

Imaging electron density in a two-dimensional electron gas

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Spatial profiles of the electron density in a two-dimensional electron gas were obtained from the spacing of interference fringes in coherent electron flow. Images of electron flow from a quantum point contact formed in a GaAs/AlGaAs heterostructure were recorded with a liquid He cooled scanned probe microscope. The images are decorated with interference fringes spaced by half the Fermi wavelength; the fringe spacing measures the electron density below the scanned probe microscope tip. As the density is decreased with a back gate, the fringe spacing increases in agreement with a planar capacitor model. © 2002 American Institute of Physics.
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The behavior of electrons in semiconductor nanostructures has been of interest for many years.^{1,2} But until recently, it has been difficult to image spatially electron states and electron flow.^{3–8} Information gained from images is important to grow high-quality materials, to design future electronic devices, and for fundamental science. Scanned probe microscopy (SPM) has been used to study a wide variety of phenomena in mesoscopic physics including electrons in two-dimensional electron gases (2DEGs),^{3–8} carbon nanotubes,^{9,10} and electrons on metal surfaces.^{11,12} These experiments all give local information that can not be obtained with standard transport measurements.

In this letter, we present a technique to image the density of electrons inside a 2DEG using SPM. Images of coherent electron wave flow from a quantum point contact (QPC) have been obtained using a scanned probe microscope with a charged tip by Topinka *et al.*^{3,4} at liquid He temperatures. They found images of electron flow through a 2DEG that are decorated by periodic interference fringes spaced by half the Fermi wavelength. We show here that the fringe spacing measures the density of electrons, and that images of fringes can be used to profile the electron density. By decreasing the electron density with a back gate, the spacing of the fringes can be varied. The variation of fringe spacing with back gate voltage agrees with a simple capacitor model. The success of this technique opens the way to study electron density profiles in materials and devices.

Figure 1(a) shows a schematic diagram of our measurement setup, Fig. 1(b) is a scanning electron microscope image of the QPC sample with a plot of its quantized conductance plateaus, and Fig. 1(c) is a schematic plot of the conduction band edge as a function of depth into the GaAs/AlGaAs heterostructure by electrostatic metal gates lithographically patterned on the surface. The heterostructure was grown by molecular-beam epitaxy on a degenerately *n*-doped GaAs substrate that can

be used as a back gate. The layers of the heterostructure are, in growth order, smoothing GaAs/AlGaAs superlattice, 1000 nm GaAs, 22 nm Al_{0.3}Ga_{0.7}As, Si δ -doping layer, 30 nm Al_{0.3}Ga_{0.7}As and a 5 nm GaAs cap layer. The 2DEG resides 57 nm below the surface at the interface between the GaAs and AlGaAs layers. Its measured mobility was $\mu = 1.0 \times 10^6$ cm²/Vs, and its measured average density from Shubnikov–de Haas oscillations was $n_s = 4.2 \times 10^{11}$ cm⁻², both at liquid He temperatures.

The QPC samples were mounted in an atomic force microscope, and the sample and microscope were cooled to 1.7 K. A negative voltage applied between the QPC gates and the

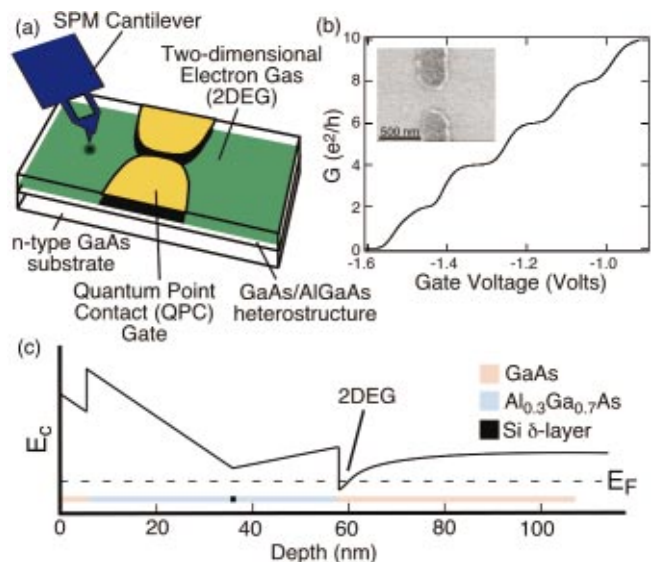


FIG. 1. (Color) (a) Schematic diagram of a QPC sample mounted in the SPM. The SPM tip is negatively charged, creating a small depleted region below in the 2DEG that backscatters electrons. An image of electron flow is obtained by measuring the change in QPC conductance as the tip is scanned across the sample. (b) QPC conductance G vs gate voltage at $T = 1.7$ K. Conductance plateaus at integer multiples of $2e^2/h$ are clearly visible. The inset is a scanning electron microscope image of the QPC device. (c) Schematic plot of the conduction band edge as a function of depth into the GaAs/AlGaAs heterostructure, with the location of the 2DEG indicated.

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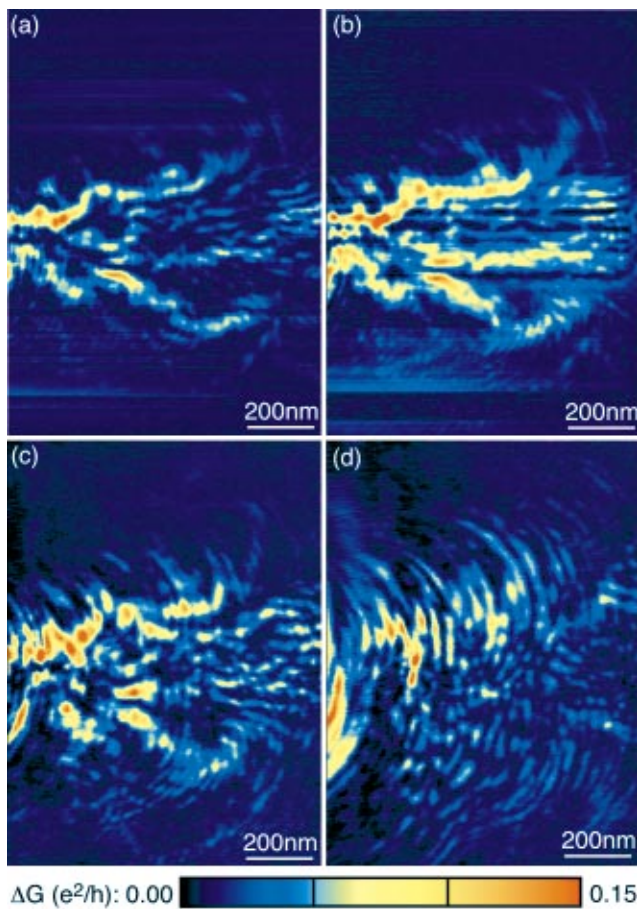


FIG. 2. (Color) Images of coherent electron flow from a QPC biased on the first conductance plateau for a series of back gate voltages that progressively reduce the electron density: (a) $V_{bg} = -0.00$ V, (b) $V_{bg} = -1.00$ V, (c) $V_{bg} = -3.00$ V, and (d) $V_{bg} = -5.00$ V.

2DEG created a variable-width channel. The QPC conductance G was measured using lock-in techniques with two ohmic contacts located far away from the channel. Figure 1(b) is a plot of G versus gate voltage. Well-defined conductance plateaus at multiples of $2e^2/h$ are clearly visible.^{13,14}

The imaging technique is illustrated in Fig. 1(a). To image electron flow and electron density, a SPM tip was held at a fixed height above the sample surface. A negative voltage applied between the tip and the 2DEG creates a small depleted region below the tip that scatters electron waves. When the electron flow beneath the tip is high, the flow backscattered to the QPC is large, reducing its conductance substantially; when the electron flow beneath the tip is low, the QPC conductance is reduced by a correspondingly small amount. By measuring the conductance change ΔG as the tip is scanned across the sample, an image of the electron flow can be obtained.^{3,4} The width of the depleted region is ~ 100 nm, but the spatial resolution from backscattered electrons is sufficient to image fringes separated by half the Fermi wavelength, as shown next.

Figure 2 shows a series of images of electron flow from a QPC on the first conductance plateau as the electron density is reduced by varying the back gate voltage: Fig. 2(a) $V_{bg} = -0.00$ V, Fig. 2(b) $V_{bg} = -1.00$ V, Fig. 2(c) $V_{bg} = -3.00$ V, and Fig. 2(d) $V_{bg} = -5.00$ V. The QPC gates are located 500 nm to the left-hand side of the images. The red and yellow areas in the images have high electron flow while

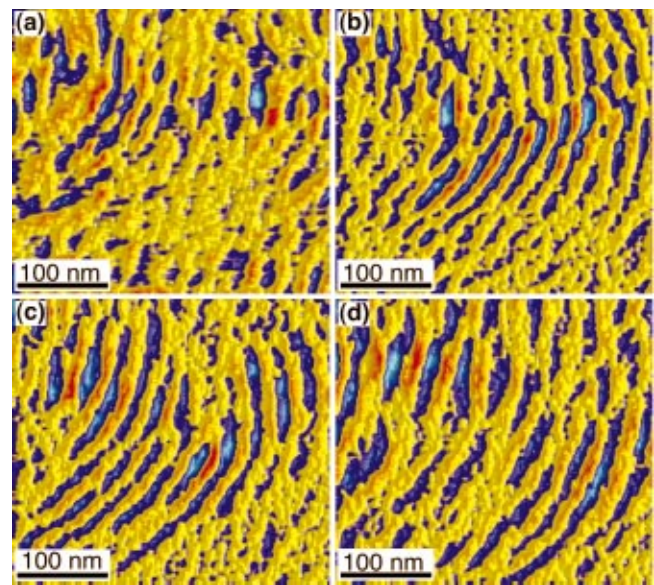


FIG. 3. (Color) High pass spatially filtered images of coherent electron flow from a small region of Figs. 2(a)–2(d) at back gate voltages (a) $V_{bg} = -0.00$ V, (b) $V_{bg} = -1.00$ V, (c) $V_{bg} = -3.00$ V, and (d) $V_{bg} = -5.00$ V. The fringe spacing increases as the electron density is decreased by the back gate.

the black areas have little or no electron flow; the corresponding conductance change ΔG is indicated by the color bar. Two main features of these images are branches of electron flow, and interference fringes spaced by half the Fermi wavelength. The branches are formed by small angle scattering in high mobility material from dopant and impurity atoms, as discovered by Topinka *et al.*,⁵ the electrons are not merely guided by valleys in the potential. The fringes arise from constructive and destructive interference of electron waves backscattered from the tip.⁴ As the electron density is decreased [Figs. 2(a)–2(d)], the branches become weaker as the electron flow becomes more diffuse. However, the fringes persist and actually become a larger percentage of the overall signal. We use the spacing of these fringes to image the local density of electrons.

Figures 3(a)–3(d) are images of electron flow that show how the fringe spacing changes with electron density. These figures were taken from a small area of Fig. 2 at the same back gate voltage Fig. 3(a) $V_{bg} = -0.00$ V, Fig. 3(b) $V_{bg} = -1.00$ V, Fig. 3(c) $V_{bg} = -3.00$ V, and Fig. 3(d) $V_{bg} = -5.00$ V. High pass spatial filtering was used to remove the envelope of the flow but preserve the fringes. As the back gate voltage V_{bg} becomes more negative, the electron density decreases. The spacing of the fringes increases, because the wavelength of the electrons is increasing. In this way, the fringe spacing directly measures the density of electrons. The measurement is local, because changes in electron paths as the SPM tip is scanned above the sample occur below the tip.

By measuring the fringe spacing at different locations in a SPM image of electron flow, a map of the local electron density can be obtained. In a round trip from one fringe maximum to the next along a path perpendicular to the fringes, the electron phase changes by 2π rad. The accumulated phase along the round trip is $2k_F d = 2\pi$, where d is the spacing between the two fringe maxima, and k_F is the Fermi wave vector. In this way, the fringe spacing $d = \lambda_F/2$ deter-

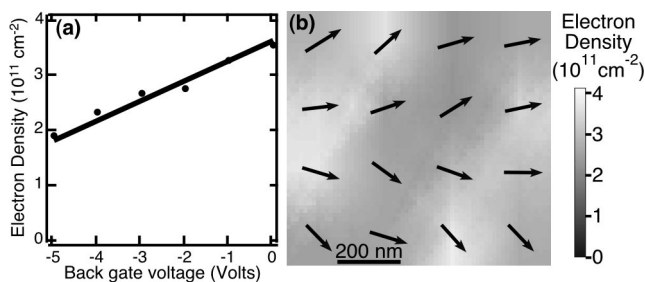


FIG. 4. (a) Average electron density vs back gate voltage over the area scanned in Fig. 3. The round points are the densities measured from the spacing of fringes in Figs. 3(a)–3(d). The solid line is the expected change in density from a parallel-plate capacitor model. (b) Image of electron density over the area scanned in Fig. 2 for a spatially uniform 2DEG. The density was obtained from an image of electron flow [Fig. 2(b)] at back gate voltage -1.00 V by using two-dimensional Fourier transforms centered on a 4×4 array of locations; a continuous gray scale was used to join densities at different locations. The arrows indicate directions perpendicular to the fringes at each location.

mines the Fermi wavelength λ_F and the electron density $n = \pi/2d^2$.

Figure 4 demonstrates how measurements of electron density from the fringe spacing agree with a simple capacitor model as the density is varied by changing the back gate voltage V_{bg} . Figure 4(a) plots the average electron density obtained over the full areas of Figs. 3(a)–3(d) versus V_{bg} . The measured density n [shown as black circles in Fig. 4(a)] was obtained from the fringe spacing in each image by taking a two-dimensional Fourier transform of the image. The peak in the direction perpendicular to the fringes determines the magnitude and direction of the wave vector k_F . The density change induced by a back gate voltage V_{bg} [shown as the solid line in Fig. 4(a)] can be found with a simple planar capacitor model. The 2DEG is separated from the back gate by a $0.82 \mu\text{m}$ thick layer of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ and by a $1.12 \mu\text{m}$ thick layer of GaAs. This gives an expected density change $\Delta n/\Delta V_{bg} = 0.36 \times 10^{11} \text{ cm}^{-2} \text{ V}^{-1}$. The measured changes in density agree very well with the expected values in Fig. 4(a), indicating that the fringe spacing accurately measures the electron density in the 2DEG. The measured value of the density $n = 3.4 \times 10^{11} \text{ cm}^{-2}$ from the fringe spacing at $V_{bg} = 0$ is slightly lower than the average value $n_s = 4.2 \times 10^{11} \text{ cm}^{-2}$ found for the GaAs/AlGaAs heterostructure from Shubnikov–de Haas oscillations. This reduction could be caused by nearby QPC gates or by coupling to the charged SPM cantilever.

Figure 4(b) is an image of the local electron density for a spatially uniform 2DEG. The image was generated from one image of electron flow [Fig. 2(b)] by taking two-dimensional Fourier transforms over circular areas of radius 100 nm centered on a 4×4 array of locations. The arrows, one centered at each location, indicate the directions of the wave vector obtained from the Fourier transforms; these are perpendicular to the fringe maxima. The electron density at each location is determined by the magnitude of the wave vector, and thus by the fringe spacing; a continuous gray scale was used to join the densities at different locations in the array.

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