Electrical and Optical Characteristics of Isoelectronic Al-doped GaN Films

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The effects of the isoelectronic Al-doping of GaN grown by metal organic chemical vapor deposition were investigated for the first time using scanning electron microscopy (SEM), Hall measurements, photoluminescence (PL), and time-resolved PL. When a certain amount of Al was incorporated into the GaN films, the room temperature photoluminescence intensity of the films was approximately two orders larger than that of the undoped GaN. More importantly, the electron mobility significantly increased from 130 for the undoped sample to 500 cm^2/Vs for the sample grown at a TMAl flow rate of 10 μmol/min, while the unintentional background concentration only increased slightly relative to the TMAl flow. The incorporation of Al as an isoelectronic dopant into GaN was easy during MOCVD growth and significantly improved the optical and electrical properties of the film. This was believed to result from a reduction in the dislocation-related non-radiative recombination centers or certain other defects due to the isoelectronic Al-doping.

1. Introduction

III-V nitride materials have been investigated for various applications in electronic and optoelectronic devices, such as blue and green light emitting diodes, laser diodes[1,2], and high-power and high-temperature HFETs[3-5]. Despite the rapid growth of group III nitride materials [6,7], it is still difficult to obtain a high quality film due to the inherent large dislocation density and deep levels resulting from a lattice mismatch between the GaN film and the sapphire substrate. Such defects generally play a role as a non-radiative recombination center in the active layer and are related with an increase in the threshold current in a nitride semiconductor laser diode and current collapse in an AlGaN/GaN HFET.

The isoelectronic doping of semiconductors is known to improve their optical and electrical properties. For example, the N-doping of GaP and In-doping of GaAs have both been reported as effective isoelectronic doping[8-10]. In the case of nitride-semiconductors, In and As have already been investigated as isoelectronic dopants and shown a remarkable enhancement in the optical properties, yet ambiguous results as regards enhancing the electrical properties[11-14]. Accordingly, in the current study, the effects of the isoelectronic Al- doping of GaN were systematically characterized for the first time using Hall measurements, photoluminescence (PL), time-resolved PL, and scanning electron microscopy (SEM).

2. Experiment and Discussion

Undoped and a series of Al-doped GaN films were grown on a (0001) sapphire substrate at a temperature of 1020℃ using metal-organic chemical vapor deposition (MOCVD). The respective Ga, N, and Al precursors were trimethylgallium (TMGa), ammonia (NH_3), and trimethylaluminum (TMAl). Prior to the epilayer growth, the wafer was cleaned by H_2 ambient at 1020℃ and a 23 nm-thick low temperature buffer layer at 550℃. During the growth, the chamber pressure was maintained at 300 torr. The Al-doped GaN samples were grown at four different TMAl flow rates of 3, 6, 10, and 30 μmol /min, then their optical and electrical properties were compared with those of the undoped GaN sample. Figure 1 shows the Hall measurement results for the samples grown with various TMAl flow rates. When increasing the TMAl flow rate up to 10 μmol/min, the electron mobility also significantly increased from 130 to 500 cm^2/Vs, while maintaining a background doping concentration below $\sim 10^{17}/cm^3$. This substantial increase in mobility was not observed with the isoelectonic In-doping of the GaN layer. Accordingly, the increase in mobility observed in the current study is believed to have been due to a reduced dislocation-related scattering center or some other related defects. As the TMAl flow rate increased above 10 μmol, the mobility decreased possibly due to the generation of certain new defects when the incorporation of Al into GaN exceeded a critical level.

The effect of isoelectronic doping on the optical properties of GaN was also investigated using room temperature PL, as shown in figure 2. An He-Cd laser operating at 325 nm was used for the above band gap exciting. Band-to-band recombination was observed at the same wavelength of 359 nm for all samples, indicating that Al was incorporated into the GaN film at the doping level. As the TMAl flow rate increased, both the band-to-band recombination peak and the yellow peak intensity became much stronger than those of the undoped GaN. This is different from the In-doping of GaN, which shows an increase in the band-to-band transition yet a diminishing yellow peak relative to the radiative transition[15]. In contrast to the mobility, the PL intensity continued to increase with TMAl flow rates higher than 10 μmol. When the TMAl flow rate was 30 μmol, the PL intensity increased to a value approximately two orders larger than that of the undoped GaN. The yellow peak intensity also increased at the same rate as the band-to-band transition at a low TMAl flow rate, then slowed down and became almost saturated at a higher TMAl flow rate. As such, the Al-doping of GaN would appear to be more effective at killing non-radiative recombination centers near the band edge transition than near the yellow peak transition. However, the reason for this discrepancy in the electrical and optical properties according to the TMAl flow rate is still unclear and requires additional study.

To further investigate the effect of Al-doping, time-resolved PL measurements were carried out using a tunable picosecond pulsed laser system as an excitation source and a streak camera system for detection. The output laser pulses were frequency tripled into the ultraviolet spectral region by nonlinear crystals. The overall time resolution of the system was better than 10 ps.

Figure 3 shows the temporal evolution of the band-edge emissions from undoped GaN and Al-doped GaN samples grown at a TMAl flow rate of 10 μmol/min measured at 10 K. The time evolution for both samples was dominated by exponential decay. The decay time of the band-edge emission was ~ 20 ps for the undoped GaN and ~ 58 ps for the Al-doped GaN at 10 K. Note, the 10 K decay time for the Al-doped GaN sample was roughly three times longer than that for the undoped GaN sample. Based on the higher emission intensity and longer decay time for the GaN band-edge emission in the Al-doped GaN sample compared with the undoped sample, it would appear that the optical properties of the GaN band-edge emission can be enhanced by a small amount of Al incorporation during the growth of GaN.

SEM micrographs of the undoped and four different Al-doped GaN films are shown in fiqure 4. With the incorporation of Al into the films, the growth rate reduced from 400 Å/min to 120 Å/min due to the pre-reaction between the TMAI and the NH_3 reactants, however, the surfaces of the Al-doped samples were as smooth as that of the undoped sample. To more fully understand the isoelectonic Al-doping effect, additional studies involving transmission electron microscopy (TEM), secondary ion mass spectroscopy(SIMS), and deep-level transient spectroscopy (DLTS) are currently underway.

3. Conclusions

An examination of the optical and electrical properties of isoelectronic Al-doped GaN found that the optical and electrical properties of the GaN epilayer are much improved without a significant change in the bandgap energy. The band-edge emission intensity and decay time for the Al-doped GaN samples were both observed to be much larger than those of the undoped GaN, indicating that even a small amount of Al incorporation was efficient in reducing any non-radiative recombination centers. When increasing the TMAl flow rate up to 10 μmol/min, the electron mobility significantly increased from 130 to 500 cm^2/Vs while maintaining a background doping density of below $\sim 10^{17}/cm^3$. This is believed to be mainly due to a reduction in the dislocation-related scattering centers or certain other related defects. Accordingly, optimized isoelectronic Al-doping could greatly enhance the performance of GaN-based devices.

Acknowledgments

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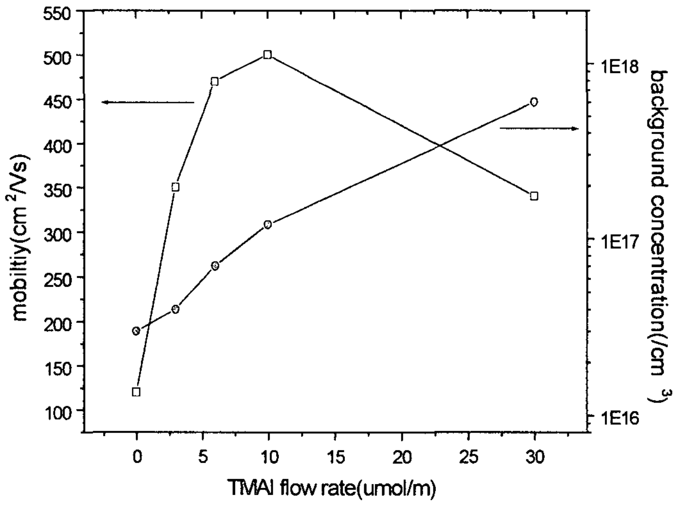


Fig. 1. Hall measurement for various TMAl flow rates

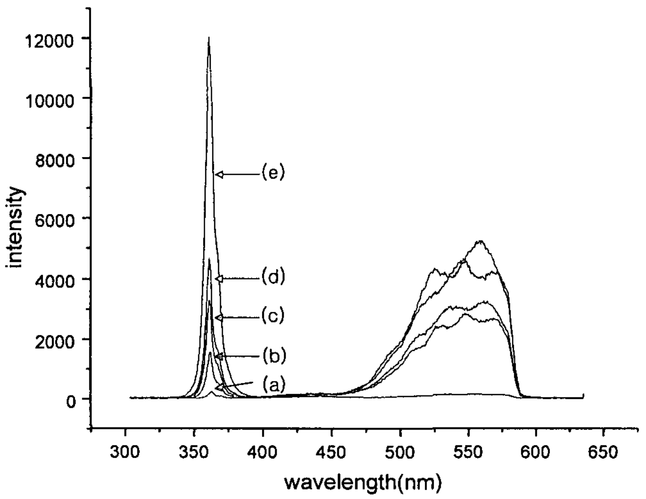


Fig. 2. PL intensity for various TMAl flow rates
(a) undoped GaN, TMAl flowrate of (b) 3, (c) 6, (d) 10, and (e) 30 μmol/m

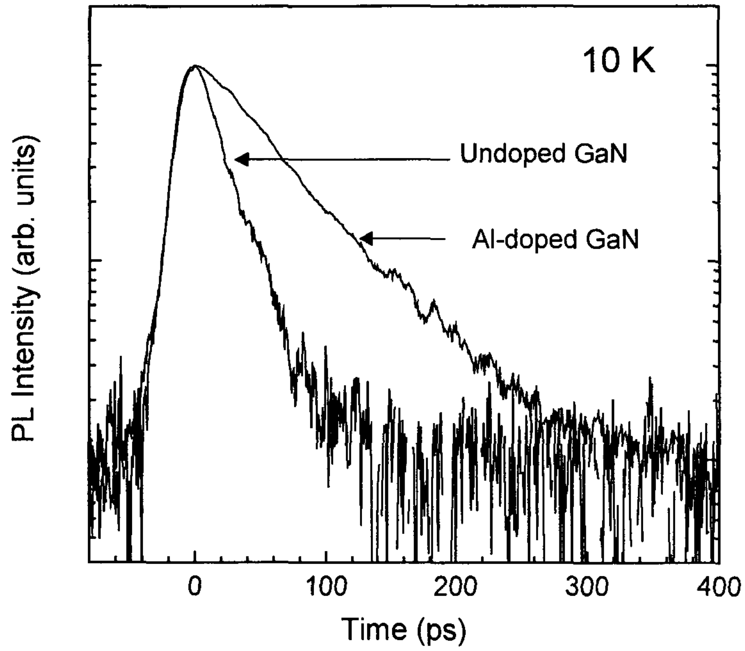
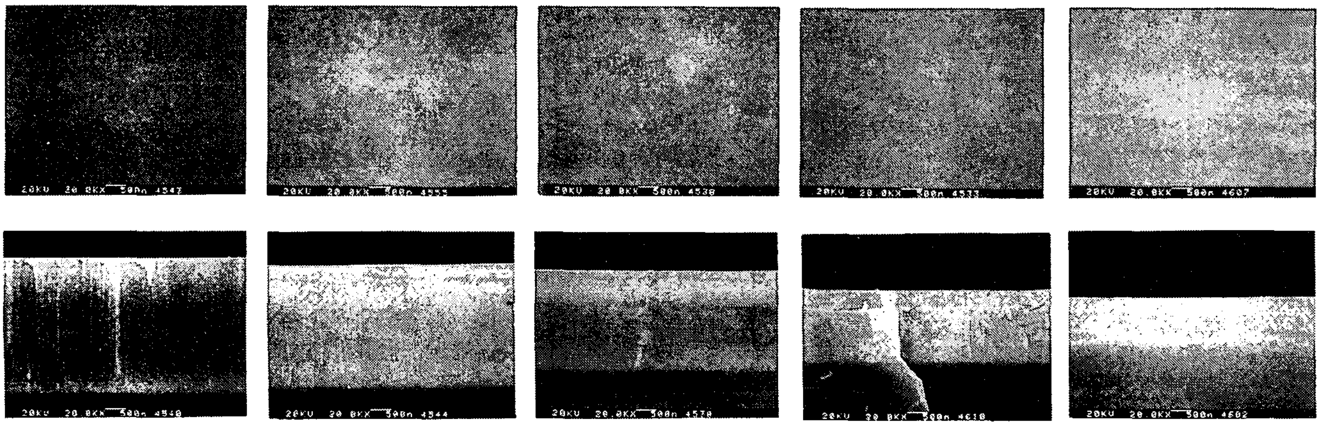


Fig. 3. TRPL spectra of 10 K temporal evolution of band-edge emission of undoped GaN and Al-doped GaN (TMAl flow rate of 10 μmol/min) samples



(a) (b) (c) (d) (e)

Fig. 4. SEM photographs of undoped GaN and Al-doped GaN films
(a) undoped GaN, TMAl flow rate of (b) 3, (c) 6, (d) 10, and (e) 30 μmol