Detection of Spin-Flip Relaxation Using Quantum Point Contacts

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We measure the influence of spin-flip relaxation on the inter-Landau level scattering in a quantum Hall conductor. The scattering rate increases sharply when hot electrons injected into the spin-down Landau level are able to spin flip and relax into the spin-up Landau level. Spin-flip relaxation provides energy for inelastic scattering at the sample edge. This is important for understanding the anomalous bias dependence observed between spin-resolved longitudinal resistance peaks. [S0031-9007(98)07986-1]

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In a quantum Hall conductor, power dissipation occurs as hot electrons relax directly between Landau level (LL) states. This is observed in the far infrared (FIR) emission spectrum of a two-dimensional electron gas (2DEG) in a high magnetic field, where the vast majority of the emission is at the cyclotron frequency [1]. Phonon emission at the cyclotron frequency has also been detected [2]. Power dissipation can also occur as hot electrons relax between a pair of spin-resolved LLs associated with a single orbital state. Conclusive evidence for this spin-relaxation process has not been reported, however. The relatively low sensitivity of standard microwave detection methods makes it difficult to measure emission at biases commensurate with the spin-split energy.

Power dissipation via spin-flip relaxation should influence quantum Hall electron transport. In a quantum Hall conductor, current flows through a series of dissipationless edge channels that form where the LLs intersect the Fermi energy E_F due to the confining potential [3]. Power dissipates chiefly at the corners of the 2DEG, where the current is injected from the Ohmic contacts, and within bulk LL states, through which transport occurs as each LL is aligned with E_F. Inter-LL scattering is strongly dependent on the background acoustic phonon population [4]. In addition, the application of FIR radiation to the sample can be used to enhance the scattering rate [5], and resonant inter-LL scattering has been observed at microwave frequencies [6].

In this paper, we report measurements of the edge/bulk scattering rate as a function of dc bias and show that it can be used as an accurate detector of the spin-flip relaxation process. Following previous experiments [7], we separate the bias dependence of the edge/bulk scattering from the bias dependence of the bulk resistivity by performing longitudinal resistance measurements via quantum point contacts (QPC)s to the 2DEG. We observe that the edge/bulk scattering rate increases dramatically when the conditions necessary for hot electron spin-flip scattering are achieved: injection of electrons into the higher energy spin level, and an availability of empty states in the lower energy spin level. We thus provide evidence for the spin-flip relaxation process and describe its potential importance in determining the normal longitudinal resistivity.

Figure 1(a) shows a scale drawing of our Hall bar device. Our samples are made from an AlGaAs/GaAs heterostructure with an electron density of 2.8×10^{11} cm^{-2} and a mobility of 1.7×10^6 cm^2/V s. The Ohmic contacts are diffused AuGeNi and have a zero field 0.3 K contact resistance of $\approx 150\ \Omega$. We apply a variable dc bias modulated by a 10 μV ac bias to contact 4, while contact 1 is fixed to ground. The magnetic field B is

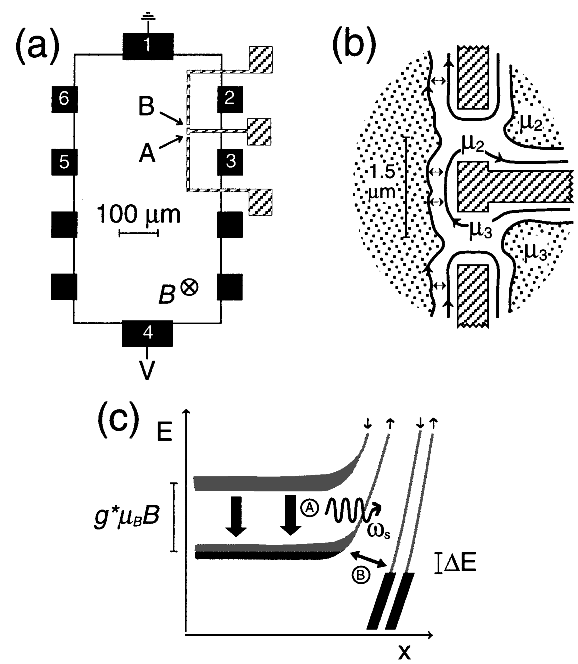

FIG. 1. (a) Scale drawing of our Hall bar device. (b) Close-up of the conducting states near the two QPCs. The chemical potential of the edge channels changes due to scattering between the edge and bulk. (c) The available electron energy levels as a function of distance near the edge of the sample. The two steps of the spin-relaxation process (described in text) are (A) hot electrons relax from the spin-down level to the spin-up level and emit energy $\hbar\omega_s$; (B) inelastic scattering occurs between edge and bulk.

directed into the page, and the edge current flows in a counterclockwise direction. We use three Ti/Au gates to define QPC_A and QPC_B, with a separation of 1.5 μm. A negative bias applied to the gates depletes the underlying electron gas, so that the voltage probes 2 and 3 contact only the undepleted regions within each constriction. By further electrostatic squeezing, individual LLs are decoupled one by one at the QPCs [7].

In our experiments, we measure the dc bias dependence of the differential resistance between contacts 2 and 3 as the B field is swept through a pair of spin-resolved Shubnikov–de Haas (SdH) peaks. The gates are set to reflect the dissipative bulk states, and the voltage probes detect only the nondissipative edge channels [see Fig. 1(b)]. Edge channels emitted from QPC_A are filled to a chemical potential μ_3, equal to the potential measured by probe 3 [8]. As the edge current flows downstream, scattering with the bulk states will tend to bring the chemical potential of the edge channels closer to that of the bulk. At QPC_B, the edge channels have reached a new chemical potential μ_2, which is then detected by probe 2. The magnitude of $R_{14,23} = (\mu_3 - \mu_2)/I_{14}$ is determined by the change in the edge channel potential over the distance between the QPCs. If no edge/bulk scattering occurs, $\mu_2 = \mu_3$ and $R_{14,23} = 0$; if the edge potential decreases due to scattering with the bulk, $\mu_2 < \mu_3$, and $R_{14,23}$ increases.

Figure 2(a) shows the B dependence of the differential resistance measured between normal probes 6 and 5 ($R_{14,65}$) at $T = 0.3$ K, for 10 different values of the dc bias ($V_{dc} = 5$ to 9.5 mV in 0.5 mV steps). We sweep the magnetic field from 2.95 to 1.95 T, so that the filling factor, or the number of LLs below E_F, increases from 4 to 6. SdH peaks are observed as the $\nu = 5$ (spin-up polarized) and $\nu = 6$ (spin-down polarized) LLs move through E_F with a decreasing magnetic field. In agreement with other groups' measurements [9], we observe that the dc bias has a much stronger influence on the spin-up peak than on the spin-down peak. Figure 2(b) shows the QPC resistance $R_{14,23}$ measured simultaneously with $R_{14,65}$, using the same 10 dc biases. The gates are set so that, at $\nu = 6$ ($B = 1.95$ T), the conductance of each QPC is quantized at $4e^2/h$ [10]. The voltage probes detect four spin-resolved edge channels ($\nu \leq 4$), while the $\nu = 6$ and 5 LLs are reflected. For $V_{dc} < 5$ mV, $R_{14,23}$ is zero over the whole B-field range, implying that no edge/bulk scattering occurs between the QPCs. This agrees with Ref. [7] in which the edge and bulk channels were shown to be completely decoupled over a distance of 1.5 μm at zero dc bias. Above $V_{dc} = 5$ mV, a peak appears in $R_{14,23}$ that grows with increasing bias. The peak lies within the high-field side of the normal SdH peak, corresponding to the point where the $\nu = 5$ spin-up LL moves through E_F. No similar peak is observed as the $\nu = 6$ spin-down LL moves through E_F.

In the inset to Fig. 2(b), we compare the bias dependencies of $R_{14,23}$ and $R_{14,65}$ measured at the peak maximum

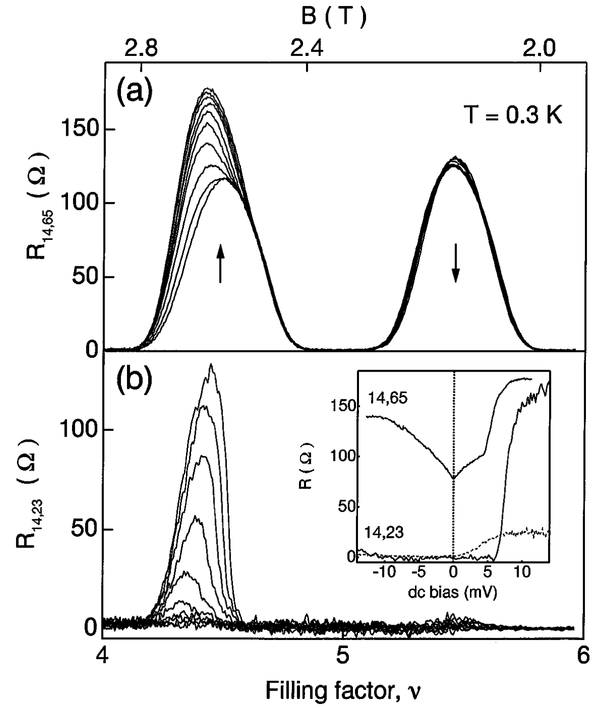

FIG. 2. (a) Differential resistance $R_{14,65}$ measured between normal probes 6 and 5, and (b) $R_{14,23}$ measured between QPC probes 2 and 3 as a function of a filling factor for ten different values of the dc bias between probes 1 and 4 ($V_{dc} = 5$ to 9.5 mV in 0.5 mV steps). The magnetic field decreases from 2.95 to 1.95 T as the filling factor increases from 4 to 6. The QPCs are set so that the bulk LLs are backscattered and not detected by probes 2 and 3. Inset: $R_{14,65}$ and $R_{14,23}$ as a function of bias at the peak maximum ($B = 2.63$ T). The dashed line is $R_{14,23}$ measured at 4.2 K.

($B = 2.63$ T). Both resistances increase steeply above 5 mV, although the exact turn-on bias is lower for $R_{14,65}$ than for $R_{14,23}$. The QPC resistance is also plotted for $T = 4.2$ K (dashed line). As the spin resolution disappears, the turn-on smears out, and the peak height drops. Note that enhancement is observed only in the forward bias direction, when electrons are injected from contact 1. In the negative bias direction (electrons injected from contact 4), $R_{14,65}$ increases gradually with bias, while $R_{14,23}$ remains near zero. We also performed measurements (not shown) of the resistance across the voltage probes near contact 4. For these probes, turn-on occurs at negative rather than positive bias; thus, the voltage probes must lie near the electron injection point for enhancement to be observed.

Figure 3 shows the bias dependence of the QPC resistance across the other pairs of spin-resolved SdH peaks observable at $T = 0.3$ K. In each case, the B field is swept to increase the filling factor ν from $n - 1$ to $n + 1$. The gates are set so that the bulk LLs ($\nu = n + 1$ and $\nu = n$) are completely reflected [as in Fig. 2(b)]. The dashed lines show the normal resistance $R_{14,65}$, measured at zero dc bias—SdH peaks are observed as the spin-up and spin-down LLs move through E_F. The solid

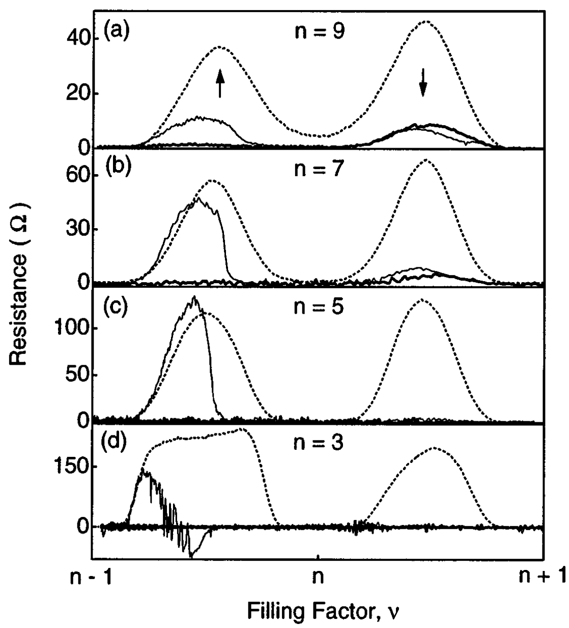

FIG. 3. Normal resistance $R_{14,65}$ (dashed lines) and QPC resistance $R_{14,23}$ (solid lines) across four pairs of spin-split SdH peaks. The filling factor increases from $n - 1$ to $n + 1$, where (a) $n = 9$, (b) $n = 7$, (c) $n = 5$, and (d) $n = 3$. In each case, $R_{14,65}$ is plotted for $V_{dc} = 0$. The thick lines show $R_{14,23}$ for $V_{dc} = 0$, and the thin lines show $R_{14,23}$ for V_{dc} set so that $R_{14,23}$ reaches its saturated value: (a) $V_{dc} = 6$ mV, (b) $V_{dc} = 8$ mV, (c) $V_{dc} = 9.5$ mV, and (d) $V_{dc} = 20$ mV.

lines are the QPC resistance $R_{14,23}$ for zero dc bias (thick line) and finite dc bias (thin line). For each pair of spin-resolved peaks, the results agree with those of Fig. 2(b). A peak appears in $R_{14,23}$ on the high B-field side of the spin-up SdH peak. The peak turn-on occurs at a bias $V_{dc} = V_t(B)$, which increases with B field from peak to peak. These results show that for each pair of spin-resolved peaks, edge/bulk scattering is enhanced by dc bias as the spin-up LL moves through E_F.

Note that at zero bias, the spin-down peak is actually larger than the spin-up peak [thick lines in Figs. 3(a) and 3(b)]. This is understandable. Previous work [4,9] showed that the width of the incompressible region separating the edge and the bulk decreases with decreasing B, i.e., the edge/bulk separation is less when E_F intersects the spin-down level than when E_F intersects the spin-up level, so that scattering occurs preferentially between the edge and the spin-down level.

It is surprising then that the bias has a strong effect on the spin-up peak and only a weak effect on the spin-down peak. This cannot easily be explained by breakdown of the incompressible region between the edge and bulk. Instead, we consider the influence of spin-flip relaxation on the edge/bulk scattering rate. Figure 1(c) shows the available electron energy levels as a function of distance towards the edge of the sample. The situation is generalized to depict two spin-resolved edge channels, and two spin-resolved, disorder broadened bulk levels, separated by an energy $g^* \mu_B B$. At equilibrium, the spin-up LL is at E_F and is partially filled with electrons. An energy difference ΔE created by the Hall potential separates the bulk and the edge states. At high dc bias, hot electrons are injected from the current contact into the bulk spin-down LL. After traveling some distance λ_s through the bulk, the hot electrons spin-flip scatter and lose their extra energy as they relax into the spin-up LL. This releases an energy $\hbar\omega_s = g^* \mu_B B$, most likely in the form of acoustic phonons. The released energy can reexcite a second electron from the spin-up LL, or for $\hbar\omega_s > \Delta E$, provide the energy necessary for electrons to scatter inelastically between the edge and the bulk states. In this way, spin-flip relaxation provides a means by which dc bias can promote edge/bulk scattering.

This mechanism explains why the edge/spin-up LL scattering rate is so sensitive to the applied dc bias compared with the edge/spin-down LL scattering rate. For energy relaxation to occur, there must be states available in the spin-up LL for hot electrons to drop into. Since the equilibrium electron population of the spin-up LL increases with decreasing magnetic field, the hot electron relaxation rate will drop off due to a lack of available states, and the edge/bulk inelastic scattering mechanism will shut off. This explains why the QPC resistance drops off near the center of the zero-bias spin-up SdH peak in Figs. 2 and 3, since here, the density of empty states in the spin-up LL drops rapidly with decreasing B field. No enhancement occurs for the spin-down SdH peak because, at this B field, there are almost no available states in the spin-up LL. Thus, the bias dependence of the edge/spin-down LL scattering rate is relatively weak.

This spin-flip relaxation mechanism also explains the unusual nonlinear bias dependence of the edge/bulk scattering rate. Consider the measurement configuration of Fig. 1(a). The dc bias is distributed between the two contact resistance R_1 and R_4 and the 2DEG resistance, $R_{14,14}$. If the bias across contact 1 is greater than the spin splitting $g^* \mu_B B$, electrons are injected into the spin-down LL, and spin-flip relaxation can occur (see inset, Fig. 4). This condition defines the turn-on bias,

$$V_t(B) = 2g^* \mu_B B(R_{14,14} + R_1 + R_4)/eR_1 . \quad (1)$$

We cannot calculate $V_t(B)$ exactly from the measured two-terminal resistance, since $R_{14,14}$ is generally unknown. At integer filling factors ν, however, $R_{14,14} = h/\nu e^2$, and we can then determine $(R_1 + R_4)$ by subtracting $R_{14,14}$ from the measured two-terminal resistance. Figure 4 shows the results of this estimation of $V_t(B)$ for two limiting cases: (1) $R_1 = R_4$, and (2) $R_1 \gg R_4$. (The contacts act as weak Schottky diodes, so that $R_1 \geq R_4$ at positive bias [11].) The measured values for $V_t(B)$ are also plotted in Fig. 4 (black dots) and are seen to lie between the two limiting cases. The onset of the edge/bulk scattering (as measured by the appearance of the

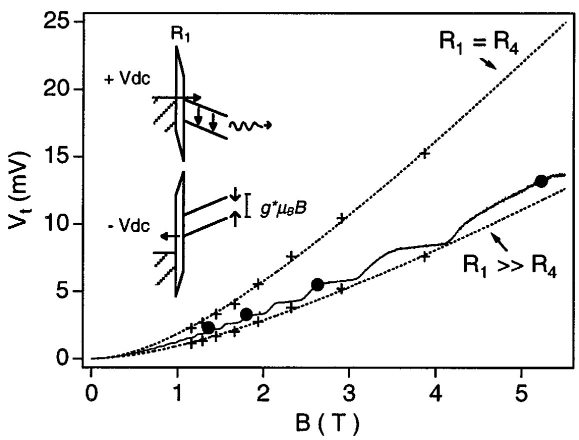

FIG. 4. Turn-on bias V_t of the QPC resistance peak as a function of a magnetic field. The dots show the value of V_t measured for each $R_{14,23}$ peak shown in Fig. 3. The crosses are estimations of V_t (see text), while the dashed lines are guides to the eye. The solid line is a fit of the experimental points to Eq. (1). Inset: Electron energy drop across contact 1 for positive (top) and negative (bottom) bias at contact 4.

resistance peak) therefore occurs at the same bias that electrons are injected from contact 1 into the spin-up LL. We can also fit the measured values of V_t to Eq. (1), noting that $(R_{14,14} + R_1 + R_4)$ is simply the measured two-terminal resistance. Our fitting parameter is then the contact resistance R_1, which is taken to increase linearly with magnetic field from its zero field value of 150 Ω. As shown in Fig. 4, the fit accurately describes the data and gives $R_1 = 150\ \Omega + 87\ \Omega/\mathrm{T} \times B(\mathrm{T})$.

For the energy emitted by the spin-flip process to influence the QPC resistance, the spin flip must occur before the excited electrons reach the QPC. Using $\lambda_s = 200\ \mu\mathrm{m}$ and $v_F = 2 \times 10^5$ m/s this gives a spin-flip time of $t_s = 1$ ns. This is considerably lower than the spin-lattice relaxation time T_1 predicted by theory [12] and recently measured by NMR [13] (~100 ms). However, Ref. [12] assumes that the electron population is localized, and that a small number of excited electrons are attached to individual holes. This is not valid in our case, where a large number of hot electrons are injected into the excited spin state, and a dc current flows. Thus we expect T_1 to be reduced closer to what is observed in ordinary metals (~50 ps for Au [14]).

We turn finally to the influence of spin-flip relaxation on the normal resistance. The shape of the SdH peaks is determined by a nontrivial combination of the dissipation of the bulk state and inter-LL scattering between the edge channels and the bulk [15]. Previous experiments on relatively low mobility, narrow samples measured a strong bias dependence of the SdH peaks for $kT > g^* \mu_B B$ [16]. Clearly, this cannot be explained by spin-flip relaxation. In our experiment, however, the bias dependence of the normal resistance corresponds to the bias dependence of the QPC resistance, and both smear out as the spin resolution disappears at high T. This suggests that the spin-flip relaxation also contributes to the bias dependence of the spin-resolved peaks.

In conclusion, we have demonstrated that the edge/bulk scattering rate, as measured by the QPC resistance, is enhanced when the spin-flip relaxation mechanism is established, i.e., the bias must be high enough to inject electrons into the higher energy spin level, and empty states must be available in the lower energy spin level. In this way, the QPC resistance acts as a detector of the energy emitted by the spin-flip process. Similarly, the energy released by spin-flip relaxation increases the normal longitudinal resistance, and its appearance is important for understanding the bias dependence of the spin-resolved SdH peaks. We hope that future work will describe the nature of the energy emitted in the spin-flip relaxation process.

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