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High-temperature resistivity measured at $\nu = \frac{5}{2}$ as a predictor of the two-dimensional electron gas quality in the $N = 1$ Landau level

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We report a high-temperature ($T = 0.3$ K) indicator of the excitation gap $\Delta_{5/2}$ at the filling factor $\nu = \frac{5}{2}$ fractional quantum Hall state in ultrahigh-quality AlGaAs/GaAs two-dimensional electron gases. As the lack of correlation between mobility μ and $\Delta_{5/2}$ has been well established in previous experiments, we define, analyze, and discuss the utility of a different metric $\rho_{5/2}$, the resistivity at $\nu = \frac{5}{2}$, as a high-temperature predictor of $\Delta_{5/2}$. This high-field resistivity reflects the scattering rate of composite fermions. Good correlation between $\rho_{5/2}$ and $\Delta_{5/2}$ is observed in both a density-tunable device and in a series of identically structured wafers with similar density but vastly different mobility. This correlation can be explained by the fact that both $\rho_{5/2}$ and $\Delta_{5/2}$ are sensitive to long-range disorder from remote impurities, while μ is sensitive primarily to disorder localized near the quantum well.

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The two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures remains the preeminent semiconductor platform for the study of strong electron-electron correlations in reduced dimensions. As the design of GaAs/AlGaAs 2DEG structures becomes more sophisticated and ultralow-temperature experiments become more complicated, the question of how best to make a preliminary assessment of sample quality becomes increasingly important [1]. This is especially true for heterostructures designed to explore the most fragile fractional quantum Hall states (FQHSs) in the $N = 1$ Landau level (LL), a regime in which many distinct phases are separated by small intervals in the filling factor $\nu = hn/eB$ (h is Planck's constant, n is the 2DEG density, e is the charge of the electron, and B is the magnetic field) that must be examined at temperatures below 50 mK. For example, transport signatures of the putative non-Abelian $\nu = \frac{5}{2}$ and $\nu = \frac{12}{5}$ FQHS and reentrant integer quantum Hall effect (RIQHE) states are strongest at temperatures $T \leqslant 20$ mK. Traditionally, zero-magnetic-field mobility measured at much higher temperatures ($0.3\ \text{K} \leqslant T \leqslant 2$ K) has been used as a primary metric of 2DEG quality, but a large body of experimental and theoretical evidence has now shown that mobility does not necessarily encode all information needed to predict high-field behavior in the fractional quantum Hall regime [1–5]. Evidently, additional methods must be employed to predict behavior at lower temperatures and high magnetic field in the highest-quality samples [4]. In the context of the present work, quality is quantified by the size of the energy gap of the FQHS at $\nu = \frac{5}{2}$, $\Delta_{5/2}$. We note that samples with high $\Delta_{5/2}$ generally show high-quality transport throughout the $N = 1$ LL.

Composite fermion (CF) theory replaces a system of highly interacting electrons with a system of weakly interacting composite fermions by vortex attachment [6–8] and explains the physics around the filling factor $\nu = \frac{1}{2}$ in the $N = 0$ LL. Extending this theory to other half fillings in higher LLs, we expect that at $T = 0.3$ K, the state at $\nu = \frac{5}{2}$ is also described by composite fermions experiencing a zero effective magnetic field $B_{\text{eff}} = 0$. Indeed, Willett and collaborators [9] demonstrated the existence of a Fermi surface at $\nu = \frac{5}{2}$ at $T = 0.3$ K using surface acoustic wave techniques. The CF model has also been successfully used to analyze energy gaps of odd denominator FQHSs around $\nu = \frac{5}{2}$ by using the CF cyclotron energy [10,11]. In the CF picture, the fractional quantum Hall state that emerges at $T \leqslant 100$ mK is viewed as a condensation of CFs driven by a BCS-like p-wave pairing instability [12,13]. In this Rapid Communication, we assume that at $T = 0.3$ K, a Fermi sea of CFs forms at $\nu = \frac{5}{2}$, and measure the resistivity of this metallic phase $\rho_{5/2}$ analogously to the zero-field resistivity. We investigate this high-field resistivity as a high-temperature ($T = 0.3$ K) indicator of the strength of the $\nu = \frac{5}{2}$ FQHS at low temperatures.

The longitudinal resistance as a function of magnetic field B measured at $T = 0.3$ K in the vicinity of $\nu = \frac{5}{2}$ is plotted in the inset of Fig. 1. A resistance minimum is observed at $\nu = \frac{5}{2}$. It is noteworthy that the positive magnetoresistance near $\nu = \frac{5}{2}$ resembles the transport behavior near $\nu = \frac{3}{2}$ and $\nu = \frac{1}{2}$ [14–16], but contrasts with the negative magnetoresistance often observed near zero field. The temperature dependence of resistance at $\nu = \frac{5}{2}$ is shown in Fig. 1. In this exemplary Arrhenius plot, R_{xx} at $\nu = \frac{5}{2}$ shows activated behavior below 100 mK: it increases as temperature increases, following $R_{xx} \propto e^{-\frac{\Delta}{2k_B T}}$. A linear fit through the activation region yields an energy gap $\Delta_{5/2} = 570$ mK. However, R_{xx} at $\nu = \frac{5}{2}$ starts to saturate when temperature exceeds 150 mK, and at $T = 300$ mK it is insensitive to temperature. The very weak temperature dependence observed around $T = 0.3$ K is an important attribute: it indicates that a description based on a gapped FQHS with a dilute population of thermally activated FQHS quasiparticles is no longer justified as it is at significantly lower temperatures. It is appealing to consider this change a temperature-driven transition to a CF Fermi sea. As

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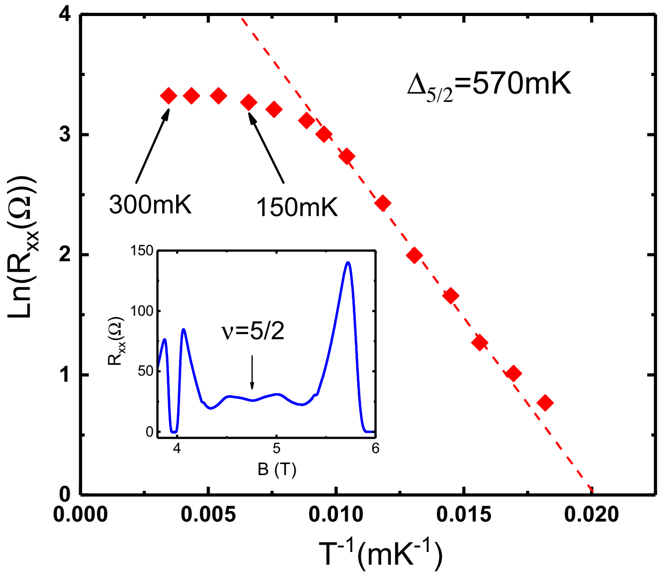

FIG. 1. Arrhenius plot at $\nu = \frac{5}{2}$ where the gap is measured to be 570 mK. Magnetoresistance at $T = 0.3$ K in a larger field range is shown in the inset.

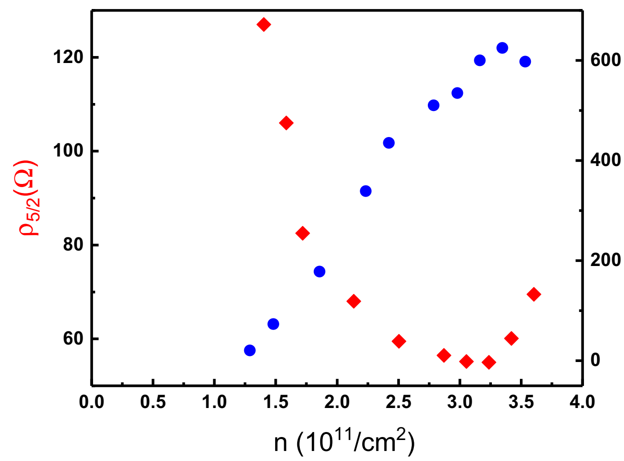

FIG. 2. $\nu = \frac{5}{2}$ resistivity $\rho_{5/2}$ measured at $T = 0.3$ K (red) and $\Delta_{5/2}$ (blue) as a function of 2DEG density n for the *in situ* back-gated sample.

a purely practical matter, the temperature insensitivity of $\rho_{5/2}$ suggests the utility of our method of characterization in much the same way that $B = 0$ mobility is insensitive to temperature below $T \sim 1$ K in ultrahigh-quality samples. The resistivity measured at $\nu = \frac{1}{2}$ is equal to the CF resistivity. It can be shown that the resistivity measured at $\nu = \frac{5}{2}$ is equivalent to CF resistivity up to a numerical scale factor [8,15].

We have studied two types of samples. The first sample is a density tunable device: an *in situ* back-gated 2DEG. The 2DEG is grown by molecular beam epitaxy (MBE) and resides in a 30 nm GaAs quantum well bounded by $Al_{0.24}Ga_{0.76}As$ barriers with Si δ-doping in a narrow GaAs layer flanked by pure AlAs layers placed 66 nm above the principal 30 nm GaAs quantum well. This design has been shown to yield the largest gap energy for the $\nu = \frac{5}{2}$ FQHS [4,17–19]. It is believed [2] that low-conductivity electrons confined in the X band of the AlAs barriers surrounding the narrow GaAs doping wells screen potential fluctuations caused by remote donor impurities, promoting the expression of large gap FQHSs in the $N = 1$ LL. This particular sample displays the largest excitation gap for the $\nu = \frac{5}{2}$ FQHS reported in the literature, attesting to its high quality [20]. The *in situ* gate consists of an n^+ GaAs layer situated 850 nm below the bottom interface of the quantum well. There is an 830 nm GaAs/AlAs superlattice between the 2DEG and back gate to minimize leakage current. The device is a 1 mm×1 mm lithographically defined van der Pauw (vdP) square with eight Ni\Ge\Au\Ni stack contacts diffused along the sample edges; processing details have been described in Ref. [20].

In a second set of experiments we examine a series of samples, each sharing the same heterostructure design: a 30 nm GaAs quantum well with 2DEG density $n = 3.0\times10^{11}/\text{cm}^2$. The quantum well is flanked by symmetric Si δ-doping in GaAs doping wells, as described previously [4]. These samples are grown in a single MBE growth campaign; sample mobility improves as the unintentional impurities emanating from the source material decrease with increasing growth number. Each specimen consists of a 4 mm×4 mm vdP square with eight diffused indium contacts on the edges. We perform standard low-frequency (13–85 Hz) lock-in measurements. The excitation currents for resistivity measurement and gap measurement are 10 and 2 nA, respectively. We use the van der Pauw method for measuring resistivities; the quoted resistivity is the usual average of four distinct resistance measurements. The samples are homogeneous such that the resistances measured along different crystallographic directions are similar. Typically, the difference is less than a factor of 2, both at $\nu = \frac{5}{2}$ and zero field.

In Fig. 2(a) we present the dependence of $\rho_{5/2}$ (left axis) and $\Delta_{5/2}$ (right axis) for various densities of the *in situ* back-gated GaAs 2DEG. The typical uncertainty for gap and resistivity measurement is ±5%. As n increases, $\Delta_{5/2}$ increases and $\rho_{5/2}$ decreases. A clear correlation between $\rho_{5/2}$ and $\Delta_{5/2}$ is observed in this density-tunable device.

In the density-tunable device, we expect that as density increases, the resistivity $\rho_{5/2}$ should decrease due to the increasing carrier concentration, and the energy gap $\Delta_{5/2}$ should increase due to the increase of the Coulomb energy scale. It is also possible that the scattering rate may change with changing density [1,8], so the change of $\rho_{5/2}$ and $\Delta_{5/2}$ with changing density likely reflects both their explicit density dependence and the effects of scattering. The strong correlation we observe between $\rho_{5/2}$ and $\Delta_{5/2}$ in this device indicates that $\rho_{5/2}$ captures both the density dependence and the effects of scattering on the energy gap.

We note that at high densities, $\rho_{5/2}$ begins to increase and $\Delta_{5/2}$ plateaus and decreases slightly. This has been explained by occupation of the first excited subband of the quantum well [20], and may be responsible for the slight mismatch between the minimum of $\rho_{5/2}$ and the peak of $\Delta_{5/2}$; evidently, the correlation between $\rho_{5/2}$ and $\Delta_{5/2}$ is not as strong when there is parallel conduction through an excited subband.

We then measured $\rho_{5/2}$ for the series of wafers with an identical heterostructure design and fixed 2DEG density. The

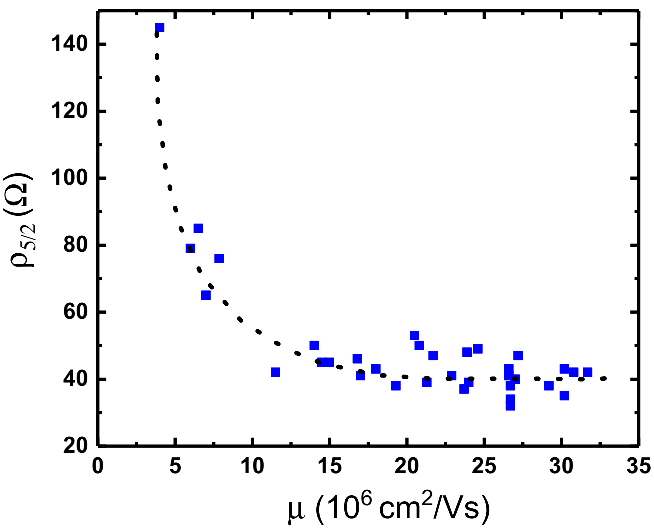

FIG. 3. $\nu = \frac{5}{2}$ resistivity $\rho_{5/2}$ measured at $T = 0.3$ K vs mobility for samples grown during a single MBE growth campaign. All samples have the same heterostructure design: a symmetrically doped GaAs quantum well with density $n = 3.0\times10^{11}/\mathrm{cm}^2$. The dashed line is a guide to the eye.

relationship between $\rho_{5/2}$ and μ is illustrated in Fig. 3: $\rho_{5/2}$ initially drops monotonically as mobility increases, but it saturates at $\mu \sim 15\times10^6$ cm^2/V s even though mobility keeps increasing over the course of the MBE growth campaign. In this high-mobility range, $\rho_{5/2}$ and μ appear to have no relationship to one another; samples with the same $\rho_{5/2}$ may have vastly different μ.

A few samples with various combinations of $\rho_{5/2}$ and μ are chosen from the sample set in Fig. 3 to measure energy gaps ($\Delta_{5/2}$) of the fractional quantum Hall state that forms at $\nu = \frac{5}{2}$ at lower temperatures. Figure 4(a) displays the relation between $\Delta_{5/2}$ and $1/\rho_{5/2}$ for those samples: $\Delta_{5/2}$ increases monotonically as $1/\rho_{5/2}$ increases. For the largest $1/\rho_{5/2}$, where $\rho_{5/2}$ is 39 Ω, $\Delta_{5/2}$ reaches 570 mK, among the largest gaps at this density ever reported in literature [10,17,20]. Here, in this comparison of different samples with the same density but different levels of disorder, we also observe a strong correlation between $\Delta_{5/2}$ and $\rho_{5/2}$, indicating that $\rho_{5/2}$ is sensitive to the scattering mechanisms that limit $\Delta_{5/2}$. We also plot $\Delta_{5/2}$ vs μ for these samples. As shown in Fig. 4(b), in the low-mobility range where $\mu < 10\times10^6$ cm^2/V s, $\Delta_{5/2}$ increases as μ increases. However, no correlation exists in the high-mobility range where $\mu > 10\times10^6$ cm^2/V s.

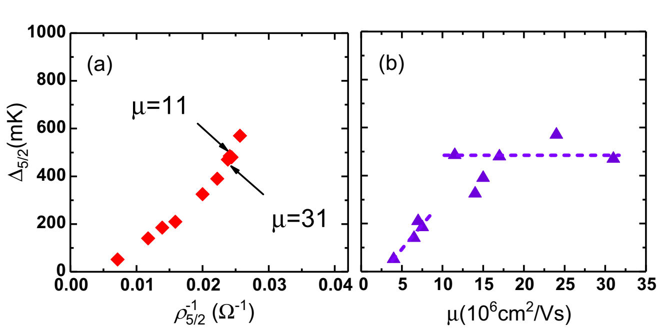

FIG. 4. The $\nu = \frac{5}{2}$ energy gap $\Delta_{5/2}$ vs (a) $1/\rho_{5/2}$ and (b) mobility μ for samples chosen from Fig. 3. The arrows in (a) indicate two samples with the same $\rho_{5/2}$ and $\Delta_{5/2}$ but vastly different μ, and the units for the listed μ are 10^6 cm^2/V s. The dashed lines in (b) are guides to the eye.

We briefly discuss why the CF resistivity measured by $\rho_{5/2}$ may contain different information than the zero-field mobility and show a stronger correlation with the low-temperature $\nu = \frac{5}{2}$ FQHS. Zero-field resistivity is dominated by large-angle scattering [1]. Because of this, the zero-magnetic-field mobility is primarily limited by Coulomb scattering from impurities located directly in the quantum well [1,17,21,22], while remote impurities primarily cause small-angle scattering, which has significantly less impact on mobility. Composite fermions at half filling are also scattered by impurities, however, remote charged impurities also induce spatial variations in the effective magnetic field $B_{\rm eff}$ due to variations in the 2DEG density [8,23]. These effective magnetic field variations cause increased large-angle scattering of CFs, resulting in an enhanced contribution by remote impurities to the CF resistivity [8,15,24]. Because of this, we expect that $\rho_{5/2}$ is more sensitive to remote impurities than the zero-field mobility and thus contains different information about the distribution of impurities in the system. This increase in large-angle scattering has been observed experimentally at $\nu = \frac{1}{2}$ [14]. However, the connection between CF resistivity at $\nu = \frac{5}{2}$ and FQHS gap strength has not been previously studied. Our data suggest that variations of $B_{\rm eff}$ from remote impurities dominate the measured $\rho_{5/2}$. We mention that for the high-density samples which show a large $\Delta_{5/2}$, $\nu = \frac{3}{2}$ and $\nu = \frac{1}{2}$ occur at high magnetic fields which are not easily accessible by most superconducting magnets, so we did not investigate the CF resistivity at those half fillings; however, we do not exclude the possibility that they may also correlate with the energy gaps of FQHSs.

Other experiments [15,16,25] and theory [26,27] at $\nu = \frac{1}{2}$ have shown that short-range CF-CF interactions via gauge field fluctuations result in an additional correction to the CF scattering rate and resistivity which is not present at zero field. This may be another reason that $\rho_{5/2}$ provides information about the disorder potential from impurities that μ does not.

Next, we address the sensitivity of the strength the $\nu = \frac{5}{2}$ FQHS to disorder. It has been shown through computational methods that the size of quasiparticles and quasiholes in the $\nu = \frac{5}{2}$ state is unusually large, on the order of at least 12 times the magnetic length [2]; this large size is expected to make $\Delta_{5/2}$ sensitive to long-range disorder from remote charged impurities [2,5]. Experiments studying the effects of remote doping schemes have confirmed that remote impurities from ionized donors do indeed have a large impact on $\Delta_{5/2}$, but a minimal effect on μ [3,28]. A particularly illuminating experiment is detailed in Ref. [17]: It was found that intentionally placing short-range disorder directly in the quantum well drastically reduced mobility but had a comparatively small effect on $\Delta_{5/2}$, confirming that μ is limited by short-range disorder while $\Delta_{5/2}$ is more sensitive to long-range disorder from remote impurities. The fact that both $\Delta_{5/2}$ and $\rho_{5/2}$ are sensitive to long-range disorder from remote impurities explains the strong correlation we observe between the two quantities and the lack of correlation with μ.

Additionally, if the $\nu = \frac{5}{2}$ FQHS is considered to be a p-wave Cooper-paired state of composite fermions as in the Moore-Read Pfaffian state [12,13], then it is natural to compare our results to what is observed in p-wave superconductors. In p-wave superconductors, as the normal-state resistivity increases due to impurity scattering, the superconducting transition temperature T_c is expected to decrease [29–31], and strong suppression of T_c with increasing normal-state resistivity has been observed experimentally in the putative p-wave superconductor Sr_2RuO_4 [31,32]. Therefore, the direct correlation we observe between the normal-state CF resistivity at $T = 0.3$ K and the low-temperature $\nu = \frac{5}{2}$ FQHS energy gap is in qualitative agreement with the strong dependence of T_c on normal-state resistivity in p-wave superconductors.

We mention that the quantum scattering time τ_q measured by low-field Shubnikov–de Haas oscillations [33,34] is also expected to be sensitive to long-range disorder, and thus might be expected to be a predictor of $\Delta_{5/2}$ [1]. However, a previous experiment in a density-tunable device [2] showed no correlation between τ_q and the strength of the $\nu = \frac{5}{2}$ FQHS. We also measured τ_q in our back-gated device and found no correlation with $\Delta_{5/2}$ (data not shown here); a detailed analysis of quantum scattering time in our samples will be presented in a forthcoming publication.

In conclusion, we observe a strong correlation between $\rho_{5/2}$ and $\Delta_{5/2}$ in both a density-tunable device and in a series of samples with fixed 2DEG density. Therefore, we propose the use of $\rho_{5/2}$ measured at $T = 0.3$ K as a metric to predict the strength of $\nu = \frac{5}{2}$ FQHS at low temperatures. The fact that we observe this correlation both when the electron density is varied (in the back-gated device) and when the level of disorder is varied (in the series of fixed-density samples) makes our method a robust tool for predicting $\Delta_{5/2}$. A possible physical origin for the correlation is that $\rho_{5/2}$ is sensitive to large-angle scattering by remote impurities due to the variation of the B_{eff} and to short-range CF-CF interactions, neither of which are reflected in the zero-field mobility.

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