one-dimensional quantum graphene devices

Herre van der Zant

TU Delft
Delft University of Technology
Faculty Of Applied Sciences

KAVLI INSTITUTE of Nanoscience Delft

GRAPHENE FLAGSHIP

MARIE SKŁODOWSKA-CURIE ACTIONS
Research Fellowship Programme

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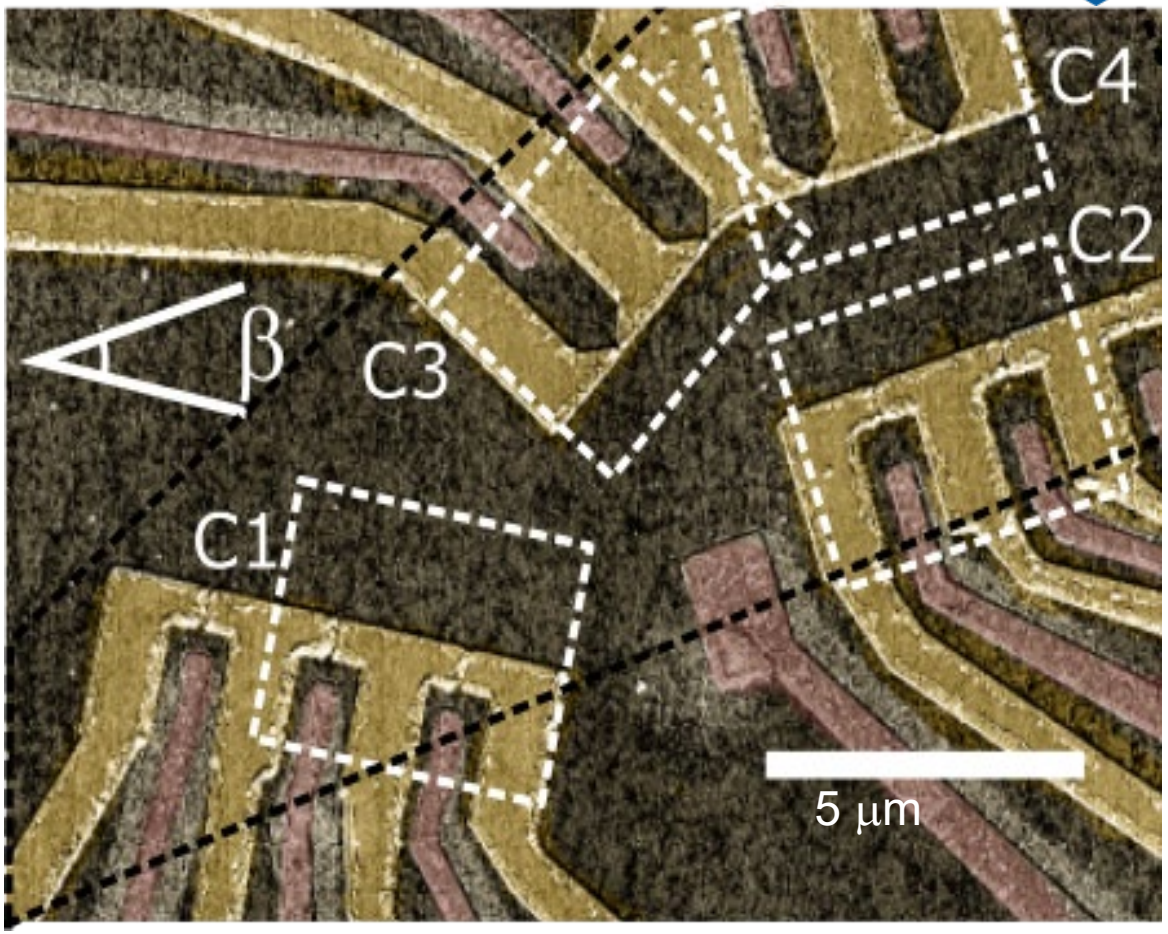
vanderZant lab
https://vanderzantlab.tudelft.nl/

quantum electronics:

- single molecules
- bionanowires
- graphene nanoribbons
- (spin transition) nanoparticles
- 2D materials

nanomechanics:

- 2D magnetic materials
- CDW systems
- Ferroelectrics



What is a quantum device?

(and what would one need to make them?)

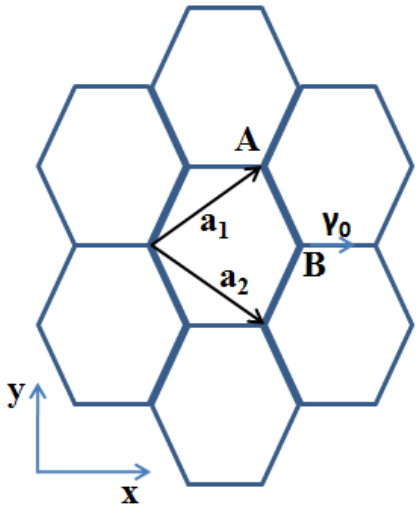
What is a quantum device?

Two levels of quantum-ness:

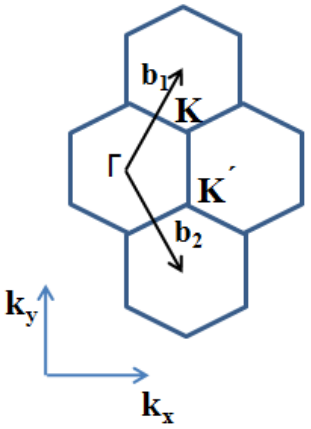
1) Devices that operate using discrete levels or through interference effects involving the electron's phase of the wave function (quantum wires, quantum point contacts, charge sensors, THz (radiation) sensors, Quantum Hall standard, ….)

2) Devices that use a coherent superposition state (quantum coherence, sensors at the quantum limit, qubits, quantum encryption and information processing, …)

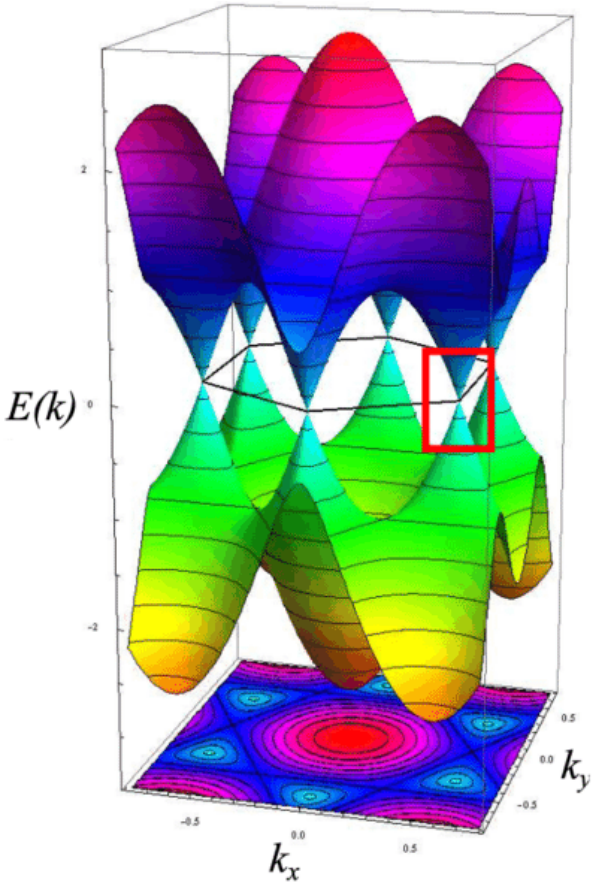
graphene band structure: two Dirac cones, two valleys, K and K’ (or sometimes denoted as -K)

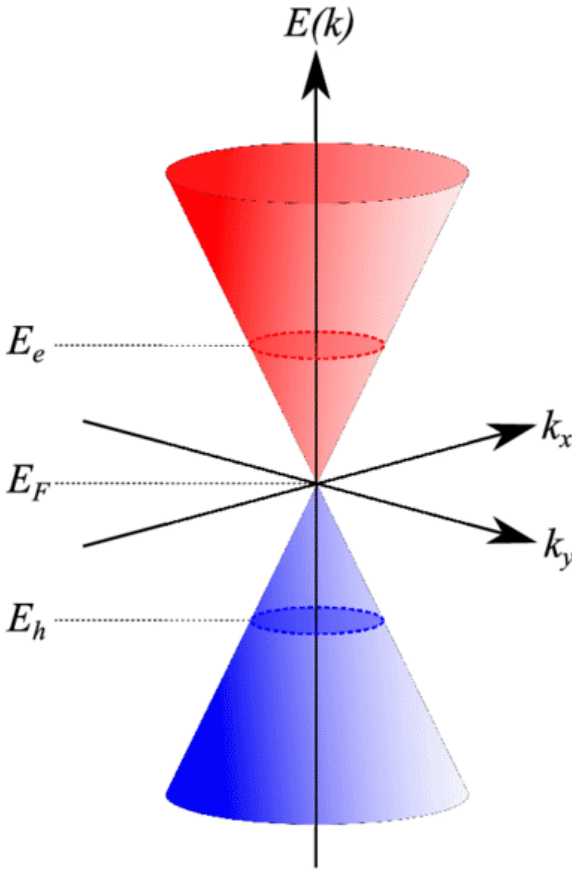


real space



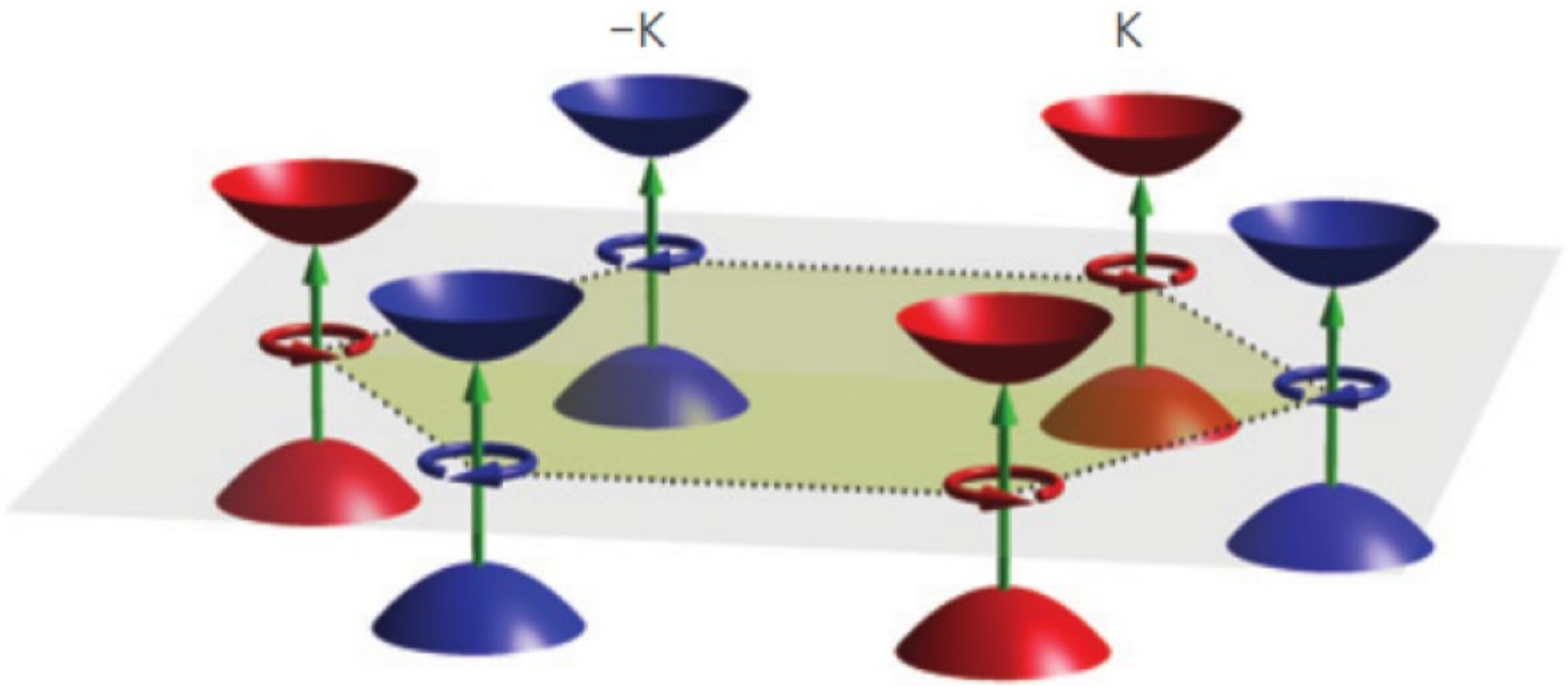
reciprocal space





2D material quantum devices electronics, spintronics, valleytronics

- electronics: electrons as information carriers
- spintronics: electron spin as information carrier
- valleytronics: valley-dependent carrier transport and optoelectronic response



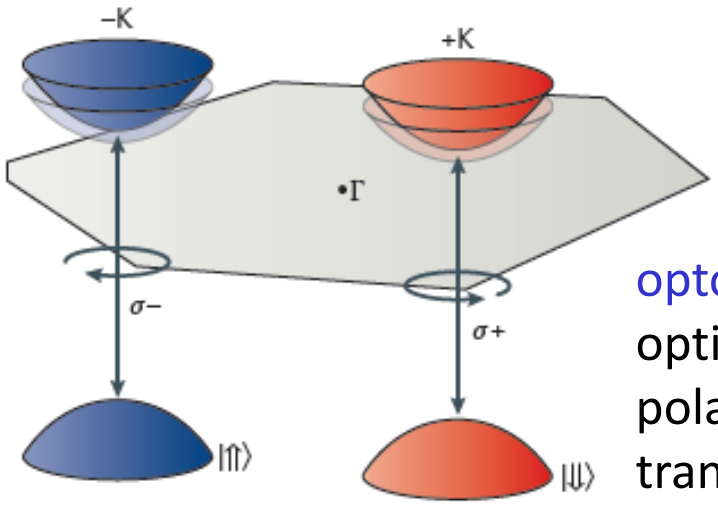
Valleys can be represented by a binary pseudospin behaving like a spin-1/2 system; electrons in the +K valley can be labelled as valley-speudospin up and electrons in the –K with valley-pseudospin down. Carrier polarization in one of the valleys can thus store binary information.

REVIEWS

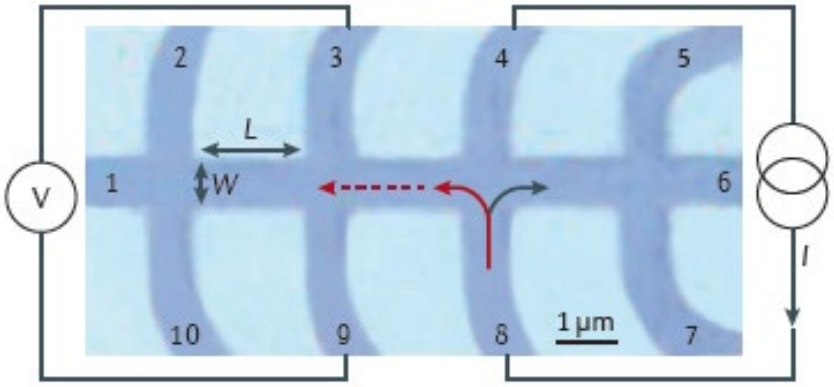
Nature Reviews Materials ***1*** *(2016)* 16055

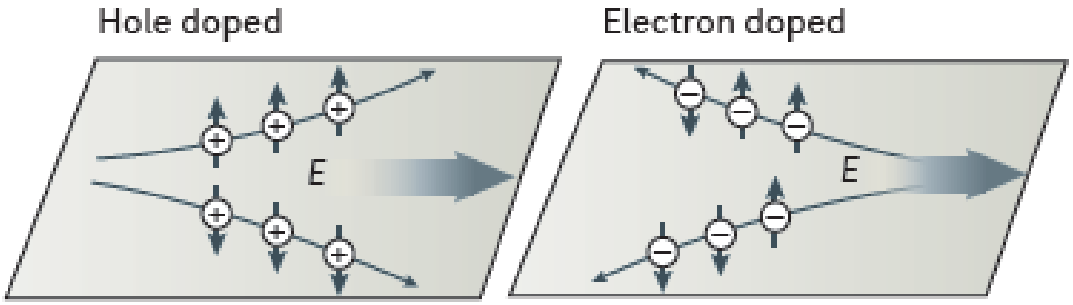
Valleytronics in 2D materials

John R. Schaibley[1], Hongyi Yu[2], Genevieve Clark[3], Pasqual Rivera[1], Jason S. Ross[3], Kyle L. Seyler[1], Wang Yao[2] and Xiaodong Xu[1,3]



optoelectronics: valley dependent optical selection rules, e.g. left circular polarized light couples to interband transitions in the –K valley



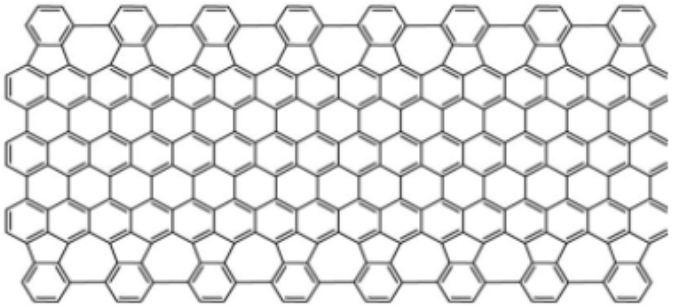


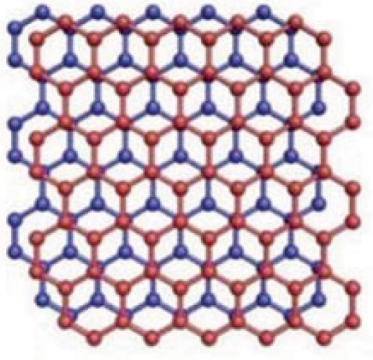
valley Hall effect with opposite Berry curvature (acts as an effective magnetic field) for the different valleys in presence of broken inversion symmetry

1D graphene quantum devices different approaches, different platforms

• graphene nanoribbons: bottom-up defined atomically precise

ac-zigzag
APR

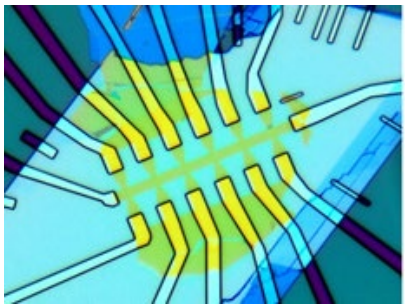




AB-stacked
bilayer-graphene

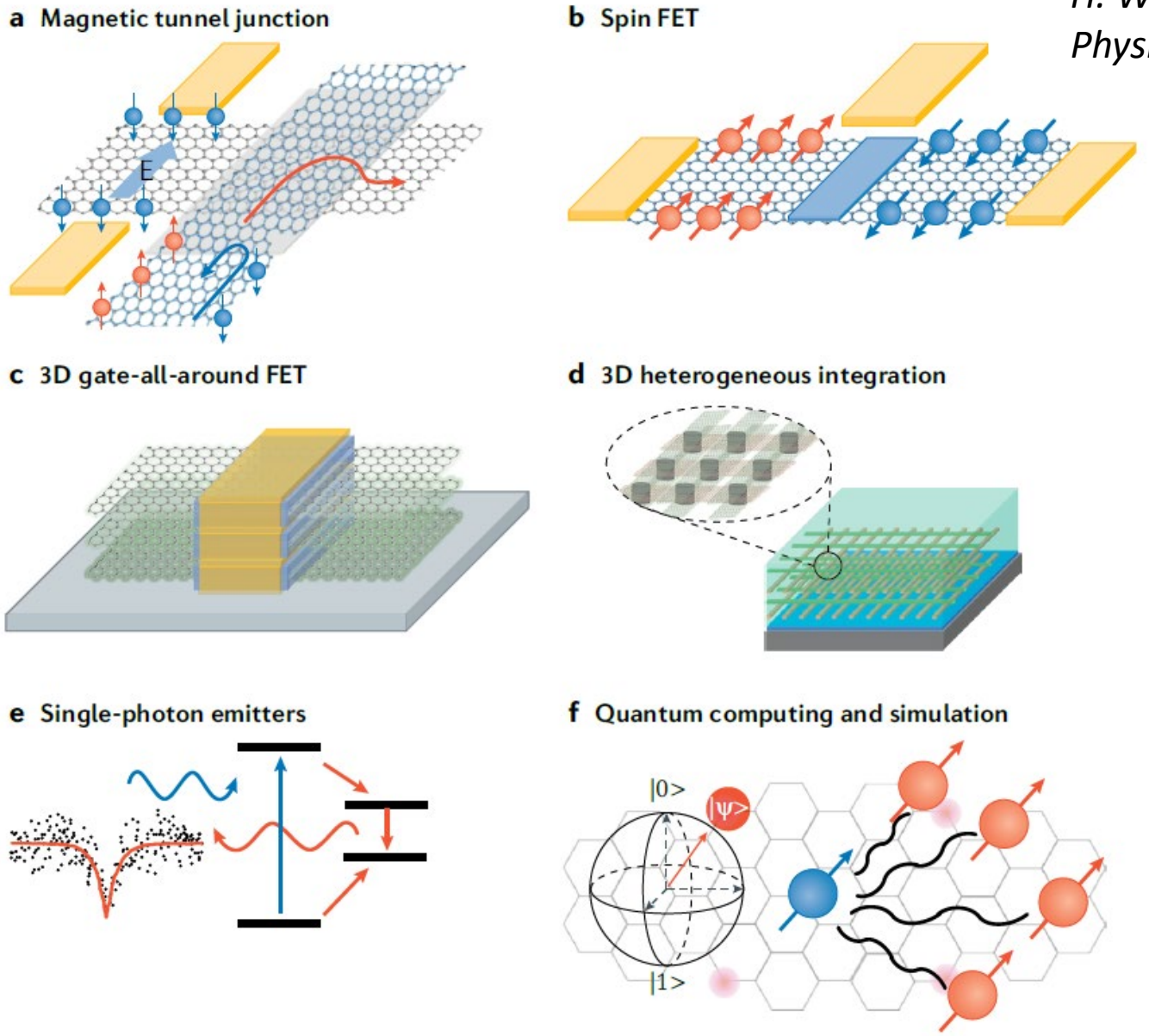
• bi-layer graphene (not twisted): band gap and electrostatically defined device geometries

• quantum Hall states in heterostructures with graphene to introduce broken inversion symmetry



graphene nanoribbons for quantum electronics and spintronics

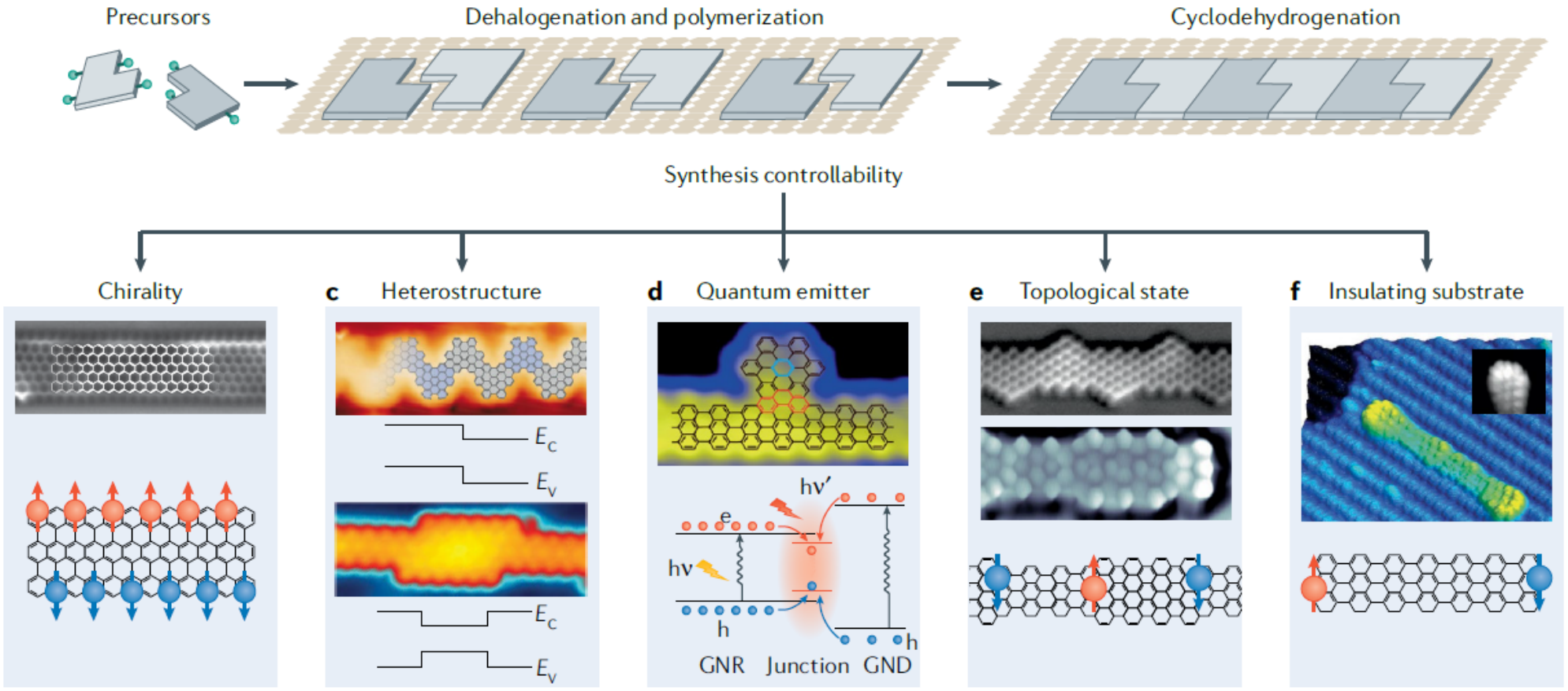
*H. Wang et al., Nature Reviews Physics **3** (2021) 791–802*



bottom-up atomically precise graphene nanoribbons

H. Wang et al., Nature Reviews Physics ***3*** *(2021) 791–802*

to avoid irregular edges introduced in top-down etched devices



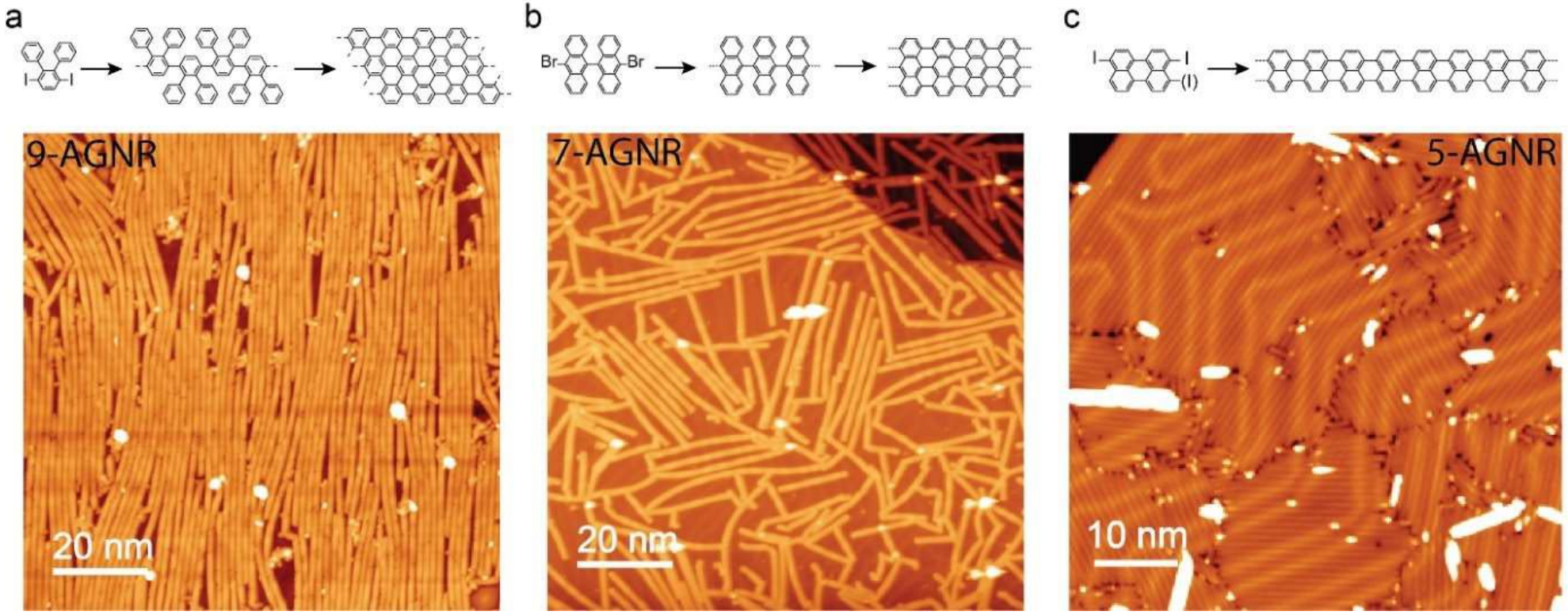
grown in ultra-high vacuum on gold surfaces but for a device one has to (i) transfer the nanoribbons from the substrates made in vacuum and (ii) make contacts to them

non-functionalized graphene nanoribbons

Armchair GNRs can be divided into three families, depending on whether their width is:

3p (medium bandgap), 3 p + 1 (large bandgap) or 3p+2 (small bandgap) where p is an integer.

Within each family, the bandgap increases monotonically as the width decreases.

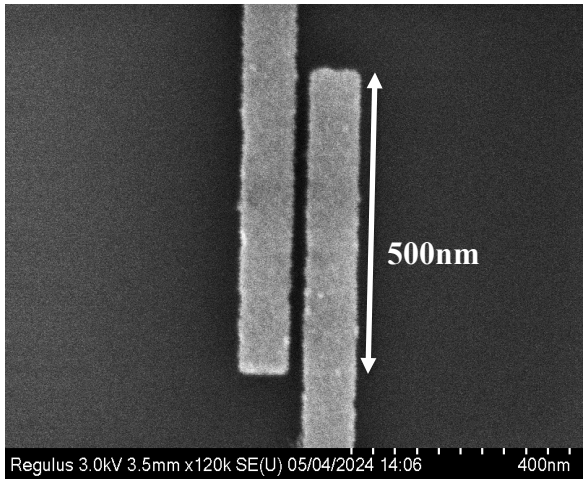


our target: 9-atom wide graphene nanoribbon (armchair): lengths (up to 40 -50 nm) and relatively stable; bandgap: 1.4 eV

nanoribbons grown at EMPA: G. Borin Barin and R. Fasel

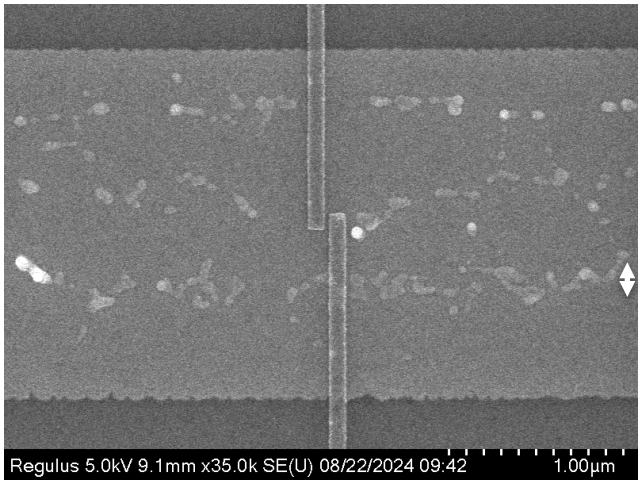
pre-patterned electrodes

different contact and gate geometries and different metals (Pt, MoRe, Pd)



global back gate

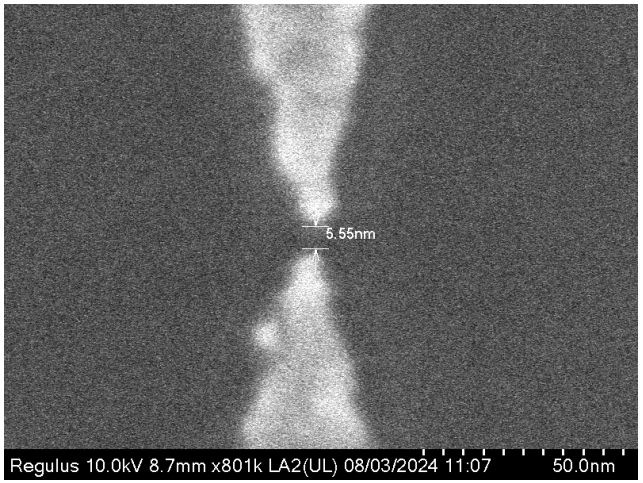
large overlap to contact several APRs in parallel



local back gate

large overlap to contact several APRs in parallel

as we found that the global gate can be very inefficient

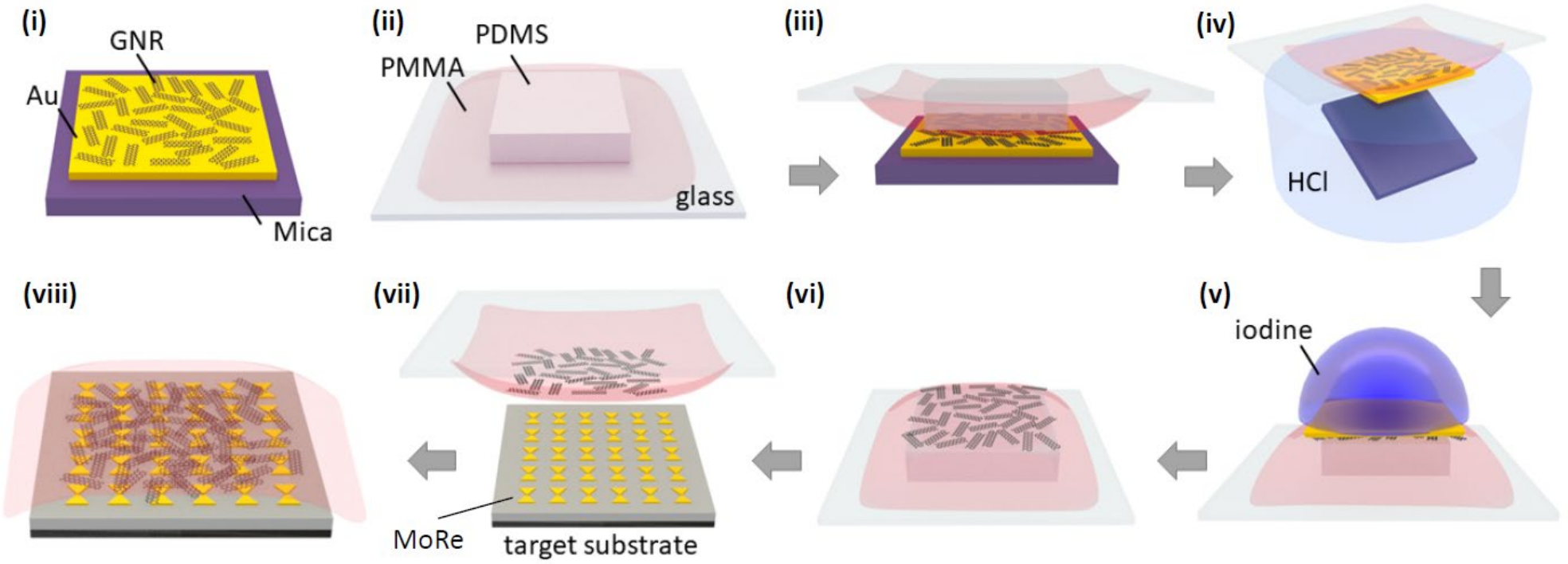


global/local back gate

small overlap to contact a single APR

transferring atomically precise graphene nanoribbons

a PMMA-membrane transfer method was developed that avoids contact of the target substrate with liquids; GNRs can then be deposited in an aligned manner using a dry transfer stage



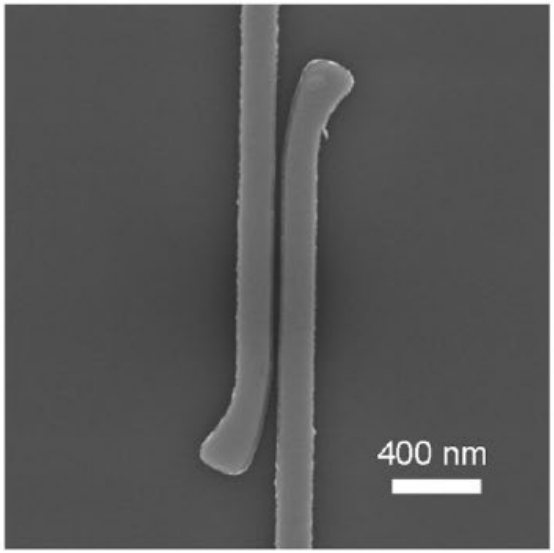
MoRe Electrodes with 10 nm Nanogaps for Electrical Contact to Atomically Precise Graphene Nanoribbons

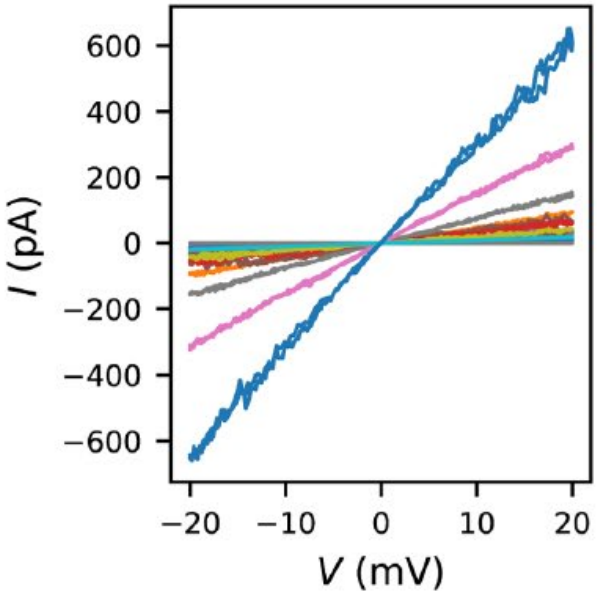
Damian Bouwmeester,* Talieh S. Ghiasi, Gabriela Borin Barin, Klaus Müllen, Pascal Ruffieux, Roman Fasel, and Herre S. J. van der Zant

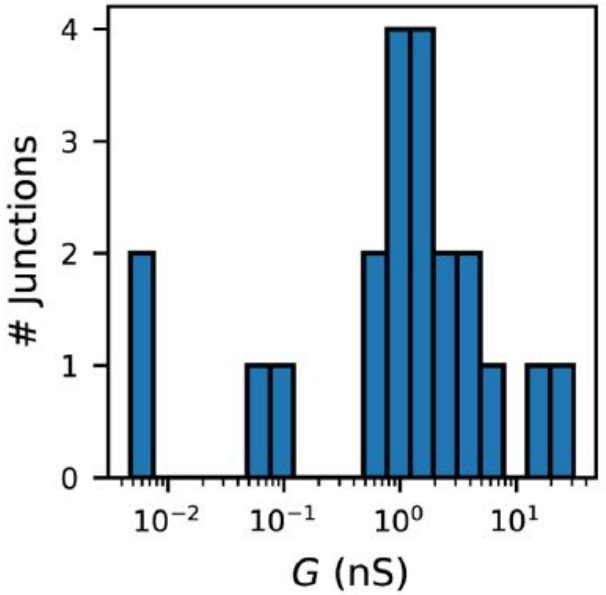
ACS APPLIED NANO MATERIALS

bottom contacting graphene nanoribbons

use same strategy as for contacting carbon nanotubes (MoRe and Pd as electrodes)







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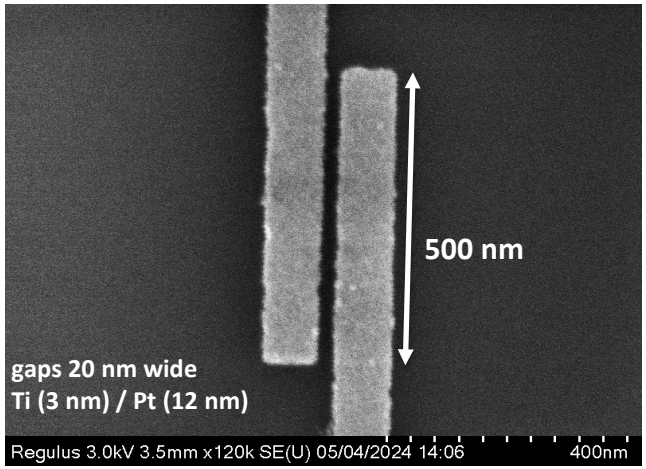
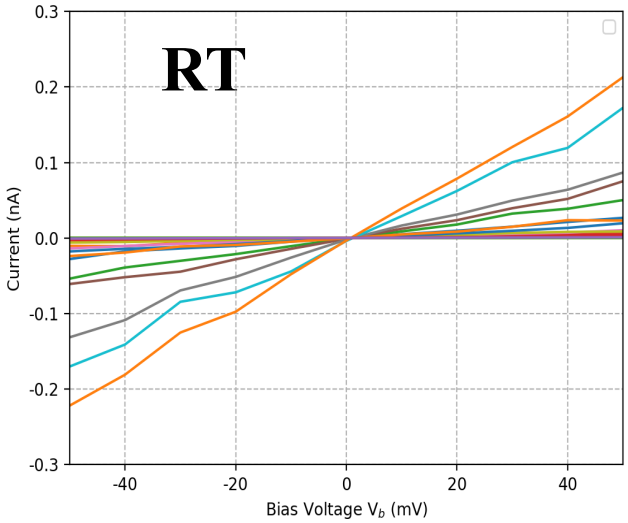
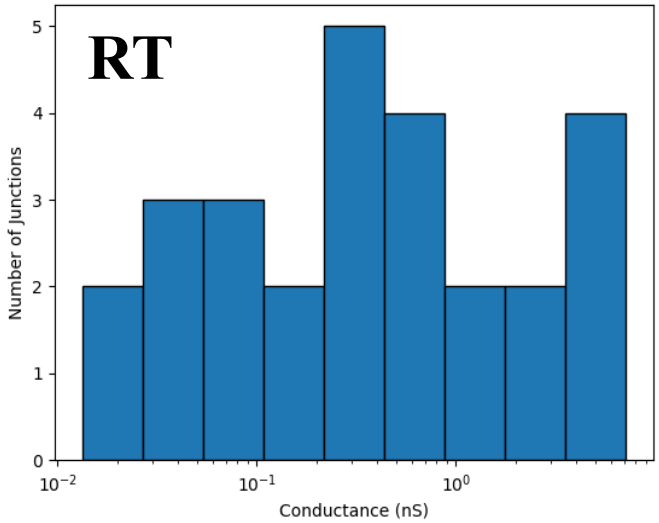
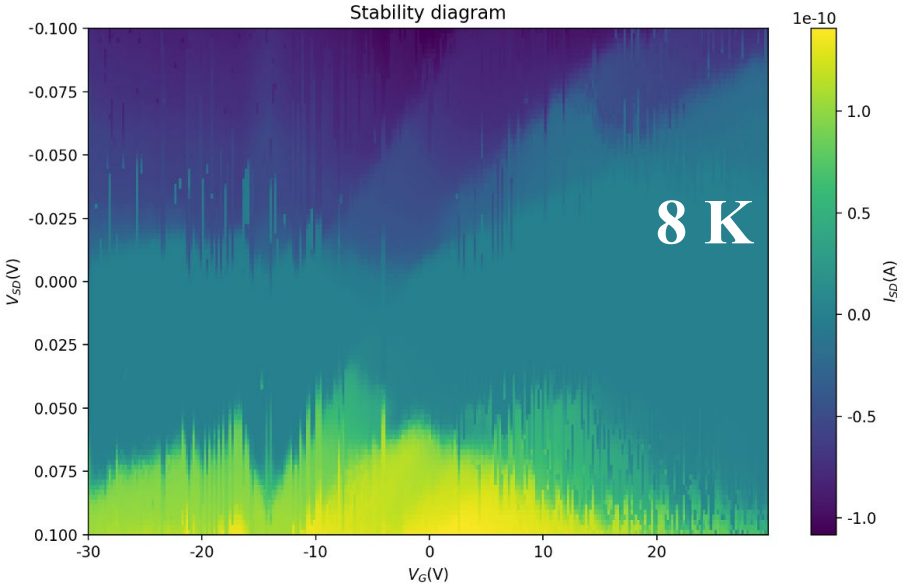
ACS APPLIED NANO MATERIALS

Pt bottom contacting graphene nanoribbons





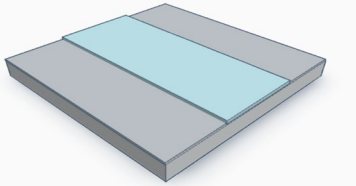




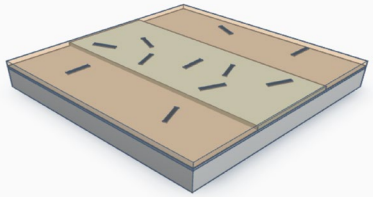
- successfully captured 9AGNRs by using pre-patterned electrodes
- IV measurements can be performed at room and low temperatures
- the long gaps capture multiple GNRs in between, leading to multi-dot behaviour (with GNRs in series) in the stability diagram at low temperatures

top contacts with sub-10 nm spacing

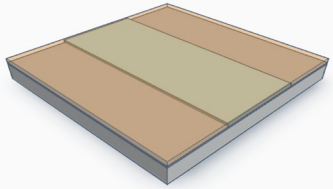
local back gate: 1 nm Ti and 7 nm Pd



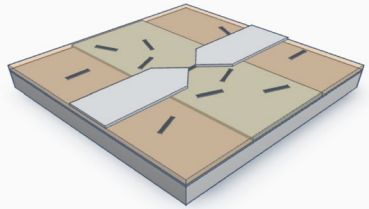
9-AGNRs are transferred

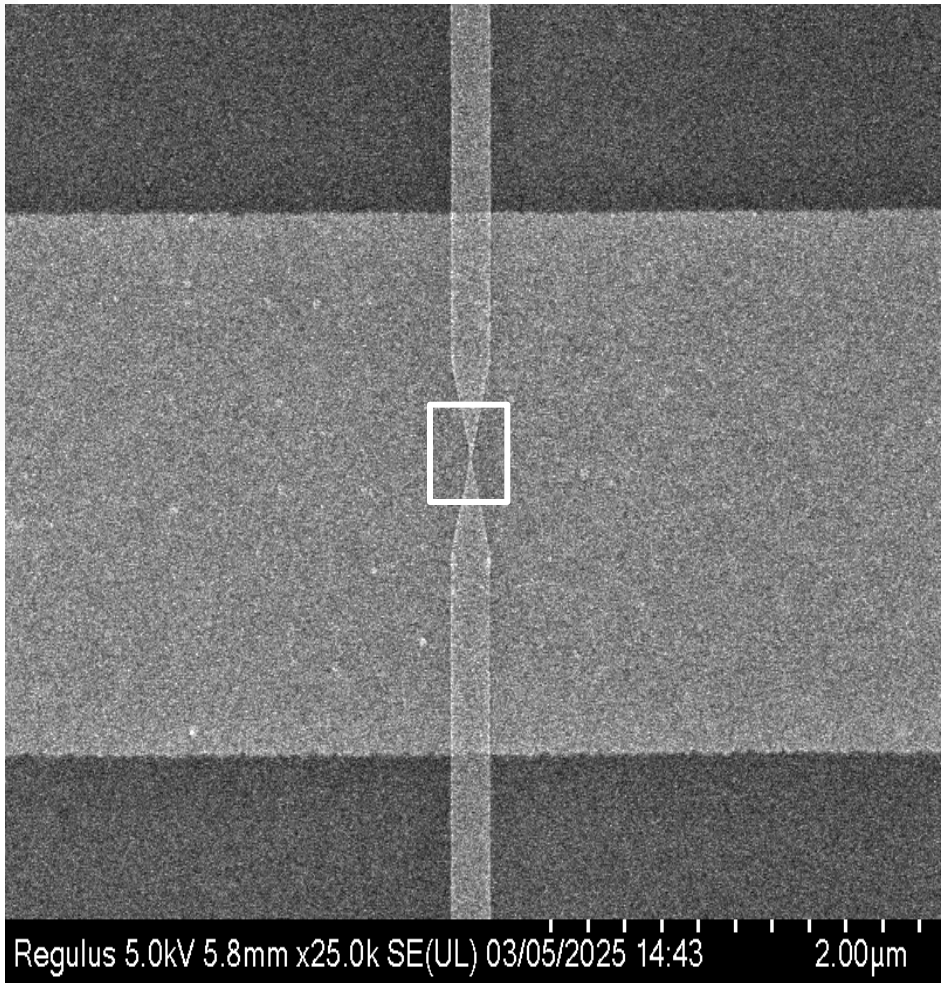


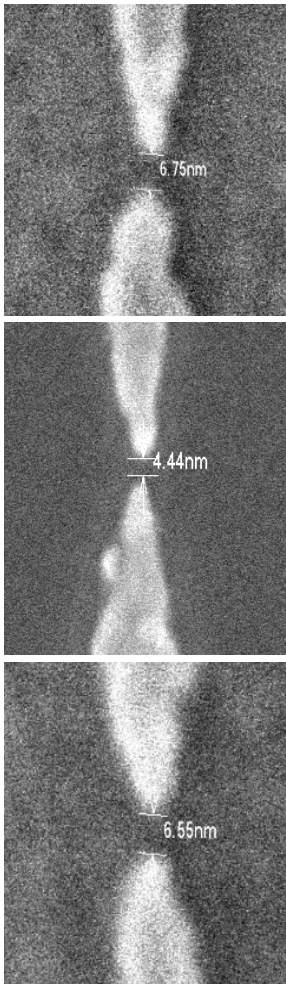
7 nm ALD grown HfO_2



needle-like 12 nm Pd electrodes are then patterned on top



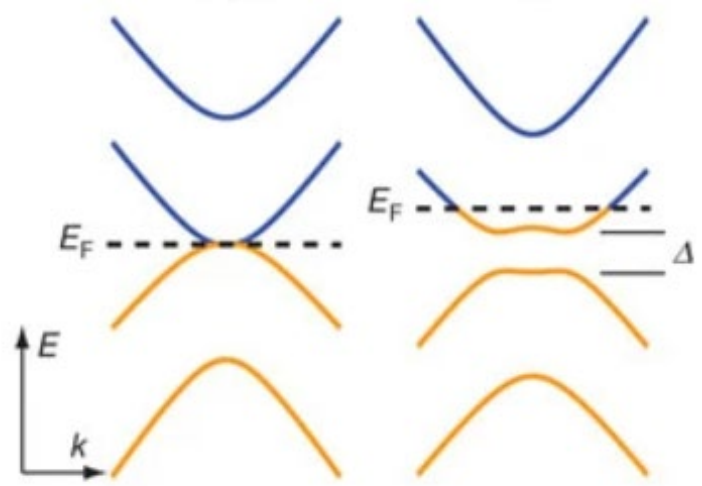


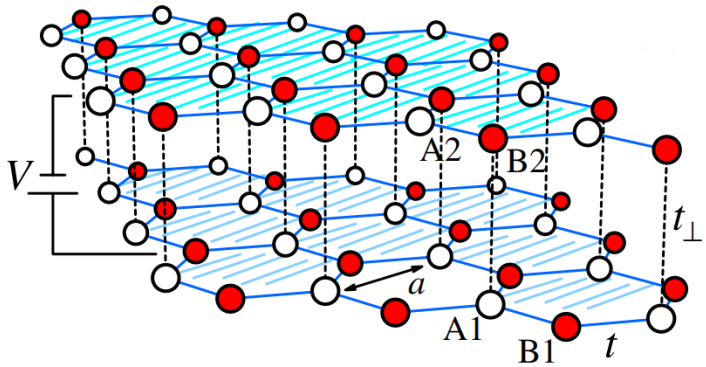


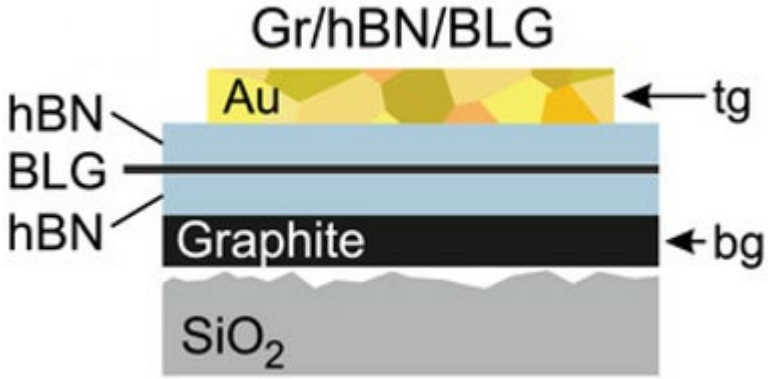
bi-layer graphene quantum devices

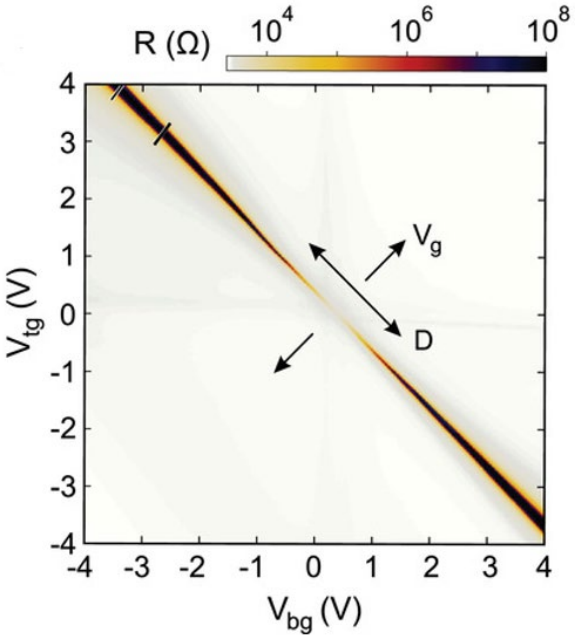
bi-layer graphene quantum devices

inversion symmetry broken by an electric applied across the two layers: band gap opens up







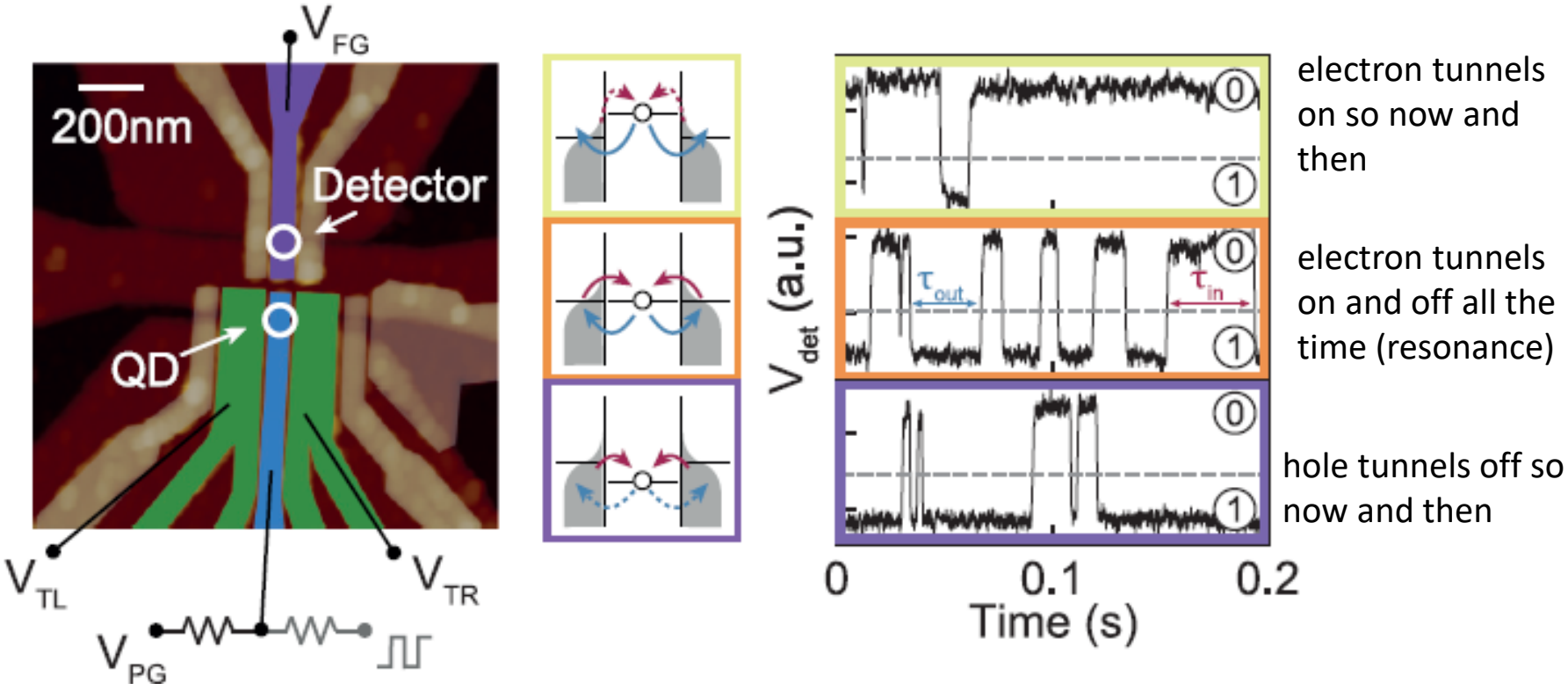


Icking et al., Adv. Elec. Mater. ***8*** *(2022) 2200510*
Zhang et al., Nature ***459*** *(2009) 820*

Counting statistics of single electron transport in bilayer graphene quantum dots

Rebekka Garreis,[1,*] Jonas Daniel Gerber,[1] Veronika Stará,[2] Chuyao Tong,[1] Carolin Gold,[1,3] Marc Röösli,[1] Kenji Watanabe,[4] Takashi Taniguchi,[4] Klaus Ensslin,[1] Thomas Ihn,[1] and Annika Kurzmann[1,5]

two capacitively coupled quantum dots: one acts as the detector of the charge in the other



electron tunnels on so now and then

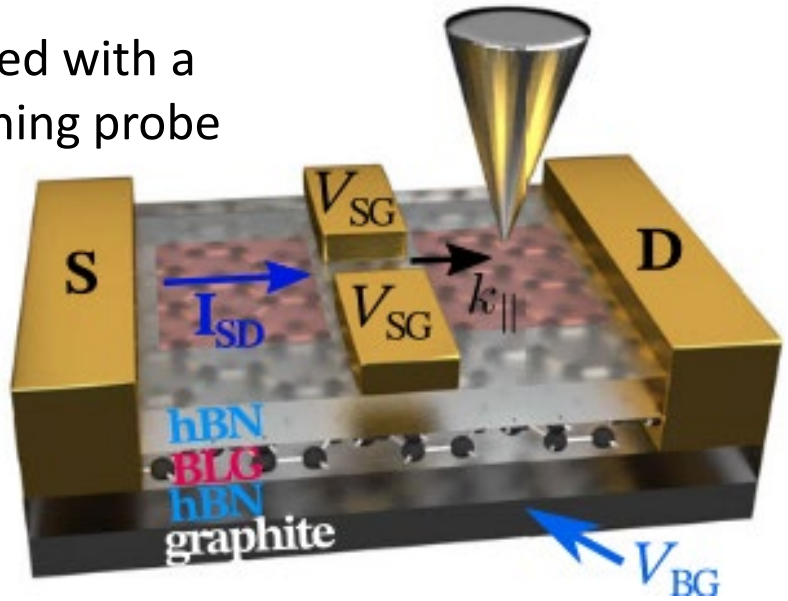
electron tunnels on and off all the time (resonance)

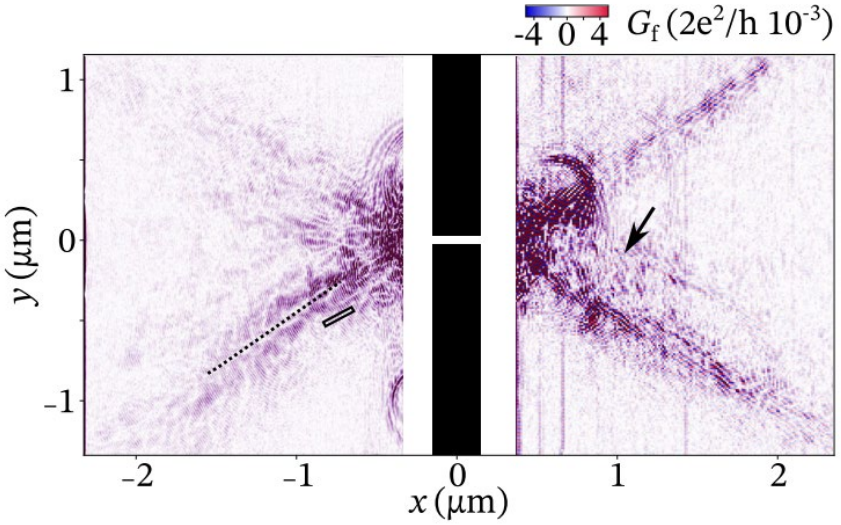
hole tunnels off so now and then

high-quality devices wit a high degree of control

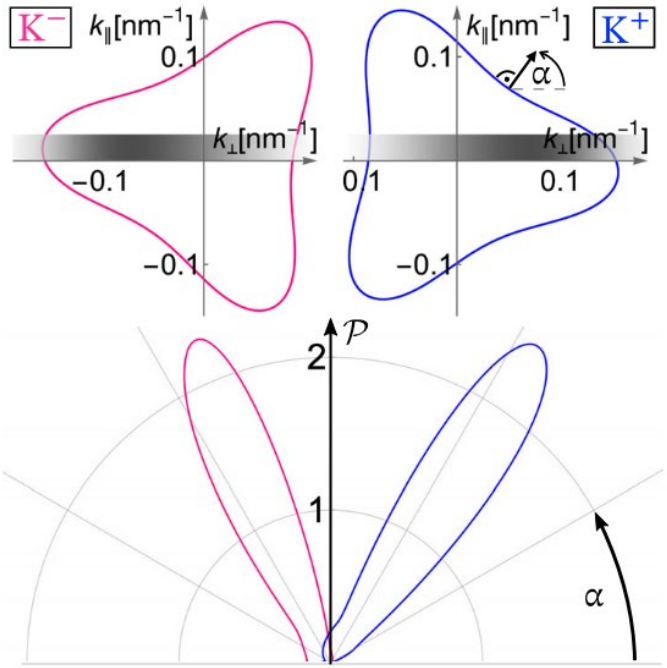
valley polarized electron jets due to triagonal warping in bilayer graphene (BLG)

imaged with a scanning probe



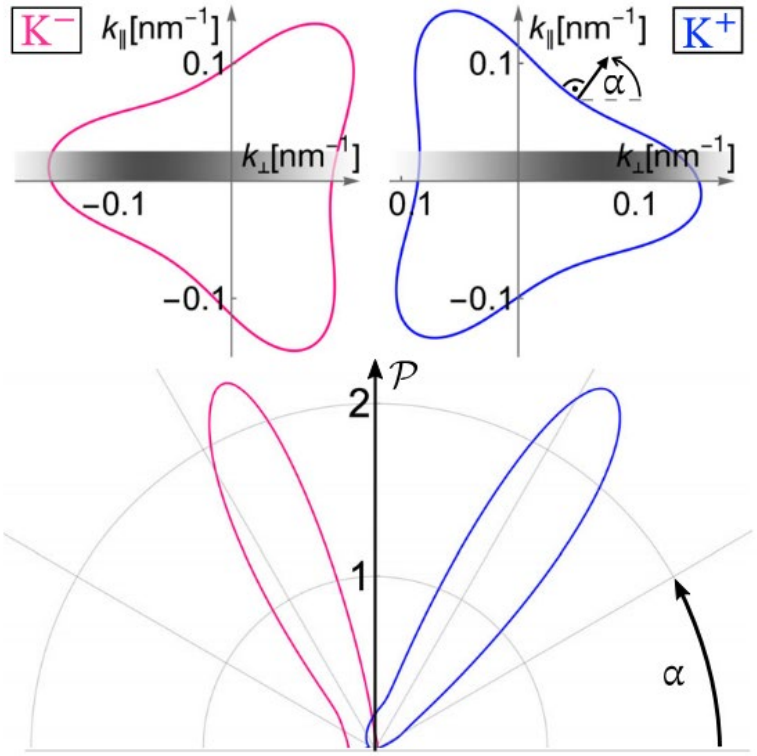


the Fermi surfaces are not spherical in BLG and is different (rotated) for the two valleys



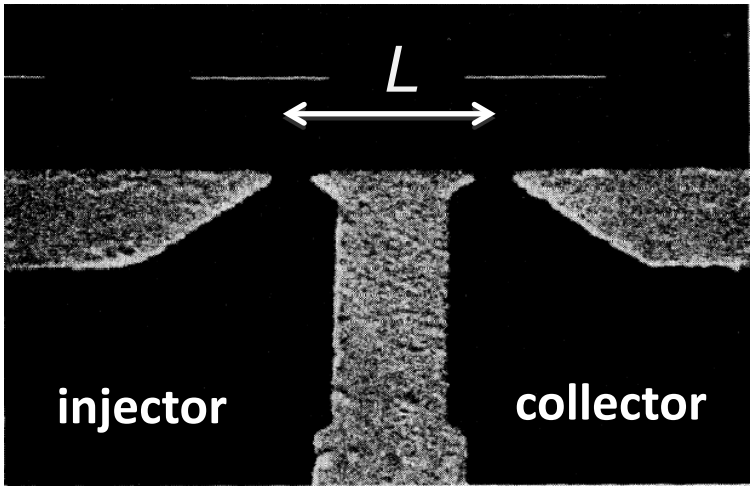
Gold et al., Phys. Rev. Lett. ***127*** *(2021) 046801*

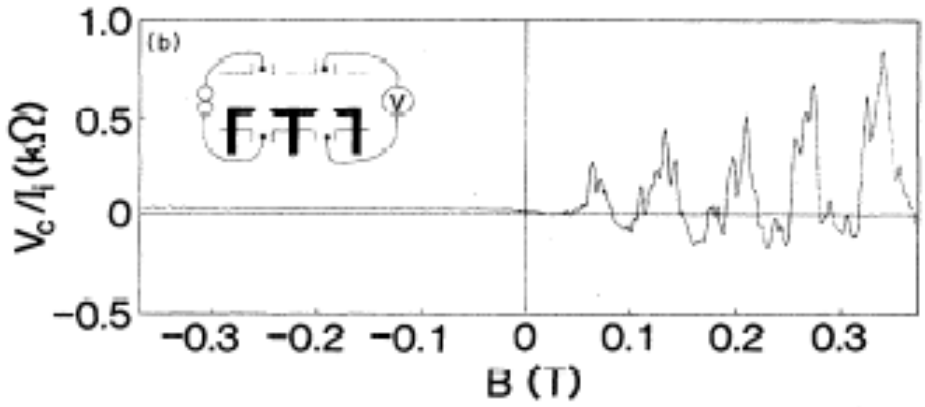
How to control valley-polarized currents in a device?



using electron jets steered by a magnetic field in transverse electron focussing with quantum point contacts as injectors and collectors

classical ballistic transport: transverse electron focusing





use perpendicular magnetic field to focus electron jets leading to peaks in the non-local voltage

top-gate structure
2DEG (GaAs-$Al_xGa_{1-x}As$)

n = 3.5 10^{15} m^{-2}
μ = 90 m^2/Vs
L = 3 μm
ℓ_e = 9 μm (mean free path, no scattering within this length scale)

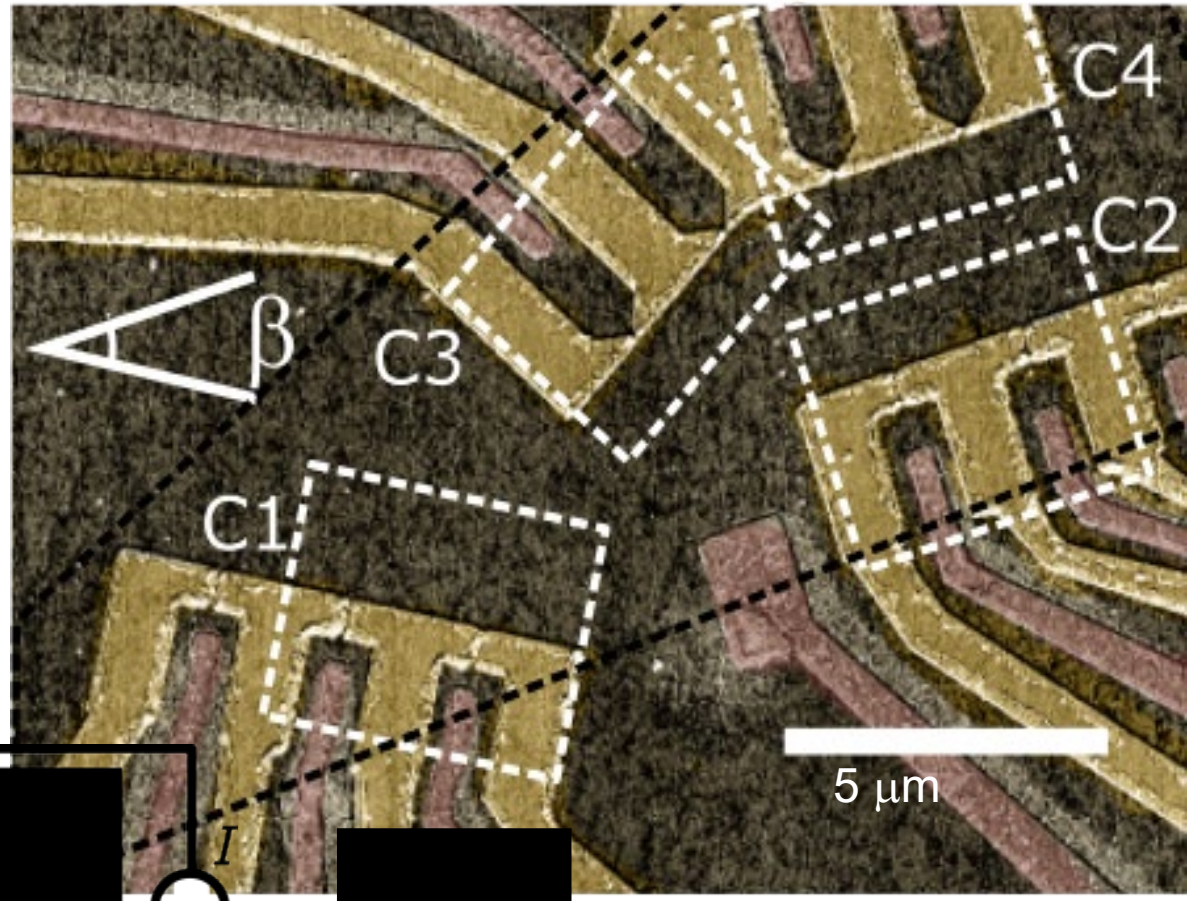
cyclotron radius: $r_c = mv_F/eB$
$B_p = p^*(2mv_F/eL)$
$(p-1)$ = number of reflections

Van Houten et al., PRB 1989

our BLG device

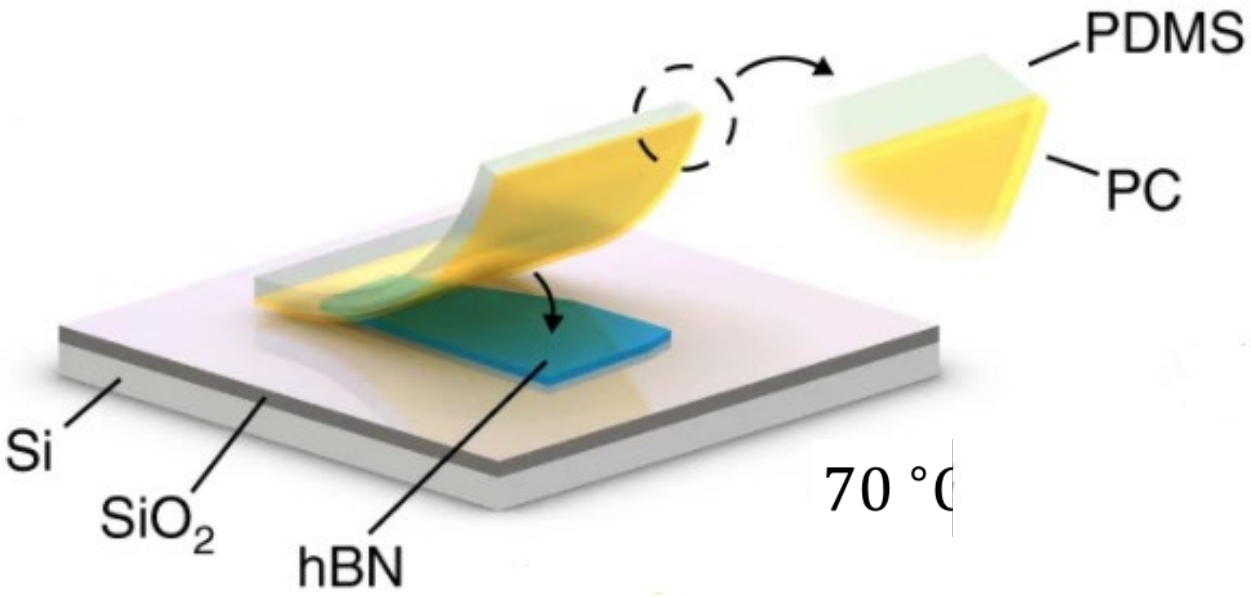
Josep Ingla-Aynés

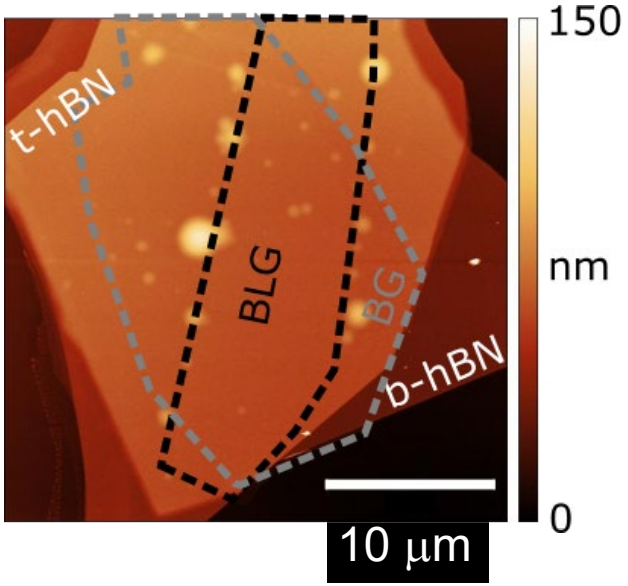
MARIE SKŁODOWSKA-CURIE ACTIONS
Research Fellowship Programme



J. Ingla-Aynés et al., Nano Lett. ***23*** *(2023) 5453 – 5459*

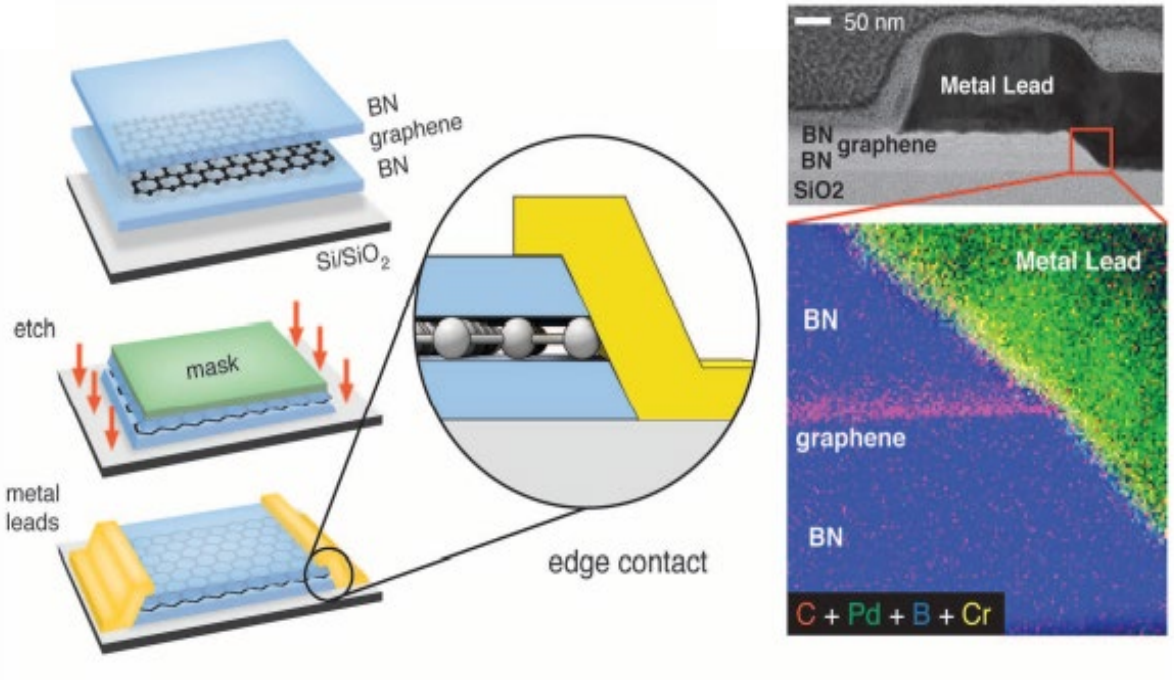
fabrication: dry transfer technique (4 layered materials)



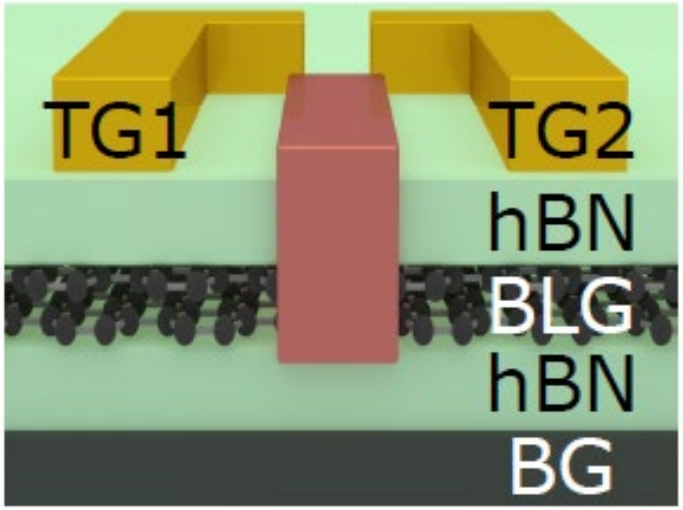


Purdie et al. Nature Commun. ***9*** *(2018) 5387 (2018)*
Zomer et al. Appl. Phys. Lett. ***105*** *(2014) 013101 (2014)*

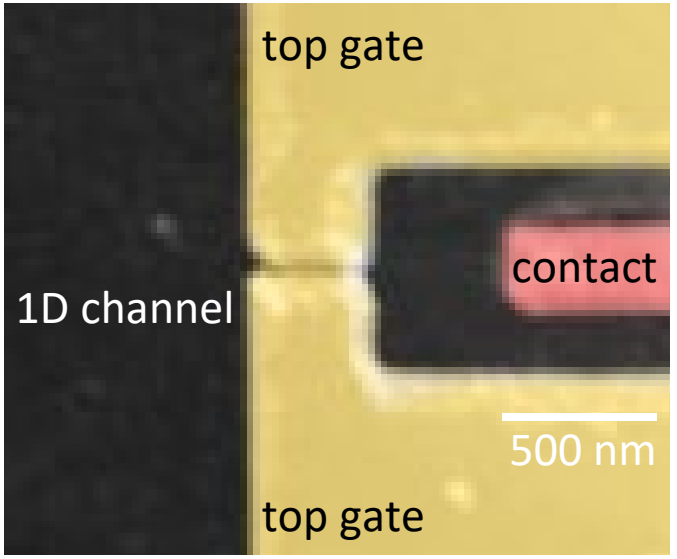
fabrication: side (edge) contacts to the BLG and metallic top gates



*L. Wang et al. Science **342** (2013) 614*

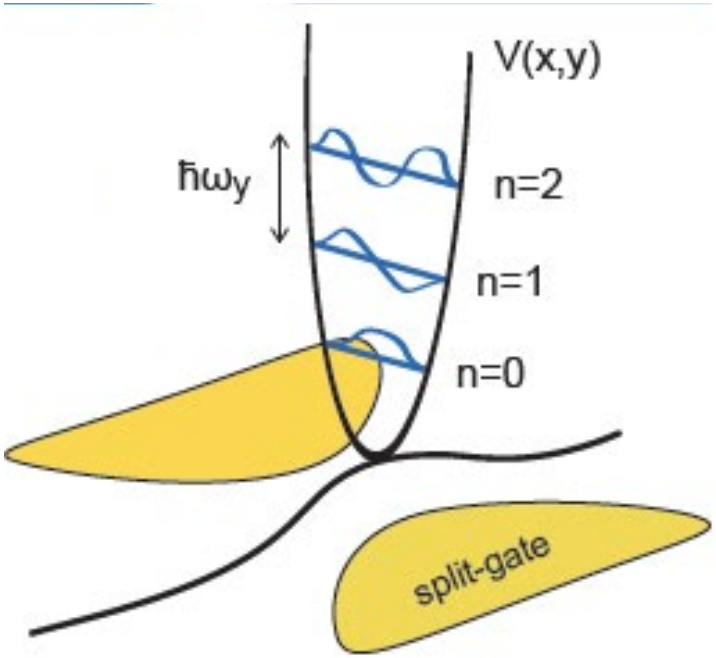


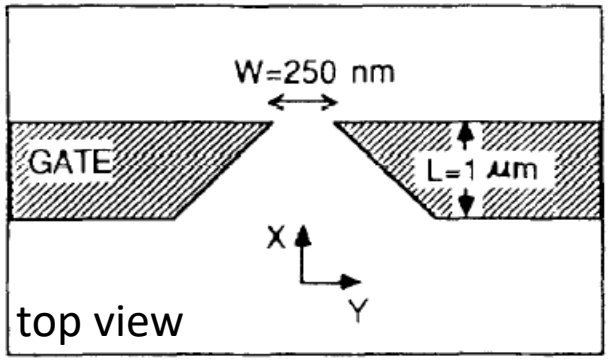
side view quantum point contact



top view quantum point contact

intermezzo: quantum point contacts and quantized conductance





2DEG (GaAs-$Al_xGa_{1-x}As$)

VOLUME 60, NUMBER 9 PHYSICAL REVIEW LETTERS 29 FEBRUARY 1988

Quantized Conductance of Point Contacts in a Two-Dimensional Electron Gas

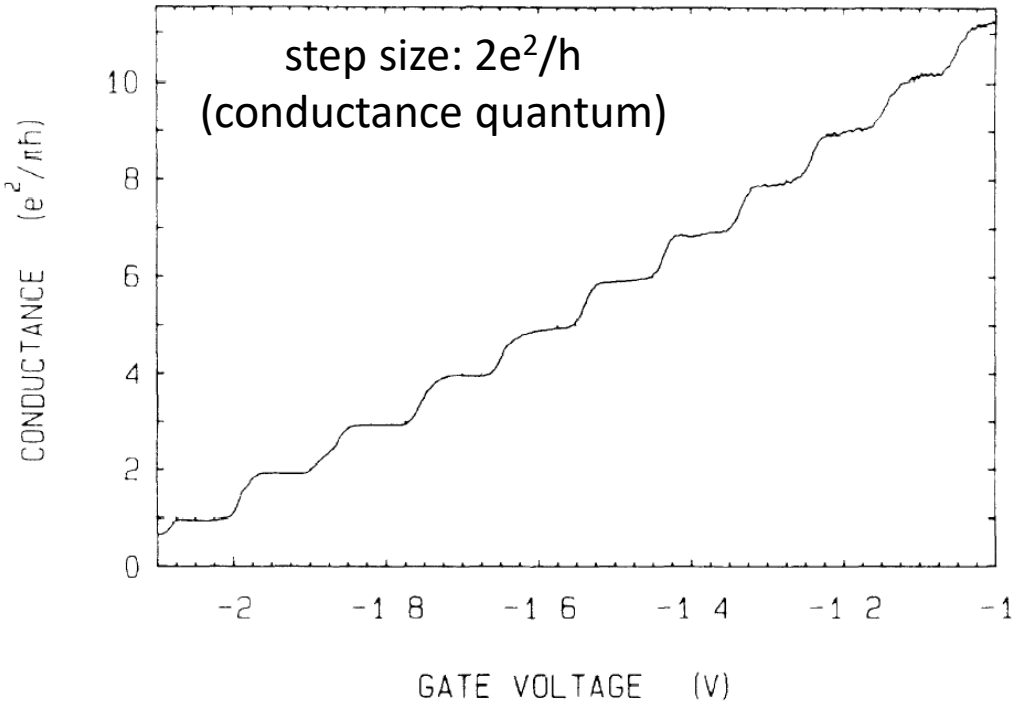
B. J. van Wees
Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands

H. van Houten, C. W. J. Beenakker, and J. G. Williamson,
Philips Research Laboratories, 5600 JA Eindhoven, The Netherlands

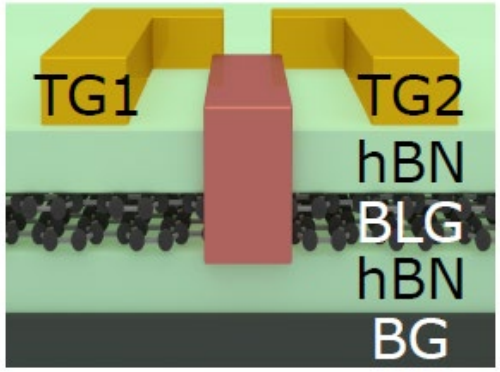
L. P. Kouwenhoven and D. van der Marel
Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands

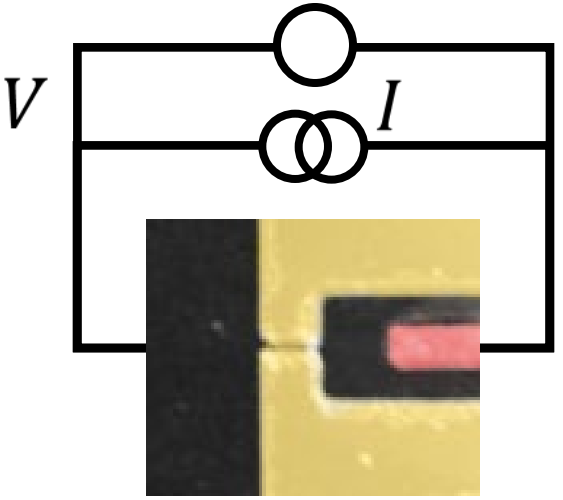
and

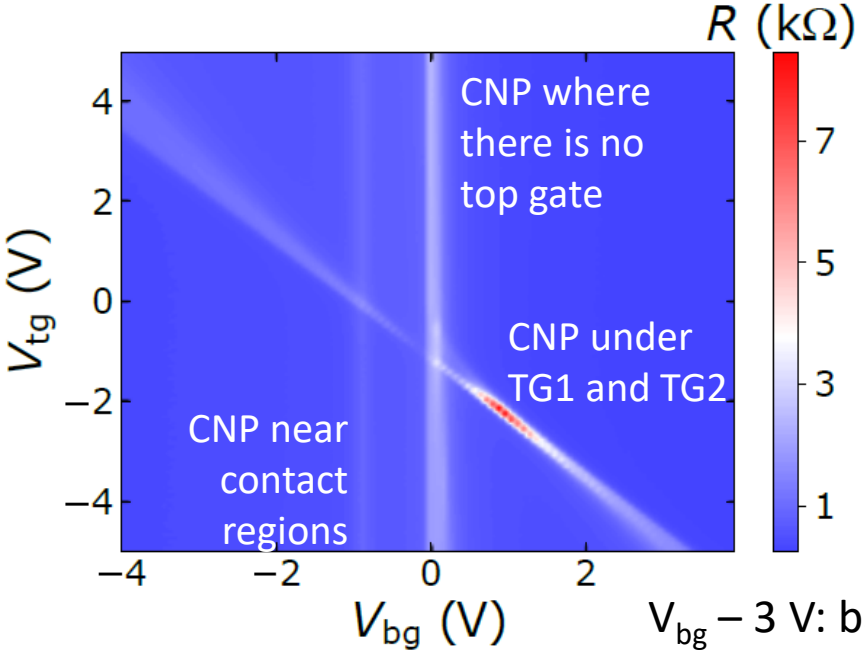
C. T. Foxon
Philips Research Laboratories, Redhill, Surrey RH1 5HA, United Kingdom
(Received 31 December 1987)



basic characterization: band gap and quantum point contacts

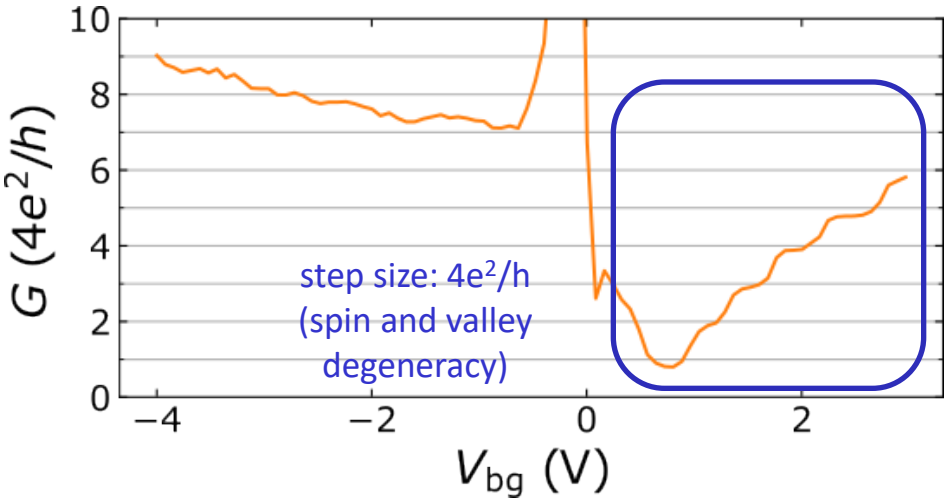






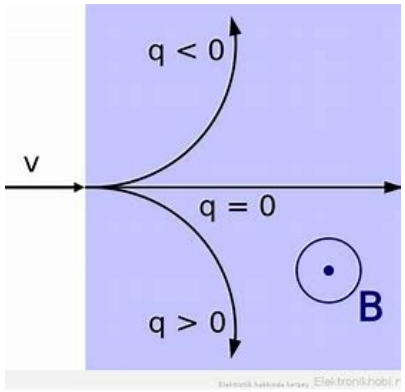
V_{bg} – 3 V: band gap about 45 meV

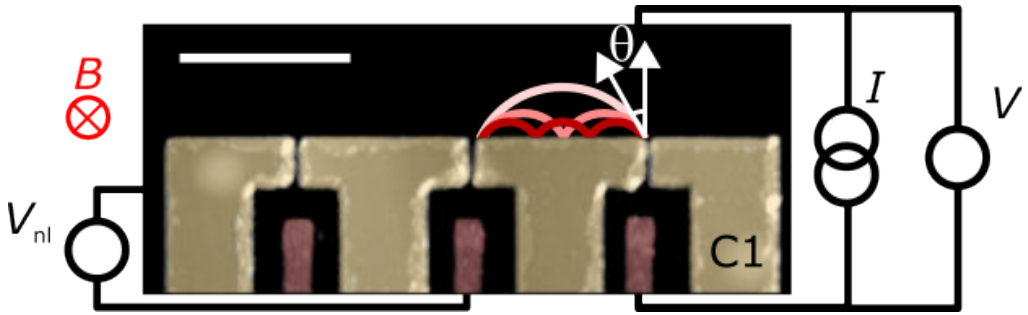
quantized steps for electron side of the charge neutrality point (CNP)

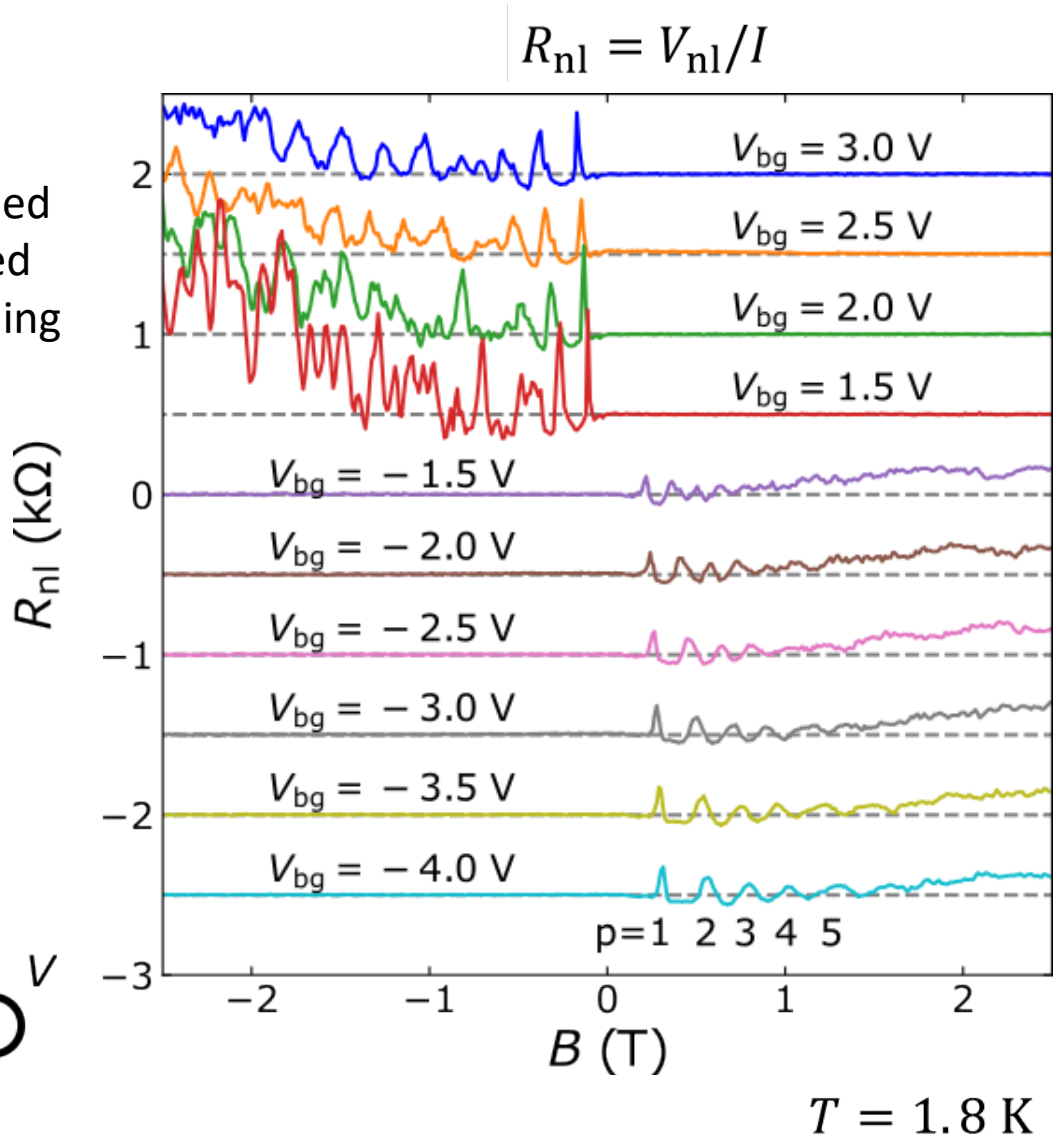


transverse electron focusing BLG

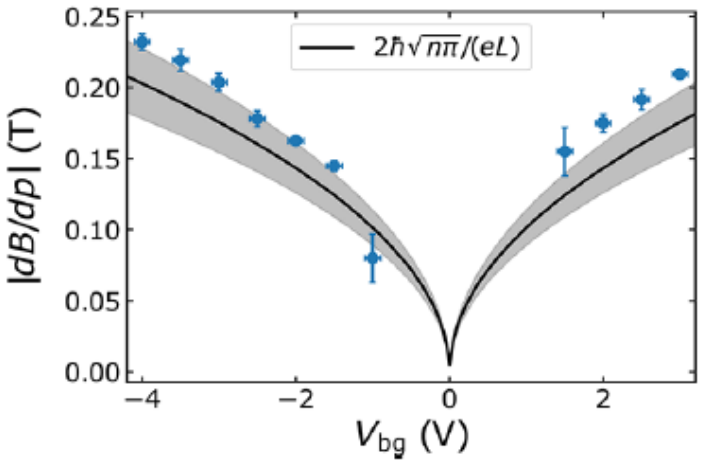
- clear peaks observed indicating focussing
- electron side gives peaks for negative applied magnetic field and holes for positive applied fields, as expected (Lorentz force; has nothing to do with valleys)







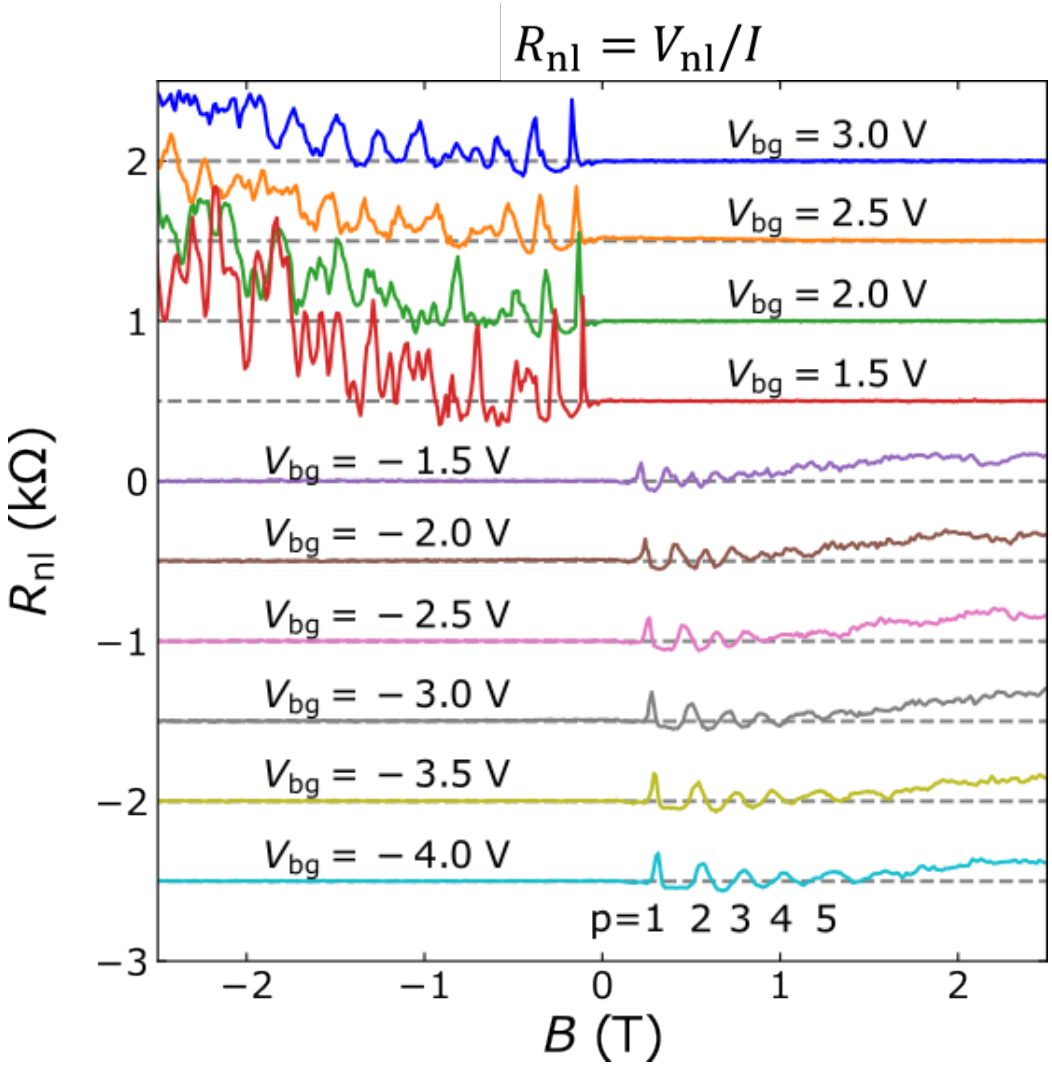
transverse electron focusing: peak spacing increases with gate voltage



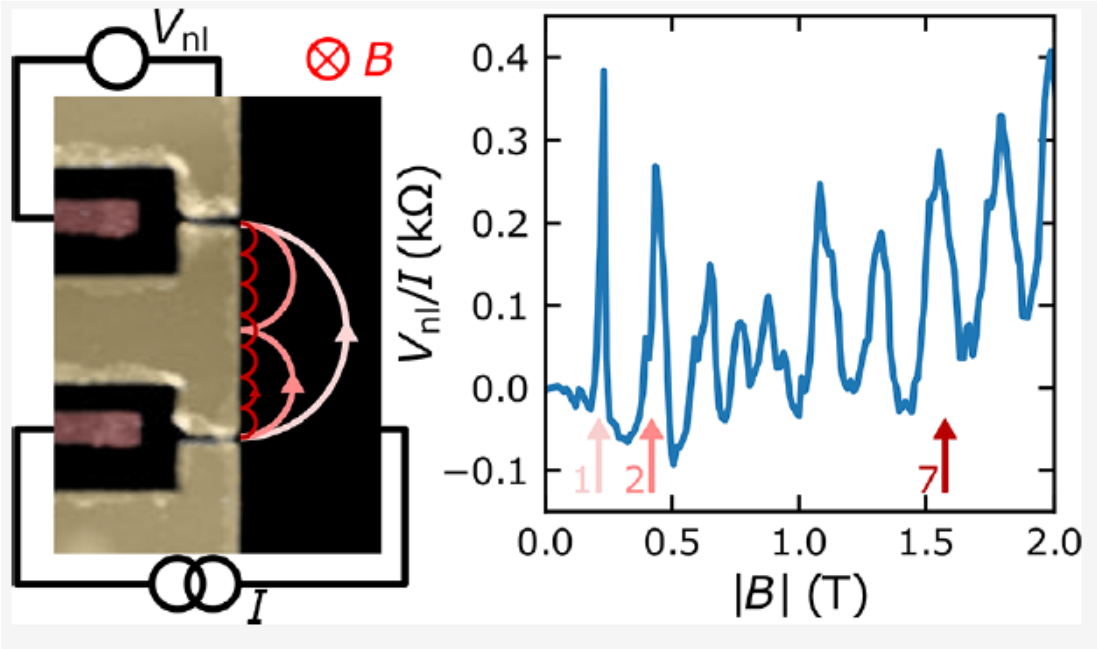
$B_p = p*(2mv_F/eL)$ (p = integer)

peak spacing: $dB/dp = 2mv_F/eL$

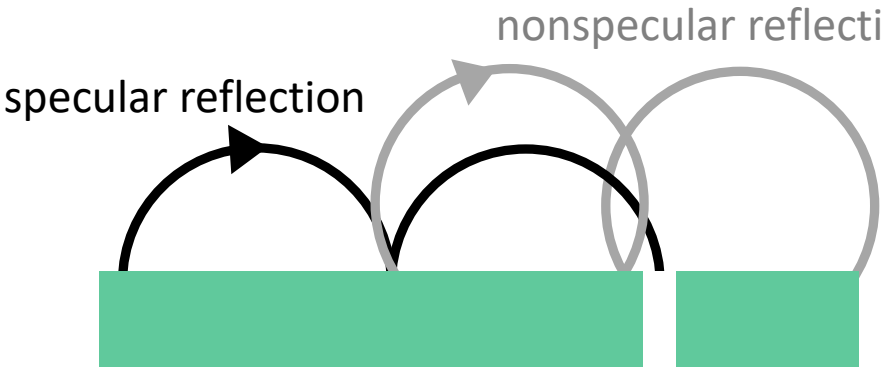
$mv_F = \hbar k_F = \hbar(n\pi)^{1/2}$

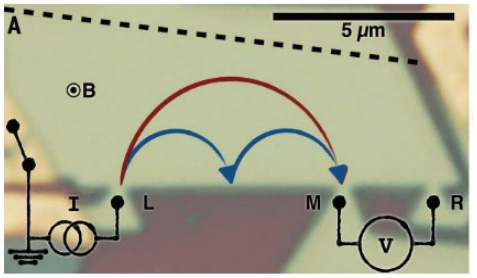


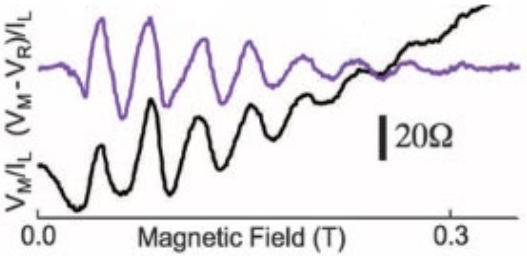
transverse electron focusing: specular reflection



- previous work: only a few peaks observed due to incomplete specular reflection (graphene edges defined by etching)
- our work: electrostatically defined edges lead to the observation of many more peaks (specular reflection)



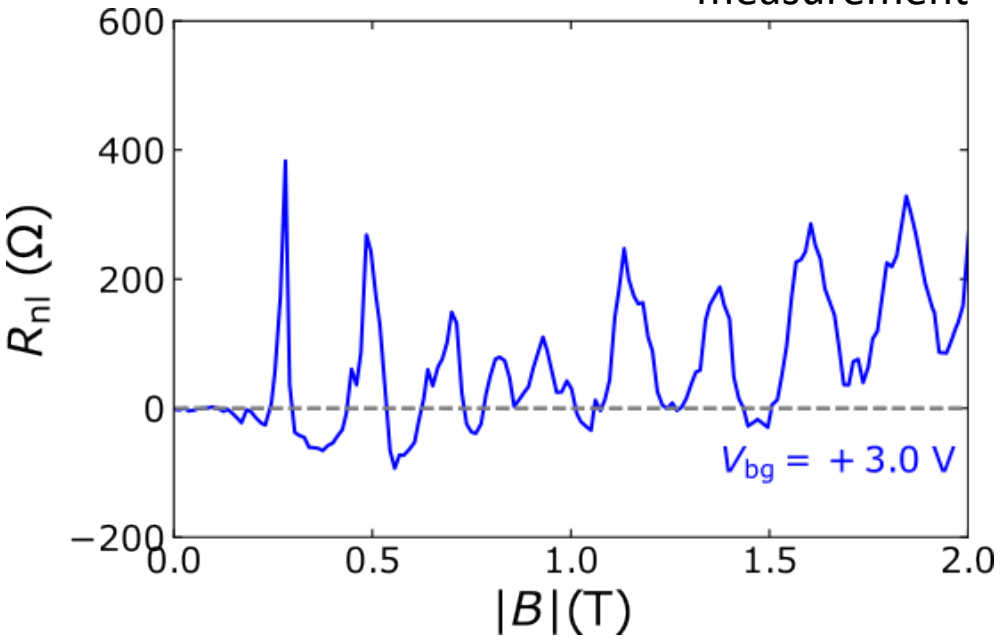




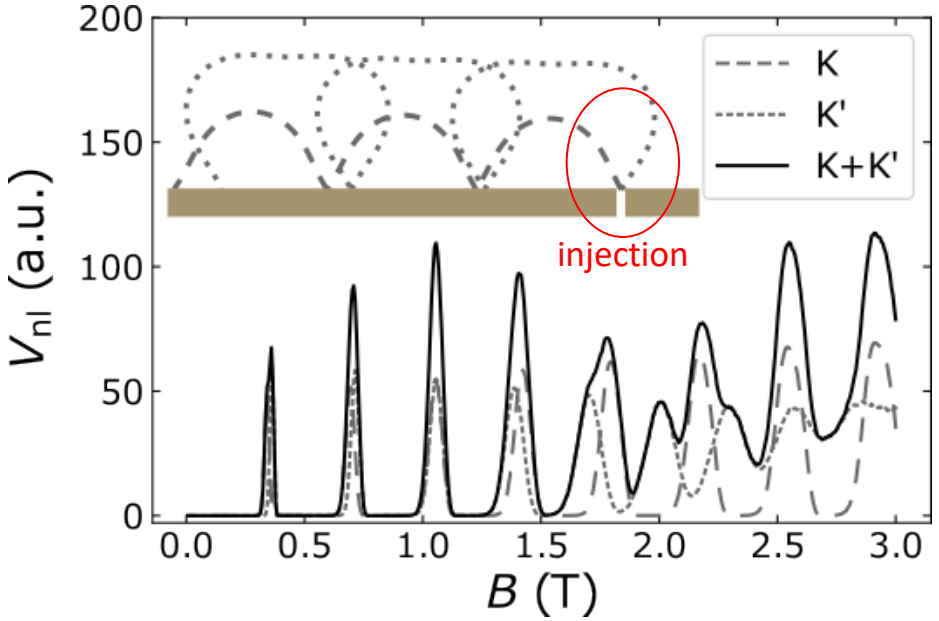
*M. Lee et al. Science **353** (2016) 1526*

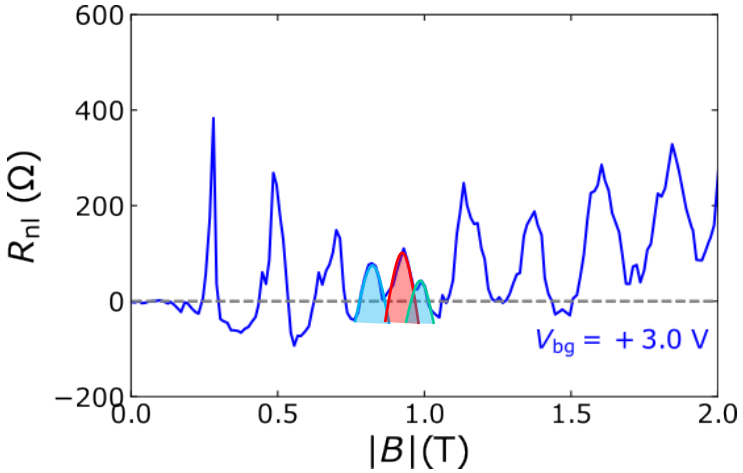
transverse electron focusing: signatures of triagonal warping

measurement



calculation



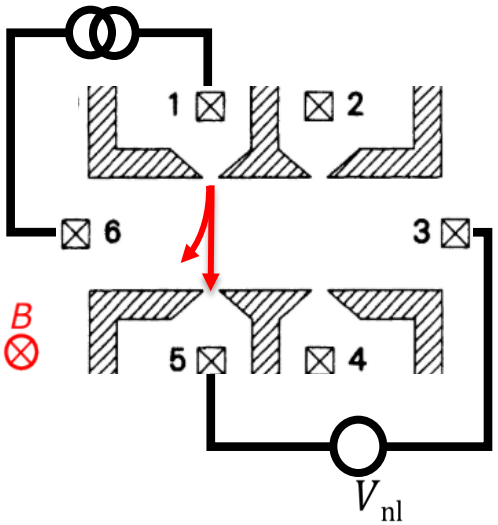


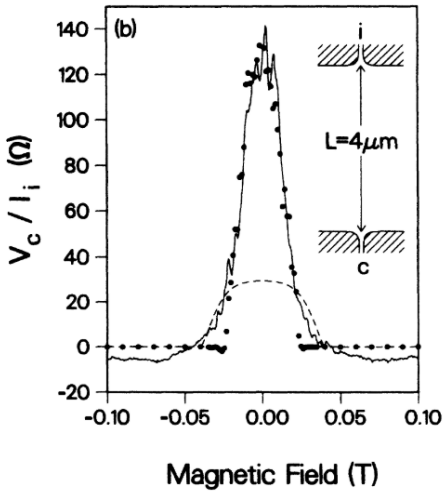
Valley selective focusing?

No definite proof because certain impurity configurations could in principle lead to similar behavior (unlikely though).

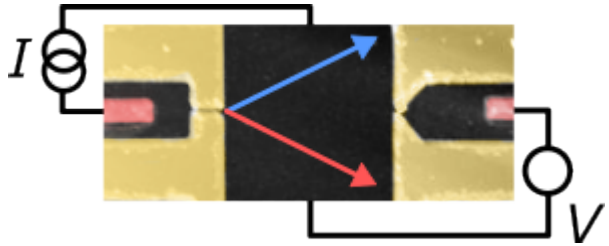
collimation experiments with electron jets in ballistic BLG samples

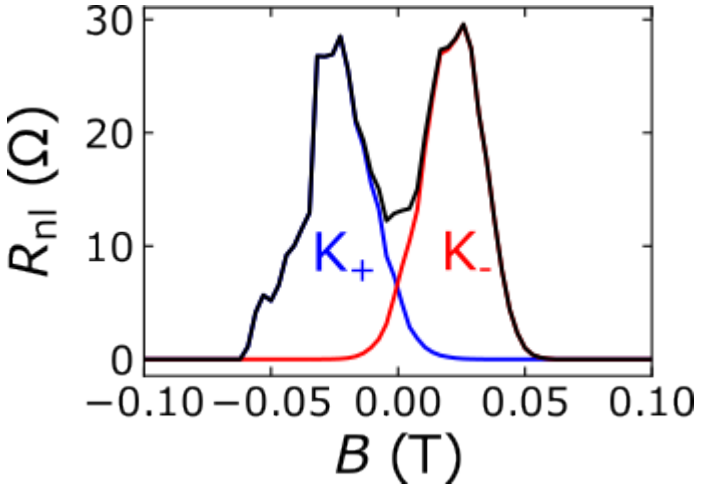
spherical Fermi surface: electron jet in one direction





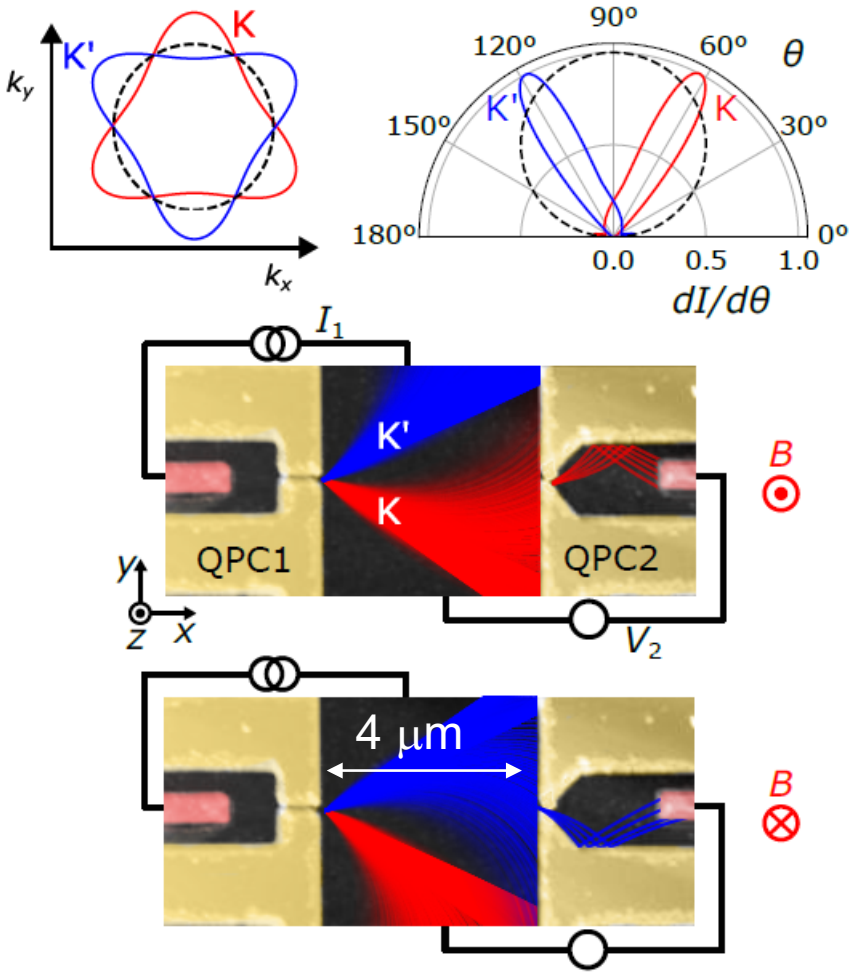
Fermi surface BLG: valley polarized jets in different directions

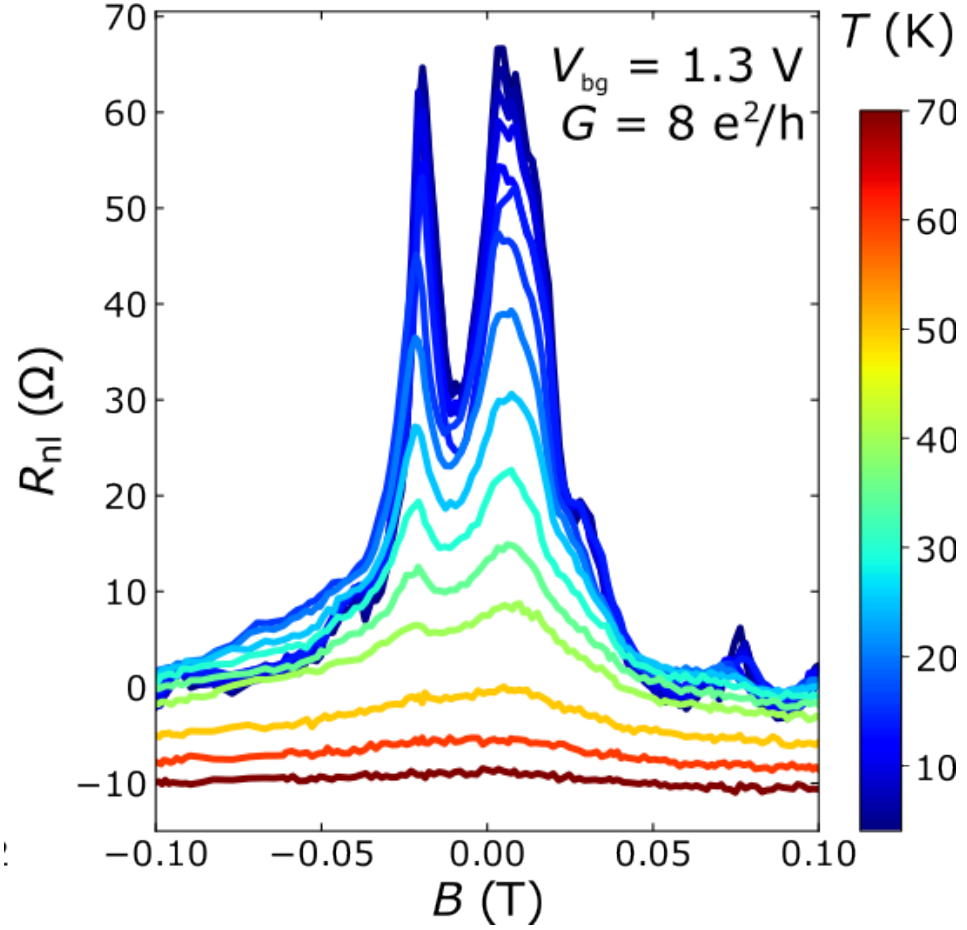




*L. Molenkamp et al. Phys. Rev. B **41** (1990) 1274(R)*

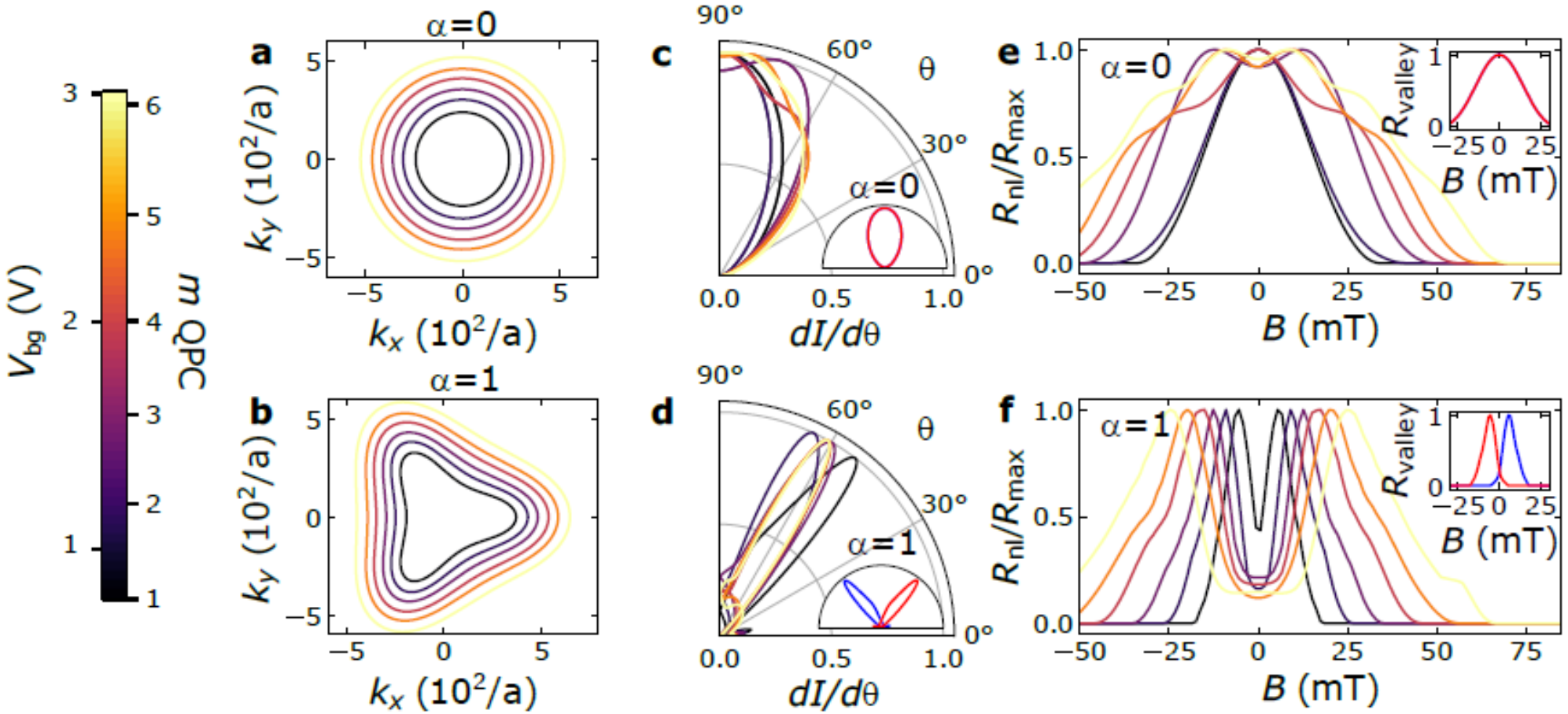
collimation experiments in ballistic BLG samples





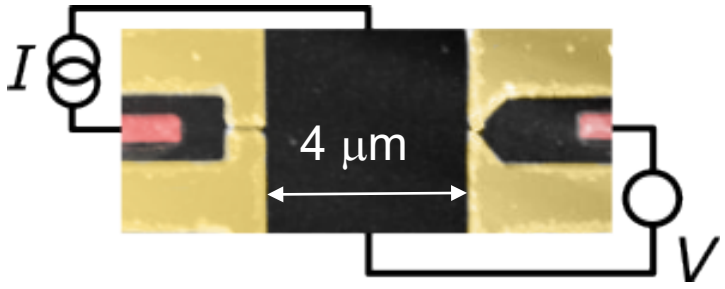
J. Ingla-Aynés et al., Phys. Rev. Lett. ***133*** *(2024) 156301*

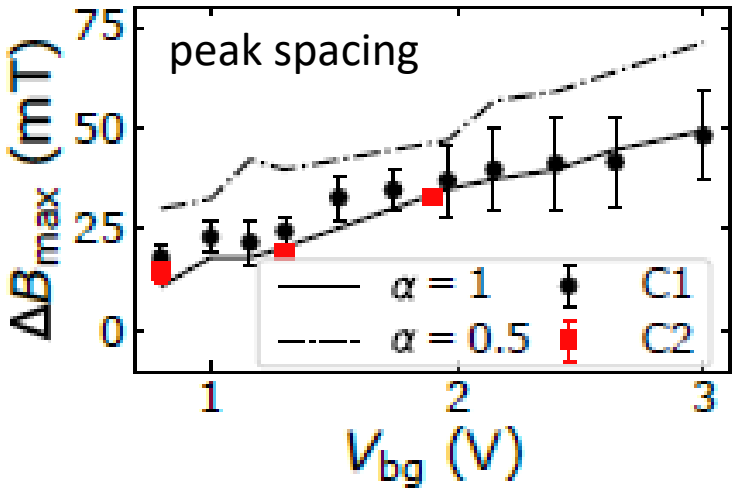
semi-classical simulations for different back gate voltages

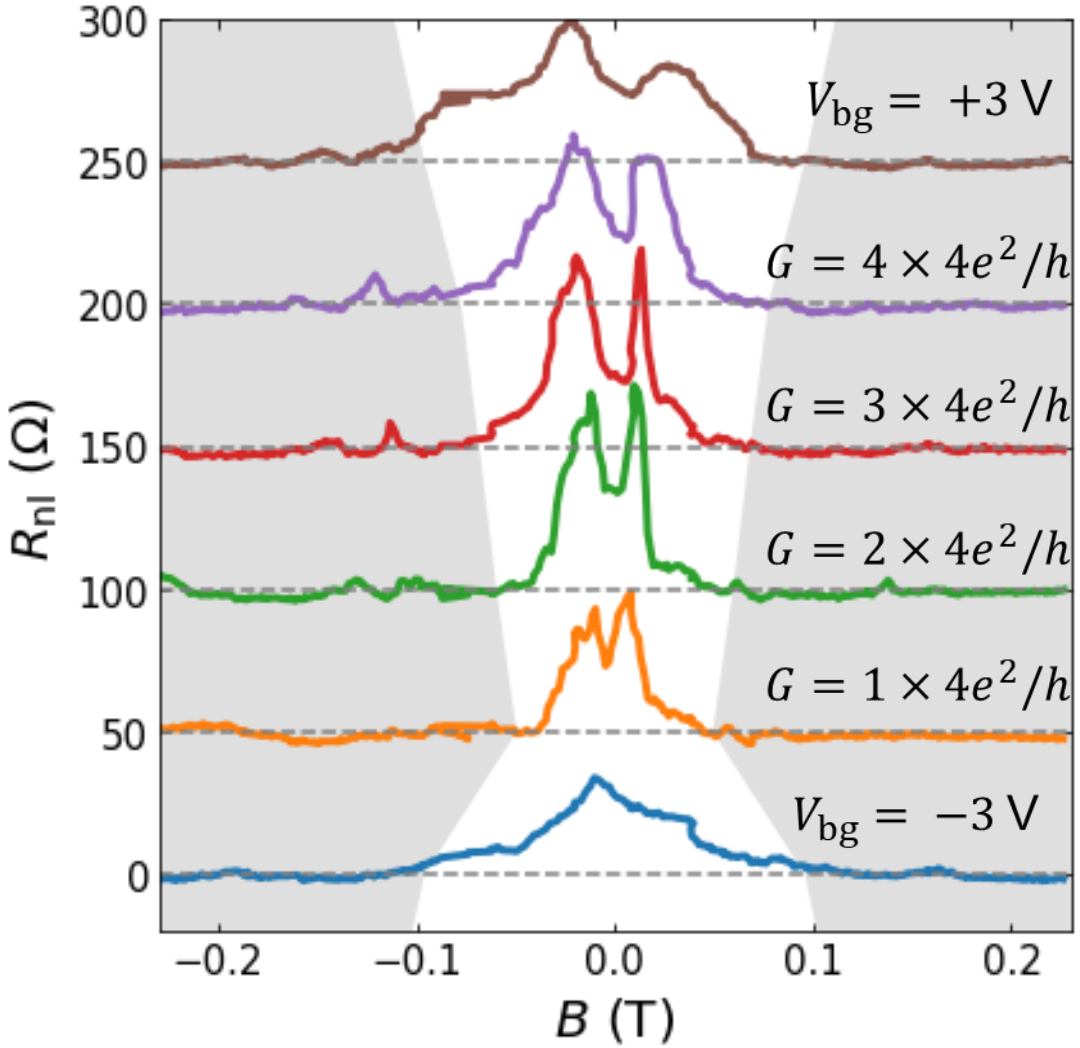


the peak spacing in the case of trigonal warping increases with doping (increasing back gate voltages)

collimation experiments for different gate voltages





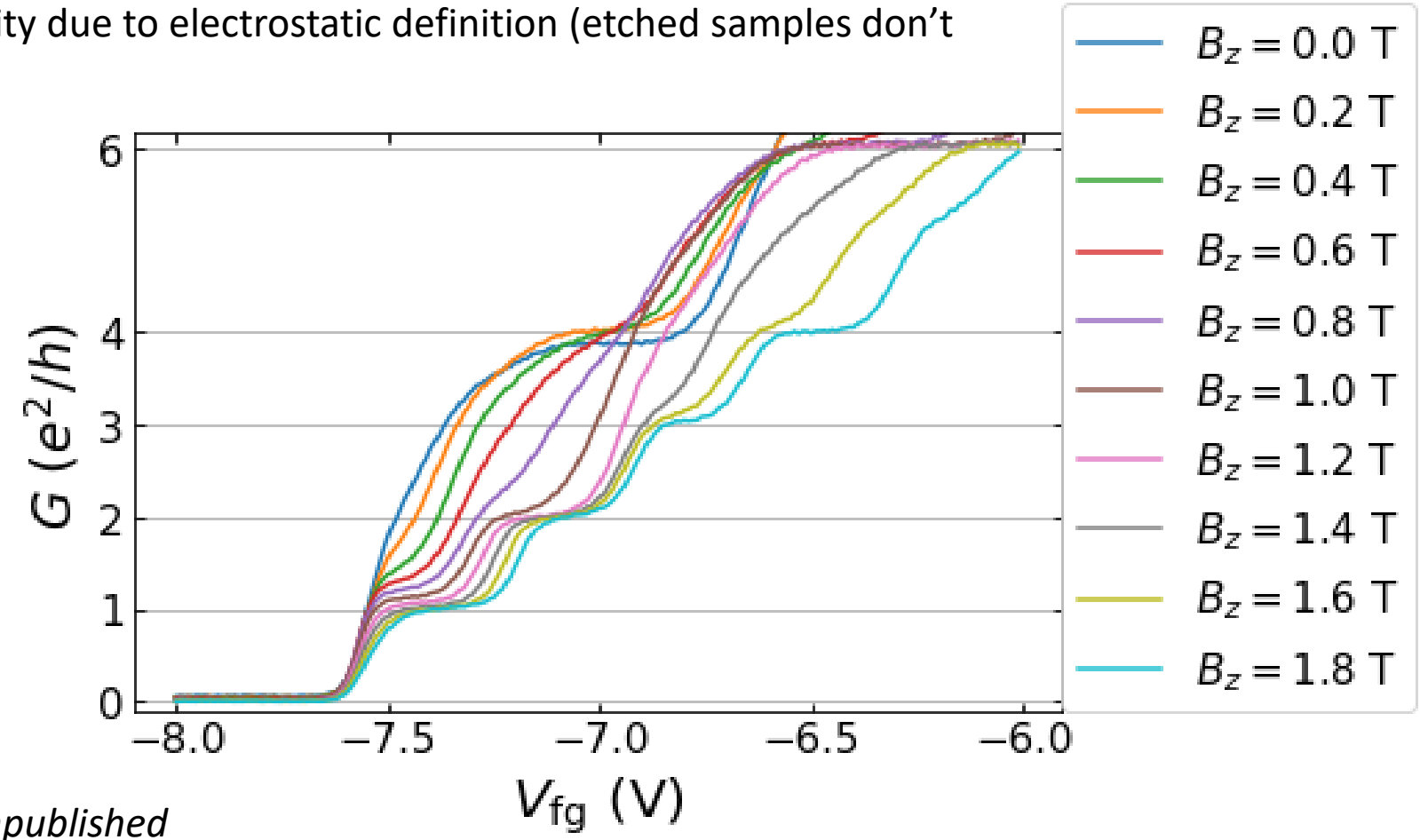


good agreement between semi-classical model and experiments indicating full trigonal warping (α = 1); visible only at the electron side where focusing works well

Can we create spin-valley polarized currents?

quantum point contact (ballistic one-dimensional channel)

- quantized conductance steps (e^2/h)
- perpendicular magnetic field lifts both valley and spin degeneracy (B > 1.5 T)
- high sample quality due to electrostatic definition (etched samples don't show this)



J. Ingla-Aynés et al., unpublished

quantum spin Hall states in graphene

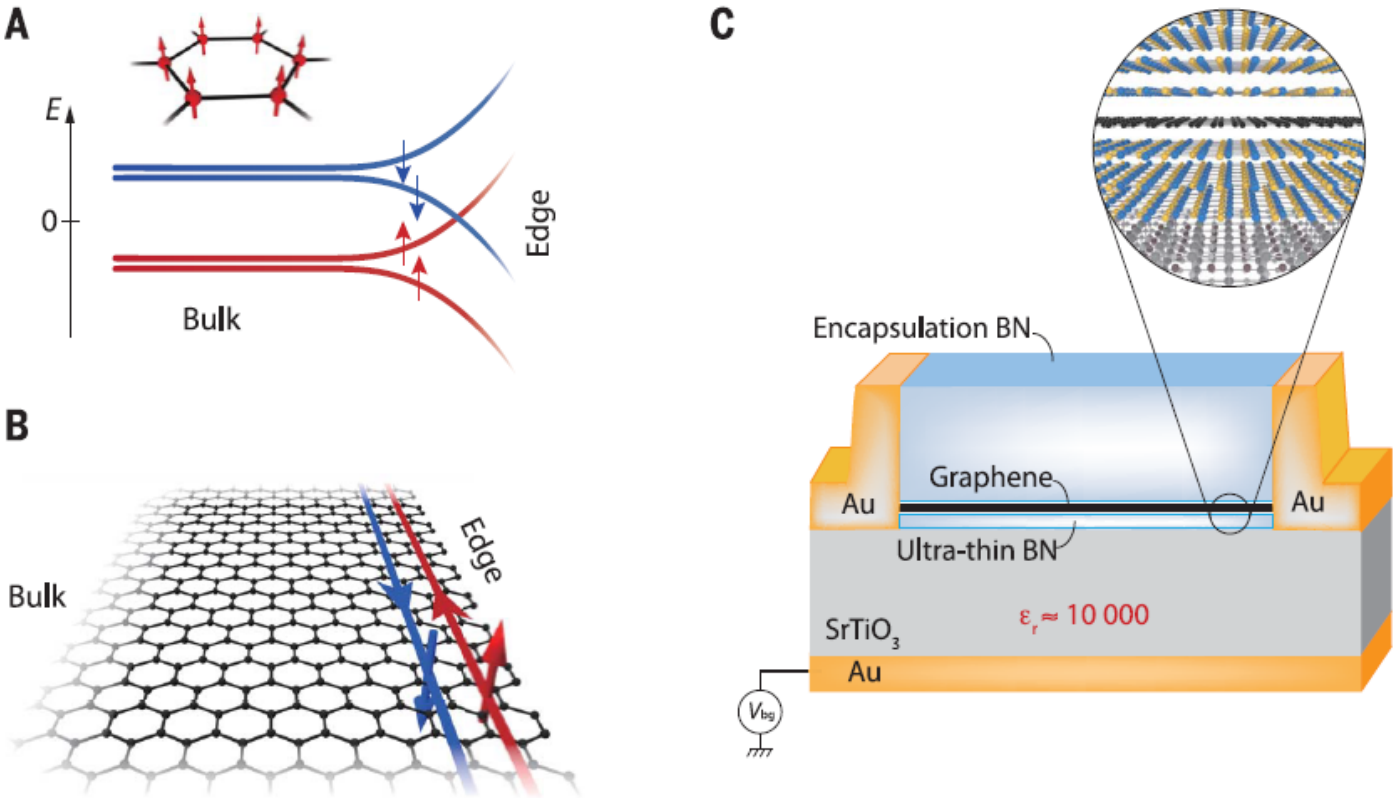
quantum spintronics at zero (low) magnetic field

TOPOLOGICAL MATTER

Veyrat *et al.*, *Science* **367**, 781–786 (2020)

Helical quantum Hall phase in graphene on $SrTiO_3$

Louis Veyrat[1], Corentin Déprez[1], Alexis Coissard[1], Xiaoxi Li[2,3,4], Frédéric Gay[1], Kenji Watanabe[5], Takashi Taniguchi[5], Zheng Han[2,3,4], Benjamin A. Piot[6], Hermann Sellier[1], Benjamin Sacépé[1]*



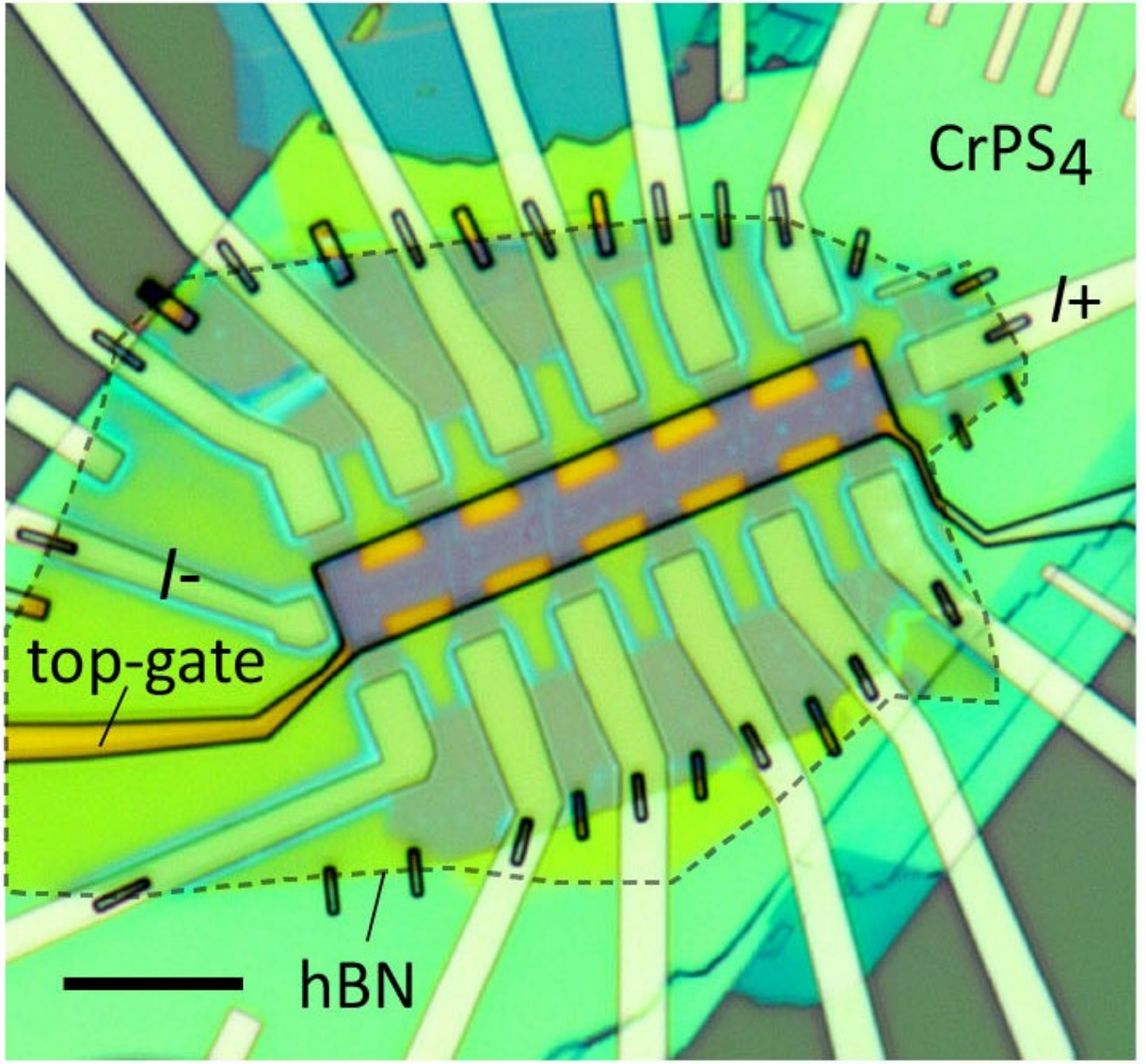
- quantum Hall topological insulator due suitable screening of the Coulomb interaction with the high dielectric constant of the substrate
- helical edges states that are spin and valley filtered observed for magnetic fields as low as 1 T

induce magnetism in graphene Hall bar by the proximity of a 2D magnet

Talieh Giashi

combine the best of two materials:

- conducting graphene: long spin diffusion length
- insulating $CrPS_4$ (from Eugenio Coronado group): magnetism and introduces the broken inversion symmetry

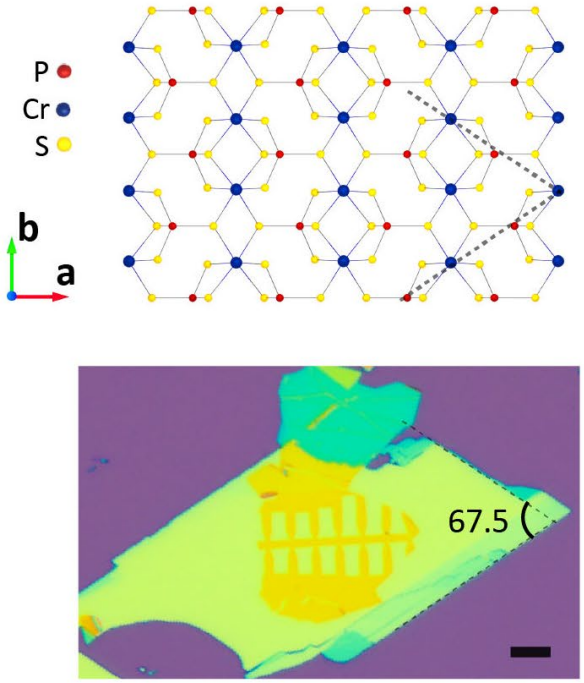


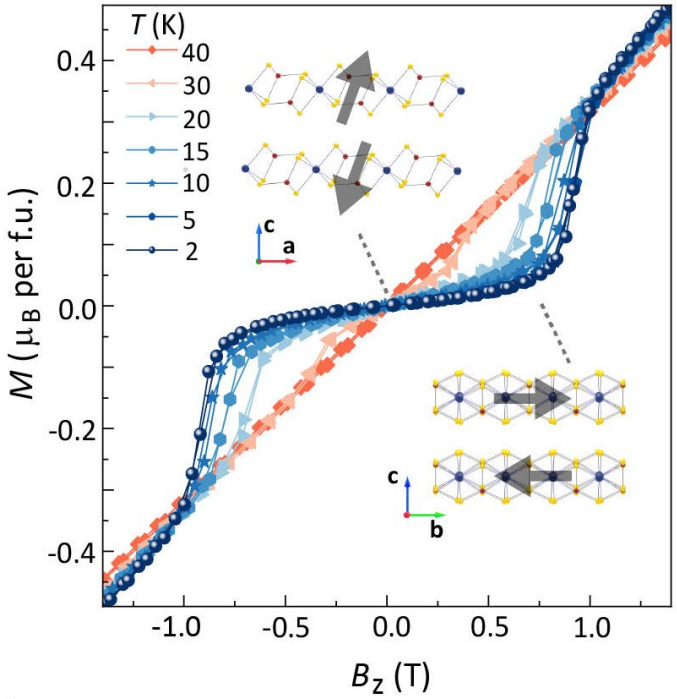
T.S. Ghiasi et al., accepted Nature Communication

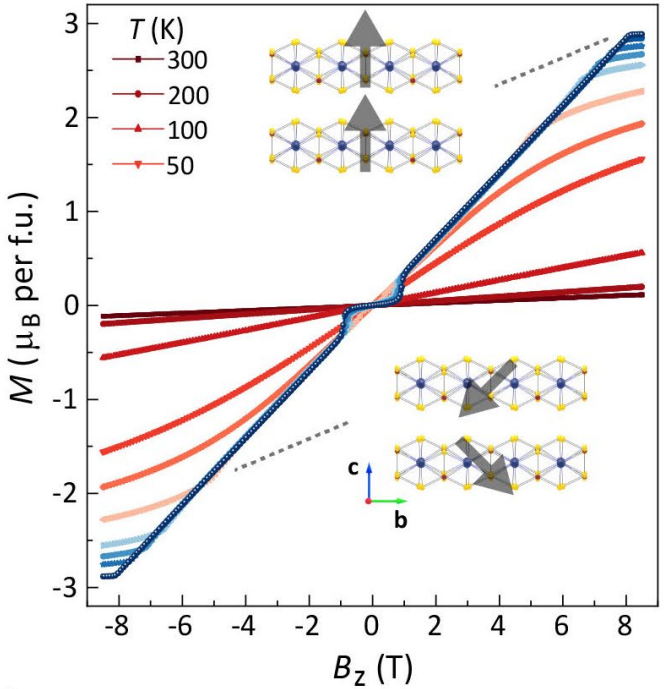
the van der Waals 2D magnet $CrPS_4$

Samuel Mañas Valero

- interlayer antiferromagnet; more or less air-stable semiconductor with a bandgap of ~1.3 eV and a Néel temperature of 38 K
- increasing B_z above the spin-flop transition field (B_{sf} ~0.8 T at 2 K) results in canting of the magnetic moments towards the *c*-axis with full saturation at B_z = 8 T

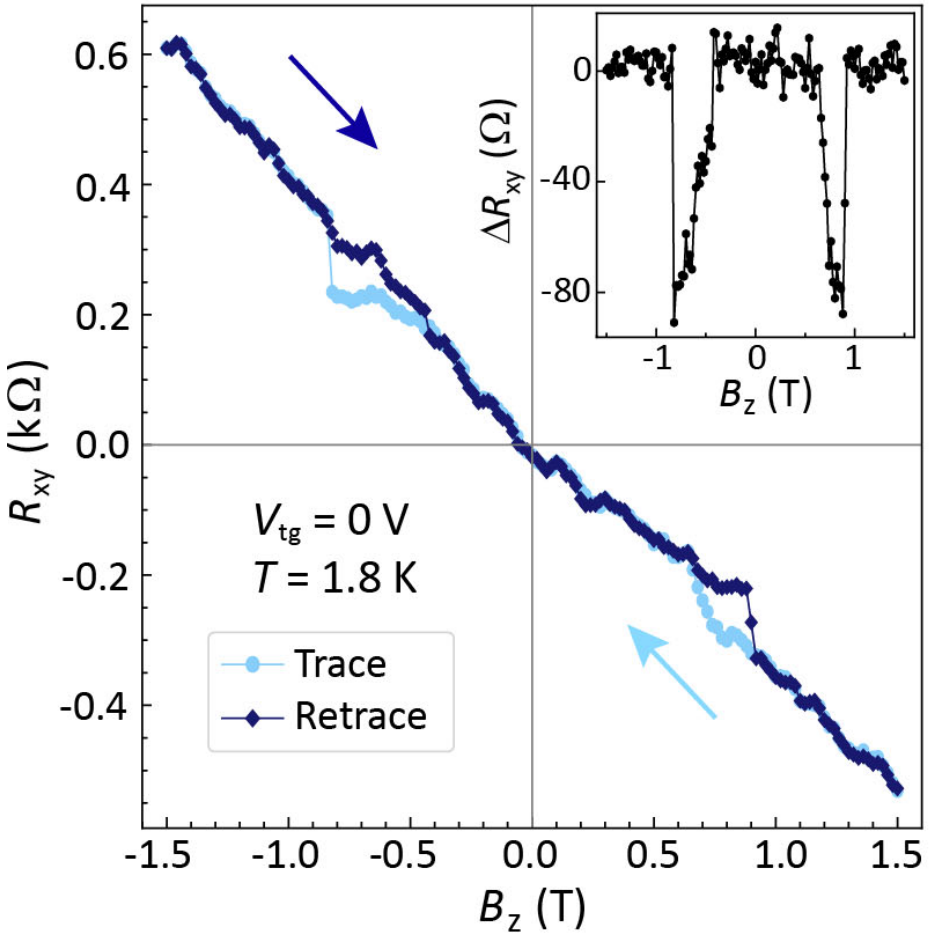




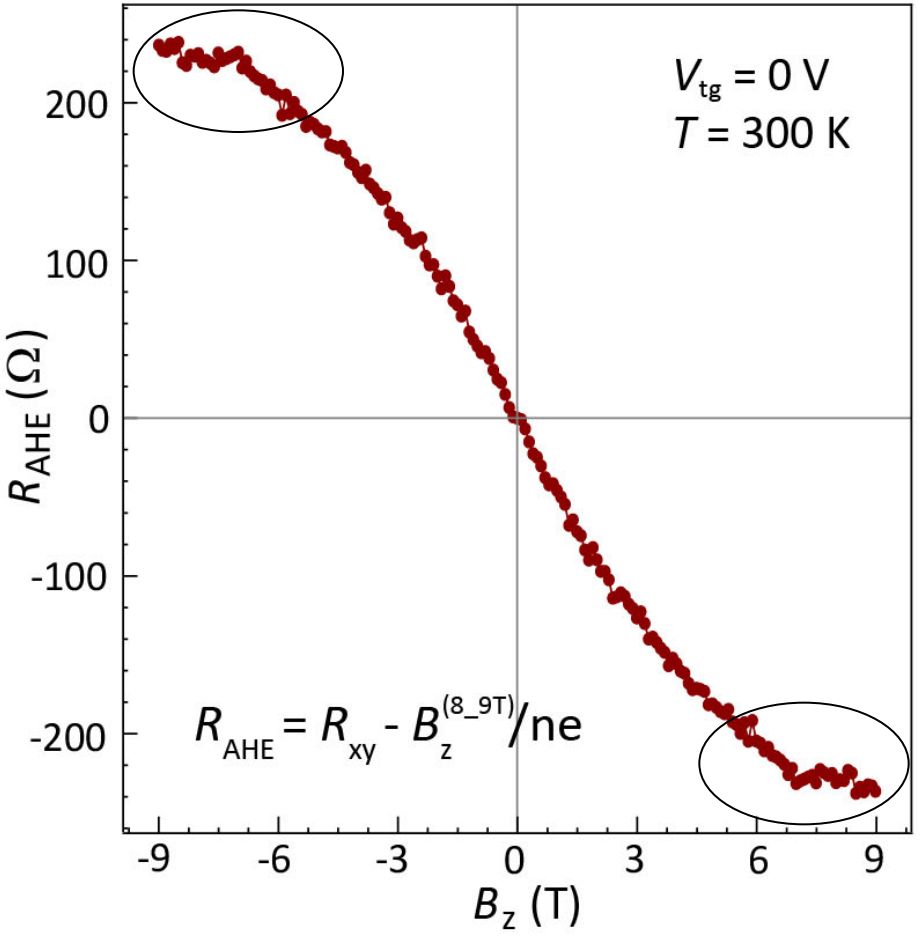


signatures of magnetized graphene

hysteresis near the spin-flop transition

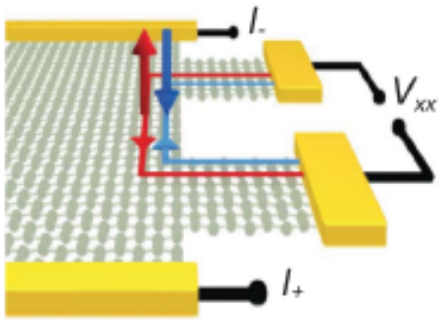


anomalous Hall effect: saturation of the Hall resistance at the saturation field

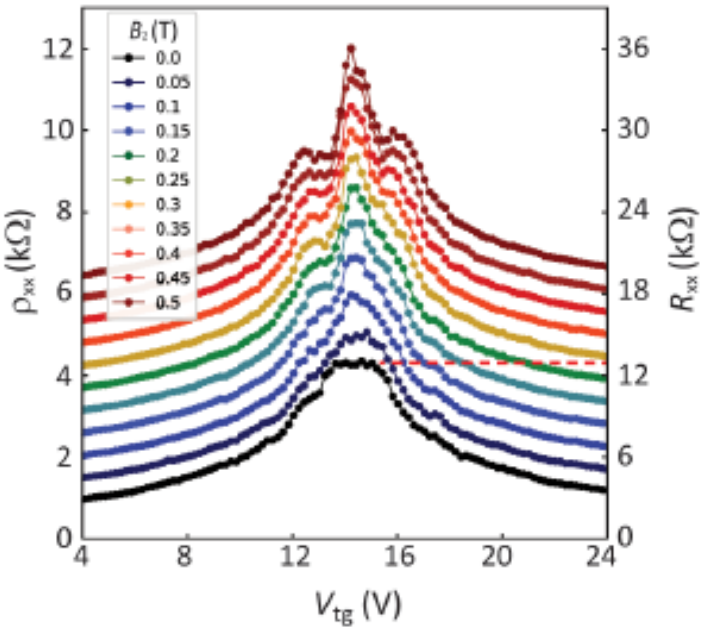


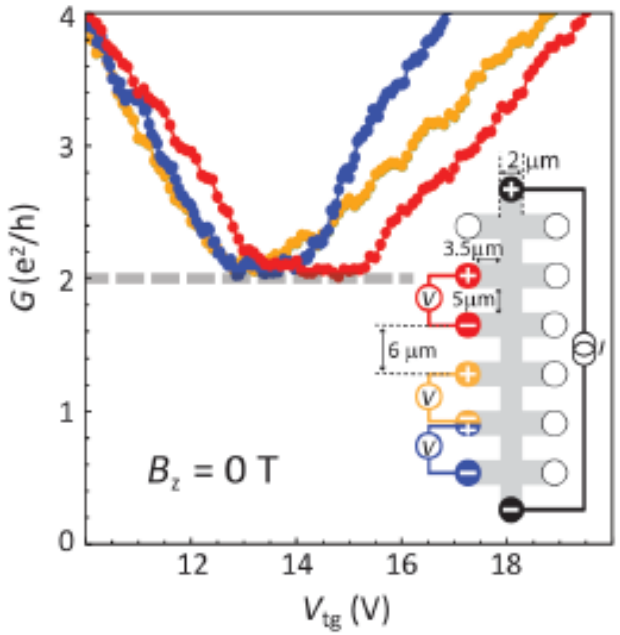
The observation of a sizable signal of 200 Ω is a signature of the co-presence of large induced spin-orbit and exchange interactions in the proximitized graphene up to room temperature

quantum spin Hall states near zero magnetic field



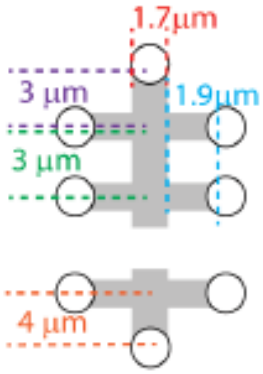
helical states are spin-polarized electron- and hole-like bands that counter propagate at the edges of the magnetized graphene

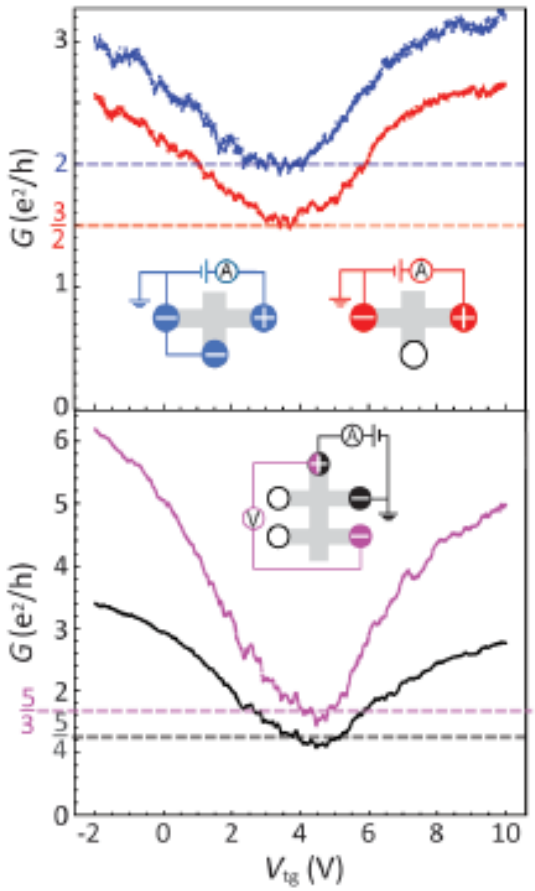


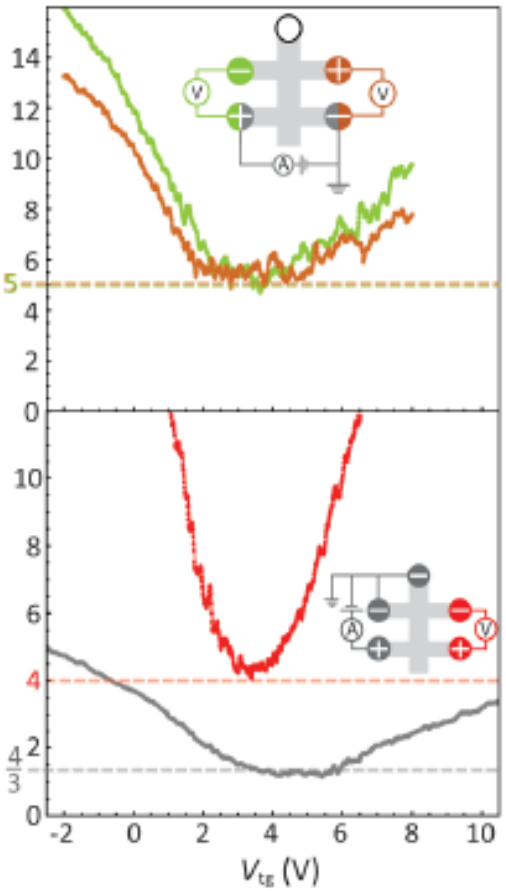


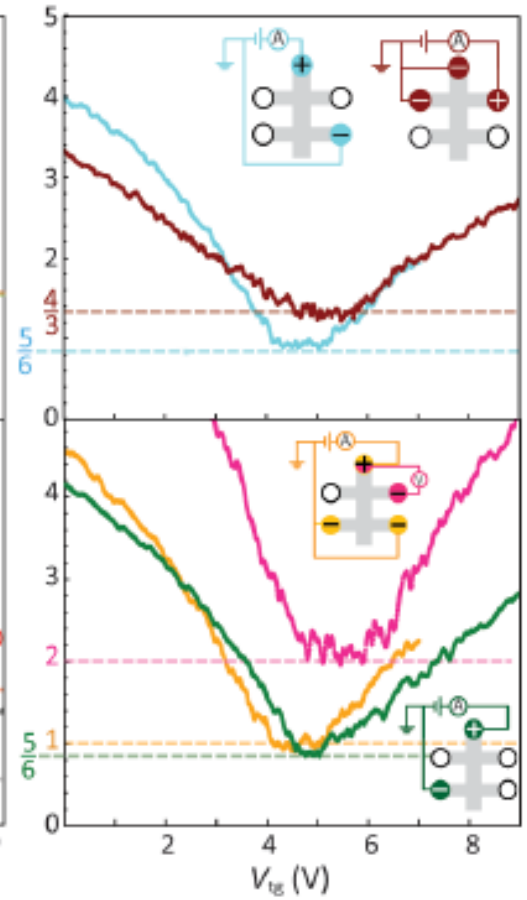
broadened resistance peak (conductance dip at $2e^2/h$) is a sign for the existence of two edge states measured for different voltage pairs

quantum spin Hall states at zero magnetic field









$$G_{2T} = \frac{e^2}{h}\left(\frac{1}{N_L+1}+\frac{1}{N_R+1}\right)$$

$N_{L,R}$: number of floating probes along left/right edges

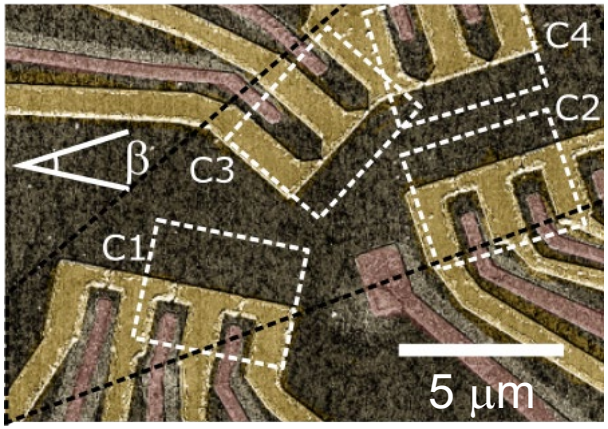
$$G_{4T} = G_{2T}\frac{N_I+1}{N_V+1}$$

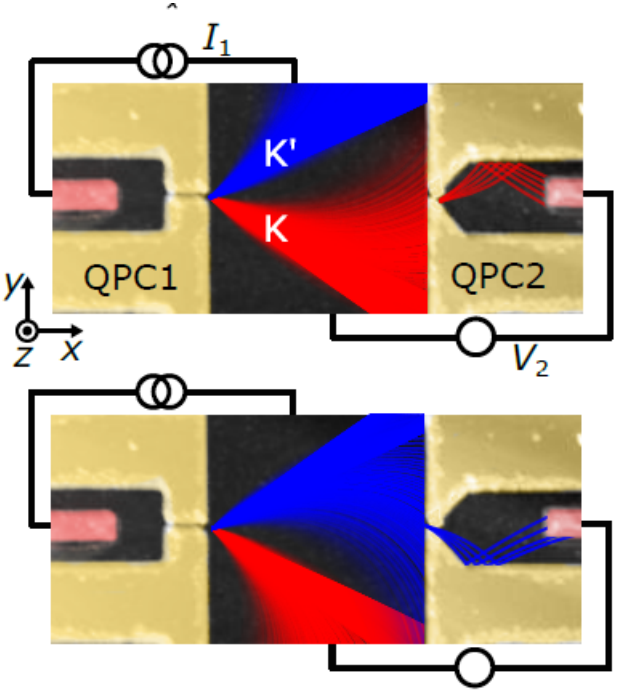
N_I: number of floating probes along edge where voltage is measured

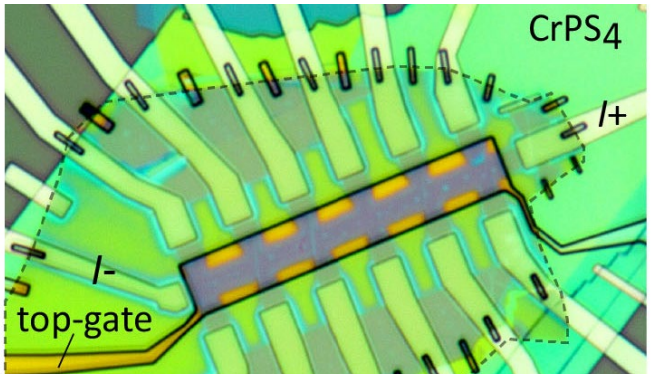
N_v: number of probes between voltage probes

conclusion

- in 2D materials electrons, their spin and their presence in specific valleys can be used for quantum devices using different technology platforms
- broken inversion symmetry needed to access the valleys; bilayer graphene: use perpendicular electric field
- with electron focussing experiments valley polarized electron jets have been demonstrated in BLG
- next step: combine the different components into more complex devices







heterostructures of 2D materials offer many possibilities to fabricate new quantum devices