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Observation of a fractional quantum number

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New experiments on the two-dimensional electrons in GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructures at $T\sim0.14$ K and $B\leq190$ kG demonstrate that the quantum number of the quantized Hall resistance, close to $\frac{1}{3}$ filling of the last Landau level, is $\frac{1}{3}$ to better than 1 part in 10^4.

The notion of a fractional quantum number has been central to many recent theoretical discussions.[1] It is the purpose of this Communication to present an experimental result which shows unambiguously the observation of such a fractional quantum number. The observation was made on the macroscopic quantization of the Hall resistance of a two-dimensional (2D) electron system, which has an unprecedentedly high electron mobility.

Unlike usual three-dimensional systems, the Hall resistance R_H of a 2D system is identical to the off-diagonal resistivity tensor ρ_{xy}. It is now well known that R_H is quantized to[2]

$$R_H=\frac{h}{ie^2}\ , \tag{1}$$

where h is Planck's constant, e is the electronic charge, and i is the quantum number. In the case of integral quantization, i are integers and have been identified as the number of filled Landau levels of the 2D system. More recently,[3] it was discovered that in the 2D electron system in GaAs-$Al_xGa_{1-x}As$ heterostructures at $T\lesssim5$ K, when the last Landau level is $\frac{1}{3}$ and $\frac{2}{3}$ filled, plateaus are developed in R_H, approaching that given by Eq. (1) with $i=\frac{1}{3}$ and $i=\frac{2}{3}$, respectively. Concomittantly, minima are developed in the diagonal resistivity tensor ρ_{xx}, similar to the development of the zero resistance minima[4] at integral values of i. The phenomenon, more pronounced on samples with higher electron mobilities and at lower T, was indicative of a fractional quantum effect and was attributed to the condensation of electrons into a new ground state.

We have investigated this new quantum phenomenon in magnetic fields up to $B=190$ kG at dilution refrigerator temperatures, using samples with electron mobilities considerably higher than that employed in the previous experiment. Our results show unambiguously that R_H is fractionally quantized. In the case of $\frac{1}{3}$ filling of the last Landau level, the quantum number is demonstrated to equal $\frac{1}{3}$ to better than 1 part in 10^4, thus providing for the first time a direct experimental observation of a fractional quantum number.

The two samples were GaAs-$Al_xGa_{1-x}As$ heterostructures, consisting of 1-μm undoped GaAs, 370-Å undoped $Al_{0.3}Ga_{0.7}As$, and 400-Å Si-doped ($2\times10^{18}/cm^3$) $Al_{0.3}Ga_{0.7}As$. The 2D electron gas, resulting from ionized Si donors in $Al_{0.3}Ga_{0.7}As$ is confined to the undoped GaAs at the GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunction. The densities and the mobilities were $n=1.48\times10^{11}$ and $1.40\times10^{11}/cm^2$ and $\mu=4.5\times10^5$ and 4.0×10^5 cm^2/V sec, respectively. The dilution refrigerator employed a specially designed epoxy mixing chamber to minimize eddy current heating and the samples, mounted on a sapphire plate, were placed directly inside the mixing chamber. The temperature of the mixing chamber was measured by using a calibrated carbon glass thermometer, which has a low and known magnetic field coefficient.[5]

Figures 1 and 2 show, respectively, the data on ρ_{xx} and and ρ_{xy}, at the three temperatures, as a function of B. At 4.2 K, the apparent structures in both ρ_{xx} and ρ_{xy} are those due to integral quantization at integral values of the Landau level filling factor ν. No structure was discernible for $\nu<1$ at $B\gtrsim80$ kG. As the temperature was lowered to 0.88 K,

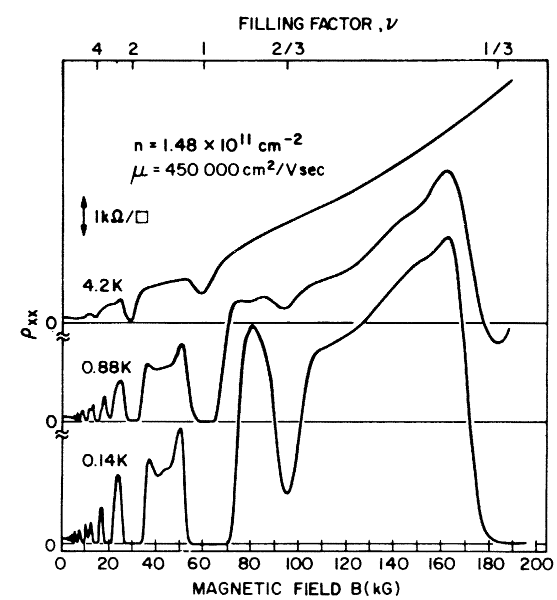

FIG. 1. Magnetic field dependence of the diagonal resistivity ρ_{xx} at $T=4.2$, 0.88, and 0.14 K.

the structures due to integral quantization at $\nu = 1$ and 2 become fully developed: The minima developed into zeros in ρ_{xx} and the change in slope in ρ_{xy} developed into flat plateaus. It is well known that the value of these Hall plateaus is quantized according to Eq. (1) to an accurracy much better than 1 part in 10^6.[6] In fact, it constitutes a new resistance standard and the resistance at the $i = 1$ plateau (25 812.80 Ω) is being considered as the value for the reproduction of the ohm in laboratories for maintaining standards.[7]

At 0.88 K, it is already apparent in the data shown in Fig. 1 that ρ_{xx} has well-defined minima at $\nu = \frac{1}{3}$ and $\frac{2}{3}$. At still lower T, these minima at fractional filling of the last Landau level become more pronounced and, in addition, much weaker structures also become discernible (at ~155, ~80, and ~40 kG), which have been identified as due to higher-order fractional quantum series based on the inverse of odd integers.[8] Here, we focus on the most prominent structure at $\frac{1}{3}$ filling, where ρ_{xx} shows a four order-of-magnitude decrease, from 5×10^3 Ω/■ at 4.2 K to ~0.5 Ω/■ at ~0.14 K. The residual resistance observed at the lowest temperature was due primarily to the pickup of noises in the high magnetic field environment.

The Hall resistance (Fig. 2) at ~0.14 K shows a well-defined plateau at $\frac{1}{3}$ filling and also a change in slope, suggestive of the development of a plateau at $\frac{2}{3}$ filling. The $\frac{1}{3}$ plateau was demonstrated to be flat to better than 1 part in 10^4 in the field range from $B = 180$ to 190 kG, which was our highest field. Its value was measured against the quantum resistance standard h/e^2 (i.e., 25 812.80 Ω), using the $i = 1$ Hall plateau at 61 kG. We obtained $3(h/e^2)$ to an absolute accuracy better than 1 part in 10^4. An identical result was obtained from the second sample. This result demonstrates unambiguously that the Hall resistance at fields corresponding to the $\frac{1}{3}$ filling of the last Landau level is indeed quantized according to Eq. (1), with a fractional quantum number $i = \frac{1}{3}$. This is a direct experimental observation of a fractional quantum number, independent of any theoretical assumptions.

Finally, we remark on the temperature development of ρ_{xx}. At both the $\frac{1}{3}$ and the $\frac{2}{3}$ fillings, it was observed to follow $\rho_{xx} \sim \exp(-\Delta/kT)$ down to ~0.4 K. No reliable measurements were made at lower T, due to the increasing difficulties with thermometry in the high magnetic field environment. In this limited temperature range, the electronic process can be characterized by a characteristic energy $\Delta = 0.28$ meV at the $\frac{1}{3}$ filling and $\Delta = 0.033$ meV at the $\frac{2}{3}$ filling. These energies may be attributed to the existence of energy gaps that separate the ground-state condensate from its excited states. The very recent calculations of Laughlin[9] and of Yoshioka, Halperin, and Lee[10] suggest that the ground state at $\frac{1}{3}$ filling of the last Landau level is an incompressible quantum fluid. An energy gap is believed to exist, separating the electron fluid from its excitations.

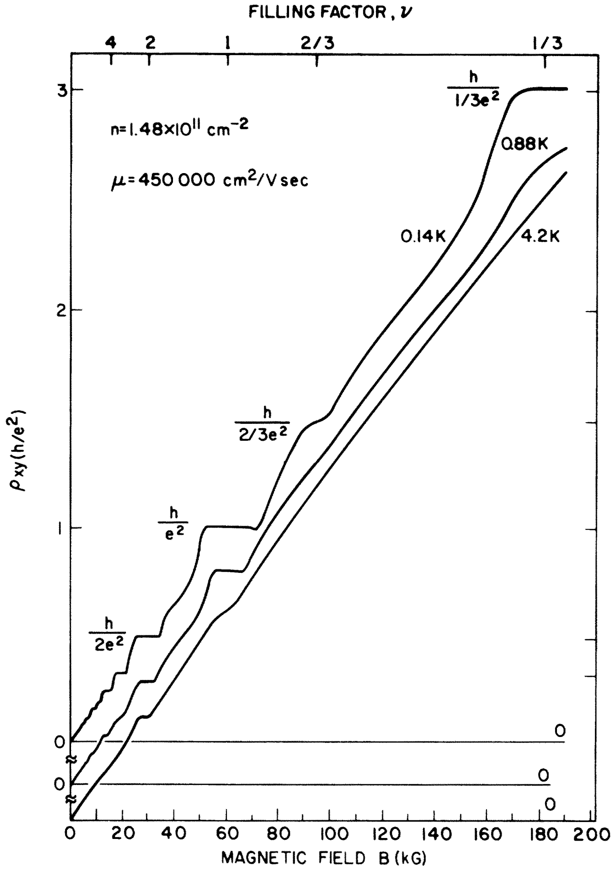

FIG. 2. Magnetic field dependence of the Hall resistance, which is identical to ρ_{xy} in two dimensions, at $T = 4.2$, 0.88, and 0.14 K.

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