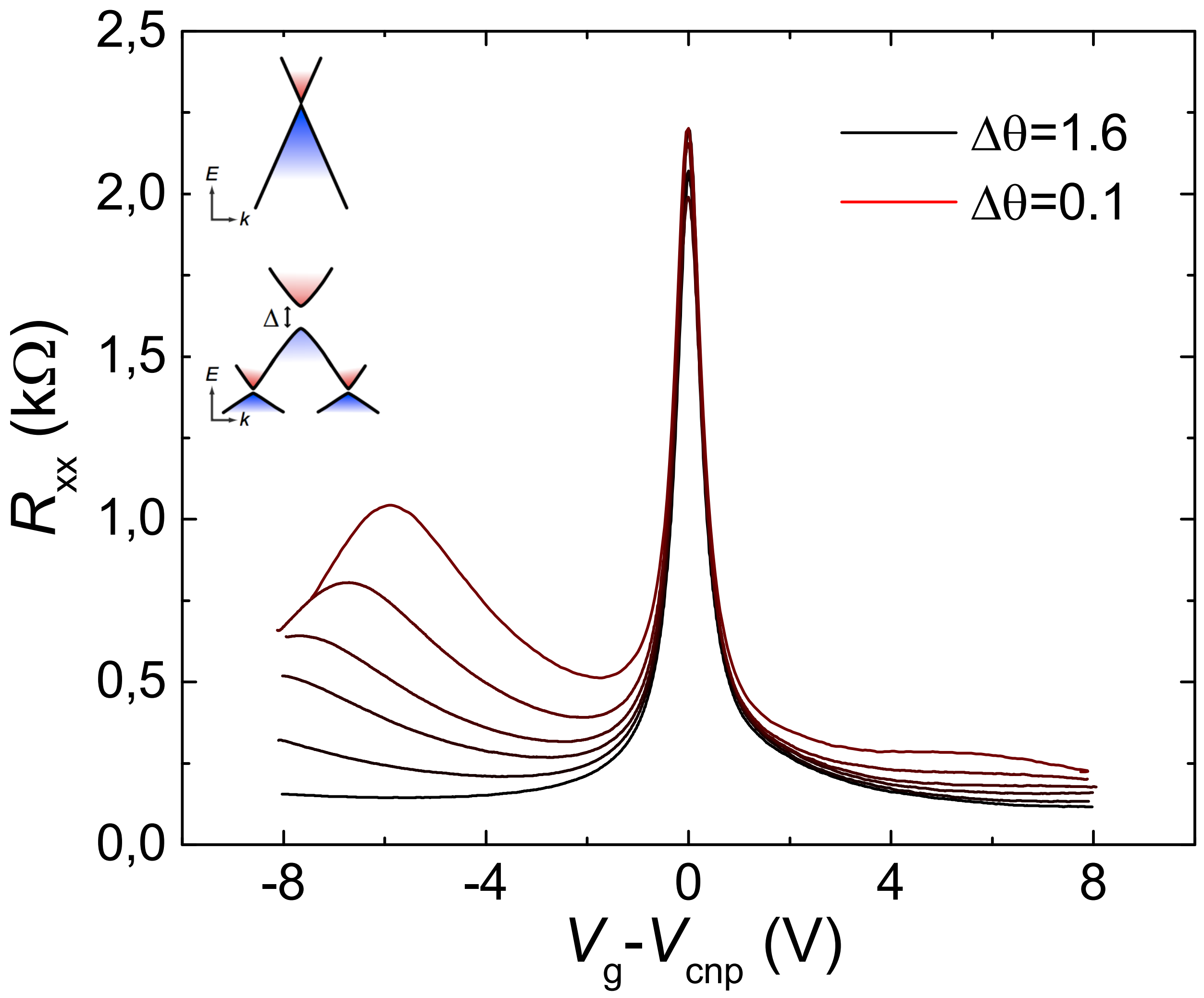
BN on graphene (band structure manipulation)



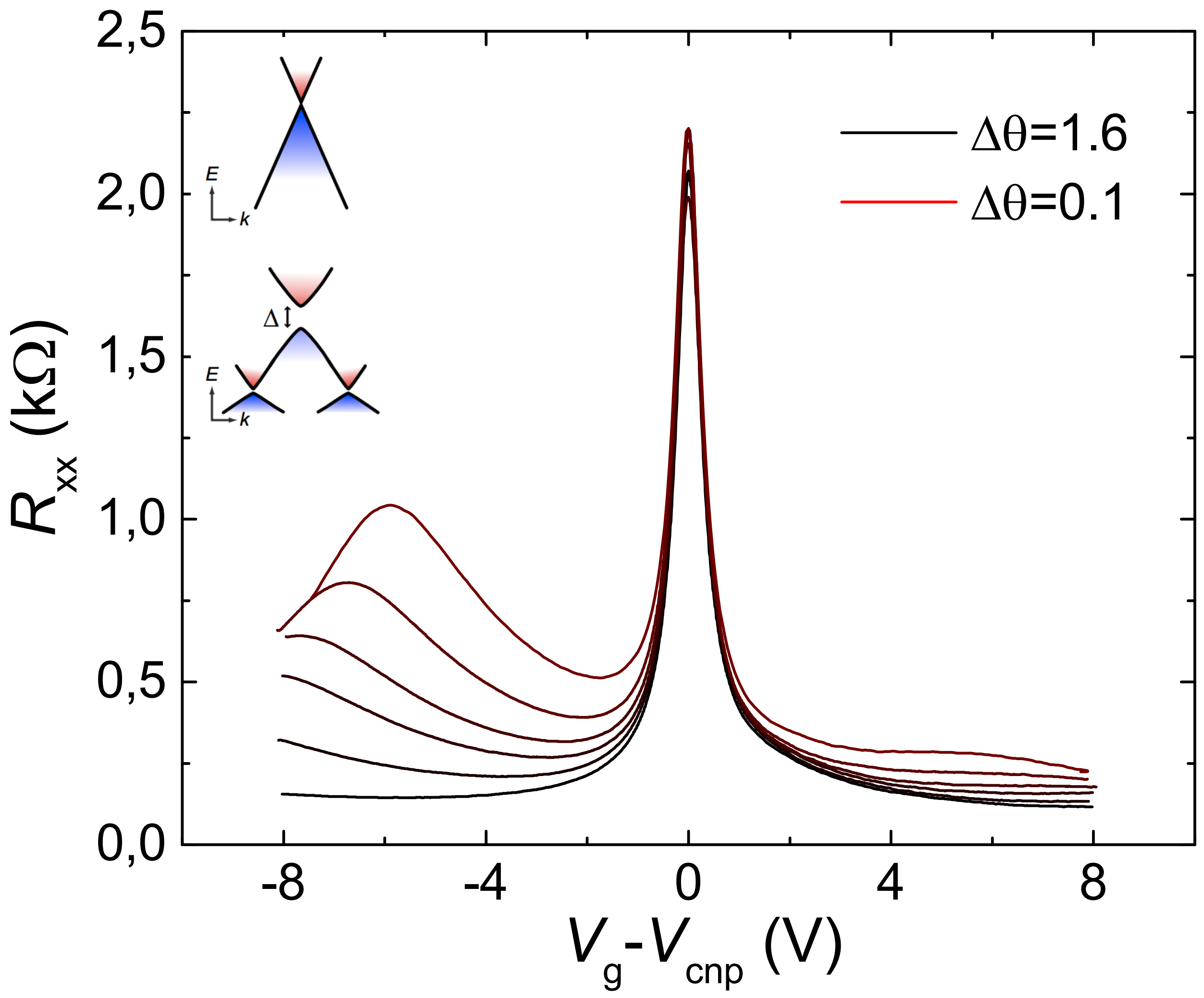
BN on graphene (band structure manipulation)

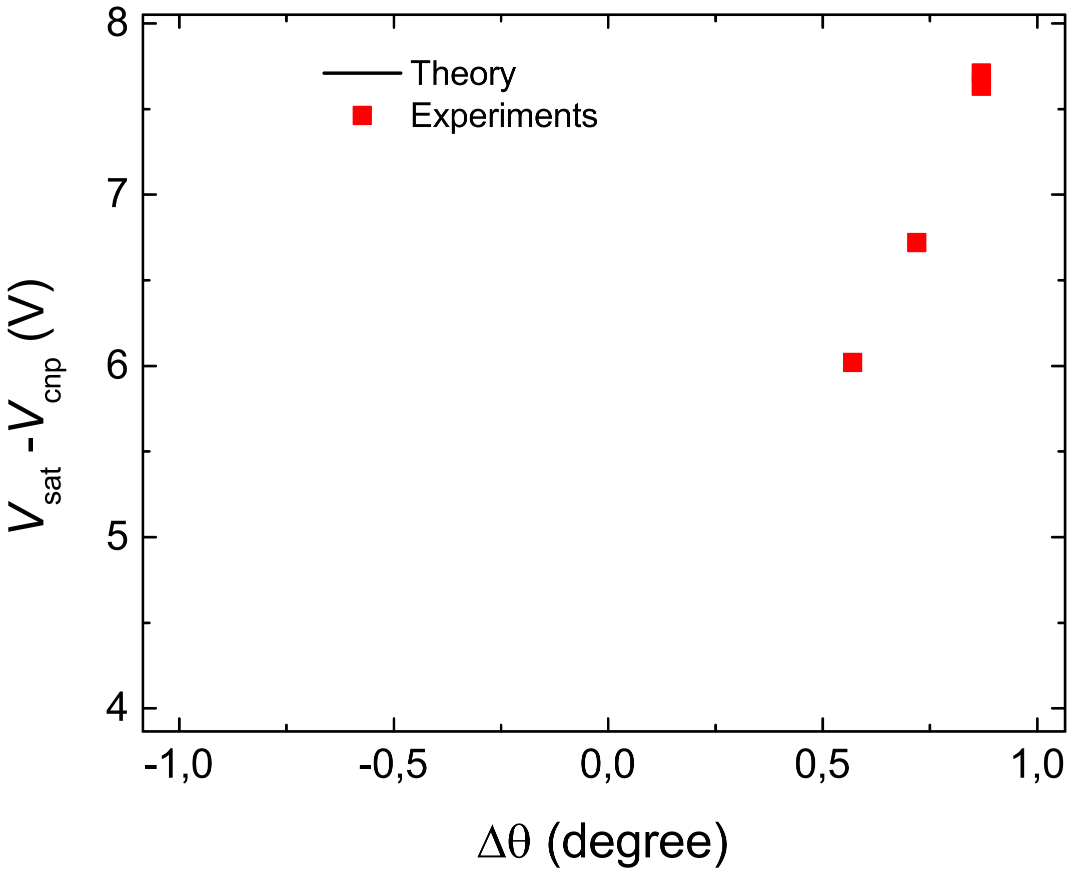


BN on graphene (band structure manipulation)

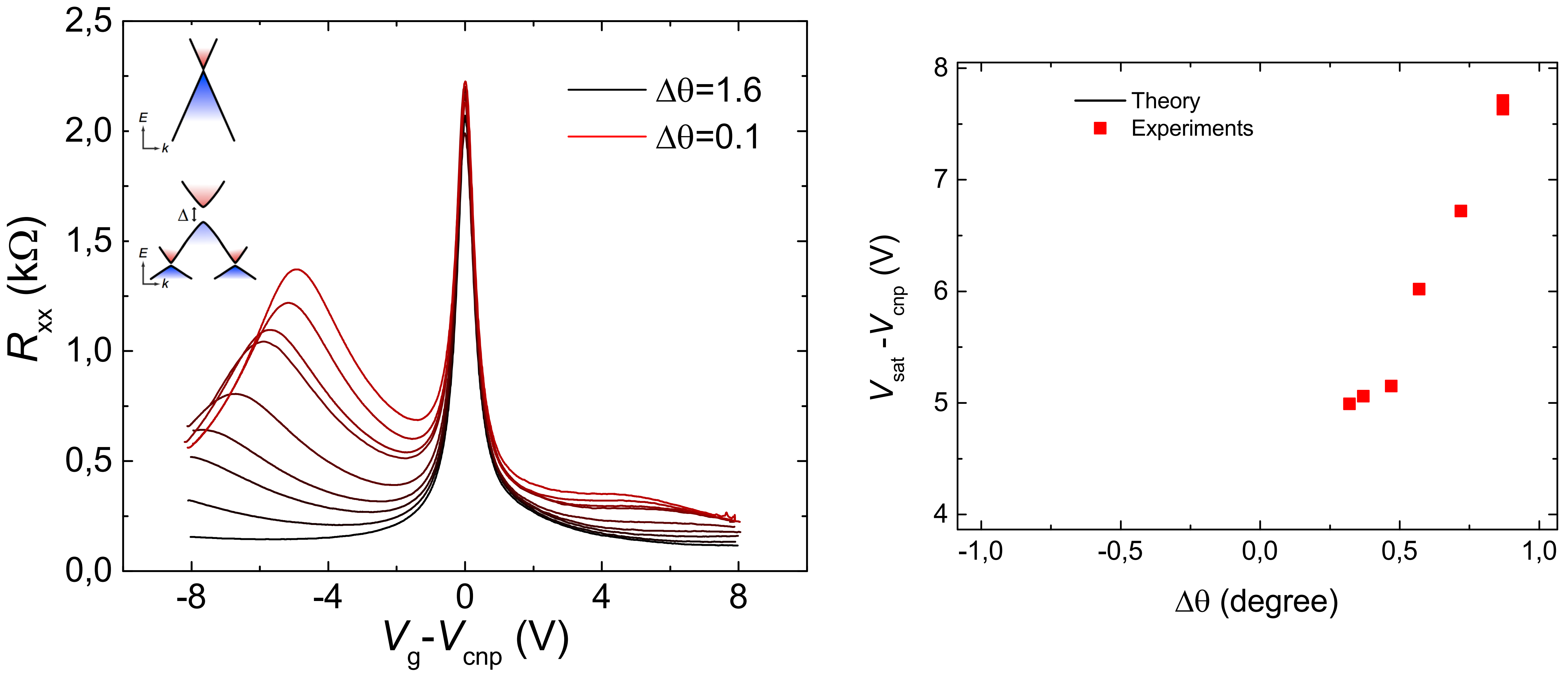


BN on graphene (band structure manipulation)

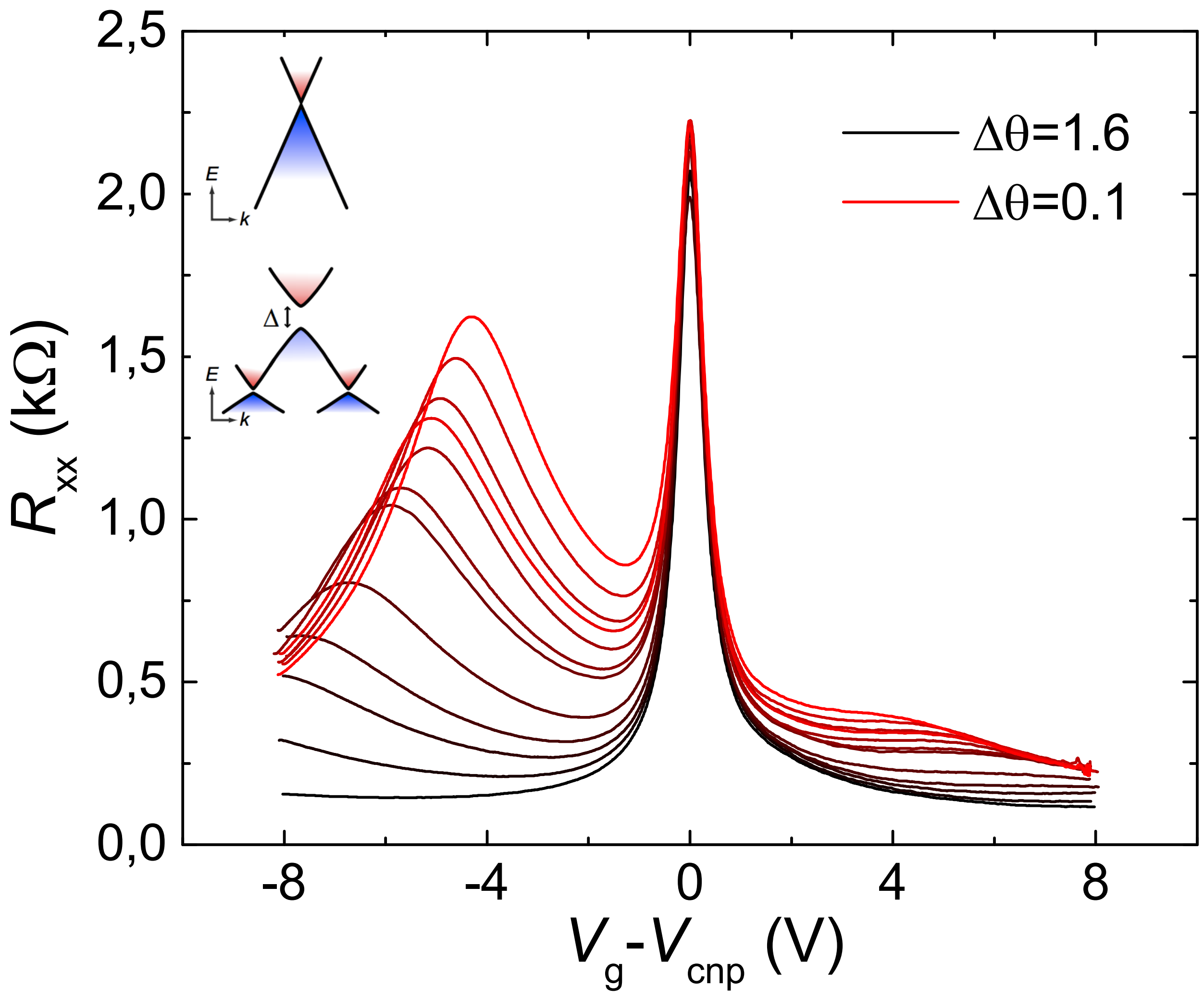


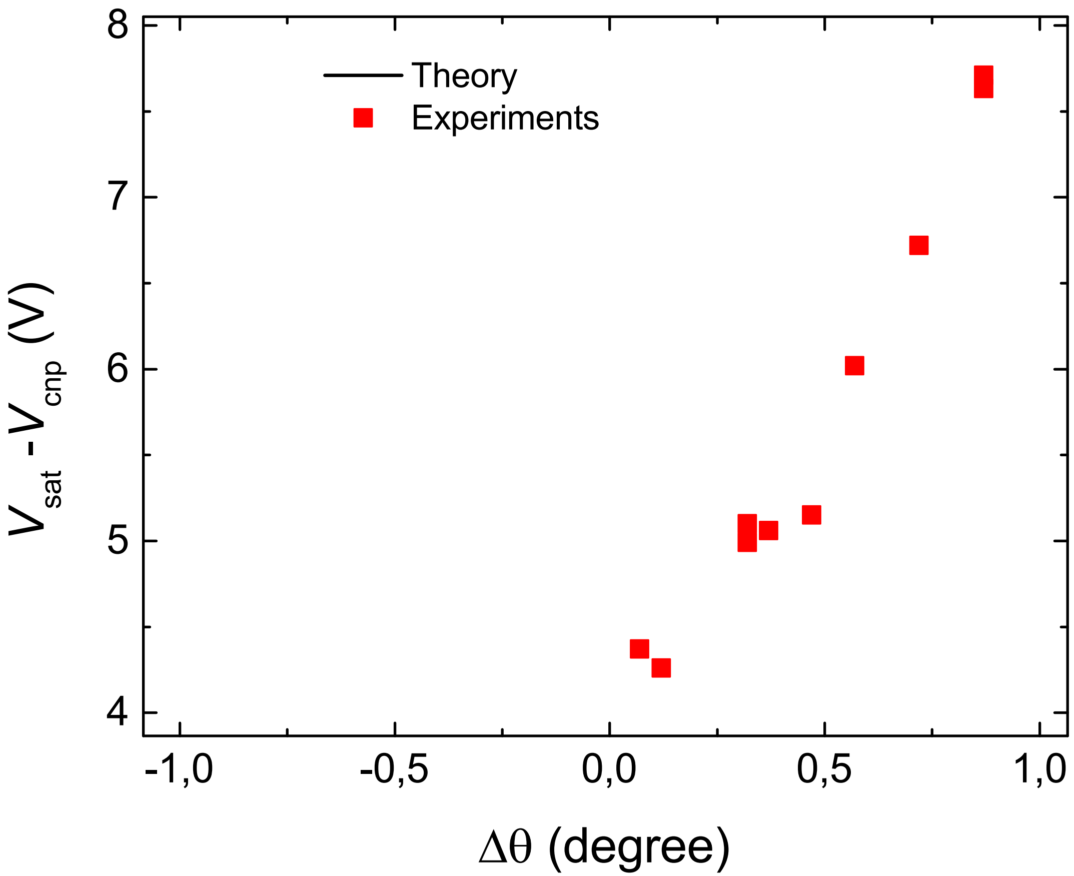


BN on graphene (band structure manipulation)

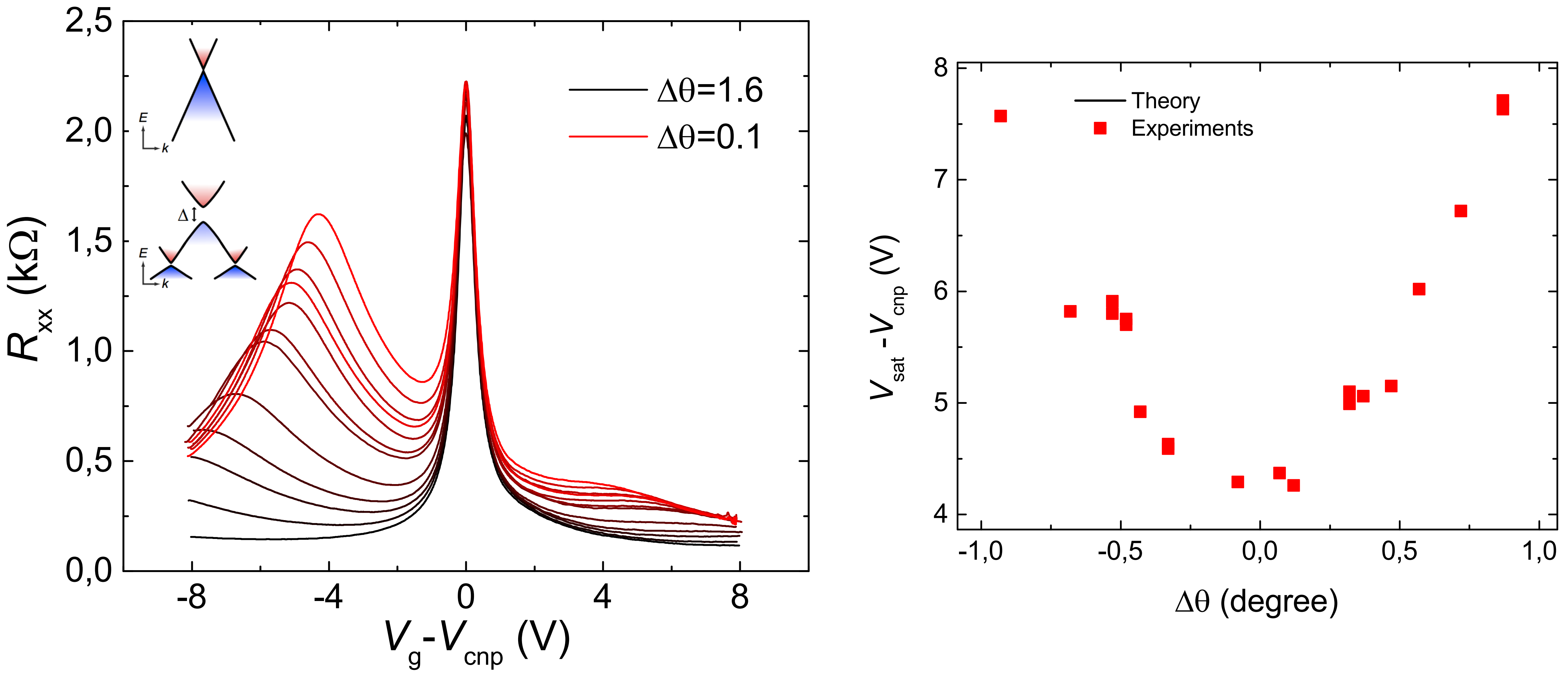


BN on graphene (band structure manipulation)

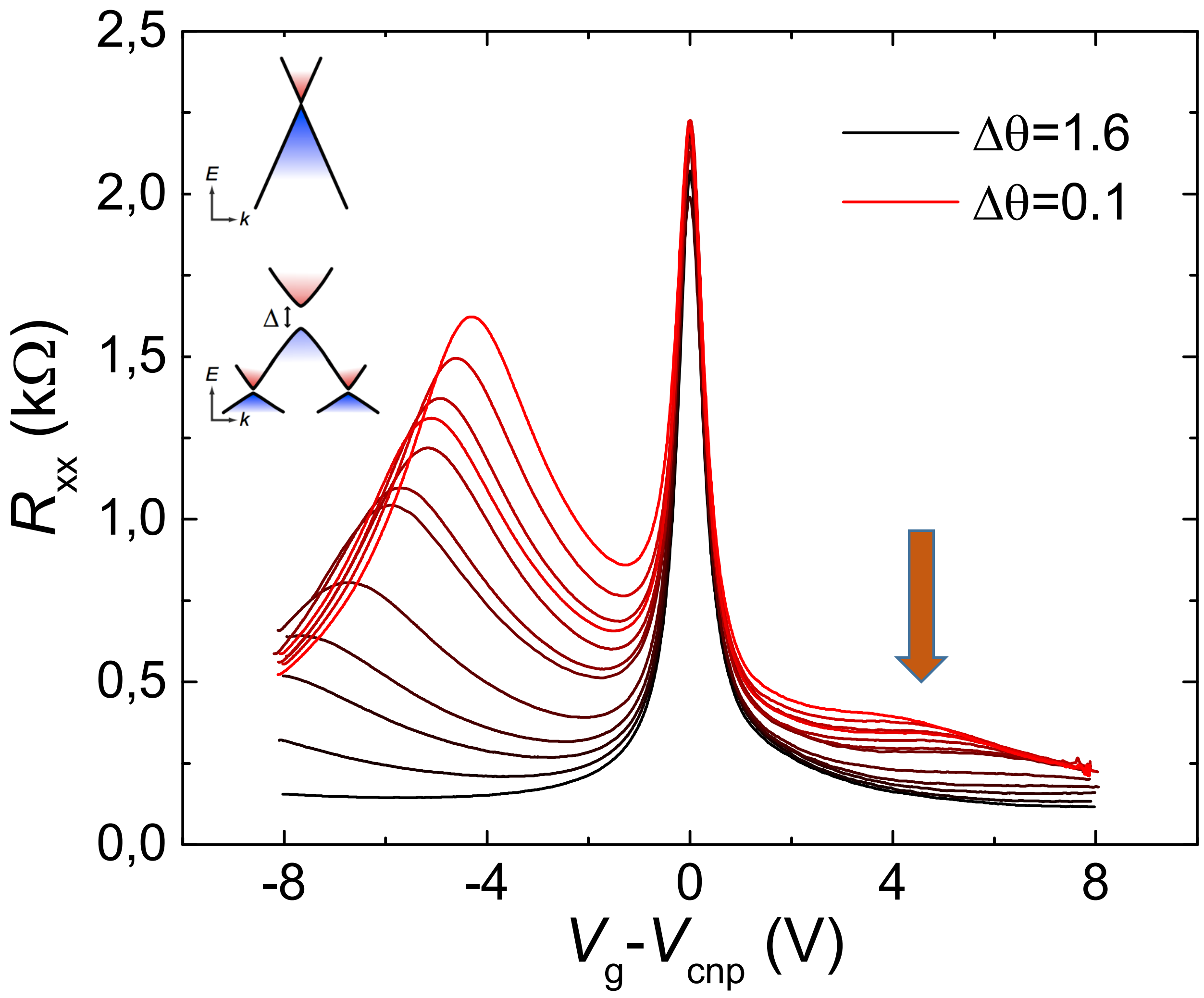


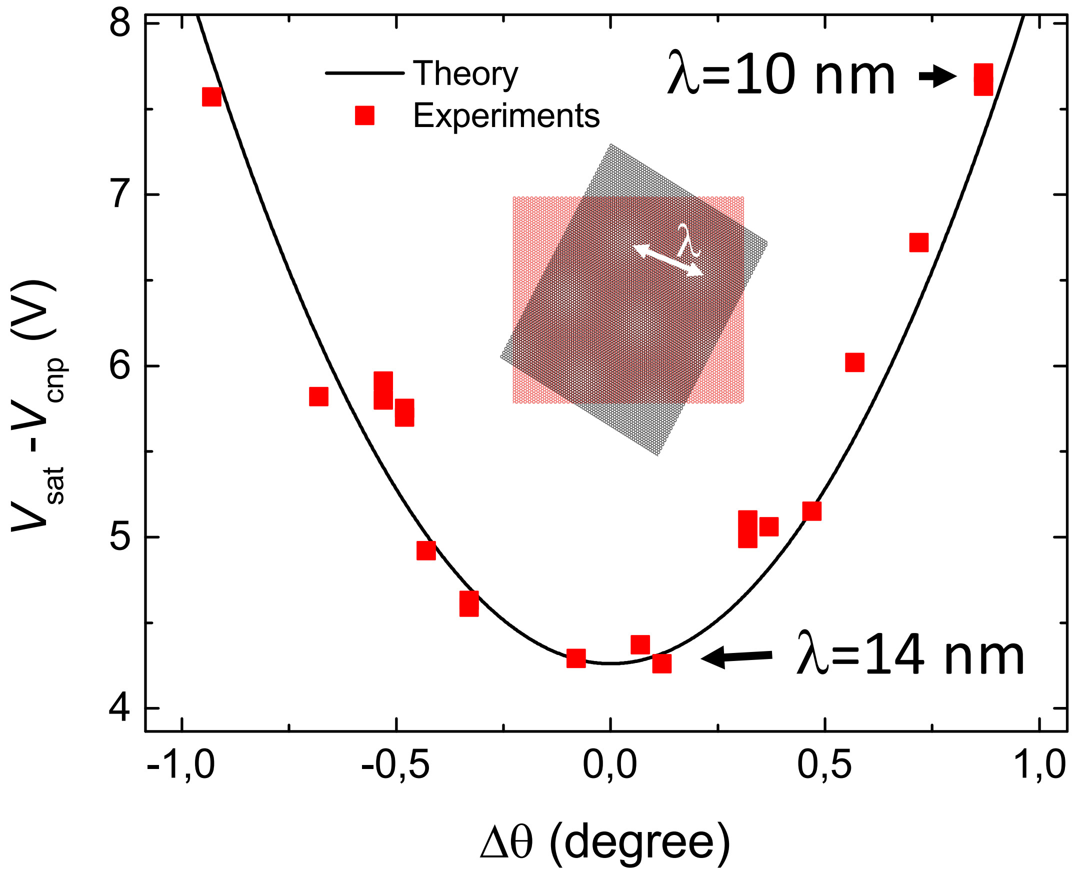


BN on graphene (band structure manipulation)

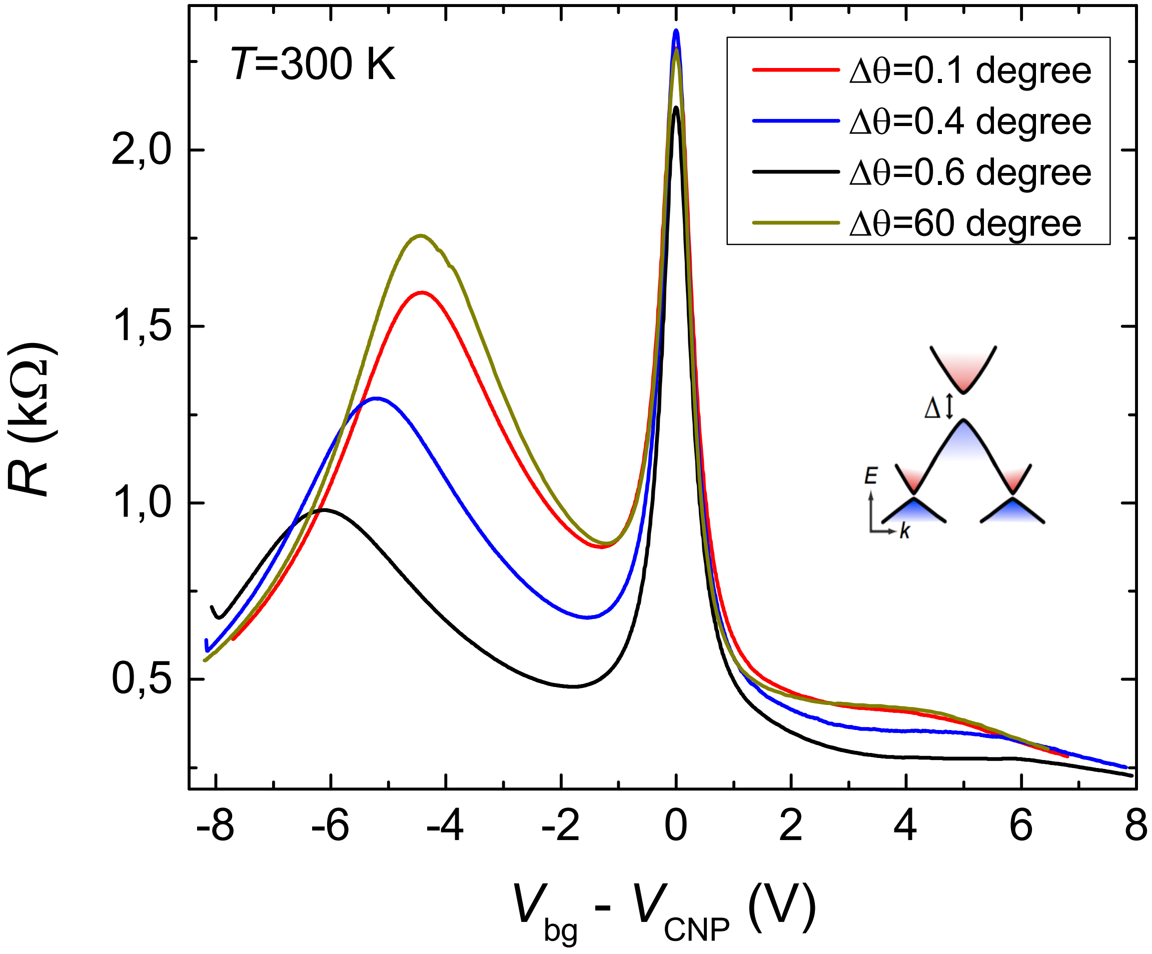


BN on graphene (band structure manipulation)

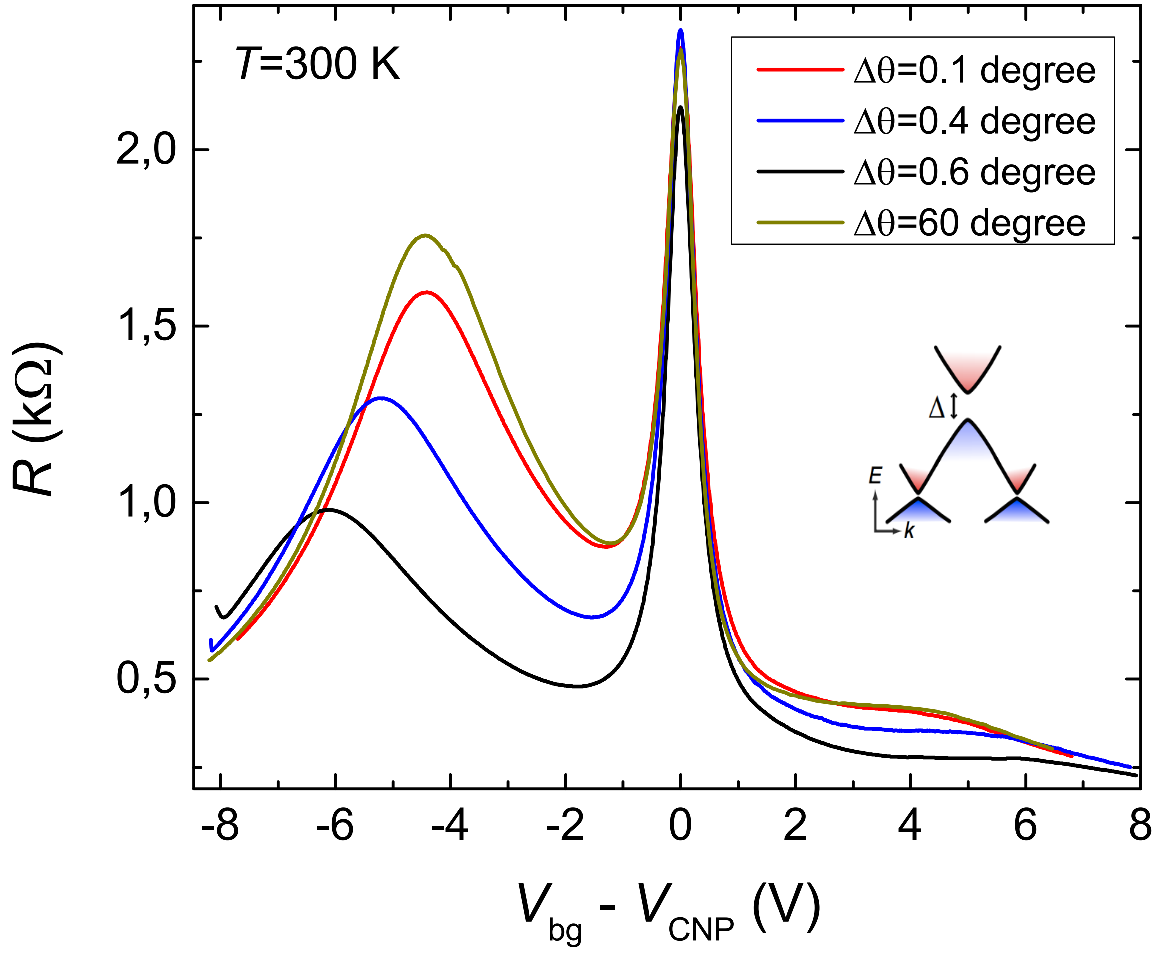


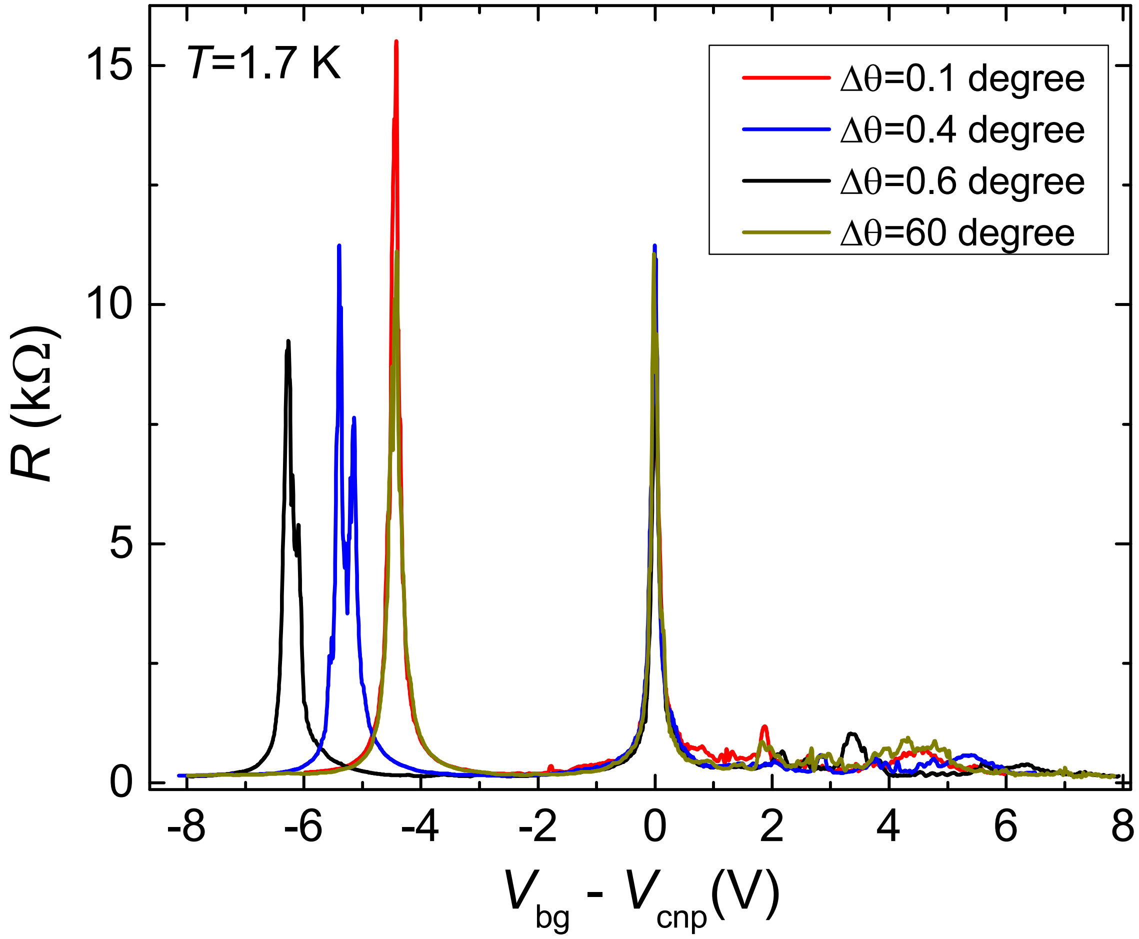


BN on graphene (what is limiting us)

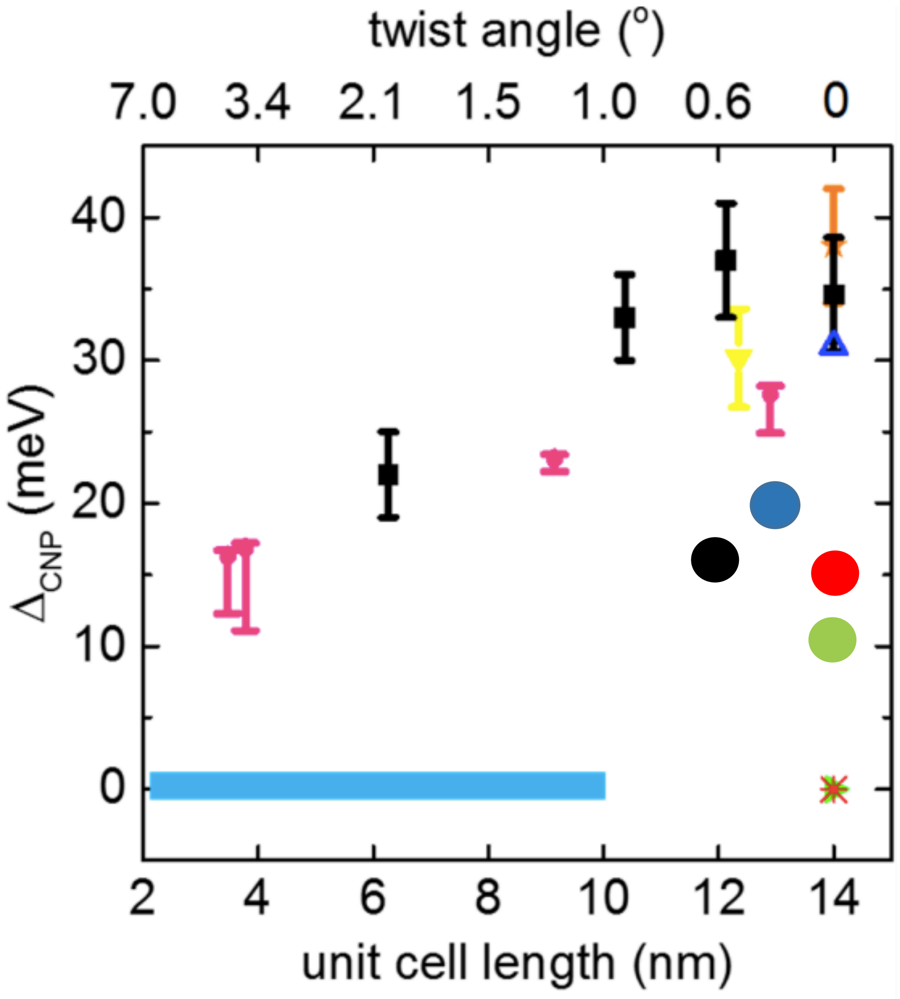


BN on graphene (what is limiting us)

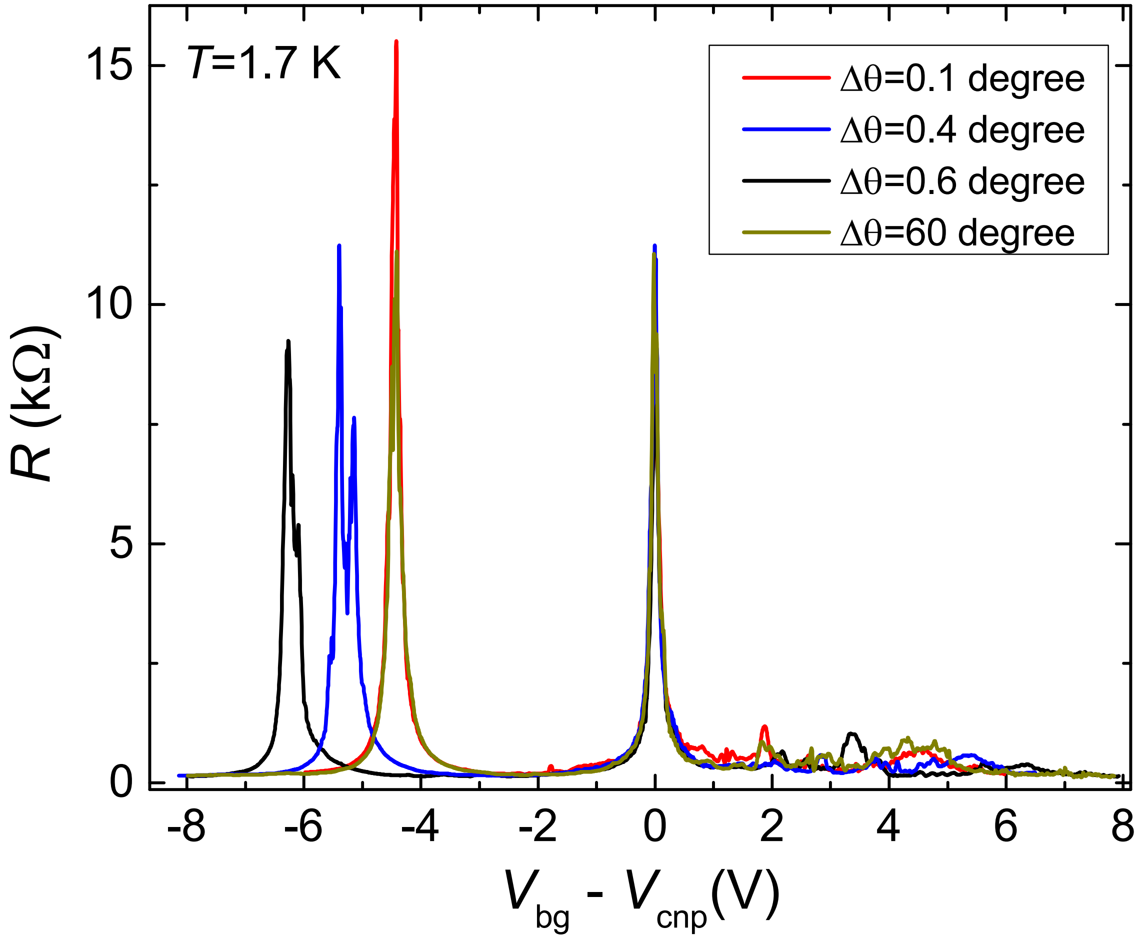




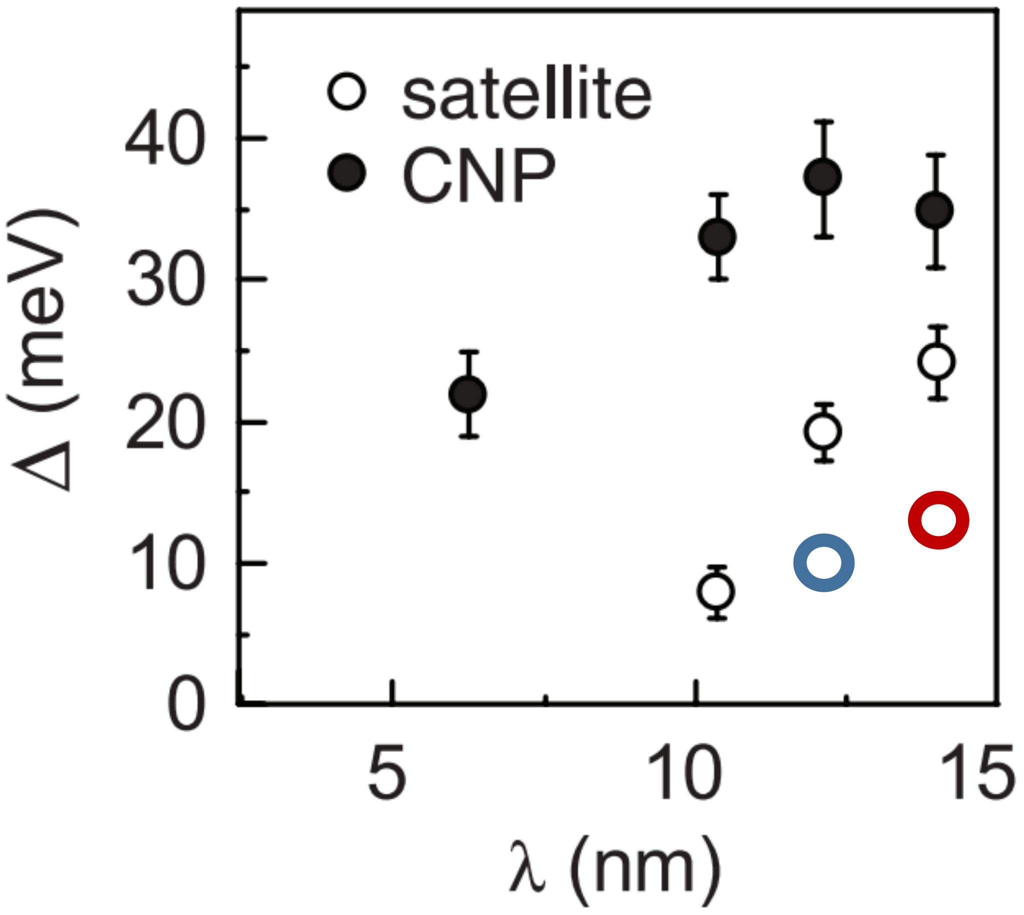
BN on graphene (what is limiting us)



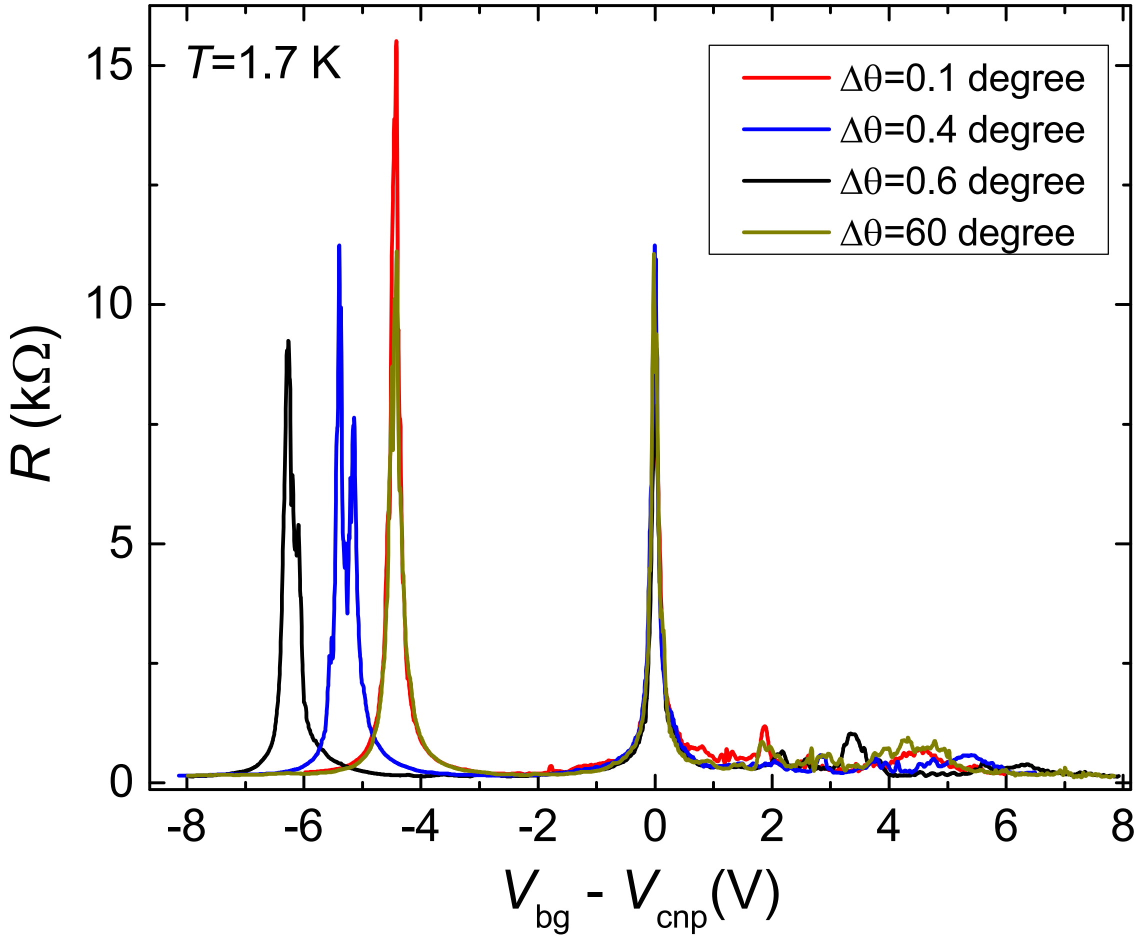
L. Wang *et al.*, Science (2015)



BN on graphene (what is limiting us)

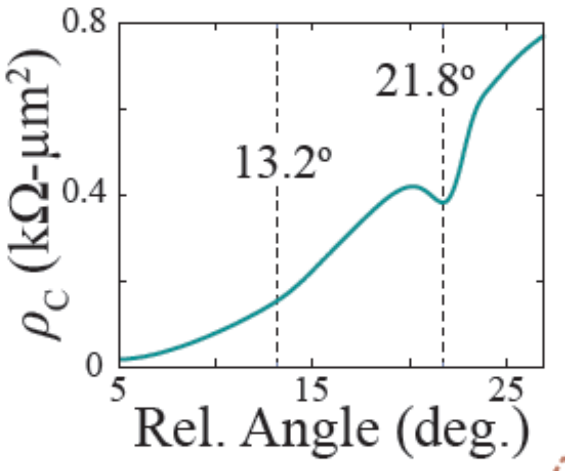


L. Wang *et al.*, Science (2015)

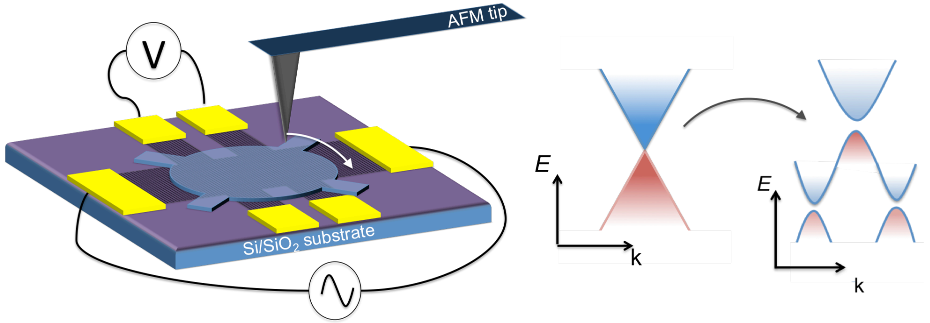


Conclusions

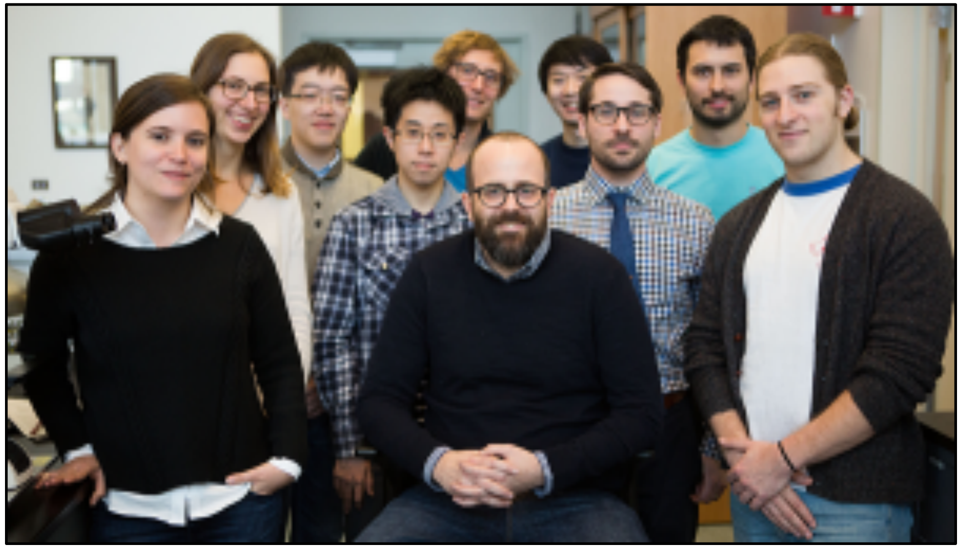
- Precise probe of long range commensurability between the lattices.



- First demonstration of *in-situ* modification of a 2D crystal band structure by controlled rotation of its angular orientation to an encapsulating crystal.



Dean Lab



Tarun Chari

Kursti DeLello

Thanks for your attention