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Contact Resistance and Leakage Current of GaN Devices with Annealed Ti/Al/Mo/Au Ohmic Contacts

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Abstract—**In recent years, the on-resistance, power loss and cell density of Si power devices have not exhibited significant improvements, and performance is approaching the material limits. GaN is considered an attractive material for future high-power applications because of the wide band-gap, large breakdown field, high electron mobility, high switching speed and low on-resistance. Here we report on the Ohmic contact resistance and reverse-bias characteristics of AlGaN/GaN Schottky barrier diodes with and without annealing. Annealing in oxygen at 500℃ resulted in an increase in the breakdown voltage from 641 to 1,172 V for devices with an anode-cathode separation of 20 μm. However, these annealing conditions also resulted in an increase in the contact resistance of 0.183 Ω-mm, which is attributed to oxidation of the metal contacts. Auger electron spectroscopy revealed diffusion of oxygen and Au into the AlGaN and GaN layers following annealing. The improved reverse-bias characteristics following annealing in oxygen are attributed to passivation of dangling bonds and plasma damage due to interactions between oxygen and GaN/AlGaN. Thermal annealing is therefore useful during the fabrication of high-voltage GaN devices, but the effects on the Ohmic contact resistance should be considered.**

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Index Terms—**GaN, AlGaN, Schottky barrier diode, breakdown voltage, annealing**

I. Introduction

Power semiconductor devices are used as switches in power factor correction circuits, DC/DC converters, DC/AC inverters and switched-mode power supplies. Silicon power devices are robust and exhibit low specific on-resistance, high cell density, high breakdown voltage, and low switching power losses [1]; however, these characteristics have not improved in recent years, largely because of the material limits of Si [2]. GaN is a wide-band-gap semiconductor, and is particularly promising for high-power applications because of its high breakdown voltage, fast switching speed and low intrinsic charge carrier concentration at high temperatures [2-4]. AlGaN/GaN heterostructures exhibit large electron mobilities, with highly conductive channel layers via a two-dimensional electron gas (2DEG), as well as low on-resistances. Furthermore, Baliga's figure of merit for GaN power transistors has been reported to be 500 [2] or 900 [5] times higher than that for Si. For these reasons, GaN is particularly attractive for high-power devices.

GaN devices include Schottky barrier diodes [6] and high-electron-mobility transistors [7], with applications in power switching and RF amplification. Schottky-contact-controlled devices can achieve high-frequency operation, owing to the low capacitance. However, the high leakage current through the Schottky contacts is a problem [8-11], and emission of electrons from trap states near the metal/(Al)GaN interface has been identified as an important cause of leakage currents [11].

Various oxygen-annealing methods have been used during the fabrication of GaN devices [12-17], and can result in an increased electron concentration of the 2DEG [12], as well as modified Schottky barrier heights and Fermi-level pinning due to the increased density of donor states [13]. Ohmic contacts to *p*-type GaN require annealing in an O_2 ambient environment at a relatively low temperature [14]. We have previously reported the use of O_2 [15, 16] and H_2O [17] annealing techniques for GaN devices to suppress the leakage current. Although annealing in the presence of oxygen can increase the breakdown voltage and suppress the leakage current, it may also result in an increased contact resistance as a result of oxidation of the metal alloy.

The purpose of this work is to investigate the effects of annealing in O_2 on the Ohmic contact resistance R_c and leakage current of AlGaN/GaN Schottky barrier diodes. Ohmic contacts were formed with deposited Ti/Al/Mo/Au electrodes, the lateral devices were annealed in ambient O_2, and R_c was measured before and after annealing. In addition, we measured the leakage current and the breakdown voltage of the devices before and after annealing.

II. Fabrication

AlGaN/GaN was grown on a 150-mm-diameter Si(111) substrate using metal-organic chemical vapor deposition. A 1.7-μm-thick undoped GaN buffer layer was grown followed by a 20-nm-thick undoped $Al_{0.23}Ga_{0.77}N$ barrier layer to form the 2DEG. A 4-nm-thick undoped GaN cap layer was then grown. Etched mesa structures were formed to isolate individual devices using an inductively coupled plasma etcher. The depth of the mesa-etch was 380-420 nm. A 20/100/20/200-nm-thick Ti/Al/Mo/Au metal stack was then deposited using e-beam evaporation, patterned using lift-off, and alloyed at 890℃ for 30 s in an N_2 ambient environment using rapid thermal annealing to form Ohmic contacts.

The devices were then annealed for 300 s in an ambient O_2 environment in a furnace at temperatures of 200, 500 or 800℃. The photolithography pattern for the 100-μm-wide Schottky contacts was aligned using a contact aligner. The area of the GaN diode was 10^{-3} mm^2 if the anode-cathode separation was 10 μm which defines the length of the active region.

The surface of the Schottky contacts was dipped in 6:1

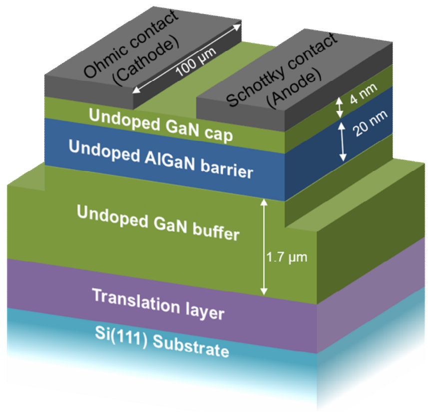
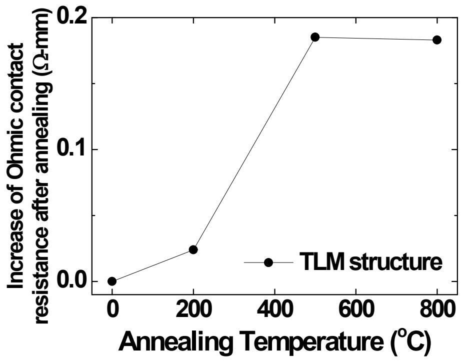


Fig. 1. A cross-sectional view of AlGaN/GaN Schottky barrier diodes.

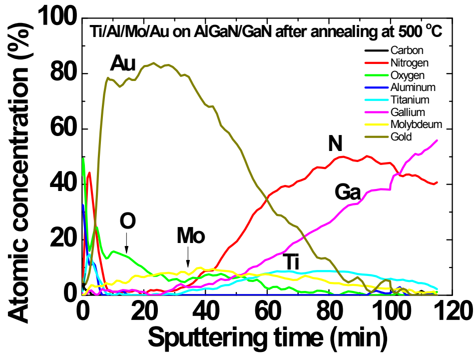
buffered oxide etchant (BOE) to remove oxides, where the exposure time was determined experimentally. The photoresist patterns were not deformed during this process. Non-annealed devices were exposed to the BOE for 30 s, and the exposure time for the annealed devices was varied depending on the temperature; i.e., 45 s for devices annealed at 200ºC, 180 s for devices annealed at 500ºC, and 270 s for devices annealed at 800℃. A 50/150-nm-thick Ni/Au layer was then deposited using e-beam evaporation, and Schottky contacts were formed using lift-off.

III. Results and Discussion

Structures were fabricated for transmission line method measurements to determine R_c before and after annealing. Before annealing, the contact resistance was is in the range $0.343 < R_c < 0.578$ Ω-mm. We may expect the magnitude to decrease and the uniformity to improve if the electron concentration of the 2DEG were to increase. However, the AlGaN/GaN heterostructure was designed for high-voltage devices. The measured sheet resistance of the 2DEG was as high as 501 Ω/sq (c.f. 356 Ω/sq for a highly conductive heterostructure for RF applications) [18]. Fig. 2(a) shows R_c measured before and after annealing. Following annealing at 200℃, R_c was almost identical to the original value; however, following annealing at 500ºC R_c increased by 0.183 Ω-mm, and following annealing at 800ºC it increased by 0.185 Ω-mm. Oxidation of the AlGaN/GaN may be expected to lead to an increase in R_c, and we may expect oxygen diffusion around the contact area. Fig. 2(b)



(a)



(b)

Fig. 2. (a) Measured values of R_c before and after thermal annealing, (b) Auger electron spectroscopy depth profiles around the Ohmic contact.

shows depth profile Auger electron spectroscopy around the region, which confirms this, as well as diffusion of Au into the AlGaN/GaN following annealing, which is also expected to lead to an increase in R_c [19]. When the annealing temperature was 1,100℃, the Ohmic contacts were destroyed.

Hall patterns were fabricated for investigating the electron sheet density and mobility of the 2DEG, and annealed at 300 s for 200, 500, 700, 800 or 900℃. Fig. 3 shows the resulting electron sheet density and mobility. The non-annealed electron sheet density was 6.77×10^{12} /cm^2 and the mobility was 1,840 cm^2/Vs. Following annealing at 800℃, the electron sheet density increased to 8.33×10^{12} /cm^2 and the mobility decreased to 1,550 cm^2/Vs. The electron sheet density increased as the annealing temperature increased further. The increased carrier concentration in the 2DEG is attributed to the incorporation of oxygen donor impurities [12]. The decrease in the electron mobility following annealing is attributed to increased electron-electron scattering.

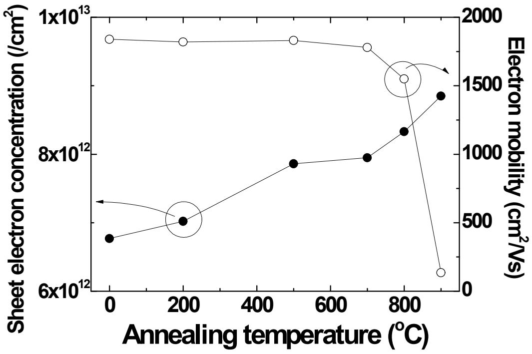


Fig. 3. The measured electron sheet density and mobility from Hall patterns before and after annealing.

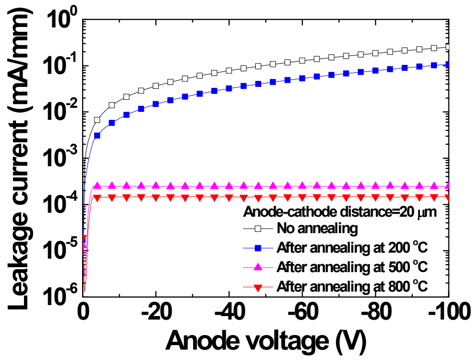


Fig. 4. The measured leakage current of AlGaN/GaN Schottky barrier diodes before and after annealing.

Although R_c increased following annealing, the leakage current of AlGaN/GaN Schottky barrier diodes was significantly smaller. Fig. 4 shows the measured leakage currents of fabricated devices with an anode-cathode separation of 20 μm. Without annealing, the leakage current was 2.52×10^{-1} mA/mm at -100 V. Following annealing at 200, 500 and 800℃, the leakage currents were 1.07×10^{-1}, 2.47×10^{-4} and 1.46×10^{-4} mA/mm, respectively. Annealing at ≥ 500℃ suppressed the leakage current by approximately three orders of magnitude.

Fig. 5 shows the measured leakage current of the devices with various anode-cathode separations. The applied bias was -100 V. The non-annealed devices and the device annealed at 200℃ exhibited a decrease in the leakage current as the anode-cathode separation increased. However, the devices annealed at ≥ 500℃ exhibited a leakage current that did not depend on the anode-cathode separation. This is because the leakage current was very small (approximately 10^{-4} mA/mm, or 10^{-8} A).

The surface of the active region may contain dangling bonds, and the mesa-etched region may include plasma

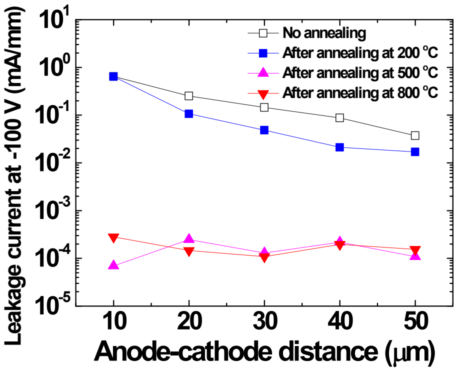


Fig. 5. The measured leakage current of AlGaN/GaN Schottky barrier diodes as a function of the anode-cathode separation.

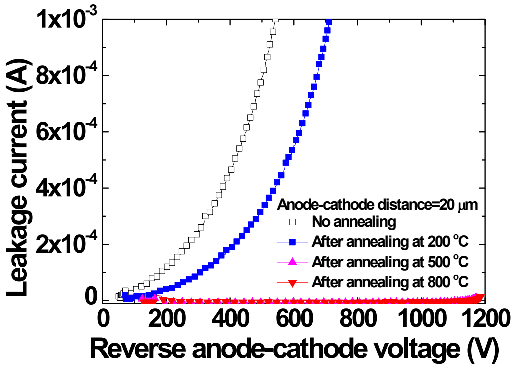


Fig. 6. The measured breakdown voltage of AlGaN/GaN Schottky barrier diodes before and after annealing.

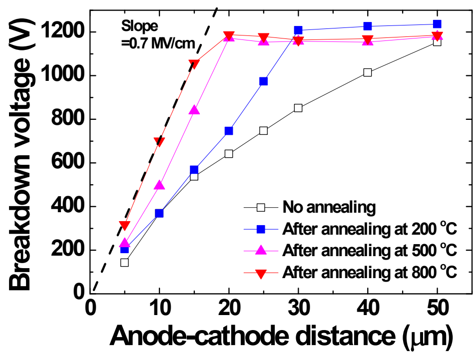


Fig. 7. The measured breakdown voltage of AlGaN/GaN Schottky barrier diodes as a function of anode-cathode separation.

damage. The annealing process can stabilize surface leakage via passivation of dangling bonds and plasma damage, which improves the reverse-bias device characteristics. Annealing in oxygen may transform the dangling bonds to stable complexes such as group-III oxides, where these effects are more significant at higher temperatures.

We measured the breakdown voltage of the devices in liquid Fluorinert using a curve tracer. We defined the breakdown voltage as the reverse-bias voltage at which the leakage current increased to ~10 mA/mm, or where thermal breakdown occurred. Devices with a small leakage current exhibited burned contacts following thermal breakdown. Fig. 6 shows the measured breakdown voltages of devices with an anode-cathode separation of 20 μm. The breakdown voltage of the non-annealed device was 641 V. The breakdown voltages of devices annealed at 200, 500 and 800℃ were 746, 1,172 and 1,188 V, respectively. Annealing led to hard breakdown, with a reduced leakage current. SiO_2 passivation of GaN devices results in similar effects. This suppressed leakage current and increased the breakdown voltage, indicative of deep surface traps and enhanced vertical depletion [20].

Fig. 7 shows the measured breakdown voltage as a function of the anode-cathode separation. With short anode-cathode separations, the annealed devices exhibited similar breakdown voltages as the non-annealed devices. With larger anode-cathode separations, the annealed devices exhibited higher breakdown voltages at a given anode-cathode separation than the non-annealed devices; however, the breakdown voltage saturated at ~1.2 kV, regardless of annealing. Note that breakdown of the 1.7 μm-thick GaN buffer limits the reverse blocking voltage to approximately 1.2 kV. A linear fit to the breakdown voltage as a function of the anode-cathode separation gave 0.7 MV/cm, which is smaller than the critical field of 3.0 MV/cm for GaN, and suggests that the breakdown field was limited by the quality of the epitaxy [2] or by process-induced defects.

Analysis of the forward-bias *I-V* characteristics of these devices is not straightforward. Etching of the native oxide immediately prior to evaporation of metal layer used to form the Schottky contact is required to eliminate parasitic barrier effects and minimize the contact resistance. However, this etch depended on the annealing conditions because the annealing conditions determine the thickness of the native oxide, as well as the density of surface states and pinning of the Fermi-level.

Annealing in oxygen at ≥ 500℃ resulted in significant improvements in the leakage current and breakdown voltage of the GaN devices. It is also suggests that there is a trade-off between the Ohmic contact resistance and the reverse-bias characteristics. However, overall we may conclude that thermal annealing is suitable for the fabrication of GaN devices for power switching applications.

IV. CONCLUSIONS

We fabricated high-voltage AlGaN/GaN Schottky barrier diodes on Si substrates. Annealing in oxygen resulted in significant reductions in the leakage current, as well as increased breakdown voltages. However, R_c of the Ohmic contact increased following annealing, which is attributed to the formation of metal oxides, as well as diffusion of Au into the AlGaN/GaN layers. The annealed devices exhibited suppressed leakage currents until breakdown, whereas the non-annealed devices exhibited soft breakdown with large leakage currents. The annealed devices exhibited higher breakdown voltages at a given anode-cathode separation than the non-annealed devices. The breakdown voltage was limited to 1.2 kV because of breakdown of the 1.7-μm-thick GaN buffer layer. When thermal annealing in oxygen is employed during the fabrication of GaN power devices, we should consider the trade-off between degradation of the Ohmic contacts and the suppression of the leakage current and increased breakdown voltage.

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REFERENCES

[1] D. Disney and Z. J. Shen, "Review of Silicon Power Semiconductor Technologies for Power Supply on Chip and Power Supply in Package Applications," *Power Electronics, IEEE Transactions on*, Vol.28, No.9, pp.4168-4181, Sep., 2013.

[2] N. Ikeda, et al, "GaN Power Transistors on Si Substrate for Switching Applications," Proceedings of the IEEE, Vol.98, No.7, pp.1151-1161, July, 2010.

[3] M. Ishida, et al, "GaN on Si Technologies for Power Switching Devices," *Electron Devices, IEEE Transactions on*, Vol.60, No.10, pp.3053-3059, Oct., 2013.

[4] O. Seok and M.-W. Ha, "AlGaN/GaN MOS-HEMTs-on-Si employing sputtered TaN-based electrodes and HfO_2 gate insulator," *Solid-State Electronics*, Vol.105, pp.1-5, Jan., 2015.

[5] T. P Chow and R. Tyagi, "Wide Bandgap Compound Semiconductors for Superior High-Voltage Unipolar Power Devices," *Electron Devices, IEEE Transactions on*, Vol.41, No.8, pp.1481-1483, Aug., 1994.

[6] W. Chen, et al, "High-performance AlGaN/GaN lateral field-effect rectifiers compatible with high electron mobility transistors," *Applied Physics Letters*, Vol.92, pp.253501, June, 2008.

[7] S. Y. Jang, et al, "Investigation of Buffer Traps in AlGaN/GaN Heterostructure Field-Effect Transistors Using a Simple Test Structure," *Semiconductor Technology and Science, Journal of*, Vol.14, No.4, pp.478-483, Aug., 2014.

[8] S. Mizuno, et al, "Large Gate Leakage Current in AlGaN/GaN High Electron Mobility Transistors," *Applied Physics, Japanese Journal of*, Vol.41, No.8, pp.5125-5126, Aug., 2002

[9] S. Arulkumara, et al, "Temperature dependece of gate-leakage current in AlGaN/GaN high-electron-mobility transitors," *Applied Physics Letters*, Vol.82, No.18, pp.3110-3112, May, 2003.

[10] D. Yan, et al, "On the reverse gate leakage current of AlGaN/GaN high electron mobility transistors," Applied Physics Letters, Vol.97, pp.153503, Oct., 2010.

[11] H. Zhang, E. J. Miller and E. T. Yu, "Analysis of leakage current mechanisms in Schottky contacts to GaN and $Al_{0.25}Ga_{0.75}N$/GaN grown by molecular-beam epitaxy," *Applied Physics, Journal of*, Vol.99, pp.023703, Jan., 2006.

[12] H. W. Jang, et al, "Investigation of Oxygen Incorporation in AlGaN/GaN Heterostructures," *Semiconductor Technology and Science, Journal of*, Vol.3, No.2, pp.96-101, June, 2003.

[13] M. Higashiwaki, et al, "Effects of oxidation on surface chemical states and barrier height of AlGaN/GaN heterostructures," *Applied Physics Letters*, Vol.97, No.22, pp.222104, Nov., 2010.

[14] W. Hou, T. Detchprohm, and C. Wetzel, et al, "Effects of oxygen thermal annealing treatment on formation of ohmic contacts to n-GaN," Applied Physics Letters, Vol.101, No.24, pp.242105, Dec., 2012.

[15] S.-C. Lee, et al, "Suppression of Leakage Current

of Ni/Au Schottky Barrier Diode Fabricated on AlGaN/GaN Heterostructure by Oxidation," *Applied Physics, Japanese Journal of*, Vol.45, No.4B, pp.3398-3400, April, 2006.

[16] M.-W. Ha, et al, "On the Relationship between Ohmic Contact Resistance of Ti/Al/Mo/Au and Leakage Current of O_2-Annealed GaN Devices," *Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices (AWAD)*, pp.132-134, June, 2015.

[17] W. Ahn, et al, "High-performance AlGaN/GaN High-electron-mobility transistors employing H_2O annealing," *Crystal Growth, Journal of*, Vol.378, No.378, pp.600-603, Sep., 2013.

[18] J. W. Chung, et al, "AlGaN/GaN HEMT With 300-GHz fmax," *IEEE Electron Device Letters*, Vol.31, No.3, pp.195-197, March, 2010.

[19] D. Selvanathan, et al, "Long-Term Thermal Stability of Ti/Al/Mo/Au Ohmic Contacts on n-GaN," *Electronic Materials, Journal of*, Vol.32, No.5, pp.335-340, 2003.

[20] N.-Q. Zhang, et al, "Effects of surface traps on breakdown voltage and switching speed of GaN power switching HEMTs", *International Electron Devices Meeting Technical Digest*, pp. 589-592, Dec., 2001.

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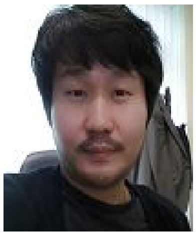

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