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Citation	Japanese Journal of Applied Physics. Pt. 2, Letters & express letters, 45(4-7), L111-L113 https://doi.org/10.1143/JJAP.45.L111
Issue Date	2006-02
Doc URL	http://hdl.handle.net/2115/33075
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Type	article (author version)
File Information	JJAP-Letter-06.pdf

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Japanese J. Applied Physics **45**, L111-113 (2006)

Surface Control Process of AlGaN for Suppression of Gate Leakage Currents in AlGaN/GaN Heterostructure Field Effect Transistors

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(Received

We proposed a surface control process for suppressing the tunneling leakage of Schottky gates on AlGaN/GaN heterostructures. For the recovery of nitrogen-vacancy-related defects and reduction in the amount of oxygen impurities at the AlGaN surface, the process consisted of nitrogen radical treatment, the deposition of an ultrathin Al layer, UHV annealing and finally the removal of the Al layer. Ni/Au Schottky gates fabricated on processed AlGaN surfaces showed pronounced reduction in leakage current and a clear temperature dependence of I-V characteristics, indicating the effective suppression of tunneling leakage in current transport through AlGaN Schottky interfaces.

KEYWORDS: AlGaN, GaN, gate leakage current, tunnel, surface control, XPS

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AlGaN/GaN heterostructure field effect transistors (HFETs) using Schottky gates suffers from serious gate leakage problems[1,2] that not only impede device reliability but also degrade power efficiency and noise performance. To control leakage current, much effort has been devoted to clarify the leakage mechanism through Schottky interfaces fabricated on GaN and AlGaN surfaces.

Yu *et al.*[3] and Miller *et al.*[4] discussed the leakage mechanism in GaN and AlGaN Schottky interfaces on the basis of field-emission tunneling transport assuming a triangular Schottky potential. However, unreasonably higher donor densities than the actual doping concentration were necessary in their calculation to reproduce experimental data. Thus, they expected some other processes such as defect-assisted tunneling to increase leakage current. Sawada *et al.*[5] proposed a surface patch model to explain forward current characteristics. Miller *et al.*[6] have recently suggested a leakage mechanism associated with a variable-range-hopping conduction through threading dislocations.

We have reported[7] that the enhancement of tunneling transport processes by barrier thinning caused by processing-induced surface-defect donors is the dominant mechanism associated with large leakage currents through GaN Schottky interfaces. The most possible surface donors are nitrogen-vacancy (V_N)-related defects.[8,9] On the basis of this model, we could reproduce experimental *I-V-T* curves of GaN Schottky diodes for both forward and reverse biases at different temperatures.[7] However, this is not the case for Schottky interfaces fabricated on AlGaN/GaN heterostructures. Figure 1 shows typical I-V characteristics of Ni/Au contacts with a diameter of 600 μm on *n*-GaN ($n = 1 \times 10^{17}$ cm^{-3}) and AlGaN/GaN heterostructures, both grown by metal-organic vapor phase epitaxy (MOVPE). The Schottky dot was surrounded by a ring-shaped Ti/Al/Ti/Au ohmic contact. In spite of the fact that these samples were prepared by the same process at the same time, much larger leakage currents appeared in the AlGaN/GaN samples than in the GaN sample. In addition, the AlGaN/GaN samples showed a pronouncedly poor temperature dependence of current. These results clearly indicate the enhancement of tunneling components in leakage currents through Schottky interfaces on AlGaN/GaN heterostructures, particularly for the sample having a higher Al composition. It is noted that the nearly flat behavior of leakage current at a reverse bias arises from the channel pinch-off under a Schottky gate. If processing-induced V_N-related donors play a dominant role in the tunneling leakage mechanism, a similar leakage behavior could be observed in the heterostructure samples. This requires the contribution of additional surface donor states to the leakage mechanism in AlGaN Schottky interfaces.

High-density oxygen impurities were detected in AlGaN layers grown by molecular beam epitaxy.[10,11] By a chemical analysis using scanning photoemission spectroscopy, Jang *et al*.[12] observed the incorporation of high-density oxygen impurities into the AlGaN surface grown by MOVPE. Recently, a secondary ion mass spectroscopy has shown the existence of oxygen atoms with a density of 8×10^{18} cm^{-3} in MOVPE AlGaN.[13] Oxygen impurities incorporated into GaN act as shallow donors with an activation energy of about 30 meV.[14,15] Thus, we considered oxygen impurities as one of the most possible candidates for additional donor states, as shown in Fig. 2, which can enhance tunneling transport at the AlGaN Schottky interfaces.

In this regard, we have developed a surface control process for suppressing tunneling leakage through AlGaN Schottky interfaces, as schematically shown in Fig. 3. The process focused on the recovery of V_N vacancies and the reduction in the amount of oxygen impurities from the AlGaN surface. We used the $Al_{0.25}Ga_{0.75}N$/undoped GaN/buffer GaN/sapphire structure with an AlGaN thickness of 25 nm. After cleaning the sample in organic solutions, rf-excited nitrogen radicals were introduced into the AlGaN surface at 300 ºC for 5 min in a molecular-beam epitaxy (MBE) chamber. The base pressure of the chamber was 5 x 10^{-10} Torr. This process is effective in improving the surface electronic properties of GaN and AlGaN.[16-18)] An Al layer with a nominal thickness of 1 nm was deposited at a rate of 0.5 nm/min using a Knudsen cell at room temperature (RT), followed by *in situ* annealing at 700 ºC for 10 min. The deposited Al layer was then removed in a buffered HF solution. Finally, we fabricated a Ni/Au Schottky contact on the processed AlGaN surface by standard electron-beam deposition. The gate area was 1 x 60 μm. The gate-source and the gate-drain distances were 2 μm.

To investigate the chemical properties of the AlGaN surface, we carried out *in situ* X-ray photoelectron spectroscopy (XPS) using Perkin Elmer PHI 1600. The XPS chamber is connected to the MBE chamber via an ultra-high vacuum (UHV) transfer chamber. Figure 4 shows the Al2*p* core-level spectra from the $Al_{0.25}Ga_{0.75}N$ surface after the deposition of the 1-nm thick Al layer and the subsequent UHV annealing. Immediately after the Al deposition, a clear metallic Al peak was observed in the XPS spectrum. By angle-resolved analysis, we confirmed the layer formation of Al. A weak faint peak indicated that a small amount of natural oxide remained on the AlGaN surface even after the N* radical treatment.

Surprisingly, the metallic Al peak disappeared after the UHV annealing, as shown in the upper spectrum in Fig. 4. Furthermore, we found a marked increase in the oxide peak whose energy position is very close to that of Al_2O_3. A residual oxide of AlGaN consists of Al and Ga oxides.[17)] Ga oxide component seems to convert to Al oxide during the UHV annealing, because of the high reactivity of Al and the higher heat of formation of Al oxide than that of Ga oxide. The Ga3*d* spectrum (not shown here) supported this reaction. Jung *et al*.[19)] reported a similar conversion of an ultrathin SiO_2 layer into an Al oxide layer by an assist of a thin Al layer during the UHV annealing at 800 ºC. In addition, it was likely that the UHV annealing induced a gettering of oxygen impurities from the AlGaN surface into the Al layer, as shown in Fig. 3, also because of the high reactivity of Al with oxygen.

Thus, after removing the topmost layer in BHF solution, it was expected that the densities of V_N-related defects and oxygen impurities significantly devreased from the AlGaN surface. To investigate the effect of the present surface process on gate leakage characteristics in AlGaN/GaN HFETs, we carried out I_{GS}-V_{GS}-T measurements under the open-drain condition.

Figure 5 shows a comparison of I_{GS}-V_{GS}-T characteristics of Ni/Au Schottky gates on $Al_{0.25}Ga_{0.75}N$/GaN HFETs without and with the surface control process. Both devices showed almost the same threshold voltages and source resistances. Again, large leakage currents and a poor temperature dependence of the I-V characteristics were observed for the sample without the control process. On the other hand, the Schottky gate with the surface process showed a significant reduction in leakage currents at RT as well as at low temperatures, as shown in the bottom curves in Fig. 5. In addition, a clear temperature dependence of the I-V characteristics was observed, indicating the effective suppression of the tunneling leakage component especially in the low gate-bias region. A similar effect was also observed for the Ni/Au Schottky diodes with the surface process and having large areas (diameter: 200-600 μm). It is noted that an increase in current at larger negative biases at 150 K is a result of an intrinsic tunneling effect caused by a rather thin AlGaN barrier, which was confirmed by theoretical calculation. Although separate experiments showed that either nitrogen radical treatment or the process consisting of Al deposition and UHV annealing could reduce gate leakage current, the combination of both processes was found to be most effective in reduction in the tunneling leakage currents through a Schottky barrier. Thus, the result obtained reflects that the present surface process seems to reduce the amount of V_N-related defects and/or oxygen impurities near the AlGaN surface, suppressing the turbulence of the potential distribution. Since it is expected that the densities of point defects and residual impurities in AlGaN are dependent on Al composition, further study of the leakage mechanism using AlGaN layers with various Al compositions is necessary.

In summary, we proposed a surface control process for reducing the tunneling leakage current of Schottky gates on AlGaN/GaN heterostructures. The process consisted of nitrogen radical treatment, the deposition of an ultrathin Al layer, UHV annealing and finally the removal of the Al layer. Ni/Au Schottky gates fabricated on processed AlGaN surfaces showed a pronounced reduction in leakage current and a clear temperature dependence of I-V characteristics, indicating the effective suppression of tunneling leakage in current transport. Thus, the present surface process can improve AlGaN Schottky interface properties, probably as a result of the reduction in the amount of V_N-related defects and oxygen impurities.

This work was partly supported by 21st Century COE Project on "Meme-Media-Based Next-Generation ITs" from MEXT, Japan.

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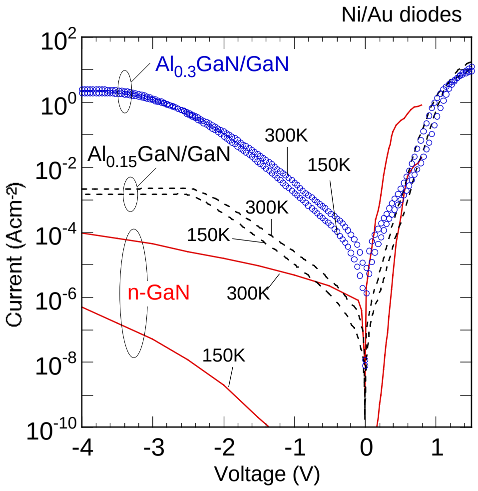

Fig.1 Typical I-V-T curves of Ni/Au Schottky contacts with a diameter of 600 μm on GaN and AlGaN/GaN heterostructures. The thickness of AlGaN barrier layer is 23 nm.

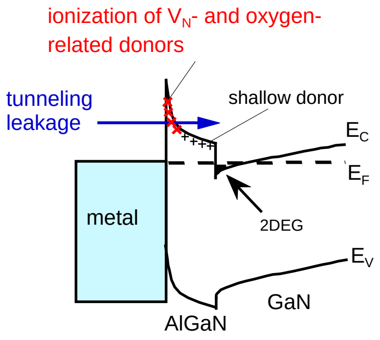

Fig.2 Schematic of thinning of Schottky potential in AlGaN/GaN heterostructure caused by the ionization of V_N- and oxygen-related donors.

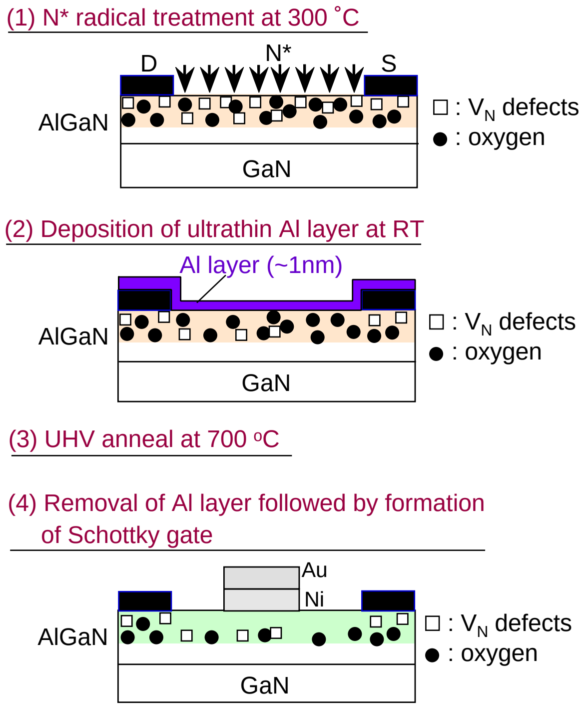

Fig.3 Flow chart of surface control process for suppressing tunneling leakage.

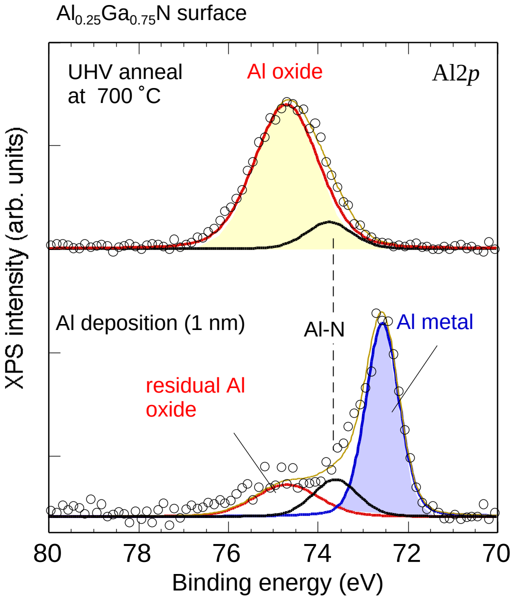

Fig.4 XPS Al2*p* spectra from the Al0.25Ga0.75N surface after deposition of Al layer and subsequent UHV annealing.

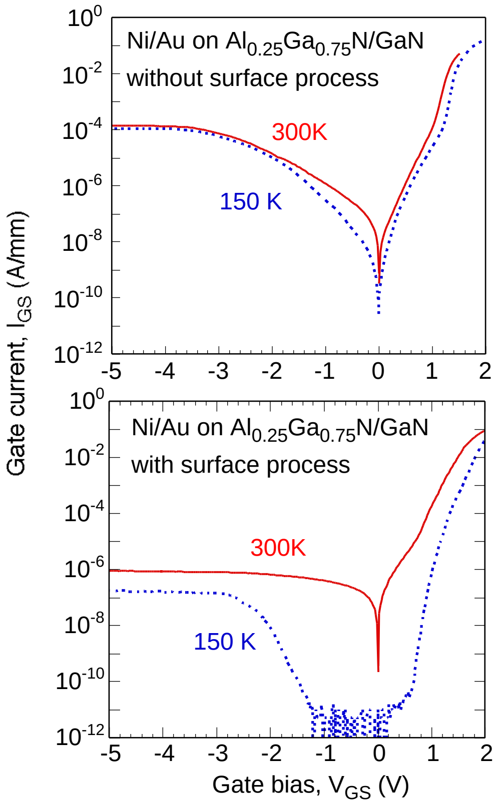

Fig.5 Gate I-V characteristics of Al0.25Ga0.75N/GaN HFETs without and with surface control process. The gate area is 1 x 60 μm. The gate-source and the gate-drain distances are 2 μm.