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Phosphorus Implantation Effects in Mg Doped GaN Epilayers

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1. Introduction

Impuritites determine the electrical, optical and many other properties of semiconductors. Mg is a widely used p-type impurity in GaN. However, hole concentration in p-GaN is still low due to the large ionization energy and self-compensation of Mg atoms [1]. Compared with single impurity doping, one can improve the doping efficiency by using co-doping technic. Peatron et al. [2] reported that the coimplantation of P with Mg under low dose conditions could effectively improve p-type GaN conductivity, which is attributed to the reduction of N vacancy and the enhanced Mg substitution. However, no relevant report on the optical properties have been documented. The co-existence of two kinds of impurities may render new luminescence centers in the host materials. Thus, it is important to thoroughly understand the optical characteristics of co-doping effect first before any attempt on finding plausible optical applications. In this study, we adopt ion implantation procedure for doping P into MOCVD grown Mg-doped GaN, because it can produce less implantation-induced damages than coimplantation method. It is also easier to incorporate P into GaN than the MOCVD process. We discuss the P implantation effects in Mg doped GaN such as electrical and optical properties by Hall effect and PL measurements.

2. Experiment

Prior to implantation, Mg-doped GaN samples are grown at 1000 ^{o}C by MOCVD on c-plane sapphire substrates. The sample structure is consist of a low-temperature buffer layer/ undoped layer/ Mg-doped layer with thicknesses of 30nm, 2μm, and 1μm, respectively. After growth, thermal annealing is performed at 700 ^{o}C for 20 min in N_2 ambient to obtain a low-resistivity p-type GaN. The Mg concentration as determined by SIMS is about 4×10^{19} cm^{-3}. Then, the Mg-doped GaN samples are implanted with P ions using multiple implantation technology to produce a uniform P concentration of 4×10^{16} cm^{-3} corresponding to P/Mg ratio of 0.001 (sample #1) with a depth of ~0.2μm. Different P doses are subsequently implanted by using the same method to produce uniform P concentrations corresponding to P/Mg ratios of 0.002 (sample #2), and 0.01 (sample #3). After implantation, samples are annealed in N_2 ambient at 1100 ^{o}C and 1200 ^{o}C for 10 s capped with an undoped GaN wafer in a face-to-face geometry.

3. Results and discussion

The resistivity, hole concentration, and mobility of Mg-doped GaN are 3 Ω-cm, 3×10^{17} cm^{-3}, and 7 cm^{2}/V-s, respectively. Table 1 shows the electrical characteristics for a series of the P implanted Mg-doped GaN samples. All of the P implanted samples after post-implantation annealing at 1100 ^{o}C show a lower hole concentration than the unimplanted Mg-doped GaN, probably due to the implantation-induced damages are not removed sufficiently at this annealing temperature. On the other hand, the hole concentration of the implanted samples after annealing at 1200 ^{o}C are obviously improved and increases as P/Mg ratio. This suggests such an annealing condition leads to a sufficient recovery of crystal quality. Furthermore, the additional P atoms can help to reduce self-compensation and to enhance Mg acceptors activtion for the highly Mg-doped GaN. The best hole concentration and activation efficiency are obtained to be 6.9×10^{17} cm^{-3} and ~1.7%, respectively, for the implanted sample with P/Mg=0.01 (sample #3) annealed at 1200 ^{o}C.

Figure 1 shows 10K PL spectra of the implanted samples #1, #2 and #3 annealed at 1200 ^{o}C. An unimplanted Mg-doped sample is also plotted for comparison. The Mg-doped sample shows a typical blue emission band caused by deep donor-acceptor pair (DDAP) at 2.92eV for highly doped self-compensated GaN [3]. For the implanted samples, it can be seen clearly that the intensity of blue emission band increases with the P/Mg ratio, which is attributed to a decrease in deep donors that results in the reduction of self-compensation and more recombination centers A^{-}. The PL characteristics are in agreement with the observed results by Hall effect measurements. Besides, the PL peak positions of these samples are also different. For sample #1 with low P/Mg ratio, the donor-acceptor (DAP) [3] emission at 3.27 eV followed by two LO phonon replicas with ~90 meV separation are the dominant peaks. This is reasonable because the reduction of deep donors as induced by implanted P atoms helps to enhance the recombination probability of the native shallow donors to Mg acceptors. As the P/Mg ratio increases, however, the PL signal of a new P-related transition at 3.24 eV becomes prominent.

Temperature dependent PL measurements are performed to identify the origin of the P-related transitions. Figure 2 shows PL spectra as a function of temperature for sample #3 after annealing at 1200 ^{o}C. The DAP peak at 3.27 eV shows blue shift while the P-related transitions at 3.24 eV and its phonon replica are red shifted as the temperature increases. The isoelectronic P atoms in GaN are expected to form the hole traps since the electronegativity of P (2.19) is smaller than that of the host N atom (3.04). If the isoelectronic P trap remains to be a stable charged state after trapping a hole, the trapped hole will recombine radiatively with an electron located at a distant donor to form a donor-isoelectronic trap pair (D-I pair), otherwise it will capture an electron in the conduction band and subsequently create a bound exciton. The D-I pair is different from the normal DAP recombination since the isoelectronic hole traps are neutral prior to the hole capture process, resulting in a red shift as the temperature increases [4]. Similar red shift has also been observed by Jadwisienczak and Lozykowski [5] from the P implanted GaN samples. They found that the D-I pair emission decreased with increasing temperature, but a blue emission band at 2.88 eV as result of the recombination of excitions bound to isoelectronic P traps, became dominant at high temperatures (i.e. > 150 K). Their results seem to imply that charged state of isoelectronic P traps tends to become unstable at high temperature, and through Coulomb interaction free electrons are captured in the end to form bound excitons. However, the related emission due to the excitons bound to isoelectronic P traps is not observed from our P implanted Mg-doped GaN samples even at room temperature. Such a result suggests that the isoelectronic P trap forms a stable charged state in P implanted Mg-doped GaN samples, which differs from those reported in P-doped GaN [5-7].

4. Conclusions

We have systematically studied P implantation effects on MOCVD grown Mg-doped GaN. It is found that the hole concentration can be increased due to the reduction of self-compensation by P atoms incorporation. Unlike the usual DAP emission peaks, the P-related transitions exhibit red shifts when the temperature is increased. The P-related emission is found to be associated with the recombination of electrons from the shallow native donors with holes previously captured in isoelectronic P traps. The PL study suggests that the isoelectronic P trap forms a stable charged state in the P implanted Mg-doped GaN

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Table 1 Implantation conditions and electrical characteristics for a series of the annealed P implanted Mg-doped GaN samples.

	Annealing Temp (°C)	Type	Resistivity (Ω-cm)	Mobility (cm^2/V s)	Carrier Conc. (cm^{-3})
Sample #1	1100	p	10.7	9.5	6.2×10^{16}
P/Mg = 0.001	1200	p	0.9	12.2	6.0×10^{17}
Sample #2	1100	p	5.8	9.0	1.2×10^{17}
P/Mg = 0.002	1200	p	0.8	12.0	6.4×10^{17}
Sample #3	1100	p	3.6	8.2	2.1×10^{17}
P/Mg = 0.01	1200	p	0.8	11.7	6.9×10^{17}

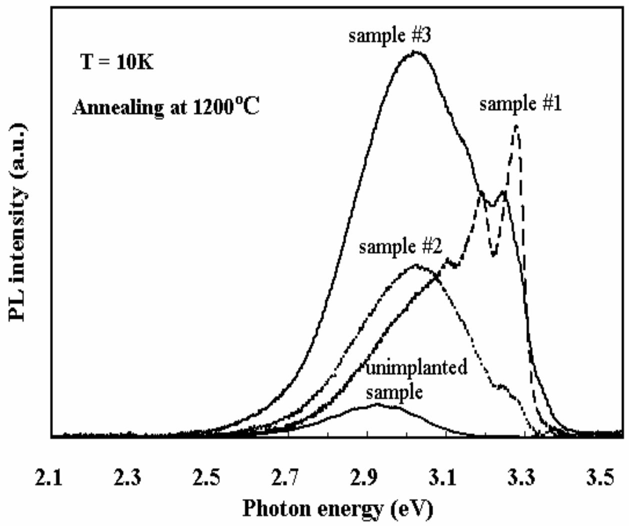

Fig. 1 PL spectra of the implanted samples #1, #2 and #3 annealed at 1200°C.

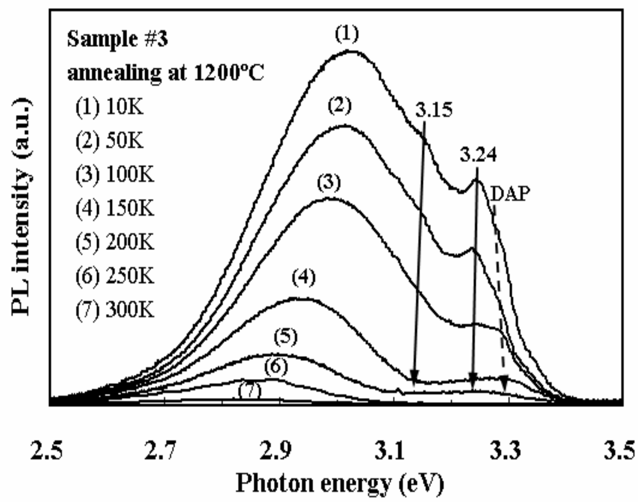

Fig. 2 Temperature dependence of PL spectra for sample #3 annealed at 1200°C.