Design and Analysis of High-k Dielectric Super junction Schottky Barrier Diodes Beyond Unipolar Figure of Merit

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Abstract

This study presents design guidelines for a high-k dielectric Superjunction Schottky barrier diode (SBD) to further enhance the already impressive unipolar power figure of merit (PFOM) of Ultra-wide bandgap (UWBG) materials. We employed analytical modeling to optimize the device parameters, accounting for the appropriate dielectric and semiconductor dimensions including the aspect ratio and the dielectric constant of the high-k material. Our findings reveal that device performance is intimately linked to structural dimensions and the dielectric constant of the insulator. Specifically, we observed that the dielectric superjunction SBD exhibits behavior akin to a conventional SBD, where the effective doping density in the drift layer decreases by a factor dependent on semiconductor and dielectric width, aspect ratio and the dielectric constant of the insulator. We discuss optimal design guidelines for achieving a 10 kV $\text{I}_2\text{-Ga}_2\text{O}_3$ SBD with a PFOM of 50 GW/cm$^2$, a significant improvement over the conventional unipolar PFOM of 34 GW/cm$^2$ for $\text{I}_2\text{-Ga}_2\text{O}_3$. Additionally, we conducted a comparative analysis of the switching energies between the superjunction Schottky barrier diode and a conventional Schottky barrier diode. We provide design guidelines to minimize switching energies for a desired PFOM in $\text{I}_2\text{-Ga}_2\text{O}_3$ SBDs. This underscores the immense potential of such structures in advancing vertical power electronics to unprecedented levels of performance.
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Abstract—This study presents design guidelines for a high-k dielectric Superjunction Schottky barrier diode (SBD) to further enhance the already impressive unipolar power figure of merit (PFOM) of Ultra-wide bandgap (UWBG) materials. We employed analytical modeling to optimize the device parameters, accounting for the appropriate dielectric and semiconductor dimensions including the aspect ratio and the dielectric constant of the high-k material. Our findings reveal that device performance is intimately linked to structural dimensions and the dielectric constant of the insulator. Specifically, we observed that the dielectric superjunction SBD exhibits behavior akin to a conventional SBD, where the effective doping density in the drift layer decreases by a factor dependent on semiconductor and dielectric width, aspect ratio and the dielectric constant of the insulator. We discuss optimal design guidelines for achieving a 10 kV $\beta$-Ga$_2$O$_3$ SBD with a PFOM of 50 GW/cm$^2$, a significant improvement over the conventional unipolar PFOM of 34 GW/cm$^2$ for $\beta$-Ga$_2$O$_3$.

Additionally, we conducted a comparative analysis of the switching energies between the superjunction Schottky barrier diode and a conventional Schottky barrier diode. We provide design guidelines to minimize switching energies for a desired PFOM in $\beta$-Ga$_2$O$_3$ SBDs. This underscores the immense potential of such structures in advancing vertical power electronics to unprecedented levels of performance.

Index Terms—Ga$_2$O$_3$, High-k dielectric, Schottky diode, Superjunction, Power Device.

I. INTRODUCTION

In recent years, $\beta$-Ga$_2$O$_3$ has garnered significant attention for its potential in power device applications, primarily due to its remarkably high breakdown field. With a band gap of 4.6 eV, $\beta$-Ga$_2$O$_3$ surpasses both GaN and SiC with an estimated critical breakdown field of 8 MV/cm. The Baliga Figure of Merit (BFOM), relevant to power switching conduction loss, can be 2000-3400 times better than Si, surpassing the figures for SiC or GaN by several multiples. By combining low-doped drift layers with wide band gap materials, it becomes possible to achieve extremely high breakdown voltages, leading to recent demonstrations of various vertical power devices utilizing $\beta$-Ga$_2$O$_3$ with high breakdown voltage [1–9].

Superjunction structures, which employ complementary doped columns of silicon, have been used in silicon power devices to improve the trade-off between breakdown voltage and on-resistance. This advancement has enabled the use of silicon-based devices in high-voltage applications, despite their low unipolar Figure of Merit (FOM) [10–13]. In conventional superjunction structures, multiple p and n pillars are utilized,
and by carefully balancing the charge in these pillars, the entire drift region can be depleted at much lower voltages than conventional devices as shown in Fig. 1(b), resulting in higher breakdown voltages for the same specific on-resistance. In these structures, due to the charge sharing between the p and n layers, a lateral electric field component is induced, resulting in an overall vertical field profile transition from triangular to rectangular, resulting in an increase in breakdown voltage. The higher doping in a superjunction device significantly improves the on resistance, thereby outperforming the unipolar figure of merit. Nonetheless, conventional superjunction structures have very stringent requirements for charge balance, posing growth and fabrication challenges [14], [15]. In β-Ga₂O₃ based devices, the absence of shallow acceptors makes realizing conventional superjunction structures extremely challenging.

To address the issue of a lack of shallow acceptors in gallium oxide, the dielectric superjunction technique has been explored [16]–[19]. High-k dielectrics have been recently investigated for electric field management in lateral and vertical device structures based on wide band gap semiconductors [20]–[22]. The fringing electric field within the high-k dielectric layer engenders a lateral electric field within the drift layer, a phenomenon akin to traditional superjunction structures, as depicted in Fig. 1(c). To minimize potential drops across the dielectric and intensify the lateral field strength within the drift layer, a high-permittivity dielectric material is favored, with a minimum threefold greater permittivity compared to the semiconductor material. However, achieving performance improvements requires meticulous design, as the outcome is highly sensitive to the structural dimensions.

In this study, we have developed an analytical model for the dielectric superjunction structure by solving Poisson’s equation in both the drift layer and the dielectric. We have validated our model by comparing the results with numerical TCAD simulations, employing Synopsis Sentaurus software.

Furthermore, our investigation has led to the determination of optimal dimensions for the dielectric superjunction structure, along with the provision of design guidelines aimed at achieving the optimal configuration. We have extended our analysis to estimate switching energy losses for dielectric superjunction Schottky Barrier Diodes (SBDs) and compared them with conventional SBDs. Additionally, we have offered design guidelines to trade-off switching losses with the conduction loss related Power Figure of Merit (PFOM).

II. ANALYTICAL MODELING: STATIC CHARACTERISTICS

The 2-D Poisson equation of a dielectric superjunction structure with doped n-type semiconductor drift region as shown in Fig. 2, can be written as,

\[
\frac{\partial^2 \psi(x, y)}{\partial x^2} + \frac{\partial^2 \psi(x, y)}{\partial y^2} = -\frac{\rho}{\epsilon}
\]

(1)

where,

\[
\rho = \begin{cases} 
qN_D, & x > 0 \\
0, & x < 0
\end{cases}
\]

where, \(\psi(x, y)\) is the electrostatic potential, \(q\) represents the electron charge, \(N_D\) is the ionized donor concentration inside the drift region.

The boundary conditions at top and bottom contacts are considered as,

\[
\psi_S(x, 0) = 0
\]

(2)

\[
\psi_S(x, L) = V_R
\]

(3)

where \(V_R\) is the applied reverse bias voltage. For the dielectric side, the Poisson’s equation becomes Laplace’s equation due to the absence of charge in the dielectric, which can be solved using the following boundary conditions.
The semiconductor side from (11) can be written as,

\[ \frac{d\psi_D(y = L)}{dy} = 0 \]  

\[ \frac{d\psi_D(x = -W_D/2)}{dx} = 0 \]

The first boundary condition (4) is derived from the requirement that the electric field at the cathode terminal must be zero. The second boundary condition (5) is a consequence of the symmetry of the device around the midpoint of the dielectric. Similarly, the potential boundary conditions for \( y = 0 \) and \( y = L \) can be written as,

\[ \psi_D(x, 0) = 0 \]

\[ \psi_D(x, L) = V_R \]  

Now in the semiconductor side, Neumann boundary condition of continuity of electric displacement can be applied at the dielectric semiconductor interface as,

\[ \epsilon_S \frac{\partial \psi_D(x = 0^+)}{\partial x} \bigg|_y = \epsilon_D \frac{\partial \psi_D(x = 0^-)}{\partial x} \bigg|_y \]

or

\[ \epsilon_S E_S(x = 0^+) \bigg|_y = \epsilon_D E_D(x = 0^-) \bigg|_y \]

where, \( E_S(x = W_S/2) = 0 \) due to the symmetry of the device along the semiconductor half-width. Now, using the values of \( E_S(x = W_S/2) \) and \( E_S(x = 0^+) \) from (8), (10), and (11), the gradient of electric field in the x-direction for the semiconductor side from (11) can be written as,

\[ \frac{\partial E_S(x)}{\partial x} = \frac{2V_R W_D \epsilon_D}{L^2 W S \epsilon_S} \]

Note the 2-D Poisson equation (1) for the semiconductor side can be alternatively written as,

\[ \frac{\partial E_S(y)}{\partial y} = \frac{qN_D}{\epsilon_S} = \frac{\partial E_S(x)}{\partial x} = \frac{q N_{eff}^D}{\epsilon_S} \]

where, \( N_{eff}^D \) is the effective doping concentration in the dielectric superjunction SBD. Fig. 3(b) presents a comparison between the distribution of the electric field magnitude obtained from the analytical model for \( \beta\text{-Ga}_2\text{O}_3 \) and the 2D numerical simulation of a dielectric SJ Schottky diode using Sentaurus TCAD [23]. The figure shows that as the dielectric constant of the dielectric material increases, the electric field profile changes from a triangular shape to a rectangular shape for \( L/W_S = 10 \) and \( W_D/W_S = 1 \). Although we have considered hypothetical dielectric materials in this study, there are several potential high-k material options available, particularly perovskites that offer high dielectric constants [21]. Some discrepancy between the model and the simulation can be observed, especially near the electrodes. This discrepancy arises due to the absence of lateral depletion effects close to the metal electrodes in the model. This issue could be addressed by introducing a correction factor into the electric field expression [24, 25]. However, for the sake of preserving the model’s simplicity and intuitiveness, we have chosen not to incorporate such correction factors. Now integrating (13) along y-direction and applying the boundary condition (3), we can express \( V_R \) as,

\[ V_R = \frac{q N_D}{2 W_S} \frac{L^2}{1 + \frac{W_D \epsilon_D}{W S \epsilon_S}} = \frac{q N_{eff}^D}{2 W_S} L^2 \]

Thus, the effective doping concentration \( N_{eff}^D \) can be expressed as,

\[ N_{eff}^D \approx \frac{N_D}{1 + \frac{W_D \epsilon_D}{W S \epsilon_S}} \]

Therefore, when comparing the dielectric superjunction Schottky Barrier Diode (SBD) to the conventional SBD, the effective doping concentration in the dielectric superjunction SBD is reduced by a factor of \( 1 + \frac{W_D \epsilon_D}{W S \epsilon_S} \) compared to the conventional SBD. Consequently, the breakdown voltage for the dielectric SJ SBD can be derived in a manner similar to the conventional case, with the only difference being the substitution of \( N_D \) with \( N_{eff}^D \). Furthermore, in the scenario where \( W_D \epsilon_D \gg W S \epsilon_S \), the dielectric SJ SBD approaches the limits of a conventional p/n superjunction structures.

The breakdown voltage \( V_{BR} \) for the dielectric SJ SBD can be expressed as,

\[ V_{BR} = E_C L - \frac{q N_{eff}^D L^2}{2 W_S} \]

\[ = E_C L - \frac{q N_D L^2}{2 \epsilon_S \left(1 + \frac{W_D \epsilon_D}{W S \epsilon_S}\right)} \]

Now the specific on-resistance \( (R_{on-sp}) \) for the dielectric SJ SBD considering the entire footprint of the device can be expressed as,

\[ R_{on-sp} = \frac{L}{q \mu_n N_D} \left(1 + \frac{W_D}{W_S}\right) \]

The optimum doping concentration \( (N_{D,opt}) \) to achieve the maximum breakdown voltage can be derived by differentiating (16) and equating it to zero as,

\[ N_{D,opt} = \sqrt{\frac{2 \epsilon_S E_C \left(1 + \frac{W_D}{W_S}\right)}{3 \mu_R R_{on-sp}}} \]
breakdown voltage saturates beyond a width ratio of 0.5 for a width ratio exceeding 1. Furthermore, Fig. 4(b) reveals that the total device area. Therefore, it is not advantageous to have a reduction in the current conducting area relative to the width ratio increases, the $R_{on-sp}$ while achieving an optimal breakdown voltage, it is advisable to maintain the width ratio within the range of 0.5 to 1.

In Figure 4(c), we can observe how the width ratio affects the effective doping concentration ($N_{eff}^{D}$) to achieve the optimal trade-off between $V_{BR}$ and $R_{on-sp}$ for a specific aspect ratio and dielectric constant. A minimum $N_{eff}^{D}$ leads to a constant field profile and hence a minimal $N_{eff}^{D}$ is desired. Notably, an increase in the dielectric constant of the column leads to a reduction in the effective doping concentration, primarily due to the higher lateral depletion effect. Furthermore, it becomes apparent that for a device with a specific dielectric material, the effective doping concentration ceases to be sensitive to the width ratio ($W_{D}/W_{S}$) when the dielectric constant reaches a sufficiently high value, affording more flexibility in selecting the appropriate widths for the dielectric and semiconductor columns to attain the desired Figure of Merit (FOM).

Using all the design constraints mentioned above, i.e.,
- Constraint 1: $L/W_{S} > 1$
- Constraint 2: $0.5 \leq W_{D}/W_{S} \leq 1$

the design of a 10kV $\beta$-Ga$_2$O$_3$ SBD is outlined as follows:

Step 1: Begin by specifying the breakdown voltage ($V_{BR}=10$ kV), specific on-resistance ($R_{on-sp} = 2 \, m\Omega \cdot cm^2$) and the critical breakdown field ($E_{C}=8$ MV/cm).

Step 2: Select an appropriate dielectric material with a known dielectric constant (Assume $\varepsilon_{D}=300$).

Step 3: If the chosen dielectric material has a lower breakdown field than $\beta$-Ga$_2$O$_3$, then set $L > V_{BR}/E_{BR-D}$, where $E_{BR-D}$ represents the breakdown field of the dielectric. In this scenario, assume $E_{BR-D} > E_{C}$, resulting in $L > V_{BR}/E_{C} = 12.5 \mu m$.

Step 4: Calculate $N_{D}$ using equation (19) by assuming a width ratio based on constraint 2. Assuming $W_{D}/W_{S} = 0.5$, find $N_{D} = 3 \times 10^{16} \, cm^{-3}$.

Step 4: Determine an appropriate $L/W_{S}$ using (16). In this case $L/W_{S} = 6.5$. Since $L = 13 \mu m$, calculate $W_{S} = 2 \mu m$.

Step 5: Calculate $W_{D}$ based on constraint 2. Assuming $W_{D}/W_{S} = 0.5$, find $W_{D} = 1 \mu m$.

By following the above design approach, considering an ideal case, a power figure of merit ($V_{eff}^{2}/R_{on-sp}$) of approximately 50 $GW/cm^2$ can be achieved. These dimensions and doping levels are practical and realizable. In contrast, the conventional unipolar figure of merit for $\beta$-Ga$_2$O$_3$ stands at about 34 $GW/cm^2$. This proposed approach can be extended to other wide bandgap materials such as GaN, SiC, and ultra-wide bandgap materials like AlN and Diamond, providing an alternative to pn superjunction structures. This approach allows to avoid the complexities of achieving charge balance in p and n regions in these material systems. This approach can also be a solution in achieving high performance in UWBG semiconductors where only one type of doping is available.

For instance, applying the design rule mentioned above, a 1.2kV dielectric superjunction device for GaN ($E_{C} = 3 \, MV/cm$, $\mu_{n} = 1000 \, cm^2/Vs$) can be designed using a dielectric material with a dielectric constant of 300. The design parameters would include a drift layer thickness ($L$) of 33

III. DESIGN GUIDELINES FOR STATIC OPERATIONS

In Fig. 3(c), we illustrate the impact of the dielectric constant of the dielectric column on the trade-off between $V_{BR}$ (breakdown voltage) and $R_{on-sp}$ for $\beta$-Ga$_2$O$_3$, considering an aspect ratio ($L/W_{S}$) of 10 and a width ratio ($W_{D}/W_{S}$) of 1 (The rationale behind selecting these dimensional ratios will be elucidated in the subsequent paragraphs). Notably, as the dielectric constant increases, the $V_{BR}$-$R_{on-sp}$ trade-off surpasses the unipolar figure of merit for $\beta$-Ga$_2$O$_3$. However, it’s important to highlight that achieving these benefits requires precise and deliberate design considerations compared to conventional unipolar devices.

To gain insights into the impact of device dimensions, we have plotted breakdown voltage against aspect ratio and width ratio in Fig. 4(a) and (b), respectively. Fig. 4(a) clearly indicates that achieving an enhancement in breakdown voltage compared to the conventional case is feasible only when the aspect ratio exceeds one ($L/W_{S} > 1$). Consequently, the length of the device drift layer ($L$) must surpass the width of the semiconductor column ($W_{S}$) to achieve performance beyond the unipolar figure of merit. Moving on to Fig. 4(b), we observe that, for a specific aspect ratio, the breakdown voltage increases with an increase in the width ratio ($W_{D}/W_{S}$). However, it’s important to note that, as per Equation (18), as the width ratio increases, the $R_{on-sp}$ also increases due to a reduction in the current conducting area relative to the total device area. Therefore, it is not advantageous to have a width ratio exceeding 1. Furthermore, Fig. 4(b) reveals that the breakdown voltage saturates beyond a width ratio of 0.5 for most of the high-permittivity dielectric. Hence, to minimize $R_{on-sp}$ while achieving an optimal breakdown voltage, it is advisable to maintain the width ratio within the range of 0.5 to 1.
μm, semiconductor column width ($W_S$) of 3.3 μm, dielectric column width ($W_D$) of 1.65 μm, and drift layer doping concentration ($N_D$) of $4.66 \times 10^{15}$ cm$^{-3}$. This designed GaN high-k superjunction diode would yield a power figure of merit of approximately 17.2 GW/cm$^2$, a significant improvement compared to the 5.97 GW/cm$^2$ unipolar figure of merit for GaN.

IV. SWITCHING CHARACTERISTICS

A significant concern when using high-k superjunction SBDs is the potential increase in capacitance due to the high dielectric constant of the dielectric column. This elevated capacitance can lead to higher switching losses, making it crucial to optimize these losses for real device applications. Switching losses can be estimated by considering the total charge that needs to be either removed or added during switching events. For SBDs, we focus solely on capacitive charge that needs to be either removed or added during switching events. For SBDs, we focus solely on capacitive charge storage, as there is no minority carrier storage in these unipolar devices.

Because high-k superjunction SBDs always operate at the punch-through voltage near breakdown, caused by lateral depletion, we can derive the switching losses by considering the parallel combination of the dielectric capacitance and the semiconductor depletion capacitance. Consequently, the total capacitance for the device can be expressed as follows:

$$C_{\text{Total}} = C_{\text{Dielectric}} + C_{\text{Semiconductor}} = \frac{\varepsilon_S W_S + \varepsilon_D W_D}{L(W_S + W_D)} \quad (20)$$

where, $C_{\text{Dielectric}}$ and $C_{\text{Semiconductor}}$ are the dielectric and semiconductor capacitance respectively. The switching energy for the dielectric superjunction SBD can be written as,

$$\varepsilon_{\text{sw-DSJ}} = \int_{V_{\text{PT-DSJ}}}^{V_{\text{BR}}} Q_{\text{Total}} v_R \, dv_R \quad (21)$$

Where, $Q_{\text{Total}}$ is the total charge in the device and can be written as $C_{\text{Total}} \times V_R$. $V_{\text{PT-DSJ}}$ is the punch-through voltage for the dielectric superjunction SBD and can be written as,

$$V_{\text{PT-DSJ}} = \frac{qN_D L^2}{\varepsilon_S 1 + \frac{W_D}{W_S}} \quad (22)$$

Now, Using (20) and (22) in (21), $\varepsilon_{\text{sw-DSJ}}$ can be written as,

$$\varepsilon_{\text{sw-DSJ}} = \frac{\varepsilon_S W_S + \varepsilon_D W_D}{2L(W_S + W_D)} (V_{\text{BR}}^2 - V_{\text{PT-DSJ}}^2) \quad (23)$$

For conventional SBDs, the switching energy loss after punch-through can be expressed as,

$$\varepsilon_{\text{sw-conv}} = \frac{\varepsilon_S}{L} (V_{\text{BR}}^2 - V_{\text{PT-conv}}^2) \quad (24)$$

And the punch-through voltage ($V_{\text{PT-conv}}$) for the conventional SBDs can be written as,

$$V_{\text{PT-conv}} = \frac{qN_D L^2}{2\varepsilon_S} \quad (25)$$

The switching energy for one cycle of full charge and discharge for optimally designed dielectric superjunction SBDs, with breakdown voltage ($V_{\text{BR}}$) ranging from 200V to 10kV and utilizing a dielectric constant of 300 for the dielectric column, is illustrated in Fig. 5(a). It is evident that these dielectric superjunction SBDs exhibit significantly higher switching energy (over 20 times) when compared to conventional SBDs. Therefore, it becomes imperative to redesign the dielectric SJ SBDs to minimize these switching energy losses and trade it off with increased conduction loss, towards a minimized total loss.

In Fig. 5(b), the switching energy is depicted as a function of drift layer length ($L$) for different dielectric constants ($\varepsilon_D$). The results indicate that the switching energy decreases with an increase in drift layer length and a decrease in the dielectric constant of the dielectric column ($\varepsilon_D$). This trend is due to the total capacitance of the drift layer and the dielectric column decreasing with the increase in $L$ and decrease in $\varepsilon_D$. However, it’s important to note that analytical solutions for a minimum $\varepsilon_{\text{sw-DSJ}}$ cannot be obtained, as (25) is a monotonic function. Consequently, specific values of $\varepsilon_D$ must be manually selected based on allowable $\varepsilon_{\text{sw-DSJ}}$ and practical constraints.

To redesign the β-Ga2O3 dielectric SJ SBD for a specific power figure of merit and an allowable switching energy, the following design rules can be employed:

Step 1: Begin by specifying the breakdown voltage ($V_{\text{BR}}$=10kV), the desired power figure of merit (50 GW/cm$^2$), and the acceptable switching energy ($\varepsilon_{\text{sw-DSJ}} \leq 0.05$ J/cm$^2$).

Step 2: Select a dielectric material with a sufficiently low dielectric constant ($\varepsilon_D$) while considering practical dimensions to achieve the desired power figure of merit. From Fig. 4(b), it can be observed that $\varepsilon_D=80$ and $L \geq 30$ μm can provide an $\varepsilon_{\text{sw-DSJ}} \leq 0.05$ J/cm$^2$.

Step 3: Calculate the value of $R_{\text{on-sp}}$ based on PFOM = $V_{\text{BR}}$. In this case, $R_{\text{on-sp}} = 2 \, m\Omega \cdot cm^2$.

Step 4: Determine the value of $W_S$ using (22). In this case, $W_S = 2 \, \mu m$ to yield a $\varepsilon_{\text{sw-DSJ}} = 0.05$ J/cm$^2$.

Step 5: Choose $W_D$ based on constraint 2. Assuming $W_D/W_S = 0.5$, $W_D = 1 \, \mu m$.

Step 6: Obtain $N_D$ using (18) to get desired $R_{\text{on-sp}}$. In this case, $N_D = 9.3 \times 10^{16} \, cm^{-3}$.

Fig. 6 presents a plot depicting the relationship between $R_{\text{on-sp}}$ and $V_{\text{BR}}$ for β-Ga2O3 at various switching energies. It becomes evident that as the power figure of merit (PFOM)}
design optimization can effectively minimize these losses to achieve the desired PFOM. Thus, the overall advantages of this novel device architecture outweigh the minor disadvantages. It is worth mentioning that further research into the high-k dielectric/β-Ga$_2$O$_3$ interface will be essential for maximizing the potential of such superjunction structures in the development of high-performance power electronic devices.

**References**


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**Fig. 6.** $R_{on}-sp$ vs $V_{BR}$ plot for different switching energy losses showing the dependence of $E_{sw}$ on PFOM.

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V. Conclusion

Detailed design guidelines for achieving a higher power figure of merit (PFOM) in dielectric superjunction Schottky Barrier Diodes (SBDs) are discussed. The use of a dielectric superjunction addresses a fundamental challenge in gallium oxide, namely, the absence of p-type doping. This approach alters the electric field profile in the drift region, resulting in a rectangular shape that significantly enhances the breakdown voltage ($V_{BR}$). By optimizing the device structure, it is possible to push the already impressive $V_{BR}$-$R_{on}-sp$ trade-off of β-Ga$_2$O$_3$ beyond its unipolar limit. Although switching energy losses are found to be somewhat higher compared to conventional SBDs, it is important to note that proper


