Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp239-240

Effect of GaN drift-layer thicknesses in vertical Schottky Barrier Diodes on free-standing GaN substrates

S. Abhinay[1], S. Arulkumaran[2,3], G.I. Ng[1,2], K. Ranjan[1,2], M. Deki[3], S. Nitta[3] and H. Amano[3]
[1]School of EEE, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798.
[2]Temasek Laboratories@NTU, Nanyang Technological University, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553.
[3]Center for Integrated Research of Future Electronics (CIRFE), Institute of Materials and Systems for Sustainability (IMaSS), Nagoya University, Nagoya 464-8603, Japan.

Abstract

Vertical Schottky Barrier Diodes (SBD) were fabricated and the effects of GaN drift-layer thicknesses (DLT) on free-standing GaN substrate were studied. SBDs exhibited average barrier heights (Φ_B) of 0.72 eV, 0.77 eV and 0.76 eV and ideality factors (n) of 1.1, 1.03, and 1.09 for DLTs of 2 µm, 5 µm and 30 µm, respectively. Decrease of reverse leakage current (I_R) and increase of breakdown voltage (BV_R) of SBDs with the increase of DLT were realized. SBDs with 30 µm DLT exhibited a BV_R of 2400 V is the highest reported value. The reverse conduction mechanism of the fabricated SBDs was found to be dominated by thermionic field emission (TFE).

1. Introduction

Schottky Barrier Diodes (SBD) fabricated on GaN epitaxial layer grown on GaN substrate (GaN on GaN) have great advantage over GaN SBDs on hetero-epitaxial substrates as the Threading Dislocation Density (TDD) are 3-4 orders of magnitude lower. Employing the advantages of reduced TDD of free-standing GaN substrate and vertical SBD, researchers have reported Ni-based SBD with improved ideality factor (n) of 1.01 [1], barrier height (ϕ_B) of 1.1 eV [2], and low reverse leakage current of 26.5 µA/cm^2 at -400 V [2].

Even though the electrical characteristics of a SBD are primarily dependent on material properties of metal/semiconductor interface (i.e. TDD, metal stack and etc.), other factors such as diode area, drift-layer concentration [3], drift-layer growth-rate [4] and drift-layer thickness (DLT) also play an important role. As reported in [5], SBDs with lower concentration and thicker DLT plays a key role for the design of radiation detectors. Recently, Munir et al. studied the effects of DLT in SBDs by theoretical simulations [6]. Till now, no reports have studied the effects of DLT on the performance of vertical SBDs on free-standing GaN substrates. In this work, we have systematically studied the effects of GaN DLT on the electrical performances of vertical SBDs using current-voltage (*I-V*), current-voltage-temperature (I-V-T) and Reverse Breakdown Voltage (BV_R) measurements.

2. Experimental Procedure

Un-intentional doped GaN drift layers were grown on 2-inch diameter n$^+$-GaN substrate using Metal Organic Chemical Vapour Deposition (MOCVD) method. The thicknesses of drift layer were 2, 5, and 30 µm respectively. Vertical SBDs were fabricated on the free-standing GaN with different DLTs by the evaporation of ohmic metal stack of Ti/Al/Ni/Au (20/120/40/50 nm) on N-face of GaN followed by annealing (775 °C for 30 sec in N_2 atmosphere) and the Schottky contact of Ni/Au (50/1000 nm) was formed on Ga-face of GaN. For comparison, SBDs were also fabricated on the free-standing GaN substrate. Figure 1(a) shows the schematic cross-section of the fabricated vertical SBDs. The SBD characteristics such as *I-V*, I-V-T measurements and BV_R measurements were performed using Agilent B1505A Power Device Analyser.

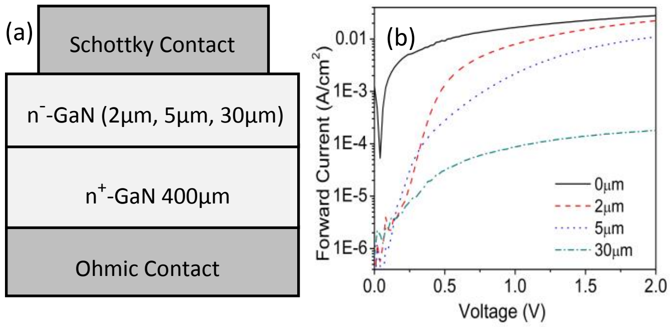

Figure 1: (a) Schematic cross-section of the fabricated vertical SBD on free-standing HVPE grown GaN with different drift layer thickness grown by MOCVD and (b) forward *I-V* characteristics of vertical SBDs with different DLTs

3. Results and Discussion

Figure 1(b) shows the measured forward *I-V* characteristics of the fabricated vertical SBDs with different DLTs. The SBD with DLT of 2 µm exhibited highest forward saturation current density (I_{sat}) of 0.226 A/cm^2. However, the SBD with DLT of 30 µm exhibited lowest I_{sat} of $1.8 \times 10^{-4}\ A/cm^2$. The decrease in I_{sat} with the increase of DLT is primarily due to the increase of series resistance of SBD.

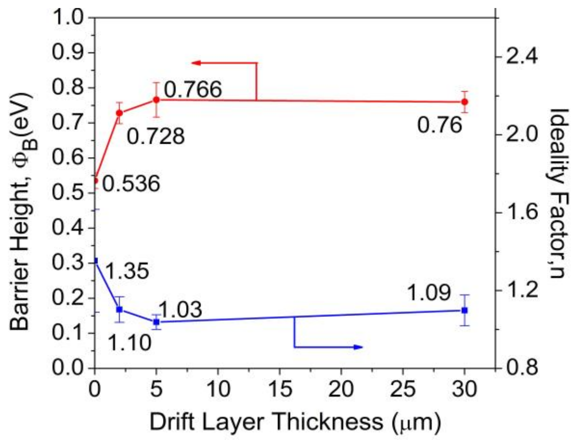

Figure 2: Schottky Barrier Height and Ideality Factor of vertical SBD (10 diodes) with different DLT on free-standing GaN.

Figure 2 shows the extracted Ideality Factor (n) and Barrier Height (ϕ_B) (from *I-V* characteristics) of the fabricated SBD with different DLT. For statistical accuracy, 10 SBDs were measured on each wafer. The obtained n is almost close to 1.0 for SBDs on all DLT, which is an indication of the formation of high quality metal-semiconductor interface. SBDs with different DLT exhibited an average ϕ_B value of 0.73 eV (2 µm), 0.77 eV (5 µm) and 0.76 eV (30 µm). Similar ϕ_B values have also been reported by other research groups using Ni-based vertical SBD [10-12]. From this, it is clear that the measured ϕ_B of SBDs is independent of DLT.

Figure 3 shows the reverse leakage current density (I_R) at -20 V and measured BV_R for SBDs with different DLT. For comparison, the breakdown voltage of SBD was also simulated using Silvaco and included in Figure 3. I_R of SBDs decreases at higher rate with the increase of DLT up to 5 µm, while at a lower rate of I_R for the DLT of 30 µm. Lower rate of I_R reduction for SBDs with DLT greater than 5 µm may be due to the saturation of leakage paths from substrate to drift layer.

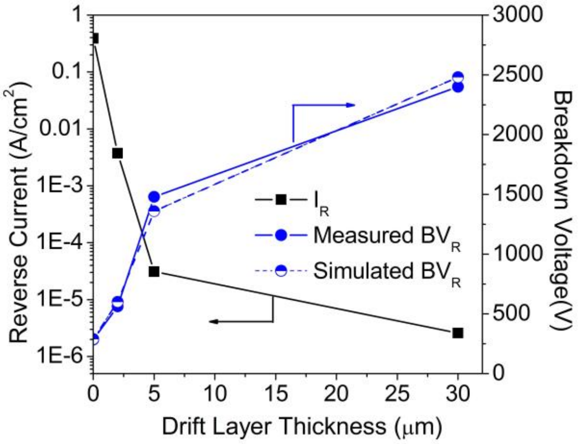

Figure 3: Reverse leakage current density, measured and simulated breakdown voltages for different DLT.

For the measurement of BV_R, the wafers were immersed in flourinert FC-40 and the current compliance was fixed at 1.0 A/cm^2. The measured BV_R values of 562 V, 1480 V and 2400 V for SBDs with DLT of 2 µm, 5 µm and 30 µm, respectively were obtained (See Table I). The increase of BV_R with DLT is consistent with the decrease of I_R with DLT (See Figure 3). The measured BV_R of 2400 V on vertical SBDs with DLT of 30 µm is the highest reported and is almost close to the simulated BV_R. The increase of BV_R with DLT is consistent with the decrease of I_R with DLT (See Figure 3).

Table I: Benchmarking of measured BV_R of Ni-based SBDs with different DLT with state of art vertical SBDs

Affiliation	DLT [µm]	BV_R [V]
University of Notre Dame [7]	0.3	100
Army Research Labs [8]	2	450
Toyoda Gosei [2]	10	719
Sumitomo Industries [10]	5	1100
Shenzhen University [11]	13	1200
This Work	**2**	**562**
	5	**1480**
	30	**2400**

Table I shows the reported state-of-the art BV_R for Ni-based vertical SBDs. Saitoh et al realized the BV_R of 1100 V for the SBDs with DLT of 5 µm after the incorporation of field plate [10]. However, our SBDs with same 5 µm of DLT exhibited higher BV_R without any additional field plate. This may be due to the improved crystalline quality with reduced dislocation density of the grown drift-layer on free-standing GaN substrate.

To study the conduction mechanism of the fabricated vertical SBDs, I-V-T measurements were carried out by varying the temperature from 25 ºC to 150 ºC in steps of 25 ºC. Figure 4(a) shows the forward I-V-T characteristics of SBDs with DLT of 2 µm. The increase in current density with the increase of temperature is mainly due to thermionic emission. The effective barrier height (ϕ_{Beff}) was also calculated from the Richardson's plot (see figure 4(b)). No significant change in ϕ_{Beff} was observed for SBDs with different DLT which is in good agreement with ϕ_B measured at room temperature. The I_R increases (at -20 V) with increasing temperature for SBDs with different DLT is shown

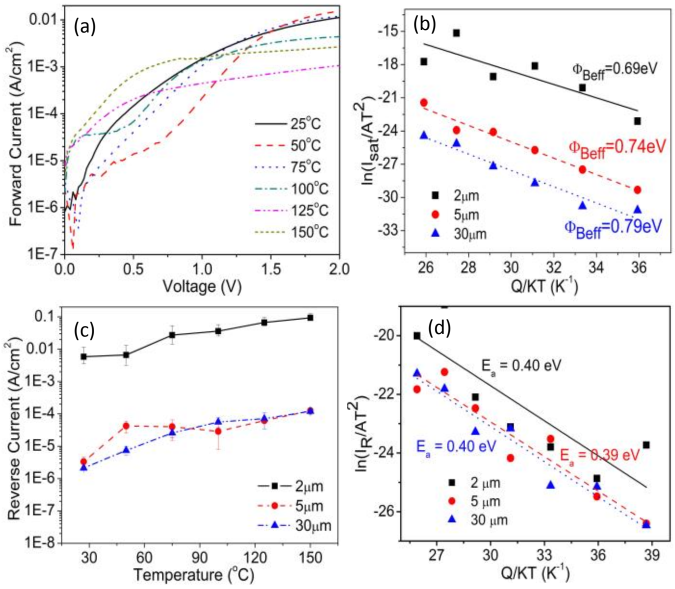

Figure 2: (a) Forward I-V-T characteristics of SBD with DLT of 2µm; (b) Richardson's plot for forward current; (c) Reverse leakage current density (-20V) as a function of temperature; (d) Richardson's Plot for reverse leakage current.

in Figure 4(c). The extracted activation energy (E_a) of ~0.4 eV for SBDs with different DLTs (see Figure 4(d)) could be due to emission from trap state to a continuum band of states, which might be located within the bandgap associated with threading screw dislocations [12]. Though SBDs with 2 µm DLT exhibited higher I_R but the extracted E_a for SBDs on all DLT is the same. The low value of activation energy and high n at higher temperatures validate the current conduction mechanism is dominated by thermionic field emission [13].

4. Summary

We have studied the effects of DLT on the *I-V*, I-V-T and reverse breakdown characteristics of vertical SBDs on free-standing GaN. The measured Schottky parameters n, ϕ_B, ϕ_{Beff} are independent of DLT. The decrease of I_R and increase of BV_R with the increase of DLT has been observed in the fabricated vertical SBDs. The measured BV_R of SBDs with DLT of 30µm (2400 V) is the highest reported in the literature and is close to the simulated value (2480 V). Reverse conduction mechanism was observed to be thermionic field emission. The vertical SBDs with thick DLT is a viable method to realize low leakage current, and higher breakdown voltages without affecting other SBD parameters even at high temperatures, which makes it suitable for radiation detection.

References

[1] H. Yamada et al., Appl. Phys. Exp.,10 (2017)041001
[2] N. Tanaka et al., Appl. Phys. Exp.,8 (2015)071001
[3] H. Fu et al., IEEE Electron. Device Lett.,38 (2017)763
[4] B. Ren et al., Appl. Phys. Exp.,10 (2017)051001
[5] J. Grant et al., Nuc. Inst. And Met. In Phys. Res.,576(2007) 60
[6] T. Munir et al., IEEE ICSE, USA,2006
[7] P. Zhao et al., CS Mantech, Chicago, USA, 2013
[8] R.P. Tompkins et al., J. Elect. Mat.43(2014)850
[9] G. Greco et al., Phys. Stat. Solidi,(2017) 1700613
[10] Y. Saitoh et al., Appl. Phys. Exp.,3 (2010) 081001
[11] Q.L. Z. Liu et al, Jpn. J. Apl. Phys.,56 (2017) 026501
[12] A. Fontsere et al, Appl. Phys. Lett., 101 (2012) 093505
[13] J. Suda et al., Appl. Phys. Exp., 3 (2010) 101003