Temperature Independence of Dynamic Switching in 4.8 A /3.6 kV NiO/β-Ga_2O_3 High Power Rectifiers

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Abstract

The fabrication and switching characteristics of unpackaged vertical geometry NiO/β- Ga_2O_3 rectifiers with a reverse breakdown voltage of 3.6 kV (0.1 cm diameter, 7.85 x10^{-3} cm^2 area) and an absolute forward current of 4.8 A fabricated on 10 µm thick epitaxial β-Ga_2O_3 drift layers and a double layer of NiO to optimize breakdown and contact resistance were measured with an inductive load test circuit. The Baliga figure-of-merit of the devices was 8.64 GW.cm^{-2}, with a differential on-state resistance of 1.5 mΩ.cm2. The on/off ratio was above 2.8x10^{13} over a broad range of switching voltages. The recovery characteristics for these rectifiers switching from the forward current of 1 A to reverse off-state voltage of -550 V showed a measurement-parasitic-limited recovery time (trr) of 100 nanoseconds, with a peak current value of 1.4A for switching from 640V. Also, for 200 µm diameter rectifiers, the reverse recovery time of ~21 ns was independent of temperature, with the Irr monotonically increasing from 15.1 mA at 25°C to 25.6 mA at 250°C and dropping at 300°C. The dI/dt increased from 4.2 to 4.6 A/µs over this temperature range. The turn-on voltage decreased from 2.9 V at 25 °C to 1.7 V at 300°C.

Introduction

There is great current interest in the development of power electronic devices based on monoclinic β-Ga_2O_3 [1-16]. There have been demonstrations of high breakdown voltages above 8kV in relatively small devices of both vertical rectifiers [8] and lateral transistors intended for lower current applications [11-13]. A promising recent development has been the use of NiO as a p-type conducting layer to produce p-n heterojunctions with the n-type Ga_2O_3 [17-31]. This to some extent mitigates the lack of a native p-type doping capability for Ga_2O_3. There remain many challenges, including optimizing edge termination, and managing heat dissipation, which will be needed if adequate device reliability is to be achieved [1,3,32-39]. Another crucial focus is to have larger area devices to achieve high conduction currents, while simultaneously retaining the kV breakdown characteristics [32,34-44]. Qin et al.[1] recently reviewed the status of packaging and device performance of Ampere-class Ga_2O_3 Schottky, Junction Barrier Schottky, heterojunction rectifiers and MOSFETs and their switching recovery characteristics, and surge-current and over-voltage ruggedness.

While small area devices now have breakdown voltages exceeding the unipolar limit of both SiC and GaN power devices, large area, Ampere-class Ga_2O_3 vertical devices have not yet reached this milestone [1].

In this paper, we demonstrate 1 mm^2, 4.8A, 3.6 kV V_B vertical planar NiO/Ga_2O_3
rectifiers, with performance above the unipolar limit of both GaN and SiC. The power figure of merit is FOM of 8.64 GW.cm^{-2}, with reverse recovery time of 42 ns.

EXPERIMENTAL

Figure 1(top) shows a schematic of the vertical heterojunction rectifier structure. The drift region was a 10 µm thick, lightly Si doped (8x10^{15} cm^{-3}) layer grown by halide vapor phase epitaxy (HVPE) on a (001) surface orientation Sn-doped β-Ga_2O_3 single crystal (Novel Crystal Technology, Japan). For comparison, we also fabricated devices in the identical fashion on structures with drift region doping 2x10^{16} cm^{-3}, also obtained from Novel Crystal Technology. The backside Ohmic contact used e-beam evaporated Ti/Au with a total thickness of 100 nm. This was annealed at 550°C for 60s under N_2 [10, 32,33]. The p-n heterojunction was formed by rf magnetron sputter deposition of a bilayer of NiO [10]. The working pressure was 3mTorr at 80W power. The deposition rate of 0.06 Å.sec^{-1}. Contact to the NiO was made through e-beam deposition of 100 nm total thickness of Ni/Au with contact diameter 1 mm. An optical image of the completed devices is shown in Figure 1(bottom).

Current-voltage (I-V) characteristics were recorded in Fluorinert atmospheres at 25°C on a Tektronix 371-B curve

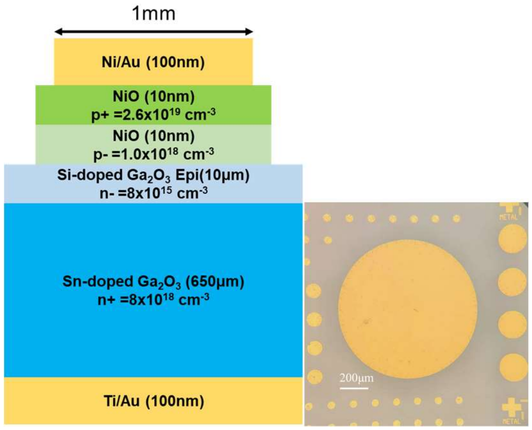

Fig. 1. (Left) Schematic of NiO/Ga$_2$O$_3$ heterojunction rectifier. (Right) optical micrograph of array of 1 mm^2 rectifiers.

tracer and Glassman high voltage power supply. An Agilent 4156C was also used for forward and reverse current characteristics. The reverse breakdown voltage was obtained from the standard definition of reverse current reaching 1 mA.cm^2. The I-V characteristics were reproducible over areas of 1 cm^2 on the wafer, with absolute currents within 20 % at a given voltage.

RESULTS AND DISCUSSION

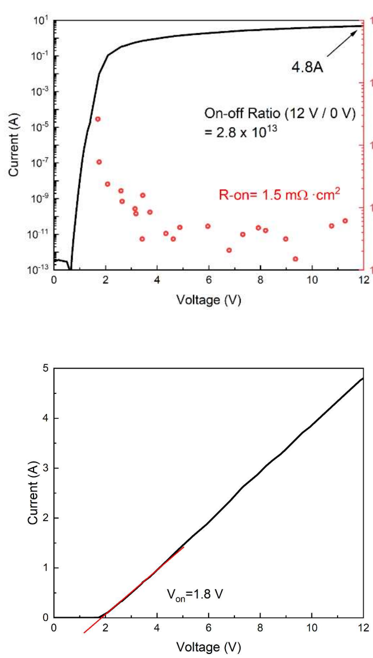

Fig. 2. (top) Log plot of forward current densities and R_{ON} values of NiO/Ga$_2$O$_3$ heterojunction rectifiers (bottom) linear plot of forward I-V characteristics of NiO/Ga$_2$O$_3$ heterojunction rectifiers.

The forward I-V characteristics are shown in Figure 2 (a) for the 1mm diameter devices fabricated with the 8x10^{15} cm^{-3}drift layers. The maximum forward current was 4.8A, with 1A reached at 4V forward. This shows the presence of the p-n junction does not prevent reaching high forward currents at moderate biases. The on-resistance was 1.5 mΩ. cm^{-2}. The on-off ratio was 2x10^{13} for switching from 12V/0V. The same data is shown in linear form in Figure 2 (bottom), showing the turn-on voltage was 1.8 V.

The reverse I-V characteristics are shown in Figure 3 (top) for the devices fabricated on both the 8x10^{15} cm^{-3} and 2x10^{16} cm^{-3} drift layers. The former exhibit V_B values of 3.6 kV, the highest yet reported for large area Ga$_2$O$_3$ rectifiers [1]. The decrease in drift layer carrier concentration has a significant effect on V_B, with the devices with higher doping having breakdown voltages roughly half that of the lower doped devices. The power figure of merit was 8.64 GW.cm^{-2} for the 3.6 kV devices. This is approximately 25% of the theoretical maximum for β-Ga$_2$O$_3$, showing there is still room for optimizing device design and material defect density [1-5]. The average electric field strength was 3.56 MV/cm, an appreciable fraction of the expected maximum near 8MV.cm^{-1} and among the highest reported, particularly for large area devices [1,2]. The bottom of Figure 3 shows the reverse I-V up to -100V, with the current density being <10^{-10} A.cm^{-2} to this voltage.

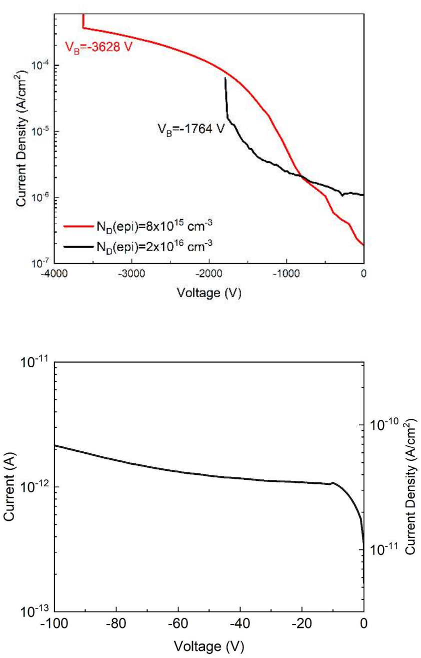

Fig. 3. (top) Reverse I-V characteristics and breakdown voltage of NiO/Ga$_2$O$_3$ heterojunction rectifiers. (bottom) expanded view of reverse leakage current-bias voltage characteristics to -100V.

The on/off ratio when switching from 12V forward to the reverse bias on the x-axis is shown in Figure 4 for the 1mm ^{2}

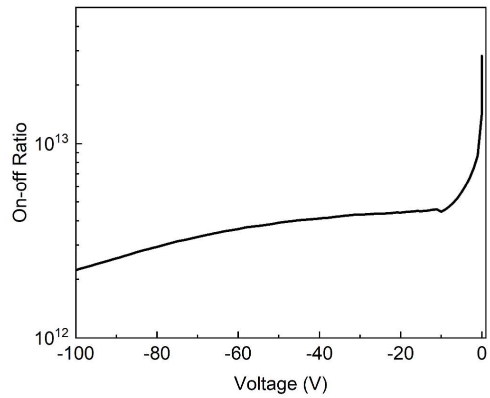

Fig. 4. On-off ratio of NiO/Ga_2O_3 heterojunction rectifiers in which the bais was switched from 5V forward to the voltage shown on the x-axis.

devices with the low drift layer concentration. The values are > $2x10^{12}$ when switching to -100V, showing the excellent rectification characteristics of these large area devices and the highest yet reported [1].

Figure 5 shows the reverse recovery waveform when switching from 120 mA forward current. The reverse recovery time is 42 ns, with a reverse recovery current of 34 mA. Th recovery time is approximately twice that for small rectifiers with areas 5-8 $x10^{-3}$ mm^2, ie 100-200 x smaller than the $1mm^2$ devices [10].

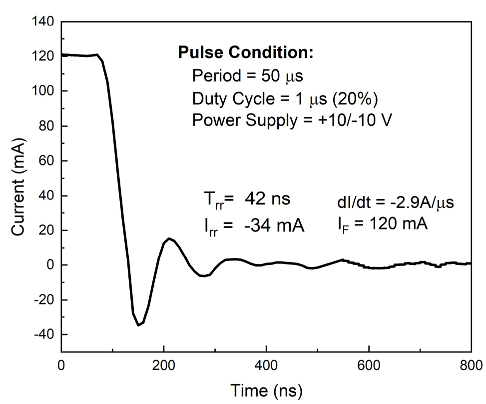

Fig. 5. Switching waveform for NiO/Ga_2O_3 heterojunction rectifiers.

To place the work in context, Figure 6 shows a compilation of reported Ron versus V_B results reported in the literature for Ampere-class rectifiers and includes conventional Schottky barrier or JBS rectifiers and NiO/Ga_2O_3 heterojunction rectifiers [33-44]. The theoretical lines for the 1D unipolar limits of SiC, GaN and Ga_2O_3 are also shown. The result in this work is the first demonstration of large area, Ampere-class Ga_2O_3 rectifiers surpassing the theoretical limits of GaN and SiC.

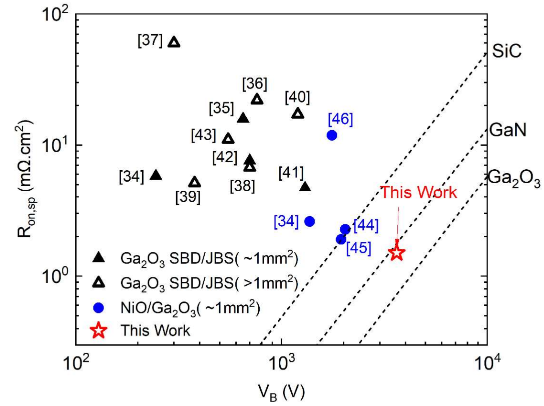

Fig. 6. Compilation of Ron versus V_B of conventional and NiO/Ga_2O_3 heterojunction rectifiers reported in the literature.

Figure 7 shows a compilation of on/off ratios as a function of the Baliga FOM for large area Ga_2O_3 rectifiers. The results in this current work show how lowering the drift region carrier concentration and optimization of the device processing parameters have led to improvement in device performance.

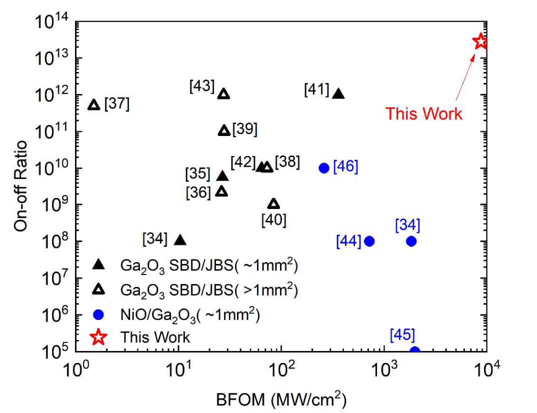

Fig. 7. Compilation of on-off ratio versus BFOM of conventional and NiO/Ga_2O_3 heterojunction rectifiers reported in the literature.

Finally, we measured the switching performance, as can be seen in the conducting-to-blocking transition waveforms of Fig. 8, the reverse recovery time is basically independent of temperature. Though the changes were small, we found in general that the peak reverse recovery current increased with increasing dI/ dt, and the recovery time decreased with increasing dI/ dt.

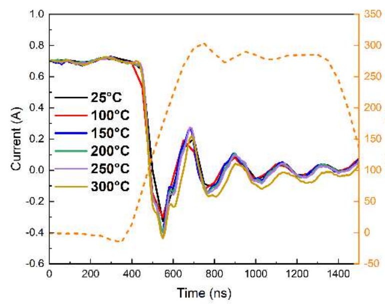

Fig. 8. Temperature dependence of switching characteristics of vertical rectifiers under pulsed conditions (Period = 50 uS, Duty Cycle = 0.1 uS (2%) Power Supply = 300 V with circuit board.

CONCLUSIONS

In summary, we report large area NiO/β-Ga2O3 p-n heterojunction rectifiers with V_B 3.6 kV, on/off ratio> $2x10^{12}$ up to 100V, with Ron of 1.5 mΩ·cm2 and a figure-of-merit (V_b^2/R_{on}) of 8.64 GW.cm^{-2}. The results show that with state-of-the-art epitaxial structures, the use of the NiO p-layer to form a heterojunction with the Ga_2O_3, a simple, planar fabrication technology produces results exceeding the 1D unipolar performance of GaN and SiC. This is very encouraging considering the other advantages of Ga_2O_3, including low production costs and scalable bulk growth technology. A key area for future work is to reduce the damage created by sputtering of the NiO, perhaps by using direct MOCVD growth, as demonstrated recently [47].

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