Direct Observation of Edge Channels in the Integer Quantum Hall Regime

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The (differential) lateral photoeffect has been used as an imaging technique to study edge channel transport in a two-dimensional electron gas under quantum Hall conditions. By controlling the total number of electrons as well as the gradient in the electron concentration, we are able to image the edge channels. The observed width of the channels is in quantitative agreement with the theoretically predicted compressible and incompressible regions in the integer quantum Hall regime.

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Edge channels play a crucial role in the magnetoquantum transport phenomena in two-dimensional electron gases (2DEG's) under quantum Hall (QH) conditions [1]. The confining potential near the boundaries of a 2DEG bends the Landau levels and edge channels are formed at the intersections with the constant Fermi level. This results in a steplike dependence of the electron concentration on position near the sample edges. It has been shown theoretically [2,3] that compressible (partly filled Landau levels) and incompressible strips (fully filled Landau levels) are formed if long-range Coulomb interaction and the effect of screening in high magnetic fields is taken into account. The compressible strips are predicted to be much wider than the incompressible ones and their widths depend only on the electron concentration gradient for a given magnetic field.

There have been numerous experiments convincingly demonstrating the applicability of the edge state model. Almost a decade ago, measurements on Hall bar devices with peripheral and interior contacts [4–6] already showed that in QH plateaus the voltage drops in narrow regions close to the sample edges. Magnetotransport experiments using either quantum-point contacts [7] or contacts with a cross gate [8,9] proved the possibility to selectively populate and detect edge channels. Contactless spatially resolved techniques additionally reveal the edge character of the electrical transport in magnetically quantized 2DEG systems [10–13]. The Hall potential distribution was obtained by utilizing the electro-optic effect in GaAs [10]. The fountain pressure of superfluid He was used to show where dissipation takes place under QH conditions [11]. Nonequilibrium population of edge states was made clear by photoconductivity measurements in the far infrared. An increased cyclotron resonance amplitude was observed at the edge where nonequilibrium populated states propagate [12]. By scanning an intense beam of phonons across an entire area of the 2DEG, electron-phonon interaction has been studied by measuring the change in the two-terminal resistance [13]. Although all of these experimental results provide qualitative confirmations of theoretical predictions about edge states, numerical values of the spatial separation and the width of the edge channels themselves are scarce. Only recently experimental evidence for finite-width edge channels was given: The breakdown of the integer and fractional QH effect in a narrow 2DEG could only be explained if the band of edge states were much wider than the magnetic length [14].

Quantitative information about edge states can only be obtained either by an enhancement of the spatial resolution of the detection technique or by substantially increasing the edge channel separation and width. In this Letter, we show that positions and widths of edge states can indeed be controlled by an in-grown gate and directly detected by the (differential) lateral photoelectric effect.

The sample used in this work consists of two parallel layer structures: a $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructure containing a 2DEG located 75 nm below the surface on top of a two-dimensional hole gas (2DHG), formed by a δ-doped Be layer 795 nm below the surface. This device is basically the same as we have used previously [15], but without the AlAs etch-stop layer in between the 2DHG and the 2DEG. Additionally, before the actual device was grown, a $GaAs/Al_{0.33}Ga_{0.67}As$ superlattice (25 Å/25 Å 100×) had been grown to improve the sample quality. The 2DEG has an electron concentration of 4.5×10^{11} cm^{-2} and an electron mobility of 5.0×10^5 cm^2/V s after illumination at 1.2 K. From van der Pauw measurements on a different sample from the same wafer we derive a hole concentration and mobility of 2.3×10^{12} cm^2 and 85 cm^2/V s, respectively. A Hall bar (5×2 mm^2) was defined by wet-chemical etching and 8 Ohmic contacts were made to the 2DEG, using Ni/AuGe/Au as a contact material. Electrical contact to the 2DHG was made by two large contacts (Zn/Au) on both sides of the Hall bar, see Fig. 1(a). The 2DHG was used to control the electron concentration (V_{G1}) and also to create a gradient in the electron concentration (V_{G2}) across the width of the Hall bar. The sample was mounted in a split-coil cryomagnet with an optical access. Light from a He-Ne laser ($\lambda = 633$ nm) was coupled into a fiber, the end of which sits on a parallel bimorph piezoelectric crystal attached to an x-y translation stage. The light emerging from the fiber was then focused onto the sample, forming a spot approximately 15 μm in diameter.

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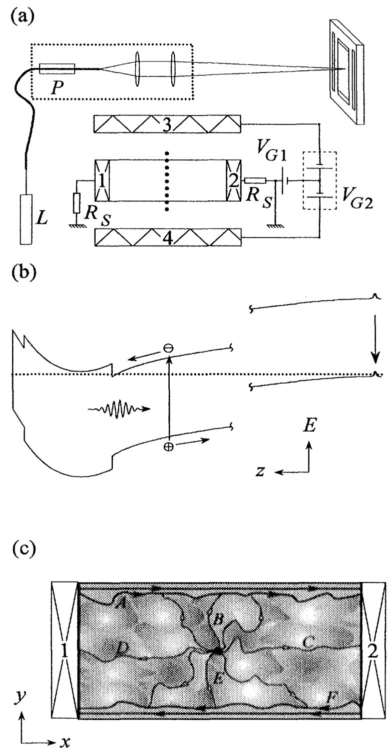

FIG. 1. (a) Setup and top view of the sample used in this work. Light from a He-Ne laser (L) is coupled into a fiber, the end of which is attached to a parallel bimorph piezoelectric crystal (P). The elements in the dotted box are mounted on an x-y translation stage. The scan direction across the sample is indicated by the black dots (y direction). The (differential) lateral photovoltage is measured across contacts 1 and 2; contacts 3 and 4 are connected to the 2DHG. The total number of electrons in the 2DEG is controlled by voltage source V_{G1}, while voltage source V_{G2} is used to generate the gradient in the electron concentration. The side arms and side contacts to the 2DEG have been omitted for clarity. (b) Schematic picture of the band structure of the device, consisting of a heterostructure and a δ-doped Be layer (arrow). (c) Illustration of current paths in a Hall bar under QH conditions. The edge states are labeled by A and F and $B-E$ show the highly resistive percolating paths from the spot position to the contacts.

The laser power incident on the sample was approximately 1 μW. A slight increase in temperature of the illuminated area which may result does not noticeably influence the photosignal. In contrast to other spatially resolved techniques, in our experiments, the light spot does not interact with the edge channels. The spot acts as a current injecting contact, and can be regarded to be a thermalizing electron reservoir in the same way as a metallic contact. The spot can be scanned across the sample in the x and y directions, whereas the spot position can be modulated by applying an ac voltage on the piezoelectric crystal.

All measurements presented here were performed in a magnetic field which was directed perpendicular to the conducting layers at a temperature of 1.2 K under a constant background (daylight) illumination. The band diagram given in Fig. 1(b) shows schematically that the photons entering the sample on the n-type side of the heterostructure generate electron-hole pairs in the GaAs at the point of illumination. The built-in electric field separates the electron-hole pairs and a photocurrent develops between the 2DEG and the 2DHG. The electrons entering the 2DEG flow laterally away from the illuminated spot and give rise to the lateral voltage drop in the 2DEG. Finally, the electrons flow to the 2DHG via the shunt resistors R_S (10 kΩ) where they recombine with the holes.

At room temperature and zero magnetic field, the voltage difference $V_1 - V_2 \equiv V_{12}$ measured across contacts 1 and 2 depends linearly on position in the x direction [16–18]. No dependence on position is observed if the scan is made across the width of the device (y direction). One intuitively expects that under QH conditions this picture changes dramatically.

Let us consider Fig. 1(c) which shows the case where one (spin-split) Landau level is filled and the Fermi level resides in the localized states. In this situation, two relatively high conducting edge channels (A and F) are present near the boundaries of the 2DEG, whereas the resistance between the spot position and one of the edges (paths of type $B-E$) becomes extremely high. In this respect, the illuminated spot can be regarded as a movable Corbino-like contact, acting as a current injector. If the illuminated spot moves to the upper edge in Fig. 1(c), most of the lateral current flows via paths of type B and A to contact 2 while at the opposite side of the sample the current predominantly flows via paths E and F to contact 1. If a scan is made across the width of the Hall bar, one expects to see an "image" of the lateral resistance between the spot position and the contacts 1 and 2.

Figure 2(a) presents the lateral photovoltage between contacts 1 and 2 (V_{12}) under QH conditions. The voltage V_{G1} is set to -1.5 V, and the magnetic field is 3.14 T,

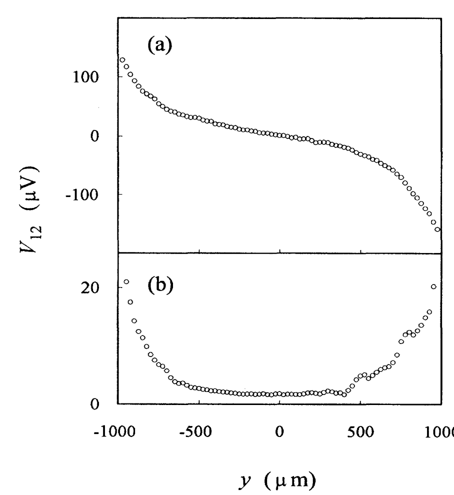

FIG. 2. (a) Scan across the width of the Hall bar showing the direct lateral photoeffect. (b) The corresponding differential lateral photoeffect.

corresponding to a bulk integer filling factor of 4. The scan has been performed in the middle of the Hall bar and the distance between the measured points is 25 μm. Clearly seen are the tails near the sample edges. The sign of the signal V_{12} corresponds to the direction in which most of the lateral electron current flows. It is clear from these data that the currents near the edges of the sample flow in opposite directions.

Figure 2(b) shows the first derivative of the photovoltage (differential lateral photoeffect) at a modulation frequency of 238 Hz. The amplitude of the modulation is 20 μm and is directed along the y axis. Although this differential photoeffect once more evidences the existence of edge channels just as in previously reported techniques [10–13], the spatial resolution of this technique is still not sufficiently high to resolve the channels individually. However, the positions and widths of the edge channels can be influenced by applying a gate voltage V_{G2} across the 2DHG [15].

Figure 3(a) shows the result for various values of V_{G2} at a fixed magnetic field of 3.14 T. Voltage source V_{G1} is set to -1.5 V to prevent a forward bias between the 2DHG and the 2DEG for large values of V_{G2}. The bottom trace in Fig. 3(a) is similar to the one in Fig. 2(b). We use

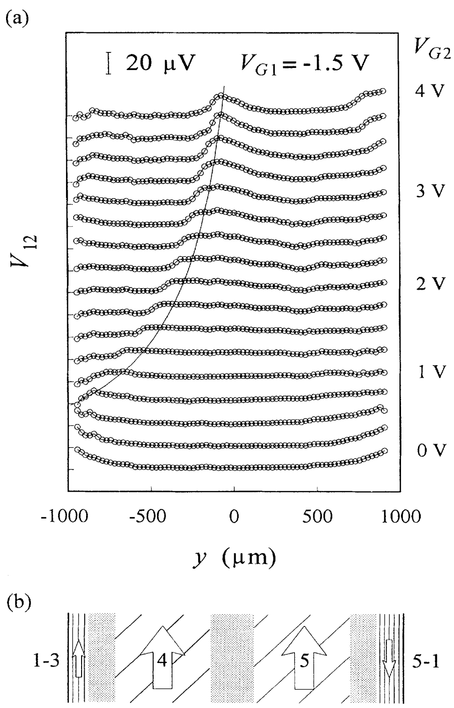

FIG. 3. (a) The differential lateral photovoltage V_{12} as a function of the transverse position for increasing gradients in the electron concentration determined by V_{G2}. The values of V_{G2} are indicated along the right hand side vertical axis. The scans are shifted by 20 μV with respect to each other. (b) A schematic picture of the positions and widths of the edge channels for $V_{G1} = -1.5$ V and $V_{G2} = 4$ V (uppermost curve) showing the two macroscopically wide channels (4 and 5) in the bulk of the sample.

a symmetric voltage source V_{G2} to keep the local filling factor constant at $y = 0$ μm (in this case 4). As the voltage across the 2DHG is increased, we see that a peak develops when $V_{G2} \approx 0.5$–0.75 V. This peak follows a hyperbola of constant electron concentration (local filling factor of 3.75) as V_{G2} is further increased.

We attribute this peak to the transition from the localized states to the extended states. On the left hand side of this peak, a macroscopically wide edge channel is formed, which we interpret as a compressible strip. While for $y < 0$ μm, the local electron concentration decreases as a function of V_{G2}, for $y > 0$ μm an energetically higher lying spin-split Landau level starts to be filled. At $V_{G2} = 4$ V, the total difference in the local filling factor across the width of the Hall bar is more than 2, so that we have two macroscopically wide compressible strips in the bulk of the sample flowing in the same direction, see Fig. 3(b). The corresponding transition peak of the second compressible strip (edge channel 5) is just seen at about $y \approx 750$ μm in the uppermost curve of Fig. 3(a). The distance between the two transition peaks is approximately 750 μm. The maximum width of a compressible strip is given by [2,3]

$$w = \frac{eB/h}{\Delta n/\Delta y}. \tag{1}$$

At $V_{G2} = 4$ V, $\Delta n/\Delta y$ is approximately 1×10^{11} cm^{-2}/mm. Substituting this value and a magnetic field of $B = 3.14$ T into Eq. (1), we indeed derive a maximum width w of about 750 μm.

The remaining three compressible strips are located near the edge where $y = -1000$ μm, where the local filling factor drops from 3 to 0. The five compressible strips going in the opposite direction are located near $y = 1000$ μm, where the local filling factor drops from 5 to 0. Since the electron concentration falls off very rapidly near the sample edges, the separation between these edge channels is far too small to be detected.

By contrast, the edge channels near $y = -1000$ μm can be made visible when the total number of electrons in the 2DEG is decreased while keeping the gradient in the electron concentration (and the magnetic field) constant. This situation is illustrated in Fig. 4. Voltage source V_{G2} is set to 4 V to create the constant electron concentration gradient and V_{G1} is decreased from -1.5 to -3.5 V with steps of 0.25 V. The solid lines labeled by the numbers 1–5 represent the positions *in the bulk* of the Hall bar where integer local filling factors are expected. The lower scan ($V_{G1} = -1.5$ V, $V_{G2} = 4$ V) is the same as the upper scan in Fig. 3(a). Two macroscopically wide channels are present in this scan. The first one is positioned between local filling factors 3 and 4 (edge channel 4) and the second is formed between the local filling factors 4 and 5 (edge channel 5). Each channel has a width of approximately 750 μm. From Fig. 4 it is clear that when V_{G1} is decreased, the innermost edge channel starts to broaden near $y = -1000$ μm (low-electron concentration

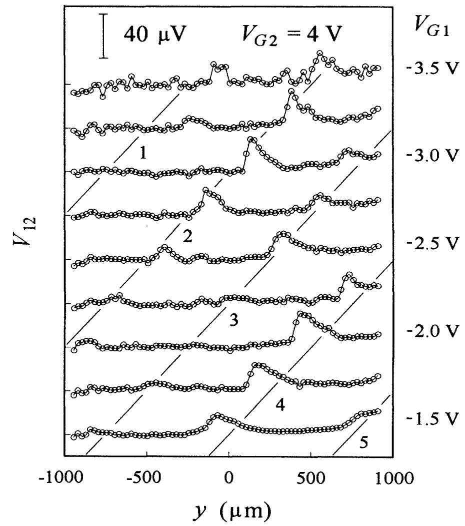

FIG. 4. The differential lateral photovoltage V_{12} as a function of position for a fixed gradient ($V_{G2} = 4$ V) and decreasing electron concentration (V_{G1}). The scans are shifted by 40 μV. The solid lines give the positions in the bulk of the Hall bar where integer local filling factors are expected. The values of V_{G1} are indicated along the right hand side vertical axis.

side of the sample), subsequently moves across the width of the Hall bar, and finally disappears near $y = 1000$ μm. This process is repeated until the electron gas near $y = -1000$ μm is fully depleted. Combining the results presented in Figs. 3 and 4 leads to the conclusion that four edge channels are present in the case where $V_{G1} = -1.5$ V and $V_{G2} = 0$ V, just as we derive from Hall measurements.

Looking more closely at Fig. 4, it is obvious that not all transition peaks are clearly resolved. Taking the measurement for which $V_{G1} = -2.25$ V, for example, the transition peak between edge channel 3 and edge channel 4 (spin gap, expected at $y \approx 0$ μm) is hardly visible. This can be understood in the following way. Edge channels 3 and 4 flow in the same direction (toward contact 2) and are spatially separated from the edge channels going in the opposite direction by an incompressible strip near $y \approx 750$ μm (Landau gap). This implies that all spot positions between $y \approx -700$ and ≈ 700 μm result in the same lateral photovoltage V_{12}. The differential photovoltage as measured by spot position modulation then gives a constant signal in this interval. For $V_{G1} = -2.50$ V, the electrons generated near local filling factor 3 have the possibility to scatter back to contact 1 via the edge channels going in the opposite direction. This results in the appearance of the transition peak near local filling factor 3. The increasing probability of backscattering also explains why the transition peaks at even local filling factors grow in amplitude when V_{G1} is lowered.

In conclusion, we have demonstrated that the (differential) photovoltage measured as a function of position under QH conditions gives quantitative information about the geometry of edge channels in a 2DEG with a built-in gradient in the electron concentration. Our measurements reveal the positions and the widths of the edge channels as a function of the local filling factor. The width of the edge channels, obtained from the spatially resolved measurements, is in perfect agreement with the theoretically predicted width of compressible strips by Chklovskii *et al.* [2,3].

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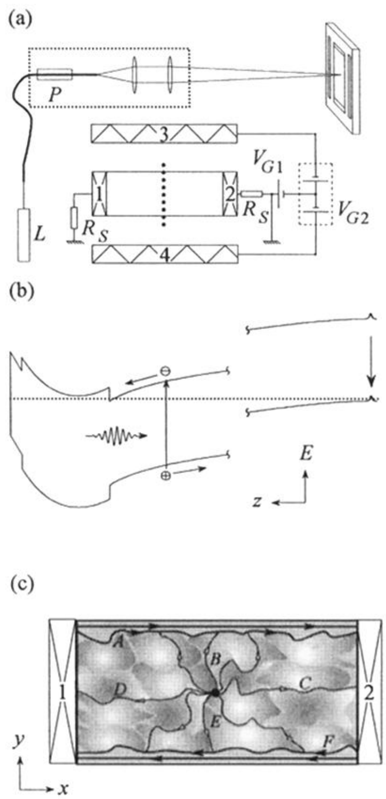

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