

NiO/ β -(Al_xGa_{1-x})₂O₃ /Ga₂O₃ Heterojunction Lateral Rectifiers with Reverse Breakdown Voltage > 7kV

Running title: NiO/ β -(Al_xGa_{1-x})₂O₃ /Ga₂O₃ Heterojunction Lateral Rectifiers

Running Authors: Wan et al.

Hsiao-Hsuan Wan¹, Jian-Sian Li¹, Chao-Ching Chiang¹, Xinyi Xia¹, Fan Ren¹, Hannah N. Masten², James Spencer Lundh², Joseph A. Spencer^{3,4}, Fikadu Alema⁵, Andrei Osinsky⁵, Alan G. Jacobs³, Karl Hobart³, Marko J. Tadjer³ and S.J. Pearton^{6,a)}

¹Department of Chemical Engineering, University of Florida, Gainesville, FL 32611 USA

²National Research Council Postdoctoral Fellow at U.S. Naval Research Laboratory

³U.S. Naval Research Laboratory, Washington, DC, USA

⁴Virginia Tech, Blacksburg VA, USA

⁵Agnitron Technology, Inc, Chanhassen, MN, USA

⁶Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611 USA

a) Electronic mail: spear@mse.ufl.edu

NiO/ β -(Al_xGa_{1-x})₂O₃ /Ga₂O₃ heterojunction lateral geometry rectifiers with diameter 50-100 μ m exhibited maximum reverse breakdown voltages >7kV, showing the advantage of increasing the bandgap using the β -(Al_xGa_{1-x})₂O₃ alloy. This Si-doped alloy layer was grown by Metal Organic Chemical Vapor Deposition with an Al composition of ~21 %. On state resistances were in the range 50-2180 Ω .cm², leading to power figures-of-merit up to 0.72 MW.cm⁻². The forward turn-on voltage was in the range 2.3-2.5 V, with maximum on/off ratios >700 when switching from 5V forward to reverse biases up to -100V. Transmission line measurements showed the specific contact resistance was 0.12 Ω .cm². The breakdown voltage is among the highest reported for any lateral geometry Ga₂O₃-based rectifier.

I. INTRODUCTION

There is significant recent interest in development of Ga_2O_3 power devices due to their capability for high temperature operation, reduced on-state and switching losses due to lower on-resistance for high voltage devices, and potentially higher frequency switching capability⁽¹⁻⁸⁾. These are targeted for renewable energy transmission systems, electric vehicle (EV) traction inverter and motor control systems, fast charging stations and more electric aircraft^(9,10). Since the efficiency of EV powertrain inverters is partially determined by the efficiency of the switching transistors, it is of interest to examine ultra-wide-bandgap semiconductor electronics. The successful development of these power transistors is expected to significantly increase the longevity of a battery charge and the resultant cost of an EV. For devices in EV inverter applications, in addition to low switching loss and good thermal capability, high power and good robustness are highly desirable. In addition, the currently used passive and active filtering used to mitigate switching transients on motor drive systems in electro-hydrostatic and electromechanical actuators for air platforms could be replaced by optically-gated power semiconductor devices⁽¹¹⁾. The absence of a native p-type doping capability has led to use p-type oxides such as Cu_2O ⁽¹²⁾ or NiO ⁽¹³⁻¹⁷⁾ in heterojunctions with n-type Ga_2O_3 .

An additional advance comes from use of the wider bandgap alloy $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ in place of Ga_2O_3 . $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ alloys with compositions up to $x = 40\%$ have been grown with good crystalline quality on (010)-oriented $\beta\text{-Ga}_2\text{O}_3$ substrates, and $x \geq 50\%$ can be obtained on (100) and (-201) $\beta\text{-Ga}_2\text{O}_3$ substrates when the layers are grown by Metal Organic Chemical Vapor Deposition (MOCVD)⁽¹⁸⁻²³⁾. Phase pure β -

$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ films with Al content up to 27% have been grown with this technique ⁽²¹⁻²³⁾, which is promising from the viewpoint that this is the standard epitaxial growth method for most compound semiconductors. While most Ga_2O_3 -based rectifiers to date have been vertical geometry to increase the current-carrying capability ⁽²⁴⁻³²⁾, there is also interest in lateral geometry devices ⁽³³⁾, whose breakdown voltage can be more easily scaled by increasing the contact separation distance. Sundaram et al. ⁽²⁰⁾ showed that addition of a 30 nm-thick $\beta\text{-(Al}_{0.22}\text{Ga}_{0.78})_2\text{O}_3$ cap to an n-type $\beta\text{-Ga}_2\text{O}_3$ layer grown by metal organic chemical vapor deposition increased the breakdown voltage. The cap increased the surface Schottky barrier with Pt metal, resulting in reduced carrier injection under reverse bias. Masten et al. ⁽¹⁹⁾ reported $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ heterostructure MESFETs with on/off current ratio ~ 300 and drain current of 1.8 mA/mm at a gate bias of 5 V and drain bias of 30 V.

In this paper, we demonstrate breakdown voltages $> 7\text{kV}$ in lateral NiO/ $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3$ / Ga_2O_3 heterojunction rectifiers, with the basic layer structure grown by MOCVD, with the bilayer NiO deposited by sputtering. The devices show promising on/off ratio and low Ohmic contact resistance.

II. EXPERIMENTAL

The $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ heterostructures were grown in an Agnitron Agilis 500 MOCVD reactor with trimethylaluminum (TMAI), triethylgallium (TEGa), and oxygen (5N) as precursors, and argon (6N) as carrier gas ^(19, 20). The TMAI and TEGa precursors were used to grow 70 nm thick Si doped $\beta\text{-(Al}_x\text{Ga}_{1-x})_2\text{O}_3$ layer on ~ 300 nm UID $\beta\text{-Ga}_2\text{O}_3$ buffer layer, respectively, on a Fe doped (010) $\beta\text{-Ga}_2\text{O}_3$ 1" substrate (Synoptics). The

AlGaO layer was Si-doped using silane diluted in nitrogen (SiH_4/N_2) as the source with the targeted doping concentration of $\sim 4 \times 10^{17} \text{ cm}^{-3}$. The growth pressure was 15 Torr, and the growth temperature was 800°C , while the oxygen flow rate for the growth of the AlGaO was 600 sccm. The gas phase $[\text{TMAI}]/([\text{TMAI}]+[\text{TEGa}])$ molar flow rate ratio was $\sim 8.4\%$, producing an Al concentration of 20.6% calculated from X-ray diffraction (XRD). Room temperature Hall measurements showed a sheet resistance of $R_{\text{SH}} = 7636 \Omega/\text{sq.}$, with a sheet carrier concentration of $7.2 \times 10^{12} \text{ cm}^{-2}$ and associated electron mobility of $114 \text{ cm}^2/\text{V}\cdot\text{s}$. It should be noted that the unintentionally doped buffer is also somewhat conductive, around 10^{15} cm^{-3} , so the Hall measurements do not isolate the transport properties of the doped AlGaO layer.

The NiO bilayer was deposited on top of the epi layer by magnetron sputtering from dual NiO targets at 3mTorr and 150W of 13.56 MHz power. We used two targets to increase the deposition rate to $\sim 0.2 \text{ \AA}\cdot\text{sec}^{-1}$. The Ar/O₂ gas ratio during sputtering was used to control the doping in the NiO in the range 2×10^{18} - $2 \times 10^{19} \text{ cm}^{-3}$, with mobility $< 1 \text{ cm}^2 \cdot \text{V}^{-1} \text{ s}^{-1}$. The bandgap was 3.8 eV, consistent with literature values⁽³⁴⁾. We employed a bilayer of NiO of two different doping levels to both increase breakdown voltage and obtain low sheet resistance. The band alignment for the NiO on Ga₂O₃ is type II, staggered gap, allowing facile transport of holes across the heterojunction⁽³⁵⁾. The front-side of the device structure was contacted by 100 nm of Ni/Au metal, with circular contacts of 50-100 μm . Ohmic contacts to the lateral rectifier structure were made by 100nm of Ti/Au. A schematic is shown in Figure 1(a), while the different size rectifiers and the Transmission Line Measurement (TLM) pattern used to extract contact resistance is shown in Figure 1(b).

The current-voltage (I-V) characteristics were recorded on a Tektronix 371-B curve tracer at high voltage while an Agilent 4156C was used for forward and reverse current measurements at low biases. The reverse breakdown voltage was defined as the bias for a reverse current density reaching 0.1 A.cm^{-2} .

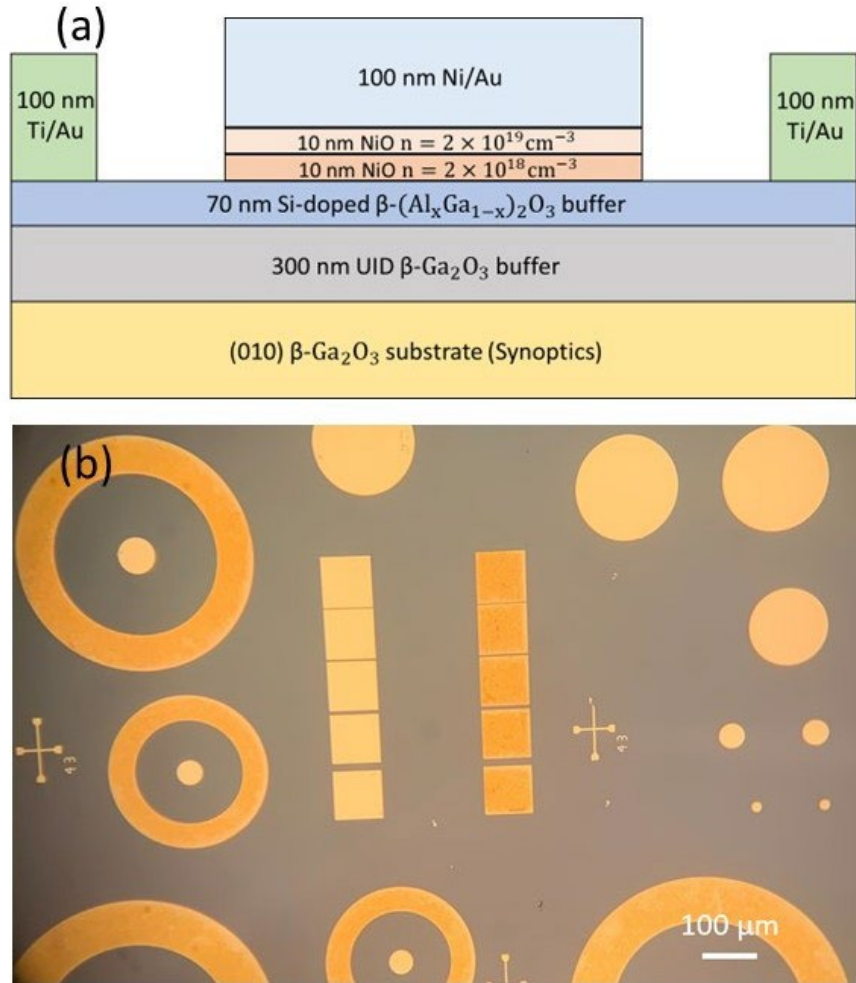


Fig. 1. (a) Schematic of lateral diode (b) Optical image of diodes and contact metals for TLM measurement.

III. RESULTS AND DISCUSSION

The TLM data for the structure is shown in Figure 2. The specific contact resistance was $0.12 \, \Omega \cdot \text{cm}^2$, with a transfer length of $1.48 \, \mu\text{m}$. The sheet resistance under the Ohmic contact was $5.3 \times 10^6 \, \Omega/\text{square}$, with a total resistance of $8.1 \, \text{k}\Omega \cdot \text{mm}$. These are reasonable values given the low doping in the wide bandgap $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ alloy.

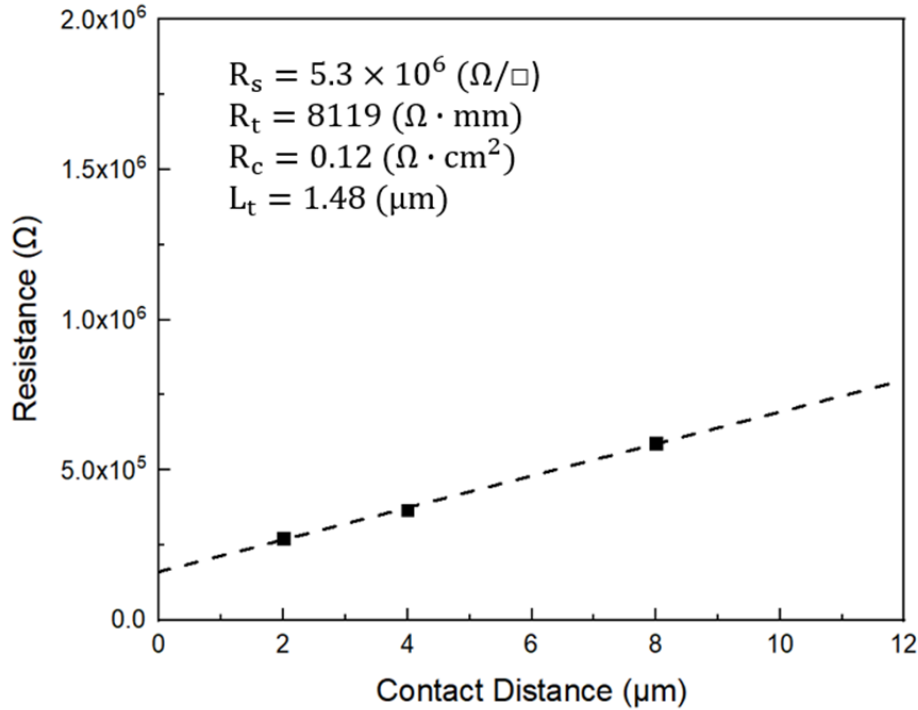


Fig. 2. TLM measurement data, showing the parameters extracted from the plot of resistance as a function of contact distance.

Figure 3 shows the forward current density characteristics and associated on-state resistances, R_{ON} , for three different rectifier diameters. The power figure-of-merit (FOM), V_B^2/R_{ON} , where V_B is the reverse breakdown voltage, for the $50 \mu\text{m}$ rectifier was $0.01 \, \text{MW} \cdot \text{cm}^{-2}$, for $75 \mu\text{m}$ was $0.34 \, \text{MW} \cdot \text{cm}^{-2}$, while for $100 \mu\text{m}$, FOM was $0.72 \, \text{MW} \cdot \text{cm}^{-2}$. These are well below the values for vertical geometry $\text{NiO}/\text{Ga}_2\text{O}_3$ rectifiers because of the higher on-state resistance in lateral devices⁽¹⁴⁻¹⁶⁾. The forward current was still dominated by thermionic emission current.

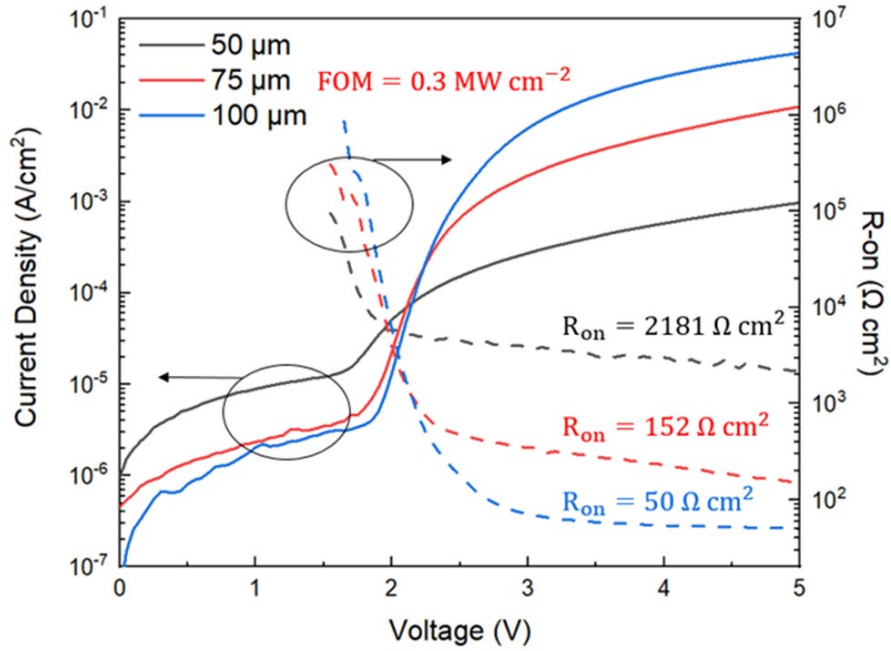


Fig. 3. Forward current density and on-state resistance for rectifiers of three different diameters.

Figure 4 shows linear plots of forward current to extract the forward turn-on voltage. This was in the range 2.3-2.5, consistent with previous reports for NiO/Ga₂O₃ rectifiers and demonstrating that the inclusion of the alloy did not degrade the turn-on voltage to a significant degree ⁽¹⁵⁻¹⁷⁾.

The breakdown voltages were extracted from the reverse I-V characteristics, as shown in Figure 5. The maximum value we obtained was over 7kV. This is the highest reported value for a lateral Ga₂O₃ rectifier. Bhattacharya et al.⁽³⁶⁾ reported 4.4 kV breakdown in Ga₂O₃ metal semiconductor (MESFETs), while values <4kV are reported for MESFETs and MOSFETs ⁽³⁷⁻⁴⁰⁾. The highest breakdown voltage for a lateral MOSFET is 8.56MV for 60 μm gate-drain separation, obtained after vacuum annealing and slightly higher than unannealed devices ^(41,42).

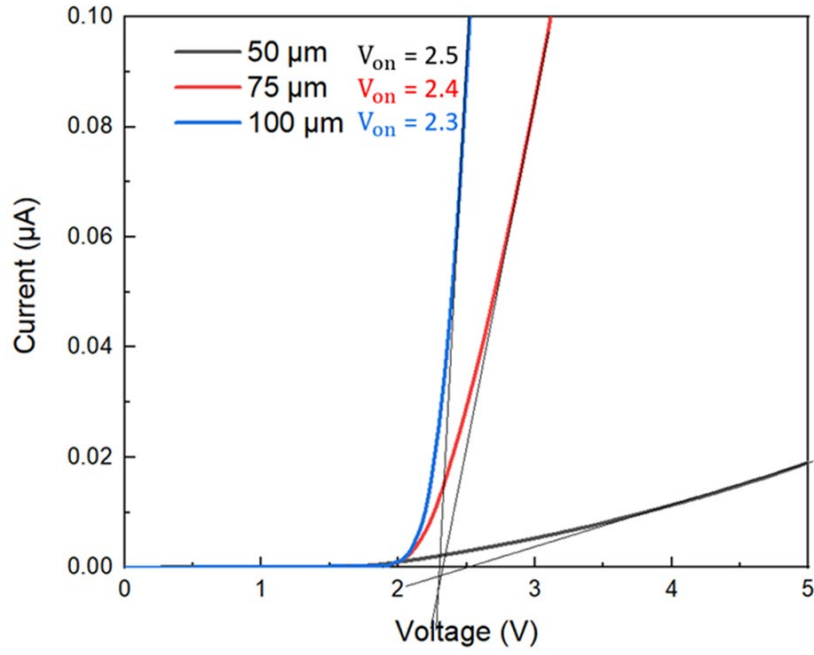


Fig. 4. Forward turn-on voltage for the three rectifier different diameters.

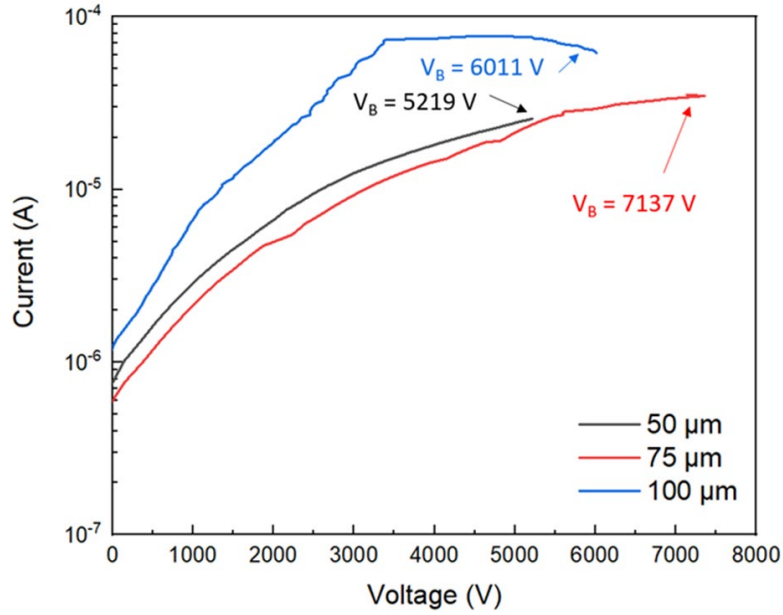


Fig. 5. Reverse I-V characteristics of rectifiers of three different diameters, showing the associated breakdown voltages.

A more detailed view of the reverse current at low biases, up to -100V, is shown in Figure 6. This reverse leakage current was dominated by thermionic field

emission (TFE) in this bias range. At $> \sim 300\text{V}$, electron injection into the drift region produced an $I \propto V^n$ relationship, where $n < 2$. This is typical of trap-assisted space-charge-limited conduction.

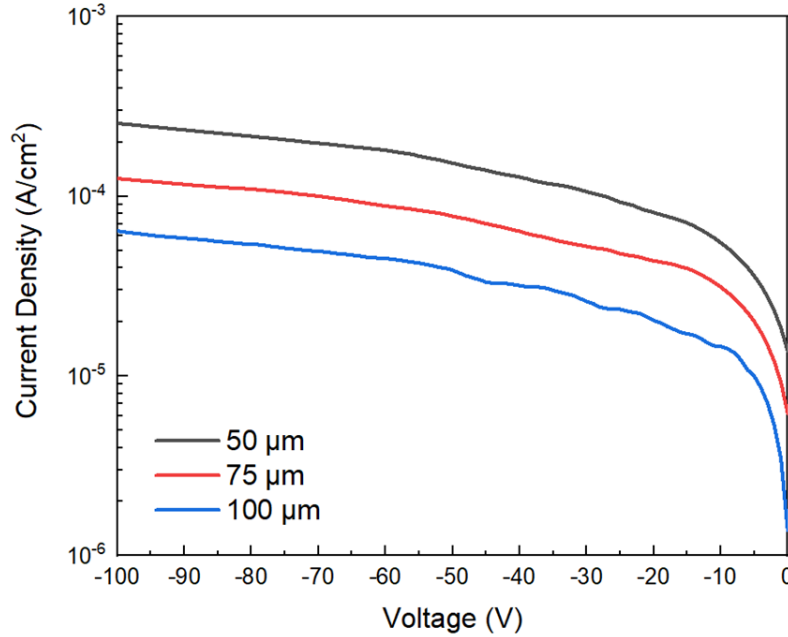


Fig. 6. Reverse I-V characteristics at low biases.

Figure 7 shows the diode on-off ratio for the NiO/ Ga₂O₃ heterojunction rectifiers when switching from -5V forward voltage to reverse voltages shown on the x-axis, ie. up to 100V. The maximum on/off ratio was > 700 .

To put the results in context, Figure 8 shows a compilation of reported breakdown voltages and on-state resistances from different institutions⁽³⁸⁻⁴²⁾. The device types are mainly either MESFETs or various types of MOSFET geometries, which we have included under the general heading of lateral FETs. Our results are among the highest figures of merit for lateral Ga₂O₃ devices, showing the advantage of both the ternary alloy to increase bandgap and the use of the NiO-(Al_{0.21} Ga_{0.79})₂O₃ p-n heterojunction. Since both switching devices and rectifiers are needed for inverter

systems, it is worth developing both lateral and vertical geometry devices in this ultra-wide bandgap materials system. The clear need is to lower the on-state resistance, while retaining the high breakdown voltages in our devices. Note that all of the reported figures of merit for lateral devices fall well short of the theoretical values for Ga_2O_3 , with only some being superior at this stage to the limits for Si. This emphasizes how much more development is needed for Ga_2O_3 power electronics.

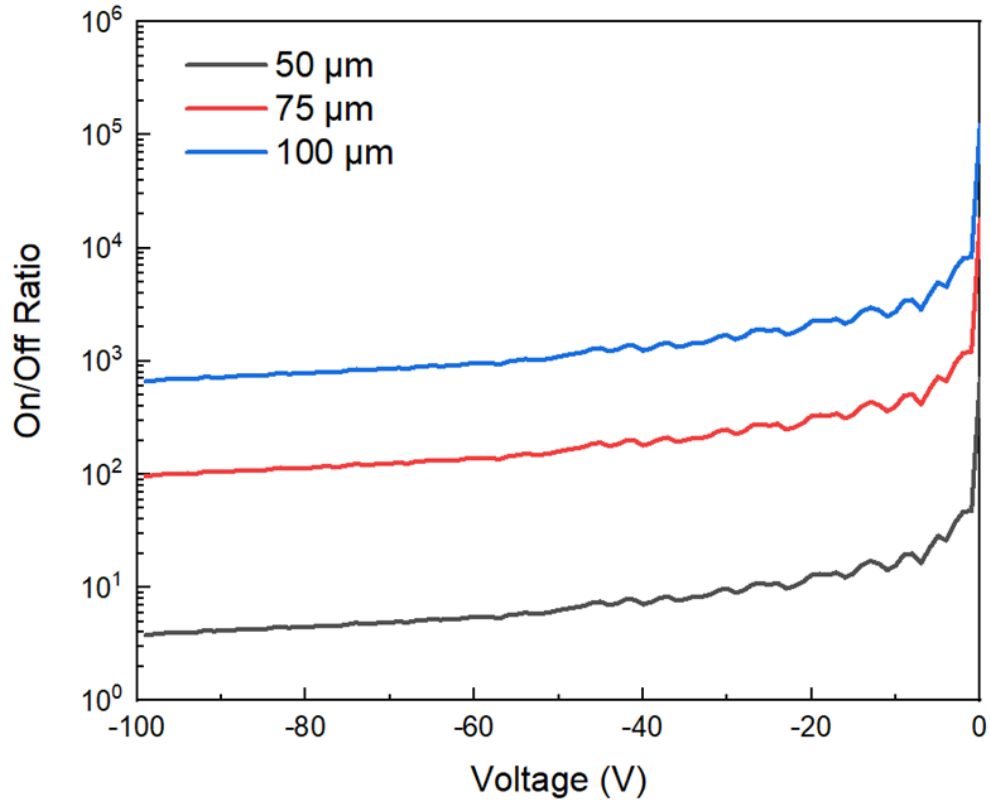


Fig 7. On/off ratio when switching from -5V to the value shown on the x-axis for three different diameter rectifiers.

and avoidance of mesa etching processes are all advantages of the approach outlined in this work.

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AUTHOR DECLARATIONS

Conflicts of Interest

The authors have no conflicts to disclose

DATA AVAILABILITY

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

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