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Fractional quantum Hall valley ferromagnetism in the extreme quantum limit

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Electrons multiple quantum degrees of freedom can lead to rich physics, including a competition between various exotic ground states, as well as novel applications such as spintronics and valleytronics. Here we report magneto-transport experiments demonstrating how the valley degree of freedom impacts the fractional quantum states (FQHSs), and the related magnetic-flux-electron composite fermions (CFs), at very high magnetic fields in the extreme quantum limit when only the lowest Landau level is occupied. Unlike in other multivalley two-dimensional electron systems such as Si or monolayer graphene and transition-metal dichalcogenides, in our AlAs sample we can continuously tune the valley polarization via the application of *in-situ* strain. We find that the FQHSs remain exceptionally strong even as they make valley polarization transitions, revealing a surprisingly robust ferromagnetism of the FQHSs and the underlying CFs. Our observation implies that the CFs are strongly interacting in our system. We are also able to obtain a phase diagram for the FQHS and CF valley polarization in the extreme quantum limit as we monitor transitions of the FQHSs with different valley polarizations.

The valley degree of freedom, i.e. the availability of multiple conduction-band minima, opens new avenues for exciting physics and engineering. Similar to the spintronics, a new 'valleytronics' field has emerged, aiming to utilize the valley degree of freedom to make functional devices [1–8]. The role of valley degree of freedom in stabilizing different many-body ground states of low-disorder, two-dimensional electron systems (2DESs) is also of great fundamental importance [3, 9–21]. Of particular interest is quantum Hall valley ferromagnetism, namely the interaction-induced valley polarization of quantum Hall states, both at integer and fractional Landau level (LL) filling factors (ν). Here we study a fundamental characteristics of the valley degree of freedom, namely its persistence even in the extreme quantum limit where the 2D electrons occupy only the lowest LL ($\nu < 1$). We find that the fractional quantum Hall states (FQHSs) flanking $\nu = 1/2$ are always present, implying a very robust quantum Hall valley ferromagnetism. As we tune the valley occupancy via applying *in-situ* strain, the FQHSs make multiple transitions, reflecting the change in their valley polarization.

Our material platform is a 2DES, with density $n = 1.45 \times 10^{11} \text{ cm}^{-2}$, and mobility $\mu = 7.5 \times 10^5 \text{ cm}^2/\text{Vs}$ confined to a 45-nm-wide AlAs quantum well (QW). Electrons in bulk AlAs occupy three ellipsoidal valleys (X, Y, and Z) centered at the X point of the Brillouin zone with their major axes lying in the [100], [010], and [001] crystallographic directions, respectively [Fig. 1(a)]. However, this three-fold degeneracy is lifted when we grow an AlAs QW on a GaAs substrate because the biaxial compression originating from the lattice mismatch between AlAs and GaAs pushes the Z valley higher in energy relative to X and Y valleys (we denote the growth direction as [001]). For a sufficiently wide AlAs QW such as ours, the

2D electrons occupy only the X and Y valleys, with their major axes lying in the plane [Fig. 1(b)] [3, 22]. The 2D electrons in each valley possess an anisotropic Fermi sea with longitudinal and transverse effective masses of $m_l = 1.1m_0$ and $m_t = 0.20m_0$, leading to an in-plane effective mass of $m^* = (m_l m_t)^{1/2} = 0.46m_0$, where m_0 is the free electron mass. In the absence of any external strain that breaks the in-plane symmetry, the X and Y valleys are degenerate in energy. We can control the relative occupancy of X and Y by applying an in-plane, uniaxial strain $\varepsilon = \varepsilon_{[100]} - \varepsilon_{[010]}$, where $\varepsilon_{[100]}$ and $\varepsilon_{[010]}$ are the strain values along [100] and [010] [3]. The valley-splitting energy is given by $E_V = \varepsilon E_2$, where E_2 is the deformation potential, which in AlAs has a band value of 5.8 eV [3]. In our experiments, we glue the sample to a piezo-actuator, as displayed in Fig. 1(c), and apply a voltage bias (V_P) to its leads to control the amount of strain ($3.3 \times 10^{-7} \text{ V}^{-1}$). We used standard lock-in techniques for resistance measurements which were carried out in a dilution refrigerator and in a ^3He cryostat with base temperatures of $T \simeq 0.03 \text{ K}$ and 0.3 K , respectively.

Figure 1(d) demonstrates how we tune and monitor the valley occupancy. Here we show the sample's piezoresistance as a function of V_P . At point β , the 2DES exhibits isotropic transport, namely, the resistances measured along [100] and [010] ($R_{[100]}$ and $R_{[010]}$) are equal, even though the individual valleys are anisotropic. At this point $\varepsilon = 0$ and the two valleys are degenerate. Note that a finite V_P is often required to attain $\varepsilon = 0$ because of a sample- and cooldown-dependent residual strain [3]. For $\varepsilon > 0$, as electrons transfer from X to Y, $R_{[100]}$ decreases [black trace in Fig. 1(d)] because the electrons in Y have a small effective mass and therefore higher mobility along [100]. (Note that the total 2DES density remains fixed as strain is applied.) The resistance

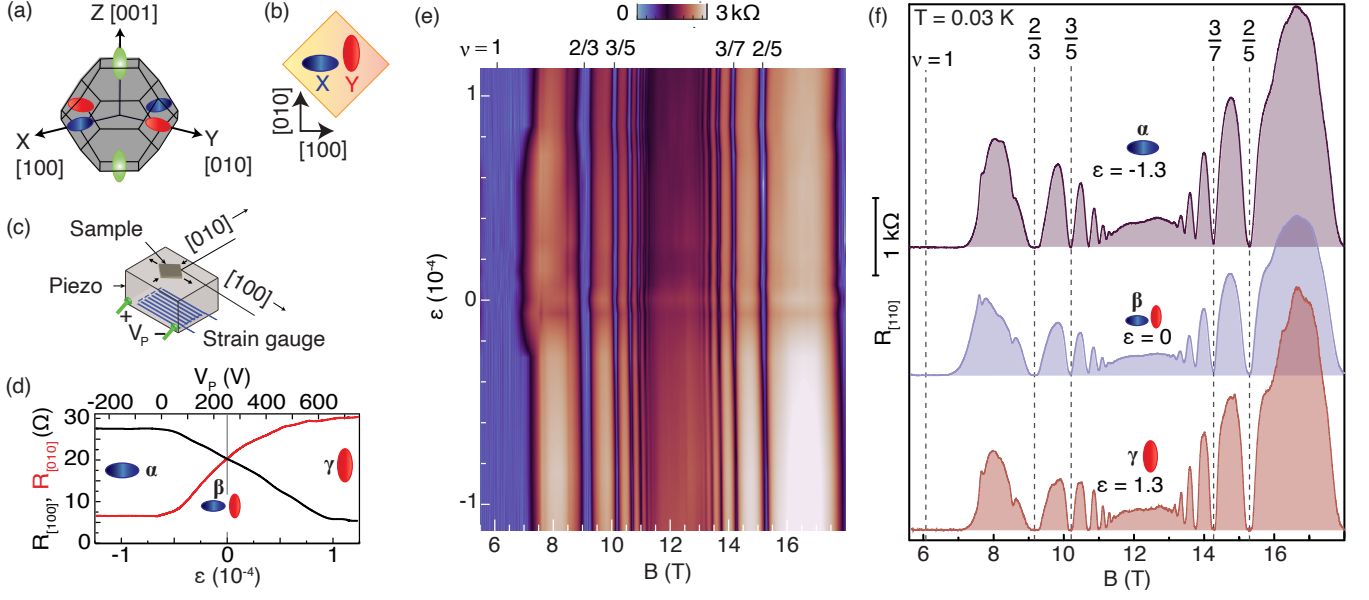


FIG. 1. Sample description and characterization. (a) First Brillouin zone of bulk AlAs, showing anisotropic conduction band valleys. (b) Sample geometry, showing the orientation of the two occupied valleys (X and Y) and the measured resistances ($R_{[100]}$ and $R_{[010]}$). (c) Experimental setup for applying in-plane strain (ε). (d) Piezoresistance of the sample at $B = 0$ and $T \approx 0.03$ K, measured as a function of ε . α - γ mark the valley occupancies. (e) Magnetotransport data at $T \approx 0.03$ K, measured along $[110]$, as a function of ε showing numerous odd-denominator FQHSs in the lowest LL. Some of the LL fillings are marked in the top axis. (f) Magnetoresistance traces ($R_{[110]}$) for different valley occupancies. Traces are shown at three strain values as indicated (in units of 10^{-4}), which correspond to the cases when the 2D electrons occupy only X valley, only Y valley, and both X and Y valley equally. Well-developed FQHSs, some of which are marked with dashed vertical lines, are seen in all traces.

eventually saturates (point γ), when all electrons are in Y [3, 15, 23]. For $\varepsilon < 0$, $R_{[100]}$ increases and saturates (point α) as the electrons are transferred to X which has a large mass and low mobility along $[100]$. As expected, the behavior of $R_{[010]}$ is the opposite of $R_{[100]}$; see the red trace in Fig. 1(d). Such a continuous valley tuning is not possible in other multivalley systems, such as Si [10] or single-layer graphene [20, 21].

When we apply a perpendicular magnetic field (B) to the sample, the kinetic energy of the 2DES is quenched and the density of states becomes quantized into a set of LLs. Our focus here is the extreme quantum limit where the lowest-energy LL is partially occupied ($\nu < 1$). The physics of the 2DES is dominated by electron-electron interaction, as manifested by series of FQHSs at odd denominator fillings flanking $\nu = 1/2$ [24, 25]. We show in Fig. 1(e) magnetoresistance of the sample for $\nu < 1$ as a function of ε and B , covering the complete spectrum from only X ($\varepsilon = -1 \times 10^{-4}$) to only Y ($\varepsilon = 1 \times 10^{-4}$) valley occupancies. (Note that the resistance shown here, $R_{[110]}$, is measured along the $[110]$ direction to minimize the impact of the change in mobility with valley occupancy on resistance [13].) In Fig. 1(f) we show examples of magnetoresistance traces for the three cases marked in Fig. 1(d); α : only X, γ : only Y, and β : equal X and Y valley occupancies. Pronounced resistance minima, signaling well-developed FQHSs at $\nu = 2/3, 3/5, 4/7, ,$

and $1/3, 2/5, 3/7$, are seen on the two sides of $\nu = 1/2$ throughout the applied strain range. The presence of such a rich set of FQHSs, up to $\nu = 7/15$ and $7/13$, attests to the extremely high quality of our sample.

An understanding of FQHS data can be provided by the composite fermion (CF) theory in which, at $\nu = 1/2$, two magnetic flux quanta are attached to each electron to form a CF [24–27]. In a mean-field theory, the flux attachment cancels the applied magnetic field and, at $\nu = 1/2$, the CFs form a Fermi sea. The FQHSs on the flanks of $\nu = 1/2$ can then be explained as the integer quantum Hall states (IQHSs) of CFs. The key concept is that, akin to the LLs of electrons, CFs also form quantized energy levels, termed Λ -levels (Λ ls) [24], in the presence of an *effective* magnetic field measured relative to the field at $\nu = 1/2$. This maps a FQHS at electron LL filling ν to a CF Λ L filling p according to $\nu = p/(2p+1)$. Now, if CFs have a valley degree of freedom, the FQHS near $\nu = 1/2$ should follow the Λ L fan diagram schematically shown in Fig. 2(e) where the Λ ls of the X valley are drawn in blue and those of the Y valley in red [28]. According to this diagram, FQHSs at different fillings should go through multiple transitions. For example, the FQHSs at $\nu = 2/3$ and $2/5$ ($p = 2$) should be strong at $\varepsilon = 0$, become weak or disappear at a specific value of $|\varepsilon|$ where the X and Y valley Λ ls cross, and then become strong again and remain strong at larger values of $|\varepsilon|$. In contrast, the

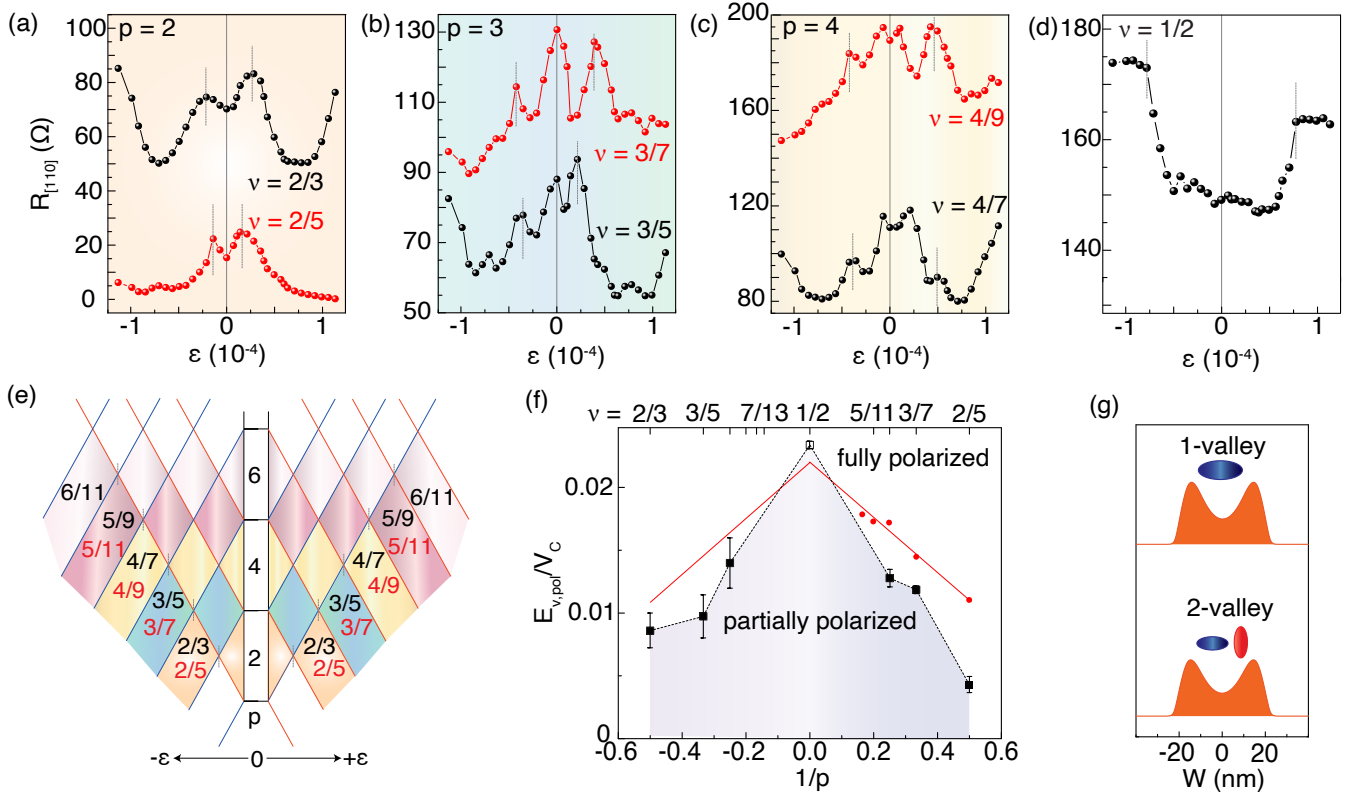


FIG. 2. Valley transitions in the extreme quantum limit. (a-c) Piezoresistance along [110] at $p = 2 - 4$, all taken at $T \simeq 0.3$ K, showing oscillations as a function of ϵ until full valley polarization is reached. The ϵ values for full valley polarization are marked with vertical dotted lines for different fillings. (d) Piezoresistances along [110] at $\nu = 1/2$. (e) Lambda level (ΛL) diagram as a function of applied strain. p denotes the ΛL index. The ΛL s of the two valleys split as we apply ϵ and instigate energy level coincidences and the consequent diamond-shaped regions as a function of ϵ ; this in turn causes piezoresistance oscillations in panels (a-c). (f) Full valley polarization phase diagram in the extreme quantum limit extracted from the dotted vertical lines in panels (a-d). These energies are normalized to the Coulomb energy for various FQHSs and the CF Fermi sea at $\nu = 1/2$, and are plotted versus $1/p$. The data points are obtained from the average $|\epsilon|$ values for full valley polarization for $\epsilon > 0$ and $\epsilon < 0$, and the differences between the two sides are shown as the error bars. The data point at $\nu = 1/2$ is based on $|\epsilon|$ beyond which piezoresistance at $\nu = 1/2$ saturates; see Fig. 2(d), also [29]. The black dotted lines connecting the data points represent the boundary between the partially and fully valley polarized phases. Theoretically calculated spin polarization energy of CFs [31] is shown using red circles (at positive p values) and are joined by a red line. A particle-hole symmetric red line is also drawn for negative p . (g) Charge distribution and Fermi sea for our AIs sample when the electrons occupy single valley (top) and two valleys equally (bottom), obtained from self-consistent quantum mechanical calculations [30].

FQHSs at $\nu = 3/5$ and $3/7$ ($p = 3$), should be weak at $\epsilon = 0$ and then, as a function of $|\epsilon|$, become strong, weak, and then strong again. Such an evolution of FQHSs has been reported near $\nu = 3/2$ [12, 13]. A qualitatively similar *electron* LL diagram has also been used to explain the evolution of the *IQHSs* with strain [1].

In our data taken at $T = 0.03$ K in the extreme quantum limit, at first sight it appears that the CFs have lost their valley degree of freedom, as the FQHSs remain quite robust and do not show any sign of transitions in Figs. 1(e) or (f) in the entire range of ϵ . However, re-measuring the magnetoresistance traces at $T = 0.30$ K, and carefully analyzing the evolution of the values of the FQHS resistance minima, reveal that the FQHSs do indeed undergo transitions. The higher temperature of 0.3 K lifts

the resistances at FQHS fillings from zero and allows us to observe changes as a function of applied ϵ . The data are presented in Figs. 2(a-c) for $p = 2$ ($\nu = 2/3$ and $2/5$), $p = 3$ ($\nu = 3/5$ and $3/7$), and $p = 4$ ($\nu = 4/7$ and $4/9$). In these plots, the resistance at a given FQHS filling oscillates as a function of ϵ and the number of oscillations depends on ν . For example, at $\nu = 3/7$ [Fig. 2(b)], the resistance is high at $\epsilon = 0$, reflecting a weak FQHS. As $|\epsilon|$ is increased, the resistance first drops, signaling a stronger FQHS, then shows a maximum reflecting a weakening of the FQHS, and then eventually becomes small and remains small consistent with a strong and fully valley-polarized FQHS. This is exactly the evolution expected from Fig. 2(e) ΛL diagram [32]. Data at other fillings [Figs. 2(a,c)] also exhibit oscillations which

are consistent with Fig. 2(e).

The results shown in Figs. 2(a-c) indicate that the FQHSs undergo transitions as their valley degree of freedom is tuned. However, as seen in Figs. 1(e-f), there are always FQHSs at these fillings as manifested by the very strong magnetoresistance minima. (Strong magnetoresistance minima are also observed at 0.3 K [33]). This indicates that quantum Hall valley ferromagnetism, evinced by the presence of IQHS minima at LL crossings in *interacting* 2DESs [3, 11, 17, 38], persists in the FQHS regime [16], suggesting that there is interaction between CFs near $\nu = 1/2$. It is worth mentioning that, near $\nu = 3/2$, the FQHSs in AlAs 2DESs completely disappear or become very weak at AL crossings [13, 16]. This is also true in a high-mobility Si 2DES, where two out-of-plane valleys are occupied [10]. However, in contrast to the AlAs data near $\nu = 1/2$ reported here, in the two-valley Si 2DES only the $\nu = 1/3$ is observed and the other odd-numerator FQHSs (e.g., at $\nu = 3/5$ and $3/7$) are extremely weak or absent [10]. It is possible that the extremely high quality of the AlAs 2DESs is responsible for the very strong FQHSs we observe even at AL crossings and the implied robust FQH ferromagnetism. Another difference is that the 2DES in Si occupies two out-of-plane (Z) valleys which have circular and overlapping Fermi seas once projected on the 2D plane, while in AlAs the electrons are in X and Y valleys which are anisotropic and have non-overlapping projected Fermi seas [Fig. 1(b)].

Note in Fig. 2(e) that, beyond the last AL coincidence, the system should be fully valley polarized. We can therefore determine the energy for full valley polarization ($E_{V,pol}$) of a given FQHS from the value of strain (ε_{pol}) for the last resistance maximum in Figs. 2(a-c) and using the expression $E_{V,pol} = E_2 \varepsilon_{pol}$, where $E_2 = 5.8$ eV is the deformation potential for the AlAs conduction band [3, 13]. In Fig. 2(f), we summarize the measured valley polarization energies, normalized by the Coulomb energy $V_C = e^2/4\pi\kappa\varepsilon_0 l_B$, for different FQHSs; κ is the dielectric constant of AlAs ($\simeq 10$) and $l_B = (\hbar/eB)^{1/2}$ is the magnetic length. In Fig. 2(f) we have also included a point for full valley polarization of CFs at $\nu = 1/2$ from the value of $|\varepsilon|$ above which the piezoresistance at this filling saturates [Fig. 2(d)]. Qualitatively similar piezoresistance traces have been reported at $\nu = 3/2$ and $1/2$ [13, 14, 18] and are attributed, partly, to the loss of screening as the CFs become valley polarized; see, e.g. [18, 29].

As seen in Fig. 2(f), the valley polarization energy increases for higher-order FQHSs as $\nu = 1/2$ is approached. This is qualitatively similar to what has been reported for the valley polarization of FQHSs near $\nu = 3/2$ in AlAs 2DESs [13], or spin polarization in GaAs 2DESs [39]. It is also qualitatively consistent with what is theoretically expected for the *spin* polarization of FQHSs and the underlying CFs [31]; see the red lines in Fig. 2(f). (No

theoretical calculations are available for the valley polarization of FQHSs.)

Despite the above qualitative similarities, there are two noteworthy features. First, in Fig. 2(f), except for the data point at $\nu = 1/2$ [29], the experimental data for the CF spin polarization are well below the theoretical boundary (red curves). This is qualitatively similar to the case of spin polarization of FQHSs in GaAs [39], where the difference is partly attributed to the non-zero thickness of the electron layer and the finite energy separation between the LLs, namely, LL mixing [40]. Note that the 2DES in our 45-nm-wide AlAs QW has a reasonably large layer thickness and the charge distribution is bilayer like (see Fig. 2(g)) [30]. Moreover, we expect the large effective mass in AlAs to lead to significant LL mixing [41]. The observed lower experimental boundary for full valley polarization compared to the calculated boundary in Fig. 2(f) is therefore not unexpected. Second, in our AlAs 2DESs, including the present sample, we find that the valley polarization energies for FQHSs near $\nu = 3/2$ (e.g., at $\nu = 4/3$) are about 2 to 3 times larger than the equivalent FQHSs near $\nu = 1/2$ (e.g., at $\nu = 2/3$) [14]. Similarly, the spin polarization energies are found to be larger near $\nu = 3/2$ compared to $1/2$ in high-mobility GaAs 2DESs [39]. In both valley and spin cases, the disparity has been attributed to a breakdown of particle-hole symmetry, triggered by LL mixing [14, 39].

Before closing we point out another noteworthy feature of our data. A recent theory [42] predicts that the CFs at and near $\nu = 1/2$ in 2DESs with a highly anisotropic effective mass should spontaneously valley polarize. This is analogous to the Stoner model of ferromagnetism [43] except that here the transition is induced by anisotropy instead of density. Ref. [42] suggests that the threshold of the effective mass anisotropy for the onset of spontaneous CF valley polarization is ~ 7 . This is larger than the anisotropy in our 2DES where $m_l/m_t \simeq 5$. Nevertheless, Ref. [42] concluded that the spontaneous valley polarization was indeed observed in AlAs 2DESs, based on the $\nu = 3/5$ experimental data of Ref. [14]. We emphasize that, our data shown in Fig. 2(b), which were taken on a much higher quality AlAs 2DES, clearly indicate that the $3/5$ FQHS is *not* fully valley polarized and requires a finite amount of strain for valley polarization. Besides quality, however, one should keep in mind that our 2DES here has a much larger layer thickness compared to the samples used in Ref. [14] or considered in Ref. [42].

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- [28] The Λ L diagram of Fig. 2(e) assumes that CFs are fully spin polarized. This is the case at the high magnetic fields where we are analyzing our data.
- [29] We caution, however, that the shape of the piezoresistance in Fig. 2(d) is different from the parabolic shape seen in previous measurements [13, 14, 18]. Moreover, the values of $|\epsilon|$ above which the resistance at $\nu = 1/2$ saturates in Fig. 2(d) saturates is very close to where we observe full valley polarization of *electrons* at $B = 0$; see Fig. 1(d). (Note that there is also a rise in resistance at several FQHSSs, e.g., at $\nu = 2/3, 3/5$, and $4/7$ [see Figs. 2(a-c)] at the same $|\epsilon| \simeq 0.8 \times 10^{-4}$.) Considering the above observations, we show the data point in Fig. 2(f)

- at $\nu = 1/2$ by an open symbol to distinguish it from data points at other fractions.
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