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Observation of inductively coupled-plasma-induced damage on *n*-type GaN using deep-level transient spectroscopy

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The effects of inductively coupled plasma (ICP) etching on electrical properties of *n*-type GaN Schottky contacts were investigated by observing ion damage using deep-level transient spectroscopy. An electron trap, not previously seen, localized near the contact, as well as a pre-existing trap, was observed in the ICP-etched sample. The ICP-etched surface was found to be N-deficient, which means that N vacancies (V_N) were produced by ICP etching. From these, the origin of the ICP-induced electron trap was suggested to be V_N or a V_N-related complex of point defects. The ICP-induced traps provided a path for the transport of electrons, leading to the reduction of Schottky barrier height and increase of gate leakage current. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557316]

Because of the inherent chemical stability of GaN, device fabrication processes involving GaN-based material system usually rely on dry etching, which is known to cause surface damage.[1] In particular, surface damage induced during a recessed gate process in the fabrication of AlGaN/GaN heterostructure field-effect transistors could drastically reduce the gate breakdown voltage unless very low plasma power is used.[2]

Dry-etch-induced damage is attributed to the formation of a nonstoichiometric surface due to preferential loss of one of the elements.[3] Another possible origin for the degradation is the generation of trapping centers on the etched surface. Inductively coupled plasma (ICP) etching of GaN led to severe degradations of the Schottky contact, the decrease of Schottky barrier height, and the increase of reverse leakage current by several orders of magnitudes.[4]

Deep-level transient spectroscopy (DLTS) is an effective tool in obtaining information about traps in semiconductors. In particular, the depth distribution of deep levels is easily obtained, which is critical in interpreting the electrical properties of the devices.[5,6] This technique has been widely employed to investigate deep levels in GaN. In DLTS measurements on *n*-type GaN irradiated by high-energy electrons, shallow levels with activation energies in the range of 0.18 and 0.22 eV were commonly observed, and were suggested to be related to N vacancy (V_N).[7,8] However, little work has been reported on DLTS measurements on ICP-induced damage of *n*-type GaN.

In this work, changes in the surface morphology and chemical composition of *n*-type GaN were investigated using atomic force microscopy (AFM) and angle-resolved synchrotron radiation photoemission spectroscopy (SRPES), and electrical properties of Schottky contacts on an ICP-etched surface were evaluated through *I*–*V* measurements. The surface damage induced by ICP etching was characterized using DLTS. From these, the mechanism for degradation of electrical properties of GaN Schottky diodes was suggested.

The *n*-type GaN sample used in this study was a 1.5-μm-thick, unintentionally doped layer grown by metalorganic chemical vapor deposition (MOCVD) on *c*-plane sapphire. The epitaxial relationship between GaN and *c*-plane sapphire was determined to be (0001) GaN//(0001) Al₂O₃ from x-ray diffraction measurements. In Hall-effect measurements performed at room temperature, the hole mobility and concentration was determined to be 550 cm^2/V s and 5 $\times 10^{16}$/cm^3, respectively. The free-electron concentration was determined to be 1×10^{17} cm^{-3} from capacitance–voltage measurements. Ti/Al/Ni/Au (30/120/40/50 nm) ohmic contacts were deposited in sequence using electron beam evaporator, followed by rapid thermal annealing in the N₂ ambient at 600 °C. Prior to the deposition of 50-nm-thick Pt Schottky metal, the surface of GaN was etched using ICP with a mixture of Cl₂ (6 sccm) and BCl₃ (4 sccm) for 1 min at the inductive power of 400 W and the rf chuck power of 20 W. For reference, Schottky diodes without ICP etching were also prepared.

Figure 1 shows forward and reverse *I*–*V* characteristics of Pt Schottky diodes for the reference and the ICP-etched
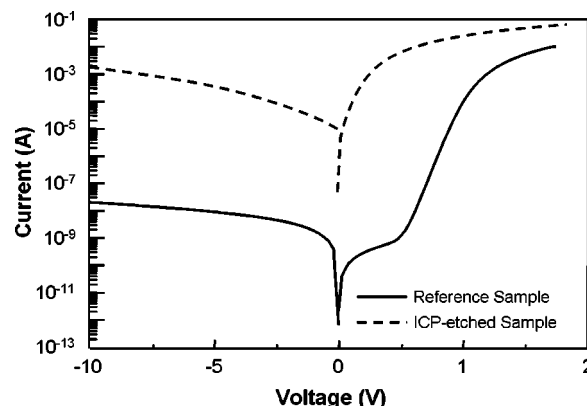
FIG. 1. *I*–*V* characteristics of Pt Schottky diodes fabricated on both the reference and ICP-etched surfaces.

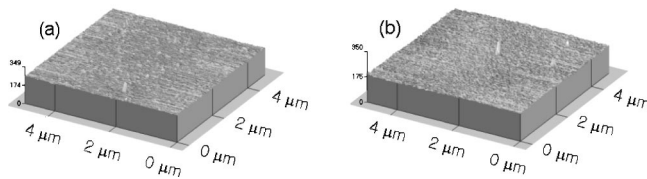[a)]Author to whom correspondence should be addressed; electronic mail: jllee@postech.edu

FIG. 2. Three-dimensional AFM images of a 5-μm$\times$5-μm area of GaN surface (a) before and (b) after 120 nm of GaN was removed using Cl_2 +BCl_3 ICP etching.

samples. It is clearly seen that ICP etching caused severe degradations in electrical properties. Namely, ϕ_B was reduced from 1.0 to 0.43 eV and I_R increased by five orders of magnitude after ICP etching. Furthermore, the linear region in the forward I–V curve of the ICP-etched sample almost disappeared and η was increased from 1.08 to 1.34. This suggests that electron transport mechanism at the metal–semiconductor interface can be no longer described in terms of a thermionic emission model.

It was reported that dry etchings carried out at high bias voltages or powers could produce roughened surfaces, perhaps due to the preferential loss of nitrogen.[1,3] Figure 2 shows three-dimensional AFM images of a 5-μm$\times$5-μm area of GaN surface (a) before and (b) after 120 nm of GaN was removed by ICP etching. As seen in the figure, surface morphology of the etched surface still remains fairly smooth. The rms surface roughness was decreased slightly from 4.67 to 3.24 Å after etching. This indicates that degradations in electrical properties after ICP etching, as shown in Fig. 1, are not related to the surface morphology.

Figure 3 displays DLTS spectra of the reference and the ICP-etched samples. In the reference sample, an electron trap was observed at 270 K ($T1$). In the ICP-etched one, however, another electron trap as well as $T1$ was observed at 145 K ($T2$). In order to obtain depth information of these traps, the reverse (V_m) and the pulse bias (V_p) were simultaneously changed. As the depletion layer width increased deep into the bulk by changing the bias condition from (V_p = 1 V, V_m = 0 V) to (V_p = 0 V, V_m = −2 V), $T2$ completely disappeared. This result suggests that ICP-etching-induced trap $T2$ was localized near the contact, but $T1$ was distributed deep into the bulk.

The temperature dependency of each trap is shown in the inset of Fig. 3, from which E_a and σ_n were determined and summarized in Table I. The E_a and σ_n of $T1$, 0.58 ±0.01 eV and 8.84×10^{-15} cm^2, agree well with 0.59 eV and 2.9×10^{-15} cm^2 of $E2$ observed in GaN grown by MOCVD.[9] The peak temperature of $T1$ moved towards the higher temperature region at (V_p = 0 V, V_m = −2 V), resulting in a slight increase of E_a by 0.03 eV. This can be explained by reduction in the barrier height for thermal emission of electrons by the electrical field or the Poole–Frenkel effect.[10] Namely, electric field strength in a Schottky contact is highest at the metal–semiconductor interface and then linearly decreases away from the contact into the semiconductor. Thus, the E_a of $T1$ near the Schottky contact is smaller than that far from the contact.

Electron capture dynamics into the ICP-induced traps was investigated by monitoring the change in the magnitude of DLTS peak heights on the filling pulse duration t_p. The
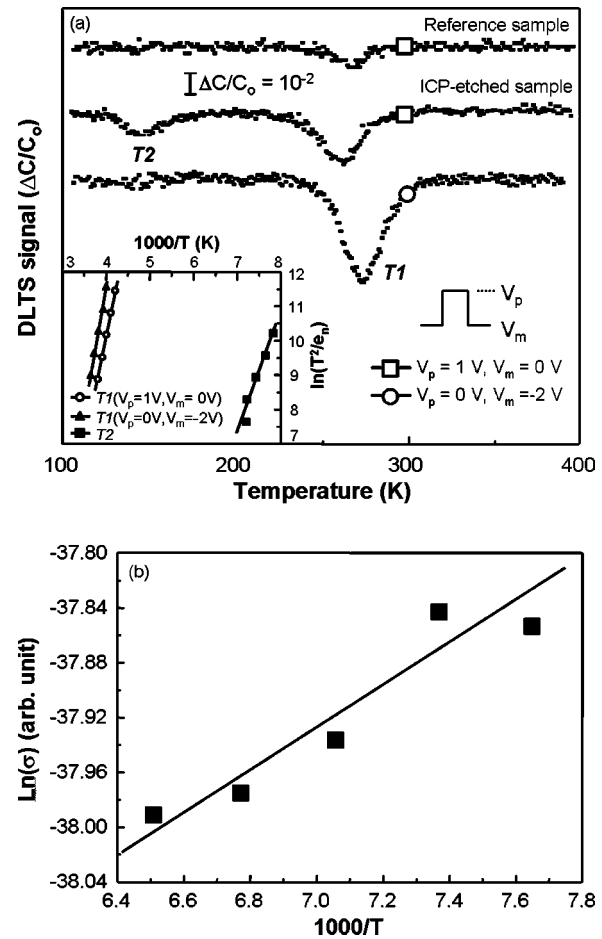

FIG. 3. (a) Capacitance DLTS spectra of Schottky diodes fabricated on both the reference and ICP-etched surfaces. The inset shows the temperature dependency of emission rate of each trap. (b) Dependence of capture cross section of the ICP-induced trap on the peak temperature T_m. Energy barrier for electron capture was determined to be 0.0134 eV from the slope of the linear fitting of the plot.

DLTS signal is dependent on both t_p and capture rate C_n; $\Delta C(t_p) = \Delta C_{max}[1-\exp(-C_n t_p)]$,[11] where ΔC_{max} is the maximum change of the capacitance due to filling all the traps. In addition, $C_n = \sigma \langle v_{th} \rangle n = \sigma_\infty \langle v_{th} \rangle n \cdot \exp(-E_B/kT_m)$, where σ is the electron capture cross section, $\langle v_{th} \rangle$ the electron average thermal velocity, n the free-electron concentration, E_B the capture energy barrier, and T_m the peak temperature. Figure 3(b) shows the temperature dependence of σ. From the slope of the linear fitting of the plot, the capture barrier energy was determined to be 0.0134 eV.

In order to suggest the origin for the ICP-induced trap $T2$, the change in chemical composition was investigated using angle-resolved SRPES measurements. At a smaller take-off angle θ, the intensity of photoelectrons emitting from the surface becomes dominant due to the inelastic mean free path of photoelectrons λ. The atomic percentage of each peak was determined using the peak area and the atomic

TABLE I. E_a and σ_n for $T1$ and $T2$ traps.

Trap level	E_a (eV)	σ_n (cm^2)
$T1$ (V_p = 1 V, V_m = 0 V)	0.55±0.02	7.91×10^{-15}
$T1$ (V_p = 0 V, V_m = −2 V)	0.58±0.01	8.84×10^{-15}
$T2$	0.23±0.02	5.34×10^{-17}

TABLE II. Atomic percentage determined by integrating the area of each SRPES spectrum and the ratio of Ga/N on the as-grown and the ICP-etched surfaces with the take-off angle θ. Values were normalized to that at $\theta = 90°$.

|	θ (°)	Ga	N	O	C	Ga/N
As-grown	90	76.6	9.5	7.8	6.1	1.00
(at. %)	60	73.0	9.2	10.2	7.2	0.94
	30	65.4	8.2	11.0	15.4	0.99
ICP-etched	90	72.7	7.8	12.7	6.8	1.00
(at. %)	60	71.5	8.2	12.2	8.1	0.93
	30	65.9	4.5	13.3	16.3	1.57

FIG. 4. Schematic illustration of electron transport through the interface of metal with ICP-etched GaN: (a) forward bias condition and (b) reverse bias condition.

sensitivity factor of each element are summarized in Table II. The ratio of Ga/N increased significantly on the ICP-etched surface at $\theta = 30°$. This means that the GaN surface became N-deficient and a number of V_N were produced by ICP etching. Thus, it can be suggested that the origin of $T2$ is V_N or a V_N-related complex of point defects.

The thickness of the ICP-induced damage region can be estimated using the definition of λ. Namely, λ is defined as the depth from the surface, where $1/e$ of the photoelectrons produced there can escape and is a function of the electron kinetic energy. When the incident photon energy is 600 eV, which is used in the present measurements, the electron kinetic energy originating from Ga $3d$ core level is 580 eV, and λ corresponds to about 10 Å.[12] The maximum escape depth can be assumed to be about three times λ ($1/e^3 = 0.05$) or 30 Å in this case. As seen in Table II, the ratio of Ga/N of the ICP-treated sample is nearly the same as that of the as-grown one above $\theta = 60°$. Thus, the thickness of ICP-induced damage can be assumed to be from 15 Å ($\theta = 30°$) to 26 ($\theta = 60°$).

The electrical degradation of Schottky diodes by the ICP etching in Fig. 1 could be explained by tunneling of electrons via ICP-induced traps. Under forward and reverse biases, electrons could be transported across the contact by (i) thermionic emission of electrons over the Schottky barrier and (ii) tunneling of electrons through the ICP-induced traps, shown in Fig. 4. The transport of electrons through the ICP-induced traps is highly probable because the ICP-induced traps provide a conducting path with lower energy barrier, which can easily be surmounted by the injected electrons.[13] This caused the increase in I_R and the deviation of the forward $I-V$ characteristics from those described by the thermionic emission model, as shown in Fig. 1.

In summary, ICP etching of n-type GaN caused the degradation of the Schottky diode, the decrease of ϕ_B and increases of η and I_R. In DLTS spectra of the ICP-etched
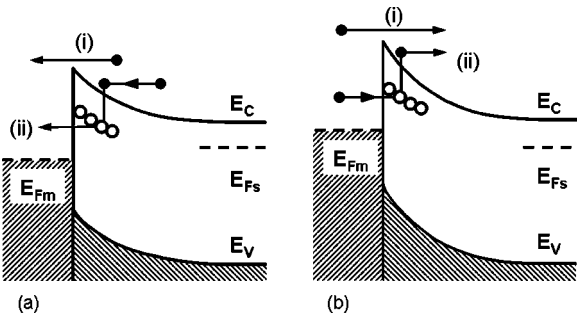
sample, an electron trap $T2$ ($E_a = 0.23 \pm 0.02$ eV), not previously seen, localized near the contact, as well as a pre-existing trap $T1$ ($E_a = 0.58 \pm 0.01$ eV) were observed. From angle-resolved SRPES measurements, the ICP-etched surface was found to be N-deficient, which means that a number of V_N were produced by ICP etching. From these, the origin of $T2$ was suggested to be V_N or a V_N-related complex of point defects. Degradations in electrical properties of the Schottky diode could be explained by the role of the ICP-induced traps as a conducting path for electrons with lower energy barrier.

[1] I. Adesida, C. Youtsey, A. T. Ping, F. Khan, L. T. Romano, and G. Bulmann, MRS Internet J. Nitride Semicond. Res. **4S1**, G1.4 (1999).
[2] C.-H. Chen, S. Keller, E. D. Haberer, L. Zhang, S. P. Denbaars, E. L. Hy, and Y. Wu, J. Vac. Sci. Technol. B **17**, 2755 (1999).
[3] C. R. Eddy, Jr. and B. Molnar, J. Electron. Mater. **28**, 314 (1999).
[4] X. A. Cao, H. Cho, S. J. Pearton, G. T. Dang, A. P. Zhang, F. Ren, R. J. Shul, L. Zhang, R. Hickman, and J. M. Van Hove, Appl. Phys. Lett. **75**, 232 (1999).
[5] K. J. Choi and J.-L. Lee, IEEE Trans. Electron Devices **48**, 190 (2001).
[6] K. J. Choi, J.-L. Lee, and H. M. Yoo, Appl. Phys. Lett. **75**, 1580 (1999).
[7] Z.-Q. Fang, J. W. Hemsky, D. C. Look, and M. P. Mack, Appl. Phys. Lett. **72**, 448 (1998).
[8] S. A. Goodman, F. D. Auret, M. J. Legodi, B. Beaumont, and P. Gibart, Appl. Phys. Lett. **78**, 3815 (2001).
[9] P. Hacke, T. Detchprohm, K. Hiramatsu, N. Sawaki, K. Tadatomo, and K. Miyake, J. Appl. Phys. **76**, 304 (1994).
[10] P. A. Martin, B. G. Streetman, and K. Hess, J. Appl. Phys. **52**, 7409 (1981).
[11] B. Massarani, F. G. Awad, M. Kaaka, and R. Darwich, Phys. Rev. B **58**, 15614 (1998).
[12] S. Hüfner, *Photoelectron Spectroscopy* (Spring, Berlin, 1995), p. 8.
[13] E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contacts* (Clarendon, Oxford, 1988), pp. 38–41.