Clean two-dimensional (2D) electron systems provide one of the most fertile grounds for the observation of many-body phenomena in nature. When the 2D system is cooled to low temperatures and placed in high, perpendicular magnetic fields to minimize the electrons' kinetic energy, it exhibits fascinating and often unexpected phenomena originating from electron-electron interaction. Examples include the fractional quantum Hall effect, electron Wigner crystallization, and the formation of spin textures (Skyrmions) \[1\]. Two decades ago the composite fermion (CF) picture was put forth, initially to describe the fractional quantum Hall effect \[2, 3, 4\]. The CFs are formed by attaching an even number of magnetic flux quanta to each electron at high magnetic fields (Fig. 1). With this transformation, since the attached flux exactly cancels out the external magnetic field at half-filled Landau-levels (LLs), the CFs should ignore the very large external magnetic field and behave as if they are at zero field. Such remarkable behavior has indeed been confirmed in various experiments \[2\]–\[5\]. One particularly fundamental property of CFs at exactly half-filled LLs is that they form a Fermi sea and therefore possess a Fermi surface (FS) \[5\]. This has also been verified in several experiments \[1, 2, 5\].

A natural question that arises is: In a 2D system with an anisotropic electron effective mass and FS (at zero magnetic field), do the CFs retain such anisotropy? The answer to this question is not obvious. One might argue that, since the CFs are a manifestation of the electron-electron interaction, their physical properties should only depend on the magnitude of the magnetic field which quantifies this interaction, and not on the electrons’ zero field \((B = 0)\) properties. On the other hand, the interaction could be anisotropic if the effective mass of electrons is anisotropic. In our study, we measure and compare the piezo-resistance of electrons at \(B = 0\) and of CFs at LL filling factors \(\nu = 1/2\) and \(3/2\) in a 2D electron system confined to an AlAs quantum well. In this system, the electrons can be re-distributed, via the application of strain, between two conduction band valleys each of which has an anisotropic FS. The piezo-resistance of CFs exhibits anisotropic transport, qualitatively similar to the electrons’ at \(B = 0\).

We note at the outset that in a system with a parabolic energy vs. wave vector dispersion, such as AlAs electrons at \(B = 0\), the anisotropies of the effective mass and the FS are linked. In a simple (Drude) model, the transport anisotropy in such a system is a direct consequence of the effective mass anisotropy and the FS anisotropy which typically leads to an anisotropic scattering time. The applicability of a parabolic dispersion or Drude model to CFs is not clear. We would like to emphasize, how-

![FIG. 1: Schematics of 2D electrons and composite fermions in real and reciprocal spaces. Top panel: Schematics of 2D electrons and composite fermions in real space. Lower panels: Schematics of isotropic and anisotropic electron (left) and corresponding composite fermion (right) Fermi surfaces.](image-url)
ever, that our data provide evidence that the transport anisotropy we observe is not merely a consequence of scattering time anisotropy of the CFs, but rather points to an anisotropy of the CF mass and FS.

We studied 2D electrons confined to a 12 nm-wide AlAs quantum well which was grown by molecular beam epitaxy on a (001) GaAs substrate. In the absence of in-plane strain, the 2D electrons in this system occupy two energetically degenerate conduction-band valleys. The valleys are centered at the X-points of the Brillouin zone, and have an anisotropic FS \[6\], characterized by longitudinal and transverse effective masses, \(m_l = 1.05\) and \(m_t = 0.205\) (measured in units of free electron mass).

The two valleys have their major axes along either the [100] or the [010] crystal directions and we refer to these as X and Y valleys, respectively. Their degeneracy can be lifted by applying in-plane symmetry-breaking strain \(\varepsilon = \varepsilon_{[100]} - \varepsilon_{[010]}\), where \(\varepsilon_{[100]}\) and \(\varepsilon_{[010]}\) are the strain values along [100] and [010]. 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. Positive strain pushes the energy of the X valley up relative to the Y valley causing electrons to transfer from X to Y, and vice versa for negative strain \[6\]. To apply tunable strain we glued the sample to one side of a piezo-electric (piezo) stack actuator and used a strain gauge glued to the other side to measure the applied strain \[6\]. We studied a sample patterned into a standard Hall bar mesa with its length along the [100] crystal direction. Using a metal gate deposited on the sample’s surface we varied the 2D electrons density range of our study, the parameters for AlAs are such that the Zeeman energy is larger than the cyclotron energy. Therefore, all the LLs that are of concern here \((\nu < 2)\) have the same spin.

An example of a piezo-resistance trace taken at \(B = 0\) is shown in Fig. 2. The data is consistent with the conventional piezo-resistance seen in multi-valley semiconductors \[7, 8\]. The resistance drops for positive values of strain as electrons are transferred to the Y valley whose mobility along the current direction (the [100] direction) is higher because of its smaller effective mass \(m_l\) along this direction (Fig. 2(f)). For negative values of strain, the resistance rises because now the electrons are transferred to the X valley which has a large effective mass along [100] (Fig. 2(d)). At large enough values of strain (either positive or negative) the resistance saturates once one of the valleys is completely depleted and inter-valley electron transfer stops. The saturation value of the resistance when all electrons are in X valley is about a factor of 3 larger than the resistance when electrons are in Y valley. This is a direct consequence of the mass and FS anisotropy of the valleys at zero field \[6, 8, 10\].

Before discussing the \(\nu = 1/2\) data shown in Fig. 2, we first describe the energy level structure of the 2D system in a perpendicular magnetic field. The magnetic field quantizes the orbital motion of the electrons and forces them to occupy a discrete set of energy levels (LLs) separated by the cyclotron energy, \(h\omega_c = eB/m^*\), where \(B\) is the magnetic field and \(m^* = \sqrt{m_l m_t}\) is the cyclotron effective mass. In our system, there are four sets of these LLs, one for each spin and valley combination. The energy splitting between oppositely polarized spin levels is given by the Zeeman energy, while the levels corresponding to different valleys are separated by \(E_V\). We label each of the energy levels according to their valley (X or Y), spin (\(\uparrow\) or \(\downarrow\)) and LL index \((0, 1, 2)\). However, for the density range of our study, the parameters for AlAs electrons are such that the Zeeman energy is larger than the cyclotron energy. Therefore, all the LLs that are of concern here \((\nu < 2)\) have the same spin.

The piezo-resistance trace in Fig. 2 taken at \(\nu = 1/2\) qualitatively shows a very similar behavior to the \(B = 0\) trace. The resistance decreases (increases) towards positive (negative) values of strain and at high enough strains it saturates. For very negative values of strain, the \(\nu = 1/2\) CFs form in the lowest LL of the X valley, namely...
FIG. 3: The piezo-resistance data of electrons at $B = 0$ and composite fermions at $\nu = 3/2$. (a) and (c) The piezo-resistance of electrons at $B = 0$ at densities $n = 2.10$ and $4.86 \times 10^{11}$ cm$^{-2}$. (b) The piezo-resistance of composite fermions at $\nu = 3/2$ for several densities, given in units of $10^{11}$ cm$^{-2}$. The traces are offset vertically for clarity.

X0 (Fig. 2(a)). For very positive values of strain, the CFs are transferred to the lowest LL of the Y valley, i.e., Y0 (Fig. 2(c)). If the CF mass and FS were both isotropic, we would expect to observe a symmetric piezo-resistance as the resistance should be the same whether the CFs are either in X0 or Y0. The asymmetry of the piezo-resistance at $\nu = 1/2$ therefore indicates that the CFs qualitatively retain the anisotropy of $B = 0$ electrons.

Although the piezo-resistance traces at $B = 0$ and $\nu = 1/2$ are qualitatively very similar, there are two important quantitative differences. First, as can be seen in Fig. 2, at $\nu = 1/2$ the resistance changes and saturates with strain more quickly compared to $B = 0$. This is because, as reported previously, the (valley splitting) energy required to fully polarize the CFs is smaller than the energy needed to valley polarize the electrons [11]. Second, in the density range of $1.2 - 1.9 \times 10^{11}$ cm$^{-2}$ the resistance value when $\nu = 1/2$ CFs are formed in X0 is only a factor of 1.5 to 2 larger than the resistance value when CFs are formed in Y0. This resistance ratio of CFs ($r_{CF}$) is about a factor of two smaller than the resistance ratio of electrons ($r_e$) at $B = 0$. We will return to this difference later in the paper.

The piezo-resistance traces measured at $\nu = 3/2$, while more subtle, provide additional, strong evidence for the anisotropy of CF mass and FS. Data taken for a range of densities are shown in Fig. 3. The $\nu = 3/2$ data reveal remarkably more features than the $B = 0$ or $\nu = 1/2$ data. Instead of changing monotonically with strain and showing only one transition, the piezo-traces at $\nu = 3/2$ exhibit a non-monotonic behavior with strain, suggesting multiple transitions. The other striking feature of the piezo-resistance at $\nu = 3/2$ is that for small values of strain (near zero) it shows the opposite trend compared to the $B = 0$ and $\nu = 1/2$ data: The resistance increases with increasing strain, instead of decreasing. As we will discuss below, all of these features can be understood in the context of CFs with an anisotropic mass and FS.

In Fig. 3, the $\nu = 3/2$ piezo-resistance traces show four regions, highlighted in yellow, where the resistance stays constant for certain ranges of strain which depend on the 2D density. These provide the key to understanding the data. The regions are labeled by X0, Y0, X1, and Y1, indicating the energy level in which the Fermi energy ($E_F$) resides. Note that the X0 and Y0 regions become narrower and get closer to each other as the density is lowered. Also, given the range of strain accessible in our experiments, we can observe the regions X1 and Y1, where the resistance saturates, only at the lowest densities.

In Fig. 4, we focus on the piezo-resistance trace at $\nu = 3/2$ at a density of $4.51 \times 10^{11}$ cm$^{-2}$. The opposite trend of the piezo-resistance near zero strain compared to the $B = 0$ or $\nu = 1/2$ data is obvious. At $B = 0$, positive strain pushes the X valley up in energy and electrons are transferred from the X valley to the Y valley. Similarly, at $\nu = 1/2$ CFs are transferred from X0 to Y0 with positive strain. But as seen in the energy level diagrams of Figs. 4(a) and (c), this situation is reversed for the case of CFs formed at $\nu = 3/2$. At $\nu = 3/2$, for finite values of
strain, there is exactly one full LL and one half-filled LL. For small but finite positive values of strain, the LLs of the X valley move up compared to the Y valley, but $E_F$ stays at the X0 level since this is the second lowest energy level (Fig. 4(c)). The Y0 level is of course completely full and therefore inert. Thus, although the majority of the electrons are in the Y0 level, it is the minority electrons in the X0 level which are at $E_F$ and should dominate the electrical transport at $\nu = 3/2$. For negative but small values of strain the X0 level becomes fully occupied and inert and $E_F$ follows the Y0 level which contains minority electrons (Fig. 4(a)). The opposite trends of the piezo-resistance traces at $\nu = 1/2$ and 3/2 (at small magnitudes of strain) can therefore be understood by considering the position of $E_F$ and again assuming an anisotropic CF mass and FS.

Note that if the magnitude of strain is sufficiently small so that the cyclotron energy is larger than the valley splitting energy, but large enough so that the CFs are formed fully in the X0 or Y0 levels, we expect a region of constant resistance as seen and marked by X0 and Y0 in Figs. 3 and 4 data. Interestingly, the ratio of the resistance values for X0 and Y0 regions for $\nu = 3/2$ traces is between 1.5 and 2.3 in our available density range; this is similar to the ratio $r_{CF}$ seen for the $\nu = 1/2$ traces.

In Fig. 5 we demonstrate what happens at lower densities where we can apply sufficient strain to transfer all the electrons from one valley to the other. This happens when the valley splitting energy is larger than the cyclotron energy so that all the electrons occupy the X valley (i.e., the X0 and X1 levels) or the Y valley (Y0 and Y1). The $E_F$ then lies either at the X1 level for very large negative values of strain (Fig. 5(a)), or at the Y1 level for very large positive strains (Fig. 5(b)). The piezo-resistance trace in Fig. 5 and other low-density traces in Fig. 3 reveal that, as the electrons become fully valley polarized for either positive or negative strains, the resistance increases. This is likely because of the loss of screening upon full valley and spin polarization [12, 13]. Most remarkable, however, is that the resistance rises much more for negative values of strain compared to positive strains. The saturation value for very large negative strains is in fact higher than the saturation value for positive strains, similar to the $B = 0$ and $\nu = 1/2$ data. These observations provide evidence for the CF transport anisotropy even when the $\nu = 3/2$ CFs are formed in the second LL.

As we mentioned before, the piezo-resistance at $B = 0$ stems from the anisotropy of the effective mass and FS. The FS anisotropy, however, typically leads to an anisotropic scattering time which can also affect transport. In a simple Drude model, assuming isotropic scattering, the resistance ratio ($r_c$) is equal to the mass ratio along the two directions ($m_l/m_t$). For our system we measure $r_c \approx 3$ which is smaller than the simple Drude prediction $m_l/m_t = 5.1$. This discrepancy can be understood by incorporating a scattering time that is longer along the larger mass direction. This is a reasonable assumption since along the large mass direction the Fermi wave vector is larger and hence electrons should scatter less because of their larger momentum [9, 10, 14]. Note that, in the most realistic scenario, the anisotropic scattering time comes about because of the anisotropy of the FS and can only reduce $r_c$ below the mass anisotropy ratio.

The interpretation of the resistance ratio $r_{CF}$ for the CFs is less clear. We emphasize that experimentally we measure a sizable $r_{CF}$ but $r_{CF}$ is always smaller than $r_c$. In a simple Drude model, this observation implies that either the mass anisotropy ratio for CFs is smaller than for electrons at $B = 0$ or the scattering for CFs is more anisotropic. The mass anisotropy ratio for CFs being smaller than for electrons is plausible. In an ideal, isotropic 2D system, all the physical quantities of CFs are determined by the Coulomb interaction ($\propto 1/\sqrt{x^2 + y^2}$) where $x$ and $y$ are components of the distance between two electrons. Note that, at a fixed filling factor, this interaction is solely quantified by the magnetic length $l_B = \sqrt{\hbar/eB}$ [2, 3, 4]. Now a system with an anisotropic FS at $B = 0$ can be mapped to a system with isotropic FS at $B = 0$ and an anisotropic Coulomb interaction ($\propto 1/\sqrt{x^2 + y^2 + \gamma^2}$), where $\gamma = (m_l/m_t)^{1/4}$. Obviously, in such a case the strength of the Coulomb interaction depends not only on $l_B$ but also on the direction and $\gamma$. If one assumes that the transport mass of CFs

![Figure 5](image-url)
along some direction is determined by the strength of the Coulomb interaction along that direction, then the mass anisotropy ratio of CFs is given by \( \gamma^2 = \sqrt{m_l/m_t} \) rather than \( m_l/m_t \), consistent with the observation that \( r_{CF} < r_e \).

A theoretical study [12] that takes into account the mass anisotropy of electrons at \( B = 0 \) predicts that the form of the FS for CFs is identical to the zero field FS but that, despite this anisotropy, the CF effective mass is almost isotropic. It is not obvious what this theory would predict for the resistance of the CFs. If the CF scattering time followed the anisotropy of its FS, however, in a simple Drude model an isotropic CF mass would imply an \( r_{CF} \) which has the opposite behavior to what we observe experimentally. On the other hand, our data do not rule out a hypothetical situation where the effective mass is anisotropic but the FS is isotropic.

Can the anisotropic transport we observe for CFs come only from anisotropic scattering? For example, it is known that disorder-induced density variations at \( B = 0 \) are accompanied by fluctuations in the effective magnetic field of CFs, resulting in more pronounced scattering [4]. If such variations have a preferred crystal direction (e.g., along the strain axis) and their magnitude increases with strain, then they could lead to anisotropic transport of CFs. Our data, however, provide strong evidence against such scenario. First, the piezo-resistance we observe at \( \nu = 1/2 \) and 3/2 is clearly linked to the valley occupation of CFs and not simply the magnitude of strain: The resistance only changes while the valleys are partially occupied and it saturates once the CFs are fully valley polarized. Second, for small values of strain near zero, the \( \nu = 3/2 \) piezo-resistance shows the opposite trend compared to the \( \nu = 1/2 \) case. The CF piezo-resistance anisotropy we observe therefore cannot result from a fixed anisotropic scattering in a preferred direction, and is most likely related to the effective mass and FS anisotropy of CFs.

The piezo-resistance results presented here demonstrate that, in a 2D electron system with an anisotropic effective mass and FS at zero magnetic field, the CFs at filling factors 1/2 and 3/2 also exhibit anisotropic transport, consistent with a qualitative transference of the electron mass and FS anisotropy to the CFs. Better theoretical treatment is clearly needed to describe the CFs in an anisotropic system and in particular quantitatively determine their resistance and mass or FS anisotropy. Also helpful would be measurements that directly probe the FS and its anisotropy, such as commensurability oscillations in 2D systems with a periodically modulated electron density [10, 17].

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[1] Sarma, S.D. & Pinczuk, A., Perspectives in Quantum Hall Effects : Novel Quantum Liquids in Low-Dimensional Semiconductor Structures. (Wiley, New York, 1997).
[2] Jain, J.K., Composite Fermions. (Cambridge University Press, 2007).
[3] Jain, J.K., Phys. Rev. Lett. 63, 199 (1989).
[4] Halperin, B.I., Lee, P.A. & Read, N., Phys. Rev. B 47, 7312 (1993).
[5] More properly, the CFs should have a constant-energy (Fermi) contour.
[6] Shayegan, M. et al., Phys. Stat. Sol. (b) 243, 3629 (2006).
[7] Smith, C.S., Phys. Rev. 94, 42 (1954).
[8] Shkolnikov, Y.P., Vakili, K., DePoortere, E.P. & Shayegan, M., Appl. Phys. Lett. 85, 3766 (2004).
[9] Dorda, G., Eisele, I. & Gesch, H., Phys. Rev. B 17, 1785 (1978).
[10] Ando, T., Fowler, A.B. & Stern, F., Rev. Mod. Phys. 54, 437 (1982).
[11] Bishop, N.C. et al., Phys. Rev. Lett. 98, 266404 (2007).
[12] Gunawan, O. et al., Nature Physics 3, 388 (2007).
[13] Vakili, K. et al., Phys. Rev. Lett. 94, 176402 (2005).
[14] Y. Tokura, Phys. Rev. B. 58, 7151 (1998).
[15] Balaguero, D.B. & Lozovik, Y.E., Phys. Rev. B. 62, 1481 (2000).
[16] Smet, J.H., von Klitzing, K., Weiss, D. & Wegscheider, W., Phys. Rev. Lett. 80, 4538 (1998).
[17] Gunawan, O., Shkolnikov, Y.P., De Poortere, E.P., Tuttuc, E. & Shayegan, M., Phys. Rev. Lett. 93, 246603 (2004).