Experimental observation of quantization of the Faraday rotation in a 2*D* electron system

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(Submitted 16 January 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 5, 255–257 (10 March 1986)

This is the first time that quantization of the microwave Faraday effect has been observed experimentally in a 2*D* electron system held in the regime of integer quantum Hall effect.

The Faraday rotation angle θ of the polarization plane of an electromagnetic wave of frequency ω ($\omega < \omega_0$, where $\hbar\omega_0$ is the characteristic amplitude of the impurity potential), which is transmitted through a 2*D* electron layer in the quantum-Hall-effect regime, must be quantized. We assume[1] $\Delta\theta = e^2/\hbar c = 1/137$rad. The attractive feature of the effect considered in Ref. 1 is that it yields information which cannot be obtained directly from the quantum Hall effect.

In this letter we report the first observation of quantization of a microwave Faraday effect in a 2*D* electron system, which manifests itself in a series of plateaus in the dependence of the Faraday rotation angle on the magnetic field *B*. The plateaus are seen in the case of integer-valued filling factors of the Landau level, $\nu = 2\pi\hbar c n_{2D}/eB$, where n_{2D} is the density of $2D$ electrons, and θ on the plateau is proportional to the corresponding value o ν.

We used samples of square-shaped GaAs/AlGaAs heterostructures of two types, which were prepared by th eliquid-phase and molecular-beam epitaxy techniques. The structure parameters were controlled with a direct current by means of photolithographed Hall bridges (type I samples) and by using the Van der Pau method (type II samples). The parameters of the $2D$ electron gas are: typeI—$n_{2D} = 3.6\times10^{11}$ cm^{-2}, mobility $\mu = (0.5\text{–}0.55)\times10^5$ cm^2/V · s); type II—$n_{2D} = (5.7\text{–}6.2)\times10^{11}$ cm^{-2} and $\mu = (1\text{–}1.2)\times10^5$ cm^2/V · s).

The samples were placed in the part of the cylindrical waveguide situated bytween two square coaxial waveguides that rotated relative to each other. The measurements were carried out at a temperature of 4.2 K at a frequency of 30 GHz. The electric field of the electromagnetic wave was 1–10 mV/cm in the plane of the sample. We measured the power level of the electromagnetic waves which were transmitted through the sample and which were polarized normal to the polarization plane of the incident waves ($P_\perp$) and parallel to them ($P_\parallel$) as a function of B. The sweep rate of B was no greater than 0.1 T/min. Measurements have shown that $P_\parallel$ does not depend on B within $\leqslant 5\%$. Since $\tan\theta$ is $\sqrt{P_\perp/P_\parallel}$ within a constant (because of an incomplete overlap of the cross section of the cylindrical waveguide by the sample), the main information about the behvaior of $\theta(B)$ is contained in $P_\parallel(B)$.

Figure 1 shows several examples of the $P_\perp(B)$ curve. $P_\perp$ peaks at $B \cong c/\mu$ (for type I samples we have $B \cong 0.02\text{–}0.025$ T and for type II samples we have $B \cong 0.01$ T)

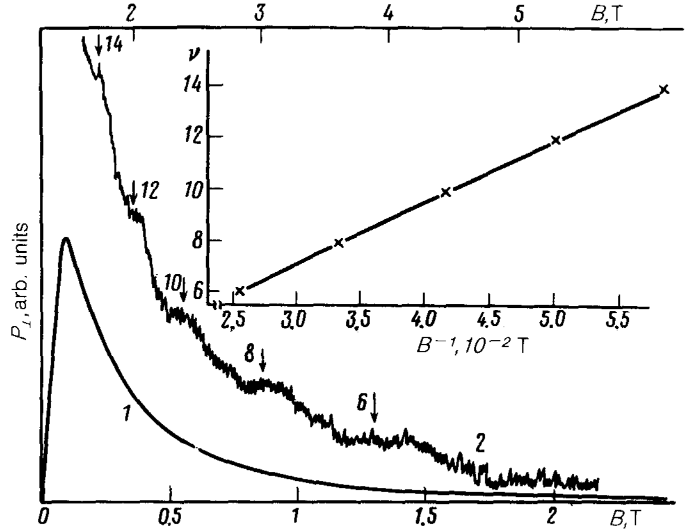

FIG. 1. $P_\perp$ versus B for different amplification levels of the measurement apparatus. Curves 1 and 2 correspond to the B scales plotted below and above the figure. The arrows indicate the locations of the structural features in $P_\perp$ and the numbers next to the arrows give the values of ν. The inset is a plot of ν versus B^{-1} for these features; type II sample, $n_{2D} = 5.8\times10^{11}$ cm^{-2}.

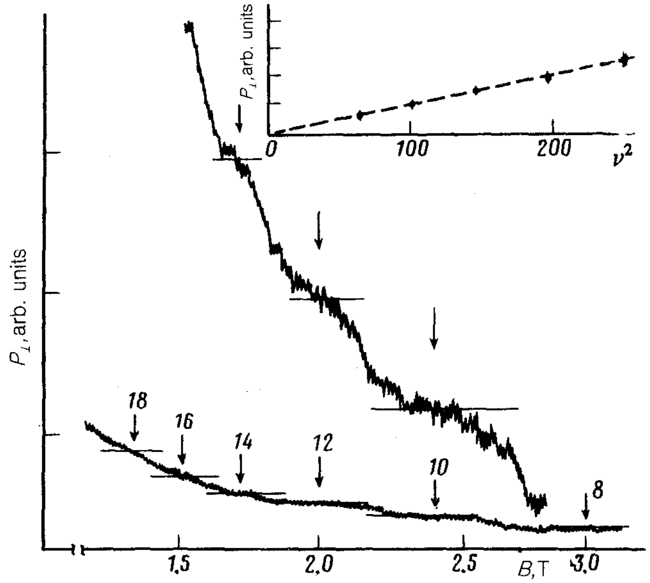

FIG. 2. $P_\perp$ versus B for the same sample as in Fig. 1, for different amplification levels of the measurement apparatus. The numbers next to the arrows give the values of ν. The inset is a plot of $P_\perp$ versus ν^2 near the plateau.

and then decreases monotonically, $P_\perp(B)$ also exhibits structural features at B, for whicih the Hall resistance has a plateau (direct-current measurements). As we can see from the inset in Fig. 1, these features are periodic in B^{-1}. The period $\Delta(B^{-1})$ coincides with the period of the Shubnikov-de Haas effect. The arrows in Fig. 1 indicate the values of B for which ν takes on integer values. We see that, within the experimental errors, the arrows fall at the midpoints of the structural features which stretch out into plateaus as B is raised.

Figure 2 shows another important systematic feature of this effect. The inset is a plot of $P_\perp$ versus ν^2 near the plateau, constructed from the experimental curves in Fig. 2. The plateaus at $\nu = 16$ and 18 are clearly seen upon further amplification of the measuring circuit. The linear function $P_\perp(\nu^2)$ shows the condition $\tan\theta \cong \theta = \beta\nu$, where β is independent of B, is satisfied.

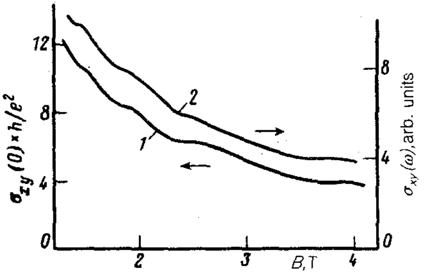

FIG. 3. $\sigma_{xy}(0)$ and $\sigma_{xy}(\omega)$ versus B for type I sample (curves 1 and 2, respectively). Curve 1 was obtained from the measurements of the quantum-Hall effect with direct current and curve 2 was obtained by smoothing out the experimental $P_\perp(B)$ curve by the method of least squares.

If the microwave radiation is absorbed only slightly, we have $\tan\theta = 2\pi\sigma_{xy}(\omega)/c$, where $\sigma_{xy}(\omega)$ is the dynamic Hall conductivity.[1] This effect can therefore be used to measure $\sigma_{xy}(\omega)$. The dynamic conductivity $\sigma_{xy}(\omega) \sim (P_{\perp}^{1/2})$ at 30 GHz which was reconstructed in this manner is shown by curve 2 in Fig. 3.

In Refs. 2 and 3, the quantum-Hall effect was measured with alternating current and the integer plateaus were found to break up into fractional plateaus at frequencies considerably lower than those used by us. We have not detected any new plateaus in the dynamic Hall conductivity compared with the static conductivity.

In our measurement arrangement, the determination of the absolute value of θ entails a large error, although the values of θ which we measured are in-order-of-magnitude agreement with those predicted in Ref. 1.

We wish to thank I. V. Altukhov and S. G. Gelakhova for assistance in preparing the experiment, M. I. Elinson for support of this study, and V. B. Sandomirskiĭ for a useful discussion.

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Translated by S. J. Amoretty