Electrical characterization of acceptor levels in Mg-doped GaN

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Thermal admittance and current deep-level transient spectroscopy techniques have been applied to Schottky diodes fabricated on Mg-doped GaN grown by metalorganic chemical vapor deposition to investigate the dependence of the Mg acceptor levels on the annealing temperature. Both measurement techniques revealed two deep acceptor levels with activation energies at ~135 and ~160 meV above the valence band. The former level was only seen when the samples were annealed at temperatures between 650 and 700 °C, and its presence corresponds with a significant increase in effective acceptor concentration, as confirmed by capacitance–voltage measurements. Therefore, this acceptor level is considered to dominate the electrical activation of Mg in GaN.
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In GaN materials and device fabrication, acceptor doping has long been a serious problem. So far, Mg is the dopant most commonly used to generate *p*-type conductivity in GaN grown by metalorganic chemical vapor deposition (MOCVD).[1,2] The acceptor levels of Mg become an important parameter in improving the performance of the doping process. Many investigations have determined that the thermal activation energy of Mg acceptors is between 120 and 250 meV by using various characterization techniques such as the Hall-effect, thermal admittance spectroscopy (TAS), and current deep-level transient spectroscopy (*I*-DLTS) measurements.[3–13] The wide range of measured data for the Mg acceptor levels may be caused by the inconsistencies in the activation conditions and/or the Mg doping concentrations in GaN:Mg. In this study, we have focused on the annealing temperature used for thermal activation of the Mg dopant and systematically investigated the acceptor levels associated with Mg doping from the viewpoint of annealing temperature by using TAS and *I*-DLTS techniques.

The epitaxial GaN:Mg films used in this study were 1.6 μm thick. They were grown on *c*-plane sapphire substrates by atmospheric pressure MOCVD at 1025 °C, on a predeposited 20 nm AlN buffer layer grown at 400 °C. Hydrogen was used both as the main process gas and as the carrier gas for metal alkyls. Trimethylgallium (TMGa), ammonia, and biscyclopentadienyl magnesium (Cp_2Mg), respectively, were used as the sources of Ga, N, and Mg. The Mg concentration of the as-grown GaN:Mg layers was determined to be $\sim 4.7\times 10^{18}$ cm^{-3} by secondary ion mass spectrometry (SIMS) measurements. After growth, activation annealing was performed systematically at temperatures between 600 and 850 °C for 10 min in flowing N_2. The annealing temperatures used for typical samples, numbered 1–6, are summarized in Table I, together with their electrical data. Electrical characterization of the acceptor levels in GaN:Mg was conducted on the lateral dot-and-ring Pt-Schottky diodes, which were fabricated as follows.[13] First, ohmic contacts were made 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 has a diameter of 500 μm, surrounded by a ring Ni-electrode, separated by 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, good rectifier characteristics were confirmed for the *p*-type Schottky diode under all of the annealing conditions that we used. Capacitance–frequency ($C-f$), conductance–frequency ($G/\omega-f$), and capacitance–voltage ($C-V$) measurements were performed at room temperature with an ac modulation level of 30 mV and frequencies ranging from 100 Hz to 10 MHz. TAS measurements were conducted at an ac modulation level of 30 mV and frequencies ranging from 100 Hz to 30 kHz, covering the temperature range from 85 to 320 K. *I*-DLTS measurements were also carried out over a temperature range from 85 to 320 K. The steady-state reverse bias and filling pulse voltages were −3 and 1 V, respectively. The width of the filling pulse was 1 ms, which ensured that even those traps with very small hole capture cross sections were completely saturated.

Figure 1 shows room-temperature $C-f$ curves at zero dc bias for the Schottky diodes based on the GaN:Mg samples (samples 1–6) annealed at various temperatures. A typical dispersion effect characteristic of deep Mg acceptors is observed under all the annealing conditions.[4,13] Depending on frequency, there is competition between the deep impurity and the dopant character. Here, the low-frequency capacitance C_L is determined by the carrier exchange between the Mg-related impurity level and the valence band, reflecting the electrical activity of the Mg dopant, whereas above the capacitance cutoff frequency f_c (impurity transition frequency), the hole modulation of the depletion layer edge, governs the electrical response. Sample 1 shows a small f_c of ~1.9 kHz and a small C_L of ~0.35 nF, which indicates that

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TABLE I. Annealing-temperture dependence of acceptor concentration studied by the room-temperature $C-V$ measurements for the GaN:Mg samples.

Sample	Annealing temperature (°C)	Acceptor concentration N_A-N_D (10^{18} cm^{-3})
1	600	0.2
2	650	2.8
3	700	4.0
4	750	2.6
5	800	2.2
6	850	13.9

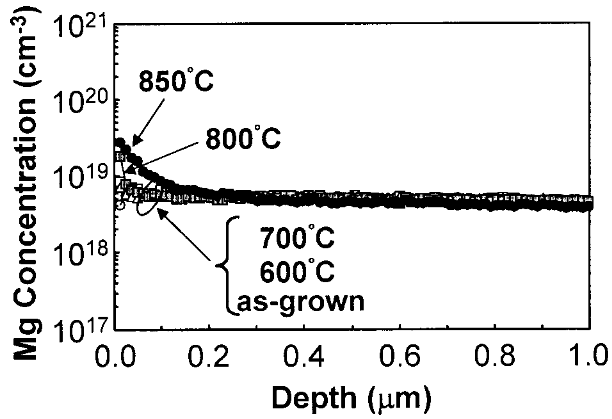

FIG. 2. SIMS profiles of Mg in GaN:Mg samples, as grown and annealed at various temperatures.

annealing at 600 °C only slightly activates the Mg dopant. In sharp contrast, a significant increase in f_c is seen in addition to a large increase in C_L for samples 2 and 3. This result suggests that the electrical activity of Mg is significantly improved by annealing at 650 and 700 °C. More importantly, an interesting behavior is observed in the high-frequency region of the $C-f$ and $G/\omega-f$ curves for these samples. Considering that the conductance G/ω presents a peak in the f_c, higher-frequency component peaks can be seen as shoulders at ~331.6 and ~400.7 kHz, apart from the main peaks at around 30 kHz, in the $G/\omega-f$ curves for these samples, as shown in the inset of Fig. 1. This indicates that shallower acceptor levels may be newly formed by annealing at 650 and 700 °C. Furthermore, decreases in f_c and C_L are seen in accordance with the disappearance of the higher-frequency component peaks for the samples annealed at 750 and 800 °C (samples 4 and 5).

From the $C-f$ data, meaningful $C-V$ measurements need to be performed at lower frequencies. Thus, effective acceptor concentrations (N_a-N_d) were estimated from the $1/C^2-V$ plots at 1 kHz, as shown in Table I. The annealing-temperature dependence of the acceptor concentration is in good agreement with the variation in C_L from the $C-f$ curves, as mentioned above. In particular, the acceptor concentration of sample 3 is in reasonable accord with the Mg concentration determined by the SIMS measurements, indicating that the activation annealing at around 700 °C significantly enhances the electrical activation rate of the Mg dopant. Furthermore, the acceptor concentration is uniformly distributed over the depth of the capacitance measurements for the samples annealed at temperatures below 800 °C (samples 1–5), whereas the concentration becomes very high for the sample annealed at 850 °C (sample 6). From the SIMS measurements, we can see that Mg diffuses out towards the near-surface region (~200 nm from the surface) when annealed at 850 °C, as shown in Fig. 2. This segregation phenomenon of the Mg dopant starts to occur when the annealing temperature is around 800 °C.

Figures 3(a) and 3(b), respectively, show a typical series of TAS and I-DLTS spectra for the Schottky diodes based on the GaN:Mg samples (samples 1–6) annealed at various temperatures. Both spectra yield identical information about the deep acceptor levels in GaN:Mg. Depending on the annealing temperature, both spectra reveal three kinds of peaks, which are denoted by A_0, A_1, and A_2. These peaks shift towards higher temperatures with an increasing hole emission rate, which can be calculated from the measurement frequency and the rate window t_1/t_2 for the TAS and the I-DLTS measurements, respectively.[13] This implies that these peaks are assigned to deep acceptor levels associated with

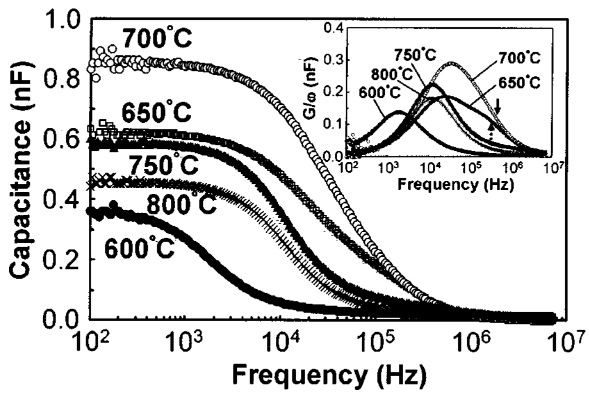

FIG. 1. Room-temperature frequency dependence of the capacitance for the fabricated Schottky diodes based on the GaN:Mg samples annealed at various temperatures. Inset shows the frequency dependence of the conductance G/ω at room temperature.

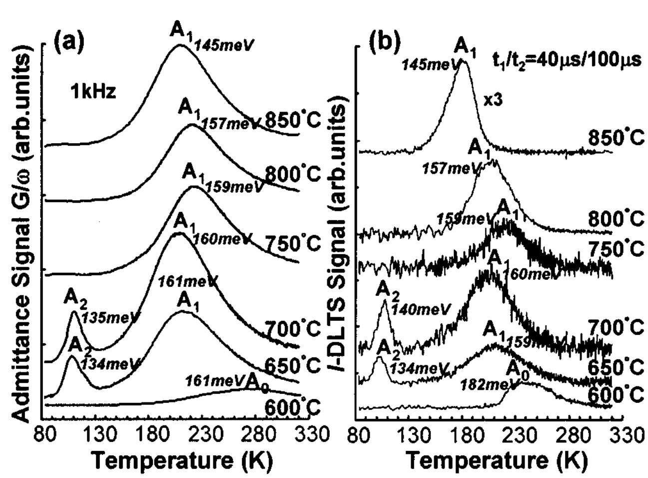

FIG. 3. (a) TAS spectra at a frequency of 1 kHz and (b) I-DLTS spectra at rate windows t_1/t_2 of 40 μs/100 μs for the fabricated Schottky diodes based on the GaN:Mg samples annealed at various temperatures.

the Mg dopant. The thermal activation energies for hole emission into the valence band were estimated from Arrhenius plots of hole emission rate e_p/T^2 for the corresponding level in the both spectra. Here, the data were analyzed under the assumption of a temperature-independent cross section. The data obtained from the TAS measurements were very close to those for the *I*-DLTS measurements. For the sample annealed at 600 °C (sample 1), the weak, broad peak A_0 is detected, corresponding to a deep acceptor level of Mg with a thermal activation energy of ~161 meV above the valence band. This acceptor level has a much smaller cross section than the other acceptor levels (A_1 and A_2), which indicates that the A_0 level probably occurs in the early stage of Mg acceptor formation, resulting in only a slight electrical activation of the Mg dopant, as mentioned above. For the samples annealed at 650 and 700 °C (samples 2 and 3), the two peaks A_1 and A_2 are observed, which are clearly different from the first peak A_0. The thermal activation energies for acceptor levels A_1 and A_2 are ~160 and ~135 meV from the valence band, respectively. These values are consistent with the values reported in the literature.[4,9,10] Moreover, the A_2 peak is seen to disappear from both of the spectra by annealing at 750 °C (sample 4). By combining these results with the $C-f$, $G/\omega-f$, and $C-V$ data, the presence of the A_2 level seems to be related to the large increases in f_c and the effective acceptor concentration, as mentioned above. In particular, the A_2 level probably corresponds to the higher-frequency component peaks observed in the $G/\omega-f$ curves for the samples annealed at 650 and 700 °C (samples 2 and 3). Thus, the shallower A_2 level is most likely to dominate the improvement in the electrical activity of Mg in GaN:Mg.[9] Furthermore, the thermal activation energy of the A_1 level is found to decrease from ~160 to ~145 meV with increasing annealing temperature from 750 up to 850 °C (samples 4, 5, and 6) in both the TAS and *I*-DLTS measurements. This lowering of the activation energy for the A_1 level may be related to diffusion of Mg induced by the high-temperature annealing process. Additionally, the *I*-DLTS spectrum shows a large increase in concentration in the A_1 level for the sample annealed at 850 °C (sample 6), which is in good agreement with the segregation phenomenon of the Mg dopant as confirmed by the SIMS measurements. Therefore, the continued reconfiguration of the local region surrounding the Mg atoms may induce an energy-level splitting of the A_1 level, resulting in the lowering of the activation energy.[14] The observed activation energies should be also subject to the Poole–Frenkel field effect, which is apt to occur in the TAS and *I*-DLTS measurement techniques.[8]

In summary, we have systematically investigated the annealing-temperature dependence of acceptor levels in GaN:Mg samples grown by MOCVD by using TAS and *I*-DLTS techniques. Both measurements reveal two deep acceptor levels with thermal activation energies of ~135 and ~160 meV from the valence band. The annealing behavior of the former level is in reasonable agreement with the variation in the effective acceptor concentration. Therefore, this acceptor level is considered to dominate the electrical activity of Mg in GaN.

[1] H. Amano, M. Kito, K. Hiramatsu, and I. Akasaki, Jpn. J. Appl. Phys., Part 2 **28**, L2112 (1989).
[2] S. Nakamura, T. Mukai, M. Senoh, and N. Iwasa, Jpn. J. Appl. Phys., Part 2 **31**, L139 (1992).
[3] W. Götz, N. M. Johnson, J. Walker, D. P. Bour, and R. A. Street, Appl. Phys. Lett. **68**, 667 (1996).
[4] J. W. Huang, T. F. Kuech, H. Lu, and I. Bhat, Appl. Phys. Lett. **68**, 2392 (1996).
[5] W. Götz, N. M. Johnson, and D. P. Bour, Appl. Phys. Lett. **68**, 3470 (1996).
[6] J. Z. Li, J. Y. Lin, H. X. Jiang, A. Salvador, A. Botchkarev, and H. Morkc, Appl. Phys. Lett. **69**, 1474 (1996).
[7] A. Krtschil, H. Witte, M. Lisker, J. Christen, U. Birkle, S. Einfeldt, and D. Hommel, J. Appl. Phys. **84**, 2040 (1998).
[8] D. J. Kim, D. Y. Ryu, N. A. Bojarczuk, J. Karasinski, S. Guha, S. H. Lee, and J. H. Lee, J. Appl. Phys. **88**, 2564 (2000).
[9] D. Seghier and H. P. Gislason, J. Appl. Phys. **88**, 6483 (2000).
[10] R. Y. Korotkov, J. M. Gregie, and B. W. Wessels, Appl. Phys. Lett. **78**, 222 (2001).
[11] E. Litwin-Staszewska, T. Suski, R. Piotrzkowski, I. Grzegory, M. Bockowski, J. L. Robert, L. Kończewicz, D. Wasik, E. Kamińska, D. Cote, and B. Clerjaud, J. Appl. Phys. **89**, 7960 (2001).
[12] N. D. Nguyen, M. Germain, M. Schmeits, B. Schineller, and M. Heuken, J. Appl. Phys. **90**, 985 (2001).
[13] Y. Nakano and T. Kachi, Appl. Phys. Lett. **79**, 1631 (2001).
[14] Y. Nakano, R. K. Malhan, T. Kachi, and H. Tadano, J. Appl. Phys. **89**, 5961 (2001).