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7.5 kV, 6.2 GW cm^{-2} NiO/β-Ga_2O_3 vertical rectifiers with on–off ratio greater than 10^{13}

Special Collection: Gallium Oxide Materials and Devices

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ABSTRACT

Vertical geometry NiO/β n-Ga_2O/n$^+$ Ga_2O_3 heterojunction rectifiers with contact sizes from 50 to 200 μm diameter showed breakdown voltages (V_B) up to 7.5 kV for drift region carrier concentration of 8×10^{15} cm^{-3}. This exceeds the unipolar 1D limit for SiC and was achieved without substrate thinning or annealing of the epi layer structure. The power figure-of-merit, V_B^2/R_{ON}, was 6.2 GW cm^{-2}, where R_{ON} is the on-state resistance (9.3–14.7 mΩ cm^2). The average electric field strength was 7.56 MV/cm, approaching the maximum for β-Ga_2O_3. The on–off ratio switching from 5 to 0 V was 2×10^{13}, while it was 3×10^{10}–2×10^{11} switching to 100 V. The turn-on voltage was in the range 1.9–2.1 V for the different contact diameters, while the reverse current density was in the range 2×10^{-8}–2×10^{-9} A cm^{-2} at −100 V. The reverse recovery time was 21 ns, while the forward current density was >100 A/cm^2 at 5 V.

I. INTRODUCTION

Recently, there has been major progress in advancing the technology of vertical geometry rectifiers based on monoclinic β-Ga_2O_3.[1–7] Thick epitaxial layers grown on large area conducting substrates are commercially available with manufacturing costs comparable or lower than SiC technology.[1–3] Breakdown voltages up to 8.32 kV with on-resistance 5.24 Ω cm^{-2} have been reported, producing a power figure-of-merit (FOM) of 13.2 GW cm^{-2}.[6] Additional processing to reduce the drift region carrier density by extended annealing in O_2, followed by substrate thinning to reduce the on-resistance were needed to achieve these results.[6] A recent report has demonstrated up to 6 kV breakdown using a vertical structure with a deep trench of SiO_2 to provide edge termination.[7] For the first time, these values exceed the unipolar limit of SiC and GaN power devices.[6–8] While less desirable for power switching applications due to total current limitations, lateral β-Ga_2O_3-based devices with breakdown voltage up to 8 kV (Refs. 9–11) and critical breakdown fields also exceeding the theoretical electric field limits of SiC and GaN have been reported.[10,11,12–14]

One of the innovations that have led to the high breakdown voltage is the use of NiO as a conducting p-type oxide to form vertical p–n heterojunctions with n-type Ga_2O_3.[4,6,8,15–30] Compared to the previous generation of Schottky rectifiers in Ga_2O_3,[12–14] these p–n junction devices show larger breakdown voltages with only a slight increase in turn-on voltages.[15–29] Zhou *et al.*[29] give a detailed account of the design trade-offs. For example, a direct comparison of heterojunction and Schottky rectifiers fabricated on the same wafer showed breakdown voltage of 4.7 kV, power figure-of-merits, V_B^2/R_{ON} of 2 GW cm^{-2}, and on-state resistance, R_{ON}, of 11.3 mΩ cm^2 for the former,[8] while Schottky rectifiers without the NiO showed V_B of 840 V and power figure-of-merit of 0.11 GW cm^{-2}.[8] The bipolar transport available in such structures can induce both conductivity modulation and low on-resistance.

In this letter, we demonstrate 7.5 kV V_B in vertical planar NiO/Ga_2O_3 rectifiers and FOM of 6.2 GW cm^{-2}. These devices are processed without the complications of wafer thinning or annealing of the drift region to reduce the carrier concentration. This simplified processing sequence is attractive from a manufacturability viewpoint. Compared to previous reports with bilayer NiO,[22] we achieve higher V_B through the lower doping in the drift region, optimization of the NiO deposition process, and simplified design without field limiting rings. In our own previous work, we achieved 4.7 kV V_B, but through use of the lower doping and optimized process, we achieve a significant improvement in breakdown voltage here and performance beyond the unipolar limit of GaN.

II. EXPERIMENT

A schematic of the vertical heterojunction rectifiers is shown in Fig. 1. The drift region was a 10 μm thick, lightly Si doped (8×10^{15} cm^{-3}) layer grown by halide vapor phase epitaxy on a (001) surface orientation Sn-doped β-Ga_2O_3 single crystal (Novel Crystal Technology, Japan). Figure 2 shows the *C–V* data confirming the carrier density of 8×10^{15} cm^{-3} in the drift region. The full area Ti/Au back Ohmic contact was deposited by e-beam evaporation and annealed at 550 °C for 60 s under a flowing N_2 ambient.[30–32] The surface was cleaned by UV/ozone exposure for 10 min. The bilayer NiO was deposited by magnetron sputtering at 3 m Torr and 80 W of 13.56 MHz power at a final rate of 0.06 Å s^{-1}. The initial deposition is done at low powers (30 W) to minimize surface damage. We also used the Ar/O_2 ratio (flow rates 5/15 SCCM) during sputtering to control the doping in the NiO. A 20/80 nm Ni/Au contact metal (50–200 μm diameter) was deposited onto the NiO layer after annealing at 300 °C under O_2 ambient.[8] The NiO extends 3 μm beyond the contact metal, so the diameter is 6 μm larger. The devices are not isolated by trenches or dielectrics but are defined by the contacts.

The current–voltage (*I–V*) characteristics were recorded with a Tektronix 370-A curve tracer, 371-B curve tracer, and Agilent 4156C was used for forward and reverse current characteristics.[30,31] A Glassman power supply was used for the reverse characteristics. The reverse breakdown voltage was defined as the bias for a reverse current reaching 0.1 A cm^2. The *I–V* characteristics were quite uniform over areas of 1 cm^2 on the wafer with absolute currents within 15% at a given voltage. We tested 40 of the 100 μm diodes and 25 of the 50 μm. Of the 65 devices, 27 are above 7.5 kV V_B and 51 above 7 kV with reverse currents within 20% of each other.

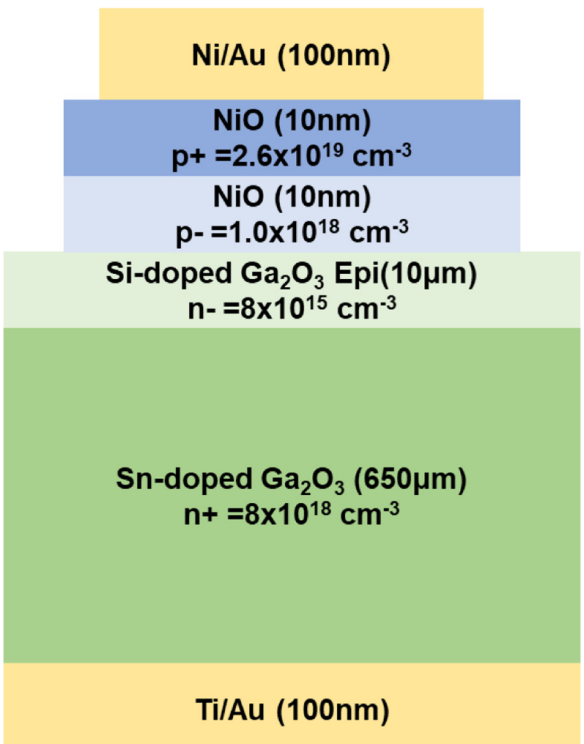

FIG. 1. Schematic of NiO/Ga_2O_3 heterojunction rectifier.

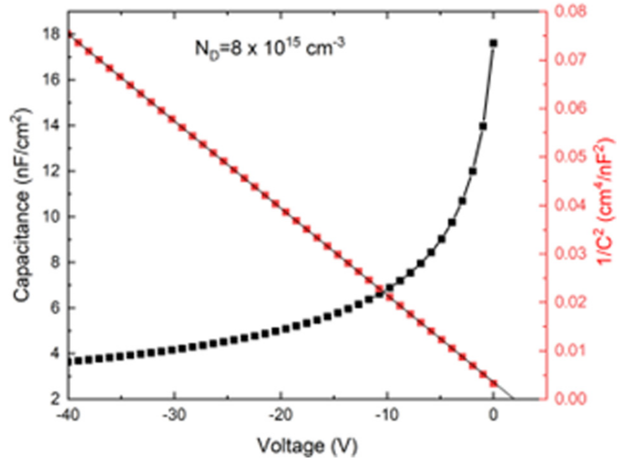

FIG. 2. *C–V* characteristics for determining carrier density in the drift region.

III. RESULTS AND DISCUSSION

The forward *J–V* characteristics are shown in Fig. 3(a) for three different device diameters. The on-resistance was in the range 9.3–14.7 mΩ cm^{-2} with forward current densities >100 A cm^{-2} at 5 V. The on–off ratio was 2×10^{13} for 5/0 V. The same data are shown in linear form in Fig. 3(b), showing the turn-on voltage was in the range 1.9–2.1 V for the different device sizes.

The reverse *I–V* characteristics are shown in Fig. 4(a) for the devices fabricated on the 8×10^{15} cm^{-3} drift layers, as well our previous result of 4.7 kV obtained on higher doped drift regions (2×10^{16} cm^{-3}).[8] Notice that the reduction in carrier density leads to a significantly higher breakdown voltage of 7.5 kV. These were measured in Fluorinert atmosphere at 25 °C. It is noteworthy that this was obtained without the need for annealing of the epi structure to further reduce carrier density or to thin the substrate to reduce on-resistance. The leakage increases sharply under biases <500 V, and we speculate in this design of NiO-based structures is due to the depletion width initially spreading sideways and leading to more leakage until the point where the edge of the NiO is reached and vertical depletion becomes dominant. The power figure-of-merit was 6.2 GW cm^{-2}. This is still lower than the theoretical maximum of ∼34 GW cm^{-2}[1,6] but shows the recent progress in material quality and edge termination design. The simplicity of this planar device design and processing sequence without trenches can reduce fabrication costs and improve yield. The rectifiers also have a high average electric field strength of

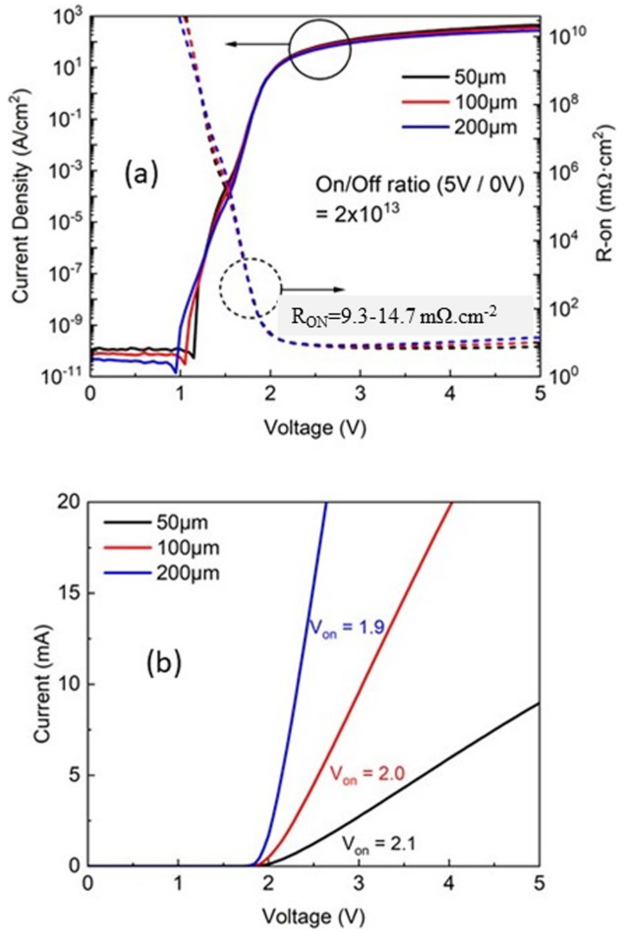

FIG. 3. (a) Log plot of forward current densities and R_{ON} values and (b) linear forward *I–V* characteristics of NiO/Ga_2O_3 heterojunction rectifiers.

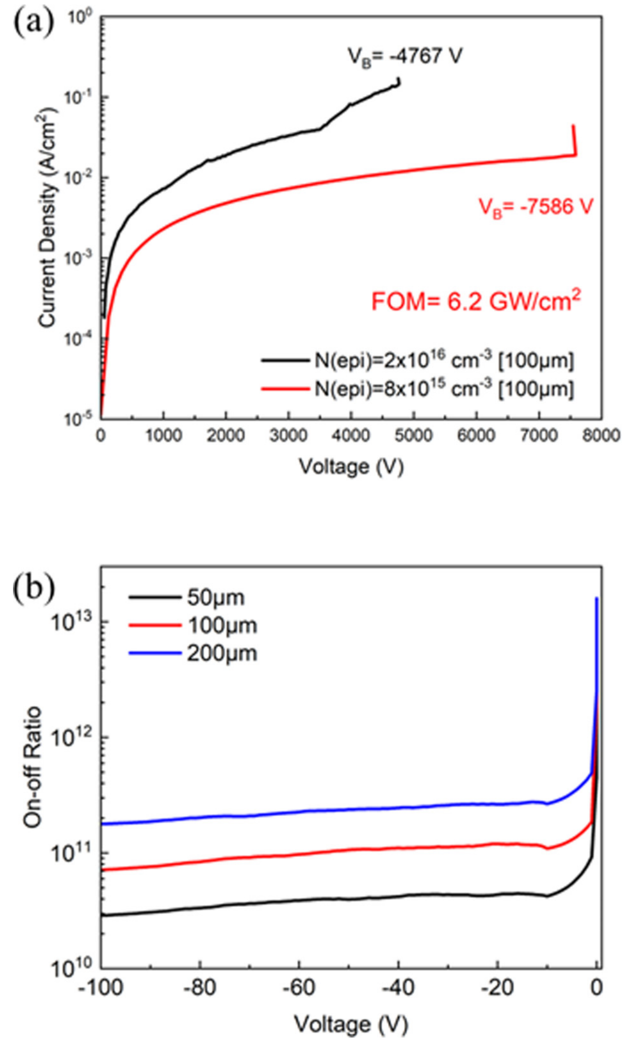

FIG. 4. (a) Reverse *I–V* characteristics and breakdown voltage and (b) on–off ratio of NiO/Ga_2O_3 heterojunction rectifiers in which the bias was switched from 5 V forward to the voltage shown on the *x* axis.

$7.58\,\text{kV}/(0.02 + 10\,\mu\text{m}) = 7.56\,\text{MV/cm}$, which is approaching the reported maximum near $8\,\text{MV cm}^{-1}$. The exact breakdown field strength is not fully addressed either theoretically or experimentally. Previous high breakdown devices have shown average fields from 6.2 to 6.5 MV/cm[6] and even as high as 6 MV/cm in Schottky designs without the p–n junction.[7] The critical field is defined as the maximum electric field that leads to avalanche breakdown in a 1D analytical model. For Ga_2O_3, there is as yet no experimental data confirming temperature-dependent behavior indicative of true avalanche breakdown. An extensive discussion in the certainties of establishing the true breakdown field in such circumstances has been given elsewhere.[33,34] A key finding was that future development of ultra wide bandgap materials is expected to change some critical field values.[33,34]

The on/off ratio when switching from 5 V forward to the reverse bias on the *x* axis is shown in Fig. 4(b) for the three different device sizes. The values are still in the range 3×10^{10}–2×10^{11} when switching to 100 V, showing the excellent rectification characteristics of the devices.

Figure 5(a) shows the reverse recovery waveform when switching from 80 mA forward current to −10 V. The details of the measurements have been reported previously.[35] The reverse recovery time is 21 ns, showing that charge storage in the p–n junction is not significant.

Figure 5(b) shows a compilation of R_{on} versus V_B results reported in the literature for conventional Schottky barrier or Junction barrier Schottky (JBS) rectifiers and NiO/Ga_2O_3 heterojunction rectifiers along with the theoretical lines for SiC, GaN, and Ga_2O_3. The present work shows that Ga_2O_3 is now achieving results beyond the 1D unipolar limits of GaN and SiC. Continued

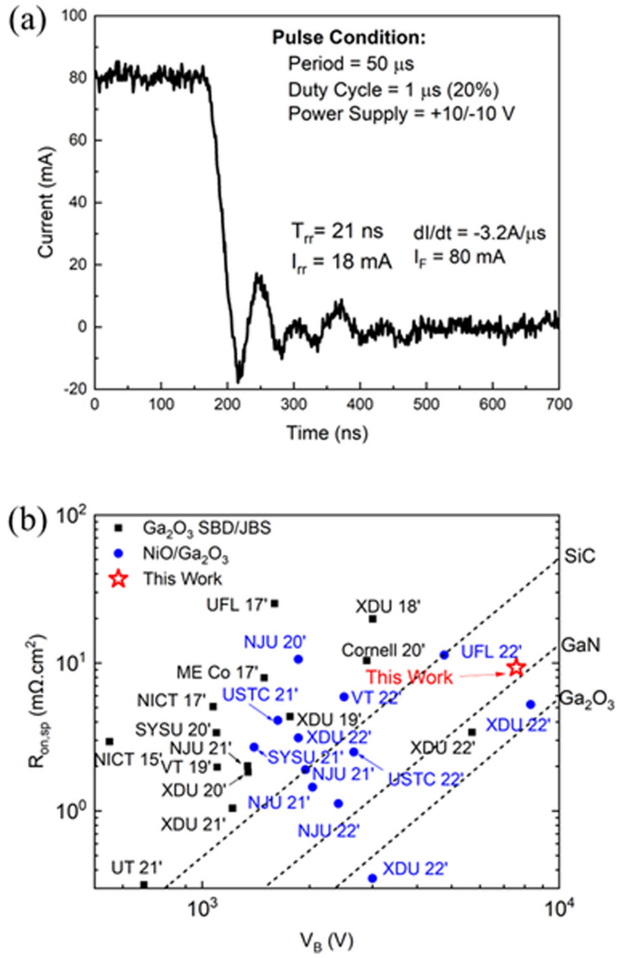

FIG. 5. (a) Switching waveform for NiO/Ga_2O_3 heterojunction rectifiers and (b) compilation of R_{on} vs V_B of conventional and NiO/Ga_2O_3 heterojunction rectifiers reported in the literature.

progress on reduced defect density in the Ga_2O_3 epi layers and optimized edge termination schemes should establish that this material has significant potential in power switching applications.

The breakdown voltages we have obtained are roughly a factor of two larger than our previous report on epi layers with doping about three times higher. We have noticed lower extended defect density in these epi layers, indicating more optimized growth and also modified our process to employ lower biases during sputter deposition of the NiO, optimized the gas flow ratio during deposition and also the surface cleaning prior to the NiO deposition. All of these lead to higher breakdown voltage without degrading on-resistance and demonstrate the potential of p-NiO as a technique for junction engineering in β-Ga_2O_3 power devices.[36,37] There is also interest in using p-NiO gates for normally off Ga_2O_3 heterojunction field effect transistors.[38] Finally, it is expected that uniformity of the wafers will improve. The trends of V_B across a wafer of the type we used have recently been published by Wang *et al.*[39]

IV. SUMMARY AND CONCLUSIONS

In summary, we report a NiO/β-Ga_2O_3 p–n heterojunction rectifier with V_B 7.5 kV with R_{on} of 9.3 mΩ cm^2 and a figure-of-merit (V_B^2/R_{on}) of 6.2 GW cm^{-2}. This work shows that existing wafer and fabrication technology is now capable of consistently exceeding the unipolar power device performance of SiC.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose

Author Contributions

Jian-Sian Li: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Chao-Ching Chiang:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Xinyi Xia:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Hsiao-Hsuan Wan:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Fan Ren:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Writing – original draft (equal). **S. J. Pearton:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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