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Spatial potential distribution in GaAs/Al_xGa_{1-x}As heterostructures under quantum Hall conditions studied with the linear electro-optic effect

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We apply the linear electro-optic effect (Pockels effect) to investigate the spatial potential distribution in GaAs/Al_xGa_{1-x}As heterostructures under quantum Hall conditions. With this method, which avoids electrical contacts and thus does not disturb the potential distribution, we probe the electrostatic potential of the two-dimensional electron gas (2DEG) locally. Scanning across the sample we observe a steep change of the Hall potential at the edges of the 2DEG over a distance of about 70 μm, the lateral resolution of the experimental setup. This change at the edges accounts for more than 80% of the total Hall voltage. The remainder of the Hall potential is distributed in the interior of the sample and varies linearly with the position. The results are interpreted in terms of unscreened charge at the edges.

Until recently, experimental access to the problem of the current and potential distribution in two-dimensional electron gases (2DEGs) under quantum Hall conditions was possible only by attaching electrical contacts[1,2] to the interior of the 2DEG. These electrical contacts, however, disturb the system to be investigated. First, the contact acts as an equipotential probe; it is an electron reservoir with a thermalized electron distribution. Second, there are problems arising from the so-called Corbino effect. Finally, by attaching an electrical contact, the chemical potential rather than the electrostatic potential is measured. With these problems in mind it is not clear whether the effects of current bunching reported in Refs. 1 and 2 are due to the presence of the electrical contacts or due to an intrinsic effect in the 2DEG.

With respect to theoretical efforts, a variety of models has been developed, of which the Büttiker[3] model received much attention recently, because of its elegant description of both the quantum Hall effect (QHE) and conductance measurements on point contacts. Büttiker describes the Hall conductance in terms of transmission probabilities of edge states at the Fermi level. Note, however, that first, the model is only valid for very low current levels and second, that the model does not imply that current flows along the geometrical edges of the sample, since the spatial current distribution is determined by all the states below the Fermi level (which acquire a nonzero drift velocity from the electric field). A large number of theoretical papers[4] addresses this more complicated problem of calculating the spatial distribution of current (rather than just the total current). We will discuss some of this work later on in this paper, in relation to our experimental results.

Our technique to determine the spatial potential distribution is based on the linear electro-optic effect[5] or Pockels effect and makes use of the effect that GaAs becomes birefringent when an electric field is applied. The application of the Pockels effect is not uncommon in the field of testing[6] of GaAs chips, but has until recently[7] never been applied under QH conditions. Since it is a technique which does not involve electrical contacts, we avoid the problems mentioned above.

As we demonstrated,[8] one can apply the Pockels effect to determine the potential difference between the 2DEG and the back gate of a GaAs/Al_xGa_{1-x}As heterostructure. For a full discussion of our technique the reader is referred to Ref. 8. In this paper we restrict ourselves to the most relevant details. We used a 1.3-μm, 1-mW semiconductor solid-state laser beam, which is focused on a GaAs/Al_xGa_{1-x}As heterostructure with a 2DEG in the (001) plane. The light is polarized along the $\langle 100 \rangle$ axis and travels in the $\langle 001 \rangle$ direction. Since the GaAs is transparent to the wavelength of 1.3 μm, the light exits on the back of the substrate, on which we evaporated a thin (80 Å) semitransparent Au layer acting as an equipotential plate. When a potential difference V is present between the 2DEG and the Au layer, the components of the light polarized along the fast and slow axes obtain a phase difference $\Delta\Gamma$. It was shown[5,6] that this phase difference $\Delta\Gamma$ is equal to

$$\Delta\Gamma = (2\pi/\lambda) n_0^3 r_{41} \int_0^d E_\perp(x,y,z)\,dz = (2\pi/\lambda) n_0^3 r_{41} V(x,y)\,, \tag{1}$$

where n_0 and r_{41} are the refractive index and the component of the electro-optic tensor of the GaAs, d is the thickness of the substrate, $E_\perp$ the component of the electric field perpendicular to the 2DEG, and λ the wavelength. The electric field parallel to the 2DEG does not enter this expression. If we position a quarter-wave plate and a polarizer in front of the detector the transmitted light intensity varies almost linearly with the phase difference $\Delta\Gamma$ and thus with the applied potential difference between the 2DEG and the Au layer.

Since we do not want the incident laser beam to ionize additional donors and thus disturb the potential distribution, we apply a constant background illumination which empties all donor states in the $Al_xGa_{1-x}As$. We carefully selected a $GaAs/Al_xGa_{1-x}As$ heterostructure to ensure that even under illumination there is no parallel conduction in the $Al_xGa_{1-x}As$ layer. This is essential, because parallel conduction might cause a large potential drop in the $Al_xGa_{1-x}As$. Since the $Al_xGa_{1-x}As$ also shows the Pockels effect, additional unwanted phase shifts in the transmitted light might then occur. However, as long as the $Al_xGa_{1-x}As$ is insulating the potential drop in the very thin $Al_xGa_{1-x}As$ layer is negligibly small.

Our sample consists of a 400-μm GaAs substrate with on one side the 80-Å Au layer kept at ground potential. On the other side a 4-μm GaAs buffer layer, a 200-Å $Al_xGa_{1-x}As$ spacer layer, a 400-Å $Al_xGa_{1-x}As$ Si-doped ($n=2\times10^{24}$ m^{-3}) layer (both with $x=0.3$), and a 180-Å GaAs cap layer are grown. The sample has a rectangular geometry of 5.4-mm length and 2-mm width without side arms. Current contacts (In) were alloyed into the 2DEG at both ends (5.4 mm apart). Prior to our experiments we checked the homogeneity of our sample with a laser-scan technique to be sure that no interruptions of the 2DEG (Ref. 9) or other major defects are present.

To avoid interference effects the sample is slightly tilted from normal incidence ($\approx 7°$). Due to this tilt angle, electric fields parallel to the 2DEG also enter Eq. (1). The impact of the error introduced by this tilting will be discussed later on in relation to the presence of fringing fields. As the potential differences to be detected are fairly small we apply an alternating current (235 Hz) through the 2DEG and thus modulate the transmitted light intensity. The detector output is hence measured with a lock-in technique. We carefully checked that the measured signals had neither an out-of-phase component nor a double-frequency component. In order to determine the local potential in the 2DEG we first perform a calibration measurement. To this end an alternating voltage of 5.6 V p.p. is applied between the 2DEG and the Au layer (which is at ground potential) and the resulting detector signal is measured. Next, an alternating current of known amplitude is sent through the 2DEG (with one current contact and the Au layer at ground potential) and again the lock-in signal is measured. Both measurements are taken at the same position of the laser beam. The ratio of the detected intensities in these two measurements yields the unknown potential at the position of the laser beam for the case of the alternating current flowing through the 2DEG. Subsequently the laser beam is scanned across the surface of the sample step by step. At each spot the calibration procedure is repeated. We checked that the results do not depend on the amplitude of the voltage applied in the calibration measurement.

The result of a two-point resistance measurement of this sample as a function of magnetic field is shown in Fig. 1. Due to the two-point character of the measurement both Hall plateaus and Shubnikov–de Haas oscillations are visible. The temperature in all experiments is 1.5 K with the sample submerged in superfluid ^{4}He (in order to avoid both disturbing influences of boiling ^{4}He in our optical experiments and unwanted heating effects). The applied current is sufficiently low to avoid heating effects. From the measurements presented in Fig. 1 an electron concentration of 5.0×10^{15} m^{-2} and a mobility of 20 m^2/V s are obtained. The results of two line scans made in the middle between the current contacts are plotted in Fig. 2. Error bars are indicated. These scans which give representative results are made at 5.0 and 5.25 T (see Fig. 1) at a current of 5 μA. The edges of the Hall bar are at ± 1 mm.

A striking result of these measurements is the observation of a steep increase of the Hall potential at the edges of the 2DEG. The presence of such a steep increase could be deduced only indirectly in Ref. 7. The width of the regions of steeply increasing potential is of the same order as the focal diameter of the spot of light (70 μm, dif-

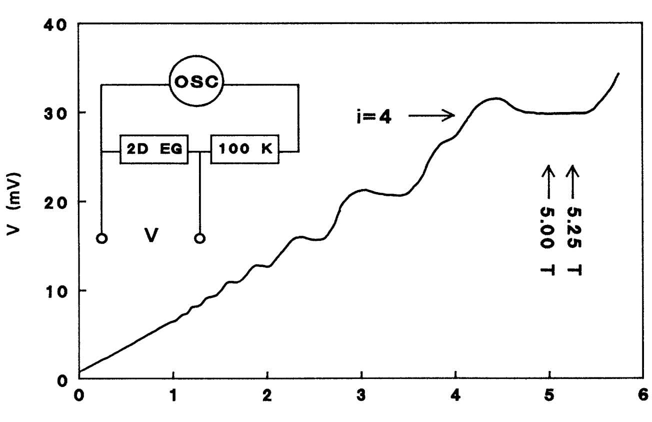

FIG. 1. Plot of the voltage across the sample vs magnetic field at a current of 5 μA_{eff}. The two-point experiment shows both plateaus and Shubnikov–de Haas oscillations. The arrows indicate the magnetic field at which line scans of the potential are made.

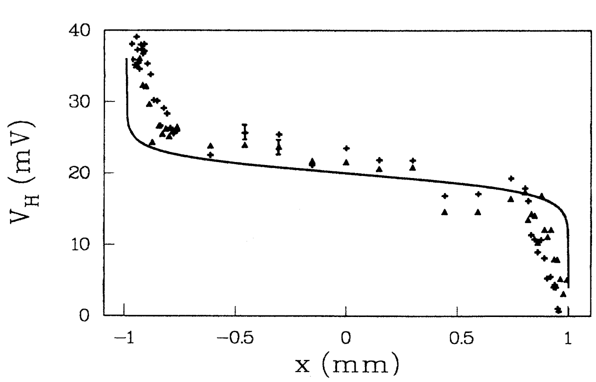

FIG. 2. Results of two line scans of the potential at magnetic fields of 5.0 T (▲) and 5.25 T (+). The solid line is the result of a model calculation.

fraction limited). It is thus possible that the true potential rise is steeper in reality. In the interior of the Hall bar the potential shows a small linear increase. The step in the potential at 0.4 mm is reproducible and is associated with a defect in the material. Other samples do not show such a step. It is clear from Fig. 2 that within experimental error the potential distribution is the same in the whole plateau region. Furthermore, these two scans are representative for all plateau regions with sufficiently developed plateaus.

The observed steep increase of the potential is not due to fringing fields at the edges. We prove the absence of fringing fields by carrying out experiments under circumstances where the QHE is absent, i.e., at temperatures of 50 K and at low temperatures but with a high current level (50 μA) where the QHE breaks down. In these experiments fringing effects, if present at all, should show up. We find a linear dependence of the Hall potential as a function of position across the Hall bar. The measured potential difference is equal to the Hall voltage measured electrically on the Hall probes. We thus rule out the presence of fringing fields. Further, the use of alternating currents with current reversal in the sample does not cause problems, since our results are the same when we apply a dc offset current (with this dc offset current we obtain a modulated current density which is not reversed). Therefore, we can rule out that a spatial switching of current paths affects our measurements. We also note that measurements performed during the same cooling-down cycle reproduce very well. To obtain a sufficiently high resolution we average every single measurement for more than 1 min.

Now we compare our experimental results with classical calculations. Let us assume a homogeneous sample with $\sigma_{xx} \neq 0$. Then it can easily be derived from $\mathrm{div}(\mathbf{J}) = 0$ and $\mathbf{J} = \vec{\sigma}\mathbf{E}$ (with $\mathbf{J}$ the current density, $\vec{\sigma}$ the local conductivity tensor, and $\mathbf{E}$ the in-plane electric field) that the Hall potential in this case is a linear function of position.[10] This behavior we indeed find experimentally at high temperatures and high current densities. However, for the quantized plateaus where $\sigma_{xx} = 0$ it has been shown[10,11] that a linear potential distribution cannot be realized self-consistently. In this case charge accumulates at the edges, and causes the potential to drop there rapidly. For the sake of simplicity let us assume that the charge is distributed as line charge with width ξ at the two edges $x = \pm W/2$ of the Hall bar of width W. If ξ is much smaller than W, then it follows from electrostatics that the Hall potential $V_H(x)$ in the plane of the 2DEG varies logarithmically across the Hall bar:

$$V_H(x) = \tfrac{1}{2} I R_H \left[\ln \frac{W}{\xi} \right]^{-1} \ln \left| \frac{x - W/2}{x + W/2} \right| , \quad \text{for } |x| \leq W/2 - \xi , \qquad (2)$$

with I the total current and $R_H = h/ie^2$ the Hall resistance in a plateau. (Note that the variation of V_H within ξ from the edge can be neglected for $\xi \ll W$.) MacDonald, Rice, and Brinkman[11] and Thouless[10] have calculated self-consistently the Hall potential in an ideal impurity-free sample with i completely filled Landau levels. Their results are remarkably close to Eq. (2), for edge charge width $\xi = il^2/\pi a$ [where $l = (\hbar/eB)^{1/2}$ is the magnetic length and $a \approx 10$ nm is the effective Bohr radius in GaAs]. In Fig. 2 we have plotted the potential distribution calculated from Eq. (2), with this value of ξ (evaluated at $B = 5$ T). The agreement with experiment is quite satisfactory in view of the fact that the theory contains no adjustable parameters.

When we assume the equation $\mathbf{J} = \vec{\sigma}\mathbf{E}$ to hold under QH conditions we can derive the current distribution from the potential distribution. This assumption is justified as long as we study effects on length scales which are much larger than the cyclotron radius. In the case $\sigma_{xx} \ll \sigma_{xy}$ it follows that $J_y = -\sigma_{xy} E_x$. Thus our measurements shown in Fig. 2 imply that more than 80% of the current flows along the edges, the remainder in the interior. Here we made the tacit assumption that σ_{xy} does not drastically vary across the sample.

As we mentioned in the introduction, different physical quantities are determined with the linear electro-optic effect and the measurements which use electrical contacts (electrostatic and chemical potential, respectively). Thus even apart from disturbances introduced by electrical contacts, we do not expect *a priori* that the two experiments yield the same results. To illustrate this difference we alloyed electrical contacts into the interior of the 2DEG and performed a Hall experiment. The results are presented in Fig. 3. It is clear that these measurements imply a current distribution which is completely different from what we measured without the alloyed electrical contacts.

In conclusion, we have shown that the Pockels experiments under quantum Hall conditions reveal the presence of an inhomogeneous electric-field distribution. These measurements are in agreement with a classical calculation in terms of line charge along the geometrical edges. Moreover, our measurements clearly demonstrate that experiments, in which electrical contacts alloyed in the interior of the sample are used, disturb the potential distribution in the sample.

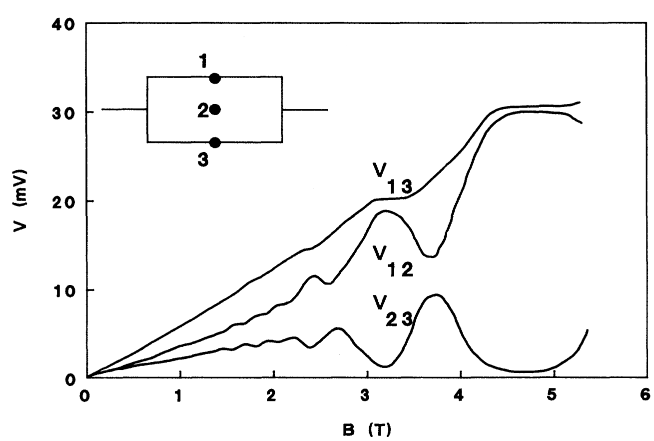

FIG. 3. Hall potential measurement as a function of B between the contacts indicated. Contrary to the results of the Pockels experiment, the current distribution seems to depend strongly on the magnitude of B in this case.

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