Research Article

High Conductivity of Mg-Doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ with $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{AlN}$ Superlattice Structure

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The highly conductance of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer using low-pressure metal organic chemical vapour deposition (MOCVD) on $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{AlN}$ superlattice structure was reported. The rapid thermal annealing (RTA) has been employed for the effective activation and generation of holes, and a minimum p-type resistivity of $3\ \Omega\text{-cm}$ for p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ was achieved. The RTA annealing impacted on electrical, doping profile and morphological properties of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ with $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{AlN}$ superlattice structure have been also discussed. The quality of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ with $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{AlN}$ superlattice structure degraded after annealing from HRXRD. At appropriate annealing temperature and time, surface morphology of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ can be improved. A step-like distribution of [Mg] and [H] in p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ was observed, and thermal diffusion direction of [Mg] and [H] was also discussed.

1. Introduction

Significant development of III-nitride based wide bandgap materials has led to the applications in microelectronics and optoelectronic device [1–6]. High hole conductivity in AlGa_N is the key for producing short-wavelength optical devices as well as high-power and high-frequency electronic devices. However, compared to GaN, it is even more difficult to control the conductivity through doping in AlGa_N alloys due to a higher concentration of defects and larger ionization energy of the dopant [7]. The fabrication of p-type AlGa_N with high Al content is still a significant challenge. A compromise can be reached by using methods [8, 9], such as Mg delta doping and Mg-doping strained AlGa_N/AlN superlattice. Meanwhile, the thermal annealing was a useful method for activation and generation of holes [10, 11].

In this paper, a strained AlGa_N/AlN superlattice structure and combination of rapid thermal annealing (RTA) methods help to obtain the high conductivity of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer. Hall, atomic force microscopy (AFM),

high resolution X-ray diffraction (HRXRD), and secondary ion mass spectroscopy (SIMS) are used to characterize the electrical, morphological, quality, and doping profile of the as-grown and annealed samples, respectively.

2. Experimental Procedures

The epitaxial layers used in the experiments were grown on c-plane sapphire substrates using a metalorganic chemical vapor deposition (MOCVD) system. Trimethylgallium (TMG), ammonia (NH_3), and bis-cyclopentadienyl magnesium ($\text{CP}_2\text{-Mg}$) were used as the Ga, N, and Mg sources, respectively. A 8-nm thick and low temperature (600°C) AlN nucleation and 200 nm thick and high temperature (1060°C) AlN nucleation were grown on the sapphire substrate. The 10 period $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ (12 nm)/AlN(8 nm) superlattices and $0.8\ \mu\text{m}$ undoped $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layers were grown at 1060°C . After the deposition of these layers, 150 nm Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layers were finally grown at 900°C .

FIGURE 1: (a) The annealing temperature and (b) annealing time dependence of the conductivity of Mg-doped AlGa_{0.3}N p-type sample annealed by RTA.

Thermal annealing was performed from 800°C to 900°C in N₂ and annealing time was 1 to 10 min. Atomic force microscope (AFM) was used to characterize the surface morphology, and a Bruker D8 high resolution X-ray diffraction (HRXRD) system was used to characterize the quality of the materials before and after RTA annealing. Hall measurement was performed at room temperature in order to evaluate the electrical properties of the Mg-doped Al_{0.3}Ga_{0.7}N layers. The [Mg] depth profile and [H] depth profile were obtained from the secondary ion mass spectroscopy (SIMS) measurements.

3. Results and Discussion

Figure 1 shows the variation of resistivity with the thermal annealing temperature and time. The measured resistivity has a sharply reduction to 3 Ω·cm with the increase of annealing temperature and time. Then, with the further increase of annealing temperature and time, the resistivity begins to increase gradually. We found that the optimization of annealing temperature and time were 850°C and 5 min from Figure 1. It was proposed that the decrease of the resistivity was caused by the depassivation of the Mg acceptor due to the hydrogen outdiffusion after the annealing [12]. Figure 1 shows the lowest resistivity obtained by RTA process (850°C (5 min)). This suggests that Mg-H complexes can be dissociated during the long period (5 min) and proper temperature (850°C), which may effectively be removed during the optimal annealing. For the observed high resistivity of p-type AlGa_{0.3}N annealed at high temperatures (>900°C) in RTA, the possible explanation is the decomposition of AlGa_{0.3}N at these high annealing temperatures. The dissociation pressure of GaN becomes significantly high at temperatures higher than 800°C [13] and GaN starts to lose nitrogen atoms at these high temperatures. It is believed that the nitrogen vacancies in the GaN film act as donors [14] and compensate the Mg acceptors. The changes of dislocation density in different RTA process sample (Figure 3) confirm that nitrogen vacancies

in the Mg-doped Al_{0.3}Ga_{0.7}N layer generate. Therefore, the resistivity increase in the Mg-doped AlGa_{0.3}N film at high temperature is attributed to the increase of nitrogen vacancies.

The RTA processes at a high temperature were found to affect the crystal quality and the surface roughness of the films because the dissociation of the Al_{0.3}Ga_{0.7}N film is gradually facilitated at 900°C. AFM images (3 × 3 μm²) of surface morphology from a subset of this series of samples are displayed in Figure 2. These four samples have relatively flat surface, indicating that it has a high crystal quality. After the annealing, the roughness of the Mg-doped Al_{0.3}Ga_{0.7}N varied with the annealing temperature. The root mean surface (RMS) of as-grown sample is about 0.352 nm. The RMS of 800°C-N₂-activated sample and 850°C-N₂-activated sample decreased to 0.225 nm and 0.299 nm, respectively. Therefore, the N₂-annealing temperature of less than 850°C can minimize the surface roughness of Mg-doped Al_{0.3}Ga_{0.7}N film. However, the RMS of 900°C-N₂-activated sample increased to 2.21 nm, and a much rougher morphology is developed with clusters of sub-100 nm grains. It indicates that the surface atoms can decompose and adsorb during high temperature annealing in N₂. The interaction of these two processes can result in the redistribution of surface atoms. At a high temperature range of 800°C–850°C, the RMS of Mg-doped Al_{0.3}Ga_{0.7}N layer can decrease. If the annealing temperature was higher than 850°C, the decomposition of N will escape into the atmosphere; thus, the surface of film will become rough.

Figure 3 shows the variation of full width at half maximum (FWHM) with the thermal annealing temperature for 5 min in N₂, which provides information on the dislocation density. The Mg-doped Al_{0.3}Ga_{0.7}N layer has 237 arcsec for 0002 scans and 1294 arcsec for 10 $\bar{1}$ 2 scans before the annealing, respectively. After 800°C annealing, the FWHM of Mg-doped Al_{0.3}Ga_{0.7}N layer slightly increased 240 arcsec for 0002 and 1330 arcsec for 10 $\bar{1}$ 2. After 850°C annealing, FWHM of Mg-doped Al_{0.3}Ga_{0.7}N layer increased 253 arcsec

FIGURE 2: $3 \times 3 \mu\text{m}^2$ AFM image for as-grown sample A (a) with RMS of 0.352 nm, at 800°C - N_2 -activated sample B (b) with RMS of 0.225 nm, 850°C - N_2 -activated sample C (c) with RMS of 0.299 nm, and 900°C - N_2 -activated sample D (d) with RMS of 2.21 nm for 5 min.

FIGURE 3: FWHM of (0002) and ($10\bar{1}2$) XRD rocking curve at different annealing temperature for 5 min in N_2 .

for 0002 and 1328 arcsec for $10\bar{1}2$. The FWHM of XRD curves for as-grown and 800°C – 850°C annealing Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ samples was noticeably unchanged, indicating that new dislocations were not significantly produced even after 800°C – 850°C annealing. When the annealing temperature was over 900°C , the FWHM of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$

layer significantly increased 399 arcsec for 0002 and 1389 arcsec for $10\bar{1}2$. It indicates that the spiral dislocation and edge threading dislocation density [15, 16] of Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer increased through annealing 900°C . It is because that annealing process induced the thermal stress in epitaxial film, and the thermal stress is released through the line defects. The higher the annealing temperature, the greater the thermal stress generated. Finally, more spiral dislocation and edge threading dislocation density may produce, which results in the degeneration of film electrical properties. In order to ensure the Mg-doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer quality, the annealing temperature should be lower than 900°C .

Figure 4 shows depth profiles of [Mg] and [H] from SIMS measurement in p-type AlGaIn epilayer before and after 850°C annealing in N_2 . A step-like distribution of [Mg] in p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ was observed in Figure 4(a). There was a transition from a monotonically increasing doping profile between p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ and undoped $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$. After 850°C annealing in N_2 , the average concentration of [Mg] decreased from $2.06 \times 10^{20} \text{ cm}^{-3}$ to $2.02 \times 10^{20} \text{ cm}^{-3}$ in p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ layer. However, there was a little increase of [Mg] concentration in undoped $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ layer after

FIGURE 4: (a) Mg and (b) H SIMS depth profiles before and after 850°C annealing in N_2 .

850°C annealing in N_2 . This indicated that the thermal diffusion of [Mg] was mainly toward the side of undoped $Al_{0.4}Ga_{0.6}N$ layer. Figure 4(b) compared the hydrogen concentration before and after 850°C annealing in N_2 . The step-like distribution of [H] in p-type $Al_{0.3}Ga_{0.7}N$ was also observed. However, the transition from a monotonically increases doping profiles at side of the p-type $Al_{0.3}Ga_{0.7}N$. The [H] concentration decreased from $1.56 \times 10^{20} \text{ cm}^{-3}$ to $1.51 \times 10^{20} \text{ cm}^{-3}$ after annealing in Mg-doped $Al_{0.3}Ga_{0.7}N$. However, the concentration profiles of [H] had no change before and after annealing in undoped $Al_{0.4}Ga_{0.6}N$ which were higher than those of [Mg] concentration. From the calculation, about 1% of Mg was activated. This indicated that the thermal annealing treatment in N_2 dissociates the Mg-H complexes and results in [H] outdiffusion from the epilayer, activating the p-type $Al_{0.3}Ga_{0.7}N$. Therefore, the optimal annealing (850°C (5 min)) can minimize the resistivity and surface roughness for p-type $Al_{0.3}Ga_{0.7}N$ films compared to the 900°C annealing process. Through the SIMS depth profiles, optimal annealing (850°C (5 min)) can effectively improve the conductivity of p-type $Al_{0.3}Ga_{0.7}N$.

4. Conclusions

The highly conductance of Mg-doped $Al_{0.3}Ga_{0.7}N$ layer using low-pressure metal organic chemical vapor deposition (MOCVD) on $Al_{0.4}Ga_{0.6}N/AlN$ superlattice structure was reported. The rapid thermal annealing (RTA) has been employed for the effective activation and generation of holes; a minimum p-type resistivity of $3 \Omega\text{-cm}$ for $Al_{0.3}Ga_{0.7}N$ was achieved. At appropriate annealing temperature and time, surface morphology of Mg-doped $Al_{0.3}Ga_{0.7}N$ can be improved. The quality of Mg-doped $Al_{0.3}Ga_{0.7}N$ with $Al_{0.4}Ga_{0.6}N/AlN$ superlattice structure degraded after annealing from HRXRD. A step-like distribution of [Mg] and [H] in p-type $Al_{0.3}Ga_{0.7}N$ was observed, and thermal activity direction of [Mg] and [H] was also discussed. We ascribed the enhanced conductivity performance of p-type $Al_{0.3}Ga_{0.7}N$ to the following two factors: (1) improvement of $Al_{0.3}Ga_{0.7}N$

crystal quality by applying the $Al_{0.4}Ga_{0.6}N/AlN$ superlattice layer to reduce the defects and scattering centres in p-AlGa N epilayer and (2) optimization of RTA conditions, including appropriate annealing time, temperature, and ambient gas.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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