Frequency dependence of the Hall conductivity of a 2D electron gas

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The frequency dependence of the quantum Hall effect has been determined experimentally for the first time. The change in the behavior of the Hall conductivity due to the increase in the frequency of the electric field is similar to the change observed as a result of raising the temperature.

Despite the passage of a considerable time since the discovery of the integer quantum Hall effect,[1] it continues to be a subject of vigorous experimental and theoretical research.[2] This interest continues because not all of the properties of the 2D system are known and because the microscopic theory which would describe this effect under actual experimental conditions so far has not been developed. The frequency dependence of the quantum Hall effect, which might contain important information about the effect, is not known yet. If a percolation model, for example, is used to describe the quantum Hall effect,[3,4] the effect becomes distorted when the frequency ω of the external field is equal to the characteristic frequency ω_i at which the electron moves along the closed trajectory in the field of the random potential of the impurities. In such a model a disruption of the quantum Hall effect is expected to occur when $\omega > \omega_i$ (Refs. 5 and 6). Consequently, the frequency dependence of this effect can probably be used to study the properties of the random potential. It is also important to compare the changes in the quantum Hall effect which occur as a result of the change in the frequency with those changes which stem from other physical forces.

In Refs. 7 and 8 a distortion and destruction of the integer quantum Hall effect were observed at low frequencies ($\omega/2\pi \lesssim 10^6$ Hz). This behavior is attributable to a capacitive coupling between the 2D layer and the gate in the test samples[9,10] and has no connection with the physical nature of the effect.

We have studied for the first time the behavior of an integer quantum Hall effect as a function of the frequency. The changes in the effect occurring as a result of the increase in the frequency of the external electric field are similar to the changes occurring as a result of raising the temperature.

An increase in ω leads to a reduction in the size of the plane region (the plateau) in the plot of the Hall conductivity $\sigma_{xy}(\omega,H)$ as a function of the magnetic field H. The plateau disappears at a certain cutoff frequency ω_0. A further increase in the frequency causes $\sigma_{xy}(\omega,H)$ to approach the Hall conductivity in the impurity-free system, $\sigma_{xy}(H) \sim H^{-1}$. A plateau with a large filling factor ν in the Landau levels collapses at lower frequencies ω.

We studied a 2D electron gas in semiconducting GaAs-AlGaAs heterojunctions. The electron density varied over the interval $(2\text{–}4)\times 10^{11}$ cm^{-2} and the electron mobility varied in the interval $(0.15\text{–}1.0)\times 10^5$ cm^2/(V·s). The measurements were carried out at a temperature of 4.2 K in the Faraday geometry.[11] The sample was inserted

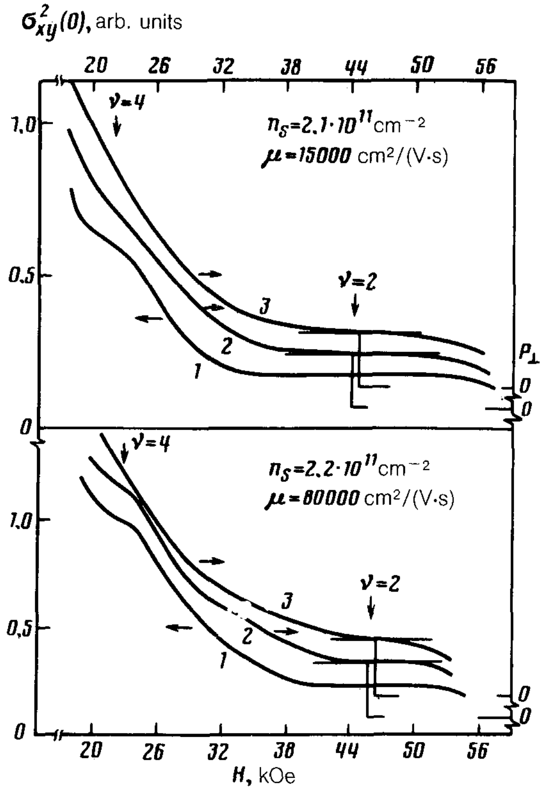

FIG. 1. The dependence $\sigma^2_{xy}(\omega,H)$ found at various frequencies for two samples. Upper plots: electron mobility—1.5×10^4 cm^2/(V·s); electron density—2.1×10^{11} cm^{-2}. Lower plots: Electron mobility 8.0×10^4 cm^2/(V·s); electron density—2.2×10^{11} cm^{-2}. Microwave frequency: 1—0 GHz; 2—30 GHz; 3—62 GHz.

into a cylindrical waveguide which connected two rectangular coaxial waveguides. These waveguides rotated smoothly around a common axis at liquid-helium temperatures. We measured the field dependence of the power level $P_\perp(H)$ of the microwave radiation transmitted through the sample when the waveguides were placed at 90° with respect to each other. The parameters of the waveguide channel were chosen in such a way that only the fundamental mode TE_{11} would be excited in the cylindrical waveguide over the entire frequency range 24–70 GHz which we were studying. The signal $P_\perp(H)$ which we measured is proportional to $|\sigma_{xy}(\omega,H)|^2$. Special experiments have shown, however, that this proportionality may be disrupted because of the mechanical irregularities of the waveguide channel and because of the various inhomogeneities of the test samples. In principle, these factors may lead to appreciable distortion of the functional dependence $\sigma_{xy}(\omega,H)$. We consider the results obtained when the following conditions are satisfied to be reliable: (1) When the ratio $P_\perp(H=0)/P_\parallel(H=0)$ is $\leqslant 10^{-4}$, where $P_\parallel(H)$ is the signal when there is no angular deviation between the waveguides; (2) when the result does not depend on the position of the sample in the waveguide and on the sample size; samples with dimensions in the range 6×6 mm–2×2 mm were studied; (3) when the ratio of the values of $P_\perp(H)$ at the center of the Hall plateau ($\nu=2$ and 4) is equal to the ratio of the square of the corresponding filling factors; and (4) when the value obtained from a sample before reducing the thickness of the substrate is the same as the result obtained from it after the substrate

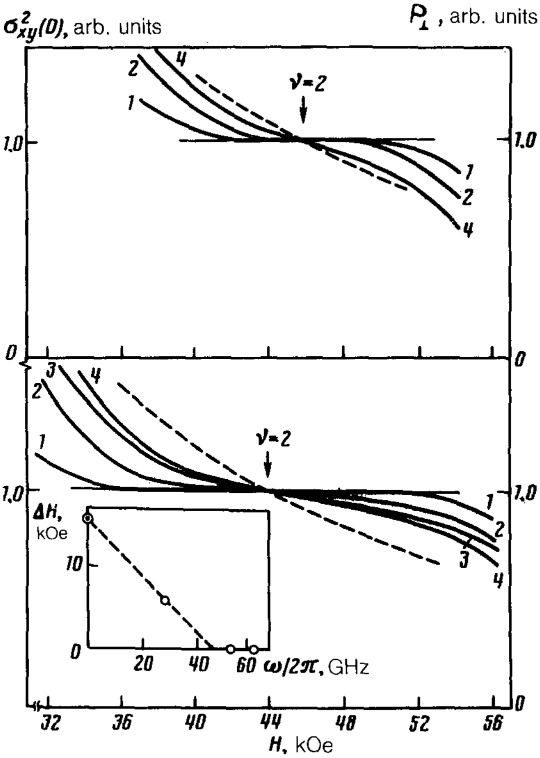

FIG. 2. The dependence $\sigma^2_{xy}(\omega,H)$ near the plateau $\nu=2$ for the same samples as in Fig. 1. Frequency: 1—0 GHz; 2—28 GHz; 3—53 GHz; 4—62 GHz. Dashed curve—$\sim H^{-2}$ plot.

thickness is reduced; the initial thickness of the substrate was 400 μm and its final thickness was 180 μm.

Figures 1 and 2 illustrate the frequency dependence of the quantum Hall effect over a wide range of variation of H and in the region of the plateau $\nu = 2$ for two samples with essentially the same electron density but different electron mobilities. The inset in Fig. 2 shows the frequency dependence of the plateau width, ΔH, measured for a 3% deviation. Since the measurement accuracy of ΔH at the frequencies 35 GHz $< \omega/2\pi <$ 50 GHz is low, we give no data for them. The point at which the dashed line crosses the abscissa gives an approximate value of the cutoff frequency for the existence of the quantum Hall effect, $\omega_0/2\pi \sim 45$ GHz. The use of samples with nearly the same parameters in the measurements showed that the plateau exists to frequencies ~ 35 GHz, which sets the lower limit for $\omega_0/2\pi$; the upper limit, 53 GHz, is determined by the measurement capabilities. We thus can say with certainty that the interval for $\omega_0/2\pi$ falls in the range of values quoted above.

It should be noted that the frequency variation of the quantum Hall effect and the cutoff frequency for the existence of the effect do not depend on the electron mobility within experimental error. With an increase in the electron density and hence with the shifting of the plateau into the region of large H, the cutoff frequency will also increase. If the plateau is situated in $\sim$60-kOe fields, for example, the flat region will be observed even at $\omega/2\pi = 62$ GHz. The results do not depend on the power of the microwave radiation incident on the sample, which varied in the range 0.1–100 μW (at the cylindrical waveguide output).

The particular features of the frequency dependence of the quantum Hall effect which were mentioned above are similar, as we have already indicated, to those changes of the effect which occur as a result of raising the temperature. This behavior is confirmed by the results of the temperature measurements of the Hall conductivity. These direct-current measurements were carried out with use of samples having the same parameters as the samples used in the frequency experiments (see Figs. 1 and 2).

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