Comprehensive Study and Optimization of Implementing p-NiO in β-Ga2O3 Based Diodes via TCAD Simulation

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Abstract: In this paper, we carried out a comprehensive study and optimization of implementing p-NiO in the β-Ga2O3 based diodes, including Schottky barrier diode (SBD) with p-NiO guard ring (GR), p-NiO/β-Ga2O3 heterojunction (HJ) barrier Schottky (HJBS) diode, and HJ-PN diode through the TCAD simulation. In particular, we provide design guidelines for future p-NiO-related Ga2O3 diodes with material doping concentrations and dimensions to be taken into account. Although HJ-PN has a ~1 V higher turn-on voltage (Von), its breakdown voltage (BV) is the highest among all diodes. We found that for SBD with p-NiO GRs and HJBS, their forward electrical characteristics and reverse leakage current are related to the total width and the doping concentration of p-NiO, the BV is only related to the doping concentration of p-NiO, and the optimal doping concentration of p-NiO is found to be $4 \times 10^{17}$ cm$^{-3}$. Compared with the SBD without p-NiO, the BV of the SBD with p-NiO and HJBS diode can be essentially improved by 3 times. As a result, HJ-PN diode, SBD with p-NiO GRs, and HJBS diode achieve a BV/specific on-resistance $\left(\text{R}_{\text{on,sp}}\right)$ of 5705 V/4.3 mΩ·cm$^2$, 3006 V/3.07 mΩ·cm$^2$, and 3004 V/3.06 mΩ·cm$^2$, respectively. Based on different application requirements, this work provides a useful insight about the diode selection with various structures.

Keywords: Ga2O3; NiO; diode; simulation; Schottky diodes; JBS; PN junction

1. Introduction

Beta-phase Ga2O3 (β-Ga2O3) has attracted tremendous attention as a promising material for power electronic applications because of its excellent physical properties, such as wide energy band gap of 4.6–4.9 eV, estimated high critical breakdown electric field of 8 MV/cm, decent electron mobility of 250 cm$^2$/Vs with high electron saturation velocity of $2 \times 10^7$ cm/s, and the cost-effective substrate through melt-grown methodology [1–5]. As a beneficial result of the excellent material properties, the Baliga’s figure of merit is yielded to be around 3000, which is several times higher than that value of SiC and GaN [6]. However, due to the challenge of acquiring p-type Ga2O3, most research attention is paid to unipolar devices, including both the lateral and vertical field effect transistors (FETs) and diodes [7–12]. In particular, vertical diodes are regarded as the most promising commercial available product within the next 2–3 years. Accordingly, a significant amount of research is invested in improving the diode performance and hence many advanced edge termination techniques are being developed, including implanted edge termination, field plate, and Fin-type trench structures. State-of-the-art Ga2O3 vertical diodes have acquired a BV of 2.89 kV and DC power figure of merit (P-FOM) of around 1 GW/cm$^2$, which are still far less than its theoretical values [13]. For the further development of Ga2O3, the implementation of p-type materials for PN junction termination is very important for wide band gap materials to alleviate the high field crowding effect at the anode edge. However, p-type Ga2O3 has been reported to be a bottleneck due to the difficulty in finding acceptor species with small activation energy. In addition, the calculated valence band structure is
found to be extremely flat, leading to a large hole effective mass; subsequently, the holes can be regarded as polartons and even the acceptor can ionize holes [14,15].

A temporary solution to resolve the p-type issue is by applying other p-type semiconductors instead of p-type Ga$_2$O$_3$ to fabricate the HJ architecture. Recently, some preliminary studies have combined p-type oxides with n-Ga$_2$O$_3$ to construct HJPN diodes for high BV purposes [16–19]. Among those p-type semiconductors, NiO is a good alternative to p-type Ga$_2$O$_3$ owing to its wide energy band gap. NiO is a material with a rock salt crystal structure and its band gap value depends on the growth condition which is between 3.8 and 4.2 eV [20–22]. Further, values for its hole mobility between 0.12 and 0.94 cm$^2$/Vs have been reported [17]. Although the NiO/Ga$_2$O$_3$ HJ diodes have been reported to improve the BV, the performance of those diodes is still far away from its ideal value and is facing significant material and device structure design challenges. For example, our recent work employed a HJ-JBS geometry to demonstrate a high P-FOM of 0.92 GW/cm$^2$, however its $V_{on}$ was around 1.5–2 V, the BV was only 1.3 kV and the simulated peak electrical field was just 3.4 MV/cm [23]. Estimating the electrical theoretical limit of p-NiO/Ga$_2$O$_3$ HJ diodes is very important for exploring the potential of NiO as a replacement of p-type Ga$_2$O$_3$, which is missing in previous work. Moreover, the physical insights into the electrical field distribution in NiO/Ga$_2$O$_3$ HJ diodes have not been fully discussed. In order to fully explore the NiO/Ga$_2$O$_3$ based HJ diode potentials and address aforementioned concerns, we carried out a comprehensive study on the SBD without p-NiO, SBD with p-NiO GRs, HJBS diode with periodic p-NiO arrays, and HJ-PN diode by performing drift layer thickness and NiO doping concentration, as well as NiO width dependent electrostatics, forward and reverse characteristic simulations. By doing this, we hope that this article can provide some hints and guidelines for future NiO/Ga$_2$O$_3$ HJ diode-related design and optimizations. It should also be noted that although we use p-NiO as the representative p-type material, this work can still offer some general guidance about Ga$_2$O$_3$ diodes by replacing the NiO with other ultra-wide band gap p-type materials.

2. Simulation Methodology

Figure 1 depicts the schematic cross-sectional images of the vertical Ga$_2$O$_3$ diodes with the incorporation of p-NiO, namely SBD without p-NiO, HJ-PN diode, SBD with p-NiO GRs, and HJBS diode. All diodes possess a substrate doping concentration of $1 \times 10^{19}$ cm$^{-3}$ and the epi-layer has a doping concentration of $1 \times 10^{18}$ cm$^{-3}$ at a thickness of 5 µm, 10 µm and 15 µm. Various drift layer thicknesses (L) are used for evaluating the compromise between $R_{on,sp}$ and BV. All the p-NiO layer is with a thickness of 0.5 µm and the initial doping concentration is set to be $1 \times 10^{18}$ cm$^{-3}$. For the diode architecture and performance optimizations, various p-NiO doping concentrations are considered and compared. For Ga$_2$O$_3$ SBDs with p-NiO GRs and HJBS diodes with various p-NiO, widths (W) and spacings (S) are also investigated.

Sentaurus TCAD device simulator from Synopsys was used to investigate device performances by considering different geometry and architecture. In the simulation, the electron mobility of Ga$_2$O$_3$ at room temperature is adjusted to be 200 cm$^2$/Vs due to the low doping concentration of $1 \times 10^{16}$ cm$^{-3}$, and the remaining Ga$_2$O$_3$ parameters provided by the existing literature are shown in Table 1. At present, there are relatively few reports on NiO materials, so that the detailed simulation parameters of NiO materials are not provided by TCAD. In this paper, the NiO parameters are obtained according to the existing literature, which is summarized in Table 1.
The workfunction value of Schottky contact is 5.1 eV. In order to capture the accurate results, the following models are used: HighFieldSaturation model, SRH recombination model, thermionic current model, and band gap narrowing model. Accurate incomplete ionization parameters are currently unknown for NiO and Ga2O3. Thus, we assume that the dopants are completely ionized. Due to the lack of parameters of doping concentration for NiO mobility, the experiment ignores the effect of doping concentration on mobility, and sets a fixed hole mobility of NiO (0.5 cm²/V s). Breakdown simulations consider the impact ionization model based on the Chynoweth law with critical electrical field values of 8 MV/cm for Ga2O3. The critical breakdown electrical field of NiO is currently unclear, but it can be estimated from the band gap of NiO. According to the relationship between band gap and breakdown field in all semiconductors

$$e_c = 1.73 \times 10^5(E_G)^{2.5}$$

It can be calculated that the breakdown field of NiO is between 4.8–6.2 MV/cm. For Schottky contact, an important injection mechanism is tunneling through the steep and thin

Table 1. Material parameters used for simulation.

| Material                        | Ga2O3     | NiO    |
|---------------------------------|-----------|--------|
| Band gap (eV)                   | 4.85 [1]  | 4 [22] |
| Electron affinity (eV)          | 3.9 [1]   | 1.8 [17]|
| Effective electron mass         | 0.25 [24] | -      |
| Relative dielectric constant    | 10 [1]    | 11.8 [25]|
| Effective hole mass             | -         | 6      |
| Room-temperature electron mobility (cm²/V s) | 200 | - |
| Room-temperature hole mobility (cm²/V s) | - | 0.5 [16] |
| Saturation electron velocity (cm/s) | $2 \times 10^7$ [1] | - |
| Critical electric field (MV/cm) | 8 [1]     | 4.8–6.2 |

Figure 1. Schematic of the vertical NiO/Ga2O3 diode; (a) SBD without p-NiO, (b) HJ-PN diode, (c) SBD with GRs, (d) HJBS diode.
Schottky barrier. Thus, the electron tunneling model should be activated at the top of the Schottky contact. As for fabricated Ga2O3 devices, the off-state leakage current is orders of magnitude higher than the simulated off-state leakage current. This is due to impurities, defects, and traps in Ga2O3 and to background radiation. An equivalent background carrier generation is simulated through the Constant Carrier Generation model.

In order to verify the rationality of the simulation model, we simulated the structure of the reference (see Figure 2a, PN_ref) [16], and the current-voltage curves obtained are shown in Figure 2b. As shown in Table 2, the turn-on voltage (Von), R_{on,sp} as well as breakdown voltage (BV), is in good agreement with the reported results in the reference [16].

![Anode](0.2 \mu m \text{NiO} (1 \times 10^{19} \text{cm}^{-3}))

β-Ga2O3 (4 \times 10^{16} \text{cm}^{-3})

Drift layer

L=8 \mu m

β-Ga2O3 (2.6 \times 10^{18} \text{cm}^{-3})

Substrate

Cathode

(a)

(b)

Figure 2. (a) Schematic of the vertical NiO/Ga2O3 PN_ref and (b) simulated forward J-V characteristics and reverse J-V characteristics of the vertical NiO/Ga2O3 PN_ref.

Table 2. The device properties comparison between TCAD simulation and experimental results.

| Device Properties | TCAD Simulation Results | Experimental Results of PN_ref |
|-------------------|------------------------|-------------------------------|
| Von (V)           | 2.4                    | 2.4                           |
| R_{on,sp} (m\Omega \cdot \text{cm}^2) | 3.0                    | 3.5                           |
| BV (V)            | 1091                   | 1059                          |

3. Results and Discussion

3.1. HJ PN Diode

One benefit of embracing the HJ-PN structure is that the Von can be reduced by minimizing the band offset and hence improve the rectifying efficiency during power switching application. Figure 3a,b shows the forward and reverse linear-scaled J-V characteristics of the p-NiO/ Ga2O3 HJ-PN diodes with different drift layer thicknesses. The turn-on voltage (V_{on}) of the HJ-PN with a drift layer thickness of 5 \mu m, 10 \mu m, and 15 \mu m is extracted to be 2.35 V when the forward current density is defined at 1 A/cm^2. This low V_{on} is around 2 V lower when compared with the Ga2O3 PN homo-junction. Figure 3a shows the R_{on,sp} of p-NiO/Ga2O3 HJ-PN diodes increases as the thickness of the drift layer increases. The R_{on,sp} of HJ-PN diode is extracted to be 2.0 m\Omega \cdot \text{cm}^2, 3.2 m\Omega \cdot \text{cm}^2, and 4.3 m\Omega \cdot \text{cm}^2 for the 5 \mu m, 10 \mu m, and 15 \mu m drift layer thicknesses, respectively. The reverse leakage current of HJ-PN diode reaches 1 A/cm^2 at a reverse bias of 2500 V, 4465 V, and 5705 V for 5 \mu m, 10 \mu m, and 15 \mu m drift layer thicknesses, respectively. Figure 4 shows the electrical field distribution of the p-NiO/Ga2O3 HJ-PN diode with various drift layer thicknesses at a reverse bias of 3000 V. The peak electrical field of PN is located at the interface of HJ-PN, as can be seen in the electrical field distribution along the cutline, shown in Figure 4d. Since the electrical field within the NiO layer is smaller than that of Ga2O3, the doping concentration of NiO should be higher than that of Ga2O3 so that the depletion region of
the HJ-PN extends toward Ga$_2$O$_3$ as much as possible. Thus, the increase in the thickness of the drift layer makes the width of the depletion region widened, and the peak electrical field decreases, rendering as the improvement of the BV. In summary, increasing the thickness of the drift layer will not change the $V_{on}$, but it will increase the $R_{on,sp}$ and increase the BV. The optimized $BV/R_{on,sp}$ is simulated to be 5705 V/4.3 m$\Omega$·cm$^2$, translating to a PFOM = $BV^2/R_{on,sp}$ = 7.57 GW/cm$^2$.

![Figure 3](image-url)

**Figure 3.** (a) Forward J-V characteristics and $R_{on,sp}$–Forward V (b) reverse J-V characteristics of p-NiO/Ga$_2$O$_3$ with 5 µm, 10 µm, and 15 µm drift layer thicknesses.

![Figure 4](image-url)

**Figure 4.** 2D electrical field distribution in HJ-PN diode with (a) 5 µm, (b) 10 µm, and (c) 15 µm drift layer thicknesses at a reverse bias of 3000 V. (d) Electrical field versus position for HJ-PN with 5 µm, 10 µm, and 15 µm drift layer thicknesses at −3000 V along the cutlines shown in the contour plots.
3.2. SBD with GRs

The Ga$_2$O$_3$ SBD with different width of p-NiO GRs and the one without GR are simulated for comparison, where the doping concentration of the p-NiO is $1 \times 18 \text{ cm}^{-3}$ and the drift layer thickness is initially set to be 10 $\mu$m. The forward and reverse J-V characteristics are summarized in Figure 5a,b. The $V_{on}$ of the Ga$_2$O$_3$ SBD with various width of p-NiO GRs and the one with no GR are all around 1.1 V. The $R_{on,sp}$ of SBD with GRs is extracted to be 2.9 m$\Omega \cdot \text{cm}^2$, 3.4 m$\Omega \cdot \text{cm}^2$, 6.4 m$\Omega \cdot \text{cm}^2$, and 9.0 m$\Omega \cdot \text{cm}^2$ for the 0 $\mu$m, 22 $\mu$m, 37 $\mu$m, and 42 $\mu$m GR width, respectively. Obviously, as the width of GR increases inward, the $V_{on}$ will not change, while the $R_{on,sp}$ increases. In SBD with GRs, the Schottky contact is turned on first, which causes the $V_{on}$ of the SBD with GRs not likely to be affected by the width of the GR. As the width of the GR increases, the part of the Schottky contact becomes smaller, which leads to a decrease in the current density of the diode and an increase in the $R_{on,sp}$. The BV of SBD with different widths of the GR is 1748 V and it is greater than that of SBD with BV = 900 V. It should be noted that with the increase of GR width, the reverse leakage current of SBD with GRs decreases, which is much smaller than that of SBD, as shown in Figure 5b.

![Figure 5](image)

**Figure 5.** (a) Forward J-V characteristics and $R_{on,sp}$ vs. forward bias and (b) reverse J-V characteristics of the Ga$_2$O$_3$ SBD with different width (W), spacing (S) of GRs and the one with no GR, at a p-NiO doping concentration of $1 \times 18 \text{ cm}^{-3}$ and a drift layer thickness (L) of 10 $\mu$m.

When the doping concentration of NiO is taken to be $1 \times 10^{18} \text{ cm}^{-3}$ and the anode bias is imposed by $-1000 \text{ V}$, the electrical field profiles of the Ga$_2$O$_3$ SBD with no GR and the one with GRs are shown in Figure 6a,b, respectively. The maximum electrical field of SBD is 6.74 MV/cm at the edge of the anode, while the maximum electric field of SBD with GRs is 4.36 MV/cm at the edge of GR, which is far away from the anode edge. Although the critical electrical field of NiO is smaller than that of Ga$_2$O$_3$, due to the existence of GR, the maximum electrical field of SBD shifts from the edge of the anode to the edge of the GR, thereby effectively alleviating the crowding effect of the electrical field at the edge of the anode, and hence enhancing the BV.
The relationship between the width of GR and the reverse leakage current can be explained by electron barrier tunneling. The tunneling of the electron barrier under the anodes of SBD with no GR and GRs is shown in Figure 7a,b, respectively. The electron barrier tunneling of SBD with no GR mainly occurs at the anode edge. Introducing the NiO GR avoids the electron barrier tunneling at the anode edge, thereby reducing the reverse leakage current. When the width of the GR decreases, the tunneling probability of the electron barrier under the anode of the SBD with GRs remains unchanged, as shown in Figure 7c, but as the width of the GR becomes wider, the tunneling path of the electron barrier becomes shorter, which makes the reverse leakage current to be reduced.

Figure 6. Electric field distribution in SBD with (a) no GR (b) GR at a reverse bias voltage of 1000 V. The doping concentration of the NiO is $1 \times 10^{18}$ cm$^{-3}$, the width of GR is 42 µm, and the drift layer thickness is set to be 10 µm.

Figure 7. Electron barrier tunneling across the Schottky interface for Ga2O3 SBD with a 10-µm thick, $10^{16}$ cm$^{-3}$ with (a) no GR, and (b) GRs at reverse bias of 500 V, when the doping concentration of the NiO is $1 \times 10^{18}$ cm$^{-3}$. (c) Electron barrier tunneling versus position for SBD with no GR and the GR width of 22 µm, 37 µm, 42 µm, at −500 V along the cutlines shown in the contour plots.
The change in the drift layer thickness of the Ga$_2$O$_3$ SBD with GRs affects the forward and reverse J-V characteristics as given by Figure 8a,b. The $V_{on}$ of the SBD with various thicknesses of the drift layer at a 42-μm-width GR ($N_A = 1 \times 10^{18}$ cm$^{-3}$) is still 1.1 V. The $R_{on,sp}$ of SBD with GRs is extracted to be 7.6 mΩ cm$^{-2}$, 10.4 mΩ cm$^{-2}$, and 11.23 mΩ cm$^{-2}$ for the 5 μm, 10 μm, and 15 μm drift layer thickness, respectively. Thus, in the SBD with GRs different thickness of the drift layer does not affect their $V_{on}$, but the $R_{on,sp}$ increases as the drift layer thickness is increased. The BV is determined to be 1231 V, 1747 V, and 1948 V for 5 μm, 10 μm, and 15 μm drift layer thickness, respectively. The change in the drift layer thickness of the Ga$_2$O$_3$ SBD with GRs also modified the electrical field distribution. As the thickness of the GR drift layer increases, the peak electrical field of the SBD with GRs at a reverse bias of 2000 V decreases from 7.72 MV/cm to 5.8 MV/cm, as shown in Figure 9d. When the thickness of the drift layer increases from 5 μm to 10 μm, the peak electrical field reduces from 7.72 MV/cm to 6.11 MV/cm; the peak electrical field is reduced from 6.11 MV/cm to 5.8 MV/cm when the thickness of drift layer increases from 10 μm to 15 μm, as depicted in Figure 9a–c. For the reverse leakage current, increasing the thickness of the drift layer from 5 μm to 10 μm can effectively reduce the leakage current to a large extent. When the thickness of the drift layer exceeds 10 μm, the capability to reduce the leakage current will be weakened.

Figure 8. (a) Forward J-V and (b) reverse J-V characteristics of the Ga$_2$O$_3$ SBD with 5 μm, 10 μm, and 15 μm drift layer thicknesses, when the width of GR is 42 μm and the doping concentration of GR is $1 \times 10^{18}$ cm$^{-3}$.

Figure 9. 2D electric field distribution in SBD with the 42-μm-width NiO for (a) 5 μm, (b) 10 μm, and (c) 15 μm drift layer thicknesses at reverse bias of 2000 V, respectively. (d) Electrical field versus position for SBD with 5 μm, 10 μm, and 15 μm drift layer thicknesses at −2000 V along the cutlines shown in the contour plots.
Doping concentration of the p-NiO GR is a critical parameter that can affect the electrical characteristics of SBD. The relationship between the doping concentration of the 12-µm-width GR and the J-V characteristics of SBD with the 10-µm-thick drift layer is shown in Figure 10a,b. The $R_{on,sp}$ of the SBD with the 12-µm-width GR is extracted to be $3.19 \, \text{mΩ} \cdot \text{cm}^2$, $3.16 \, \text{mΩ} \cdot \text{cm}^2$, $3.07 \, \text{mΩ} \cdot \text{cm}^2$, $2.97 \, \text{mΩ} \cdot \text{cm}^2$, $2.62 \, \text{mΩ} \cdot \text{cm}^2$, $2.55 \, \text{mΩ} \cdot \text{cm}^2$ for $1 \times 10^{16} \, \text{cm}^{-3}$, $1 \times 10^{17} \, \text{cm}^{-3}$, $4 \times 10^{17} \, \text{cm}^{-3}$, $1 \times 10^{18} \, \text{cm}^{-3}$, $1 \times 10^{19} \, \text{cm}^{-3}$, $7 \times 10^{19} \, \text{cm}^{-3}$ NiO doping concentration, respectively. The maximum BV of Ga$_2$O$_3$ SBD with GR width of 12 µm at GR doping concentration of $4 \times 10^{17}$ is 3006 V, as shown in Figure 10b,c. The $V_{th}$ of the Ga$_2$O$_3$ SBD with GRs is still 1.1 V, and the $R_{on,sp}$ will decrease as the NiO doping concentration increases, as shown in Figure 10a. We have also simulated the BV of Ga$_2$O$_3$ SBD with 12-µm-width GRs under the drift layer thickness of 5 µm, 10 µm, and 15 µm, as a function of NiO doping, as shown in Figure 10b. When the doping concentration of the p-NiO GRs is between $1 \times 10^{16}$–$4 \times 10^{17} \, \text{cm}^{-3}$, the BV increases with the increase of doping concentration. On the contrary, when the doping concentration of GR is between $4 \times 10^{17}$–$1 \times 10^{18} \, \text{cm}^{-3}$, the BV of Ga$_2$O$_3$ SBD with GR decreases with the increase of doping concentration. Finally, when the doping concentration of GR is greater than $1 \times 10^{18} \, \text{cm}^{-3}$, the BV of Ga$_2$O$_3$ SBD with GRs increases with the increase of doping concentration. The simulated BV versus p-NiO GR doping concentration is shown in Figure 10c. This change is caused by the transfer of the breakdown point due to the different doping concentration of GR. The breakdown point of SBD with GRs doped with different concentrations changes from the anode edge ($1 \times 10^{16} \, \text{cm}^{-3}$–$1 \times 10^{17} \, \text{cm}^{-3}$) to the junction of p-type region and n-type region below the anode ($3 \times 10^{17}$–$4 \times 10^{17} \, \text{cm}^{-3}$) and then to the edge of p-ring ($5 \times 10^{17}$–$1 \times 10^{20} \, \text{cm}^{-3}$) with the increase of doping concentration. Considering that the BV of SBD with different GR widths remains the same, the maximum BV is 2017 V, 3006 V, and 3597 V for 5 µm, 10 µm, and 15 µm drift layer thickness, respectively.

![Figure 10.](image)

Figure 10. (a) Forward J-V and (b) reverse J-V characteristics of the Ga$_2$O$_3$ SBD with different doping concentrations of the p-NiO GRs, when the width of GR is 12 µm. (c) Breakdown voltage versus p-NiO GR doping concentration with 12 µm of GR width for different drift layer thicknesses.
In summary, the forward electrical characteristics and reverse leakage current of the SBD with GRs are related to the width of the GR and the thickness of the drift layer, and the doping concentration of the GR, while its BV is related to the doping concentration of the GR and the thickness of the drift layer. Proper doping concentration of GRs and drift layer thickness can make SBD with GRs obtain ultra-high BV while keeping a small $R_{on,sp}$. The optimized BV/$R_{on,sp}$ is simulated to be $3006 \, \text{V}/3.07 \, \text{mΩ} \cdot \text{cm}^2$, translating to a PFOM = $B V^2 / R_{on,sp}$ = 2.94 GW/cm$^2$.

3.3. HJBS Diode

JBS diode is a typical SBD structure, which is used to increase BV and reduce reverse leakage current while maintaining a low $V_{on}$. In this part, we explore the use of p-NiO as the p-type material to construct Ga$_2$O$_3$ HJBS. There are 6 fins under the anode and the drift layer thickness is 10 µm. Considering the best performance of Ga$_2$O$_3$ SBD with NiO GRs when the NiO doping concentration is $4 \times 10^{17} \, \text{cm}^{-3}$, we compare HJBS with NiO doping concentration of $1 \times 10^{18} \, \text{cm}^{-3}$ and $4 \times 10^{17} \, \text{cm}^{-3}$. Meanwhile, we simulated three HJBS diode configurations with different fin widths and spacings: (1) the width of NiO fin is 8 µm, the Ga$_2$O$_3$ space is 2 µm; (2) the width of NiO fin is 8 µm, the Ga$_2$O$_3$ space is 3 µm; (3) the width of NiO fin is 5 µm, the Ga$_2$O$_3$ space is 6 µm.

The forward J-V characteristics of HJBS are affected by the doping concentration of the p-type region and the total width of NiO, as shown in Figure 11a. The $V_{on}$ of the HJBS with different fin width, spacing, and doping concentration is still 1.1 V, which is the same as the $V_{on}$ of SBD with a 10-µm-thick drift layer. The $R_{on,sp}$ of HJBS with the NiO doping concentration of $1 \times 10^{18} \, \text{cm}^{-3}$ is extracted to be $3.32 \, \text{mΩ} \cdot \text{cm}^2$, $3.29 \, \text{mΩ} \cdot \text{cm}^2$, and $2.99 \, \text{mΩ} \cdot \text{cm}^2$ for the 2 µm, 3 µm, and 5 µm Ga$_2$O$_3$ fin space width, respectively. The $R_{on,sp}$ of HJBS with the NiO doping concentration of $4 \times 10^{17} \, \text{cm}^{-3}$ is extracted to be $3.56 \, \text{mΩ} \cdot \text{cm}^2$, $3.46 \, \text{mΩ} \cdot \text{cm}^2$, and $3.06 \, \text{mΩ} \cdot \text{cm}^2$ for the 2 µm, 3 µm, and 5 µm Ga$_2$O$_3$ fin space width, respectively. The $R_{on,sp}$ of HJBS diode increases with the increase of the total width of NiO which is higher than the $R_{on,sp}$ of SBD. This result shows that the forward characteristic of HJBS is related to the total width of p-NiO and the doping concentration of p-NiO.

![Figure 11](image_url)

**Figure 11.** (a) Forward J-V characteristics and $R_{on,sp}$ vs. forward bias (b) reverse J-V characteristics of the p-NiO/Ga$_2$O$_3$ HJBS with different width, space, and doping concentration of p-NiO, when the thickness of drift layer is 10 µm.

Figure 11b shows the reverse J-V characteristics of different p-NiO width, space, and p-NiO doping concentration. The BV of HJBS diode is 1757 V and 3004 V for $1 \times 10^{18} \, \text{cm}^{-3}$ and $4 \times 10^{17} \, \text{cm}^{-3}$ p-NiO doping concentration, respectively. Obviously, the BV of the HJBS diode is related to the doping concentration of p-NiO, and less likely to be related with the total width of p-NiO. The most important point is that the BV of HJBS diode will
be approximately the same as the SBD with p-NiO GRs when their doping concentration remains the same. Thus, the maximum BV of HJBS can be obtained when the p-NiO doping concentration is \(4 \times 10^{17} \text{ cm}^{-3}\). When the p-NiO doping concentration is \(1 \times 10^{18} \text{ cm}^{-3}\), the peak electric field is on the side of the HJ-PN, which is away from the anode edge. In contrast, when the NiO doping concentration is \(4 \times 10^{17} \text{ cm}^{-3}\), the peak electric field is located at the PN junction below the anode, as shown in Figure 12. At the same time, the maximum electric field is reduced from 7.53 MV/cm to 5 MV/cm.

![Figure 12](image)

Figure 12. Electric field distribution in HJBS diode with the 8-µm-width fin, the 2-µm-width space, the doping concentration of (a) \(1 \times 10^{18} \text{ cm}^{-3}\) and (b) \(4 \times 10^{17} \text{ cm}^{-3}\) at reverse bias of \(-3000 \text{ V}\). (c) Electric field versus position for HJBS diode along the cutline shown in the contour plots.

The doping concentration and the total width of p-NiO are found to affect the reverse leakage current of the HJBS. The reverse leakage current will decrease with the increase of the total width of NiO. The low doping concentration of p-NiO leads to a slightly higher leakage current, as shown in Figure 11b. The reason for the change in leakage current is that as the doping concentration of p-NiO increases, the electron concentration in the depletion region under the anode decreases. Therefore, fewer electrons can pass through the barrier, as shown in Figure 13. Among all the HJBS diodes described above, the correlation between the forward characteristics with p-NiO doping concentration and the total width of p-NiO underneath the anode is similar to SBD with NiO GRs, and the BV of HJBS diodes are almost the same as SBD with p-NiO GRs at the same p-NiO doping concentration. HJBS has a great potential to suppress leakage current, and the capability to suppress reverse leakage current is not only related to the total length of NiO, but also to the doping concentration of p-NiO. The optimized BV/R_{on,sp} is simulated to be 3004 V/3.06 mΩ·cm², translating to a PFOM = BV²/R_{on,sp} = 2.95 GW/cm².
4. Conclusions

In summary, p-NiO/Ga2O3 diode performances were studied by using a detailed device simulation. Figure 14 summarizes some of the design recommendations. The HJ-PN diodes without any field-plate or other electric field managements can obtain a maximum BV of 5705 at a 15 µm drift layer thickness. For Ga2O3 SBD with p-NiO GRs and HJBS diodes, the $V_{on}$ is 1.1 V and the wider the total width of the p-NiO, the larger $R_{on,sp}$ with a smaller reverse leakage current will be, while maintaining the same p-type p-NiO doping concentration. When the total width of the p-NiO remains a constant, suitable doping concentration of p-NiO can effectively improve the BV. In this article, when the p-NiO doping concentration is $4 \times 10^{17}$ cm$^{-3}$, a maximum BV can be obtained. Another way to increase the BV is to increase the thickness of the drift layer. Ga2O3 SBD with p-NiO GRs and HJBS diode has the same BV under the same p-NiO doping concentration. The simulated BV and P-FOM are far beyond the performance of the state-of-the-art Ga2O3 power diode, showing the great promise of combining p-NiO in the Ga2O3 power electronics.
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