Electrical characterization of acceptor levels in Be-implanted GaN

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We have investigated electrically the acceptor levels that are present in Be-implanted GaN. Slight p-type conductivity was attained in undoped GaN films by Be implantation and subsequent annealing at 1050 °C with a SiO$_2$ encapsulation layer. Capacitance-frequency measurements showed a typical dispersion effect characteristic of deep acceptors in fabricated Schottky diodes. Thermal admittance spectroscopy measurements revealed a discrete deep level located at ~231 meV above the valence band. This energy level is in reasonable agreement with the frequency dependence of the capacitance in view of the impurity transition frequency. Therefore, this energy level can most probably be assigned to a Be-related deep acceptor. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1523633]

GaN is of increasing interest for high-temperature and high-power electronic devices.[1–3] In order to facilitate the design of these electronic devices, especially from a selective-area doping point of view, both n- and p-type implantation-doping technologies are considered as being essential. Si is generally used as a shallow n-type dopant for GaN, while shallow p-type dopants do not exist because GaN has a relatively small permittivity of ~9. Thus, acceptor doping has long been a serious problem for both GaN materials and device fabrication. The most commonly used p-type dopant is Mg, which has an ionization energy of 150–200 meV above the valence band.[4–7] In the case of Mg implantation doping, however, it is very difficult to achieve p-type conductivity at room temperature, because implantation-induced damage may easily compensate the holes generated from Mg acceptors due to its heavy ion mass in addition to their deep acceptor levels.[8,9] On the other hand, Be is expected theoretically to be a more promising candidate for p-type doping since its ionization energy is calculated to be ~60 meV when residing on Ga-lattice sites in wurtzite GaN.[10,11] Additionally, the light Be atoms can be implanted deeper into GaN for a given implantation energy, and they cause less damage in the GaN lattice than Mg atoms.

So far, Be-doped GaN (GaN:Be) films have only been grown by molecular beam epitaxy (MBE).[12,13] Recently, some data on Be acceptors have been reported; Salvador *et al.*[13] have obtained an ionization energy of about 250 meV from photoluminescence (PL) measurements of GaN:Be samples grown by MBE. Ronning *et al.*[14] have reported that isolated Be has the most shallow acceptor level, with an ionization energy of 150±10 meV from PL measurements of Be-implanted GaN samples. Clearly the literature does not provide a coherent value for these acceptor levels. In addition, no electrical characterization of the acceptor levels associated with Be doping has been reported, and the acceptor levels are an important parameter in improving the perfor-

mance of the p-type doping process. Thus, various investigations need to be performed to determine the Be acceptor levels by using electrical and optical characterization techniques. In this study, we report the electrical characterization of Be-implanted GaN by using a thermal admittance spectroscopy (TAS) technique in order to detect the electronic states associated with Be doping.

The epitaxial GaN films used in these experiments were 1 μm thick. They were grown on a-plane sapphire substrates by atmospheric pressure metalorganic chemical-vapor deposition (MOCVD) at 1050 °C, with a predeposited 20 nm AlN buffer layer grown at 400 °C. The GaN films were not intentionally doped, with a background n-type carrier concentration of ~5×10^{15} cm^{-3}. Prior to the Be implantation, a 300 nm thick SiO$_2$ layer was deposited on the top surface of the samples by radio-frequency (rf) sputtering in order to reduce the implantation-induced damage. Then, multiple step Be implantation was performed using pure Be metal as the source of the ^{9}Be species. The ^{9}Be ions were implanted at 150, 100, and 80 keV with dosages of 2.3×10^{14}, 6×10^{13}, and 6×10^{13} cm^{-2}, respectively, to produce a mean Be concentration of 1×10^{19} cm^{-3} to a depth of ~0.3 μm. As a reference, an N-implanted GaN sample was also prepared with a mean N concentration of 1×10^{19} cm^{-3} (depth $=0.3$ μm). All of the implants were carried out at room temperature, with an incident angle 7° off the surface normal. After implantation, the SiO$_2$ layer was removed and then a 500 nm thick SiO$_2$ capping layer was again deposited on the top surface of the implanted samples by rf sputtering at room temperature to provide an encapsulation cap for the subsequent implant activation annealing. All of the samples were annealed in a SiC-coated graphite susceptor at 1050 °C for 5 min in flowing H$_2$ gas at a pressure of 10 Torr. Following the annealing step, HF was used to remove the SiO$_2$ cap. The depth distribution of the implanted Be atoms was measured by secondary ion mass spectrometry (SIMS). The carrier type of the Be-implanted samples could not be determined by room-temperature Hall-effect measurements because of poor data caused by extremely small Hall volt-

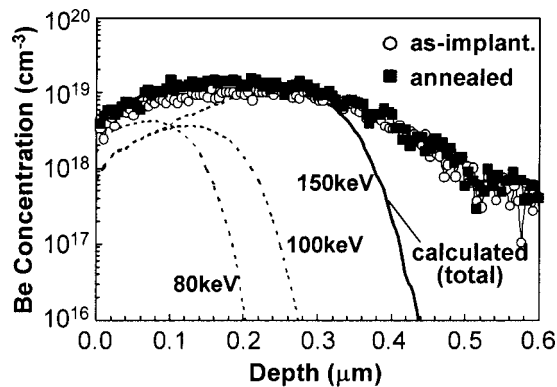[a]Electronic mail: y-nakano@mosk.tytlabs.co.jp

FIG. 1. TRIM simulated atomic profiles of implanted Be (solid line) and SIMS profiles of Be implanted in GaN, as implanted (○) and annealed (■) at 1050 °C.
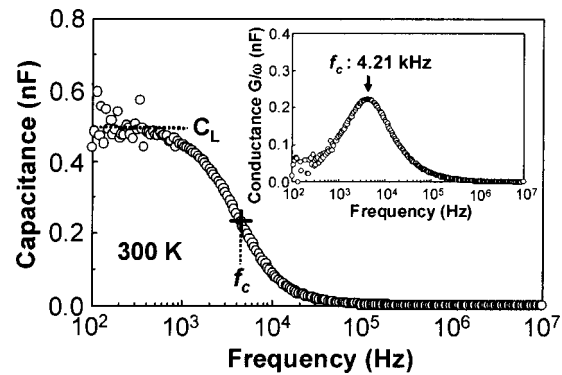

FIG. 2. Room-temperature frequency dependence of capacitance for Be-implanted GaN after annealing at 1050 °C. The inset shows the frequency dependence of conductance at room temperature.

ages, as is the case for p-type GaN in general. Instead, electrical measurements were conducted on lateral dot-and-ring Schottky diodes fabricated as follows. First, ohmic contacts were deposited by Ni evaporation and subsequent annealing at 500 °C for 30 min in flowing N_2. Then Pt was evaporated to form the Schottky contacts. The dot Pt electrode had a diameter of 500 μm, and was surrounded by a ring Ni electrode with a 1 mm gap. The area of the ring electrode was 100 times greater than that of the dot electrode. From current–voltage ($I–V$) measurements at room temperature in the dark, the Be-implanted sample showed the rectifying characteristics of a p-type Schottky diode, while the N-implanted sample displayed the characteristics of an n-type Schottky diode in the same way as the as-grown GaN before implantation. Capacitance–frequency ($C–f$), conductance–frequency ($G/\omega–f$), and capacitance–voltage ($C–V$) measurements were performed at room temperature in the dark with an ac modulation level of 30 mV and frequencies ranging from 100 Hz to 10 MHz. TAS measurements were conducted in the dark at an ac modulation level of 30 mV and frequencies ranging from 100 Hz to 30 kHz, covering the temperature range from 85 to 475 K.

Figure 1 shows SIMS profiles of the implanted Be atoms both before and after annealing at 1050 °C, together with Be atomic profiles calculated by the transport of ions in matter software (TRIM). There is little Be redistribution caused by the implant activation annealing, indicating the thermal stability of the implanted Be atoms in GaN. From this result, it is expected that diffusion of Be atoms into GaN from an external source is not practical and that ion implantation will be required if we wish to introduce Be atoms into GaN with a view to selective area doping. The mean Be concentration to a depth of ~0.3 μm is about 1×10^{19} cm^{-3}, a value that is in reasonable agreement with that of the TRIM calculation. The tails apparent on the bulk side of the experimental Be profiles may be caused by the high background due to the high resistivity of the Be-implanted samples.

Figure 2 shows room temperature $C–f$ and $G/\omega–f$ curves at zero dc bias for a Schottky diode based on the Be-implanted GaN after annealing at 1050 °C. The capacitance is seen to be strongly frequency dependent, as shown by the $C–f$ curve. The capacitance is reduced at frequencies higher than 1 kHz. This variation in capacitance is most likely to be due to a typical dispersion effect that occurs

when a deep level is unable to follow the high-frequency voltage modulation and contributes to the net space charge in the depletion region.[6,7] In addition, the N-implanted GaN sample showed frequency independence of capacitance and maintained low values. These results indicate that the deep level observed in the Be-implanted sample may be associated with Be doping. That is, the Be-related level could act simultaneously as a deep impurity and as a dopant. Depending on frequency, there is a competition between the deep impurity and the dopant character. The low frequency capacitance C_L of ~0.5 nF is determined by the carrier exchange between the Be-related impurity level and the valence band, reflecting the electrical activity of the implanted Be atoms, whereas above the capacitance cutoff frequency f_c (impurity transition frequency), the hole modulation of the depletion layer edge governs the electrical response. Considering that the conductance G/ω presents a peak at the f_c, the characteristic frequency f_c is estimated to be ~4.2 kHz, as shown in the inset of Fig. 2. From these $C–f$ and $G/\omega–f$ data, meaningful $C–V$ measurements need to be performed at frequencies lower than the f_c.

Figure 3 shows room-temperature $1/C^2–V$ plots at a frequency of 1 kHz for a Schottky diode fabricated on the Be-implanted GaN. From the slope of these plots, the effective acceptor concentration is estimated to be ~1.2 $\times 10^{17}$ cm^{-3}, which seems to be distributed almost uniformly over the depth of the capacitance measurement. Here, this value obtained at 1 kHz implies the net acceptor concentration ($N_a - N_d$) rather than the hole concentration. This effective acceptor concentration is much smaller than the Be
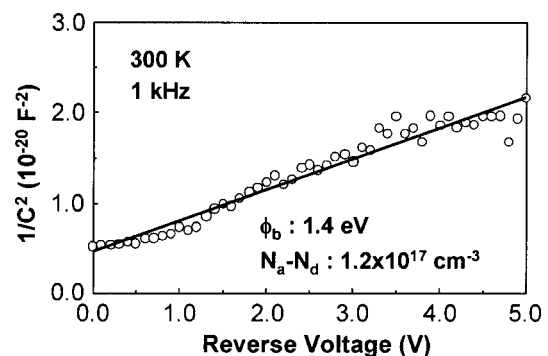

FIG. 3. Room-temperature capacitance–voltage characteristics at a frequency of 1 kHz for Be-implanted GaN after annealing at 1050 °C.
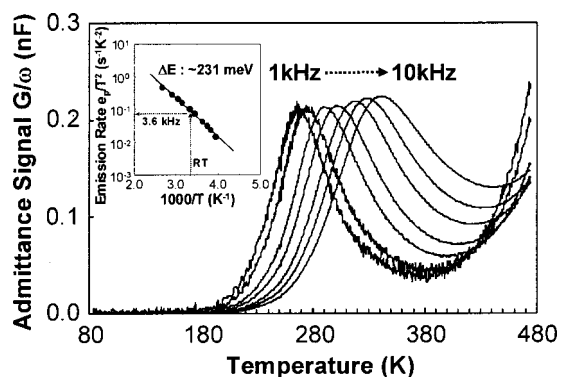
FIG. 4. TAS spectra at various frequencies between 1 and 10 kHz for Be-implanted GaN after annealing at 1050 °C. The inset shows Arrhenius plots of the hole emission rate, e_p/T^2.

concentration determined by the SIMS measurements. This indicates that the implanted Be atoms are slightly activated by annealing at 1050 °C. By extrapolating the line fitted to the $1/C^2-V$ plots to the voltage axis as shown in Fig. 3, the barrier height ϕ_b of the fabricated Pt-Schottky diode is estimated to be ~1.4 eV.

Figure 4 shows typical TAS spectra measured for the Schottky diode fabricated on Be-implanted GaN under zero dc bias. A dominant peak can be clearly seen in the spectra. This peak shifts to higher temperatures with increasing measurement frequency. Thus, this peak is assigned to a deep level. By contrast, no TAS peaks could be detected in the N-implanted GaN sample. This result implies that the deep level observed in the Be-implanted sample is not related to implantation-induced defects, because N implantation should introduce at least as much damage into the GaN as Be implantation due to its heavier ion mass. Additionally, the damage introduced by N implantation has also previously been reported to be entirely restored by high-temperature annealing.[15,16] Therefore, this deep level detected in the Be-implanted GaN is considered to be associated with the Be doping. Arrhenius analysis for the hole emission rate e_p/T^2 of the corresponding level yields an activation energy of ~231 meV for hole emission into the valence band, as shown in the inset of Fig. 4. Here, the data were analyzed under the assumption of a temperature-independent cross section. The characteristic frequency corresponding to this energy level at room temperature (300 K) is calculated to be ~3.6 kHz, which can be extracted from a line fitted to the Arrhenius plots, as shown in the inset of Fig. 4. This frequency is found to be in reasonable agreement with the f_c of ~4.2 kHz estimated from the room temperature $C-f$ and $G/\omega-f$ curves in Fig. 2. Therefore, this energy level should be assigned to the Be-related acceptor level. In addition, it makes no sense to suggest that hydrogen penetrates the thick encapsulation cap during annealing. Thus, this energy level is probably associated with isolated Be atoms rather than Be–H complexes.

This acceptor level seems to be in agreement with the value of 250 meV reported by Salvador et al.,[13] but it is apparently much deeper than the theoretically expected value of ~60 meV when Be atoms only reside at Ga-lattice sites in GaN.[10] Thus, this deepening of the activation energy for the Be acceptor may be associated with imperfect incorporation of the implanted Be atoms, which results in the slight electrical activation. Therefore, some coimplantation technique based on a site-competition effect may be effective in enhancing the electrical activation of the implanted Be atoms.[8,15,17,18]

In summary, the acceptor levels of Be-implanted and subsequently annealed GaN have been investigated electrically. TAS measurements revealed a dominant deep level with an activation energy of ~231 meV from the valence band, which is in reasonable agreement with the frequency dependence of capacitance and conductance in view of the impurity transition frequency at room temperature. Therefore, this energy level is most probably associated with a Be-related deep acceptor.

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