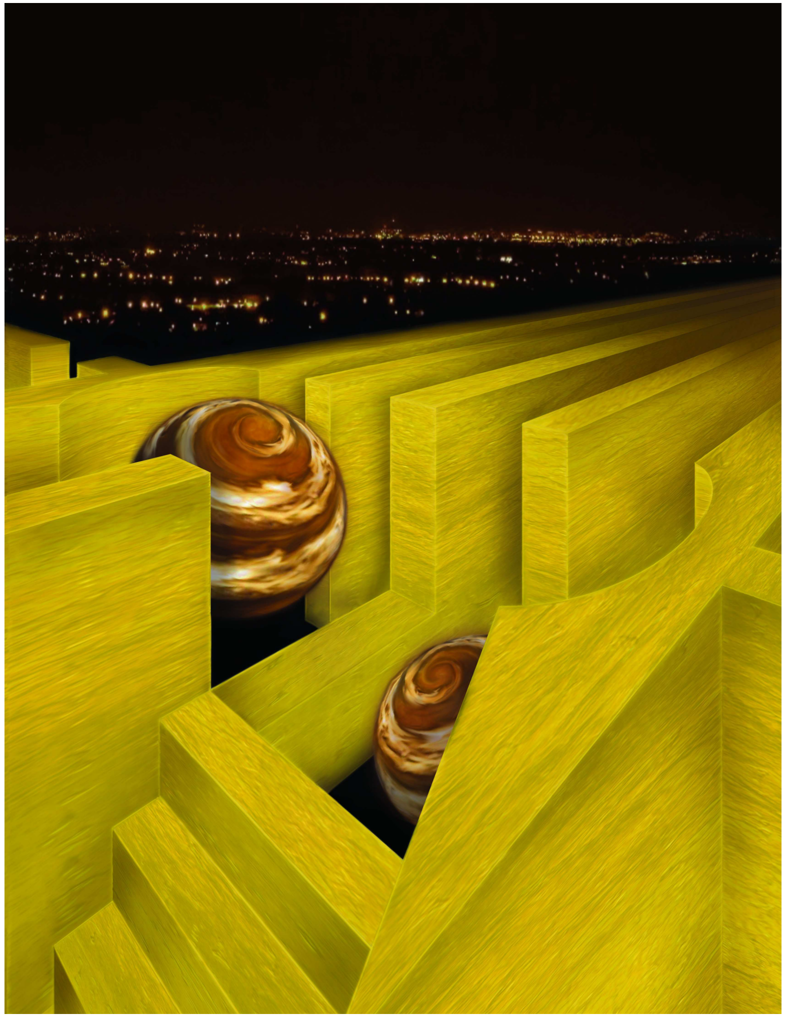
Real and futuristic spin qubits – from GaAs to graphene



Yukawa International Seminar
Kyoto, November 2007

Lieven Vandersypen

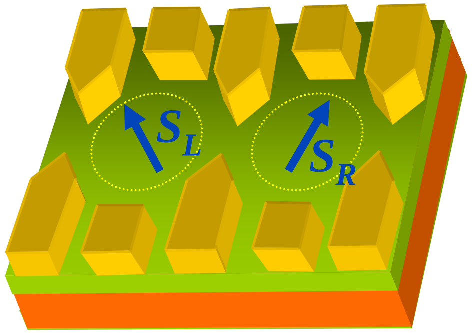
NWO FOM

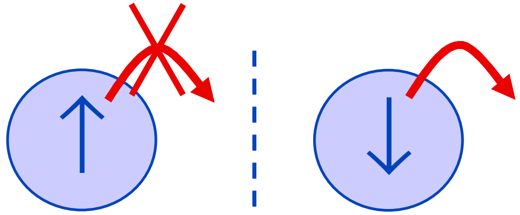
TU Delft
Delft University of Technology

Kavli Institute of Nanoscience

Spin qubits in quantum dots – key elements

Loss & DiVincenzo, PRA 1998
LMKV et al., Proc. MQC02 (quant-ph/0207059)



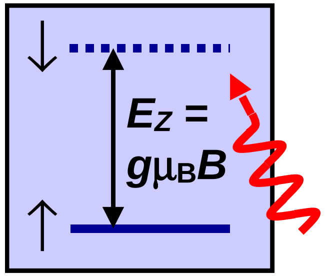


Initialization — 1 electron, low T, high B_0

Read-out — spin-to-charge conversion

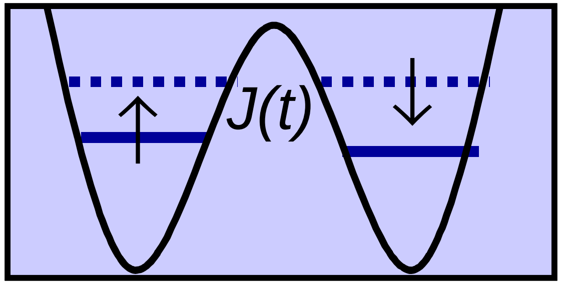
Delft Nature 2004

ESR — pulsed microwave magnetic field



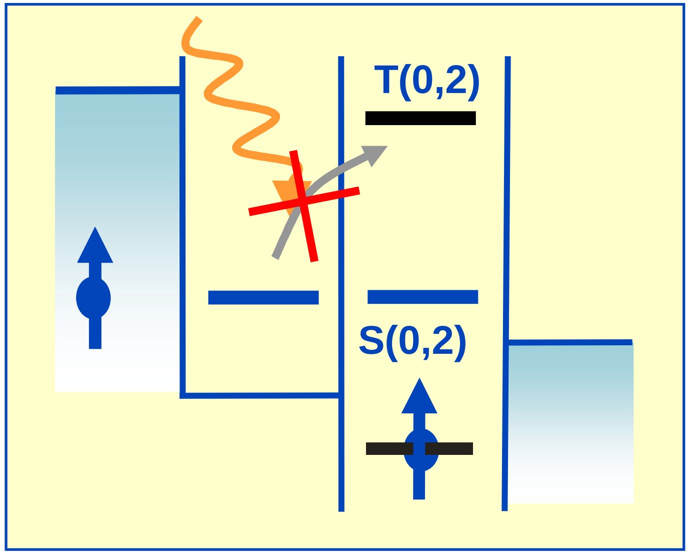
SWAP — exchange interaction

Harvard Science 2005

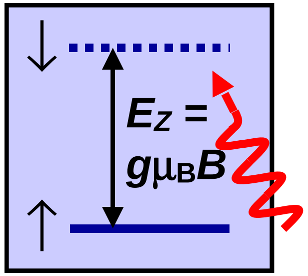


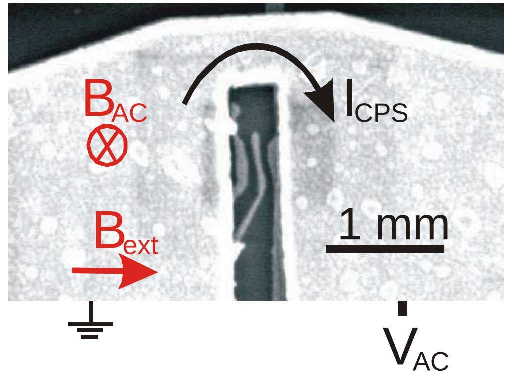
Coherence — T_1, T_2

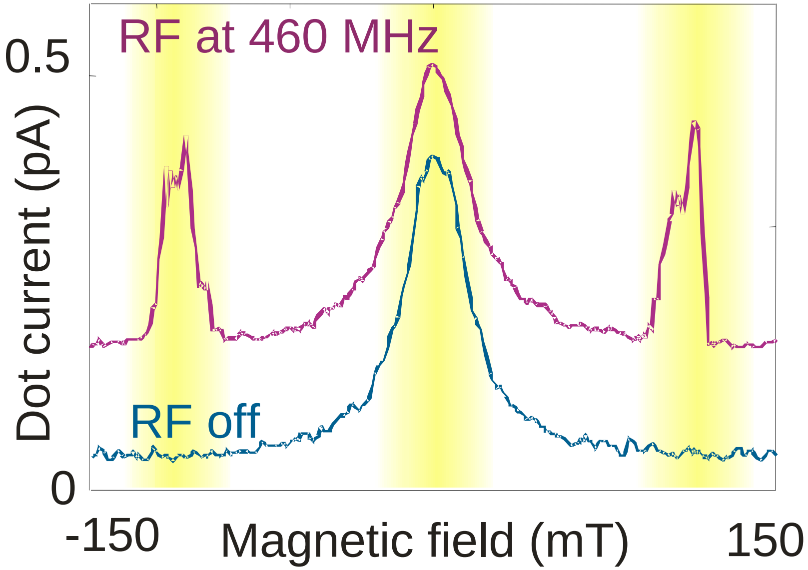
Single-electron spin resonance



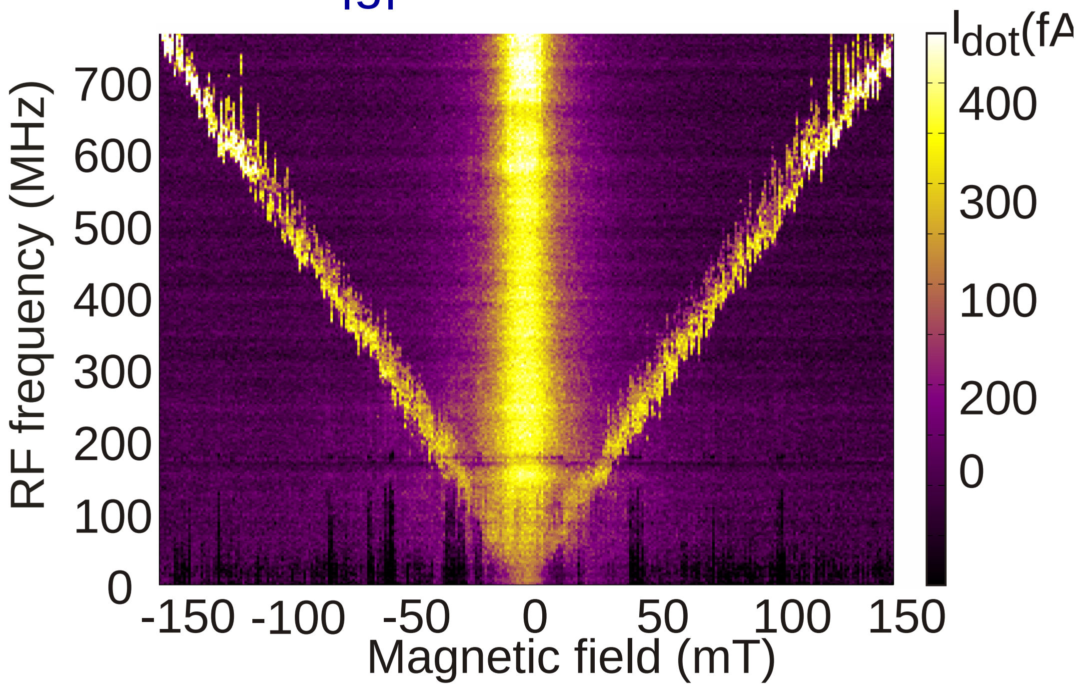
F. Koppens *et al.*, Nature 2006





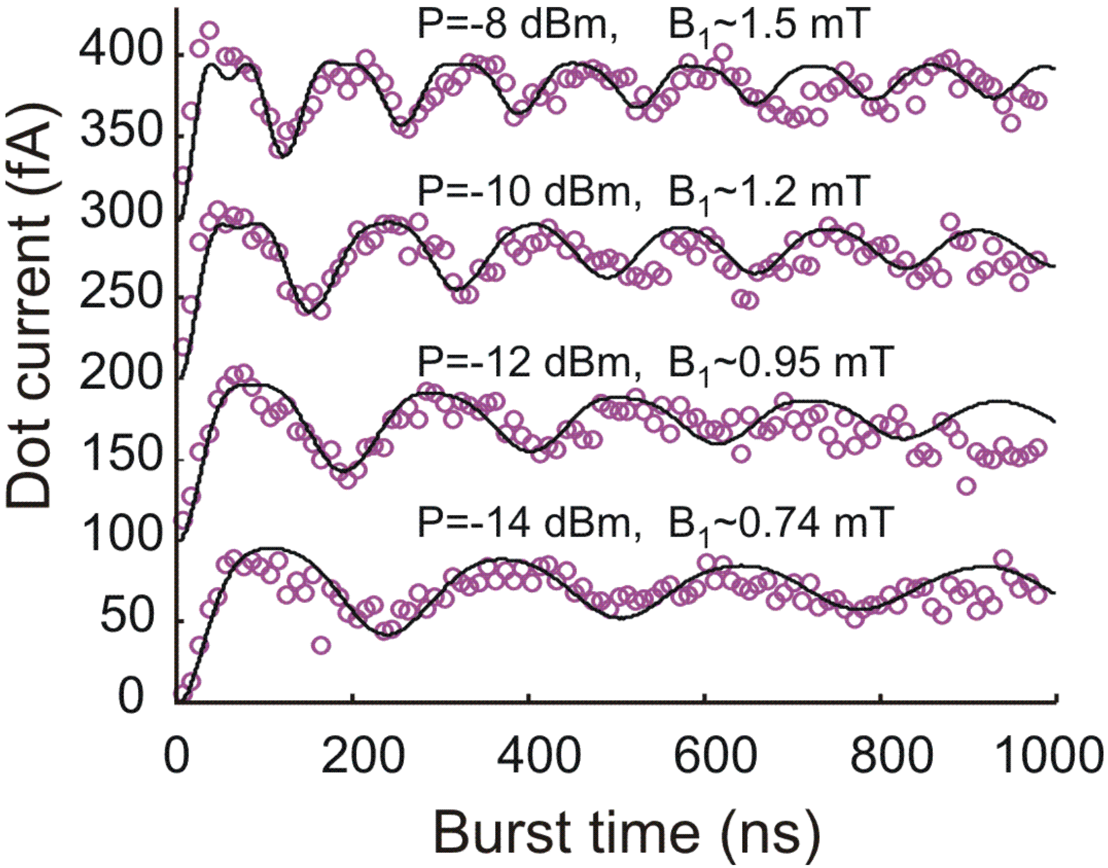


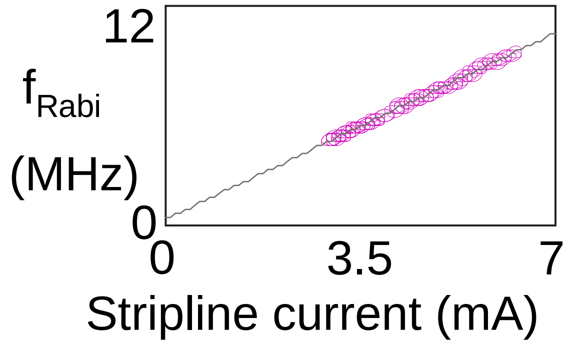
|g|-factor ~ 0.35

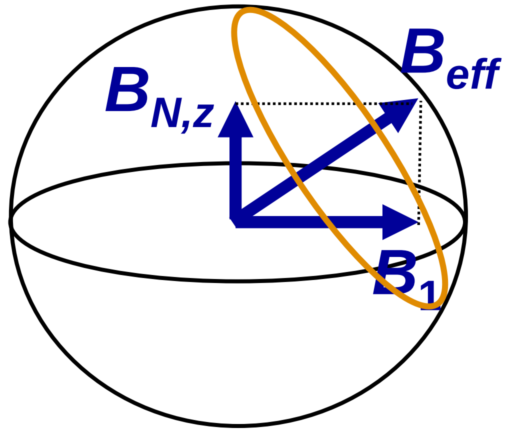


Driven rotations of a single electron spin

Koppens, Buizert, Tielrooij, Vink, Nowack, Meunier, Kouwenhoven, LMKV, Nature 2006





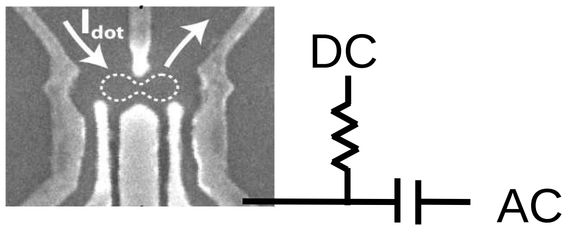


$\pi/2$ pulse in 25ns

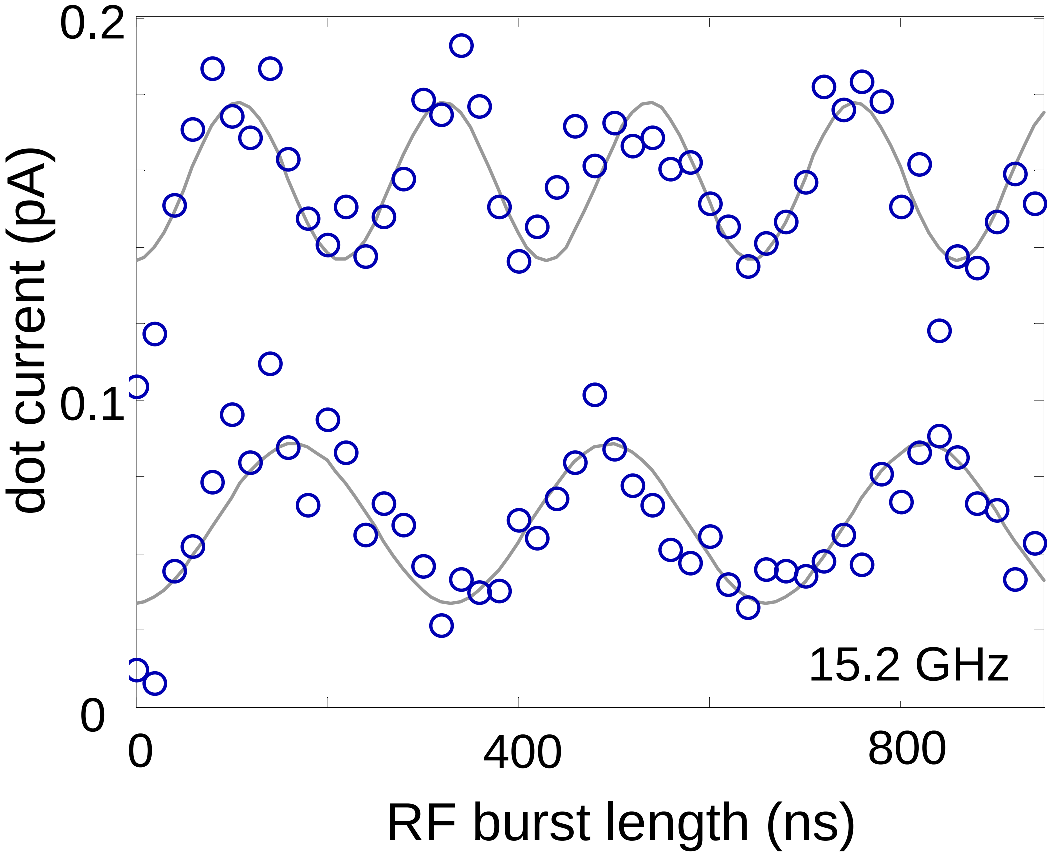
max B_1 ~ 1.9 mT, compare $B_{N,z}$ ~ 1.3 mT

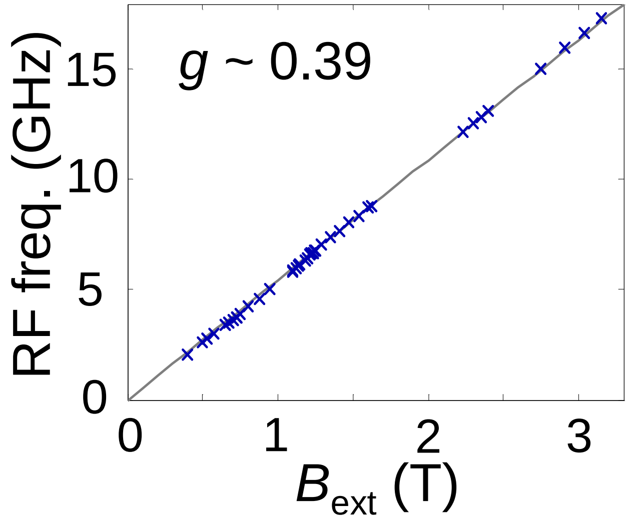
Electrical single-spin control

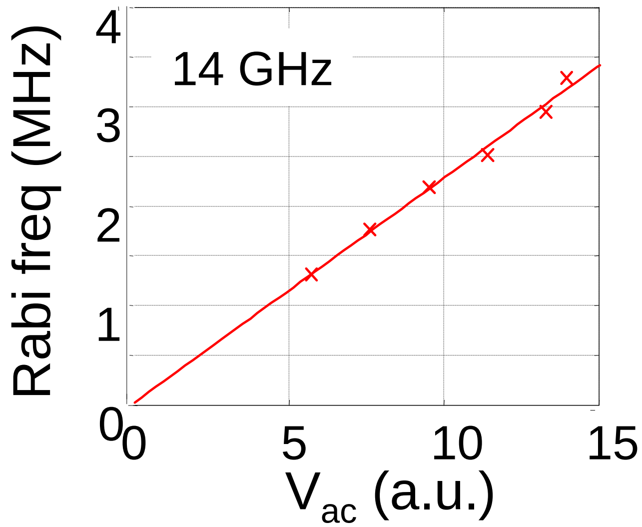
Nowack, Koppens, Nazarov, LMKV,
Science Express 2007



Easier local addressing
All-electrical control possible



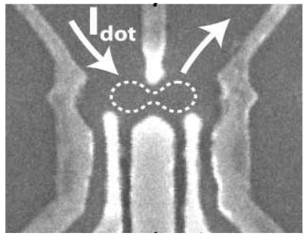




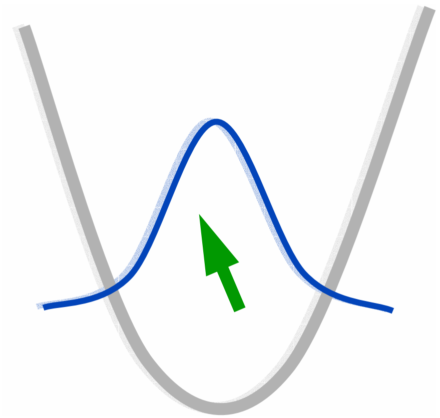
Mechanism: spin-orbit interaction

$$H_R = \alpha(\sigma_x p_y - \sigma_y p_x) + \beta(\sigma_x p_x - \sigma_y p_y)$$

Rashba Dresselhaus



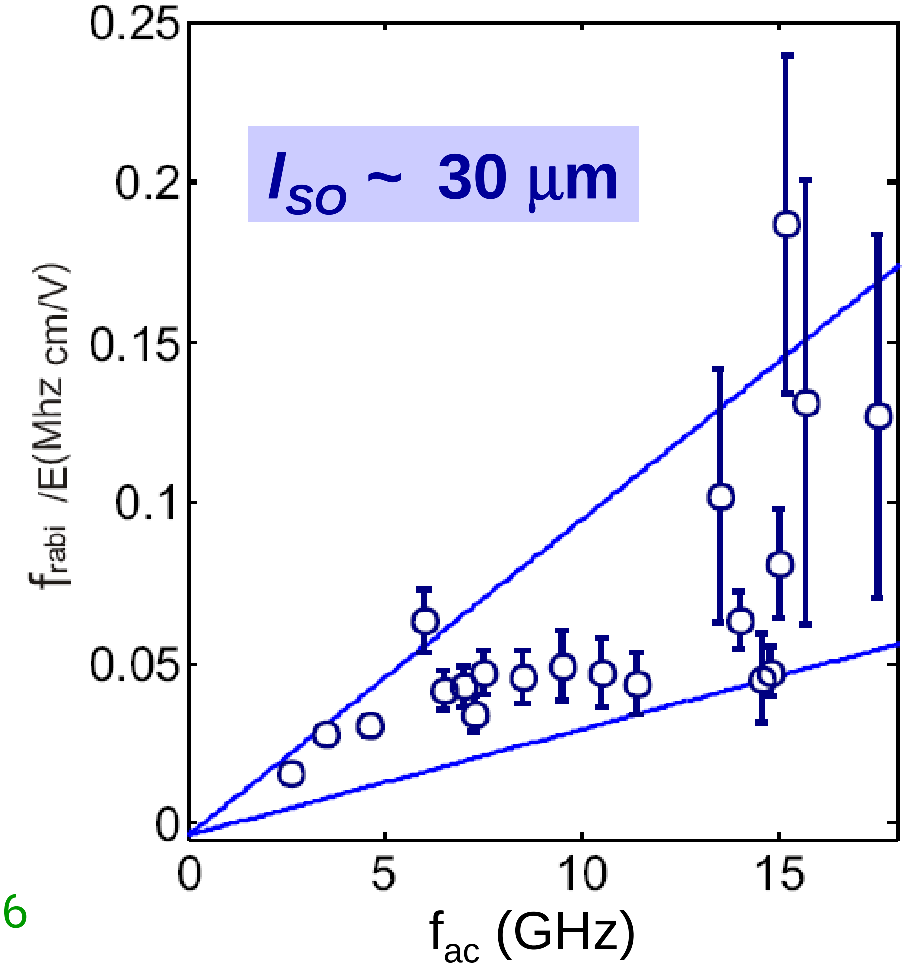
B_{ext} // $E(t)$ // [110] or [1$\bar{1}$0]



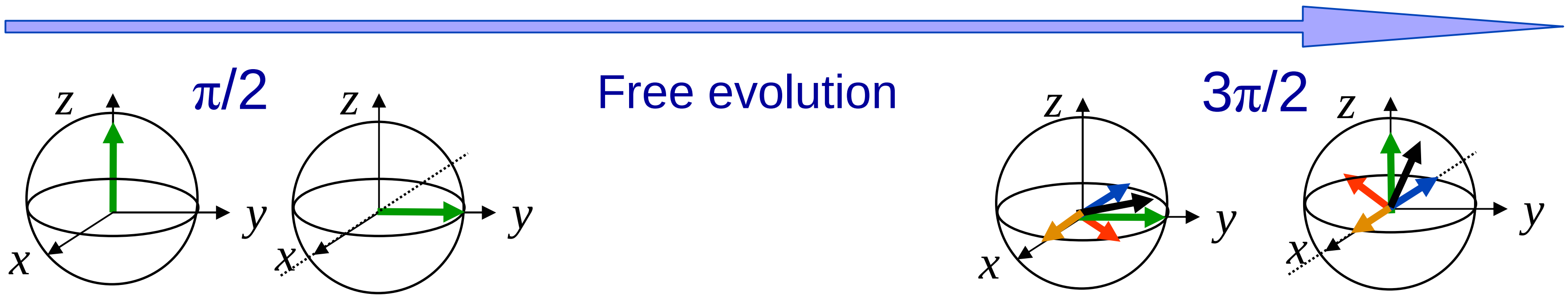
$$B_1, f_{Rabi} \sim \frac{1}{l_{SO}} f_{ac}\vec{E}$$

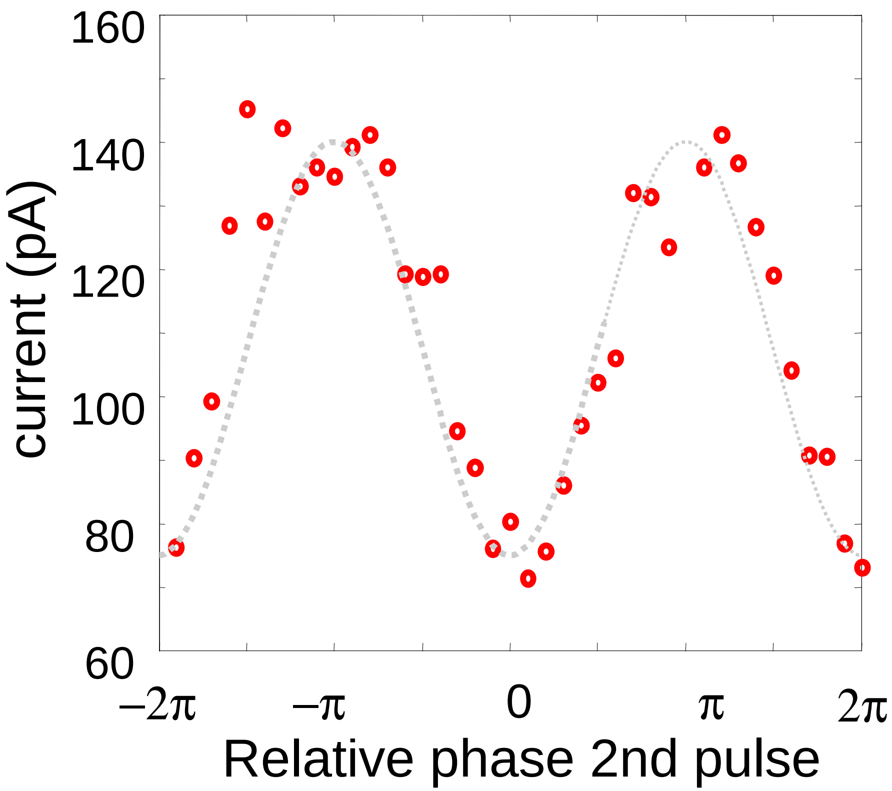
$$l_{SO} = \frac{\hbar}{m(\beta \pm \alpha)}$$

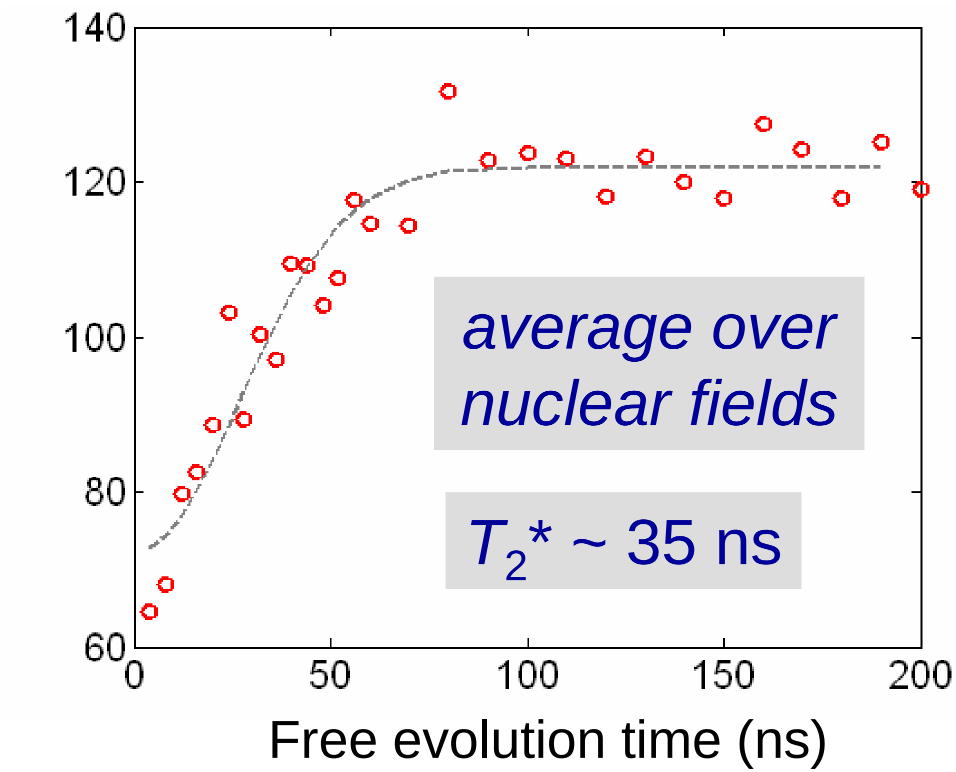
Theory: Golovach, Borhani, Loss, PRB 2006



Ramsey fringes and dephasing



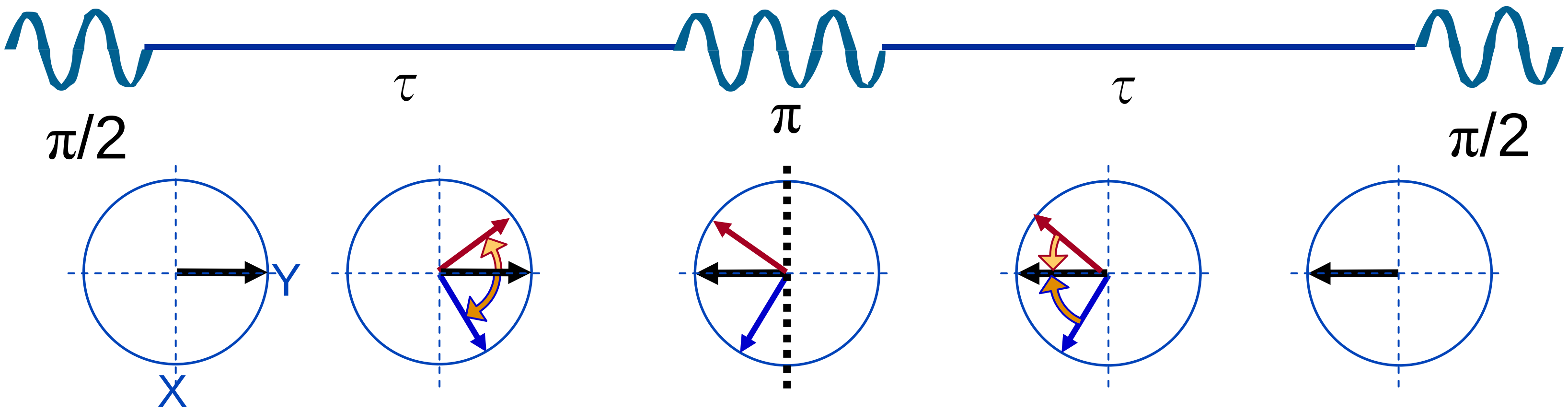


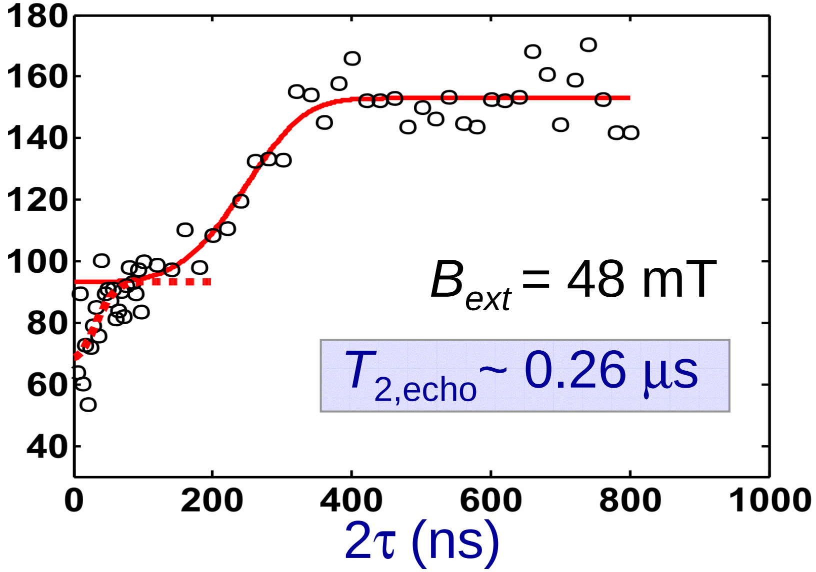


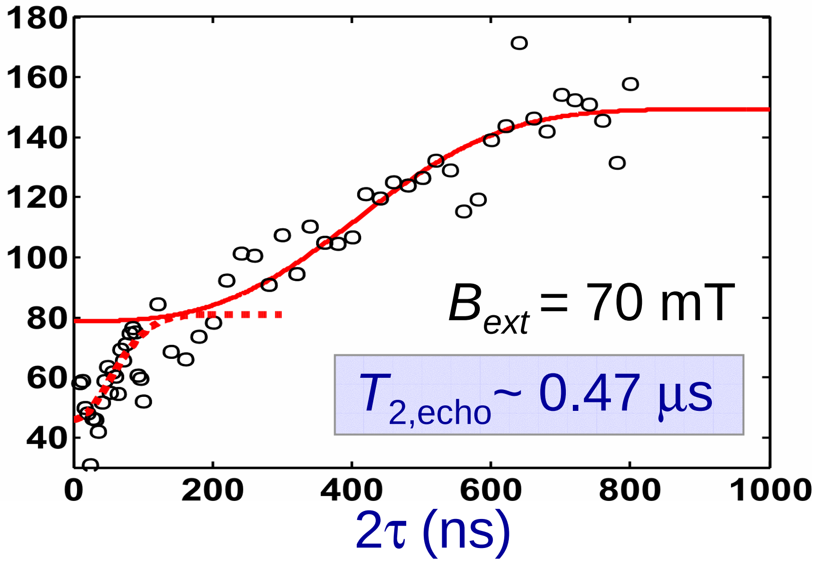
Spin echo – unwind dephasing

nuclear spins evolve only slowly

Koppens, Nowack, LMKV,
arXiv:0711.0479







Nuclear spin dynamics

- nuclear-nuclear flip-flops through direct dipole-dipole coupling (> 100 μs)
- electron-nuclear flip-flops (strongly suppressed for B ≠ 0)
- nuclear-nuclear flip-flops through two virtual electron-nuclear flip-flops

Theory:

de Sousa, das Sarma, PRB 2003
Coish, Loss PRB 2004
Witzel, de Sousa, das Sarma, PRB 2005
Yao, Liu, Sham, PRB 2006
Deng & Hu, PRB 2006
…

$T_{2,\mathrm{echo}}$ depends on ***timescale*** **(t_{nuc})** ***and magnitude*** **($1/T_2$*)** of nuclear field fluctuations

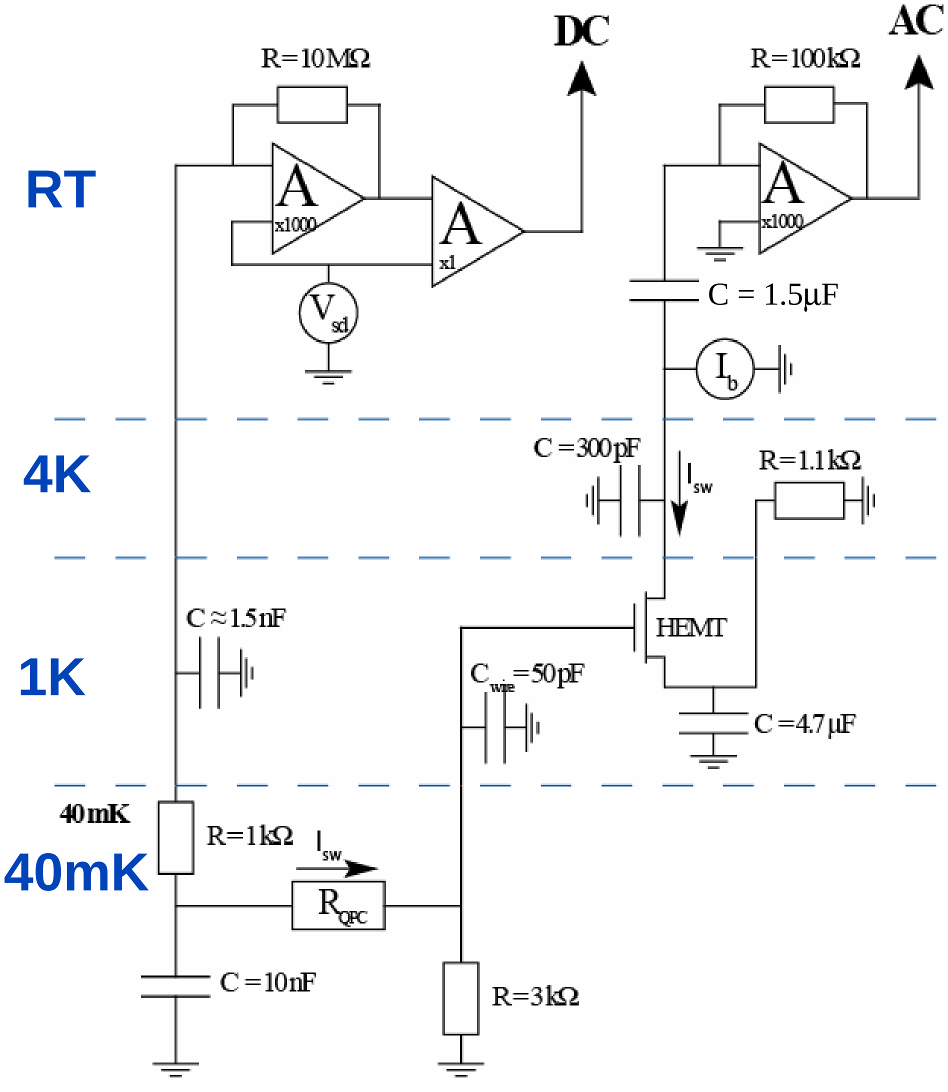
E.g. can have t_{nuc} = 10 sec, T_2^* = 10 ns, giving $T_{2,\mathrm{echo}}$ = 10 μs

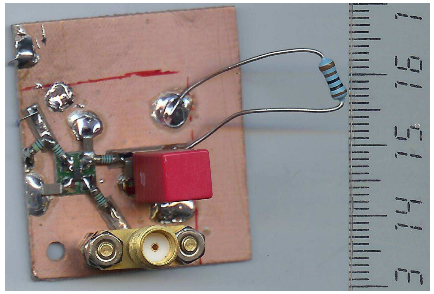
Klauder & Anderson, PR 1962

Faster charge detection (cryogenic amplifier)

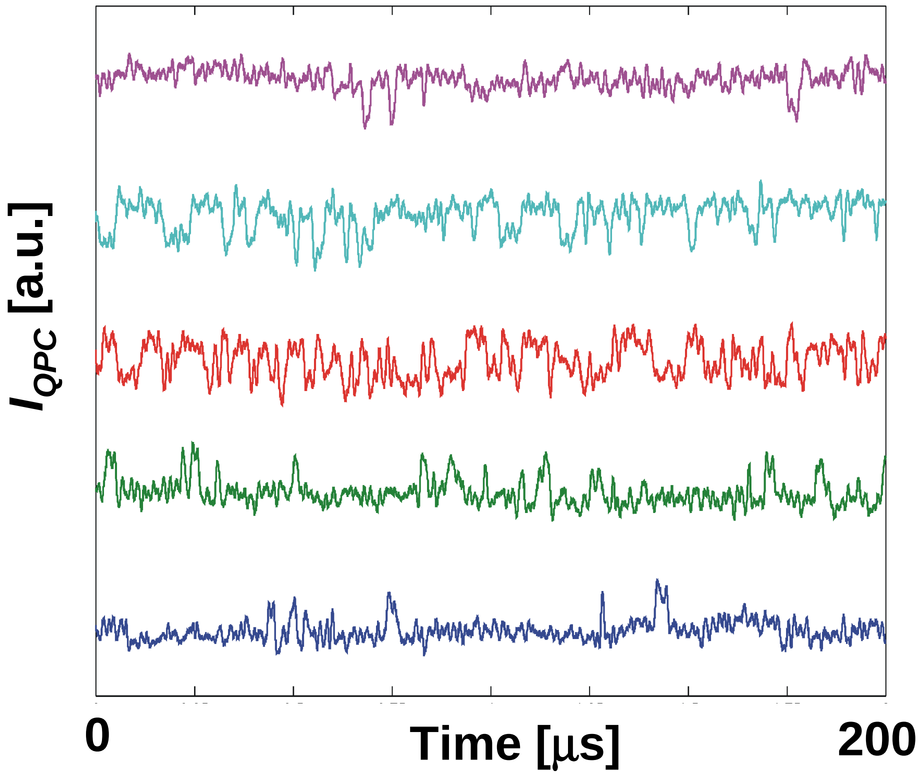
Signal bandwidth: ~1 kHz – 1 MHz

Single-charge detection in smaller bandwidth





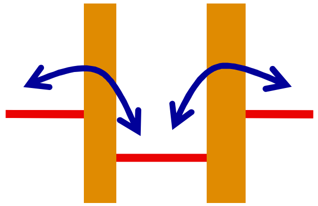
Vink, Nooitgedagt, Schouten, LMKV, APL 2007



Other decoherence mechanisms

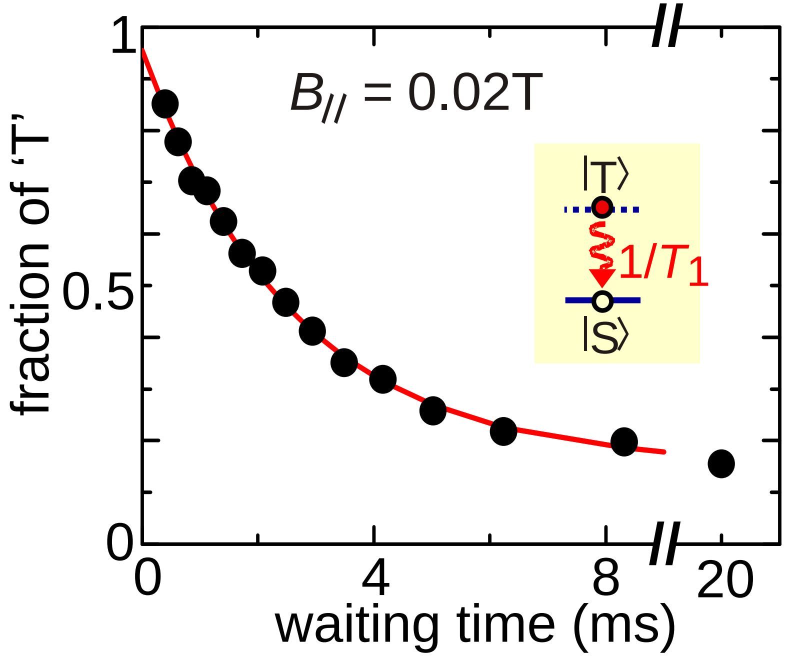
virtual tunneling processes to the reservoirs

- was limitation for max. power in ESR
- can be suppressed by raising tunnel barriers

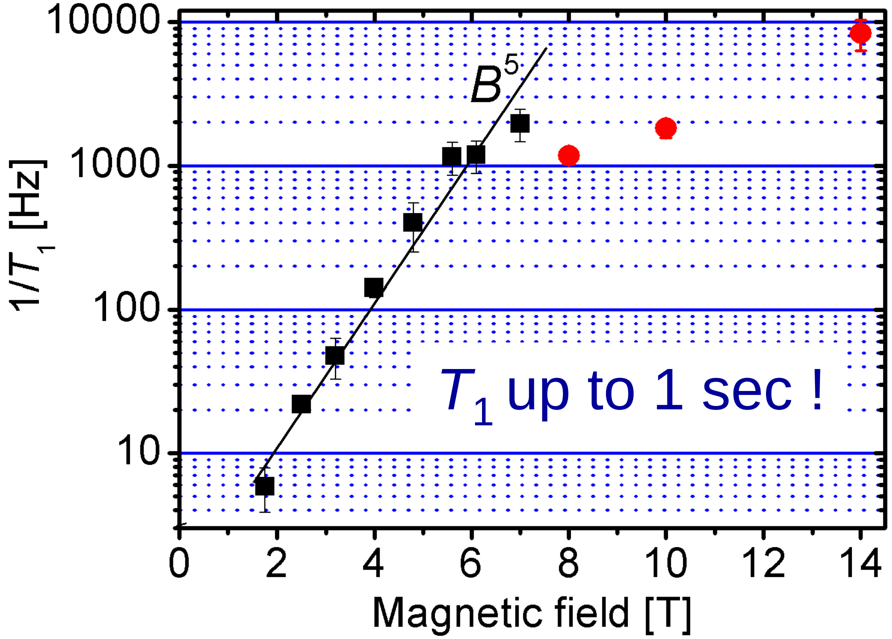


spin-orbit interaction

$T_2 = 2\ T_1$ Golovach, Khaetskii, Loss, PRL 04



Hanson *et al.*, PRL 2005

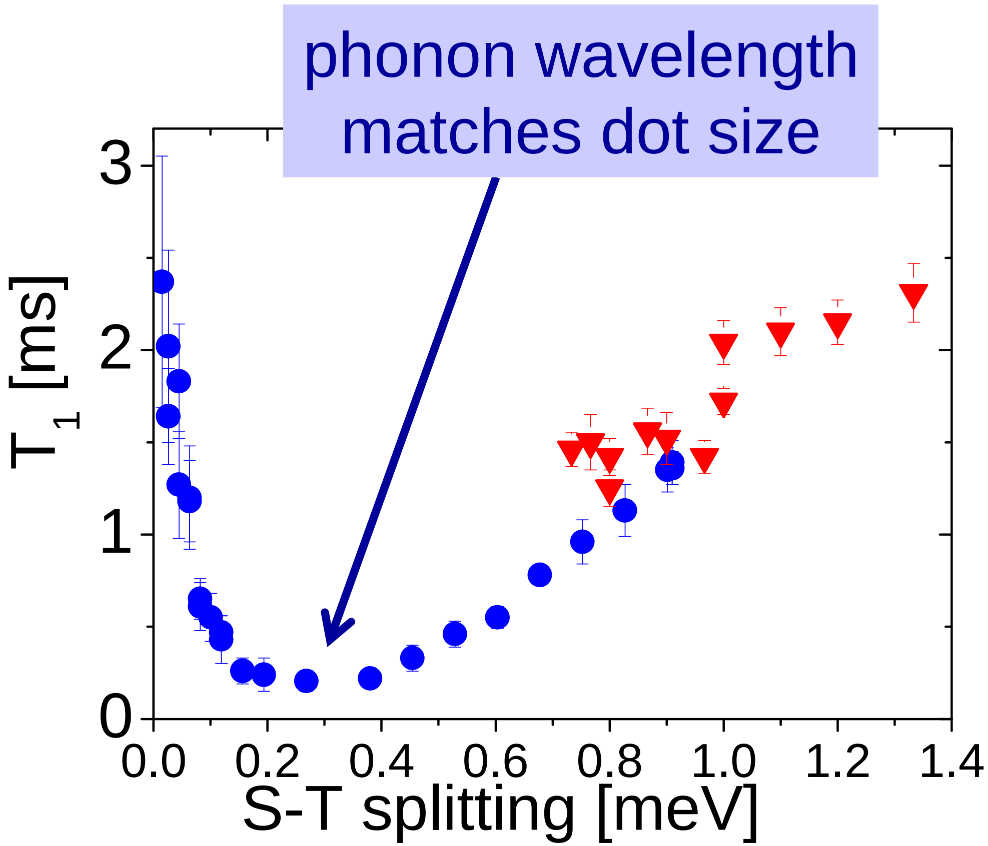


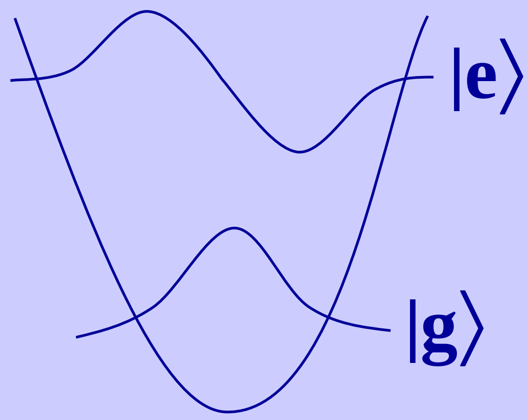
● Elzerman *et al.*,Nature 2004

■ Amasha *et al.*, cond-mat/0607110

Spin-orbit with phonons dominates T_1

Meunier, Vink, Willems v Beveren, Tielrooij, Hanson,
Koppens, Tranitz, Wegscheider, Kouwenhoven, LMKV, PRL 2007





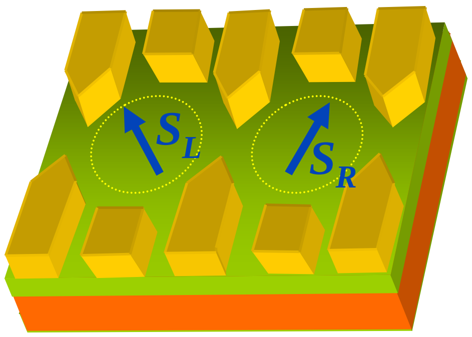
$$|`\uparrow´\rangle = |\uparrow \mathbf{g}\rangle + \alpha|\downarrow \mathbf{e}\rangle$$

$$|`\downarrow´\rangle = |\downarrow \mathbf{g}\rangle - \alpha|\uparrow \mathbf{e}\rangle$$

Theory: Golovach, Khaetskii, Loss, PRL 2004

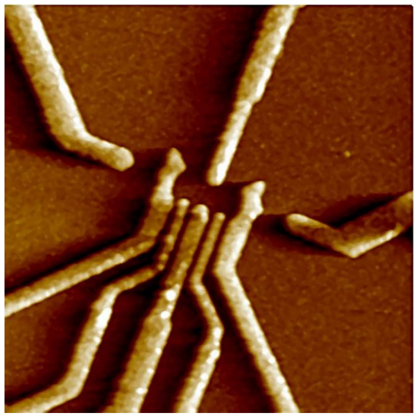
Spin qubits in quantum dots – status

See also Hanson et al, Rev. Mod. Phys. 2007



Initialization 1-electron, low T, high B_0
duration ~ 5 T_1; 99% fidelity ?

Read-out via spin-charge conversion
duration ~ 100 μs; 82-97% fidelity



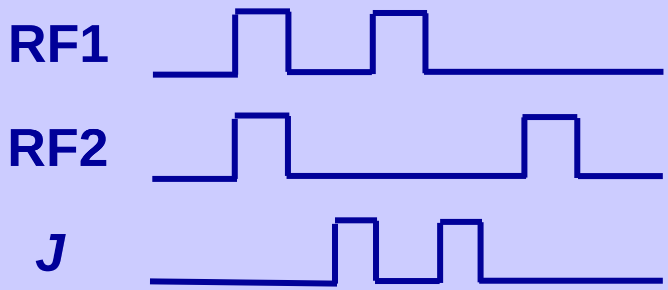
1-qubit gate electron spin resonance
gate duration ~ 25 ns; observed 8 periods

2-qubit gate exchange interaction
gate duration ~ 0.2 ns; observed 3 periods

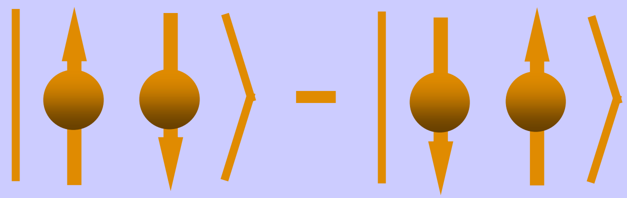
Decoherence T_1 ~ 1 ms – 1 sec spin-orbit + phonons
T_2^* ~ 20 ns; T_2 > 1 μs nuclear spins

Main themes in the coming years

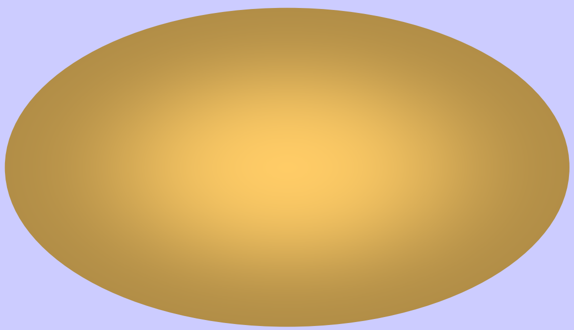
Quantum control and entanglement



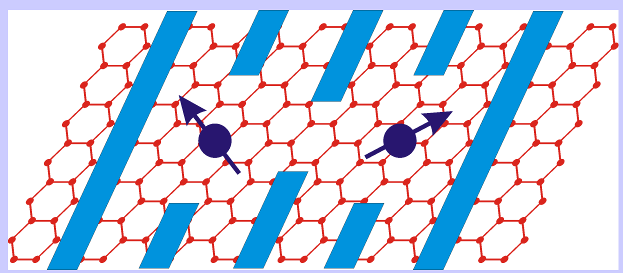
Bell's inequalities



Controlling the nuclear spin bath



Novel materials systems



Hyperfine in graphene is tiny

1) Only 1% of carbon atoms have a nuclear spin (^{13}C)

Furthermore, 99.9% pure ^{12}C is easily available,

and synthetic gr

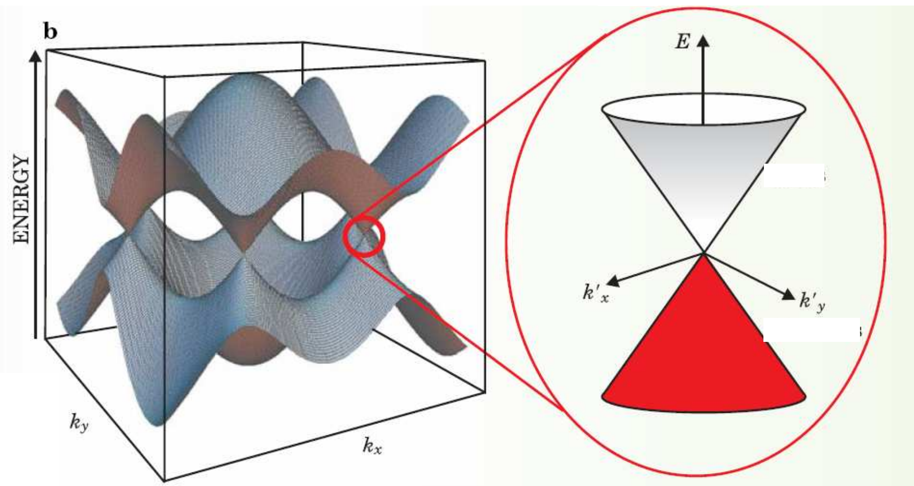
Spin coherence time ?

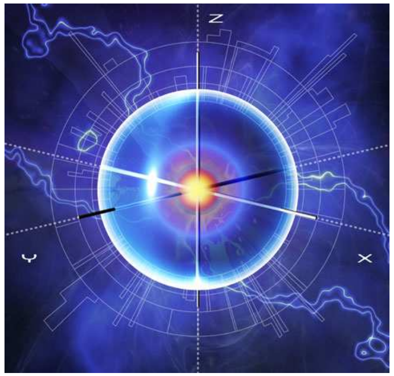
dipole dipole coupling?

anisotropic hyperfine?

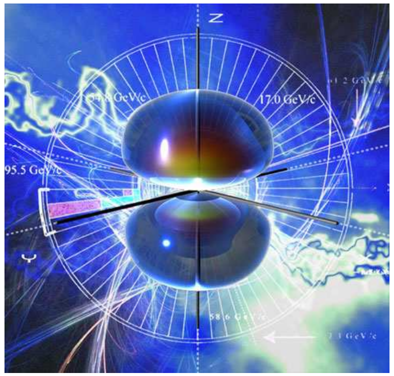
2) The conductior ... rom *p*-orbitals,

which don't overlap with the nuclei (no contact hyperfine)





2s



$2p_z$

Spin-orbit in graphene is weak as well

Carbon is a light element

sublattice, spin, valley

$H_{SO} = \lambda_{SO}\, \sigma_z\, s_z\, \tau_z$ $\lambda_{SO} \sim 0.5\ \mu eV$

$H_R = \lambda_R\, (\sigma_x\, s_y\, \tau_z$

Spin relaxation time ?
electron phonon coupling?
other heat baths?

Min et al, cond-mat/0
Yao et al, cond-mat/0
Huertas-Hernando et al, cond-mat/0606580

But: spin flip time in 2D graphene ~ few 100 ps Trombos et al., Nature 2007

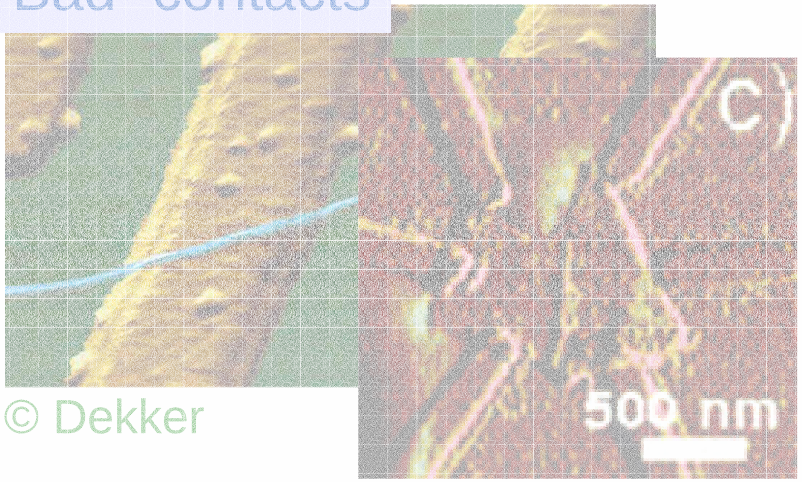
Compare GaAs:

$H_D = \beta\, (-\sigma_x\, p_x + \sigma_y p_y)$ $\beta\, p_F \sim 150\ \mu eV$ ($n=10^{11} cm^{-2}$)

$H_R = \alpha\, (\sigma_x\, p_y - \sigma_y p_x)$ comparable

Graphene quantum dots ?

“Bad” contacts



© Dekker

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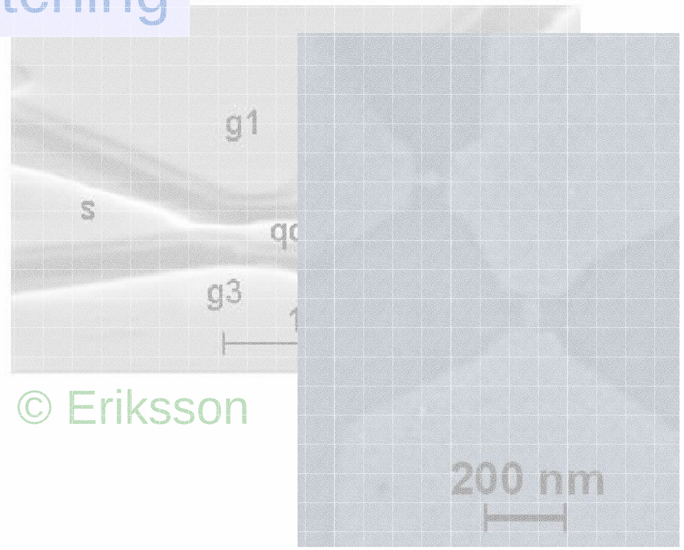
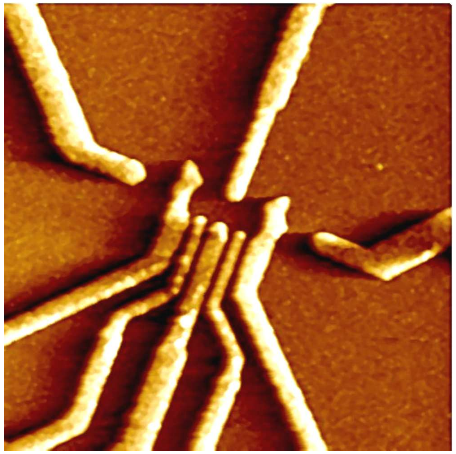
Etching



© Eriksson

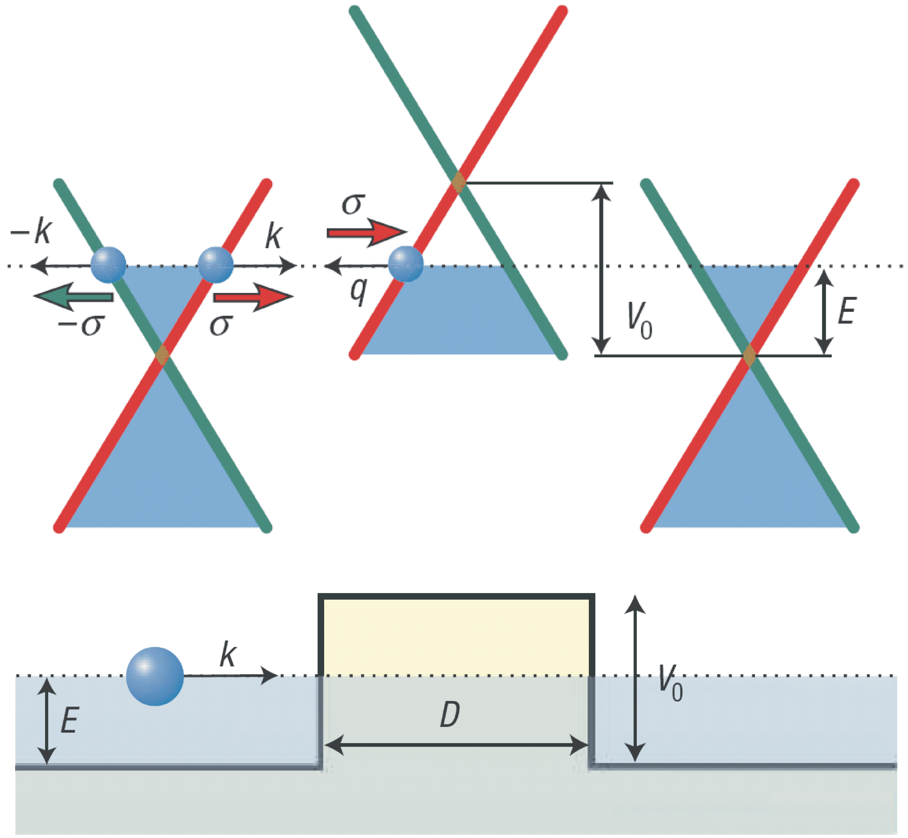
© Geim

Top gating



by far preferred
(control and tunability)

Electrostatic barriers and Klein tunneling



No electrostatic confinement!
Need to create a semiconducting gap

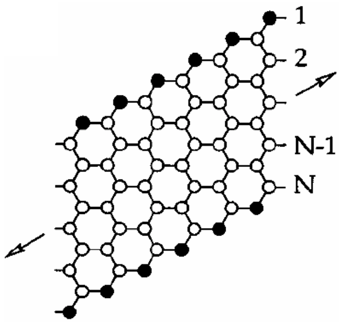
Katsnelson, Novoselov, Geim, Nature Phys. 2006

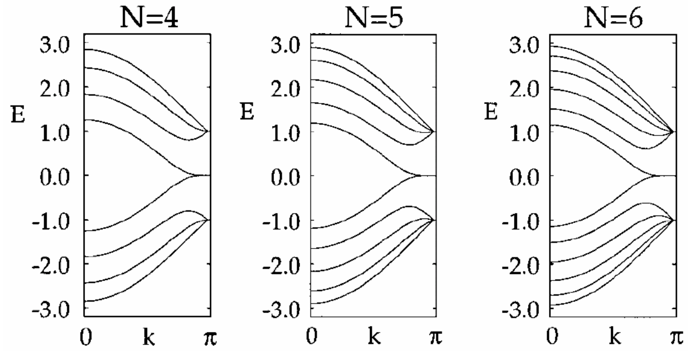
Bandgap from confinement (ribbons)

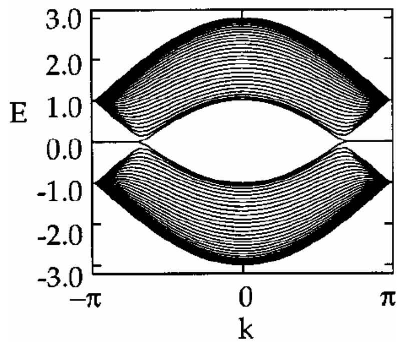
Tight binding

Nakada et al., PRB 54, 17954, 1996

Zigzag edges: always metallic (edge states at zero energy)



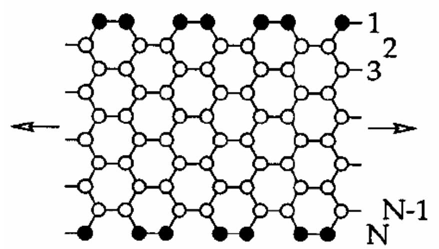


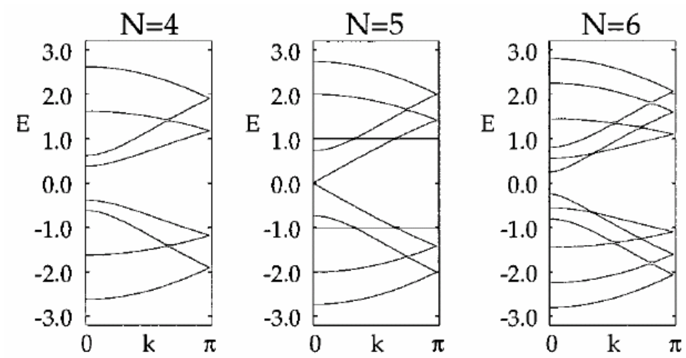


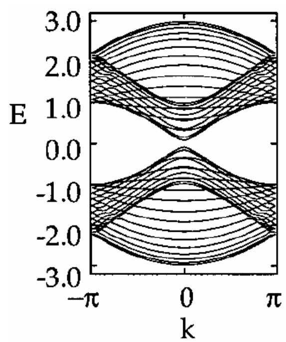
Gap from spin-ordering at edges ?

Son, Cohen, Louie PRL 2006

Armchair edges: insulating, except for $N=3n-1$





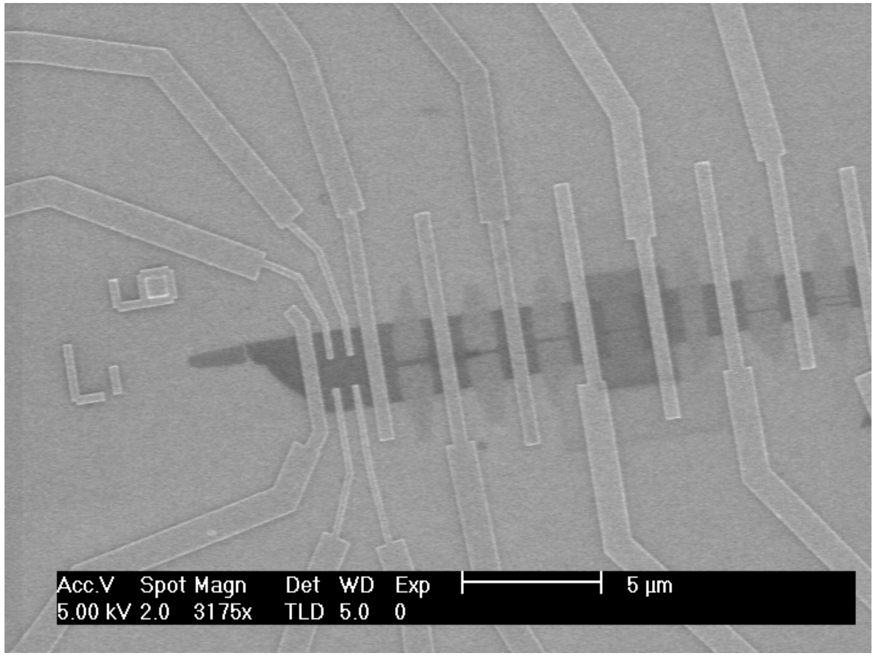


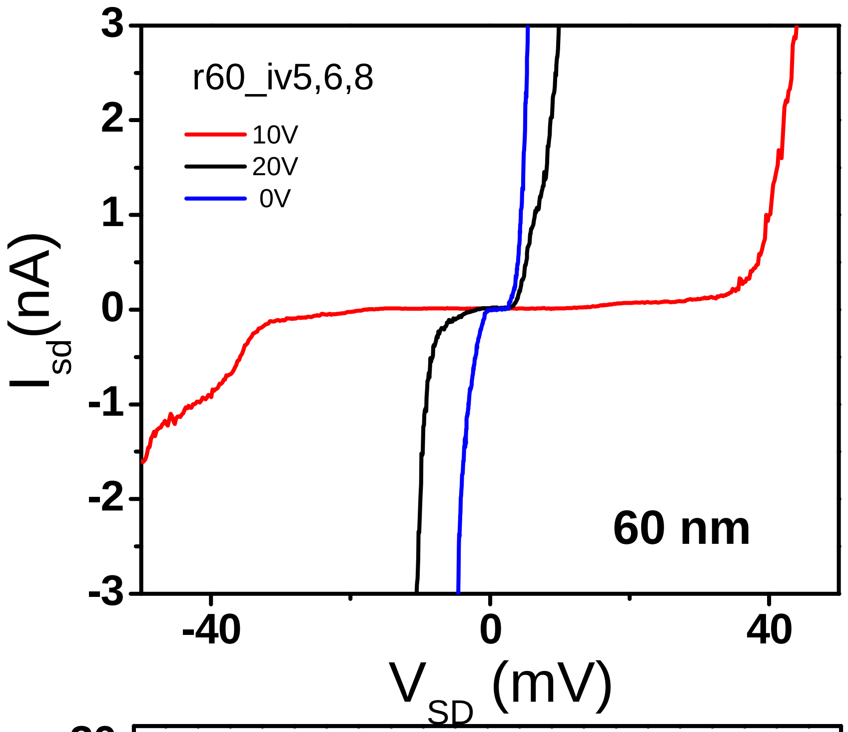
Always gap from lattice deformation at edges ?

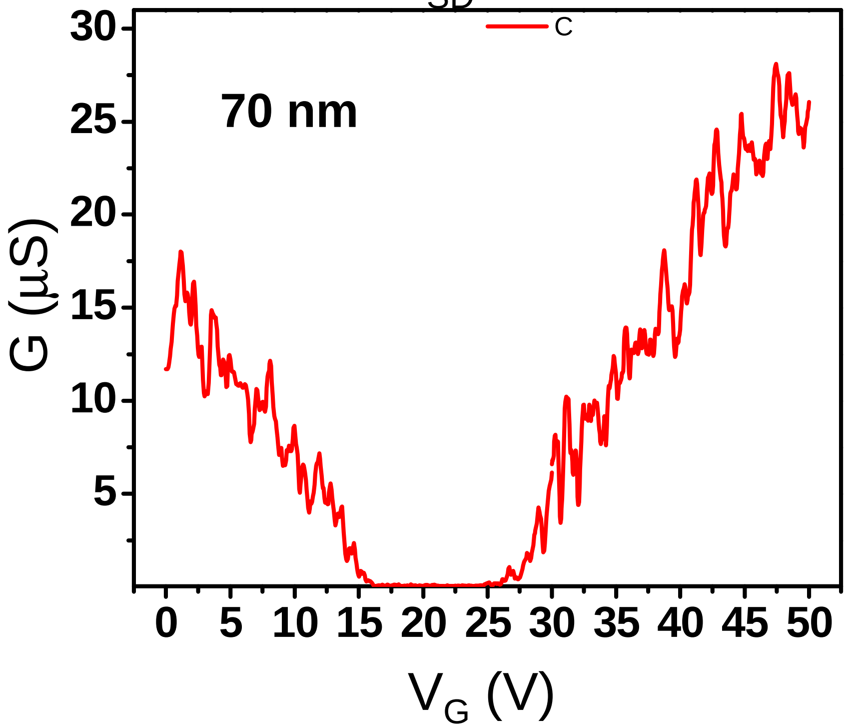
Son et al., PRL 2006

Bandgap in ribbons (1)

Wehenkel, Heersche et al,
See also Han et al, PRL 2007

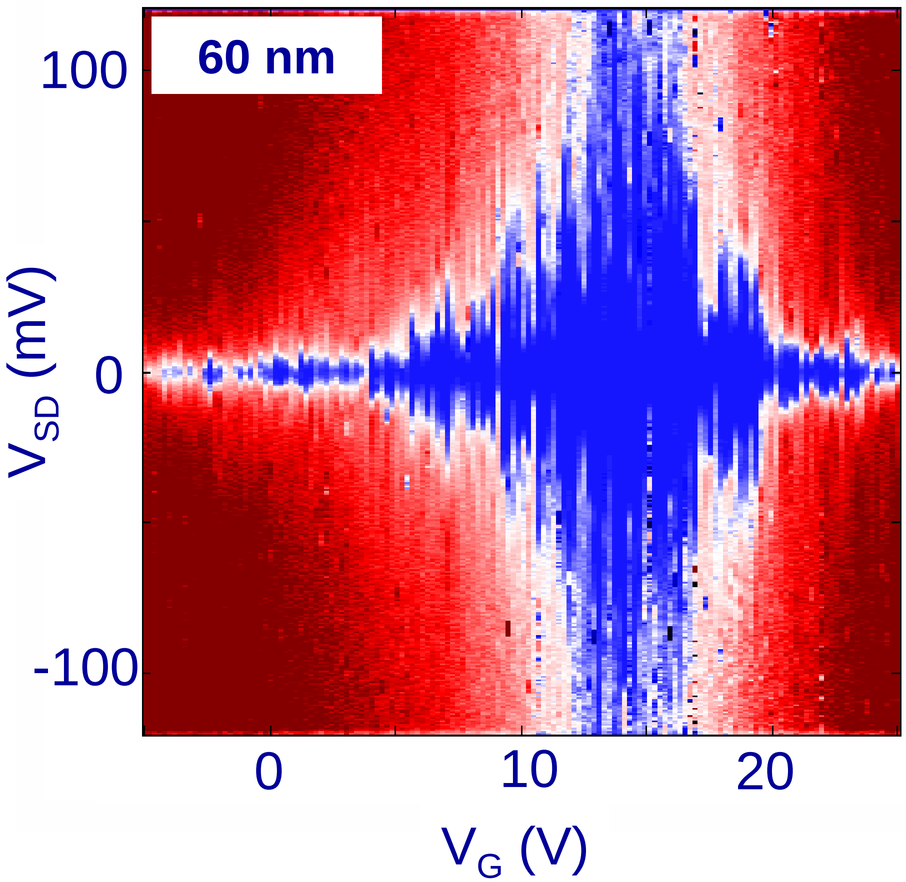




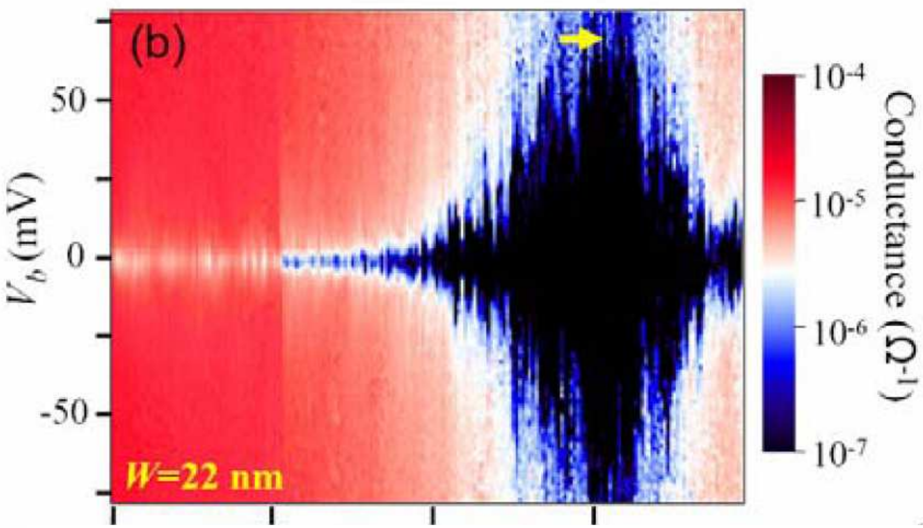


Bandgap in ribbons (2)

Delft (Wehenkel, Heersche et al)



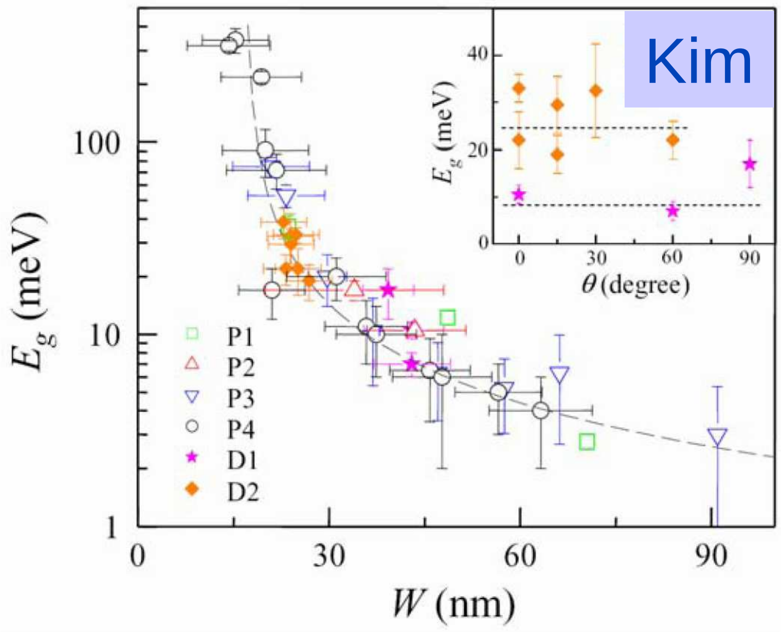
Columbia, PRL 2007

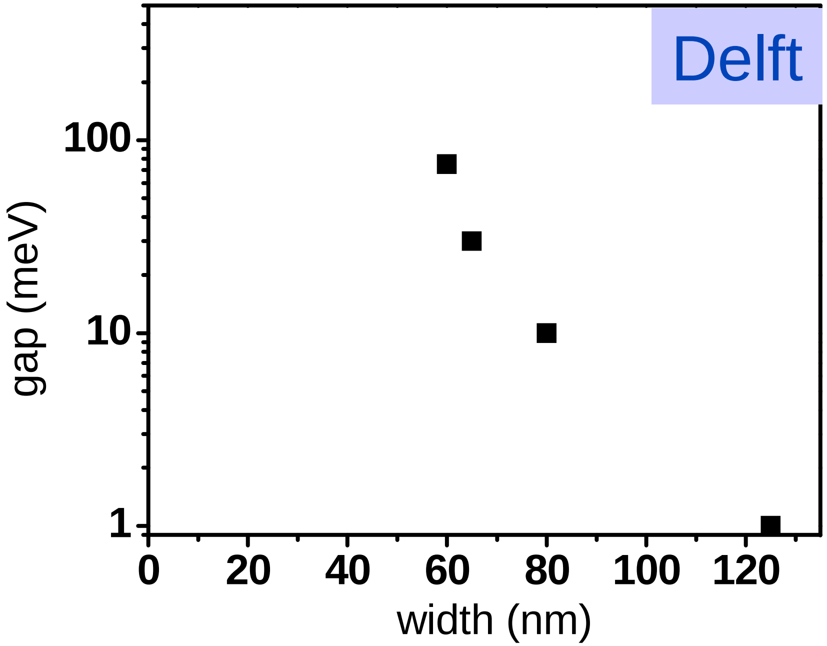


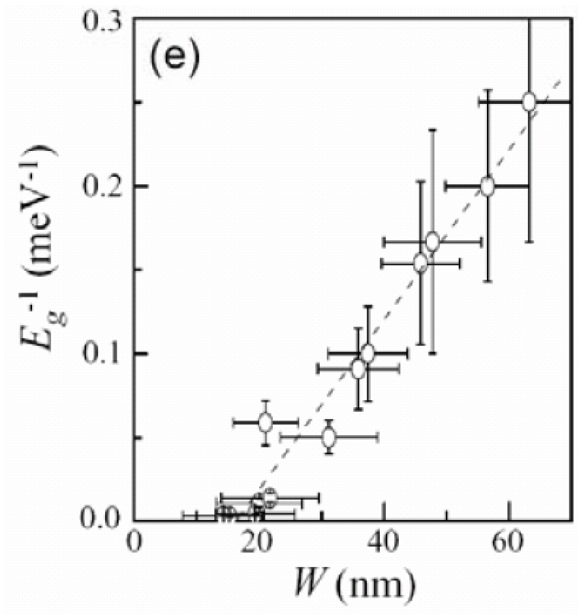
Always gapped even though edges were not controlled

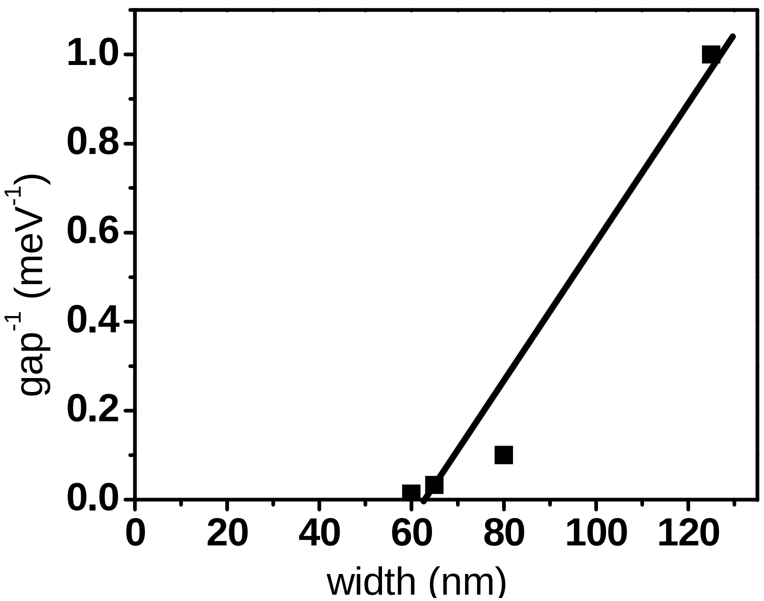
In addition: charging contribution

Extracted gap size versus ribbon width

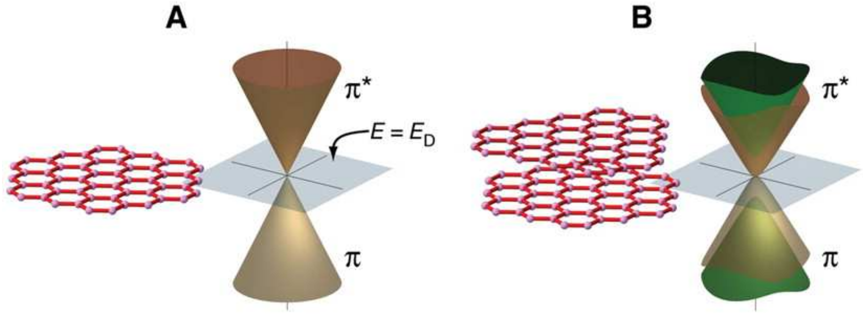




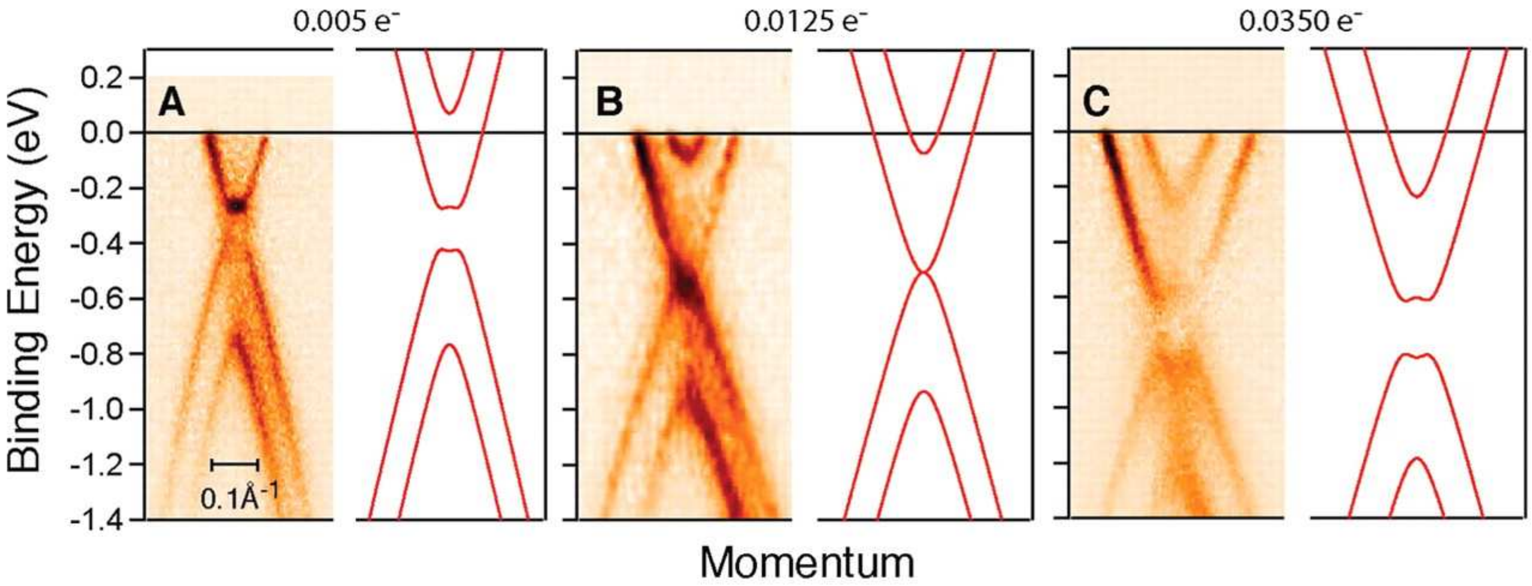




Bandgap in asymmetrically doped bilayers



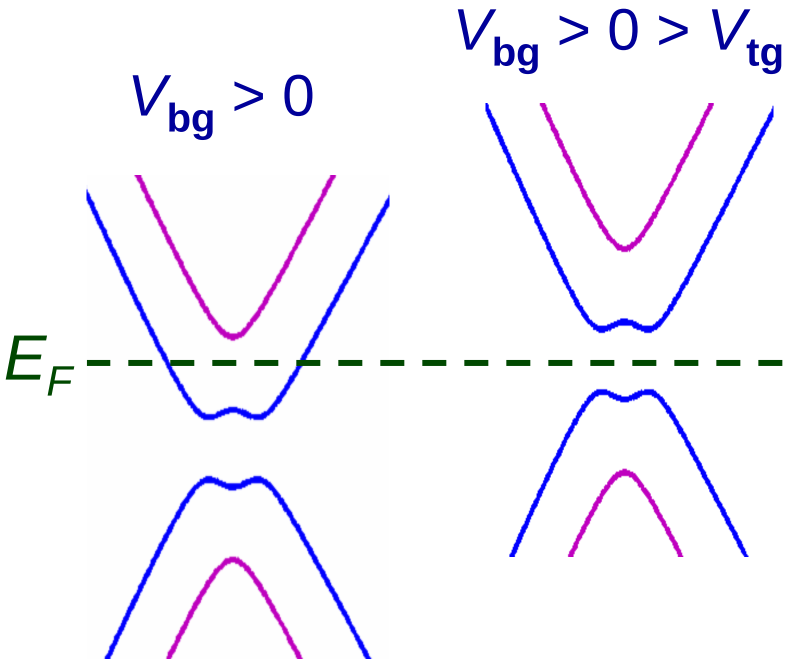
Chemical doping of top layer (SiC substrate)

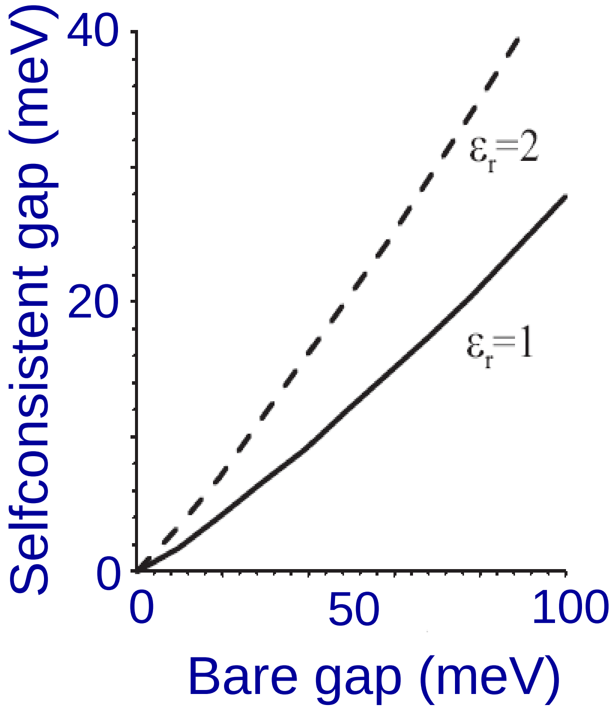


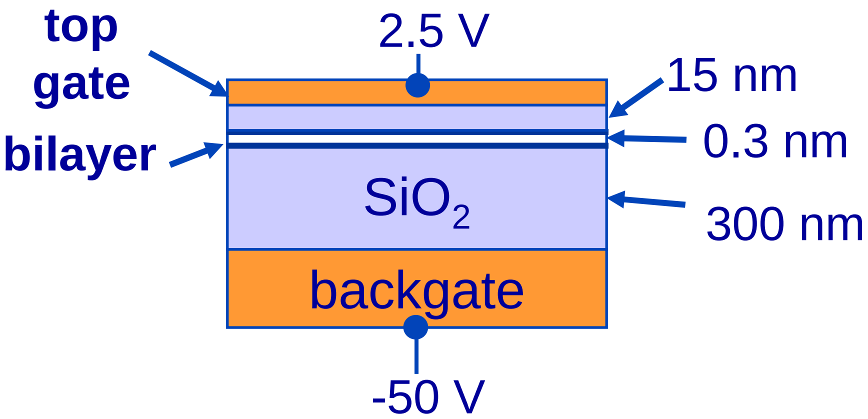
Theory: McCann & Falko, PRL 2006
McCann, PRB 2006
Min et al, PRB 2006

Expt.: Ohta et al, Science 2006
Also: Castro et al, cond-mat/0611342

Electric control of bandgap and Fermi level







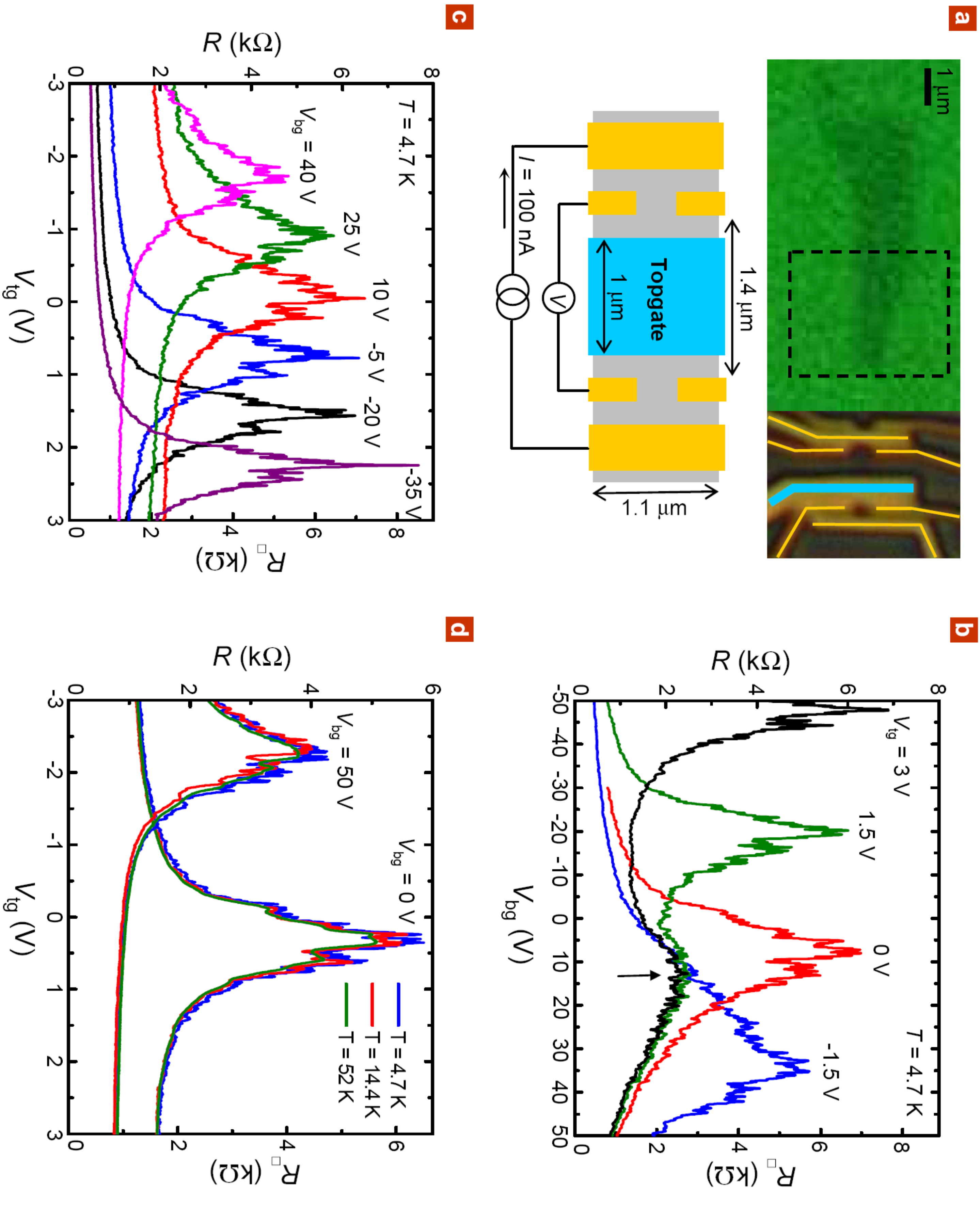
50 mV bare gap

< 10 meV actual gap

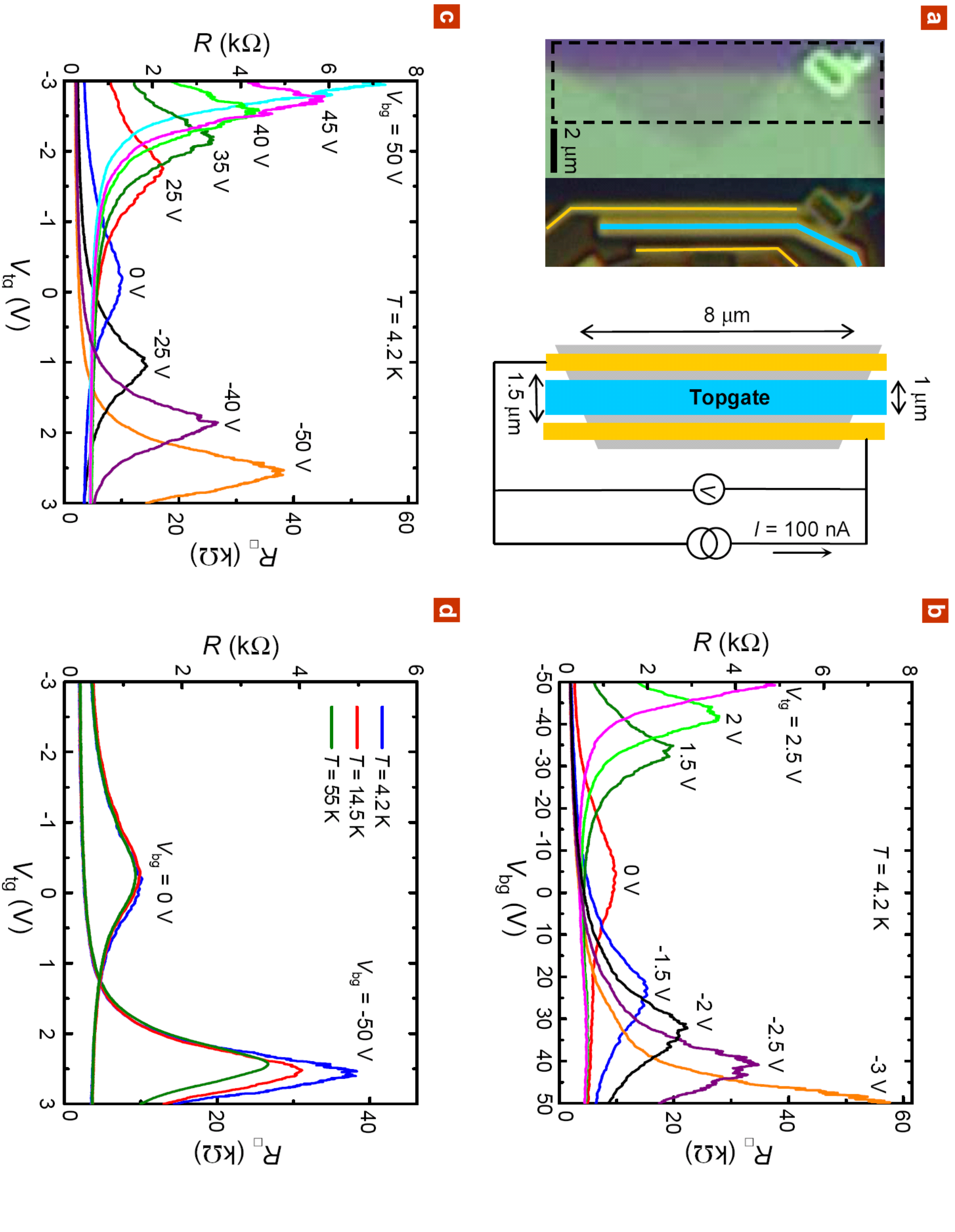
McCann, PRB 2006

Min et al, PRB 2006

Single layer

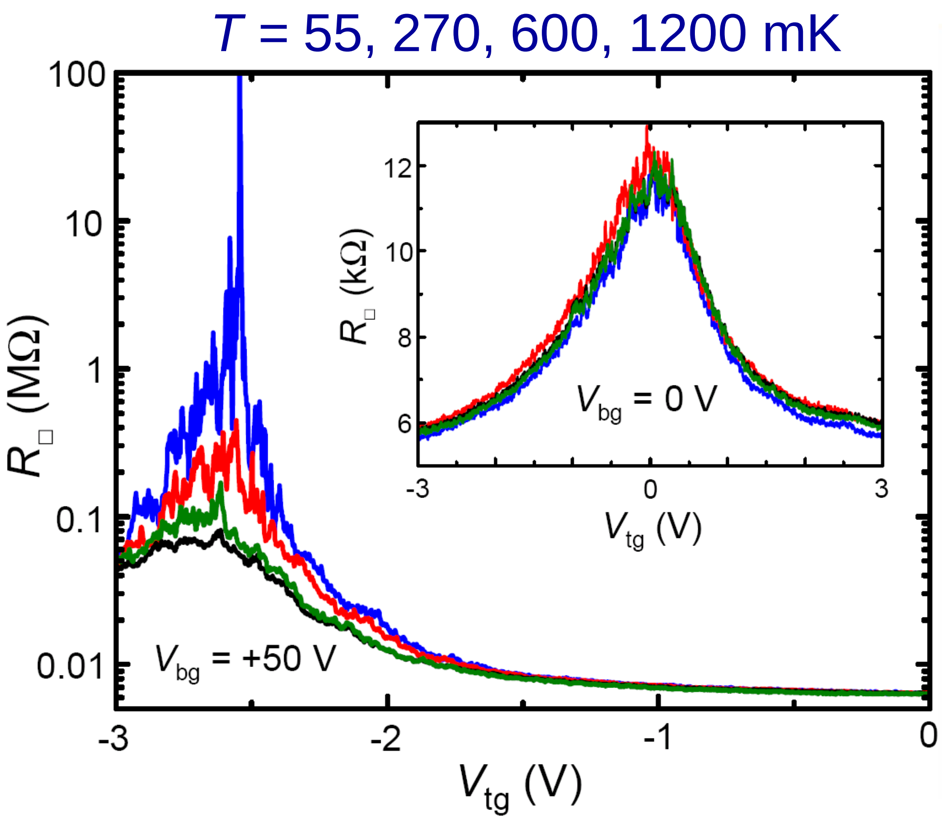


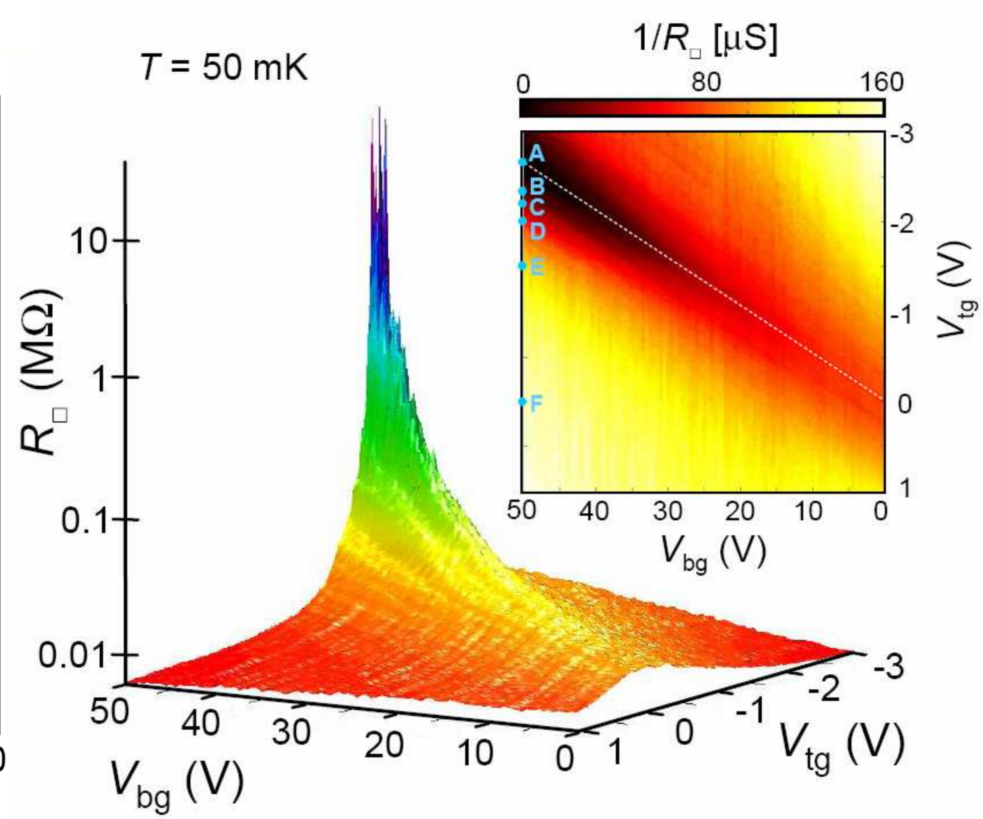
Bilayer



a
2 µm
8 µm
Topgate
1 µm
1.5 µm
V
I = 100 nA
b
R (kΩ)
T = 4.2 K
V_{tg} = 2.5 V
2 V
1.5 V
0 V
-1.5 V
-2 V
-2.5 V
-3 V
V_{bg} (V)
$R_\square$ (kΩ)
c
R (kΩ)
V_{bg} = 50 V
45 V
40 V
35 V
25 V
0 V
-25 V
-40 V
-50 V
T = 4.2 K
V_{tg} (V)
$R_\square$ (kΩ)
d
R (kΩ)
T = 4.2 K
T = 14.5 K
T = 55 K
V_{bg} = 0 V
V_{bg} = -50 V
V_{tg} (V)
$R_\square$ (kΩ)

Low temperature measurements of bilayer graphene

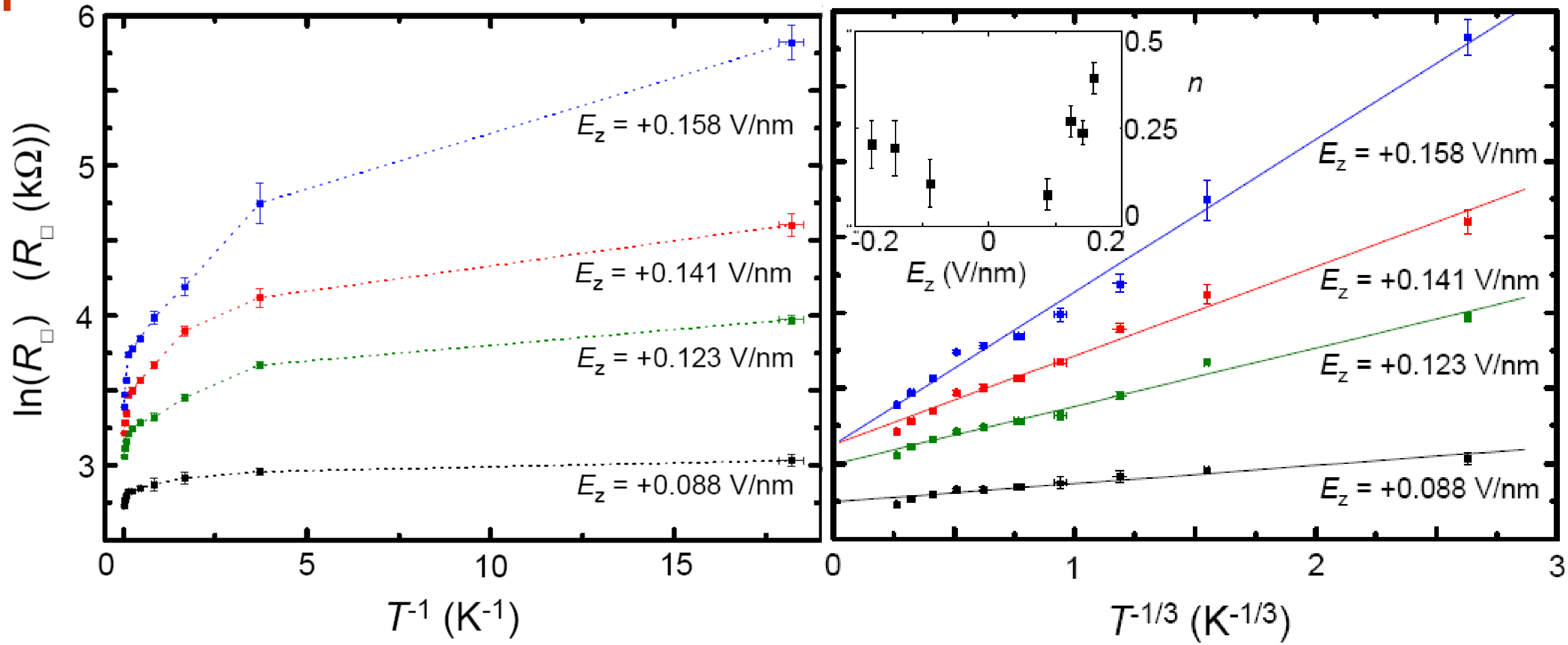




Electrically induced insulating state

Oostinga, Heersche, Liu, Morpurgo, LMKV, arXiv:0707.2487

Temperature dependence peak resistance

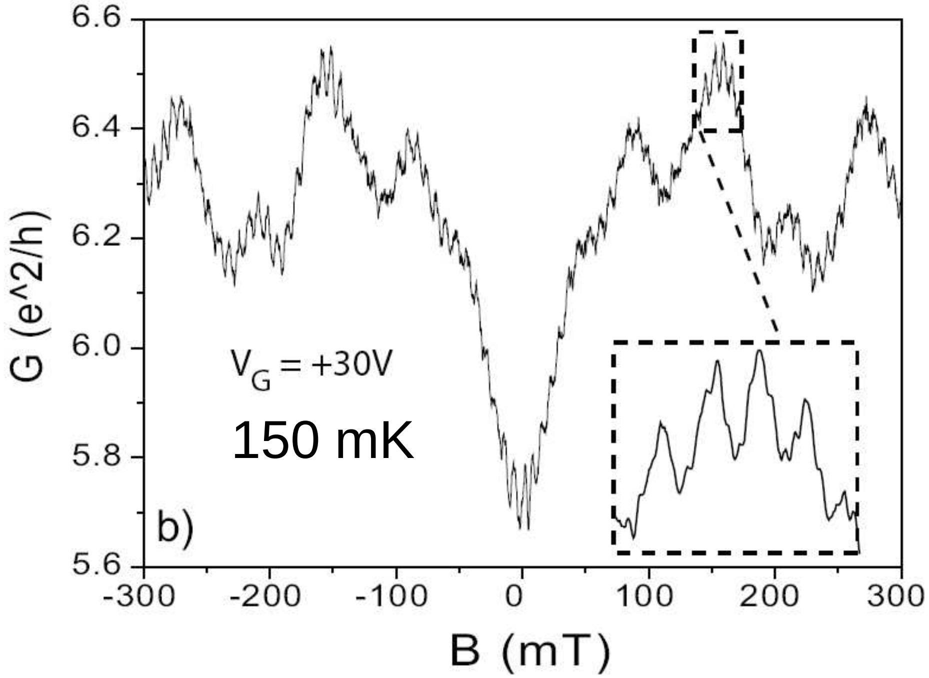


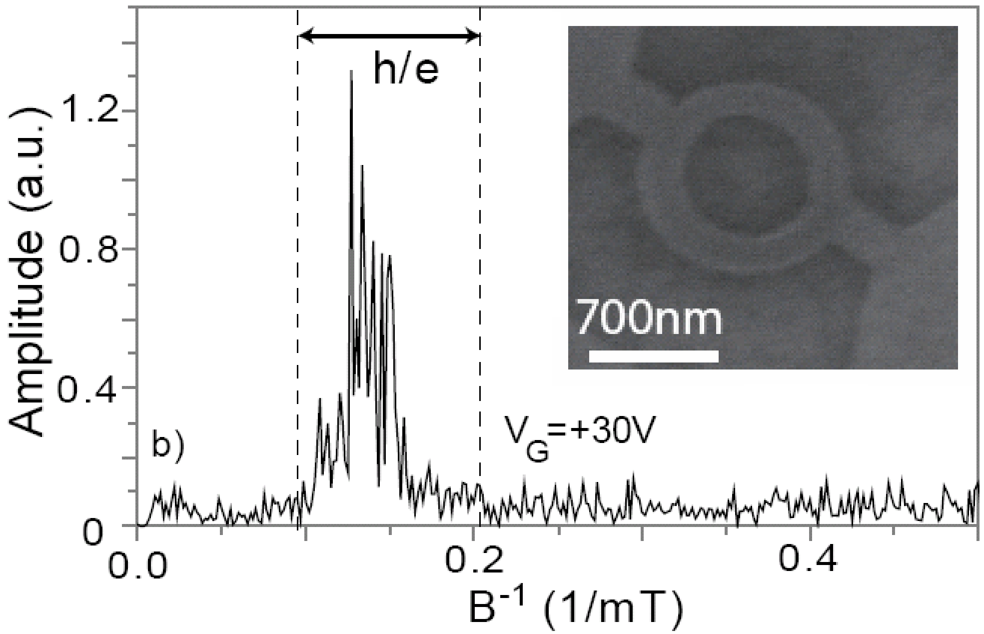
55 mK – 5 K range: variable-range hopping (for highest fields)

Points at gap with localized states inside the gap (disorder)

Oostinga, Heersche, Liu, Morpurgo, LMKV, arXiv:0707.2487

Magnetoresistance in graphene rings





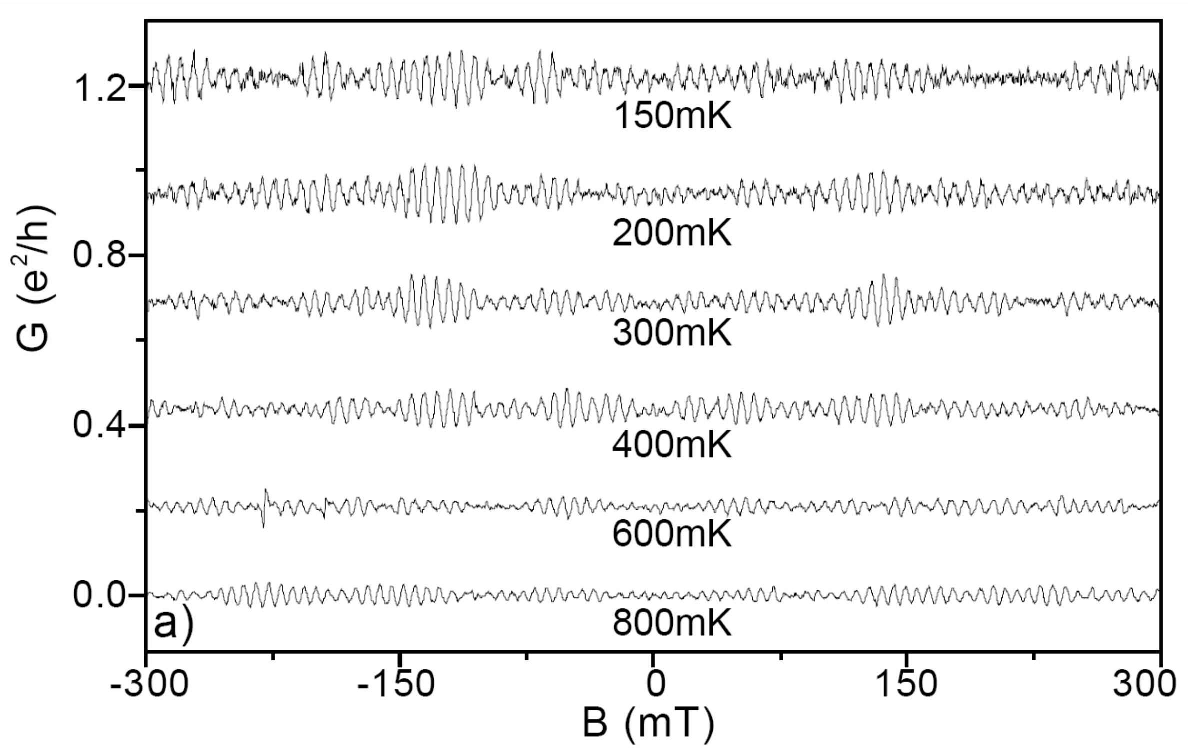
Procedure:
lock-in
two-terminal
current-biased

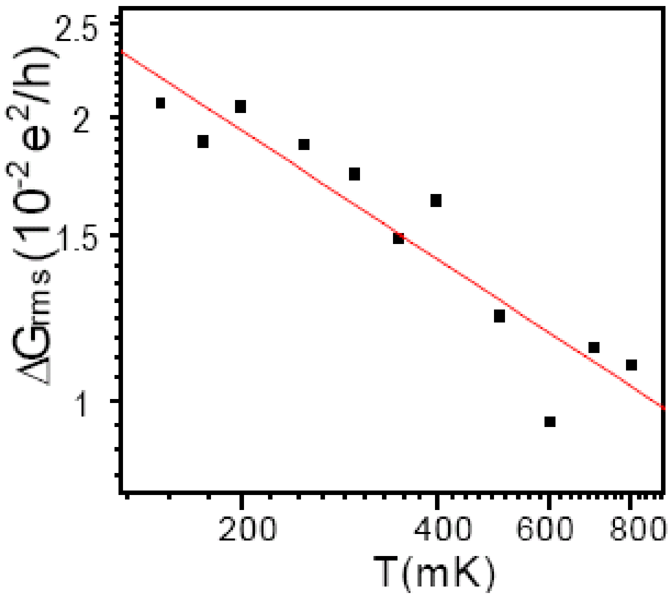
Observations:

- Weak localization (probably)
- Aperiodic conductance fluctuations
- Aharonov-Bohm conductance oscillations

Russo, Oostinga, Wehenkel, Heersche, Sobhani, LMKV, Morpurgo, arXiv:0711.0479

Temperature dependence AB amplitude





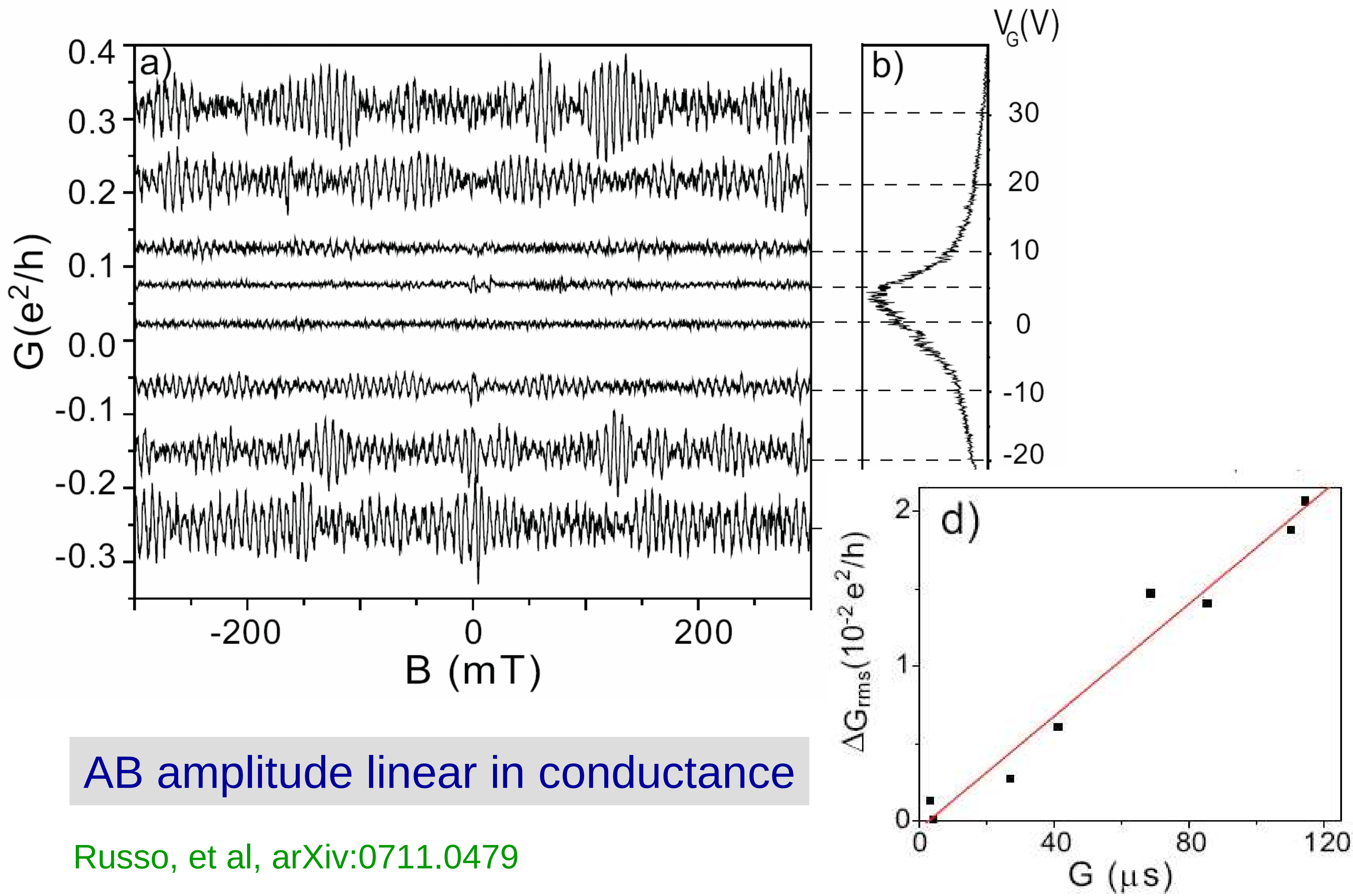
Expect $\Delta G_{rms} \sim \exp[-\pi R/L_\phi(T)]\ (E_{Th}\,/\,\mathrm{k}T)^{-1/2}$

Observe thermal averaging
(note $E_{th} \sim 10\ \mu\mathrm{eV} < 150\mathrm{mK} \sim k_B T$)

➡ Indicates $L_\phi >$ few μm

See also WL data of Tikhonenko et al, arXiv:0707.0140

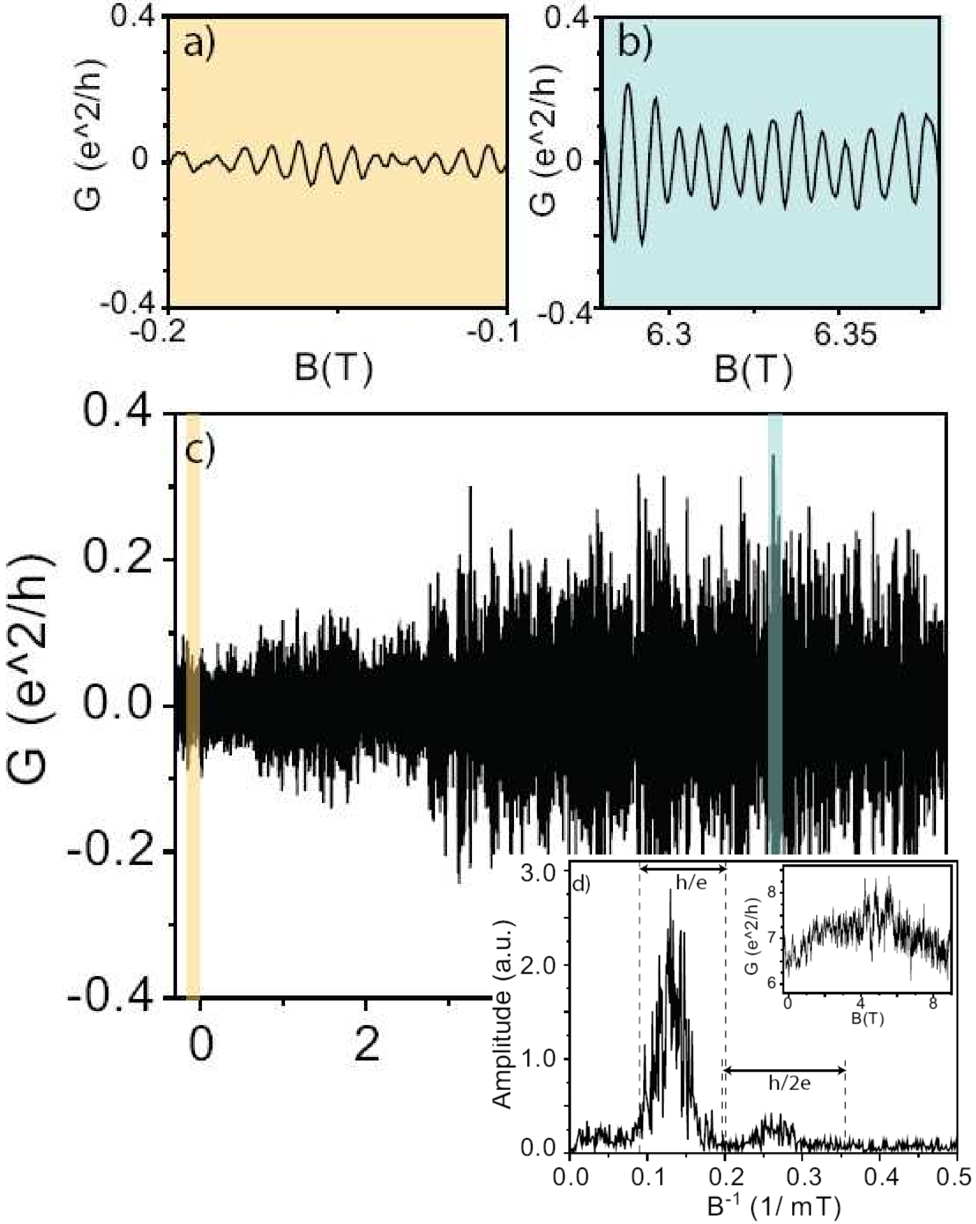
Gate voltage dependence AB amplitude

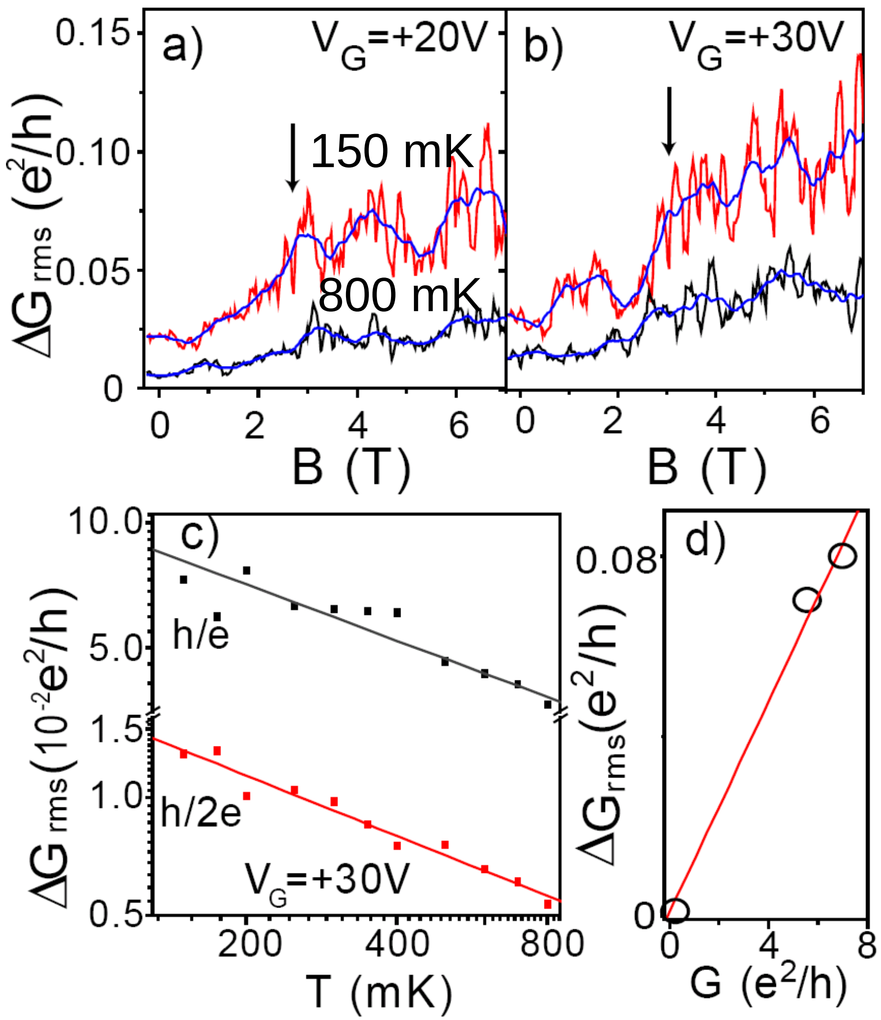


AB amplitude linear in conductance

Russo, et al, arXiv:0711.0479

Magnetic field dependence AB amplitude





Not due to magnetic impurities
Possibly orbital origin

Message for graphene spin qubits

It may be possible to define dots using electrostatic gates

Role of disorder to be explored further

Spin coherence time could be very long

People and collaborations

GaAs spin qubits

Jeroen Elzerman (ETH)
Ronald Hanson (UCSB)
Laurens Willems v Beveren (UNSW)
Josh Folk (UBC)
Frank Koppens
Ivo Vink
Christo Buizert (U Tokyo)
Klaas-Jan Tielrooij (AMOLF)
Tristan Meunier
Katja Nowack
Tjitte Nooitgedacht
Han Keijzers
Leo Kouwenhoven
Lieven Vandersypen

External collaborations

Loss group (Basel)
Nazarov (Delft)
Rudner & Levitov (MIT)
Wegscheider (Regensburg)
Tarucha group (Tokyo)

Graphene

Hubert Heersche
Pablo Jarillo-Herrero (Columbia)
Jeroen Oostinga
Xinglan Liu
Alberto Morpurgo
Lieven Vandersypen

NWO FOM

Kavli Institute of Nanoscience