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Near-midgap deep levels in $Al_{0.26}Ga_{0.74}N$ grown by metal-organic chemical vapor deposition

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A deep level with an activation energy of 1.0 eV in *n*-type $Al_{0.26}Ga_{0.74}N$ grown by metal-organic chemical vapor deposition was detected by deep-level transient spectroscopy (DLTS) with a sampling time window of several seconds. The deep-level density was 6×10^{15} cm^{-3}. At the temperatures around which the DLTS peaks were observed, capacitance transient was measured. Under the dark condition, a capacitance increase was observed, corresponding to the thermal emission of electrons from the level with 1.0 eV activation energy. After that, we observed a large capacitance increase under illumination with 2.3 eV photon energy. On the basis of potential simulation taking account of deep levels, we found that the photoinduced capacitance change arose from electron emission from additional near-midgap levels in energy ranging from $E_C-1.5$ to $E_C-2.3$ eV. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3119643]

Deep levels in AlGaN induce not only serious degradation, such as drain current instability and lack of long-term reliability, in AlGaN/GaN-based transistors[1,2] but also significant reduction in light-emitting efficiency in ultraviolet light-emitting diodes and laser diodes using AlGaN materials.[3] Although photoluminescence (PL) or cathodoluminescence (CL) investigation has shown some characteristic luminescence peaks related to deep electronic levels in AlGaN and AlN,[3–7] electrical characterization on deep levels in AlGaN or AlGaN/GaN heterostructure has been reported only a few times.[8–11] In particular, the deep-level transient spectroscopy (DLTS) method only detected deep levels with activation energies under 0.9 eV,[10] in spite of the fact that a near-midgap level can act as a dominant recombination center rather than a level near conduction or valence band. To detect near-midgap levels in AlGaN, a temperature range should extend to 800 K in a typical DLTS measurement condition. In such very high temperatures, a Schottky or a *p*-*n* junction suffers from serious leakage and thermal junction breakdown. In this letter, we characterize near-midgap deep levels in AlGaN grown by metal-organic chemical vapor deposition (MOCVD) using a combination of DLTS and photoassisted capacitance transient methods.

We used a Si-doped n-$Al_{0.26}Ga_{0.74}N$ layer with a thickness of 1.0 μm grown at 1000 °C on a sapphire substrate by MOCVD. Hall measurements determined the typical values of electron concentration and mobility of the AlGaN layer at room temperature (RT) to be 2×10^{17} cm^{-3} and 100 cm^2/V s, respectively. As a ring-shaped Ohmic contact, a Ti/Al/Ti/Au multilayer structure (20/50/20/150 nm) was deposited on the AlGaN surface, followed by an annealing at 800 °C for 1 min in N_2 ambient. A circular Schottky electrode with a diameter of 200 μm was fabricated at the center of the Ohmic ring by an electron-beam deposition of Ni.

To try to detect deep levels with large activation energies in a temperature range as low as possible in the DLTS measurement, a time window of up to several seconds was used with an optimized signal sampling system and a temperature-sweeping rate. A simple simulation assuming a capture cross section from 1×10^{-15} to 1×10^{-16} cm^2 showed that a deep level with an activation energy of 1.0 eV would have a corresponding peak temperature at around 400 K in the DLTS spectrum.

The I-V and $1/C^2$-V characteristics of the $Ni/Al_{0.26}Ga_{0.74}N$ Schottky diode, respectively, measured at RT, are shown in Figs. 1(a) and 1(b). From the forward I-V characteristics, the Schottky barrier height (SBH) and the ideality factor (n) were calculated as $SBH_{I\text{-}V}=1.2$ eV and $n=1.24$, respectively. The plot of $1/C^2$-V exhibited a built-in potential of 1.2 eV at the AlGaN surface, corresponding to $SBH_{C\text{-}V}=1.3$ eV. A good agreement between these SBH values indicated that the Ni/AlGaN structure had good interface quality without an additional interfacial layer such as an oxide layer. Although relatively high leakage currents flow at the reverse bias region,[12,13] as shown in Fig. 1(a), an excellent linearity of $1/C^2$-V plots is obtained in the given reverse bias range. This indicates that the gate control of the depletion layer was not significantly affected by leakage current. Moreover, the $1/C^2$-V linearity remained almost unchanged at temperatures up to 450 K. These results showed that a

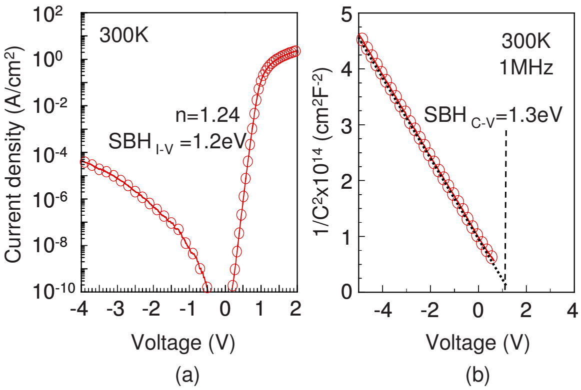

FIG. 1. (Color online) (a) Current-voltage and (b) capacitance-voltage characteristics of the AlGaN Schottky diode.

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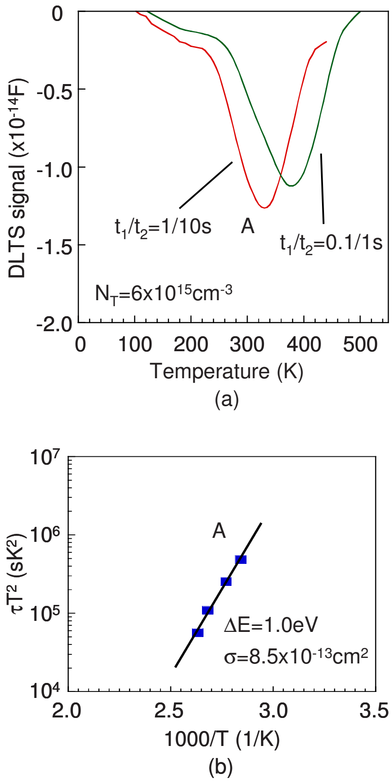

FIG. 2. (Color online) (a) DLTS signals of the AlGaN Schottky diode and (b) Arrhenius plots of the *A* peaks calculated from the corresponding time constant and the peak temperature.

stable Schottky interface was achieved and was suitable for deep-level characterization using the depletion layer control even at high temperatures.

Next, the AlGaN Schottky diode was characterized by DLTS with a filling bias of +0.5 V and an emission bias of −2 V. To focus on the detection of deep levels with large activation energies, we set the maximum time window as long as 3.9 s (the corresponding sampling times t_1 and t_2 are 1 and 10 s, respectively). In the DLTS spectra shown in Fig. 2(a), large peaks were observed at temperatures from 320 to 380 K, labeled as "A level." Arrhenius plots of the *A* peaks calculated from the corresponding time constants and peak temperatures are shown in Fig. 2(b). An activation energy of 1.0 ± 0.1 eV and a capture cross section of $8.5 \pm 1.5 \times 10^{-13}$ cm^2 were extracted from the plots, respectively. By considering partial ionization of the A level in the depletion layer (the so-called λ-effect), the density of the A level was estimated to be 6×10^{15} cm^{-3}. From the dependence of the peak height on the emission bias voltage, it was found that the A level has a constant density profile within a depth of 0.5 μm in the AlGaN layer. Osaka *et al.*[10] reported deep levels with activation energies of 0.8 and 0.9 eV in $Al_{0.09}Ga_{0.91}N$ and $Al_{0.17}Ga_{0.83}N$, respectively, grown by hydride vapor phase epitaxy (HVPE). They argued that the energy of these levels increased with increasing Al mole fraction x in $Al_xGa_{1-x}N$, referring to the bottom of the conduction band as the bandgap energy increased with x. Their model predicted the activation energy to be around 1.0 eV for $x=0.3$. Thus, there is a possibility that the origin of the present A level is related to that of those reported, although the AlGaN layer used here is not grown by HVPE but by MOCVD.

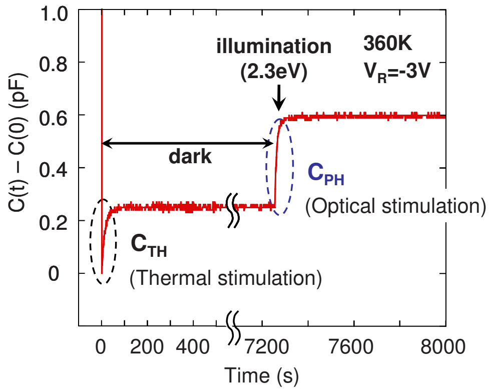

FIG. 3. (Color online) Capacitance transient of the AlGaN Schottky diode at 360 K under dark and illumination.

To further investigate near-midgap deep levels in AlGaN, a photoassisted capacitance transient measurement was carried out at 360 K, in which the DLTS peak of the A level was observed. The bias was first set to +1 V to fill the deep levels with electrons, and then the bias was switched to −3 V. Figure 3 shows a measured capacitance transient under dark and illumination conditions. Under the dark condition, the capacitance showed a fast transient, labeled as C_{TH} in Fig. 3, and then a saturation behavior within 100 s. The time constant for this transient agreed well with an emission time of electron at the A level predicted by the Schockley–Read–Hall statistics using the activation energy and the capture cross section obtained by DLTS. Furthermore, the trap density estimated from the capacitance change C_{TH} equaled to that obtained by the DLTS peak height shown in Fig. 2(a). These results showed that the first capacitance transient in the dark arose from the thermal emission of electrons in energies above the Fermi level (E_F) in a depletion region which were captured by the A level when the diode was under the positive bias.

After 2 h, the AlGaN Schottky diode was illuminated by a green laser light with a wavelength of 532 nm ($h\nu$ =2.3 eV) corresponding to the near-midgap energy of AlGaN. When the light was switched on, we observed a steep capacitance increase, as indicated by C_{PH} in Fig. 3. One of the possible mechanisms for this is a photoassisted emission of electrons remaining below E_F in the A level, as schematically shown in Fig. 4(a). As mentioned above, electrons in energies above E_F were thermally emitted from the A level to the conduction band at around 360 K, while electrons located below E_F remained in the A level under the dark condition. Under illumination, however, such electrons can be emitted to the conduction band. To evaluate this effect on the capacitance change, we carried out a potential simulation of the Schottky interface taking account of the A level with a density of 6×10^{15} cm^{-3}. The simulation result showed that the capacitance change due to the photoassisted emission of electrons remaining below E_F in the A level was 0.1 pF or lower. The experimentally observed capacitance change (C_{PH}) was much larger than the calculated one, indicating the contribution of additional deep levels to the large capacitance change under illumination, as shown in Fig. 4(b). The C_{PH} value corresponds to a trap density of 8×10^{15} cm^{-3}. A nearly constant capacitance behavior for 2 h at 360 K under the dark condition, as shown in Fig. 3, indicates that the additional deep level has the corresponding time constant or

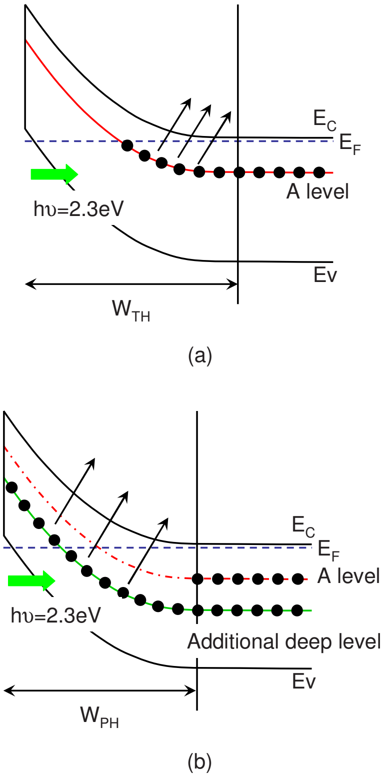

FIG. 4. (Color online) Schematic illustration of band diagrams of the AlGaN Schottky diode including (a) A level and (b) A level and an additional deep level.

larger. Assuming a capture cross section being equal to that for the A level, an activation energy of the additional level is estimated to be 1.5 eV or larger. Thus, the present study indicates that the AlGaN layer includes, at least, a near-midgap level with an energy range between 1.5 and 2.3 eV from the bottom of the conduction band.

Several groups have reported deep-level peaks in PL and CL spectra for AlGaN and AlN,[3–7] which are related to complex defects based on the III-column vacancies (V_{Al} and V_{Ga}). In particular, V_{Al}-oxygen defects have been considered to be the most possible origin for a deep-level-related luminescence observed in AlN.[6,7] It was also pointed out that those defects can act as dominant recombination centers. Further investigation is needed to clarify the origin of near-midgap levels in AlGaN detected by DLTS, correlating with optically observed emission spectra.

In summary, we detected the deep level with the activation energy of 1.0 eV in MOCVD-grown *n*-type $\mathrm{Al}_{0.26}\mathrm{Ga}_{0.74}\mathrm{N}$ by DLTS measurements using long time windows of up to several seconds. The deep-level density was 6×10^{15} cm^{-3}. At the temperatures around which the DLTS peaks were observed, a capacitance transient measurement was carried out. Under the dark condition, we observed a clear increase in capacitance, corresponding to the thermal emission of electrons from the level with 1.0 eV activation energy. After that, a further capacitance change was detected under illumination with 2.3 eV photon energy. On the basis of potential simulation taking account of deep levels, we found that the photoinduced capacitance increase arose from electron emission from additional near-midgap levels in energy ranging from $E_C-1.5$ to $E_C-2.3$ eV. Because such near-midgap levels can act as dominant recombination centers or as carrier trapping centers, investigating the correlation with instability and/or degradation issues in AlGaN-based electronic and photonic devices is important.

[1] G. Meneghesso, IEEE Trans. Device Mater. Reliab. **8**, 332 (2008).
[2] J. Joh and J. A. del Alamo, IEEE Electron Device Lett. **29**, 287 (2008).
[3] T. Onuma, S. F. Chichibu, A. Uedono, T. Sota, P. Cantu, T. M. Katona, J. F. Keading, S. Keller, U. K. Mishra, S. Nakamura, and S. P. DenBaars, J. Appl. Phys. **95**, 2495 (2004).
[4] N. Nepal, M. L. Nakarmi, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **89**, 092107 (2006).
[5] Q. Sun, H. Wang, D. S. Jiang, R. Q. Jin, Y. Huang, S. M. Zhang, H. Yang, U. Jahn, and K. H. Ploog, J. Appl. Phys. **100**, 123101 (2006).
[6] E. Monroy, J. Zenneck, G. Cherkashinin, O. Ambacher, M. Hermann, M. Stutzmann, and M. Eickhoff, Appl. Phys. Lett. **88**, 071906 (2006).
[7] T. Koyama, M. Sugawara, T. Hoshi, A. Uedono, J. F. Kaeding, R. Sharma, S. Nakamura, and S. F. Chichibu, Appl. Phys. Lett. **90**, 241914 (2007).
[8] W. Götz, N. M. Johnson, M. D. Bremser, and R. F. Davis, Appl. Phys. Lett. **69**, 2379 (1996).
[9] Y. S. Park, C. J. Park, C. M. Park, J. H. Na, J. S. Oh, I. T. Yoon, H. Y. Cho, T. W. Kang, and J.-E. Oh, Appl. Phys. Lett. **86**, 152109 (2005).
[10] J. Osaka, Y. Ohno, S. Kishimoto, K. Maezawa, and T. Mizutani, Appl. Phys. Lett. **87**, 222112 (2005).
[11] A. Armstrong, A. Chakraborty, J. S. Speck, S. P. DenBaars, U. K. Mishra, and S. A. Ringel, Appl. Phys. Lett. **89**, 262116 (2006).
[12] J. Kotani, T. Hashizume, and H. Hasegawa, J. Vac. Sci. Technol. B **22**, 2179 (2004).
[13] J. Kotani, M. Kaneko, H. Hasegawa, and T. Hashizume, J. Vac. Sci. Technol. B **24**, 2148 (2006).