

# GaN/AlGaN 2DEGs in the quantum regime: Magneto-transport and photoluminescence to 60 tesla

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Using high magnetic fields up to 60 T, we report magneto-transport and photoluminescence (PL) studies of a two-dimensional electron gas (2DEG) in a GaN/AlGaN heterojunction grown by molecular-beam epitaxy. Transport measurements demonstrate that the quantum limit can be exceeded (Landau level filling factor  $\nu < 1$ ), and show evidence for the  $\nu = 2/3$  fractional quantum Hall state. Simultaneous optical and transport measurements reveal synchronous quantum oscillations of both the PL intensity and longitudinal resistivity in the integer quantum Hall regime. PL spectra directly reveal the dispersion of occupied Landau levels in the 2DEG and therefore the electron mass. These results demonstrate the utility of high (pulsed) magnetic fields for detailed measurements of quantum phenomena in high-density 2DEGs.

The wide-bandgap semiconductor GaN is a foundational material for solid-state lighting applications and high-power electronics. Furthermore, the two-dimensional electron gas (2DEG) that forms naturally at GaN/AlGaN heterointerfaces [1–3] is of considerable interest for high-electron mobility transistors. 2DEG structures grown by molecular-beam epitaxy (MBE) have exhibited low-temperature electron mobilities exceeding  $10^5$  cm<sup>2</sup>/Vs [4, 5], galvanizing interest in quantum phenomena and novel electron correlations in GaN-based materials. Indeed, transport measurements have shown a robust integer quantum Hall effect (IQHE) in GaN/AlGaN heterojunctions [2–9], and an indication of a fractional quantum Hall state (Landau level filling factor  $\nu=5/3$ ) was reported by Manfra *et al.* nearly two decades ago [10]. In comparison with the more widely studied GaAs-based 2DEGs, electrons in GaN-based 2DEGs have significantly heavier effective masses ( $\approx 0.24 m_0$  versus  $\approx 0.07 m_0$  in GaAs, where  $m_0$  is the bare electron mass), and the dielectric constant is smaller ( $\epsilon \approx 9.5$  in GaN versus  $\approx 13$  in GaAs), so that enhanced electron-electron interactions are expected. In this regard, 2DEGs in GaN more closely resemble those found in other wide-bandgap semiconductors such as ZnO, where significant progress has recently been made [11].

However, peak mobilities in GaN-based 2DEGs are, to date, typically achieved at relatively large electron densities  $n_e \sim 10^{12}$ /cm<sup>2</sup> [12, 13], so that high magnetic fields  $B \gtrsim 40$  T are required to reach the so-called “quantum limit” wherein all the electrons reside in the lowest spin-polarized Landau level (*i.e.*,  $\nu \leq 1$ ). Such large  $B$  are (just) within reach of modern superconducting-resistive hybrid magnet technologies, but are routinely exceeded by pulsed magnets [14]. Pulsed fields can therefore enable detailed studies of high-density 2DEGs, including not only transport but also optical measurements that probe the response of the 2DEG to a photogenerated hole, which have historically proven to be a very power-

ful tool to measure screening and many-body effects in GaAs- and ZnO-based systems [15–24].

To this end, we report both transport and optical studies of a high-mobility 2DEG in a GaN/AlGaN heterojunction in pulsed magnetic fields to 60 T. We demonstrate that beyond the quantum limit, transport measurements show clear evidence for the  $\nu = 2/3$  fractional quantum Hall effect (FQHE) state. Moreover, simultaneous optical and transport studies reveal nearly-synchronous quantum oscillations of both the photoluminescence (PL) intensity and the longitudinal resistivity; however, the optical illumination required to perform PL significantly (and persistently) increases  $n_e$  to the point where only  $\nu \geq 3$  can be reached in 60 T in the same heterostructure.

The GaN/AlGaN structure (see inset, Fig. 1a) was grown by MBE on a semi-insulating single-crystal GaN substrate with low dislocation density ( $\sim 5 \times 10^4$ /cm<sup>2</sup>), following Ref. [13]. After the initial growth of a 300 nm GaN buffer layer, a thin 21 nm Al<sub>0.07</sub>Ga<sub>0.93</sub>N barrier layer was grown. A high-mobility 2DEG formed naturally at the interface due to the spontaneous polarization discontinuity across the junction [1]. The structure was capped by a final 3 nm GaN layer. For transport studies, Ti/Au contacts were deposited and annealed at the corners of 3 mm  $\times$  3 mm squares in a van der Pauw geometry. The sample was mounted in a <sup>3</sup>He cryostat in a 60 T capacitor-driven pulsed magnet. The magnet pulse pulse has a 9 ms rise time and total duration of  $\approx 90$  ms. Resistivity was measured using dc current, which avoids measurement-phase issues associated with high-frequency ac lock-in detection of high-resistance samples. Appropriate combinations of current and magnetic field direction were used to symmetrize the data and accurately measure both the longitudinal ( $R_{xx}$ ) and transverse ( $R_{xy}$ ) magnetoresistance.

Separately, photoluminescence (PL) measurements up to 60 T were performed on the same structure, which

was mounted on a fiber-coupled probe and immersed in superfluid  $^4\text{He}$  at 1.5 K for optimal heat sinking. Unpolarized excitation light from the 325 nm (3.82 eV) line of a HeCd laser was directed to the sample, and PL was collected from the sample, using a multimode optical fiber. The PL polarization was not resolved. The PL was dispersed in a 300 mm spectrometer and measured by a fast charge-coupled device (CCD). Full spectra were continuously acquired every 0.6 ms throughout the pulse [25].

In a final set of measurements, resistivity and PL were simultaneously measured in a 18 T superconducting magnet, using a fiber-coupled transport probe with the sample in superfluid  $^4\text{He}$  at 1.5 K. AC current excitation at 17 Hz and lock-in detection provided a measure of the longitudinal resistance, while high-resolution PL spectra were detected using a 500 mm spectrometer and a liquid nitrogen cooled CCD.

Figure 1a shows the transverse resistance  $R_{xy}$  up to 60 T. Data acquired during both the up-sweep and down-sweep of the pulsed field are presented, to show the overall signal-to-noise, drifts, and data quality that are achievable using dc transport methods to measure 2D electron systems in pulsed magnets. During these studies, it was observed that the 2DEG's conductivity varied from cooldown to cooldown, suggesting a history-dependent carrier density  $n_e$ . As demonstrated in early work [3], these variations arise from the history of optical illumination on the sample, as shown below.

We focus first on the black curve in Fig. 1a, which was acquired after the sample had been three days in the dark at 300 K. Well-defined IQHE plateaus were observed, with the quantum limit ( $\nu = 1$ ) achieved at  $B \simeq 27$  T, indicating 2DEG electron density  $n_e = \nu e B/h \simeq 6.5 \times 10^{11}/\text{cm}^2$ . We note that while the IQHE has been reported many times in GaN-based 2DEGs [4–9], these measurements are the first to explore transport in the FQHE regime beyond the quantum limit. Crucially,  $R_{xy}$  also shows an *additional* plateau forming at approximately 41 T, which coincides with the expected position (and quantized resistance  $R_{xy} = 3h/2e^2$ ) of the  $\nu = 2/3$  FQHE state.

The longitudinal resistance  $R_{xx}$  is shown in Fig. 1b, which was acquired during a separate cooldown, again after several days in the dark. Zero-resistance minima confirm the IQHE and a slightly larger  $n_e$  ( $\nu = 1$  occurs at 29 T; thus  $n_e \simeq 7.0 \times 10^{11}/\text{cm}^2$ ). Most importantly, the pronounced dip at 44 T again strongly supports an interpretation in terms of the  $\nu = 2/3$  FQHE state. While evidence for the fractional  $\nu = 5/3$  state in a GaN/AlGaIn 2DEG was observed previously [10], we emphasize that Fig. 1 demonstrates for the first time that phenomena beyond the quantum limit ( $\nu < 1$ ) are indeed accessible in GaN-based 2DEGs, here through the use of pulsed magnetic fields.

We now turn to the other  $R_{xy}$  curves in Fig. 1a. After measuring the black curve, the sample was briefly and weakly illuminated at 1.5 K by an *in-situ* white-light LED. Then the red curve was measured in the

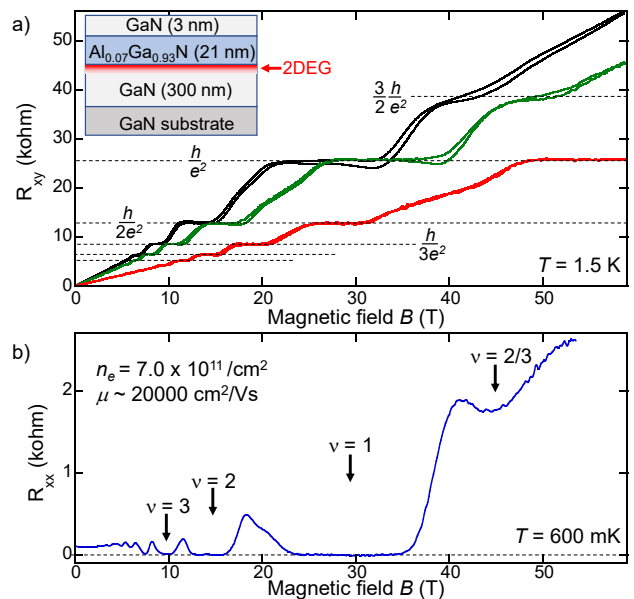


FIG. 1. a) Inset: schematic of the GaN/AlGaIn 2DEG structure. The plot shows the transverse resistance ( $R_{xy}$ ) at 1.5 K up to 60 T, showing quantized Hall resistance  $h/\nu e^2$  at integer filling factors  $\nu$ . The black trace was acquired after three days in the dark, and the quantum limit ( $\nu = 1$ ) is reached at  $\approx 27$  T. The red trace was then acquired after briefly illuminating the structure *in-situ* with white light – note that  $n_e$  approximately doubled. The green trace was then acquired after cycling the temperature up to 300 K and back to 1.5 K in the dark. b) Longitudinal resistance  $R_{xx}$  of this structure (separate cooldown;  $\nu = 1$  is reached at  $\approx 29$  T). Both  $R_{xx}$  and  $R_{xy}$  show evidence for the  $\nu = 2/3$  FQHE state.

dark. IQHE plateaus were again observed, but significantly shifted in field:  $\nu = 1$  occurred at  $\approx 57$  T, indicating over a two-fold increase of  $n_e$ . Then, the sample was thermally cycled (in the dark) up to 300 K for 6 hours and back to 1.5 K, and the green curve was measured. IQHE plateaus were again observed, but  $\nu = 1$  occurred at  $\approx 32$  T, indicating that  $n_e$  had (mostly) recovered back down to its initial value. IQHE plateaus in all curves shows no obvious signs of inhomogeneity or disorder changes resulting from illumination.

As described in early [3] and more recent [9] studies, illumination has a significant and persistent effect on  $n_e$  in GaN/AlGaIn 2DEGs. Optical excitation of electrons out of traps and impurity states leads to a persistent increase of  $n_e$ , that can be reset by thermal cycling in the dark. These data point to the fact that – at least in this particular structure – FQHE states with  $\nu < 1$  are not accessible with 60 T fields if the sample has been recently illuminated. This limits the use of optical spectroscopy to study FQHE states (in this structure), which in GaAs-based 2DEGs have historically proven very powerful for probing electron correlations and novel phases [15–23].

Optical phenomena related to the IQHE can, however, be studied quite well in GaN/AlGaIn 2DEGs, even in low-field ( $< 20$  T) superconducting magnets. The PL

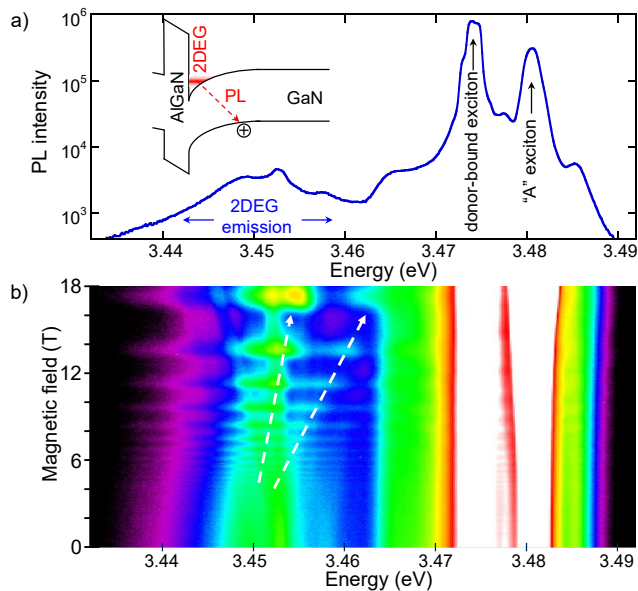


FIG. 2. a) Photoluminescence (PL) spectrum of the sample at 1.5 K; note logarithmic scale. A broad PL emission from radiative recombination of 2DEG electrons is located at low energies ( $\sim 3.45$  eV), below the sharp exciton-related PL peaks that originate from the GaN buffer layer. b) An intensity map showing the PL spectra up to 18 T. SdH-like intensity oscillations are observed in the low-energy 2DEG region; discrete peaks reveal the formation and dispersion of 2DEG LLs (see white dashed arrows), separated by the cyclotron energy  $eB/m_e$ .

spectrum from this GaN/AlGaIn structure is shown in Fig. 2a. The two bright peaks at 3.481 eV and 3.474 eV correspond to free “A”-excitons and to donor-bound excitons in the GaN buffer layer, respectively [26]. At lower energy, the broad and weak emission band in the 3.44–3.46 eV range corresponds to radiative recombination of photogenerated holes with electrons in the 2DEG, as depicted in the inset and as confirmed below.

The PL intensity map of Fig. 2b shows how this low-energy emission band evolves with  $B$  up to 18 T. Pronounced oscillations of the net PL intensity are observed, along with the formation of discrete peaks that shift linearly with  $B$ . These peaks reveal the formation and dispersion of discrete Landau levels in the 2DEG, separated by the electron cyclotron energy  $eB/m_e$ , from which an effective electron mass  $m_e \simeq 0.24m_0$  can be inferred. These data corroborate and extend recent results from Schmult *et al.* [8], who measured PL from a similar GaN/AlGaIn 2DEG up to 15 T.

Figure 3a shows how the PL intensity oscillations (red trace) compare with the simultaneously-measured longitudinal resistivity  $R_{xx}$  (blue trace). Figure 3b shows the same data plotted against  $1/B$ ; both curves have the same periodicity in  $1/B$ , as expected for Shubnikov-de Haas (SdH) quantum oscillations. However, the minima in  $R_{xx}$  – which accurately indicate integer filling factors – align only approximately with the maxima in the PL

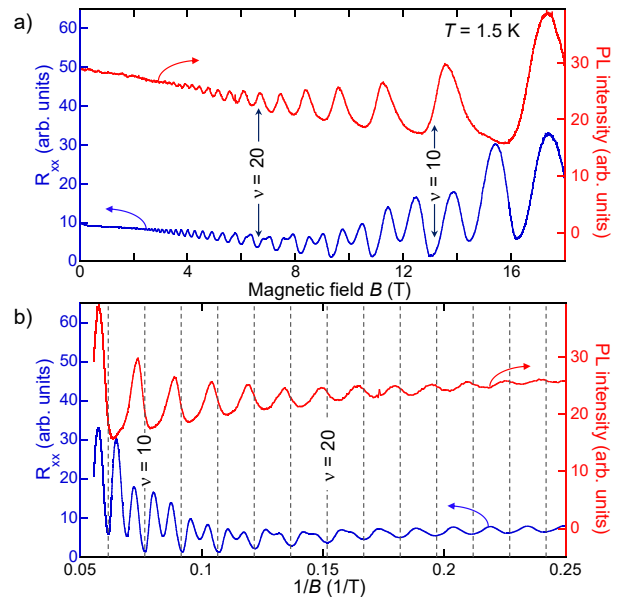


FIG. 3. a) Correlating the  $B$ -dependent oscillations of the total 2DEG PL intensity (integrated from 3.440–3.464 eV; red trace) with the simultaneously-measured resistance  $R_{xx}$  (blue trace) up to 18 T in a superconducting magnet, at 1.5 K. Due to the excitation laser, the steady-state 2DEG density is much higher than in the dark (*cf.* Fig. 1);  $n_e \simeq 3.1 \times 10^{12}/\text{cm}^2$ , and  $\nu = 1$  is not expected until  $\sim 130$  T. b) The same data vs.  $1/B$ . Dashed vertical lines are equally spaced and aligned with  $R_{xx}$  minima, and indicate even-numbered  $\nu$ . Both the PL intensity and  $R_{xx}$  are periodic in  $1/B$ , but only the latter shows odd filling factors. Note that PL maxima are slightly shifted from even-numbered  $\nu$ .

intensity. The latter exhibit a relative phase shift that is most noticeable at large  $B$ . Moreover, intensity oscillations at odd-integer  $\nu$ , which manifest clearly in  $R_{xx}$  for  $B > 7$  T, are not observed in the PL data up to 18 T.

Studies of SdH-like PL oscillations in 2DEGs have a long and rich history [15–17, 24, 27–29]. Typically, they arise from electron-hole correlations and the efficacy with which 2D electrons screen the Coulomb potential of a nearby photogenerated hole, which in turn modifies the spatial overlap of their respective wavefunctions and therefore changes the radiative recombination rate. In many models, screening is less effective when the 2DEG Fermi level lies between Landau levels (*i.e.*, in localized states, at integer  $\nu$ ). On the one hand this can lead to a reduced wavefunction overlap and smaller PL intensity; however, reduced screening can also increase electron-hole binding (exciton formation), increasing PL [15, 17]. The phase shift that is observed between the quantum oscillations of  $R_{xx}$  and PL (see Fig. 3) – which increases at large  $B$  – suggests that the interplay between these competing effects likely plays an important (and  $B$ -dependent) role. Additionally, the fact that  $R_{xx}$  clearly exhibits spin-resolved SdH oscillations (odd-integer  $\nu$ ) for  $B > 7$  T, while the PL does not, also presents an unresolved puzzle (although,  $\nu = 3$  appears in PL studies to

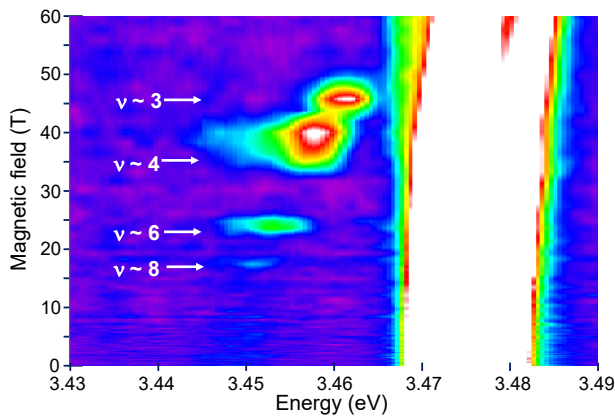


FIG. 4. PL measured up to 60 T. PL from the 2DEG brightens considerably at 17.5 T (as also seen in Figs. 2 and 3), 24 T, 39 T, and 46 T, which corresponds approximately to  $\nu \approx 8, 6, 4$ , and 3. Limited signal:noise precludes resolving the smaller intensity oscillations for  $B < 15$  T.

60 T, shown below).

Importantly, Fig. 3 also reveals that due to the weak ( $\sim 100 \mu\text{W}$ ) above-gap optical excitation that is used to enable PL measurements, the steady-state electron density is about  $5 \times$  larger than when measured in the dark (*cf.* Fig. 1). In Fig. 3,  $\nu = 10$  occurs at 13 T, indicating that  $n_e \simeq 3.1 \times 10^{12}/\text{cm}^2$ . A consequence of this photo-doping effect is that future optical studies of GaN-based 2DEGs in the  $\nu \leq 1$  regime will require structures specifically designed to host lower carrier densities.

Nonetheless, to explore the limits of high- $B$  magneto-optics in GaN-based 2DEGs, Fig. 4 shows PL studies of this same structure in a 60 T pulsed magnet. Due to the fast CCD exposure times that are used, fewer photons are collected, limiting signal:noise. Regardless, Fig. 4 clearly shows that the 2DEG emission continues to ex-

hibit pronounced intensity oscillations. A maximum is observed at 17.5 T (the same as observed in Figs. 2 and 3), and then also at  $B \approx 24$  T, 39 T, and 46 T. With the exception of the 39 T peak, these values are in reasonable agreement with the expected filling factors  $\nu=8, 6, 4$ , and also  $\nu=3$ , as indicated. The appearance of a PL maximum at the expected position of  $\nu = 3$  suggests that detailed optical studies of *spin-resolved* many-body screening in GaN-based 2DEGs are possible. Future measurements incorporating in-situ polarizers to resolve both right- and left-handed circular PL polarizations, ideally in conjunction with transport measurements performed on intrinsically lower-density 2DEGs, are expected to address this interesting regime.

Through the use of pulsed magnetic fields, these studies demonstrate that the  $\nu = 1$  quantum limit can be exceeded in high-density GaN-based 2DEGs. First evidence for the  $\nu = 2/3$  FQHE is shown by magneto-transport. PL measurements also reveal SdH-like oscillations of the intensity, from which  $n_e$  and the electron mass are inferred in a contactless approach. However, the increase of  $n_e$  associated with optical excitation currently limits PL studies to the IQHE regime, although strong indications of 2DEG screening at the spin-resolved  $\nu = 3$  state is observed at large fields.

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