Mechanism of ohmic-contact formation between Ti electrodes and Al$_{x}$Ga$_{1-x}$N
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1. Introduction
Ohmic contacts between metal electrodes and nitride semiconductors with low resistivities are required to improve the device performance. For n-type GaN, Ti-based contacts have been extensively used due to several advantages such as a low work function and cost performance [1-3]. The most important one is that Ti-based contacts decrease the resistance by a chemical reaction and behave as an ohmic characteristic by the annealing above 500 °C [4]. This behavior is explained by the creation of nitrogen vacancies at an interfacial GaN layer by the formation of metallic TiN compounds through the annealing [4,5]. Ti-based electrodes have also been examined for Al$_{x}$Ga$_{1-x}$N with low Al ratio, and the annealing process has also been performed after the deposition of electrodes [6]. To clarify the mechanism of low-resistance ohmic-contact formation at Ti/Al$_{x}$Ga$_{1-x}$N interface, the investigations for energy-band structures are required. In this study, we have investigated the chemical reaction at a Ti/n-Al$_{x}$Ga$_{1-x}$N interface by photoemission spectroscopy to discuss the mechanism of the ohmic-contact formation comparing to the results of the Ti/GaN interface.

2. Experimental
Al$_{x}$Ga$_{1-x}$N and GaN samples used in this study were grown by metalorganic chemical vapor deposition on c-plain sapphire substrates. The thicknesses of both n-type GaN and Al$_{x}$Ga$_{1-x}$N layer were 0.2 μm. To remove the surface contamination, samples were dipped into a boiled 39% HCl solution for 50 min. After that, the 0.3-nm thick Ti layer was evaporated in ultrahigh vacuum (UHV). Photoemission spectroscopy was performed at the beam line BL-1C of Photon Factory in KEK.

3. Results and discussion
Figure 1 shows current-voltage characteristics of Ti electrodes/n-Al$_{x}$Ga$_{1-x}$N before and after the annealing at 500 °C for 10 min. The annealing drastically decreased the resistances, which was consistent with the case of Ti/GaN. The degree of decrease in the resistance of Ti/Al$_{x}$Ga$_{1-x}$N was smaller than that of Ti/GaN.
Valence-band spectra for Al$_{x}$Ga$_{1-x}$N and GaN taken at hv=100 eV are shown in Fig. 2. Spectral line shapes changed by annealing after the Ti deposition, suggesting the interfaces reaction. Satellite structures in Ti 2p photoemission spectra at 500 °C indicate the formation of the TiN compound at the interface. Similar phenomena were observed for Ti/GaN interface [4]. Furthermore, Ga 3d, N 1s, and Al 2p peaks shifted to the lower binding energy by annealing. The amounts of shifts for Ti/Al$_{x}$Ga$_{1-x}$N were smaller than those for Ti/ GaN. These results indicate that the annealing process promotes the formation of TiN and AlGaN layers with N vacancies at the interface, resulting in decrease in contact resistivity.

![Figure 1: Current-voltage characteristics of Ti electrodes/n-type Al$_{x}$Ga$_{1-x}$N before and after the annealing at 500 °C](image1.png)

![Figure 2: Annealing-temperature dependence in valence-band spectra](image2.png)

References