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High-Voltage AlGaN/GaN High-Electron-Mobility Transistors Using Thermal Oxidation for NiO_x Passivation

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Abstract – We proposed AlGaN/GaN high-electron-mobility transistors (HEMTs) using thermal oxidation for NiOx passivation. Auger electron spectroscopy, secondary ion mass spectroscopy, and pulsed I-V were used to study oxidation features. The oxidation process diffused Ni and O into the AlGaN barrier and formed NiOx on the surface. The breakdown voltage of the proposed device was 1520 V while that of the conventional device was 300 V. The gate leakage current of the proposed device was 3.5 μA/mm and that of the conventional device was 1116.7 μA/mm. The conventional device exhibited similar current in the gate-and-drain-pulsed I-V and its drain-pulsed counterpart. The gate-and-drain-pulsed current of the proposed device was about 56 % of the drain-pulsed current. This indicated that the oxidation process may form deep states having a low emission current, which then suppresses the leakage current. Our results suggest that the proposed process is suitable for achieving high breakdown voltages in the GaN-based devices.

Keywords: AlGaN, GaN, HEMT, Oxidation, Nickel oxide

1. Introduction

GaN is a promising wide-band-gap material for microwave and high-power applications due to its high critical field, high electron mobility, and low intrinsic carrier concentration [1-3]. The two-dimensional electron gas which exists at AlGaN / GaN interface has the advantages of high current capability and low on-resistance [4]. A highly conductive channel is naturally formed at the interface without any intentional doping because surface states donate electrons to the channel for charge neutrality [4]. However, the surface states on AlGaN/GaN induce electron-trapping problems such as a virtual gate [5] and surface leakage current [6]. Electron trapping at shallow states on the surface occurs in the form of a leakage current path owing to the conduction and ionization on the surface [7].

In an effort to address these surface problems, various passivation methods [6-9] and surface treatments [9-12] have been studied. Si_3N_4 passivation [6,7] has widely used to suppress the RF dispersion in microwave applications. SiO_2 passivation [8, 9] reportedly improves the blocking characteristics of high-voltage switches. Post-annealing [10] or oxidation [11] methods have also been proposed to improve the breakdown voltage and gate leakage current. NiO_x has been studied as a p-type ohmic contact in GaN light-emitting diodes [12]. It has also been reported that NiO_x can be used in the gate of normally-off AlGaN/GaN high-electron-mobility transistors (HEMTs) [13] and MOS-HEMTs [14]. The authors successfully suppressed the leakage current of GaN Schottky barrier diodes via oxidation during the fabrication process [11].

In this paper, we fabricated high-voltage AlGaN/GaN HEMTs using thermal oxidation for NiO_x passivation. After the Schottky contact of the devices was constructed, metallic Ni was deposited on the surface and oxidized in O_2 ambient. Auger electron spectroscopy (AES) and secondary ion mass spectroscopy (SIMS) were used to verify the changes after oxidation. We studied the oxidation mechanisms, which were the formation of NiO_x and the diffusion of Ni and O into the AlGaN barrier. We also measured the pulsed I-V to investigate evidence of deep states formed during the oxidation process. The leakage current of the proposed device with NiO_x passivation decreased by nearly two orders of magnitude compared to that of a conventional device. The highest breakdown voltage of 1520 V in the proposed device was achieved at a gate-drain distance of 18 μm.

2. Fabrication

A cross-sectional view of the proposed AlGaN/GaN HEMT using thermal oxidation for NiO_x passivation is shown in Fig. 1. The AlGaN/GaN heterostructure was grown on a semi-insulating 4H-SiC substrate by metal-organic chemical vapor deposition. A nucleation layer, a 3-μm-thick unintentionally doped (UID) GaN buffer, a 30-

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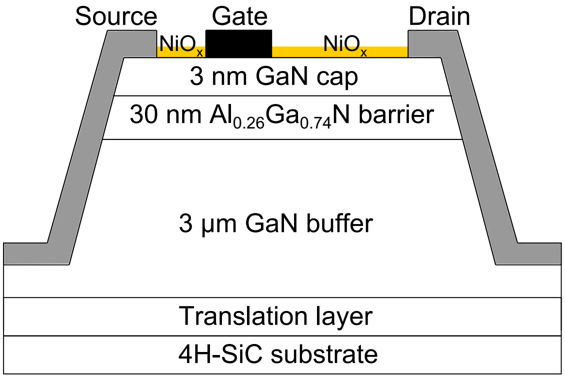


Fig. 1. Cross-sectional view of the proposed AlGaN/GaN HEMT using thermal oxidation for NiO$_x$ passivation

nm-thick UID Al$_{0.26}$Ga$_{0.74}$N barrier, and a 3-nm-thick UID GaN cap layer were grown in sequence. 270-nm-deep mesa structures were formed by Cl$_2$-based inductively coupled plasma reactive-ion etching. Ohmic contacts for the source and drain, Ti/Al/Ni/Au (20/80/20/100 nm), were deposited by an e-gun evaporator and their patterns were defined by a lift-off method. The ohmic contacts were annealed at 870 °C for 30 s in N$_2$ ambient. A Schottky contact for the gate, Ni/Au/Ni (30/150/30 nm), was deposited by the e-gun evaporator. This pattern was also defined by the lift-off method. 10-nm-thick Ni was deposited on the surface. Finally, oxidation involving the formation of NiO$_x$ in O$_2$ ambient was performed to passivate the surface. The oxidation temperature and time were 500 °C and 300 s, respectively. Conventional devices were also fabricated without a NiO$_x$ passivation layer. The widths of the devices were 50 µm. The gate-source distance, gate length, and gate-drain distance of the devices were 2, 7, and 18 µm, respectively.

3. Experimental Results and Discussion

The oxidation process was expected to form the NiO$_x$ compound on the surface because metallic Ni was exposed to O$_2$ ambient. We studied the oxidation mechanisms of the proposed AlGaN/GaN HEMTs using AES and SIMS. Test samples were prepared according to the fabrication process of the proposed devices. The oxidation temperatures were 300, 500, and 700 °C, respectively. The oxidation time was 300 s in all samples. Fig. 2 shows the AES-depth profiles of metallic Ni on AlGaN/GaN before oxidation. The elements in the samples were measured from the surface to the AlGaN barrier. The sputtering rate was 3.4 nm/s under the SiO$_2$ target. Ordinary native oxide was found at the top of Ni and Schottky interface.

However, the oxidation process mixed various elements such as Ni, O, Al, Ga, and N beneath the surface. Fig. 3 shows the Ni and O intensities of metallic Ni on AlGaN/GaN after the oxidation process. Ni and O diffused into the AlGaN barrier after the oxidation process and NiO$_x$ was formed. The thickness of the NiO$_x$ was increased by the oxidation temperature. The NiO$_x$ formed at 700 °C was thicker than the NiO$_x$ that formed at 500 °C. The NiO$_x$ layer on the surface may change the surface state and device characteristics. We cannot extract the exact thickness of the NiO$_x$ because the NiO$_x$ passivation layer contains various compounds such as GaO$_x$ and AlO$_x$. However, as the oxidation temperature increased, the NiO$_x$ thickness also increased.

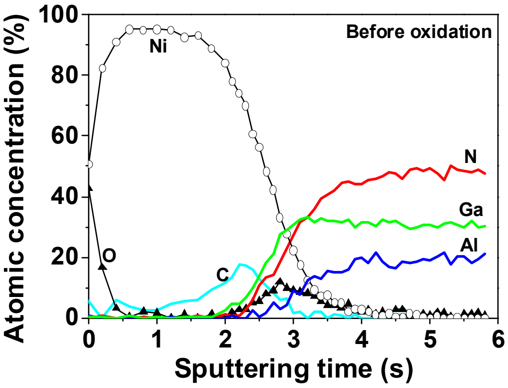


Fig. 2. AES-depth profiles of metallic Ni on AlGaN/GaN before oxidation

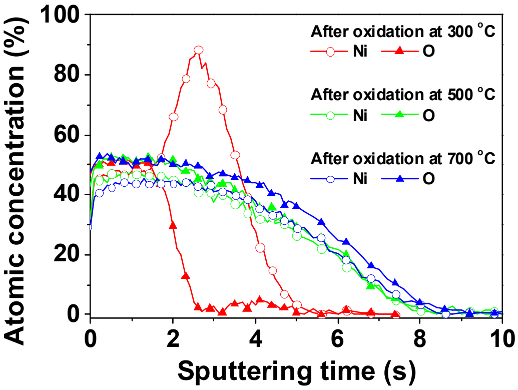
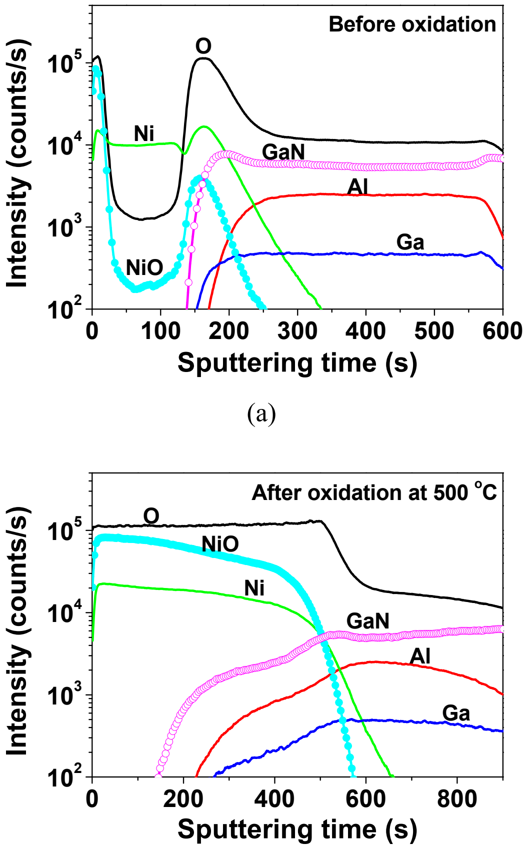


Fig. 3. Measured Ni and O intensities of metallic Ni on AlGaN/GaN after oxidation

We used the SIMS method to investigate the molecular reactions between group-III elements and O. Fig. 4 shows the SIMS depth profiles of metallic Ni on AlGaN/GaN before and after oxidation at 500 °C. The Ni- and O-depth profiles showed two peaks in the Ni surface and at the Schottky interface in a virgin sample. They existed as native oxides. However, the oxidation process broadly diffused Ni and O into AlGaN/GaN. This also formed a thick NiO layer on the surface. A mixed layer, in which GaN, Ga, Al, Ni, and O coexisted, indicates that group-III oxides possibly formed as well. Group-III oxides such as GaO$_x$ and AlO$_x$ may leave group-III (Ga or Al) vacancies [15] as deep states. The reaction process of Ni and O in the AlGaN barrier may be related to the formation of deep states. It has been reported that the deep states suppress the leakage current due to their low emission rate [9, 10].



(a)

(b)

Fig. 4. SIMS depth profiles of metallic Ni on AlGaN/GaN: (a) before and (b) after oxidation at 500 °C

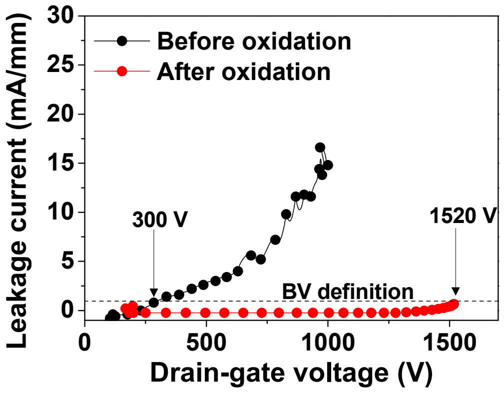


Fig. 5. Measured breakdown voltage of AlGaN/GaN HEMTs before and after oxidation

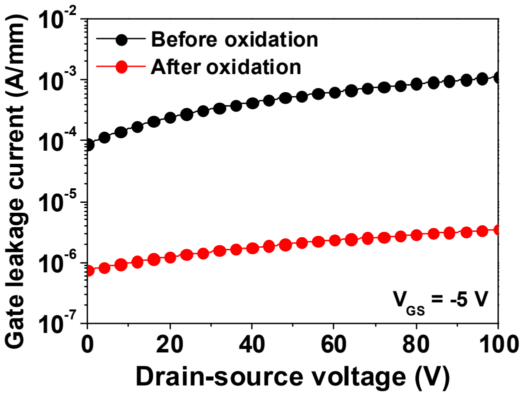


Fig. 6. Measured gate leakage current of AlGaN/GaN HEMTs before and after oxidation

We also measured test samples oxidized at 300 and other samples oxidized at 700 °C. The oxidation temperature at 300 °C cannot completely construct the NiO layer on the surface. The test sample after oxidation at 700 °C had a SIMS depth profile similar to that of the test sample after oxidation at 500 °C. The degradation of the ohmic contact resistance owing to the oxidation process should also be considered. The oxidation temperature at 500 °C is suitable for suppressing the leakage current of GaN devices.

The AlGaN/GaN HEMTs were fabricated using an oxidation process at 500 °C. First, the breakdown voltage was measured using a curve tracer. Fig. 5 shows the measured breakdown voltage of AlGaN/GaN HEMTs before and after oxidation. The breakdown voltage was defined as the reverse voltage at which the leakage current increases to 1 mA/mm. The breakdown voltage of the proposed device was 1520 V, whereas that of the conventional device was 300 V at a gate-drain distance of 18 μm. The blocking characteristics of the proposed device improved because the surface conduction was changed by the diffusion of Ni and O into the AlGaN barrier and the formation of NiO_x.

Fig. 6 shows the measured gate leakage current of AlGaN/GaN HEMTs before and after oxidation. The oxidation process suppressed the gate leakage current from 1116.7 to 3.5 μA/mm at a drain-source voltage (V_{DS}) of 100 V and a gate-source voltage (V_{GS}) of -5 V. The virgin device exhibited soft breakdown characteristics as well as a high leakage current. The proposed device sustained a low leakage current until breakdown. The oxidation process can form deep states which suppress the gate leakage current [9, 10]. The deep states as a result of the oxidation process are explained by the subsequent pulsed I-V.

We also investigated dependence of the gate-drain distance on the breakdown voltage and leakage current. We fabricated the proposed AlGaN/GaN HEMTs with different gate-drain distances of 10, 14, and 18 μm. Fig. 7 shows the dependence of the gate-drain distance on the breakdown voltage of the proposed devices. The breakdown voltage of the proposed devices was about 700, 1100, and 1500 V at gate-drain distances of 10, 14, and 18 μm. The gate leakage current of the proposed devices averaged 4.14, 4.35, and 3.63 μA/mm at gate-drain distances of 10, 14, and 18 μm. The breakdown voltage was improved by increasing the gate-drain distance. However, we did not find strong dependence of the gate-drain distance on the leakage current because the leakage current was successfully suppressed by NiO_x passivation.

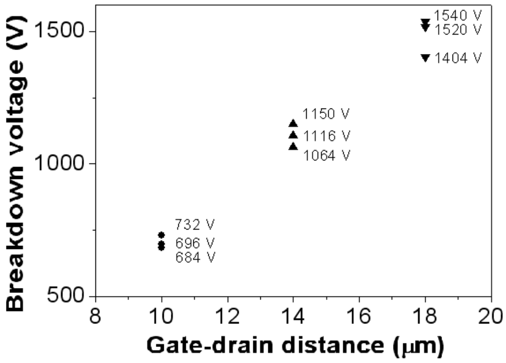
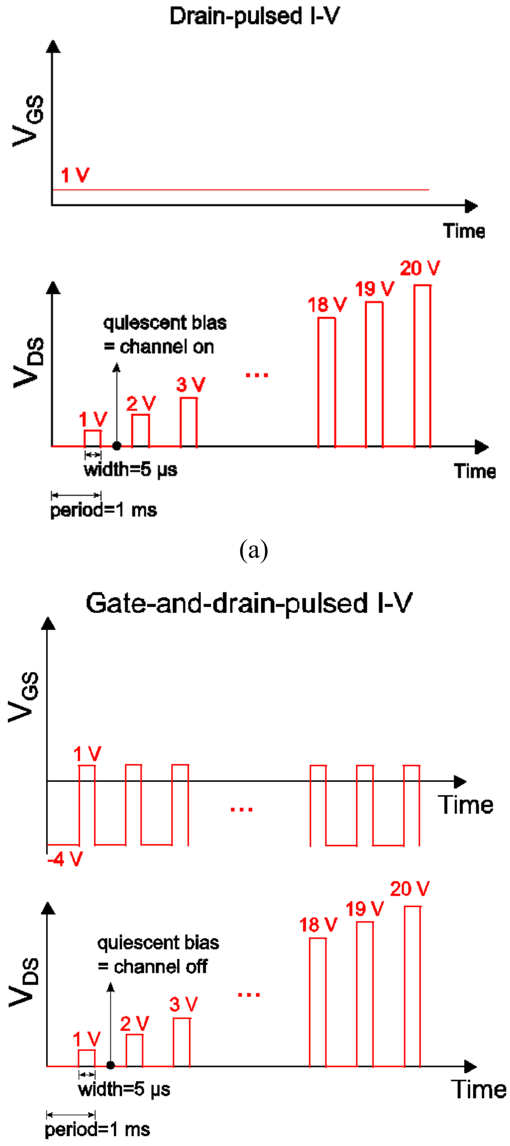


Fig. 7. Measured dependence of the gate-drain distance on the breakdown voltage of AlGaN/GaN HEMTs



(a)

(b)

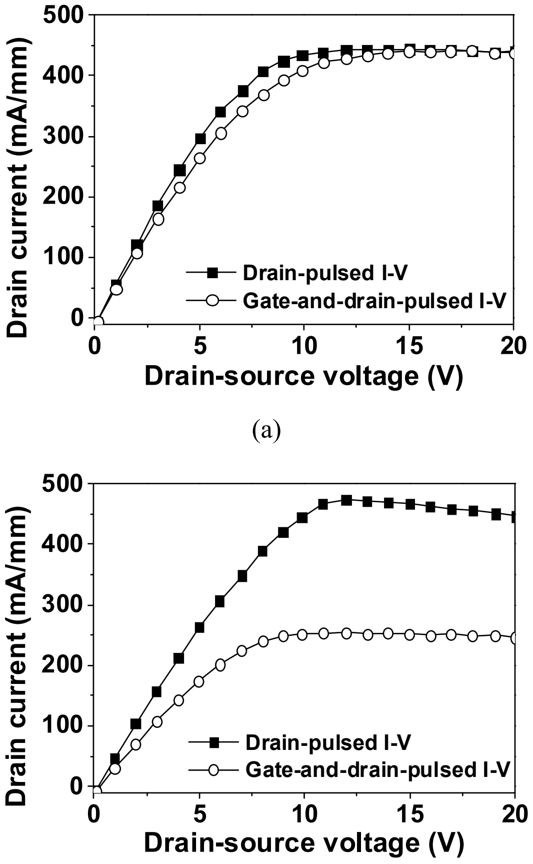
Fig. 8. Conditions for measuring: (a) the drain-pulsed and (b) the gate-and-drain-pulsed I-V of AlGaN/GaN HEMTs

The pulsed I-V of the fabricated devices was measured to investigate the trapping mechanisms that act during NiO$_x$ passivation. We measured the decrease of the forward pulsed current due to trapped electrons from a gate into surface states while excluding the effect of substrate heating. The DC I-V was affected by the substrate-heating effect, which increased scattering events at the channel. The pulsed I-V was measured in two ways: drain-pulsed and gate-and-drain-pulsed I-V measurements. Fig. 8 shows the conditions for measuring the drain-pulsed and gate-and-drain-pulsed I-V of the AlGaN/GaN HEMTs before and after oxidation. The pulse width and period were respectively 5 μs and 1 ms. The drain-pulsed I-V condition turned on the channel under quiescent bias. A constant voltage of 1 V was applied to the V$_{GS}$ while the V$_{DS}$ was pulsed from 0 to 20 V in 1 V steps during the drain-pulsed I-V measurement. The V$_{GS}$ of 1 V did not significantly affect the trapping events due to the low reverse-field or non-depletion region at the two-dimensional electron gas channel.

However, the gate-and-drain-pulsed I-V condition turned off or depleted the channel under quiescent bias. Repetitive pulses with lowest and highest voltages of -4 and 1 V, respectively, were applied to V$_{GS}$ while the V$_{DS}$ was pulsed from 0 to 20 V in 1 V steps during the gate-and-drain-pulsed I-V measurement. This quiescent bias depleted the channel, which trapped electrons at the pulse width of 5 μs. It was noted from the transfer characteristics that the threshold voltage of the proposed device was −3.9 V. If the trapping phenomena occurred on the surface, the trapped electrons were still captured at the measuring points due to the long emission time. The trapped electrons depleted the channel owing to their charge neutrality. Therefore, we can estimate the deactivation of traps by measuring the pulsed I-V after oxidation.

Fig. 9 shows the measured pulsed I-V of AlGaN/GaN HEMTs before and after oxidation. The conventional device exhibited a similar amount of current for both the drain-pulsed and the gate-and-drain-pulsed I-V. It was reported that the conventional AlGaN/GaN HEMT has shallow traps with activation energy levels below 38 meV [10]. The pulse duration of 5 μs is long enough to emit from a shallow state. Therefore, the gate-and-drain-pulsed current of the conventional device did not degrade compared to the drain-pulsed current.

However, the current of the proposed device decreased by about 56% according to the gate-and-drain-pulsed I-V measurements compared to drain-pulsed measurements. The trapped electrons in the proposed device cannot be emitted from states which induce channel depletion even with the pulse width of 5 μs. This decreases the gate-and-drain-pulsed current of the proposed device. It was also considered that the pulse duration of 5 μs was not long enough for de-trapping from the states to the conduction band. The oxidation process can form relatively deep states compared to the conventional shallow states. The emission



(a)

(b)

Fig. 9. Measured pulsed I-V of AlGaN/GaN HEMTs: (a) before and (b) after oxidation

current from deep states is lower than this from shallow states [10]. Thus, the leakage current under reverse bias was suppressed in the proposed device. The diffusion of Ni and O into AlGaN barrier and the formation of NiO_x may be responsible for the deep states and the improvement of the breakdown voltage. The proposed device suppresses the leakage current, but the trade-off relationship between the switching speed and the breakdown voltage should be considered for AC drive applications.

4. Conclusions

We fabricated high-voltage AlGaN/GaN HEMTs using NiO_x passivation. The devices were thermally oxidized by a furnace after constructing a Schottky contact. The surface reaction resulting from the oxidation process was investigated using AES and SIMS. The critical changes were the diffusion of Ni and O into the AlGaN barrier and the formation of NiO_x. The oxidation process increased the breakdown voltage from 300 to 1520 V. The gate leakage current of the proposed device was 3.5 μA/mm, while that of the conventional device was 1116.7 μA/mm. The gate-and-drain-pulsed current of the proposed device decreased by about 56% compared to the drain-pulsed current. The increase of the breakdown voltage and the decrease of the pulsed current may be caused by the formation of deep states. An oxidation process is an effective means of improving the leakage current and breakdown voltage of GaN-based power switching devices.

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