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EDGE STATE ACOUSTO- AND PHOTOCONDUCTIVITY

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The change of resistance in a quantum Hall conductor caused by a local non-equilibrium excitation by phonons or photons is considered theoretically. This excitation creates non-equilibrium electron distribution at the edge states resulting in a local conductivity change in some 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 excitation point and even may have opposite signs at the opposite sample edges, in accordance to 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**, that is in the quantum Hall regime. The first experiments of this kind have shown that the value and even the sign of the conductance change caused by local excitation with non-equilibrium phonons [1,2], interband [3] or far infrared [4] radiation depend dramatically on the position of excitation point and magnetic field strength.

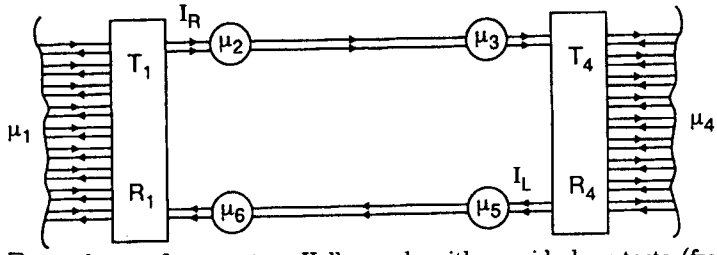

Fig.1. Equivalent scheme of a quantum Hall sample with non-ideal contacts (from [5])

The conductivity changes in [1-4] were maximal with the light or phonon beam directed at the sample edge. This 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 to the sample are non-ideal 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), the currents along the upper and the lower edges, I_R and I_L as well as the chemical potentials of 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} through the sample (between the contacts 1 and 4) is equal to $I_R - I_L$.

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

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

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

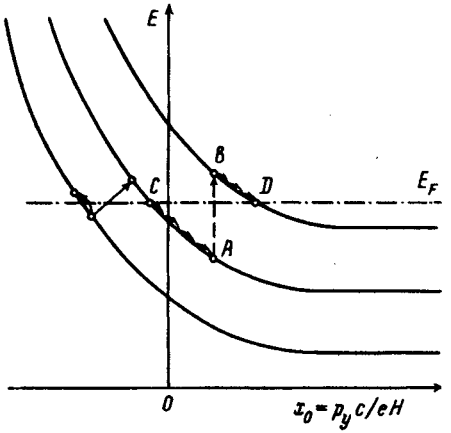

Fig.2. Intra- and inter-edge-state transitions induced by phonons (solid lines) and photons (broken line), x_0 is the position of the center of Landau oscillator ($x_0 = 0$ corresponds to the sample edge); p_y is the momentum component parallel to the edge; E_F is the Fermi energy

Now consider the effect of acoustoconductivity when a part of the sample edge between points 2 and 3 (or 5 and 6) is influenced by a non-equilibrium phonon flux. These phonons cause electron transitions inside or between edge states (Fig.2) which result in the change of electron group velocity and, hence, of the local value of current $\delta I_{R,L}$ proportional to the phonon flux. The theoretical expression for δI has been obtained in [2]. It has been shown that $\delta I(H)$ oscillates with the Shubnikov–de Haas period. The sign of δI is positive at high magnetic field when only intra-level transitions are possible and absorption of a phonon always increases the drift velocity of electron. At low magnetic field inter-level transitions begin to play a key role and the sign of δI becomes negative [2].

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

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

If the lower sample edge is excited, then $\mu_6 = \mu_5 + Nh\delta I/e$ 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. So, strictly speaking, the term "acoustoconductivity" (and, further, "photoconductivity") is not correct. We shall, nevertheless, use these terms following the traditional terminology used in the papers cited.

Hence, the total acoustoconductivity has always the same sign as the local current change δI but its amplitude depends on the properties of current contacts. At the sample edge where the direction of vertex current is opposite to the total current through the sample (the lower edge in our picture), the effect exists only for non-ideal 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 $R_1 = R_4$

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

Infrared illumination of the sample also causes interlevel transitions redistributing electrons between edge states. It is qualitatively similar to the effect of non-equilibrium phonons. Therefore, the main regularities of far infrared photoconductivity must be the same as for the acoustoconductivity and described by the same formulae (6), (7) differing only by different expression for δI. So the effect at the opposite sample edges will have the same sign but different amplitude.

Some qualitative conclusions concerning δI can be drawn without any calculations. Contrary to the phonons, infrared photons induce only interlevel transitions, vertical in the momentum space (Fig.2). Nonequilibrium electron at an upper level and "hole" at a lower one will relax 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 [2]) and, as a result, both electron and "hole" will approach the Fermi level E_F (see Fig.2). Eventually, the light-induced electron transition between states A and B results in the same final state as if it would be 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 less than in the state C, v_C (though $v_B > v_A$). This means that δI and, hence, the total photoconductivity, is negative. Since the transitions probability is proportional to the density of initial and final states, the photoconductivity for a given light frequency will oscillate with H.

The above-mentioned regularities of the far-infrared photoconductivity will take place in samples with the edge sharp enough where interlevel transitions can be caused by the light of arbitrary polarization and frequency exceeding the cyclotron one. In samples with a smooth edge interlevel transitions are caused by the 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 some $\Delta\mu$ proportional to the light intensity. Illumination of the upper edge increases μ_2 and μ_3 causing some additional current $\delta I = Ne\Delta\mu/h$ injected in the direction to the right contact. To describe it, we

must add the additional 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 are increased by $\Delta\mu$ and the additional current is injected in the direction of the left contact and, reflecting with probability R_1 gives rise to I_R. Hence, the additional term $R_1\delta I$ must be added in Eq. (1) which results in a formula identical to Eq. (7) with the positive sign of photoconductivity.

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

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