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Effects of post-oxidation on leakage current of high-voltage AlGaN/GaN Schottky barrier diodes on Si(1 1 1) substrates

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ABSTRACT

The effects of post-oxidation on the leakage current of high-voltage AlGaN/GaN Schottky barrier diodes (SBDs) on Si(1 1 1) substrates were investigated. Auger electron spectroscopy was used to study post-oxidation mechanisms. The group-III oxides, AlO_x or GaO_x, were formed as indicated the oxygen on the AlGaN layer after post-oxidation. The formation of group-III oxides resulted in passivation. The diffusion of Ni into the AlGaN layer was also detected owing to the post-oxidation annealing shallow states near the Schottky contact. When post-oxidation was performed at 600 °C, all Ni at the Schottky contact was combined with oxygen. This high post-oxidation temperature was therefore unsuitable because the Schottky interface changed from Ni/AlGaN to Au/AlGaN. Leakage current until breakdown was considerably decreased after post-oxidation at 500 °C. The breakdown voltage of GaN SBD was increased from 351 to 524 V at a drift length of 20 μm by the post-oxidation. The figure-of-merit ($BV^2/R_{on,sp}$) of identical device was also improved from 29.6 to 53.1 by the post-oxidation. Our results suggest that post-oxidation is suitable for GaN power switch fabrication.

1. Introduction

GaN devices on Si substrates have attracted considerable attention for high-voltage switching applications owing to their superior material properties [1–4]. Recently, epitaxial GaN on Si substrates with 8-in. diameter has been developed. It is known that Si substrates are not expensive compared with widely used sapphire and SiC substrates. GaN Schottky barrier diodes (SBDs) have been investigated to replace Si PiN diodes owing to their high breakdown voltage, low on-resistance, and fast reverse recovery [5,6]. It has been suggested that GaN SBDs are suitable for free-wheeling devices or DC–DC converters for power conversion.

GaN SBDs should have a safety margin for breakdown voltage to sustain their inductive energy. Various epitaxial growth methods using AlGaN/AlN buffer [7], low-temperature GaN cap [8], and AlN template [9] have been demonstrated to suppress the leakage current and soft breakdown of GaN SBDs. The process is also related to the GaN device surface leakage current, which is controlled by the Schottky contact. Surface passivation [10,11], plasma treatment [12], N_2 annealing [2,13], and oxidation [14–17] have been documented to improve the leakage current and therefore the breakdown voltage of GaN devices. We also have reported the post-oxidation of GaN SBDs with Ni-based Schottky contacts [16,17]. However, the detailed mechanism for post-oxidation has not yet been fully clarified.

The purpose of the present work was to report the effects of post-oxidation on the leakage current of high-voltage AlGaN/GaN SBDs on Si(1 1 1) substrates. Mechanisms of post-oxidation were systematically investigated on active surface as well as Ni-based Schottky contacts. Oxygen diffusion into the AlGaN was verified by Auger electron spectroscopy (AES). Formation of NiO at the Ni-based Schottky contact was also discovered. The virgin devices exhibited high leakage current at the reverse voltage. However, those oxidized sustained their low leakage current until hard breakdown. The breakdown voltage of a GaN SBD with a drift length of 20 μm was increased from 351 to 524 V owing to the post-oxidation treatment.

2. Experimental

The undoped GaN cap/undoped AlGaN/undoped GaN buffer was grown on a Si(1 1 1) substrate by metal-organic chemical vapor deposition. The thickness of the GaN cap, AlGaN, and GaN buffer was 4 nm, 20 nm, and 1.7 μm, respectively. The sheet concentration and electron mobility of the AlGaN/GaN were 7.25×10^{12} cm^2 and 1810 cm^{-2}/V s by Hall measurement, respectively. GaN SBDs were fabricated using these epitaxial layers. A

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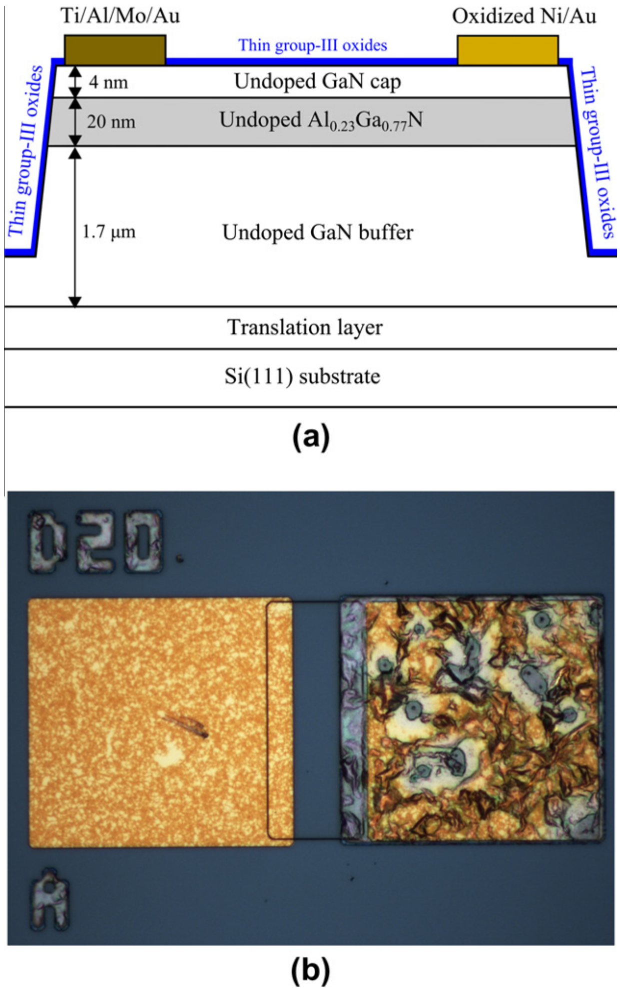

Fig. 1. (a) Cross-sectional view and (b) microscopic image of the fabricated GaN SBD using post-oxidation.

cross-sectional view and a microscopic image of the fabricated GaN SBDs are shown in Fig. 1. We fabricated four devices for post-oxidation at different temperatures. A mesa structure was formed to define active regions using BCl_3 and Cl_2. The average depth of the mesa structure for the four devices was 435 nm. A lift-off method was used to define metal patterns. The native oxide was removed during 15 s by 6:1 buffered oxide etchant. Ohmic contacts were formed by alloying Ti/Al/Mo/Au-metal stacks (20/100/25/200 nm) at 870 °C in ambient N_2 for 30 s. Schottky contacts were constructed using Ni/Au (50/500 nm). Finally, the devices were oxidized at 300, 400, 500, and 600 °C in a furnace for 300 s. The drift length was defined as the distance between Ohmic and Schottky contact, and was 5 or 20 μm. The width of the devices was 100 μm.

3. Results and discussion

3.1. Mechanism of post-oxidation

The post-oxidation treatment was expected to change the material and electrical characteristics of the GaN SBDs. We investigated its possible mechanisms using two approaches. One was measurement of the change in the active surface between Ohmic and Schottky contact while the other was measurement of the transformation of the Ni-based Schottky contact on the AlGaN. First, we measured the elements on AlGaN/GaN post-oxidized at 500 °C for 300 s by AES at an accelerating voltage of 5 keV. Fig. 2 shows the obtained AES profile of the oxidized AlGaN/GaN. The highest concentration of oxygen detected on the surface was 27.4%. The enthalpy of formation of AlN is −318.1 kJ/mol while the Gibbs formation energy of AlO_x is about −1582.3 kJ/mol, and the enthalpy of formation of GaN is −110.9 kJ/mol while the Gibbs formation energy of GaO_x is about −998.3 kJ/mol [18–20]. These theoretical values show that group-III elements including Al or Ga could outdiffuse and combine with oxygen [18]. Our AES profile indicates that the oxygen diffused into the AlGaN. The formation of AlO_x or GaO_x was also expected in AlGaN, and AlO_x was more dominant than GaO_x because the AlO_x had a lower Gibbs formation energy [18]. We also anticipated the existence of GaO_x on the mesa-etched surface as a result of the oxidation. The formation of AlO_x or GaO_x on the surface may have similar passivation features. Surface states created by process damages, dangling bonds, and threading dislocations may be passivated due to post-oxidation, and this passivation process suppresses the leakage current of GaN devices.

The transformation at the Ni-based Schottky contact on the AlGaN was also remarkable. Fig. 3 shows the measured AES profiles of Ni/Au on AlGaN after post-oxidation at 300, 400, 500 and 600 °C for 300 s. Two peaks attributed to Ni were detected at the top of Schottky contact and the interface of Ni/AlGaN, except for the sample oxidized at 600 °C. Prominent changes were the formation of NiO and the diffusion of Ni into the AlGaN. NiO was detected at the top of the Schottky contact. NiO has been pointed out as a middle layer of resistance random-access memory; ReRAM [21,22]. NiO under voltage has been found to act as a conducting filament with low resistance [21,22]. The conductance of NiO is dependent on its thickness, process conditions, and applied voltage. However, Kim et al. [23] have estimated that NiO has high resistivity under reverse operation. They fabricated AlGaN/GaN high-electron-mobility transistors with special contacts: Ni/Au on NiO (Schottky contact) and NiO/Ni/Au on alloyed Ti/Al/Mo/Au (Ohmic contact) [23]. If the NiO has high resistivity, the NiO layer in the Ohmic and Schottky contacts does not permit the flow of any current that is inconsistent with the forward current of the device. Additionally, our Schottky contact had NiO at the top of the contact, and thus was not significantly related to the Schottky interface. We therefore conclude that the conductive NiO was not considerably related to the breakdown voltage and simply increased the contact resistance.

The diffusion of Ni into AlGaN is an important oxidation mechanism. This diffusion process may anneal or passivate shallow states near Ni/AlGaN [13]. The post-oxidation of Ni-based Schottky contacts has similar characteristics to N_2 annealing because they have the diffusion of Ni into AlGaN in common. The diffusion process of Ni into AlGaN may construct new Ni and AlGaN compounds

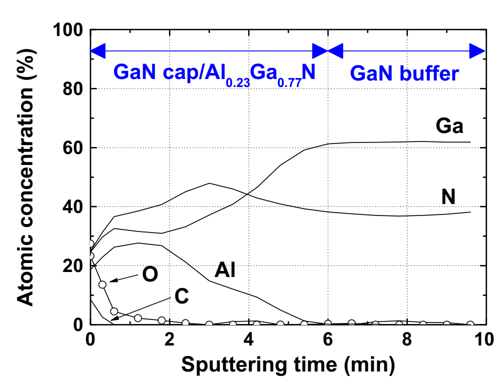

Fig. 2. Measured AES profile of AlGaN/GaN post-oxidized at 500 °C.

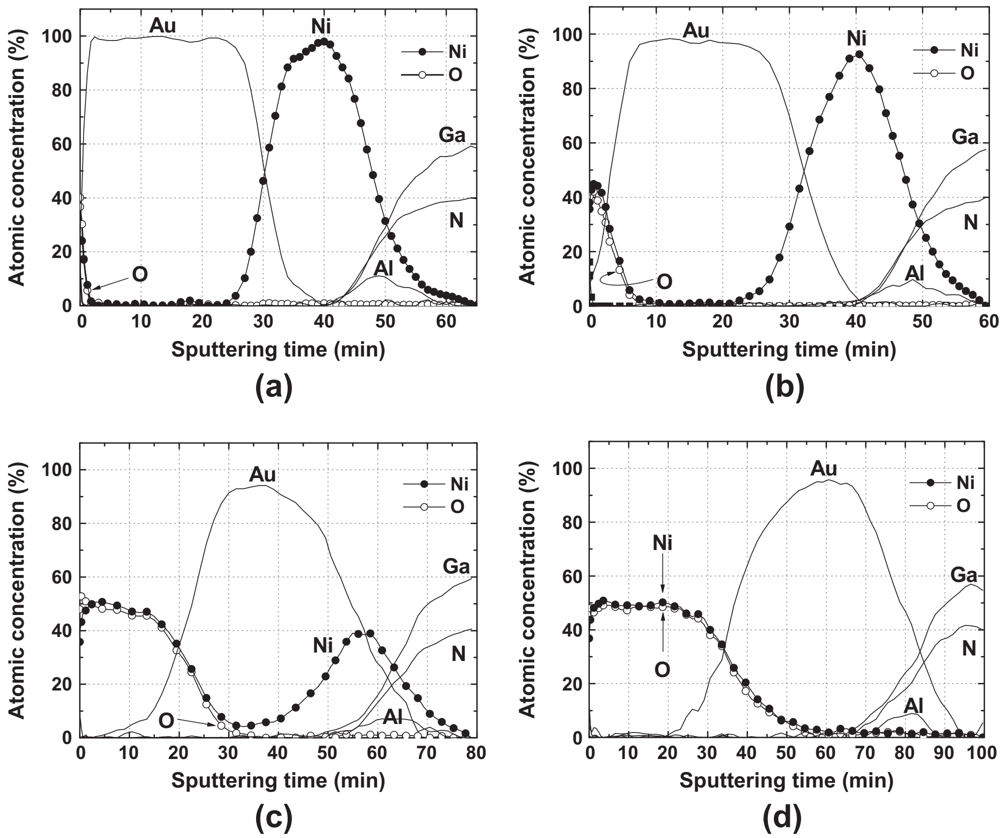

Fig. 3. Measured AES profiles of Ni/Au on AlGaN after post-oxidation at (a) 300, (b) 400, (c) 500, and (d) 600 °C.

from dangling-bonds, which activate as shallow states. The annealing of shallow states near a Schottky contact relaxes the Fermi-level pinning and suppresses the trap-assisted tunneling current. When the post-oxidation temperature was higher than 600 °C, the metallic Ni was moved to the top of the Schottky contact, which was combined with the oxygen. Additionally, the diffusion of Au into the AlGaN was increased with post-oxidation temperature. These two reactions finally changed the Schottky interface from Ni/AlGaN to Au/AlGaN when the post-oxidation was performed at 600 °C. The metal work function of Au (5.1 eV) is less than that of Ni (5.15 eV), and it is widely known that Ni has a relatively high metal work function and good adhesion on GaN [24]. A temperature 600 °C or above is not suitable for post-oxidation owing to critical change of the Schottky contact and the degradation of contact resistance.

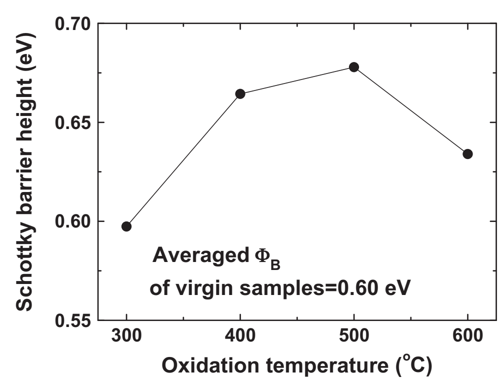

Fig. 4. Measured Schottky barrier height of GaN SBDs after post-oxidation at 300, 400, 500, and 600 °C.

3.2. Electrical characteristics of AlGaN/GaN SBDs

GaN SBDs on Si(1 1 1) substrates were fabricated and the electrical characteristics were measured. The Schottky barrier height (Φ_B) was extracted from *I–V* at the room temperature. The effective Richardson constant of 26.4 A/cm^2/K^2 was used to calculate the Schottky barrier height [25]. Fig. 4 shows the Φ_B measured after post-oxidation. The four devices had an average Φ_B of 0.60 eV before post-oxidation, but had Φ_B of 0.60, 0.66, 0.68, and 0.63 eV after oxidation at 300, 400, 500, and 600 °C, respectively. While diffusion of Ni into AlGaN was observed at 300 °C, the annealing was not enough strong to anneal the shallow states to increase Φ_B. Post-oxidation at 400 or 500 °C increased Φ_B owing to the annealing effect. Post-oxidation at 600 °C rather decreased the Φ_B because an Au/AlGaN interface was newly formed. The oxidation effect is also controlled by time; when the oxidation time is longer or shorter than our condition of 300 s, the experimental trends will change.

Fig. 5 shows the measured *I–V* of GaN SBDs before and after post-oxidation at 500 °C. The drift length of the devices was 5 or 20 μm. The post-oxidation shifted the turn-on voltage towards the positive direction. A forward voltage drop was defined at a current density of 100 A/cm^2. The forward voltage at the drift length of 5 μm increased from 0.58 to 1.06 V after post oxidation. The increases in Φ_B and the series resistance were responsible for the increases in turn-on voltage and forward voltage drop. As a result, the trade-off relationship of the post-oxidation between forward and reverse characteristics must be considered. The specific on-resistance ($R_{on,sp}$) at the drift length of 5 μm increased from 0.95 to 1.70 mΩ cm^2 after post-oxidation. The specific

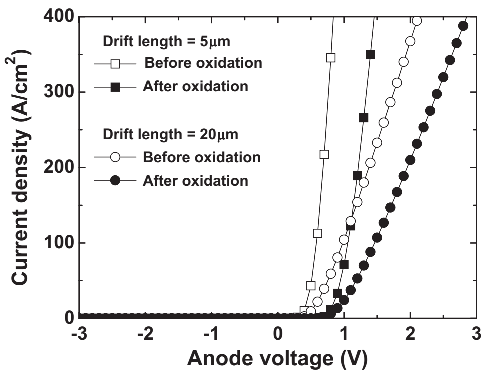

Fig. 5. Measured I–V of GaN SBDs before and after post-oxidation at 500 °C.

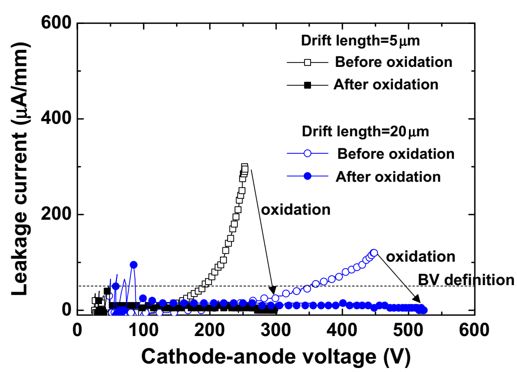

Fig. 6. Measured breakdown voltage of GaN SBDs before and after post-oxidation at 500 °C.

on-resistance at the drift length of 20 µm also increased, from 4.16 to 5.17 mΩ cm^2, after post-oxidation. However, the specific on-resistance of the post-oxidized GaN SBDs was still less than that of conventional Si PiN diodes. The leakage current at the drift length of 5 µm was successfully decreased from 2.53×10^{-1} to 6.08×10^{-3} A/cm^2 at -100 V after the post-oxidation.

We measured the breakdown voltage of the GaN SBDs after covering the devices with Fluorinert liquid to prevent surface arcing. The breakdown voltage is usually defined as the reverse voltage at which the leakage current increases to 1 mA/mm [26]. However, our devices had a low leakage current with hard breakdown characteristics. Therefore, we strictly defined the breakdown voltage as at a leakage current of 50 µA/mm. Fig. 6 shows the measured breakdown voltage of the GaN SBDs before and after post-oxidation at 500 °C. The virgin devices exhibited leaky characteristics, while the oxidized ones sustained low leakage current until breakdown. The post-oxidation increased the breakdown voltage from 189 to 298 V at the drift length of 5 µm, and from 351 to 524 V at the drift length of 20 µm. When the post-oxidation was performed at 300 and 400 °C, the breakdown voltage at the drift length of 20 µm was between 454 and 471 V. When the post-oxidation was done at 600 °C, the breakdown voltage was rather degraded to 408 V at the drift length of 20 µm owing to the newly formed Au/AlGaN. The figure-of-merit of $BV^2/R_{on,sp}$ was improved from 29.6 to 53.1 MW/cm^2 at the drift length of 20 µm owing to the post-oxidation. The post oxidation considerably suppresses the leakage current and increases the breakdown voltage of GaN SBDs. In addition, the present post-oxidation process is simple and does not require any additional photolithography.

4. Conclusions

We have fabricated high-voltage GaN SBDs on Si(1 1 1) substrates using post-oxidation performed after the formation of Ni-based Schottky contacts. We have measured the elements on the AlGaN/GaN and Ni/AlGaN after post oxidation. Post-oxidation was found to produce AlO_x or GaO_x on the surface, which may have given passivation features that suppressed the leakage current. The diffusion of Ni into AlGaN during the post-oxidation can anneal shallow states near the Schottky contact. The post-oxidation also formed a conductive NiO film at the Schottky contact but this was not related to the breakdown voltage. When the post-oxidation was done at 600 °C, the Schottky barrier height was rather degraded because the Ni was fully converted to NiO and the Schottky contact was changed from Ni/AlGaN to Au/AlGaN. The breakdown voltage was increased from 351 to 524 V at the drift length of 20 µm by the post-oxidation. The figure-of-merit of $BV^2/R_{on,sp}$ was also improved from 29.6 to 53.1 MW/cm^2 at the drift length of 20 µm. This study suggests that the simple post-oxidation process is suitable for fabrication of high-voltage GaN devices.

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