Universal Conductance Fluctuations in Silicon Inversion-Layer Nanostructures

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We measure the conductance variations of submicrometer inversion-layer segments in silicon devices, systematically changing the length, width, inelastic diffusion length, gate voltage, magnetic field, and temperature. Results agree with the theory of universal conductance fluctuations, demonstrating that random quantum interference causes rms conductance changes $\Delta G = e^2/h$ in each phase-coherent subunit of each segment. The random quantum interference is extremely sensitive to change of a single scatterer.

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It is now well understood that low-temperature conductance changes due to weak localization (coherent backscattering) are an example of electron quantum interference in disordered metals.[1] In recent theoretical investigations,[2–8] a new type of sample-specific random quantum interference of a surprisingly universal character is asserted to affect to varying degrees all conductance measurements on disordered metals. In this Letter, we experimentally confirm key predictions of this theory of "universal conductance fluctuations."

Random quantum interference arises from the scattering of electron waves by the particular disordered configuration of scatterers ("impurities") in each specimen. A single specimen should exhibit different conductances G corresponding to changes of magnetic field (phase) and electron energy (wavelength) sufficient to rerandomize the interference. Macroscopically similar specimens—having the same dimensions, electron density, and average density of scatterers—should show a similar range of specimen-to-specimen variation due to microscopic differences of configuration. In both cases, for phase-coherent specimens, the theory predicts an rms variation δG with a universal magnitude of approximately $e^2/h = (25.8\ \mathrm{k}\Omega)^{-1}$. For specimens consisting of N phase-coherent subunits, it predicts that the fractional fluctuations are smaller by $N^{1/2}$ because of self-averaging.

Two manifestations of this random interference are the aperiodic magnetoresistance fluctuations observed in small metal wires[9,10] and narrow Si inversion layers,[11,12] and the periodic h/e Aharonov-Bohm oscillations observed in metal[13–15] and quantum-well[16] rings. Prior comparisons between theory and the aperiodic phenomena have been based on one or two devices with very small fractional effects. In the present Letter, we systematically confirm a broad range of key predictions of the universal conductance fluctuations theory, including systems in which the fractional effect is of order unity.

We have fabricated dozens of Si inversion-layer segments of various lengths and widths in the range 0.04–1.0 μm and have measured the conductance of each at a variety of gate voltages, magnetic fields, and temperatures. Our devices are n-channel metal-oxide-silicon field-effect transistors (MOSFETs) with multiple contacts and narrow channel segments. The device structure and fabrication is described in Mankiewich.[17] Each device contains a narrow channel of width W with several side branches that are used as voltage-measuring probes, defining segments of length L, as shown in Fig. 1. The conductance $G = I/V$ of a given segment is defined as the fixed dc bias current I through the segment, divided by the measured voltage drop V across it. Currents in the nanoampere range are used, so that voltage drops remain less than $k_B T/e$, to minimize electron heating.

Figure 2 shows three typical experimental traces at 4.2 K from the device segment 4–2 indicated in Fig. 1 ($L = 0.3\ \mu$m, $W = 0.1\ \mu$m), with conductance expressed in units of e^2/h. [$g = G/(e^2/h)$.] The conductance varies aperiodically with magnetic field (electron phase) and the pattern evolves with changes of gate voltage (electron energy).[11] Each set of about a dozen such traces can be summarized by an average

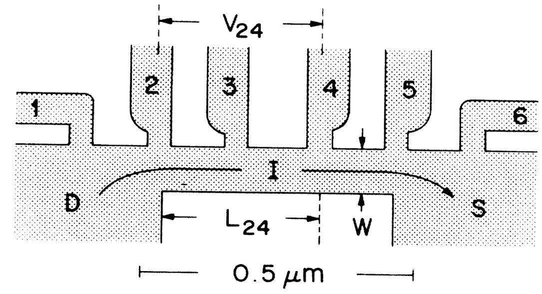

FIG. 1. Typical geometry of a MOSFET inversion layer with six voltage probes.

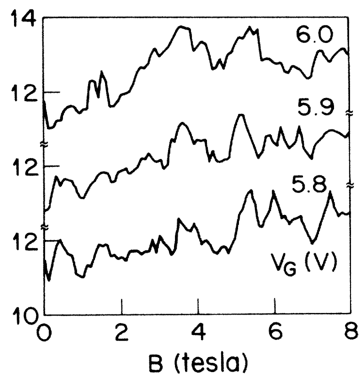

FIG. 2. Dimensionless conductance vs magnetic field at three gate voltages, for the inversion layer segment indicated in Fig. 1, showing aperiodic conductance variations of order e^2/h.

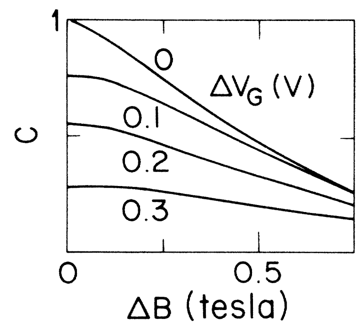

FIG. 3. Normalized correlation function vs. displacements of magnetic field and gate voltage, for data set including data of Fig. 2.

conductance $\langle G\rangle$, a root-mean-square deviation δG, and a conductance correlation function[4] C that depends on magnetic field displacement ΔB and gate-voltage displacement ΔV_G. The function C sums products of deviations, computed here with respect to the average value for each magnetic field trace. This isolates random interference phenomena from average dependences of the conductance on gate voltage. Figure 3 shows the correlation function (normalized to the variance) for a set that includes the data in Fig. 2, with $\langle G\rangle = 11.7e^2/h$, and $\delta G = 0.65e^2/h$. The correlation function has half-widths $B_c = 0.48$ T and $V_{Gc} = 0.22$ V. These correspond respectively to a magnetic flux of $3.5h/e$ in the area of the segment, and to a chemical-potential change in the inversion layer of $\mu_c = 1.6$ meV $= 4.5k_BT$.

In order to compare such experimental results with theory, it is necessary to consider the phase coherence within the device. In the absence of magnetic impurity scattering, the length scale for destruction of phase information is set by the inelastic diffusion length $L_{in} = (D\tau_{in})^{1/2}$, where $D = v_F l/d$ is the diffusion constant for dimensionality d with respect to the mean free path l, and τ_{in} is the inelastic scattering time. For two-dimensional electron-electron scattering, τ_{in} is proportional to D/T and D is proportional to the average conductance of a square $\langle g_\square\rangle = \langle G\rangle L/W(e^2/h)$. Weak-localization experiments on large MOSFETs[18] and parallel arrays of long, narrow MOSFET channels[19–21] agree (to better than a factor of 2) with

$$L_{in} = 15\langle g_\square\rangle (T/[1\ \mathrm{K}])^{-1/2}\ \mathrm{nm}. \tag{1}$$

For completeness we note that a different diffusion length $L_T = (hD/k_BT)^{1/2}$ governs the process by which simultaneously diffusing waves at different energies retain phase information but tend to get "out of step." In our MOSFETs, unlike most metals, we have $L_{in} < L_T$, allowing us to ignore the latter effect in the discussion and equations that follow.[22]

In our case, if one or more dimensions of the system being studied exceed L_{in}, then the appropriate length L or width W can be divided into $N = L/L_{in}$ or $M = W/L_{in}$ phase-coherent subunits. These subunits, differing by typically $\delta G_1 = e^2/h$, can be combined with use of classical series-parallel addition[23] to yield a combined fluctuation of relative size $(MN)^{-1/2}$ and absolute size $\delta G = M^{1/2}N^{-3/2}e^2/h$. The magnetic field change B_c characterizing the phase correlation of the random interference then corresponds to putting several flux quanta h/e in the area of each phase-coherent subunit. (Reference 4 finds that the characteristic flux is $\approx 2.4h/e$ for a strip longer than it is wide.) The chemical potential change μ_c characterizing the energy correlation of the interference corresponds to the lesser of $E_c = \pi^2\hbar/\tau_{in}$ and several k_BT, with the latter case applying in all of our devices.[22]

Experimentally, L and W are measured from electron micrographs of the devices, and L_{in} is determined from Eq. (1) and the average conductance of each data set. In terms of L, W, and L_{in}, the 1D and 2D theoretical predictions described above (for the relevant case $L_{in} < L_T$) reduce to

$$\delta g = [\max(L_{in}, W)/L]^{1/2}[L_{in}/L], \tag{2}$$

$$\mu_c = \min(\pi^2\hbar/\tau_{in},\ \text{several}\ k_BT), \tag{3}$$

$$B_c = (2.4h/e)/[L_{in}\min(W, L_{in})]. \tag{4}$$

For the data set corresponding to Fig. 3, $L_{in} = 0.25$ μm, so that $W < L_{in} < L$. Thus the segment consists of slightly more than one quantum subunit, and the measured quantities are in excellent agreement with these predictions.

Figure 4 compares Eq. (2) with the measured δg for many dozens of data sets, limited to $B > 2$ T so that weak localization effects are small. The various triangles and squares represent data sets from a comprehensive survey of device segments at three different widths (0.06, 0.1, and 0.25 μm), three different lengths (0.15, 0.3, and 0.45 μm), two different tem-

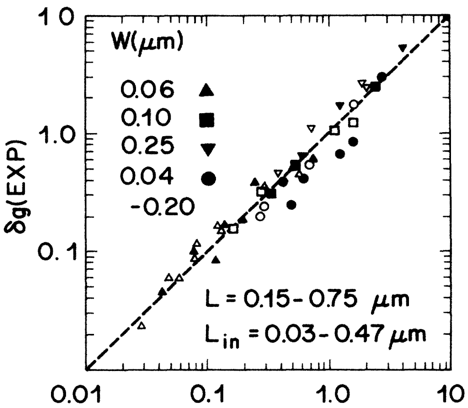

FIG. 4. Measured vs predicted rms fluctuation amplitude in units of e^2/h for many data sets with a wide range of experimental parameter values. (Open symbols, 4.2 K; solid 2 K.)

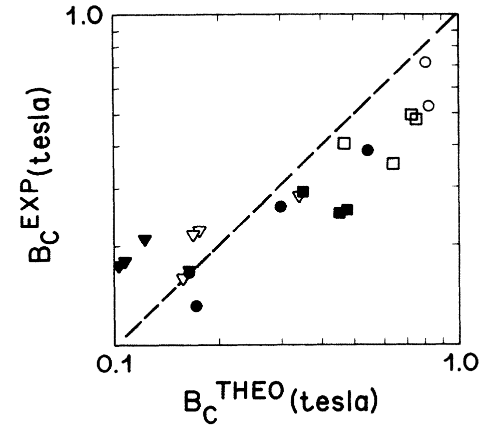

FIG. 5. Measured vs predicted magnetic field correlation half-width. The key is the same as for Fig. 4.

peratures (4.2 and 2 K), and various different gate-voltage ranges, corresponding to values of L_{in} ranging from 0.03 to 0.42 μm. The circles represent miscellaneous data sets from other devices with an even wider range of parameters. Excellent agreement is obtained over two and a half decades of fluctuation amplitude. *Moreover, all changes corresponding to a systematic variation of one of the parameters follow the predicted trend.* Thus, the amplitude e^2/h of the conductance fluctuations of the individual quantum subunits is confirmed to within the factor of 2 experimental uncertainty.

Figure 5 compares the experimental magnetic-field-correlation half-width with Eq. (4) for all devices with the predicted B_c less than 1 T. Both the magnitude and trend are accounted for. Data outside this range correspond to specimens with anomalously short L_{in} because of radiation damage induced during repeated examination in the electron microscope. In this case, random trap switching, discussed later, may account for the limited magnetic field correlations observed during long field sweeps. The observed energy correlations μ_c for the various data sets are also consistent with the theoretical value of $3k_{\text{B}}T < E_c$, within the experimental scatter of about a factor of 2.

The case of short, narrow segments with long inelastic lengths is worthy of special note. For segments with $L_{\text{in}} > L > W$, the effective quantum area deduced from the measured B_c systematically exceeds the area between the voltage probes, by up to a factor of 3. Similarly the measured δG exceeds e^2/h. We speculate that this arises because the average conductance of the measured segment is *larger* than the conductance of the phase-coherent area. This situation has not been considered in recent theories because they have been applied to disordered conductors with perfect leads. Our voltage probes measure segments connected to an additional disordered conductor, and quantum interference from scattering outside the probes as well as between them is clearly allowed. This picture is consistent with the model of quantum conductance measurement with voltage probes adopted by Engquist and Anderson.[24]

Another result worthy of note is the extreme sensitivity of the quantum conductance to the change of a *single* scatterer.[6,7] Figure 6 shows selected magnetic field sweeps at 2 K for a segment with $L = 0.3\ \mu$m, $W = 0.06\ \mu$m, and $L_{\text{in}} = 0.07\ \mu$m, thus containing about four quantum subunits. This corresponds to the prediction $\delta g \approx 0.1$ and $B_c \approx 2$ T. The expected smooth, reproducible conductance variations are cut short by sudden switching, of magnitude comparable to δg. In larger devices at higher temperatures, we have extensively studied switching phenomena caused by the fluctuating occupancy of a single electron trap,[25-27] representing one scatterer turning on and off. Here, the top trace ($V_G = 4.5$ V) can be interpreted as repeated switching among a small number of different "magnetofingerprints," each corresponding to a particular configuration of scatterers with its own quan-

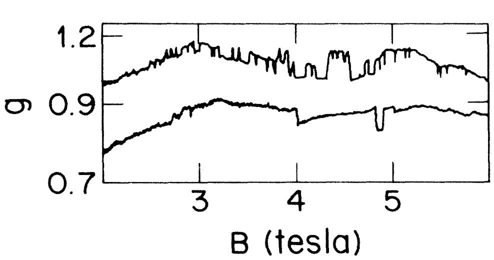

FIG. 6. Top trace: A small, low-mobility device at 2 K with $V_G = 4.5$ V shows random time switching between different "magnetofingerprints," most likely corresponding to different configurations of scatterers. Lower trace: At 4.4 V, only an occasional glitch is observed.

tum interference pattern. The lower trace ($V_G = 4.4$ V) shows only an occasional glitch. Such switching was encountered most frequently in devices with an anomalously high density of scatterers (small $g_\square$).

In a related experiment on a 0.1-μm-wide device,[21] three out of the five gate-voltage ranges that showed interface trap switching at 4.2 K showed simultaneous switching effects in three adjacent segments, roughly consistent with all three segments sampling a single quantum area of size L_{in} that contained the particular trap. Further study of this and related phenomenon should be of considerable interest.

Finally, we have already noted in Fig. 9 of Ref. 12 that the transverse Hall resistance R_{xy} shows conductance fluctuations comparable to those of the longitudinal R_{xx} reported here, as predicted by Ref. 5.

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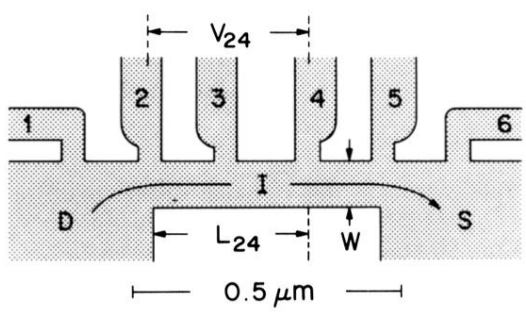

FIG. 1. Typical geometry of a MOSFET inversion layer with six voltage probes.