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P6-9

# P-type doping for Be/C co-implantation in GaN

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Ion implantation is an enabling technology for selectively doping a large number of elements into certain areas within the sample with a precise control of dopant concentration and depth distribution. Efficient n-type doping in GaN has been proved can be obtained by implantation of Si donor [1]. In the case of p-type doping, where Mg is widely used as an acceptor, a large ionization energy and self-compensation resulting from implantation-induced N vacancies limit the number of holes even with high temperature post-implantation annealing process [1]. So far, only few successes in p-type GaN were achieved by ion implantation technique [1-3]. Beryllium is an attractive choice because of the low damage level it creates in GaN [4] and the theoretical evidence that it has a shallow acceptor level in GaN [5]. However, the problem associated with Be doping is that they tend to stay at interstitial sites ($Be_{int}$) acting as double donors to produce self-compensation [6]. It has been reported that co-doping with O atoms into Be-doped GaN improved the doping efficiency and established p-type conductivity [3]. On the other hand, Carbon doping in GaN is an interesting topic because it likely becomes a donor when incorporated on the Ga site ($C_{Ga}$), and an acceptor on the N site ($C_N$). It has been predicted that the incorporation of C on N site is preferred [7], but it is accompanied by efficient self-compensation of $C_N$ acceptors and $C_{Ga}$ donors [8, 9]. Considering that light C atom may introduce much less damage in the lattice than O atom. In this study, we have systematically investigated the Be+C co-implantation characteristics in GaN with different dopant concentration ratios. Co-doping effects such as electrical and optical properties were characterized by Hall and photoluminescence (PL) measurements.

The un-doped GaN samples used in this study were all grown by metalorganic chemical vapor deposition (MOCVD) on c-plane sapphire substrates. 2-μm-thick undoped layer was deposited at 1000°C right after the growth of a 30 nm low-temperature buffer layer at 550°C. After the growth, the un-doped GaN samples were co-implanted with Be+C using a multiple-step implantation technology. Multiple energy Be implants were first performed with total dose of $2.5\times10^{14}$ cm$^{-2}$ to produce uniform Be concentration of $5\times10^{18}$ cm$^{-3}$ with a depth of 0.5 μm. Different C doses were then implanted to produce uniform C concentrations corresponding to Be/C ratios of 1 and 2, respectively. After implantation, samples were annealed in $N_2$ ambient separately at 1100°C and 1200°C for 10s capped with an un-doped GaN wafer in a face-to-face geometry.

The as-grown GaN samples were high resistivity with the background electron concentrations of $3\sim5\times10^{16}$ cm$^{-3}$ at room temperature. Table 1 shows the electrical characteristics for a series of the implanted samples. Be- or C-implanted samples after post-annealing remained n-type conductivity, which could be attributed to the insufficient removal of implantation-induced N vacancies and $Be_{int}$ or $C_{Ga}$ donors overcompensated the acceptors. The similar examples were also observed by some research groups for their Be- or C-implanted GaN experiments [10, 11]. Compared with individual Be- and C-implantation, the Be+C co-implantation converted to p-type conductive characteristics for the sample co-implanted with a relatively lower C dose (Be/C = 2 sample) and 1100°C post-annealing. This result seemed reasonable since more defects tend to be introduced by the higher C dose implantation (Be/C = 1 sample) that overcompensate the activated acceptors. Besides, the excessive annealing treatments could lead to dopants out-diffusion resulting in high resistivity for Be/C = 2 co-implanted sample annealed at 1200°C, in spite of the identical Be/C dose ratios for both samples. The origin of the improved activation efficiency can be considered into two possibilities. One is the C atom probably acts as a donor in our samples, so that co-doping with $C_{Ga}$ donors and Be acceptors will increase the interaction of both types of impurity which can result in a reduction of impurity energy level and an increase in the state density near the band edge. Another possibility is that the implanting additional C atoms occupy on N vacancy sites caused by Be-implantation and enhance both Be and $C_N$ acceptors substitutions. The outcomes of which would increase the activation efficiency and solubility of impurities, and eventually achieve p-type conductive characteristics for the Be/C = 2 co-implanted sample after an appropriate annealing treatment.

Figure 1 shows 10K PL spectra of Be, C and Be/C = 2 implanted samples after annealing at 1100°C. An un-doped GaN sample was also plotted for comparison. The PL spectrum of un-doped sample have shown a strong exciton bound to neutral donor peak ($I_2$) line at 3.47 eV and donor-acceptor pair (DAP) transitions caused by the contamination of C impurity at 3.28 eV followed by two phonon replicas with ~90 meV separation [12]. For the

Be-implanted sample, a weak blue emission band at 2.9 eV was observed. The origin of the observed blue emission is less well understood. It was probably due to the deep donor-acceptor pair (DDAP) recombination involving deep donor and shallow acceptor for a typical highly self-compensated semiconductor [13]. In addition, the Be implantation has resulted a large enhancement of a broad yellow band (YB) transition centered around 2.35 eV, which indicates a poor Be activation [14]. Similar YB transition was also observed for C-implanted GaN sample as shown in Fig. 1. Ogino and Aoki [15] have reported that doping with C enhances YB of GaN, which is attributed to a transition between a shallow donor and a deep acceptor complex involving C and a native defect. On the other hand, the Be/C = 2 co-implanted p-type sample exhibited that the YB vanishes and the new PL peaks appear at 3.35, 3.32, 3.23 and 3.14 eV. The 3.35 eV emission line was probably due to the localized excitons bound by some deep centers [16]. We believe these new PL peaks at 3.32, 3.23 and 3.14 eV were attributed to acceptor-related DAP and its LO phonon replicas which were related to the C atoms either substituting the Ga sites or filling into the N vacancy sites that help to enhance the activation efficiency of acceptors. The PL characteristics were in agreement with the observed results by Hall measurements. The optical activation energy of acceptor was estimated to be 155 meV by setting Coloumb interaction $E_C \sim 0$, the shallow donor activation energy of 30meV and energy gap of 3.505 eV for $T = 0$K. The exact nature of acceptor is not fully understood for our Be+C co-implanted GaN. However, it is possibly assigned to Be-related rather than C-related acceptors because the value of optical activation energy is very close to that reported for Be-implanted GaN (150 meV) [14] in contrast to that of C-doped GaN (230 meV) [12].

In conclusion, C co-implanting with Be atoms in GaN contributed to p-type conductive characteristics, which were essentially related to the Be/C dopant concentration ratio and annealing condition. These results believably were attributed to either co-doping with donors and acceptors or the decrease of N vacancies enhanced the activation efficiency of acceptors. The observed PL results have confirmed the Be as a shallow-level acceptor in GaN and have also shown the possibility of p-type doping by Be+C co-implantation. The activation efficiency of Be acceptor is still very low, more research works still need to be done in order to improve p-type conductivity.

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Table 1. Electrical characteristics. * : total dose of $1.25\times10^{14}$ $cm^{-2}$ corresponding with Be/C = 2 dose.

| | Annealing Temp (°C) | Type | Mobility ($cm^2$/Vs) | Carrier Conc. ($cm^{-3}$) |
|---|---|---|---|---|
| C * | 1100 | n | 160.0 | $6.7\times10^{17}$ |
| | 1200 | n | 167.0 | $5.6\times10^{17}$ |
| Be | 1100 | n | 68.6 | $4.7\times10^{16}$ |
| | 1200 | n | 65.7 | $7.8\times10^{16}$ |
| Be/C=1 | 1100 | high resistivity | | |
| | 1200 | high resistivity | | |
| Be/C=2 | 1100 | p | 4.6 | $8.0\times10^{16}$ |
| | 1200 | high resistivity | | |

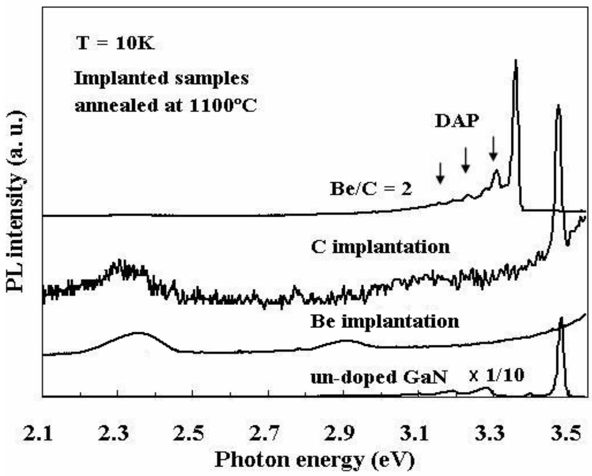


Fig. 1 10K PL spectra of the Be, C and Be/C = 2 implanted GaN samples annealed at 1100°C. C dose is consistent with that of Be/C = 2 sample.