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EVALUATION OF Mg-ION-IMPLANTED GaN LAYERS GROWN ON FREE-STANDING GaN SUBSTRATES

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Abstract

Mg ion implanted layers on free-standing GaN substrate were evaluated. Mg ions were implanted into n^--GaN layers at two different energies of 30 keV and 60 keV with total dose of 1.0×10^{14} cm^{-2}, followed by high temperature annealing at 1230 °C for 1 min in N_2 ambient. Evaluation of Photoluminescence (PL) spectroscopy and I-V measurements revealed that Mg-ion implanted layers consisted of uniform p-type crystalline area and localized crystal defects having n-type conduction.

KEYWORD: GaN, free-standing GaN substrate, Mg ion implantation

I. Introduction

Gallium Nitride (GaN) is suited for applications in high power, high frequency, and high temperature devices, because GaN has a wide band gap, a high breakdown electric field, a high saturation-drift velocity for electrons, and high thermal conductivity [1)]. A selective area doping technology, which is frequently used in processing silicon (Si) and silicon carbide (SiC) devices, is required for making high performance GaN devices. Ion implantation is usually used as a method of the selective area doping but formation of the p-type conductive layer by ion implantation has been difficult for GaN. Usually, GaN epitaxial layers are grown on the sapphire or SiC substrate. But those GaN epitaxial layers include large misfit-dislocation density over 10^8 cm^{-2}. We have reported the first evidence for p-type conversion of Mg-ion implanted n^--GaN layers supported by formation of device-quality p-n junction as a result [2)], which have been realized by using epitaxial layers grown on a high quality free-standing GaN substrate fabricated by void-assisted separation (VAS) method [3,4)]. In this paper, we demonstrate evaluation of Mg ion implanted p-type layers using I-V and optical characteristics measurements.

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II. Experiment

A 2.5-μm thick Si-doped GaN layer with electron concentrations about 1×10^{15} cm^{-3} was grown by metal-organic vapor phase epitaxy (MOVPE) on the free-standing GaN substrate with low dislocation densities in 10^6 cm^{-2} range. Prior to ion implantation, the surface of the substrate was coated with a 30-nm thick silicon nitride (SiN) film so that the maximum concentration of Mg atoms should be located at the interface between the SiN cap and the surface of the GaN layer. Mg ions were implanted into the GaN layers at two different energies of 30 keV and 60 keV with doses of 3.5×10^{13} cm^{-2} and 6.5×10^{13} cm^{-2} , as shown in Fig.1. After implanting Mg ions, 50-nm thick SiN film was deposited at the top and bottom of the substrate as annealing protection layer. The samples were then annealed at 1230 °C for 1 min in N_2 gas ambient. PL measurements were performed at 77 K with excitation by a He-Cd laser and PL mapping images were taken at room temperature. Vertical-structure p-n diodes were fabricated by depositing circular Pd electrodes (0.3-100 μm in diameter) on the surface of the Mg-implanted GaN layer and Ti/Al electrodes [5)] at the bottom of the GaN substrate.

III. Results and discussion

Forward-biased light emitting diode and room-temperature electroluminescence (EL) spectrum in our previous works were shown in Figs. 3 and 4. The light emitted from the diode was in the ultraviolet (UV) and blue-green regions. The results of the EL measurement indicated the occurrences of Mg related electron-acceptor (e-A) and donor-acceptor pair (DAP) recombination at about 3.1 eV [6)]. These results were the evidences of an p-n junction formed by Mg ion implantation.

Low temperature PL measurements were performed on the annealed samples for confirming activation of Mg ions. The PL spectrum indicated three main peaks of Mg related DAP [7, 8, 9)] recombination, acceptor bound exciton (ABE) [9)], and defects related yellow luminescence (YL), as shown in Fig.5. In addition, there are phonon replicas of ABE and DAP. This sharp spectrum suggests that high crystallinity is maintained after the annealing for the homo-epitaxial GaN layers on the free-standing GaN substrates.

Figure 6 shows room-temperature (RT) PL mapping image. The measured area was 300×300 μm^2. The local bright areas indicated lots of defects when the surface of as-annealed samples was viewed under the optical microscope. These areas were thought to be n-type GaN with donors of nitrogen vacancies formed by partial decomposition of GaN. Figure 7 shows PL spectrum taken at RT. This PL spectrum indicated donor-related ultraviolet luminescence (UVL) at about 3.26 eV [6)] and near-band edge (NBE) at about 3.39 eV. UVL emission was observed in the local bright areas. From these results, we considered that the local bright areas, as shown in Fig.6, indicated n-type conduction and other areas indicated p-type conduction.

The characteristics of the contact between Pd and Mg implanted layer were evaluated using transmission line method (TLM) test structure. Results are shown in Fig. 8, indicating non-Ohmic contact and back-to-back diode characteristics. Turn-on voltage of the diode was about 1.5 V. Figure 9 shows the I-V characteristics of the diode by fabricated Mg ion implantation. The diode has a turn-on voltage of about 5 V, which is higher than that made by epitaxially grown p-n junction diodes. To clarify the higher turn-on voltage, I-V characteristics were redrawn using vertical axes in logarithmic scale as shown in Fig. 10, indicating two turn-on voltages. The first turn-on voltage was thought to be due to n-GaN Schottky barrier diode (SBD2) with ideality factor n of about 3 having series resistance of about 400 k-ohm (R2). The second one was due to GaN p-n junction with non-Ohmic contact (SBD1) as described above. The series resistance connected to the p-n junction was estimated about 50 ohm (R1). From these results, Mg implanted layers are formed by both p-type and n-type conductive layers, which consist of non-uniform p-type crystalline areas including localized crystal defects having n-type conduction. An equivalent circuit model and the estimated structure of p-n junction fabricated by the Mg ion implanted layer with Pd electrodes are shown in Figs. 11 and 12. It is considered that initial current flows in the small area of n-type conductive layers at a low voltage, then large current flows in large area of p-type conductive layers at higher voltage.

IV. Conclusion

Mg implanted layers in n^--GaN grown on a high quality free-standing GaN substrate showed p-type conduction after high temperature annealing. Mg related DAP, UVL and phonon replica emissions were observed by low-temperature and room-temperature PL spectra. Forward bias I-V characteristics also showed two turn-on voltages caused by parallel conduction of n-GaN SBD and p-n junction diodes. These indicate that Mg implanted layers are formed by both p-type and n-type conductive layers. The implanted layers consist of non-uniform p-type crystalline areas including localized crystal defects having n-type conduction.

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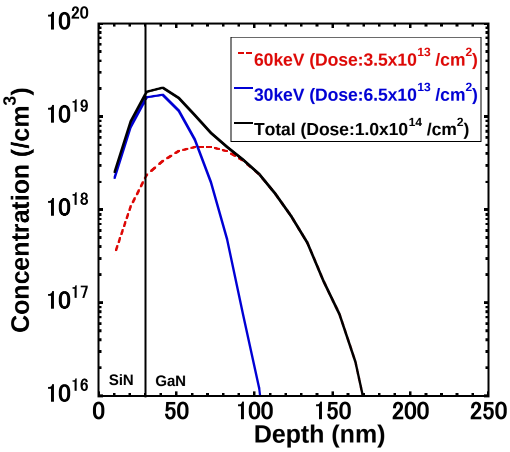


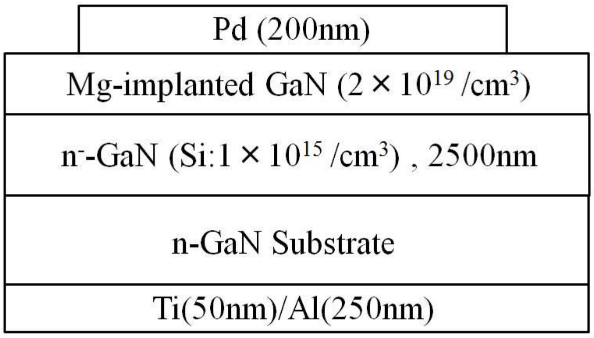
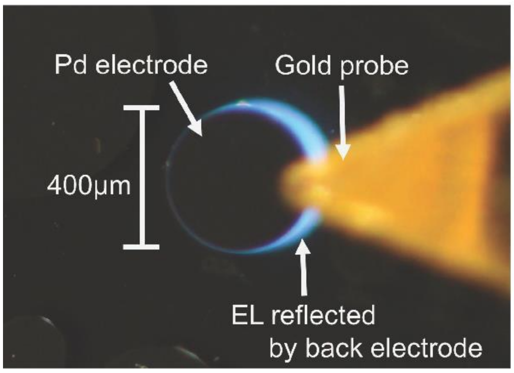


Fig. 1. Mg concentration profile from SRIM simulation.

Fig. 2. GaN p-n diode device structure.



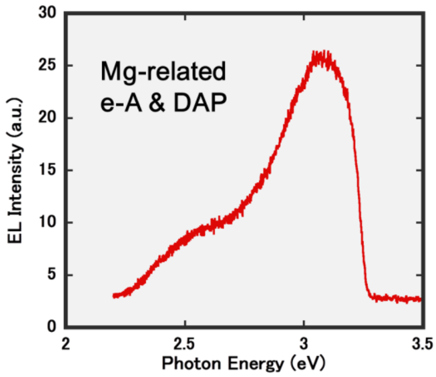
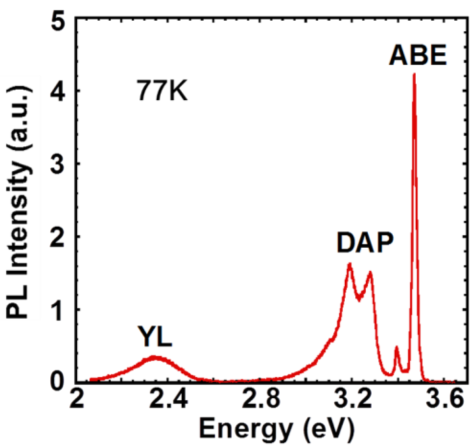


Fig. 3. Light-emitting diode fabricated by Mg ion implantation. The diameter of the electrode was 400 μm.

Fig.4. EL spectrum of the forward-biased diode.



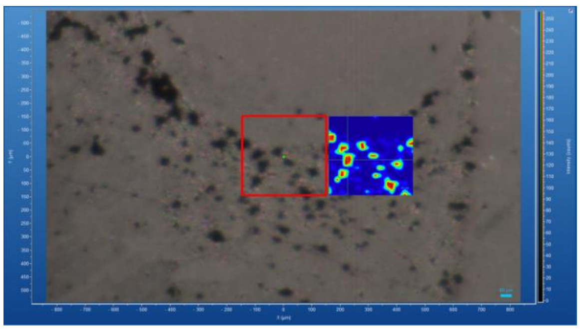


Fig.5. PL spectrum of Mg ion implanted n^--GaN layer at 77K.

Fig.6. PL mapping image of Mg ion implanted n^--GaN layer at room temperature.

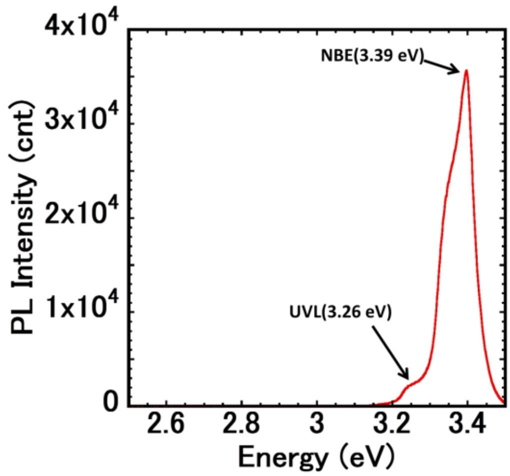


Fig.7. PL spectrum of Mg ion implanted n^--GaN layer at room temperature.

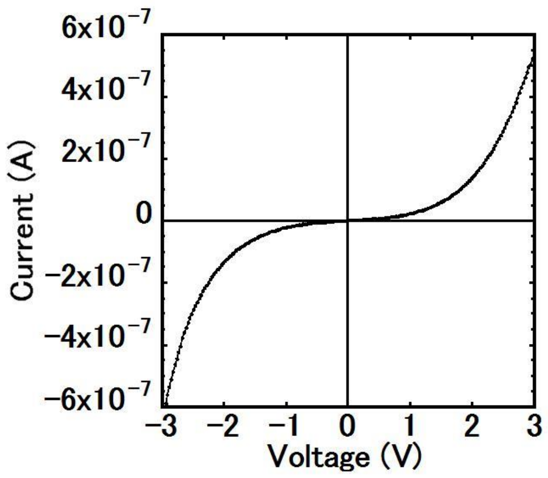


Fig.8. Pd electrode and p-GaN layer contact characteristics.

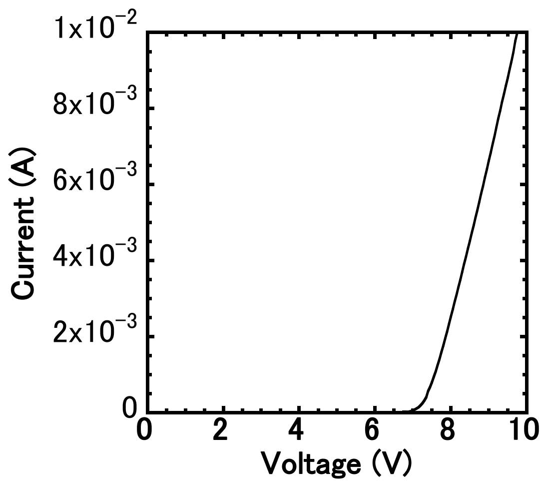


Fig.9. I-V characteristics of the GaN p-n diode.

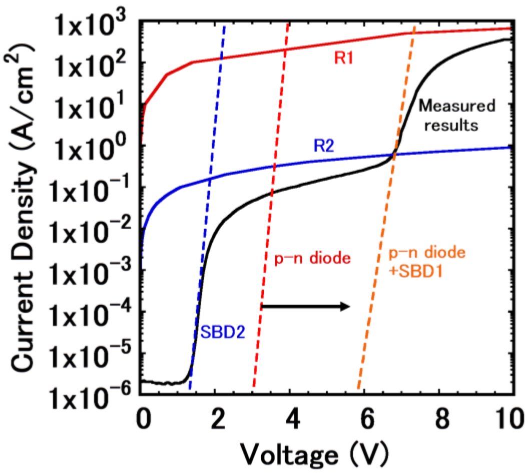


Fig.10. Log scale current density vs voltage graph of GaN p-n diode.

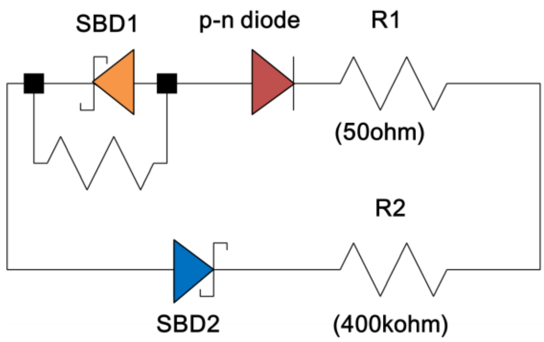


Fig.11. Equivalent circuit model of p-n junction by the Mg ion implanted layer with Pd electrodes.

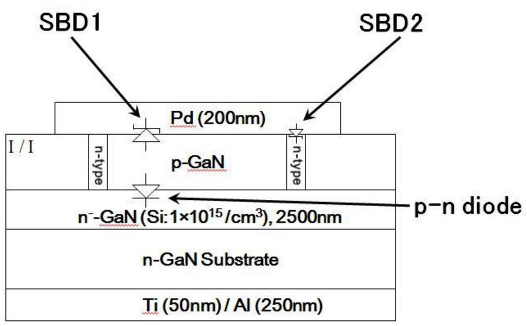


Fig.12. Estimated structure by the Mg ion implanted layer with Pd electrodes.