

# Comparison of Schottky Diodes on Bulk GaN substrates & GaN-on-Sapphire

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## ABSTRACT

The influence of dislocations on reverse leakage current and breakdown is studied by direct comparison between GaN Schottky diode on low dislocation density bulk GaN substrates and high dislocation density GaN-on-sapphire substrate. Schottky diodes on Bulk GaN substrates clearly show lower leakage and higher breakdown voltages due to their low dislocation densities.

## INTRODUCTION

Detailed understanding and improvement of GaN epitaxial crystal quality is critical for high power and high speed device applications. One of the challenges facing today is the threading dislocations of the GaN substrates propagate into the epitaxial layers grown on them. The influence of dislocations on reverse-bias leakage currents in Schottky diode has been studied extensively [1-7]. However previous studies have focused on diode with relatively large leakage currents due to high dislocation densities. In this work, we compare Schottky diodes grown and fabricated on two types of substrates: a) bulk GaN substrates (from Ammono) [8] with dislocation density  $N_{dis} \sim 10^5 \text{ cm}^{-2}$ , and b) GaN-on-sapphire substrates from Lumilog [9] with  $N_{dis} \sim 10^9 \text{ cm}^{-2}$ . The epitaxial layers of the diodes are grown in parallel, as is the entire processing steps. The results show clear advantage of bulk GaN substrates for low leakage and high breakdown Schottky diodes.

## EPIPLAYER QUALITY ANALYSIS AND DEVICE FABRICATION

The Schottky diode structure used in this study is schematically shown in Figure 1 (a). Plasma-assisted Molecular Beam Epitaxy (PAMBE) was used to grow a 300nm thick unintentionally doped (UID) GaN on bulk GaN substrate and GaN-on-sapphire substrate, the samples were co-loaded for epitaxy. The  $2\mu\text{m} \times 2\mu\text{m}$  Atomic Force Microscope (AFM) images of grown epilayer show clear atomic steps in both samples suggesting layer by layer growth (Figure 2 (b) and (d)). Some pits like defects were observed in AFM topography images of UID-GaN grown on GaN-on-sapphire substrate (Figure 2 (c) and (d)). Those pits could change the electrical characteristics of device by acting as a leakage path. Epilayer grown on bulk GaN substrate shows atomic steps even in the large area  $20\mu\text{m} \times 20\mu\text{m}$  AFM scan. Though we also observed some defect features in this large area AFM image, we believe these defects can be removed by improving the epitaxy and are not coming from the bulk GaN substrate. The transmission

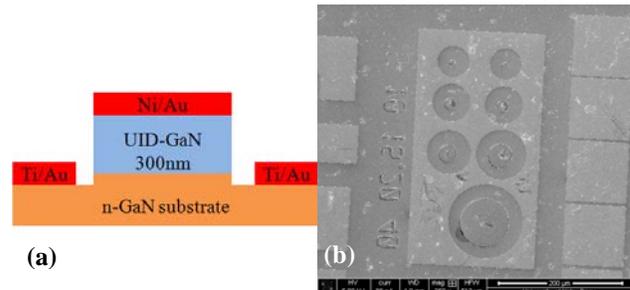


Figure 1 (a) Sketch of the cross section of the Schottky diode, (b) SEM picture of the device top-view.

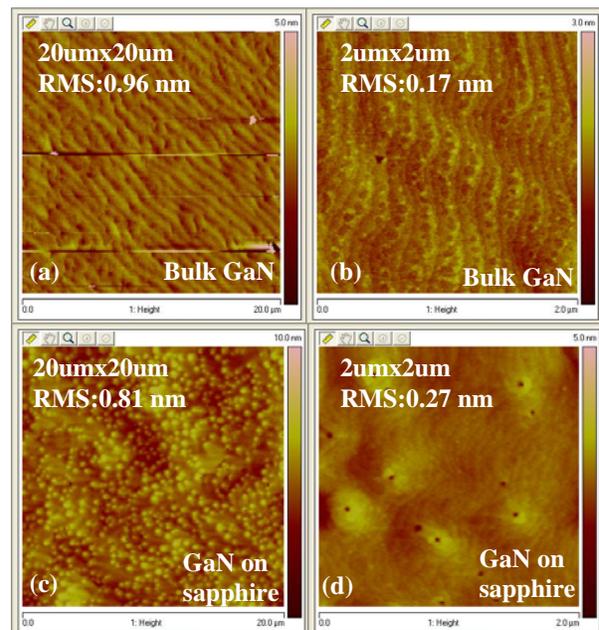


Figure 2 AFM pictures of epitaxial layer on bulk GaN substrate (a)  $20 \times 20 \mu\text{m}$  (b)  $2 \times 2 \mu\text{m}$ , and AFM picture of epitaxial layer on GaN-on-sapphire substrate (c)  $20 \times 20 \mu\text{m}$  (d)  $2 \times 2 \mu\text{m}$ .

electron microscope (TEM) images have been taken on both samples. The surface of the samples (covered by metal) are the on the right side of the pictures (Figure 3). Figure 3 (a) is the TEM image of UID-GaN on bulk GaN substrate. The growth interface between bulk GaN and epilayer is visible. The growth interface can be smoother by improving the epitaxy or more careful surface cleaning before growth. No defect can be seen in the bulk GaN substrate and the epilayer. The TEM picture of epilayer on GaN-on-Sapphire substrate clearly shows threading dislocation from the substrate, which could extend into the epilayer (Figure 3(b)).

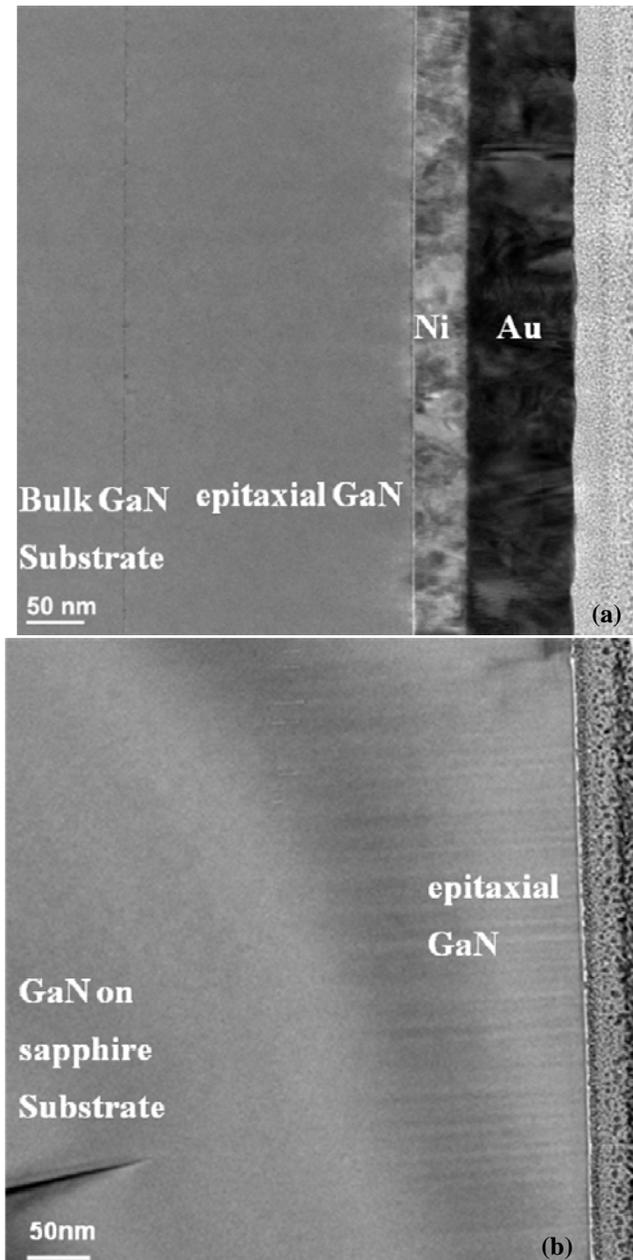


Figure 3 TEM picture of (a) epitaxial GaN on bulk GaN substrate with no visible dislocation, TEM picture of (b) epitaxial GaN on GaN-on-Sapphire substrate, the growth interface is not clear, but one dislocation can be seen in the substrate region.

Figure 1 (b) is the SEM picture of the device top-view. The Schottky metal pad is a circle with radii  $R$  varying from 5-40  $\mu\text{m}$  using Ni/Au (50/100nm). Reactive-ion etching (RIE) is used for MESA isolation for about 350nm depth to remove all the UID GaN and stop in the  $n^+$  GaN region. A non-alloy ohmic contact is formed using Ti/Au (20/100nm) on the  $n^+$  GaN region with contact resistance less than 0.3 $\Omega\text{mm}$ .

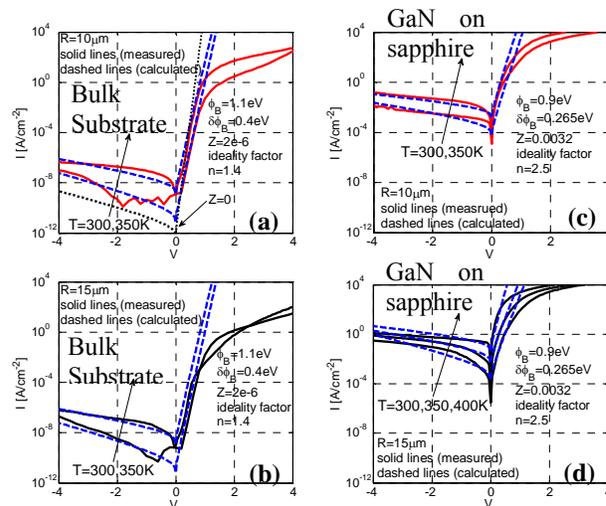


Figure 4  $I$ - $V$  characteristics of Schottky diode on bulk GaN sample with (a)  $R = 10\mu\text{m}$  and (b)  $R = 15\mu\text{m}$ .  $I$ - $V$  characteristics of Schottky diode on GaN-on-sapphire sample with (c)  $R = 10\mu\text{m}$  and (d)  $R = 15\mu\text{m}$ .

#### DEVICE RESULTS AND ANALYSIS

The  $I$ - $V$  measurement of the GaN Schottky diode was performed over the range of 150 - 400K on a Lakeshore cryogenic probe station using a Keithley 4200 semiconductor characterization system on both bulk GaN sample and GaN-on-sapphire samples (Figure 4). Using the estimated Schottky barrier height due to the difference between metal work function and GaN electron affinity, the ideal reverse thermionic emission current density is close to  $10^{-11}\text{A}/\text{cm}^2$  at 300K. However the measured reverse current density is higher than the ideal reverse thermionic emission current density. The increase of reverse current can be contributed to a) dislocations in the epilayer [1-5], and b) thin surface barrier due to deep donors related with nitrogen vacancy near the surface [10]. The growth condition is metal rich for our epitaxy, thus the nitrogen vacancy can be ignored. The purpose of this work is aiming to analyze the influence of dislocation on the reverse leakage current.

The epilayer on bulk GaN substrate has much lower dislocation density compare with the epilayer on GaN-on-sapphire substrate as can be seen in the AFM and TEM images. The  $I$ - $V$  characteristics comparison between two samples show significant differences, as the leakage current density of Schottky diode on bulk GaN sample is about six orders of magnitude lower than that of GaN-on-sapphire sample. Assuming a perfect material with expected Schottky barrier height the thermionic emission current density is given by:

$$J_s^H = A^* T^2 \exp\left(-\frac{\phi_B - \delta\phi}{k_B T}\right) \quad (1)$$

where  $A^*$  is the Richardson constant,  $J_s^H$  is the saturation current density with normal Schottky barrier height  $\phi_B$ .  $\delta\phi$

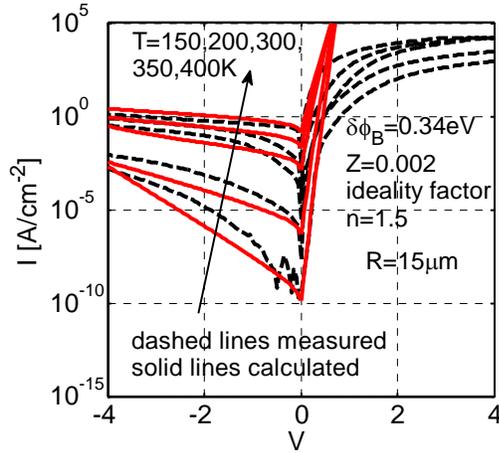


Figure 5 Temperature dependent  $I$ - $V$  characteristic compare with calculated results including both thermionic emission current and field assisted tunneling current for GaN-on-sapphire sample.

is the barrier lowering due to image charges effect [11]. Previous studies proposed that dislocation may cause the barrier lowering [1,5], which act as a local higher current density path with lower barrier height:

$$J_S^L = A^* T^2 \exp\left(-\frac{\phi_B - \delta\phi - \delta\phi_B}{k_B T}\right) \quad (2)$$

$J_S^L$  is the saturation current density with a barrier lowering  $\delta\phi_B$  due to a local dislocation. The total current density thought the entire diode will be the summation of currents flow around dislocation with lower barrier height and currents pass through area without defect:

$$J_S = \{J_S^L (AN_{dis}\pi r^2) + J_S^H (A - AN_{dis}\pi r^2)\} / A \quad (3)$$

where  $J_S$  is the total saturation current density through the diode,  $A$  is the total diode area. Ignoring the possible surface depletion at the MESA sidewall,  $A = \pi R^2$ , where  $R$  is the radius of diode (Figure 1 (b)). The effective area of a single dislocation is  $\pi r^2$ , ( $r$  is assumed equal to Debye length) and  $A_{dis} = AN_{dis}\pi r^2$  is the total area of dislocation. Parameter  $Z = A_{dis}/A$  is defined as the area percentage of dislocation over the entire diode.

Without any dislocation, at  $Z = 0$  (dotted line in Figure 4 (a)), the ideal leakage current density is only about one order of magnitude less than the measured reverse current density of Schottky diode on bulk GaN substrate. The low leakage current demonstrates the high material quality of bulk GaN substrate with less dislocation. While the Schottky barrier lowering effect due to dislocation significantly increases the current density in the Schottky diode on GaN-on-sapphire substrate. Using eqs. (1) - (3), the barrier height lowering  $\delta\phi_B$  due to dislocations and area percentage of dislocations  $Z$  are two fitting parameters in our model. The calculated current density is compared with the measured current density at different temperature and various diode radii shown in Figure 4 (the detail of thermionic emission model is shown in Ref. 11).

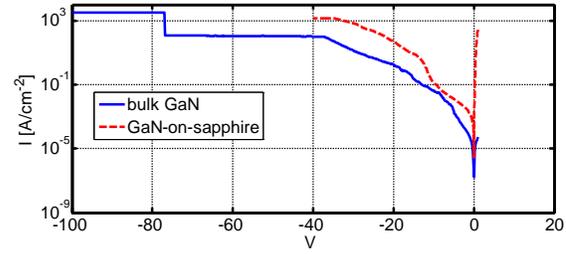


Figure 6 Comparison of breakdown voltage between Schottky Diode on bulk GaN substrate and Schottky diode on GaN-on-sapphire substrate.

TABLE I  
Calculated dislocation density for Schottky diode with different diode radius on bulk GaN substrate.

	Dislocation density (cm <sup>-2</sup> )
R=10μm	1.46x10 <sup>6</sup>
R=15μm	1.46x10 <sup>6</sup>
R=20μm	1.22x10 <sup>7</sup>

TABLE II  
Calculated dislocation density for Schottky diode with different diode radius on GaN-on-sapphire substrate.

	Dislocation density (cm <sup>-2</sup> )
R=10μm	7.8x10 <sup>8</sup>
R=15μm	2.24x10 <sup>9</sup>
R=20μm	1.95x10 <sup>7</sup>
R=40μm	2.93x10 <sup>9</sup>

The estimations of dislocation density at different diode area are listed in Table I for bulk GaN sample and Table II for GaN-on-sapphire sample. The estimated dislocation density for bulk GaN sample is about  $10^6 \sim 10^7$  cm<sup>-2</sup>, which is higher than the dislocation density of the GaN bulk substrate. Some defects could be introduced during the growth as discussed in the AFM pictures (better epitaxy quality has been achieved in latest growth on bulk GaN substrate). The estimated dislocation density of GaN-on-sapphire sample is similar as the substrate dislocation density.

In Figure 5, we compare the measured  $I$ - $V$  of Schottky diode on GaN-on-sapphire substrate with the proposed model from 150K to 400K. The  $I$ - $V$  characteristics at different temperature are well explained by the dislocation induced barrier lowering model. Because of the reverse leakage current at low temperature is less than  $10^{-15}$  A for Schottky diode on bulk GaN substrate, which is beyond the measurement limits. The temperature dependence analysis is not available for Schottky diode on bulk GaN substrate.

The breakdown performance comparison between Schottky diode on bulk GaN substrate and GaN-on-sapphire substrate is shown in Figure 6. Much higher breakdown

voltage can be measured on Schottky diode on bulk GaN substrate. Using the relationship [12]:

$$V_{BR} = E_C W - \frac{q N_D W^2}{2 \epsilon_s} \quad (4)$$

where  $N_D$  is the doping concentration in GaN epilayer, which is about  $3 \times 10^{16} \text{ cm}^{-3}$  based on CV measurement.  $W$  is the depletion width, about the same as the epilayer thickness. The corresponding electrical field at breakdown voltage is 3.3MV/cm for Schottky diode on bulk GaN Substrate, which is close to theory predicted critical field 3.5~3.8MV/cm for GaN. The Schottky diode on GaN-on-sapphire substrate suffers from severe leakage problem with electrical field at breakdown voltage close to 1.5MV/cm.

#### CONCLUSIONS

We compared the performance of GaN Schottky diode on bulk GaN substrates and GaN-on-sapphire substrate. Schottky diode on Bulk GaN substrate clearly shows lower leakage current and higher breakdown voltages due to low dislocation densities. The barrier lowering effect due to dislocation is added into the thermionic emission model which explained the temperature dependence  $I$ - $V$  characteristics.

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