Vertical β-Ga_2O_3 Schottky Barrier Diodes with Enhanced Breakdown Voltage and High Switching Performance

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Herein, vertical Schottky barrier diodes (SBDs) based on a bulk β-Ga_2O_3 substrate are developed. The devices feature an ion-implanted planar edge termination (ET) structure, which can effectively smoothen the electric field peak and reduce the electric field crowding at the Schottky junction edge. Greatly enhanced reverse blocking characteristics including $\approx 10^3\times$ lower reverse leakage current and $1.5\times$ higher breakdown voltage (V_B) are achieved, whereas good forward conduction such as a reasonably high on-state current density and near-unity ideality factor is maintained. In addition, the switching performance of the fabricated vertical β-Ga_2O_3 SBDs is investigated using a double-pulse test circuit. When switching from an on-state current of 350 mA to a reverse-blocking voltage of -100 V, the vertical β-Ga_2O_3

β-Ga$_2$O$_3$ ... (E).

≈2.6×10^{18} $^{-3}$. ... $(N_D - N_A)$ $^-$-β-Ga$_2$O$_3$ ... ≈4×10^{16} $^{-3}$ (**Figure 2**), ... (C–V) ...

$$N_D - N_A = -\frac{2}{q\varepsilon \; (1/C^2)/ \; V} \quad (1)$$

N_D, N_A, q, ... ε ... $^-$-β-Ga$_2$O$_3$ ... β-Ga$_2$O$_3$, ...

... (D) ... A ... 300 ... 2 ... (EC D) ... A ... E ... A ... β-Ga$_2$O$_3$, ...

... β-Ga$_2$O$_3$. ... 30, 40, 60, ... 80 ... >100 ... 1 × 10^{14} $^{-2}$ ... A ... (M) ... A ... 10^{18} $^{-3}$ ... fi ... $^-$-Ga$_2$O$_3$ ... ≈4×10^{16} $^{-3}$. A ... 2 ... / /A (20/100/100) ... 100 μ ... 5 μ ... E ... F ... /A /A (50/150/200) ... $^+$-β-Ga$_2$O$_3$ ... F ... BD ... E ... [22] ... **Figure 3**, ... fi ... (M FE) ... fi ... (5) ... DC ... (V_{DD} = 100) ... (D) ... M FE ... D ... M FE ... D ...

3. Results and Discussion

3.1. Static Characteristics

Figure 4 ... (I–V) ... B ... E ... I–V ... fi ... (R) ≈4 Ω ^{2} ... ≈0.3 A $^{-2}$. ... (V), ... 1 A $^{-2}$, ... ≈1.0 ... BD , ... /β-Ga$_2$O$_3$ BD ...

10^{13}.

(n) /β-Ga_2O_3 BD 1.02

BD.

β-Ga_2O_3

β-Ga_2O_3.

Figure 5 I–V

β-Ga_2O_3 BD E.

BD E $\approx 3\times10^{-5}$ A $^{-2}$

-200 V, E

$\approx 5\times10^{-8}$ A $^{-2}$

-200 V, ≈ 3

(I_{ON}/I_{OFF})

fi 4 V

0 -200 V F 4.

I_{ON}/I_{OFF}

fi fi **Figure 6**

β-Ga_2O_3 BD

E, V_B fi

450 μA $^{-2}$ I_{ON}/I_{OFF} 10^6. C

BD V_B 257 V,

E V_B 391 V.

E

A

fi

BD , A

BD

fi

V_B. fi

β-Ga_2 (.)4100F

10

Figure 7. a) A simulated electric field contour map in the vicinity of the anode electrode at a reverse bias of 250 V for the β-Ga_2O_3 SBDs with and without ET. b) Line profile of simulated electric field along the surface of the β-Ga_2O_3 drift layer.

.[23,24] A . **Figure 7**, 250 , fi β-G 3 BD 6.5 4.5 M $^{-1}$ E . A β-G 3 fi .[15] A E 300 °C 30 , V_B β-G 3 BD , A E 300 °C. E , ( ) β-G 3 BD. , -β-G 3 , R V_B [14,17,19] F -β-G 3 .

3.2. Switching Performance

(I_{rr}) . **Figure 8** β-G 3 BD F D 350 A −100 fi I_F/ t = 10 A μ $^{-1}$. C F D (F , F4004), β-G 3 BD 12× (I_{rr}, ≈38 A) 5.5× (t_{rr}, ≈14.1). (Q_{rr}) β-G 3

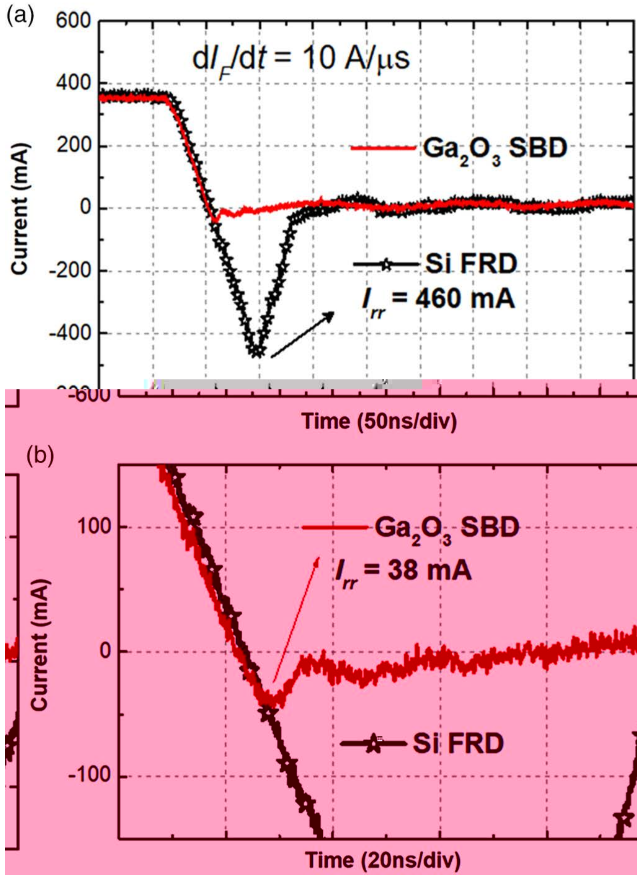

Figure 8. a) Current waveforms of the β-Ga_2O_3 SBD and Si FRD (Fairchild, UF4004) during reverse recovery. b) The zoomed-in image at the point where the β-Ga_2O_3 SBD's peak reverse recovery current occurs.

BD 0.34 C, 1.7% F D. **Table 1** β-G 3 BD F D . C β-G 3 M BD[25] fi BD ,[26] (Q_{rr}) β-G 3 , Q_{rr} 4 × 10^{-4} C $^{-2}$. E ,[26] β-G 3 BD (I_{rr}), .

Table 1. Summary of the parameters during reverse recovery.

Parameter[a)]	β-Ga_2O_3 SBD	Si FRD
I_{rr} (mA)	38	460
t_{rr} (ns)	14.1	77.5
Q_{rr} (nC)	0.34	19.6

[a)]Parameters during reverse recovery of β-Ga_2O_3 SBD and Si FRD (Fairchild, UF4004), from a forward current of 350 mA to a reverse-blocking voltage of −100 V.

Figure 9 −100 β-G 2 3 BD F D. F F D, I t fi 100 200 350 A. β-G 2 3 BD.

4. Conclusions

β-G 2 3 BD E A E $\approx 10^3\times$ V_B 257 391, fi . D (350 A −100 $I_F/t = 10$ A μ $^{-1}$), β-G 2 3 BD F D, $\approx 12\times$ I, $\approx 5.5\times$ t, $\approx 57\times$ Q. β-G 2 3 BD.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

breakdown voltages, edge termination, reverse recovery, Schottky barrier diodes, β-Ga_2O_3

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