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Interference Effects in Nonplanar Wires with a Two-Dimensional Electron Gas

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We have studied the universal conductance fluctuations (UCF) due to quantum interface in a two-dimensional electron gas (2DEG) grown on the substrates with pre-patterned, sub-micron wires. The dependence of UCF on the angle between the direction of the magnetic field and the substrate has been investigated. We found, that magnetoresistance traces for different angles are completely uncorrelated. A non-planar character of electron motion is responsible for these angular conductance fluctuations. We compared the experimental results with a simple geometrical model.

The interference of electron waves in metallic samples with size comparable to the phase coherence length is responsible for conductance fluctuations, with amplitude close to the universal value e^2/h [1]. Such fluctuations have been observed as a function of magnetic field [2], the Fermi energy [3] and configuration of impurities [4]. Magnetic field introduces the phase shift between typical closed interference paths due to the Aharonov-Bohm effect. Therefore, the characteristic fluctuation period B_c, the correlation field, is equal to

$$B_c = \Phi_0/L_\varphi^2, \tag{1}$$

where $\Phi_0 = hc/e$ is the flux quantum, L_φ is the phase coherence length, for samples with size larger than L_φ [1]. For a strictly two-dimensional electronic system the correlation field is determined by the normal component of the magnetic field to the planes with two-dimensional electron gas (2DEG) $B_c = B\sin\phi$, where ϕ is the angle between direction of the magnetic field and the substrate [5].

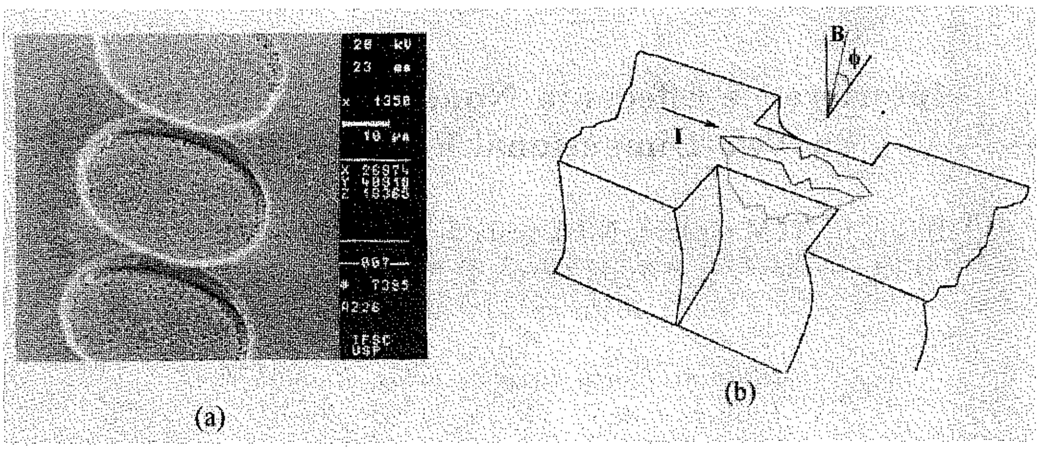

Figure 1. (a) A plane view scanning micrograph of nonplanar wires. (b) Schematic diagram of the sample and electron closed trajectories which contribute to the universal conductance fluctuations.

Recently 2DEG has been grown on nonplanar substrates [6,7]. Since the 2DEG is sensitive only to the normal component of B, electrons in such structures move in a spatially inhomogeneous or random magnetic field. Weak localization effects and UCF have been studied in "dimpled" 2DEG [7], where characteristic magnetic field in parallel external B was found to be governed by the second order corrections to the flux through the closed electron trajectories. In the present work we studied UCF in nonplanar wires with 2DEG. Such a system allows to apply a simple geometrical model to determine the correlation magnetic field and correlation angle. However, when we compared this model to experimental results, we found that the value of coherence length determined by this method is several times larger than that obtained from Eg.(1).

Samples were fabricated by MBE overgrowth of GaAs and AlGaAs materials on pre-patterned GaAs substrate. Pre-patterning consists of wires produced by electron beam lithography at the center of a conventional Hall bar. After selective deep wet etching, three wires with a trapezoidal cross section (diameter 0.5–1 μm and length 10 μm) were created (Fig.1). 2DEG in the plane between wires (circles in Fig.1a) has been eliminated by microlaser local etching. Thus, the current passes only through the planar part and facets of the wires (Fig.1b). Magnetoresistance at 50 mK was measured in magnetic field up to 15 T, for different angles ϕ between the field and the vertical to substrate plane using an in situ rotation of the sample. Fig.2 (a) shows the magnetoresistance fluctuations for different angels ϕ in the magnetic field ranging from 0 to 1.6 T at 50 mK. The curves are shifted for clarity. We can see, that when the external

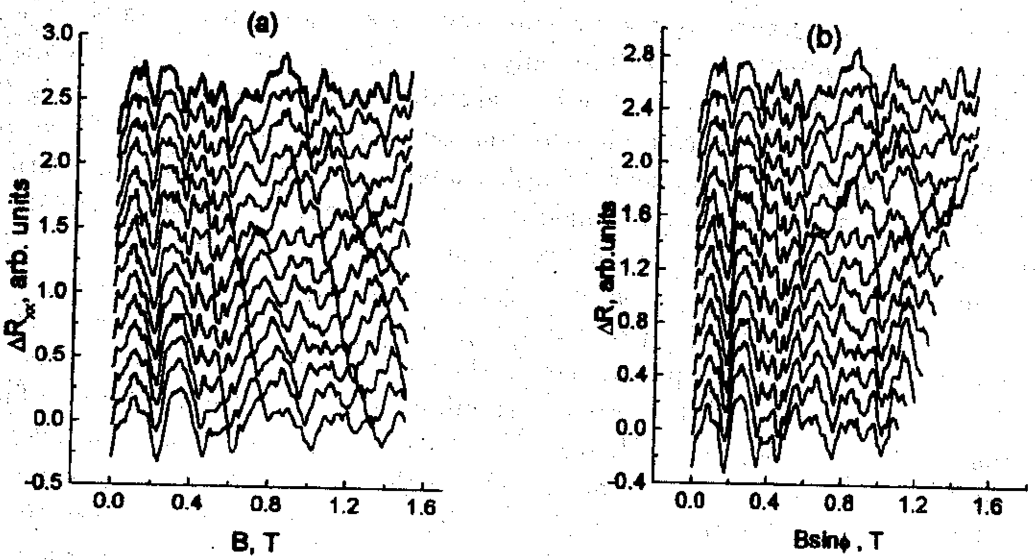

Figure 2. Magnetoresistance of the nonplanar wires as a function of B (a), and component perpendicular to the substrate (b), for different angles between the applied magnetic field and normal to the substrate (top – 90°, bottom – 45°), $T = 50$ mK. The curves are offset for clarity.

field is tilted away from the normal to substrate several fluctuations are shifted towards a higher magnetic field, following the $(\sin\phi)^{-1}$ law as expected. Fig.2 b presents the magnetoresistance as a function of magnetic field component perpendicular to the substrate showing that the curves for the angles equal to 90° and 45° are only weakly correlated. It is not possible to reproduce the 90° fluctuations pattern using the scaling B by any factor. The magnetoresistance has been measured several times under the same experimental conditions to check the reproducibility the measurements from 90° to 0° range. We found that the cross-correlation for traces (90°) under the same conditions (reproducibility) is 96%. We have also calculated the correlation magnetic field as a function of angle ϕ. We found that in the angles range $90° - 45°$ B_c scales as $(\sin\phi)^{-1}$ suggesting that a decrease in the correlation between the curves obtained for different angles are not connected with the differences in scale of B axes. For $\phi > 45°$, B_c increases more slowly than $(\sin\phi)^{-1}$. In this case we have different signs of the magnetic field at both sides of the wires facets. We consider the situation when the magnetic field changes the sign in the end of this paper. Because the fluctuation pattern is changed with B-tilting, we can measure the magnetoresistance fluctuations as a function of ϕ at fixed normal component of magnetic field $B_\perp$. Fig.3a shows such fluctuations for 3 different values of $B_\perp$. We see the angular fluctuations in resistance with approximately the same amplitude as the magnetoresistance fluctuations. Because only few oscillations are seen in this angle range, we should average fluctuations for all values of the magnetic field. Fig.3b shows the results of this averaging-correlation function between the trace for 90° and magnetoresistance traces for other angles. Similarly to the correlation field B_c, we define a correlation angle ϕ_c as the value at which the correlation function falls down by a factor of two. From Fig.3b we obtain $\phi_c \approx 75°$. To explain the change in correlation of magnetoresistance curve in tilted magnetic field we consider a simple geometric model shown in Fig.1b. The closed interference paths are lying on the planar part of the wire and facets; thus the magnetic field and flux enclosed by these path are inhomogeneous. Total magnetic flux through the closed loop is $BS(1 + S_f/S)$, where $S = L_\varphi^2$, S_f is the area covered by coherent trajectories on the facets. The angle between facets and substrate is equal approximately to $45° - 60°$. As the external magnetic field is tilted away from the normal, the flux through the planar area increases, while the flux through the facets, on the contrary, decreases. The difference between these two fluxes of the order of Φ_0 is necessary to produce a fluctuation of conductance of the order of e^2/h, or reduce the correlation between two magnetoresistance curves. This gives $(S_f/L_\varphi^2)\sin(\phi_c - 45°) - \sin\phi_c \approx 1$ For $\phi_c = 75°$ we found, that $S_f/L_\varphi^2 \approx 2$. This is impossible because all trajectories are coherent, and $S_f < L_\varphi^2$. In this case we should suggest that trajectories on the facets from both side of wires contribute to the interference, and therefore $2S_f/L_\varphi^2 \approx 2$. From the amplitude of the universal conductance fluctuations we found that $L_\varphi \approx 1$ μm. It is somewhat smaller than $L_\varphi \approx 0.45$ μm deduced from the value of the correlation magnetic field $B_c = \alpha\Phi_0/L_\varphi^2$ for $\alpha = 1$. The coefficient α is probably less than unity for $L_\varphi < L_T$, where L_T is the thermal length. Thus, the area S_f should be less than 1 μm^2, because the total area $WL_\varphi + 2S_t = L_\varphi^2$, where W is the width of the top part of wire, and also $WL_\varphi \ll S_f$. From the scanning electron microscope picture of the wires we determine $W \approx 0.5 - 1$ μm. This gives $L_\varphi = 1.25 - 2.5$ μm, which is still larger than the value obtained from UCF amplitude and correlation field; however, we should take into account the approximate character of our estimation. Another discrepancy is that in Fig.2a one sees that a number of fluctuations move to higher fields as $(\sin\phi)^{-1}$. This means that the trajectories mainly contribute from the top part of the wire; therefore $WL_\varphi > S_f$. We do not know to resolve this discrepancy. Further theoretical works are needed to calculate the angular dependence of UCF in wires with nonplanar 2DEG.

In near parallel magnetic fields we also observe UCF caused by the flux through the electron trajectories lying in the facets. Naively, this flux should

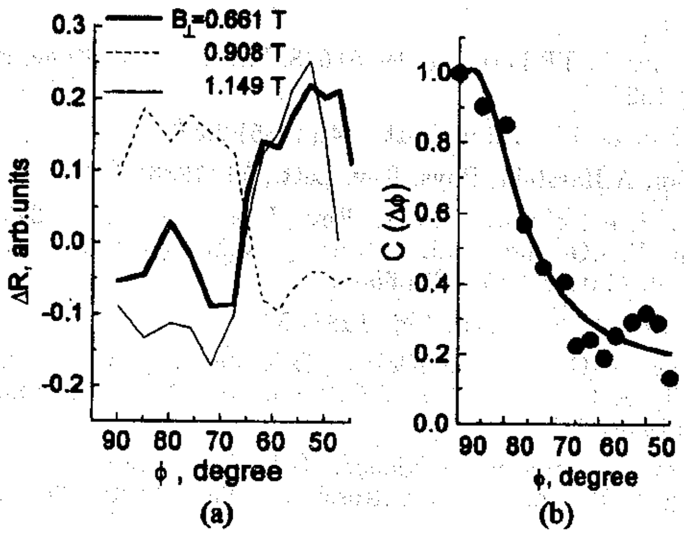

Figure 3. (a) Resistance fluctuations as a function of angle ϕ for three different magnetic fields. (b) Normalized correlation function of the resistance fluctuations for $\phi = 90°$ and for other angles.

be cancelled due to the different signs of magnetic field on the different facets. However, some trajectories are not coherent, therefore we should consider closed loops on the different facets separately. In this case the correlation magnetic field should be the projection of B_c on the perpendicular field and $B_c^{||} \approx B_c^{\perp}/\sin 45° \simeq 1.4B_c^{\perp}$. In the experiment we have found $B_c^{||} \approx 3B_c^{\perp}$. This means that the trajectories on different wires facets are coherent and we should take into account the flux cancellation effect. To estimate the correlation field in parallel external magnetic field we apply the random walk model considered in [7] for the dimpled surface. In this model electron travels randomly from one side wire to another due to impurity scattering and feels a random effective magnetic field. The second order corrections to the flux should be taken into account [7], which gives $B_c^{||}/B_c^{\perp} = L_\varphi/l$ where l is the correlation length of the "random" magnetic field. In our case l is of the order of electron mean free path due to the impurity scattering $\sim 0.3\ \mu$m. For the value of $L_\varphi = 1-2\ \mu$m, this gives $B_c^{||}/B_c^{\perp} = 3.3-6.5$ which is in satisfactory agreement with experiment.

Acknowledgements

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