A Wafer-Level Uniformity Improvement by the Substrate Off Angle Control for the Vertical GaN-on-GaN Power Switching Devices

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Abstract

To mass produce GaN-on-GaN vertical power devices, the wafer-level uniformity of net donor concentration, $N_D - N_A$, of the n^--drift layer in a range of 10^{15} cm^{-3} is an important factor, because it determines the breakdown voltage, V_B. In this study, we demonstrated the improvement in wafer-level uniformity of a GaN Schottky barrier diode by controlling the off-angle of GaN substrates. Epi-structures were grown by MOVPE on free-standing GaN substrates with various off-angles and deviations. The variation in $N_D - N_A$ was carefully analyzed using capacitance-voltage measurement (C–V), photoluminescence (PL), and secondary ion mass spectrometry (SIMS). A carbon related variation in N_A resulted in the non-uniformity of $N_D - N_A$, which is found to be related to the substrate off-angle of the wafer. The $N_D - N_A$ uniformity can be improved by minimizing variation in the off-angle.

INTRODUCTION

Vertical structured GaN power switching devices fabricated on GaN substrates are quite promising for high efficiency power-conversion systems, because the devices provide extremely low on-resistances (R_{on}) combined with high breakdown voltages (V_B) [1-3]. Minimizing the killer defects, that are fatal to device yield and reliability, is an important issue. The mechanism of the initial failure in the GaN-on-GaN diodes has been reported [4], where the diodes with epi-pits showed hard breakdown at very low reverse voltage. In addition, recently, it was reported that the surface roughness affects the reliability [5].

The net donor concentration in the n^--drift layer must be controlled in the range 10^{15} cm^{-3} to obtain high V_B, while carbon (C) impurities are introduced using a metal organic (MO) source [6]. Through low donor content, the peak electric field at the p-n or Schottky interface can be suppressed under negatively biased conditions [7, 8]. However, there are few reports about the wafer-level uniformity of the net donor concentration in the vertical GaN-on-GaN devices.

In this study, we demonstrated an improvement in the wafer-level uniformity of a GaN Schottky barrier diode by controlling the off-angle of the GaN substrates. The epi-structures were grown by MOVPE on free-standing GaN substrates with various off-angles and deviations. The net donor concentration and PL intensities of the n^--drift layer were revealed as functions of the substrate off-angle. Methods of reducing the variation in the net donor concentration are also discussed.

EXPERIMENTS

The epi-structures of the GaN Schottky barrier diode, as shown in Fig. 1, were grown on freestanding GaN substrates by Metal Organic Chemical Vapor Phase Epitaxy (MOVPE). Trimethylgallium (TMG), ammonia (NH_3), and silane (SiH_4) were used as precursors [9]. The n^--drift layer consists of an n-GaN layer with a nominal Si concentration of 9×10^{15} cm^{-3} and a thickness of 13 μm. n^+ layers of thickness 2 μm were also grown between the n^--drift layer and n-type GaN substrates. The Si-doped n-type GaN substrates have a carrier concentration of approximately $1–2 \times 10^{18}$ cm^{-3}.

The free-standing GaN substrates used in this study were produced using our void-assisted separation (VAS) method [10]. Specifically, this method of employing hydride vapor phase epitaxy (HVPE) growth of a thick GaN layer was performed on a GaN template with a thin TiN film on top. After the cooling process of the HVPE growth, the thick GaN layer was easily separated from the template with the assistance of a large number of voids generated around the TiN film. As a result, a freestanding GaN wafer was obtained. The VAS-GaN substrate has a low density of dislocations, approximately $2–5 \times 10^6$ cm^{-2}, uniformly spread over the surface. This uniform characteristic helps produce power devices conveniently. However, the off-angle of the VAS-GaN substrate deviates around the wafer, which is the angle between the surface normal and *c*-axis [0001], because of the difference in the thermal expansion coefficient between the GaN and sapphire–template. The cross-sectional VAS-GaN substrates were sliced from the concave as-grown HVPE substrate, as shown in Figs. 2 (a) and 2 (b). Here, we defined the substrate specification as off-orientation between the surface normal and *c*-axis toward the *a*- or *m*-axis, which are *a*-axis oriented VAS and *m*-axis oriented VAS, respectively (hereafter referred to as the "*a*-off VAS" and "*m*-off VAS"-GaN substrate, respectively). In addition, we modified the deviation in the substrate off-angle, which was defined as the "*m*-off modified VAS-GaN" substrate. This modified VAS-GaN was obtained simply by increasing the thickness of the HVPE growth compared to the usual VAS-GaN. The off-angle deviations are related to the reciprocal number of the curvature of the as-grown VAS-GaN substrate. It was reported that the curvature decreases with the thickness of the as-grown VAS-GaN substrate [11]. Thus, substrates with a small off-angle deviation are revealed owing to thicker HVPE growth. The off-angles of the substrates were measured using X-ray diffraction.

PL was measured using a micro PL measurement system (HORIBA, LabRAM HR Evolution). A He-Cd laser (325 nm) was used with a laser power of 1.25 mW. The laser spot size was 5 μm in diameter; thus, the irradiation intensity was approximately 6.4×10^3 (W/cm^2). PL mapping was conducted at intervals of 500 μm in the wafers. A non-contact C–V measurement was performed using the FAaST-210 (Semilab Semiconductor Physics Laboratory Co., Ltd.) [12]. Si and C concentrations were also confirmed using a secondary ion mass spectrometry (SIMS).

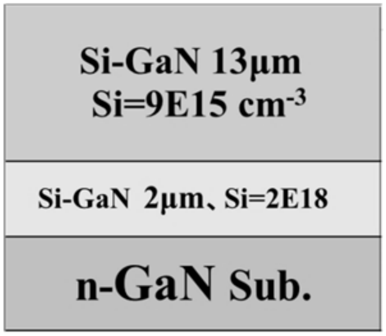

Fig. 1. Structure of GaN Schottky diode. Epitaxial layers grown on VAS-GaN substrates using MOVPE method.

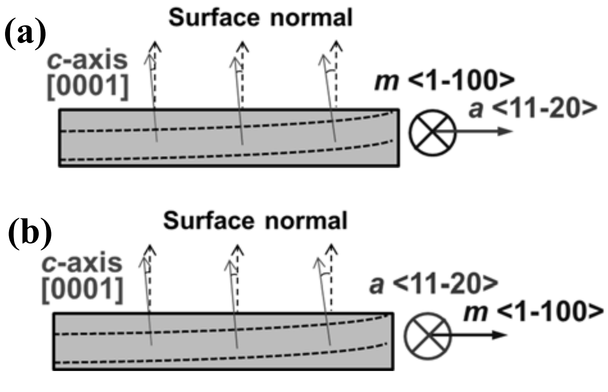

Fig. 2. Cross-sectional schematic of sliced VAS-GaN substrate. (a) toward *a*-axis, (b) toward *m*-axis.

RESULTS AND DISCUSSION

Figure 3 shows the schematic of the substrate off-angles, PL mappings of the near band edge (NBE) (3.4 eV) and normalized YL (2.2 eV) peak intensity of the NBE around two-inch wafers. The PL intensity of the NBE was high in the large off-angles regions. In contrast, the normalized YL intensity of the NBE was high in the low off-angle region. The YL peak of PL corresponds to deep level of GaN for C or V_{Ga} [13-16]. Thus, the PL-mapping of YL might indicate high C concentration in the low-off angle regions. C and V_{Ga} play roles for the acceptors in the n-GaN, which compensates for the Si.

Figure 4 (a) shows the PL intensity of the NBE as a function of wafer position. The off-angle has a linear relationship with the wafer position in the VAS-GaN substrate [11]. Here, we simply converted the wafer position to the substrate off-angle based on this relationship; that is, *a*-off VAS against wafer-top (25 mm) to wafer-orientation-flat (-25 mm). Figure 4 (b) shows the *m*-off VAS and *m*-off modified VAS against wafer-right (25 mm) to wafer-left (-25 mm). The center of the wafers act as coordinate origins, as shown in Fig. 4 (b). Figure 4 (b) indicates that the Int_{NBE} clearly depends on the substrate off-angles. In addition, a uniform PL was obtained by using a substrate with a small deviation in the off-angle.

Figure 5 shows the net donor concentration measured using the non-contact C–V measurement, $N_D - N_A$, as a function of the wafer position. These results clearly indicate that the net donor concentration in the wafer can be made uniform by using a substrate with a small deviation in the off-angle.

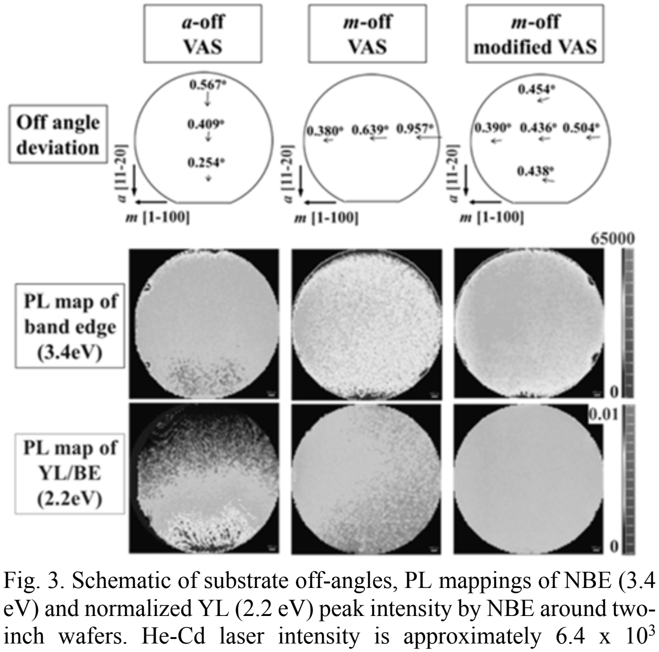

Fig. 3. Schematic of substrate off-angles, PL mappings of NBE (3.4 eV) and normalized YL (2.2 eV) peak intensity by NBE around two-inch wafers. He-Cd laser intensity is approximately 6.4 x 10^3 (W/cm^2).

The average Si concentration obtained from SIMS is approximately 8.32×10^{15} cm^{-3} which is largely uniform across the wafers. The C concentration slightly increased with a decrease in the substrate off-angle. That is, the N_A variation resulted in the non-uniformity of $N_D - N_A$, which is found to be related to the substrate off-angle of the wafer. The reason for the off-angle dependence of the C concentration is still unclear. In another, Sarzynski reported that incorporating indium into the InGaN layer depends on the substrate off-angle when the MOVPE is used on the GaN substrate [17]. That is, high Indium content of InGaN was obtained in the low-off angle region. Furthermore, we developed substrates that have an improved off-angle deviation by employing a homo-epitaxial HVPE growth technique combined with the Na-flux method as a seed crystal [18].

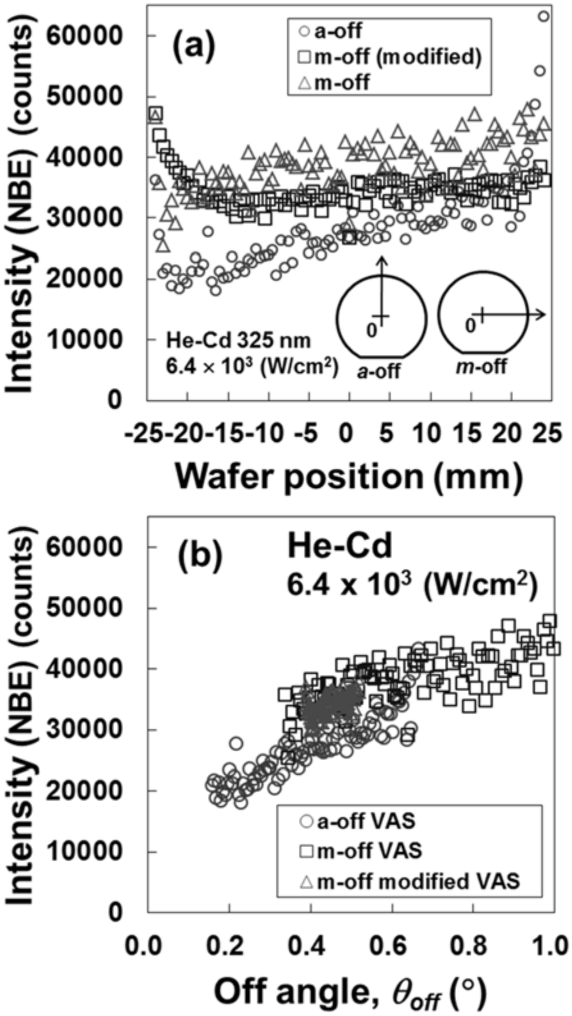

Fig. 4. PL intensities of NBE. Irradiation intensity is approximately 6.4×10^3 (W/cm^2). *a*-off VAS, *m*-off VAS, and *m*-off modified VAS, are indicated using circles, squares, and triangles, respectively. (a) As a function of wafer position. (b) As a function of substrate off-angle.

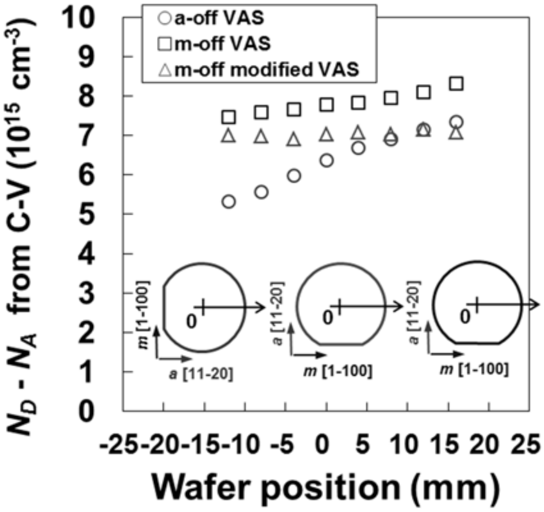

Fig. 5. Net donor concentration, $N_D - N_A$, as a function of the wafer position. *a*-off VAS, *m*-off VAS, and *m*-off modified VAS are indicated using circles, squares, and triangles, respectively.

CONCLUSIONS

We demonstrated the improvement in the wafer-level uniformity of a GaN Schottky barrier diode by controlling the off-angles of the GaN substrates. The variation in $N_D - N_A$ was carefully analyzed using C–V, PL, and SIMS. The variation in N_A resulted in the non-uniformity of $N_D - N_A$, which is found to be related to the substrate off-angle of the wafer. The net donor concentration, $N_D - N_A$, in the wafer level can be made uniform by minimizing the variation in the off-angle.

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ACRONYMS

R_{on}: Specific differential on-resistance
V_B: Breakdown voltages
VAS: Void-assisted separation
MOVPE: Metal-organic vapor phase epitaxy
NBE: Near band edge
PL: Photoluminescence
HVPE: Hydride vapor phase epitaxy