Ultra-Low Reverse Leakage in Large Area Kilo-Volt class $\beta$-Ga2O3 Trench Schottky Barrier Diode with High-k Dielectric RESURF

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Abstract

We present our findings on the utilization of a high permittivity dielectric, RESURF, in $\beta$-Ga2O3 trench Schottky barrier diodes. Our research demonstrates the achievement of ultra-low reverse leakage current in both small-scale and large-scale devices, with a breakdown voltage exceeding 1kV, thanks to the high-k RESURF technology. Furthermore, we assess the switching performance of these large-area devices and illustrate their competitive standing when compared to state-of-the-art commercial SiC devices. Additionally, we provide evidence of the superior thermal stability exhibited by high-k trench devices in comparison to SiC devices.
Ultra-Low Reverse Leakage in Large Area Kilo-Volt class $\beta$-Ga$_2$O$_3$ Trench Schottky Barrier Diode with High-k Dielectric RESURF

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We introduce vertical Schottky Barrier Diodes (SBDs) based on $\beta$-Ga$_2$O$_3$ with trench architecture, featuring a high-permittivity dielectric RESURF structure. These diodes are designed for applications demanding high voltage and current capacities while maintaining ultra-low reverse leakage currents. The trench design plays a pivotal role in reducing the electric field at the metal-semiconductor junction, thereby yielding minimal reverse leakage attributed to field emission under high reverse bias conditions. Additionally, the incorporation of a high-k dielectric helps to suppress leakage through the trench bottom corner dielectric layer. The small area trench SBD (200×200 $\mu$m$^2$) demonstrates a breakdown voltage exceeding 3kV, accompanied by a reverse leakage current of less than 1 $\mu$A/cm$^2$ at 3kV. Moving on to larger area devices, the 1×1 mm$^2$ and 2×2 mm$^2$ devices exhibit breakdown voltages of 1.8kV and 1.4kV, while accommodating pulsed forward currents of 3.5A and 15A, respectively. The capacitance, stored charge, and switching energy of the trench SBDs are also found to be less than the similarly rated commercial SiC SBDs, reinforcing their potential for enhanced switching efficiency.

$\beta$-Ga$_2$O$_3$ has emerged as a pivotal material for the next generation of power electronics due to its exceptionally wide bandgap range of 4.6-4.8 eV and high critical electric field strength$^{1}$, resulting in a superior power figure of merit (PFOM) compared to other wide bandgap materials such as SiC and GaN. Moreover, the availability of high-quality bulk substrates grown through melting techniques contributes to improved epitaxial layer growth$^2$ and holds the potential for cost reduction. The rapid strides in materials advancement$^3$ have facilitated the realization of cutting-edge devices in both vertical and lateral geometries$^{4–21}$. Vertical devices, in particular, have garnered significant attention for high-voltage applications due to their inherent capacity to scale up to high currents. To meet the demands of such applications, thick, high-quality, low-doped drift layers are essential. These layers need to accommodate substantial reverse blocking voltages while simultaneously delivering high carrier mobility to mitigate on-state resistance. Notably, commercially available 10 $\mu$m thick (001)-$\beta$-Ga$_2$O$_3$ epitaxial layers, grown using halide vapor phase epitaxy (HVPE)$^{22}$, exhibit a doping concentration of less than 10$^{16}$ cm$^{-3}$, presenting a highly promising avenue for the development of vertical devices capable of operating in the multi-kilovolt range.

However, the absence of p-type doping in $\beta$-Ga$_2$O$_3$ presents certain fundamental challenges in device design$^{23}$. P-type doping is commonly employed in Si and SiC power devices to establish pn junctions and alleviate the concentration of electric field lines at device edges and corners. Furthermore, in Schottky diodes under high reverse bias, the parallel plane electric field attains exceptionally high values, resulting in elevated reverse leakage currents due to thermionic field emission. Schottky barrier diodes (SBDs) utilizing metals with lower Schottky barrier heights exhibit exceedingly high reverse leakage currents even at electric fields significantly lower than the critical electric field of $\beta$-Ga$_2$O$_3$.

Trench Schottky barrier diodes$^{6,24,25}$ usually overcome this limitation by leveraging RESURF (reduced surface field) effects, which efficiently divert the electric field away from the metal-semiconductor junction. In practical devices, the breakdown of trench SBDs is constrained by dielectric breakdown rather than breakdown at the metal-semiconductor junction. However, it’s worth noting that the electric field within the dielectric can attain exceptionally high levels when subjected to applied reverse bias, potentially resulting in dielectric leakage in these devices. While thicker dielectrics can endure high reverse bias, their application might compromise the impact of RESURF in the fin regions. However, the use of high-k dielectrics$^{10,13,26}$ instead of low-k dielectrics offers a solution. High-k dielectrics exhibit significantly lower internal electric fields, effectively mitigating dielectric leakage without exerting any influence on the RESURF effect in the fin regions.

In the realm of power switching for industrial applications,
large-area devices are particularly essential as they need to drive large loads. Industrial power devices are tasked with handling currents in the order of several amperes during the on-state, while also being required to withstand voltages of at least several hundred volts in the off-state. All of this occurs at operational frequencies that often reach tens to hundreds of kilohertz. However, a noteworthy challenge emerges as the device area expands: a simultaneous increase in reverse leakage currents, resulting in escalated off-state power loss. Despite concentrated endeavors, all showcased large area β-Ga2O3 based Schottky Barrier Diodes (SBDs) exhibit reverse leakage currents surpassing 1 mA/cm². Although pn-heterojunction diodes utilizing NiO27–29 have exhibited lower reverse leakage currents, these devices are plagued by exceedingly high turn-on voltages, which inevitably lead to amplified on-state power loss. Hence, large-area devices with lower turn-on voltage and lower off-state reverse leakage currents are essential for the successful commercialization of β-Ga2O3 based devices.

In this study, we have successfully demonstrated trench Schottky barrier diodes (SBDs) based on β-Ga2O3 with a high-permittivity dielectric RESURF approach. For the RESURF dielectric, we employed BaTiO3 (BTO) with a dielectric constant of 248.30 Our fabrication process included the creation of both small-scale (200×200 μm²) devices and larger-scale devices (1×1 mm² and 2×2 mm²), spanning ampere-level currents. The 1 mm² and 2 mm² devices demonstrated maximum forward currents of 3.5A and 15A, respectively. These devices also showcased substantial breakdown voltages of 1.8kV and 1.4kV respectively. In contrast, the smaller area devices exhibited an even higher breakdown voltage, surpassing 3kV. To further assess the performance characteristics, we conducted capacitance-voltage measurements on the larger area devices. This analysis allowed us to estimate the stored charge and switching energies of the fabricated devices, providing valuable insights into their operational behavior.

The fabrication process for the trench Schottky barrier diode (SBD) depicted in Fig. 1(a) was carried out on an 11 μm thick epilayer grown through Halide Vapor Phase Epitaxy (HVPE) on a conducting substrate (NCT Japan). The creation of the 1 μm deep fins involved BCl3-based Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE) using a Ni/SiO2 hard mask.5,15 Subsequent to the dry etching, the samples underwent a 15-minute immersion in HCl to eliminate dry etch-induced damage31, followed by a 5-minute dip in HF. A 300nm-thick layer of BaTiO3 (BTO) was then sputter-deposited at room temperature, followed by annealing at 700 °C in an O2 environment to enhance the dielectric constant26. To enable contact deposition, the top of the fin regions was exposed through SF6/Ar-based ICP RIE etching of the BTO, utilizing a Ni-hard mask. Subsequently, Pt contact material was deposited using electron beam evaporation with planetary rotation to achieve a conformal coating. A passivation dielectric layer of SiN was then applied to the sample using plasma enhanced chemical vapor deposition (PECVD). Contact vias were created by dry etching the SiN, followed by the deposition of Ni/Au probe pads. Lastly, Ti/Au ohmic contacts were deposited via electron beam evaporation on the back side of the sample.

Fig. 2(a) illustrates a comparison of the linear current-voltage relationship among the small area high-k RESURF trench SBD, the standard SBD30, and a BTO field-plated SBD30. The differential specific on-resistance values are determined as 6.8 mΩ·cm², 7.1 mΩ·cm², and 10.8 mΩ·cm² for the simple, field-plated, and trench SBDs, respectively. The higher specific on-resistance observed in the trench SBD might stem from the dry-etch-induced damage on the sidewalls of the fins, which can be avoided using low-etch damage techniques including wet etching using hot phosphoric acid31 or gallium etching32.

Moving to larger area devices, Figs. 2(b) and (c) display the current-voltage characteristics of the SBDs. For the 1 mm² SBD, a maximum current of 3.7A is achieved at 5V with a 10% duty cycle, while a current of 1.9A is attained with a 95% duty cycle. The reduction in current at higher duty cycles can be attributed to self-heating effects within the SBDs. Notably, the 95% duty cycle measurement closely approximates a DC scenario, providing valuable insights into their operational behavior.

The temperature-dependent I-V plots for the trench Schottky Barrier Diode (SBD) are shown in Fig. 2(d). The turn-on voltage decreases from around 0.9V at room temperature to approximately 0.6V at 150 °C. In the inset of Fig. 2(d), the temperature dependence of the differential on resistance (Ron) is displayed. By fitting the Ron values in accordance with the power law expression Ron = Ron,300K(T/300)α, the temperature coefficient of resistance (α) for the trench SBD is deter-
FIG. 3. (a) Electric field contour plot of the low-k and high-k RESURF trench SBD extracted using SILVACO ATLAS simulation (Dielectric boundaries are marked with yellow dashed lines). (b) Experimentally measured I-V characteristics of the BTO (high-k) and SiNₓ (low-k) MISCAPs. (c) Electric field profile for the low-k and high-k RESURF trench SBD along AA’ cutline.

determined to be 0.87. This α value aligns well with the previously reported value (0.7333) for β-Ga2O3-based SBDs and is significantly lower compared to the SiC SBDs (2.9536). This suggests superior thermal stability for the β-Ga2O3-based devices.

Addressing the reverse characteristics, Fig. 3(a) displays the contour plot of the electric field, simulated using SILVACO ATLAS, for the trench Schottky Barrier Diode (SBD) with low-k (ε_r = 8.5) and high-k (ε_r = 248) RESURF techniques. It is evident that the low-k dielectric exhibits a significantly higher electric field within it compared to the high-k dielectric counterpart. This higher electric field for the low-k dielectric structure results in dielectric leakage and eventual breakdown, as also evidenced in the fabricated Metal Insulator Semiconductor Capacitor (MISCAP) structure illustrated in Fig. 3(b) (Pt/Au and Ti/Au was used as the anode and cathode contacts respectively). Specifically, the planar MISCAP utilizing low-k 300nm thick (SiNₓ) succumbs to breakdown at 2.1kV with substantial dielectric leakage. Conversely, the BTO-based MISCAP surpasses a 3kV breakdown voltage with negligible leakage current (<10^-7 A/cm²). Fig. 3(c) demonstrates the electric field profile along the AA’ cutline for both the low-k and high-k RESURF trench SBDs. In the case of the low-k RESURF structure with a dielectric thickness of 300nm, the electric field at the metal-semiconductor junction reaches approximately ~1.5MV/cm. Conversely, for the high-k RESURF structure with the same thickness, the electric field at the metal-semiconductor interface remains below 0.5MV/cm, indicating a superior RESURF efficiency when employing a high-k dielectric.

The reverse characteristics of the fabricated devices are presented in Figure 4. Figure 4(a) illustrates the reverse current-voltage (I-V) plot for the simple, BTO field plated, and high-k RESURF trench SBDs. The breakdown voltages are determined as 816V, 2.1kV, and >3kV for the simple, BTO field plated, and high-k RESURF trench SBDs, respectively. At breakdown, the extracted leakage current densities are 2mA/cm² for the simple SBD, 4mA/cm² for the BTO field plated SBD, while for the trench SBD, the reverse leakage current at 3kV is 1µA/cm² due to the reduction in the electric field at the metal-semiconductor interface owing to the trench structure. The reverse I-V characteristics for the larger-area devices are displayed in Figure 4(b). The 1mm² device demonstrates a breakdown voltage of approximately ~1.8kV, and the 4mm² device exhibits a similar breakdown voltage of approximately ~1.4kV. At the breakdown voltages, the extracted leakage currents are 4 and 5 µA for the 1mm² and 4mm² trench SBDs, respectively. This decline in breakdown voltage and simultaneous increase in leakage current with device area can be attributed to the presence of killer defects in the material, which suggests that further material development is crucial for unlocking the full potential of β-Ga2O3. Nevertheless, it is noteworthy that the extracted leakage currents for the larger-area devices are the lowest among all the
ampere class $\beta$-Ga$_2$O$_3$ based devices with similar dimensions.

The switching losses of the large-area devices are estimated through high-voltage capacitance-voltage (CV) measurements conducted at a frequency of 1MHz and the results are plotted in Fig. 5(a-c). The capacitance of the 1mm$^2$ and 4mm$^2$ SBDs is measured to be 8.4pF and 35pF, respectively, at a bias of $-1kV$. The capacitive stored charge ($Q_c$) is estimated using,

$$Q_c = \int_{0}^{V_R} C(v_R) \, dv_R$$

(1)

and the stored energy ($E_c$) is calculated using,

$$E_c = \int_{0}^{V_R} C(v_R) v_R \, dv_R$$

(2)

where $V_R$ denotes the applied reverse voltage. The extracted stored charge amounts to 12nC and 44nC, while the stored energies are 4.4µJ and 17.5µJ for the 1mm$^2$ and 4mm$^2$ SBDs, respectively. A comparison of the capacitance, stored charge, and stored energy with Wolfspeed SiC SBDs is provided in Table I. Notably, the $\beta$-Ga$_2$O$_3$ trench SBDs exhibit considerably lower capacitance, stored charge, and stored energy in comparison to the commercial SiC devices. The only drawback is the higher forward voltage drop for the $\beta$-Ga$_2$O$_3$ SBDs due to their higher on-resistance which includes the contribution from the doped thick substrates (650 µm). It’s worth noting that the leakage currents for the trench SBDs are also substantially lower compared to the SiC SBDs. The on-resistance of the $\beta$-Ga$_2$O$_3$ based trench SBDs can potentially be further reduced by utilizing lower damage etching techniques to create the fins and by thinning down the substrates and accessing higher fields which will enable thinner drift regions and further lower the on-resistance.

A comparative benchmark plot showcasing the leakage current at breakdown versus the turn-on voltage for the $\beta$-Ga$_2$O$_3$ based diodes is presented in Figure 6. Notably, the pn-heterojunction diodes exhibit lower leakage currents ($I_{leakage}$) but possess higher turn-on voltages ($V_{on}$), whereas the Schottky Barrier Diodes (SBDs) display lower $V_{on}$ values but higher leakage currents. The high-k RESURF trench SBDs highlighted in this study demonstrate the most favorable $V_{on}$/$I_{leakage}$ product among any $\beta$-Ga$_2$O$_3$ based power devices featuring both a current exceeding 1A and a breakdown voltage surpassing 1kV.

In conclusion, we demonstrated $\beta$-Ga$_2$O$_3$ based power device by introducing large area, high-permittivity RESURF trench Schottky barrier diodes. The larger devices, spanning 1mm$^2$ and 4mm$^2$ areas, showcase impressive forward currents reaching 3.5A and 15A respectively, accompanied by breakdown voltages of 1.8kV and 1.4kV. Moreover, the extracted temperature coefficient of resistance ($\alpha = 0.87$) for $\beta$-Ga$_2$O$_3$ SBDs, lower than that of SiC, underlines the superior thermal stability of the technology. Small area devices exhibit a remarkable breakdown voltage exceeding 3kV with minimal reverse leakage current, demonstrating their robustness. Crucially, the analysis of capacitance, stored charge, and switching energies underscores the superior switching capabilities of $\beta$-Ga$_2$O$_3$ based SBDs, positioning them as a viable alternative to commercially available SiC SBDs. These achieve-

![Fig. 5](image_url)

FIG. 5. (a) Measured capacitance voltage, (b) calculated capacitive stored charge, and (c) capacitive stored energy for the 1mm$^2$ and 4mm$^2$ high-k RESURF trench SBD.

TABLE I. Comparison with commercial SiC devices

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Area (mm$^2$)</th>
<th>$V_F$ (V)</th>
<th>$I_{leakage} @ 1200V$ (µA)</th>
<th>$C_f @ 800V$ (pF)</th>
<th>$Q_c @ 800V$ (nC)</th>
<th>$E_c @ 800V$ (µJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolfspeed (E4D02120E) SIC SBD (1200V/2A)</td>
<td>—</td>
<td>1.8</td>
<td>10</td>
<td>14</td>
<td>16</td>
<td>5.6</td>
</tr>
<tr>
<td>This work (1200V/2A)</td>
<td>1</td>
<td>3</td>
<td>0.007</td>
<td>8.4</td>
<td>10.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Wolfspeed (E4D02120E) SIC SBD (1200V/15A)</td>
<td>—</td>
<td>1.8</td>
<td>35</td>
<td>50</td>
<td>77.5</td>
<td>22</td>
</tr>
<tr>
<td>This work (1200V/15A)</td>
<td>4</td>
<td>5</td>
<td>0.06</td>
<td>35</td>
<td>37.4</td>
<td>11.3</td>
</tr>
</tbody>
</table>
ments, however, represent only a stepping stone, as further enhancements through material refinement and the implementation of low-damage etching techniques, substrate thinning, and thermal management hold the potential to unlock even greater performance, paving the way for the next generation of power electronics.

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