Surface decomposition and annealing behavior of GaN implanted with Eu

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Abstract *Investigations on surface decomposition of GaN implanted with low* energy (80 keV) Eu ion to a low dose ($1\times10^{14}\,cm^{-2}$), and its annealing behavior under high temperature (1050°C) in N_2 are performed. The as-grown, as-implanted and annealed GaN films are characterized by proton elastic scattering (PES), Rutherford backscattering spectrometry (RBS), photoluminescence (PL) and atomic force microscopy (AFM). The results show that Eu ion implantation induces radiation defects and decomposition of GaN. The GaN surface decomposition is more serious during high temperature annealing. The atomic ratio of N in as-grown, as-implanted and annealed GaN film is 47 at.%, 44 at.% and 40 at.%, respectively. As a result, a rough Ga-rich layer is formed at the surface, though the lattice defects are partly removed after high temperature annealing.

Keywords Surface decomposition, Annealing behavior, GaN, Implantation

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1 INTRODUCTION

For the past decades, GaN has been extensively studied for the promising applications in electronic and photonic devices. And significant progress has been made in this field.[1] As one of the most attractive aspects, considerable achievements in doping GaN with rare earths (RE) have been made in fabricating light emitting devices in a wide spectral region.[2−5]

Semiconducting materials can be doped during growth or by ion implantation. In planar device technique, ion implantation is a mature doping technique, well-known in silicon technology. The main advantage is to introduce nearly all elements of periodic table into materials, with precise control of dopant concentration and depth distribution. However, the radiation damage induced by ion bombardment is the main shortcoming of this technique, which is not easy to be removed by annealing, specially for compound semiconductor.

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The references on damage behaviors in GaN with ion implantation are still limited. Only a few groups have investigated on the problems.[6–8] Kucheyev *et al.*[6] showed the loss of N and disorder buildup in GaN under both light (^{12}C) and heavy (^{197}Au) ion bombardment. Tan *et al.*[9] studied the amorphization of GaN implanted with Si at liquid nitrogen temperature at moderate dose, concluded the amorphization "nucleated" at the surface. Most of studies were focused on the amorphization of GaN with high energy ion implantation at high dose. However, implantation with keV ions at low dosage is widely used in device fabrication.

In this paper, we studied the surface decomposition and annealing behavior of GaN implanted with low energy (80 keV) Eu ions at low dosage ($10^{14}cm^{-2}$). The different samples were characterized by several analytical techniques, including PES, RBS, PL and AFM.

2 EXPERIMENT

GaN films were grown on (0001) oriented sapphire substrates by atmospheric pressure metalorganic chemical vapor deposition (MOCVD) in a vertical reactor. The thickness of films is 2.5–3.0 μm. Trimethylgallium (TMG) and blue-ammonia (NH_3) were used for Ga and N sources, respectively. The mixed gases of hydrogen (H_2) and nitrogen (N_2) were used as the carrier gases. Before deposition, a thin film with thickness of about 15 nm was grown at 520°C and recrystallized at 1060°C for 6 minutes, as a buffer layer on sapphire.

Implantation was performed at room temperature (RT) in an electromagnetic isotope separator (EMIS-SINR-02). 80 keV ^{153}Eu ions were implanted into GaN samples to a dose of 1×10^{14} cm^{-2}. The projected range, R_p, and the straggling, ΔR_p, were 37.5 nm and 13.5 nm, respectively, as calculated using the TRIM92 code. The resulting peak Eu concentration $[Eu]_m$ was 2×10^{19} cm^{-3}. Some implanted samples were annealed at 1050°C for 60 minutes under a continuous flow of nitrogen gas.

The composition and depth distribution of elements were profiled by proton elastic scattering (PES) with 2.8 MeV H ion beam and by Rutherford backscattering spectrometry (RBS) with 2.0 MeV He ion beam on a 4MV pelletron. The incident beam was normal to sample surface, and the detector was fixed at 170° with incident beam.

Photoluminescence (PL) characterization was performed at room temperature (RT) with a He-Cd laser at 325 nm (15 mW), above the GaN band gap (~3.4 eV). The near band edge emission of all GaN films was studied by PL spectrometry.

The surface topography and roughness analysis of the films were also investigated by atomic force microscopy (AFM), which were carried out in air at RT using a Digital Instruments Nanoscope IIIa in tapping mode.

3 RESULTS AND DISCUSSION

The as-grown GaN films are single crystalline with very smooth surfaces. The root mean square (RMS) roughness of the surfaces is 1.6 nm analyzed by AFM.

PES spectra of the implanted GaN before and after annealing are Shown in Fig.1. The spectrum of the as-grown GaN (not shown) is similar to that of as-implanted one.

According to PES spectra (Fig.1), the thickness of GaN films is about 2.8 μm. Analyses from RBS (not shown here) shows that the atomic ratio of N in as-implanted film is 44 at.%, less than that in the as-grown GaN film, 47 at.%. The loss of N indicates that Eu ion implantation induces radiation defects and decomposition of GaN in the ion projected range region. Comparing the annealed GaN film with the as-implanted one, it is easy to see that the yields of elements N and Ga decrease. Both Al peak and O peak shift towards high energy position, that means much of N and a portion of Ga escape from the GaN surface during annealing. RBS analysis also proves that the atomic ratio of N decreases to 40 at.% in the annealed GaN surface region. The results indicate that the implanted GaN surface is severely decomposed during high temperature annealing. From the PES and RBS spectra, more details show that a Ga-rich surface about 40 nm is formed at the surface, and the result of x-ray photoelectron spectroscopy (XPS) indicates that the Ga-rich surface is a bit oxidized, mostly because the rough surface exposes in air. The results reported here are consistent with the early studies.[9,10]

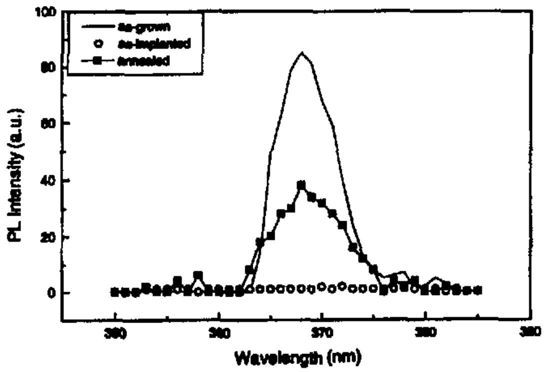

Fig.1 PES spectra obtained with 2.8 MeV H ion

Fig.1 is showing the variance of composition in GaN films: the as-implanted GaN film (the solid line); the annealed GaN film at 1050°C for 60 minutes in N_2 (the line with open circle). The arrows mark positions of the surface scattering energy ($K_M E_O$) for corresponding elements

Fig.2 shows photoluminescence (PL) spectra that illustrate the GaN near band edge emission of the different samples. The He-Cd laser's excitation line is 325 nm (3.81 eV), above the GaN band gap (~3.4 eV). The as-grown film emits an intense near band edge emission (the solid line) at 368 nm with a full width at half maximum (FWHM) of ~7.2 nm (60 meV), which manifests the rather good monocrystalline quality of as-grown GaN film. However the 368 nm peak disappears after Eu ion implantation (see the open circle). The quenching of near band edge emission proves that ion implantation produces crystal lattice defects in projected range and severely destroys the crystal structure of GaN. High temperature annealing can recover the crystalline quality and activate the dopants in GaN.[5] The near band edge emission of annealed film (see the line with solid square) obviously reveals that the lattice defects are partly removed.

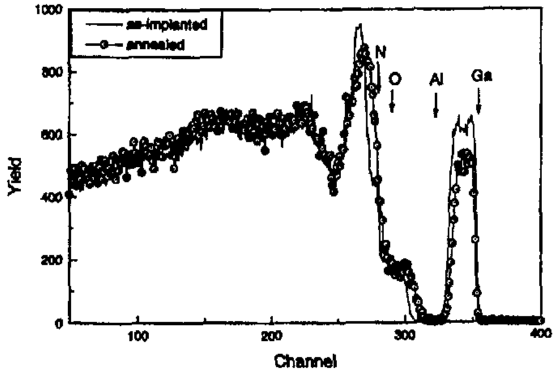

Fig.2 PL spectra that illustrate the GaN near band edge emission of the different films the as-grown GaN film (the solid line); the as-implanted GaN film (the open circle) and the annealed GaN film (the line with solid square). The PL is performed at RT with a He-Cd laser at 325 nm

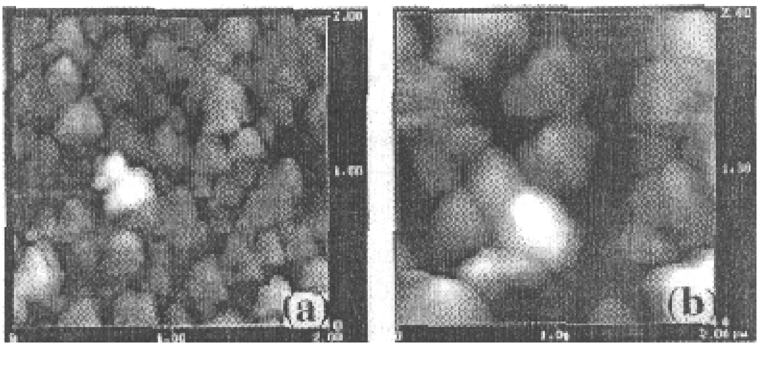

Fig.3 AFM images of GaN films
(a) the surface topography of the as-implanted GaN film; (b) the surface topography of the annealed GaN film

Moreover, AFM study of surface topography and roughness analysis supports the above views powerfully. The top-view AFM images of as-implanted and annealed GaN surface are shown in Fig.3(a) and 3(b), respectively. The root mean square (RMS) roughness for as-implanted is 2.0 nm, a little bit rougher than 1.6 nm for as-grown film, while the RMS roughness for the annealed GaN surface is ~60nm, much higher than that for the as-implanted. The result indicates that the implanted GaN surface was decomposed severely and recrystallized into big grains after annealing, though the high temperature annealing removes some radiation defects. This feature has been attributed to high defect mobility and high efficiency of GaN surface to trap migrating point defects.[10] These phenomena also have been observed in GaN bombarded with high energy ion at high dosage.[11,12]

4 CONCLUSION

In summary, the surface decomposition of GaN implanted with low energy (80 keV) Eu ion to a low dose of $1\times10^{14}\,\mathrm{cm}^{-2}$, and its annealing behavior under high temperature (1050°C) in N_2 were investigated. The Eu ion implantation produces surface damage, induces the decomposition and N deficiency in GaN, and the quenching of the near band edge emission at 368 nm. After annealing, lattice defects are partly removed. However the surface decomposition and loss of N are more serious. A Ga-rich layer is formed and the surface becomes very rough. This feature mostly ascribes to the trapping of migrating defects by GaN surface. The results reported here may have significant technological implications to the GaN device fabrication using keV ion implantation.

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