Locating an individual quantum hall island inside a quantum ring

F. Martins, S. Faniel, M. G. Pala, H. Sellier, S. Huant, L. Desplanque, X. Wallart, V. Bayot, and B. Hackens

Citation: AIP Conference Proceedings **1566**, 299 (2013); doi: 10.1063/1.4848404
View online: http://dx.doi.org/10.1063/1.4848404
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1566?ver=pdfcov
Published by the AIP Publishing

Locating an individual quantum Hall island inside a quantum ring

F. Martins*, S. Faniel†, M. G. Pala**, H. Sellier‡, S. Huant‡, L. Desplanque§, X. Wallart§, V. Bayot‡,* and B. Hackens*

*Université catholique de Louvain, IMCN/NAPS, Louvain-la-Neuve, Belgium
†Université catholique de Louvain, ICTEAM/ELEN, Louvain-la-Neuve, Belgium
**IMEP-LAHC, Grenoble INP, Minatec, BP 257, F-38016, Grenoble, France
‡Institut Néel, CNRS and Université Joseph Fourier, BP 166, F-38042, Grenoble, France
§IEMN, Cité scientifique, BP 60069, F-59652, Villeneuve d'Ascq, France

Abstract. Scanning gate microscopy is used to find the position of a quantum Hall island (QHI) which controls the electron transport through a mesoscopic quantum ring. Such QHIs emerging around potential inhomogeneities are tunnel-coupled with edge states. Approaching a polarized metallic tip over the QHIs gradually changes their surface and generates Coulomb blockade oscillations. This mechanism permits the identification of the center of the QHIs. Here, by sweeping the distance between the tip and the two dimensional electron gas, we clearly locate the center of an individual QHI.

Keywords: scanning gate microscopy, quantum Hall effect
PACS: 73.21.La,73.23.Ad,03.65.Yz,85.35.Ds

Soon after the discovery of the Quantum Hall (QH) effect, it was realized that the mechanism behind it was based on current flowing through spatially separated edge states (ES), i.e. one dimensional channels located close to the borders of the sample. Since scattering is prohibited between opposite ES in a macroscopic Hall bar, the electron mean free path in the QH regime can reach several millimeters. Moreover, when the Fermi energy lies between Landau levels in the bulk of the sample, contributions from electrons trapped in ES pinned around potential inhomogeneities, called Quantum Hall Islands (QHIs), is negligible.

This picture changes radically when the dimensions of the device become comparable to the size of the QHIs [1]. In this case, ES are brought close to each other and electrons can either directly tunnel between them, or through QHIs tunnel coupled to the ES. But the question about the microstructure of the QHIs and "where" these events take place still remains.

Recently, an atomic force microscopy (AFM) based technique named scanning gate microscopy (SGM) was designed with the intention of accessing this information, i.e. imaging electronic transport through buried two-dimensional electron gases (2DEGs). It consists in measuring the conductance of a device as the electrically polarized AFM tip scans over the surface. The tip acts as a flying nano-gate, which induces a local perturbation for charge carriers. In the vicinity of the tip, the transmission of carriers is modified, which causes a change of the device conductance and permits to obtain conductance maps as a function of the tip position.

SGM has been extensively used in studying systems such as quantum point contacts [2], quantum dots [3] or to probe local density of states of mesoscopic systems [4]. In the QH regime SGM was able to image the local backscattering in a Hall Bar [5] and the depopulation of a narrow constriction [6].

In a previous work [7], we used SGM to locally explore the role of QHIs in electrical transport through a quantum ring (QR) in the integer QH regime. Indeed, at high magnetic field, the magnetoresistance of the QR exhibits a rich spectrum of oscillations. Thanks to SGM we were able to conclude that these oscillations stem from Coulomb blockade between ES and QHIs [7]. In this case, different sets of QHIs were found to be active in different ranges of magnetic field on the same QH plateau, so that the complexity of the magnetoresistance fluctuations in this regime could be decrypted.

Here we complement these observations by sweeping the distance between the tip and the 2DEG (D_{tip}). This way, the number of QHIs tunnel coupled to the ES is tuned which we demonstrate to be useful to identify the position of the center of an individual QHI.

Our sample is a QR defined in InGaAs/InAlAs heterostructure by means of electron beam lithography and wet etching (see ref. [7] for more details). The 2DEG, located 25 nm below the surface, has at low temperature T an electron density and a mobility of 1.4×10^{16} m^{-2} and 4 m^2/Vs, respectively. As sketched in Fig. 1(a), ohmic contacts 1 and 2 are used to inject current whereas ohmic contacts 3 and 4 measure voltage drop along one side of the QR.

The Physics of Semiconductors
AIP Conf. Proc. 1566, 299-300 (2013); doi: 10.1063/1.4848404

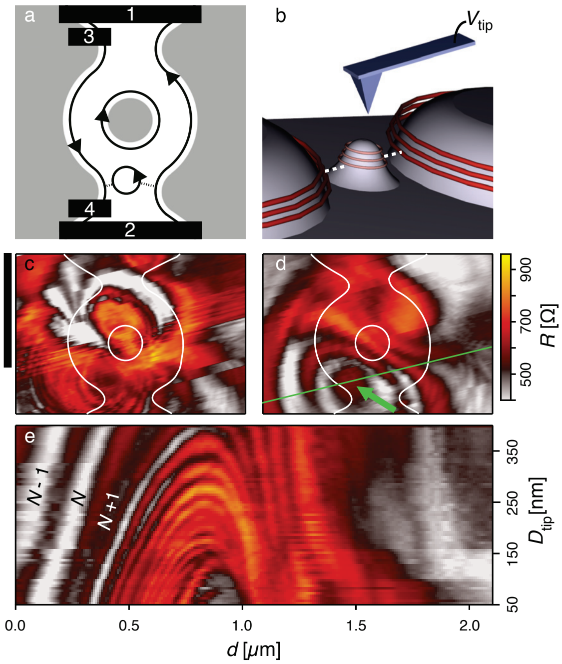

FIGURE 1. (a) Schematic representation of our device showing a QHI connecting opposite edge channels through tunnel barriers (dotted lines). Current carrying contacts (1-2) and voltage probes (3-4) allow resistance measurements. (b) Artistic view of the QHI tunnel coupled to the ES. For simplicity we only draw three ESs. The polarized tip induces a local perturbation which tunes the height of the potential hill pinning the QHI. (c-d) SGM resistance maps obtained at B = 9.65 T, T = 100 mK, V_{tip} = -1 V with $D_{tip} = 50$ nm and $D_{tip} = 350$ nm, respectively. Continuous white lines indicate the position of the quantum ring. The lateral black bar represents 1 μm. The green arrow indicates the position of an individual QHI. (e) D_{tip}-dependence of resistance profiles over the green line (d).

The experiments are performed with a low-T AFM that was designed to fit inside a ^{3}He/^{4}He dilution refrigerator (T = 100 mK) equipped with a superconducting coil that provides a magnetic field up to 17 T [7]. It makes use of a commercial conductive AFM tip attached to a quartz tuning fork to perform topography and, consequently, to locate the QR. Fig. 1(b) presents an idealized view of the experiment, where a potential inhomogeneity, formed close to a constriction, gives rise to a QHI, connected through tunnel barriers (in white) to ESs. The tip bias V_{tip} tunes the height of the potential inhomogeneity and the tunnel barriers, and thus modifies the resistance R of the device.

A SGM resistance map showing this effect is presented in Fig. 1(c). It was obtained at $B = 9.65$ T (close to filling factor 6 in the bulk), $V_{tip} = -1.0$ V and $D_{tip} =$ 50 nm. The solid white line superimposed to the image indicates the location of the QR. In this image we can observe several sets of concentric fringes in the vicinity of the QR. As detailed in [7], we understand these oscillations within a Coulomb-dominated model. As the negatively biased tip approaches the QHI it gradually raises the potential and enlarges the island area which, in turn, induces an energy imbalance between the QHI and the propagating ES. This imbalance is thereafter compensated by tunneling events between the QHI and the ES in the Coulomb blockade regime. Hence, each set of concentric fringes corresponds to a set of Coulomb blockade lines encircling one single QHI.

In order to find the position of an isolated QHI, in Fig. 1(d) we performed SGM with the tip retracted to $D_{tip} = 350$ nm and keeping all the other parameters constant. For most of the QHIs, the potential change induced by the tip is no longer sufficient to tunnel couple the QHIs with the ES and, thus, they do not contribute to the SGM image. Noticeably, in Fig. 1(d) only few QHIs remain active which allow us to identify, for instance, a QHI pointed by the green arrow.

Finally, the effect of D_{tip} is better illustrated in Fig. 1(e). It consists of scanning always the same line (marked in Fig. 1(d) with a green line and whose coordinate is denoted as d in Fig. 1(e)) while sweeping the distance D_{tip}. As the tip is retracted a set of fringes can be clearly tracked which correspond to Coulomb blockade charging events, as discussed above. In this image, we expressly denote the evolution from $N-1$ to N and to $N+1$ electron charges in the QHI.

We therefore demonstrate the ability of SGM to investigate a single QHI by tuning the tip-induced perturbing potential using either V_{tip} or D_{tip}. We believe that this capacity may prove useful in unveiling the local electronic structure of the QHIs.

REFERENCES

1. C. Zhou, and M. Berciu, *Phys. Rev. B* **72**, 085306 (2005); E. Peled *et al.*, *Phys. Rev. Lett.* **93**, 236802 (2003).
2. M. A. Topinka *et al.*, *Science* **289**, 2323–2326 (2000).
3. A. Pioda *et al.*, *Phys. Rev. Lett.* **93**, 216801 (2004). P. Fallahi *et al.*, *Nano Lett.* **5**, 223–226 (2005).
4. R. Crook *et al.*, *Phys. Rev. Lett.* **91**, 246803 (2003); B. Hackens *et al.*, *Nature Phys.* **2**, 826–830 (2006); F. Martins *et al.*, *Phys. Rev. Lett.* **99**, 136807 (2007); M. G. Pala *et al.*, *Phys. Rev. B* **77**, 125310 (2008); M. G. Pala *et al.*, *Nanotechnology* **20**, 264021 (2009); M. G. Pala *et al.*, *Phys. Rev. Lett.* **108**, 076802 (2012).
5. S. Kicin *et al.*, *Phys. Rev. B* **70**, 205302 (2004).
6. N. Aoki *et al.*, *Phys. Rev. B* **72**, 155327 (2005).
7. B. Hackens *et al.*, *Nature Commun.* **1**,39 (2010).