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Effects of metal spikes on leakage current of high-voltage GaN Schottky barrier diode

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ABSTRACT

We have investigated effects of metal spikes on the leakage current of high-voltage GaN Schottky barrier diodes (SBDs) on Si substrate. The metal spikes are formed underneath Ohmic contacts during a thermal annealing. The diffusion of Ti/Al/Mo/Au into GaN is analyzed by measuring Auger electron spectroscopy (AES). Ti/Al/Mo/Au on GaN is stripped by a wet etchant and its surface is observed to verify metal spikes by scanning electron microscope (SEM) and atomic force microscopy (AFM). The annealing temperature of the Ohmic contact is proportional to the diffusion depth of the metal spikes and the leakage current. The reverse current of GaN SBD with an Ohmic alloy at 700 °C is 0.37 A/cm^2 at −100 V while that of GaN SBD with the Ohmic alloy at 800 °C is 13.45 A/cm^2 at −100 V. The metal spikes in GaN power devices should be suppressed for the low power loss and the high breakdown voltage. The reverse current of GaN SBD is further decreased by a recessed Schottky contact because the Schottky contact is closer to unintentionally-doped (UID) GaN buffer and the depletion is increased. The reverse current of GaN SBD with the recessed Schottky contact is finally decreased to 0.05 A/cm^2 at −100 V. When an anode–cathode distance (D_{AC}) is 5 μm, the measured on-resistance, breakdown voltage and figure-of-merit ($BV^2/R_{on,sp}$) are 3.15 mΩ cm^2, 320 V, and 32.5 MW/cm^2, respectively. When D_{AC} is increased to 20 μm, fabricated devices show the breakdown voltage of 450 V and good device-to-device uniformity.

1. Introduction

GaN devices are promising for high-voltage switching applications due to a wide band gap, a high critical field, a high electron mobility, a high saturation velocity, and a low intrinsic carrier generation [1–4]. Recently, an epitaxial GaN on Si substrate has been attracted considerable attentions due to a large diameter to 8 in. [4–7]. Additionally, Si substrate is not expensive compared with widely used sapphire and SiC substrates. GaN Schottky barrier diodes (SBDs) have been investigated to replace Si diodes due to their high breakdown voltage, low on-resistance, and fast reverse recovery [5–14]. Various SBDs on n$^-$ GaN [8,9], AlGaN/GaN [5–7,10,11], and bulk GaN [12–14] have been reported. Various processes of GaN SBDs such as plasma treatments [6,7] and floating metal rings [14] have improved electric characteristics. The buffer leakage of GaN transistors has been reported to be caused by the nature of alloyed Ohmic contacts [15]. Effects of Ohmic contacts on reverse characteristics of GaN SBDs on Si substrate should be more specified.

The purpose of our work is to report effects of metal spikes on the leakage current of high-voltage GaN SBDs on Si substrate. We have measured the metal spikes underneath the Ohmic contact. They are related to the leakage current and an annealing temperature. The metal diffusion into GaN is verified by measuring Auger electron spectroscopy (AES). Scanning electron microscope (SEM) and atomic force microscopy (AFM) are measured to verify metal spikes. The suppression of the metal spikes achieves the low buffer leakage current and the low reverse current of GaN SBDs.

The reverse current of GaN SBD is further decreased by recess etching the area of the Schottky contact. The recessed Schottky contact increases the depletion because the Schottky interface is closer to unintentionally-doped (UID) GaN buffer. A fabricated GaN SBD with an anode–cathode distance (D_{AC}) of 5 μm achieves the low on-resistance of 3.15 mΩ cm^2 and the high breakdown voltage of 320 V. Fabricated 50 devices with D_{AC} of 20 μm show the uniform breakdown voltage about 450 V.

2. Experimental

The doped GaN/UID GaN was used as a starting material. The epitaxial GaN layers were grown on Si (111) substrate by a metal-organic chemical vapor deposition. The thickness of the doped and the UID GaN were 200 nm and 1 μm, respectively. The doped GaN was a thick channel and that was suitable for a high-current

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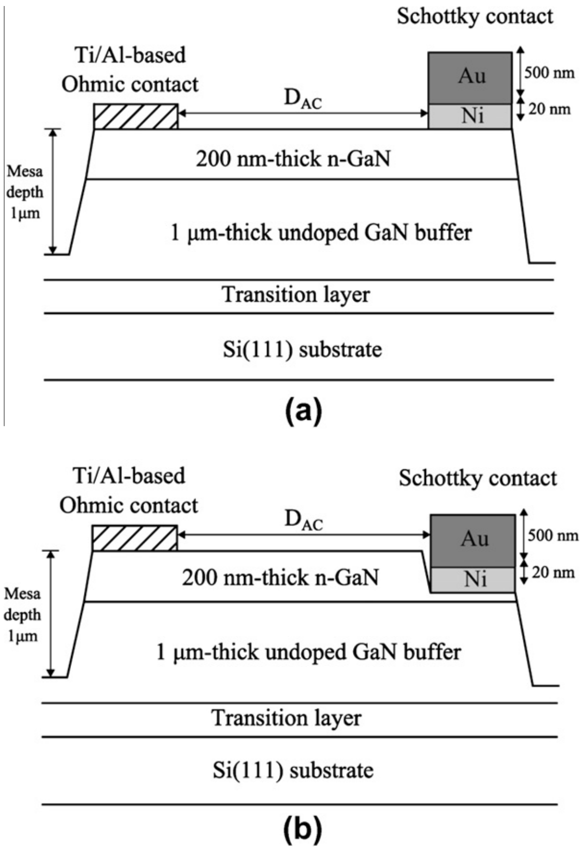

Fig. 1. Cross-sectional views of the: (a) conventional and (b) proposed GaN SBDs.

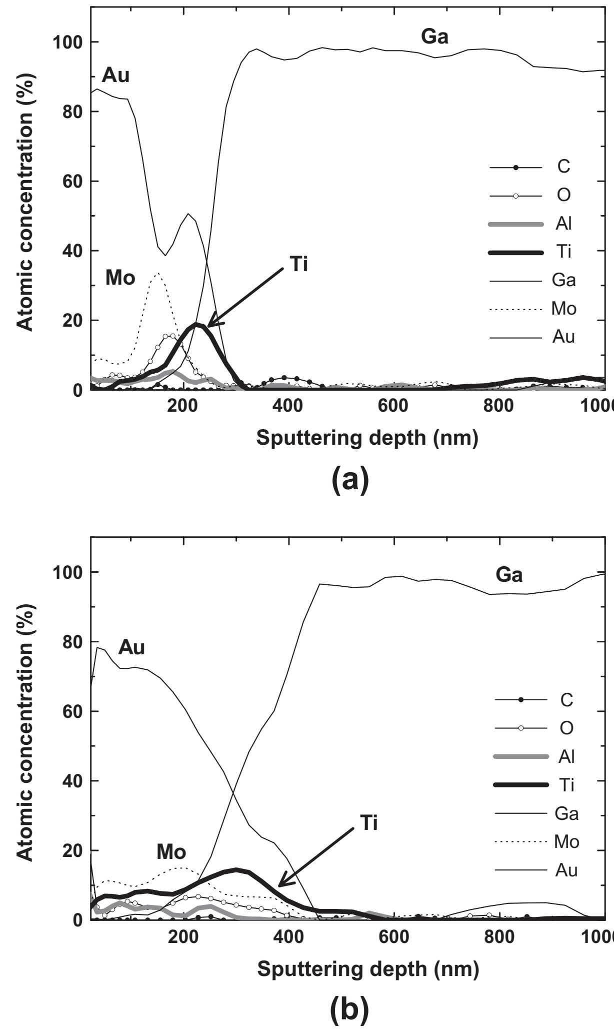

Fig. 2. Measured AES-depth profiles of Ti/Al/Mo/Au-on-GaN samples after annealing at: (a) 700 and (b) 800 °C.

operation. Averaged doping concentration and electron mobility of the doped GaN were 4.2×10^{17} cm^{-3} and 318.1 cm^2/Vs by Hall measurements. Cross-sectional views of a conventional and a proposed GaN SBDs are shown in Fig. 1. The proposed device had a recessed Schottky contact while the conventional one had a planar Schottky contact. The 1 μm-deep mesa was formed to define active regions. BCl_3 and Cl_2 were used to etch GaN in an inductively coupled plasma etcher. A lift-off method was used to define metal patterns. The native oxide is removed by the 6:1 buffered oxide etchant. Ti/Al/Mo/Au (10/40/25/200 nm) was evaporated by an electron beam and that was annealed at 700 and 800 °C, respectively, for the Ohmic contact. The annealing time was fixed to 30 s.

The doped GaN where the Schottky contact would be formed was etched for a recessed anode. The etched surface was annealed to cure plasma damages at 500 °C under N_2 ambient. The measured depth of the recess was between 160 and 190 nm by a surface profiler. The Schottky contact was not directly connected to the UID GaN. However, the Schottky contact can increase the depletion because that was closer to the UID GaN. Additionally, a post annealing was also applied after the evaporation of Ni/Au on the recessed surface. The diffusion of Ni into GaN should be considered. The post annealing was performed at 500 °C under N_2 ambient. The thickness of Ni/Au was 20/500 nm. Conventional devices with the planar Schottky contact were also fabricated.

3. Results and discussion

3.1. Metal spikes under Ohmic contacts

Metal diffusion into GaN buffer may decrease the resistivity of GaN buffer and cause the leakage current [15]. We investigated the metal spikes of GaN SBDs. Ti/Al/Mo/Au-on-GaN samples were fabricated and annealed at 700 and 800 °C, respectively, by a rapid thermal annealing (RTA). The diffusion of Ohmic metals into GaN was measured by AES at an accelerating voltage of 5 keV. Fig. 2 shows measured AES-depth profiles of annealed Ti/Al/Mo/Au on the doped GaN/UID GaN. The samples were sputtered until elements of a translation layer were detected. The diffusion depth of metals was extracted by using the AES-depth profiles and the thickness of active GaN.

The annealing at 700 °C exhibits the diffusion depth as 324 nm (Au), 324 nm (Ti), and 367 nm (Mo) while the annealing at 800 °C shows the diffusion depth as 458 nm (Au), 583 nm (Ti), and 458 nm (Mo). A higher temperature results in the deeper diffusion of the metals into GaN. Especially, Mo does not block the interdiffusion of Au during the annealing. The deep spikes of Mo and Au, TiN through dislocations [16], and the contamination at an annealing chamber are responsible for the leakage current. Additionally, Mo should be sufficient thick to block the interdiffusion of Au.

When the alloyed metal on GaN is stripped by a wet etchant, the metal spikes are evidenced by pits of surface measurements. Ti/Al/Mo/Au-on-GaN samples were etched away by 3:1 HCl:HNO_3 solution for 900 s. Finally, etched samples were fully rinsed with the deionized water. We have confirmed that the solution stripped the Ohmic contact by measuring cross-sectional SEM. There are some residues on the cleaved GaN surface after the wet etch. The thickness of the Ohmic contact is increased from 275 to 446 nm after the annealing at 800 °C. That indicates that the annealing process makes various GaN–metal complexes. The GaN–metal complexes are not completely etched by the $HCl:HNO_3$ solution. Especially, Ti is not dissolved by the $HCl:HNO_3$ solution. The residues are uniformly found in wet-treated samples.

Fig. 3 shows surface SEM images of the etched surface. The sample without the annealing exhibits the residues and any pit is not found. A small number of shallow pits are found after the annealing at 700 °C. However, considerable amount of deep pits are observed after the annealing at 800 °C. The annealing at a high temperature induces extensive and deep metal spikes. The most salient feature of surface images is that the annealing temperature is proportion to the density of the metal spikes. The metal spikes underneath the Ohmic contact should be suppressed because they are plausible for the leakage path of GaN power devices.

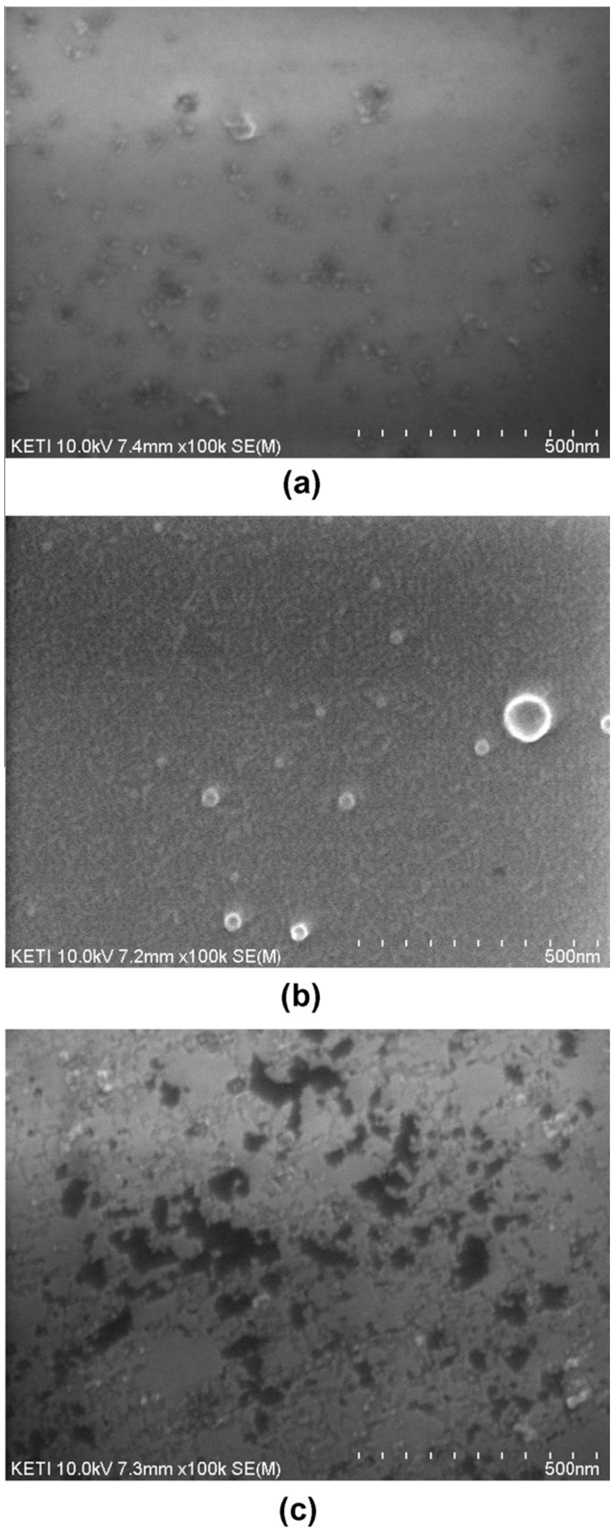

Fig. 3. Measured surface SEM images of (a) unannealed, annealed at: (b) 700 and (c) 800 °C Ti/Al/Mo/Au-on-GaN samples after stripping metals.

We fabricated the samples again to measure AFM of the etched surface. Ti/Al/Mo/Au-on-GaN samples were etched away by 3:1 $HCl:HNO_3$ solution for 1800 s. Finally, etched samples were fully rinsed with the deionized water. The scan area was 1×1 μm. Fig. 4 shows AFM images of the etched surface. The sample without the annealing shows grain surface and residues. The residues of bright spots are shown as in AFM images. The annealed samples have also residues on the surface. The annealed sample at 800 °C shows more pits of dark spots than the one annealed at 700 °C. AFM measurement cannot analyze the diffusion depth profile of the metal spikes. The body of GaN–metal complexes has already been stripped by the solution. The pit is only as a result of the tip of metal spikes. Additionally, it is difficult to measure the depth of narrow-mouthed pits.

3.2. Electrical characteristics of GaN SBDs

The high resistivity of the UID GaN buffer should be required for sustaining a higher reverse bias. A test structure was fabricated to measure the buffer leakage current between two Ohmic contacts which were isolated by a mesa. The width of the test structure was 100 μm. A distance between two Ohmic contacts was 25 μm. The buffer leakage current was measured at 100 V. Fig. 5 shows measured buffer leakage current of the test structures. When the Ohmic contact is annealed at 700 and 800 °C, the buffer leakage current is 9.7 and 782.0 nA, respectively. When the annealing temperature is increased from 700 to 800 °C, the resistivity of GaN buffer is decreased from 10.31 to 0.13 GΩ at 100 V. It is concluded that the high-temperature annealing for the Ohmic contact induces the high leakage current through the UID GaN buffer. The annealing can also increase the surface leakage current because the high-temperature process may form dangling bonds which act as surface states [17].

We fabricated GaN SBDs with the planar and recessed Schottky contacts. The anode–cathode distance (D_{AC}) and the width were 5 and 100 μm, respectively. Fig. 6 shows measured reverse current of GaN SBDs. The Ohmic contact of GaN SBDs was annealed at 700 and 800 °C, respectively. The reverse current of the planar GaN SBD with the Ohmic alloy at 800 °C is 13.45 A/cm^2 at -100 V. However, that of the planar device with the Ohmic alloy at 700 °C is 0.37 A/cm^2 at -100 V. The high-temperature annealing of the Ohmic contact induces the higher reverse current. The reverse current of GaN SBD is further suppressed by the recessed Schottky contact. The reverse current of the recessed GaN SBD with the Ohmic alloy at 700 °C is only 0.05 A/cm^2 at -100 V. The depletion under the Schottky contact is increased due to the recess structure.

Fig. 7 shows measured forward *I–V* of GaN SBDs. A forward voltage drop is defined at 100 A/cm^2. When the annealing temperature of the Ohmic contact in the planar devices is 700 and 800 °C, the forward voltage drop is 0.97 and 1.04 V, respectively. The difference is caused by a contact resistance. When the annealing temperature is increased from 700 to 800 °C, the contact resistance is decreased from 0.60 to 0.41 Ω mm. The measured contact resistance is reasonable because the doped GaN layer makes the Ohmic contact easier. The formation of the metal spikes is inversely proportion to the contact resistance. We can design trade-off between the metal spikes and the contact resistance. The annealing at

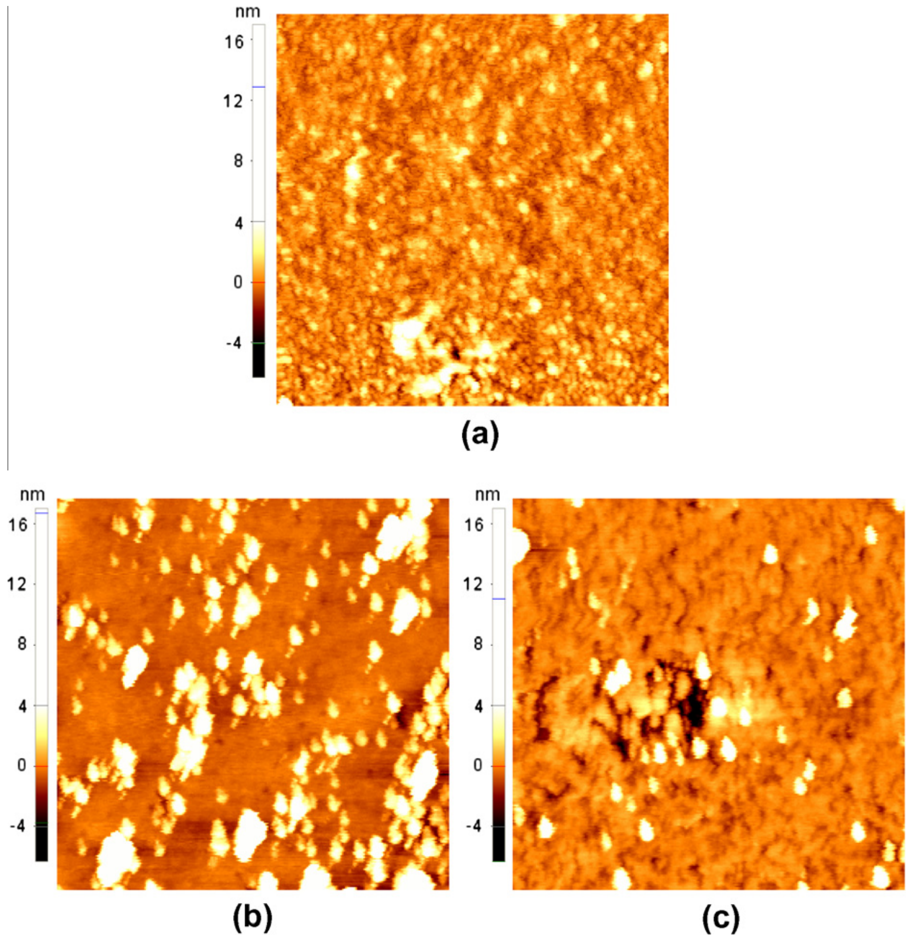

Fig. 4. Measured AFM images of (a) unannealed, annealed at: (b) 700 and (c) 800 °C Ti/Al/Mo/Au-on-GaN samples after stripping metals.

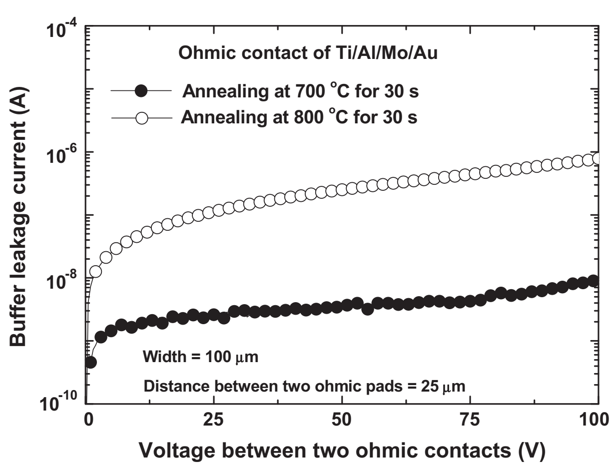

Fig. 5. Measured buffer leakage current of the test structures.

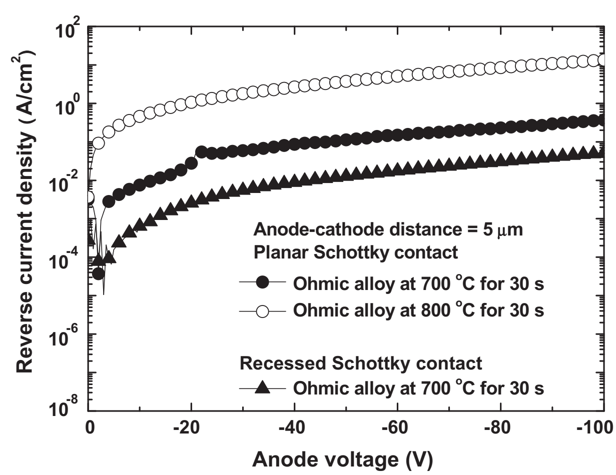

Fig. 6. Measured reverse current of the GaN SBDs with the planar and recessed Schottky contact.

750 °C is also a good condition for suppressing the metal spikes and achieving the low contact resistance.

The forward voltage drop of the recessed device is 2.13 V because the Schottky barrier height is increased and *I*–*V* is positively shifted. The extracted Schottky barrier height of the recessed device is 0.81 eV from *I*–*V* and the effective Richardson constant of 26.4 $A/cm^2/K^2$ [18]. The Schottky barrier height is lower than the theoretical value because the Fermi-level pinning limits the Schottky barrier height and increases the reverse saturation current density [17,19]. The specific on-resistance ($R_{on,sp}$) is defined at about 100 A/cm^2. The specific on-resistance of the planar devices with the Ohmic alloy at 700 and 800 °C are 2.75 and 1.86 $m\Omega\,cm^2$, respectively. The recessed device with the Ohmic alloy at 700 °C has the specific on-resistance of 3.15 $m\Omega\,cm^2$. The on-resistance of the recessed device is slightly increased compared with that of the planar devices. But the fabricated GaN SBDs still have the lower specific on-resistance than that of Si PiN diodes.

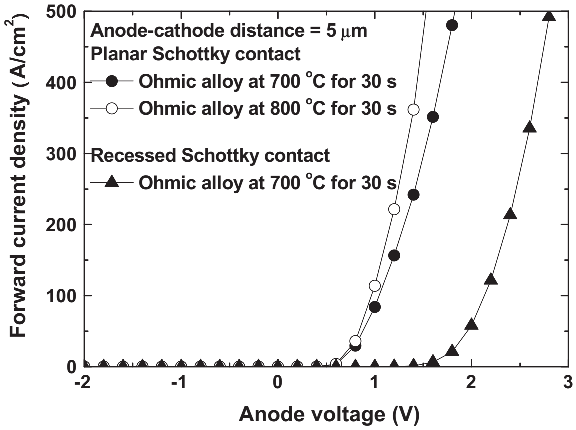

Fig. 7. Measured forward *I–V* of GaN SBDs with the planar and recessed Schottky contact.

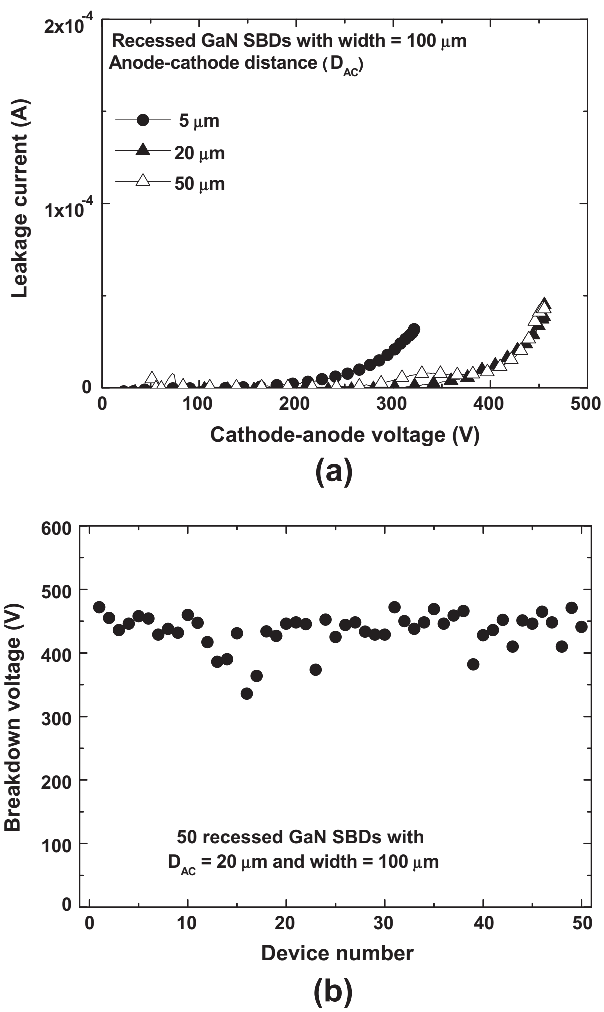

Fig. 8. (a) Measured breakdown voltage of recessed GaN SBDs with various D_{AC}, (b) measured breakdown voltage of 50 devices with D_{AC} of 20 μm.

Fig. 8 shows measured breakdown voltage of the recessed devices. The breakdown voltage of the recessed device with D_{AC} of 5 μm is 320 V. The figure-of-merit of $BV^2/R_{on,sp}$ is 32.5 MW/cm^2. The breakdown voltage of the recessed device with D_{AC} of 20 and 50 μm are almost identical to 450 V. The longer D_{AC} than 20 μm is not effective for a high-voltage design because an electric field is concentrated at a contact edge. Fifty recessed devices with D_{AC} of 20 μm show the uniform breakdown voltage about 450 V. The proposed process promises uniform characteristics between unit cells. Some planar devices with the Ohmic alloy at 800 °C show the low breakdown voltage of 350 V at D_{AC} of 20 μm. However, the difference between the planar devices and the recessed ones is not critical in the statistics. The result suggests that 1 μm-thick GaN buffer is fully depleted at the breakdown. The thick GaN buffer on Si substrate should be required for the high-voltage operation. The annealing temperature of the Ohmic contact and a top semiconductor layer affect a trade-off relationship between the contact resistance and the metal spikes. It is expected that the metal spikes are also controlled by a thickness of the blocking metal. The suppression of the metal spikes, the low contact resistance and the thick GaN buffer are necessary for power GaN SBDs.

4. Conclusions

We have fabricated the high-voltage GaN SBDs on Si substrate by suppressing the metal spikes. The metal spikes are generated during the annealing of the Ohmic contact. The metal spikes are evidenced by measuring AES, SEM, and AFM. The metal spikes are related to the annealing temperature of the Ohmic contact. They are responsible for the leakage current of GaN SBDs. The annealing of the Ohmic contact on the doped GaN at 700 °C achieves the low contact resistance as well as the low buffer leakage current. When the annealing temperature of the Ohmic contact is increased from 700 to 800 °C, the resistivity of the UID GaN buffer is reduced from 10.31 to 0.13 GΩ at 100 V. When the Ohmic contact is annealed at 700 and 800 °C, the reverse currents of the planar GaN SBDs are 0.37 and 13.45 A/cm^2 at −100 V, respectively. The recessed structure of the Schottky contact further decreases the reverse current from 0.37 to 0.05 A/cm^2 at −100 V. GaN SBD with the anode–cathode distance of 5 μm achieves the forward voltage drop of 2.13 V at 100 A/cm^2, the on-resistance of 3.15 mΩ cm^2 and the breakdown voltage of 320 V. When the anode–cathode space is increased to 20 μm, the breakdown voltage of GaN SBD is further increased to 450 V with good device-to-device uniformity. The metal spikes should be suppressed for the low-power loss and the high-voltage operation of GaN power devices.

Acknowledgments

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