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ABSTRACT
Obtaining high quality, wurtzite InN films with p-type conductivity is a challenge, and there is limited information about the photoluminescence (PL) characteristics of such films. In this study, we present a comprehensive PL study and discuss in detail the recombination processes in Mg-doped InN films with varying Mg concentrations. We find that at low Mg-doping of \(1 \times 10^{18} \text{ cm}^{-3}\), which yields p-type conductivity, the PL in InN is spatially inhomogeneous. The latter is suggested to be associated with the presence of n-type pockets, displaying photoluminescence at 0.73 eV involving electrons at the Fermi edge above the conduction band edge. Increasing the Mg concentration to \(2.9 \times 10^{19} \text{ cm}^{-3}\) in p-type InN yields strong and spatially uniform photoluminescence at 0.62 eV and 0.68 eV visible all the way to room temperature, indicating homogeneous p-type conductivity. An acceptor binding energy of 64 meV is determined for the Mg acceptor. Further increase of the Mg concentration to \(1.8 \times 10^{20} \text{ cm}^{-3}\) leads to switching conductivity back to n-type. The PL spectra in this highly doped sample reveal only the emission related to the Mg acceptor (at 0.61 eV). In the low-energy tail of the emission, the multiple peaks observed at 0.54 – 0.58 eV are suggested to originate from recombination of carriers localized at stacking faults.

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I. INTRODUCTION
InN has attracted a considerable research interest due to the prospects of using it in next generation optoelectronics and high-frequency electronic devices. In 2002, the low temperature (2 K) bandgap of wurtzite InN with a relatively low free electron concentration of \(2 \times 10^{18} \text{ cm}^{-3}\) was revised to 0.7 eV, being much lower than the previously reported value close to 2 eV. With improving material quality, more accurate bandgap values have been presented. Currently, both theoretical predictions and experimental results show a low temperature bandgap value of 0.69 eV. Control of doping of InN and understanding its effects on the optical properties are crucial for realizing the potential of InN in future optoelectronic devices. Obtaining p-type conductivity in InN is difficult due to the high intrinsic residual electron concentration in this material. Even undoped InN samples tend to have a high concentration of donors incorporated, lifting the Fermi level into the conduction band, and thus making the material degenerate. Different causes of the unintentional electron doping of InN have been suggested. Currently, it is commonly accepted that impurities, such as hydrogen and oxygen are the major sources of the unintentional n-type doping. Impurities and intrinsic point defects in InN tend to have a lower formation energy for forming donor-like states as compared to acceptor-like states, in turn leading to a high
free electron concentration, and accordingly the Fermi level moves up towards the branch point energy.\textsuperscript{16–18} Mg is now established as the only known acceptor for InN leading to p-type conductivity. High concentrations of the Mg dopant need to be incorporated into the material to overcompensate the residual n-type doping. However, increasing the Mg concentration in InN beyond a certain critical value typically leads to switching back to n-type conductivity and an increase in the density of structural defects, such as stacking faults.

Measuring free hole parameters by standard electrical contact based techniques is a challenge, because of the commonly observed electron accumulation layer at the surface, not only in n-type samples, but also in p-type InN.\textsuperscript{17,19,20} In order to assess the p-type doping, methods such as thermopower measurements,\textsuperscript{21} electrolyte capacitance-voltage (ECV) measurements,\textsuperscript{19} multilayer modeling of Hall measurements,\textsuperscript{22,23} infrared spectroscopic ellipsometry (IRSE),\textsuperscript{24} and optical Hall effect have been developed.\textsuperscript{25}

Emission from degenerately doped InN n-type films related to electrons at the Fermi edge above the conduction band edge has been observed, however not clearly shown together with emission related to electrons at the bottom of the conduction band.\textsuperscript{24,22} Due to the difficulty in achieving p-type InN and the relatively low crystalline quality, the reports on photoluminescence (PL) properties of p-type InN material are scarce. PL spectra of Mg-doped InN films with p-type conductivity have been reported, however Mg doping does not always result in radiative recombination processes.\textsuperscript{19,21} The lack of luminescence was partly attributed to built-in fields separating the charge carriers. PL was observed from Mg-doped InN films upon irradiation with He+ ions, but the recombination processes were not specified.\textsuperscript{19} Recently, with improving the crystalline quality of the Mg-doped InN epitaxial layers, emission related to the Mg acceptor have been regularly observed.\textsuperscript{22,28–31} In moderately doped samples (\(\sim 1 \times 10^{18} \text{ cm}^{-3}\)), the low-temperature PL spectra are usually dominated by band-to-acceptor emission (at 0.61 eV).\textsuperscript{22} In partially compensated n-type InN films doped with Mg, PL peaks at 0.67 eV and 0.60 eV, attributed to band-to-band and band-to-acceptor transitions, respectively, were reported.\textsuperscript{30,31} However, in these works, no PL was observed for p-type InN films at room temperature and only weak PL intensity was observed at 14 K, which was attributed to electron trapping by deep states. Mg-doped InN nanowires, which are believed to not suffer from strain and structural defects, have been shown to emit at 0.67 eV and 0.61 eV (at 7 K).\textsuperscript{32} These emissions have been attributed to band-to-band transitions and donor-acceptor pair transitions, respectively. However, no information about the conductivity type, nor on the Mg concentration was given in this study. So far, no recombination involving states above the conduction band edge for p-type InN films, nor PL from heavily Mg-doped InN films have been reported.

Recently, we have reported a comprehensive study on free charge carrier and structural properties of nominally undoped and a series of Mg-doped (both n- and p-type) InN films.\textsuperscript{24,33} In this work, we present and discuss the effect of Mg doping on the PL properties of InN epitaxial layers. In p-type material, we observed recombination involving electrons at the Fermi level and holes localized near the valence band edge, as well as band-to-acceptor recombination. From temperature dependent PL measurements, the Mg acceptor binding energy was extracted, and the valence band energy fluctuation was estimated. The PL properties of highly Mg-doped InN are also investigated and discussed in view of the presence of structural defects.

### II. EXPERIMENTAL DETAILS

Samples studied here were grown by Plasma Assisted Molecular Beam Epitaxy (PA-MBE) on 4.1-μm-thick Metal Organic Chemical Vapor Deposition (MOCVD) grown GaN layers on sapphire substrates. 400 nm thick Mg-doped InN layers were grown on top of approximately 50 nm thick undoped InN buffer layers. The sample set consists of a nominally undoped (n-type) and three Mg-doped InN samples (two p-type and one n-type). The intentionally doped samples have Mg concentrations of \(1 \times 10^{18} \text{ cm}^{-3}\) (p-type), \(2.9 \times 10^{19} \text{ cm}^{-3}\) (p-type), and \(1.8 \times 10^{20} \text{ cm}^{-3}\) (n-type), as determined by secondary ion mass spectroscopy (SIMS). The conductivity type and free carrier concentration were determined by IRSE.\textsuperscript{24} Detailed information about the growth, structural and free charge carrier properties of the InN films can be found elsewhere.\textsuperscript{24,25,34} A summary of the Mg doping concentration, the free carrier concentration and the mobility of the samples is given in Table I. The densities of the threading dislocations (TDs) and the stacking faults (SFs) as estimated by transmission electron microscopy (TEM) are also shown in Table I.

| Table I. Mg concentration ([Mg]), bulk free carrier concentration (N), mobility (\(\mu\)), threading dislocation (TD) density, and stacking fault (SF) density of the studied InN samples. |
|---------------------------------|
| [Mg] (cm\(^{-3}\)) | N\(\times 10^{17} \text{ cm}^{-3}\) | \(\mu \text{ cm}^{2}\text{V}^{-1}\text{s}^{-1}\) | TD density (cm\(^{-2}\)) | SF density (cm\(^{-3}\)) |
|---|---|---|---|---|
| undoped | 11.6 ± 0.5 (n) | 1601 ± 87 | 7 \times 10^9 | - |
| 1\(\times 10^{18}\) | 3.3 ± 0.1 (p) | 21 ± 1 | 6 \times 10^9 | - |
| 2.9\(\times 10^{19}\) | 3.3 ± 0.1 (p) | 30 ± 2 | 5 \times 10^9 | - |
| 1.8\(\times 10^{20}\) | 9.20 ± 0.04 (n) | 1079 ± 40 | 6 \times 10^9 | 4 \times 10^{10} |

\(\text{a}\)Reference 24
\(\text{b}\)Reference 33
PL measurements were performed by exciting the samples with a tunable Titanium Sapphire laser emitting at 840 nm (820 nm for one experiment). The PL was diffracted by a double grating (600 gr/mm) monochromator with an 850 mm focal length and detected by a liquid nitrogen cooled InGaAs diode detector. The samples were cooled down to 2 K in a liquid helium bath cryostat. When the PL from the samples was studied at various temperatures, the sample position was kept fixed. Because slight changes in the sample position occur when the sample holder temperature is varied, the sample position was manually adjusted to study a fixed position, but small deviations from the original position might have occurred. The monochromator was flushed with nitrogen gas to minimize the appearance of absorption lines due to absorption of the luminescence by water vapor.

III. RESULTS AND DISCUSSION

Representative PL spectra of the studied samples, obtained at 2 K, are shown in Fig. 1. The emission of the nominally undoped n-type sample is peaking at 0.69 eV. The p-type sample with Mg concentration of \(1 \times 10^{18}\) cm\(^{-3}\) exhibits three emission bands, at 0.62 eV, 0.68 eV, and 0.73 eV. The higher doped p-type sample with Mg concentration of \(2.9 \times 10^{19}\) cm\(^{-3}\) shows two emission bands centered at 0.62 eV and 0.68 eV, respectively. Finally, the highly Mg doped sample (n-type) with a Mg concentration of \(1.8 \times 10^{20}\) cm\(^{-3}\) shows emission centered at approximately 0.61 eV.

A. Nominally undoped InN

The nominally undoped sample (n-type with a free electron concentration of \(1.16 \times 10^{18}\) cm\(^{-3}\)) exhibits strong emission even at low excitation powers (2-5 mW), reflecting a relatively high crystal quality. The energy position of the PL band at 0.69 eV is consistent with previous PL studies of undoped, n-type InN layers.\(^8\)\(^9\)\(^26\)\(^27\)\(^35\) The observed emission is attributed to the recombination of the electrons at the Fermi level with the nonequilibrium holes located in the valence band tail.\(^9\) It is worth noting that despite very strong intensity at low temperatures, the luminescence from the undoped sample quenches fast with increasing temperature above 100 K, indicating the presence of a high density of non-radiative native defects in the film.

It is worth noting that no exciton related emission is expected to be seen in PL spectra of nominally undoped InN, even at low temperature (2 K). The binding energies of free excitons and hydrogen-like donors in InN are estimated to be 4.9 meV and 5.2 meV, respectively. In these estimates, isotropically averaged electron and A-valence band hole effective masses are used. The exciton effective mass of 0.045\(m_o\) is calculated with \(m_{e,\perp} = 0.05m_o\) and \(m_{e,\parallel} = 0.037m_o\) as determined from optical Hall effect measurements.\(^36\) (The symbols \(\perp\) and \(\parallel\) mean the masses in directions perpendicular and parallel to the c-axis of the wurtzite crystal, respectively, and \(m_o\) is the free electron mass). The A-valence band hole effective mass of 0.19\(m_o\) is calculated using \(m_{hh,\perp} = 0.13m_o\) and \(m_{hh,\parallel} = 1.81m_o\).\(^10\) Note that the hole effective mass (0.42-0.7)\(m_o\) extracted from the experimentally measured binding energy of the Mg acceptor\(^37\)\(^38\) corresponds to the combined heavy hole and light hole effective mass and it is not the hole effective mass that should be used in the calculation of the binding energy of the A free exciton. For the static dielectric constant \((\varepsilon_{\infty})\) we use a value of 10.83 determined from the high-frequency dielectric constant \((\varepsilon_{\infty} = 7.04)\) and TO and LO phonon frequencies measured by IRSE for samples studied here and the Lyddane-Sachs-Teller relation. Due to the small exciton binding energies, all Coulomb interactions are completely screened at a free carrier concentration above \(3 \times 10^{17}\) cm\(^{-3}\) (as in samples studied here), and no exciton effects appear in the PL spectra.

B. Mg-doped p-type InN

The PL spectra of the p-type InN sample with a Mg concentration of \(1 \times 10^{18}\) cm\(^{-3}\) and a free hole concentration of \(3.3 \times 10^{17}\) cm\(^{-3}\) were found to vary depending on the excitation spot position on the sample surface. The spectra consist of either two bands (0.62 eV and 0.68 eV) or three bands (0.62 eV, 0.68 eV and 0.73 eV), as represented graphically in Fig. 2.
The shape and position of the peaks at 0.62 eV and 0.68 eV agree well with spectra for low-defect density Mg-doped InN nanowires. The high-energy band at approximately 0.73 eV has not been observed before for Mg-doped InN. This high-energy emission band is detected in most sample positions measured, although in some positions on the sample it is only weakly seen as a shoulder of the main emission band at 0.68 eV.

The main PL band at 0.68 eV has an energy position close to that observed for the undoped sample. This indicates that the emission originates from a similar recombination process. However, in this case electrons at the conduction band edge are involved in the recombination because the sample is p-type and the Fermi level is within the bandgap. This can explain the slightly lower PL energy compared to the undoped sample.

The low energy emission at approximately 0.62 eV is positioned roughly 60 meV below the main PL band and is related to Mg acceptors. The emission is suggested to originate from the recombination of electrons at the bottom of the conduction band with holes bound to Mg acceptors. In principle, the emission at 0.62 eV could possibly also involve donor-acceptor-pair transitions, however, as the donor binding energy is only 5.2 meV, such transitions are not resolvable even at low temperatures. The 0.62 eV emission shows a linear power dependence, with no saturation even at a high excitation power (up to 50 mW) indicating a large incorporation of Mg acceptors in our InN film.

The third PL band at 0.73 eV is not visible in all positions of the sample and is not seen in the other sample studied here. This recombination process, yielding emission with an energy higher than the bandgap energy, is likely to involve electrons at the Fermi level in a degenerate n-type material and holes localized near the valence band edge. Such a recombination (without momentum conservation) is facilitated by the weak energy dispersion of the holes localized at the valence band potential fluctuations. On the other hand, the energy position of this emission band rules out a contribution of the holes localized at Mg acceptors. A similar recombination process was previously reported for n-type InN with free electron concentrations of the order of 3.5×10^{18} cm^{-3}. As our sample shows net p-type conductivity (Table I), the Fermi level should be reasonably close to the valence band. However, we observe a recombination of electrons from the Fermi level inside the conduction band. Most of the excitation photons are absorbed in the Mg-doped layer. Even with the potential of weakly exciting the nominally undoped layer underneath, the 0.73 eV emission does not originate from that layer, as this emission is only observed in one sample, even though all samples studied had the same layer structure and thickness. Another potential origin of the 0.73 eV emission is a recombination process involving electrons from the electron inversion layer, which is typically present at the surface of p-type conductive InN films. This could explain the high Fermi level, but not the spatial inhomogeneity of the high-energy PL band. We also note that such an inversion layer should also occur in the other p-type InN samples, where no 0.73 eV emission is observed (see Fig. 1). Thus, PL related to the surface inversion layer can also be ruled out as a possible explanation for the 0.73 eV emission. Based on the evidence at hand, we speculate that the high position of the Fermi level inside the conduction band can be attributed to the existence of n-type pockets inside the otherwise p-type InN film, due to an inhomogeneous incorporation of Mg acceptors, which also explains the spatially inhomogeneous emission. The ascription of the 0.73 eV emission as a recombination of electrons from the Fermi level inside the conduction band with the holes localized at the valence band potential fluctuations is supported by the observed small blueshift of the emission with increasing excitation power. Such a behavior is expected as the increase of optically excited (non-equilibrium) electrons in n-type pockets will result in a rise of the Fermi level. Unfortunately, in our measurements the range of the excitation power used is limited because of heating and damaging of the sample, which prevented us from reaching a definite conclusion from the power dependent PL measurements.

Comparing the emission energy of 0.73 eV at 2 K in our sample with experimental data given by Wu et al., where the PL peak emission of InN at 12 K is plotted as a function of the free electron concentration, we obtain a free electron concentration of 4×10^{18} cm^{-3} in the n-type pockets. We also compared our result with some calculations of the absorption edge as a function of the free electron concentration that fit well with experimental data. For this comparison, we set the absorption edge of our sample measured at 2 K to the energy corresponding to half of the maximum intensity, on the high-energy side of the peak, which is 0.76 eV (the Stokes shift is not accounted for). Comparing this to the reports of Wu et al. and Walukiewicz et al., in both cases we obtain a free electron concentration of 5×10^{18} cm^{-3} for the n-type pockets.

A reasonable question that arises from the above estimations is why the free electron concentration in the n-type pockets is higher than the electron concentration in the nominally undoped InN sample. First of all, we note that due to the uncertainty in the exact position of the 0.73 eV emission (related to broadening, and overlapping with the 0.68 eV emission), and the comparison with data reported for samples grown at different conditions, the estimated values of (4-5)×10^{18} cm^{-3} should be only regarded as an upper limit for the free electron concentration in the n-type pockets. Secondly, it has been shown that Mg doping in InN introduces donor-like defects such as Mg_{n=O} complexes, which have very low formation energies. As the net charge concentration of our InN sample is p-type it is thus plausible to suggest that nonuniform distribution of such defect complexes could provide a possible explanation for the observed high electron concentration in the n-type pockets. The net p-type conductivity of the sample is determined by IRSE and confirmed by electrolyte capacitance voltage measurements. Note that in IRSE measurements, information about the entire sample...
area is obtained, which is 1\times1 \text{cm}^2.\textsuperscript{14,24,25} In PL measurements, however, the diameter of the excitation spot is about 70 \mu m. Since the n-type pockets most likely occur within regions with a diameter of the order or below hundreds of \mu m it is not surprising that PL measurements provide a more detailed spatial information and the emission at 0.73 eV associated with the n-type pockets varies with the position of the excitation spot.

For the sample with a Mg concentration of 2.9\times10^{19} \text{cm}^{-3}, a homogeneous emission is observed independent of the sample position, and no emission at 0.73 eV is detected. As seen in Fig. 1, this sample shows a weak PL band at 0.62 eV, while the dominating PL contribution comes from a band at 0.68 eV. The temperature dependence of the PL spectra is shown in Fig. 3. As the temperature is increased, the band at 0.68 eV quenches quickly, similarly to the nominally undoped sample. As for the lower Mg-doped sample, this band is attributed to the recombination of electrons at the conduction band edge with localized holes at the valence band potential fluctuations. The emission at 0.62 eV is 62 meV below the main PL band, and is attributed to a band-to-acceptor recombination process involving photo-generated electrons in the conduction band and holes at Mg acceptors.

The integrated intensity of each of the two bands (0.62 eV and 0.68 eV) as a function of temperature is shown in Fig. 4. The integrated intensities of the bands were obtained by fitting each spectrum in Fig. 3 with two asymmetric Voigt functions. The Arrhenius plot of the integrated PL at 0.68 eV yields two activation energies, 6.2 meV and 16 meV. The first one is attributed to the depth of the valence band fluctuations, where the holes are localized. The physical origin of the second activation energy is not clear yet; it could be related to deeper localized holes or to shallow non-radiative defects. For comparison, the temperature quenching of the luminescence of the undoped sample yields a single activation energy of 7.5 meV. With increasing temperature, the main emission (0.68 eV at 5 K) initially blue shifts and then follows the red shift of the InN bandgap. The fitting of the PL energy position as a function of temperature with the Varshni equation yields a binding energy of 2-8 meV, which overlaps with the activation energy of 6.2 meV obtained from the Arrhenius fit, and could be related to the localization potential due to valence band energy fluctuations.

The PL band at 0.62 eV starts to quench at 70 K, which is due to ionization of the Mg acceptors. Analyzing the integrated intensity of this emission with the Arrhenius equation gives an activation energy of 64 meV (Fig. 4). This energy is in very good agreement with the previously reported values for the binding energy of the Mg acceptor in InN.\textsuperscript{34,35,37,42,43} It is worth noting that the Mg acceptor binding energy extracted from the thermal quenching analysis of the band-to-acceptor emission is much more reliable than that from the energy separation between this emission and the band-to-band emission, since the energy position of the band-to-band emission in highly-doped InN does not exactly correspond to the bandgap energy.\textsuperscript{9,35} This is probably the reason for the reported temperature dependent Mg acceptor binding energy in Ref. 37 despite that in principle the binding energy of the acceptor (and donor) states is independent of the temperature. On the other hand, it is well known that due to the overlapping of the Coulomb potentials of closely spaced impurities, the binding energy of acceptors (and donors) decreases with the impurity concentration. The value for the Mg acceptor in InN we estimated is for a sample with a Mg concentration of 2.9\times10^{19} \text{cm}^{-3}. For lower doping concentrations, a slightly higher value could be expected. Note that an acceptor with a binding energy of 85 meV has been reported for nominally undoped (n-type) InN but the origin of this acceptor was not identified.\textsuperscript{9}

C. Highly Mg-doped n-type InN

Increasing the Mg concentration further, to 1.8\times10^{20} \text{cm}^{-3}, causes the sample to revert to n-type conductivity. A representative PL spectrum of this sample is shown in
Fig. 1. Only the emission related to the Mg acceptors is observed. The slightly lower emission energy (0.61 eV) is attributed to the lower compressive in-plane strain compared to that in the lower Mg doped and undoped samples, as deduced by x-ray diffraction measurements of the lattice parameters.\textsuperscript{24}

The PL spectrum of the highly Mg-doped n-type InN sample further shows multiple peaks in the low energy tail (0.54–0.58 eV) of the emission (Fig. 1). Water vapor absorption is ruled out as the origin of these peaks, since it is expected to occur at 0.633–0.692 eV and 0.835–0.922 eV. We note that the highly Mg-doped InN film contains stacking faults (SFs) with a high density of $4 \times 10^{10} \text{ cm}^{-2}$.\textsuperscript{33} Stacking faults in InN can be viewed as inclusions of zinc-blende material in a wurtzite crystal, forming quantum well like structures. The bandgap alignment of wurtzite and zinc-blende InN is shown in Fig. 5, where the bandgap and band offset energies are average values taken from theoretical calculations.\textsuperscript{44} We should note that the bandgap of a thin zinc-blende InN inclusion into wurtzite matrix is not the same as the bandgap of bulk zinc-blende InN. The discontinuity of the spontaneous polarization at interfaces leads to a polarization-induced field and quantum confined Stark effect (QCSE). As a result, the bandgap of the embedded zinc-blende InN is considerably reduced compared to the bandgap of bulk zinc-blende InN. As can be seen, transitions from carriers localized at SFs are expected to occur above 0.48 eV, which could explain the observed multiple peaks at 0.54–0.58 eV. Both type-I\textsubscript{1} and type-I\textsubscript{2} SFs, which have different thicknesses, i.e. different quantum well widths, are observed in the InN film.\textsuperscript{35} In addition, locally, SFs can form bundles with different thicknesses.\textsuperscript{35} Also, the confinement levels in the SFs can be perturbed by nearby Mg acceptors. This can explain the multiple-peak structure observed in the PL spectrum. Therefore, we speculate that the 0.54–0.58 eV emission observed in the highly Mg-doped InN film with n-type conductivity can be associated with transitions involving carriers localized at SFs.

![Fig. 5. Band alignment for InN zinc-blende inclusions (stacking faults) in wurtzite InN. The bandgap and band offset energies are average values taken from Ref. 44.](image)

IV. CONCLUSIONS

Mg doped InN films grown by PA-MBE have been studied by means of photoluminescence spectroscopy. The nominally undoped (n-type) InN sample showed low temperature photoluminescence at 0.69 eV, attributed to the recombination of electrons at the Fermi level inside the conduction band and holes localized at the valence band potential fluctuations. A Mg concentration of $1 \times 10^{18} \text{ cm}^{-3}$ was found to yield p-type conductivity and spatially inhomogeneous PL. Three emission bands located at 0.62 eV, 0.68 eV, and 0.73 eV were observed at 2 K. The 0.62 eV and 0.68 eV emissions originate from recombination of the electrons at the conduction band edge and holes localized at Mg acceptors and valence band potential fluctuations, respectively. The high energy PL band at 0.73 eV involves electrons at the Fermi edge inside the conduction band and was suggested to occur inside n-type pockets in the otherwise p-type material. These n-type pockets were estimated to have free electron concentrations in the range of $(4-5) \times 10^{18} \text{ cm}^{-3}$. Increasing the Mg concentration to $2.9 \times 10^{19} \text{ cm}^{-3}$ results in the disappearance of the high energy PL band and the transition to homogeneous emission properties, indicating an improved material quality. Only the emissions at 0.62 eV and 0.68 eV were observed. From analysis of the temperature dependent PL spectra, an activation energy of 64 meV has been extracted for the 0.62 eV emission. This value is a good estimate of the binding energy of Mg acceptors in InN. Upon further increasing the Mg concentration to $1.8 \times 10^{20} \text{ cm}^{-3}$, the sample becomes degenerate n-type and low temperature PL spectra showed only a broad conduction band-to-acceptor emission at 0.61 eV. The multiple peaks at 0.54–0.58 eV in the low energy tail of the emission are attributed to the recombination of carriers localized at stacking faults forming quantum well like structures. In conclusion, we have shown that the doping concentration greatly affects the emission properties of Mg doped InN layers. Depending on the doping level and the type of conductivity, recombination processes related to degenerated electrons at the Fermi edge, Mg acceptors, shallow localized holes, and stacking faults could be manifested in the PL spectra.

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