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ARTICLES

2.83-kV double-layered NiO/β-Ga_2O_3 vertical p-n heterojunction diode with a power figure-of-merit of 5.98 GW/cm^2

Tingting Han[‡], Yuangang Wang[‡], Yuanjie Lv[†], Shaobo Dun, Hongyu Liu, Aimin Bu, and Zhihong Feng[†]

National Key Laboratory of Application Specific Integrated Circuit (ASIC), Hebei Semiconductor Research Institute, Shijiazhuang 050051, China

Abstract: This work demonstrates high-performance NiO/β-Ga_2O_3 vertical heterojunction diodes (HJDs) with double-layer junction termination extension (DL-JTE) consisting of two p-typed NiO layers with varied lengths. The bottom 60-nm p-NiO layer fully covers the β-Ga_2O_3 wafer, while the geometry of the upper 60-nm p-NiO layer is 10 μm larger than the square anode electrode. Compared with a single-layer JTE, the electric field concentration is inhibited by double-layer JTE structure effectively, resulting in the breakdown voltage being improved from 2020 to 2830 V. Moreover, double p-typed NiO layers allow more holes into the Ga_2O_3 drift layer to reduce drift resistance. The specific on-resistance is reduced from 1.93 to 1.34 mΩ·cm^2. The device with DL-JTE shows a power figure-of-merit (PFOM) of 5.98 GW/cm^2, which is 2.8 times larger than that of the conventional single-layer JTE structure. These results indicate that the double-layer JTE structure provides a viable way of fabricating high-performance Ga_2O_3 HJDs.

Key words: β-Ga_2O_3; breakdown voltage; heterojunction diode (HJD); junction termination extension (JTE); power figure-of-merit (PFOM)

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1. Introduction

Gallium oxide (Ga_2O_3) is considered to be competitive for high-power applications in the next generation because of its outstanding characteristics. For instance, its bandgap is ultra-wide (~4.8 eV), furthermore the theoretical breakdown field is as high as 8 MV/cm[1]. To evaluate the suitability of semiconductor materials for high-power applications, the Baliga's figure-of-merit is commonly used, which is extremely high for Ga_2O_3, almost 4 times and 10 times larger than GaN and SiC[1].

After years of development, there has been remarkable progress in Ga_2O_3-based metal–oxide–semiconductor field effect transistors (MOSFETs), Schottky barrier diodes (SBDs)[2–10] and photodetectors[11, 12]. Nevertheless, the absence of p-type Ga_2O_3 is still a main obstacle for the bipolar devices based on Ga_2O_3. To conquer the difficulty, a natively p-typed oxide of NiO is brought in to realize p-NiO/n-Ga_2O_3 HJDs[13]. Based on this technology, devices with $R_{on,sp}$ and V_{br} of 10.6 mΩ·cm^2/1860 V and 3.5 mΩ·cm^2/1059 V have been reported[14, 15]. However, the V_{br} and PFOM (PFOM = $V_{br}{}^2/R_{on,sp}$) of reported NiO/β-Ga_2O_3 heterojunction p–n diodes were still far from the theoretic limit of the material.

In this work, we demonstrated p-NiO/n-Ga_2O_3 vertical HJDs with a double-layer junction termination extension (DL-JTE) consisting of two p-typed NiO layers with varied lengths. The double-layer JTE structure effectively avoids electric field concentration and also allows more holes into the Ga_2O_3 drift layer to reduce drift resistance. The fabricated device with DL-JTE demonstrates high breakdown voltage of 2830 V and a small $R_{on,sp}$ of 1.34 mΩ·cm^2, generating a high PFOM of 5.98 GW/cm^2. The result indicates that the DL-JTE structure has great potential for fabricating high power devices.

2. Material characterization and device fabrication

Fig. 1 schematically illustrates the cross-sectional structure of the devices with JTE and DL-JTE fabricated on the same wafer. By using halide vapor phase epitaxy (HVPE), a drift layer of 7-μm lightly Si-doped n-type β-Ga_2O_3 was grown on a heavily Sn-doped (001) β-Ga_2O_3 substrate. The electron concentration of the β-Ga_2O_3 substrate and the drift layer is 1×10^{19} and 1.5×10^{16} cm^{-3}, respectively. Electron-beam evaporation was employed for Ohmic metal deposition of 30/300 nm Ti/Au on the back of the wafer. Then a rapid thermal annealing was performed in a N_2 atmosphere at 480 °C for 1 min to improve Ohmic contact. After that, RF magnetron sputtering was used to coat a full area NiO layer with 60-nm thickness on the upper surface of the sample at room temperature. Subsequently, another 60-nm p-NiO layer with 10 μm larger than the square anode electrode was sputtered with a lift-off process to form a double-layer junction termination extension (DL-JTE) structure. The power of the RF magnetron sputtering and the deposition rate of NiO are 80 W and 0.85 nm/min. The ratio of Ar/O_2 is chosen to be 15/10 sccm. The target material is NiO ceramics with 99.99% purity. The hole concentration of the grown p-NiO layer is found to be around 1×10^{18} cm^{-3} after Hall measurements. Finally, the

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Tingting Han and Yuangang Wang contributed equally to this work and should be considered as co-first authors.

Correspondence to: Y J Lv, yuanjielv@163.com; Z H Feng, ga917vv@163.com

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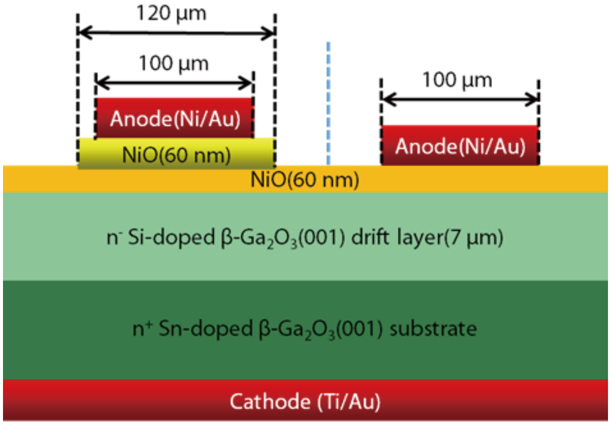

Fig. 1. (Color online) Cross-sectional schematic of the devices with DL-JTE/ JTE.

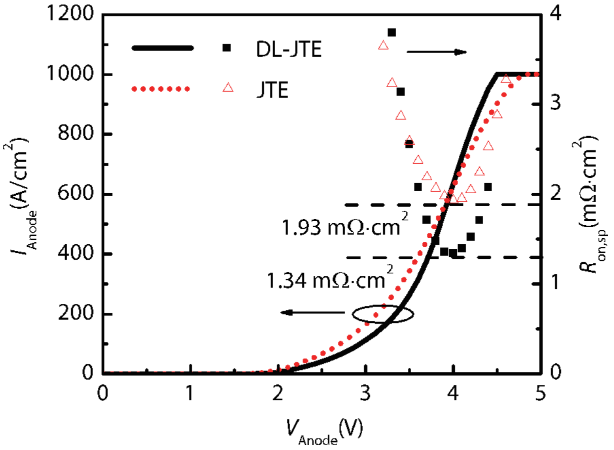

Fig. 3. (Color online) Forward I–V curves and $R_{on,sp}$ of devices with DL-JTE/ JTE.

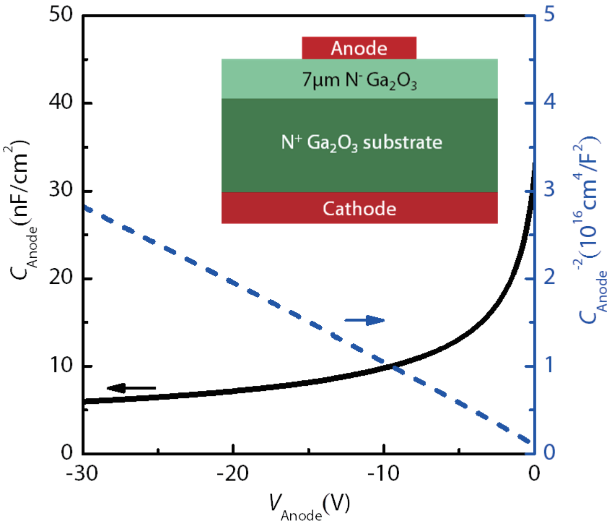

Fig. 2. (Color online) C–V and $1/C^2$–V characteristics of the Ga_2O_3 SBD without termination.

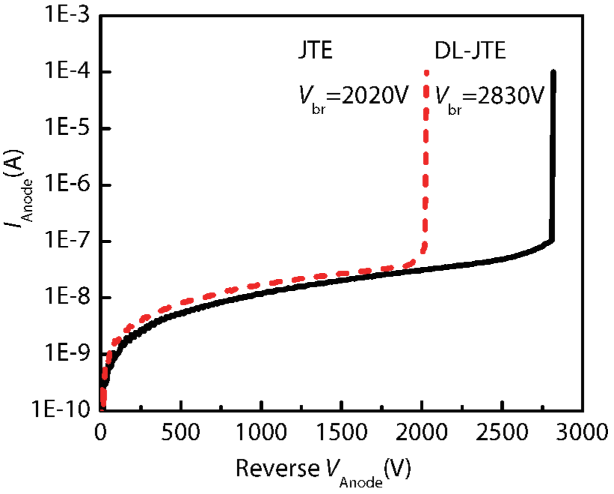

Fig. 4. (Color online) Breakdown characteristics of devices with DL-JTE/ JTE.

Ni/Au (50/300 nm) metal stack was formed on the p-NiO layer by electron-beam evaporation and lift-off process to make an Ohmic contact. The area of anode electrode is 100 × 100 μm^2. Besides, the p-NiO/ n-Ga_2O_3 heterojunction diode with a single-layer JTE structure was also fabricated on the same wafer using the same device processing.

3. Results and discussion

The C–V and $1/C^2$–V characteristics of the β-Ga_2O_3 SBD without termination under 1 MHz are shown in Fig. 2. The concentration of N^- drift layer is confirmed to be around 1.5×10^{16} cm^{-3} according to

$$N_d = \frac{2}{q\varepsilon_s\varepsilon_0 A^2} \times \frac{1}{\dfrac{dC^{-2}}{dV_{Anode}}}, \tag{1}$$

where q, ε_s, ε_0 , A is the electron charge, relative dielectric constant, vacuum dielectric constant and the anode area, respectively.

The forward current–voltage (I–V) characteristics in the linear-scale and $R_{on,sp}$ of the fabricated NiO/β-Ga_2O_3 vertical HJDs with JTE and DL-JTE are shown in Fig. 3. The device with DL-JTE exhibited a lower $R_{on,sp}$ (1.34 mΩ·cm²) than that with JTE (1.93 mΩ·cm²). The electron concentration and thickness of the NiO layer are only 1×10^{18} cm^{-3} and 60 nm, respectively, which cannot inject enough holes into the Ga_2O_3 drift layer. The second NiO layer under the anode is introduced in the DL-JTE, which will inject more holes into the Ga_2O_3 drift layer to reduce drift resistance. Therefore, a lower $R_{on,sp}$ is realized by introducing DL-JTE. The turn-on voltage for both devices was about 2 V, which is higher than most Ga_2O_3-based SBDs, suggesting a higher barrier height.

The reverse breakdown characteristics of the fabricated vertical HJDs with JTE and DL-JTE are shown in Fig. 4. Compared with the heterojunction diode with JTE exhibiting a V_{br} of 2020 V, the one with DL-JTE yielded a much higher V_{br} of 2830 V. With V_{anode} rising reversely, an almost constant leakage current was observed till the breakdown points were reached for both devices.

To further evaluate the effect of the JTE and DL-JTE structure on the device electric field engineering, the electric field distributions of both devices were simulated using commercial TCAD software. As shown in Fig. 5, when V_{Anode} reaches –2020 V, for the heterojunction diode with JTE, a peak electric field of 8 MV/cm is observed at the anode edge resulting from electric field concentration effect, while for that with the DL-JTE structure, the electric field spreads and the crowding is effectively relieved, resulting in a decreased peak field of 4.7 MV/cm at the anode edge, which increases to 8.1 MV/cm

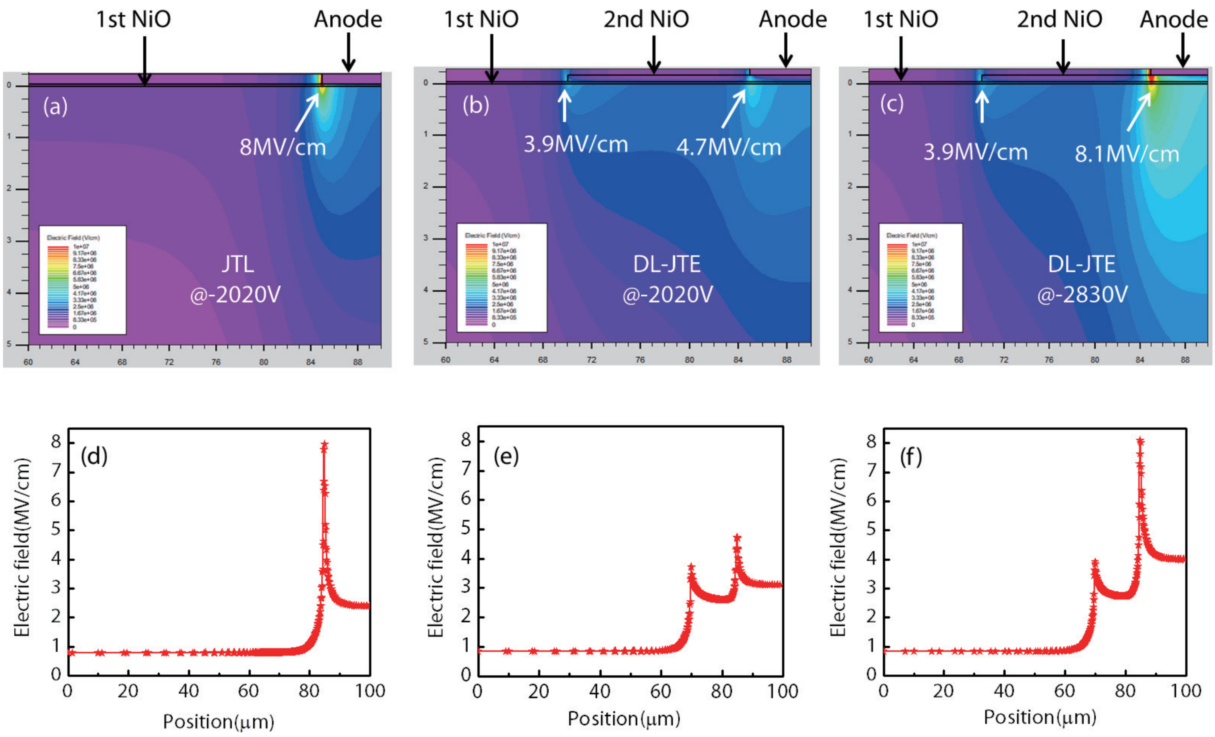

Fig. 5. (Color online) Simulated distributions of the electric field for the fabricated HJD with (a) JTE, (b) DL-JTE at bias of –2020 V, (c) DL-JTE at bias of –2830 V, and (d–f) the corresponding distribution of electric field versus position.

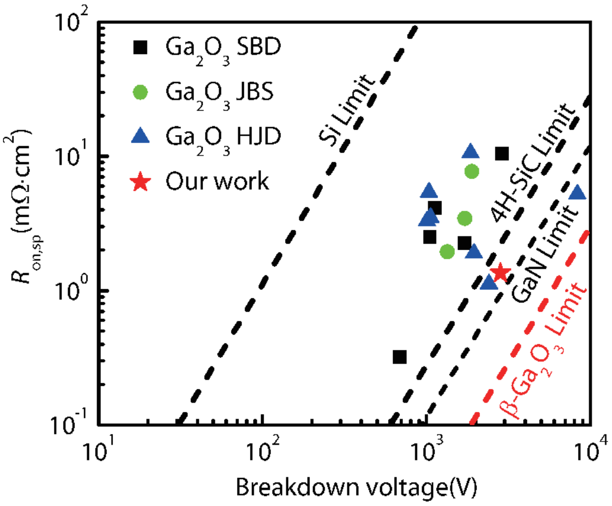

Fig. 6. (Color online) V_{br} versus $R_{on,sp}$ of β-Ga_2O_3-based diodes reported against our NiO/β-Ga_2O_3 HJD with DL-JTE.

when reverse bias grows to 2830 V, while the other peak field around the second NiO layer remains at 3.9 MV/cm.

Fig. 6 shows the V_{br} vs $R_{on,sp}$ plot of the most advanced HJDs[14–21], hetero-junction barrier Schottky (HJBS)[22–24] diodes, and SBDs[2–6] based on β-Ga_2O_3. Our HJD with DL-JTE is marked using a red star. As shown, the fabricated device with DL-JTE structures achieves a high V_{br} of 2830 V. Together with the low $R_{on,sp}$ value of 1.34 mΩ·cm^2, a PFOM of 5.98 GW/cm^2 is gotten, which is 2.8 times larger than that of a conventional single-layer JTE structure.

4. Conclusion

By introducing a double-layer junction termination extension structure, NiO/β-Ga_2O_3 vertical HJDs with significant improvement were realized. Compared with the one with JTE fabricated on the same sample, the device with DL-JTE has a lower $R_{on,sp}$ of 1.34 mΩ·cm^2 and a higher breakdown voltage of 2830 V, corresponding to a high power figure-of-merit of 5.98 GW/cm^2, suggesting that NiO/β-Ga_2O_3 HJDs with DL-JTE have great potential in high power applications.

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References

[1] Zhang H Z, Wang L J, Xia C T, et al. Research progress of wide-gap semiconductor β-Ga_2O_3 single crystal. J Synth Cryst, 2015, 44, 2943

[2] Hu Z Z, Lv Y J, Zhao C Y, et al. Beveled fluoride plasma treatment for vertica β-Ga_2O_3 Schottky barrier diode with high reverse blocking voltage and low turn-on voltage. IEEE Electron Device Lett, 2020, 41(3), 441

[3] Xiong W H, Zhou X Z, Xu G W, et al. Double-barrier β-Ga_2O_3 Schottky barrier diode with low turn-on voltage and leakage current. IEEE Electron Device Lett, 2021, 42(3), 430

[4] Saurav R, Arkka B, Praneeth R, et al. High-k oxide field-plated vertical (001) β-Ga_2O_3 Schottky barrier diode with Baliga's figure of merit over 1 GW/cm^2. IEEE Electron Device Lett, 2021, 42(8), 1140

[5] 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(2), 264

[6] Li W S, Kazuki N, 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(1), 107

[7] Tetzner K, Treidel E B, Hilt O, et al. Lateral 1.8 KV β-Ga_2O_3 MOSFET with 155 MW/cm^2 power figure of merit. IEEE Electron Device Lett, 2019, 40(9), 1503

[8] Lv Y J, Liu H Y, Zhou X Y, et al. Lateral β-Ga_2O_3 MOSFETs with high power figure of merit of 277 MW/cm^2. IEEE Electron Device Lett,

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2020, 41(4), 537

[9] Hu Z Y, Nomoto K, Li W S, et al. Enhancement-mode Ga_2O_3 vertical transistors with breakdown voltage >1 kV. IEEE Electron Device Lett, 2018, 39(6), 869

[10] Sharma S, Zeng K, Saha S, et al. Field-plated lateral Ga_2O_3 MOSFETs with polymer passivation and 8.03 kV breakdown voltage. IEEE Electron Device Lett, 2020, 41(6), 836

[11] Zheng Z Y, Qiao B S, Zhang Z Z, et al. High detectivity of metal–semiconductor–metal Ga_2O_3 solar-blind photodetector through thickness-regulated gain. IEEE Trans Electron Devices, 2022, 69(8), 4362

[12] Qiao B S, Zhang Z Z, Xie X H, et al. Quenching of persistent photocurrent in an oxide UV photodetector. J Mater Chem C, 2021, 9, 4039

[13] Yoshihiro K, Shohei K, Shinji N. All-oxide p–n heterojunction diodes comprising p-type NiO and n-type β-Ga_2O_3. Appl Phys Express, 2016, 9(9), 091101

[14] Gong H H, Chen X H, Xu Y, et al. A 1.86-kV double-layered NiO/β-Ga_2O_3 vertical p–n heterojunction diode. Appl Phys Lett, 2020, 117, 022104

[15] Lu X, Zhou X D, Jiang H X, et al. 1-kV sputtered p-NiO/n-Ga_2O_3 heterojunction diodes with an ultra-low leakage current below 1 μA/cm^2. IEEE Electron Device Lett, 2020, 41(3), 449

[16] Gong H H, Zhou F, Xu W Z, et al. 1.37 kV/12 A NiO/β-Ga_2O_3 heterojunction diode with nanosecond reverse recovery and rugged surge-current capability. IEEE Trans Power Eletron, 2021, 36(11), 12213

[17] Gong H H, Wang Z P, Yu X X, et al. Field-plated NiO/Ga_2O_3 p-n heterojunction power diodes with high-temperature thermal stability and near unity ideality factors. Electron Device Soc, 2021, 9, 1166

[18] Zhou F, Gong H H, Xu W Z, et al. 1.95-kV Beveled-mesa NiO/β-Ga_2O_3 heterojunction diode with 98.5% conversion efficiency and over million-times overvoltage ruggedness. IEEE Trans Power Eletronics, 2022, 37(2), 1223

[19] Hu Z Z, Li J G, Zhao C Y, et al. Design and fabrication of vertical metal/TiO_2/β-Ga_2O_3 dielectric heterojunction diode with reverse blocking voltage of 1010 V. IEEE Trans Electron Devices, 2020, 67(12), 5628

[20] Wang Y G, Gong H H, Lv Y J, et al. 2.41 kV vertical p-NiO/n-Ga_2O_3 heterojunction diodes with a record Baliga's figure-of-merit of 5.18 GW/cm^2. IEEE Trans Power Eletronics, 2022, 37(4), 3743

[21] Zhang J C, Dong P F, Dang K, et al. Ultra-wide bandgap semiconductor Ga_2O_3 power diodes. Nat Commun, 2022, 13, 3900

[22] Yan Q L, Gong H H, Zhang J C, et al. β-Ga_2O_3 hetero-junction barrier Schottky diode with reverse leakage current modulation and $BV^2/R_{on,sp}$ value of 0.93 GW/cm^2. Appl Phys Lett, 2021, 118, 122102

[23] Gong H H, Yu X X, Xu Y, et al. β-Ga_2O_3 vertical heterojunction barrier Schottky diodes terminated with p-NiO field limiting rings. Appl Phys Lett, 2021, 118, 202102

[24] 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 Eletronics, 2021, 36(6), 6179

Tingting Han was born in Hengshui, Hebei Province in 1986, senior engineer with a master's degree in microelectronics and solid state electronics. She graduated from Shandong University in 2011, mainly works in the research of gallium oxide devices.

Yuanjie Lv was born in Tai'an City, Shandong Province in 1985, professor. He got doctor's degree in microelectronics and solid-state electronics from Shandong University in 2012. He mainly works in the research of wide-gap semiconductor electronic devices.