SCIENCE CHINA
Information Sciences

• LETTER •

November 2026, Vol. 69, Iss. 11, 219403:1–219403:2
https://doi.org/10.1007/s11432-025-4862-4

3.23 GW/cm^2 power figure of merit and 0.69 V turn-on voltage β-Ga_2O_3 heterojunction barrier Schottky diodes with p-i-n junction termination

Pengfei DONG[1,2†], Jianghan ZHAO[1†], Chenlu WANG[1*], Anqi YE[1], Xin FENG[1,2], Min ZHOU[1], Kui DANG[1,2], Hong ZHOU[1,2*], Yue HAO[1] & Jincheng ZHANG[1,2*]

[1]*Key Lab of Wide Band Gap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an 710071, China*
[2]*Guangzhou Wide Bandgap Semiconductor Innovation Center, Guangzhou Institute of Technology, Xidian University, Guangzhou 510555, China*

Received 23 August 2025/Revised 8 December 2025/Accepted 11 March 2026/Published online 15 October 2026

Citation Dong P F, Zhao J H, Wang C L, et al. 3.23 GW/cm^2 power figure of merit and 0.69 V turn-on voltage β-Ga_2O_3 heterojunction barrier Schottky diodes with p-i-n junction termination. Sci China Inf Sci, 2026, 69(11): 219403, https://doi.org/10.1007/s11432-025-4862-4

β-Ga_2O_3 has attracted extensive interest for high-voltage power electronics owing to its ultra-wide bandgap and high critical electric field [1]. However, the lack of reliable p-type β-Ga_2O_3 fundamentally restricts the realization of high-performance bipolar devices [2]. Heterojunction structures employing p-type oxides, particularly NiO_x, provide a feasible pathway [3], yet they often suffer from a trade-off between breakdown voltage (BV) and turn-on voltage (V_{on}). Specifically, enhancing voltage blocking capability typically requires a higher effective barrier height, which inevitably increases forward conduction loss. Fermi-level engineering via acceptor doping offers an alternative strategy to improve voltage blocking without excessively increasing V_{on}. Nitrogen (N), a promising acceptor candidate, has been demonstrated to function as a current-blocking layer in β-Ga_2O_3 devices [4]. Moreover, recent theoretical studies suggest that dual-impurity co-doping can provide more efficient electronic modulation than single-impurity doping [5].

In this work, we report β-Ga_2O_3 HJBS diodes incorporating a p-i-n anode termination formed by N/P co-doping in conjunction with a p-NiO_x termination. The co-doped region introduces a compensated internal junction that modulates the electric-field distribution near the anode edge. The proposed structure achieves a BV of 3.9 kV and a specific on-resistance ($R_{on,sp}$) of 4.75 m$\Omega \cdot$cm^2, corresponding to a power figure of merit (P-FOM) of 3.23 GW/cm^2, while maintaining a low V_{on} of 0.69 V and an ideality factor of 1.07.

Experiments. The schematic cross-sectional structure of the n-β-Ga_2O_3/p-NiO_x HJBS diode is illustrated in Figure 1(a). The devices were fabricated on an HVPE-grown β-Ga_2O_3 epitaxial layer with a drift thickness of 13 μm. As shown in Figure 1(b), the donor concentration was extracted as 1.7×10^{16} cm^{-3} from the slope of the $1/C^2$–V characteristics.

For N/P co-implantation, the projected depth was 800 nm for both species, with plateau concentrations of 1×10^{18} cm^{-3} for N and 1×10^{16} cm^{-3} for P, respectively. Post-implantation annealing was performed at 1000°C in N_2 for 10 min to activate dopants and recover lattice damage. Ti/Au (60/200 nm) was deposited on the backside as the cathode, followed by rapid thermal annealing at 475°C for 1 min in N_2 to form an Ohmic contact.

The NiO termination rings were deposited by magnetron sputtering at room temperature, consisting of a 60 nm layer with a doping concentration of 1×10^{18} cm^{-3} and a 30 nm layer with 1×10^{19} cm^{-3}. Each NiO ring was designed with a width of 6 μm and an interspacing of 5 μm.

Results and Discussion. Figure 1(c) presents the linear-scale current density–voltage (J–V) characteristics and the extracted $R_{on,sp}$ of the HJBS diode. The $R_{on,sp}$ and forward current density at 3 V are 4.75 m$\Omega \cdot$cm^2 and 425 A/cm^2, respectively. The semi-logarithmic forward J–V curve is shown in Figure 1(d), from which an ideality factor of 1.07 is extracted, indicating a high-quality heterointerface. The turn-on voltage, defined at a forward current density of 1 A/cm^2, is 0.69 V.

Figures 1(e) and (f) show the temperature-dependent forward characteristics from 25°C to 150°C. The extracted V_{on} and $R_{on,sp}$ as functions of temperature are summarized in Figure 1(g). The J_{on}/J_{off} ratio remains on the order of 10^7 even at 150°C. As illustrated in Figure 1(h), both the ideality factor and barrier height exhibit minimal variation with temperature, suggesting that the co-doping-induced junction modulation remains stable under elevated thermal conditions.

The reverse I–V characteristics are shown in Figure 1(i), where the cathode is grounded, and the anode is negatively biased until breakdown occurs. Solid lines represent devices with N/P implantation, while dashed lines correspond to control devices without implantation. Both structures share identical configurations except for the implanted termination.

* Corresponding author (email: chenluwang@stu.xidian.edu.cn, hongzhou@xidian.edu.cn, jchzhang@xidian.edu.cn)
† These authors contributed equally to this work.

© Science China Press 2026

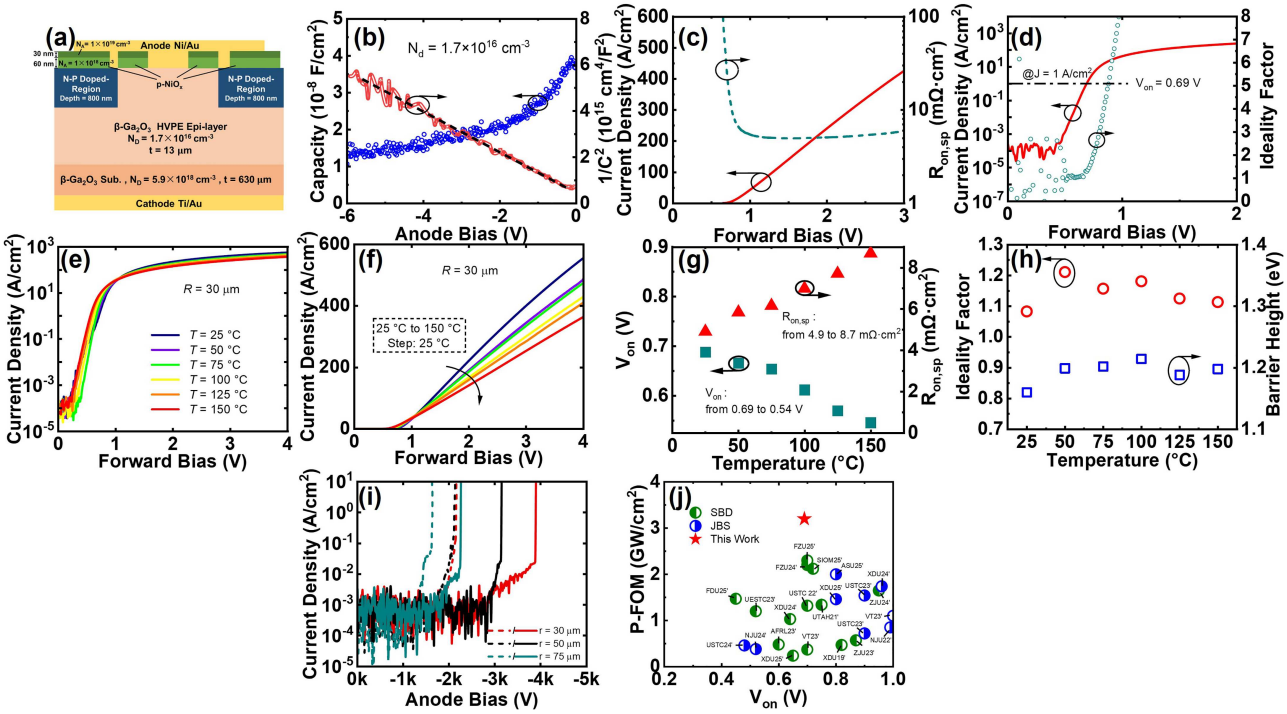

Figure 1 (Color online) (a) Schematic image of the cross-sectional vertical β-NiO/Ga_2O_3 HJBS diodes with N/P ion implantation. (b) Measured C–V and extracted $1/C^2$–V curves of Ga_2O_3 HJBS diodes with a radius of 150 μm. (c) Linear-scale J–V curves and log-scale $R_{on,sp}$. (d) Log-scale J–V characteristics and the extracted ideality factors. (e) Log-scale and (f) linear-scale T-dependent J_F–V_F curves measured in steps of 25°C from 25°C to 150°C. (g) Extracted V_{on} and $R_{on,sp}$ versus temperature from 25°C to 150°C. (h) T-dependent ideality factor and barrier height characteristics at T ranging from 25°C to 150°C. (i) Breakdown characteristics for devices in this work (solid lines) and devices fabricated without ion-implanted termination (dashed lines). (j) V_{on} versus P-FOM benchmark plot comparing our Ga_2O_3 HJBS diodes and other state-of-the-art Ga_2O_3 SBDs and JBS diodes.

For device radii ranging from 30 to 75 μm, the HJBS diodes with co-doping achieve BVs of 3.9, 3.0, and 2.3 kV, respectively. Notably, the BV increases from 2.0 to 3.9 kV after incorporating N/P co-doping, demonstrating the effectiveness of the compensated p-i-n termination in alleviating electric-field crowding near the anode edge.

With a BV of 3.9 kV and an $R_{on,sp}$ of 4.75 mΩ · cm^2, a P-FOM (BV^2/$R_{on,sp}$) of 3.23 GW/cm^2 is achieved. As shown in Figure 1(j), the proposed device exhibits a competitive P-FOM among reported β-Ga_2O_3 diodes with $V_{on} \leqslant 1$ V, while maintaining a low V_{on} of 0.69 V.

Conclusion. In summary, NiO/β-Ga_2O_3 HJBS diodes incorporating an N/P co-doped p-i-n termination were demonstrated. The compensated implantation region effectively enhances voltage blocking capability while preserving low forward conduction loss. The devices achieve a BV of 3.9 kV and an $R_{on,sp}$ of 4.75 mΩ·cm^2, corresponding to a P-FOM of 3.23 GW/cm^2. Additionally, stable electrical characteristics up to 150°C indicate robust thermal performance. These results provide an effective strategy for simultaneously improving breakdown capability and conduction efficiency in β-Ga_2O_3 power devices.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 62222407, 62421005) and Guangdong Basic and Applied Basic Research Foundation (Grant No. 2023B1515040024).

Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Zhou H, Zhou M, Xiang M, et al. Heterogeneous integration of ultrawide bandgap semiconductors for radio frequency power devices. Sci Adv, 2025, 11: eadw6167
2 Varley J B, Janotti A, Franchini C, et al. Role of self-trapping in luminescence and p-type conductivity of wide-band-gap oxides. Phys Rev B, 2012, 85: 081109
3 Wang Z, Gong H H, Yu X X, et al. Trap-mediated bipolar charge transport in NiO/Ga_2O_3 p^+-n heterojunction power diodes. Sci China Mater, 2023, 66: 1157–1164
4 Wong M H, Lin C H, Kuramata A, et al. Acceptor doping of β-Ga_2O_3 by Mg and N ion implantations. Appl Phys Lett, 2018, 113: 102105
5 Yan C, Su J, Wang Y, et al. Reducing the acceptor levels of p-type β-Ga_2O_3 by (metal, N) co-doping approach. J Alloys Compd, 2021, 854: 157247