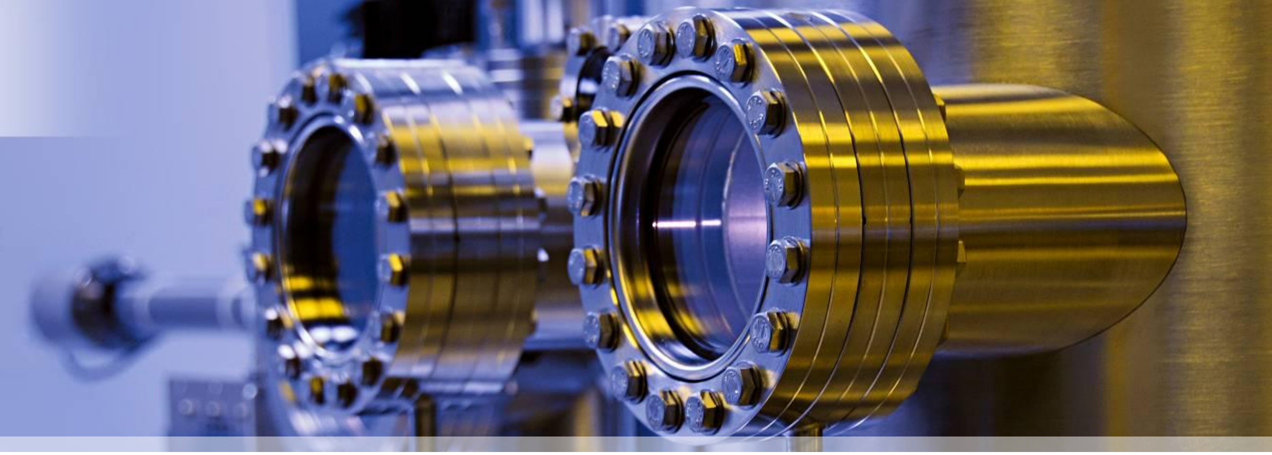
university of groningen

physics of nanodevices



Charge and spin transport in high quality suspended and boron nitride based graphene devices

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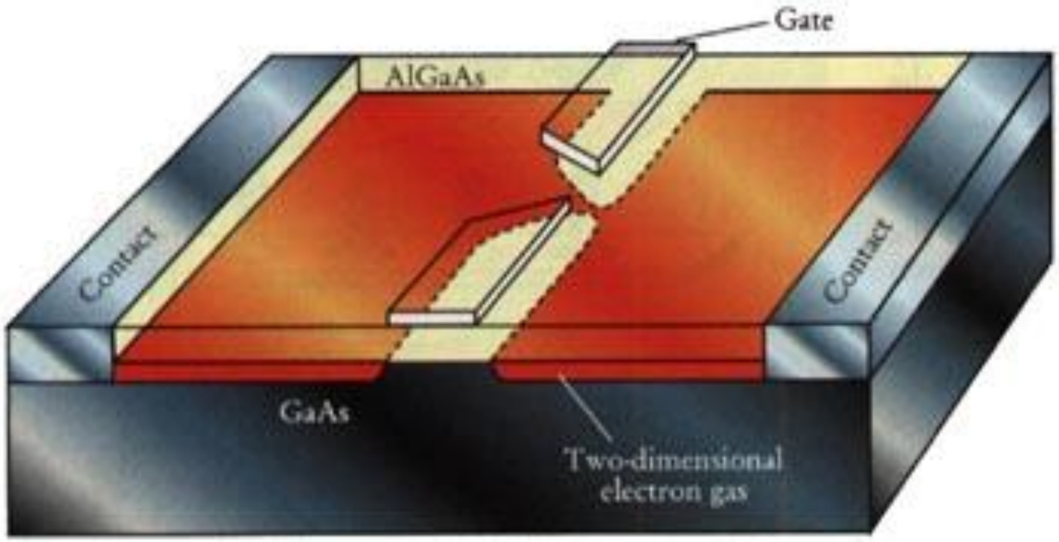
HFML

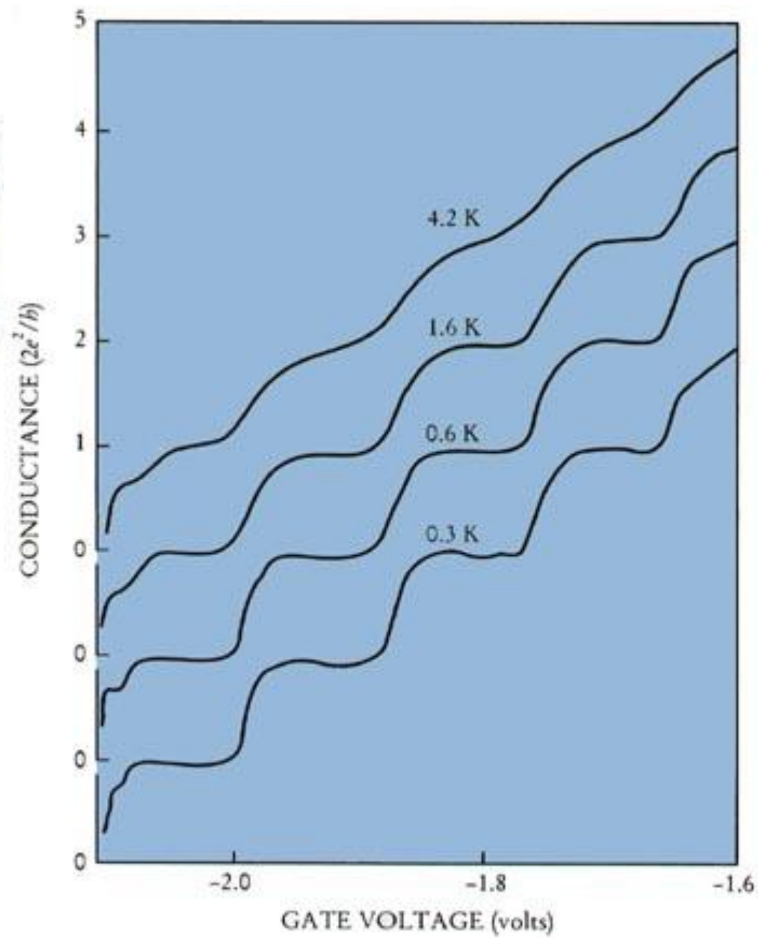
Science in High Magnetic Fields

University of Groningen
Zernike Institute
for Advanced Materials

NWO
Netherlands Organisation for Scientific Research

Conductance quantization of quantum point contacts in GaAs/AlGaAs 2DEG (1988)

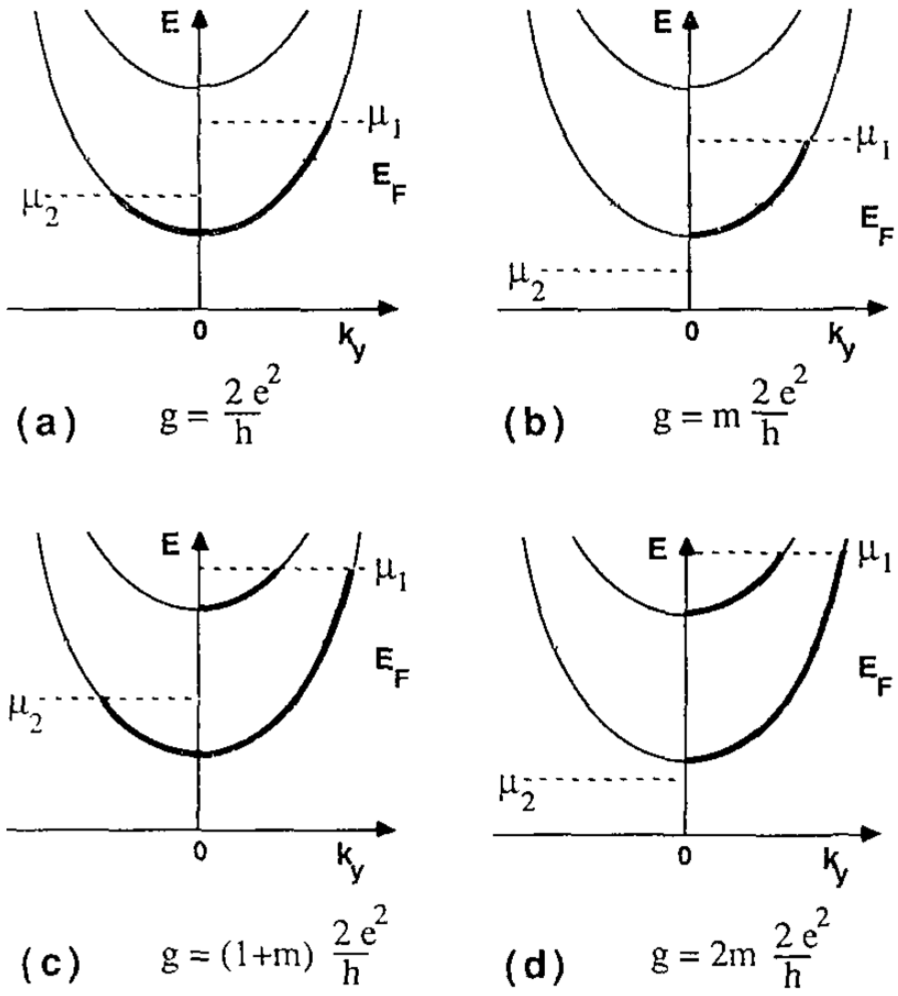




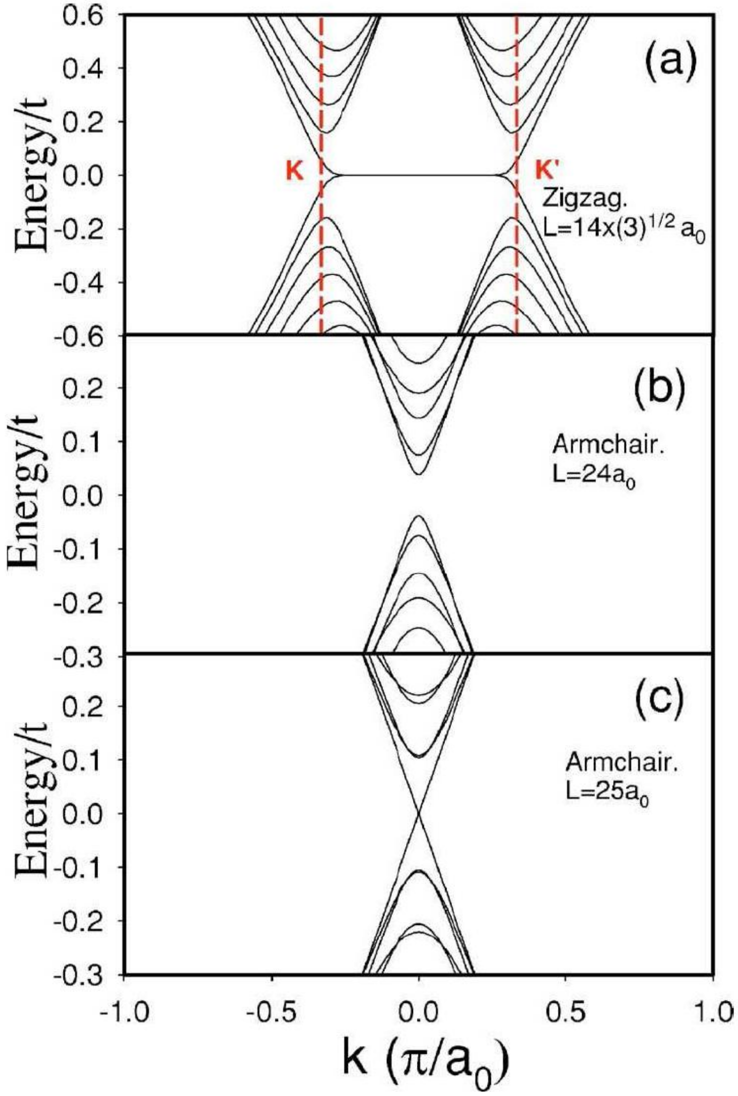
Landauer formula:

$$G = \frac{2e^2}{h} \sum_n t_n,$$

Quantized conductance of one-dimensional channels



Energy spectrum of graphene nanoribbons



quantization sequence:

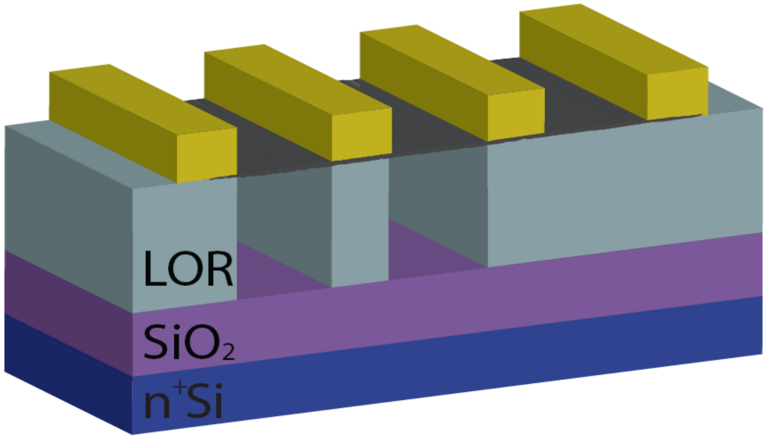
$2e^2/h$, $6e^2/h$, $10e^2/h$, …

0, $2e^2/h$, $4e^2/h$, $6e^2/h$, …

$2e^2/h$, $4e^2/h$, $6e^2/h$, …

Brey and Fertig, PRB 2006

New polymer based process:



* Fully resist based process: only organic solvents used
 -> compatible with most materials

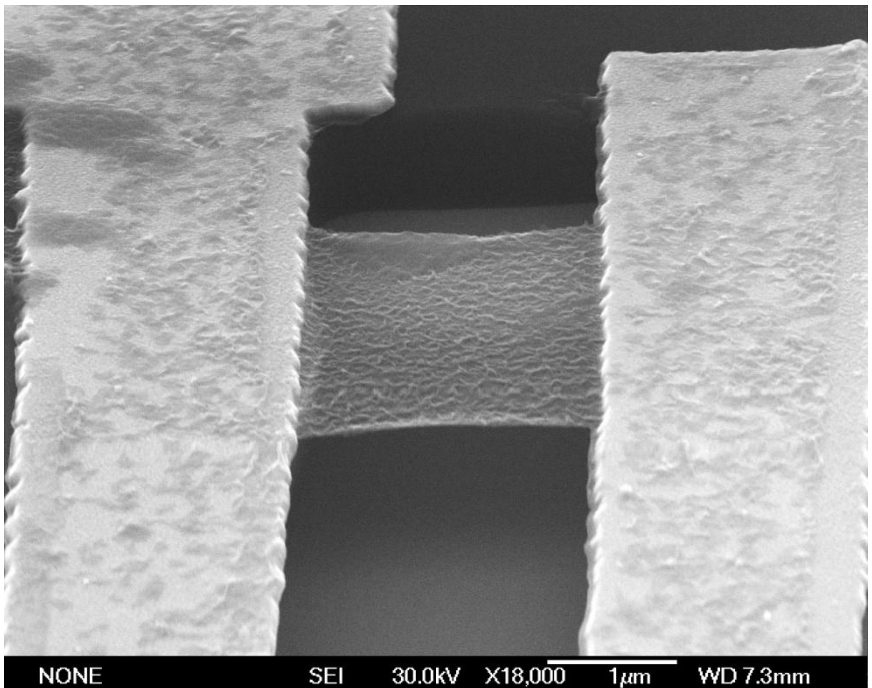
* Very low contact resistances (required for two-terminal measurements)

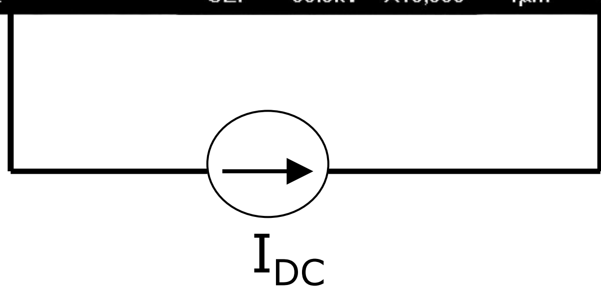
LOR = polydimethylglutarimide based organic resist

N. Tombros, A.Veligura, J. Junesch, J. J. van den Berg, P. J. Zomer, I. J.Vera Marun, H. T. Jonkman, and B.J. van Wees, *Large yield production of high mobility freely suspended graphene electronic devices on a PMGI based organic polymer*, J. Appl. Phys. 109, 093702 (2011) , arXiv:1009.4213

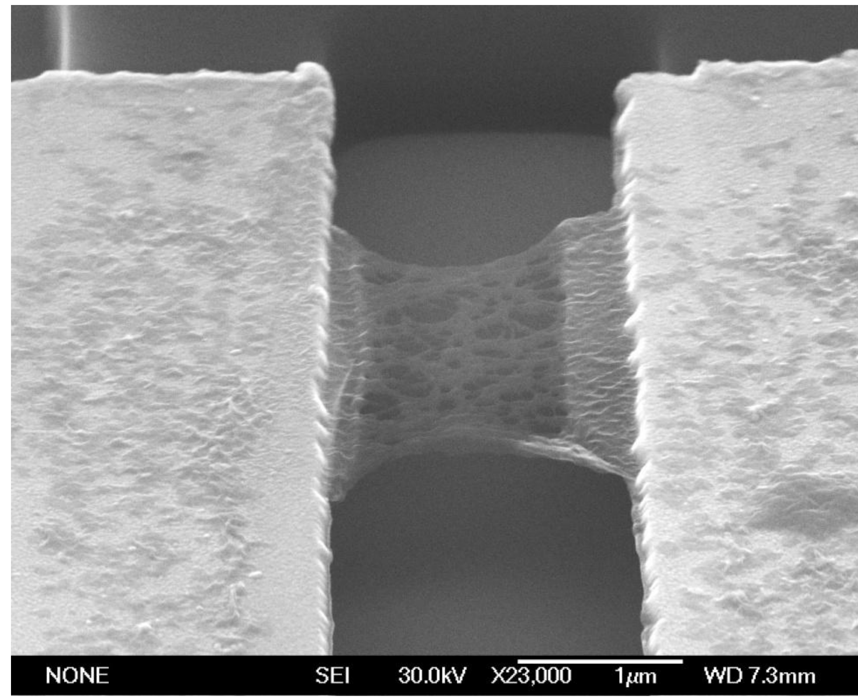
Current annealing: 30-40 % yield!

Not annealed



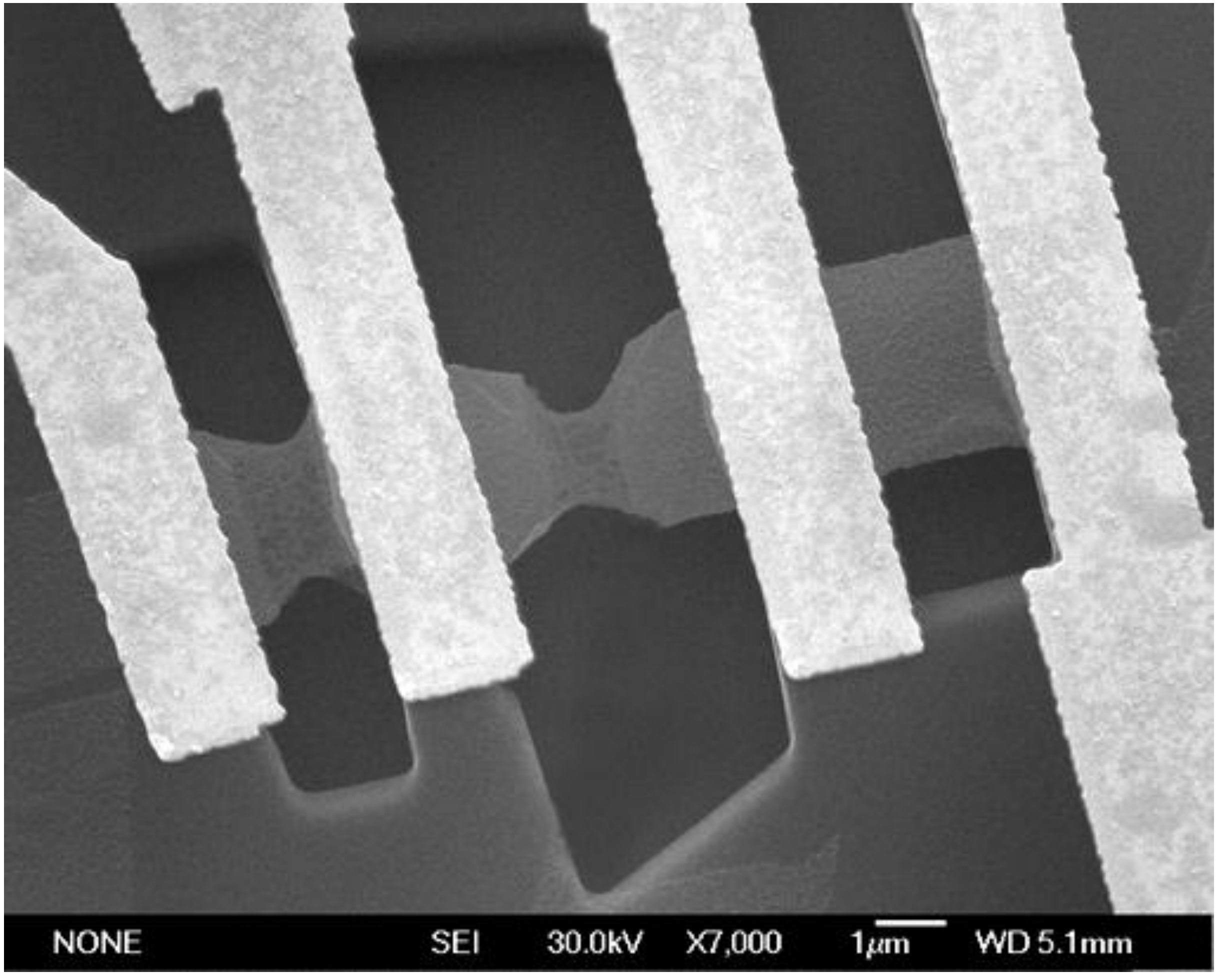


Annealed

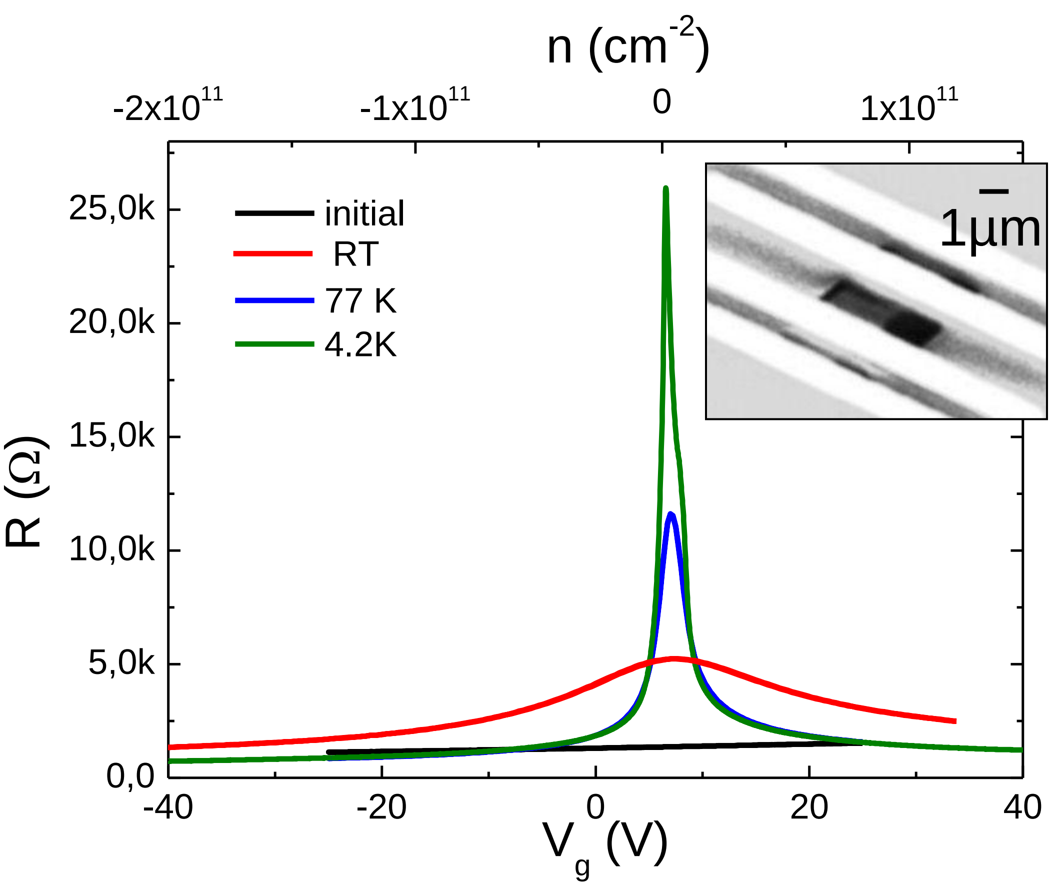


- j > 1 mA/μm/layer; P>0.5 mW

Formation of constrictions during current annealing



Large improvement in graphene quality



$$\mu = \frac{1}{n \cdot e \cdot R_{sq}}$$

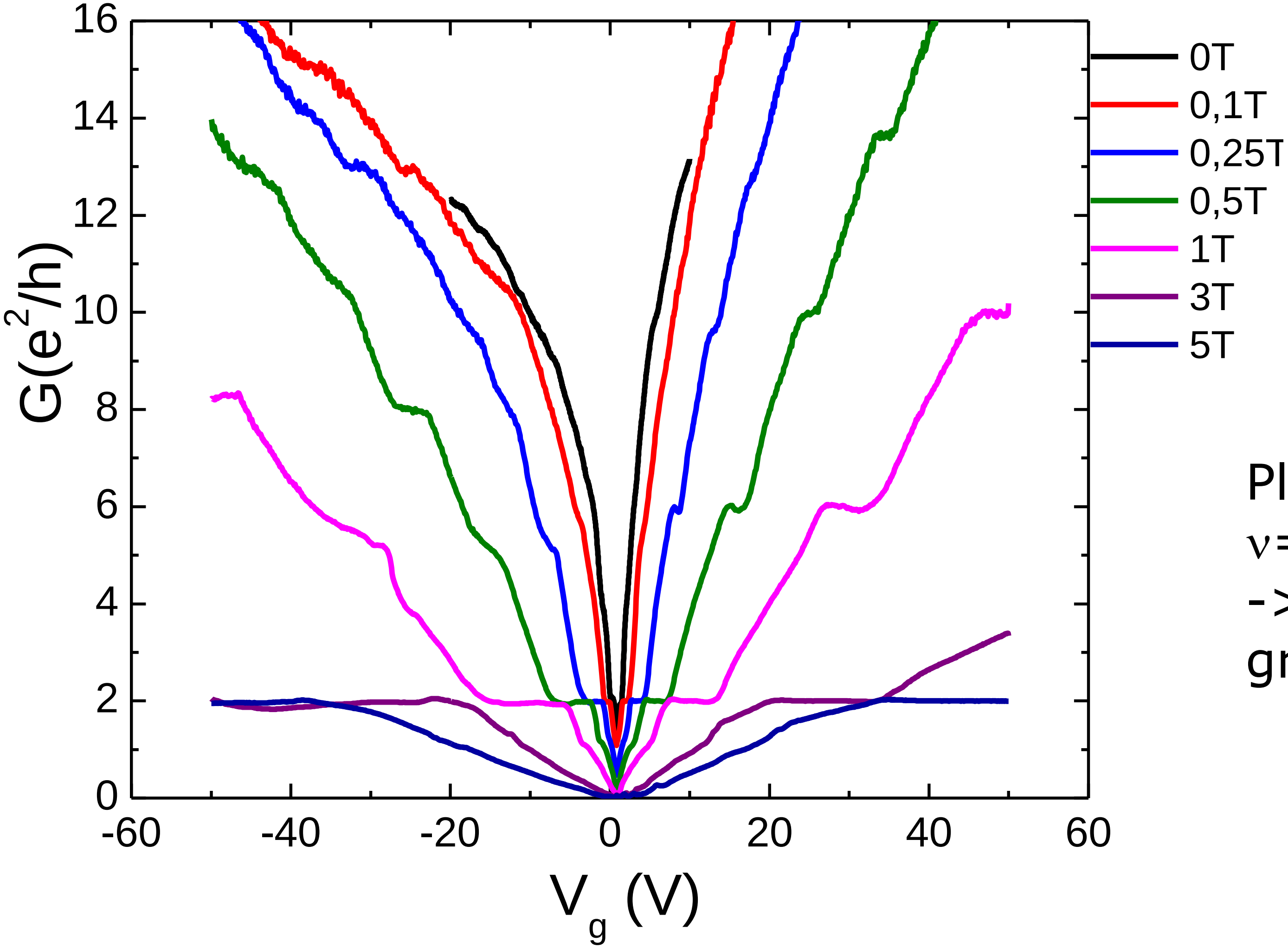
$$n = \alpha V_g$$

$$a = 0.45 \cdot 10^{10}\ cm^{-2} V^{-1}$$

μ_{SL} >260.000 $cm^2V^{-1}s^{-1}$
at
n= $2 \cdot 10^{10}$ cm^{-2}

Ballistic transport:
λ_{mfp}~(250-500) nm

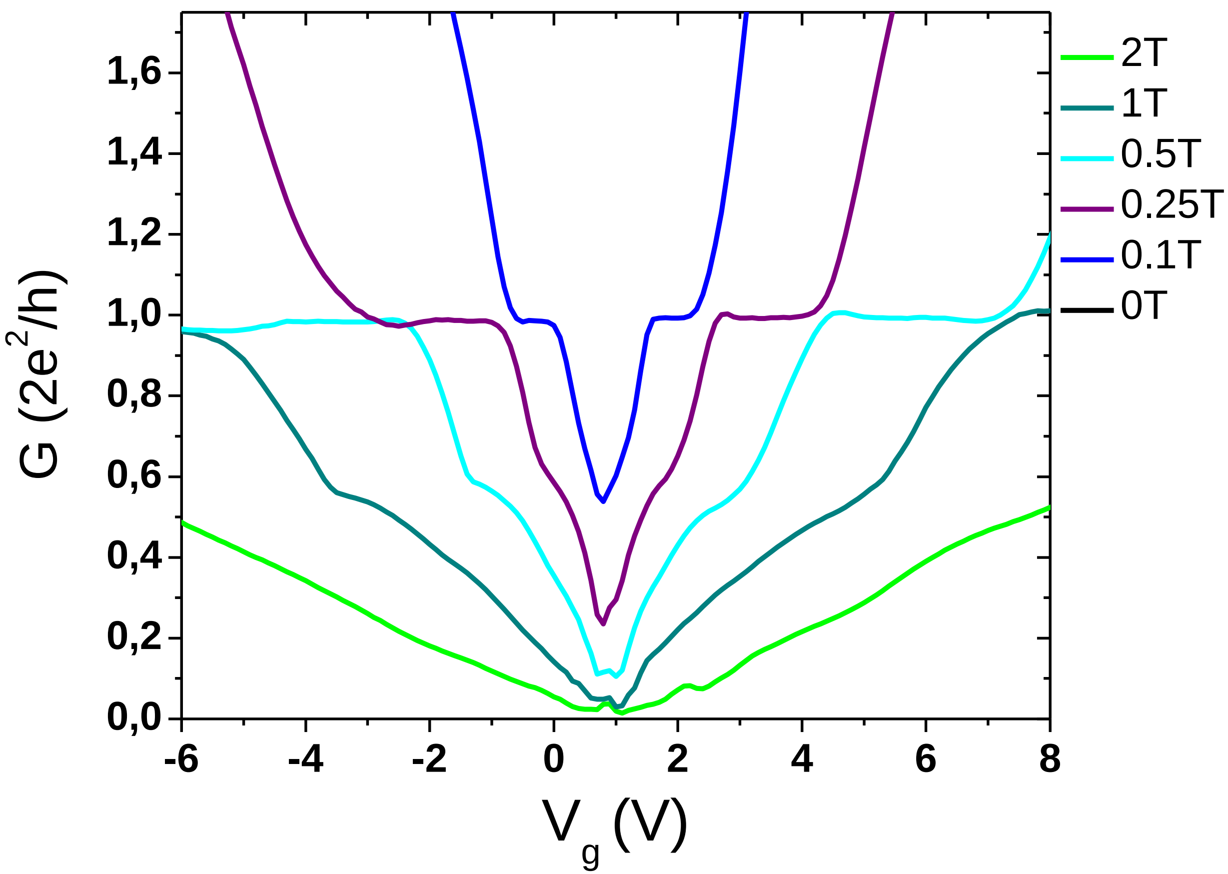
Two-terminal quantum Hall effect at 4.2 K



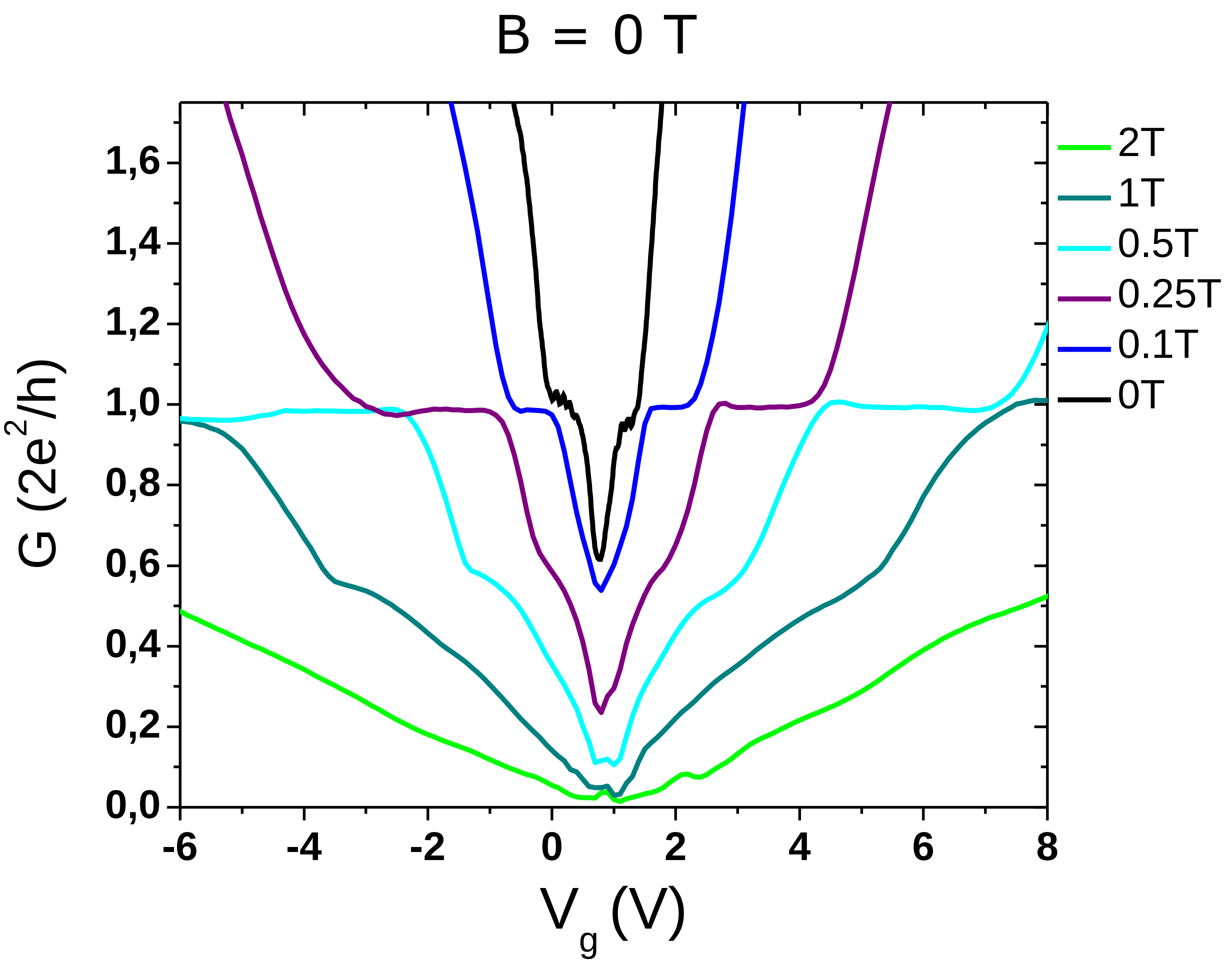
$$E_{SL} = \pm\sqrt{2\hbar c^2 eB|N|}$$

Plateaus at
ν= 2, 6, 10, etc
-> single layer graphene

Low magnetic field regime



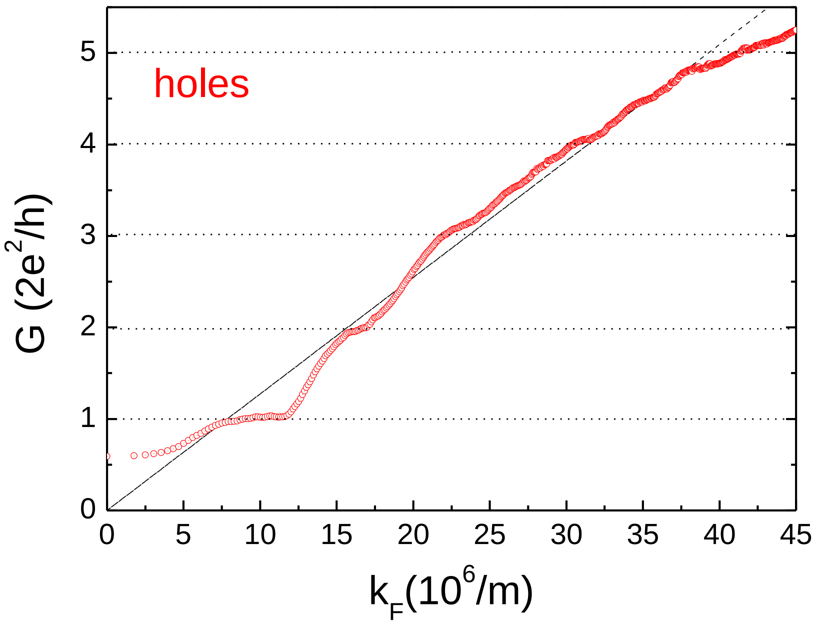
Quantization at zero B!



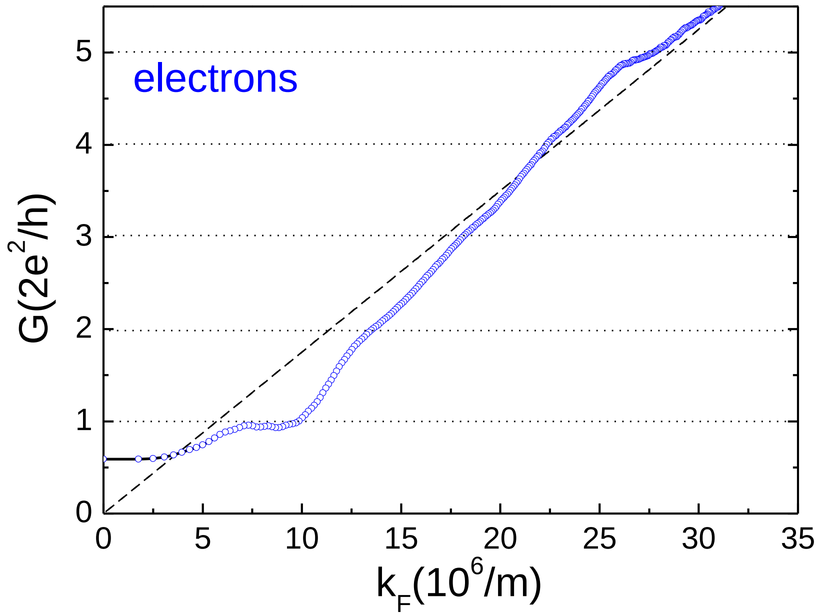
Conductance quantization of electrons / holes.

N. Tombros et al. Nature Physics 7, 697–700 (2011)

W_h= 275 nm



W_e=200 nm



Calculate k_F from density n:

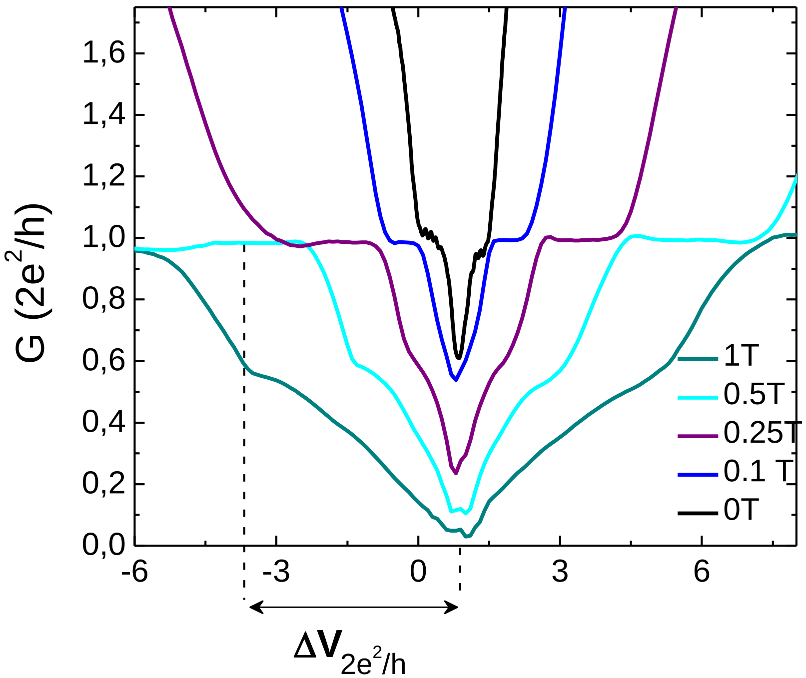
$k_F = \sqrt{\pi n}$

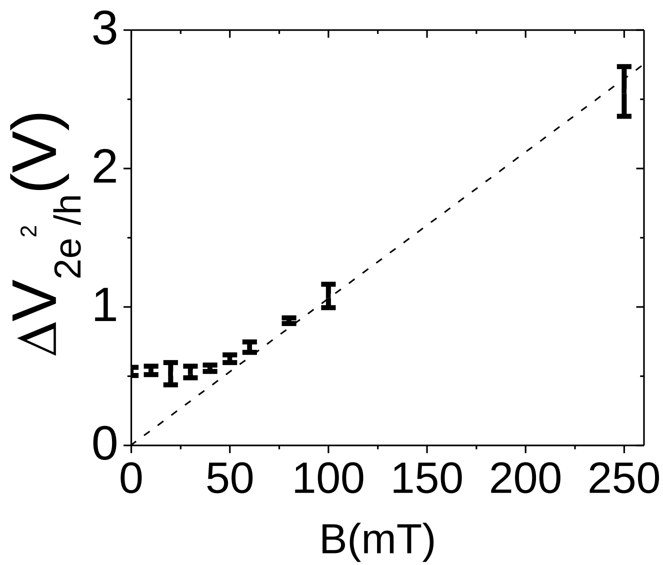
$k_F = 2\pi/\lambda_F$

$$G = 1\frac{2e^2}{h},\quad 2\frac{2e^2}{h},\quad 3\frac{2e^2}{h},\quad 4\frac{2e^2}{h}$$

$$G = \frac{4e^2}{h}\frac{k_F W}{\pi} \Longleftrightarrow G = D_{deg} \cdot N_{modes}$$

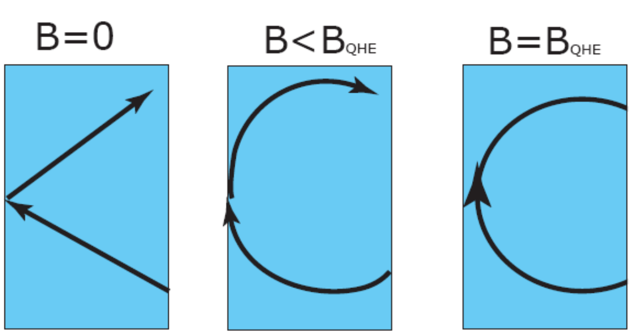
Transition from quantum confinement to quantum hall regime





$$W = \frac{2\hbar k_F}{eB}$$

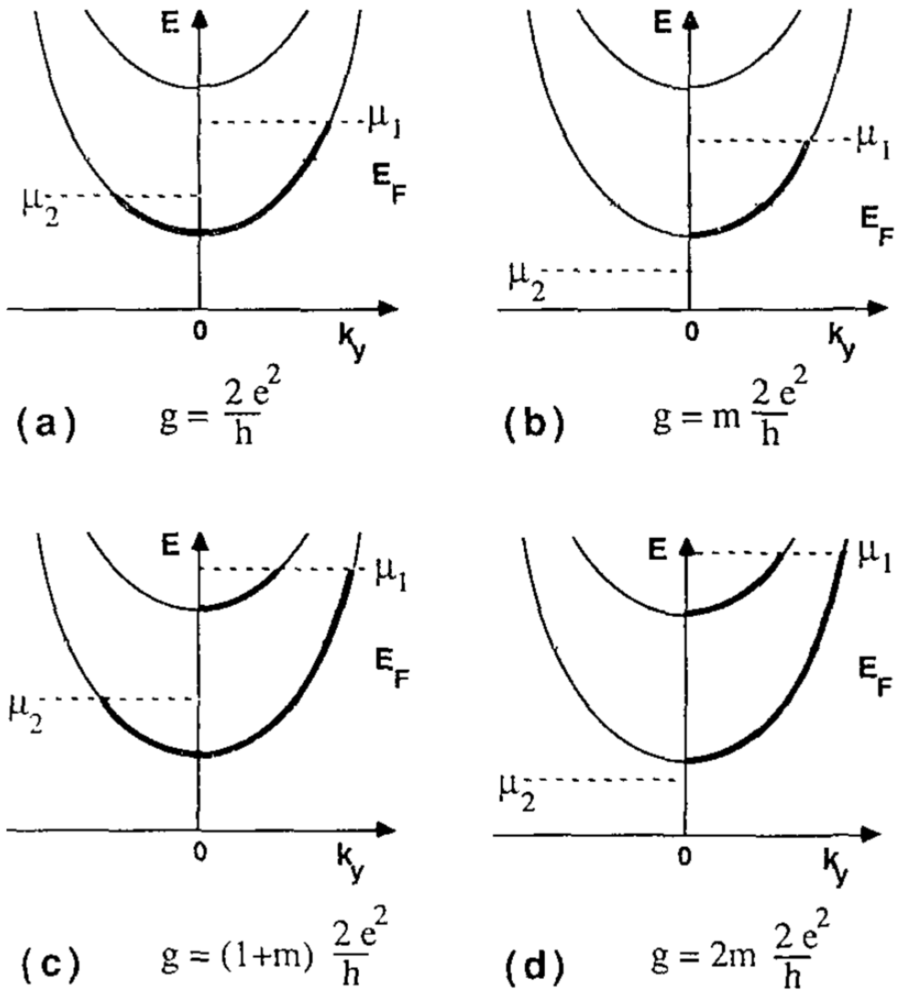
$$\nu = \frac{n_\nu h}{eB}$$



B=60 mT

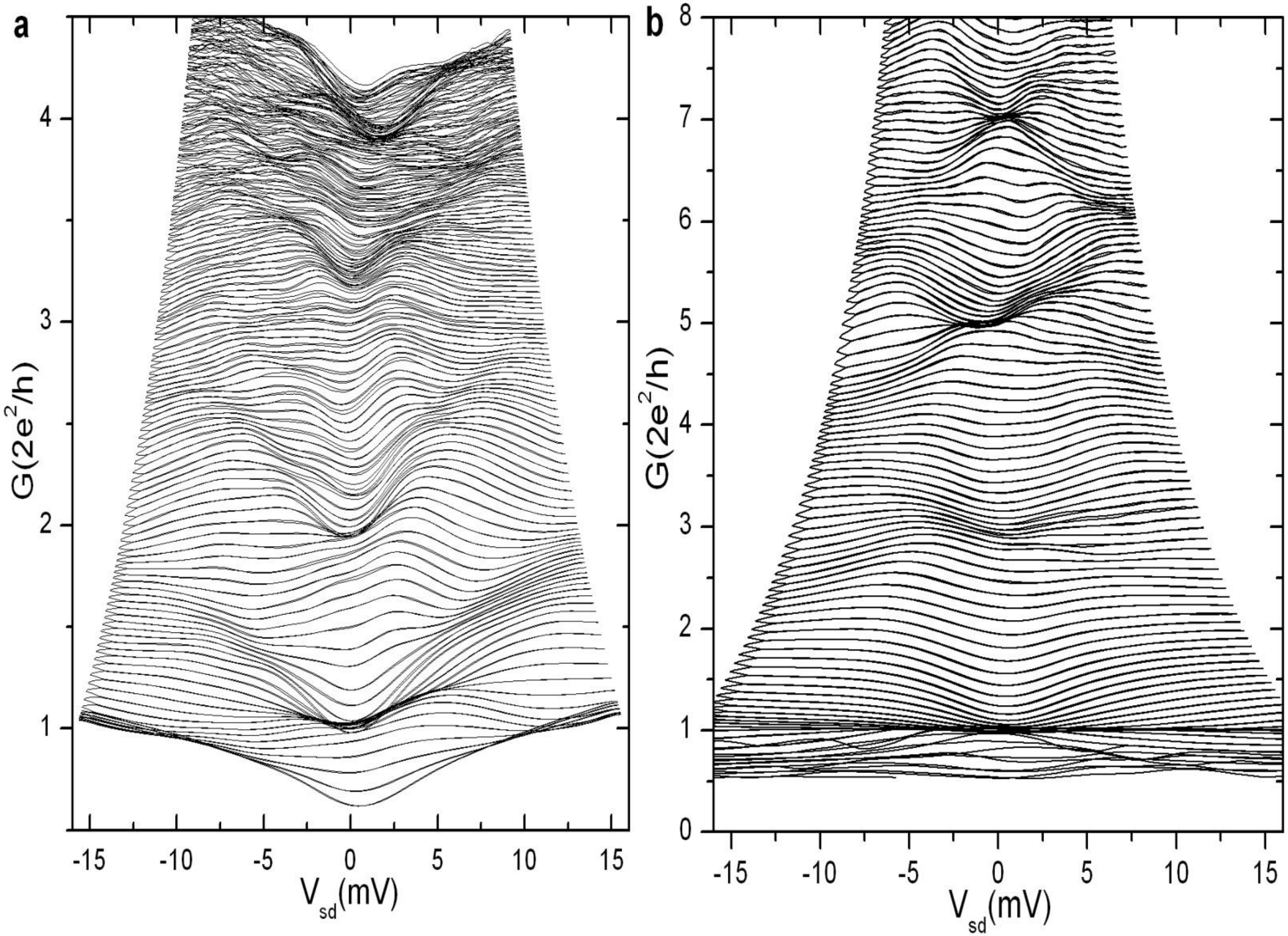
W=300 nm

Quantized conductance of one-dimensional channels



Voltage biased energy spectroscopy

B=0T B=0.5T



B=0.5T

$$E_{SL} = \pm\sqrt{2\hbar c^2 eB|N|}$$

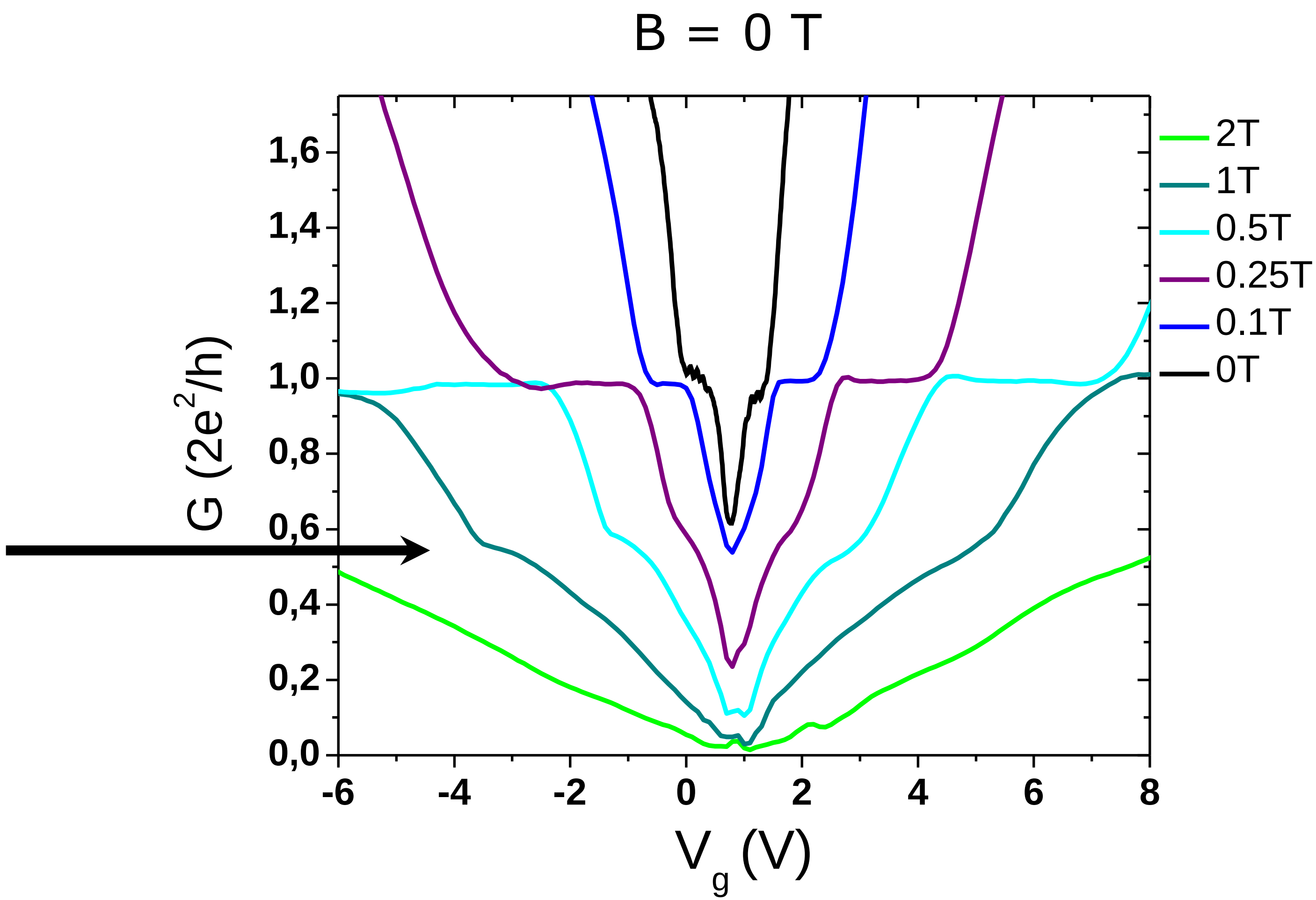
B=0T

$$\Delta E_{12} = 8\,meV$$

$$W = \frac{k_f \pi}{\Delta E} = \frac{\hbar v_f \pi}{\Delta E}$$

W=240 nm

“0.6 structure”



Conclusions

- Conductance quantization at B=0 due to quantum confinement in a narrow and short constriction

- "Effective" boundary conditions at edges

-> valley degeneracy lifted, gap formation at zero density

- Continuous evolution into quantum Hall edge channels

- $2e^2/h$ plateau is surprisingly accurate and flat

- "0.6 structure" :signature of electron-electron interaction

- Fermi velocity renormalization? (to be checked)

- More devices needed!!!

Spin orbit interaction in graphene

*Intrinsic SO interaction in graphene (weak).

*Rashba type (effective SO fields in x-y plane, perpendicular to electron velocity)

Type 1: Electric field from top/bottom gate (homogeneous SO fields)

Type 2: Curvature induced (SO fields fluctuate with zero average)

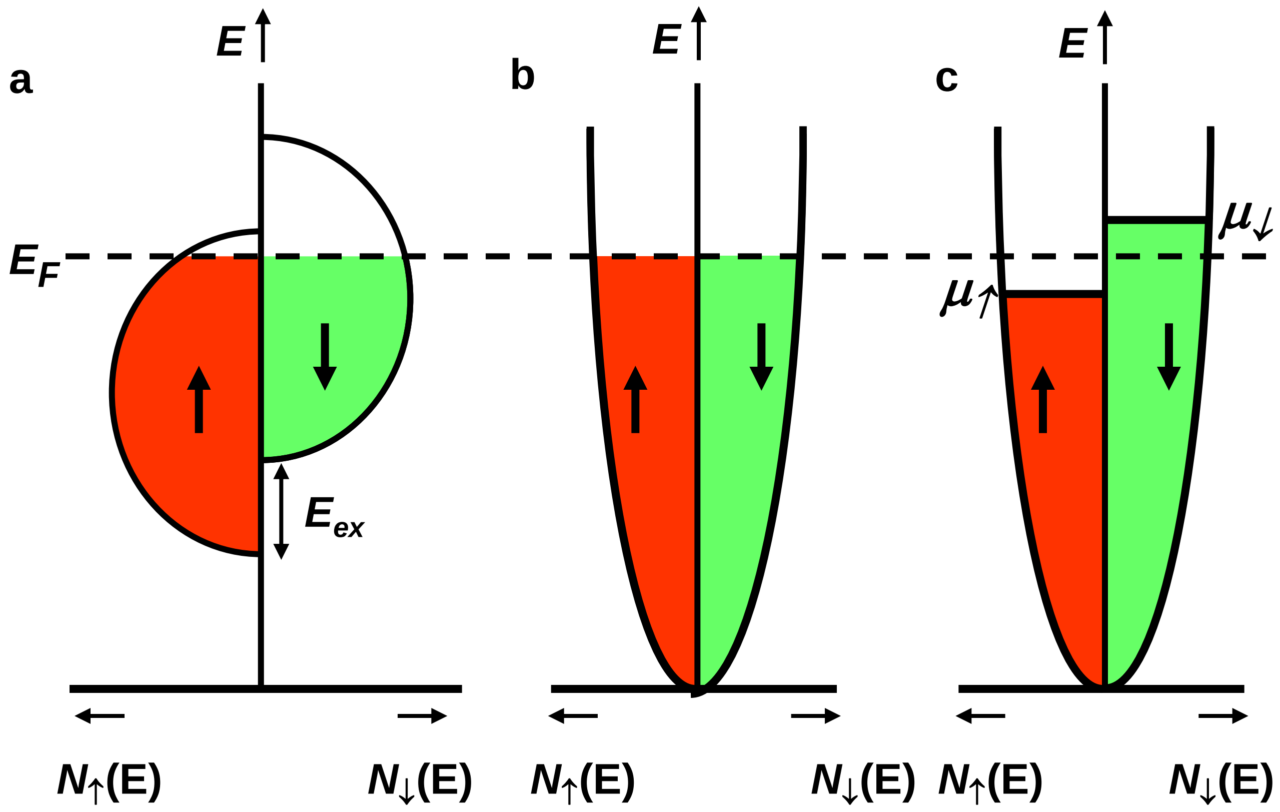
*Scattering induced SO interaction. (Elliot-Yafet mechanism)

Different scaling with mobility:

Dyakonov-Perel: spin relaxation time ~ 1/ momentum relaxation time

Elliot-yafet: spin relaxation time ~ momentum relaxation time

Spin injection/detection scheme



ferromagnet

paramagnet

Bloch equations for spin accumulation

$$\frac{\partial \vec{\mu}}{\partial t} = D\nabla^2 \vec{\mu} - \frac{\vec{\mu}}{\tau} + \left(\frac{g\mu_B}{\hbar} \vec{B} \times \vec{\mu} \right)$$

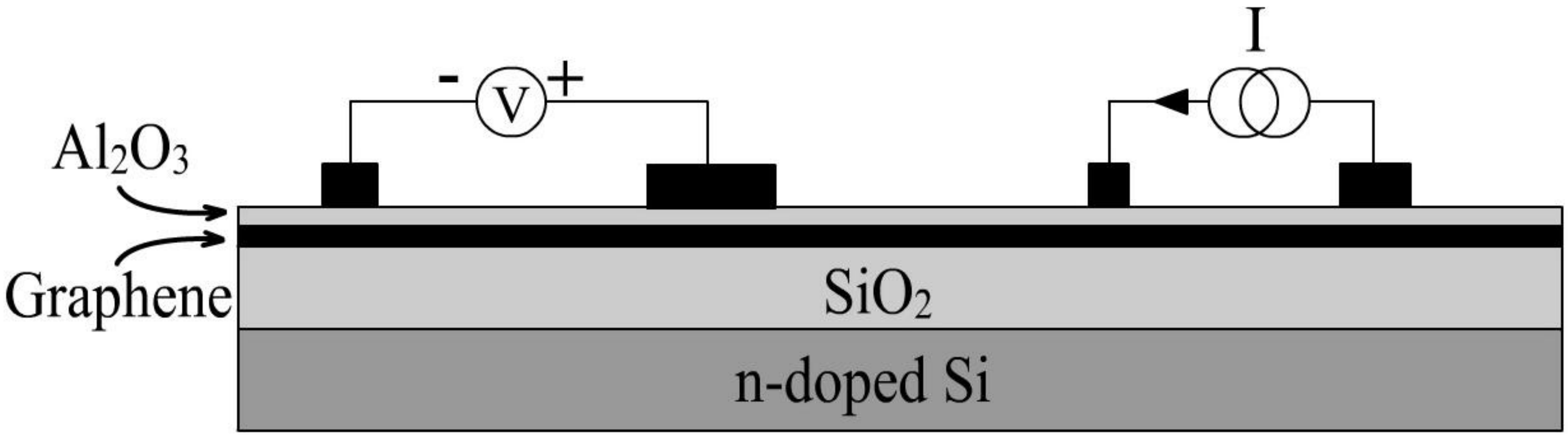
1) Diffusion D : diffusion constant

2) Relaxation τ : spin relaxation time

3) Larmor spin precession: g ~ 2

Spin relaxation length: $\lambda = \sqrt{D\tau}$

Field effect transistor + non-local technique



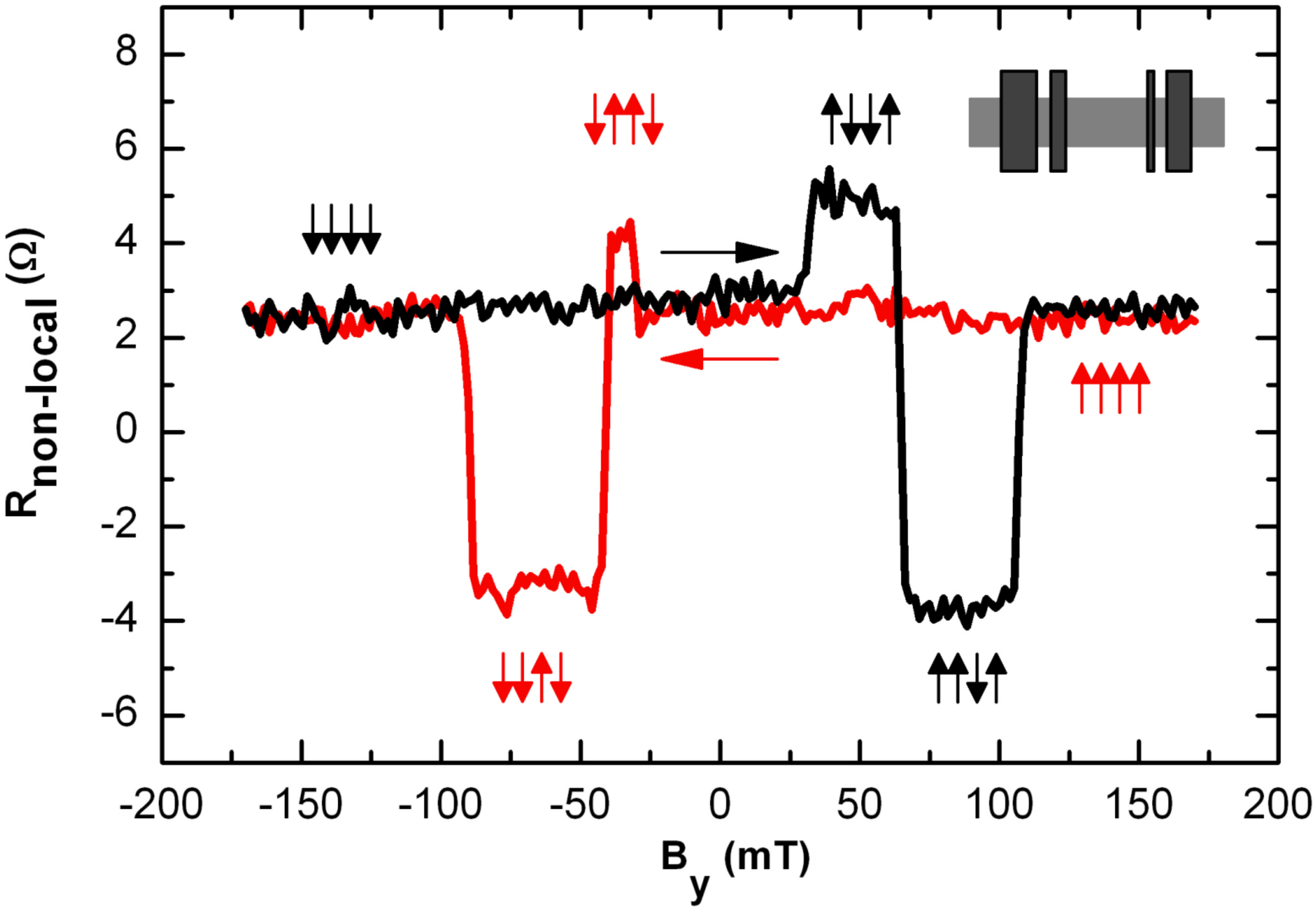
Optimize spin injection/detection by 1 nm Al_2O_3 oxide layer

Current contacts: inject spin current

Voltage contacts: measure spin dependent voltage

Gate voltage: applied between graphene and n-doped Si

Room temperature spin transport



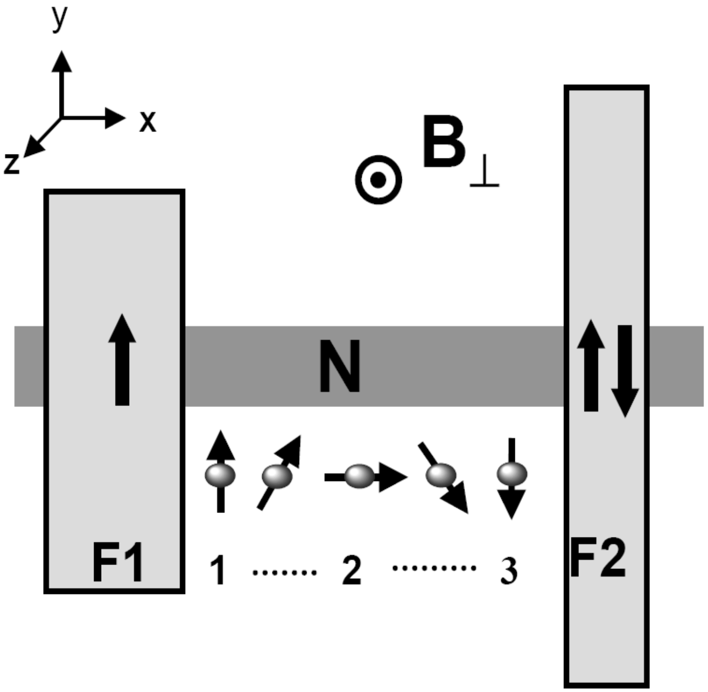
N. Tombros et al. Nature (2007)

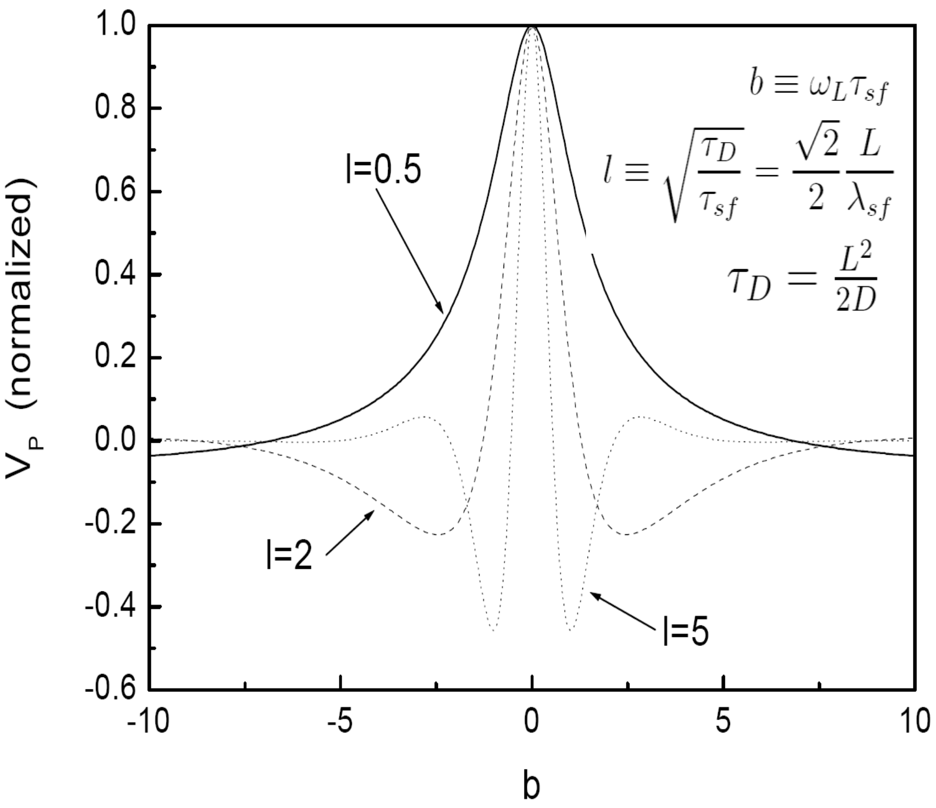
Spin polarization ≅ 10%

Spin relaxation length

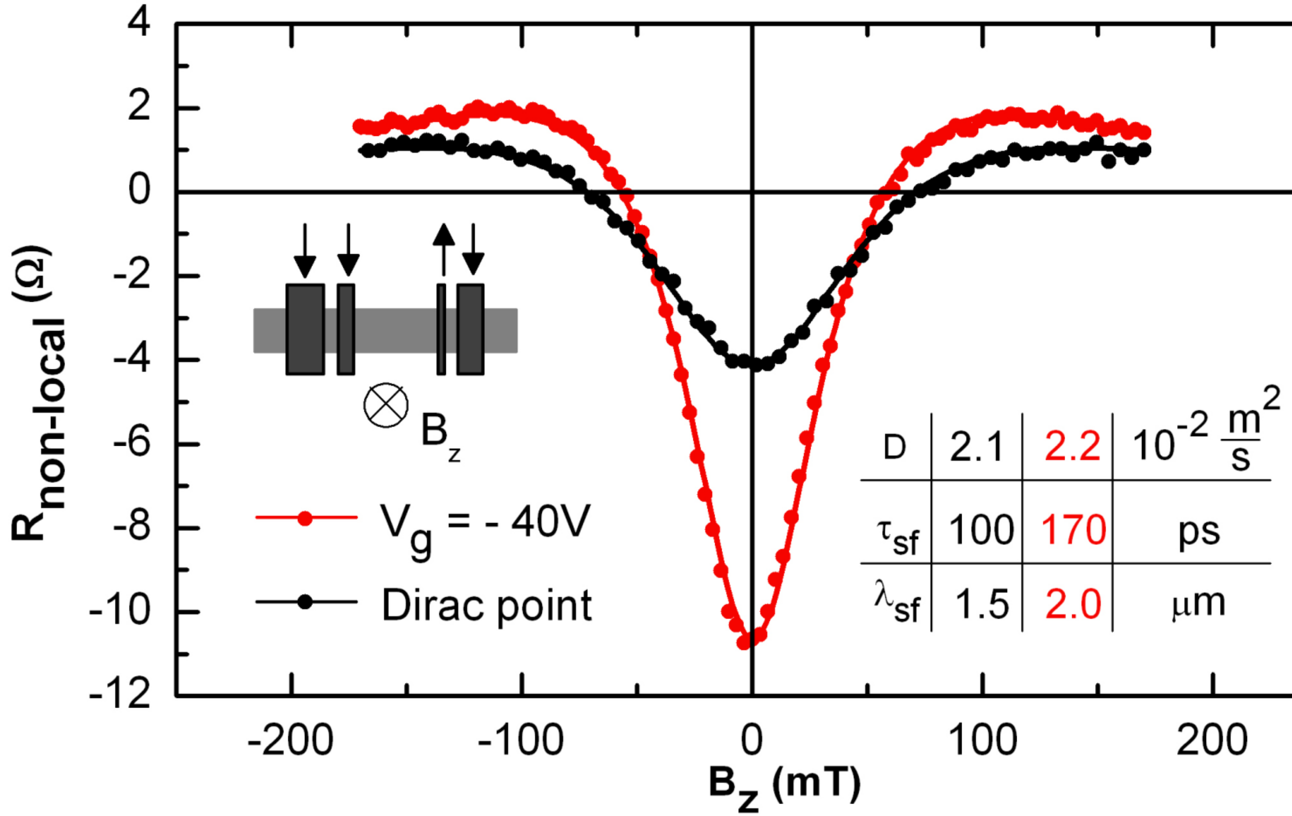
≅ 1.5 μm

Hanle spin precession

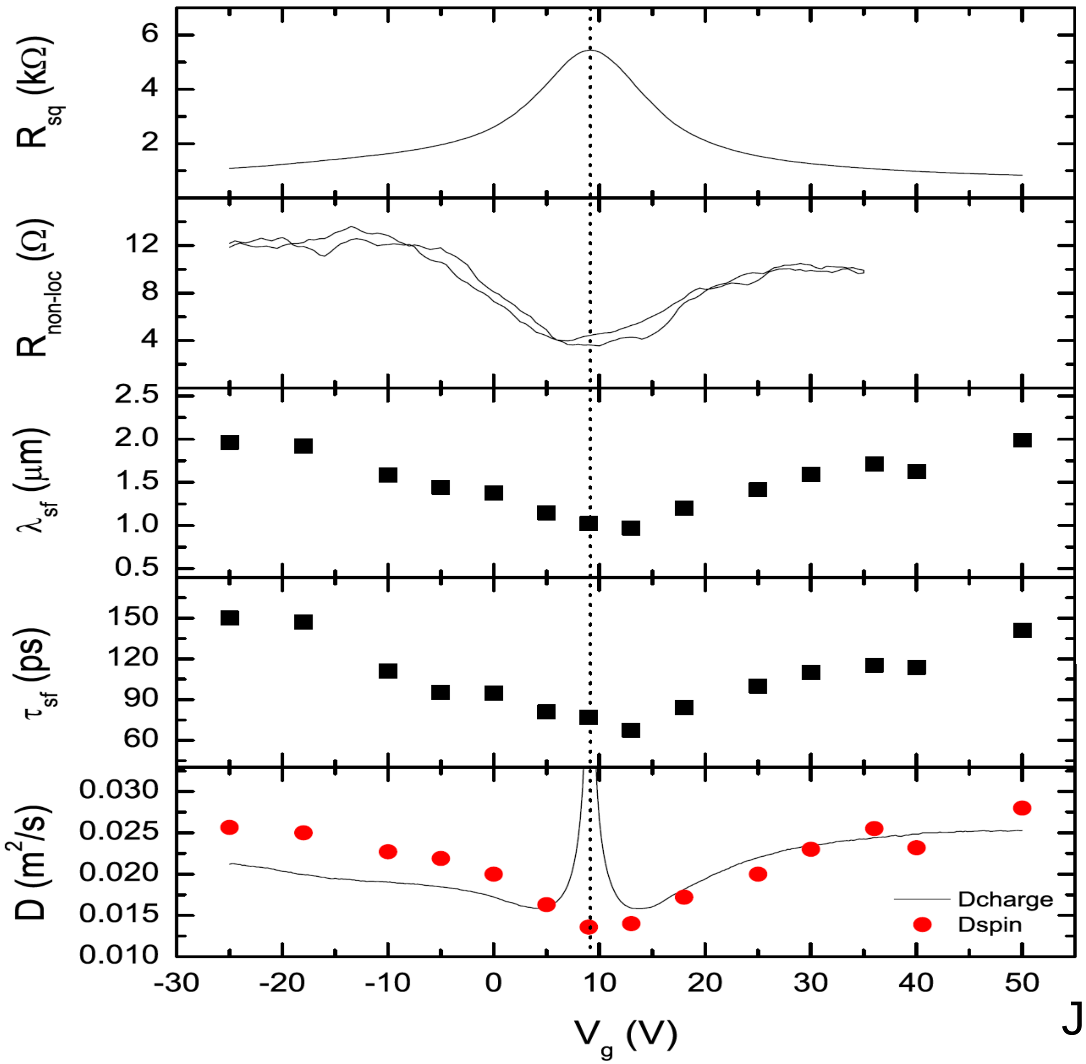


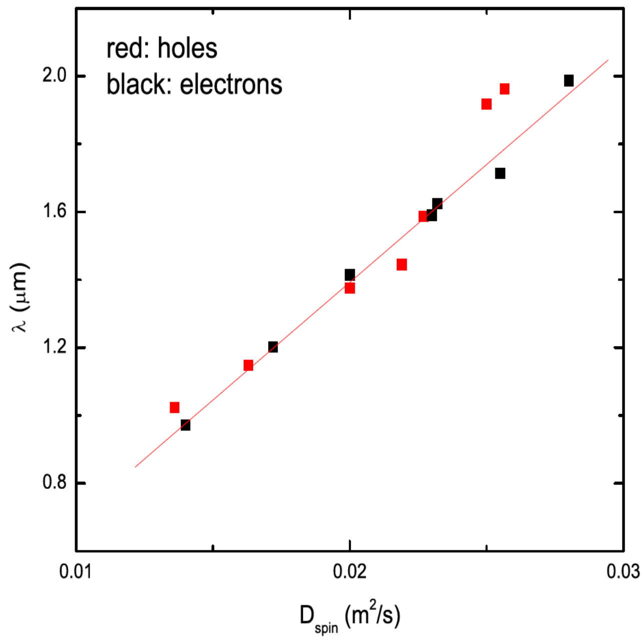


Spin precession (anti-parallel state)



Spin relaxation vs. diffusion constant



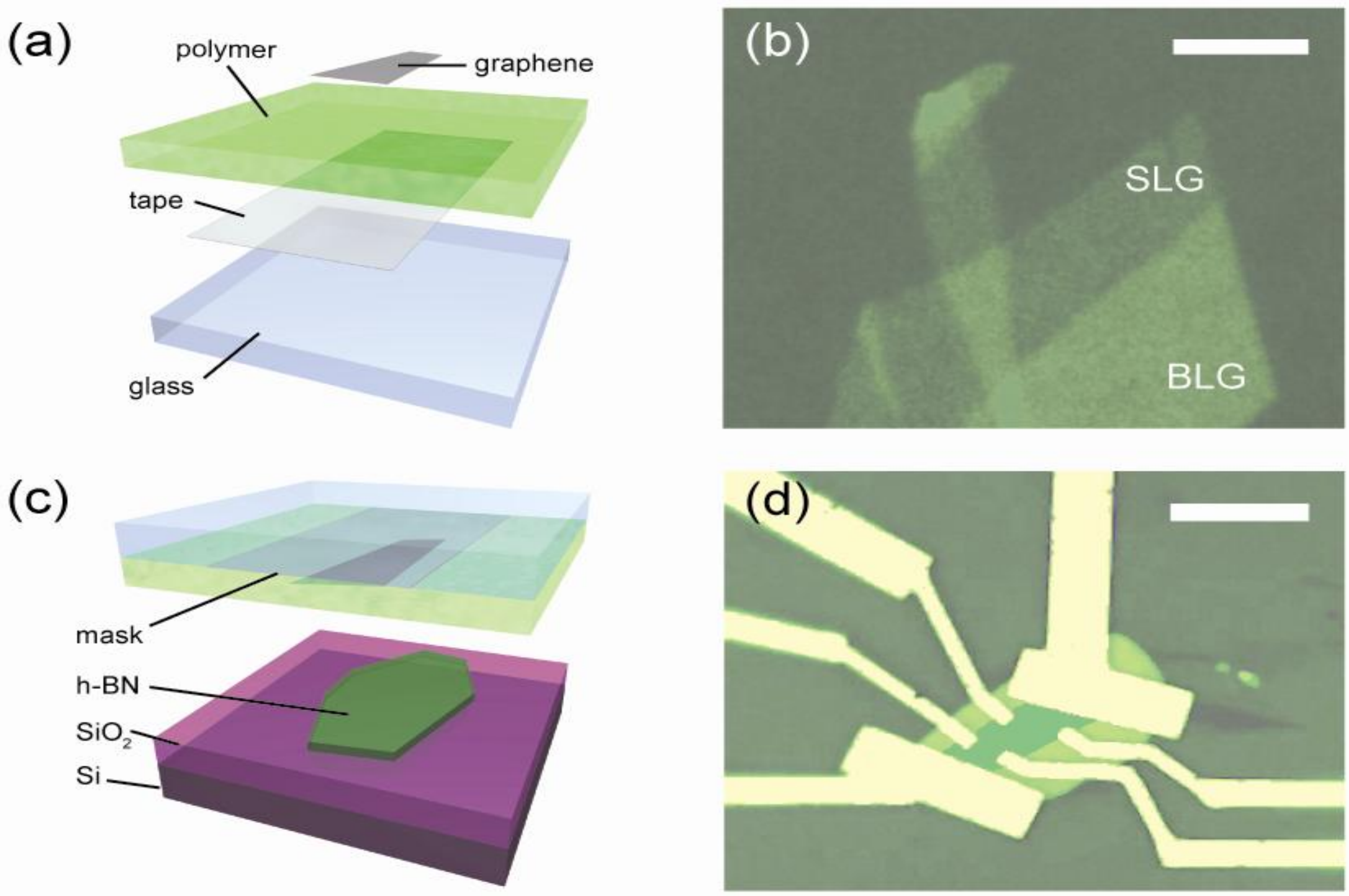


linear scaling between spin relaxation length and momentum scattering length!

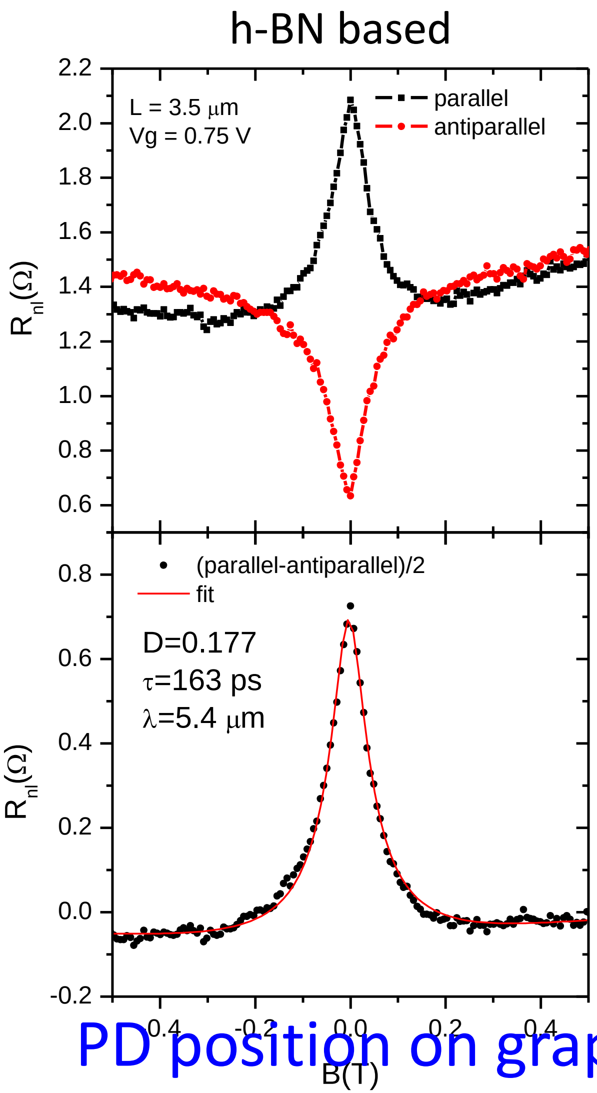
Jozsa et al, PRB, 241403(R) (2009)

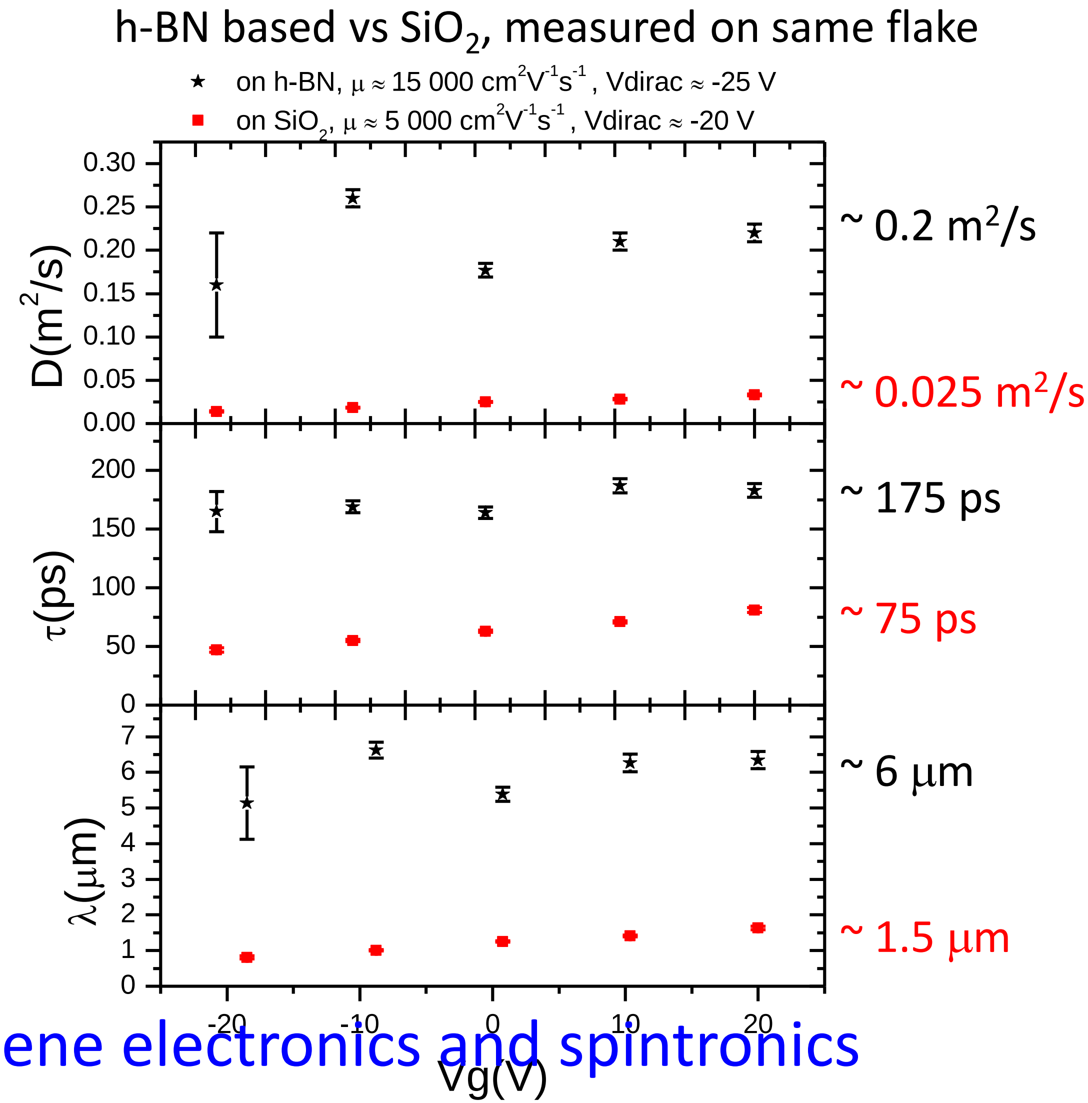
Graphene on boronnitride

P. Zomer et al.,Appl. Phys. Lett. 99, 232104 (2011).



Comparison between BN and SiO2





PD position on graphene electronics and spintronics

Thx to Physics of Nanodevices group