Non-ohmic out-of-plane conductance in a multilayered quantum Hall system

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Abstract

Out-of-plane transport in a GaAs/AlGaAs superlattice in the quantum Hall regime exhibits a strong non-ohmicity. At low temperatures and low current bias, the out-of-plane conductance G_{zz} scales with the sample perimeter. These are signatures of the chiral surface state. At higher temperatures or higher current bias, G_{zz} becomes scaled with the sample area, suggesting a crossover to bulk transport. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: GaAs/AlGaAs superlattice; Non-ohmicity; Quantum Hall effect; Vertical transport

Multilayered quantum Hall systems have recently gained renewed interest by recent theoretical predictions of chiral surface state [1,2]. At the edge of each two-dimensional electron gas (2DEG) layer in the quantum Hall effect (QHE) state, edge channels are formed which are free from backscattering because of their chirality. When interlayer transfer is introduced, the edge states in adjacent 2D planes are coupled to form a 2D conducting channel at the periphery of the sample, called chiral surface state. Druist et al. [3] have found that the out-of-plane conductivity in the QHE regime scales with the sample perimeter at low enough temperatures. At higher temperatures or away from the QHE condition, it scales with the sample area. In this paper, we show that the out-of-plane transport in the QHE regime exhibits prominent nonlinearity [4].

Superlattice samples consisting of 100 units of GaAs(10 nm)/$Al_{0.15}Ga_{0.85}As$(15 nm) were grown by molecular beam epitaxy. Samples for out-of-plane transport experiments were grown on n$^+$ GaAs substrate, and were shaped in square columnar mesas of different cross-sections by photolithography and wet chemical etching. For in-plane transport measurements, identical superlattices were grown on semi-insulating GaAs substrate, and shaped in a standard Hall bar pattern. Magnetotransport measurements was carried out using a dilution refrigerator down to 30 mK in a superconducting solenoid up to 15 T.

The upper panel of Fig. 1 shows the in-plane magnetoresistance and Hall resistance at 30 mK. From these data, we obtain the sheet carrier density $n = 2.3 \times 10^{15}$ m^{-2}/layer and the mobility $\mu = 6300$ cm^2/V s. The lower panel of Fig. 1 shows the out-of-plane magnetoresistance R_{zz} in three samples with different mesa sizes. The R_{zz} curve becomes maximum when the in-plane tranport shows the QHE. The inset of Fig. 1 shows the scaling of the out-of-plane conductance $G_{zz} = 1/R_{zz}$ at $v = 2$ with the mesa perimeter, indicating that the current is carried by the surface channels at 30 mK.

At temperatures above ~ 100 mK, G_{zz} is scaled by the mesa area. Above 100 mK, the measured conductance G_{zz} shows a thermally activated behavior, $G_{zz} \propto \exp(-E_a/k_B T)$ with activation energy $E_a = 0.95 \pm 0.05$ K which is much smaller than $\hbar\omega_c/2 = 4.1$ meV = 48 K. Although some reduction of the activation energy is expected by the presence of a band of extended states at the center of each Landau subband, the band width 4t = 0.12 meV is too small to explain the observed low value of the activation energy. The relevant conduction process is, thus, not the excitation to the extended states at the center of Landau subbands but hopping among the localized states.

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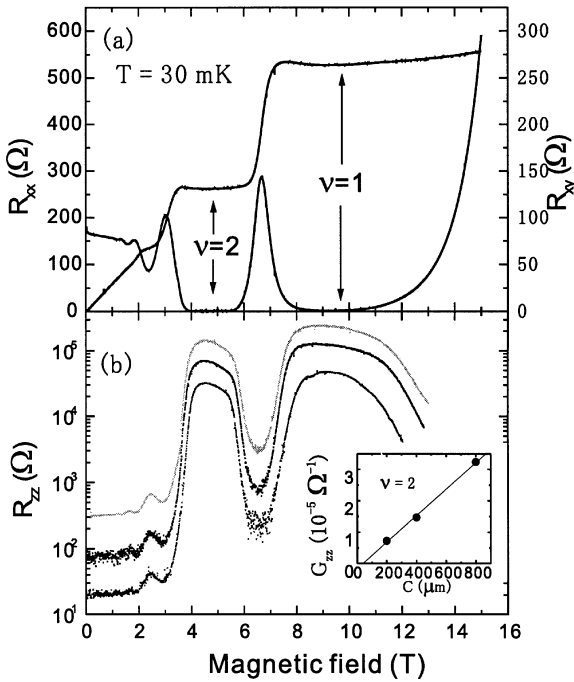
Fig. 1. (a) The in-plane magnetoresistance and Hall resistance exhibiting quantum Hall effect features. (b) The out-of-plane resistance of three mesas with area 50×50, 100×100, and $200 \times 200 \ \mu m^2$. Note that the ordinate is log scale. The inset shows the conductance G_{zz} at $v = 2$ versus the sample perimeter C.

Fig. 2 shows the out-of-plane differential conductance dI/dV at $v = 2$ as a function of the DC bias voltage. The differential conductance curves for three samples are scaled by C/L and by S/L (L is the total thickness of the superlattice). In the low-voltage region, the former set collapses onto a single curve, while the latter set does at higher voltages. The crossover from surface to bulk transport occurs in a fairly narrow voltage range. Similar non-ohmic behavior is observed at $v = 1$.
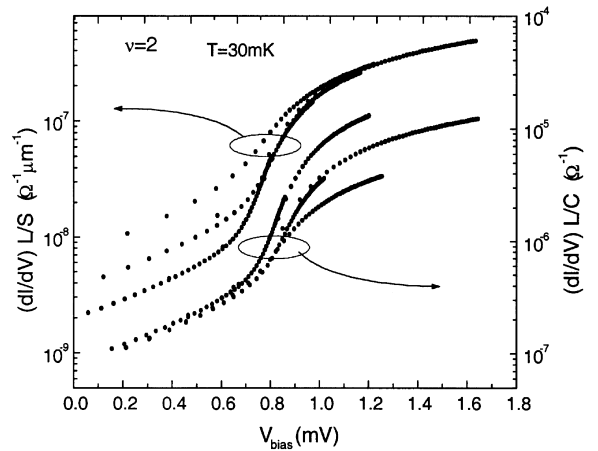

Fig. 2. The voltage dependence of the differential resistance dV/dI at $v = 2$ and $T = 30$ mK.

Beside the strong non-ohmicity in the crossover region, the differential conductance exhibits weaker but substantial voltage dependence on both sides of the crossover. The non-ohmicity on the high-voltage side (bulk transport regime) is attributed to the non-linearity in the hopping process among the localized states near the Fermi level. Non-ohmicity is also observed on the low-voltage side (surface transport regime), where the differential conductance is nearly temperature independent. This non-ohmicity, together with the sheet conductivity much smaller than e^2/h, seems to be one of the characteristics of the metallic chiral sheath.

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