Scanning gate microscopy and individual control of edge-state transmission through a quantum point contact

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Motivation

Interference phenomena are a fundamental manifestation of the quantum mechanical nature of electrons and have promising applications in solid-state quantum information technology. In particular, the realization of electronic Mach–Zehnder (MZ) interferometers in Quantum Hall (QH) systems appears at present a sound technology for the implementation of quantum information schemes [1]. Despite this success, the edge topology of the single-channel MZ limits the complexity of these circuits to a maximum of two interferometers [2]. In order to overcome this constraint, new device architectures were recently proposed [3], where interference paths are built using two different parallel edge channels. In this configuration, control over the interaction between the different edge channels is challenging owing to the complex edge structure.

In order to address these issues we are exploring the use of scanning gate microscopy (SGM) to control the trajectory and interaction of edge channels based on our previous results on quantum point contact (QPC) devices in the QH regime [4,5]. In the present work, the two split gates of the QPC play a double role: they not only allow us to bring the edges in close proximity, but they also provide the ability to select the edges that are sent to the center of the QPC.

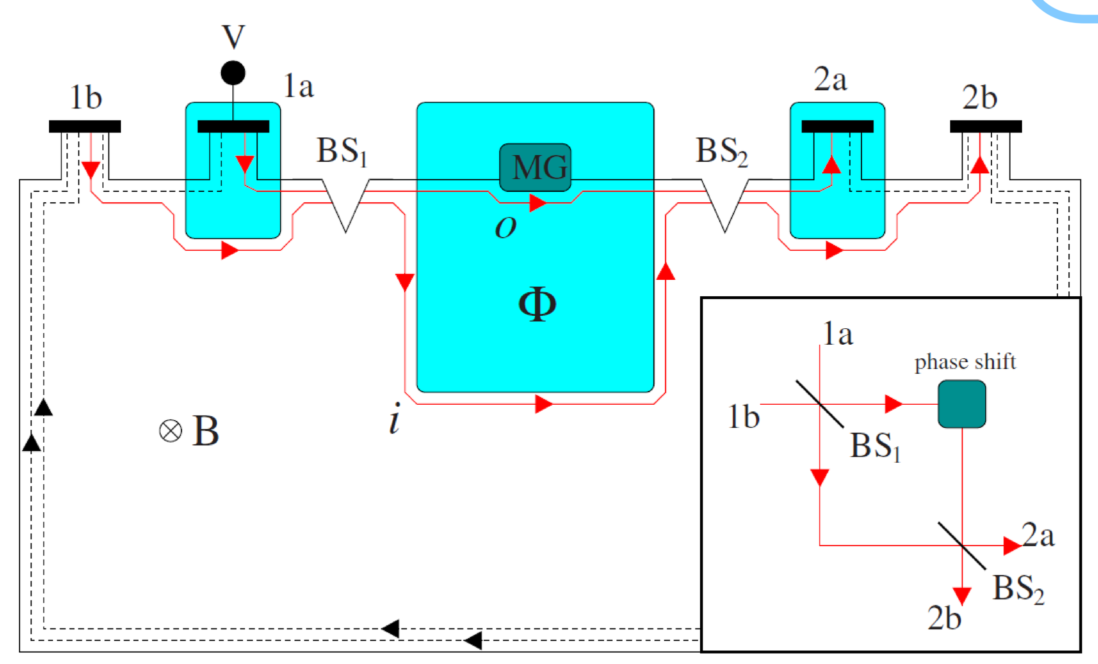
[1] Y. Ji et al. Nature **422**, 415 (2003).

[2] I. Neder et al., Nature **448**, 333 (2007).

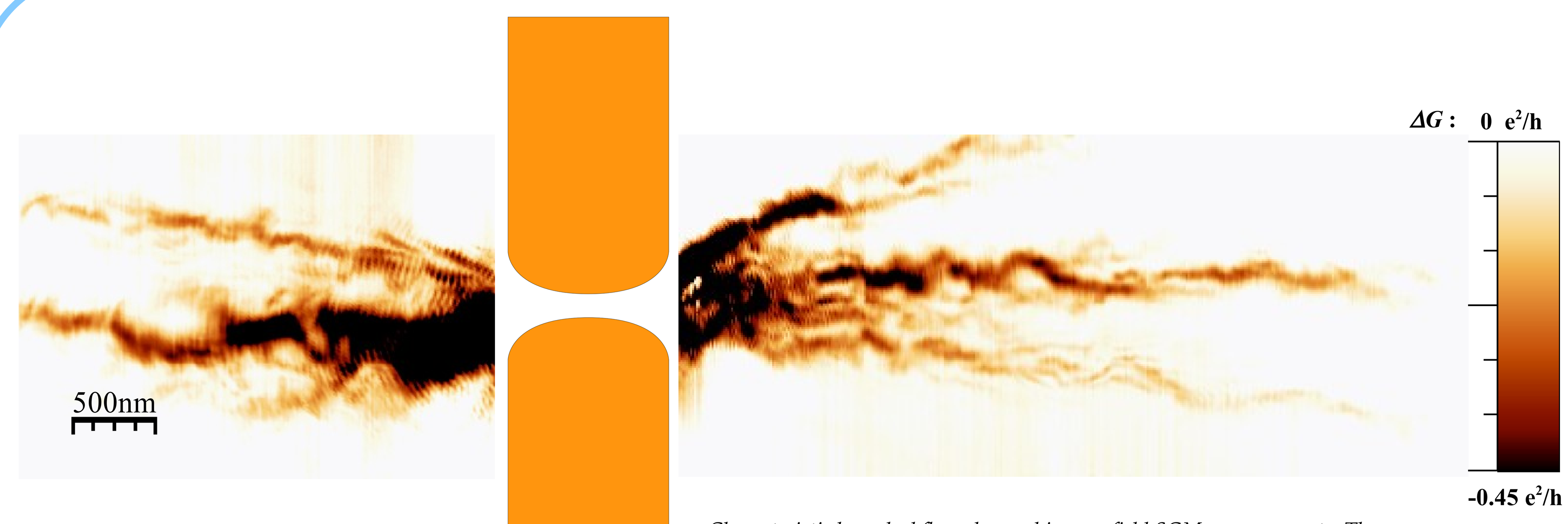
[3] V. Giovannetti et al., Phys. Rev. B **77**, 155320 (2008).

[4] S. Roddaro et al., Phys. Rev. Lett. **95**, 156804 (2005).

[5] S. Roddaro et al., Phys. Rev. Lett. (in press).



Sketch of the proposed multichannel architecture for electronic QH interferometry; from Ref. [3].



- 2DEG e⁻ density $n = 3.37 \cdot 10^{11}$ cm^{-2}
- dark mobility $\mu = 2.62 \cdot 10^{-6}$ cm^2/V·s
- tip voltage V_{tip} = -5 V; height h_{tip} = 10 nm
- temperature 400 mK
- QPC conductance $G = 6e^2/h$ (3rd plateau)

Characteristic branched flow observed in zero-field SGM measurements. The dark regions in the color plot (low conductance) correspond to the actual electron path and depend on the details of the local potential. The fringes which decorate the branches are a signature of the electron phase coherence.

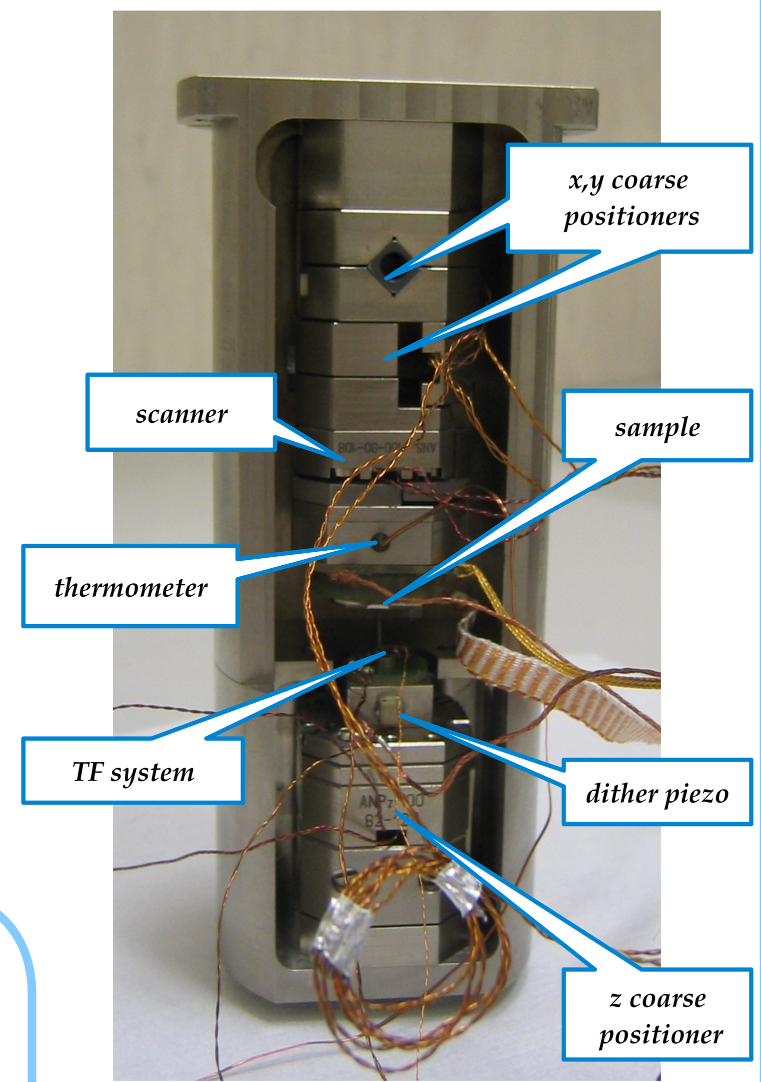
The SGM setup

The fundamental element of our setup is the AFM head. It is constructed with a stack of actuators for both the coarse and fine control of the tip-sample position. The sample, mounted on a chip carrier, is positioned on top of this stack, while the tip is connected to a tuning fork (TF) which is fixed. The AFM head is mounted on the cold finger of a ^{3}He cryostat with a base temperature of 300 mK. A superconducting coil can provide a magnetic field up to 9 T.

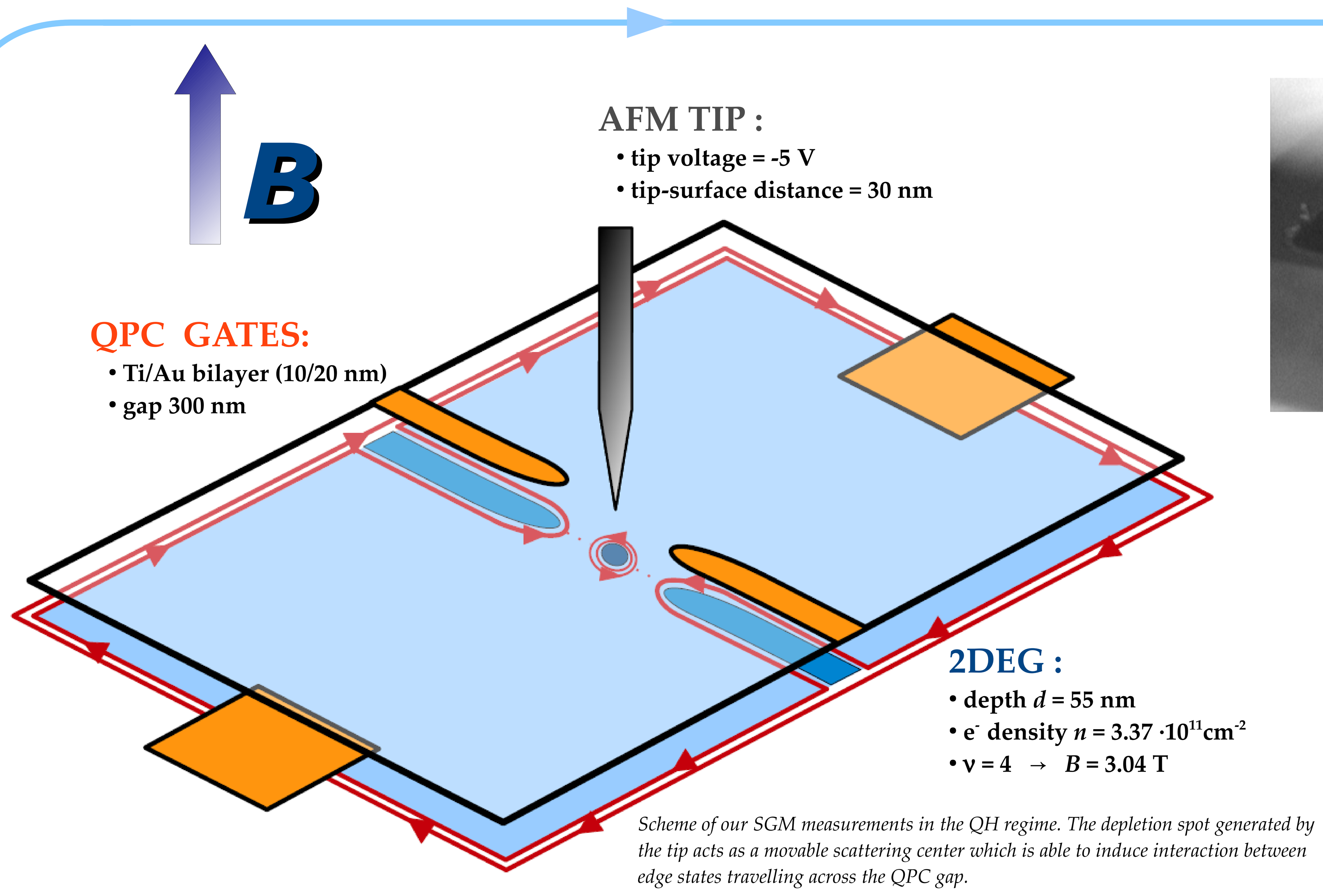
The sample topography is obtained by controlling the oscillation damping of the TF due to the tip-sample shear force (non-contact mode). The SGM measurements are performed in constant height mode. The negatively biased tip yields a local depletion of the 2DEG. Conductance maps are obtained by measuring the source-drain current point-by-point during the scan.

The reliability of our experiments on QPC is tested by SGM measurements at zero field. As reported in literature [6], when the QPC conductance is quantized, the backscattering of the electrons with the depletion spot induced by the tip yields a change in the conductance which depends on the local electronic paths. The conductance map shows the characteristic branched flow of electrons. These branches are decorated with fringes due to the self-interference of the electrons. They extend over a length scale of several microns, due to the high mobility of the 2DEG.

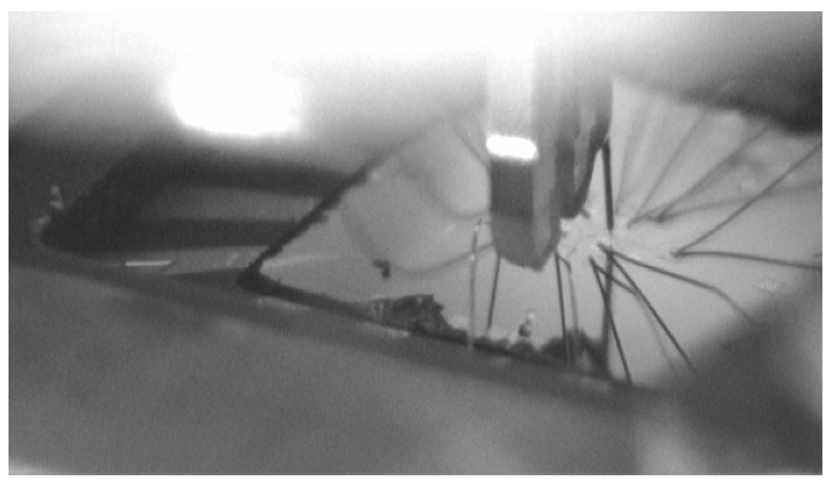
[6] M. A. Topinka et al., Science **289**, 2323 (2000).



Picture of the AFM head used in these SGM measurements



Scheme of our SGM measurements in the QH regime. The depletion spot generated by the tip acts as a movable scattering center which is able to induce interaction between edge states travelling across the QPC gap.



Selective control of edge channel trajectories by SGM

We are exploring the use of SGM to control the trajectory and interaction of edge channels in quantum point contact (QPC) devices in the QH regime. Samples are fabricated starting from high-mobility GaAs/AlGaAs heterostructures and Schottky split-gate QPCs. SGM experiments were performed at 400 mK. The figure below shows the QPC conductance G as a function of the position of the biased SGM tip (V_{tip}= -5 V). The (bulk) 2DEG filling factor is set to $\nu_{bulk} = 4$ (2 spin-degenerate edge channels; B = 3.04 T) while the QPC gates partially or completely deplete the 2DEG underneath. In (a), the gate-region spin-degenerate filling factors are $g_1 = g_2 = 0$. When the biased tip is brought close to the QPC, edge channels are backscattered one by one, and the conductance through the QPC decreases in a step-like manner to 0. The split-gate QPC however also allows to bias the individual gates asymmetrically and pre-select edges that can then be manipulated by the SGM tip. For instance, in (b) for the case $g_1 = 0$, $g_2 = 2$, only the inner edge channel can be backscattered by the local action of the tip, while the outer either flows far from the constriction (under the lower gate) or has no counterpart for the backscattering process to occur (upper gate). In this case, the conductance value remains $G = 2e^2/h$ even when the tip completely pinches off the constriction region. The same holds for the mirrored gate configuration (c) with $g_1 = 2$ and $g_2 = 0$. Since it is impossible to backscatter the unpaired edge, the SGM measurements in the configurations (b) and (c) are virtually identical to the measurement in the configuration (d) with identical filling factors $g_1 = g_2 = 2$ under the split-gates. These results clearly show that the lower bound for the conductance is determined by the number of paired edge channels which can be backscattered, and that unpaired edges are unaffected by the gating action of the tip. Our results are a crucial first step for the implementation of multi-edge beam mixers and interferometers.