Extended Abstracts of the 2001 International Conference on Solid State Devices and Materials, Tokyo, 2001, pp. 358–359

E-6-2

N/Ge Co-Implantation into GaN for N-Type Doping

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1. Introduction

GaN is of increasing interest for high-temperature and high-power applications. Various electronic devices based on GaN have already been reported. For the design of the electronic devices, implantation doing of GaN has gradually gained practicality [1]. Several n- and p-type implantation into GaN has already been reported with the use of Si for n type and Mg and Ca for p type. It is theoretically expected that these dopants substituted on a Ga-lattice site in GaN have low formation energy and form donor or acceptor levels. However, in the case of conventional implantation, in which one kind of dopants is used, the generation of many N vacancies and the self-compensation induced by site-switching may occur in the implanted region during activation annealing. So, to suppress the generation of N vacancies, the N-rich condition needs to be created prior to implantation of the dopant atoms. Here, we propose sequential co-implantation of N atoms and the dopant, based on the site competition effect [2]. In this study, we have selected Ge as a new n-type dopant for GaN and investigated doping characteristics and structural defects in N/Ge co-implanted and subsequently annealed GaN.

2. Experimental

Epitaxial GaN films were 4μm thick, grown on a-plane sapphire substrates by MOCVD at 1025°C, with a 20nm GaN buffer layer grown at 550°C in advance. The GaN films were unintentionally doped, with a background n-type carrier concentration of ~$2x10^{16}cm^{-3}$ and a mobility of ~$500cm^2/Vs$. After growth, the GaN samples were implanted with a conventional ion implanter, using pure N_2 and GeF_4 gases as the sources of ^{14}N and ^{74}Ge species, respectively. Firstly N^+ ions were implanted at 35 keV to place the ion peak ~50nm from the surface. Then Ge^+ ions were implanted at 150keV to place the ion peak at the same position as N^+ one. Here, the implanted N and Ge dosages were varied from $2x10^{13}$ to $3x10^{15}cm^{-2}$ with keeping the N/Ge ratio ~1. After implantation, a 500nm SiO_2 layer was deposited at 250°C on the surface of the samples by PE-CVD to provide an encapsulation cap for activation annealing. All the samples were annealed at 1300°C for 5min in flowing H_2 under a pressure of 10Torr. HF was used to remove the SiO_2 cap and Al contacts were then formed at the corners of each sample by EB-evaporation. The Carrier activation was characterized by the room-temperature Hall effect measurements. The depth distribution of the implanted Ge atoms was measured by SIMS. The structure of the implanted region of the GaN samples was analyzed by cross-sectional TEM (XTEM). Variable energy positron annihilation spectroscopy (VE-PAS) was employed at room temperature to determine the depth distribution and species of defects in the implanted samples.

3. Results and Discussion

Figure 1 shows the room-temperature sheet carrier concentration and mobility versus implant Ge dosage for the N/Ge co-implanted and subsequently annealed GaN samples. It is found that the sheet carrier concentration increases monotonically with increasing Ge dosage. Especially, the higher Ge activation above 90% can be achieved even at the Ge dosage of $1x10^{15}cm^{-2}$. The mobility decreases gradually with increasing Ge dosage. This behavior is consistent with the variation in the sheet carrier concentration. Therefore, good doping characteristics of the Ge implant in GaN can be successfully achieved by the N/Ge co-implantation. For the conventional Ge implantation, however, the Ge activation was roughly estimated to be as low as 40% because of the insufficiency of N atoms from GaN stoichiometry.

Figure 2 shows XTEM images of the Ge- and N/Ge-implanted samples with the Ge dosage of $1x10^{15}cm^{-2}$ after annealing at 1300°C, respectively. In the conventional Ge-implanted sample, a dark band exists in the vicinity of ~40nm from the surface as shown in Fig.2(a). The position of this band is in good agreement with the distribution of the implanted Ge atoms measured by SIMS. So, this dark image corresponds to the crystal damage introduced by the Ge-implantation. Probably, the implantation-induced damage cannot be removed completely by annealing even at 1300°C, because N atoms are essentially insufficient in the implanted region in view of GaN stoichiometry. In contrast, no dark band can be observed in the N/Ge co-implanted GaN after annealing, as shown in Fig.2(b). This indicates that the damage introduced by the N/Ge co-implantation is entirely restored by annealing at 1300°C under the N-rich condition. Therefore, the N/Ge co-implantation is significantly effective in reconstructing GaN-lattice in the implanted region, resulting in an improvement in the crystallinity of the electrically activated region.

Figure 3 shows S parameter as a function of incident positron energy E for the Ge- and N/Ge-implanted GaN samples with the Ge dosage of $1x10^{15}cm^{-2}$ before and after annealing at 1300°C, respectively. As for the as-implanted GaN before annealing, little difference between the Ge and N/Ge implantation can be seen in the VE-PAS spectra of the implanted samples. The S parameter at E<50keV reflecting the characteristics of the GaN layer, however, increases largely as compared with that of the as-grown sample. In addition, the S parameter decreases gradually with increasing E for the as-implanted samples. This indicates that part of the Ga vacancies (V_{Ga}) [3] introduced in the implanted region diffuses into deeper region during the implantation. This long-range diffusion of the V_{Ga} may be related to dislocations characteristic of the heteroepitaxial GaN. As for the annealed GaN samples, no difference can be seen between the Ge and N/Ge implantation in the VE-PAS spectra. However, a marked difference in the VE-PAS spectra can be seen between the annealed and as-implanted samples. A striking peak with a much higher S parameter value of ~0.500 is detected at E of 0-4keV for both the Ge- and N/Ge-implanted samples. This higher S value indicates that the positron-electron momentum distribution is much narrower. Probably, the narrowing is due to positrons annihilating as trapped at a new type of vacancy defects. The depth range, corresponding to the 0-4keV range is found to be in good agreement with the implanted region. Therefore, this significant increase in the S parameter is associated with the electrical activation of the Ge dopant. That is, this is considered to be attributed to a vacancy complex between the V_{Ga} and the Ge dopant substituted on the Ga-lattice site [4], which is newly created by the activation annealing at 1300°C for both the Ge- and N/Ge-implanted samples.

4. Conclusion

We have demonstrated good doping characteristics with high Ge activation efficiencies of ~90% in the N/Ge co-implanted and subsequently annealed GaN for n-type doping. XTEM observations reveal that the implantation-induced damage is entirely recovered by activation annealing for the N/Ge co-implantation compared with the conventional Ge implantation process. However, VE-PAS measurements suggest the new creation of defect complexes between the V_{Ga} and the Ge-atom in the electrically activated region for both the Ge and N/Ge implantation.

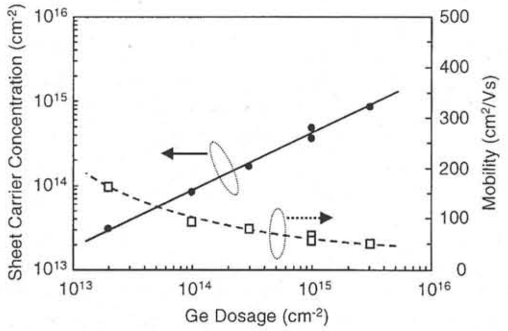

Fig. 1 The sheet carrier concentration and mobility as a function of implant Ge dosage for N/Ge co-implanted samples after annealing at 1300°C.

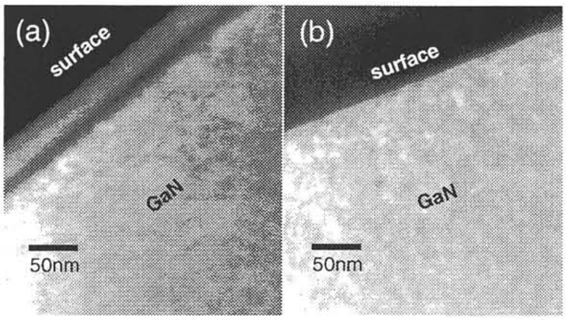

Fig.2 XTEM micrographs of (a) Ge- and (b) N/Ge-implanted GaN samples after annealing at 1300°C.

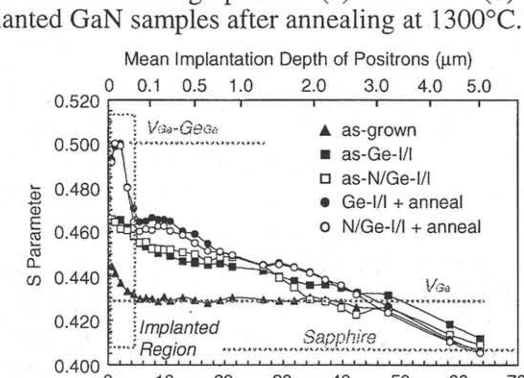

Fig.3 The S parameter as a function of incident positron energy for Ge- and N/Ge-implanted GaN samples before and after annealing at 1300°C.

References

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