PHYSICAL REVIEW B VOLUME 47, NUMBER 24 15 JUNE 1993-II

Edge-state tunneling through ultrashort gates

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(Received 11 February 1993)

The gating of edge states by ultrashort gates (50 nm) placed on normal quantum Hall effect devices is studied. In longer-gate devices, plateaus in the longitudinal resistance are found when an integer number of edge states is reflected from the gate. The expected quantized values of longitudinal resistance do not appear in the ultrashort gate devices, indicating that tunneling of the edge states through the depletion barrier continuously occurs for biases less than that needed to completely deplete the region near the gate.

INTRODUCTION

In recent years, the study of the quantum Hall effect, in which the Hall resistance is quantized exactly in units of h/e^2, has focused upon the role played by the edge states in the transport through the overall device.[1] The edge states provide essentially dissipation-free transport from the current-injecting contact to the current-sinking contact, so that the quantized Hall conductance can be computed from the Büttiker-Landauer formula[2] in terms of transmission coefficients through the structure. The role of these edge states has previously been examined by the use of metal gates to selectively reflect a fraction of the occupied edge states.[3,4] Both Büttiker[5] and van Houten *et al.*[6] have shown that when a quantum Hall bar is biased with a perpendicular magnetic field, such that the filling factor away from the gate is an integer N, a gate barrier which reflects K edge states leads to quantized longitudinal resistance in accordance with

$$R_{\text{long}}=\frac{h}{e^2}\frac{K}{N(N-K)} . \tag{1}$$

Previous studies of the gated transport of quantum Hall bars have provided agreement with this relationship, and have shown plateaus in the longitudinal resistance when N and K are integers.[3,4]

Equation (1) is valid whenever the edge states are divided into classes which are either completely transmitted or completely reflected from the gate region. In the case of ultrashort gates, however, tunneling through the gate depletion region is sufficiently strong that complete reflection of edge states does not occur. Moreover, the longitudinal resistance measured as the gate bias is varied depends upon where in the plateau the bulk portion of the device is biased (with magnetic field). In this paper, we describe the gating effects measured from quantum Hall devices in which gates of 50-nm gate length are used to bias the transmission of the edge states. The quantized values predicted by (1) are not reached for reasonable gate voltages, presumably due to the incident edge channels tunneling through the depletion region.

EXPERIMENTAL PROCEDURE AND RESULTS

Samples were prepared on GaAs/$\text{Al}_x\text{Ga}_{1-x}$As heterojunction materials, in which the undoped GaAs was molecular-beam epitaxy grown to a thickness of 1 μm on top of the substrate. This was followed by a 20-nm $\text{Ga}_{1-x}\text{Al}_x$As $(x=0.3)$ undoped spacer layer and a 1×10^{18} cm^{-3} Si-doped layer 30 nm thick. This was followed by an undoped GaAs cap layer 5 nm thick. The two-dimensional density was nominally 4×10^{11} cm^{-2} and the mobility was 400 000 cm^2/V s, both at 1.4 K. The samples consisted of six-sided quantum Hall effect bars with four gates placed between adjacent sidearms, and with gate lengths of 1, 2, 5, and 10 μm. The measurements were performed using a lock-in technique with a current bias as low as 10 nA, at 1.4 K, and with magnetic fields up to 9 T.

Results of measurements of the longitudinal resistance with varying gate bias for the four gates are shown in Fig. 1 for the $\nu=4$ plateau ($B=4.25$ T). In each case, three gates are grounded (which insures an open channel for the present device) and a negative voltage is applied to the remaining gate, so that only a single gate works to deplete the electron gas and reflect the edge states. The sample is prepared with six sidearms, and an ungated region of the sample is used to check that the grounded gates are truly removed from the measurement, by comparing the longitudinal Shubnikov–de Haas traces for the ungated region with that of the region in which the gates are located. In Fig. 1, all four gates display roughly equivalent quantization corresponding to the $N=4$, $K=2$ case using (1). However, the plateau values observed are not precisely at the values expected from (1).

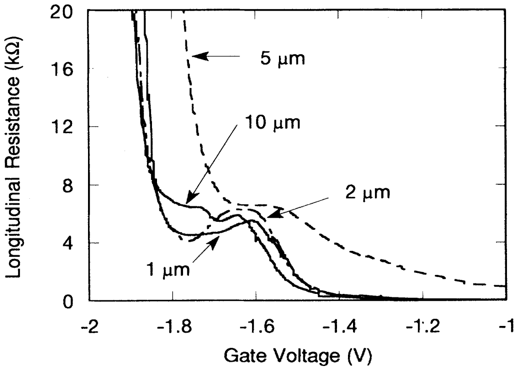

FIG. 1. Longitudinal resistance as a function of gate voltage for the $\nu=4$ plateau ($B=4.25$ T), for four values of gate length.

Odd values of K were not observable in these samples. The offset of the 5-μm gate is possibly due to a slight variation in local density. The difference in the shape of the curves for different gates is expected to be due to different regions of saddle-point tunneling (near the center of the sample under the gate) and non-saddle-point tunneling near the sample edges, as discussed by Haug *et al.*[7] Surprisingly, the most interaction between saddle-point and non-saddle-point tunneling occurs in the 1- and 10-μm gate lengths, but this is uncorrelated with the geometry of the gates themselves (the ordering of the gates on this sample was 5, 2, 1, and 10 μm).

A second set of devices was fabricated in which gates of length 50±5 nm (as measured with a scanning electron microscope) were placed on the Hall bar. In these samples, sweeping the gate voltage was difficult because of the long-time constants of the system, previously reported by Haug *et al.*[7] These are presumably due to the slow relaxation of the carriers in the gated region. To circumvent the long-time constant, a series of sweeps in the magnetic field were performed for various gate biases, and then the values for the fixed magnetic field were taken to create equivalent curves to Fig. 1. Figure 2 shows the longitudinal resistance across the $\nu=2$ plateau as the magnetic field is varied for various values of the gate bias. As the gate voltage is increased, the series resistance of the barrier is increased, destroying the zero, as expected from the behavior for long-gate devices. However, the value of longitudinal resistance varies across the plateau. This behavior is somewhat different than that found with the long gates, and the longitudinal resistance measured with gate bias depends upon the value of the magnetic field. In Fig. 3, the longitudinal resistance values at several positions across the plateau are plotted as a function of the gate voltage. For these latter curves, the shape remains approximately the same for the different positions across the plateau, supporting the conclusion that the tunneling resistance is a series resistive element. The curves show a pseudoplateau (inflection) near -3.5 V that is not predicted by (1), but the sharp rise at -5.5 V shows no additional structure up to quite high resistances (well above the value h/e^2). Similar behavior is observed in the magnetoresistance as a function of the gate voltage. This behavior was observed in several devices.

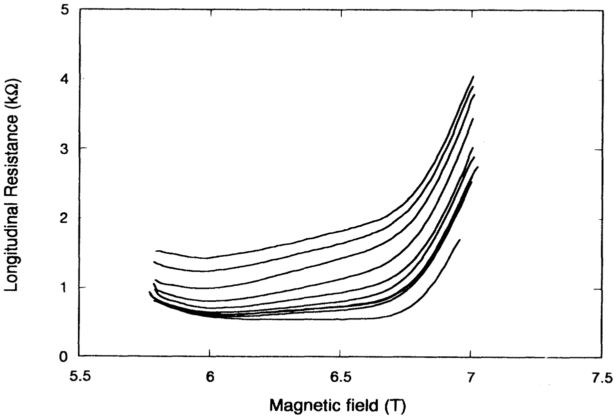

FIG. 2. Series of magnetic-field sweeps across the $\nu=2$ plateau for various gate voltage values, for a device with a single 50-nm gate. The lowest curve is for -0.01 V and each curve is for a step of -0.5 V, reaching a maximum of -5 V.

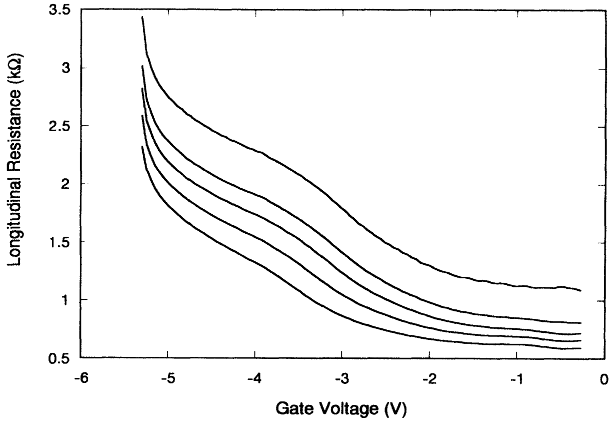

FIG. 3. Variation of longitudinal resistance with gate voltage, determined from the data for the curves in Fig. 2, for different values of the magnetic field on the $\nu=2$ plateau. The curves are, from the top, for magnetic fields of 6.8, 6.7, 6.6, 6.4, and 6.2 T.

DISCUSSION

The devices with long gates (> 1 μm) clearly exhibit the interplay between saddle-point tunneling and non-saddle-point tunneling, in the notation of Haug *et al.*[7] The lack of exact quantization to the value expected from (1) is probably not due to leakage, as some values lie above the expected level, while others are below it. However, particularly in the curves for the 1- and 10-μm gates, the interplay between the two classes of edge-state tunneling is quite evident, and it may well be likely that particularly the non-saddle-point tunneling induces some nonequilibrium behavior in the edge-state populations.[8] The presence of the multiple gates may well allow the existence of significant nonequilibrium populations between the gates even though every attempt has been made to neutralize the role of the unbiased gates.

For the barriers produced by the ultrashort gates, the edge channels will have some nonzero tunneling probability throughout the bias range rather than being completely reflected. Tunneling will have an exponential relationship with the barrier width as given approximately by[9]

$$T(\varepsilon)=\exp\left\{-\frac{2}{\hbar}\int[2m^*(V-\varepsilon)]^{1/2}dx\right\}, \qquad (2)$$

where $T(\varepsilon)$ is the transmission coefficient, V is the one-dimensional potential barrier, and ε is the energy associated with movement in the edge-state direction. Because the series resistance significantly changes the local energy throughout the plateau region, the actual tunneling coefficient of the edge state is expected to depend upon the magnetic field, and be a nonlinear function of its own resistance, which causes a variation in the Fermi energy within the barrier region. The slope of the resistance increase apparent in Fig. 2 is thought to be a result of the shift of the Fermi level in the magnetic field. We can discuss this using the model and notation of Haug *et al.*[7] The magnetic field is such that two positive flowing edge channels are present. The longitudinal slope in the Fermi level is a result of current flow in the device and is a function of $(\mu_L - \mu_R)$, the difference in the Fermi level on either side of the gate. The velocity is proportional to the transverse slope of the Landau level in the edge state.[5] The difference in currents on either side of the sample, e.g., in the left- and right-going channels, must remain constant and this difference is equal on either side of the gate, since the Hall resistance remains a quantized value in this magnetic-field region, and the bias current is constant. The longitudinal resistance, however, is a measure of the difference in the currents across the gate, in either edge-state set. As the Fermi energy is shifted due to the longitudinal resistance, the ratio of currents on either side of the sample changes and an increased resistance as a function of magnetic field is observed. These effects will not be observed when the edge states are either fully transmitted or are fully reflected, and the details depend upon the exact tunneling coefficient.

Similar resistive effects are seen in long-gate devices, and allow one to probe the properties of the region under the gate itself in the composite Shubnikov–de Haas measurements, which will be discussed elsewhere. The ultrashort gate allows sufficiently strong tunneling through the barrier so that it is not possible to selectively reflect only a single edge state, and total reflection only occurs when the bias is sufficiently high to totally deplete the region under the gate and over an area sufficiently large to cut off the tunneling completely.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research. The authors would like to acknowledge helpful discussions with Y. Takagaki and T. Yamada.

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