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Universal Conductance Fluctuations in a Narrow Channel of Two-dimensional Electron Gas under Gradient Magnetic Field with Zero Mean

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We have investigated universal conductance fluctuations (UCF) in a narrow channel of two-dimensional electron gas subjected to a gradient magnetic field with a vanishing average, generated from a cobalt strip deposited along the center line of the channel. We find that the fluctuation amplitude ΔG tends to be a larger value in the low-temperature limit and the characteristic field B_c is less temperature sensitive, compared with those for UCF in a uniform magnetic field.

KEYWORDS: 2DEG, UCF, gradient magnetic field, flux cancellation
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An artificially designed spatially varying magnetic field can be imposed on two-dimensional electron gas (2DEG) by depositing a microfabricated ferromagnetic element on the top surface of the 2DEG wafer.[1–8] Such mesoscopic ferromagnet/2DEG hybrid structures open the door to a new experimental stage in fundamental physics. Conductance fluctuations as a function of magnetic field or carrier concentration due to the quantum interference effect are observed when the sample size is comparable to phase coherence length.[9] The root-mean-square (rms) deviation of the conductance G from its average takes a universal value $\Delta G \sim e^2/h$ regardless of sample size or impurity configurations. The universal conductance fluctuations were theoretically predicted by Al'tshuler–Lee–Stone[10–12] in the diffusive transport regime and experimentally observed not only in diffusive metal wires but also in quasi-ballistic 2DEG narrow channels.[13]

In a previous work,[14] we studied electrical transport in a narrow channel under a gradient magnetic field, and reported conductance enhancement and the rectification effect under DC bias current. Resistance fluctuations were observed at $T = 1.3$ K under both the gradient field and the uniform field. In the present work, we report the behaviors of the conductance fluctuations in a lower temperature range (20–900 mK) and compare the results with those for a uniform magnetic field.[15]

Samples were fabricated from a GaAs/AlGaAs single-heterojunction wafer grown by means of molecular beam epitaxy. The density and mobility of the 2DEG before processing were $3.1 \times 10^{15}\,\mathrm{m}^{-2}$ and $67\,\mathrm{m}^2/(\mathrm{V\,s})$, respectively. The electron mean free path was 6.1 μm. The depth of the 2DEG plane below the sample surface was 65 nm. A schematic diagram of the sample configuration is shown in Fig. 1(a). Narrow channels of 2DEG were formed by chemical wet etching with the geometrical widths of 1.5 μm (sample #1) and 1.8 μm (sample #2). The physical width of the 2DEG channel is somewhat smaller due to depletion at both edges. The separation between the two voltage probes used to measure the longitudinal resistance R_{xx} of the 2DEG narrow channel was 12 μm. A cobalt strip of 75 nm thickness and 0.5 μm width was placed on top along the center line of the channel. The device was fabricated in such that the electron transport in the cobalt wire could be measured simultaneously with that in the 2DEG wire, in order to monitor the magnetization process of the former.

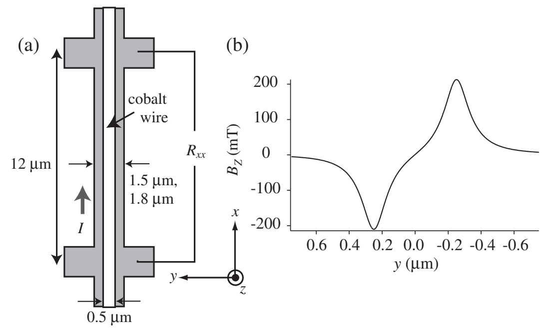

Fig. 1. (a) Schematic diagram of the sample configuration. (b) Calculated stray magnetic field profile B_z at the 2DEG plane with magnetic field applied in the y direction. The calculation was carried out adopting 1.8 T as the value of the saturation magnetization of cobalt.

Measurements were carried out using a low-frequency AC lock-in technique at an excitation current of 3 nA for the 2DEG and at 100 nA for the cobalt wire to prevent current heating. Since the temperature was far below the Curie temperatures of cobalt, the magnetic behavior of the cobalt strip was temperature independent. A dilution refrigerator/15 T magnet system equipped with a sample rotator was used for the measurements. The sample rotator enabled us to change the direction of the magnetic field in situ with respect to the plane of 2DEG, without temperature cycling. This was essential in the study of the quantum interference phenomena since the random potential configuration might be changed by temperature cycling.

The resistance traces of the 2DEG narrow channel as a function of external magnetic field swept in the z direction and in the y direction are shown in Figs. 2(a) and 2(b), respectively. Resistance fluctuations are observed for both configurations, and their amplitude is seen to increase with decreasing temperature. The simultaneously measured resistance of the cobalt strip shown in Fig. 2(c) reveals its magnetization process. At zero external field, the magnetization of the cobalt strip tends to be aligned along the length

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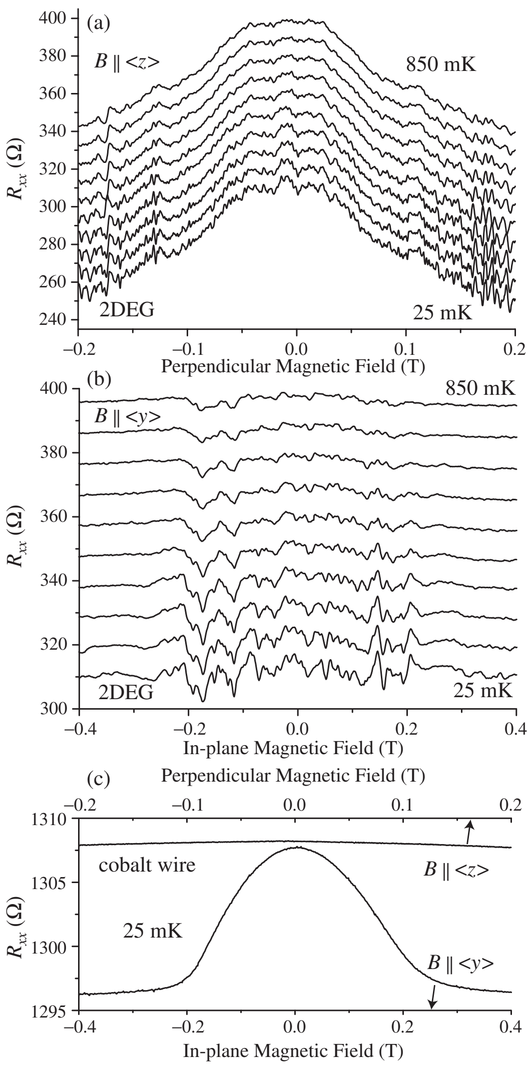

Fig. 2. (a) Resistance of 2DEG narrow channel for sample #2 at temperatures between 25 and 850 mK, under sweeping magnetic field in z (normal) direction and (b) in y (in-plane) direction. Each data is offset by 10 Ω for clarity. (c) Simultaneously measured resistance of the cobalt wire at $T = 25$ mK.

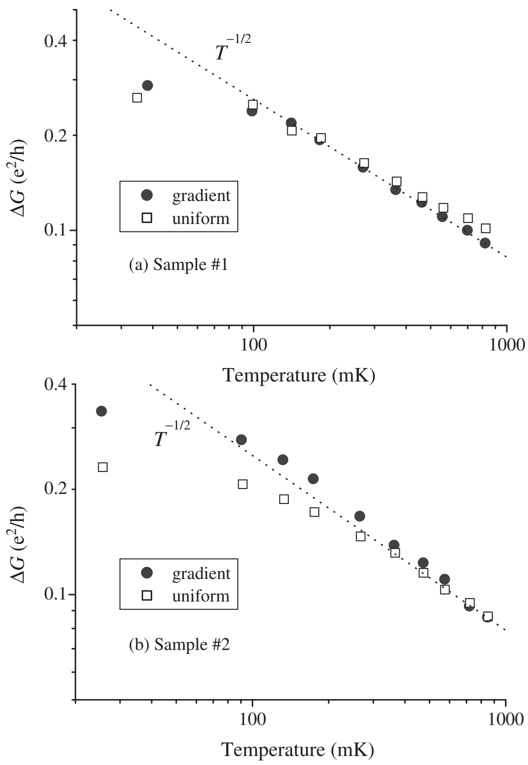

Fig. 3. Temperature dependence of the amplitude of conductance fluctuations for samples #1 (a) and #2 (b). Closed circles and open squares correspond to gradient field and uniform field, respectively. The dotted line shows a slope of $T^{-1/2}$.

of the strip due to shape anisotropy, and is segmented by domains of opposing magnetization. A weak stray field generated at the domain walls has a minimal influence on the 2DEG transport. This was confirmed by the fact that the 2DEG shows no magnetoresistance for B parallel to the x-axis. For $B \parallel z$, the magnetization of the cobalt strip remains along the easy (x) direction for small external fields, and is forced in the z direction only at B as high as $\sim$3 T. Below 0.2 T, the stray magnetic field from the cobalt strip is negligible and the magnetic field is expected to be uniform over the sample. For $B \parallel y$, the resistance of the cobalt strip shows a typical anisotropic magnetoresistance (AMR) effect that saturates at $|B| \sim 0.2$ T. This indicates that the direction of magnetization gradually rotates with $|B|$ from the x direction to the y direction, and the rotation is completed at $|B| \sim 0.2$ T. The y component of magnetization generates a spatially varying magnetic field with zero mean at the 2DEG plane. Figure 1(b) shows the profile of the magnetic field (the normal component B_z) across the 2DEG channel calculated by a simple magnetostatic model when the magnetization of cobalt is saturated. The peak amplitude of B_z is approximately 200 mT. The situation corresponds to the case in which the magnetization is fully oriented to the y direction ($|B| \gtrsim 0.2$ T). For $|B| \lesssim 0.2$ T, the amplitude of B_z varies with $|B|$, according to the change in the y component of the magnetization. In the following, we assume that the amplitude varies linearly with $|B|$ for simplicity. The external magnetic field is precisely aligned to the 2DEG plane by measuring the Hall voltage, and thus the normal component of the magnetic field arises only from the stray field generated by the cobalt strip.

Figure 3 shows the temperature dependence of the amplitude of conductance fluctuations $\Delta G = \sqrt{\mathrm{Var}(G)}$ for samples #1 (narrow) and #2 (wide). For the uniform field, ΔG is extracted from the data between -0.1 and 0.1 T in Fig. 2(a), where the contribution of Shubnikov–de Haas oscillations can be neglected, while for the gradient field, data between -0.2 and 0.2 T in Fig. 2(b) are used. The temperature dependence obeys a $T^{-1/2}$ law at higher temperatures, which is consistent with the temperature dependence of the thermal length $\ell_T = \sqrt{\hbar D/k_B T}$. At these temperatures, ℓ_T is expected to be smaller than the phase coherence length ℓ_ϕ and to dominate the temperature dependence of ΔG. As the temperature is reduced, ℓ_T increases and eventually exceeds ℓ_ϕ, since ℓ_ϕ has a much weaker temperature dependence. The amplitude of the fluctuations will then tend to saturate. This is apparent in Fig. 3. The observed crossover temperature is roughly in agreement with that estimated from ℓ_T and ℓ_ϕ; a simple calculation reveals that $\ell_T \sim 2.4$ µm at 1 K and $\sim$7.5 µm at 100 mK in these samples,[16] while ℓ_ϕ at the lowest temperature can be deduced to be $\sim$3 µm from the fact that the

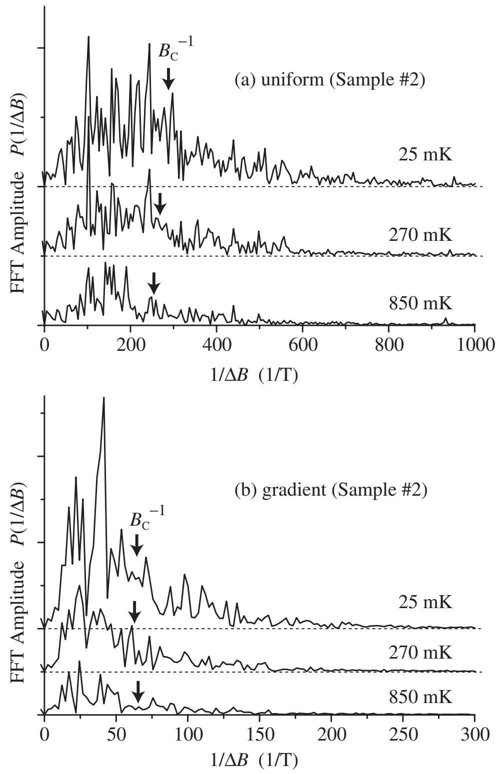

Fig. 4. Fourier spectra of the conductance fluctuations for sample #2 under uniform field (a) and gradient field (b) at $T = 25$, 270 and 850 mK. Each trace is shifted vertically. Arrows indicate the average positions of the spectra, which define B_c^{-1}.

amplitude of the conductance fluctuations ΔG is approximately $0.3e^2/h$.[17] It can be seen from Fig. 3 that the saturation value of ΔG is higher for the gradient field than for the uniform field. The difference is more apparent for sample #2. This issue will be discussed later in relation to the flux cancellation effect.

Figure 4 shows the Fourier transform of the conductance fluctuations $P(1/\Delta B)$. The arrows indicate the average positions of the frequency. We define the characteristic magnetic field B_c as

$$\frac{1}{B_c} \equiv \frac{\int \frac{1}{\Delta B} P\left(\frac{1}{\Delta B}\right) \cdot \mathrm{d}\left(\frac{1}{\Delta B}\right)}{\int P\left(\frac{1}{\Delta B}\right) \cdot \mathrm{d}\left(\frac{1}{\Delta B}\right)}, \tag{1}$$

which is the characteristic value of magnetic field that corresponds to one flux quantum h/e per phase coherent area.

Figure 5 shows the characteristic magnetic field B_c as a function of temperature. In the case of a uniform magnetic field, B_c is approximately 4 mT, which corresponds to a correlation area of $\sim 1\,\mu m^2$. B_c increases with temperature, reflecting the loss of the spectral weight of the high-frequency region in the FFT spectrum. This is attributable to the reduction of the phase coherence length ℓ_ϕ, and hence to the reduction of the phase-coherent area. The value of B_c and its temperature dependence are in agreement with those previous reported.[13] For the gradient field, B_c is approximately 16 mT, which is four times as large as the value for the uniform field. Note, however, that Fig. 2(b) was plotted against an externally applied in-plane magnetic field. To make a quantitative comparison, B_c for the gradient field

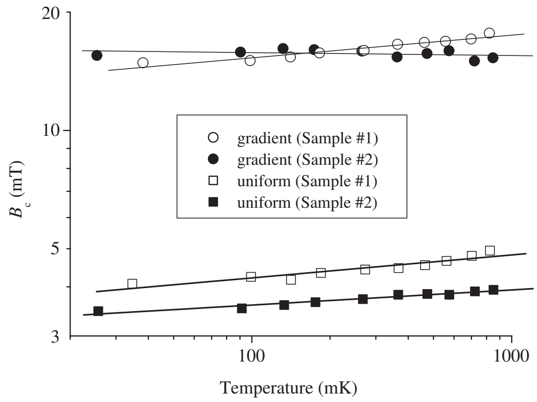

Fig. 5. Temperature dependence of characteristic magnetic field B_c. Solid lines are just a guide for the eyes.

must be translated into a value in terms of the normal component B_z of the stray magnetic field generated by the cobalt strip [Fig. 1(b)]. The average of $|B_z|$ across the channel is 50–80 mT when the cobalt strip is fully magnetized in the y direction. As mentioned earlier, the magnetization is fully oriented to the y direction at the in-plane magnetic field of ~ 0.2 T. Therefore, B_c for the gradient field should be reduced by a factor of 3–4. The resulting value is close to B_c for the uniform field. Figure 5 reveals that the temperature dependence of B_c is weaker for the gradient field, particularly for sample #2. The difference in the temperature dependence here and in the low-temperature value of ΔG seen in Fig. 3 seem to have a common physical origin, namely, the flux cancellation effect in the gradient field. The effect is explained in the following.

Figure 6 illustrates magnetic flux Φ enclosed by two trajectories propagating from r to r'. In the case of the uniform field, Φ does not depend on the actual paths followed by electrons as long as the area S enclosed by the paths does not change. Under the gradient field, on the other hand, Φ depends on the paths even when B and S are identical. As shown in Fig. 6, Φ can be nearly zero when the enclosed region contains both positive and negative magnetic fields.

The difference in the temperature dependence of B_c between the two cases displayed in Fig. 5 is considered to be the manifestation of the difference in the physical situation mentioned above. As the temperature decreases, the phase-coherent area becomes larger, leading to the decrease in B_c under the uniform field. In comparison, the increase in the phase-coherent area affects B_c less efficiently under the gradient field, since the flux in the newly added area may act

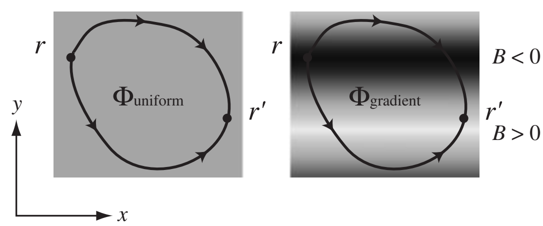

Fig. 6. Schematic illustrations of magnetic flux Φ enclosed by two quantum interfering paths under uniform and gradient magnetic fields.

to partially cancel the flux in the original area, or in some cases, flux enclosed in the newly added area is small due to the flux cancellation within the area. The experimental results for sample #2 corroborate the above model. The behavior of sample #1 is less clear. We attribute this to a difference in the deviation from perfect symmetry. Lithographical misalignment of the cobalt strip from the exact center line of the 2DEG channel gives rise to a deviation from the ideal situation of a gradient field with a vanishing average. For a certain amount of misalignment, the effect is grater for the narrower sample (#1).[18]

The difference in the amplitude ΔG of UCF at low temperatures where ΔG is limited by ℓ_ϕ reflects the difference in their symmetry, namely presence or absence of flux cancellation effect. It is known that the amplitude depends on the universality class of the system. The system under uniform magnetic field belongs to the unitary class, where the amplitude of the conductance fluctuations is smaller than that for the zero magnetic field (orthogonal), since the contribution of the cooperon propagator is suppressed in a diagrammatic description.[11,12] For the gradient magnetic field, on the other hand, the contribution from the cooperon is partially restored due to the flux cancellation effect. This makes the fluctuation amplitude larger, consistent with the observation in Fig. 3.

In conclusion, we have reported that the UCF under the gradient magnetic field exhibits behaviors different from those under the uniform magnetic field. We attribute the difference to the partial flux cancellation under the gradient field.

Acknowldgment

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18) Misalignment of the cobalt strip from the center line of the 2DEG narrow channel is unavoidable and inevitably results in non-vanishing average of the gradient field. If we assume misalignment of 0.1 μm, the averaged value of the field profile in Fig. 1(b) is 2.4 mT for the narrower sample (#1) and 0.9 mT for the wider sample (#2).