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High-Voltage β-Ga_2O_3 Schottky Diode with Argon-Implanted Edge Termination

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Abstract

The edge-terminated Au/Ni/β-Ga_2O_3 Schottky barrier diodes were fabricated by using argon implantation to form the high-resistivity layers at the periphery of the anode contacts. With the implantation energy of 50 keV and dose of 5×10^{14} cm^{-2} and 1×10^{16} cm^{-2}, the reverse breakdown voltage increases from 209 to 252 and 451 V (the maximum up to 550 V) and the Baliga figure-of-merit (V_{BR}^2/R_{on}) also increases from 25.7 to 30.2 and 61.6 MW cm^{-2}, about 17.5% and 140% enhancement, respectively. According to the 2D simulation, the electric fields at the junction corner are smoothed out after argon implantation and the position of the maximum breakdown electric filed, 5.05 MV/cm, changes from the anode corner at the interface to the overlap corner just under the implantation region. The temperature dependence of the forward characteristics was also investigated.

Keywords: β-Ga_2O_3 Schottky diode, Argon implantation, Edge termination

Background

Development of high-power devices using ultra-wide-bandgap semiconductor materials such as Ga_2O_3, AlN, diamond, etc. is accelerating in recent years. The bandgap of β-Ga_2O_3 is as large as 4.8–4.9 eV and the breakdown field of β-Ga_2O_3 is estimated to be 8 MV/cm, about three times larger than that of 4H-SiC and GaN. The Baliga's figure of merit, 3400, is at least ten times larger than that of 4H-SiC and four times larger than that of GaN [1]. Furthermore, the large single crystal and low-cost β-Ga_2O_3 substrate can be fabricated with melt-growth methods such as floating-zone (FZ) [2] and edge-defined film-fed growth (EFG) [3, 4]. The electron density can be controlled over a wide range from 10^{16} to 10^{19} cm^{-3} by doping with Sn, Si, or Ge [5–7]. These excellent properties make β-Ga_2O_3 ideal for low loss, high-voltage switching and high-power applications, including high-breakdown voltage Schottky barrier diode (SBD) and metal-oxide-semiconductor field-effect transistor (MOSFET) [8–12]. Schottky barrier diodes possess the advantages of fast switching speed and low forward voltage drop in comparison with p-n junction diode, which can decrease the power loss and improve the efficiency of power supplies.

Although large breakdown voltages of 1016 V, 2300 V, and 1600 V have been obtained in β-Ga_2O_3 Schottky barrier diodes without edge termination, they are all about 34%, 8%, and 10% of the ideal value [10, 13, 14]. To relieve the electric field crowding effect and fully realize the voltage potential of β-Ga_2O_3, suitable edge terminations must be designed. There are a number of edge termination techniques to increase the device breakdown voltage such as field plates, floating metal rings, trench MOS structure, implanted guard rings, and junction termination extension (JTE) [12, 15–17]. However, implanted guard rings and JTE structure are not applicable to Ga_2O_3 Schottky diode due to the lack of p-type doping. H. Matsunami and B. J. Baliga put forward an edge termination structure, using argon implantation to form a high-resistivity amorphous layer at the edges of anode, to reduce the electric field crowding [18–22], which is a simple technique with no multi-photolithography or deep trench etching steps required, and it is widely used in SiC and GaN rectifiers to smooth out the electric field distribution around the rectifying contact periphery [15, 23, 24].

In this paper, the vertical edge-terminated β-Ga_2O_3 Schottky diodes were fabricated with argon implantation at the edges of Schottky contacts. The capacitance–

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voltage (C–V) and temperature-dependent current density-voltage (J-V) characteristics were recorded using Keithley 4200 semiconductor characterization system and the electric field distribution was also analyzed.

Methods/Experimental

The drift layer with the thickness of 10 μm was obtained from high-quality Sn-doped (100)-oriented β-Ga_2O_3 bulk substrate by mechanical exfoliation. The β-Ga_2O_3 bulk was grown by EFG technique with 4 N pure Ga_2O_3 powder as the starting material. Excellent crystal quality and smooth surface were confirmed by high resolution x-ray diffraction (HRXRD) and atomic force microscope (AFM) measurements, as presented in Fig. 1a, b. The full width at half-maximum(FWHM) and root mean square (RMS) were estimated to be 37.4 arcsec and 0.203 nm, respectively. Figure 1c shows the distribution of β-Ga_2O_3 substrate sheet resistance with the thickness of 10 μm by a four-point probe measurement. Using carrier concentration of $(1.3 \pm 0.04) \times 10^{17}$ cm^{-3} and sheet resistance of $(563 \pm 18.5)\Omega/\square$, the electron mobility is calculated to be 85.3~95.2 cm^2/Vs by $\mu_n = 1/(R_{Sheet} \times n \times q \times t)$, where $\mu_{n,}$ $R_{Sheet,}$ n, q, and t are the electron mobility, the sheet resistance, the electron concentration, electron charge, and the thickness of β-Ga_2O_3 substrate, similar to the reported results [25]. Argon ion implantation with an energy of 50 keV, the dose of 2.5×10^{14} cm^{-2}, and high temperature annealing at 950 °C for 60 min in N_2 atmosphere were first

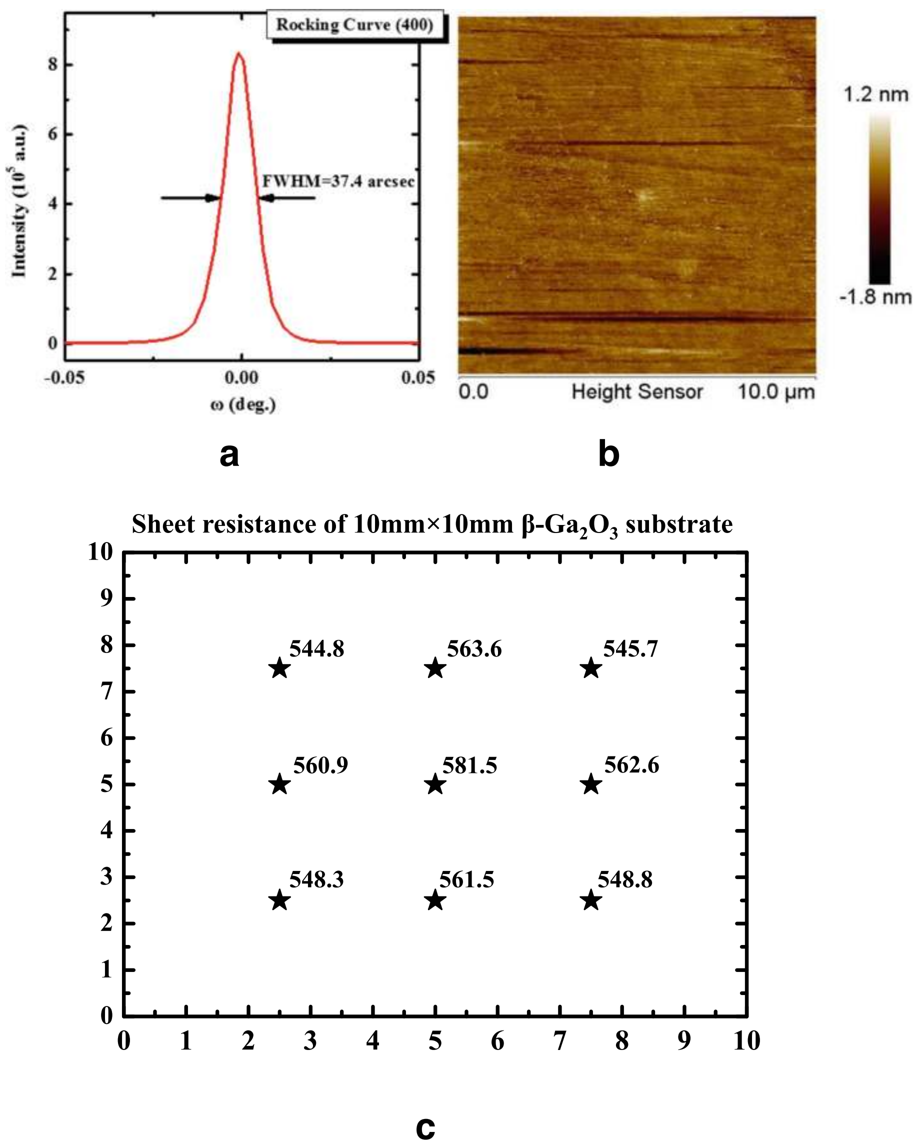

Fig. 1 **a** XRD rocking curve and **b** AFM image of the β-Ga_2O_3 drift layer mechanically exfoliated from (100) β-Ga_2O_3 substrate **c** measured sheet resistance of 10 mm × 10 mm β-Ga_2O_3 substrate

performed on the back side, followed by E-beam evaporation of a Ti/Au (20 nm/100 nm) ohmic metal stack and rapid thermal annealing at 600 °C for 60 s in N_2 ambient. Then the 2-μm-thick photoresist was used as the mask for argon implantation at room temperature with an energy of 50 keV and the dose of 5×10^{14} cm^{-2} (sample B) and 1×10^{16} cm^{-2} (sample C), respectively. In order to repair the implantation damage and reduce the leakage current under reverse bias, the implanted samples were subjected to a rapid thermal annealing at 400 °C for 60 s under N_2 ambient [13, 26]. Finally, the circular Schottky anode electrodes with diameter of 100 μm were fabricated on the front side by standard photolithographic patterning, evaporation of Ni/Au (30 nm/200 nm) stack, and lift-off. The reference device without argon implantation was also fabricated (sample A). Figure 2a depicts cross-section TEM of fabricated-Ga_2O_3 Schottky diode with argon-implanted edge termination. An almost surface amorphous β-Ga_2O_3 layer was created in the implantation region. The actual photograph of the terminated β-Ga_2O_3 Schottky diode is shown in Fig. 2b. Figure 2c represents the measurement setup of forward current–voltage (*I-V*) characteristics of the β-Ga_2O_3 SBD, while the measurement voltage ranges between 0 and 3 V and the step is 10 mV. Figure 2d depicts the measurement setup of reverse current–voltage (*I-V*) characteristics of β-Ga_2O_3 Schottky rectifiers to obtain the breakdown voltage, while the measurement voltage ranges between 0 and − 500 V and the step is − 1 V.

Results and discussion

Figure 3 shows the experimental $1/C^2$ versus V characteristics of three SBD samples at room temperature. The effective carrier concentration N_d-N_a of β-Ga_2O_3 drift layer and built-in potential (eV_{bi}) are extracted to be $(1.3 \pm 0.04) \times 10^{17}$ cm^{-3} and (1.30 ± 0.08) eV, respectively. According to the following equations, the Schottky barrier height ϕ_{b_CV} is calculated to be (1.32 ± 0.08) eV.

$$\frac{1}{C^2} = \frac{2}{q\varepsilon A^2(N_d - N_a)}(V_{bi} - V) \tag{1}$$

$$e\phi_b = eV_{bi} + (E_c - E_f) - e\Delta\phi \tag{2}$$

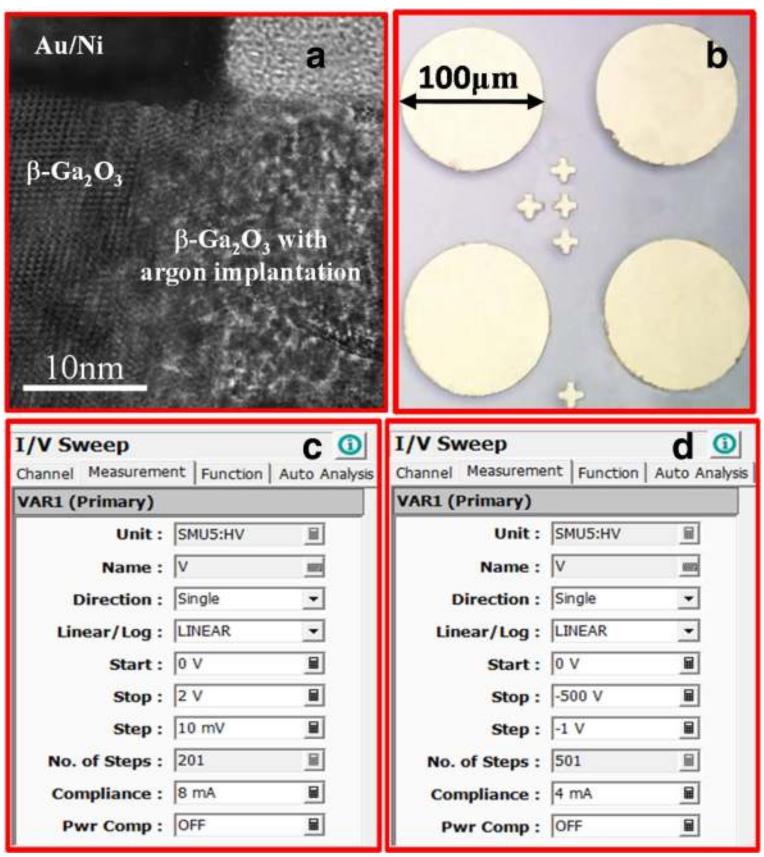

Fig. 2 **a** TEM image of sample C and **b** photograph of the terminated β-Ga_2O_3 Schottky diode **c** the measurement setup of forward current and **d** reverse current-voltage (I-V) characteristics of the β-Ga_2O_3 SBD to obtain the breakdown voltage

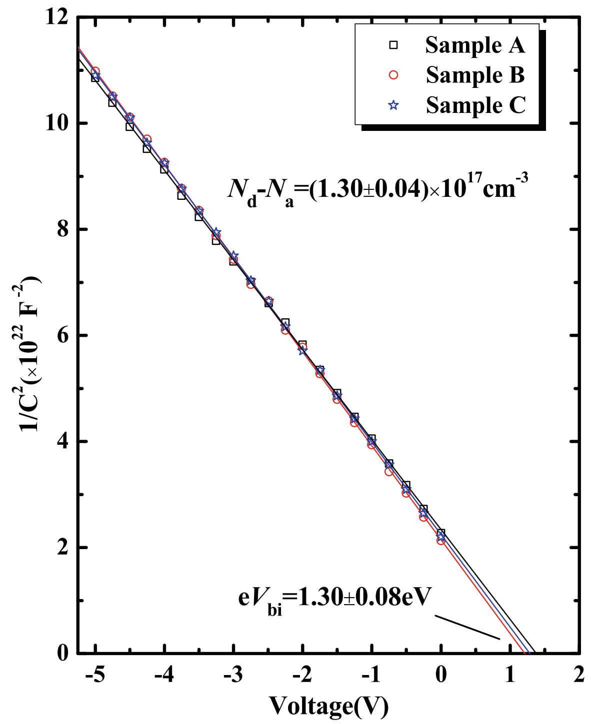

Fig. 3 $1/C^2$-V plots of three β-Ga_2O_3 SBD samples

$$E_c - E_f = kT \ \ln\left(\frac{N_c}{N_d - N_a}\right) \tag{3}$$

$$e\Delta\phi = \left\{\frac{e}{4\pi\varepsilon}\left[\frac{2eV_{bi}(N_d - N_a)}{\varepsilon}\right]^{1/2}\right\}^{1/2} \tag{4}$$

where A, q, and ε are Schottky contact area, electron charge, and permittivity of β-Ga_2O_3. E_c, E_f, $e\Delta\phi$, k, T, and N_c are the conduction band minimum, Fermi level, potential barrier lowering caused by the image force, Boltzmann constant, absolute temperature in K, and effective density of states of the conduction band, respectively.

Figure 4a represents the forward current density-voltage(J-V) characteristics of the β-Ga_2O_3 SBD. Under the forward bias, the argon implantation has no significant effect on the electrical characteristics. The threshold voltage are determined to be 0.91 V, 0.92 V, and 0.95 V for three samples, the I_{on}/I_{off} ratios are all larger than 10^9 at room temperature and by fitting the linear region, the specific on-resistances (R_{on}) are 1.7,2.1 and 3.3 mΩ cm^2, and forward current densities at 2 V are 857, 699, and 621 A/cm^2 for three samples, respectively, as shown in Fig. 4a inset. The current densities are higher and the specific on-resistances are lower than or comparable to the reported values for the higher conductivity and carrier density in the drift layer [12, 13, 26–30].

In order to investigate the effects of argon implantation on the temperature dependence of the forward characteristics, the forward J-V measurements of sample C are conducted from 300 to 423 K, as shown in Fig. 4b. The ideal factor n and Schottky barrier height ϕ_{b_JV} are determined to be 1.06 and 1.22 eV at room temperature, lower than the ϕ_{b_CV} of (1.32 ± 0.08) eV, according to the thermionic emission (TE) model [31, 32]. With the temperature increasing, the n decreases from 1.06 to 1.02 and the barrier height reduces slightly but is almost constant at 1.21 ± 0.01 eV over the temperature range, which is contrary to the barrier height decrease of an ideal Schottky diode with temperature increase but has been observed in fabricated β-Ga_2O_3 SBD [26]. Using the equation $\ln(Js/T^2) = \ln(A^*)\text{-}q\phi_b/kT$, the barrier height ϕ_b and the effective Richardson constant A* are

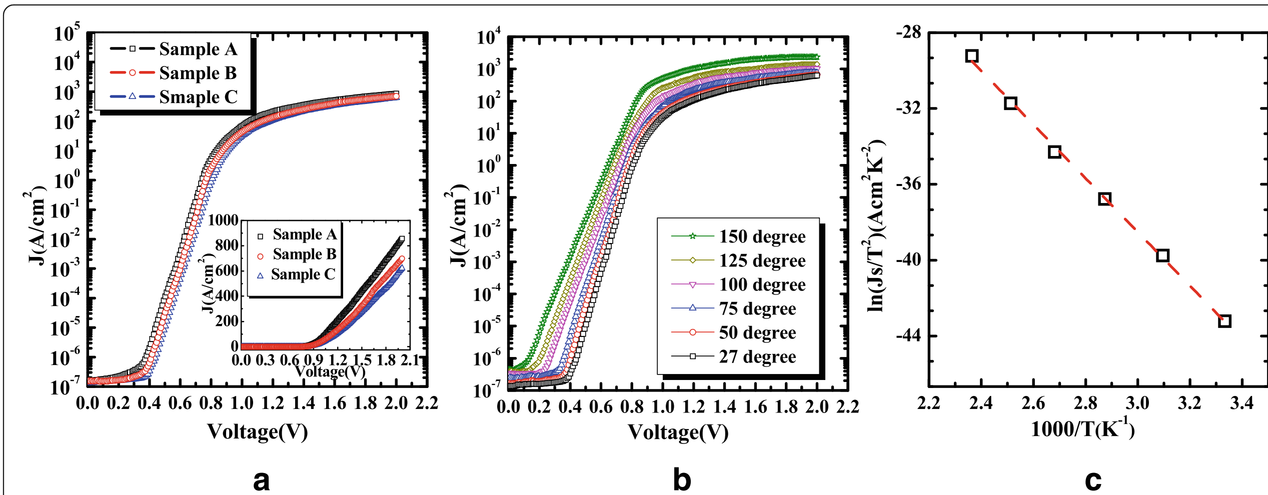

Fig. 4 **a** The forward J-V characteristics of the terminated and unterminated β-Ga_2O_3 at room temperature and **b** the temperature-dependent forward J-V characteristics of sample C from 300 to 423 K. **c** Richardson's plot of ln(Js/T^2) vs 1000/T of sample C

determined to be 1.22 eV and 48.5 A/cm^2 K^2 for sample C from the slope and the *y*-axis intercept of the linear region of the plot, as shown in Fig. 4c. Furthermore, the extracted A* values for tens of devices on the three samples are between 24 and 58 A/cm^2 K^2, consistent with the previous experiment results and theoretical value, 24–58 A/cm^2 K^2, with the effective electron mass $m^* = 0.23–0.34\ m_0$ of β-Ga_2O_3 [33–37].

Figure 5a depicts the reverse *J-V* characteristics of the samples. After argon implantation, the breakdown voltage increases from 209 to 252 and 451 V and the Baliga figure-of-merit (V_{BR}^2/R_{on}) for three samples are approximately 25.7, 30.2, and 61.6 MW cm^{-2}, respectively. During implantation, some defects may be introduced and lead to the significant and undesirable increase in leakage current, which was also reported in SiC and GaN Schottky diode devices [18–20]. Although the thermal annealing was conducted after argon implantation, there are still slightly larger leakage currents for samples B and C. Therefore, the investigation detail of the post annealing temperature and duration on the forward and reverse electrical characteristics should be addressed in the following paper.

Figure 5b, c presents the distribution of breakdown voltages of β-Ga_2O_3 Schottky rectifiers with and without argon implantation. The ideal plane parallel breakdown voltages of these devices are determined as 553 ~598 V, using the critical electrical field of 5.1~5.3 MV/cm [11, 39]. The breakdown voltage without argon implantation is about 110 ~310 V, which is around the 50% of the ideal values. However, with argon-implantation dose of 5×10^{14} cm^{-2}, the breakdown voltage increases to 150~350 V, not much larger than the reference device, while with the dose of 1×10^{16} cm^{-2}, the breakdown

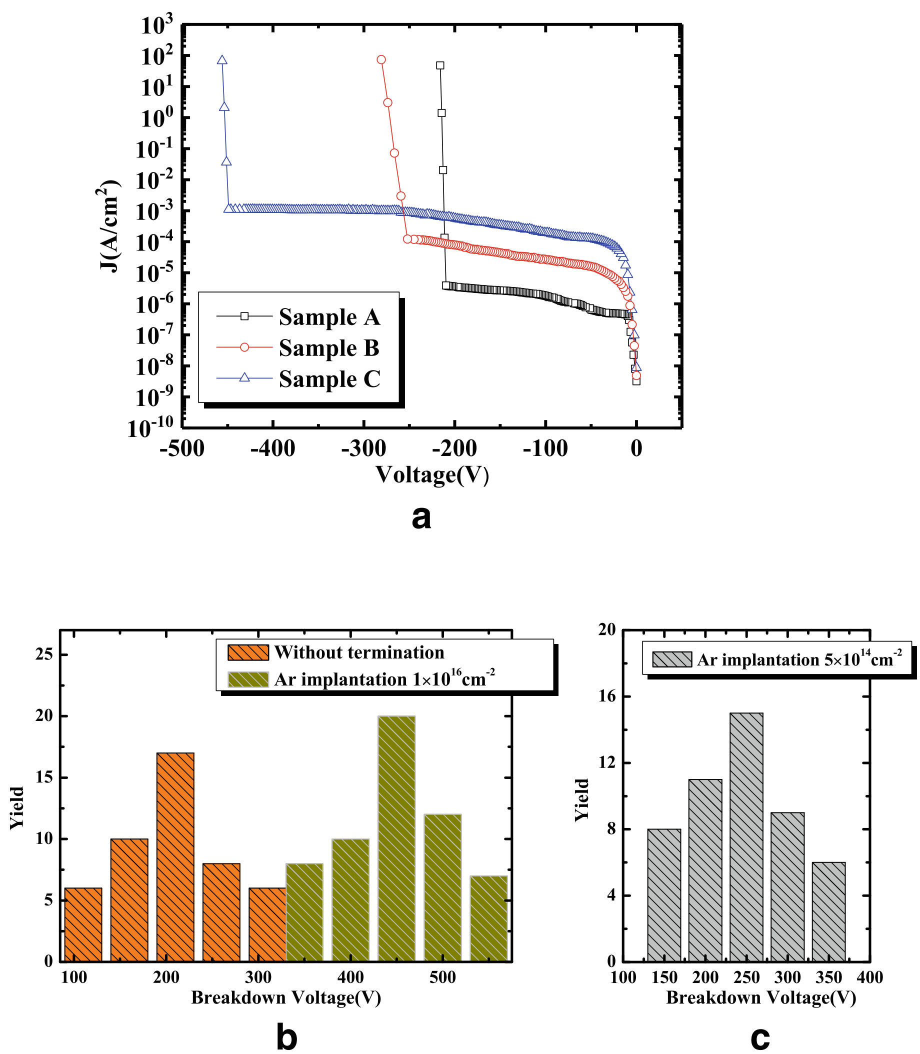

Fig. 5 **a** The reverse *J-V* characteristics of the β-Ga_2O_3 samples at room temperature. **b** and **c** Distribution of breakdown voltages of β-Ga_2O_3 SBDs with and without argon implantation

voltage is approaching the ideal values. In this work, the maximum breakdown voltage of 550 V can be obtained. In addition, the electric field distribution at the breakdown voltage was simulated. For simplification, a single midgap acceptor level was added with the implantation depth of 50 nm determined by the TRIM simulation and the incomplete ionization model was also considered [38], as shown in Fig. 6. Obviously, the high-resistivity layer effectively smooths out electric field at the junction corners and enhances the breakdown voltage greatly in

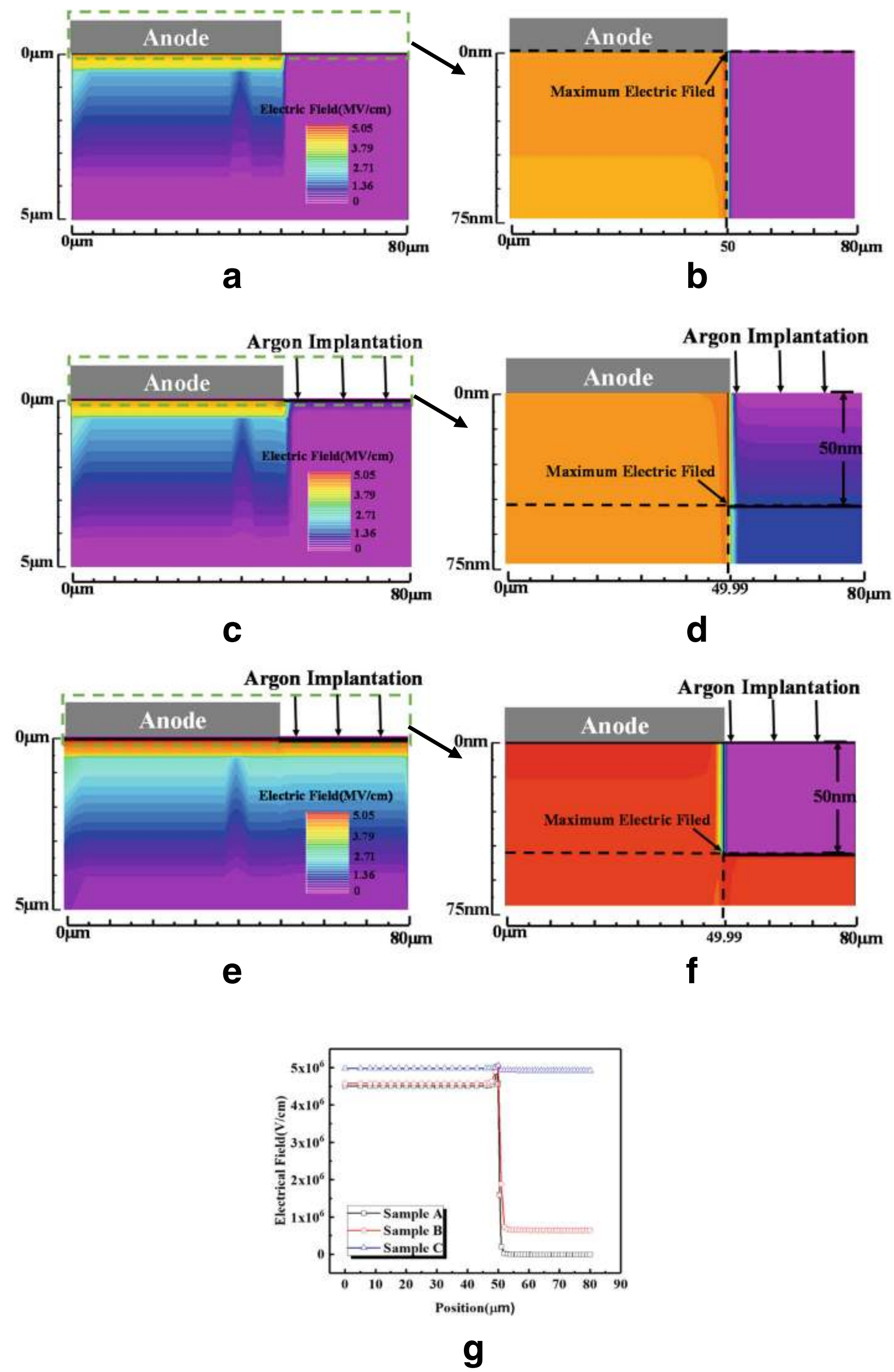

Fig. 6 Simulation of the electric field distribution at breakdown voltage of samples A–C (**a**, **c**, **e**), the magnified image of selected regions in dashed box (**b**, **d**, **f**, **g**), the simulated electric field vs the position along the dashed line in (**b**, **d**, **f**) for three samples, Au/Ni/β-Ga_2O_3 interface for sample A, 50 nm below the interface for samples B and C, respectively. The maximum field is 5.05 MV/cm

comparison with the reference sample. The maximum electric fields at breakdown voltage are all about 5.05 MV/cm, similar to the reported results [11, 39], while the position changes from the anode corner at the interface to the overlap corner just under the implantation region, as indicated in Fig. 6d, e.

Conclusions

Vertical Au/Ni/β-Ga_2O_3 Schottky barrier diodes with edge termination formed by argon implantation were fabricated on β-Ga_2O_3 drift layer mechanically exfoliated from high-quality (100)-oriented β-Ga_2O_3 bulk substrate. Compared with the control device, the specific on-resistances (R_{on}) increases from 1.7 to 2.1 and 3.3 mΩ cm^2 and the breakdown voltage increases from 209 to 252 and 451 V for implantation dose of 5×10^{14} cm^{-2} and 1×10^{16} cm^{-2}, respectively, with a larger reverse leakage current. The maximum electric field at breakdown voltage is about 5.05 MV/cm, much larger than that of SiC and GaN.

Abbreviations

AFM: Atomic force microscope; EFG: Edge-defined film-fed growth; FWHM: The full width at half-maximum; FZ: Floating-zone; HRXRD: High resolution x-ray diffraction; JTE: Junction termination extension; MOSFET: Metal-oxide-semiconductor field-effect transistor; RMS: Root mean square; SBD: Schottky barrier diode; TE: Thermionic emission

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Availability of Data and Materials

The datasets supporting the conclusions of this article are included with in the article.

Authors' Contributions

QF and JZ proposed the research work. YG carried out the simulation, analyze the experiment results, and wrote the paper. AL fabricated and investigated the characteristics of the device. ZH and ZF prepared the XRD and SEM. WM and ZJ provided the (100)-oriented β-Ga_2O_3 bulk substrate. All authors helped to correct and polish the manuscript and read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Publisher's Note

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