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Scaling properties of universal conductance fluctuations in quasiballistic split-gate wires: Probing geometrical effects

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We have studied the universal conductance fluctuations observed in the low-temperature magnetoresistance of quasiballistic, split-gate quantum-wire structures. Since transport in such devices is determined by scattering from only a small number of impurities, it is of interest to know whether the fluctuations exhibit the same universal features characteristic of corresponding metallic systems. In this paper, we discuss results obtained in split-gate wire structures of two different lengths ($L=2$ and 6 μm). These indicate that, although the fluctuations scale *qualitatively* as expected as the system size is varied, the *amplitude* of the scaling, expressed via the adjustable constant β, is more than an order of magnitude smaller than the case for corresponding diffusive systems. We relate these features to the variation in the coherence area, the effective area over which electron interference takes place, for quasiballistic wire structures of different length and width.

The observation of universal conductance fluctuations (UCF) in the low-temperature magnetoresistance (MR) of small metallic wire and ring structures provides a striking illustration of the role of electron wave interference effects in mesoscopic systems.[1] The fluctuations result from the interference between distinct electronic trajectories across the device, and are typically observed in device structures whose size is comparable to the phase coherence length of the electrons l_ϕ. In metallic systems, where the electronic motion is diffusive, this interference no longer averages to zero and can strongly affect the electrical properties of the device. Furthermore, the interference can be modulated by an applied magnetic field or gate voltage, giving rise to conductance fluctuations with a universal amplitude e^2/h.[2]

In high-mobility semiconductor systems electronic motion is no longer necessarily diffusive and so it is unclear to what extent the universal nature of the fluctuations is preserved. Recent studies of semiconductor point contact structures,[3] in which electronic motion is quantized into discrete subbands, indicate that in the absence of intersubband scattering that the UCF are completely quenched. In contrast, studies of the low-temperature transport properties of etched semiconductor wires,[4–6] in which the electronic transport was essentially diffusive, revealed the presence of UCF in the magnetoresistance. These contrasting results suggest that studies of the UCF in quasiballistic systems, in which transport is determined by scattering from only a small number of impurities, may reveal interesting information on the role of mutliple scattering events in establishing the universal nature of the UCF.

In this paper we report on studies of quasiballistic quantum-wire structures defined using a split-gate technique. Since the dimensions of such devices can be easily varied via the negative bias applied to the metal gates, they provide us with an ideal opportunity to study the role of the device geometry in transport. Previously, we have employed this approach to study the amplitude of the Shubnikov–de Haas oscillations (SdH) in quasiballistic wires, which were found to be strongly affected by the boundary scattering of electrons.[7,8] Here we discuss studies of the UCF in split-gate wires of different lengths, in order to characterize the nature of transport in the quasiballistic regime. Our results reveal that while the fluctuations scale *qualitatively* as expected as the system size is varied, the *amplitude* of the scaling, expressed via an adjustable constant β, is more than an order of magnitude smaller than the case for corresponding diffusive systems. We relate these features to the variation in the coherence area, the effective area over which electron interference takes place, for wire structures of different length and width.

The split metal gate structures were fabricated on $GaAs/Al_xGa_{1-x}As$ wafers, grown by molecular-beam epitaxy, with a typical low-temperature mobility $\mu=8$ $m^2/V\,s$ and elastic mean free path $l_{mfp}=1$ μm. The wafers were patterned in to standard Hall bar geometries with a width of 100 μm and a voltage probe separation of 120 μm. The aluminum gates, which were defined by electron beam lithography and a subsequent liftoff, covered a small fraction of the area between the voltage probes.[9] Two different types of gate structure were fabricated, in which the lithographic length L of the gates was 2 and 6 μm, respectively. The lithographic gap W between the gates was kept constant at 0.6 μm, and so transport in these devices was expected to be in the quasiballistic regime.

The samples were mounted in a ^{3}He cryostat and low-temperature magnetoresistance measurements were performed at 1.2 K and in magnetic fields of up to 8 T. At this temperature the thermal diffusion length of the electrons $L_T = \sqrt{(hD/2\pi k_B T)}$ was estimated to be approximately 1.2 μm. A negative voltage applied to the gates depleted the region of a two-dimensional electron gas (2DEG) underneath them, enabling narrow quantum wires to be realized. The resulting carrier concentration of the wires was determined from the periodicity of the high-field SdH oscillations and was found to be 7×10^{15} m^{-2}, essentially independent of the applied gate voltage. This feature indicates that, at least over the gate voltage range of interest, the mobility and other electrical properties of the wires were constant. The effective length and width of the wires (L_{eff} and W_{eff}) could then be calculated by assuming a uniform, gate-voltage-dependent, depletion layer to exist around the gates (Fig. 1), and by associating the change in the channel resistance R, as the gate voltage was varied, with a change in the width W_d of this layer.[10]

The electrical measurements were performed using a local geometry[11] but, by restricting the applied magnetic field to less than 1 T, the influence of the SdH oscillations was found to be vanishingly small and clear UCF were observed in the magnetoresistance. In diffusive systems, the physical properties of these fluctuations are now known to be well described by a theoretical description in terms of the correlation function,[12]

$$F(\Delta B) = \langle \Delta G(B) \Delta G(B+\Delta B) \rangle \ , \tag{1a}$$

$$\Delta G(B) = G(B) - \langle G(B) \rangle \ , \tag{1b}$$

where $G(B)$ is the conductance at magnetic field B, and $\langle\ \rangle$ indicate an ensemble average taken over a suitable magnetic-field range. The correlation field B_c can then be defined as the half width of the correlation function, $F(B_c) = 0.5F(B=0)$, and can be considered as being determined by the phase-coherent area over which electron interference takes place. In keeping with the convention adopted in the literature, for diffusive systems we can write[11]

$$B_c = \beta(\Phi_0/S) \ , \tag{2}$$

where $\Phi_0 = (h/e)$ is the flux quantum, S is the area over which coherent electron interference occurs, and β is some sample configuration-dependent constant. The exact form of Eq. (2) depends on the relative size of the various electronic length scales and the sample dimensions but in the case where $l_\phi > W_{eff}$, corresponding to the one-dimensional transport regime, it has previously been shown that for metallic systems $S = W_{eff} l_\phi$ and $\beta = 0.25$, *almost* independent of the thermal diffusion length.[11–13] Clearly, the important feature of this result is that it predicts specific scaling properties of the correlation field as the system size is varied; in the one-dimensional transport regime B_c should scale inversely with the channel width. Since B_c is determined directly from the experimental properties of the fluctuations, an important test of the nature of UCF in the quasiballistic regime will therefore be the extent to which B_c scales in accordance with this prediction.

In addition to the UCF, the low-field magnetoresistance was also found to exhibit a monotonic and weak negative behavior (NMR), consistent with one-dimensional weak localization effects. The experimentally observed amplitude of this effect can also be related to theoretical predictions, to provide an estimate of the phase-breaking time τ_ϕ of the electrons,[14]

$$\delta G(B) = -\frac{e^2}{h}\frac{2\sqrt{D}}{L_{eff}}\left[\left(\frac{1}{\tau_\phi}+\frac{1}{\tau_B}\right)^{-1/2} - \left(\frac{1}{\tau_\phi}+\frac{1}{\tau_B}+\frac{1}{\tau_e}\right)^{-1/2}\right] \ , \tag{3a}$$

$$\delta G(B) = G(B) - G(B=0) \ , \tag{3b}$$

$$\tau_B = l_{mfp}^4 / K_1 W_{eff}^3 v_F + l_{mfp}^2 \tau_e / K_2 W_{eff}^2 \ , \tag{3c}$$

where D is the diffusion constant,[15] v_F is the Fermi velocity, τ_e is the elastic scattering time, and τ_B is a relaxation time due to the presence of the applied magnetic field. K_1 and K_2 are constants related to the nature of the boundary scattering properties of the wire, which in our samples we suppose to be specular ($K_1 = 0.11$ and $K_2 = 0.23$).[8] Since all other parameters in Eq. (3) are experimentally determined, a single parameter fit to the low-field NMR will therefore enable us to determine τ_ϕ (and so l_ϕ from $l_\phi = \sqrt{\tau_\phi D}$).[16]

In Fig. 2 we show the variation of the phase-breaking length, determined from Eq. (3), for both the 2- and 6-μm length channels. In both cases, the derived value of l_ϕ is found to be around 1 μm and is essentially independent of the channel width. This again provides a good indication that the transport properties of the quantum wires are essentially independent of the applied gate voltage. Furthermore, since in all cases we find that $l_\phi > W_{eff}$ transport can be considered as one dimensional and the correlation field should, as discussed earlier, scale inversely as

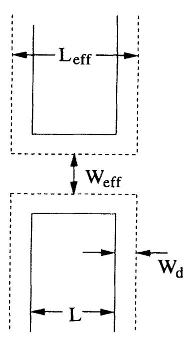

FIG. 1. Schematic diagram of the depletion layer induced around the gate edges by the negative bias. The solid line represents the actual gate geometry, while the dashed line represents the extent of the depletion layer. In reality, electron screening will round the corners and our assumption of a "hard-wall potential" will be only approximate.

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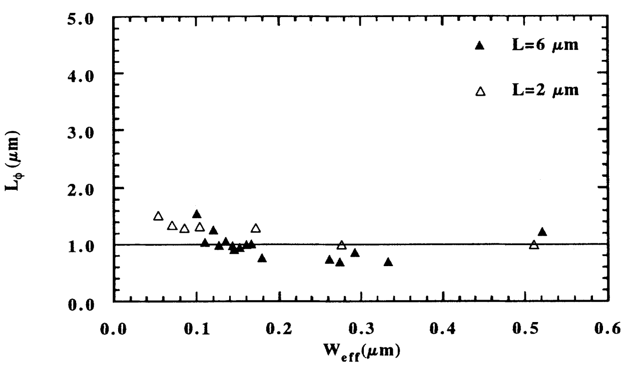

FIG. 2. The width dependence of the phase coherence length in the 6- and 2-μm length channels. The value of l_ϕ was derived by fitting Eq. (3) to the experimentally observed NMR, and is seen to be essentially independent of channel width and length.

a function of width.

In Fig. 3(a), we show the experimentally observed variation of B_c with channel width in both the 2- and 6-μm wires. While the actual value of B_c is smaller in the 2-μm wires than in the 6-μm wire, in both cases B_c is seen to steadily increase as the width of the channel is decreased. In Fig. 3(b) we replot the data to show that the correlation field does indeed vary roughly inversely with W_{eff} in both the 2- and 6-μm wires. These results indicate several interesting features of the UCF in the quasiballistic regime. First, we note that the scaling behavior revealed in Fig. 3(b) is *qualitatively* consistent with the behavior expected for diffusive systems. However, using Fig. 3(b) to calculate an average value for β, assuming a phase coherence length of 1 μm, we find that $\beta(2\ \mu m)=0.018$ and $\beta(6\ \mu m)=0.035$, in both cases *an order of magnitude smaller than the expected value* $\beta=0.25$. Furthermore, the different values of β for the two different length samples is somewhat surprising since B_c is not normally expected to show a dependence on sample length [see Eq. (2)]. We therefore conclude that *the experimentally observed scaling of the correlation function with channel width is qualitatively consistent with the geometrical predictions of Eq. (2) but that the adjustable parameter* β *is an order of magnitude smaller in these quasiballistic devices than for the corresponding diffusive systems.* To our knowledge these results represent the first detailed investigation of the scaling properties of the UCF in a single device structure, and have significant implications for our understanding of quantum transport.

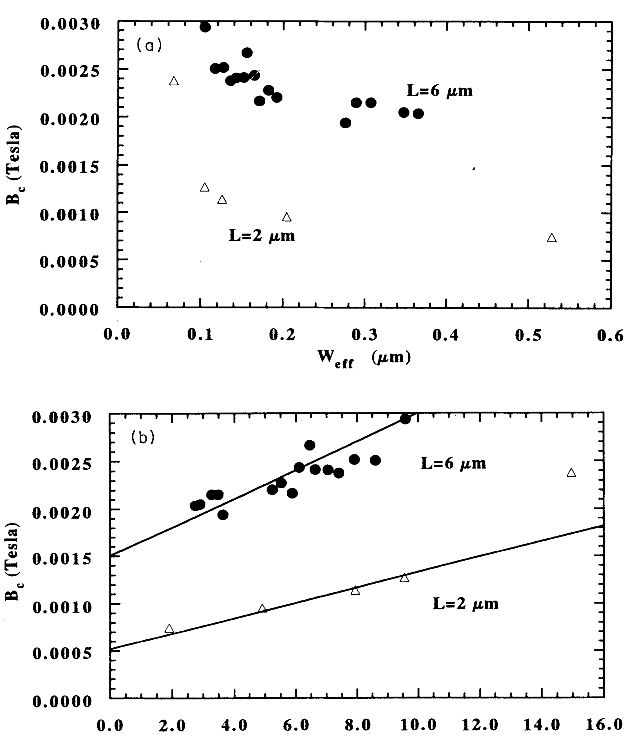

FIG. 3. (a) The experimentally observed variation of B_c with channel width in both the 2- and 6-μm channels. (b) The data of (a) replotted to show the approximately inverse relationship between B_c and W_{eff}.

To understand the anomalous scaling of the fluctuations in these devices we believe it is important to consider the specific nature of the device geometry; since l_ϕ is comparable to the gate length, the area over which significant electron interference may occur is no longer simply defined by the gate geometry. In particular, we regard the interference effects in these devices to be associated with contributions from two distinct geometries (Fig. 4): from the confined segment A, defined by the region between the split gates, and from the unconfined segment B, which extends into the undepleted 2DEG. This situation is very different from the etched wires studied previously in the literature,[1,4–6,11] in which the device dimensions could essentially be considered as being defined by the etched geometry of the sample. Obviously, the ratio of the areas of segments A and B will be different for different length samples, and the effect of segment B will be expected to become of increasing importance for shorter wire lengths. While it is well known that in quasiballistic systems that the boundary scattering introduces a flux-cancellation effect,[17] causing an enhancement of B_c, this enhancement will be absent in segment

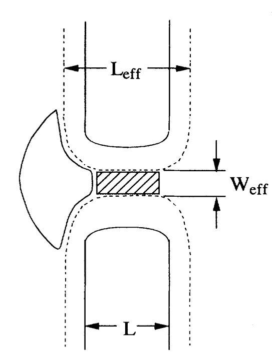

FIG. 4. Presumed form of the actual sample geometry, consisting of a confined region A, associated with the split metal gates, and an unconfined region B, which extends into the 2DEG. Since l_ϕ is comparable to L, electrons in region A will in some sense be nonlocally influenced by electrons in region B.

B. We therefore expect that in the shorter length wires, interference effects associated with segment B may become effective in reducing the enhancement of B_c, and that this effect is responsible for the reduced value of the correlation field shown in Fig. 2. Furthermore, we might expect some relationship between the β and the ratio of the areas of the segments A and B, with values of β close to 0.25 (the diffusive value) for large ratios A/B (long wires). Unfortunately, however, we do not have sufficient data yet to enable us to precisely determine the L dependence of β and so can only conclude that β is reduced in quasiballistic systems.

In conclusion, we have studied the universal conductance fluctuations observed in the low-temperature magnetoresistance of quasiballistic, split-gate quantum-wire structures. Since the dimensions of such devices can be easily varied via the negative bias applied to the metal gates, they provide us with an ideal opportunity to study the role of the device geometry in transport. At low temperatures and at magnetic fields, the low-temperature magnetoresistance of the devices was found to exhibit UCF, whose properties were studied as the systems size was varied. Our results indicate that although the fluctuations scale *qualitatively* as expected as the system size is varied, the *amplitude* of the scaling, expressed via the adjustable constant β, is more than an order of magnitude smaller than the case for corresponding diffusive systems. We suspect that these differences result from the importance of geometrical effects in our devices, in which the phase coherence area S may not be clearly defined.

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