Imaging coherent electron flow in a two-dimensional electron gas

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Abstract

Images of coherent electron flow through a two-dimensional electron gas in a GaAs/AlGaAs heterostructure from a quantum point contact (QPC) were obtained at liquid He temperatures by using a scanning probe microscope with a charged tip that backscatters electrons. Near the QPC, at distances less than 500 nm, the images show angular lobes of electron flow in patterns determined by the quantum modes of the QPC. At greater distances, narrow branches of electron flow are observed, formed by the cumulative effects of small-angle scattering. In addition, the images show fringes spaced by half the Fermi wavelength, evidence that the electron flow is coherent. These observations agree well with theoretical simulations of electron flow.

Key words: scanning probe microscopy; two-dimensional electron gas; image electron flow;

1. Introduction

The development of ways to image the motion of electrons inside semiconductor heterostructures at low temperatures is central for our understanding of nanoscale electronics, both the fundamental theory and the characteristics of actual devices. New approaches to scanning probe microscopy have been used to image electron flow through a two-dimensional electron gas in zero magnetic field and in the quantum Hall regime [1] to [8].

2. Imaging Electron Flow

In this paper, we show how a scanning probe microscope (SPM) can be used to image the coherent flow of electrons through a quantum point contact (QPC) in a two-dimensional electron gas (2DEG) [1] to [3]. Figure 1 illustrates the technique. A negatively charged SPM

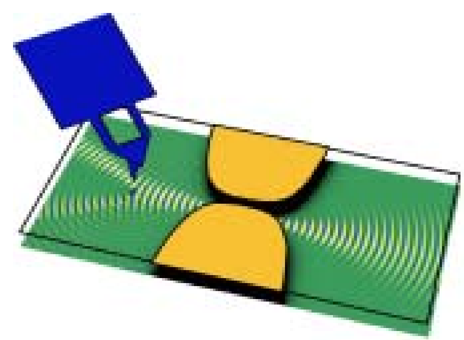

Fig. 1. Illustration of the experimental technique. A charged scanning probe microscope tip capacitively couples to a two-dimensional electron gas below and backscatters electron waves, as shown by the theoretical simulations inserted into the diagram.

tip capacitively depletes a small divot immediately below the tip in the 2DEG. As shown by the theoretical simulations in Fig. 1, the divot scatters electron waves that have passed through the QPC; electrons scattered directly back to the QPC reduce its conductance G. By

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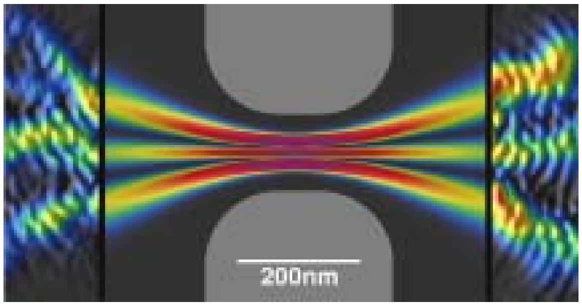

Fig. 2. Image of electron flow through the third mode of a quantum point contact on the third conductance step at $6e^2/h$. Theoretical simulations are shown inside.

recording G as the tip is raster scanned above the sample, an image of the electron flow can be obtained. The sample and the SPM can be cooled to liquid He temperatures; for this paper the images were recorded at 1.7 K. The QPC samples were fabricated by patterning electrostatic gates on a GaAs/AlGaAs heterostructure that contained a 2DEG located 57 nm below the surface. At low temperatures the measured 2DEG density was 4.2×10^{11} cm^{-2} and the mobility was 1.0×10^6 cm^2/Vsec. The heterostructure was grown on a degenerately n-doped GaAs substrate that could be used as a back gate to change the electron density.

The conductance of a quantum point contact without a tip present is quantized into multiples of the fundamental constant $2e^2/h$ by the quantization of transverse modes of electron waves passing through its narrow gap [9], [10]. When the width of the gap is approximately 1/2 the Fermi wavelength λ_F, electrons can pass through the first mode of the QPC, and the conductance forms a step at $2e^2/h$. As the width is increased to λ_F, electrons can also pass through the second mode, and G increases to $4e^2/h$. This process continues to create a series of conductance steps at integer multiples of $2e^2/h$ as the width of the QPC is increased.

Figure 2 shows an experimental image of the flow of electrons through the third mode of a QPC at distances less than 500 nm (outside) and a theoretical simulation of the flow (inside). The image was obtained by subtracting an image of electron flow on the second conductance step from an image on the third step - the difference in G is due to the third mode of the QPC. The image and the simulations in Fig. 2 are in excellent agreement - both show three smooth angular lobes of flow, as expected for the third mode of a QPC. In addition, the experimental image shows fringes spaced by $\lambda_F/2$ that demonstrate the coherence of electron wave flow. These fringes are present in all of the data presented in this paper.

Figures 3(a) to 3(d) show how the fringe spacing in images of electron flow from a quantum point contact

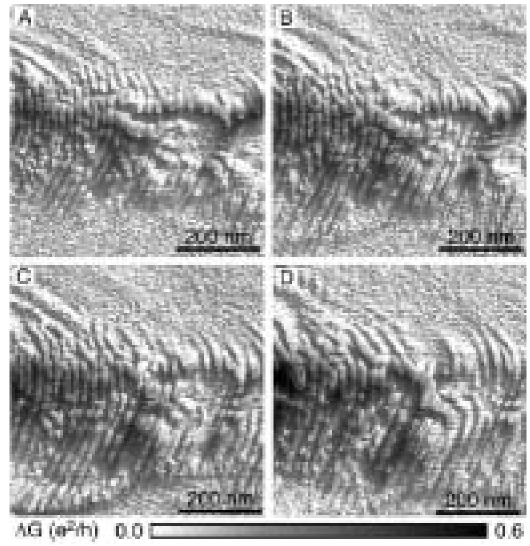

Fig. 3. (a) to (d) Images of fringes in the electron flow from a quantum point contact that demonstrate how the fringe spacing increases as the electron density is reduced by applying back gate voltages of 0, -1.0 V, -2.0 V and -3.0 V respectively.

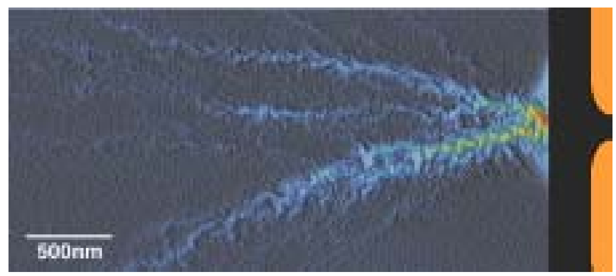

Fig. 4. Image of electron flow on the first conductance step of a quantum point contact that shows narrow branches produced by small-angle scattering.

increases as the electron density is reduced by applying voltages of 0, -1.0 V, -2.0 V and -3.0 V respectively, between the back gate and the 2DEG. Over this range the fringe spacing and the electron density are reduced by a factor of approximately 0.8, in good agreement with the reduction predicted by a simple parallel plate capacitor model. The fringe spacing provides a local measure of the electron density, and it has been used to spatially profile the density of the electron gas in a two-dimensional electron gas [3].

Figure 4 is an experimental image of electron flow through a QPC on the first conductance step, shown at distances that are greater than for Fig. 2. Instead of forming one smooth lobe, as expected for the first mode of a QPC in an ideal system, the electron flow forms a number of small branches [2]. This behavior occurs at distances much shorter than the mean free path 11 μm obtained from the electron mobility for this sample, and the direction of motion does not change

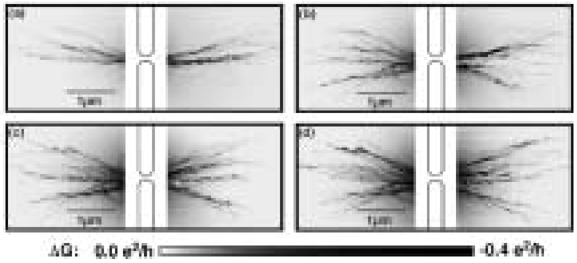

Fig. 5. (a) to (d) Images of electron flow for the first four modes of a quantum point contact, respectively, that show how the angular range explored by branches increases with mode number.

substantially in Fig. 4. The formation of branches was found to be characteristic of electron flow through a 2DEG at low temperatures. It is caused by small-angle scattering from charged donor and impurity atoms located out of the plane of the 2DEG, as discussed below. Images of branches such as those shown in Fig. 4 were found to be static and reproducible at liquid He temperatures, evidence that the locations of the impurity charges did not shift substantially. Fringes spaced by $\lambda_F/2$ are present throughout Fig. 4, demonstrating the coherence of electron flow.

Figures 5(a) to 5(d) show a series of images of electron flow through the first to fourth modes of a QPC. These images were obtained in the same way as for Fig. 2 by recording a series of images on the first to fourth conductance steps, and then subtracting images from subsequent steps to image the second to fourth modes. As shown in Fig. 5 images of electron flow for all of the modes show branches similar in nature to those in Fig. 4. The angular range covered by the branches increases with mode number, as the width of the QPC is increased to allow the passage of electrons through higher modes.

Figure 6 illustrates how branches in electron flow are produced by small-angle scattering inside semiconductor heterostructures. It shows a theoretical simulation of the flow of classical electron paths away from a QPC in a two-dimensional electron gas. Ionized donors and impurity atoms in semiconductor heterostructures located outside the plane of the 2DEG cause small-angle scattering that continuously bends electron trajectories. Small-angle scattering limits the mobility of high quality 2DEGs, and its properties are understood from macroscopic measurements and theory. The inset in Fig. 6 shows how an accumulation of electrons (shown below) created by a charged donor or impurity atom acts as a lens to bend the trajectories in a fan of electron paths (shown above) and produce a fold in classical phase space that forms a branch. The full simulation shown in Fig. 6 shows the cumulative effect of many charged donors and impurities to produce long-lived branches similar to those observed in the experiments. Large perturbations in electron density are not required, so branches can form in high-mobility 2DEGs such as those used for this research.

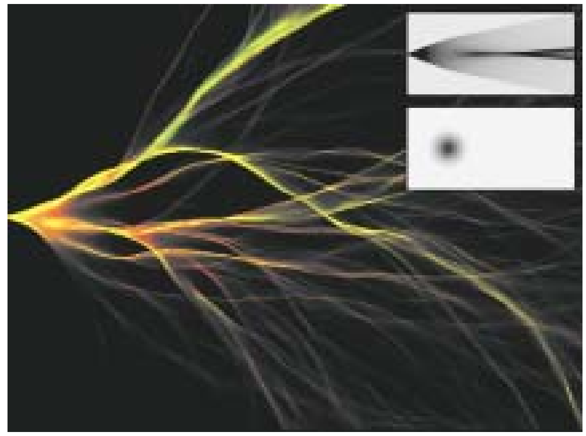

Fig. 6. Theoretical simulation of classical electron trajectories from a quantum point contact that shows branches in electron flow produced by small-angle scattering. The inset shows how a branch can be formed by a single charged impurity atom out of the plane of the two-dimensional election gas.

Acknowledgements

This work was supported in part by ONR grant N00014-95-1-0104 and by NSF grants DMR-98-09363 and PHY-01-17795.

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