Cryogenic scanning probe characterization of semiconductor nanostructures

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We demonstrate the use of a scanned probe microscope (SPM) at 4 Kelvin to study electron transport through a ballistic point contact in the two-dimensional electron gas inside a GaAs/AlGaAs heterostructure. The electron gas density profile is locally perturbed by the charged SPM tip providing information about the electron flow through the point contact. As the tip is scanned, one obtains a spatial image of the ballistic electron flux as well as the topographic profile of the structure. Calculations indicate the spatial resolution is comparable to the electron gas depth. © *1996 American Institute of Physics.* [S0003-6951(96)03031-8]

Scanned probe microscope[1] (SPM) techniques show promise for the study of subsurface two dimensional electron gas (2DEG) systems in semiconductor nanostructures at low temperatures. Extensive use of SPM techniques has been made to characterize semiconductors at room temperature: capacitance[2–4] and resistance[5] profiling of carrier distributions has been demonstrated, and trapped charge has been deposited and observed via both force[6] and capacitance[7] microscopy. Characterization of semiconductor nanostructures used for the study of quantum phenomena presents additional difficulties: operation of the SPM at cryogenic temperatures, and imaging the electron gas beneath the sample surface.

In this letter, we demonstrate the use of a scanned probe microscope at 4.2 K to study the ballistic flow of electrons through a narrow constriction in a 2DEG. Electron flow through point contacts has been studied previously by using complex gate arrangements and by steering electron trajectories with a magnetic field.[8–10] In the experiment presented here, the SPM tip locally perturbs the electron gas density via capacitive coupling. Tunneling between the tip and the electron gas does not occur, because the 2DEG is located ~500 Å beneath the surface. The density perturbation, which can have a radius comparable to the electron gas depth, obstructs the current flow by scattering electrons. By scanning the perturbation, we image the ballistic flow of electrons through the contact. Because the width of the density perturbation induced by the SPM tip is comparable to the Fermi wavelength, $\lambda_F \sim 400$ Å, this technique can provide spatial information on a size scale approaching the spacing of electrons in semiconductor nanostructures ($\sim\lambda_F/2$).

The SPM used in this experiment was constructed specifically for the study of semiconductor nanostructures at liquid helium temperatures.[11] The microscope is mounted in vacuum attached to the cold plate of a liquid He Dewar at 4.2 K, surrounded by liquid He cooled radiation shields. A piezoresistive cantilever[12] is used to provide the topographic profile of the nanostructure, eliminating the need for optical deflection sensors which can produce undesired changes in photosensitive samples. The conducting cantilever provides electrical contact to the tip without the addition of a metallic coating. A relatively long piezoelectric tube scanner (3 in. ×0.25 in.×0.020 in.) is used to give a large (20 μm) scan range at 4 K. Symmetric stage design resulted in a small, repeatable 90 μm thermal drift on cooldown from room temperature, permitting alignment of the tip and nanostructure at room temperature.

Figure 1(a) shows a topographic image of a ballistic point contact obtained at 4.2 K using this microscope. The point contact was fabricated in a GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure containing a 2DEG in a remotely doped accumulation layer located 520 Å beneath the surface. Low temperature Hall measurements determined the sheet density $n_s = 3.0\times10^{11}$ cm^{-2}, the mobility $\mu = 540\,000$ cm^2/V s, and the electron mean free path $\ell = 5.0$ μm. The point contact was defined via electron beam lithography and fabricated using a liquid mesa etch; from Fig. 1(a) its width is 2.9 μm. After subtraction of the lead and spreading resistance, the point contact resistance[13] is $R_{pc} = 100\ \Omega$.

Figure 1(b) shows an image of the change in point contact resistance ΔR induced by the charged SPM tip as the tip was scanned over the point contact. Figures 1(a) and 1(b) were acquired simultaneously; the outline of the point contact from Fig. 1(a) is shown as the white lines in Fig. 1(b). To obtain the image in Fig. 1(b), an ac voltage $V_{ac} = 0.5$ V rms at 400 Hz was applied between the tip and the electron gas. Capacitive coupling between the tip and the electron gas induces a local modulation in sheet density with tip voltage which deflects electrons passing through the ballistic point contact. The resulting change in resistance ΔR was measured by passing a dc current I_{dc} through the point contact and measuring the ac voltage drop with a lockin amplifier. The measured signal ΔR was unaffected by tip to surface force, as well as the circuit monitoring the cantilever deflection.

Figure 1(b) provides an image of electron flow through the ballistic point contact, as explained by the following model. The mean free path ℓ is greater than the dimensions of the point contact, therefore the resistance R_{pc} is deter-

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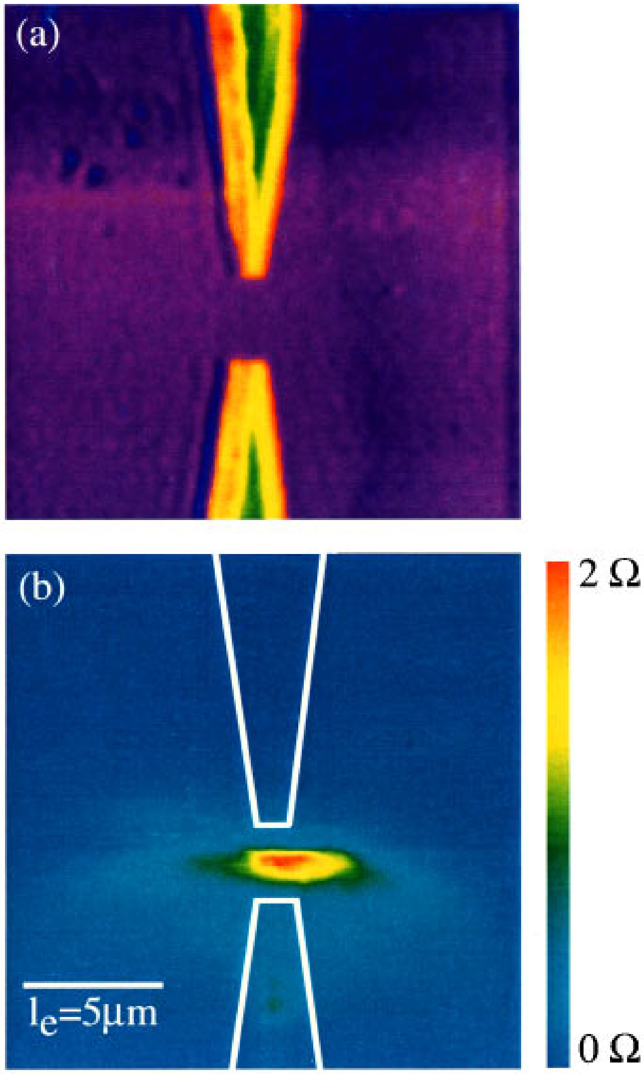

FIG. 1. (a) AFM image of the point contact taken at 4.2 K. Total image size is 19 μm, and the point contact is 2.9 μm wide. (b) Simultaneously recorded image of the change in point contact resistance. Tip voltage is 0.5 Vrms, and the full color scale range is 2 Ω.

mined solely by the ballistic flux of electrons through the point contact and is independent[13] of ℓ. The tip produced a local sheet density perturbation which scatters electrons: if the scattering event changes the flux through the point contact the resistance R_{pc} changes, otherwise the change in resistance is negligible. As shown in Fig. 1(b), the signal ΔR is constant far away from the point contact, and increases by a factor $\sim$100 to $\Delta R=2.07\ \Omega$ in the center. We found ΔR to be proportional to V_{ac}. The influence of the tip on the point contact resistance is confined to a region within half a mean free path, $\ell/2$, of the center of the contact, because the trajectories of electrons scattered by the tip are randomized by disorder over a distance ℓ in accord with the simple model above. The image also shows a pronounced collimation of the electron flow through the point contact in agreement with previous measurements of ballistic electron flow using magnetic fields.[9] From the measured peak resistance change in the point contact $\Delta R \sim 0.02 R_{\mathrm{pc}}$, we estimate the effective

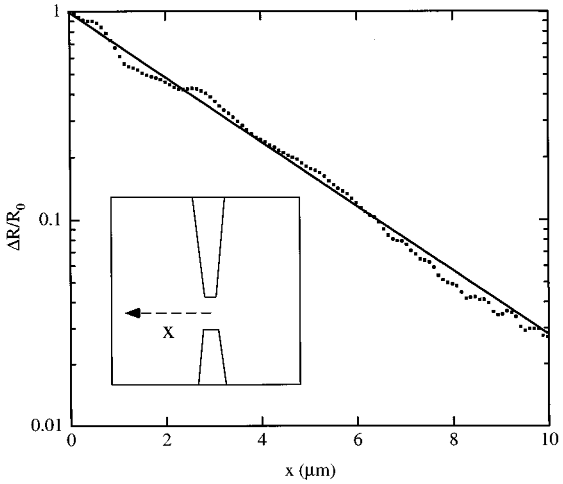

FIG. 2. Normalized change in resistance $\Delta R/R_0$ from Fig 1(b) along a line perpendicular to the point contact, as shown schematically in the inset. The solid line is an exponential fit to the data.

diameter of the density perturbation to be $2\delta r = w\Delta R/R_{\mathrm{pc}} \sim 600$ Å, where $w=2.9\ \mu$m is the point contact width, assuming that the electron gas is fully depleted under the tip and in agreement with numerical calculations below.

Figure 2 is a semilog plot of the normalized resistance change $\Delta R/R_0$ from Fig. 1(b) vs distance x along the line perpendicular to the point contact, as indicated in the inset. As shown, the resistance change caused by the density perturbation decays exponentially with distance away from the point contact; the decay length from Fig. 2 is 2.8 μm. According to the simple model above, the decay length should be one half the mean free path ℓ, because the round trip distance between the density perturbation and point contact is $2x$. The mean free path inferred via this argument from the decay length is 5.6 μm in good agreement with the mean free path $\ell=5.0\ \mu$m from the mobility. This simple argument neglects an algebraic correction to ΔR due to angular spreading of the electron flow.

Figure 3 is a plot of the normalized resistance change $\Delta R/R_0$ from Fig. 1(b) vs angle θ along an arc 4 μm away

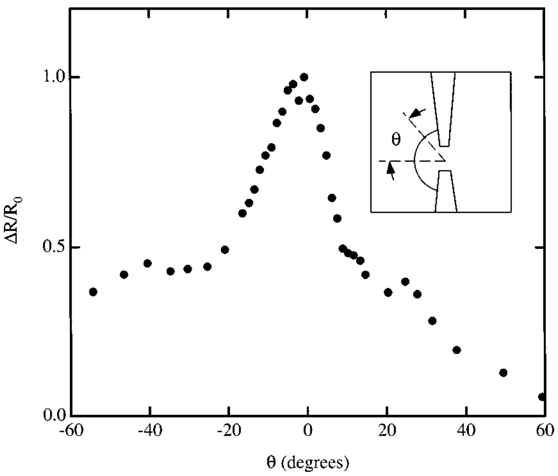

FIG. 3. Normalized change in resistance $\Delta R/R_0$ from Fig. 1(b) along an arc with radius 4 μm as in the inset.

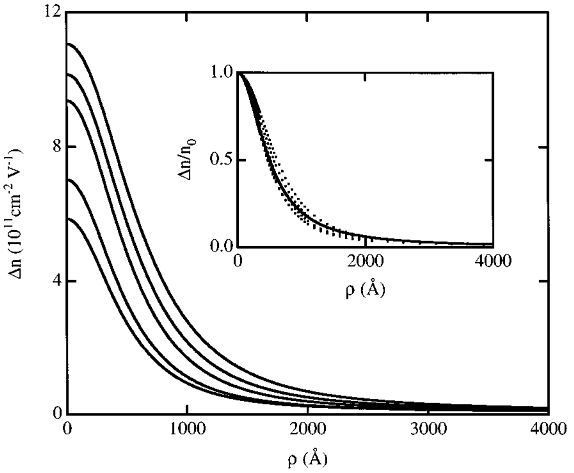

FIG. 4. Calculated density perturbation as a function of radial distance ρ in the plane of the 2DEG. From top to bottom the radii of curvature are 2000, 1000, 500, 100, and 20 Å. the gas depth is 520 Å, axial symmetry is assumed, and the tip angle was 20°. The inset shows the same curves collapsed to a normalized value of unity directly under the tip. The solid line corresponds to Eq. (1).

from the center of the point contact, as indicated in the inset. The resistance change shows a pronounced collimation of the ballistic electron flux perpendicular to the point contact: ΔR is strongly peaked at $\theta = 0\,°$, and has a half width at half maximum of $\Delta\theta = 20\,°$. Collimation of the ballistic electron flux through point contacts due to flaring of the entrance and exit is a well known phenomenon previously studied by Molenkamp *et al.*[9] and others.

In order to learn more about the change in sheet density profile Δn induced by the tip voltage and to estimate the spatial resolution, we numerically calculate the electric field distribution between the tip and electron gas. We assume an axially symmetric conical tip with radius of curvature r_c supported by a planar cantilever. The tip touches the interface between a vacuum and an insulating dielectric medium with $\epsilon = 12.24$, appropriate for $\mathrm{Al_{0.3}Ga_{0.7}As}$, containing a planar electron gas located a distance $d = 520$ Å below the surface. Figure 4 shows a plot of Δn as a function of the radial distance ρ from the tip in the plane of the 2DEG, for a series of tip radii r_c from 20 to 2000 Å as indicated in the caption. The half width at half maximum δr of the induced density change varies slowly with r_c and is approximately equal to the electron gas depth $d = 520$ Å. This occurs because the electron gas is set back from the tip, and because the large dielectric constant discontinuity reduces the apparent depth of the electron gas beneath the surface. As shown in the inset, the normalized density profiles collapse to a curve given empirically by

$$\Delta n(\rho) = \frac{n_s}{1+(\rho/d)^2}\left(\frac{V}{V_d}\right) + \frac{\epsilon\epsilon_0}{d+\epsilon h}V, \tag{1}$$

where V_d is the voltage at which the gas first starts to deplete, and h is the height of the planar cantilever above the surface. For $r_c = 500$ Å, we calculate $V_d = 0.3$ V for $n_s = 3\times 10^{11}$ cm^{-2}, implying that the electron gas was depleted under the tip for the data above. The second term due to the cantilever is simply the parallel plate capacitor solution, and is negligible for our geometry. The narrow width of the perturbation Δn is in agreement with the small (2%) change in resistance found in this experiment.

In conclusion, we have demonstrated that cryogenic SPMs can locally modify the sheet density of a subsurface 2DEG, and we have used this technique to image the current flow through a ballistic point contact. The images locally measure the electron mean free path and the collimation of the flow through the point contact. Numerical calculations indicate that the spatial resolution of this technique is determined primarily by the depth of the electron gas beneath the surface, and can approach the electron spacing.

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