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Charge screening in the quantum Hall regime probed by the lateral photoelectric effect

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Abstract

Electrons are photoelectrically injected into the two-dimensional electron system (2DES) near a standard AlGaAs–GaAs heterojunction by a focussed light spot. The photovoltage *in the plane of* the 2DES exhibits quantum oscillations with magnetic field that are basically out of phase with respect to the oscillations of the conductivity σ_{xx}. This is evidence for the influence of screening effects on the injected charge. At low filling factors a dip is superimposed on the maxima, which points to a competition between screening properties and the expected diffusion effects. © 2001 Elsevier Science B.V. All rights reserved.

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The ability to screen external electric fields, as well as their variation with magnetic field and spatial position, is one of the most intricate properties of the two-dimensional electron system (2DES) in the quantum Hall regime. A few years ago, the lateral photovoltage resulting from inhomogeneous illumination of the heterojunction containing the 2DES was first introduced as a direct and local probe of the electrical properties of a quantum Hall system [1]. The experimental results were qualitatively discussed using a model of outdiffusing electrons, but clear deviations from this model were also observed [1–3]. Here we demonstrate that the lateral photoelectric effect exhibits a direct signature of the screening and related effects.

Light is focused on the sample either by using room temperature scanning optics through windows in the cryostat [1], or by employing a single mode fiber a few microns above the sample surface in a cryogenic scanning device [4]. The sample is immersed in a pumped liquid helium bath ($T \sim 1.1$–$1.4\,\mathrm{K}$). The light spot diameter is approximately $20\,\mu\mathrm{m}$ in the first, and $5\,\mu\mathrm{m}$ in the second setup. Sample 1 was a standard GaAs–$\mathrm{Al}_{0.33}\mathrm{Ga}_{0.67}\mathrm{As}$ heterojunction. Sample

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2 was similar but with a separately contacted p-type δ-doped layer in the GaAs at 0.72 μm distance from the 2DES [1]. Both samples had a 2DES mobility $\mu \sim 50\,\mathrm{m^2/V\,s}$ and a 2DES density n of the order of $\sim 5\times10^{15}\,\mathrm{m^{-2}}$.

The light beam, with a wavelength of 630 nm and a power of the order of 1 μW, is chopped at a frequency near 70 Hz and the signal induced at two ohmic contacts at the perimeter of the rectangular sample (see Fig. 1a) is measured using a lock-in detector. The electron–hole pairs generated in the GaAs are spatially separated by the internal band bending so that the excess electrons are injected into the 2DES (Fig. 1b). The amplifier input impedance is high enough so that no external currents will flow in the case of sample 1. Sample 2, however, has been used with the p-layer either electrically floating or connected to the 2DES via two 10 kΩ resistors [1]. In the latter case external currents may flow. Internal lateral currents may flow in all cases, balanced by a spatially varying recombination current as sketched in Fig. 1c.

Characteristic experimental results are shown in Fig. 2 for two samples. As a reference, the upper traces in Fig. 2 display the measured oscillations of the transport parameters (conductivity $\sigma_{xx}(B)$, or resistivity $\rho_{xx}(B)$, B magnetic field), as measured on the same sample. The most important observation is that the magnitude of the photovoltage oscillations peaks near the minima of σ_{xx} (or ρ_{xx}). In case of sample 2, it does not depend on the exact configuration with respect to the connection of the p-layer.

The behavior in Fig. 2 is counterintuitive, as the qualitative models assumed that the signal would be controlled by the diffusion processes of the electrons and so be proportional to σ_{xx} [1–3]. Instead, the out-of-phase character of the photosignal with respect to the transport is a clear signature that the screening of the injected charge by the 2DES, which is inversely correlated to σ_{xx}, also controls the signal. A possible simple scaling with a $1/\sigma_{xx}$ Corbino-like resistance can be rejected from the asymmetric oscillation lineshape. Moreover, the asymmetry reflects the carrier density in the upper (screening) Landau level, and could therefore be a direct consequence of the screening as well.

Another remarkable feature that usually shows up in the data is that the maximum is accompanied by a superimposed sharp dip at low filling factors. An example is visible in Fig. 2a at $\nu = 6$ ($B \sim 4\,\mathrm{T}$). A similar phenomenon was also observed in a sample with mobility a nearly 10 times higher. From this, it is concluded that the signal is built up from two competing effects: the unexpected screening and the diffusion anticipated previously.

The shape of the signal near $B \sim 4\,\mathrm{T}$ in Fig. 2a is remarkably similar to the signal shape predicted theoretically for the drag transresistance [5] of two closely spaced interacting 2DESs. The transresis-

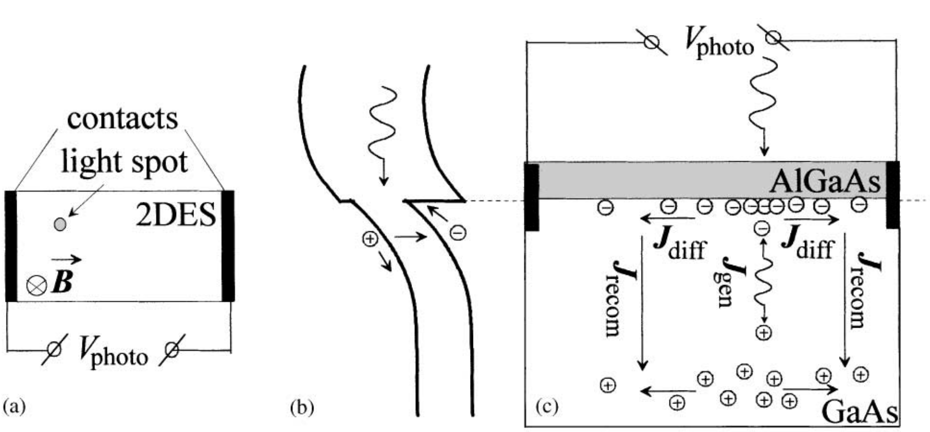
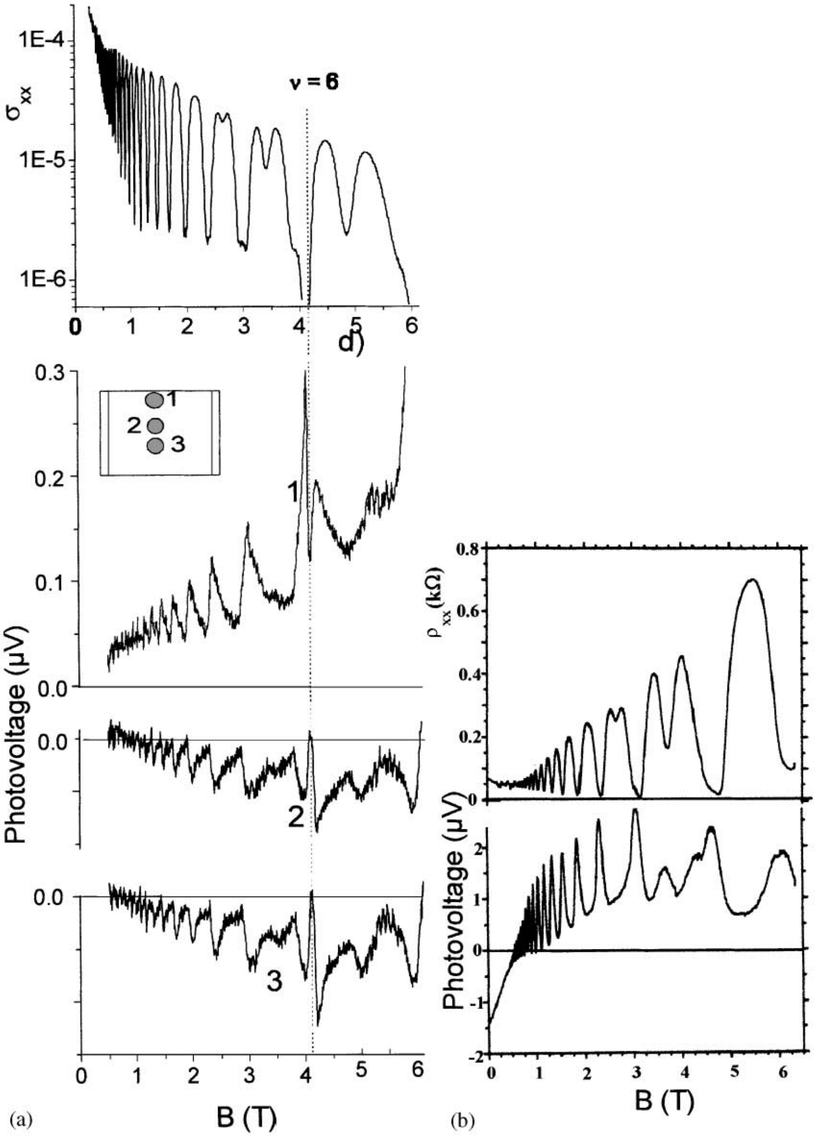


Fig. 1. (a) Lay-out of sample with contacts and light spot. (b) Schematic of heterojunction (c) Sketch of internal generation, diffusion and recombination currents. Note that none of the dimensions is on scale.



(a)

(b)

Fig. 2. Left: Sample 1 without, and right sample 2, with resistive p-layer. The upper traces in left and right give the Shubnikov de Haas oscillations of σ_{xx} (left) or ρ_{xx} (right). The photovoltage for (a) is given at three positions in the sample (see inset), the photovoltage for (b) is given for a position near the edge.

tance is the ratio of the voltage induced in one layer to the current imposed upon the other. Naturally, the transresistance is expected to be proportional to the (joint) density of states in the two layers and so to the conductivity. In the theory, however, the influence of the screening effects leads to almost the opposite dependence, except when the conductivity becomes extremely small. When combined, these effects lead to a double peak structure near the conductivity minima. Interestingly, it has not been possible to unambiguously observe this structure experimentally, because of the complicating influence of spin splitting effects that might be enhanced in drag [6,7]. More recently, however, it has been shown that the drag experiments are governed by entirely different, spin-related phenomena [8].

A competition between conductivity and screening is also observable in the attenuation of surface acoustic waves (SAW) [9] and the associated acoustoelectric effect [10]. The latter is the induced DC voltage as a result of the charge dragged along with the acoustic wave. Theoretical expressions exist for the induced DC acoustoelectric fields along (x, E_x) and across (y, i.e. Hall-like, E_y) the SAW propagation direction [10]:

$$E_x \propto \Gamma\left(\rho_{xx}\frac{\mathrm{d}\sigma_{xx}}{\mathrm{d}B} + \rho_{xy}\frac{\mathrm{d}\sigma_{xy}}{\mathrm{d}B}\right),$$

$$E_y \propto \Gamma\left(\rho_{xx}\frac{\mathrm{d}\sigma_{xy}}{\mathrm{d}B} - \rho_{xy}\frac{\mathrm{d}\sigma_{xx}}{\mathrm{d}B}\right).$$

The screening is contained in the SAW-attenuation $\Gamma = C(\sigma_{xx}/\sigma_m)/(1 + (\sigma_{xx}/\sigma_m)^2)$ where C and σ_m are constants. The terms in parentheses for E_i describe the charge transport. The close correspondence of these terms to the expressions for longitudinal and transverse (Nernst–Ettingshausen) thermopower should be noted [3]. A search for direct heating effects was made by investigating the power dependence of the photovoltage oscillations. From the entirely different signal shape at high power levels ($> 10\,\mu$W), consistent with thermopower, it is concluded that heating is not the origin of the signals discussed in the present work. It is natural, however, that the transport of the photo-injected charge in the present experiments is closely related to the transport of nonequilibrium charge distributions created by a temperature gradient. If in addition the screening is taken into account, the present experiment would have all the features contained in the above expressions. In general, there is no imposed directionality in the present case, so that the occurrence of an admixture of both terms is likely.

The field dependence of the terms in parentheses exhibits a very rich structure. In particular, the sign changing behavior of $\mathrm{d}\sigma_{xx}/\mathrm{d}B$ when traversing a σ_{xx}-minimum is remarkable. No systematic investigation of the oscillation pattern dependence on the position of the spot with respect to the contacts has been made so far. Fig. 3 shows, however, two examples of patterns that were observed on the same sample 1, which differ considerably from Fig. 2a. In Fig. 3b at fields below 2.5 T, the signal has a part with a close correspondence to $-\mathrm{d}\sigma_{xx}/\mathrm{d}B$, superimposed on a slowly increasing background. Above 2.5 T, it even seems to emphasize a particular structure in $\sigma_{xx}(B)$, that is attributed to the Landau level density of states shape. The data of Fig. 3b might be slightly in the nonlinear regime, as they are taken at a somewhat higher power level. Complex patterns like the one in Fig. 3c are sometimes also observed. They are not understood, but might reflect a structure resulting from a combination of the four terms in the formula. Note that the asymmetric lineshape in Fig. 3c shows a sudden drop at the high field side, in contrast to Fig. 2a which displays a sudden rise at the low field side. Slight phase shifts in $1/B$ might be present between the tracks in Fig. 3 because they are made in different runs on different samples.

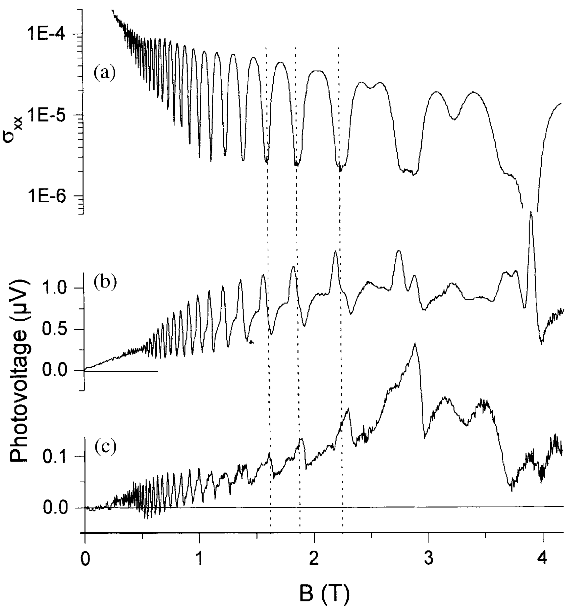


Fig. 3. (a) Conductivity oscillations (sample 1). (b) and (c) Photovoltage oscillations at two arbitrary positions on the sample. In (b) the light intensity is a factor of 5 higher than in (c).

Summarizing, screening effects dominate the lateral photoelectric effect in the Quantum Hall regime. The competition between screening and

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[3] For a recent overview of magnetothermoelectric effects in 2D, see Ref. [11]

transport leads to a characteristic double peak structure, analogous to the one predicted for double layer drag and observed for SAW attenuation. Further experimental and theoretical work is necessary to fully understand and exploit the rich magnetotransport phenomena present in the lateral photovoltage.

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