

# Surface Analysis of AlGa<sub>N</sub> Treated with CF<sub>4</sub> and Ar Plasma Etching\*

Shohdai Hirai<sup>†</sup> and Masahito Niibe

*Laboratory of Advanced Science and Technology for Industry,  
University of Hyogo, Kouto 3-1-2, Kamigori, Ako-gun, Hyogo 678-1205, Japan*

Retsuo Kawakami and Tatsuo Shirahama

*Institute of Socio-Techno Science Technology, Tokushima University,  
2-1 Minami-Josanjima, Tokushima 770-8506, Japan*

Yoshitaka Nakano

*Institute of Science and Technology, Chubu University,  
1200 Matsumoto-cho, Kasugai, Aichi 487-8501, Japan*

Takashi Mukai

*Nichia Corporation, 491 Oka, Kaminaka-cho, Anan, Tokushima 774-8601, Japan*

(Received 14 January 2015; Accepted 17 November 2015; Published 19 December 2015)

To understand the surface damage of AlGa<sub>N</sub> film caused by plasma etching in detail, we etched AlGa<sub>N</sub> film with CF<sub>4</sub> and Ar plasmas. The intensity of ultraviolet (UV) light emitted from the CF<sub>4</sub> plasma was very weak at each gas pressure investigated. However, in the case of Ar, a certain degree of UV intensity was observed at gas pressures between 50 and 100 mTorr. The surface etched with the CF<sub>4</sub> plasma was as smooth as that of the as-grown film. In the case of Ar, surface roughening occurred at gas pressures between 50 and 100 mTorr. The Al/N and Ga/N ratios of the AlGa<sub>N</sub> surface etched with Ar plasma increased more significantly than those of the surface etched with CF<sub>4</sub> plasma, as determined by X-ray photoelectron spectroscopy (XPS). The peak shape of the near-edge X-ray absorption fine structure (NEXAFS) spectra in the N-K absorption edge was broadened by the plasma etching with increasing processing-time. The broadening observed in the case of Ar etching was greater than that during CF<sub>4</sub> plasma etching. The observed changes in the surface morphology and crystalline structure of the AlGa<sub>N</sub> are considered to be caused by the synergistic effect of UV light irradiation from the plasma and ion bombardment of the sample surface. The changes in surface composition, surface roughening, and the disordering of the crystalline structure were found to occur within a shallow region from the surface, and did not occur in deeper regions of the sample. F atoms (ions) were found to penetrate the surface to a depth of about 10 nm in the AlGa<sub>N</sub> etched with CF<sub>4</sub> plasma.

[DOI: 10.1380/ejsnt.2015.481]

Keywords: X-ray photoelectron spectroscopy; Near-edge extended X-ray absorption fine structure (NEXAFS); Plasma processing; Surface structure, morphology, and roughness; Gallium nitride

## I. INTRODUCTION

AlGa<sub>N</sub>/Ga<sub>N</sub> heterostructures have been studied as high electron mobility transistors (HEMT) operable at high frequency, high power, and high temperature [1, 2]. In these structures, a two-dimensional electron gas (2DEG) with a high carrier concentration and high mobility is induced at the AlGa<sub>N</sub>/Ga<sub>N</sub> interface [3]. However, there are several problems facing the practical application of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs. An AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT essentially has a normally-on operation owing to the 2DEG, and the drain current flows even if the gate voltage is 0 V. However, in view of the need for fail-safe operation in power devices, normally-off operation is desired so that the drain current does not flow when the gate voltage is 0 V [4]. Power saving can also be expected if it is possible for AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs to have a normally-off operation [5–7].

Recently, it has been reported that AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs can be made normally-off by treating the AlGa<sub>N</sub> film with CF<sub>4</sub> plasma [5]. The achievement of the normally-off operation is considered to arise from the incorporation of fluorine ions into the AlGa<sub>N</sub> surface during the CF<sub>4</sub> plasma process [5]. However, the mechanism and the related surface damage are not yet known. Previously, we investigated the effect of Ar plasma etching on *n*-Ga<sub>N</sub> surfaces [8–10]. We reported that surface roughening clearly occurs in *n*-Ga<sub>N</sub> by a synergistic effect between UV light irradiation from the plasma and ion bombardment of the sample surface [8–10]. However, we have not yet fully investigated this phenomenon for a AlGa<sub>N</sub> sample. Therefore, we have etched AlGa<sub>N</sub> film with CF<sub>4</sub> and Ar plasmas, and analyzed the treated surface with various methods. Although we have reported part of the study, such as the resulting variation in surface shape, elsewhere [11], a microscopic understanding of the etching damage is not sufficient. The damage caused by CF<sub>4</sub> plasma etching is more easily understood by comparing the etching damage caused by both CF<sub>4</sub> and Ar plasmas using the same etching device. In this study, the changes in surface composition and crystalline structure of AlGa<sub>N</sub> etched by CF<sub>4</sub> and Ar plasmas were analyzed using X-ray

\* This paper was presented at the 7th International Symposium on Surface Science, Shimane Prefectural Convention Center (Kunibiki Messe), Matsue, Japan, November 2-6, 2014.

<sup>†</sup> Corresponding author: hirai.s@lasti.u-hyogo.ac.jp

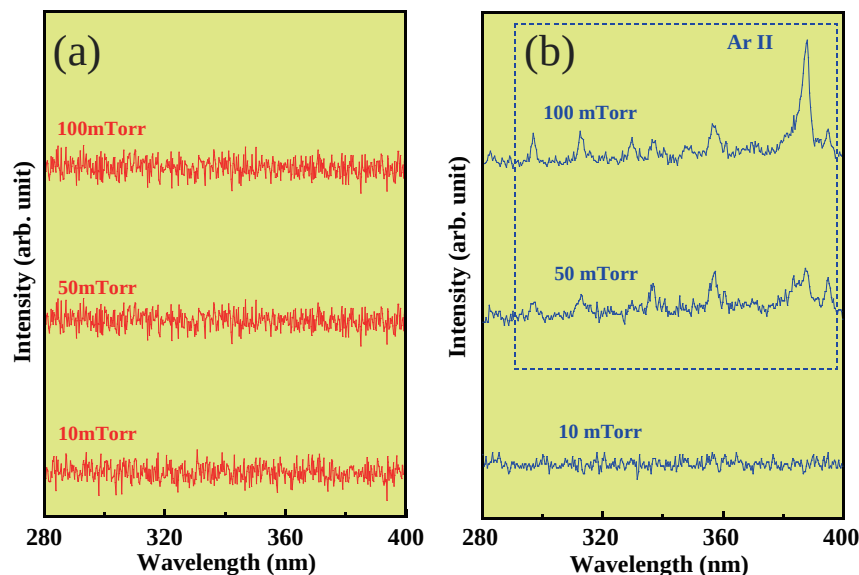


FIG. 1. Spectra of the light emitted from (a)  $\text{CF}_4$  and (b) Ar plasmas during etching.

photoelectron spectroscopy (XPS) and near-edge X-ray absorption fine structure (NEXAFS) measurements. We discuss the difference between the etching damage caused by the  $\text{CF}_4$  and Ar plasmas in detail.

## II. EXPERIMENTAL PROCEDURE

The sample was a 100-nm-thick AlGaIn ( $\text{Al}_{0.24}\text{Ga}_{0.76}\text{N}$ ) film grown on a GaN surface by metal organic chemical vapor deposition (MOCVD). An HEMT is usually formed by depositing an AlGaIn heterofilm on GaN to about 20 nm thick. However, in this study, we used a 100-nm-thick AlGaIn film to enable the damage of the AlGaIn layer to be more easily extracted by reducing the influence of the underlying GaN film. Plasma etching was carried out using a capacitively coupled plasma (CCP) with a radio frequency (13.56 MHz) of 200 V.  $\text{CF}_4$  and Ar were used as the plasma source gases. The gas pressure of the plasma was varied between 10 and 100 mTorr. The duration of the plasma etching was varied from 5 to 100 min [8]. The spectrum of the ultraviolet (UV) light emitted from the plasmas was measured using a visible-ultraviolet spectrometer (Ocean Optics, USB4000).

The AlGaIn surfaces etched with the plasmas were observed using a scanning electron microscope (SEM; JEOL, JSM-6390). The root mean square (RMS) roughnesses of the etched surfaces were measured using an atomic force microscope (AFM; Olympus, OLS3500-PTU). The etch depth of the sample surface was measured using a surface profilometer (Sloan Technology, DEKTAK 3030). The sample surface compositions were determined using XPS (Shimadzu, ESCA-1000). The peak area intensities of Al 2p, Ga 3d, N 1s, and F 1s were calculated using the Shirley method from the measured XPS spectra. The Al/N and Ga/N composition ratios of the as-grown sample were defined as one. After that, the composition ratio of etched samples relative to the as-grown sample has been calculated. We also determined the F/N ratio of the sam-

ples using a relative sensitivity coefficient of N 1s to F 1s of 0.42 [12]. For depth profile analysis of the AlGaIn sample, Ar ion sputtering was performed with an acceleration voltage of 1.0 kV and gas pressure of  $3.8 \times 10^{-3}$  mTorr. The sputtering rate was estimated to be 0.83 nm/min.

The change in the atomic bonding state of the sample surface was evaluated by X-ray absorption spectroscopy (XAS). We measured the NEXAFS spectrum of the N-K absorption edge (388–432 eV). The NEXAFS measurements were carried out at the analyzing station of beam-line BL-09A at the NewSUBARU synchrotron radiation facility of the University of Hyogo, Japan [13]. Total electron yield (TEY) and total fluorescent yield (TFY) measurements were performed at the same position on the same sample. The TEY method can obtain information on a shallow region of less than about 5 nm from the sample surface because of the short escape length of the photogenerated electrons. In contrast, the TFY method can obtain information on a deeper region (bulk) of the sample, to more than 100 nm, because X-ray fluorescence comes from a deeper place in the sample compared with electrons [13]. For the TFY method, we measured the amount of fluorescence with a 40 nm Al-coated photodiode to cut off visible light emission. The angle of incidence of the soft X-rays was  $90^\circ$  relative to the surface.

## III. RESULTS AND DISCUSSION

Figure 1 shows the spectra of the UV light emitted from (a)  $\text{CF}_4$  and (b) Ar plasma during the etching. As shown in Fig. 1(a), the intensity of the UV light emitted from the  $\text{CF}_4$  plasma was very weak, and the spectral peak was not clearly observed at gas pressures between 10 and 100 mTorr. In contrast, in the case of Ar, as shown in Fig. 1(b), several peaks were observed between a wavelength of about 290–400 nm at gas pressures of 50 and 100 mTorr [14], but none were seen at a gas pressure of 10 mTorr. All of the peaks were assigned to ArII (4d–

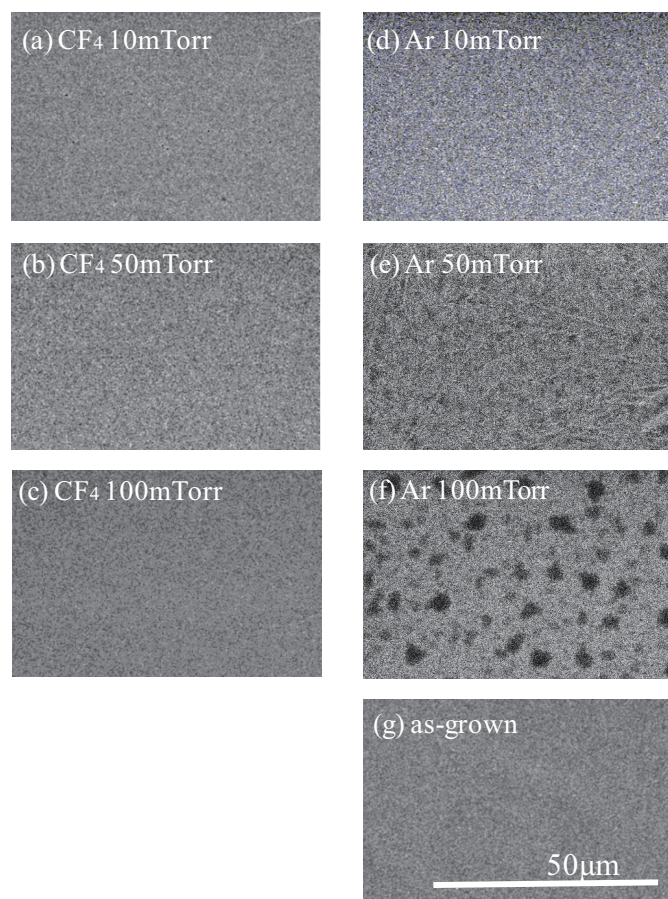


FIG. 2. SEM images of AlGaIn surfaces etched with (a–c)  $\text{CF}_4$ , (d–f) Ar plasma for 100 min, and (g) as-grown sample.

4p and/or 4d–3d) [15]. This indicates that the intensity of the UV light emitted from the  $\text{CF}_4$  plasma was much weaker than that of the Ar plasma.

The etch depth of the AlGaIn surface etched for a processing-time of 100 min was about 60 nm regardless of the gas species and gas pressure [11]. Figure 2 shows SEM images of the AlGaIn surface etched for a processing-time of 100 min. Figure 2(a–c) shows surfaces etched with  $\text{CF}_4$  plasma, Fig. 2(d–f) shows those etched with Ar plasma, and Fig. 2(g) shows that of the as-grown sample. The surfaces etched with the  $\text{CF}_4$  plasma were as smooth as the as-grown surface at every gas pressure; pronounced surface roughening did not occur. In contrast, in the case of Ar, surface roughening occurred at a gas pressure of 50 mTorr, and pit-like defects with a diameter of several  $\mu\text{m}$  were generated on the surface at a gas pressure of 100 mTorr.

Figure 3 shows the processing-time dependence of the RMS roughness of sample surfaces etched with (a)  $\text{CF}_4$  and (b) Ar plasma. As shown in Fig. 3(a), the roughness of the sample surface etched with  $\text{CF}_4$  plasma was in the range of 1–2.5 nmRMS. These values were the same as that of the as-grown sample. This indicates that surface roughening did not occur with increased gas pressure and processing-time. As shown in Fig. 3(b), the roughness of the sample surface etched with Ar plasma for 5- and 60-min processing times were the same as that of the as-grown sample. However, in the case of a processing-

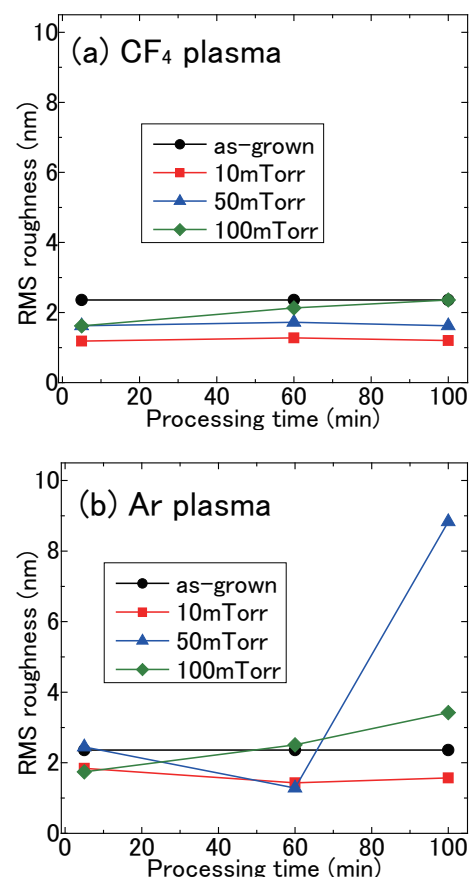


FIG. 3. Processing-time dependence of the RMS roughness of sample surface etched with (a)  $\text{CF}_4$  and (b) Ar plasma.

time of 100 min, the values increased to about 9 nmRMS at a gas pressure of 50 mTorr and to about 3.5 nmRMS at a gas pressure of 100 mTorr. This indicates that surface roughening occurred with increasing gas pressure and processing-time during etching with Ar plasma.

Figure 4 shows the processing-time dependence of the composition ratio of surfaces etched with  $\text{CF}_4$  and Ar plasmas at a gas pressure of 100 mTorr. Figure 4(a) shows the Al/N and Ga/N ratios, while Fig. 4(b) shows the F/N ratio. The Al/N and Ga/N ratios of the surface etched with  $\text{CF}_4$  plasma were increased by about 1.3 times after a processing-time of 5 min. However, after that, the ratios did not increase further with processing-time. In contrast, the values measured for the Ar plasma-etched surface continually increased with processing-time to about 2.3 times. For both  $\text{CF}_4$  and Ar plasmas, the composition ratios exhibited similar trends when etching at gas pressures of 10 and 50 mTorr (not shown here). These results indicate that Ar plasma selectively etched N atoms from the AlGaIn surface. As shown in Fig. 4(b), the F/N ratio increased to about 1.3 with processing-time.

Figure 5 shows the depth profile of the AlGaIn sample etched with  $\text{CF}_4$  plasma at a gas pressure of 10 mTorr and a processing-time of 100 min. The normalized intensities of the Al 2p, Ga 3d, N 1s, F 1s, and O 1s peaks at the unetched surface were equal to one. The intensities of the Al 2p, Ga 3d, and N 1s peaks increased to about 1.7 times their original intensities when the surface was etched to about a 2-nm depth. Each peak then gradu-

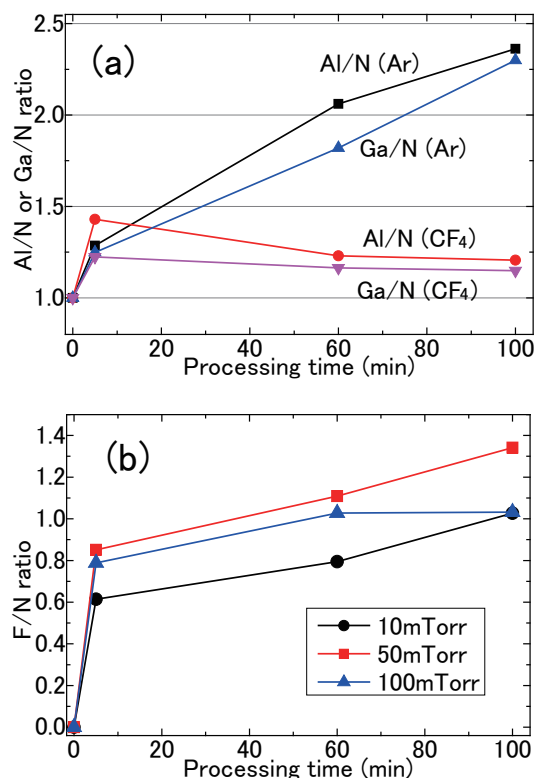


FIG. 4. Processing-time dependence of the composition ratio of the surfaces etched with CF<sub>4</sub> and Ar plasmas at a gas pressure of 100 mTorr; (a) composition ratios Al/N and Ga/N, (b) F/N ratio.

ally increased in intensity to about 2.0 times the original intensity with increasing etch depth. The reason for this sudden increase towards 2-nm depth should be that electron emission became easier after carbon contamination was removed from the sample surface. The intensities of the F 1s and O 1s peaks decreased with increasing etch depth. The F 1s peak decreased in intensity to a level below the detection limit when the etch depth reached 10 nm. This indicates that F atoms penetrated the surface of the sample to about 10 nm in depth. The O 1s peak decreased in intensity to about 0.5 when the etched depth reached 10 nm. The O 1s peak intensity of the as-grown surface was about 0.75 times that of the sample before treatment with the Ar ion beam. This should have been caused by the adsorption of oxygen atoms on the sample surface when the etched sample was exposed to air.

Figure 6 shows the N-K NEXAFS spectra obtained by the TEY method for the AlGaIn surfaces etched at a gas pressure of 100 mTorr. Figure 6(a) shows the spectra of the sample etched with CF<sub>4</sub> plasma, while Fig. 6(b) shows the spectra of the sample etched with Ar plasma. The spectrum of the as-grown sample was very similar to that of GaN [16]. The peak of the sample surface etched with CF<sub>4</sub> plasma broadened with increasing processing-time. This indicates that the crystalline structure of the AlGaIn surface was distorted. The peak of the sample surface etched with Ar plasma was more markedly broadened than that of the sample etched with CF<sub>4</sub> plasma. This indicates that the crystalline structure of the sample

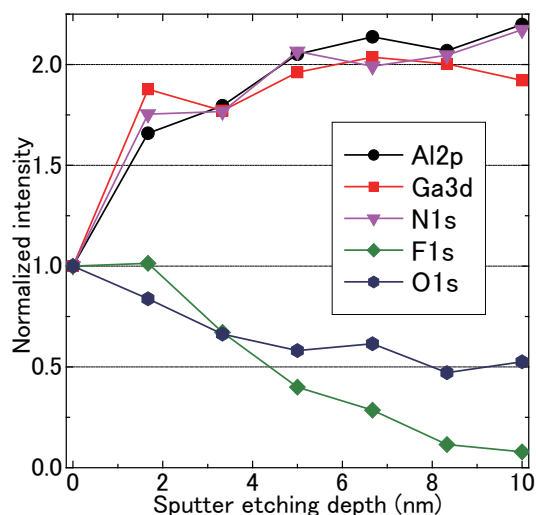


FIG. 5. Depth profile of the AlGaIn sample etched with CF<sub>4</sub> plasma at a gas pressure of 10 mTorr and a processing-time of 100 min. The normalized intensity at the unetched surface calculated using the peak intensity is equal to one.

surface etched with Ar plasma was more distorted than that with CF<sub>4</sub> plasma.

To quantitatively investigate the increase in crystalline disordering, peak fitting of the NEXAFS spectra was carried out using an Origin 8.5J peak-fitting module. As an example, the fitting result for the as-grown sample is shown in Fig. 7. A Boltzmann function was employed to remove the baseline component corresponding to the transition to continuous states [16]. The s-shaped width of the baseline function was about 0.3 eV. As shown in Fig. 7, five Gaussian peaks, G1–G5, were obtained in the energy range of 400–413 eV. Six Gaussian peaks, G1–G6, have been reported for a GaN sample in this range [16]. However, the G6 peak is negligibly small when the incident angle is 90° [17]. The Gaussian peaks G1, G3, and G6 correspond to the transition of the state of the vector orbitals along the *z*-axis obtained from the mixing of *s* and *p<sub>z</sub>* orbitals, while G2, G4, and G5 correspond to that of the plane orbitals of the *x* and *y* planes obtained from the mixing of *p<sub>x</sub>* and *p<sub>y</sub>* orbitals [16]. Further, the spectrum at the energy region higher than 413 eV could also be fitted with four Gaussian peaks.

Figure 8 shows the processing-time dependence of the G1 peak bandwidth of the N-K NEXAFS spectrum of the AlGaIn surface etched at a gas pressure of 100 mTorr, obtained by the TEY method. The reason why the G1 peak bandwidth chosen was because the G1 peak showed the most obvious change in the disturbance of the crystalline structure caused by the etching process among the peaks G1–G5. The bandwidth of the AlGaIn surface etched with CF<sub>4</sub> plasma increased to about 0.2 eV with prolonged processing-time. In contrast, that etched with Ar plasma increased to about 1.2 eV with prolonged processing-time. This result indicates that the disturbance of the crystalline structure caused by etching with CF<sub>4</sub> plasma was smaller than that with Ar plasma.

Figure 9 shows the N-K NEXAFS spectra obtained by

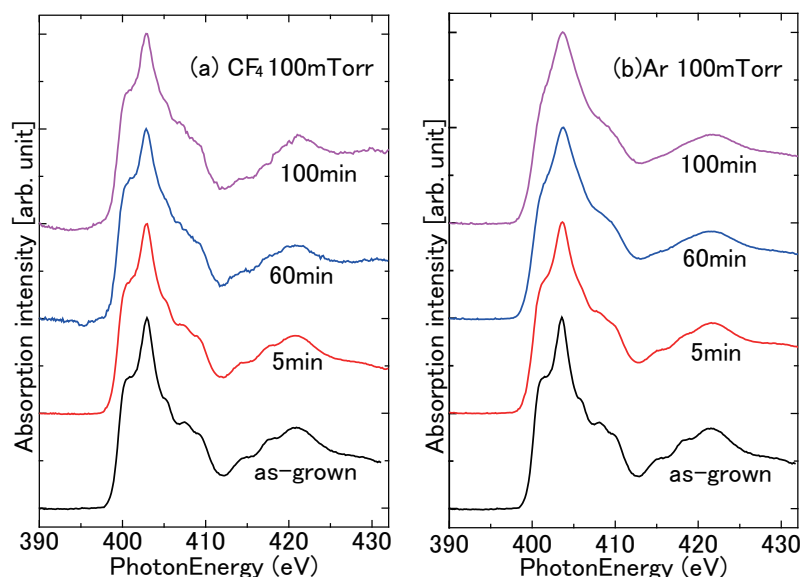


FIG. 6. N-K NEXAFS spectra of the AlGaIn surfaces etched with (a)  $\text{CF}_4$  and (b) Ar plasmas at a gas pressure of 100 mTorr, obtained by the TEY method at a soft X-ray incidence angle of  $90^\circ$  relative to the surface.

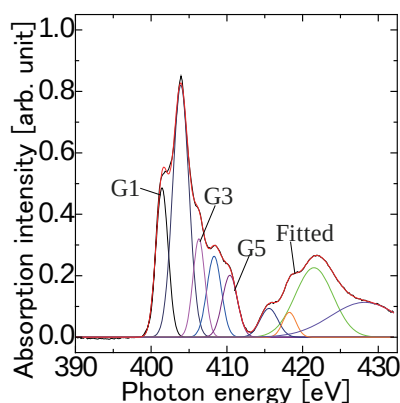


FIG. 7. Example peak fitting of the NEXAFS spectrum of the as-grown sample.

the TFY method of AlGaIn surfaces etched at a gas pressure of 100 mTorr. Figure 9(a) shows the spectra for the sample etched with  $\text{CF}_4$  plasma, while Fig. 9(b) shows the spectra for the sample etched with Ar plasma. For both  $\text{CF}_4$  and Ar plasma etching, the spectrum of the etched sample in bulk position was almost the same as that of the as-grown sample irrespective of etching time. This indicates that the crystalline structure of the AlGaIn surface was undistorted in the deep region away from the sample surface.

The surface profile and RMS roughness of the AlGaIn samples etched with  $\text{CF}_4$  plasma were the same as those of as-grown sample. However, in the case of Ar plasma, the AlGaIn surface profile was roughened significantly. The AlGaIn surface profile etched with Ar plasma was similar to that observed for  $n$ -GaIn etched with Ar plasma [8–10]. This indicates that the change in the AlGaIn surface profile was related to UV light irradiation from the Ar plasma. The effect of UV light irradiation on  $n$ -GaIn surfaces during plasma etching has also been reported in the

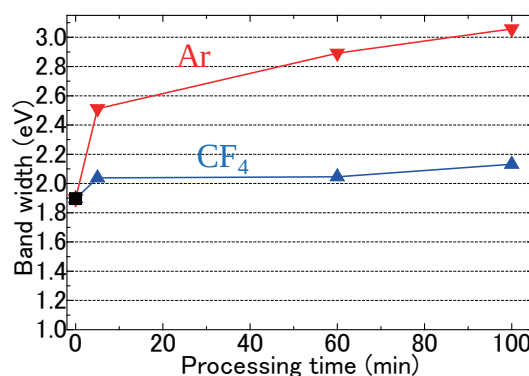


FIG. 8. Processing-time dependence of the G1 peak band-width of the N-K NEXAFS spectra of the AlGaIn surfaces etched at a gas pressure of 100 mTorr, obtained by the TEY method.

study of the UV light-assisted wet etching of  $n$ -GaIn [17, 18]. While the surface profile of  $n$ -GaIn was not changed from that of the as-grown sample when wet etching using a KOH solution, surface roughening was found to occur by wet etching under UV light irradiation at a wavelength of 365 nm [18, 19]. This should be caused by the holes generated by the UV irradiation causing surface dissolution through chemical reaction, which is distributed unevenly owing to the dislocation of the  $n$ -GaIn surface [18, 19]. Therefore, the same mechanism should occur in the case of dry etching; the observed surface roughening of AlGaIn should have been caused by the effect of UV light emitted from the plasma.

Using the XPS and NEXAFS measurements, we found that the change in the surface composition and the disordering of the crystalline structure, which could not be seen in SEM observations, also occurred during  $\text{CF}_4$  plasma etching. The surface composition and crystalline structure of the AlGaIn etched by Ar plasma changed more

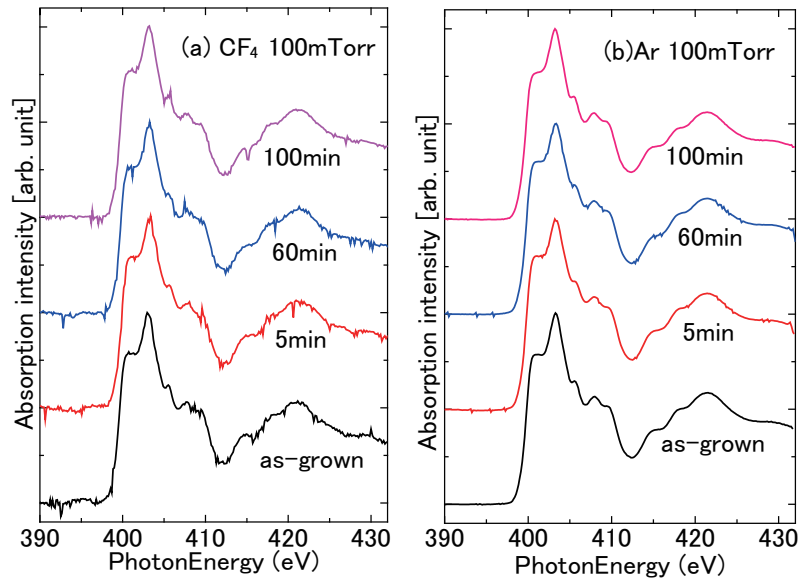


FIG. 9. N-K NEXAFS spectrum of the AlGaIn surfaces etched with (a)  $\text{CF}_4$  and (b) Ar plasmas at a gas pressure of 100 mTorr, obtained by the TFF method at a soft X-ray incidence angle of  $90^\circ$  relative to the surface.

significantly than in the case of  $\text{CF}_4$  plasma etching. Previously, we reported that the surface roughening of  $n$ -GaIn induced by He plasma etching was increased by UV light irradiation of the  $n$ -GaIn using a black light [21]. This should be because the Ga-N bond is weakened by UV irradiation. Therefore, in the same manner, the Ar plasma would have selectively etched the N atoms from the AlGaIn surface because the bond between the Ga-N and Al-N atoms was weakened by the UV light from the Ar plasma. In contrast, the main species of  $\text{CF}_4$  plasma should be  $\text{CF}_3^+$  ions and F radicals [14]. The formation of non-volatile fluorine compounds of  $\text{Al}(\text{OH})_x\text{F}_y$  and  $\text{GaF}_x$  has previously been suggested for AlGaIn surfaces etched with  $\text{CF}_4$  plasma even for a short time [11]. Thus, the suppression of the selective etching of N would have been caused by the formation of these fluorine compounds protecting the AlGaIn surface.

#### IV. SUMMARY

The AlGaIn surface etched with  $\text{CF}_4$  plasma was as smooth as the as-grown sample; pronounced surface roughening did not occur. In contrast, in the case of Ar plasma etching, surface roughening occurred at a gas pres-

sure of 50 and 100 mTorr. The Al/N and Ga/N ratios of the AlGaIn surface etched with  $\text{CF}_4$  increased by about 1.3 times with prolonged processing-time. In the case of Ar, the ratios increased by about 2.3 times. The N-K NEXAFS peak observed for the sample etched with Ar plasma became more significantly broadened with increasing processing-time than that of the  $\text{CF}_4$  plasma-etched sample. Thus, the damage to the crystalline structure by the  $\text{CF}_4$  plasma was smaller. The observed changes in the shape and crystalline structure of the AlGaIn surface were considered to be caused by the synergistic effect of UV light irradiation from the plasma and ion bombardment of the sample surface. F atoms (ions) penetrated the sample surface to a depth of about 10 nm. The results of this study provide important information for understanding defect formation when considering the mechanisms of normally-off of HEMT devices processed with  $\text{CF}_4$  plasma.

#### ACKNOWLEDGMENTS

This study is supported by a Grant-in-Aid from the Ministry of Education and Science of Japan through the Scientific Research Program (C) (No. 26390066).

- [1] T. Katsuno, T. Manaka, T. Ishikawa, H. Ueda, T. Uesugi, and M. Iwamoto, *Appl. Phys. Lett.* **104**, 252112 (2014).
- [2] A. Soltani, M. Rousseau, J.-C. Gerbedoen, M. Mattallah, P. Bonanno, A. Telia, N. Bourzgui, G. Patriarche, A. Ougazzaden, and A. BenMoussa, *Appl. Phys. Lett.* **104**, 233506 (2014).
- [3] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer *et al.*, *J. Appl. Phys.* **85**, 3222 (1999).
- [4] H. Kambayashi, Y. Satoh, S. Ootomo, T. Kokawa, T. Nomura, S. Kato, and T. P. Chow, *Solid-State Electron.* **54**, 660 (2010).
- [5] Y. Cai, Y. Zhou, K. M. Lau, and K. J. Chen, *IEEE Trans. Electron Devices* **53**, 2207 (2006).
- [6] P. Kotara, O. Hilt, H. Kirmse, J. Würfl, W. Neumann, and G. Tränkle, *Phys. Status Solidi C* **8**, 2207 (2011).
- [7] W. J. Ha, S. Chhajed, S. J. Oh, S. Hwang, J. K. Kim, J. H. Lee, and K. S. Kim, *Appl. Phys. Lett.* **100**, 132104 (2012).

- [8] R. Kawakami, T. Inaoka, S. Minamoto, and Y. Kikuhara, *Thin Solid Films* **516**, 3478 (2008).
- [9] R. Kawakami, T. Inaoka, A. Kuwahara, K. Tominaga, and T. Mukai, *Jpn. J. Appl. Phys.* **47**, 6863 (2008).
- [10] R. Kawakami, M. Niibe, Y. Nakano, M. Konishi, Y. Mori, A. Takeichi, K. Tominaga, and T. Mukai, *Jpn. J. Appl. Phys.* **52**, 05EC05 (2013).
- [11] R. Kawakami, M. Niibe, Y. Nakano, T. Shirahama, S. Hirai, and T. Mukai, *Proc. International Symp. Dry Process (DPS2014)* P69 (2014).
- [12] C. D. Wagner, L. E. Davis, M. V. Zeller, J. A. Taylor, R. H. Raymond, and L. H. Gale, *Surf. Interface Anal.* **3**, 211 (1981).
- [13] M. Niibe, T. Kotaka, and T. Mitamura, *J. Phys. Conf. Ser.* **425**, 132008 (2013).
- [14] R. Kawakami and T. Inaoka, *Vacuum* **83**, 490 (2008).
- [15] NIST Physics Laboratory, <http://physics.nist.gov/>.
- [16] M. Katsikini, E. C. Paloura, and T. D. Moustakas, *J. Appl. Phys.* **83**, 1437 (1998).
- [17] M. Niibe, T. Kotaka, R. Kawakami, Y. Nakano, T. Inaoka, K. Tominaga, and T. Mukai, *Jpn. J. Appl. Phys.* **52**, 01AF04 (2013).
- [18] C. Youtsey, I. Adesida, and G. Bulman, *Appl. Phys. Lett.* **71**, 2151 (1997).
- [19] S. J. Cho, S. Doğan, S. Sabuktagin, M. A. Reshchikov, and D. K. Johnstone, *Appl. Phys. Lett.* **84**, 3070 (2004).
- [20] C. Youtsey, L. T. Romano, R. J. Molnar, and I. Adesida, *Appl. Phys. Lett.* **74**, 3537 (1999).
- [21] R. Kawakami, M. Niibe, Y. Nakano, T. Shirahama, K. Aoki, K. Oba, M. Takabatake, and T. Mukai, *Thin Solid Films* **570**, 81 (2014).