

## LETTER

# Anisotropic electrical properties of $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$ $p$ - $n$ heterojunctions on (201), (001), and (010) crystal orientations

To cite this article: Dinusha Herath Mudiyanse et al 2023 *Appl. Phys. Express* **16** 094002

View the [article online](#) for updates and enhancements.

## You may also like

- [D'yakonov–Perel and Elliot–Yafet spin relaxation rates in InGaAs/InAlAs multiple quantum wells at room temperature](#)  
Ayuki Arikawa, Yasuhito Saito, Koichi Nakanishi et al.
- [Output-power equivalence of two- and four-terminal photovoltaic-thermoelectric hybrid tandems](#)  
Jun Sakuma, Kenji Kamide, Toshimitsu Mochizuki et al.
- [Heteroepitaxial growth of  \$\text{-Ga}\_2\text{O}\_3\$  thin films on single crystalline diamond \(111\) substrates by radio frequency magnetron sputtering](#)  
Takafumi Kusaba, Phongsaphak Sittimart, Yuki Katamune et al.



# Anisotropic electrical properties of $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$ $p$ - $n$ heterojunctions on $(\bar{2}01)$ , $(001)$ , and $(010)$ crystal orientations

Dinusha Herath Mudiyanse<sup>1</sup>, Ramandeep Mandia<sup>2</sup>, Dawei Wang<sup>1</sup>, Jayashree Adivarahan<sup>1</sup>, Ziyi He<sup>1</sup>, Kai Fu<sup>3</sup>, Yuji Zhao<sup>4</sup>, Martha R. McCartney<sup>5</sup>, David J. Smith<sup>5</sup>, and Houqiang Fu<sup>1\*</sup>

<sup>1</sup>School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, AZ 85287, United States of America

<sup>2</sup>School of Engineering for Matter, Transport and Energy, Arizona State University, Tempe, AZ 85287, United States of America

<sup>3</sup>Department of Electrical and Computer Engineering, The University of Utah, Salt Lake City, UT 84112, United States of America

<sup>4</sup>Department of Electrical and Computer Engineering, Rice University, Houston, TX 77005, United States of America

<sup>5</sup>Department of Physics, Arizona State University, Tempe, AZ 85287, United States of America

\*E-mail: [houqiang@asu.edu](mailto:houqiang@asu.edu)

Received August 1, 2023; revised September 2, 2023; accepted September 11, 2023; published online September 25, 2023

$\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions fabricated on  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$   $\beta\text{-Ga}_2\text{O}_3$  substrates show distinctly anisotropic electrical properties. All three devices exhibited excellent rectification  $\geq 10^9$ , and turn-on voltages  $> 2.0$  V. The  $(010)$  device showed very different turn-on voltage, specific on-resistance, and reverse recovery time compared with  $(\bar{2}01)$  and  $(001)$  devices. Moreover, it is calculated that the interface trap state densities for  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  plane devices are  $4.3 \times 10^{10}$ ,  $7.4 \times 10^{10}$ , and  $1.6 \times 10^{11}$   $\text{eV}^{-1}\text{cm}^{-2}$ , respectively. These differences in the  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunctions are attributed to the different atomic configurations, the density of dangling bonds, and interface trap state densities.

© 2023 The Japan Society of Applied Physics

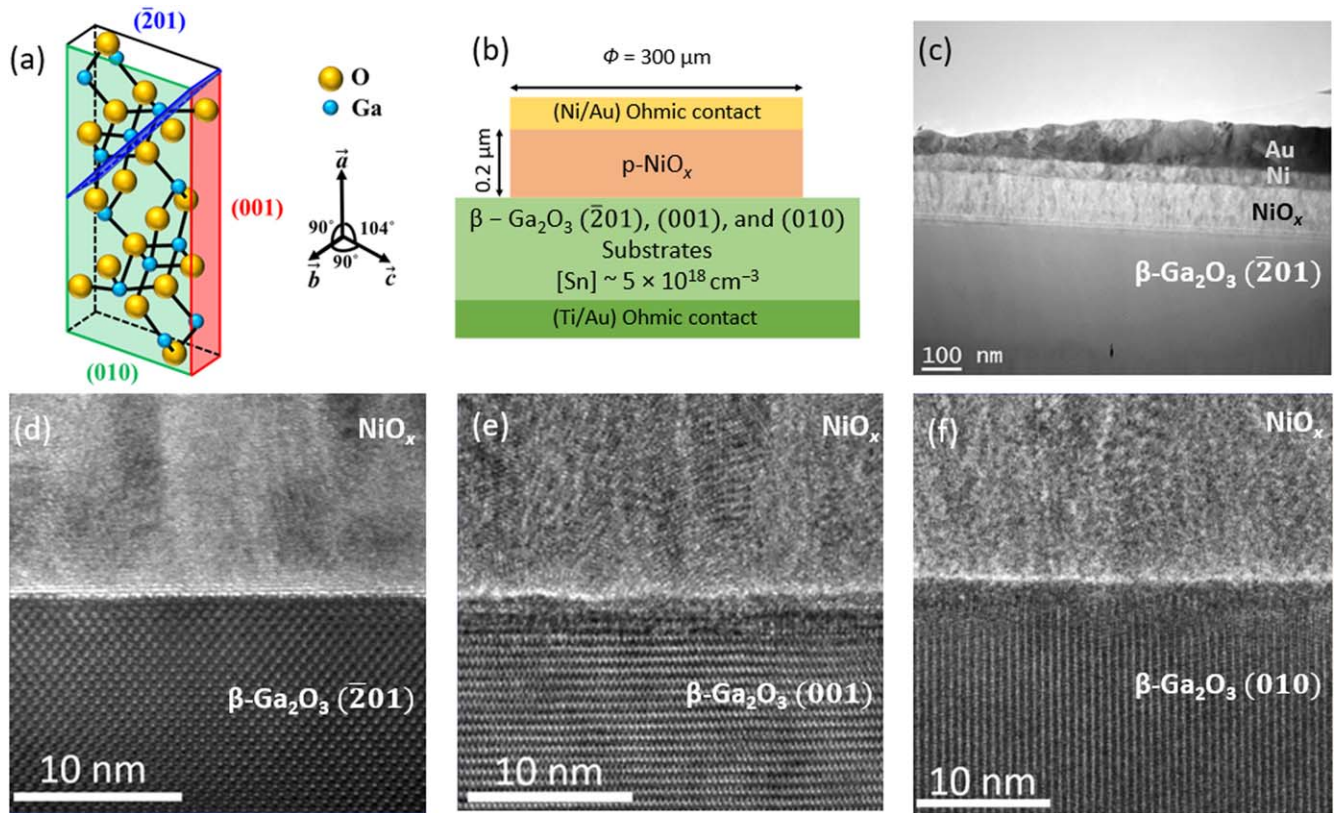
There has been substantial recent interest in ultra-wide bandgap (UWBG) semiconductors, such as gallium oxide ( $\beta\text{-Ga}_2\text{O}_3$ ),<sup>1</sup> aluminum nitride,<sup>2</sup> diamond,<sup>3</sup> and boron nitride<sup>4</sup> for power electronics due to their large bandgaps and high critical field. These properties can result in higher operating voltages, larger currents, increased efficiencies, and smaller device footprint compared to devices based on traditional semiconductors such as silicon and wide bandgap semiconductors such as silicon carbide and gallium nitride.<sup>5</sup> As an emerging UWBG material,  $\beta\text{-Ga}_2\text{O}_3$  has attracted much attention for electronic and photonic device applications.<sup>1</sup> However, a significant challenge for  $\beta\text{-Ga}_2\text{O}_3$  is its lack of  $p$ -type conductivity. Theoretical predictions indicate a difficulty in obtaining holes due to the high activation energy ( $> 1$  eV) of acceptors for  $\beta\text{-Ga}_2\text{O}_3$ .<sup>6</sup> Moreover, due to the flat valence band maximum, the heavy hole effective mass leads to low hole mobility<sup>7</sup> while holes tend to be localized in  $\beta\text{-Ga}_2\text{O}_3$  as polarons due to lattice distortion.<sup>8</sup> Thus, most reported  $\beta\text{-Ga}_2\text{O}_3$  devices, such as field effect transistors<sup>9</sup> and Schottky barrier diodes,<sup>10</sup> are unipolar. The demonstration of  $p$ - $n$  junctions in  $\beta\text{-Ga}_2\text{O}_3$  is critical for the development of bipolar devices and advanced  $\text{Ga}_2\text{O}_3$ -based electronic devices.

Recently,  $p$ - $\text{NiO}_x$  has emerged as a popular choice for the formation of  $\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions due to its easy deposition and extensive use as a hole contact in high-efficiency solar cells.<sup>11,12</sup> Kokubun et al.<sup>13</sup> demonstrated the first  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunction with Li-doped  $\text{NiO}_x$  epitaxial layer. Several  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunctions, including  $p$ - $n$  diodes<sup>14–16</sup> and junction barrier Schottky diodes<sup>17–19</sup> have been demonstrated with excellent electrical characteristics, such as low on-resistance, high on/off ratio, and large reverse blocking voltage. Moreover,  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunctions are versatile with a wide range of applications, including edge terminations in  $\beta\text{-Ga}_2\text{O}_3$  power diodes<sup>20</sup> and all-oxide-based UV photodetectors.<sup>21</sup>

The low crystal symmetry of monoclinic  $\beta\text{-Ga}_2\text{O}_3$  results in highly anisotropic material with a direct impact on several key physical and electronic properties, such as dielectric constant,<sup>22</sup> thermal conductivity,<sup>23</sup> and electron mobility<sup>24</sup>

which are different along different crystallographic directions. This anisotropy poses challenges for device fabrication and results in discrepancies in device performance. Fu et al.<sup>24</sup> compared Schottky contacts on  $(\bar{2}01)$  and  $(010)$   $\beta\text{-Ga}_2\text{O}_3$  planes and observed that the  $(010)$  orientation had higher barrier height and lower reverse leakage. Sasaki et al.<sup>25</sup> reported that the rate of epitaxial growth on the  $(100)$  plane was slower compared to the  $(010)$  plane due to the low adhesion energy on  $(100)$  terraces. Jang et al.<sup>26</sup> found that the etch rate and ability to form Ohmic contacts on  $(\bar{2}01)$  plane was higher compared to  $(010)$  plane owing to the higher density of oxygen dangling bonds. However, the anisotropic properties of the widely used  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunctions are not well understood. In this work, a systematic comparative analysis of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions with  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  substrate orientations has been carried out. Temperature-dependent electrical measurements, reverse recovery characteristics, and capacitance–frequency ( $C$ - $f$ ) measurements, were performed to provide a better understanding of the anisotropic nature of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions.

Figure 1(a) shows the crystal structure of  $\beta\text{-Ga}_2\text{O}_3$  and the corresponding planes used as substrates for this study. These  $\beta\text{-Ga}_2\text{O}_3$  planes are widely used for  $\beta\text{-Ga}_2\text{O}_3$  devices. Previous literature has shown clear differences between  $(\bar{2}01)$  [or  $(001)$ ] and  $(010)$  plane dangling bond densities, which were calculated to be  $2.68 \times 10^{15}$  [or  $2.69 \times 10^{15}$ ] and  $1.74 \times 10^{15}$   $\text{cm}^{-2}$ , respectively.<sup>27</sup> Edge-defined film-fed grown  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$   $\beta\text{-Ga}_2\text{O}_3$  substrates from Novel Crystal Technology were used for this study.<sup>28</sup> The substrates had similar  $n$ -type [Sn] doping concentrations of  $\sim 5 \times 10^{18}$   $\text{cm}^{-3}$ , similar thickness, and good crystalline quality, as verified by XRD measurements. To prepare the substrates, a standard cleaning procedure was implemented, which included cleaning with acetone, isopropyl alcohol, and deionized water, aided by sonication. The back contacts of Ti/Au (20/130 nm) were deposited using electron beam (E-beam) evaporation, followed by rapid thermal annealing at 500 °C in an  $\text{N}_2$  environment. All back contacts showed very low contact resistance of  $< 0.01$   $\text{m}\Omega\text{cm}^2$ . Standard



**Fig. 1.** (a) Monoclinic crystal structure of  $\beta\text{-Ga}_2\text{O}_3$  with crystal planes of  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  labeled. (b) Schematic of fabricated  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions. (c) TEM image of the interfaces of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunctions fabricated on  $(\bar{2}01)$  plane. HRTEM images of the  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  interface of (d)  $(\bar{2}01)$ , (e)  $(001)$ , and (f)  $(010)$  devices.

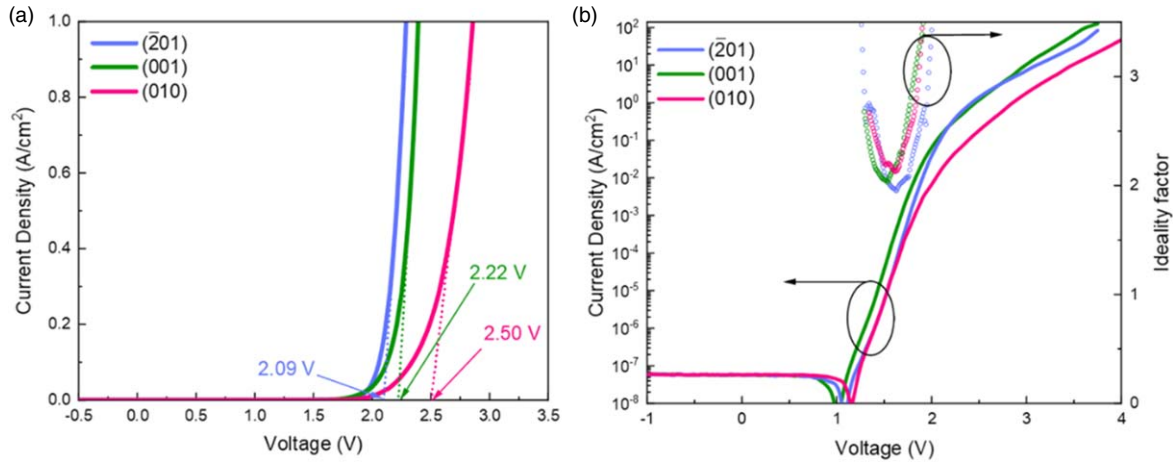
photolithography was then performed to define circular patterns for the deposition of  $\text{NiO}_x$  and the anode (diameter of  $300\ \mu\text{m}$ ).  $200\ \text{nm}$   $\text{NiO}_x$  and the anode  $\text{Ni}/\text{Au}$  ( $20/130\ \text{nm}$ ) were deposited using E-beam evaporation, followed by a lift-off process. The fabricated device structure and device dimensions are shown in Fig. 1(b). The anode, cathode, and  $\text{NiO}_x$  layers were deposited simultaneously for all samples to avoid any inconsistencies in fabrication. All  $\text{NiO}_x$  layers were highly doped with a similar hole density of  $>2 \times 10^{18}\text{ cm}^{-3}$ , and the Ohmic contacts to  $\text{NiO}_x$  layers had a similar contact resistance of  $\sim 0.3\ \text{m}\Omega\text{cm}^2$ . After device fabrication, all samples were annealed at  $350\ ^\circ\text{C}$  in  $\text{N}_2$  ambient for 1 min. This annealing step was expected to improve the device performance by forming an Ohmic contact between the  $\text{Ni}/\text{NiO}_x$  interface and reducing the number of interface states at the  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunction.<sup>29)</sup>

Electrical characterization was conducted using a probe station equipped with a controllable thermal chuck, Keithley 4200-SCS parameter analyzer, and ultra-fast pulse measurement units. Cross-sectional transmission electron microscope (XTEM) images were taken for all samples. The TEM samples were prepared using a Thermo Fisher Helios 5UX Dualbeam system with final thinning in a Gatan precision ion-polishing system. The milling started with a Ga-focused ion beam at  $30\ \text{keV}$ , followed by thinning at  $5$  and  $2\ \text{keV}$ , and subsequent Ar-ion thinning at  $2$  and  $1\ \text{keV}$ . Devices with  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$   $\beta\text{-Ga}_2\text{O}_3$  substrate normals were imaged along their respective  $[010]$ ,  $[100]$  and  $[001]$  zone axes. High-resolution TEM (HRTEM) images were taken using a Philips CM 200 operated at  $200\ \text{kV}$  and an image-corrected FEI Titan 80–300 operated at  $300\ \text{kV}$ . Figure 1(c)

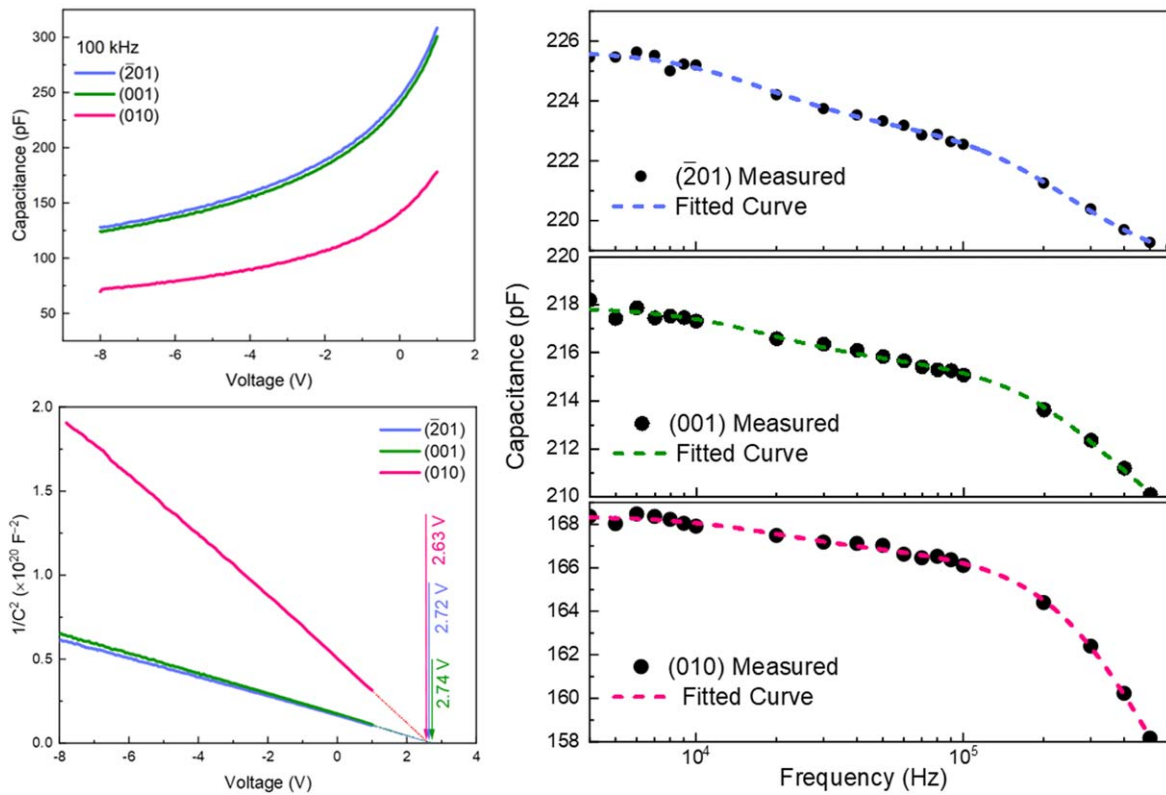
shows an XTEM image of the full diode structure consisting of the top electrode (Au, Ni),  $\text{NiO}_x$ , and  $\beta\text{-Ga}_2\text{O}_3$  substrate. Figures 1(d)–1(f) show HRTEM images of the  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  interface for samples grown on  $(\bar{2}01)$ ,  $(001)$  and  $(010)$  substrates, respectively. The polycrystalline nature of  $\text{NiO}_x$  layers was evident in HRTEM images, and abrupt  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  interfaces were clearly visible.

Figure 2(a) shows  $I$ - $V$  curves for the three  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  diodes, where the turn-on voltages were  $2.09$ ,  $2.22$ , and  $2.50\ \text{V}$  for  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  substrates, respectively. Devices on  $(\bar{2}01)$  and  $(001)$  planes had excellent rectification ratios of  $\sim 10^{10}$  at  $\pm 3.75\ \text{V}$ . However,  $(010)$  devices showed a smaller on/off ratio of about  $\sim 10^9$  at  $\pm 3.75\ \text{V}$ . Furthermore, devices on  $(\bar{2}01)$  and  $(001)$  planes exhibited specific on-resistances of  $2.92$  and  $1.55\ \text{m}\Omega\text{cm}^2$ , while the  $(010)$  device showed a specific on-resistance of  $6.50\ \text{m}\Omega\text{cm}^2$ . Ideality factors were  $1.95$ ,  $2.03$ , and  $2.13$  for  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  planes, respectively. These large ideality factors indicate that the current recombination in the heterojunction is dominant compared to diffusion currents.

The  $C$ - $V$  measurements were performed at a frequency of  $100\ \text{kHz}$  [Fig. 3(a)], and the devices showed built-in potentials of  $2.72$ ,  $2.74$ , and  $2.63\ \text{V}$  on  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  devices, respectively [Fig. 3(b)]. The built-in voltages were comparable in all three devices since there is no current transport through the devices in  $C$ - $V$  measurements. The built-in voltages determined by  $I$ - $V$  and  $C$ - $V$  measurements showed some discrepancies. In general,  $C$ - $V$  measurements are mainly affected by the doping concentration of  $\text{NiO}_x$  and  $\beta\text{-Ga}_2\text{O}_3$ , as well as the charges from the interface states. However, they do not provide information about the current



**Fig. 2.**  $I$ - $V$  characteristics of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions on three crystallographic orientations: (a) linear scale and (b) semi-log scale.



**Fig. 3.** (a)  $C$ - $V$  measurements, and (b)  $1/C^2$ - $V$  plots of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions for three crystallographic orientations. The  $C$ - $f$  characteristics with corresponding fitting curves for devices on (c)  $(\bar{2}01)$ , (d)  $(001)$ , and (e)  $(010)$  planes.

conduction through the interface. Conversely, extraction of built-in voltage through  $I$ - $V$  measurements is influenced by the crystal anisotropy and interface states. The effective carrier concentration  $(N_d - N_a + N_t)^{30)}$  calculated from the  $C$ - $V$  measurements was  $4.7 \times 10^{18}$ ,  $4.5 \times 10^{18}$ ,  $1.6 \times 10^{18} \text{ cm}^{-3}$  for  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  devices, respectively, where  $N_d$  is the ionized donor concentration,  $N_a$  is the ionized acceptor concentration, and  $N_t$  is the equivalent charge concentration of traps. Since the  $\beta\text{-Ga}_2\text{O}_3$  and  $\text{NiO}_x$  film in the three samples had similar carrier concentrations, the observed variation in the effective carrier concentrations is likely related to the different  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunction interfaces caused by the crystal anisotropy, which is verified by  $C$ - $f$  measurements.

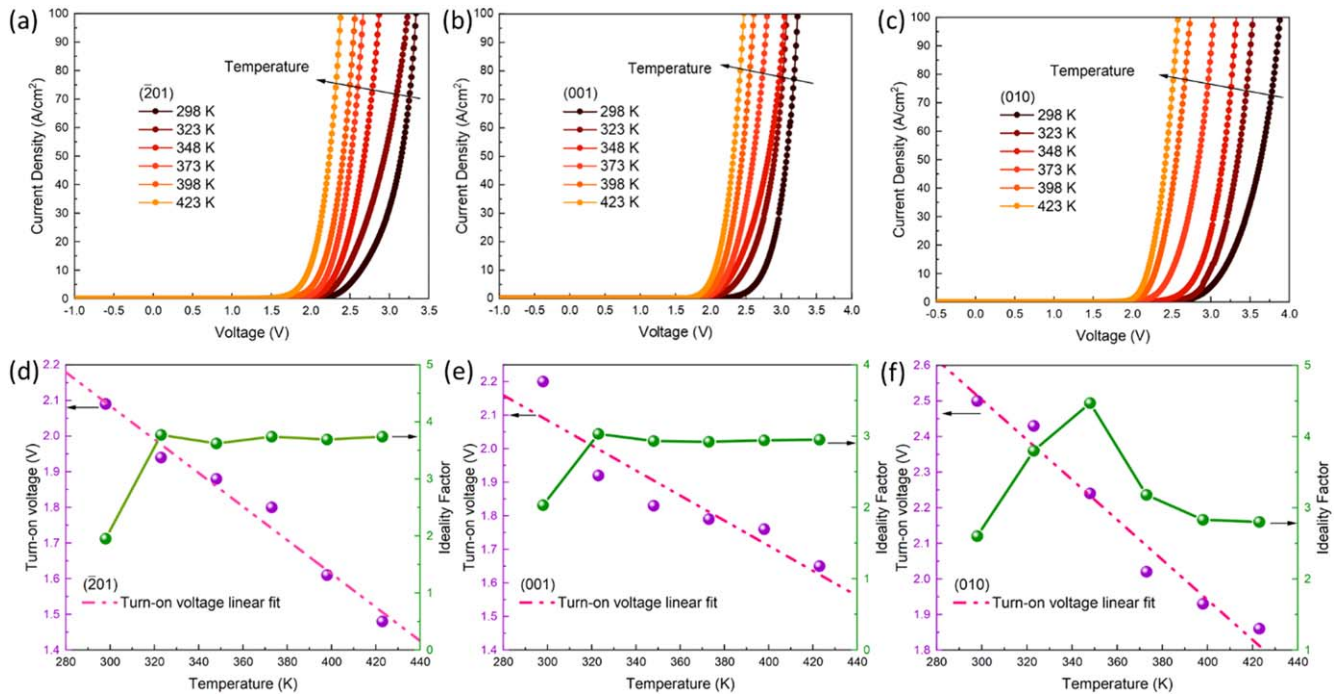
Figures 3(c)–3(e) show  $C$ - $f$  measurements for the devices on  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  substrates to evaluate the interface trap state density ( $D_{it}$ ). The  $C$ - $f$  measurements are fitted using the equations below, assuming the interface states are distributed in two energy levels.<sup>31,32)</sup>

$$C = C_{sc} + \frac{C_{it-1}}{(1 + 2\pi f\tau_1)^2} + \frac{C_{it-2}}{(1 + 2\pi f\tau_2)^2} \quad (1)$$

$$D_{it} = C_{it}/q^2A \quad (2)$$

where  $C_{sc}$  is the capacitance of the space charge region, and  $C_{it-1}$  ( $C_{it-2}$ ) is the capacitance of the first state (second state) with their corresponding relaxation time  $\tau_1$  ( $\tau_2$ ).  $C_{it-1}$  represents an energy level that corresponds to interface states closer to the





**Fig. 4.** Temperature-dependent  $I$ - $V$  curves for the devices on (a)  $(\bar{2}01)$ , (b)  $(001)$ , and (c)  $(010)$ . Variation of turn-on voltage and ideality factor of corresponding  $I$ - $V$  curves are shown in (d), (e), and (f).

**Table I.** Interface state parameters extracted from  $C$ - $f$  curve fitting.

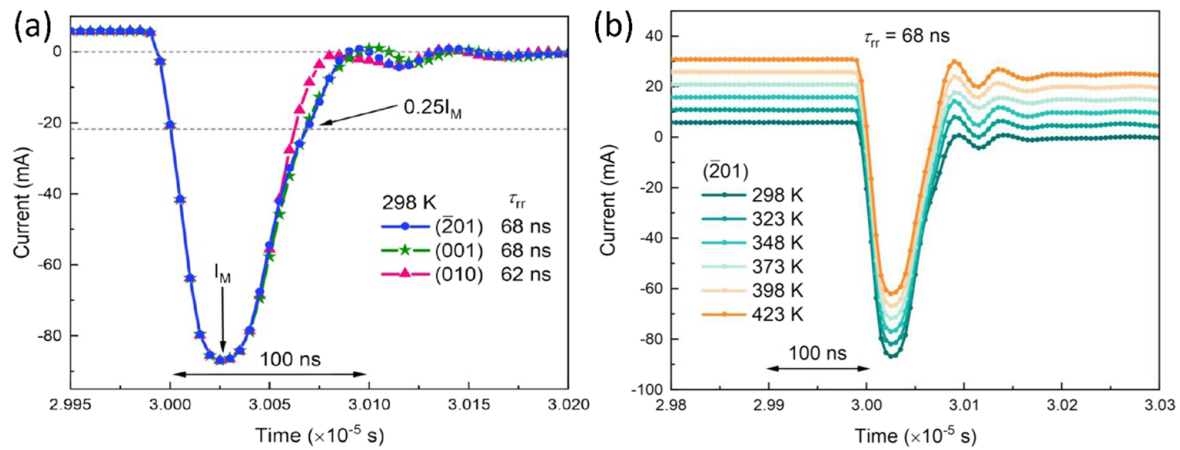
Orientation	$C_{it-1}$ (F)	$C_{it-2}$ (F)	$\tau_1$ (s)	$\tau_2$ (s)	$D_{it-1}$ ( $\text{eV}^{-1}\text{cm}^{-2}$ )	$D_{it-2}$ ( $\text{eV}^{-1}\text{cm}^{-2}$ )
$(\bar{2}01)$	$4.80 \times 10^{-12}$	$2.50 \times 10^{-12}$	$0.64 \times 10^{-6}$	$8.69 \times 10^{-6}$	$4.3 \times 10^{10}$	$2.2 \times 10^{10}$
$(001)$	$8.36 \times 10^{-12}$	$2.27 \times 10^{-12}$	$0.43 \times 10^{-6}$	$8.57 \times 10^{-6}$	$7.4 \times 10^{10}$	$2.0 \times 10^{10}$
$(010)$	$1.79 \times 10^{-11}$	$1.62 \times 10^{-12}$	$0.34 \times 10^{-6}$	$8.02 \times 10^{-6}$	$1.6 \times 10^{11}$	$1.4 \times 10^{10}$

conduction band with a smaller relaxation time, and  $C_{it-2}$  represents a deep energy level with a considerably larger relaxation time. A similar  $C_{it-2}$  of  $\sim 2 \times 10^{-12}$  F was observed with a relaxation time of about  $\sim 8 \mu\text{s}$  for all devices. This may represent deep-level states (e.g., vacancies) with relaxation time much larger than the interface states. However,  $C_{it-1}$  varied significantly for devices on different crystal orientations. The relaxation time for  $C_{it-1}$  was 0.64, 0.43, and  $0.34 \mu\text{s}$  for  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  devices, respectively, which are consistent with previous reports.<sup>31,32</sup>  $C_{it-1}$  changed with crystal orientation, while  $C_{it-2}$  remained relatively constant. It should be noted that the exact nature of the defect states in  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  diodes is still unclear and demands further investigation. The extracted interface trap densities ( $D_{it-1}$ ) from  $C_{it-1}$  were  $4.3 \times 10^{10}$ ,  $7.4 \times 10^{10}$ , and  $1.6 \times 10^{11} \text{eV}^{-1}\text{cm}^{-2}$  for  $(\bar{2}01)$ ,  $(001)$ , and  $(010)$  devices, respectively.<sup>29,31,32</sup> The interface states derived from  $C_{it-1}$  are much closer to the conduction band, and thus may play an important role in the device performance. Table I summarizes all the parameters extracted through  $C$ - $f$  curve fitting.

The differences in electrical properties of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions can be attributed to several factors. First, the difference in interface states may be significantly promoted by the density of dangling bonds. If the number of dangling bonds is high, then the adhesion of the  $\text{NiO}_x$  layer is promoted, exhibiting fewer interface states. Due to the higher dangling bond density in  $(\bar{2}01)$  and  $(001)$  plane, it is easier to form better-quality  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$  heterojunction with high

surface energy.<sup>27</sup> This is analogous to the fact that forming Ohmic contacts on  $(\bar{2}01)$  and  $(001)$  planes is easier than on  $(010)$  plane.<sup>26</sup> Second, different doping concentrations can be induced in the heterojunction due to interface states. The interface states can have a big impact on net charge density. It is likely that there are lower compensating trap states in  $(\bar{2}01)$  and  $(001)$   $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions as indicated by the  $C$ - $f$  measurement, contributing larger net charge densities. This is further evidenced by the different gradients in the  $I/C^2$ - $V$  plot. The observed differences are primarily influenced by the presence of interface states, considering three  $\text{NiO}_x$  and  $\beta\text{-Ga}_2\text{O}_3$  in the three samples had similar carrier concentrations. As discussed later, a difference in reverse recovery time ( $t_{rr}$ ) of the devices was observed, indicating that carrier recombination on different planes is affected by the crystal anisotropy.

The temperature-dependent forward characteristics of three  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  diodes are presented in Figs. 4(a)–4(c). The observed temperature-dependent behavior was stable and reproducible, and the initial  $I$ - $V$  curves were retained even after heating and cooling down, indicating excellent thermal stability of the heterojunction.<sup>16,29</sup> The device ideality factor and turn-on voltage were extracted as a function of temperature, as shown in Figs. 4(d)–4(f). The turn-on voltage decreased linearly with the temperature, which can be attributed to the reduction of depletion width facilitating diffusion of holes.<sup>33</sup> The ideality factor varied between 1.95–3.77, 2.03–2.95, and 2.13–4.47 in  $(\bar{2}01)$ ,  $(001)$ , and



**Fig. 5.** (a) Reverse recovery of  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions on three crystallographic orientations. (b) Temperature-dependent reverse recovery of  $p$ - $n$  diodes on (201) plane.

**Table II.** Electrical properties of the  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  diode heterojunctions grown on (201), (001), and (010) substrates.

Orientation	$V_{on}(I-V)$ (V)	$V_{bi}(C-V)$ (V)	$R_{sp-on}(\text{m}\Omega\text{cm}^2)$	on/off ratio	$\eta$	$t_{rr}$ (ns)	$D_{it}$ ( $\text{eV}^{-1}\text{cm}^{-2}$ )
(201)	2.09	2.74	2.92	$10^{10}$	1.95	68	$4.3 \times 10^{10}$
(001)	2.22	2.72	1.55	$10^{10}$	2.03	68	$7.4 \times 10^{10}$
(010)	2.50	2.63	6.50	$10^9$	2.13	62	$1.6 \times 10^{11}$

(010) devices, respectively. This behavior of turn-on voltage and ideality factor is consistent with previous reports.<sup>29,33</sup> The ideality factor of (201) and (001) devices remained almost constant under high temperatures. However, the ideality factor in (010) devices first increased and then decreased. This behavior can be attributed to the fact that there are 10 times more interface trap states in (010) heterojunction compared to (201) and (001) heterojunctions. With increasing temperature, the carrier emission from interface traps is enhanced, affecting the ideality factor.

The  $t_{rr}$  of the diode is defined as the time it takes to reach  $0.25I_M$  after switching off, where  $I_M$  is the maximum current during the reverse recovery period. The  $t_{rr}$  of the diodes is affected by several factors, including the doping concentration, the width of the depletion region, crystal anisotropy, and the applied voltage. In this work, all three samples were subject to voltages of  $\pm 5$  V to observe the reverse recovery of the diode. The (201) and (001) devices had a  $t_{rr}$  of 68 ns, while (010) devices took 62 ns to recover [Fig. 5(a)]. The shorter reverse recovery time for (010) is likely due to larger interface defect densities that promote electron/hole recombination with a faster recovery time and mobility variation along different crystal orientations. All devices had a peak current of about 86 mA and showed temperature independence<sup>33</sup> in reverse recovery time, as shown in Fig. 5(b), where the y-axis is offset for clarity. This indicates that the junction capacitance and stored charges in the depletion region are independent of temperature. The forward current during the reverse recovery test was  $\sim 6$  mA. Additionally, the  $di/dt$  of three samples for the reverse recovery characteristics was  $3.95 \text{ A } \mu\text{s}^{-1}$ , which is comparable to previously reported values.<sup>33</sup> The reverse recovery charge was 4.47, 4.54, and 4.26 nC for (201), (001), and (010) devices, respectively. The different  $t_{rr}$  in different crystal orientations indicate carrier recombination is influenced by the interface states. Table II summarizes the device parameters of the three  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$

heterojunctions, where  $D_{it}$  of the devices is based on the dominant  $D_{it-1}$  values.

In conclusion,  $\text{NiO}_x/\beta\text{-Ga}_2\text{O}_3$   $p$ - $n$  heterojunctions fabricated on (201), (001), and (010) substrates showed considerable differences in electrical properties in terms of turn-on voltages, ideality factor, on-resistance, and reverse recovery time. The (010) device exhibited the highest turn-on voltage of 2.50 V, the highest ideality factor of 2.13, the largest on-resistance of  $6.50 \text{ m}\Omega\text{cm}^2$ , and the lowest recovery time of 62 ns. The  $C$ - $f$  measurements indicate an interface trap density of  $4.3 \times 10^{10}$ ,  $7.4 \times 10^{10}$ , and  $1.6 \times 10^{11} \text{ eV}^{-1}\text{cm}^{-2}$  for (201), (001), and (010) plane devices, respectively. All devices were fabricated simultaneously and exhibited excellent rectifying behaviors with a high on/off ratio of  $\geq 10^9$  and high-quality interfaces between  $\text{NiO}_x$  and  $\beta\text{-Ga}_2\text{O}_3$ , as confirmed by HRTEM. These differences in device electrical properties are attributed to the different atomic configurations, the density of dangling bonds, and interface trap state densities. These results indicate the anisotropic nature of  $\beta\text{-Ga}_2\text{O}_3$  in heterojunction-based  $p$ - $n$  diodes and should serve as a valuable reference for future development of  $\text{Ga}_2\text{O}_3$  heterojunction bipolar devices.

**Acknowledgments** This research is supported as part of ULTRA, an Energy Frontier Research Center funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES), under Award # DE-SC0021230. This work is also partially supported by the National Science Foundation (NSF) under Award # 2302696. The authors also acknowledge the use of facilities within the John M. Cowley Center for High Resolution Electron Microscopy at Arizona State University, supported in part by NSF grant ECCS-2025490.

**ORCID iDs** Dinusha Herath Mudiyansele <https://orcid.org/0000-0001-8611-9296>  
Houqiang Fu <https://orcid.org/0000-0002-1125-8328>

- 1) M. Higashiwaki, *AAPPS Bull.* **32**, 3 (2022).
- 2) M. Hiroki, Y. Taniyasu, and K. Kumakura, *IEEE Electron Device Lett.* **43**, 350 (2022).
- 3) D. Araujo, M. Suzuki, F. Lloret, G. Alba, and P. Villar, *Materials (Basel)* **14**, 7081 (2021).

- 4) N. Izyumskaya, D. O. Demchenko, S. Das, Ü. Özgür, V. Avrutin, and H. Morkoç, *Adv. Electron. Mater.* **3**, 1600485 (2017).
- 5) R. J. Kaplar, A. A. Allerman, A. M. Armstrong, M. H. Crawford, J. R. Dickerson, A. J. Fischer, A. G. Baca, and E. A. Douglas, *ECS J. Solid State Sci. Technol.* **6**, Q3061 (2017).
- 6) J. L. Lyons, *Semicond. Sci. Technol.* **33**, 05LT02 (2018).
- 7) H. He, R. Orlando, M. A. Blanco, R. Pandey, E. Amzallag, I. Baraille, and M. Rérat, *Phys. Rev. B* **74**, 195123 (2006).
- 8) T. Gake, Y. Kumagai, and F. Oba, *Phys. Rev. Materials* **3**, 044603 (2019).
- 9) K. D. Chabak et al., *Semicond. Sci. Technol.* **35**, 013002 (2020).
- 10) X. Ji, C. Lu, Z. Yan, L. Shan, X. Yan, J. Wang, J. Yue, X. Qi, Z. Liu, and W. Tang, *J. Phys. D: Appl. Phys.* **55**, 443002 (2022).
- 11) X. Lu, Y. X. Deng, Y. L. Pei, Z. M. Chen, and G. Wang, *J. Semicond.* **44**, 061802 (2023).
- 12) B. Zhang, J. Su, X. Guo, L. Zhou, Z. Lin, L. Feng, J. Zhang, J. Chang, and Y. Hao, *Adv. Sci.* **7**, 1903044 (2020).
- 13) Y. Kokubun, S. Kubo, and S. Nakagomi, *Appl. Phys. Express* **9**, 091101 (2016).
- 14) J.-S. Li, C.-C. Chiang, X. Xia, T. J. Yoo, F. Ren, H. Kim, and S. J. Pearton, *Appl. Phys. Lett.* **121**, 042105 (2022).
- 15) X. Lu, X. Zhou, H. Jiang, K. W. Ng, Z. Chen, Y. Pei, K. M. Lau, and G. Wang, *IEEE Electron Device Lett.* **41**, 449 (2020).
- 16) J. Zhang et al., *Nat. Commun.* **13**, 3900 (2022).
- 17) K. Sasaki, S. Yamakoshi, and A. Kuramata, *Proc. SPIE* **10919**, 1091913 (2019).
- 18) Q. Yan et al., *Appl. Phys. Lett.* **118**, 122102 (2021).
- 19) Y. Lv et al., *IEEE Trans. Power Electron.* **36**, 6179 (2021).
- 20) B. Wang, M. Xiao, J. Spencer, Y. Qin, K. Sasaki, M. J. Tadjer, and Y. Zhang, *IEEE Electron Device Lett.* **44**, 221 (2023).
- 21) Y. Wang, C. Wu, D. Guo, P. Li, S. Wang, A. Liu, C. Li, F. Wu, and W. Tang, *ACS Appl. Electron. Mater.* **2**, 2032 (2022).
- 22) P. Gopalan et al., *Appl. Phys. Lett.* **117**, 252103 (2020).
- 23) Z. Guo, A. Verma, X. Wu, F. Sun, A. Hickman, T. Masui, A. Kuramata, M. Higashiwaki, D. Jena, and T. Luo, *Appl. Phys. Lett.* **106**, 111909 (2015).
- 24) H. Fu, H. Chen, X. Huang, I. Baranowski, J. Montes, T.-H. Yang, and Y. Zhao, *IEEE Trans. Electron Devices* **65**, 3507 (2018).
- 25) K. Sasaki, A. Kuramata, T. Masui, E. G. Villora, K. Shimamura, and S. Yamakoshi, *Appl. Phys. Express* **5**, 035502 (2012).
- 26) S. Jang, S. Jung, K. Beers, J. Yang, F. Ren, A. Kuramata, S. J. Pearton, K. H. Baik, and J. Alloys, *Compd* **731**, 118 (2018).
- 27) Y. Kim, M.-K. Kim, K. H. Baik, and S. Jang, *ECS J. Solid State Sci. Technol.* **11**, 045003 (2022).
- 28) A. Kuramata, K. Koshi, S. Watanabe, Y. Yamaoka, T. Masui, and S. Yamakoshi, *Jpn. J. Appl. Phys.* **55**, 1202A2 (2016).
- 29) W. Hao, Q. He, K. Zhou, G. Xu, W. Xiong, X. Zhou, G. Jian, C. Chen, X. Zhao, and S. Long, *Appl. Phys. Lett.* **118**, 043501 (2021).
- 30) S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (Wiley, New Jersey, 2007) 3rd ed.
- 31) H. Gong, X. Chen, Y. Xu, Y. Chen, F. Ren, B. Liu, S. Gu, R. Zhang, and J. Ye, *IEEE Trans. Electron Devices* **67**, 3341 (2020).
- 32) Q. Yan, H. Gong, H. Zhou, J. Zhang, J. Ye, Z. Liu, C. Wang, X. Zheng, R. Zhang, and Y. Hao, *Appl. Phys. Lett.* **120**, 092106 (2022).
- 33) J.-S. Li, C.-C. Chiang, X. Xia, F. Ren, and S. J. Pearton, *J. Vac. Sci. Technol. A* **40**, 063407 (2022).