Temperature dependence of the nonlocal resistance under conditions corresponding to the quantum Hall effect

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The nonlocal electrical resistance of a single heterojunction of a special shape in a quantizing magnetic field has been studied experimentally. Comparison of the experimental results with theoretical predictions for filling factors close to $i = 1.5$ reveals the temperature dependence of the frequency of transitions between quantum levels. The experimental results are explained in terms of an electron–phonon scattering accompanied by a spin flip at the boundaries of the sample.

Several theoretical and experimental studies have demonstrated the role played by edge states in current transport in Hall bridges under the conditions of the integer quantum Hall effect (e.g., Refs. 1–5). It has been observed, in particular, that the populations of various edge states equalize over macroscopic distances. This circumstance raises the hope that edge states would have a significant influence on the potential distribution along a Hall bridge even under dissipative conditions.[6] Evidence for a possible contribution of edge states to the current under dissipative conditions comes from the observation of nonlocal effects,[7–9] from a reported dependence of the resistivity on the width of a sample,[10,11] and from a reported dependence of the resistivity on the distance between the potential contacts.[12–15]

Under dissipative conditions, the distance (λ) over which the population of the edge states equalizes with the population of the upper Landau level, which is responsible for the dissipative conductivity, plays a governing role. We believe that λ could conveniently be measured by utilizing nonlocal effects in samples with the special geometry shown in Fig. 1. In this case one would measure nonlocal resistances R^{+}_{1234} and $R^{-}_{1234} = R^{+}_{3412}$. (The first pair of subscripts here specifies the current contacts, and the second pair the potential contacts. The plus and minus signs indicate the two possible directions of the magnetic field, which is perpendicular to the plane.) Nonlocal effects are observable under the condition $a < \lambda$, while at $\lambda > b_1$, b_2 we have $R^{+}_{1234} \neq R^{-}_{1234}$ if $b_1 \neq b_2$. The nonlocal resistance can be calculated from a simple model which assumes that the upper Landau level can be described in terms of a conductivity tensor. The current component from the low-lying levels is determined exclusively by the populations of the edge states. The exchange between the upper Landau level and the other quantum levels is characterized by the relaxation time τ of the electrochemical potential. Using the procedure described in Ref. 6, we find the following expression for R^{+}_{1234}:

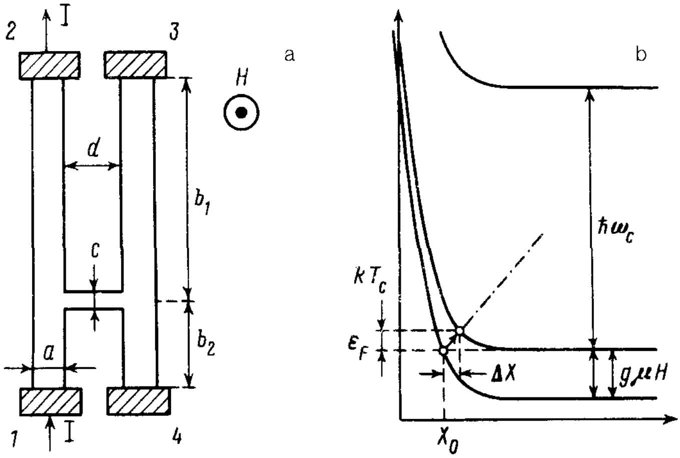

FIG. 1. a: Schematic diagram of a sample. For the field direction and the choice of current contacts indicated here, the nonlocal resistance R^{+}_{1234} is measured. b: Schematic diagram of the spectrum near the boundary of the sample. The arrow shows an electronic transition between quantum levels accompanied by the absorption of a phonon. The dot-dashed straight line is $\epsilon_0(x_0) + \hbar s\Delta x/l^2$.

$$R^{+}_{1234} = \alpha\left(\frac{\lambda}{L}\right)^3 \frac{2L\sigma_{xx}/a}{\sigma_{xx}^2+\sigma_{yx}^2}\,\frac{1+\alpha\exp(-(b_1+b_2)/\lambda)}{1-\alpha\exp(-(b_1+b_2)/\lambda)}\times$$

$$\times\frac{(1-\exp(-b_1/\lambda))^2(1+\alpha\exp(-b_2/\lambda))^2}{(1-\alpha^2\exp(-2b_1/\lambda))(1-\alpha^2\exp(-2b_2/\lambda))+\alpha^2(1-\exp(-2b_1/\lambda))(1-\exp(-2b_2/\lambda))};$$

$$\alpha = \frac{2-\delta a/\lambda}{2+\delta a/\lambda}\,\frac{L/\lambda-1}{L/\lambda+1};\ \delta = \frac{2L\sigma_{yx}/a}{n+\sigma_{yx}+2L\sigma_{xx}/a};$$

$$\lambda = L\left(\frac{\sigma_{xx}^2+\sigma_{yx}^2}{\sigma_{xx}^2+(n+\sigma_{yx})^2+2Ln\sigma_{xx}/a}\right)^{1/2}. \qquad (1)$$

Here n is the number of completely filled Landau levels. We assume for simplicity that there is a rapid exchange of electrons between these levels, over times short in comparison with τ. The conductivities σ_{xx} and σ_{yx}, divided by e^2/h, correspond to the upper Landau level. Here we are using a length $L = V\tau$, where V is the average group velocity of the hopping electrons. Expression (1) was derived under the conditions

$$a \ll \lambda; \quad a \ll b_1, b_2; \quad d \sim c \sim a. \qquad (2)$$

The expression for R^{+}_{3412} can be found from (1) by letting $b_1 \to b_2$, $b_2 \to b_1$.

It can be seen from (1) that λ is determined not exclusively by the time τ but also by the width of the sample (a) and the conductivities σ_{xx} and σ_{yx}. Near the point $(\sigma_{xx},\sigma_{yx}) = (0,1)$, the mixing length λ is equal to L, within a numerical factor, and the resistances R^{+}_{1234} and R^{+}_{3412} are proportional to each other.

In this letter we are reporting some preliminary experiments carried out to observe nonlocal effects on a sample of the corresponding shape. In the experiments we studied the temperature dependence of the nonlocal resistances R^{+}_{1234} and R^{+}_{3412} in a single AlGaAs/GaAs heterojunction with an electron density of 4.9×10^{11} cm^{-2} and a mobility of 60 m^2/V·s). Below 1.5 K we observed peaks in the nonlocal resistance for half-integer filling factors below 6. At large filling factors, there was no spin splitting. We studied the temperature dependence of the nonlocal resistances near a filling factor of 1.5. We chose this particular value because in this case there is only one Landau level below the Fermi level, so there is no problem concerning an equalization of the populations of the various edge states.

Figure 2 shows some representative experimental results. At the left edge of the line, i.e., near the point (0,1), the resistances R^{+}_{1234} and R^{+}_{3412} differ by only a temperature-dependent numerical factor. Working from the magnitude of this numerical factor along with (1), one can determine the temperature dependence of the length L. For our sample, the geometric dimensions were $b_1 = 350$ μm, $b_2 = 30$ μm, $a = 6$ μm, and $c = d = 3$ μm. The doped region, however, did not cover the contact areas completely. The dimensions b_1 and b_2 could thus be greater than the geometric dimensions. This matter was significant only for the small dimension b_2, whose magnitude can be estimated to be 30 μm $< b_2 <$ 4 60 μm. For the calculations we used the value $b_2 = 50$ μm, but when we varied b_2 over the specified range we found no substantial changes in the results reported below. It was thus possible not only to describe the temperature dependence of the ratio of the nonlocal resistances but also to qualitatively explain the temperature dependence of each of them.

Figure 3 shows the temperature dependence of L over the temperature interval 0.3–1.5 K. We see that there is a region of temperatures in which the rate at which

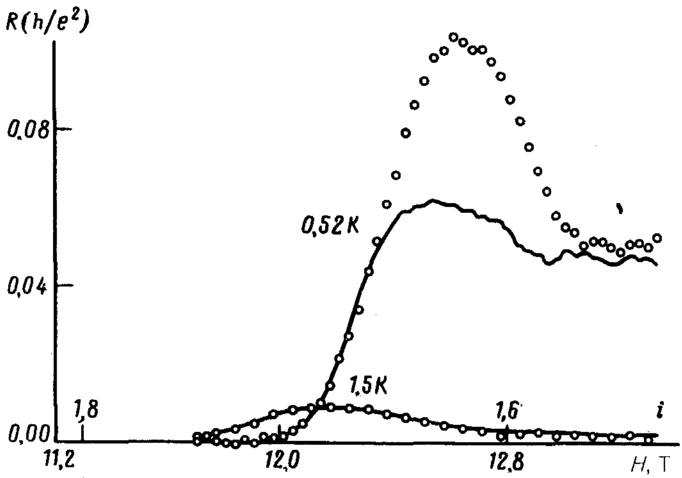

FIG. 2. Experimental results on the nonlocal resistances R^{+}_{1234} (solid lines) and R^{+}_{3412} (points) versus the magnetic field at two temperatures. The values of R^{+}_{3412} at 1.5 K have been multiplied by a factor of 5.5, and those at 0.52 K by a factor of 14.

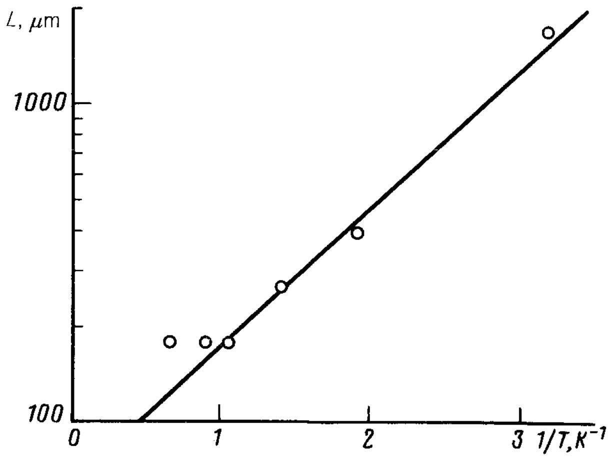

FIG. 3. The length L versus the reciprocal temperature. The slope of the straight line corresponds to $T_c = 1$ K.

electrons are exchanged between edge states and the higher of the filled Landau levels has an activation dependence, $\tau^{-1} = V/L \sim \exp(-T_c/T)$. Assuming a phonon scattering mechanism, and using conservation of the momentum component directed along the edge, we can find the shift of the center of the orbit of the electrons upon the scattering:

$$\Delta x = \frac{kT_c l^2}{\hbar s}, \tag{3}$$

where l is the magnetic length, and s the sound velocity. The experimental value of the activation energy corresponds to a shift $\Delta x = 18$ Å $= 0.24l$ if we use 4×10^5 cm/s as the average sound velocity.

This scattering process is associated with a spin flip. The spin splitting is much smaller[16] than the cyclotron splitting, and it is very sensitive to the filling factor i. For a transition of an electron from one quantum level to another there exists a minimum energy transfer kT_c, which plays the role of an activation energy (Fig. 1). The values of this energy and of the corresponding shift Δx are related to the value of the g-factor. This relationship can be derived from the energy and momentum conservation laws and the approximate expression $\epsilon_0(x_0) \approx \hbar\omega_c(1/2 + \exp(-x_0^2/l^2))$ for the energy:

$$\Delta x/l \approx \left(\ln \frac{\omega_c l}{s(\Delta x/l)}\right)^{1/2} - \left(\ln \frac{\hbar\omega_c}{g\mu H}\right)^{1/2}, \tag{4}$$

where ω_c is the cyclotron frequency, and $g\mu H$ is the energy of the spin splitting.

An estimate of the g-factor from (4) yields 0.45, in agreement with the bulk value of the electron g-factor in GaAs. The value found for the g-factor at $i \approx 1.7$ does not contradict the known picture of the oscillations in the value of the g-factor in single GaAs heterojunctions.

The interpretation of the experimental results leans heavily on the assumption that the contacts are ideal, i.e., that all the electrochemical potentials are equal near a contact. It has been established[17] that the contacts in real samples may be less than ideal. The extent to which they deviate from an ideal state increases with decreasing temperature. In our experiments, this circumstance would signify only a weakening of the temperature dependence of the ratio of the nonlocal resistances and a lowering of the activation energy. A deviation of the contacts from an ideal nature is quite noticeable in our sample at temperatures below 0.3 K.

In summary, this experiment has revealed a temperature dependence of the distance over which the populations of the edge states and the highest filled Landau level equalize. The temperature dependence observed can be explained in terms of an electron–phonon scattering accompanied by a spin flip at the boundaries of the sample.

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