Hall photovoltage imaging of carrier flux in a 2DEG using an optical fibre

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ABSTRACT: We report experiments using a Hall photovoltage imaging technique to investigate the carrier transport in a two-dimensional electron gas (2DEG). A laser-beam is coupled into an optical fibre, which can be scanned by a mechanical cryogenic micropositioning device. This technique allows a resolution better than 5μm to visualise the potential profile of the 2DEG in a standard Hall bar device at low temperatures and in high magnetic fields. We see flux channels (10μm large) due to the edge confining potential and in agreement with the theory of skipping orbits. So-called light-induced Shubnikov-de Haas oscillations have been investigated near the edges.

1. INTRODUCTION

Experiments aimed at measuring the electrostatic potential distribution were initially carried out by attaching electric contacts to the interior of the 2DEG and measuring the voltage difference between adjacent contacts. These electric contacts however disturb the system under investigation. Real space-resolved contactless measurements are one alternative to interior contacts. Standard real-space resolved techniques (STM, SFM, SEM) have resolutions in the order of 0.1μm but are difficult to apply since the 2DEG is buried tens of nm under a semiconducting layer and high magnetic fields represent a complicated environment. Nevertheless Tessmer et al. (1998) succeeded in doing so.

Fontain (1988) et al. used for the first time the photoelectric effect in GaAs to inject carriers into the 2DEG: The sample is locally illuminated by a light spot with a diameter of ~100μm. This region of illumination acts as a current injection contact (photo-induced electrons) and can be scanned across the sample. These measurements were restricted to room temperaturs. In 1995 van Haren et al. extended the technique to measurements at liquid helium temperatures and high magnetic fields with a spot size of 25 μm. In 1997 Shaskin et al. improved the resolution to 5 μm. The method presented here represents an extension of this work. Here the light spot is not controlled by means of scanning mirrors from the exterior of a glass cryostat, but the positioning takes place within the cryostat by the means of an optical fibre as used for scanning near field optic microscopes (SNOMs).

2. EXPERIMENTAL SET-UP

Fig. 1 shows a scheme of the setup. A He-Ne laser beam is chopped with a frequency of ~100Hz and coupled into an optical fibre, the end of which is brought ~20μm close to the sample surface. An area of ~5μm^2 is illuminated with a power of ~0.1mW. All experiments are performed with the sample immersed in liquid He^4 at temperatures of 1.1K. At the point of illumination electron-hole pairs are generated in the GaAS layer. Electrons enter the 2DEG by diffusion, where they can propagate with the mobility of μ=3·10^6 cm^2 /Vs (mean free path l^*~15μm). To record an image of the carrier flux, the fiber is scanned across the Hall bar. The so-called lateral photovoltage (LPV) V_{12} between the contacts 1 and 2 is recorded as a function of the fibre position. A purely mechanic scanning device realises the positioning of the fibre. In 1995 Heil has shown that the resolution and reproducibility of such a versatile cryogenic scanning unit is 1μm within a scanning range of several mm.

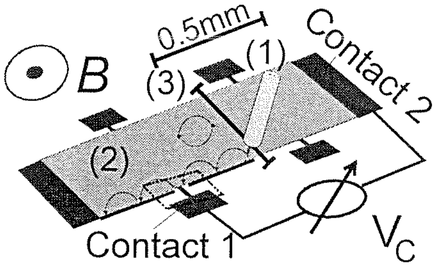

Fig. 1 : Experimental Set-up. (1) optical fibre, (2) Standard Hall bar, (3) position of line-scans

3. LINESCANS

Linescans have been performed across the sample as indicated in Fig. 1. The results for different magnetic fields from 0 to 6.3 T are shown in Fig. 2. The magnetic field corresponds to integer and non-integer filling factors. In both cases the lateral photoelectric voltage has opposite polarities at opposite edges. Together with the fact that the polarities reverse upon reversing the magnetic field, this points to the Hall-effect origin of the signal. At magnetic fields above 3T a strong response is observed only at the edge. In this field range at the edge a peak of approximately 10μm HWFM is observed. These experimental results were modeled by means of an integral equation for the self-consistent Hall voltage profile in an ideal impurity-free sample with i completely filled Landau levels. Beenakker (1991) has shown that in a Hall bar with width W the potential distribution as a function of the position x perpendicular to the current flux is given by

$$V_{12} = \frac{1}{2} I R_H \cdot \ln\left|\frac{x-W/2}{x+W/2}\right| \cdot \left(1+\ln\frac{W}{\varsigma}\right)^{-1} \quad \text{with} \quad \zeta = \frac{i l_B}{\pi \alpha^*}\ , \quad l_B = \sqrt{\frac{\hbar}{eB}} \quad \text{and} \quad \alpha^* = \frac{\varepsilon\hbar}{m^* e^2}\ ,$$

where l_B is the magnetic length, α^* is the effective Bohr radius and m^* is the effective mass. The

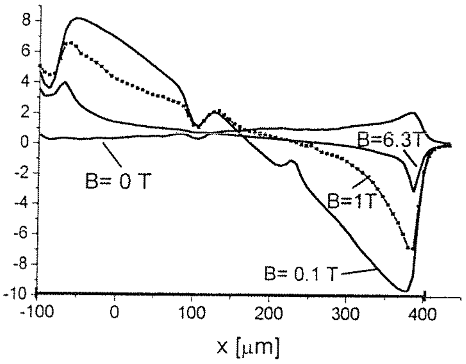

Fig. 2: Line-scans across the sample (line (3) in Fig.1) for different magnetic fields B. A strong response at high magnetic fields is only observed at the edges of the sample. With increasing magnetic field the lateral photo-voltage changes from linear space dependence to a logarithmic one. The breakdowns in the middle of the sample are caused by an optical gate structure, which covers partly the sample surface.

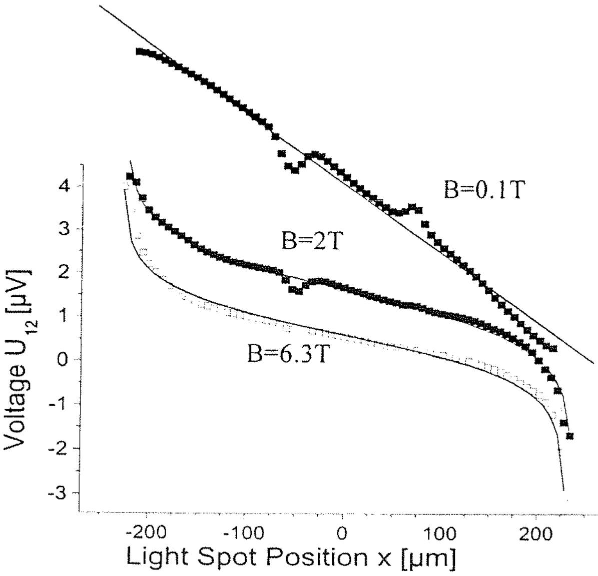

Fig. 3 : The region between the two peaks at opposite edges of the line-scans shown in Fig.2 are fitted with the theoretical self-consistant Hall voltage profile in an ideal impurity-free sample (see text). The line-scan at B=0.1T is fitted with a linear function.

fitting parameter is IR_H, where I is the current and R_H is the Hall resistance. IR_H is in the range of 12µV (6.3T) to 45µV (1T). Assuming that R_H=ih/e^2, this corresponds to a current in the order of 1nA.

From Fig.3 it is can be seen that the model is in a good agreement with the experimental observations at magnetic fields $B \geq 2$T. This proves that the measured signal corresponds to the confining potential in the 2DEG. However, the observed potential profile does not depend on the filling factor ν. In high magnetic fields the measurements always agree with the model calculation whether the filling factor is an integer value or not. As a consequence this would mean that at high magnetic fields the photo-induced electrons accumulate at the edges even if $\sigma_{xx} \neq 0$.

In 1991 Beenaker estimated the nonequilibrium current density $j(x)$ from the potential distribution V_{12} by $j(x) = \frac{en}{B} \bullet \frac{dV_{12}(x)}{dx}$

In Fig. 4 the $j(x)$ for the right half of the sample are plotted. From this it can be estimated that beyond filling factor 2 within 50µm near to the edge 75% of the total current flowes.

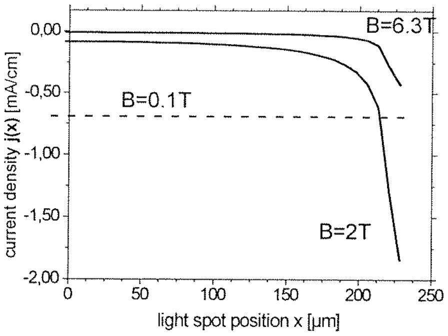

Fig. 4: The current density distribution at the right half of the sample obtained by deriving the fit function of Fig.3 and dividing by the corresponding magnetic fields. At B=0.1T the current density distribution is constant. With increasing field the edge contributes more and more to the total current.

4. IMAGING OF THE CONFINING POTENTIAL NEAR THE CONTACTS

The potential distributions at the edge at filling factor ν≤1 have been imaged. Ballistic carriers move inside the 2DEG on circular orbits (cyclotron radius r_c~nm) and thus cannot contribute to the signal. Only scattering processes permit them to propagate towards the contacts, where they can be detected. The carriers in vicinity of the 2DEG-edge (B) can skip along the border towards the contact 1. This produces the bright structures in Fig. 5(b) (next page). This phenomenon is in agreement with the theory of so-called "skipping orbits". Carriers from edge (A) skip away from contact 1 and cannot contribute to the signal. In Fig. 5(c) the magnetic field (6.3 T) is inverted and thus the carriers can skip only in the A-B direction. The bright signal corresponds to the carriers moving from edge (A) into the contact 1. The dark structures (negative signal) are created from carriers moving out of the contact I and skipping into contact II. Thus they create a negative signal.

5. LIGHT INDUCED QUANTUM EFFECTS

If V_{12} is recorded as a function of the magnetic field at position x indicated in Fig. 5, oscillations periodic in 1/B are clearly visible. The frequency of these so-called Light-Induced Shubnikov-de Haas Oscillations (LISHO) is direct proportional to the electron density of the 2DEG. The quantum limit is reached at B=4T. Spin splitting is visible above 1 T. The origin of the oscillations can be explained by Landau quantization of the electron states and the occurrence of back-scattering at non-integer filling factors.

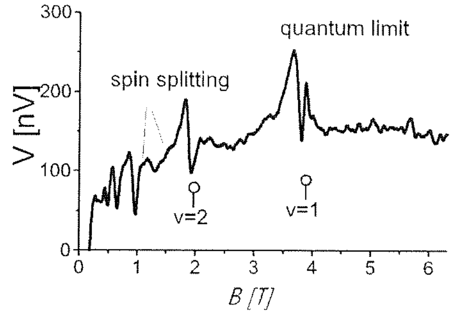

Fig. 6: V_{12} is recorded at position x in Fig. 5 as a function of the magnetic field B. The oscillations are proportional to 1/B.

6. CONCLUSION

A simple technique to image the confining potential in a standard Hall bar has been presented. A purely mechanical device scans an optical fibre. Carriers are injected locally due to the photoelectric effect without disturbing the system. The potential distribution near the edge and in vicinity of the contacts was nicely imaged. line-scans can be well described by the theoretical Hall voltage profile proving that the measured signal presents directly the potential distribution in the sample. The current density can be obtained by the derivative. At higher fields the potential profile is peaking near the edge with an HWFM of 10μm. This means that 75% of the total current moves within 50μm near the edge. So-called light-induced Shubnikov-de Haas oscillations have been observed near the edges.

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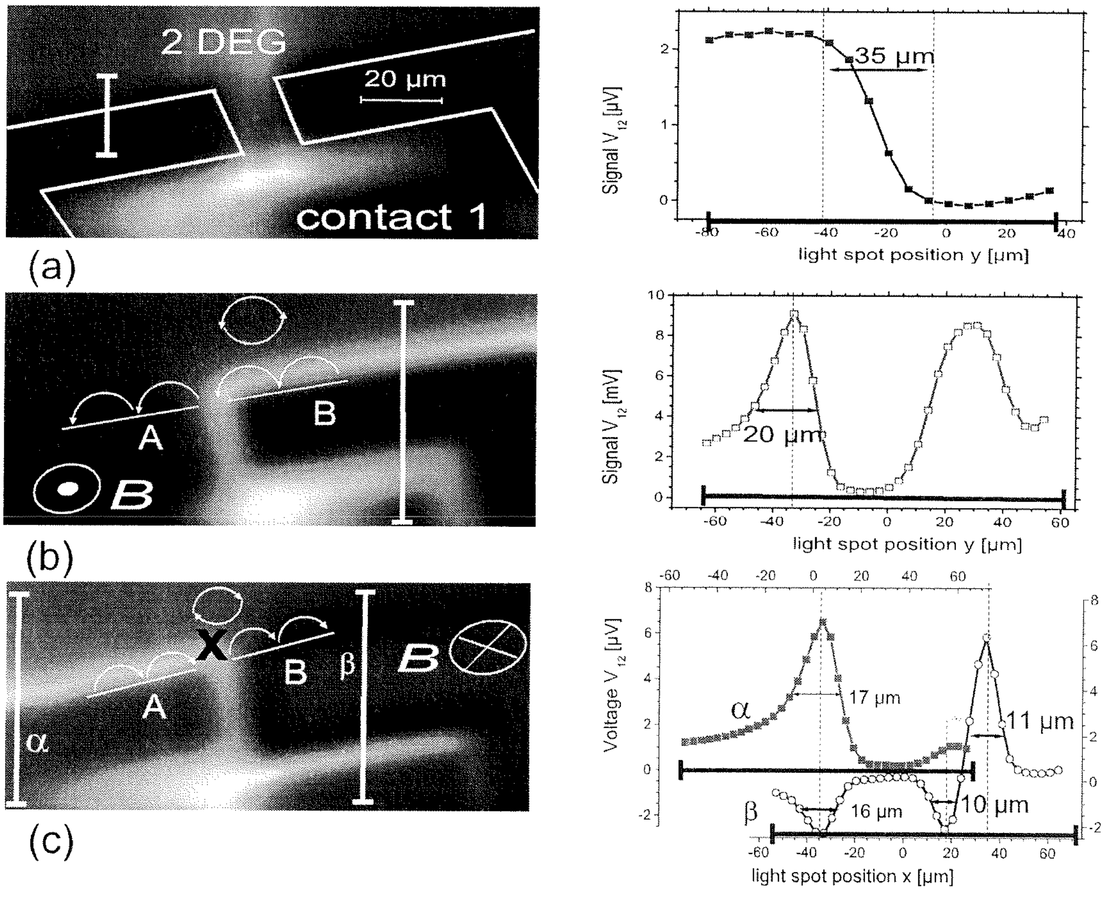

Fig. 5: Image of the lateral photoelectric voltage at (a) B=0T, (b) B=6.3T and (c) B=-6.3T. The images cover an area of 270x120μm with 40x18 data points. Line-scans are taken vertically through the images (a) – (c). The electrons injected in the bulk 2DEG are localised. Only at the vicinity of the edge the electrons can move in skipping orbits along the edge and reach the contact1, where they generate a positive signal (white). For B=-6.3T electrons can move out of contact 1 and skip towards contact 2, where they generate a negative signal (black)