NANONIS APPLICATION NOTE

# PROBING QUANTUM TRANSPORT by SCANNING GATE MICROSCOPY (SGM)

Most scanning probe microscopy techniques are ideal to investigate the properties of the first few atomic layers of a surface, but are useless when the system of interest is buried deeper. For example, scanning tunneling microscopy (STM) yields extremely detailed information on the surface electrons, but fails to operate on electrons buried below oxides. Scanning Gate Microscopy (SGM) overcomes this limitation by scanning the electrically biased tip in a plane parallel to the electron of interest, and simultaneously recording a map of the variations of electrical resistance of the system. In other words, the tip induces a local electrostatic potential perturbation, which affects the electron transport.

We use SGM to explore the *quantum Hall effect* regime, present at high magnetic field and cryogenic temperatures in two-dimensional electron systems, where the electrons are transmitted along the edges of the device, through "ideal" one dimensional channels. When such edge channels are brought close to each other in nanodevices, electrons can tunnel between them, either directly, or through "electron islands".

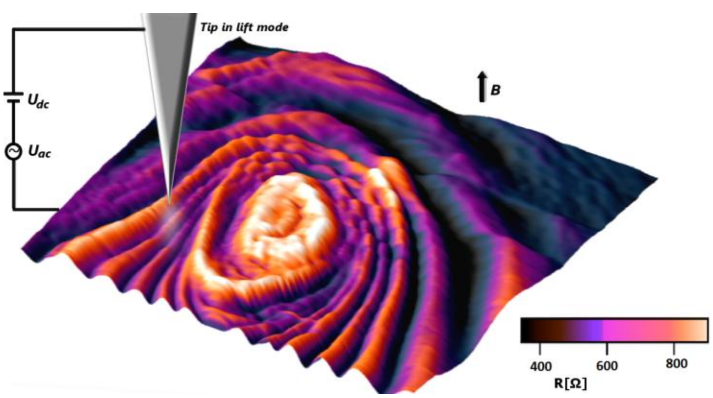


Figure 1. 3D view of a resistance R[Ω] map obtained at T = 0.1 K and B = 9.65 T. The center of the concentric fringes signals the location of a quantum Hall Coulomb island, inside one arm of a quantum ring. The image size is 3x3 µm.

To probe this regime, we performed SGM measurements with a home-built scanning probe microscope, built into a 3He/4He dilution refrigerator, where the sample can be cooled down to 100 mK, and submitted to a magnetic field of up to 17 T. The probe consists of a metalized atomic force microscope (AFM) cantilever glued on a piezoelectric tuning fork (figure 2).

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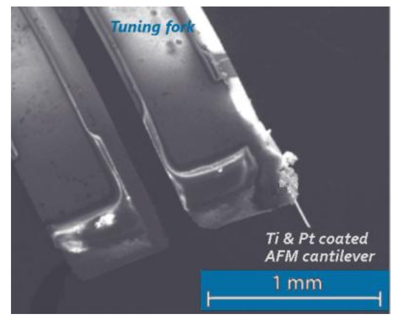


Figure 2. Electron micrograph of the force sensor. The two prongs of the tuning fork are visible; a commercial AFM cantilever coated with 20 nm of Ti and 10 nm of Pt (nominal tip radius ~40 nm) was glued on one prong of a quartz tuning fork using conductive silver epoxy. Non-contact AFM control mode of the tuning fork.

## System:

- Home-built LT-SGM: dilution refrigerator-100mK
- Tuning forks sensors

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The nanodevice surface was imaged in non-contact AFM mode, where the amplitude, phase and frequency shift of the tuning fork were monitored using the Nanonis control system equipped with a PLL (OC4). The tip was then lifted a few nm above the sample surface, and the system is operated in SGM mode with the biased tip scanning parallel to surface. The nanodevice electrical resistance (R[Ω]) is measured using a lock-in technique: either the Nanonis digital lock in (LI), or an external one, whose signal is acquired using one Nanonis input channels of the controller.

Thanks to this system, we measured SGM resistance maps in the quantum Hall regime on a 1 µm-diameter quantum ring, patterned in an InGaAs heterostructure, and hosting a two-dimensional electron system 25 nm below the sample surface (figure 1). The SGM images show concentric resistance fringes, and we show that the center of each set of fringes corresponds to the location of an "active" electron island tunnel-coupled to edge channels, where a small number of electrons are confined in quantized energy levels. Using suitable tip biases we can control the electron tunneling through each island, and selectively "destroy" each of them or create new islands.

The LabVIEW Programming Interface (PI) has been extensively used to program sequences of data acquisition with the Nanonis controller. SGM image sequences were acquired overnight by automatically changing the tip voltage and various bias voltages on the sample using Nanonis external outputs. Moreover, the additional input channels were useful to test new SGM imaging modes, such as scanning gate transresistance microscopy.

In the future, we plan to extend the SGM technique to the mapping of other device properties (i.e. not only the electrical resistance), and to combine SGM with the use of a "smart tip" equipped, for example, with a single electron transistor at its apex.

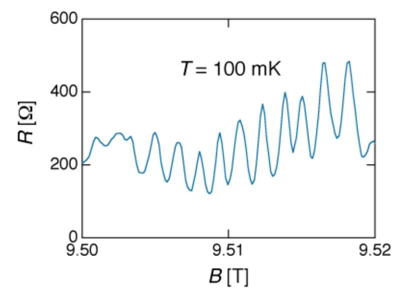


Figure 3. In mesoscopic systems electronic transmission turns out to be more complex giving rise to a large spectrum of magnetoresistance oscillations. Here is the R[Ω] of the quantum ring (QR) on the quantum Hall (QH) plateau for $\nu$ = 6 and $T$ = 100mK. The periodicity of the oscillations in $R$ versus $B$ is $\Delta B$ = 1.5 mT.

## Nanonis Modules in Use:

- Base Package (BP4)
- Digital lock-in (LI)
- Oscillation Controller (OC4)
- High Voltage Amplifiers (HVA4)
- Control over the AttoCube motors via serial integration of ANC150.
- LabVIEW Programming Interface (PI)
- Multipass scanning technique

*References:*

*[1] B. Hackens et al.,* Imaging Coulomb islands in a quantum Hall interferometer, ***NATURE Communications*** **1**, 39 (2010).