Institute of Physics Publishing Journal of Physics: Conference Series **38** (2006) 79–82
doi:10.1088/1742-6596/38/1/020 NPMS-7/SIMD-5 (Maui 2005)

Study of quantum point contact via low temperature scanning gate microscopy

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Abstract. Two types of quantum point contacts have been studied by low temperature scanning gate microscopy. In addition to the usual bright spot, which corresponds to a large conductance change at the constriction, ring structures are observed near the center of the quantum point contact. The ring diameter shrinks with increasing base conductance when the side gate voltage is changed. The rings are thought to relate to the observation of impurity potentials in the constriction region.

1. Introduction

Quantized conductance in quantum point contacts (QPC) have been studied in semiconductors, where a quantized conductance given by the number of 1d quantized levels below Fermi level [1]. An anomalous plateau at $0.7G_0$ (G_0 is $2e^2/h$) has been observed in high mobility samples, and has been discussed as a spin-dependent phenomenon [2,3]. Recently, scanning probe microscopy (SPM) has been studied, not only for imaging the surface topography, but also for detecting a magnetic or electric field in small structures. Scanning gate microscopy (SGM), in which a bias is applied to the scanning probe tip, has shown promise for the investigation of semiconductor nano-structures. Imaging of electron flow from a QPC [4,5] and Coulomb blockade [6] at a closed quantum dot have been investigated by this method. Usually, the topography of the surface metal gates provides an obstacle for scanning the entire structure due to their interference with the scanning tip. Recently, we have succeeded visualizing the SGM image inside a QPC fabricated by trenches using wet etching. In the QPC of InGaAs sample, we have visualized quantum interference based on the random potentials [7], and also the quantum Hall edge state in the channel [8]. Other SGM studies of a QPC, using a high mobility GaAs sample, have shown only a boring bright spot at the constriction of QPC [9]. In this paper, we also study QPCs of a GaAs heterostructure, and find a ring structure in the SGM image.

2. Sample and experiment

Two types of QPCs have been fabricated on a modulation-doped AlGaAs/GaAs heterostructure, whose two dimensional electron gas (2DEG) is located 60 nm below the surface. QPC-1 is a constriction consisting of an open quantum dot and is asymmetrical in shape as shown in Fig.1a. The gate voltage is applied on the upper-right side-gate to tune the conductance. QPC-2 has a symmetrical

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Study of Quantum Point Contact Via Low Temperature Scanning Gate Microscopy**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University Tempe, AZ 85287-5706**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
THE SEVENTH INTERNATIONAL CONFERENCE ON NEW PHENOMENA IN MESOSCOPIC STRUCTURES & THE FIFTH INTERNATIONAL CONFERENCE ON SURFACES AND INTERFACES OF MESOSCOPIC DEVICES 27 November2 December 2005, Maui, Hawaii, USA

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

shape as shown in Fig.1b, and the gate voltage is applied on the upper and lower gates simultaneously. These structures are fabricated using 80 nm deep trenches defined via wet etching, which allows us to scan the entire surface area and to apply an in-plane gate voltage. The carrier concentration and the mobility are 4.7 $\times 10^{11}$ /cm^2 and 4.2 $\times$ 10^5 cm^2/Vs, respectively, which gives a mean free path of 4.7 μm. The SGM measurements are performed at 300 mK with a piezo-resistive cantilever, whose tip is coated by 20 nm of PtIr or Cr for QPC-1 and QPC-2, respectively. During the SGM measurement, the tip was held 100 nm above the surface while applying a weak negative voltage.

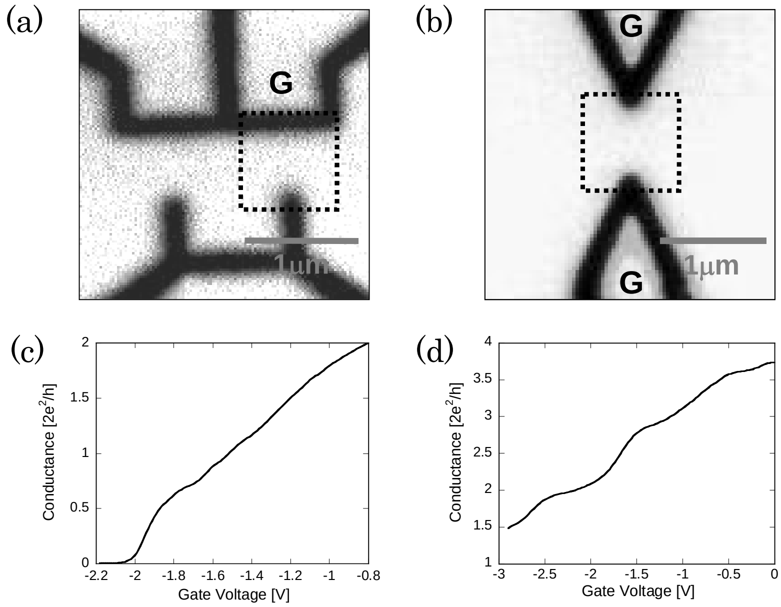

Figure 1. Topographic images of the samples. The dark regions indicate trenches etched 100 nm below the surface. (a) QPC-1 is the right constriction of the open quantum dot. (b) QPC-2 is a usual finger-type constriction. The dotted square indicates the scan area during the SGM measurement. The regions indicated by "G" act as in-plane gates. (c) and (d) The transmission of QPC-1 and QPC-2 by changing the side-gate voltage.

3. Results and discussion

The transmission curve of QPC-1 and QPC-2 are shown in Fig. 1c and Fig.1d, respectively. Because of the series connection of the quantum dot, the conductance quantization is not as clear in QPC-1, when compared with QPC-2. Nevertheless, the last plateau is clearly visible near $0.7G_0$. The SGM images of the QPC-1 at different base conductance are shown in Fig. 2a-c. A bright spot, where the conductance is lower than in the surrounding region, is observed at the center region of QPC-1, when the base conductance is near $1G_0$. In addition to the single bright spot, ring structures appear as a superposition upon the bright spot below $0.8G_0$. As the average conductance is reduced, the ring diameter increases up to ~500 nm. Moreover, a second ring begins to appear at the center of the outer ring at a conductance of 0.5-$0.6G_0$, forming concentric rings as shown in Fig. 2b. The outer ring disappears at a conductance below $0.4G_0$. The gate voltage dependences of the inner and outer diameter of the rings are shown in Fig. 2d. In QPC-1, no significant ring structure was observed above $0.8G_0$. Similar ring structures were observed at the constriction of QPC-2, however they survive at conductances above $1G_0$, and also exhibit multiple rings. Figure 3a-c shows the SGM images taken at the center region of QPC-2. As the base conductance increases, the rings shrink and then disappear around the plateau at $2G_0$. However, another ring appears above $2G_0$, as shown in Fig. 3d. This latter ring shrinks again as the base conductance increases.

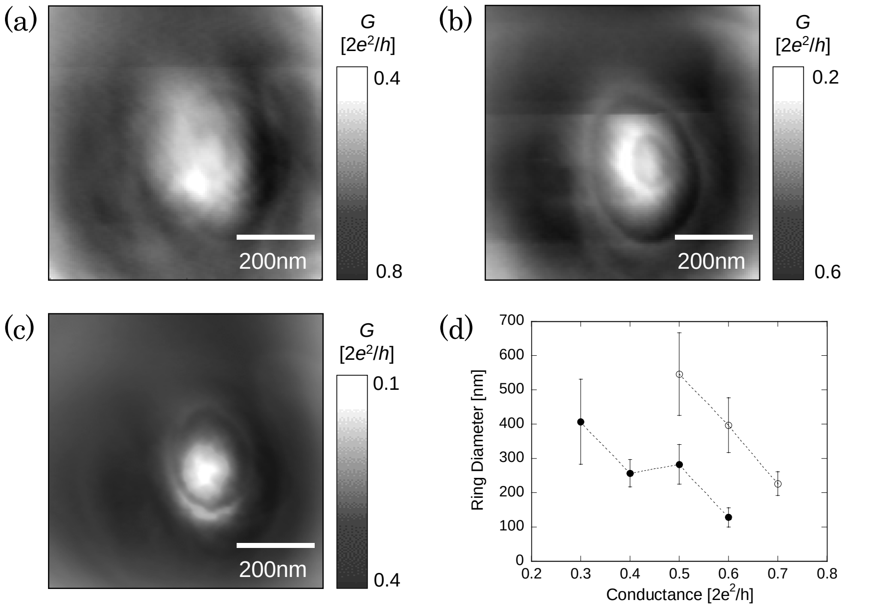

Figure 2. SGM images taken at the base conductance of $0.8G_0$ (a), $0.6G_0$ (b), and $0.4G_0$ (c) in QPC-1. The dotted circles are guides to the eye to highlight the ring structures. The color scales indicate conductance in the SGM images. (d) Base conductance dependence of the ring diameter. The open circles indicate the dependency of the inner ring, and the closed circles indicate that of outer ring. The error bars indicate the length of the major and minor axis of the ring.

The common features of the ring structure of the SGM images for QPC-1 and QPC-2 are: (1) the ring diameter shrinks as the base conductance increases, (2) multiple rings can appear, (3) the rings disappear as the base conductance approaches a plateau of the quantized conductance, (4) no extra plateaus in the transmission curves are observed. The effect of the scanning tip is to slightly deplete the 2DEG underneath the tip due to the small-negative voltage applied. When the depleted spot comes close to the constriction of the QPC, it decreases the local carrier density within the channel. Considering the fact in (4), the tip is thought to both create and image the ring structures. The ring shape implies an equipotential region around the central spot, which does not depend on the direction of approach of the tip nor the channel direction of the QPC.

The mechanism of the ring structure has not yet been clarified, however the tip potential could manipulate an energy level within a QPC. If we can assume that a decrease of the carrier density at QPC contributes to the spin-polarization [3], the rings might relate to a spin-gap which appears at each quantized energy level [10]. The fact that the intensity of the ring structure is much clearer at a lower conductance supports this because the spin gaps are larger at lower carrier density [11]. The difference of the characteristic between QPC-1 and QPC-2 may be based on the shape of the structure, although this may well point toward a different mechanism, and that is the presence of impurity potentials in the QPC region. As the density is lower near the QPC than in the bulk, there exist ionized donors in this region. Ring-shaped structures have recently been observed in a high magnetic field [12]. In this latter study, it is assumed that these rings are related to short-range disorder (impurities), in which the quantum Hall effect provides the localization. The tip then can induce resonant tunneling into the impurity site. A similar effect can occur here, where the localization around the impurity is provided by the QPC. The impurity already has a slight barrier to capture, which is the origin of the persistent photoconductivity. The tip then induces a second barrier which provides a path into/out of the impurity well via resonant tunneling.

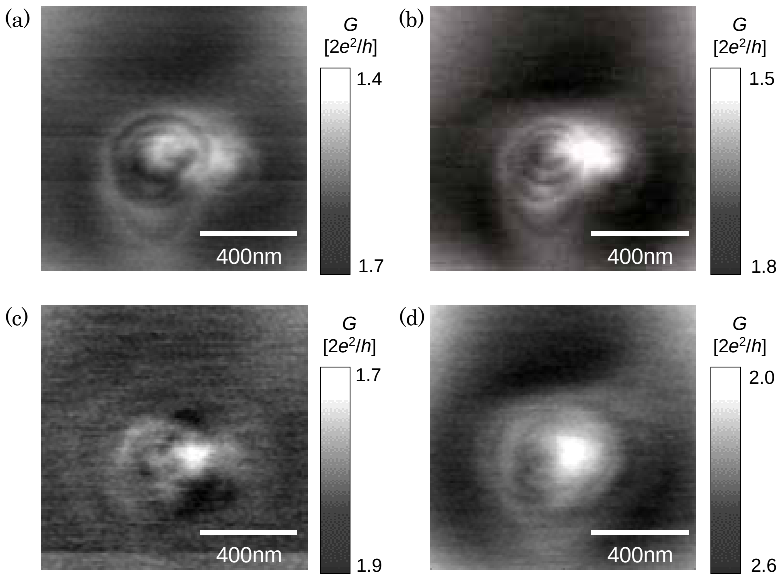

Figure 3. SGM images taken at the base conductance of $1.7G_0$ (a), $1.8G_0$ (b), $1.9G_0$ (c), and $2.6G_0$ (d) in QPC-2. The dotted circles are guides to the eye to highlight the ring structures. The color scale indicates conductance in the SGM images.

4. Summary

In summary, ring structures are observed in low temperature SGM images of two different QPC samples. The ring diameter shrinks as the conductance increases, and disappears near the conductance plateaus. The rings may relate to a spin-gap which appears at each quantized energy level, or to the present of impurity potentials in the material. Final explanations must await further work in this area.

This work was supported by the Office of Naval Research; N. Aoki was supported by JSPS Postdoctoral Fellowships for Research Abroad 2004.

References

[1] van Wees B J, van Houten H, Beenakker C W J, Williamson J G, Kouwenhouven L P, van der Marel D, and Foxon C T 1988 *Phys. Rev. Lett.* **60** 848
[2] Thomas K J, Nicholls J T, Simmons M Y, Pepper M, Mace D R, and Ritchie D A 1996 *Phys. Rev. Lett.* **77** 135
[3] Reilly D J, Facer G R, Dzurak A S, Kane B E, Stiles P J, Clark R G, Hamilton A R, Pfeiffer L N, and West K W 2001 *Phys. Rev. B* **63** 121311
[4] Topinka M A, LeRoy B J, Shaw S E J, Heller E J, Westervelt R M, Maranowski K D, and Gossard A C 2000 *Science* **289** 2323
[5] Topinka M A, LeRoy B J, Westervelt R M, Shaw S E J, Fleischmann R, Heller E J, Maranowski K D, and Gossard A C 2001 *Nature* **410** 183
[6] Pioda A, Kicin S, Ihn T, Sigrist M, Fuhrer A, Ensslin K, Weichselbaum A, Ulloa S E, Reinwald M, and Wegscheider W 2004 *Phys. Rev. Lett.* **93** 216801
[7] Aoki N, Cunha C R da, Akis R, Ferry D K, and Ochiai Y 2005 *Appl. Phys. Lett.* **87** 223501
[8] Aoki N, Cunha C R da, Akis R, Ferry D K, and Ochiai Y 2005 *Phys. Rev. B* **72** 155327
[9] Crook R, Smith C G, Graham A C, Farrar I, Beere H E, and Ritchie D A 2003 *Phys.Rev. Lett.* **91** 246803
[10] Meir Y, Hirose K, and Wingreen N S 2002 *Phys. Rev. Lett.* **89** 196802
[11] Wang C-W and Berggren K-F 1996 *Phys. Rev. B* **54** 14257
[12] Steele G A, Ashoori R C, Pfeiffer L N, and West K N 2005 *Phys. Rev. Lett.* **95**, 136804