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QUANTUM CORRECTIONS TO A CONDUCTANCE OF AlGaAs/GaAs-BASED QUANTUM QUASIBALLISTIC WIRES

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Quantum conductance corrections (QCC) due to weak localization and interaction effects of quantum quasiballistic wires have been investigated for the first time. At temperatures in the range $2\,\text{K} < T < 12\,\text{K}$ a crossover of these corrections from one-dimensional behavior to zero-dimensional one have been observed. It is shown that phase coherence length in the wires studied is less than length $L_T = (\hbar D/kT)^{1/2}$ at all temperatures. It is found that the conventional theory of QCC describes correctly the experimental temperature dependence of QCC but gives much lower value than the experimental one.

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Quantum interference effects in wires of AlGaAs/GaAs heterostructures such as Aharonov – Bohm effect, universal conductance fluctuations, weak localization effect have been the most interesting of study in physics of low-dimensional systems for a decade or so [1, 2]. Investigations of the quantum corrections to the conductance of wires has a significant place in this field of research. In [3 – 6] it has been shown that the temperature dependence of a conductance G and the behavior of a magnetoconductance of the wires are in good consistency with the theoretical predictions of weak localization and interaction effects in the one-dimensional (1D) with the boundary scattering effects taken into account [6]. However, all the previous works have been concentrated on the investigation of the quantum conductance corrections (QCC) of wires in quasiclassical diffusive regime, in which the mean free path l is much less than the length (L) of the wire and the width (W) of the wire is much larger than the electron wave length l. It is also well known that, in the other limit of $l \gg L$, and $W \sim \lambda$ (i.e. quantum ballistic regime) in the absence of diffusive scattering from the wire boundaries, the effects of weak localization and interaction do not occur, but instead a quantized conductance is manifested [1]. However, very often one also encounters a situation where l is comparable to or slightly larger than L and some diffusive boundary scattering occur at the same time (i.e. quasiballistic regime). All the quasiballistic and ballistic interferometers operate under such a condition [7 – 9]. To our knowledge, no experimental studies QCC of the wires in this regime have been reported. Thus, it will be interesting to examine whether the characteristics of QCC in the quasiballistic regime are similar to those in the diffusive or ballistic regime. In this study we report, for the first time, the temperature dependence of the conductance of the quantum quasiballistic wires under conditions of $l \geq L \gg W \sim \lambda$ and boundary scattering. We have observed clean quantum correction effects to the conductance of the wires as well as the one-dimension-to-zero-dimension (0D) crossover of the corrections. We also show that phase coherence length L_ϕ in the structures studied is less than $L_T = (\hbar D/kT)^{1/2}$.

In this study measurement were taken for 4 samples. The samples had the geometry of a Aharonov – Bonm-type interferometer with the lithographic width of the wire of 0.4 μm as shown in the inset of Fig.1. The samples were fabricated by means of electron lithography and plasma etching on the basis of the high mobility two-dimensional electron gas formed in ALGaAs/GaAs heterostructures with the electron mobility and the carrier concentration of $\mu = 4 \cdot 10^5$ cm^2/Vs, $N_S = 2 \cdot 10^{11}$ cm^{-2} and $l = 2.8\,\mu$m, respectively. The ring was located at the central of Hall bridge with the wire width of 50 μm and spacing of 100 μm between potentiometric contacts. The total wire length taking into account the size of depletion region was approximately $L \approx 2\,\mu$m and effective wire width was about $W \approx 50 - 100$ nm. The wire width W was determined from the value of magnetic field corresponding to the suppression of Aharonov – Bohm oscillations where magnetic length L_H becomes less than $W/2$. Data were taken in the temperature range of 0.2 K $< T <$ 20 K in magnetic fields up to 9 T applied perpendicular to the plane of a substrate. The wire resistance was taken using the conventional phase sensitive detection technique with the low bias current of $1 \div 10$ nA to avoid heating.

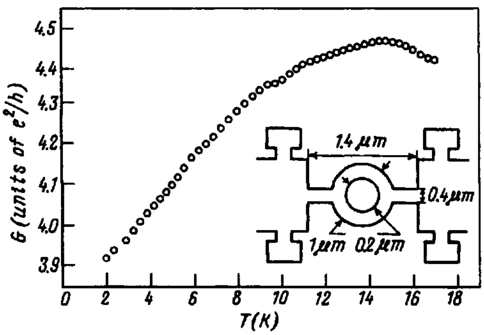

Fig.1. The typical temperature dependence of conductance G for a sample. Inset: the sample geometry

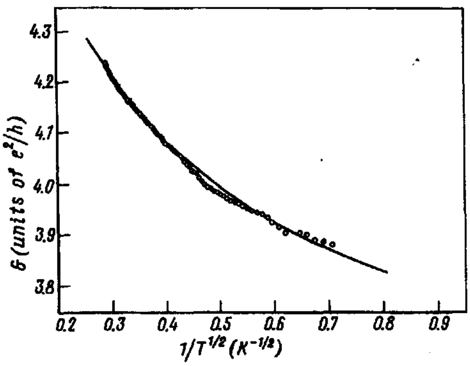

Fig.2. A replot of the conductance G in Fig.1 as a function of $T^{-1/2}$. The solid line is a fit to Eq. (1) with $D = 4 \cdot 10^3$cm^2/Vs, $g_{1D} = 7.8$ and $G_o = 5.34 \cdot e^2/h$

Fig.1 shows the typical temperature dependence of the conductance of wire in the temperature range of $2 \div 17$ K. It the figure we can identify two temperature regions. In the first one for $T > 15$ K the conductance increases as the temperature decreases, which is due to the conventional phonon scatterings. But, in the lower temperature region below $T < 15$ K the conductance G decreases as the T decreases. In this study we concentrate on the behavior in the latter temperature region. We believe that the decrease of the conductance in the temperature region was caused by a corrections to G due to the weak localization effect. According to the theoretical predictions the quantum correction to G due to the localization in 1D has the temperature dependence as $\Delta G \propto T^{-1/2}$ for min $\{L_\phi, L_T\} \gg W$ and max$\{L_\phi, L_T\} \ll L$. Fig.2 demonstrate the typical temperature dependence of ΔG as function of $T^{-1/2}$ in the temperature range of 2 K $< T <$ 13 K. It is seen that for $T > 6$ K ΔG well follows the $T^{-1/2}$ temperature dependence but the data begin to deviate slightly from the dependence for $T < 6$ K, showing a less sensitivity to the temperature change. It implies that under these conditions max$\{L_\phi, L_T\}$ becomes comparable with the wire length of the wire L and 1D-to-2D dimensional crossover takes place at around 6 K. At the present no theory is available for a quantitative description for the temperature dependence of ΔG in the quasiballistic regime ($l \geq L$) as in a our samples. In a our samples we have one more factor of complications. It stems from the fact that our samples have a double connected geometry. However, still we can analyze the data of our samples in terms of a 1D singly connected wire, since the data in Figs. 1 and 2 were taken in zero magnetic field. Also the behavior of ΔG in Fig.2 is very similar to the one from the quasiclassical disordered wires so that one can try to fit the data to the theory which is valid for the case of $\lambda \ll l \ll W \ll L$ in a singly connected wire. Including the interaction effect, theory gives the following expression [4, 10] for ΔG for all the temperatures including $T = 0$:

$$\Delta G = -g_{1D}\frac{e^2}{\sqrt{2}\pi^2\hbar}\left[\frac{2}{\pi L_T} + \frac{1.79}{L}\right]^{-1} - \frac{e^2}{\pi\hbar}\left[\mathrm{cth}\left(\frac{L}{L_\phi}\right) - \frac{L_\phi}{L}\right], \qquad (1)$$

where $g_{1\mathrm{D}}$ is the constant depending on the electron-electron interaction in 1D wires. As can be seen in Eq.(1) value of ΔG is determined by L_ϕ (the weak localization term), L_T (the interaction term), and the length of the wire L. Thus, the information on the phase coherence length L_ϕ is essential to examine the behavior of the observed ΔG in terms of Eq. (1). However, the determination of L_ϕ by the usual negative magnetoresistance (MR) was impossible for our samples since no negative MR was observed in our quasiballistic samples for $T > 1.6$ K. Moreover, the theory of the MR was developed only for 1D wire systems in the quasiclassical diffusion regime where the conditions of $\lambda \ll W$ and $l \ll L$ were satisfied [1]. We determined L_ϕ in the wire portion composing an interferometer in a sample. In Fig.3 the typical MR of the wire whose G are shown in Figs.1 and 2 are presented at different temperatures. At temperatures above 1.6 K, we observe the clear positive MR up to $B = 0.1$ T which remains essentially the same regardless of the temperature change above 1.6 K. This implies that in our samples the MR is governed by the slight diffusive scattering from the boundaries [1]. Also the Aharonov – Bohm oscillations (ABO) are seen in the data which become more prominent as soon the temperature decrease below 2 K. This indicates that the phase-coherence length L_ϕ becomes comparable with the wire length at $T < 2$ K. At the same time, as mentioned above, $\max\{L_\phi, L_T\}$ should be comparable with L at $T < 6$ K since in this temperature range the temperature dependence of ΔG begins to deviate from the $T^{-1/2}$ dependence, indicating that our wires in the temperature range of 2 K $< T <$ 6 K were under the condition of $L_T > L_\phi$. The phase-coherence length L_ϕ can be found from the temperature dependence of ABO. The amplitude of the ABO is proportional to $\exp(-L_P/L_\phi)$ for the case of $L_P > L_\phi$, where L_P is one half of the ring circumstance which can be determined from period of ABO if one assumes $L_\phi = \alpha T^{-1/2}$. The fit in Fig.2 was done with the value of $L_\phi[\mu m] = 0.4\,T^{-1/2}[\mathrm{K}]^{-1/2}$ determined in this way and three fitting parameters of the diffusion coefficient $D = 4{\cdot}10^3\ \mathrm{cm}^2/\mathrm{Vs}$, the constant $g_{1D} = 7.8$ and the conductance value at $T \to \infty$ when the phonon scattering is not taken into account $G_o = 5.34 \cdot \mathrm{e}^2/\mathrm{h}$. The value $D = 4{\cdot}10^3\ \mathrm{cm}^2/\mathrm{Vs}$ means that mean free path in wire l_w is 2.2 μm. It is sugnificantly larger than the estimation of l_w from conductance value (l_w 0.5 μm). The value of $g_{1\mathrm{D}} = 7.8$ turns out to be rather lager comparing to the approximate value of to unity [1] as observed previously in AlGaAs/GaAs systems. We believe that the discrepancies occurred mainly because we adopted in the fit ordinary theory of QCC developed for dirty quasiclassical wires in the diffusive scattering regime, which thus supposedly had no justification for the application to the ones in the quantum quasiballistic regime. More theoretical study is necessary to describe the quantum conductance corrections behavior in this regime.

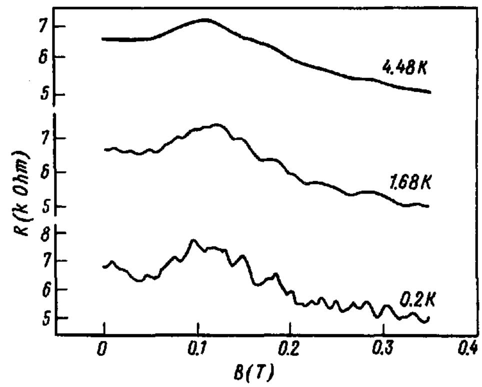

Fig.3. The magnetoresistance of the same wire sample whose G is shown in Figs. 1 and 2 at various temperatures

In summary, we have studied the quantum corrections to the conductance of a AlGaAs/GaAs-based quantum quasiballistic wires. A 1D-to-0D crossover of the corrections has been observed. It is found that the conventional theory of quantum conductance corrections which is supposedly valid for the diffusive regime only also well describes the observed temperature dependence of the conductance corrections in quantum quasiballistic regime, but it gives the value of QCC much less than those measured in experiment.

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