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Nonlocal Effects in Mesoscopic Ballistic Conductors

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As the width and thickness of samples become comparable to or less than the wavelength of electrons, and the sample length approaches less than the mean distance between the scattering centers, the classical concept of the conductance does not work. For example, the apparent low temperature resistance can be negative and depends upon the voltage and current leads combinations and details of the sample geometry. The resistance could be measured even when the voltage leads are away from the classical current path. Alternatively to the impurity scattering, electron reflections at the junctions with the external leads and/or at irregular channel boundary play a significant role in the anomalous resistances observed.

Introduction

Recent experiments in GaAs-AlGaAs submicron structures have revealed a large number of intriguing phenomena. The remarkable features in the mesoscopic regime are based on the nonlocality of the transport properties. Even when voltage probes are set at a point where classically no net current flows, the four-terminal resistances (defined as the voltage difference divided by the current) fluctuate as a function of magnetic fields B or the Fermi energy E_F as far as the measured point is apart from the classical path by less than the phase coherence length L_ϕ or the elastic mean free path l_e.

The resistance can be described in terms of the transmission property of carriers through a barrier as proposed by Landauer [1]. This approach was generalized by Büttiker to treat multi-terminal cases [2,3]. A current flowing through a lead i is described using the probabilities T_{ij} for carriers incident in lead j to be transmitted into lead i as [2]

$$I_i = (e^2/h)\,(N_i V_i - \sum_j T_{ij} V_j)\ , \qquad (1)$$

where N_i and V_i are the number of channels and the potential at lead i, respectively. By setting the current at voltage leads zero, one obtains the resistance formulae for Hall resistance R_H and bend resistance R_B in a symmetrical cross as

$$R_H = (h/e^2)(T_L - T_R)/K\ , \qquad (2)$$
$$R_B = (h/e^2)(T_L T_R - T_F^2)/K\ , \qquad (3)$$
$$K = (T_L+T_R)(2(T_F+T_L+T_R)T_F+T_L^2+T_R^2)\ ,$$

where T_F is the transmission probability for the motion straight on the cross and T_L (T_R) corresponds to the one turning around the junction to the left (right) side-lead. In the following we assume that upon application of magnetic field the Lorentz force favors the left side-lead.

Bend Resistance: R_B

When the size of the cross is less than l_e, electrons prefer going straight on the junction to turning around the bend, i.e.,

$T_F >> T_L$, T_R due to momentum conservation. As a result, one expects that R_B is negative in the ballistic cross [3,4]. In Figs. 1 and 2, we show magnetoresistances in wires with W=0.2∿0.3μm and W≲0.1μm, respectively. The bend resistance was negative in the absence of B, since ballistic electrons enter the facing voltage terminal [4]. In a presence of B, cyclotron orbital motion reduces T_F, leading to a disappearance of the negative resistance via an overshoot at an intermediate B. Comparing Figs. 1 and 2 one can see that the amplitude of the negative R_B grows as W is narrowed.

Hall Resistance: R_H

In two-dimensional (2D) system, R_H increases in proportion to magnetic field until Landau subbands are well-defined. However, Roukes et al. [5] found that an average slope of R_H in ballistic narrow cross remains zero over a wide range of B (quenching of R_H: see Fig. 2) and after R_H appeared it first exceeds and gets back a 2D value resulting in a plateau-like structure in a moderate B where quantized Hall plateau is not resolved yet (last plateau: see Figs. 1 and 2). These anomalies were also enhanced with decreasing W.

The experimental result that the negative R_B was suppressed even in weak B where R_H was still quenched indicates that $T_L \simeq T_R$ was maintained, although T_F was suppressed once B was introduced. This mechanism for distributing the decrement of T_F evenly among two side-probes is known as the rebound (Fig. 3(a)) and scrambling (Fig. 3(b)) effects in a rounded junction [6,7]. A beam collimation in the slow tapered junction plays an important role in working these mechanisms effectively. When B becomes sufficiently strong for the guiding effect (Fig. 3(c)) taking place, all transmission probabilities vanish except the one along the skipping orbit motion. Inserting this into Eqs. (2) and (3) yields $R_H=h/Ne^2$ and $R_B=0$. The number of channels N is independent of B until the channels are magnetically depopulated, i.e., the last plateau occurs in R_H coinciding with the disappearance of the negative resistance in R_B.

Longitudinal Resistance: R_L

The longitudinal resistance R_L increased when magnetic field was applied and a camel back shape appeared with the maximum at B=0.2T and 0.5T for Figs. 1 and 2, respectively. Two types of scattering, junction scattering and diffuse boundary scattering, are supposed to cause this behavior. As

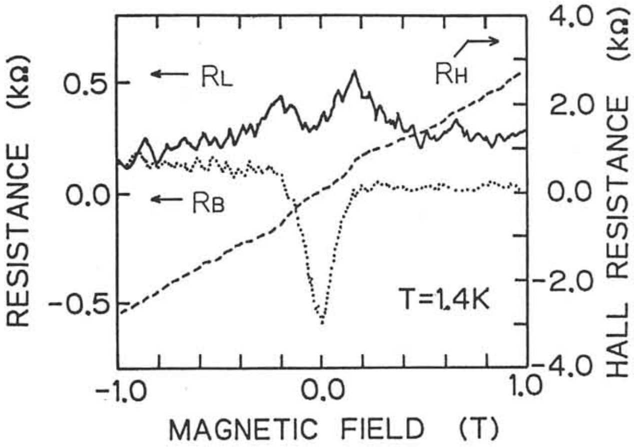

FIG.1 Magnetoresistances in a W=0.2∿0.3μm wire.

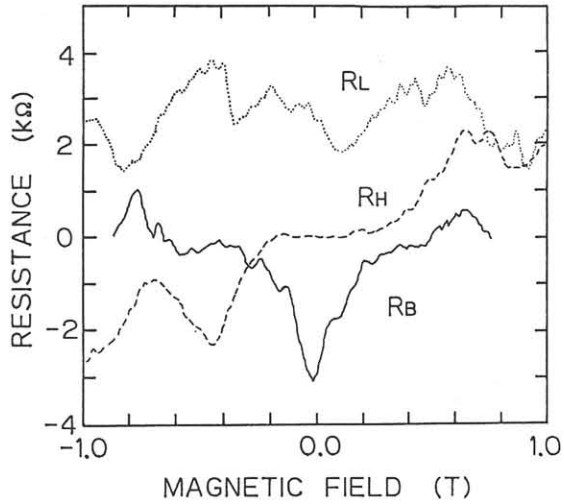

FIG.2 Magnetoresistances in a W≲0.1μm wire.

previously discussed the multiple electron reflections in the rounded junction are crucial. The backward scattering at the rounded corner [6] shown in Figs. 3(a) and 3(b) leads to the increase in R_L until the electron guiding is completed.

The other mechanism was studied by Thornton et al. In low magnetic field electrons travel mainly through the center of the wire. However, when magnetic field is increased electrons move bouncing frequently upon the wire boundary. If the boundary reflections are not completely specular, R_L increases until the cyclotron orbit fits with the channel and electrons no longer interact with the rough surface [8]. Since we measured short (L=1.2μm) wires, we expect that the junction scattering is a dominant mechanism. This is supported by the line up of the overshoot in R_B and the maximum in R_L.

Transfer Resistance

In mesoscopic regime, the electrical conduction is nonlocal, so that, even if voltage leads do not touch the classical current path, voltage differences are observed. The transfer resistance (see Fig. 4) measures the amount of electrons ejected from the left-hand cross and reached the right-hand cross while conserving the momentum-memory. Therefore, the magnitude of the signal at zero field, which corresponds to the negative bend resistance, when the transferred distance dL=0, decreases exponentially with increasing dL as seen in the inset of Fig. 5. In Fig. 5, we show the decay length, ballistic mean free path L_B, in wires with various widths. The value L_B was always significantly less than l_e, indicating that electrons suffer more scatterings than expected from the mobility. The transfer resistance is affected not only by the backward scattering, which mainly determines the mobility, but also by the forward scattering. The former prevents electrons from arriving at the voltage leads, whereas the latter equalizes the transmission probabilities to each voltage lead as shown in Fig. 4. The decay becomes rapid as the width is less than the mean distance between the scattering events, since the diffuse boundary scattering also contributes to the momentum-memory breaking.

Recently, Beenakker and van Houten have suggested that chaotic fluctuations [7] may appear in the transfer resistance even when the quantum interference effect is not taken into account. This fluctuations come from the chaotic scrambling of the trajectories after multiple reflections in the rounded

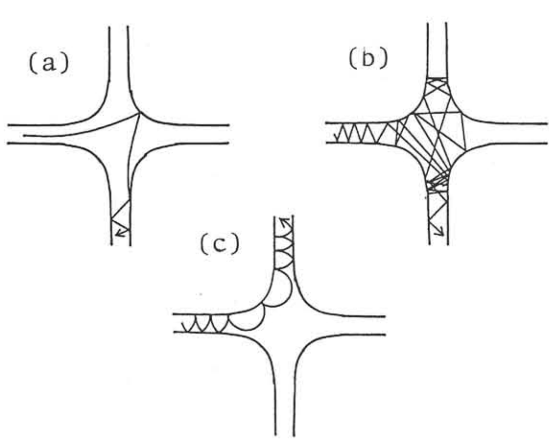

FIG.3 Electron trajectories in a rounded cross: (a) rebound, (b) scrambling and (c) guiding effects.

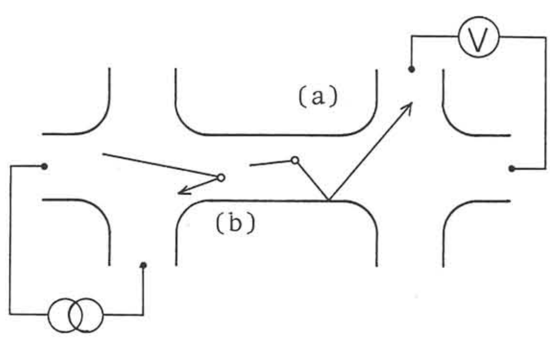

FIG.4 Both (a) forward and (b) backward scatterings reduce the magnitude of the zero-field signal in the transfer resistance. The open circles represent elastic scatterers.

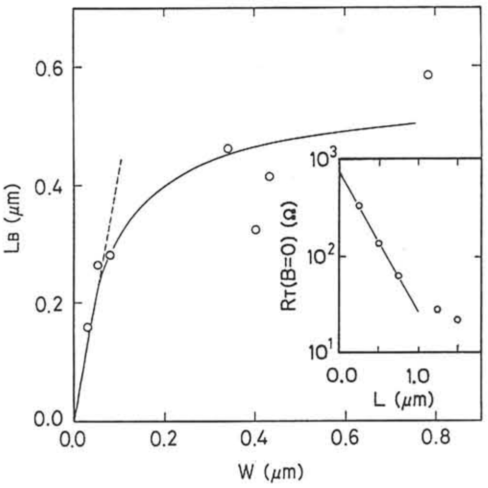

FIG.5 Ballistic mean free path L_B in narrow wires. The strong suppression of L_B at W< 0.2μm is due to diffuse bondary scattering. Inset: Spatial decay of the transfer resistance. The lines are guide to the eye.

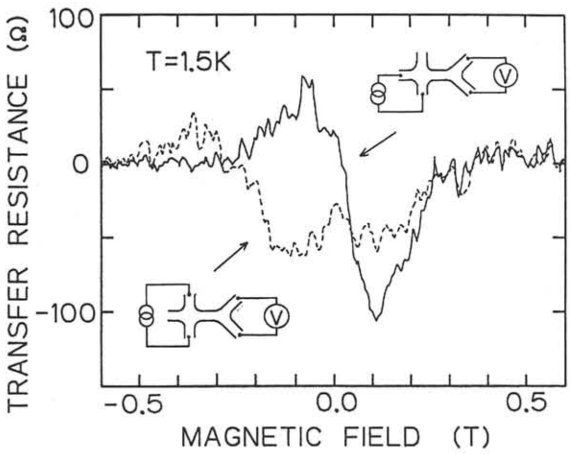

FIG.6 Fluctuations in the transfer resistance. The inset illustrates the geometry of the 5-probe electron waveguide.

junction and a narrow wire focusing effect which converts the chaotic injection angle into a visible quantity in the resistance. In Fig. 6, we show an example of the experimental results. Although the resistance irregularly fluctuated as B is varied, we could not conclude, at present time, whether the fluctuations are related to the classical chaos or to the quantum interference. The paths relevant to the classical chaotic scattering require long path lengths and many boundary reflections so that the momentum-memory may likely be lost during the traversal, and the observation in the actual measurement may be difficult.

Summary

We have shown that the four-terminal nature of the resistance measurement plays an essential role in mesoscopic ballistic structures, where the electron transport is highly nonlocal. The negative resistance clearly indicates that the resistances in mesoscopic regime is not simply related to the energy dissipation in the conductor. As the impurity scattering is sparse, the scatterings from the junction to the external leads or the roughness at the channel boundary becomes dominant mechanism for the momentum relaxation. The phase- or momentum-memory is shifted over the whole sample as the location of the boundary is altered by an amount of the Fermi wavelength, which, consequently, results in a modification of the irregular pattern of magnetoresistance, i.e., a new "magnetofinger prints".

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