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Applied Surface Science 210 (2003) 134–139
applied surface science
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Imaging coherent electron flow in a two-dimensional electron gas

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Abstract

Scanning probe microscopy (SPM) has been used to obtain images of electron flow through a two-dimensional electron gas from a quantum point contact (QPC) inside a GaAs/AlGaAs heterostructure at liquid He temperatures. A negatively charged SPM tip depletes the electron gas immediately below and decreases the conductance of the QPC by backscattering electrons. Images of electron flow are obtained by recording the conductance, as the tip is scanned across the structure. At distances less than 1 μm from the QPC, the electron flow shows angular lobes that are characteristic of the quantum modes of the QPC. At distances greater than 1 μm, well-defined branches of electron flow are observed that are caused by the cumulative effects of small angle scattering by ionized donor and impurity atoms. Interference fringes spaced by half the Fermi wavelength decorate all of the images of electron flow; their spacing gives a spatial profile of the electron density.

PACS: 85.30.Vw; 73.23.-b; 73.23.Ad; 07.79.-v

Keywords: Scanning probe microscopy; Two-dimensional electron gas; Quantum point contact; GaAs

Scanning probe microscopy (SPM) is able to image and characterize mesoscopic phenomena on spatial scales that are not accessible in standard transport measurements. A SPM has been used to study a variety of mesoscopic systems including quantum point contacts (QPCs), the quantum Hall effect, and carbon nanotubes [1–8]. Recently it has become possible to image, electron flow from a QPC in two-dimensional electron gas (2DEG) by using a scanning probe microscope [1,2]. The images provide spatial information about electron flow over distances approaching the electron wavelength. The ability to image electron flow over mesoscopic size scales is important for the design of future electronics as well as for possible implementations of quantum information processing.

In this paper, we present images of electron flow from a QPC in a 2DEG at liquid He temperatures. At distances less than 1 μm from the QPC, the electron flow shows angular lobe patterns that are characteristic of the quantum modes of the QPC—the first mode has one lobe, the second mode has two, and the third mode has three [1]. At larger distances from the QPC, the electron flow forms narrow branches; theoretical simulations show that these branches are caused by small angle scattering from ionized donor and impurity atoms [2]. Interference fringes spaced by half the

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doi:10.1016/S0169-4332(02)01493-9

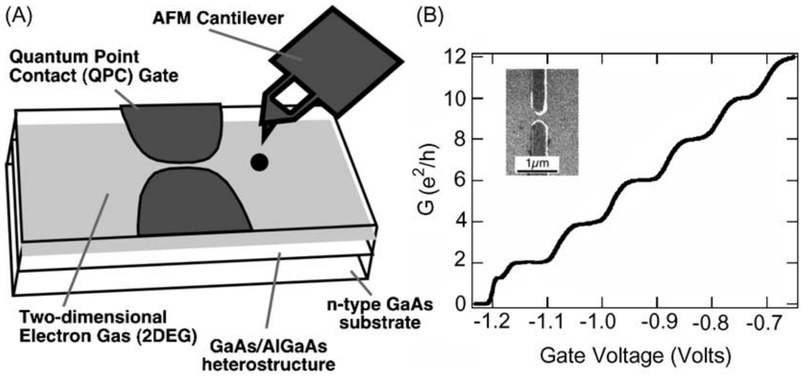

Fig. 1. (A) Schematic diagram showing the measurement setup used to image coherent electron flow. (B) QPC conductance vs. gate voltage showing well-defined conductance plateaus. The inset is a scanning electron micrograph of the QPC device.

Fermi wavelength decorate the images and persist throughout the entire scanned area. The spacing of these fringes has been used to profile the electron density in the 2DEG [3].

Fig. 1A illustrates the technique used to image electron flow. The QPC samples were mounted in vacuum inside a custom built SPM and cooled to the temperature $T = 1.7$ K. Images of electron flow were obtained by applying a negative voltage between the SPM tip and the 2DEG, the charged tip capacitively couples to the 2DEG and depletes a small disk directly below as indicated in Fig. 1A. The depleted region backscatters electron waves arriving from the QPC, and decreases its conductance by an amount that is proportional to the electron flux. Images of electron flow were obtained by raster scanning the tip across the sample and recording the QPC conductance as a function of tip position. When the tip is above an area of high electron flow, the backscattering produces a large reduction in conductance. However, when the tip is over areas of little or no flow, a correspondingly small decrease in conductance occurs. The tip is held about 10 nm above the surface to avoid straining the sample.

The QPC devices were fabricated by patterning two metal gates on the surface of a GaAs/AlGaAs heterostructure. The heterostructure was grown by molecular beam epitaxy on a n-type GaAs substrate in the following order: GaAs/AlGaAs smoothing superlattice, 1 μm GaAs, 22 nm $Al_{0.3}Ga_{0.7}As$, δ-doped Si donor layer, 20 nm $Al_{0.3}Ga_{0.7}As$ and 5 nm GaAs cap layer. The 2DEG is formed at the interface between the GaAs and $Al_{0.3}Ga_{0.7}As$ layers that is located 57 nm below the surface. By applying a negative voltage between the gates and the 2DEG, a variable width channel is formed. The conductance through a QPC increases in steps of height $2e^2/h$, as the width of the channel is increased new modes of the QPC become accessible—the first conductance step is produced by the first mode, the second by the first and second modes, and so on [9,10]. Fig. 1B shows the measured QPC conductance as a function of its width, controlled by the gate voltage. Well-defined conductance plateaus at multiples of $2e^2/h$ are clearly visible. The inset to the figure is a scanning electron micrograph of one of the QPC devices.

Fig. 2A–C show three images of coherent electron flow recorded at short distances from the QPC on the first three conductance plateaus [1]. As the QPC is opened, new lobes of current appear at each new plateau of conductance, and the overall width of the pattern of electron flow increases. Fig. 2A shows the electron flow on the first plateau of the QPC, from the first mode, which is characterized by a single angular lobe. Fig. 2B shows electron flow on the second plateau of the QPC, which contains contributions from the first two modes, and Fig. 2C shows electron flow on the third plateau of the QPC, which contains contributions from the first three modes. All of the images are decorated by interference fringes spaced by half the Fermi wavelength, which can be used to profile the electron density spatially [3].

Fig. 3A–C show images of electron flow from individual modes of the QPC. Because the total electron

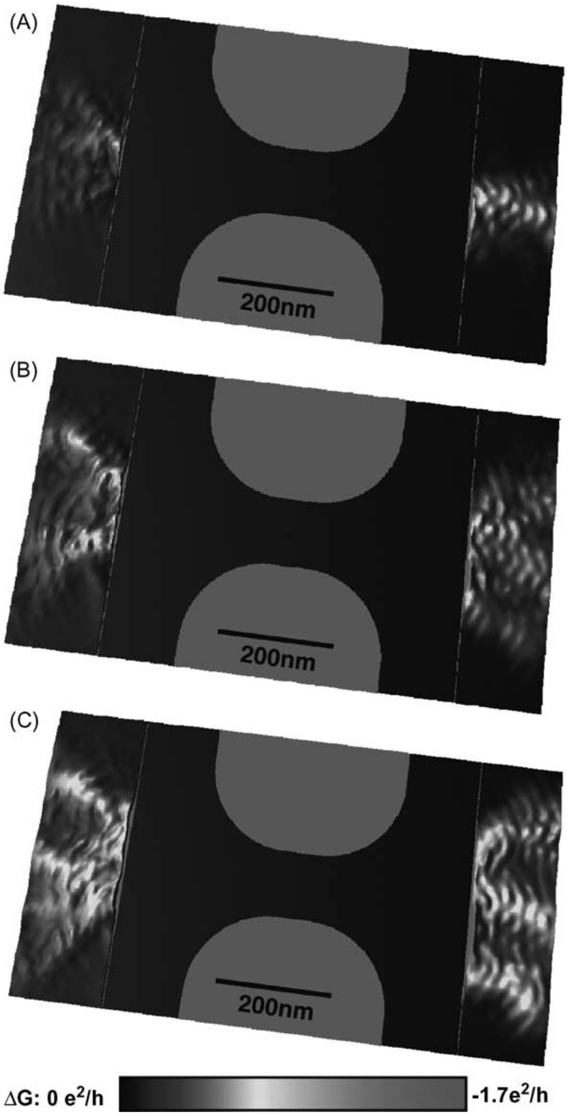

Fig. 2. Images of coherent electron flow from the (A) first, (B) second and (C) third plateau of a QPC. As the width of the QPC is opened new lobes of current appear and the electron flow pattern becomes wider. Interference fringes spaced by half the Fermi wavelength are visible throughout the images [1].

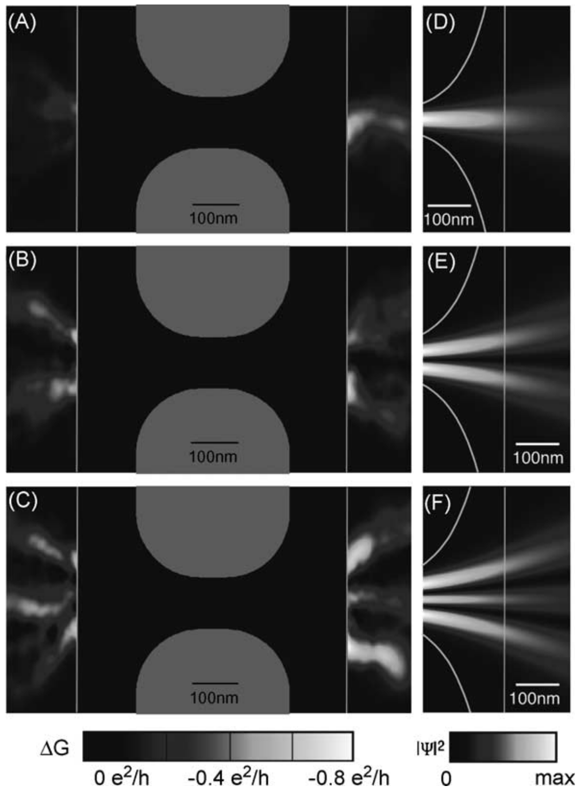

Fig. 3. Images of the flow of electron waves from the (A) first, (B) second and (C) third mode of the QPC. Quantum mechanical simulations of electron flow from the (D) first, (E) second and (F) third mode of the QPC. As each new mode is added to the conductance of the QPC, a new lobe of current appears in agreement with the quantum mechanical simulations [1].

flow, shown in Fig. 2, is the sum of flow through the available modes of the QPC, images of the flow through individual modes can be obtained by subtracting images of the total flow recorded on successive conductance plateaus. Fig. 3A shows the electron flow from the first mode of the QPC recorded on the first plateau. To obtain the flow from the second mode of the QPC, shown in Fig. 3B, an image of electron flow was recorded on the second plateau, which contains contributions from the first and the second mode, then the contribution from the first mode was removed by subtracting an image recorded on the first plateau. A similar procedure was used to isolate the pattern of electron flow from the third mode shown in Fig. 3C. Fringes were removed from the images of flow in Fig. 3 by adding a 3 mV_{rms} ac voltage across the QPC to heat the electrons; this procedure leaves the flow pattern unchanged.

Theoretical simulations of electron flow from the first three modes of the QPC are shown in Fig. 3D–F for an ideal sample. The theory is in good agreement with the experimental images. Together they gave the following simple picture. As a new mode of current is

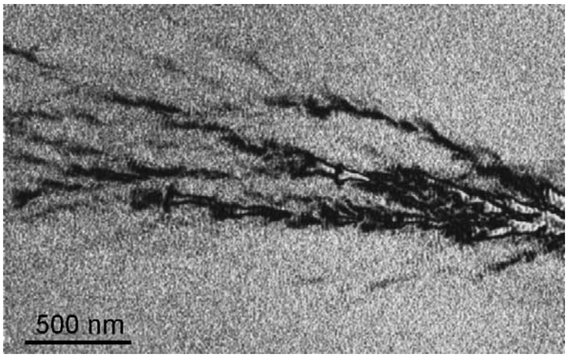

Fig. 4. Image of electron flow on the first conductance plateau of a QPC that shows narrow branches of electron flow. Interference fringes spaced by half the Fermi wavelength are present throughout the scanned area. The center of the QPC is located 500 nm to the right of the image.

opened by increasing the width of the QPC, the pattern of electron flow corresponding to this mode is added to the total electron flow [1]. For an individual mode of the QPC, the number of angular lobes equals the mode number—one lobe for the first mode, two lobes for the second mode, and so on.

Fig. 4 is an image of coherent electron flow from a QPC at greater distances than those shown in Fig. 2 or 3. This image was recorded on the first conductance plateau of the QPC, located 500 nm to the right of the image. The electron flow starts as, one lobe near the QPC, but quickly forks into a number of narrow branches at distances much shorter than the 11 μm momentum relaxation length (mean free path), calculated from macroscopic measurements of the electron mobility and density. The formation of branches is a cumulative effect of small angle scattering from ionized Si donor and impurity atoms, the same mechanism that limits the mobility [2]. These ionized atoms create a smooth potential energy landscape that continuously changes the direction of electron flow by small amounts as shown in Fig. 4. The branches are not the result of the electron flow being forced to flow in a valley in the potential, because the Fermi energy is much greater than the average modulation of the potential energy [2]. Fringes are observed throughout Fig. 4, demonstrating that, the electron flow remains coherent over the field of view.

Fig. 5 illustrates how branches can be formed by a dip in the potential energy created by an ionized donor atom that is located out of the plane of the 2DEG. The top panel shows the potential dip, the middle panel shows the effect of the dip, on a fan of electron rays emanating from a single point at the left, and the bottom panel shows the effect of the dip on electron trajectories in the phase space consisting of the position y and momentum p_y of electrons. As shown in Fig. 5, the dip acts as a lens that bends electron rays toward the dip—this action causes the electron rays to overlap vertically and form a caustic in the electron flow that produces a pair of branches. The fan of electron rays in the middle panel, models the action of a QPC—the rays start at the same position y and fan out due to the uncertainly in their momentum p_y. As the rays approach the dip, the ones with positive p_y are bent downwards, causing the momenta of some rays to

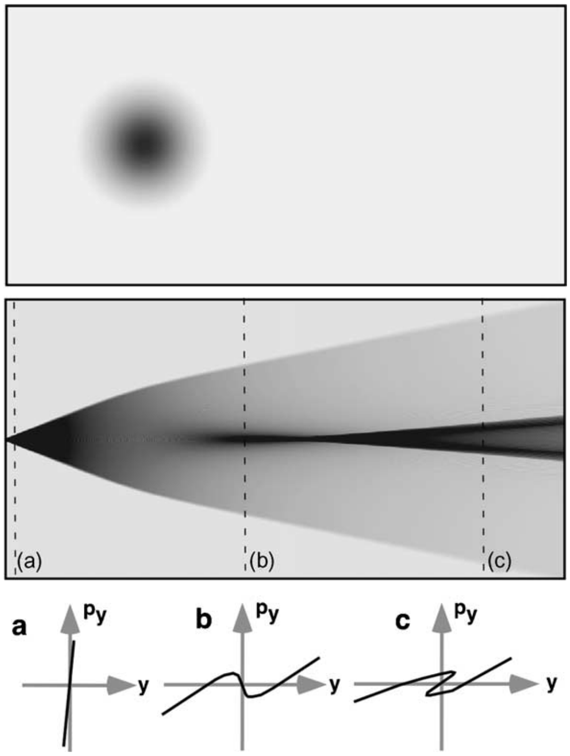

Fig. 5. Model potential consisting of a single dip to illustrate the formation of branches in electron flow (top panel). The trajectories of electrons passing over the single dip showing the formation of two branches of electron flow downstream from the dip (middle panel). Phase space plots of the vertical position y and momentum p_y at three horizontal positions indicated by the letters (a), (b) and (c) (bottom panel).

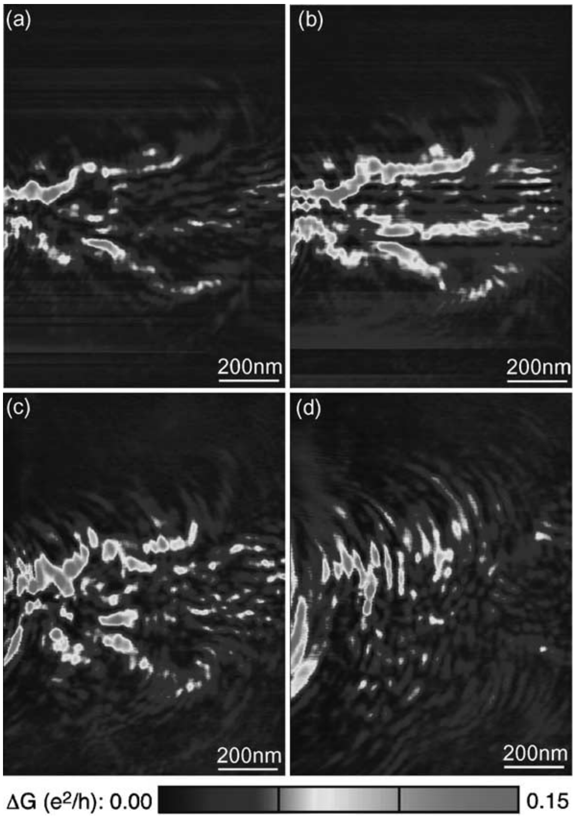

Fig. 6. Images of electron flow for four back gate voltages: (A) 0.0 V, (B) −1.0 V, (C) −3.0 V and (D) −5.0 V. As the density is decreased, the spacing of the fringes increases. The flow also becomes more diffuse, because the bumps and dips in the potential become a larger percentage of the Fermi energy [3].

change signs, creating a fold in phase space. Analogous behavior occurs for electrons starting with negative p_y. As electrons move away from the QPC, two folds are created in phase space that produce a caustic and lead to the appearance of the two branches.

The images in Fig. 6 demonstrate how the fringe spacing and pattern of electron flow change when the electron density is reduced by applying a negative voltage between the back gate and the 2DEG [3]. As the density is reduced, the fringe spacing d increases, as shown in Fig. 6A–D. The electron density n can be determined from the fringe spacing d by using the simple relation $n = \pi/2d^2$, because the fringe spacing $d = \lambda_F/2$ is half the Fermi wavelength λ_F. The measured change in electron density with back gate voltage agrees with a simple parallel plate capacitor model [3]. Another effect of reducing the density is to, make the bumps and dips in the potential from small angle scattering a larger percentage of the Fermi energy, causing the pattern of electron flow to become more diffusive.

Developing ways to image the flow of electrons through mesoscopic electronic devices is important, both for practical and for fundamental reasons. In this paper we have shown that the coherent flow of electrons through a 2DEG inside a GaAs/AlGaAs heterostructure can be imaged at liquid He temperatures by using SPM. At short distances from a QPC, the flow forms the spatial patterns that are expected for the flow of electron waves through ideal samples. At larger distances, narrow branches of electron flow are created by small angle scattering—the source of diffusive scattering that limits the electron mobility. Because the scattering centers do not move appreciably while the images are recorded, the spatial nature of the diffusion of quantum waves is displayed at distances less than the momentum relaxation length (mean free path). Fringes spaced by half the Fermi wavelength demonstrate that the electron flow is coherent.

Acknowledgements

This work was supported at Harvard by ONR grant N00014-95-1-0104, by the NSF through the Nanoscale Science and Engineering Center grants PHY-0117795 and CHE-9610501, and at the University of California at Santa Barbara by the NSF Science and Technology Center QUEST.

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