Universal Conductance Fluctuations in Narrow Si Accumulation Layers

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We have observed the effect of magnetic field orientation on reproducible aperiodic structure in the low-field magnetoconductance ($H < 1.5$ T) of weakly localized, pinched, Si accumulation layers. We demonstrate for the first time that the structure depends on the perpendicular component of applied magnetic field. This implies that the structure arises from interference between electronic wave functions which represent conduction paths enclosing different amounts of flux. The observed magnitude of the structure is in good agreement with theory.

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Reproducible aperiodic structure in the magnetoconductance of small, weakly localized samples has been observed by various workers studying metallic wires,[1] narrow GaAs rings,[2] and narrow Si metal-oxide-semiconductor field-effect transistors (MOSFET's).[3] Al'tshuler[4] has discussed the existence of conductance fluctuations from one disordered sample to another. Stone[5] has suggested that the observed aperiodic magnetostructure is due to interference between different electronic conduction paths, and is identical to sample-to-sample fluctuations. The interference arises from the differing phases in the electronic wave functions. This results in small fluctuations in the conductance as the Fermi energy or the magnetic flux threading the interfering paths is varied. Al'tshuler[4] and Lee and Stone[6] predict that when the inelastic diffusion length is longer than the sample dimensions, the zero-temperature magnitude of these universal conductance fluctuations is of order e^2/h. The fluctuation amplitude begins to decrease with increasing temperature when the number of incoherently averaged conduction paths increases. Several workers[7-9] predict that as the sample size begins to exceed the inelastic diffusion length, L_{in}, averaging of the incoherent regions of the sample further reduces the fluctuation amplitude. The observed fluctuation amplitude in a narrow sample therefore decreases with sample size and becomes negligibly small in macroscopic samples.

In order to test these theories, we have measured the magnetoconductance of pinched-channel Si MOSFET's at several orientations of the magnetic field. We have also measured the conductance of these samples as a function of gate voltage. In these samples at low temperature, the conduction paths run parallel to the sample surface. Therefore, only the normal component of the magnetic field should affect the aperiodic structure. We demonstrate for the first time that the magnetoconductance fluctuations depend on this normal component, which is a more direct indication of quantum interference than was shown in Ref. 3. We also find that the magnitudes of the magnetoconductance structure and the gate-voltage–dependent structure are consistent with theory.[5,8,9]

The samples used in these experiments are pinched-accumulation-layer MOSFET's made on 10-Ω-cm n-type [100] Si substrates. The device layout shown in Fig. 1(a) has been described in considerable detail in previous papers.[10] A narrow conducting channel is formed between the depletion region of two p^+ control electrodes. The source and drain contacts are n-type diffusions. Contact is made to the narrow

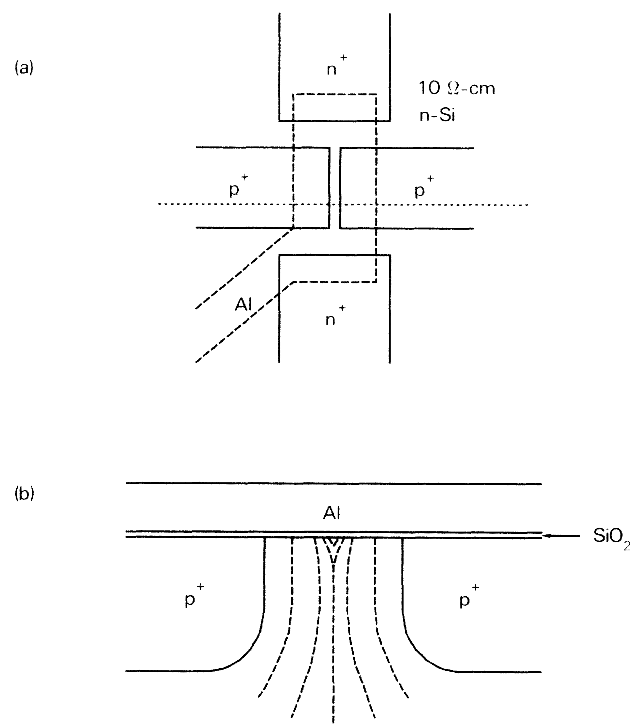

FIG. 1. (a) Device layout. The two p^+ control electrodes define the channel. The width between the controls is approximately 1 μm. The length of the narrow region is approximately 10 μm. The two n^+ regions are the source and drain. (b) Cross section taken along the dotted line in (a). The diffusions are about 0.5 μm deep and the oxide is 30 nm thick.

channel by wide accumulation layers formed where the Al gate extends past the channel region. The gate oxide is 30 nm thick, and the channel length is about 10 μm. A cross-sectional view of the device is shown in Fig. 1(b) in which equipotential lines are schematically drawn. During this experiment the control electrodes were shorted to the substrate.

We have made magnetoconductance measurements using an ac lock-in technique at 375 Hz. A source-drain voltage of 5 μV (rms) was used to avoid heating of the electrons. The current through the channel was monitored with an Ithaco 1201 current-sensitive preamplifier and a PAR 5301 lock-in amplifier. Data were logged by means of a multichannel-analyzer program running on an IBM personal computer. The resultant current noise amplitude was of order 5×10^{-13} A. Measurements were made in the gate-voltage range 9 V $< V_G <$ 13 V, and the magnitude field range $H < 1.5$ T. The angle between the sample normal and the field was varied from 0° to 90°, with the magnetic field always oriented perpendicular to the channel.

The magnetoconductance data are shown in Fig. 2(a), for $V_G = 11$ V and a temperature $T = 0.47 \pm 0.02$ K. The conductance for $H=0$ was $G = 2.3\times10^{-4}$ S. The slowly varying magnetoconductance background has been subtracted[11] in order to more clearly show the small fluctuations. We have observed no asymmetry in these curves when the magnetic field was reversed. Each curve was taken at a different angle θ between the vector normal to the sample surface and the magnetic field. Several of the peaks and dips on each curve appear at greater values of the magnetic fields as θ increases. The motion of some of these structures is shown by dashed lines. As the field is further increased, additional features appear. These are Shubnikov–de Haas oscillations with a period of H^{-1}. The presence of these magnetoconductance oscillations makes it difficult to observe the relatively smaller conductance fluctuations in higher fields, although they ought to be present there.

The positions of the Shubnikov–de Haas oscillations are dependent on $H_\perp = H\cos\theta$.[12] They may therefore be used as fiducial marks for determining θ. We have used this procedure to eliminate zero-offset and gear-backlash errors in the determination of θ. In Fig. 2(b), the same data are plotted versus the perpendicular component of the applied magnetic field. We see that many of the fluctuations lie at nearly the same value of $H_\perp$. This shows for the first time that universal conductance fluctuations are dependent on the amount of applied flux.

It is also apparent that some structures appear to gradually change shape as θ is increased. Part of these changes may be due to changes in the sample as it is temperature cycled from day to day. Additional changes may be due to the magnetic field: Although the perpendicular component of the field is roughly the same in each curve for a particular structure, the total applied field is not. The presence of structure in the nearly parallel curves shown in Fig. 2 may also be due to this effect.

The rms amplitude of the conductance fluctuations, $\delta G_{\rm rms}$, was calculated for $\theta = 0$ with use of all data points in the range 0.1 T $< H <$ 0.5 T. We found $\delta G_{\rm rms} \sim 2\times10^{-7}$ S. This is to be compared to an estimate based on the theories of Refs. 7 and 8. The rms fluctuation amplitude is theoretically predicted to be roughly equal to $G_0 \equiv e^2/h \sim 3.9\times10^{-5}$ S at $T=0$ K and when inelastic scattering is negligible. At finite temperatures, thermal smearing results in an average

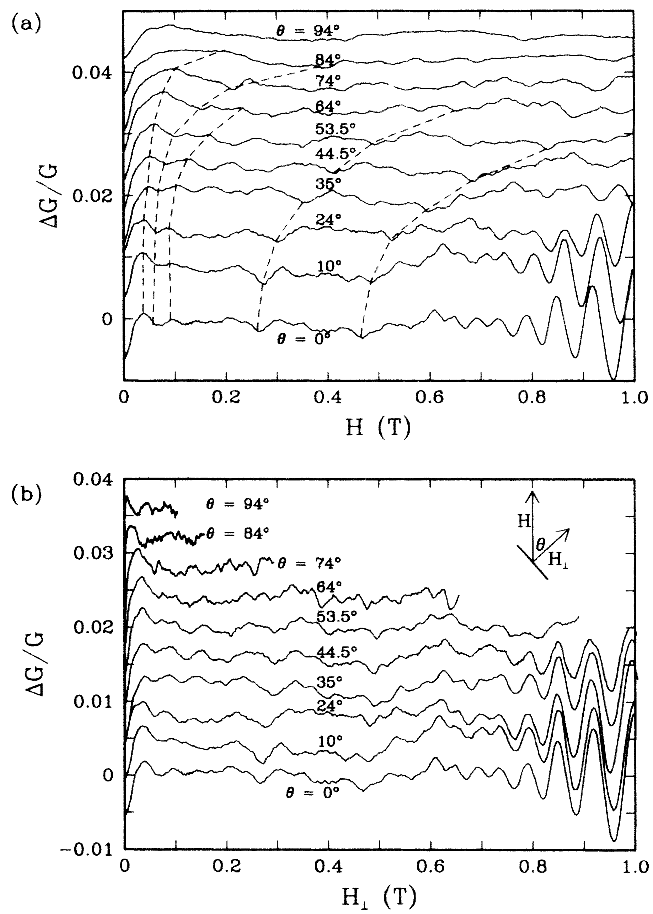

FIG. 2. (a) Fractional change in the magnetoconductance of a pinched Si accumulation layer for various values of the angle θ between the magnetic field axis and the vector normal to the sample surface. The slowly varying background has been subtracted. $V_G = 11$ V and $T = 0.47 \pm 0.02$ K. The dashed lines are used to track several structures from curve to curve as θ is varied. (b) The same data plotted vs the perpendicular component of the magnetic field. Values of θ have been adjusted as discussed in the text.

over the number of uncorrelated conduction paths. The phases of the electronic wave functions along different paths are correlated when the differences in electronic energies are less than

$$E_C \equiv \hbar \pi^2 D/L^2, \tag{1}$$

where D is the diffusion constant and L is the channel length. E_C is the uncertainty in energy which arises from the diffusion of electrons within the sample. Alternatively, one can estimate the correlation energy[13] using the scaling theory of weak localization[14]:

$$E_C = 2(G/G_0)\Delta E, \tag{2}$$

where ΔE is the energy level spacing. The number of uncorrelated conduction paths which are averaged is $\sim k_B T/E_C$. The rms fluctuation amplitude when $k_B T >> E_C$ should decrease by a factor $(k_B T/E_C)^{1/2}$. In addition, if the sample length is longer than the inelastic diffusion length, $L_{\rm in}$, the sample must be viewed as $L/L_{\rm in}$ uncorrelated samples of length $L_{\rm in}$. The correlation energy, E_C', for each length is given by substitution of $L_{\rm in}$ for L in Eq. (1). When $L >> L_{\rm in}$, the contribution from each length to the rms fluctuation amplitude is decreased by a factor $(L/L_{\rm in})^{1/2}$. The total conductance is another factor $L/L_{\rm in}$ smaller. In this limit, the fluctuation amplitude is predicted to be[7]

$$\delta G_{\rm rms} \sim (E_C'/k_B T)^{1/2} (L_{\rm in}/L)^{3/2} G_0. \tag{3}$$

If $E_C'/k_B T > 1$, only one path is averaged in each length. Therefore, the appropriate expression is[8,9]

$$\delta G_{\rm rms} \sim (L_{\rm in}/L)^{3/2} G_0. \tag{4}$$

To determine $L_{\rm in}/L$, we have measured the low-field magnetoconductance ($H \lesssim 0.2$ T). As H increases, the correction to the resistance due to weak localization decreases. For a sample of width W, for $H < \Phi_0/W^2$, and in the absence of spin-flip scattering, the magnitude of this correction is given by[15]

$$\left(\frac{2G_0}{\Delta G}\right)^2 = L^2\left\{L_{\rm in}^2 + \left(\frac{e}{\hbar}\right)^2 \frac{W^2 H^2}{3}\right\}. \tag{5}$$

A typical set of data for $V_G = 11$ V and $\theta = 0°$ is shown in Fig. 3. [We emphasize that the low-field data shown in Figs. 2(a) and 2(b) have most of this low-field correction subtracted.] We plot $(2G_0/\Delta G)^2$ vs H^2 to compare directly to Eq. (5). The presence of conductance fluctuations produces deviations from the fit. The best fit to the data results in estimates of $L_{\rm in} \sim 0.3$ μm and $W \sim 0.1$ μm. We believe these estimates to be accurate to about a factor of 2. We note that the spacing of the magnetoconductance fluctuations is ~ 0.1 T, which is consistent with these dimensions. The presence of the first fluctuation maximum at ~ 0.05 T is not inconsistent with these estimates.

In order to determine an experimental estimate of E_C', we have measured conductance fluctuations as V_G was varied, as shown in Fig. 4. We note that the magnitude of these fluctuations is approximately the same as for the magnetoconductance data shown in Fig. 2. This is in accord with theory.[6] The energy scale of these fluctuations should be of order E_C'.[9] The observed peak-to-peak distance is $\Delta V_G \sim 0.2$–0.3 V. We convert the gate voltage scale to an energy scale by using the gate capacitance, 1.15×10^{-3} F/m^2, and an average density of states at the Fermi surface appropri-

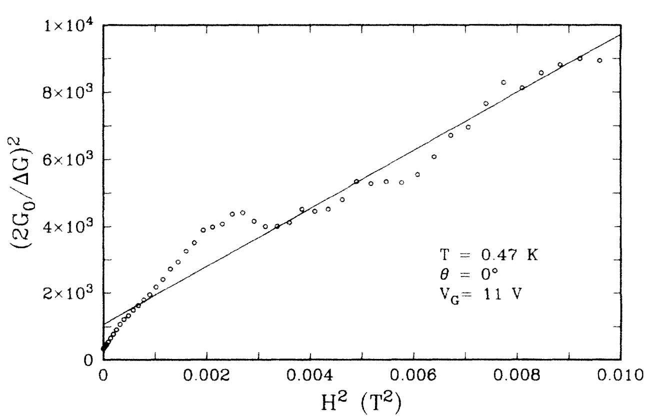

FIG. 3. Inverse of the square of ΔG, the deviation of the magnetoconductance from its saturation value (at $H \sim 0.3$ T), plotted against the square of the applied magnetic field. The straight line is the best fit to the data.

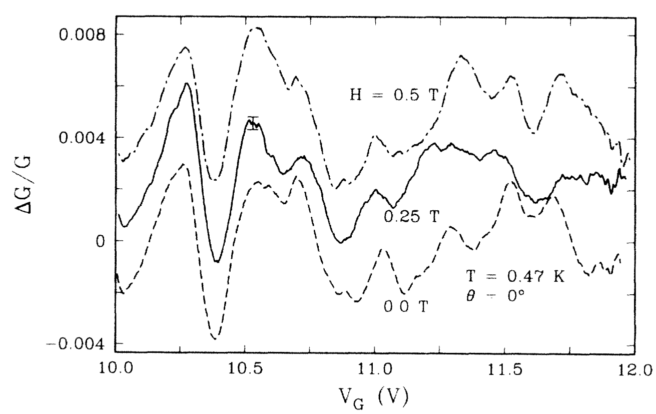

FIG. 4. Fractional change in the conductance of a pinched Si accumulation layer as a function of the gate voltage V_G for different values of the magnetic field H. Note that the change in V_G from peak to peak is ~ 0.2–0.3 V. The magnitude of the conductance fluctuations near $V_G = 11$ V is approximately equal to those seen in the magnetoconductance data shown in Fig. 2.

ate for a two-dimensional electron gas.[16] We base this assumption on the presence of Shubnikov–de Haas oscillations in these samples.[17] At $T = 0.47$ K, we obtain $E_C' \sim 1\text{–}1.5$ meV, which is much greater than $k_B T \sim 4 \times 10^{-2}$ meV. Theoretical estimates using Eqs. (1) and (2) yield even larger estimates for E_C'. We are therefore operating in the low-temperature limit.[18] We use Eq. (4) and find $\delta G_{\rm rms} \sim 2 \times 10^{-7}$ S. The observed rms fluctuation amplitude of $\sim 2 \times 10^{-7}$ S is in agreement with this estimate. We consider the degree of agreement to be fortuitous, considering the nature of the approximations made.

In conclusion, we have studied the aperiodic conductance fluctuations in narrow-channel Si MOSFET's as the magnetic field, magnetic field orientation, and gate voltage were varied. We show for the first time that such magnetoconductance fluctuations depend on the normal component of magnetic field, which gives rise to interference between electronic wave functions representing parallel conduction paths in the plane of the sample. The magnitude of the fluctuations is found to be roughly the same whether the magnetic field or the gate voltage is varied. These observations imply that both types of conductance fluctuations arise from a common quantum interference phenomenon. The measured rms fluctuation amplitudes agree well with theoretical estimates, which are based on a model in which the sample is represented as a series array of segments, each of length $L_{\rm in}$. Our data, as well as theoretical estimates for the correlation energy, indicate that thermal averaging does not reduce the amplitude of the fluctuations in each segment. However, the fluctuation amplitude in these long samples is substantially reduced by stochastic averaging of the contributions from each of the segments.

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