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Physica E 12 (2002) 678–683

PHYSICA E

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Imaging coherent electron wave flow in a two-dimensional electron gas

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Abstract

We present images of coherent electron wave flow from a quantum point contact (QPC) formed in a two-dimensional electron gas (2DEG). Near the QPC these images closely resemble the expected wavefunctions for electrons passing through the lowest transverse modes of the QPC. Farther away from the QPC the flow through the 2DEG bulk shows strong branching behavior. The branching behavior is due to the cumulative effect of electrons passing over many small bumps and dips in the potential that they feel in the 2DEG. All of the images are decorated with fringes spaced by half the Fermi wavelength that persist out to the edges of the areas scanned. Images showing the effect of moving the position of the QPC are also presented. © 2002 Published by Elsevier Science B.V.

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

Keywords: Quantum point contact; Scanning probe microscopy; Mesoscopic physics

Over the past several decades, two-dimensional electron gases (2DEGs) formed in semiconductor heterostructures have been at the center of many experimental and theoretical advances [1,2]. A wide variety of new phenomena have been discovered, and many different 2DEG nanostructures, ranging from quantum dots and quantum point contacts (QPCs) to Aharonov–Bohm rings and electron optics elements, have been and continue to be actively investigated. One thing in the study of 2DEGs and device physics that has been difficult to achieve, however, are images containing direct spatial information about the details of how the electron waves flow. Recently it has become possible to directly image the current flow in semiconductor nanostructures using Scanning Probe Microscopes (SPM) [3–9]. In this paper we present spatial images showing the electron flow from the lowest transverse modes of a quantum point contact (QPC). We also present images showing surprising features of the flow farther away from the QPC ($d \gtrsim 500$ nm). All of the scans are decorated with fringes spaced by half the Fermi wavelength and directed perpendicular to the current flow.

The samples are grown by Molecular Beam Epitaxy on an n-type GaAs substrate, which serves as a backgate to control the density of electrons. The 2DEG is formed at an interface between GaAs and AlGaAs located 57 nm beneath the surface. The density of the 2DEG without a voltage on the substrate is $4.2 \times 10^{11}/\text{cm}^2$ resulting in a Fermi wavelength

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1386-9477/02/$ - see front matter © 2002 Published by Elsevier Science B.V.
PII: S1386-9477(01)00375-7

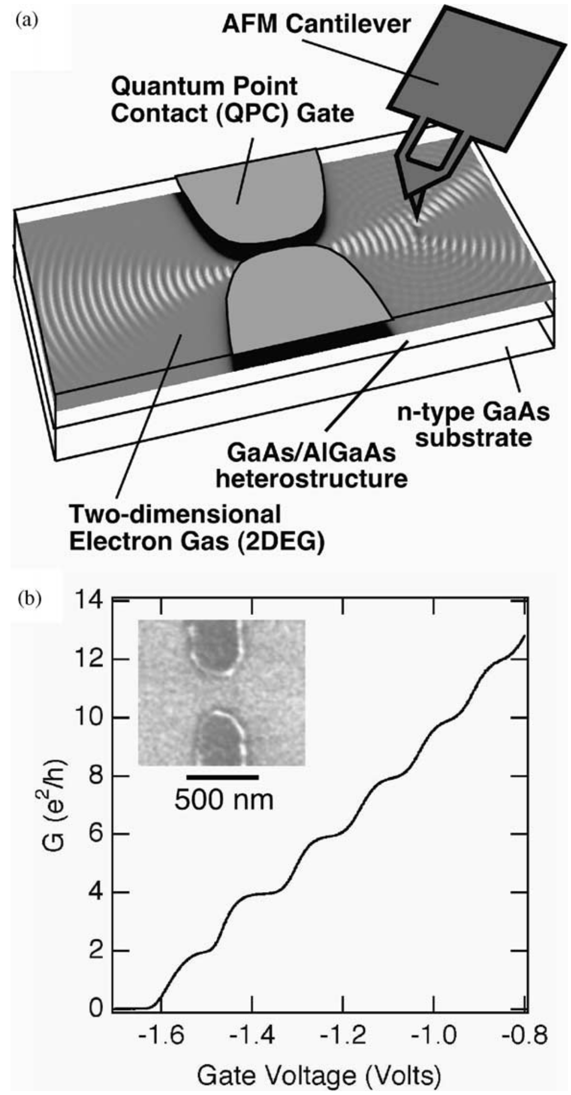

Fig. 1. (a) Schematic of the measurement setup. The conductance through a QPC is measured as a function of AFM tip position. The tip is charged negatively which creates a perturbation in the two-dimensional electron gas (2DEG) that can backscatter electrons. (b) Conductance across the QPC as a function of gate voltage showing plateaus in steps of $2\,e^2/h$. The inset shows an SEM image of a typical device used in these experiments.

$\lambda_F = 39$ nm and a Fermi energy $E_F = 15$ meV. The mobility of the 2DEG is $1.0 \times 10^6\ cm^2/(V)$ giving a mean free path of 11 μm.

Fig. 1a is a schematic of the measurement setup [3,5]. The QPC gates are charged negatively with respect to the 2DEG, depleting the 2DEG underneath

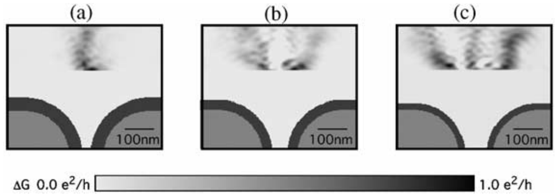

Fig. 2. Images of electron flow from the (a) first, (b) second and (c) third mode of a QPC. The light gray areas outline the gates of the QPC. The dark gray areas are the expected depletion regions in each of the images. The images show the modal structure of the wavefunction leaving the QPC. These images contain the expected feature that the wavefunction of the Nth QPC mode contains N lobes.

them and creating a variable width constriction for electrons to pass through. Images of current flow are acquired by scanning the Atomic Force Microscope (AFM) tip a fixed distance above the surface of the GaAs/AlGaAs heterostructure. A negative voltage is applied to the tip, creating a depletion disc in the 2DEG that backscatters electrons through the QPC. When the tip is over areas of high electron flow a large number of electrons will be backscattered, reducing the conductance through the QPC; whereas when the tip is over areas of little electron flow there is no change in the conductance. By raster scanning the tip over the sample and measuring the conductance as a function of tip position an image of the current flow is produced. These images can only be acquired when the voltage on the tip is sufficiently negative to deplete the electron gas and backscatter electrons [10]. Fig. 1b shows the effect of changing the width of the QPC. The conductance through the QPC drops in steps of $2\,e^2/h$ as the width of the constriction is decreased [11,12]. The inset to the figure shows a scanning electron microscope image of a typical device used in these experiments.

Fig. 2 shows the current pattern from the first three QPC modes near the exit of a QPC at a temperature of 1.7 K. Images showing the modal patterns for higher electron temperatures have been presented elsewhere [5]. Fig. 2a shows the contribution to the current from the first mode of the QPC. This image is taken with the QPC biased on the first plateau ($G = 2\,e^2/h$). There is one main lobe of current along the central axis of the QPC. Fig. 2b shows the current from the second mode of the QPC. This image is obtained from an image of the current flow on the second plateau ($G = 4\,e^2/h$)

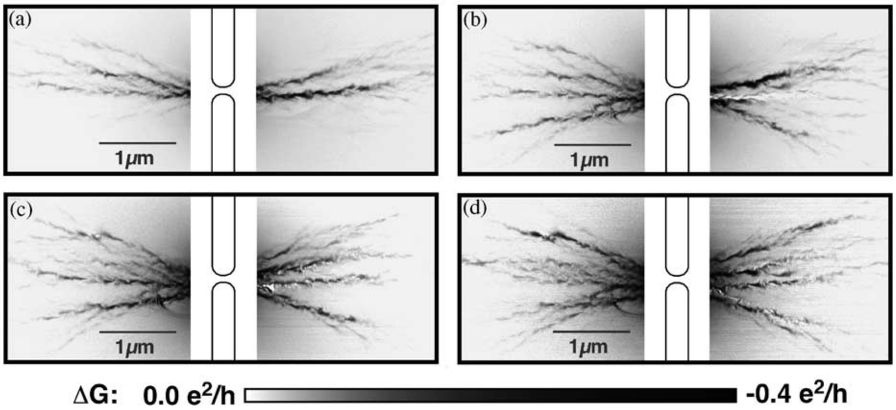

Fig. 3. Images showing the branching behavior of the current flow from the (a) first, (b) second, (c) third and (d) fourth mode of a QPC. The branches are formed by the cumulative effect of passing over many small bumps and dips in the potential.

that contains contributions from both the first and second modes. The contribution from the first mode is subtracted away leaving just the image of the current from the second mode. In this image there are two main branches of current, one to the left of the central axis and the other to the right. Fig. 2c shows the current from the third mode of the QPC. This image was obtained by a similar subtraction method as in Fig. 2b. Here there are three main lobes of current. These images agree with a quantum mechanical simulation of the expected current from the first three modes of a QPC; in both theory and experiment the wavefunction of the Nth mode has N lobes and the observed angular widths agree [5]. In each of these images the light gray area is a schematic outline of the electrostatic gate. The darker gray areas surrounding the gates are a schematic of the expected depletion. These images are all less than 500 nm from the exit of the QPC.

Moving farther away from the QPC ($d \gtrsim 500$ nm), one finds that, in agreement with theory [3,13], the lobes of current seen above break up into narrow channels that persist throughout the entire scanned region. Fig. 3 shows the electron flow at these larger distances from the QPC. Fig. 3a is an image of the electron flow with the QPC biased on the first plateau. In this image the electrons enter and exit the QPC in one main branch oriented roughly along the axis of the QPC, but then quickly fork into several narrow rivulets further from the QPC that themselves continue to fork throughout the scan. Fig. 3b shows the current pattern from the second mode of the QPC. This image is obtained by the same subtraction method as was used for the images in Fig. 2. There are now new branches of current and the overall width of the pattern is wider. Figs. 3c and d show the pattern for the third and fourth modes. In all of these images the current is quickly branching even though the distance from the QPC is much less than a mean free path. The branches themselves are not seen to widen as one moves away from the QPC. Instead, new branches split off from the main branch, but the overall width of each branch stays quite narrow.

These branches are essentially a classical effect and are formed by the cumulative effect of electron trajectories being slightly bent as they travel over many bumps and dips in the potential felt by the electrons in the 2DEG [3,13]. These bumps and dips come from the ionized Si donor atoms located 22 nm above the 2DEG and also from impurities located throughout the heterostructure. The size of the fluctuations in the potential is small relative to the Fermi Energy of the electrons (previous calculations have yielded potentials with ripples on the order 10% E_F) so these branches are not due to direct guiding of flow by corrugations in the potential as a valley might guide a river. Rather, the key to the formation of the branches lies in what happens as electrons pass over dips in the potential. As the electron trajectories pass over each dip in the potential they are focused and two caustics appear downstream of the dip [13]. These caustics are the reason for the observed branching behavior. They

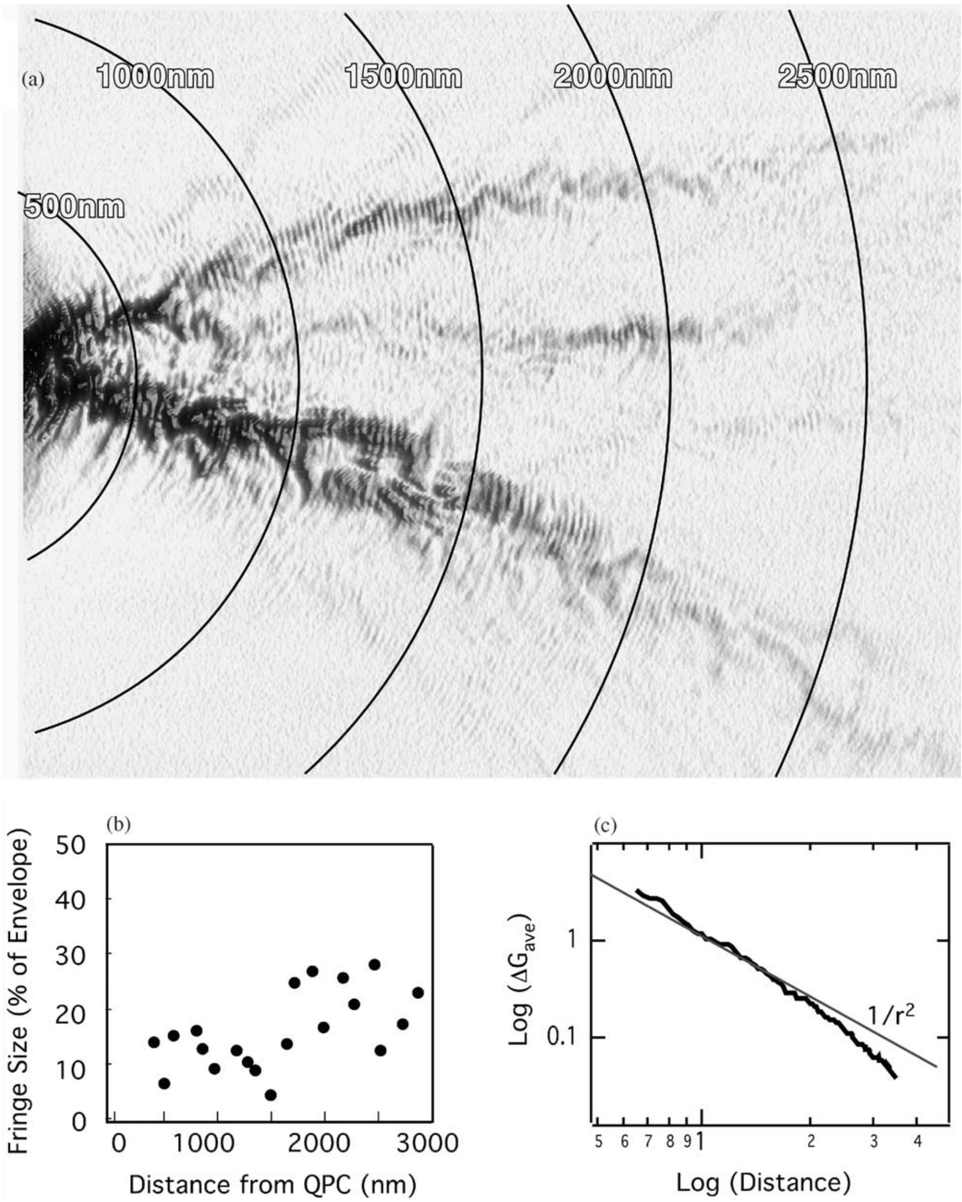

Fig. 4. (a) Image of coherent electron flow showing interference fringes throughout the scan area. (b) Graph showing the size of the fringes relative to the total signal as a function of distance from the QPC. The size of the fringes does not decrease with increasing distance. (c) Graph of average signal versus distance from QPC.

are stable features in the flow from that point on and remain narrow precisely because they are caustics.

Fig. 4a shows an image of current flow taken at $G = 2\,e^2/h$. Fringes spaced by half the Fermi wavelength decorate all of the images in Figs. 2 and 3 and are also here in Fig. 4a. These fringes arise from interference between waves backscattered from the tip to the QPC and waves backscattered by impurities in the sample. Additional discussion of these fringes can be found elsewhere [3,14]. As the tip to QPC distance is

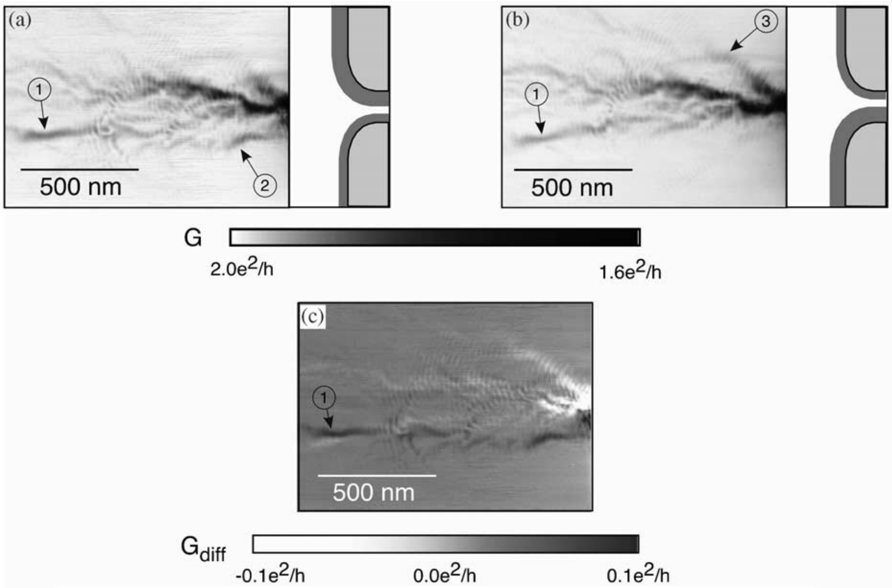

Fig. 5. Images showing the center of the QPC channel being shifted up and down by using unequal gate voltages. (a) −0.3 V extra on the top gate, (b) −0.3 V extra on the bottom gate. The light gray areas indicate the outline of the QPC gates, while the darker gray regions show schematically the expected depletion regions underneath the gates. (c) Shows the difference between the scans in (a) and (b).

changed this interference will alternate from constructive to destructive giving the fringes seen in the scans. Fig. 4a shows an image of electron flow taken at a temperature of 1.7 K. Fringes can be seen throughout the entire scan. Fig. 4b is a plot of the relative amplitude of the fringes as a function of distance from the QPC. The fringes do not decrease in fractional amplitude with distance from the QPC. For a simple tip to QPC gate resonance, the fringes should begin to blur at distances greater than that at which two electrons at $E_F + kT$ and $E_F - kT$ drift 1 radian out of phase. This length is given by $l_{th} = \hbar^2\pi/m\lambda_F k_B T = (1/2\pi)(E_F/k_B T)\lambda_F$ and is 640 nm in our sample at 1.7 K. The observed fringes persist much farther than this (indeed up to the limits of our scan range).

The persistence of these fringes past l_{th} is in agreement with theory [14]. Impurities located at nearly the same radial distance from the QPC as the tip $(r = r_{tip} \pm l_{th})$ backscatter flux to the QPC with a given total amplitude and phase relative to the flux backscattered from the tip. Different electrons (each with different energies between $E_F + kT$ and $E_F - kT$) each accumulate different total phase on the round trip, but the key fact is that the *relative* phase between the flux from the tip and the total flux from the impurities is independent of the electron's energy. As the tip moves farther or closer to the QPC, this flux from the tip and impurities moves in and out of phase, resulting in the observed perpendicular fringes. This mechanism is resistant to the blurring that comes from having a spread in energies of electrons at the Fermi surface (roughly between $E_F + kT$ and $E_F - kT$), but it is not resistant to phase decoherence. Intrinsic phase decoherence will blur these fringes, so it may be possible to directly spatially image the phase coherence length of electrons in the 2DEG by observing the length at which these fringes die out. The fringes also allow a new local measurement of the electron density in the 2DEG by relating the observed fringe spacing to $\lambda_F/2$ [15].

Fig. 4c shows that the average signal in our images falls off as $1/r^2$ with distance. A simple model for understanding this dependence follows. As electrons travel out from the QPC the current density falls off as $1/r$ since the circumference is increasing as r. When part of that flow strikes the depletion region underneath the tip it is reflected back towards the QPC and this flux again falls off as $1/r$. The expected average signal is proportional to the amount of flux backscattered from the tip through the QPC, and is therefore equal to the product of these two factors, $1/r^2$. The observed dependence is close to $1/r^2$, but falls off slightly faster than $1/r^2$ at large r.

Fig. 5 shows the effects of laterally shifting the center of the QPC channel. This can be accomplished by putting unequal negative voltages on the two surface gates. In Fig. 5a there is -0.3 V more voltage on the top gate, which shifts the position of the QPC downward. Fig. 5b has -0.3 V more on the bottom gate than the top, shifting the position of the QPC upward. Here the current flow has also shifted upwards with branches appearing or becoming stronger in the top half of the image and branches disappearing or becoming weaker in the bottom half. Fig. 5c shows Fig. 5b subtracted from Fig. 5a. We see that near the QPC the main change in flow is that the flow has shifted-less current flows in some branches and more flows in others (see arrows nos. 2 and 3). However, farther away from the QPC, the branches themselves begin to move in unpredictable ways from the randomizing effect of passing over many bumps and dips. Arrow no. 1 points to a branch which appears to be pivoting downwards from 5a to b as the QPC channel is moved upwards.

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