Spin-resolved conductance quantization and evidence for zitterbewegung in InAs

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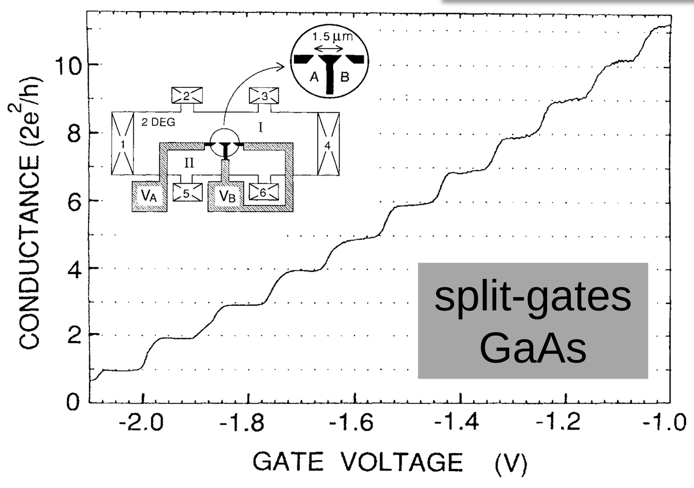
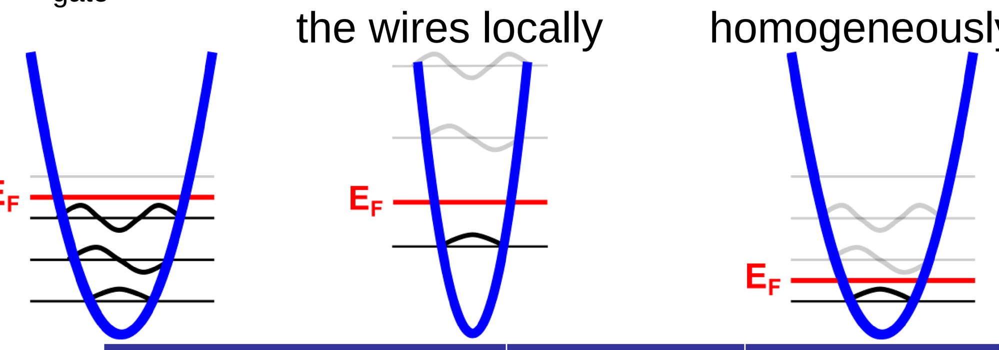
Quantum Point Contacts



$V_{gate} = 0$	side-gate voltage: electrically narrow the wires locally	top-gate voltage: depopulate 2DEG homogeneously



	GaAs	--- InAs ---
Rashba parameter	≈ 1 meV nm	≈ 20 meV nm

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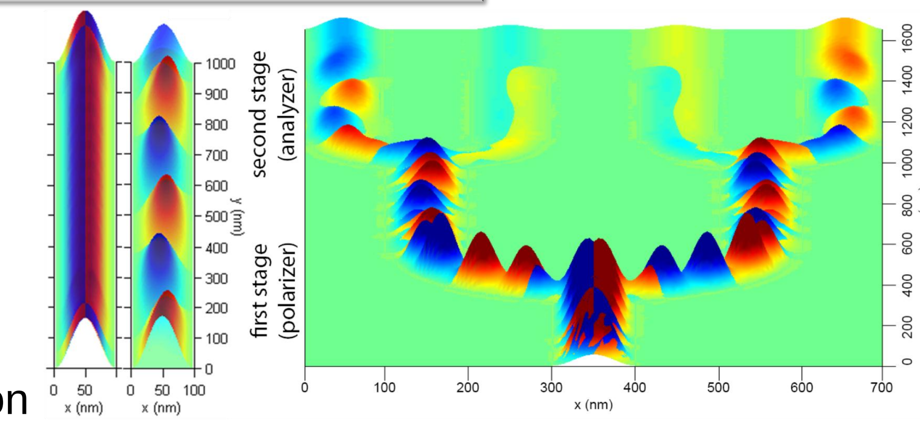
S. J. Koester et al., Phys. Rev. B **53**, 13063 (1996)

Spin-Filter Cascades

three terminal junction:
- generation of spin-polarized currents due to the spin Hall effect

second filter stage:
- electrical detection of spin polarization

polarized injection:
- spin state alternates due to spin precession
- force exerted by the spin Hall effect alternates in direction → oscillatory motion **(zitterbewegung)**



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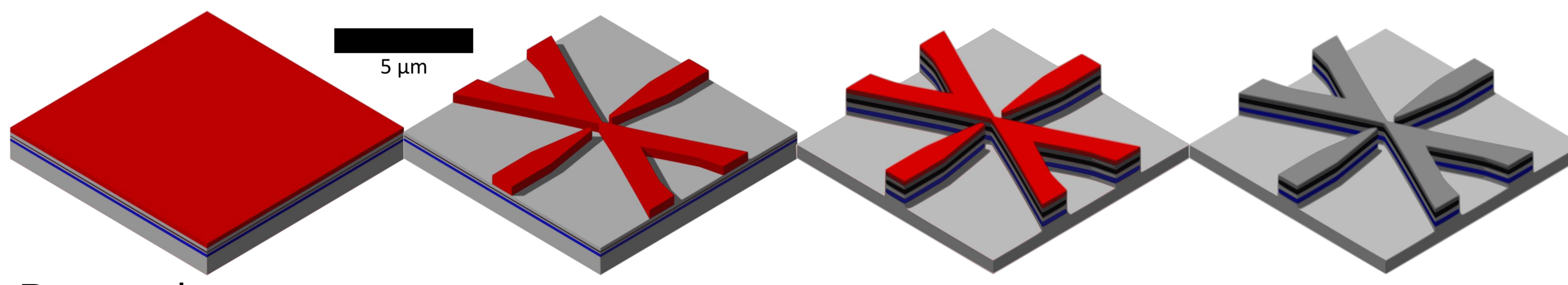
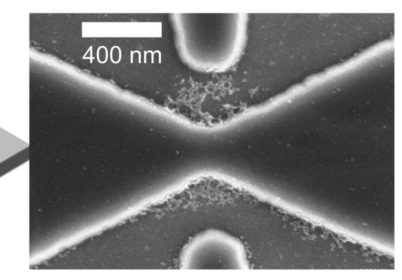
J. Jacob, H. Lehmann, U. Merkt, S. Mehl, and E. M. Hankiewicz, J. Appl. Phys. **112**, 013706 (2012)

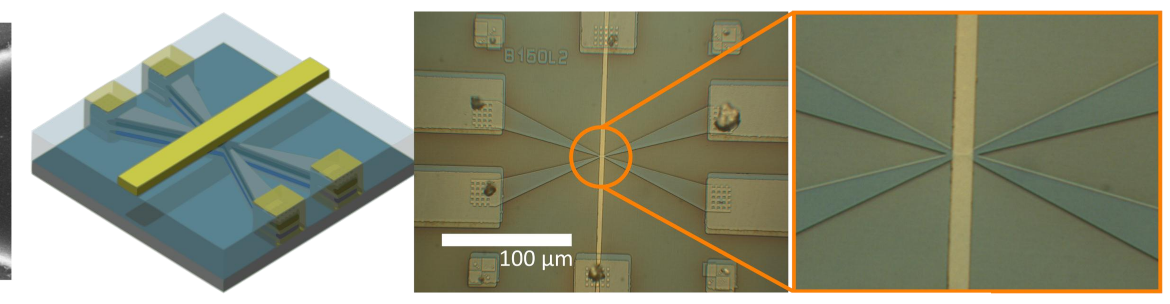
Sample Processing

thickness (nm)	WAFER LAYOUT	
36.0	$In_{0.76}Al_{0.24}As$	capping
13.5	$In_{0.76}Ga_{0.24}As$	
4.0	InAs	2DES
2.5	$In_{0.76}Ga_{0.24}As$	
10.0	$In_{0.76}Al_{0.24}As$	
7.0	$In_{0.76}Al_{0.24}As$:Si	doping
300.4	$In_{0.76}Al_{0.24}As$	lattice adjustment
100.3	$In_{0.67}Al_{0.33}As$	lattice adjustment
100.3	$In_{0.57}Al_{0.43}As$	lattice adjustment
99.9	$In_{0.47}Al_{0.53}As$	lattice adjustment
99.9	$In_{0.37}Al_{0.63}As$	lattice adjustment
99.9	$In_{0.26}Al_{0.74}As$	lattice adjustment
99.2	$In_{0.16}Al_{0.84}As$	lattice adjustment
2.0	AlAs	20x super lattice
2.0	GaAs	20x super lattice
50.2	GaAs	
	GaAs	substrate





side-gate pair



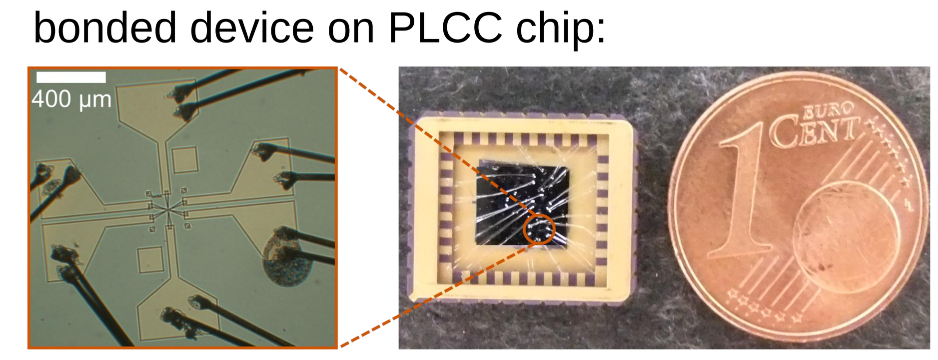
top-gate electrode

Preparation process:
(a) negative electron-beam resist
(b) scanning-electron lithography
(c) reactive-ion etching
(d) wet-chemical cleaning
(e) UV-sensitive positive resist
(f) optical lithography (mask aligner)
(g) thermal evaporation of AuGe
(h) lift-off process, contact wires end in bond pads

$N_e \approx 1.1 \cdot 10^{12}$ cm^{-2}
$\mu_e \approx 108\ 000$ cm^2/Vs

Additional fabrication steps for top-gate electrodes:
(I) Spin-on glass (HSQ) for the insulating layer between InAs channel and top-gate electrode.
(II) Optical lithography, thermal evaporation of AuGe, and a lift-off process form the top-gate electrode
(III) HSQ on top of the bond pads has to be removed

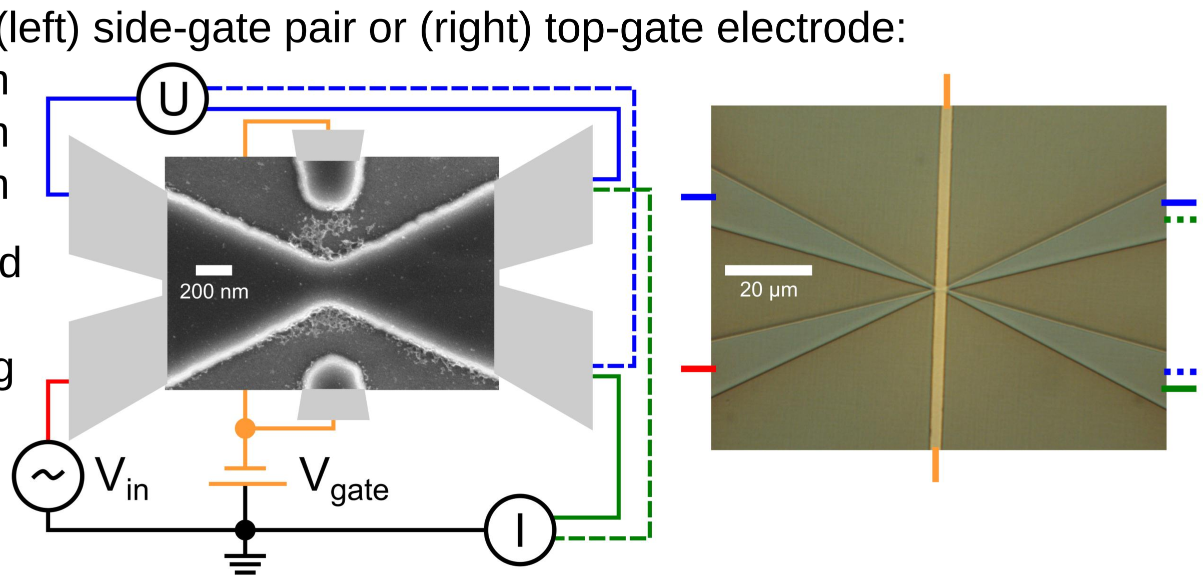
bonded device on PLCC chip:

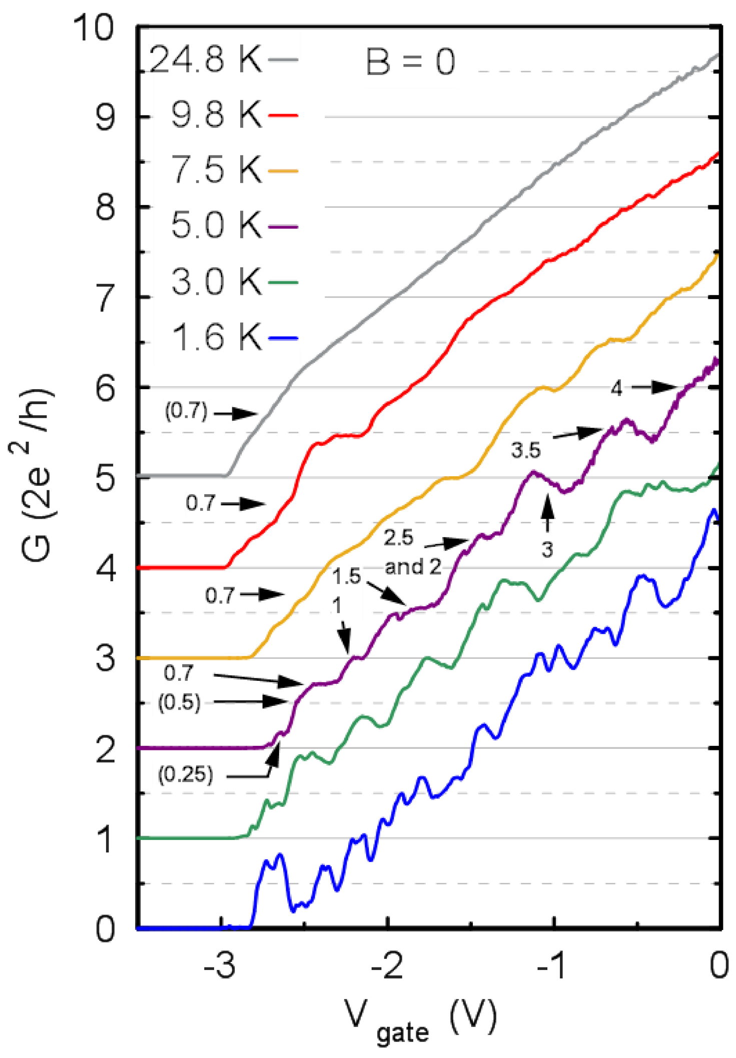


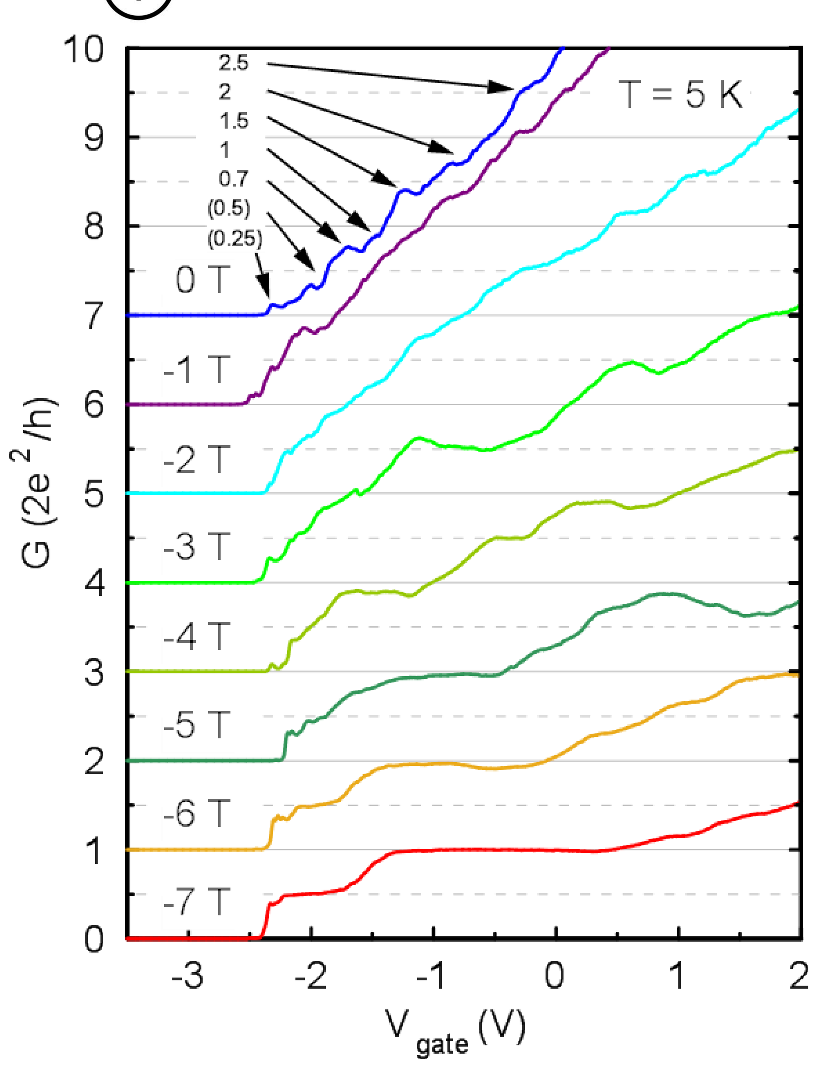
Results

quantum point contact with (left) side-gate pair or (right) top-gate electrode:
- wire width 150 nm
- side-gate distance 400 nm
- top-gate spacing 240 nm

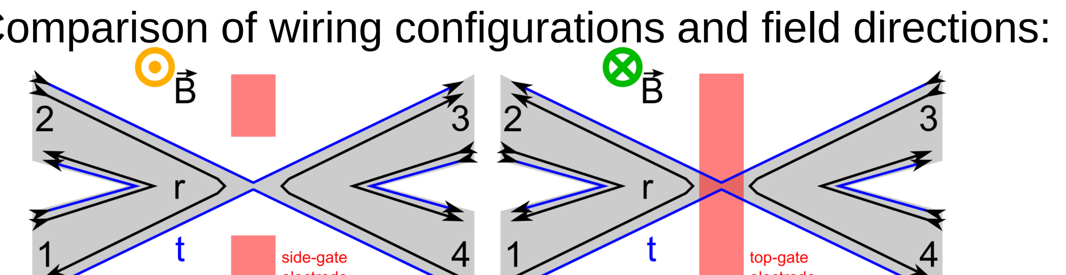
The conductances are reduced at negative gate voltages and measured in two distinct wiring configurations:
- straight (solid lines)
- crossed (dashed lines)







- At a temperature of 5 K the best resolved conductance quantization is observed.
- In high out-of-plane magnetic fields the electrons condense onto Landau levels
  → clearly pronounced quantization steps that perfectly match integer and spin-resolved half-integer multiples of 2e²/h (at least in crossed wiring and negative fields).
- Comparison of wiring configurations and field directions:



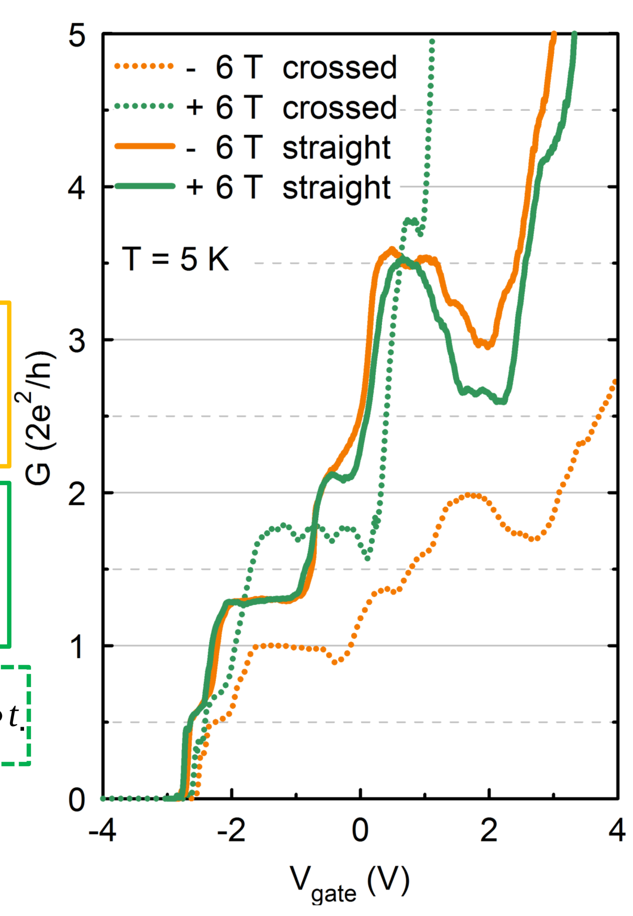
According to the Landauer-Büttiker formalism with $U = e \cdot \Delta\mu$ one obtains for straight ($I_1 = -I_4 = I$ and $I_2 = I_3 = 0$) and crossed ($I_1 = -I_3 = I$ and $I_2 = I_4 = 0$) wiring

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = 2\frac{e}{h} \cdot \begin{pmatrix} (r+t) & -r & 0 & -t \\ -(r+t) & (r+t) & 0 & 0 \\ 0 & -t & (r+t) & -r \\ 0 & 0 & -(r+t) & (r+t) \end{pmatrix} \cdot \begin{pmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \end{pmatrix}$$

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = 2\frac{e}{h} \cdot \begin{pmatrix} (r+t) & -(r+t) & 0 & 0 \\ -r & (r+t) & -t & 0 \\ 0 & 0 & (r+r) & -(r+t) \\ -t & 0 & -r & (r+t) \end{pmatrix} \cdot \begin{pmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \end{pmatrix}$$

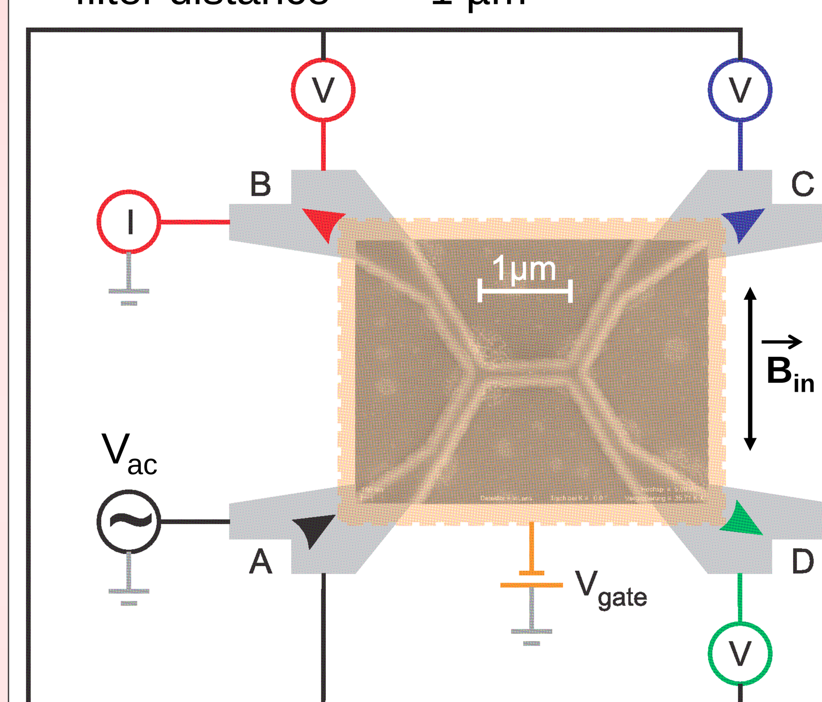
the conductances $G = 2\frac{e^2}{h} \bullet t$, $\frac{t+r}{r} \bullet 2\frac{e^2}{h} \bullet t$, $\frac{t+r}{r-t} \bullet 2\frac{e^2}{h} \bullet t$.

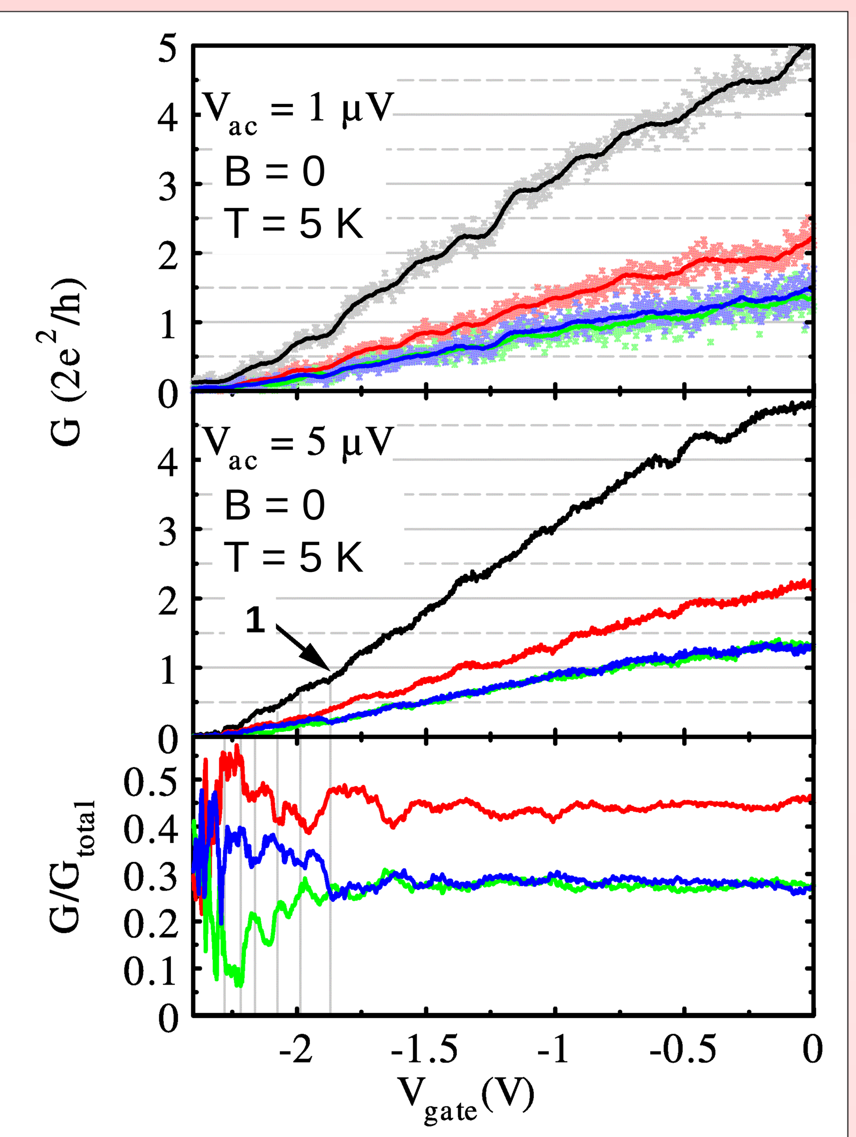
for: t = 1 ; r = 4 →	1 :	1.25 :	1.66
for: t = 2 ; r = 3 →	2 :	3.33 :	10



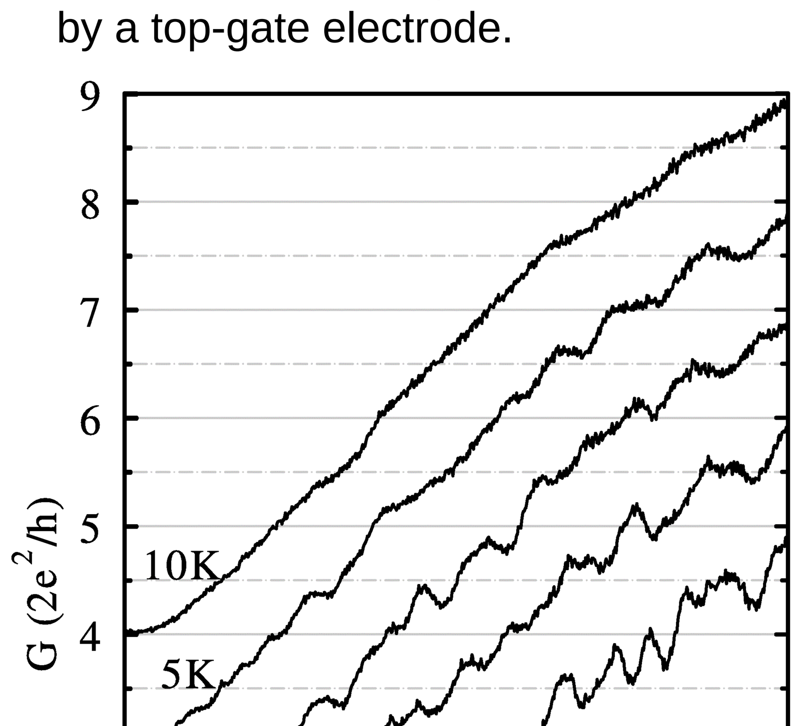
H. Lehmann, T. Benter, I.v. Ahnen, T. Matsuyama, W. Hansen, C. Heyn, U. Kunze, A. D. Wieck, D. Reuter, U. Merkt, and J. Jacob, **in preparation**

spin-filter cascade with top-gate electrode:
- wire width 150 nm
- filter distance 1 µm

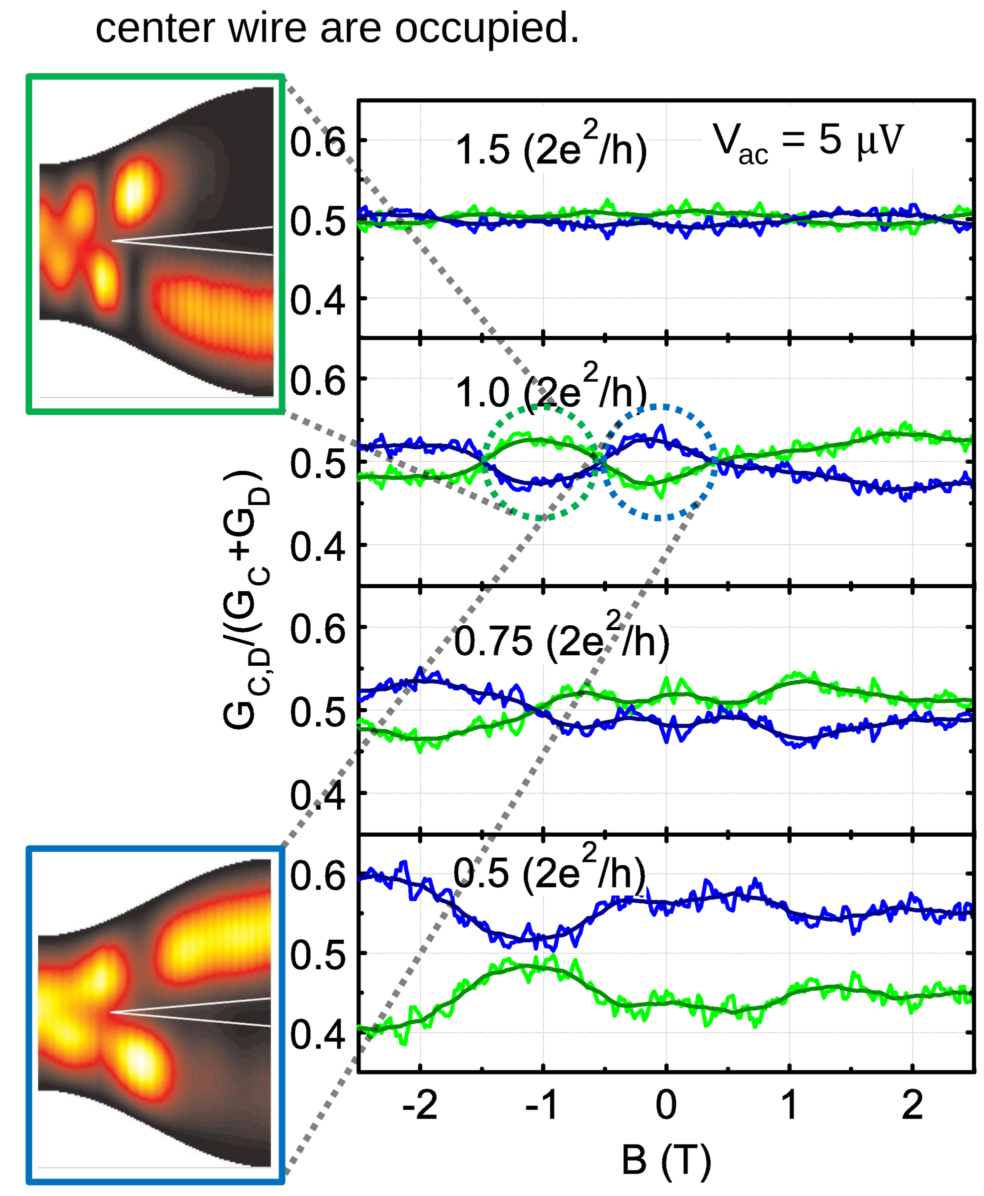




- The electron density has been varied by a top-gate electrode.



- A conductance imbalance of the second filter's output terminals indicates spin polarization.
- At a temperature of 5 K the best resolved conductance quantization is observed.
- An oscillatory behavior is most prominent when only few transport modes in the center wire are occupied.



- The period of the zitterbewegung can be tuned by an in-plane magnetic field that enhances or weakens the effective Rashba field.
- From theory we expect an oscillatory behavior in the conductances of the detector stage's two outputs.
- The period should be about 1 T.

P. Brusheim, H. Q. Xu, **arXiv**:0810.2186v2 [cond-mat.mes-hall], (2009)
T. Benter, H. Lehmann, T. Matsuyama, W. Hansen, C. Heyn, U. Merkt, and J. Jacob, Appl. Phys. Lett. **102**, 212405 (2013)

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