1.3.4 Quantum Hall Interferometry – Scanning Gate Microscopy

Two-dimensional electron systems based on GaAs/AlGaAs heterostructures in a strong magnetic field were used to investigate the physics of edge modes in the quantum Hall regime. These electron states realize an ideal chiral one-dimensional electron beam which can be used both for the study of transport phenomena in one dimension and as a building block for the construction of advanced electron interferometers.

The interest in the development of solid state quantum devices goes well beyond fundamental research on many-body systems. An example is the quantum mechanics concept of *entanglement*. In the last decade entanglement has become synonymous with quantum computing. A number of physical systems were already proposed as possible candidates as quantum computing hardware. In this context, the peculiar properties of quantum Hall (QH) systems can be very useful. First of all, since these are implemented within solid state devices, they can be easily miniaturized and integrated on chip by means of well-established semiconductor-technology fabrication methods. More importantly, QH circuits operate with electrons: due to their fermionic statistics, it is much easier to obtain a single-electron rather than a single-photon source. Moreover, in QH systems, the Lorentz force compels electrons to move along counter-propagating chiral channels at sample edges. When Landau levels (LLs) in the bulk are fully occupied, backscattering between counter-propagating edge states is drastically suppressed. When several LLs are populated, edge channels consist of a series of dissipationless edge states that can be easily separated and independently contacted much like a computer bus [1]. Edge channels in the fractional QH regime are even more interesting, since their excitations are expected to display anyonic statistics.

A two-particle entangler can in principle be obtained in a two-channel conductor, for example employing two edge channels in the integer QH regime. Coherent mixing between two counter-propagating edge states was achieved by means of quantum point contacts and employed to realize an all-electronic Mach-Zehnder interferometer. Such devices have nevertheless several drawbacks caused by their non-simply connected topology. It is not obvious how to concatenate many devices in series, i.e. how to achieve scalability. On the contrary, Giovannetti and coworkers recently theoretically showed that if a coherent mixer between co-propagating edges is realized, scalable simply-connected interferometers can be build. Such devices could in principle work with many modes, if implemented in QH systems with filling factor $\nu > 2$. This advantage, along with the scalability, could be pivotal to practically access the potential of quantum circuits as electron entanglers and open the way to an innovative class of quantum computing devices.

The application of this scheme to the quantum computation of anyonic qubits crucially depends on the ability to determine (i) how parallel edge channels can be mixed, and whether this mixing is coherent or not, and (ii) the inner structure of edges, and in particular to determine possible fractional components that could be used as a bus of anyonic quasi-particles. Work at NEST is aimed at experimentally addressing these challenging questions. To this end, we combine transport measurements and a scanning probe microscopy technique to directly manipulate edge channels [2,3].

To explore the inner (fractional) structure of (integer) edges, we used the scanning gate microscopy (SGM) technique [2]. Our SGM maps provided the first images of the fractional features (corresponding to filling factors 1/3, 2/5, 3/5, and 2/3) that form the inner edge structure [4]. SGM maps showed that the edge consists of a series of alternating compressible and incompressible stripes (see Fig. 1). The high resolution of the SGM technique allowed us to directly measure stripe widths and compare them with the predictions of the edge-reconstruction theory. The experimental demonstration of fractional structures within integer edge channels represents the conclusive answer to long-time debated issues: the stripe structure explains how edge channels behave at the interface between an integer and a fractional QH phase. In this case, an integer edge is partitioned into its fractional components, so that there is continuity between the fractional incompressible stripe and the corresponding macroscopic fractional phase. This also elucidates the non-fermionic characteristics observed at NEST via finite bias measurements on point-like junctions between integer QH phases [5].

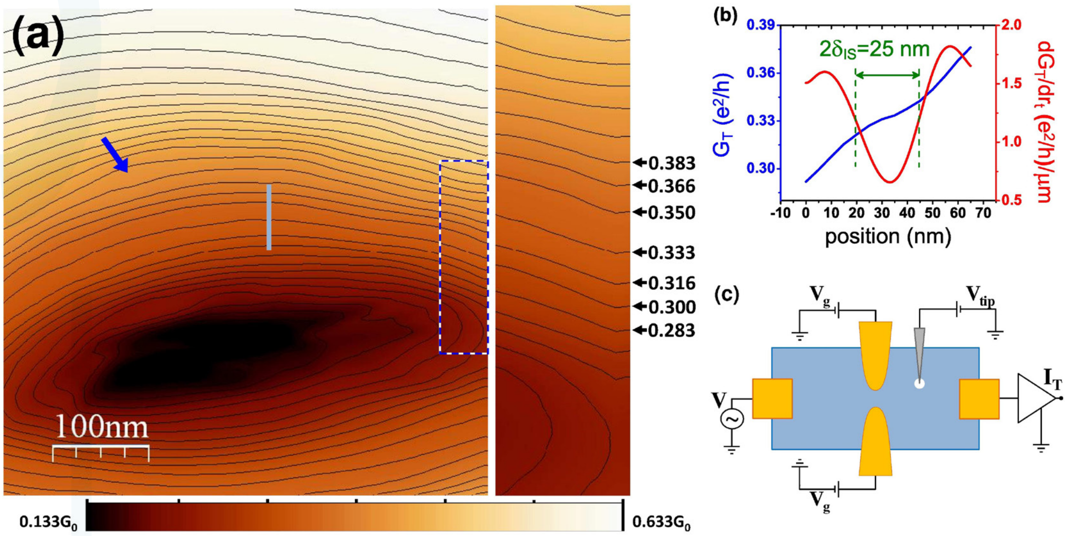

Figure 1. (a) SGM scan at the center of a QPC in a quantum Hall system at integer filling factor 1. The map shows the transmitted differential conductance as a function of the tip position, together with contour lines at constant differential conductance. On the right, a zoom of the 50 x 200 nm region corresponding to the dashed rectangle is displayed. (b) Profile of the differential conductance along the light blue line in (a), together with its derivative. (c) Scheme of the SGM experimental setup.

In these experiments we also demonstrated how to accurately control edge-channel trajectories [2]. This ability introduces a new degree of freedom in transport measurements: the device geometry itself can become a tunable experimental parameter, controllable in real time at low temperature. The unprecedented flexibility of this method has opened the way to a number of experimental opportunities, such as a QH circuit whose geometry can be controlled at low temperature by moving the tip: we used such a size-tunable QH circuit to locally investigate the microscopic processes that are responsible for the charge equilibration of bias imbalanced co-propagating channels [6,7]. These measurements clarified important findings of previous transport experiments:

on one hand our data unambiguously showed the link between inter-edge scattering and the presence of potential fluctuations [6]. On the other hand, they allowed us to explain the puzzling reduction of the threshold voltage for the onset of radiative emission [7]. Finally, our results suggest that one such device can indeed be exploited as a beam mixer for co-propagating edge channels in simply-connected Mach-Zehnder interferometers.

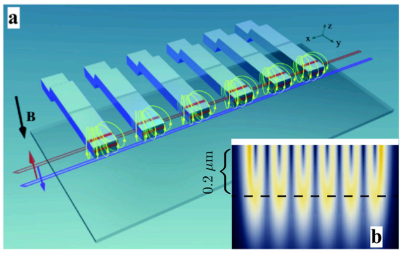

Figure 2. Schematics of the device studied. The Cobalt fingers produce a fringing field resulting in an in-plane, oscillatory, magnetic field at the level of the 2DEG residing below the top surface. The field induces charge transfer between the spin up (red line) and spin down (blue line) edge channels.

A related activity at NEST aims at experimentally demonstrating a new method to artificially couple spin-resolved edge states of a quantum-Hall insulator and induce inter-edge charge transfer associated to spin-flip scattering events. The process exploits the coupling of the electron spin with a spatially-dependent periodic in-plane magnetic field created by an array of Cobalt nano-magnets placed at the boundary of the two-dimensional electron gas (see Fig. 2). This approach could be used for the realization of scalable quantum information processing based on the spin degree of freedom of topologically-protected edge states [8].

Our results open the way to the realization of simply-connected Mach-Zehnder interferometers based on co-propagating edge channels. Our SGM work on the fractional sub-structure of edge channels furthermore indicates how to operate the interferometer with individual fractional stripes instead of single integer-edge channels. The impact of such a result can be vast since it may represent a valid step forward towards the achievement of an interferometer operating with exotic quasi-particles, like the non-abelian excitations of the $\nu=5/2$ QH phase. Such an advance would in perspective lead to the implementation of fault-tolerant quantum computers, because of the nonlocal encoding of the quasiparticle states, which makes them immune to errors caused by local perturbations.

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