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The two-dimensional electron system in an InAs quantum well has emerged as a prime candidate for hosting exotic quasi-particles with non-Abelian statistics such as Majorana fermions and parafermions. To attain its full promise, however, the electron system has to be clean enough to exhibit electron-electron interaction phenomena. Here we report the observation of fractional quantum Hall effect in a very low disorder InAs quantum well with a well-width of 24 nm, containing a two-dimensional electron system with a density $n = 7.8 \times 10^{11}$ cm^{-2} and low-temperature mobility 1.8×10^6 cm^2/Vs. At a temperature of $\simeq 35$ mK and $B \simeq 24$ T, we observe a deep minimum in the longitudinal resistance, accompanied by a nearly quantized Hall plateau at Landau level filling factor $\nu = 4/3$.

Two-dimensional electron systems (2DESs) confined to InAs quantum wells have been of interest for decades [1–12, 15–17]. The small electron effective mass, combined with the relatively high purity of the epitaxially grown InAs layers, leads to very high electron mobilities, rendering the InAs 2DES a system of choice for high-speed transistors and sensors [3, 4]. Moreover, thanks to their strong spin-orbit coupling, InAs 2DESs have long been prime candidates for spintronic devices [5–7]. Interest in InAs 2DESs has surged to new heights recently because of the possibility of inducing superconductivity through the proximity effect in these systems [8, 9]. Theoretical proposals indeed suggest that such systems might host exotic topological states of matter with non-Abelian quasi-particles, namely Majorana fermions, and thus be useful for topological quantum computing [10]. There are even experiments on InAs-superconductor systems whose results appear to be consistent with the existence of Majorana fermions [11, 12].

Thanks to the increased interest and activity, there have been numerous recent reports [8, 15–17] of improved quality of InAs 2DES samples, achieving low-temperature electron mobilities exceeding 2×10^6 cm^2/Vs [16]. Many of these reports demonstrate the high quality through the observation of well-developed integer quantum Hall effect (IQHE) states at high Landau level filling factors (ν). Conspicuously absent, however, is any signature of the fractional quantum Hall effect (FQHE), a hallmark of interacting electrons. Here we report the observation of FQHE at $\nu = 4/3$ in a recently fabricated, high-quality InAs 2DES [16]. Our observation places InAs among a handful of semiconductors which exhibit the FQHE: GaAs [18, 19], Si [20–22], AlAs [23–26], GaN [27], CdTe [28], ZnO [29], and Ge [30]; another 2DES hosting FQHE is, of course, graphene [31–33]. Besides being of general importance, the presence of FQHE in InAs 2DESs paves the way for the realization of *parafermions* [34–37], quasi-particles that are even more exotic than Majoranas. Prafermions, which can be

viewed as fractionalized Majoranas, are excitations of *interacting* topological systems such as FQHE edge states and, unlike the standard Majoranas, can be used to implement *universal* topological quantum computation.

The details of our sample fabrication and parameters are reported in Ref. [16]. As shown in Fig. 1 right inset, the sample hosts a 2DES in a 24-nm-wide InAs quantum well, grown on a nearly lattice-matched GaSb substrate via molecular beam epitaxy. Our sample is from wafer M as described in Table III of Ref. [16]. The structure starts with a 600-nm-thick GaSb layer, followed by a 10-period Al$_{0.33}$Ga$_{0.67}$Sb superlattice. The quantum well, located 25 nm below the surface, is flanked by a 200-nm-thick Al$_{0.33}$Ga$_{0.67}$Sb lower barrier and a 20-nm-thick AlSb upper barrier. The structure ends with a 5-nm-thick GaSb cap layer. The 8×8 $\boldsymbol{k} \cdot \boldsymbol{p}$ simulations show that the structure is a quasi-single-interface quantum well [16]. The 2DES has density $n = 7.8 \times 10^{11}$ cm^{-2} and low-temperature mobility of 1.8×10^6 cm^2/Vs [16]. The sample we measured has a 4 mm$\times$ 4 mm van der Pauw geometry. Contacts to the 2DES are made by annealing In at 200 °C for 5 minutes. The transport measurements were carried out in a superconducting-resistive hybrid magnet system with a maximum field of 45 T, and a dilution refrigerator with a base temperature of $\simeq 35$ mK. We used a low-frequency lock-in technique and an excitation current of ~ 100 nA to measure the transport properties.

Figure 1 highlights our main result: the observation of FQHE in an InAs 2DES. It shows the full-field longitudinal (R_{xx}) and Hall (R_{xy}) magnetoresistance traces up to 45 T at $T \simeq 35$ mK. The vertical marks in Fig. 1 indicate a number of filling factor positions in magnetic field. These marks are determined from the slope of R_{xy} vs. B at low magnetic fields, and they match all the resolvable R_{xx} minima positions to within 1%. Between 19 and 26 T, as shown in expanded plots in Fig. 2, we observe a deep R_{xx} minimum at $\nu = 4/3$, signaling a developing FQHE at this filling. This minimum is concomitant with
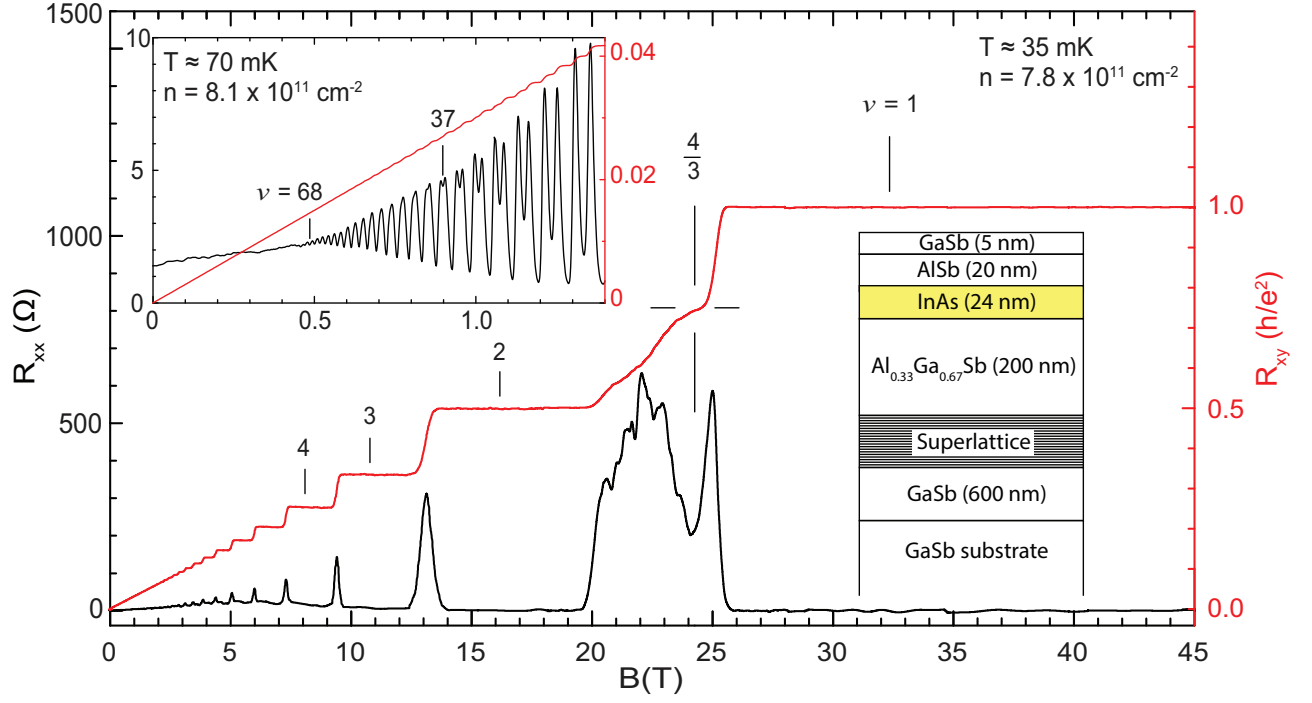
FIG. 1. The longitudinal resistance R_{xx} and Hall resistance R_{xy} vs. perpendicular magnetic field B from 0 to 45 T for a 24-nm-wide InAs/Al$_{0.33}$Ga$_{0.67}$Sb quantum well at $\simeq 35$ mK. The details of the structure are shown in the right inset. The vertical marks in the main figure indicate the field positions of integer fillings $\nu = 1$ to 4 as well as the expected $\nu = 4/3$ R_{xx} minimum position. The expected R_{xy} quantization value ($3h/4e^2$) is marked with horizontal lines. The upper left inset shows the low-field R_{xx} and R_{xy}. The Shubnikov-de Haas oscillations are resolvable at magnetic fields as low as $\simeq 0.5$ T ($\nu = 68$), and become spin-resolved for $B > 0.9$ T ($\nu \leqslant 37$).

a nearly quantized R_{xy} plateau with a Hall resistance within 1% of the expected value ($3h/4e^2$).

The FQHE at $\nu = 4/3$ is observed thanks to the very high quality of the sample, as demonstrated by the left inset in Fig. 1 which captures more details of the data at lower magnetic fields. The inset includes R_{xx} and R_{xy} traces taken at $n = 8.1 \times 10^{11}$ cm^{-2} and $T \simeq 70$ mK; these were measured in a different system with a superconducting magnet only. They show that the Shubnikov-de Haas oscillations are resolvable at magnetic fields as low as $\simeq 0.5$ T ($\nu = 68$). Also, the oscillations are spin-resolved down to $B \simeq 0.9$ T ($\nu = 37$). These features attest to the very high quality of the 2DES.

Aside from the pronounced low-field oscillations, however, we also observe wide R_{xx} minima and R_{xy} plateaus in Fig. 1 at intermediate and high magnetic fields. At the highest fields, above 26 T, there is an extremely wide R_{xx} minimum, accompanied by a $\nu = 1$ quantized Hall plateau, spanning over a field range of $\simeq 20$ T and likely even beyond. These very wide plateaus indicate that the Landau levels are significantly broadened and that, despite the very high mobility, there is still a fair amount of disorder present. Assuming the remote, ionized background impurities and defects [38, 39] in the barriers to be the main scattering source [16], a rough estimate based

on experimental data and calculations for mobility vs. density in GaAs 2DESs [40–45] gives an ionized impurity/defect concentration in the barriers of $\simeq 5 \times 10^{16}$
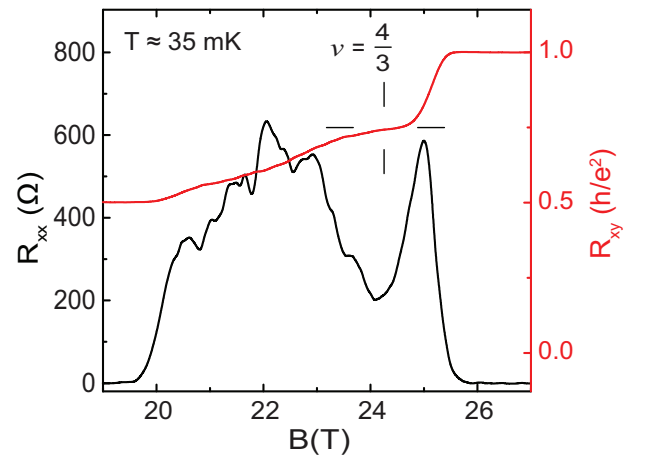

FIG. 2. R_{xx} and R_{xy} traces are shown near $\nu = 4/3$. The vertical lines mark the expected magnetic field position for $\nu = 4/3$. The horizontal lines indicate the expected corresponding R_{xy} quantized value ($3h/4e^2$).
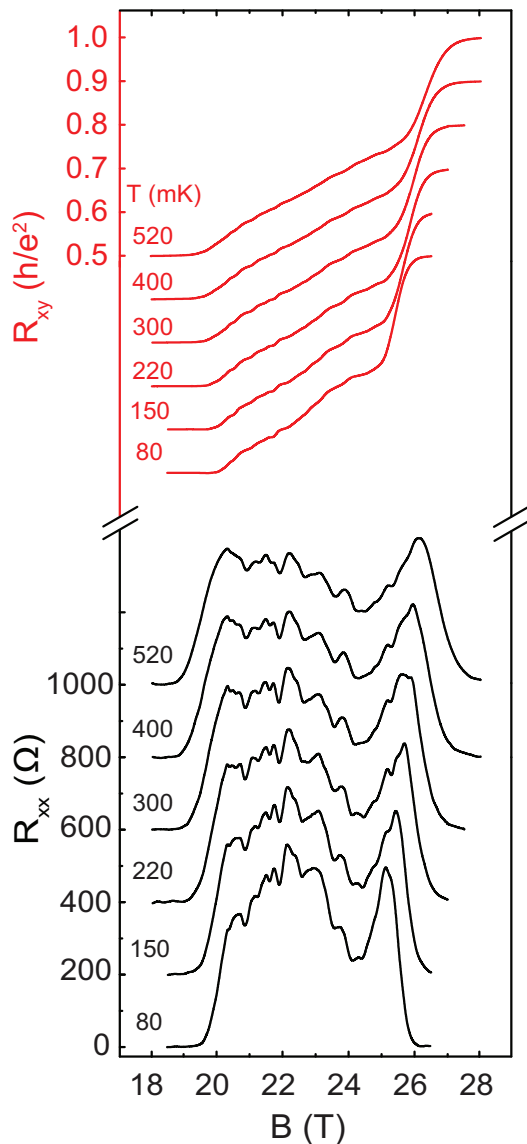
FIG. 3. Temperature dependence for the R_{xx} and R_{xy} traces between $\nu = 1$ and $\nu = 2$. For clarity, starting from the 80 mK trace, each R_{xx} trace is shifted up vertically by 0.2 kΩ. Similarly, each R_{xy} trace is shifted vertically by $0.1(h/e^2)$ as well.

cm^{-3} for the InAs sample in our present study. For comparison, the best GaAs samples grown in ultra-clean molecular beam epitaxy chambers have a background impurity concentration of $\simeq 1 \times 10^{13}$ cm^{-3}, nearly four orders of magnitude smaller [40–45]. This still relatively high amount of disorder in InAs samples gives a tentative explanation for the weakness of the $\nu = 4/3$ FQHE and the absence of FQHE at more filling factors. We also examined another sample with a similar structure but narrower well-width (15 nm), with density $n = 8.6 \times 10^{11}$ cm^{-2} and mobility 0.98×10^6 cm^2/Vs. No features except for a single R_{xx} maximum is observed between $\nu = 1$

and $\nu = 2$.

The R_{xx} and R_{xy} data in Fig. 1 exhibit two other noteworthy features. First, we observe an asymmetry in the well-quantized, wide Hall plateaus at intermediate and high magnetic fields, namely, the plateaus extend farther on the high-field side of a given integer filling factor. Similar asymmetries have been reported for 2DESs in other materials with moderate quality [46–48]. We note that, as might be expected, the plateaus we observe in Fig. 1 data are in fact reasonably symmetric in *filling factor* with respect to integer values. For example, the $\nu = 2$ Hall plateau extends from $\nu = 2.37$ ($B = 13.6$ T) to $\nu = 1.64$ ($B = 19.7$ T); these ν are nearly equidistant from $\nu = 2$ ($B = 16.1$ T). Regardless of its origin, the plateau asymmetry can explain the absence of a $\nu = 5/3$ FQHE in Figs. 1 and 2 despite the presence of a clear $\nu = 4/3$ FQHE: The field position for $\nu = 5/3$ ($B = 19.4$ T) overlaps with the extended $\nu = 2$ plateau [49].

Another noteworthy feature in the data of Figs. 1 and 2 is the presence of numerous small, oscillatory features seen in R_{xx} in the field range $20 < B < 25$ T. As best seen in the temperature dependence data shown in Fig. 3, these features are reproducible, although their amplitude diminishes at higher temperatures. This reproducibility implies that the oscillations are not random noise. In our experiments we find that, while the oscillations are reproducible in a given cool-down from room temperature and for a fixed current-voltage configuration, their detailed features (field positions and amplitudes) depend on the cool-down and the measurement configuration. Figure 4 shows R_{xx} and R_{xy} traces for a different cool-down and with a different current-voltage configuration. The small oscillatory features have changed but the R_{xx} minimum
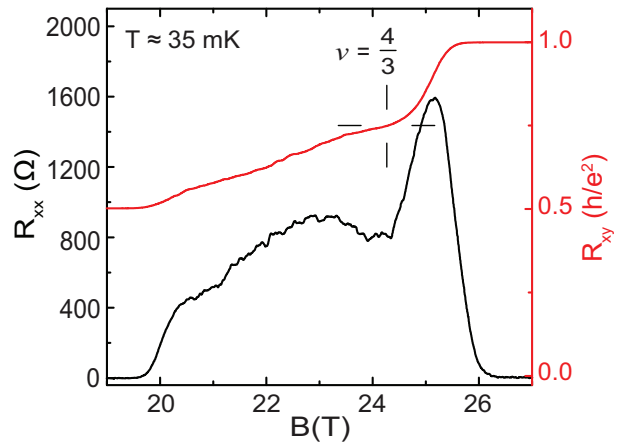

FIG. 4. R_{xx} and R_{xy} traces are shown near $\nu = 4/3$ for a different cool-down and a different current-voltage configuration compared to Fig. 3. The vertical lines mark the expected magnetic field position for $\nu = 4/3$, and the horizontal lines indicate the expected quantized R_{xy} value $(3h/4e^2)$.

and R_{xy} quantization near $\nu = 4/3$ are consistently reproducible. A more thorough study is needed to discern the origin of these intriguing oscillations.

Finally, we highlight the temperature evolution of the R_{xx} minimum at $\nu = 4/3$. Figure 3 data indicate that, as temperature decreases, the R_{xx} minimum only becomes relatively deeper, meaning that the resistance value at the minimum remains nearly constant while the resistance maxima on both flanks increase. A qualitatively similar behavior is seen for other FQHE states when they are not particularly strong [50]. Unfortunately, this temperature dependence precludes us from measuring an accurate gap energy for the $\nu = 4/3$ FQHE.

In summary, we report the observation of FQHE in an InAs 2DES, namely a deep R_{xx} minimum at $\nu = 4/3$ along with a nearly quantized Hall plateau at the expected value $(3h/4e^2)$. This observation is an important step towards the realization of exotic quasi-particles such as parafermions which could find use in the realization of universal topological quantum computing. The relative fragility of the observed $\nu = 4/3$ FQHE, and the absence of other FQHE states, however, highlight the significant disorder still present in the currently available samples and the need for future improvements.

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