Edge state acoustoconductivity and photoconductivity

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The change of resistance in a quantum Hall conductor caused by a local nonequilibrium excitation by phonons or photons is considered theoretically. This excitation creates a nonequilibrium electron distribution at the edge states, which results in a local conductivity change in a certain part of the sample. The resulting change of the total sample resistance is found in terms of the Büttiker's formalism. It may depend on the position of the excitation point and even may have opposite signs at the opposite sample edges, in accordance with the experimental data.

In this paper we consider theoretically the effect of local optical or acoustical excitation in a two-dimensional electron system in a strong magnetic field **H** which is in the quantum Hall regime. The first experiments of this kind have shown that the value and even the sign of the change in the conductance caused by a local excitation by nonequilibrium phonons,[1,2] by the interband,[3] or by far-infrared[4] radiation depend dramatically on the position of the excitation point and on the magnetic field strength.

The conductivity changes in Refs. 1–4 were maximal when the light or the phonon beam was directed at the edge of the sample. This result confirms the crucial role played by the edge states and allows us to use the Büttiker's approach[5] to describe these phenomena. If the contacts of the sample are nonideal and, as in Fig. 1, can be characterized by the coefficients of reflection R_1, R_4 and transmission $T_1=N-R_1$, $T_4=N-R_4$ (N is the number of occupied edge states), then the currents along the upper and the lower edges, I_R and I_L, and the chemical potentials of the contacts, μ_i, can be found from the following relations[5]

$$I_R=(e/h)T_1(\mu_1-\mu_4)+(e/h)R_1(\mu_6-\mu_4), \tag{1}$$

$$I_R=(e/h)N(\mu_2-\mu_4), \tag{2}$$

$$I_L=(e/h)R_4(\mu_3-\mu_4), \tag{3}$$

$$I_L=(e/h)N(\mu_5-\mu_4). \tag{4}$$

The total current I_{14} flowing through the sample (between the contacts 1 and 4) is equal to I_R-I_L.

At the integral filling factor of the Landau levels, ν, corresponding to the quantum Hall plateau, the diagonal component of the conductivity is $\sigma_{xx}=0$. In this case the sample edges far from the contacts are equipotentials: $\mu_2=\mu_3$, $\mu_5=\mu_6$, and the sample resistance is

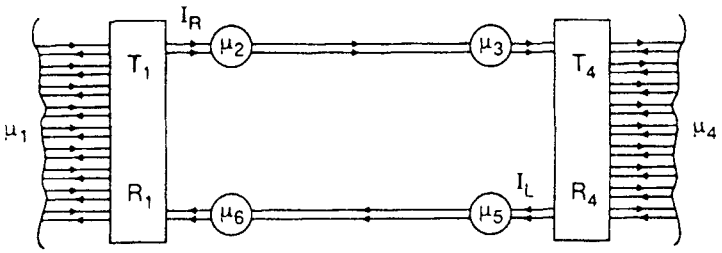

FIG. 1. Equivalent scheme of a quantum Hall sample with nonideal contacts (from Ref. 5).

$$r=\frac{\mu_1-\mu_4}{eI_{14}}=\frac{h}{e^2}\frac{N_2-R_1R_4}{NT_1T_4}. \tag{5}$$

The value of r is equal to the "classical" quantum Hall value $r_0=h/Ne^2$ at $R_1=R_4=0$ and it increases with the reflection coefficients at the contacts. Hence, the deviation of the two-probe resistance from r_0 can be used as a measure of the contact nonideality.

Let us now consider the effect of acoustoconductivity when a part of the sample's edge between points 2 and 3 (or 5 and 6) is influenced by a nonequilibrium phonon flux. These phonons cause electron transitions inside or between edge stages (Fig. 2), which lead to the change in the electron group velocity, and hence the local value of the current $\delta I_{R,L}$ which is proportional to the phonon flux. The theoretical expression for δI was obtained in Ref. 2. It was shown that $\delta I(H)$ oscillates with the Shubnikov–de Haas period. The sign of δI is positive in a high magnetic field when only intralevel transitions are possible, and when the absorption of a phonon always increases the drift velocity of the electron. In a low magnetic field the interlevel transitions begin to play a key role and the sign of δI becomes negative.[2]

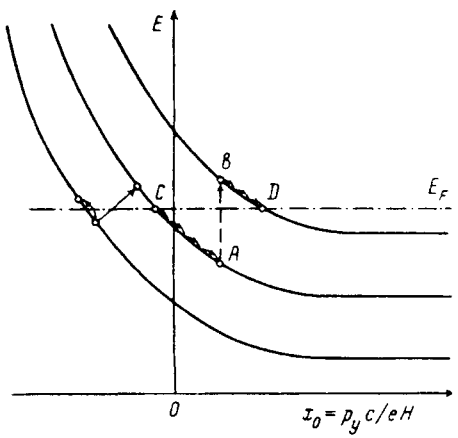

FIG. 2. Intra- and inter-edge-state transitions induced by phonons (solid lines) and photons (broken line); x_0 is the position of the center of the Landau oscillator (x_0 corresponds to the edge of the sample); P_y is the momentum component parallel to the edge, and E_F is the Fermi energy.

In order to maintain the continuity of the current along the whole edge, an additional difference in the chemical potentials arises between the boundaries of an excited region. If the phonon beam strikes the upper edge of the sample between contacts 2 and 3, then $\mu_3=\mu_2+Nh\delta I/e$ and from Eqs. (1)–(4) we obtain

$$I_{14}^{23}=\frac{\mu_1-\mu_4}{er}+\frac{NT_4}{N^2-R_1R_4}\,\delta I=\frac{\mu_1-\mu_4}{er}+\Delta I_{14}^{23}. \tag{6}$$

If the lower edge of the sample is excited, then $\mu_6=\mu_5+N\delta I/e$ and

$$I_{14}^{56}=\frac{\mu_1-\mu_4}{er}+\frac{R_1T_4}{N^2-R_1R_4}\,\delta I=\frac{\mu_1-\mu_4}{er}+\Delta I_{14}^{56}. \tag{7}$$

Note that the second term in (7) is not proportional to the applied voltage. Strictly speaking, the term "acoustoconductivity" (and "photoconductivity") is therefore not correct. We shall, nevertheless, use these terms, following the traditional terminology used in the papers cited here.

Hence, the total acoustoconductivity has always the same sign as the local current change, δI, but its amplitude depends on the properties of the current contacts. At the sample's edge, where the direction of the vertex current is opposite to the total current through the sample (the lower edge in our picture), the effect exists only for nonideal contacts. Hence, the deviation of the sample resistance r from r_0 must correlate with the difference between I_{14}^{23} and I_{14}^{56}. For a symmetrical structure with $R_1=R_4$ we have

$$\frac{r}{r_0}=\frac{1+\Delta_{14}^{56}/\Delta I_{14}^{23}}{I-\Delta I_{14}^{56}/\Delta I_{14}^{23}}. \tag{8}$$

Infrared illumination of the sample also causes interlevel transitions which redistribute electrons between the edge states. It is qualitatively similar to the effect of nonequilibrium phonons. Therefore, the main regularities of the far infrared photoconductivity must be the same as those for the acoustoconductivity, and they are described by the same equations [(6) and (7)], which differ only in the expressions for δI. The effect at the opposite edges of the sample will therefore have the same sign but different amplitudes.

Some qualitative conclusions concerning δI can be drawn without any calculations. In contrast with the phonons, infrared photons induce only interlevel transitions which are vertical in the momentum space (Fig. 2). A nonequilibrium electron at the upper level and a "hole" at the lower can be relaxed inside the level by emitting acoustic phonons. The rate of this process typically exceeds that of the interlevel transitions (some estimates can be found in Ref. 2). As a result, the electron and the "hole" approach the Fermi level E_F (see Fig. 2). Eventually, the light-induced electron transition between states A and B will lead to the same final state as if it were created by the transition from C to D. It can be shown that the electron group velocity $v=\partial\epsilon/\partial p$ in the state D, v_D, is lower than that in the state C, v_C (although $v_B>v_A$). This means that δI, and hence the total photoconductivity, is negative. Since the transition probability is proportional to the density of the initial and final states, the photoconductivity for a given light frequency will oscillate with H.

The above-mentioned regularities of the far-infrared photoconductivity are found in samples with a sufficiently sharp edge, in which interlevel transitions can be caused by light of arbitrary polarization and frequency that exceeds the cyclotron frequency. In samples with a smooth edge the interlevel transitions are caused by light of the same frequency and polarization as the cyclotron resonance. As a result, edge-state photoconductivity cannot be separated from the bulk cyclotron-resonance photoconductivity and our predictions are difficult to prove experimentally.

In the case of interband optical excitation the situation is different. Such kind of excitation creates additional carriers, and hence increases the chemical potential in the illuminated region by $\Delta\mu$, which is proportional to the light intensity. Illumination of the upper edge increases μ_2 and μ_3, which causes an additional current, $\delta I = Ne\Delta\mu/h$, which is injected in the direction of the right contact. To describe it, we must add the term δI to the right-hand side of Eq. (2). This gives

$$I = \frac{\mu_1 - \mu_4}{er} - \frac{NT_4}{N^2 - R_1 R_4}\,\delta I. \tag{9}$$

The final result is similar to Eq. (6), but the change of conductivity is negative.

If the lower edge is illuminated, μ_5 and μ_6 increase by $\Delta\mu$ and the additional current is injected in the direction of the left contact. Reflecting with the probability R_1, this current gives rise to I_R. Hence, the additional term $R_1\delta I$ must be included in Eq. (1), which results in a formula identical to Eq. (7) with a positive sign of the photoconductivity.

In conclusion, we have demonstrated that in the quantum Hall regime the local excitation of the edge of the sample by a phonon or photon flux changes the resistivity of the sample. The amplitude of the effect oscillates with H and depends on which edge of the sample is illuminated. In contrast with the acoustoconductivity and long-wavelength photoconductivity, the interband photoconductivity must have the opposite sign in the case in which two opposite edges of the sample are illuminated. All these regularities were observed in the experiments on acoustoconductivity[2] and photoconductivity[3] under the conditions of the quantum Hall effect.

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