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Boundary-related scattering processes in quasiballistic narrow wires

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$GaAs/Al_xGa_{1-x}As$ narrow wires in the quasiballistic-transport regime exhibit two scattering times for electrons obtained from Shubnikov–de Haas oscillations of the magnetoresistance at high and low fields. We investigate the boundary magnetic field in the intermediate field ranges, varying the temperature, electron density, and effective conduction width of the wire. By considering the effective conduction width to cyclotron radius ratio at the boundary field, we obtain evidence for a size effect in the quasiballistic-transport regime of narrow wires.

I. INTRODUCTION

One-dimensional narrow wires have been obtained in confined two-dimensional electron-gas (2DEG) systems, and low-dimensional transport and ballistic conduction phenomena have been extensively studied in the last several years. In the absence of carrier scattering in the wire, the transport is purely ballistic and can be explained by simple classical transport models, such as the billiard model explaining the quenching of the Hall effect in quantum wires.[1] On the other hand, if there are many scattering centers in the wire, this simple model for the electron transport is no longer applicable and one must then take into account quantum interference effects between coherent propagating electron waves. Even if the number of scattering centers are low, the ballistic nature of the transport should be captured in the model.

By analyzing the amplitude of Shubnikov–de Haas (SdH) oscillations, one can obtain the carrier concentration n and the single-particle relaxation time τ_s. Although the SdH oscillations in low-temperature magnetoresistance have been studied widely in two-dimensional samples, there is no detailed analysis of the oscillation amplitudes in quantum wires. On the other hand, boundary scattering in narrow wires is very important in the ballistic scattering regime because of the diffusive nature of electron transport as indicated by the appearance of an anomalous peak in the low-field magnetoresistance.[2]

In this paper, we discuss scattering processes in a narrow wire by means of an amplitude analysis of the SdH oscillations. Some modification of electron trajectories due to the presence of side-wall edges in these wires is expected which depends on the magnetic-field strength. In a previous paper,[3] we found that even in a diffusive wire the interference area for aperiodic conductance fluctuations changes gradually as the field increases. Furthermore, two single-particle relaxation times, τ_{sh} and τ_{sl}—in high and low magnetic fields, respectively—were observed in such a quasiballistic wire when the ballistic region was approached.[4] Therefore it is very important to elucidate the relation between electron trajectories and edge channel formation in quasiballistic narrow wires.[5]

II. EXPERIMENTS

Narrow-wire samples used in this work were obtained from two different wafers, both having 2DEG between undoped GaAs and undoped $Al_xGa_{1-x}As$ spacer layers followed by the Si-doped $Al_xGa_{1-x}As$ barrier layer. The two wafers had different dopant concentrations in the $Al_xGa_{1-x}As$ layer (samples Nos. 3 and 6, 2×10^{18} cm^{-3}; samples Nos. 1, 2, 4, and 5, 1×10^{18} cm^{-3}). The Hall-bar-type wires were defined by electron-beam lithography and a dry-etching technique. Ohmic contacts to the wire were provided by formation of Au-Ge alloyed electrodes. Since the side-wall depletions are not negligible after dry etching, the effective conduction width of the wire should be smaller than the lithographic width which was determined by optical-microscopy and scanning-electron-microscopy observations. We estimate it to be 0.4 μm totally in the dark condition by the scaling relation between the lithographic width and the resistances in all samples.

TABLE I. Wire-sample characteristics.

Sample	No. 1	No. 2	No. 3	No. 4	No. 5
n_s (10^{11} cm^{-2})	4.0	6.9	4.8	4.1	3.3
l_{MFP} (μm)	0.62	0.89	0.87	1.36	1.05
τ_t (ps)	2.3	2.5	3.3	4.5	4.3
τ_{sl} (ps)	$\cdots$	0.4	0.39	0.42	0.26
τ_{sh} (ps)	0.22	0.19	0.182	0.162	0.12
B_c^* (T)	$\cdots$	0.9	1.21	1.64	2.7
W_e (μm)	1.0	0.83	0.53	0.41	0.20
r_c^* (μm)	$\cdots$	0.125	0.094	0.064	0.035

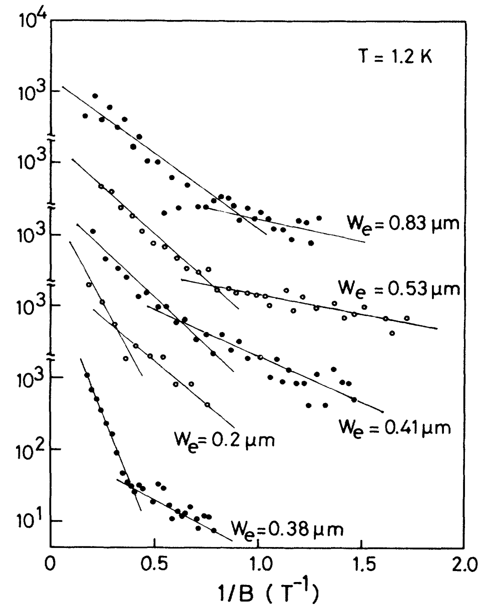

FIG. 1. Amplitude of SdH oscillations as a function of the inverse magnetic field for five narrow wires (samples Nos. 2, 3, 4, 5, and 6).

The length between the voltage probes is about 2 μm in all these wires. The sample characteristics and the main parameters used in this study are shown in Table I. As for the $W_e = 0.38$-μm sample (No. 6) shown in Fig. 1, the parameters have already been reported in Ref. 4. The carrier concentration n was estimated by the Hall coefficient and the period of the SdH oscillations, and all parameters in the table were taken at 1.2 K. l_{MFP} stands for the mean free path of the wire. The magnetoresistance measurements were made with magnetic fields up to 8 T by using a ^{3}He cooling system.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

SdH oscillations due to Landau quantization have been observed in the low-temperature magnetoresistance in all wire samples. Figure 1 shows amplitudes of the oscillations in five narrow wires. The one with the lowest amplitude in the figure is a previously published result[4] obtained in wire sample No. 6. The amplitude ΔR is roughly expressed by the relation[6]

$$\Delta R \propto \exp(-\pi/\omega_c \tau_f) , \tag{1}$$

where ω_c is the cyclotron angular frequency and $1/\tau_f = 1/\tau_s + 1/\tau_T$. Here, τ_T is the temperature broadening equivalent time and is negligible below about 10 K.[4] The slope of the amplitude corresponds to the exponential damping factor in relation (1). The amplitude has two slopes in this field range. We can find the boundary field B_c^* where the slope of the amplitude is switched by changing the field; however, such a boundary field was not found in the widest wire (sample No. 1). Therefore only τ_{sh} was determined from the slope, as listed in Table I.

The B_c^* seems to shift to high fields as the effective conduction width W_e becomes narrow. Thus, a certain scaling between the corresponding cyclotron radius r_c ($r_c = \hbar k_F / e B_c^*$) and the width W_e can be considered. If W_e does not strongly depend on the change of carrier concentration n, B_c^* is proportional to $n^{1/2}$ from the relation

$$W_e / r_c = W_e B_c^* e / \hbar k_F = \text{const} \tag{2}$$

where $k_F = (2\pi n)^{1/2}$. B_c^* vs $n^{1/2}$ is plotted in Fig. 2, allowing various crossover fields, B_c^* to be obtained by using persistent photoconductivity. B_c^* of each wire are almost fitted to straight dotted lines passing through the origin, as suggested by the above relation. It implies that there is a scaling which is given by the ratio of B_c^* to the field B_c at which the cyclotron radius is just equal to the width W_e. In Fig. 3, the values B_c^* in the wires are plotted against the corresponding B_c. One can find the linear dependence between B_c^* and B_c, which is expressed by the scaling relation $B_c^* / B_c = 6$. This ratio is three times larger than the

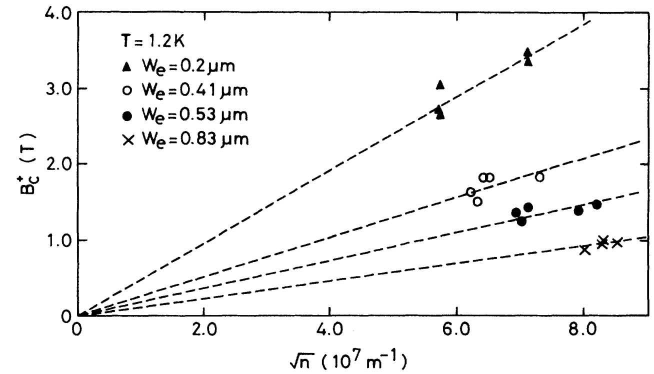

FIG. 2. The $n^{1/2}$ dependence for four different wires (samples Nos. 2, 3,4, and 5).

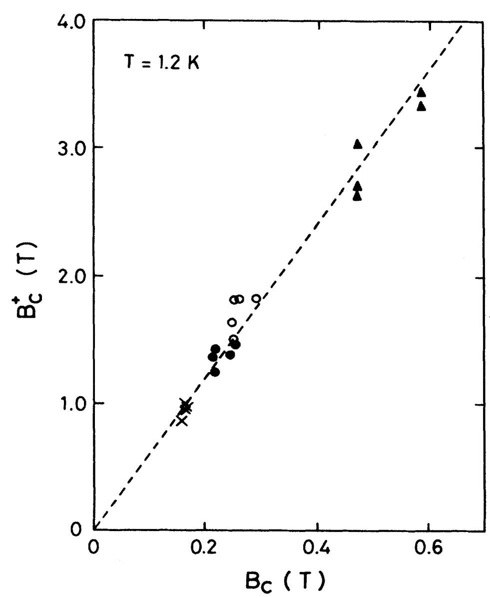

FIG. 3. B_c^* vs B_c for the four wires (samples Nos. 2, 3, 4, and 5) in Fig. 2. The dashed line is a guide for the eyes. The carrier concentration was controlled by the illuminations.

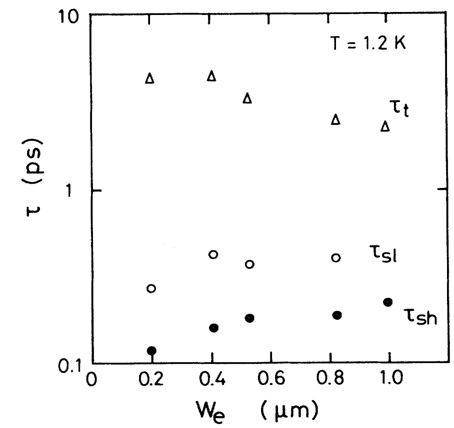

FIG. 4. Transport scattering time and two kinds of single-particle relaxation times as a function of the effective conduction width. The relaxation times were determined from the slope of the amplitude in Fig. 1 by means of Eq. (1).

criterion of edge-channel formation for ballistic narrow wires.[7] It is noted here that there are no scatterers in ballistic wires, which is different from the present case. Therefore this enhancement factor of 3 must come from the existence of few scatterers in quasiballistic narrow wires.

The single-particle relaxation time τ_s comes from quantum-level broadening and can be derived from the amplitude analysis of SdH oscillations. The transport scattering time τ_t comes from the electric-field response of the Boltzmann equation and is determined by conductivity measurements. Although the relaxation time τ_s is sensitive to all scattering events, the scattering time τ_t is sensitive only to large-angle scattering. The large difference between τ_s and τ_t has been pointed out in the theoretical study of the screening effect in the GaAs 2DEG system by Das Sarma and Stern.[8] As shown in Fig. 1, the wire has two relaxation times, τ_{sh} and τ_{sl}, in high and low magnetic fields, respectively. τ_t, τ_{sh}, and τ_{sl} are plotted together against the width in Fig. 4. τ_t is 1 or 2 orders of magnitude larger than τ_s and the difference agrees with theory.[8] Since τ_t is almost constant or slightly increases with narrowing width, the mobility of wire samples Nos. 1, 2, 4, and 5 is not so sensitive to the width narrowing. The high-field relaxation time τ_{sh} seems to be shorter as the width becomes narrower. Then the width narrowing has an effect only on τ_s. As for the origin of the decrease in τ_s, boundary potential scatterings at the edge channels can be considered. Since the change in trajectory of electron wave propagations is expected at B_c^*, the scattering rate will increase at higher fields.

Here, we discuss τ_s in comparison with the 2DEG case. The conduction width of a 2DEG is very broad so that quantum interference between the boundary conduction paths is ignored completely. When the central region of a 2DEG conductor is perfectly localized, adiabatic edge channels along the sidewall will be realized in the limit of high magnetic field. Since the one-particle relaxation time takes a finite value determined by the half-width of the Landau band, the value of τ_s is strongly related to the density of states in the magnetic field. The change of τ_s in high field indicates that a one-dimensional transport effect, or edge-channel effect appears in the density of states under the field. The decrease of τ_s at the high field in Fig. 4 is attributed to successive small-angle scattering with sidewalls in the edge channels. Since τ_s seems to be shorter for the narrow-width samples, such small-angle scatterings are expected to be stronger as the width decreases. As for a large difference between τ_t and τ_s in the narrow-width samples, unscreened bare potentials at the boundary may enhance small-angle scatterings because there is no spacer at the sidewalls. It is also considered that since our wires have nearly the same side-wall area, such boundary potential scatterings are more frequent as the field B_c^* increases. Therefore it is found that the Landau bandwidth in quasiballistic wires becomes broader than that in the 2DEG system even at high field. In fact, we have already reported a small deviation from the quantized Hall effect value in the plateau of Hall resistance of quasiballistic narrow wire.[4] This indicates that observation of adiabatic transport is presumably difficult in quasiballistic narrow wires as compared to the 2DEG system. Detailed calculation of the Hall effect in ballistic quantum wires has been studied by computer simulations and a similar deviation of the plateau value has been reported in this study.[9] Therefore, field-induced localization in the strong-field limit of quantum wires would be important, and should be clarified in further transport studies of quasiballistic quantum wires.

IV. CONCLUSION

We have observed a size effect for the change in trajectory of electron wave propagations in quasiballistic narrow wires. In the amplitude analysis of the SdH oscillations, the trajectory change gives different relaxation times with respect to the magnetic-field strength. τ_{sh} at high field is shorter than that at low field and shows a small decrease with the narrowing of the effective conduction width. This shortening of the relaxation time can be understood as due to the enhancement of boundary potential scatterings. We consider that this quasiballistic narrow-wire system, where the cyclotron length is nearly equal to the wire width, is very suitable to study dynamical transport properties in the edge channels of quantum wires.

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