# AlGaN/GaN Schottky Barrier Diodes Employing Diamond-like Carbon passivation

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## Abstract

**AlGaN/GaN Schottky Barrier Diodes (SBDs) employing the Diamond-like Carbon (DLC) passivation was proposed. The reverse blocking characteristics of the AlGaN/GaN SBD is degraded by the electron trapping effect through the surface trap states. In order to suppress the electron trapping effect and increase the breakdown voltage of AlGaN/GaN SBDs, the surface passivation or treatment should be performed. In this paper, we proposed the DLC film as passivation layer on AlGaN/GaN SBD which exhibits superb dielectric characteristics such as high resistivity, high critical electric field and low dielectric constant. We successfully increased the breakdown voltage of AlGaN/GaN SBDs from 204 V to 1422 V by performing the DLC passivation. The ideality factor was improved from 1.959 to 1.273. And, the Schottky Barrier height was increased from 0.67 eV to 0.8 eV after the DLC passivation. However, the forward current was degraded a little due to the intrinsic stress of the DLC film.**

## INTRODUCTION

AlGaN/GaN SBDs are attractive candidate for high power application with high frequency operation due to distinguished material characteristics such as wide bandgap, high critical electric field, low level intrinsic carrier concentration, high mobility and high thermal conductivity. In addition, the 2DEG induced by the discontinuity of conduction band and piezoelectric polarization between AlGaN and GaN layer exhibits high electron mobility (>1500 cm2/V·S) and high electron concentration (>$10^{13}$cm$^{-2}$). Hence, AlGaN/GaN SBDs have demonstrated excellent performance such as high breakdown voltage and a fast switching speed [1-2].

However, GaN-based devices have considerable surface states which are due to dislocation induced by mismatch between GaN and substrate. The electron trapped these surface states induces the surface leakage current, virtual gate effect and lowing the breakdown voltage [3]. In general, the conventional AlGaN/GaN SBD without any additional passivation process or treatment exhibits the linearity on leakage current as varying the reverse voltage regardless of the reverse blocking characteristics of the schottky contact. The performance of AlGaN/GaN SBDs can be improved by the surface passivation [4]. Therefore, the property and quality of the passivation layer strongly influence on the performance of the reverse characteristics of the AlGaN/GaN SBDs.

Various passivation materials have been considered, such as $SiO_2$, $SiN_X$, MgO, $Sc_2O_3$ and BCB [4-5]. However, the DLC passivation on AlGaN/GaN SBDs has never been reported. The DLC is the amorphous carbon containing $SP^1$, $SP^2$ and $SP^3$ with carbon-hydrogen bonding. The DLC may be suitable for the passivation of AlGaN/GaN devices due to the superb dielectric property compared to $SiO_2$ or $SiN_X$ such as high resistivity, high breakdown voltage and low dielectric constant [6-7]. We reported the AlGaN/GaN SBDs employing $SiO_2$ passvation by ICP-CVD of which breakdown voltage was 497 V [5]. In addition, the deposition temperature of the DLC is so extremely low that the schottky contact isn't influenced during deposition process.

Meanwhile, the forward current of AlGaN/GaN SBDs with the DLC passivation can be reduced a little due to the intrinsic stress of the DLC film. This stress influences on not only polarization system of AlGaN/GaN heterostructre but also 2DEG channel density. Thus, the intrinsic stress should be minimized [8].

In this paper, we successfully increased the breakdown voltage of AlGaN/GaN SBDs employing the DLC passivation layer. The breakdown voltage of the DLC passivated device was 1422 V, while that of the unpassivated device was only 204 V.

## DEVICE STRUCTURE AND FABRICATION

The schematic cross-sectional view of the DLC passivated AlGaN/GaN SBD is shown in Fig. 1. The anode-cathode distance and active width are 20 μm and 50 μm. The AlGaN/GaN heterostructure was grown on a semi-insulating 4H-SiC substrate by using MOCVD. After the nucleation layer was grown, the 3 μm-thick Fe doped GaN buffer layer, The 30 nm-thick unintentionally doped (UID) $Al_{0.26}Ga_{0.74}N$ layer and the UID GaN capping layer were grown in sequence. The mesa isolation was performed by ICP-RIE with $Cl_2/BCl_3$-based reactive ion for cutting the 2DEG channel at isolation region. The cathode, Ti/Al/Ni/Au (200/800/200/1000 Å), were formed by using an e-gun evaporator and lift-off process and annealed at 870 °C for 30 sec under $N_2$ ambient in order to form ohmic contact. Then anode, Ni/Au (300/1500 Å), was formed by lift-off process for schottky contact. Because carbon-based material has poor adhesion with Au, Ti(500 Å) was deposited on each electrode as adhesion layer between the DLC and electrode after formation of schottky contact. We performed HF cleaning in order to remove native oxide on the surface of active region and $TiO_X$ on the electrode prior to the DLC deposition. Finally, the 1200 Å-thick DLC film was deposited by rf-PECVD with methane (20 sccm) and hydrogen (80 sccm). The pressure, temperature and rf-power during the deposition process were 1 Torr, room temperature and 100 W, respectively. The pad opening process was performed by CCP-RIE with Ar( 20 sccm) and $O_2$(10 sccm) etchants. The DC-power and pressure were 200 W and 30 mTorr during the etching process.

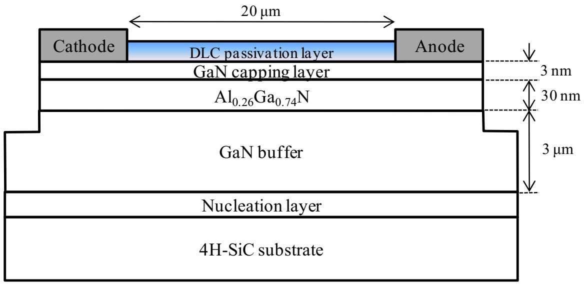

Fig. 1: the schematic cross-sectional view of AlGaN/GaN SBD with the DLC passivation layer

## EXPERIMENTAL RESULTS

The breakdown voltage of the unpassivated AlGaN/GaN SBD and the DLC passivated AlGaN/GaN SBD is shown in Fig. 1. The breakdown voltage of the DLC passivated AlGaN/GaN SBD was 1422 V, while that of the unpassivated AlGaN/GaN SBD was 204 V. The reverse blocking operation of AlGaN/GaN SBD is accompany by the schottky barrier between Ni and AlGaN. However, the unpassivated SBD shows the poor reverse characteristics. As increasing reverse voltage, the leakage current is also increased regardless of the characteristics of schottky contact. While, the DLC passivated AlGaN/GaN shows the quasi-constant current value up to around 1200 V. the breakdown voltage of the DLC passivated AlGaN/GaN SBD is higher than 497 V of AlGaN/GaN SBD employing ICP-CVD $SiO_2$ which reported by our group. It is due to the superb dielectric characteristics of the DLC passivation layer such as high resistivity, high critical electric field, low dielectric constant and high thermal conductivity.

The reverse leakage current of the unpassivated AlGaN/GaN SBD and the DLC passivated AlGaN/GaN SBD is shown in Fig. 2. We measured leakage current by sweeping the reverse voltage up to 100 V. When the 100 V of reverse bias was applied, the leakage current of the unpassivated device was 0.51 mA/mm, and that of the DLC passivated device was 0.25 mA/mm. It is note that the reverse leakage current of the DLC passivated device keeps consistent until taking place breakdown. While, the leakage current of the unpassivated device was increased linearly as increasing reverse bias.

I-V characteristics of the unpassivated AlGaN/GaN SBD and the DLC passivated AlGaN/GaN SBD are showen in Fig. 4. When the 5 V of forward voltage is applied, the forward current of the unpassivated device and the DLC passivated device were 180.7 mA/mm and 144 mA/mm, repectively. And the turn-on voltage of the unpassivated device and the DLC passivated device were 0.6 V. The DLC film has intrinsic stress that it can influence on the polar system of AlGaN/GaN heterostructure. So that, not only the 2DEG density but also the forward current is degraded a little.

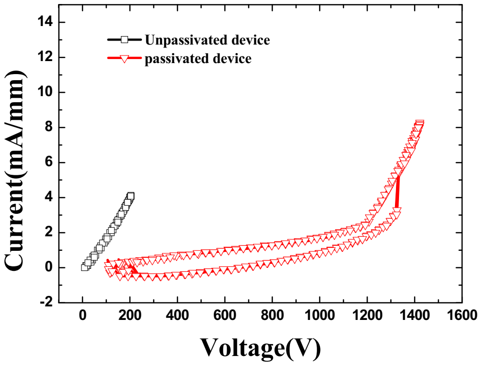

Fig. 2: Measured breakdown voltage of the unpassivatged AlGaN/GaN SBD and the DLC passivated AlGaN/GaN SBD

We obtained the ideality factor (n) and the barrier height ($\Phi_{BN}$) from I-V curve and Eq. 1, Eq. 2 [9].

$$n = \frac{qV}{KT\ln(J/J_S)} \qquad (1)$$

$$\Phi_{BN} = \frac{KT}{q}\ln(\frac{A^{**}T^2}{J_S}) \qquad (2)$$

$J_S$ is the saturation current density obtained by I-V characteristics at 0 V, $A^{**}$ is the effective Richardson constant assuming 26.64 $Acm^{-2}K^{-2}$, and the temperature is 300 K.

The ideality factor at $V_{anode}$ = 0.5 V of the unpassivated device and that of the DLC passivated device were 1.959 and 1.273, respectively. And the schottky barrier height was increased from 0.67 eV of the unpassivated device to 0.8 eV of the DLC passivated device. Higher schottky barrier height of the DLC passivated AlGaN/GaN SBD than that of unpassivated device induced high breakdown voltage of AlGaN/GaN SBD.

TABLE I

IDEALITY FACTOR AND SCHOTTKY BARRIER HEIGHT OF THE UNPASSIVATED DEVICE AND THE DLC PASSIVATIED DEVICE

| | **Ideality factor (at $V_{anode}$ = 0.5 V)** | **Schottky barrier height** |
|---|---|---|
| Unpassivated device | 1.959 | 0.67 eV |
| DLC passivated device | 1.273 | 0.8 eV |

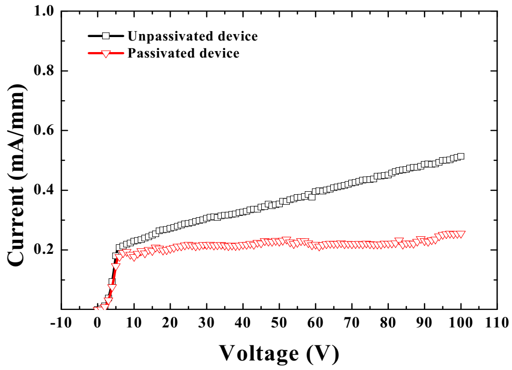

Fig. 3: Measured leakage current of the unpassivated AlGaN/GaN SBD and the DLC passivated AlGaN/GaN SBD

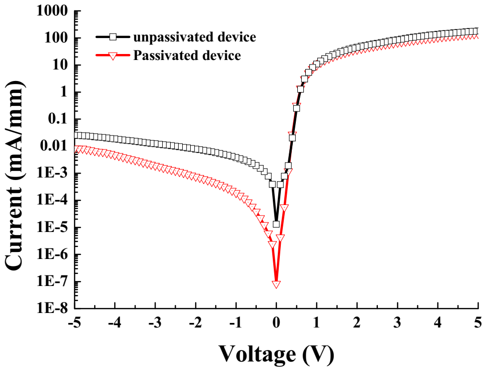

Fig. 4: Measured I-V characteristics of the unpassivated AlGaN/GaN SBD and the DLC passivated AlGaN/GaN SBD

## CONCLUSION

AlGaN/GaN SBD employing the DLC passivation was proposed. We successfully deposited the DLC film on the AlGaN/GaN SBD by rf-PECVD with methane and hydrogen and increased the breakdown voltage from 204 V to 1422 V after the DLC passivation. Our results of the breakdown voltage and reverse leakage current lead to proof about suitability of the DLC passivation on AlGaN/GaN SBD. The ideality factor was improved from 1.959 to 1.273, and the calculated schottky barrier height was increased from 0.67 eV to 0.8 eV. However, when 5V of forward voltage was applied, the forward current was degraded from 180.7 mA/mm to 144 mA/mm due to the intrinsic stress of the DLC flim.

## ACKNOWLEDGEMENTS

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## ACRONYMS

SBD: SChottky Barrier Diode
2DEG: 2 Dimensional Electron Gas
DLC : Diamond-like Carbon
ICP-CVD: Inductively Coupled Plasma Chemical Vapor Deposition
MOCVD : Metalorgarnic Chemical Vapor Deposition
ICP-RIE: Inductively Coupled Plasma Reactive Ion Etch
CCP-RIE: Capacitively Coupled Plasma Reactive Ion Et