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Current distribution in the integer quantum Hall effect: The role of bulk states

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The role of bulk and edge currents in a two-dimensional electron gas under the conditions of the integer quantum Hall effect (IQHE) was studied by means of an inductive coupling to Hall bar geometry. From this study we conclude that the extended states at the bulk of the sample below the Fermi energy are capable of carrying a substantial amount of Hall current. For Hall bar geometry sample with a back gate we demonstrated that injected current can be pushed from one edge to another by reversing the direction of the external magnetic field.

Key words: electron transport, integer quantum Hall effect, GaAs, heterostructures, current distribution.

1. Introduction

Since the discovery of the integer quantum Hall effect (IQHE) [1], the role of bulk [2, 3] versus edge [4–6] states has been discussed theoretically. The results of many experiments [7–11] addressing this issue seem to favor the edge picture over the bulk one. However, recent experimental studies [12–15] revived this controversial question by giving examples supporting the bulk picture. In these studies it has been shown that the electrostatic potential varies in the bulk of the sample. It implied the existence of Hall current carried by the bulk states.

In order to address the questions concerning the role of edge versus bulk states in the IQHE we employed an inductive coupling technique [16]. Our method utilizes a small pick-up coil in order to measure time-dependent magnetic fields induced by alternating currents in the sample. Although the sensitivity limitations of this method do not allow for a precise determination of the spatial distribution of the injected current, a quantitative analysis of our data allowed us to reaffirm the following conclusion for Corbino geometry. *In the IQHE regime the bulk states at the Fermi energy are localized*. However, *the bulk states at the Landau levels, below the Fermi energy, may carry a substantial amount of the Hall current*. The contribution of these bulk states to the Hall current depends on the details of the electrostatic potential. The latter is strongly influenced by the geometry of the sample and by the attached contacts. These results were obtained for Corbino geometry [16]. In this paper we prove that the same conclusions are valid to a Hall bar geometry as well.

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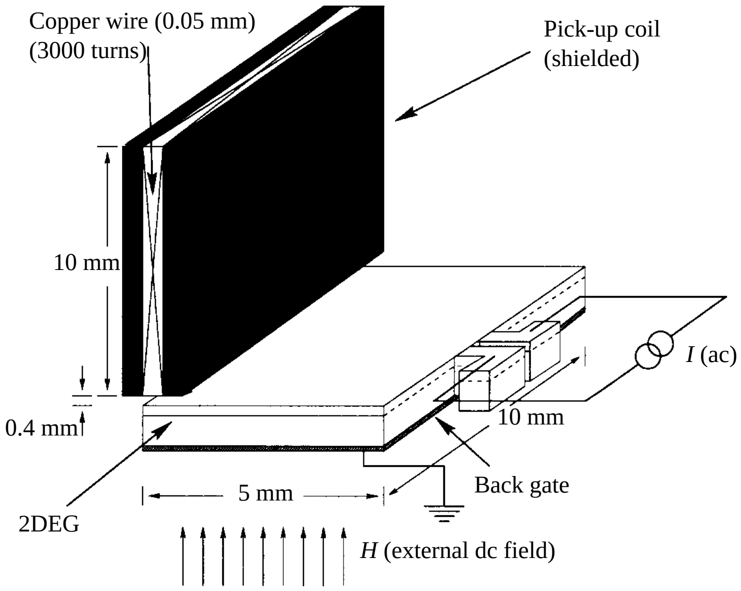

Fig. 1. Experimental setup. The pick-up coil is fixed in place, 0.4 mm above the physical edge of the 2DEG sample. An alternating current is driven through the sample using two ohmic contacts alloyed on the opposite side to the pick-up coil. Using this setup, the pick-up coil is sensitive to an alternating current that flows along the edge underneath.

2. Experimental setup

The two-dimensional electron gas sample was fabricated from GaAs/AlGaAs heterostructures. A rectangular-shaped sample with carrier concentration of 2.4×10^{11} cm^{-2} and mobility 3.8×10^5 cm^2 V^{-1}s having typical dimensions of 10×10 mm^2 was cleaved from the wafer and ohmic Au/Ge/Ni contacts were alloyed on the *same* side of the sample. A 3000-turns pick-up coil, made of copper wire with a diameter of 50 μm was placed 0.4 mm above the physical edge of the sample, opposite to the one with the ohmic contacts. The area of the pick-up coil turns varied from 2×2 mm^2 to 10×10 mm^2 so that the effective area of the coil was 5×5 mm^2.

A schematic view of the experimental setup and the position of the pick-up coil relative to the sample is shown in Fig. 1. An alternating current at frequency of 26 KHz, driven through the sample, produced an electromotive force at the same frequency in the pick-up coil circuit. The latter was measured using a standard lock-in technique. A grounded metallic shield made of brass foil was used to screen any direct electrostatic coupling between the pick-up coil and the sample. Since the distance of the shield from the sample is relatively large ($\sim$400 μm) and because the dielectric constant of the media is an order of magnitude smaller than that of GaAs we do not expect the shield to significantly alter the potential distribution in the sample.

The voltage which develops across the pick-up coil depends on the distribution of the currents in the bar and on geometrical factors of the setup. Although the value of the pick-up voltage can be estimated theoretically [17] for any given distribution of the current, we have performed an experimental calibration of the response of our pick-up coil. We have found that for homogeneous current distribution in the bar, at frequency of 26 KHz, the voltage response of the pick-up coil was 100 nV μA^{-1}. In order to demonstrate the sensitivity of the pick-up coil to changes in the current distribution, we have deposited a 1000 Å thick and 500 μm wide Au film along the periphery of a sample having the same dimensions and geometry. In this case, the pick-up response increased to 185 nV μA^{-1} at the same frequency. The Au film provided another calibration for the

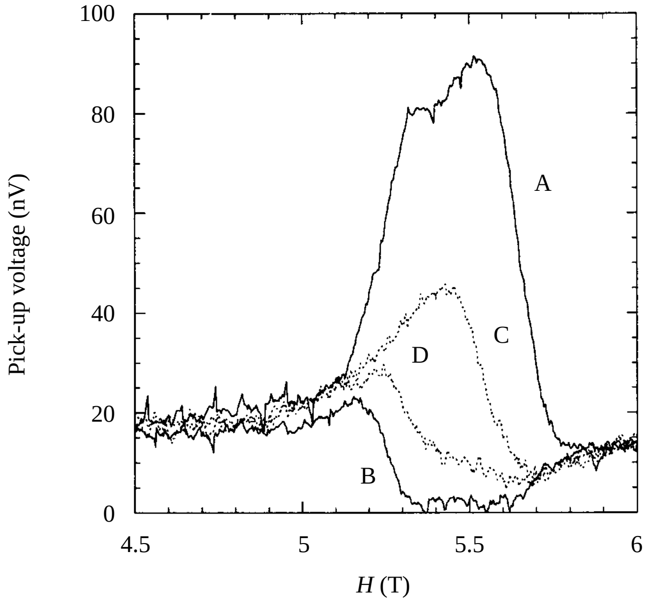

Fig. 2. Pick-up coil voltage for a Hall bar. The injected current is $I = 0.5\ \mu$A at 26 KHz. All curves were obtained for the same current amplitude and polarity of the contacts. A, positive magnetic field; back-gate at ground. B, Negative magnetic field; back-gate at ground. C, Positive magnetic field; back-gate potential is floating. D, Negative magnetic field; back-gate potential is floating.

pick-up coil. By knowing the current in the film, and its frequency, we related the voltage in the pick-up coil circuit to the current flowing in the sample.

3. Hall bar experiment

Recently we showed two important features of the IQHE [16]. In the quantum Hall plateaus, the states at the Fermi energy are located *only* along the physical edge of the sample. Hence, these states are at the contact potential. Furthermore, we proved that the 2DEG is sensitive to external potentials that may exist near the sample. In particular a grounded back-gate situated $\sim$350 μm from the 2DEG can alter the voltage profile in the sample.

The pick-up coil was mounted 0.4 mm above the physical edge of the sample (Fig. 1). Its location produces high sensitivity to current that flows along the edge underneath. In a Hall bar, the magnetic field determines the polarity of the edges so that, for a certain direction of the field one edge is at the applied voltage while the second edge is at ground and vice versa. In the IQHE plateaus the 2DEG becomes an insulator in the sense that it cannot screen external electric fields. It implies that the potential at the interior of the sample will be the back-gate potential, namely ground. This feature results in a voltage profile which is zero at one edge, zero in the interior, and reaches the applied voltage at the second edge. If the conducting states are located at the edges, then, regardless of the voltage distribution and the direction of the magnetic field, half of the current should flow along each one of the edges.

Figure 2 shows curves obtained for different back-gate voltages and directions of external magnetic field, whereas the polarity of the ohmic contacts remained fix. The source-drain current was 0.5 μA which is responsible for the background signal of the pick-up coil, outside the plateau region. The latter results from the zero field current distribution and is not related to the IQHE. Graph A corresponds to the case where the potential of the edge (underneath the pick-up coil) relative to the back-gate is at the applied voltage V and the second is at ground, namely at the back-gate potential. As clearly follows from the curves, the entire injected current in graph A flows close to the edge beneath the pick-up coil. The pick-up voltage (95 nV) is the maximal according to our calibration. In graph B the current flows along the edge of the opposite sample. It means that upon changing the direction of the magnetic field the polarity of the edges changed and therefore all the applied voltage drops on the edge opposite to the pick-up coil. This indicates that the injected current can be 'shifted' from one edge to another by reversing the direction of magnetic field which changes the polarity of Hall voltage. This proves that the distribution of the injected current depends on the electrostatics in the sample only. The vanishing signal for graph B is significant since it indicates that there is almost no current flowing near the edge underneath the pick-up coil. This is contradictory to the edge state theory. Curves C (positive field) and D (negative field) show the results for a sample with a floating back-gate potential. One can clearly see that the signal is not the maximal nor the minimal. It implies that current flows in bulk states in the 2DEG. We can conclude that Hall bar geometry is not different from Corbino geometry in the sense that edge states define the potential of the 2DEG periphery but has no importance as for carrying the Hall current.

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