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

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Abstract

We report a high temperature (T = 0.3K) indicator of the excitation gap $\Delta_{5/2}$ at the filling factor $\nu = 5/2$ fractional quantum Hall state in ultra-high quality AlGaAs/GaAs two-dimensional electron gases. As the lack of correlation between mobility $\mu$ 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 $\nu = 5/2$, 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 $\mu$ is sensitive primarily to disorder localized near the quantum well.
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 ultra-low 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 filling factor \( \nu = h n / e B \) (\( h \) is Planck’s constant, \( n \) is 2DEG density, \( e \) is the charge of the electron and \( B \) is magnetic field) that must be examined at temperatures below 50mK. For example, transport signatures of the putative non-Abelian \( \nu = 5/2 \) and \( \nu = 12/5 \) FQHS and reentrant integer quantum Hall effect (RIQHE) states are strongest at temperatures \( T \leq 20 \text{mK} \). Traditionally, zero-magnetic-field mobility measured at much higher temperatures (0.3K \( \leq T \leq 2 \text{K} \)) 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 \( \nu = 5/2 \), \( \Delta_{5/2} \). 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 [14–16] and explains the physics around filling factor \( \nu = 1/2 \) in the N=0 LL. Extending this theory to other half-fillings in higher LLs, we expect that at \( T=0.3 \text{K} \), the state at \( \nu = 5/2 \) is also described by composite fermions experiencing zero effective magnetic field \( B_{eff} = 0 \). Indeed, Willett and collaborators [8] demonstrated the existence of a Fermi surface at \( \nu = 5/2 \) at \( T=0.3 \text{K} \) using surface acoustic wave techniques. The CF model has also been successfully used to analyze energy gaps of odd denominator FQHSs around \( \nu = 5/2 \) by using the CF cyclotron energy [20, 21]. In the CF picture, the fractional quantum Hall state that emerges at \( T \leq 100 \text{mK} \) is viewed as a condensation of CFs driven by a BCS-like p-wave pairing instability [31, 32]. In this work, we assume that at \( T=0.3 \text{K} \) a Fermi sea of CFs forms at \( \nu = 5/2 \), and measure the resistivity of this metallic phase, \( \rho_{5/2} \), analogously to the zero field resistivity. We investigate
FIG. 1. (color online). Arrhenius plot at $\nu = 5/2$ where the gap is measured to be 570mK. Magnetoresistance at $T=0.3K$ in a larger field range is shown in the inset.

this high field resistivity as a high temperature ($T = 0.3K$) indicator of the strength of the $\nu = 5/2$ FQHS at low temperatures.

The longitudinal resistance as a function of magnetic field $B$ measured at $T = 0.3K$ in the vicinity of $\nu = 5/2$ is plotted in the inset of Fig. 1. A resistance minimum is observed at $\nu = 5/2$. It is noteworthy that the positive magnetoresistance near $\nu = 5/2$ resembles the transport behavior near $\nu = 3/2$ and $\nu = 1/2$ [22–24], but contrasts with the negative magnetoresistance often observed near zero field. The temperature dependence of resistance at $\nu = 5/2$ is shown in Fig. 1. In this exemplary Arrhenius plot, $R_{xx}$ at $\nu = 5/2$ shows activated behavior below 100mK: it increases as temperature increases following $R_{xx} \propto e^{-\Delta_{5/2}/k_B T}$. A linear fit through the activation region yields an energy gap $\Delta_{5/2}=570$mK. However, $R_{xx}$ at $\nu = 5/2$ starts to saturate when temperature exceeds 150mK, and at $T=300$mK it is insensitive to temperature. The very weak temperature dependence observed around $T=0.3K$ 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 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 $T \sim 1K$ in ultra-high quality samples. The resistivity measured at $\nu = 1/2$ is equal to the CF resistivity. It can be shown that the resistivity measured at $\nu = 5/2$ is equivalent to CF resistivity up to a numerical scale factor $[16, 23]$.

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 30nm GaAs quantum well bounded by Al$_{0.24}$Ga$_{0.76}$As barriers with Si $\delta$-doping in a narrow GaAs layer flanked by pure AlAs layers placed 66nm above the principal 30nm GaAs quantum well. This design has been shown to yield the largest gap energy for the $\nu = 5/2$ FQHS $[4, 7, 9, 10]$. 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 expression of large gap FQHS in the N=1 LL. This particular sample displays the largest excitation gap for the $\nu = 5/2$ FQHS reported in the literature, attesting to its high quality $[11]$. The *in situ* gate consists of an $n^+$ GaAs layer situated 850 nm below the bottom interface of the quantum well. There is an 830nm GaAs/AlAs superlattice between the 2DEG and back gate to minimize leakage current. The device is a 1mm by 1mm 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 reference $[11]$.

In a second set of experiments we examine a series of samples each sharing the same heterostructure design: a 30nm GaAs quantum well with 2DEG density $n = 3.0 \times 10^{11}/cm^2$. The quantum well is flanked by symmetric Si $\delta$-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 4mm by 4mm VdP square with 8 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 10nA and 2nA, 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, both at $\nu = 5/2$ 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, 16], 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 [11], 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 the identical heterostructure design and fixed 2DEG density. The relationship between $\rho_{5/2}$ and $\mu$ is illustrated in Fig. 3.
FIG. 3. (color online). $\nu = 5/2$ resistivity $\rho_{5/2}$ measured at $T=0.3K$ vs. mobility for samples grown during a single MBE growth campaign. All samples have same heterostructure design: a symmetrically doped GaAs quantum well with density $n = 3.0 \times 10^{11}/cm^2$. The dashed line is guide to the eye.

initially drops monotonically as mobility increases, but it saturates at $\mu \sim 15 \times 10^6 cm^2/Vs$ even though mobility keeps increasing over the course of the MBE growth campaign. In this high mobility range $\rho_{5/2}$ and $\mu$ appear to have no relationship to one another; samples with the same $\rho_{5/2}$ may have vastly different $\mu$. A few samples with various combinations of $\rho_{5/2}$ and $\mu$ 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 $\nu = 5/2$ at lower temperatures. Fig. 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$\Omega$, $\Delta_{5/2}$ reaches 570mK, among the largest gaps at this density ever reported in literature [7, 11, 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. $\mu$ for these samples. As it is shown in Fig. 4 (b), in the low mobility range where $\mu < 10 \times 10^6 cm^2/Vs$, $\Delta_{5/2}$ increases as $\mu$ increases. However, no correlation exists in the high mobility range where $\mu > 10 \times 10^6 cm^2/Vs$.

We briefly discuss why the CF resistivity measured by $\rho_{5/2}$ may contain different informa-
FIG. 4. (color online). The $\nu = 5/2$ energy gap $\Delta_{5/2}$ vs. $1/\rho_{5/2}$ (a) and mobility $\mu$ (b) 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 $\mu$, and the units for the listed $\mu$ are $10^6 \text{ cm}^2/\text{Vs}$. The dashed lines in (b) are guides to the eye.

ction than the zero-field mobility and show a stronger correlation with the low-temperature $\nu = 5/2$ 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, 6, 7, 30], 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 $B_{\text{eff}}$ due to variations in the 2DEG density [16, 17]. These effective magnetic field variations cause increased large-angle scattering of CFs, resulting in an enhanced contribution by remote impurities to the CF resistivity [16, 23, 28]. 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 $\nu = 1/2$ [22]. However, the connection between CF resistivity at $\nu = 5/2$ and FQHS gap strength has not been previously studied. Our data suggests that variations of $B_{\text{eff}}$ from remote impurities dominate the measured $\rho_{5/2}$.

Other experiments [23, 25] and theory [26, 29] at $\nu = 1/2$ 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 $\mu$ does not.

Next, we address the sensitivity of the strength the $\nu = 5/2$ FQHS to disorder. It has been shown through computational methods that the size of quasiparticles and quasiholes in the $\nu = 5/2$ 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 minimal effect on $\mu$ [3, 18]. A particularly illuminating experiment is detailed in Ref. [7]: 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 $\mu$ 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 $\mu$.

Additionally, if the $\nu = 5/2$ FQHS is considered to be a p-wave Cooper-paired state of composite fermions as in the Moore-Read Pfaffian state [31, 32], 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 [34–37], and strong suppression of $T_c$ with increasing normal-state resistivity has been observed experimentally in the putative p-wave superconductor Sr$_2$RuO$_4$ [33, 37]. Therefore, the direct correlation we observe between the normal-state CF resistivity at $T=0.3K$ and the low-temperature $\nu = 5/2$ 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 $\tau_q$ measured by low-field Shubnikov-de Hass oscillations [12, 13] 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 $\tau_q$ and the strength of the $\nu = 5/2$ FQHS. We also measured $\tau_q$ 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 is 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 $T = 0.3K$ as a metric to predict the strength of $\nu = 5/2$ 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 $B_{\text{eff}}$ and to short-range CF-CF interactions, neither of which are reflected in the zero-field mobility.

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