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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. 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. 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]. Most 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 $N_{dis} \sim 10^5$ cm^{-2}, and b) GaN-on-sapphire substrates from Lumilog [9] with $N_{dis} \sim 10^9$ 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.

DEVICE FABRICATION AND MEASUREMENT

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 2µm x 2µm Atomic Force Microscope (AFM) images of grown epilayer show clear atomic steps in both samples suggesting layer by layer growth (Figure 2). Some pit like defects were observed in AFM topography image of UID-GaN grown on GaN-on-sapphire substrate (Figure 2 (c) and (d)). Those pits may change the electrical characteristics of device by acting as a leakage path. Epilayer grown on bulk-GaN shows atomic steps even in the large area 20µm x 20µm 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. A transmission electron microscope (TEM) image on bulk GaN sample shows no visible dislocations (Figure 3). Figure 1 (b) is the SEM picture of the device top-view. The Schottky metal pad is a circle with radii varying from 5-40 µm using Ni/Au (50/100nm). An ohmic contact is formed using Ti/Au (20/100nm). Reactive-ion etching (RIE) is used for MESA isolation.

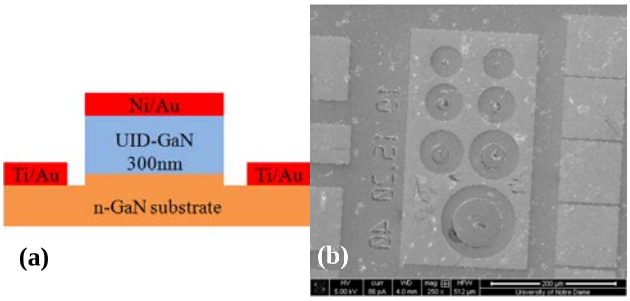

Figure 1 (a) Sketch of the cross section of Schottky diode, (b) SEM picture of the device top view.

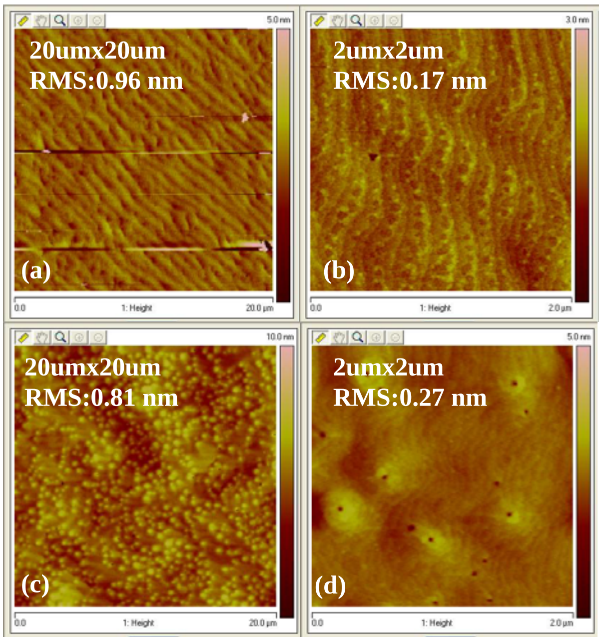

Figure 2 AFM picture of epitaxial layer on bulk GaN substrate (a) 20x20µm (b) 2x2µm, and AFM picture of epitaxial layer on GaN-on-sapphire substrate (c) 20x20µm (d) 2x2µm.

DEVICE RESULTS AND ANALYSIS

The *I-V* characteristics are shown in Figure 4, where the Schottky barrier height is extracted from Richardson plot as 1.1eV for bulk GaN sample and 0.9eV for GaN-on-sapphire sample. The leakage current density of Schottky-diode on

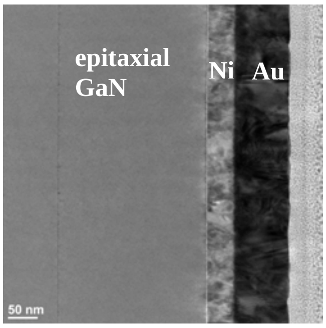

Figure 3 TEM picture of epitaxial GaN on bulk GaN substrate with Ni/Au (50/100nm) contact on top showing no dislications.

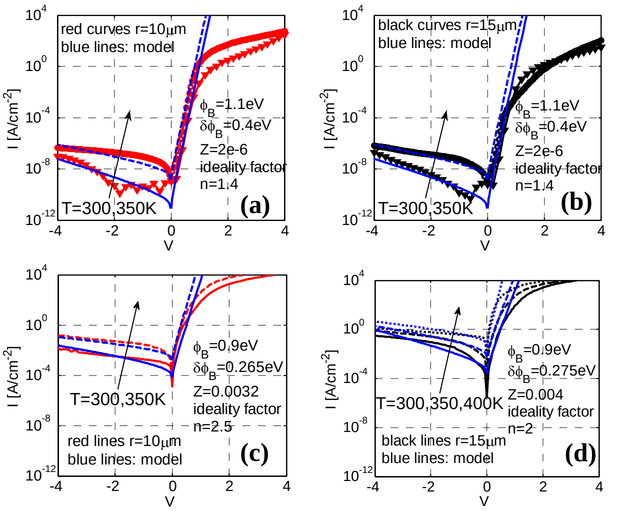

Figure 4 *I-V* characteristics of Schottky diode on bulk GaN sample (a) radius = 10μm and (a) radius = 15μm. *I-V* characteristics of Schottky diode on GaN-on-sapphire sample (c) radius = 10μm and (d) radius = 15μm.

bulk GaN sample is more than four orders of magnitude lower than that of GaN-on-sapphire sample. The larger leakage current of GaN-on-sapphire sample can be due to the barrier lowing caused by dislocations [1,5], which act in parallel with the normal Schottky barrier:

$$J_S^H = A^*T^2\exp\left(-\frac{\phi_B-\delta\phi}{k_BT}\right) \qquad (1)$$

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

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

,where A^* is the Richardson constant, J_S is the total saturation current density through the diode in thermionic emission model, J_S^H is the saturation current density with normal Schottky barrier height Φ_B, and J_S^L is the saturation current density with a barrier lowering $\delta\Phi_B$ due to a local dislocation, $\delta\Phi$ is the barrier lowering due to image charges effect, A is the total diode area. The effective area of a single dislocation is πr^2, (r is assumed equal to Debye length). $A_{dis} = AN_{dis}\pi r^2$ is the total area of dislocation, with $Z = A_{dis}/A$ defined as the area percentage of dislocation over whole

TABLE I

Calculated dislocation density for Schottky diode with different diode radius on bulk GaN sample.

	Dislocation density (cm^{-2})
r=10μm	1.46×10^6
r=15μm	1.46×10^6
r=20μm	1.22×10^7

TABLE II

Calculated dislocation density for Schottky diode with different diode radius on GaN-on-sapphire sample.

	Dislocation density (cm^{-2})
r=10μm	7.8×10^8
r=15μm	2.24×10^9
r=20μm	1.95×10^7
r=40μm	2.93×10^9

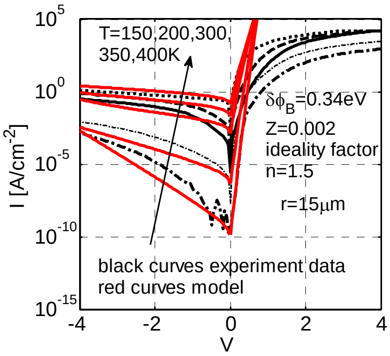

Figure 5 Temperature dependent *I-V* characteristic compare with calculated results including both thermionic emission current and field assisted tunneling current for GaN-on-sapphire sample.

diode. When $Z = 0$, without any dislocation, the ideal leakage current density is much less than the measured data. The Schottky barrier lowering due to dislocation causes significant increase of current density though the dislocation area, although other area is not leaky. Following eq. (1)-(3), the barrier height lowering $\delta\Phi_B$ due to dislocation 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 following Ref. 10). 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.

In Figure 5, the calculated currents are well matched with measured data from 150K to 400K for GaN-on-sapphire sample. Low temperature *I-V* is not available for Schottky diode on bulk GaN, because the leakage current is less than 10^{-15}A, beyond the measurement limits.

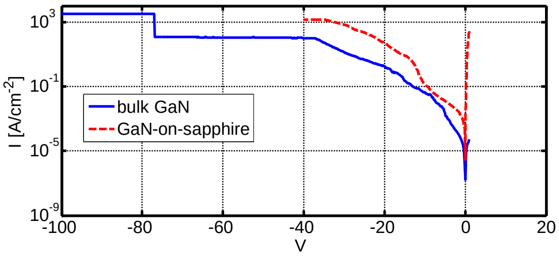

Figure 6 Comparison of breakdown voltage between Schottky Diode on bulk bulk GaN substrate and Schottky diode on GaN-on-sapphire substrate.

The breakdown performance comparison between Schottky diode on bulk GaN substrate and GaN-on-sapphire substrate is shown in Figure 6. Using the relationship [11]:

$$V_{BR} = E_C W - \frac{qN_D W^2}{2\varepsilon_S} . \qquad (4)$$

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 substrates and GaN-on-sapphire substrate. Bulk GaN sample 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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