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Spatial potential distribution in GaAs/Al$_x$Ga$_{1-x}$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$_x$Ga$_{1-x}$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 locally. Scanning across the width of the sample inside a quantized Hall plateau we observe a steep change of the Hall potential at the edges of the two-dimensional electron gas. This steep change occurs over a distance of about 70 μm, which is the lateral resolution of the experimental set-up. More than 80% of the total Hall voltage is concentrated near the edges. 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 If the plateau region is left or if the quantized Hall conditions are violated by increasing the temperature or current level the Hall potential becomes a linear function of position.

1. Introduction

Measurements of an electrostatic potential difference are usually carried out by attaching electrical contacts or potential probes to the system under study. It is generally accepted, though, that the presence of these electrical contacts disturbs the potential distribution. This certainly holds for measurements of the potential distribution in two-dimensional electron gases under quantized Hall conditions.

The contact introduces an equipotential, which gives rise to the so-called Corbino effect, it thermalizes the electron distribution and finally, by attaching an electrical contact, the electrochemical 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. [1,2] are due to the presence of the electrical contacts or due to an intrinsic effect in the two-dimensional electron gas.

Fortunately the properties of the GaAs/Al$_x$Ga$_{1-x}$As heterostructure allow for an optical technique to determine the spatial potential distribution under quantized Hall conditions. This technique makes use of the effect that GaAs becomes birefringent when an electric field is applied, the linear electro-optic effect or Pockels effect. The application of the Pockels effect is not uncommon in the field of testing of GaAs chips [3], but has until recently never been applied under quantized Hall conditions. Since it is a technique which does not involve electrical contacts we avoid the problems mentioned above.

2. Details of the experimental setup

The beam of a 1.3 μm, 1 mW semiconductor solid-state laser is focused, with a focal diameter of 70 μm, on a GaAs/Al$_x$Ga$_{1-x}$As heterostructure with a two-dimensional electron gas in the

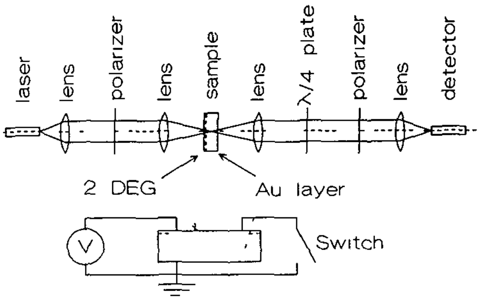

Fig 1 Experimental set-up, the electrical circuit is indicated schematically

(001) plane, see fig. 1. The light is polarized along the ⟨100⟩ axis and travels in the ⟨001⟩ 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 (8 nm) semi-transparent Au-layer acting as an equipotential plane. When a potential difference V is present between the two-dimensional electron gas and the Au-layer, the components of the light polarized along the fast and slow axes obtain a phase difference. It was shown [3] that this phase difference $\Delta\Gamma$ is equal to

$$\Delta\Gamma = (2\pi/\lambda) n_0^3 r_{41} \int_0^d E_z(x, y, z)\,\mathrm{d}z = (2\pi/\lambda) n_0^3 r_{41} V(x, y), \qquad (1)$$

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_z the component of the electric field perpendicular to the two-dimensional electron gas and λ the wavelength. The electric field parallel to the two-dimensional electron gas 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 applied potential difference between the two-dimensional electron gas 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 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 8 nm Au-layer kept at ground potential. On the other side a 4 μm GaAs buffer layer, a 20 nm $Al_xGa_{1-x}As$ spacer layer, a 40 nm $Al_xGa_{1-x}As$ Si-doped ($n_{Si} = 2 \times 10^{24}\ m^{-3}$) layer (both with $x = 0.3$) and a 18 nm 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 two-dimensional electron gas at both ends, 5.4 mm apart.

To avoid interference effects the sample is slightly tilted from normal incidence (~ 7°). Due to this tilt angle, electric fields parallel to the two-dimensional electron gas 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 two-dimensional electron gas and thus modulate the transmitted light intensity. The detector output is hence measured with a lock-in technique. We 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 two-dimensional electron gas we first perform a calibration measurement. To this end an alternating voltage of 5.6 V_{pp} is applied between the two-dimensional electron gas 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 two-dimensional electron gas, 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 two-dimensional electron gas. Subsequently the laser beam is scanned across the surface of the sample step by step. At each spot the calibration procedure is repeated. The results do not depend on the amplitude of the voltage applied in the calibration measurement. Further, the use of alternating currents with current reversal in the sample does not cause any problems, since our results are the same if 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 spatial switching of current paths affects our measurements.

3. Results

The result of a two-point resistance measurement as a function of magnetic field is shown in fig. 2. Due to the two-point character of the method both Hall plateaus and Shubnikov–de Haas oscillations are visible. From fig. 2 an electron concentration of 5.0×10^{15} m^{-2} and a mobility of 20 m^2/V · s can be derived. In the following we subsequently present and discuss line scans of the potential made at the magnetic field values indicated in fig. 2. Unless indicated otherwise the temperature at which these scans are made is 1.5 K.

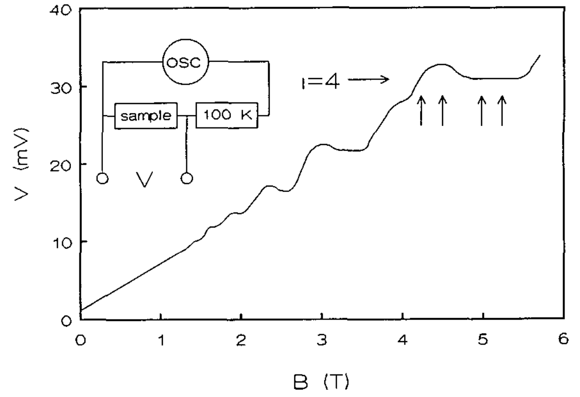

Fig 2 Voltage across the sample versus magnetic field ($I = 5$ μA, $T = 1.5$ K) Arrows indicate magnetic field values at which line scans are made

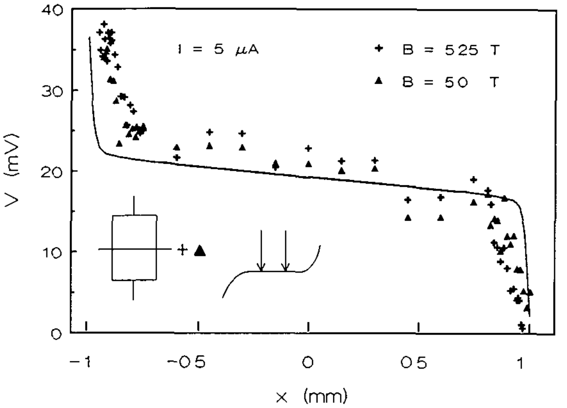

Fig 3 Line scans of the potential inside a quantized Hall plateau The solid line result from a model calculation

The first two scans, see fig. 3, are made inside the plateau with filling factor four. These are scans across the width of the Hall bar in the middle between the current contacts. The edges of the Hall bar are at ±1 mm. It is obvious from fig. 3 that the Hall potential steeply increases or decreases at the edges. In the interior a more or less linear dependence on position is observed. If the temperature is raised to 55 K, see fig. 4, the edge effects disappear and a linear dependence of the Hall potential on position is observed. This observation, in combination with the fact that the measured potential difference is equal to the Hall voltage measured electrically on the Hall probes, implies that there are no disturbing fringing fields at the edges. Prior to the presentation of further measurements we now first turn to the theoretical interpretation.

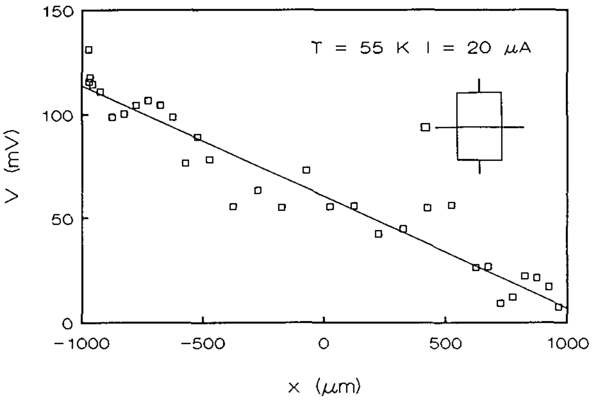

Fig 4 Line scan at 55 K, the straight line is a least-squares fit

Far away from the current contacts in a homogeneous sample also a homogeneous current distribution is expected to occur, as long as the diagonal component of the resistivity tensor $\rho_{xx} = 0$. This can easily be derived from the substitution of $j = \sigma E$ into div $j = 0$, with j the current density and σ the conductivity, which leads to

$$\sigma_{xx}(\partial^2 V/\partial x^2 + \partial^2 V/\partial y^2) = 0. \qquad (2)$$

If we assume the current to flow in the y-direction and if we assume an infinitely long sample, we can show that $\partial V/\partial y$ = constant, and hence $\partial^2 V/\partial y^2 = 0$. Thus it follows from eq. (2) that in the homogeneous case also $\partial^2 V/\partial x^2 = 0$ (if $\sigma_{xx} \neq 0$) and hence $\partial V/\partial x$ = constant, which implies a homogeneous Hall field and hence a homogeneous current distribution. This is what we observe at 55 K (fig. 4) where the quantized Hall effect is absent and hence $\sigma_{xx} \neq 0$.

If $\sigma_{xx} = 0$, however, this argument does not hold and the potential distribution has to be calculated by other means. This calculation has been carried out by MacDonald et al. [4] and Thouless [5]. They argue that at integer filling factor i a possibility exists to accommodate more charge per unit area in one Landau level. In an electric field all one electron wavefunctions are shifted in space. If the electric field depends on position this shift and hence the electron density depends on position too. In this way it is possible to maintain an integer filling factor throughout the sample despite charge redistribution. The potential and the excess density are related by Coulombs law. The resulting equation which has to be solved is [4,5]

$$V_H(x) = -\xi \int_{-W/2}^{+W/2} d^2 V_H(x_1)/\, dx_1^2 \times \ln|x_1 - x| \, dx_1, \qquad (3)$$

with $\xi = il^2/\pi a^*$, l the magnetic length, a^* the effective Bohr radius (~ 10 nm in GaAs) and W the width of the sample. This can be done numerically. For the limit of small ξ Beenakker [6] has shown that the solution of eq. (3) can be approximated accurately by:

$$V_H(x) = (I\rho_{xy}/2)(\ln W/\xi)^{-1} \times \ln|(x - W/2)/(x + W/2)|, \quad \text{for } |x| \le (W/2) - \xi. \qquad (4)$$

In our case ξ is small ($\xi = 1.6 \times 10^{-8}$ m for $B = 5$ T and a relative dielectric constant of 13 for GaAs). The variation of $V_H(x)$ within a distance ξ from the edges can be neglected. Eq. (4) approximates the potential as a result of line charge with width ξ at the two edges $x = \pm W/2$ of the Hall bar. In fig. 3 we have plotted the potential distribution calculated from eq. (4). The agreement with the experiment is remarkable in view of the fact that the theory does not contain any adjustable parameters.

Results of scans outside the plateau region are presented in figs. 5a and 5b. The almost linear

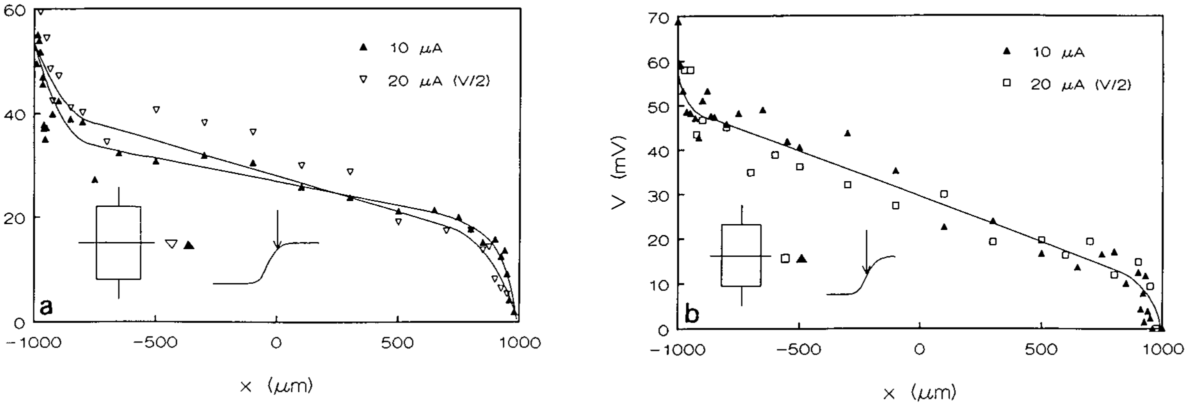

Fig. 5 Line scans at a magnetic field of 4.55 T (a) (top) and 4.25 T (b) (bottom), the lines are meant as a guide to the eye

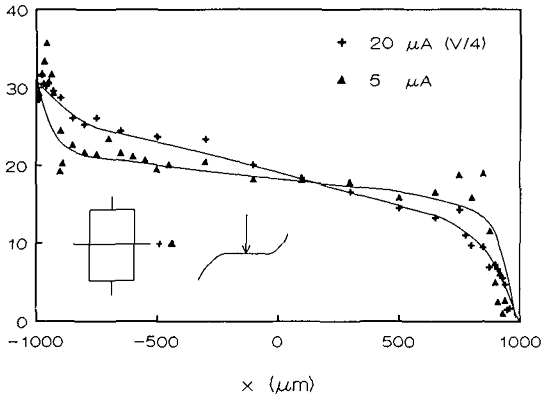

Fig 6. Line scans in the centre of a plateau at two current levels

increase of the Hall potential in the interior of the Hall bar becomes more pronounced when one leaves the plateau region. Also, outside the plateau the edge effects, although smaller, remain present. A similar transition to a linear potential distribution can be observed inside a plateau region if the current is increased, see fig. 6. This can be explained by heating effects which cause ρ_{xx} to increase.

These heating effects are most likely related to the strong piling up of electrons at the edges and the associated high electric fields. From eq. (3) we deduce that at a distance ξ from the edge with ($i=4$, $V_H = 0.1$ V), the Hall electric field equals $E_x = 3 \times 10^5$ V/m. This corresponds to a potential drop of 3 mV within a distance of 10 nm, which results in a substantial overlap of wavefunctions of adjacent Landau levels. Hence inelastic scattering processes may occur.

In between plateaus these high electric fields do not occur. The linear potential distribution which should develop if $\sigma_{xx} = \text{constant} \neq 0$ is associated by an excess electron concentration of [5]

$$n_{\text{excess}} = (2\kappa V_H/eW)x/\left(\tfrac{1}{4}W^2 - x^2\right)^{1/2}, \qquad (5)$$

with κ the dielectric constant and e the elementary charge. At a distance ξ from the edge and at $V_H = 0.1$ V, $B = 5$ T this results in $n_{\text{excess}} = 1.4 \times 10^{13}$ m^{-2}, which seems to be small regarding the magnitude of $n = 5.0 \times 10^{15}$ m^{-2}. However, since σ_{xx} can depend strongly on n, the condition σ_{xx} = constant will no longer be fulfilled, even for such a small deviation from a homogeneous electron distribution.

It is tempting to interpret the presence of edge effects in between the plateaus in terms of the above mentioned inhomogeneities induced by a large current. However, there are two major objections to such an interpretation. First, there should be a clear current dependence outside the plateau region as eq. (5) depends on V_H. This, however, is not what we observe, although this may be due to our limited range of currents used. Second, the potential distribution should be asymmetrical due to an electron excess at one edge and a shortage at the other edge. This is not the case in fig. 5.

Perhaps the clue to the presence of edge effects in between the plateaus can be found in the correspondence between the transition from inside to outside a plateau and the transition from low to high current inside a plateau. Both transitions are gradual. This resemblance probably indicates that the underlying physics of both transitions is similar. If we assume that the sample is inhomogeneous, it is possible that the quantized Hall effect breaks down locally if the current is increased. In an inhomogeneous sample even outside a plateau the quantized Hall conditions may still be fulfilled in part of the sample. In this case the transition from the situation in fig. 3 to fig. 4 is no longer abrupt.

We now turn to the influence of electrical contacts. In fig. 7 line scans along the length of the sample are presented. These scans are carried out at a current of 50 μA and $B = 5$ T. At this large current the sample is heated up to some extent, but the measuring time is considerably reduced. The influence of the ends of the Hall bar with the current contacts is clearly visible. Fig. 7 shows that the current enters at one corner of the sample and exits at the opposite corner, as expected theoretically.

The influence of internal electrical contacts is much less clear. In fig. 8 a scan at $B = 5$ T across such an internal electrical contact is shown. We also show a scan 1 mm below the internal contact. The contact is disconnected. Note, however,

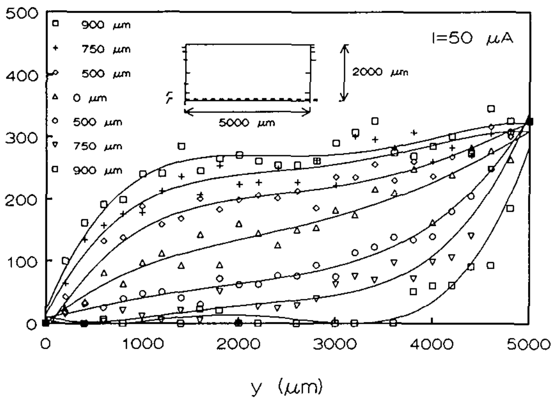

Fig 7 Line scans across the length of the sample, lines are a rather arbitrary fit with polynomials of order four $B = 5$ T

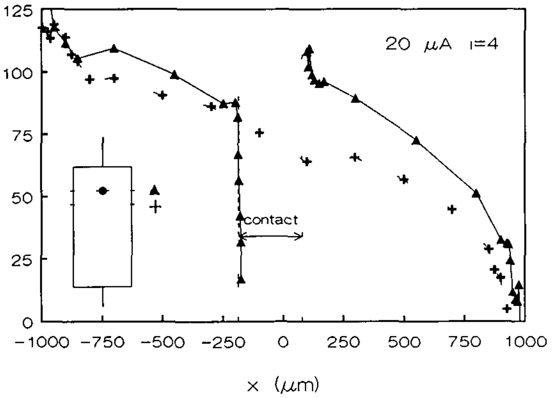

Fig 8 Line scan across and below an interior contact The lines are a connection of the data points, $B = 5$ T

that the result is not changed when we connect the contact to a lock-in amplifier with an input impedance of 100 MΩ to ground potential Apart from the edge effects at the boundary of the two-dimensional electron gas we see a sharp bending of the measured potential in the immediate neighbourhood of the contact The interpretation of this effect is yet unclear

We conclude from our experiments that the Hall potential distribution in a plateau region is well described by the presence of edge charge In between plateaus and at high current levels the Hall potential distribution becomes a linear function of position, with a gradual, sometimes incomplete change between both kinds of distributions This indicates the coexistence of both regions with $\sigma_{xx} = 0$ and regions with $\sigma_{xx} \neq 0$ under these circumstances

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