Microwave Hall conductivity of the two-dimensional electron gas in GaAs-$Al_xGa_{1-x}As$

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For the first time the quantum Hall effect was observed in σ_{xy} at microwave frequencies in the two-dimensional electron gas in GaAs-$Al_{0.35}Ga_{0.65}As$ using a crossed waveguide arrangement. These frequencies were 10^3–10^4 higher than those used in previous experiments where a so-called low-frequency breakdown of the integer quantum Hall effect was observed. Our microwave results show that this effect does not occur in GaAs-$Al_xGa_{1-x}As$ heterostructures. Therefore, we have to rule out the mechanism of an effective delocalization at low frequencies and the existence of long semiclassical orbits in the sample.

The high-frequency conductivity of the two-dimensional electron gas (2DEG) in a semiconductor heterostructure or in a Si metal-oxide-semiconductor field-effect transistor (MOSFET) is of considerable interest regarding the role of localization and the occurrence of the quantized Hall resistance. Previous experiments with short pulses of 100-ns minimum duration[1,2] and with ac frequencies up to 50 MHz,[3–5] respectively, have given controversial results. Kuchar, Meisels, Weimann, and Burkhard[1] and Woltjer, Mooren, Wolter, and André[2] found no difference between dc and 100-ns-pulse (comparable to 5 MHz) experiments concerning the integer quantum Hall effect (QHE) in GaAs-$Al_xGa_{1-x}As$.

A strong frequency dependence in the megahertz range was observed in GaAs-$Al_xGa_{1-x}As$ (Ref. 3) and in Si MOSFET's[4,5] in measuring the two-terminal resistance: Integer Hall plateaus were distorted or disappeared, the fractional plateaus were enhanced by increasing the frequency. The frequency where the deviation from the dc behavior sets in was lower in relatively low-mobility samples [$\mu=(1.5\text{–}2)\times10^4$ $cm^2/V\,s$ in MOSFET's, $\mu<10^5$ $cm^2/V\,s$ in the heterostructures]; it depended upon sample length and Landau-level filling factor. In high-mobility GaAs-$Al_xGa_{1-x}As$ samples ($\mu>10^5$ $cm^2/V\,s$) no deviation up to 50 MHz was observed. The original explanation of the effect was[6] that some of the Landau states having a localization length longer than the sample length were already effectively delocalized; the onset of the frequency effect is expected when states having a localization length less than or equal to the sample length become delocalized. Theoretically the low-frequency ($\sim$1 MHz) "breakdown" of the integer quantum Hall effect was explained by assuming the presence of semiclassical orbits in the sample.[7] This should have the effect that the diagonal component of the conductivity is not zero in the quantized regime and that the integer plateaus are destroyed.

Smith, Heiblum, and Stiles[8] performed measurements on GaAs-$Al_xGa_{1-x}As$ at frequencies below 100 kHz with capacitively coupled contacts and found results similar to those reported in Refs. 3–5. While avoiding contact effects, they introduced the effect of vanishing differential capacitance. This effect is, like σ_{xx}, related to the absence of delocalized states at the Fermi level. It replaces the Hall plateaus with minima. Recent two-terminal measurements of the same group[9] show that frequency-dependent effects appear in gated structures only. They are attributed to coupling of the signal from the 2DEG to the gate.

The main purpose of this investigation was to clarify the situation, i.e., to find out whether the integer plateaus disappear because of delocalization at high frequencies, particularly in the microwave range. There a different experimental approach than previously used has to be applied. This is a consequence of the fact that experiments with contacts on the sample cannot be done on a time scale faster than about 50 ns. The reasons are the RC time constants due to the quantized Hall resistance (~10 kΩ) and parasitic capacitances (~1 pF). This was also experimentally observed in two-terminal[1] and four-terminal arrangements[2,10] (impedance matching by MOSFET's[2] and 1 MΩ:50 Ω attenuation followed by 100$\times$ amplification in the 50-Ω technique,[10] respectively). Time constants of this order of magnitude cannot be responsible for the ac behavior observed in experiments below several megahertz. For gated structures it is most likely caused by capacitive coupling between the 2DEG and the gate, as suggested in Ref. 9.

In this Communication we report the first observation of the *Hall conductivity* σ_{xy} of the 2DEG in GaAs-$Al_{0.35}Ga_{0.65}As$ at *microwave frequencies*. Data were obtained on a 14-layer multi-quantum-well structure grown by molecular-beam epitaxy (sample 1408 of Ref. 11), with $n_s=14\times5.7\times10^{11}$ cm^{-2} and $\mu=20\,000$ $cm^2/V\,s$ at 2.2 K.

For observing σ_{xy} a crossed waveguide arrangement with the sample in the Faraday geometry was used (Fig. 1). This is equivalent to the measurement of the 90° component of the Faraday rotation. It can be shown[12] that the electric-field amplitude of the transmitted microwave radiation is proportional to σ_{xy} and, hence, the intensity proportional to σ_{xy}^2. The intensity transmitted through the crossed waveguide (length 20 cm) was measured with a liquid-helium-cooled bolometer. In order to minimize interference effects in the transmitted intensity an absorber was mounted behind the bolometer. A Hewlett-Packard 8690B sweep oscillator with a Hewlett-Packard 8697A rf unit was used as the microwave source. Without a sample the transmitted intensity was 10^{-3} of the incident intensity. With a single

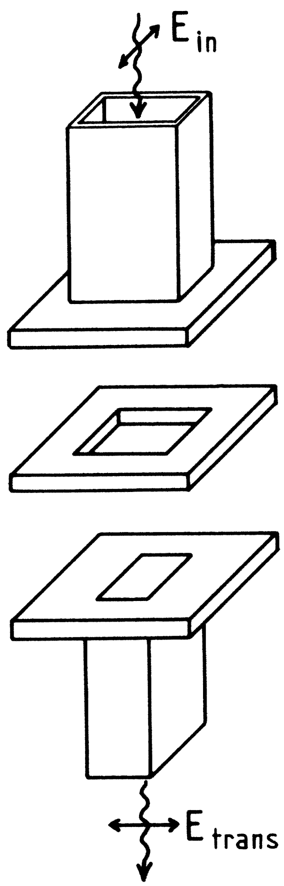

FIG. 1. Schematic drawing of the main part of the crossed waveguide arrangement. The sample is positioned in the middle flange (quadratic hole 8×8 mm^2). Over the length of the cryostat the waveguide material is stainless steel. Inner waveguide dimensions are 3.5×7 mm^2. E_{in} is the electric field vector of the incident wave. In the transmitted wave, E_{trans} is the dominating field component after several wavelengths and is proportional to σ_{xy} of the sample.

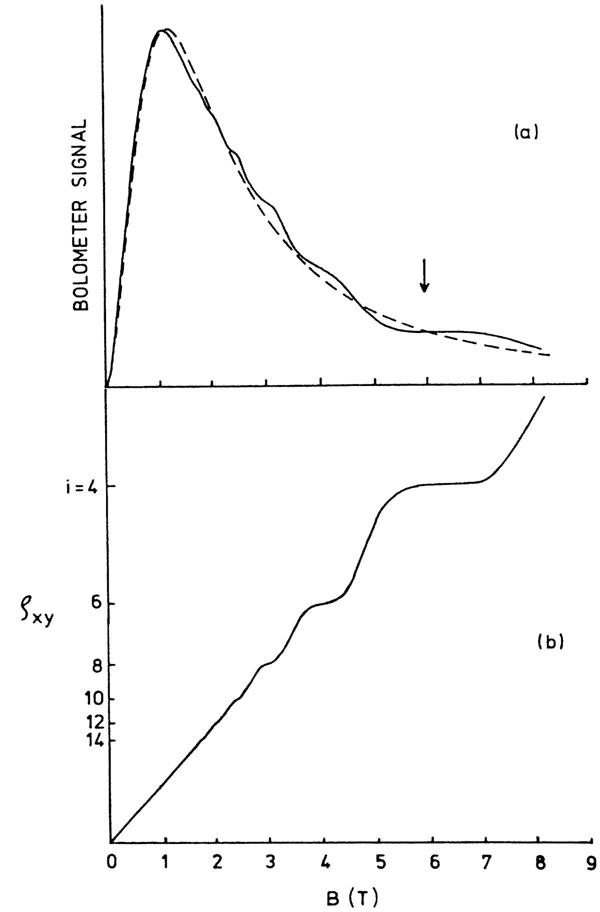

FIG. 2. (a) Bolometer signal in the crossed waveguide arrangement (solid curve). This signal is proportional to σ_{xy}^2 of the two-dimensional electron gas in the sample. A small background signal (1.5% of the peak signal) is subtracted. The dashed curve is calculated from the classical formula for σ_{xy}, Eq. (2). (b) dc results for ρ_{xy}. $T=2.2$ K. The arrow in (a) marks the intersection of the classical dc Hall resistance with the $i=4$ plateau of (b).

heterostructure the 2D σ_{xy} effect was too weak to be observed with our experimental arrangement; since the intensity is proportional to σ_{xy}^2 it should be 196 times weaker than for the 14-layer heterostructure. In principle, this measuring technique is a zero-background technique. Beside σ_{xy} contributions from the sample, misalignment of the waveguides (not ideally crossed) can add a background signal (without a sample) and a signal proportional to σ_{xx}^2 (with a sample). These effects were observed to be weakest in our experiment in the range 31.5–34 GHz. Particularly, the σ_{xx}^2 effect was negligible when averaging over the two magnetic field polarities. Figure 2(a) shows the Hall conductivity σ_{xy} observed at a frequency of 33 GHz. For comparison, ρ_{xy} obtained from a dc experiment on a sample of the same heterostructure is shown in Fig. 2(b). Both curves clearly show a QHE behavior. The $i=4$ plateau is best developed; plateaulike structure can be recognized in ρ_{xy} as well as in σ_{xy} up to $i=14$.

The classical Hall effect would yield a straight line in Fig. 2(b), according to $\rho_{xy}=B/en_s$, with intersections at the "centers" of the plateaus. Therefore, it is interesting to compare the data of Fig. 2(a) with a calculation using the classical formula for the high-frequency conductivity σ_{xy}. Generally, this is given by[12]

$$\sigma_{xy}=\frac{ne^2}{m^*}\frac{\omega_c\tau^2}{(1-j\omega\tau)^2+\omega_c^2\tau^2} \quad . \tag{1}$$

$1/\tau$ is the scattering rate at the Fermi energy, ω_c the cyclotron frequency, and ω the measuring frequency. The other symbols have the usual meaning. For $\omega\tau \ll 1$, the essential dependence on magnetic field is given by

$$\sigma_{xy}\sim\omega_c/(1+\omega_c^2\tau^2) \quad . \tag{2}$$

Thus, the intensity in the crossed waveguide is proportional to $[\omega_c/(1+\omega_c^2\tau^2)]^2$ in the classical case. This can be fitted to the experimental curve in Fig. 2(a). With $m^*=0.068m_0$, τ turns out to be 3.4×10^{-13} s. The overall shape of the experimental curve is nicely reproduced by the calculation. Most important is the agreement of the two curves at two particular positions: at the maximum and at the intersection at the center of the $i=4$ plateau. τ should be considered as a fitting parameter only, since its value obtained from the mobility is much higher. The fitting procedure using Eq.

(2) is justified, since ω equals ω_c below 0.1 T and $\omega_c\tau = 1$ at about 1.1 T (maximum of calculated curve).

Our experiments clearly show that the so-called low-frequency breakdown of the QHE does not occur in the 2DEG of GaAs-$Al_xGa_{1-x}As$ heterostructures. The sample used in this investigation has a rather low electron mobility, comparable to that of the low-mobility samples of Refs. 3–5; those low-mobility samples were the ones where the frequency dependence was observed in the MHz range. The temperatures and magnetic fields used were also comparable. While not in the millikelvin regime of the fractional Quantum Hall effect, the temperature was definitively low enough ($\hbar\omega_c >> kT$) to clearly observe the integer plateaus [Fig. 2(b)], although they were not flat enough to define the ohm. Therefore, we did not expect to observe indications of fractional quantization, even if enhanced by the extremely high frequencies used. We could, however, expect to see whether the *integer* plateaus disappear or not. Our experiments clearly show that the plateau behavior of σ_{xy} is still present at frequencies 10^3–10^4 times higher than those previously used. This excludes assumptions like (a) effective delocalization of electrons in the tails of the Landau levels at MHz frequencies[6] or (b) the existence of long semiclassical orbits in the sample.[7] Our conclusion is further justified by a pulsed 100-ns experiment performed on a Corbino sample with a low mobility (4×10^4 $cm^2/V s$). There σ_{xx} was measured where—according to Ref. 7—the deviations from the dc behavior should primarily occur. However, no difference between the dc and the 100-ns σ_{xx} curve was observed in our experiment.

If delocalization of electrons in the tails of Landau levels can be considered in a classical way at all, localization lengths much shorter than the sample dimensions (~ several mm) must be assumed, as a consequence of our results. We believe instead that the problem must be treated in a quantum-mechanical way, like hopping conduction. Then, delocalization cannot occur simply by the absorption of a microwave or even higher-frequency photon as long as $\omega < \omega_c$.

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