ARTICLES

Journal of Semiconductors
(2023) 44, 072805
doi: 10.1088/1674-4926/44/7/072805

Large-area β-Ga_2O_3 Schottky barrier diode and its application in DC–DC converters

Wei Guo, Zhao Han, Xiaolong Zhao, Guangwei Xu†, and Shibing Long†

School of Microelectronics, University of Science and Technology of China, Hefei 230026, China

Abstract: We demonstrate superb large-area vertical β-Ga_2O_3 SBDs with a Schottky contact area of 1 × 1 mm^2 and obtain a high-efficiency DC–DC converter based on the device. The β-Ga_2O_3 SBD can obtain a forward current of 8 A with a forward voltage of 5 V, and has a reverse breakdown voltage of 612 V. The forward turn-on voltage (V_F) and the on-resistance (R_{on}) are 1.17 V and 0.46 Ω, respectively. The conversion efficiency of the β-Ga_2O_3 SBD-based DC–DC converter is 95.81%. This work indicates the great potential of Ga_2O_3 SBDs and relevant circuits in power electronic applications.

Key words: β-Ga_2O_3; SBD; DC–DC converter

Citation: W Guo, Z Han, X L Zhao, G W Xu, and S B Long, Large-area β-Ga_2O_3 Schottky barrier diode and its application in DC–DC converters[J]. *J. Semicond.*, 2023, 44(7), 072805. https://doi.org/10.1088/1674-4926/44/7/072805

1. Introduction

Power devices and circuits are the most important parts of the electrical energy conversion system. Meanwhile, power devices and circuits based on ultra-wide bandgap semiconductors can contribute to reducing the power consumption in the conversion[1].

β-Ga_2O_3 is considered to have great potential in power electronic applications due to its wide bandgap of approximately 4.8 eV, high critical electric field of 8 MV/cm and high Baliga's figure of merit of 3444[2–4]. These properties make β-Ga_2O_3 power devices promising for high voltage, high power and other applications[5, 6].

In the past decade, β-Ga_2O_3 devices, especially Schottky barrier diodes (SBDs), have developed rapidly, whose performances have been improved significantly and currently approach those of SiC and GaN[7–12]. At present, the works of large-area devices mainly focus on the combination with edge termination[13–16], while the baseline devices or named termination-free SBDs are rarely investigated for large-current applications. Our recent work demonstrated that the performance of small-area SBDs can be greatly improved by interface engineering[11], thus it is a chance for large-area devices. The high-performance SBDs with free termination may better reflect the application potential of Ga_2O_3 SBD. In a word, the Ga_2O_3 SBD is more mature for applications and needs to be further demonstrated for its application potential.

In this work, we achieved a high-performance large-area vertical β-Ga_2O_3 SBD with a Schottky contact area of 1 × 1 mm^2, and then realized its application in a DC–DC converter with high efficiency. The β-Ga_2O_3 SBD obtained good forward characteristics of 8 A@5 V, a low R_{on} of 0.46 Ω and a high breakdown voltage (V_{br}) of 612 V. A prototype of the DC–DC converter is demonstrated using the β-Ga_2O_3 SBD, then a conversion efficiency of 95.81% is obtained.

Correspondence to: G W Xu, xugw@ustc.edu.cn; S B Long, shibinglong@ustc.edu.cn

Received 30 DECEMBER 2022; Revised 15 FEBRUARY 2023.

2. Device fabrication and characterization

The schematic cross section and optical image of the β-Ga_2O_3 SBD are shown in Fig. 1. The Ga_2O_3 substrate has a doping concentration about 7.0 × 10^{18} cm^{-3} with a thickness of 610 μm, and the 8.5 μm-thick Ga_2O_3 epitaxial layer grown by halide vapor phase epitaxy (HVPE) has a doping concentration of approximately 1.9 × 10^{16} cm^{-3}. After organic and acid cleaning, the upper surface of the epitaxial layer is removed by ICP180 to remove the unreliable surface[11]. Following the piranha solution, the backside of the Ga_2O_3 substrate is coated with Ti/Al/Ni/Au (20/200/50/50 nm) metal stacks by electron beam evaporation (E-beam), and then undergoes rapid thermal annealing at 470 °C in N_2 for 1 min to improve ohmic contact. The Schottky electrode with Ni/Au (50/100 nm) is deposited by the E-beam system. The Schottky contact area of the β-Ga_2O_3 SBD is 1 × 1 mm^2.

Fig. 2(a) shows the forward conduction characteristics of the β-Ga_2O_3 SBD. The forward turn-on voltage (V_F) and the on-resistance (R_{on}) are 1.17 V and 0.46 Ω, respectively. A forward current of 8 A can be obtained at a forward voltage of 5 V in pulse mode (50-μs pulse width and 1% duty cycle). Meanwhile, the V_{br} of the β-Ga_2O_3 SBD is 612 V as shown in Fig. 2(b).

The performance of the β-Ga_2O_3 SBD is benchmarked against some reported state-of-the-art large-area β-Ga_2O_3 SBDs with electrode areas above 0.2 mm^2 in the plot of $R_{on,sp}$ versus V_{br} in Fig. 3[9, 16–19]. The specific on-resistance ($R_{on,sp}$) is 4.6 mΩ·cm^2. Associated with the V_{br} of 612 V, the β-Ga_2O_3 SBD presents a FOM of 81.4 MW/cm^2. Compared with the reported work, the fabricated β-Ga_2O_3 SBD in this work exhibits superior performance.

In order to judge the relative performance of the device with the commercial SBDs based on Si and SiC, and to quantify the remaining gap to be closed in the future, we compared our β-Ga_2O_3 SBD with the commercial Si FRD (STTH1L06, 600 V/1 A) and SiC SBD (CSD01060A, 600 V/1 A) as shown in Table 1. From the results, we can obtain that our β-Ga_2O_3 SBD shows a comparable performance with commercial Si FRD and SiC SBD, while the β-Ga_2O_3 device is just in its

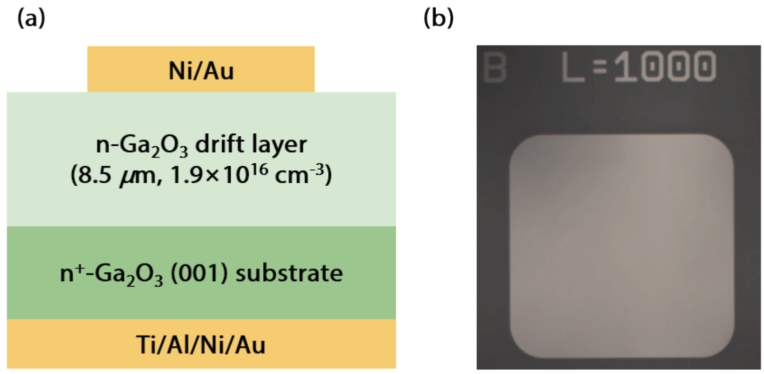

Fig. 1. (Color online) (a) Schematic cross section of the β-Ga_2O_3 SBD. (b) Optical image.

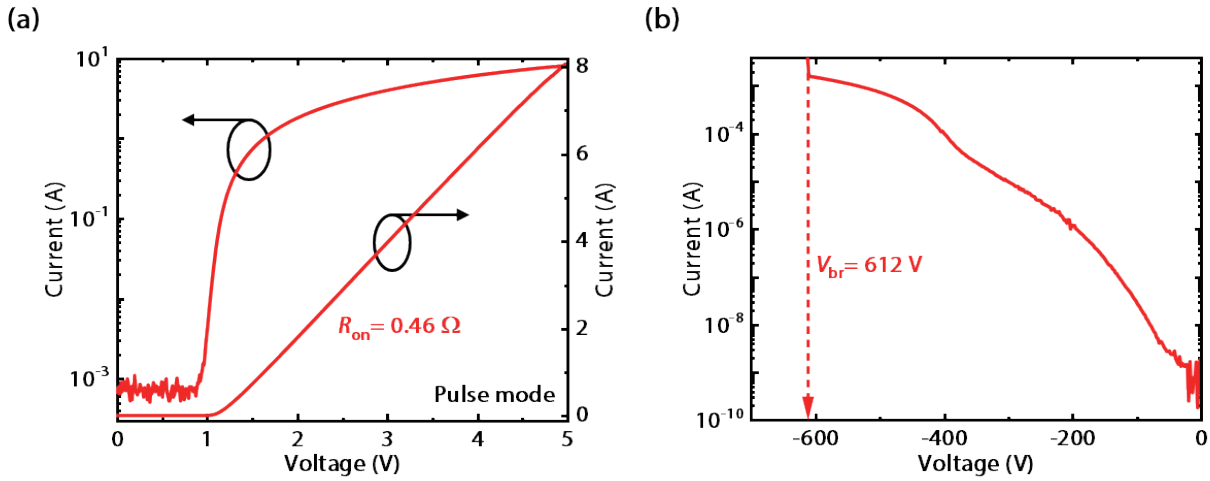

Fig. 2. (Color online) (a) Forward conduction characteristics and (b) reverse breakdown characteristics of the 1×1 mm^2.

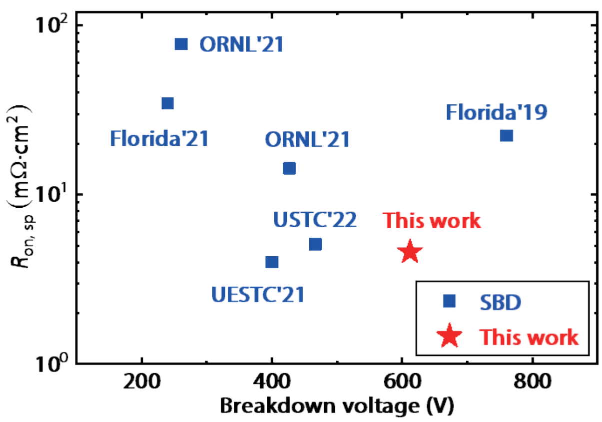

Fig. 3. (Color online) $R_{on, sp}$ versus V_{br} benchmarks of reported state-of-the-art large-area β-Ga_2O_3 SBDs with electrode areas above 0.2 mm^2.

infancy. Reducing the on-resistance and increasing the breakdown voltage are still the key points of our work in future development.

A double-pulse test (DPT) circuit was designed to evaluate the switching performance of β-Ga_2O_3 SBD[16], and the reverse recovery characteristic of β-Ga_2O_3 SBD was measured when the device switched from a forward current of 1 A to a reverse bias voltage of 100 V with a di/dt of 500 A/μs. The reverse recovery characteristics of the Si FRD, SiC SBD and β-Ga_2O_3 SBD are contrasted in Fig. 4, and the properties of the β-Ga_2O_3 with commercial Si and SiC devices are shown in Table 1. We can obtain from the experimental results that the reverse recovery characteristic of the β-Ga_2O_3 SBD has an apparent advantage over Si FRD and approaches to SiC SBD.

Table 1. Properties of the β-Ga_2O_3 with commercial Si and SiC devices.

Parameters	Si FRD	SiC SBD	β-Ga_2O_3 SBD
R_{on} (Ω)	0.17	0.38	0.46
V_{br} (V)	663	776	612
I_{rr} (A)	3.61	1.54	1.9
t_{rr} (ns)	16.9	6.8	7.4
Q_{rr} (nC)	38.34	6.50	8.69

3. Application in the DC–DC converter

In order to demonstrate the application potential, the β-Ga_2O_3 SBD is encapsulated in the TO-220 package, and then implemented in a DC–DC converter circuit. The circuit configuration of the converter is shown in Fig. 5, and the specifications of the converter are summarized in Table 2.

A 650 V/180 mΩ discrete GaN FET with part number TPH3206PSB (Transphorm) is used for switching control. The gate driver of Si8261 (Skyworks) is used to drive the GaN FET, and the gate-source voltage (V_{GS}) is +9 V during the on-state and 0 V during the off-state. The input voltage (V_{IN}) is selected to be 200 V, and the converter is operated at a switching frequency (f) of 100 kHz and a duty cycle (D) of 40%.

Fig. 6 shows the β-Ga_2O_3 SBD-based DC–DC converter and the testing platform. The square signal for the gate driver was generated by an arbitrary function waveform gener-

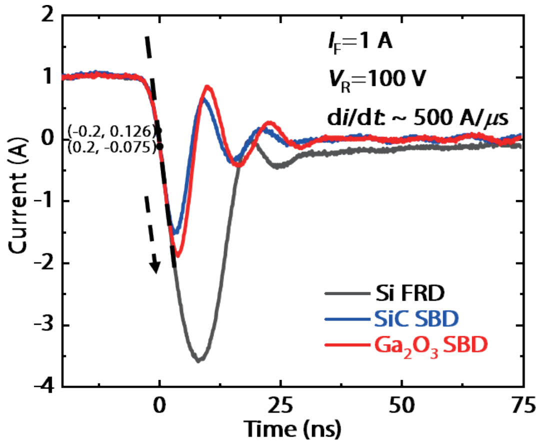

Fig. 4. (Color online) The reverse recovery characteristics of the Si FRD, SiC SBD and β-Ga_2O_3 SBD.

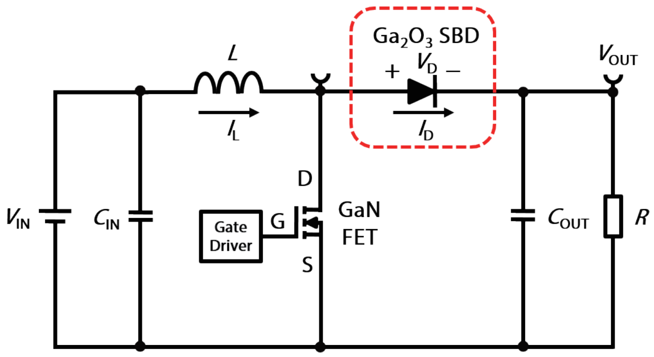

Fig. 5. (Color online) Schematic of the DC-DC converter based on the β-Ga_2O_3 SBD.

Table 2. Specifications of the DC-DC converter.

Parameters	Values	Parameters	Values
GaN FET	650 V/180 mΩ	L (mH)	1
V_{IN} (V)	200	f (kHz)	100
$C_{IN@315\,V}$ (μF)	100	D	40%
$C_{OUT@500\,V}$ (μF)	6.8	R (kΩ)	1

Table 3. Experimental results of the DC-DC converter.

Parameters	Values	Parameters	Values
V_{IN} (V)	200	P_{IN} (W)	115.28
V_{AUX} (V)	9	P_{OUT} (W)	110.45
V_{OUT} (V)	329.7	Efficiency	95.81%

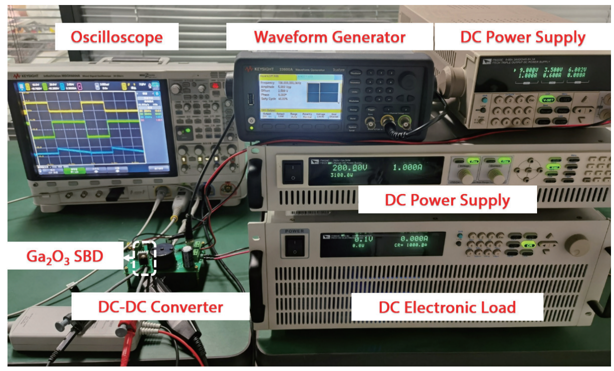

Fig. 6. (Color online) Photograph of the β-Ga_2O_3 SBD-based DC-DC converter and the testing platform.

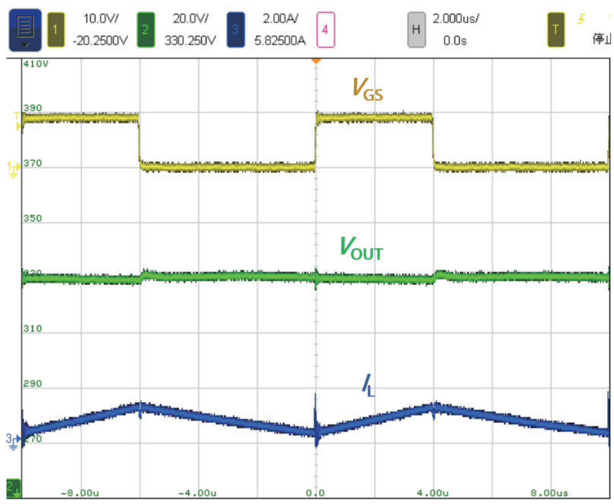

Fig. 7. (Color online) Experimental waveforms of the V_{GS}, V_{OUT} and I_L in the β-Ga_2O_3 SBD-based DC-DC converter.

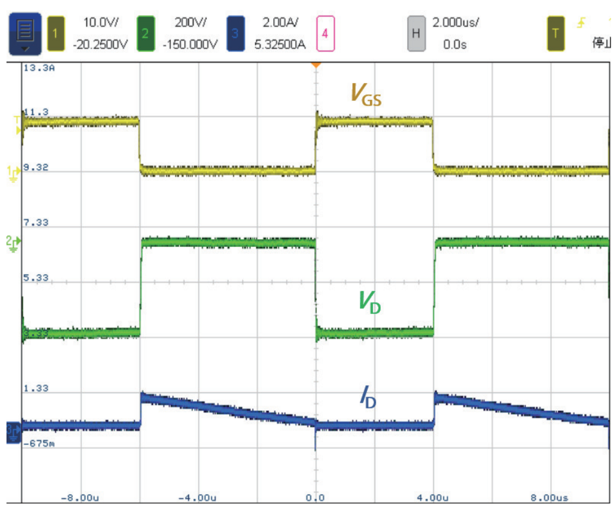

Fig. 8. (Color online) Experimental waveforms of the V_{GS}, V_D and I_D in the β-Ga_2O_3 SBD-based DC-DC converter.

ator (Keysight, 33600A), and the auxiliary voltage for the gate driver (V_{AUX}) was provided by a DC power supply (ITECH, IT6333C). The input voltage (V_{IN}) was generated by an auto range DC power supply (ITECH, IT6526C), and the output signal (V_{OUT}) was tested through a DC electronic load (ITECH, IT8902E). The voltage and current waveforms were monitored by an oscilloscope (Keysight, MSOX6004A).

The experimental waveforms of the gate-source voltage (V_{GS}), the output voltage (V_{OUT}), the inductor current (I_L), the diode voltage (V_D) and the diode current (I_D) in the β-Ga_2O_3 SBD-based DC–DC converter are shown in Figs. 7 and 8. The spike in the waveform of the diode current (I_D) is due to the reverse recovery characteristics of the SBD. The experimental results are shown in Table 3, the output voltage of the converter is approximately 329.7 V, and the output voltage ripple is less than 0.5%. The conversion efficiency of the β-Ga_2O_3 SBD-based DC–DC converter is 95.81%.

4. Conclusion

In conclusion, we have achieved a high-performance large-area vertical β-Ga_2O_3 SBD with a Schottky contact area of 1 × 1 mm^2 and obtained a high-efficiency DC–DC converter based on the device. The β-Ga_2O_3 SBD can obtain a forward current of 8 A at a forward voltage of 5 V, and has a V_{br} of 612 V. The conversion efficiency of the β-Ga_2O_3 SBD-based DC–DC converter is 95.81%. The decent performance of Ga_2O_3 SBDs and their circuits shows great potential in power electronic applications. Future works will introduce the edge termination technique to this baseline device.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) under Grant Nos. 61925110, 61821091, 62004184 and 62234007, the Key-Area Research and Development Program of Guangdong Province under Grant No. 2020B010174002. This work was partially carried out at the Center for Micro and Nanoscale Research and Fabrication of University of Science and Technology of China (USTC).

References

[1] Baliga B J. Fundamentals of power semiconductor devices. Cham: Springer International Publishing, 2019

[2] Sasaki K, Higashiwaki M, Kuramata A, et al. Ga_2O_3 Schottky barrier diodes fabricated by using single-crystal β–Ga_2O_3 (010) substrates. IEEE Electron Device Lett, 2013, 34, 493

[3] Higashiwaki M, Sasaki K, Kuramata A, et al. Gallium oxide (Ga_2O_3) metal-semiconductor field-effect transistors on single-crystal β-Ga_2O_3 (010) substrates. Appl Phys Lett, 2012, 100, 013504

[4] Pearton S J, Yang J C, Cary P H IV, et al. A review of Ga_2O_3 materials, processing, and devices. Appl Phys Rev, 2018, 5, 011301

[5] Pearton S J, Ren F, Tadjer M, et al. Perspective: Ga_2O_3 for ultra-high power rectifiers and MOSFETS. J Appl Phys, 2018, 124, 220901

[6] Ren F, Yang J C, Fares C, et al. Device processing and junction formation needs for ultra-high power Ga_2O_3 electronics. MRS Commun, 2019, 9, 77

[7] Konishi K, Goto K, Murakami H, et al. 1-kV vertical Ga_2O_3 field-plated Schottky barrier diodes. Appl Phys Lett, 2017, 110, 103506

[8] Zhou H, Yan Q L, Zhang J C, et al. High-performance vertical β-Ga_2O_3 Schottky barrier diode with implanted edge termination. IEEE Electron Device Lett, 2019, 40, 1788

[9] Ji M, Taylor N R, Kravchenko I, et al. Demonstration of large-size vertical Ga_2O_3 Schottky barrier diodes. IEEE Trans Power Electron, 2020, 36, 41

[10] Li W S, Nomoto K, Hu Z Y, et al. Field-plated Ga_2O_3 trench Schottky barrier diodes with a $BV^2/R_{on, sp}$ of up to 0.95 GW/cm^2. IEEE Electron Device Lett, 2020, 41, 107

[11] He Q M, Hao W B, Zhou X Z, et al. Over 1 GW/cm^2 vertical Ga_2O_3 Schottky barrier diodes without edge termination. IEEE Electron Device Lett, 2022, 43, 264

[12] Yang J C, Ren F, Chen Y T, et al. Dynamic switching characteristics of 1 A forward current β-Ga_2O_3 rectifiers. IEEE J Electron Devices Soc, 2018, 7, 57

[13] Lv Y J, Wang Y G, Fu X C, et al. Demonstration of β-Ga_2O_3 junction barrier Schottky diodes with a Baliga's figure of merit of 0.85 GW/cm^2 or a 5A/700 V handling capabilities. IEEE Trans Power Electron, 2021, 36, 6179

[14] Otsuka F, Miyamoto H, Takatsuka A, et al. Large-size (1.7 × 1.7 mm^2) β-Ga_2O_3 field-plated trench MOS-type Schottky barrier diodes with 1.2 kV breakdown voltage and 10^9 high on/off current ratio. Appl Phys Exp, 2022, 15, 016501

[15] Hao W B, Wu F H, Li W S, et al. High-performance vertical β- Ga_2O_3 Schottky barrier diodes featuring P-NiO JTE with adjustable conductivity. 2022 International Electron Devices Meeting (IEDM). San Francisco, CA, USA. IEEE, 2023, 9.5.1

[16] Guo W, Jian G Z, Hao W B, et al. β-Ga_2O_3 field plate Schottky barrier diode with superb reverse recovery for high-efficiency DC–DC converter. IEEE J Electron Devices Soc, 2022, 10, 933

[17] Wei Y X, Luo X R, Wang Y G, et al. Experimental study on static and dynamic characteristics of Ga_2O_3 Schottky barrier diodes with compound termination. IEEE Trans Power Electron, 2021, 36, 10976

[18] Yang J C, Fares C, Elhassani R, et al. Reverse breakdown in large area, field-plated, vertical β-Ga_2O_3 rectifiers. ECS J Solid State Sci Technol, 2019, 8, Q3159

[19] Sharma R, Xian M H, Fares C, et al. Effect of probe geometry during measurement of >100 A Ga_2O_3 vertical rectifiers. J Vac Sci Technol A, 2021, 39, 013406

Wei Guo got his BS degree from Xi'an Technological University in 2016. Now he is a PhD student at the University of Science and Technology of China under the supervision of Prof. Shibing Long and Dr. Guangwei Xu. His research focuses on DC–DC converters based on Ga_2O_3 devices.

Zhao Han got his BS degree from Anhui University in 2020. Now he is a PhD student at the University of Science and Technology of China under the supervision of Prof. Shibing Long and Dr. Guangwei Xu. His research focuses on Ga_2O_3 Schottky barrier diodes.

Guangwei Xu received his PhD degree at IMECAS in 2017. Then, he joined the University of California, Los Angeles as a postdoc. He joined the University of Science and Technology of China as an associate research fellow in Shibing Long's Group in 2019. His research focuses on wide bandgap semiconductor power device fabrication, device defect measurement and modeling.

Shibing Long is a full professor at the School of Microelectronics, University of Science and Technology of China. He received his PhD degree at IMECAS in 2005. In 2011, he was a visiting scholar at Universitat Autònoma de Barcelona for a year. Then, he joined the University of Science and Technology of China in 2018. His research focuses on ultra-wide bandgap semiconductor devices, micro and nano fabrication and memories. He has published more than 100 papers in international academic journals and conferences such as IEEE EDL, IEEE ISPSD and IEEE IEDM, SCI has cited more than 4000 times.