Observation of magnetophotoluminescence from a $GaN/Al_xGa_{1-x}N$ heterojunction

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Magnetophotoluminescence has been studied from a single undoped $GaN/Al_xGa_{1-x}N$ heterojunction with a linewidth of 2.5 meV. The peak originates from the recombination of a photoexcited hole with an electron in the two-dimensional electron gas (2DEG) formed as a result of spontaneous and piezoelectric polarizations at the interface. The photoluminescence intensity is strongly enhanced at filling factors corresponding to filled Landau levels as a result of the reduced screening of the Coulomb interaction by the 2DEG. This prevents the rapid diffusion of photoexcited holes away from the heterojunction. The energy of the magnetoexcitonic recombination indicates a very low value for the hole mass of $0.3m_0$ close to the band edge in agreement with theory.

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I. INTRODUCTION

It is already known that electric fields play a central role in GaN heterostructures as a result of the large piezoelectric constants and the presence of spontaneous polarization. This leads to the quantum-confined Stark effect in quantum wells and strong electric fields at a heterojunction.[1] Consequently previous results have shown that even without intentional doping a carrier density of about 2.6×10^{12} cm^{-2} was present at a $GaN/Al_{0.13}Ga_{0.87}N$ interface at 7 K.[2]

It was some years later that the two-dimensional electron gas (2DEG) was first detected in optical experiments from a modulation-doped structure.[3] However, the signal was small as a result of the diffusion of holes into the flat-band region within the GaN layer. In order to reduce this diffusion, a second $Al_xGa_{1-x}N$ layer was added to preserve the electron-hole overlap, successfully increasing the luminescence signal.[4] For an undoped heterojunction, only more recently has luminescence been reported, and this was achieved by comparing the spectrum before and after etching away the $Al_xGa_{1-x}N$ layer.[5]

Magnetotransport has been routinely used to characterize the 2DEG, but to date, to our best knowledge, no magnetoluminescence data has yet been reported, perhaps as a result of the broad linewidths, typically 10–30 meV,[3–5] and the primary interest for the use of this material in electronic devices. In contrast, we report magnetoluminescence from a 2DEG with a linewidth as narrow as $\sim$2.5 meV, which is comparable to the bulk exciton peaks in the same sample.

II. EXPERIMENT

We have performed magnetophotoluminescence in both steady fields up to 19 T and pulsed magnetic fields up to 54 T on two $Al_xGa_{1-x}N$ heterostructure samples, N307 and N298, with the growth axis parallel to the magnetic field (see Ref. 7 for further experimental and sample details). The 244-nm line from a cw frequency-doubled argon laser acted as the excitation source, with an excitation intensity of $\sim$0.02 W cm^{-2} for the steady fields but in order that sufficient signal could be detected a much higher value of $\sim$0.4 W cm^{-2} was used in the pulsed field experiments.

Both samples were grown by molecular-beam epitaxy (MBE), with a 1-μm thick GaN buffer layer grown before a 200-nm thick undoped $Al_{0.08}Ga_{0.92}N$ layer. Subsequently a series of quantum well (QW) structures was grown, as this was the primary intention for these samples.[6,7] The only difference in the two samples was that N307 contained a single quantum well, whereas N298 contained four of differing thicknesses. The bulk photoluminescence (PL) lines were well resolved in these two samples, and were separated from the QW emission. The quantum well features were characterized by broad PL emission both above and below the GaN band gap and could not be mistaken for the bulk lines.

III. RESULTS

The 2DEG photoluminescence was observed as a resonance phenomenon that originates from an energy of about 30 meV below the *A* free exciton emission and is shown in Fig. 1. The additional peak, with an energy between (A_0, X) and *X*, is seen to oscillate in intensity, while at the same time to increase in energy with magnetic field.[8] It has a linewidth that is comparable with the bulk features and an order-of-magnitude less than the QW emission. Using a much higher intensity from a pulsed quadrupled Nd:yttrium aluminum garnet laser at 266 nm, the 2DEG peak was found to strongly broaden, but there was no significant change in its energy. The shape of the luminescence is much clearer if a ratio is taken with respect to a zero-field spectrum, as shown in Figs. 2 and 3. The ''sawtooth'' shape of the resonance with respect to magnetic field can also be seen clearly in the cross section in Fig. 3, only decaying slowly on the high-field side.

The fields corresponding to the maxima in resonance intensity have a $1/B$ relationship with respect to consecutive integers as indicated in Fig. 4, and no similar resonances are seen in the Voigt configuration. These observations are consistent with the assignment of this transition to the recombi-

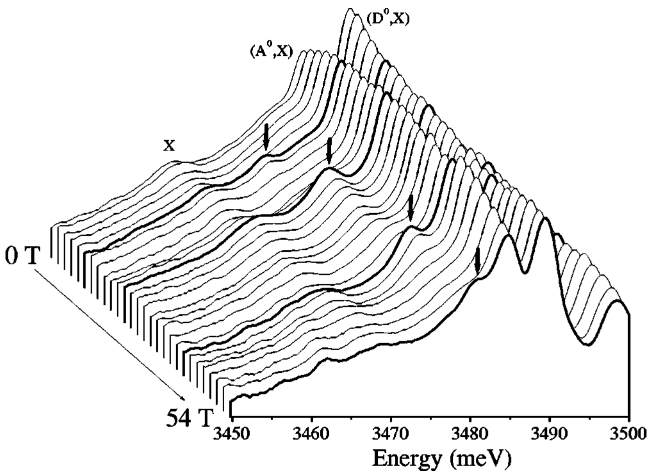

FIG. 1. Pulsed field PL for sample N307 for 0–54 T. The spectra are not equally spaced in field, with there being a higher density of spectra around the resonance fields. The small arrows mark the resonance peaks due to the 2DEG.

nation between a two-dimensional electron gas and photoexcited holes, since the filling factor, $\nu = n_e h/eB$, describing the number of filled Landau levels, passes through integer values with a $1/B$ period. The carrier concentration of $n_e = 2.77(2)\times 10^{12}\ \mathrm{cm}^{-2}$ for sample N307 that is deduced from Fig. 4 is also very similar to values already reported from transport measurements on similar structures.[2]

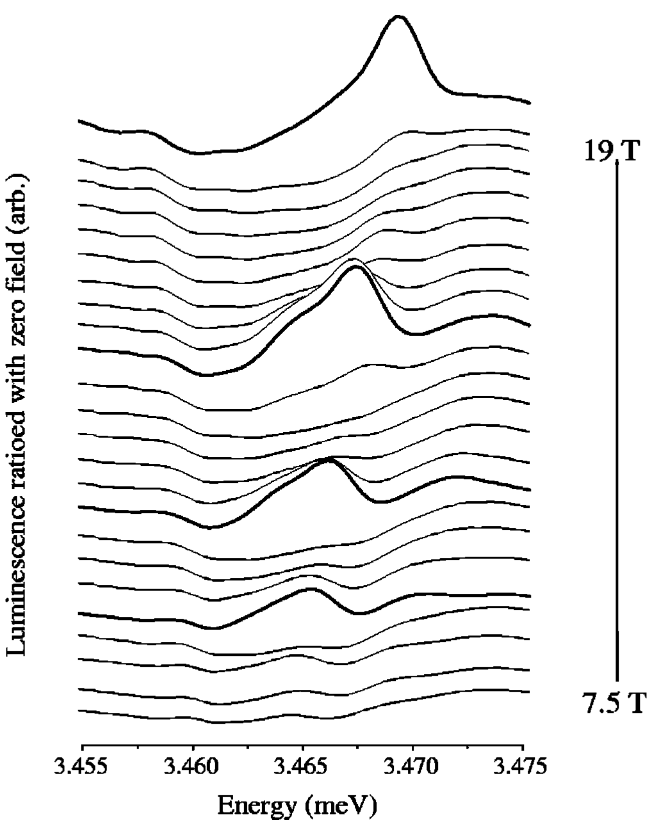

FIG. 2. Continuous field PL spectra of sample N307 after ratioing with the zero-field spectrum. The spectra are equally spaced in field with an interval of 0.5 T.

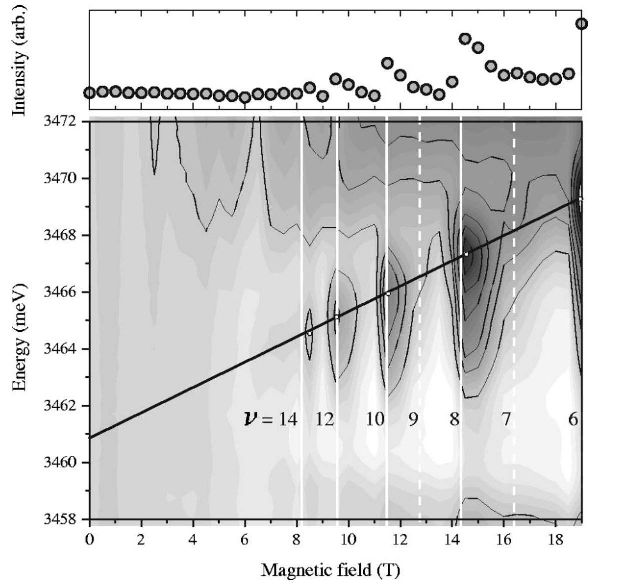

FIG. 3. Contour plot of the PL after ratioing with the zero-field spectrum. The vertical lines show the resonances with the filling factor while the diagonal line shows how the peak energy depends on field. The intensity cross section along the diagonal line is shown above the contour plot.

Subsequent transport measurements at 1.4 K on sample N307 confirm that the 2DEG is indeed present, however the Shubnikov–de Haas oscillations, shown in Fig. 5, indicate a slightly smaller carrier density of $2.58(2)\times 10^{12}\ \mathrm{cm}^{-2}$ and a mobility of $5300\ \mathrm{cm}^2/\mathrm{V\,s}$. The reduction in the density can be explained by considering that the sample underwent significant processing between the optical and transport measurements. This itself could alter the strain that is present in the heterostructure, altering the polarization and thus the carrier concentration, combined with the fact that the optics and

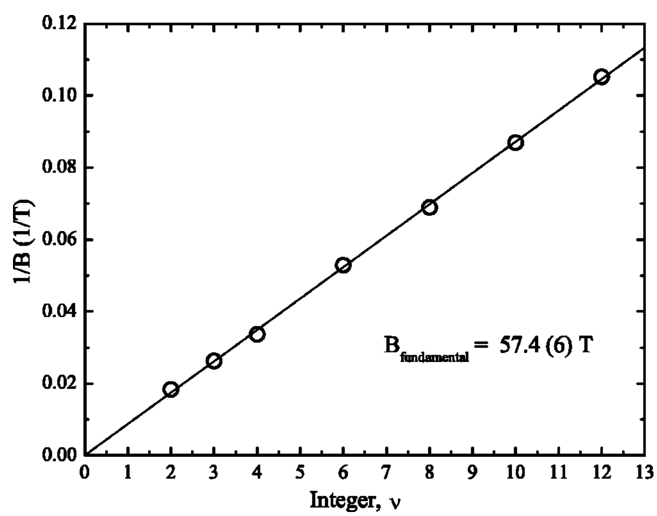

FIG. 4. Line fitting showing the $1/B$ resonance of the luminescence peaks in sample N307 with filling factor ν. For low magnetic fields strong peaks are only observed for even values of ν, whereas with the higher pulsed field a peak corresponding to spin splitting of the fundamental levels at the odd value, $\nu = 3$, can also be seen.

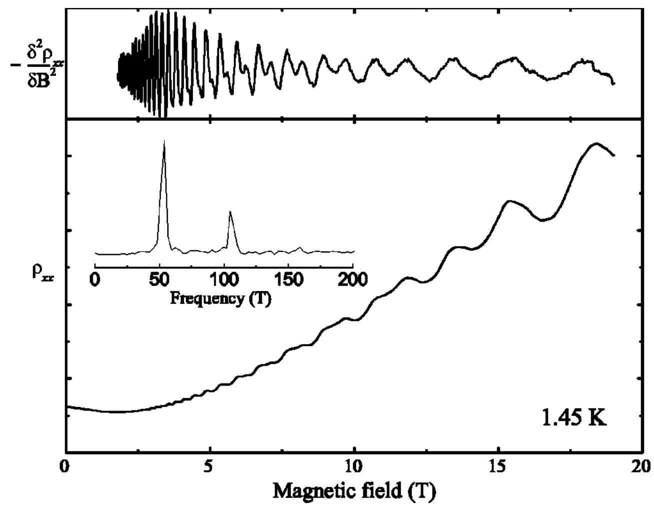

FIG. 5. Two-terminal magnetoresistance of sample N307 at 1.45 K, along with the second derivative (top). The Fourier transform (inset) indicates a second smaller peak corresponding to the spin splitting at higher magnetic fields.

transport would not necessarily measure the same position on the sample.

In sample N307, on which most of these measurements were performed, the fundamental resonance at $\nu=2$, as determined by the gradient of the graph in Fig. 4, occurs at a field just above the maximum accessible by the pulsed field system. The beginnings of the resonance can be seen in the highest-field spectrum, but not with the relative strength that would be expected from a fundamental transition. In contrast, Fig. 6 shows a similar though less complete set of spectra for sample N298 that clearly shows a fundamental peak whose intensity even eclipses that of the neutral acceptor peak. This implies that the carrier concentration in this sample is slightly less than in N307.

The 2DEG in our samples is likely to be present at the interface between the MBE-grown GaN buffer layer and the thick $Al_xGa_{1-x}N$ layer grown prior to the quantum wells. The quantum wells are unlikely to be the cause, since their

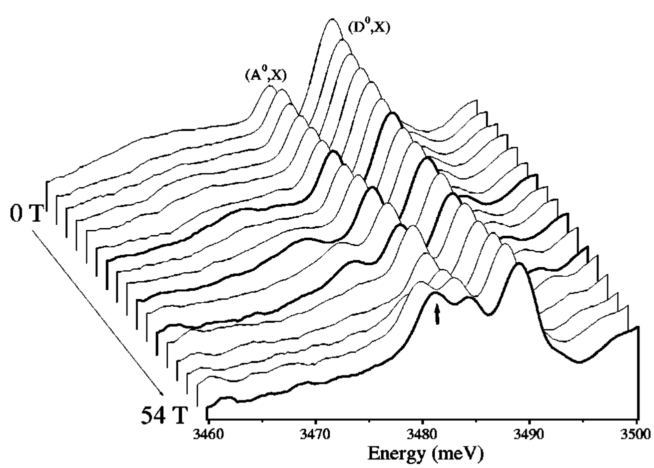

FIG. 6. Pulsed field PL for sample N298, showing the large resonance at $\nu=2$ at the highest field. The spectra are approximately equally spaced in field.

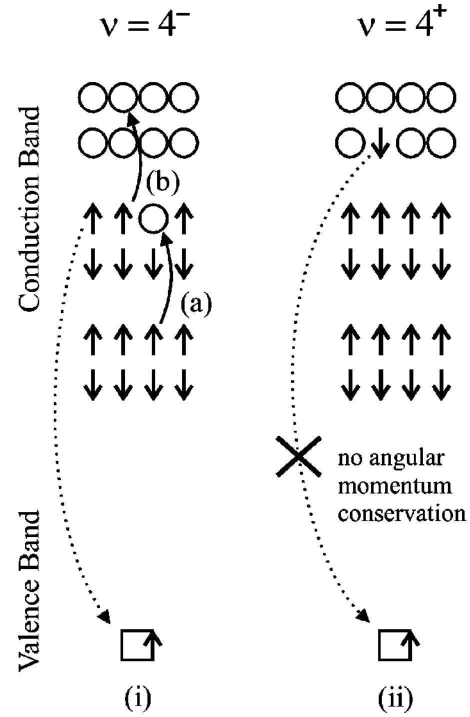

FIG. 7. A schematic diagram of the recombination process causing the heterojunction luminescence.

luminescence peaks are an order-of-magnitude wider. The narrow luminescence width for the single heterojunction suggests that the interface only causes long-range potential fluctuations, which do not broaden the PL in comparison to the quantum wells where there is a large inhomogeneous broadening due to the presence of the second interface. It could also be due to the $Al_xGa_{1-x}N$ alloy not acting as an effective barrier for the holes in the quantum well.[10]

IV. DISCUSSION

It has already been found that the luminescence from such a heterojunction is very weak due to the rapid diffusion of the photoexcited holes away from the interface into the flat-band region of GaN.[3,4] The presence of the magnetic field has increased the luminescence for certain Landau-level occupancies, reaching a maximum at the limit of even integer filling factors, as can be seen in Fig. 3. Confirmation that the integer filling factors coincide with the fields indicated in Fig. 3 can be found from Fig. 4, which shows that the intercept on the $1/B$ line passes precisely through the origin. The change of the luminescence with occupancy is most likely due to the changing efficiency of the screening of the recombining electron and hole interaction by the 2DEG. A fuller understanding of the intensity profile requires a more detailed examination of the recombination mechanism.

A hole can only bind to an electron near the Fermi energy in the 2DEG, since there must be states into which the electron can move in order to form a localized exciton. However, since there is only a small population of photoexcited holes, which will rapidly thermalize to the lowest hole level, angular momentum would not be conserved by direct recombina-

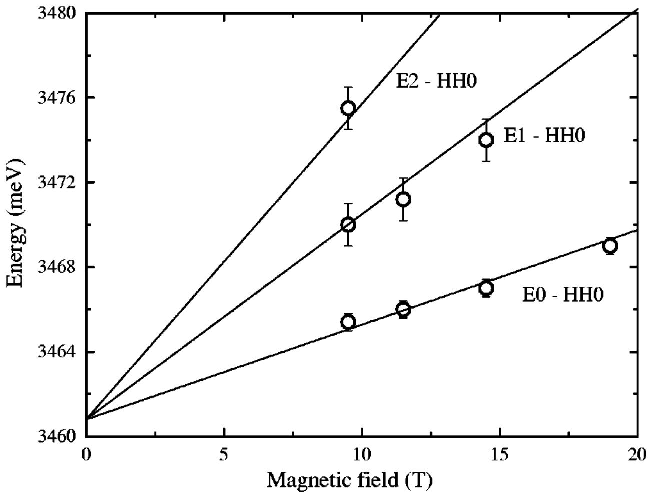

FIG. 8. Energies of the main resonance peaks ($E0$-$HH0$) along with those from smaller peaks corresponding to transitions involving higher Landau levels of the 2DEG ($E1$-$HH0$, $E2$-$HH0$). The solid lines correspond to masses; $m_e=0.222m_0$ and $m_h=0.31m_0$.

tion with an electron in a higher Landau level. Consequently, as shown schematically in Fig. 7, there is a simultaneous promotion of an electron, either (a) from the lowest filled Landau level to the partially filled level, or (b) from the partially filled level to a higher level as in an Auger process. The total recombination energy then equals that of the zeroth Landau level.

The cross section through the resonances in Fig. 3 shows that the integer even filling factors mark a threshold for the luminescence intensity, thus there is strong luminescence when the highest electron Landau level is slightly underfilled, and none when it is almost empty. This is consistent with the Auger process (b) being dominant, since the simultaneous promotion of an electron from the lowest Landau level (a) will depend on the number of holes in the highest level, while the Auger process (b) will depend on the number of electrons.

Even though the 2DEG screening of the electron-hole interaction is being inhibited around the integer filling factors, the magnitude of the binding energy is still much smaller than the bulk value as a result of the strong electric fields. Evidence of this comes from the strong linear, rather than diamagnetic, dependence of the resonance energy with field.

Further confirmation of this picture comes from careful ratioing of the PL spectra, which show much smaller peaks in the spectra that are separated from the main resonance peak by multiples of the electron cyclotron energy as a result of recombination between the zeroth hole Landau level with the first electron level. The energies of these peaks are shown in Fig. 8.

Returning to the details of Fig. 3, small peaks could also be attributed to the odd filling factors, $\mu=7,9$. Since these are much smaller than the peaks observed for even filling factors, this could suggest that the holes are strongly spin polarized due to the spin splitting of the A-valence band with $B\|c$. The observation of the peak at $\nu=3$ in the pulsed fields is therefore somewhat surprising and is probably due to a high carrier temperature caused by the much higher excitation intensity used in the pulsed field measurements, which would give a significant population of holes in the excited spin state.[7] Alternatively, it might be related to the better resolution of the Landau levels at higher field, since the spin splitting is about a fifth of the electron cyclotron splitting. The screening efficiency of the 2DEG is thus not reduced sufficiently for the higher odd integer filling factors to observe a resonant luminescence peak.

The significant low-energy tails that can be seen for the even filling factors can be explained by the range of final states that are available for the excited Auger electron. The electron can bind to the hole that it has created itself by leaving the partially filled Landau level to create a "magnetic exciton."[11] The dominant peak corresponds to creating such a "magnetic exciton" at $K=0$, with the tail resulting from an average over the dispersion relation when they are created at finite K. This behavior is very similar to that observed in $GaAs/Al_xGa_{1-x}As$ heterojunctions.[12]

The magnetic field dependence of the resonance peak energy, shown as the diagonal line in Fig. 3, corresponds to the energy of the zeroth Landau level, given by $E(B)=E_0+\frac{1}{2}\hbar\omega_c$, where $\omega_c=eB/\mu$ is the cyclotron frequency with a reduced mass of $\mu=0.13(1)m_0$. A similar analysis of magnetophotoluminescence results from a $GaAs/Al_xGa_{1-x}As$ modulation-doped heterojunction[13] also shows a strong linear dependence on magnetic field, corresponding to reasonable values of the electron and hole effective masses such as $m_e\simeq0.067m_0$ and $m_h\simeq0.3m_0$.[14] Thus from the reduced mass of $\mu=0.13(1)m_0$, and assuming a band-edge electron mass of $0.222m_0$,[15,16] the hole mass can be deduced to be $\sim0.3m_0$.

The mass value of $0.3m_0$ is considerably smaller than many other measurements of the bulk A-hole mass, which are typically between 1 and $2m_0$. However, these do not contradict our value, since it has been pointed out both theoretically[17] and experimentally[18] that the A-valence band is strongly nonparabolic in the direction perpendicular to the c axis. In fact the theoretical calculations predict $m_h\sim0.33m_0$ close to the band edge, which is much closer to our value.[17]

The values of k^2 corresponding to the zeroth Landau level for the field region shown in Fig. 3 are between 0 and $0.3\times10^{13}\ \mathrm{cm}^{-2}$; this field region was the one that was inaccessible in our previous paper on the valence band of GaN due to the strong Coulomb effects in bulk material.[18] Nonparabolicity, giving a heavier hole mass, is also probably the reason the lower filling factors, observed for $B\geqslant30$ T, do not fit the linear dependence shown in Fig. 3.

It seems that by studying the properties of a $GaN/Al_xGa_{1-x}N$ heterojunction, there is the possibility of gaining further insights into the band structure of GaN, since the electron-hole interaction has been weakened by the strong electric fields that are present without sacrificing the linewidth of the luminescence.

V. CONCLUSIONS

A magnetoluminescence resonant phenomenon caused by recombination between photoexcited holes and a 2DEG formed at a $GaN/Al_xGa_{1-x}N$ interface has been observed, with a luminescence width considerably smaller than that already seen without a magnetic field. The reduced screening of the electron-hole binding by the 2DEG around integer filling factors and the requirement to conserve angular momentum through an Auger process leads to a $1/B$ resonance phenomenon with a sawtooth profile. The energy of the luminescence suggests that the Coulomb binding is very weak and that the hole mass is very light close to the Brillouin- zone center, agreeing with theoretical predictions.

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