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Post-Annealing Temperature Effects on Electrical Characteristics of Sputtered Mo/β-Ga_2O_3 Vertical Schottky Barrier Diodes

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Abstract

In this study, Mo/β-Ga_2O_3 vertical Schottky barrier diodes (SBDs) were fabricated using a sputtering process, and the electrical characteristics were evaluated as a function of post-annealing temperature. β-Ga_2O_3 is an ultra-wide bandgap semiconductor (UWBG) with a bandgap of about 4.8 eV and a critical breakdown field of 8 MV/cm, a promising material for high-voltage power switching applications. Mo (molybdenum) has a higher work function (~4.95 eV) than the electron affinity (~4.0 eV) of β-Ga_2O_3, its melting point (2623 °C) is higher than Pt (1768 °C) and Ni (1455 °C), so it has excellent thermal stability, and it is selected as a Schottky metal. The device is a structure in which a Si-doped β-Ga_2O_3 epitaxial layer (10 μm, N_d-N_a = 2.2 × 10^{16} cm^{-3}) is grown on an Sn-doped β-Ga_2O_3 substrate (415 μm, N_d-N_a = 4.5 × 10^{18} cm^{-3}). The Ti/Au (10/40 nm) was used for the back ohmic junction and Mo (300 nm) was used for the front Schottky junction. Post-annealing treatment was performed at 400, 500, and 550 °C using a rapid thermal annealing process (RTA) in an Ar gas atmosphere, and in this process, the Schottky junction and ohmic junction were formed simultaneously. Electrical characteristics including current-voltage (I–V), capacitance-voltage (C–V), Schottky barrier height (SBH), ideality factor (n), turn-on voltage (V_{on}), on-resistance (R_{on}), on/off ratio, and breakdown voltage (BV) were evaluated. No obvious Schottky characteristics were observed before post-annealing treatment, which means that As-deposited Mo does not form a rectifying junction on the β-Ga_2O_3 without post-annealing treatment. After post-annealing treatment, the I–V curve of the Schottky rectification characteristics could be confirmed under all three conditions. Among the three conditions, the device annealed at 500 °C exhibits best performance, with an SBH of 0.96 eV, n of 1.01, V_{on} of 0.72 V, R_{on} of 13.8 mΩ·cm^2, an on/off ratio of 10^9, a breakdown voltage of −474 V, and a PFOM of 16.3 MW/cm^2. As a result of temperature-dependent I–V measurement, as chuck temperature increased, the reverse leakage current increased and SBH decreased in all devices, which is consistent with the thermally activated carrier transport. These results demonstrate that the Mo/β-Ga_2O_3 SBDs are a thermally stable contact for power device applications.

Keywords: β-Ga_2O_3; molybdenum; vertical Schottky barrier diodes; post-annealing treatment; power device; sputtering

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1. Introduction

With the rapid development of power electronic systems such as electric vehicles, solar inverters, and high frequency power converters, demand for semiconductor devices capable of high-voltage, high-temperature, and high-frequency operations is increasing.

Existing silicon (Si)-based power devices have performance limitations due to their narrow bandgap (1.1 eV) and low critical electric field value (0.3 MV/cm), and to overcome them, wide bandgap (WBG) semiconductors such as 4H-SiC (3.3 eV) and GaN (3.4 eV) are being used [1–4]. However, even this material has limitations in fully satisfying the requirements of ultra-high voltage and extreme environmental power systems. Gallium oxide, which belongs to ultra-wideband semiconductors, is receiving a lot of attention thanks to its excellent combination of material properties. The β-Ga_2O_3 has a theoretical critical breakdown field of 8 MV/cm with a bandgap of about 4.8 eV, and the Baliga figure of merit (BFOM) of about 3444, which is about 10 times that of SiC and about 4 times that of GaN [1–5]. One of the biggest practical advantages of β-Ga_2O_3 compared to competing ultra-wide bandgap (UWBG) materials such as AlN, diamond, and cubic boron nitride (c-BN) is the ability to fabricate large-area high-quality single crystal substrates with melt growth methods such as edge-defined film-fed growth (EFG) and Czochralski methods [6]. This substrate manufacturing method is suitable for industrial-scale production, enabling cost-effective wafer supply. In addition, n-type doping of β-Ga_2O_3 can be precisely controlled in a wide range from semi-insulating (Fe-doped) to a highly conductive n-type (N_d-N_a to 10^{19} cm $^{-3}$) (Sn-doped) [7]. These properties make β-Ga_2O_3 an attractive material for power device manufacturing compared to other UWBG candidate materials. Among the various β-Ga_2O_3 rectification device structures, the Schottky barrier diode (SBD) is the most actively studied structure due to its fast-switching speed and compatibility with a simple manufacturing process [8]. SBH, n (ideality Factor), R_{on}, BV, and on/off ratio, which are the main performance parameters of SBDs, vary greatly in the Schottky metal–semiconductor junction. Schottky metals commonly used in the study of gallium oxide Schottky barrier diodes (SBDs) include platinum (Pt), nickel (Ni), gold (Au), and tungsten (W), which generally have a Schottky barrier height (SBH) value in the range of 1.0 to 1.5 eV [9–12]. However, the Schottky junction between the above metal and gallium oxide exhibit low thermal stability under high-temperature operation or high-temperature post-annealing treatment conditions, which can lead to increased leakage current, reduced barrier height, and device failure [13,14]. Among the candidates for gallium oxide Schottky metals, molybdenum (Mo) has three key advantages. First, Mo has a work function of about 4.95 eV, which is higher than the electron affinity (about 4.0 eV) of n-type gallium oxide, satisfying the conditions required for Schottky barrier formation. Second, Mo's melting point is 2623 °C, which is significantly higher than that of platinum (Pt, 1768 °C) or nickel (Ni, 1455 °C), providing excellent thermal stability against deterioration of the junction with gallium oxide during high-temperature heat treatment and device operation. Third, Mo has a relatively lower Schottky barrier height (SBH, about 0.96 eV) on gallium oxide compared to Pt- or Ni-based bonding (1.0–1.5 eV), as demonstrated in a recent Mo/β-Ga_2O_3 SBD study, so it has a lower threshold voltage and higher rectification efficiency than Pt- or Ni-based devices [1,15]. Despite these advantages, Mo deposited by sputtering does not form a Schottky barrier by deposition alone, and a post-annealing treatment step is required to promote interfacial diffusion between Mo and the β-Ga_2O_3 surfaces to form a stable Schottky barrier. These thermally activated interface characteristics are combined with the intrinsic properties of Mo to make Mo/Ga_2O_3 SBD suitable for highly reliable high-temperature power device applications [1,15]. Existing studies have confirmed the possibility of a Mo-based Schottky junction on β-Ga_2O_3, but systematic studies that combine the effect of post-annealing treatment temperature on electrical properties and temperature-dependent characteristic evaluation have not been sufficiently reported. Such a study is essential for evaluating the reliability of Mo/β-Ga_2O_3 SBDs under actual operating conditions that can be exposed to high temperatures in extreme environments. In this study, Mo/β-Ga_2O_3 vertical SBDs were fabricated, the post-annealing treatment temperatures (400 °C, 500 °C, 550 °C) were system-

atically changed, and the electrical characteristics, including I–V, C–V, BV, and temperature dependence were evaluated.

2. Materials and Methods

2.1. Structure and Materials

Mo (molybdenum) (4N, iTASCO, Seoul, Republic of Korea) has a higher work function (~4.95 eV) than the electron affinity (~4.0 eV) of the β-Ga_2O_3, along with a higher melting point (2623 °C) than Pt (1768 °C) and Ni (1455 °C), providing excellent thermal stability. In this study, the Mo/β-Ga_2O_3 vertical Schottky barrier diode was fabricated on a β-Ga_2O_3 epitaxial wafer (Novel Crystal Technology, Saitama, Japan). As shown in Figure 1 and Table 1, the substrate consists of a Si-doped β-Ga_2O_3 epitaxial layer grown on the Sn-doped β-Ga_2O_3 substrate. The Si-doped n-type epitaxial layer, which acts as a drift region, is 10 μm thick and has a carrier concentration (N_d-N_a) of 2.2 × 10^{16} cm^{-3}. This relatively low doping in the drift layer enables high breakdown voltage allowing a wide depletion region to form under reverse bias. The Sn-doped n^+ substrate has a thickness of 415 μm and a carrier concentration (N_d-N_a) of 4.5 × 10^{18} cm^{-3}, and a current flows vertically through the epitaxial layer from the front Schottky junction to the back ohmic junction allowing the entire drift layer to support the breakdown voltage. Mo (300 nm thick) was used as a Schottky metal layer for the front Schottky junction. The back ohmic junction was formed by depositing a Ti/Au) (iTASCO, Seoul, Republic of Korea) double layer (Ti 10 nm/Au 40 nm) using E-beam evaporator (SHVAC, Seoul, Republic of Korea) [14,16,17]. The active area was 0.07 mm^2.

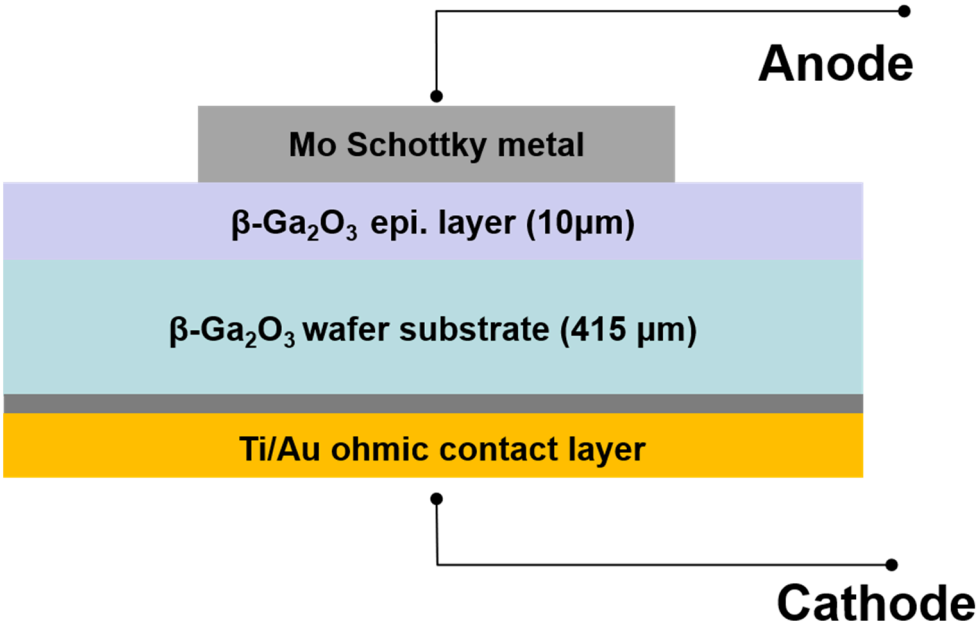


Figure 1. Schematic cross-sectional view of the Mo/β-Ga_2O_3 vertical Schottky barrier diode.

Table 1. Parameters and fabrication conditions for Mo/β-Ga_2O_3 vertical SBDs.

Material	Parameter	Value
Si-doped Ga_2O_3 epi.	N_d-N_a (cm^{-3})	2.2 × 10^{16}
Sn-doped Ga_2O_3 wafer	N_d-N_a (cm^{-3})	4.5 × 10^{18}
Back metal Ti/Au (ohmic contact)	Thickness Base Pressure Equipment	10/40 nm 4 × 10^{-6} Torr E-beam Evaporator

Table 1. *Cont.*

Material	Parameter	Value
Top metal Mo (Schottky contact)	Thickness	300 nm
	Base Pressure	2×10^{-6} Torr
	Working Pressure	3 mTorr
	Input Power	30 W
	Substrate Temperature	Room Temperature
	Active Area (mm^2)	0.07
Post-annealing treatment	Post-annealing Temp.	400 °C, 500 °C, 550 °C
	Working Gas, Working Pressure	Ar gas, 100 mTorr

2.2. Fabrication Process Flow

As shown in Figure 2, to remove organic contaminants from the surface of the β-Ga_2O_3 wafer, ultrasonic cleaning was performed in acetone, IPA (DAEJUNG Chemicals & Metals, Siheung, Republic of Korea), and deionized water, followed by drying (N_2). This cleaning process removes organic contaminants that could otherwise cause delamination. After cleaning the substrate, the plasma surface treatment (Femto Science, Hwaseong, Republic of Korea) was performed. The plasma treatment changes the surface energy of epitaxial layer for hydrophilic properties, and organic contaminants on epitaxial layer are removed to improve physical adhesion between a metal and an epitaxial layer. Then, Ti/Au back metal layer was deposited on a Sn-doped Ga_2O_3 substrate by using E-beam evaporator in a base pressure of 4×10^{-6} Torr. After that, Mo Schottky metal (300 nm thick) was deposited on the β-Ga_2O_3 epitaxial layer by using sputtering (Korea Vacuum Tech., Gimpo, Republic of Korea). Deposition was carried out at a pressure of 3 mTorr and input power of 30 W at room-temperature conditions in an Ar gas (Hanmiltd, Anseong, Republic of Korea) atmosphere. After Mo metal deposition, post-annealing treatment was performed at 400 °C, 500 °C, and 550 °C for 1 min in a 100 mTorr Ar atmosphere using a rapid thermal annealing (RTA) system (Korea Vacuum Tech., Gimpo, Republic of Korea). During RTA process, the Mo/β-Ga_2O_3 Schottky junction and back Ti/Au ohmic junction were formed simultaneously. As-deposited Mo does not form a Schottky junction with the β-Ga_2O_3 epitaxial layer, but after post-annealing treatment process, Mo atoms are partially diffused into the β-Ga_2O_3 near-surface region forming a stable Schottky junction [15,18]. The post-annealing temperatures were selected to investigate their effect on the Schottky barrier height and electrical properties of the device.

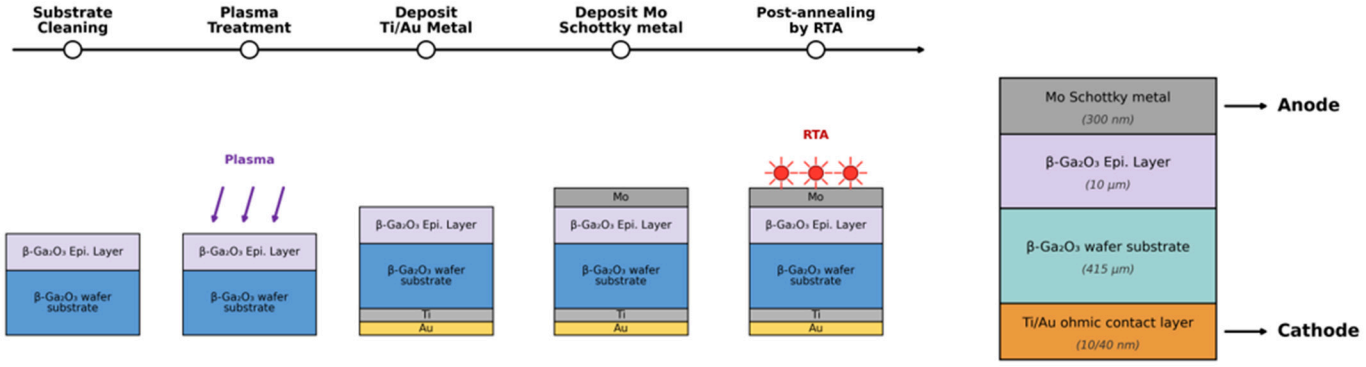


Figure 2. Fabrication process flow of the Mo/β-Ga_2O_3 vertical Schottky barrier diode. The purple arrows and the red sun symbols denote the plasma treatment and the rapid thermal annealing (RTA) process, respectively.

2.3. Electrical Properties

After device fabrication, the electrical characteristics of the Mo/β-Ga_2O_3 SBD were evaluated using a Keithley 4200A-SCS semiconductor parameter analyzer, Keithley 2410 High-Voltage SourceMeter (Keithley Instruments, Solon, OH, USA) and an 4284A LCR meter (Agilent Technologies, Santa Clara, CA, USA). I–V characteristics were measured under both forward and reverse bias to extract the main device parameters. Forward I–V characteristics were analyzed using a thermionic emission (TE) model, which describes current transport across the Schottky barrier [2,11–13]. According to the TE model, the current density is given by a diode equation:

$$J = J_0[exp\left[\left(\frac{qV}{nkT}\right) - 1\right]], J_0 = A^*T^2exp\left(-\frac{q\Phi_B}{kT}\right)$$

The reverse saturation current density (J_0) is a constant that determines the magnitude of a small leakage current flowing when a diode is in a reverse bias state. A* is the effective Richardson constant, T is the temperature, q is the electron charge, Φ_B is the Schottky barrier height, k is the Boltzmann constant, n is the ideality factor, and V is the voltage. Schottky barrier heights ($SBHs$, Φ_B) were using a Richardson plot and were also estimated from C–V curve [10–12]

$$ln\left(\frac{J_0}{T^2}\right) = ln\left(A^*\right) - \frac{q\Phi_B}{kT}$$

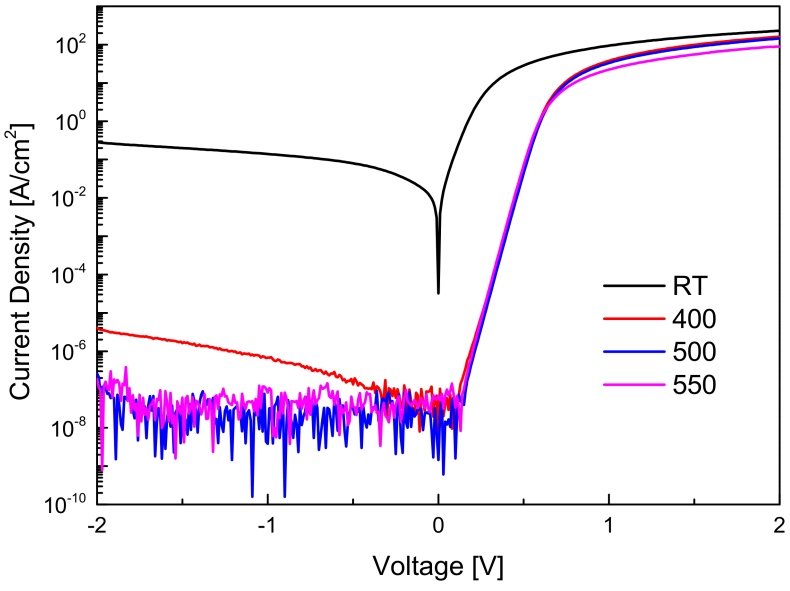
The ideality factor (n) was extracted from the slope of the ln (J) vs. V plot in the forward region. Closer to n = 1 indicates the ideal thermionic emission (TE) behavior with a defect-free Schottky barrier, where n > 1 indicates the interfacial state, barrier non-uniformity, or the presence of non-ideal current transfer mechanisms such as recombination or tunneling [10–12]. The turn-on voltage (V_{on}) was extracted by linear extrapolation of the forward I–V curve, and the on-resistance (R_{on}) was calculated from the linear region slope of the forward I–V curve at an applied voltage of +2 V. The capacitance-voltage (C–V) characteristic was measured at 100 kHz frequency at room temperature. Built-in voltage (V_{bi}) and depletion width were measured using a $1/C^2$ − V(Mott–Schottky) plot. The breakdown voltage (BV) was measured by sweeping the reverse voltage until the current reached the set compliance limit. The thermal stability of the Schottky junction under high-temperature operating conditions was evaluated by performing temperature-dependent I–V measurement while changing the chuck temperature for the post-annealing device at 500 °C and 550 °C.

3. Results

3.1. Schottky Junction Formation Mechanism and Effect of Post-Annealing Temperature

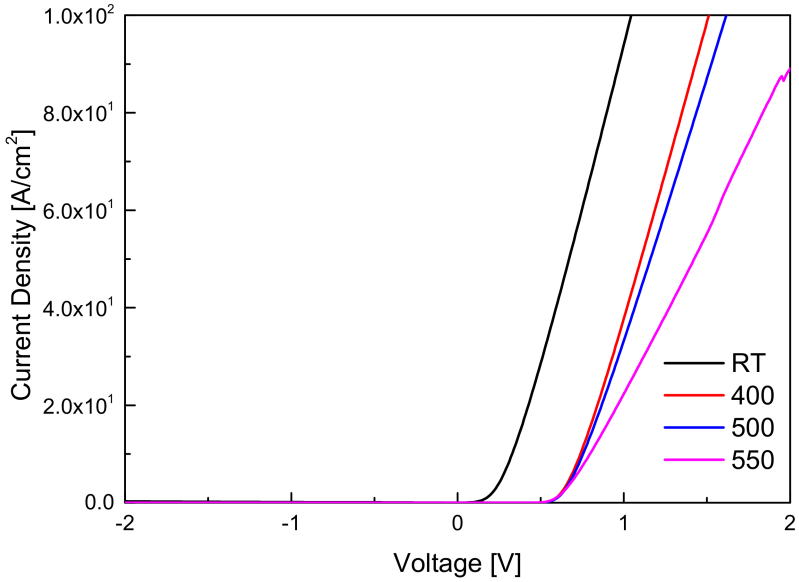
As shown in Figure 3a,b, the As-deposited Mo/β-Ga_2O_3 structure sample does form a Schottky contact, but its rectifying behavior is poor, with a low rectification ratio, high reverse leakage, and a large ideality factor. This is attributed to plasma-induced damage and surface defects generated during deposition, which create a high density of interface states and lead to Fermi-level pinning, thereby suppressing the formation of the Schottky barrier [8,15]. After post-annealing at 400, 500, and 550 °C, rectified I–V characteristics were observed in all devices, confirming that a Schottky junction has been formed. In the RTA process, Mo atoms partially diffuse into the β-Ga_2O_3 interface, modifying the interfacial properties and thereby promoting the formation of a stable Schottky junction. As summarized in Table 2, the post-annealing temperature had a significant effect on the diode characteristics. The device at 500 °C exhibited the best overall performance. It showed the highest SBH (0.96 eV), the lowest ideality factor (n = 1.01), the highest V_{on} (0.72 V), and the highest on/off ratio (10^9). The ideality factor (n) close to unity obtained at 500 °C indicates

that thermionic emission (TE) is the dominant charge transport mechanism [2,11–13]. In addition, these results suggest that the interfacial defect density is low and a spatially uniform Schottky junction is formed. On the other hand, a high on/off current ratio of about 10^9 reflects excellent rectification characteristics, which supports its applicability as a power switching device. The device annealed at 400 °C showed a low SBH (0.92 eV) and a high ideality factor (n = 1.07). When n is higher than the optimal post-annealing treatment temperature, it is determined that diffusion of Mo into β-Ga_2O_3 epitaxial layer is not sufficient. However, device annealing at 550 °C resulted in deteriorating device performance. The ideality factor was n = 1.01, which approached an ideal value, but the on/off current ratio was reduced to 10^8, and the R_{on} was increased to 22.4 mΩ·cm^2. This is approximately1.6 times higher than the R_{on} at 500 °C, indicating that an excessive annealing temperature degrades device performance. This degradation is due to excessive Mo diffusion at 550 °C and the generation of interface defects, which increases contact resistance by reducing the effective doping concentration of the epitaxial layer near the interface. As shown in Figure 4, the breakdown voltage (BV) also decreased from −474 V at 500 °C to −419 V at 550 °C, which is attributed to an increase in interfacial trap density caused by excessive annealing, resulting in a decrease in breakdown characteristics. Meanwhile, the turn-on voltage (V_{on}) decreased to 0.67 V at 550 °C compared to 500 °C, which is consistent with the slight decrease in the SBH from 0.96 eV to 0.93 eV. These results suggest that the Mo/β-Ga_2O_3 interfacial Schottky barrier was partially degraded by excessive Mo diffusion and interfacial defect formation at the highest annealing temperature [15]. Figure 5 and Table 2 show electrical parameters of Mo/β-Ga_2O_3 SBDs as a function of post-annealing temperature. Figures 6–8 show Schottky barrier height (SBH), Specific on-resistance (R_{on}, sp) and Ideality factor (***n***) of Mo/β-Ga2O3 SBDs annealed at 400 °C, 500 °C, and 550 °C.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. (**a**). Forward and reverse I–V characteristics of Mo/β-Ga_2O_3 SBDs annealed at RT, 400 °C, 500 °C, and 550 °C (log scale). (**b**). Forward and reverse I–V characteristics of Mo/β-Ga_2O_3 SBDs annealed at RT, 400 °C, 500 °C, and 550 °C (linear scale).

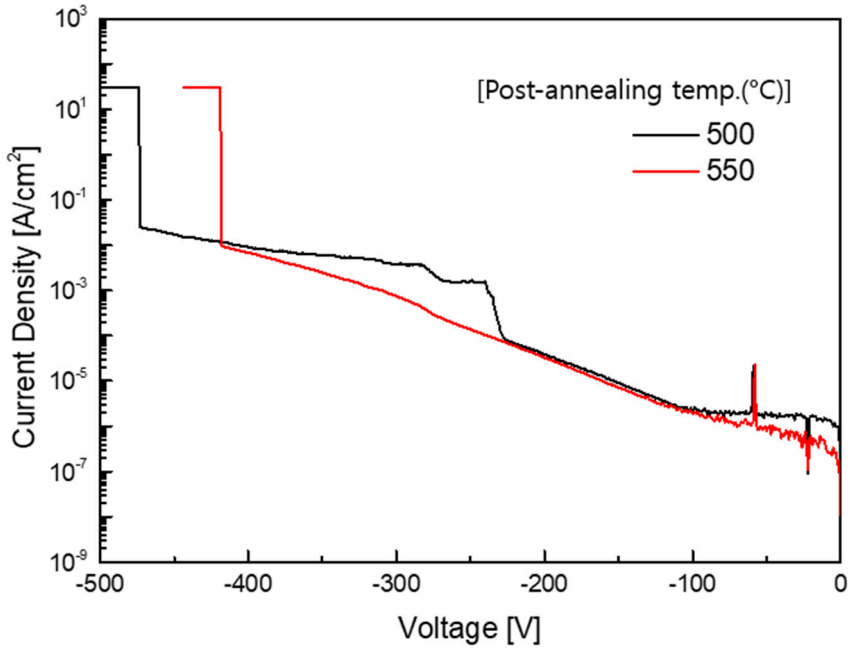


Figure 4. Reverse breakdown voltage characteristics of Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C.

Table 2. Electrical parameters of Mo/β-Ga_2O_3 SBDs as a function of post-annealing temperature (room-temperature measurement).

	Post-Annealing Temp. [°C]		
ITEM	**400 [°C]**	**500 [°C]**	**550 [°C]**
SBH [eV]	0.92	0.96	0.93
n	1.07	1.01	1.01
V_{on} [V]	0.66	0.72	0.67

Table 2. *Cont.*

	Post-Annealing Temp. [°C]		
ITEM	**400 [°C]**	**500 [°C]**	**550 [°C]**
R_{on}@2 V [mΩ·cm^2]	12.4	13.8	22.4
On/off Ratio	10^9	10^9	10^8
BV [V]	346	474	419
PFOM (MW/cm^2)	9.7	16.3	7.8

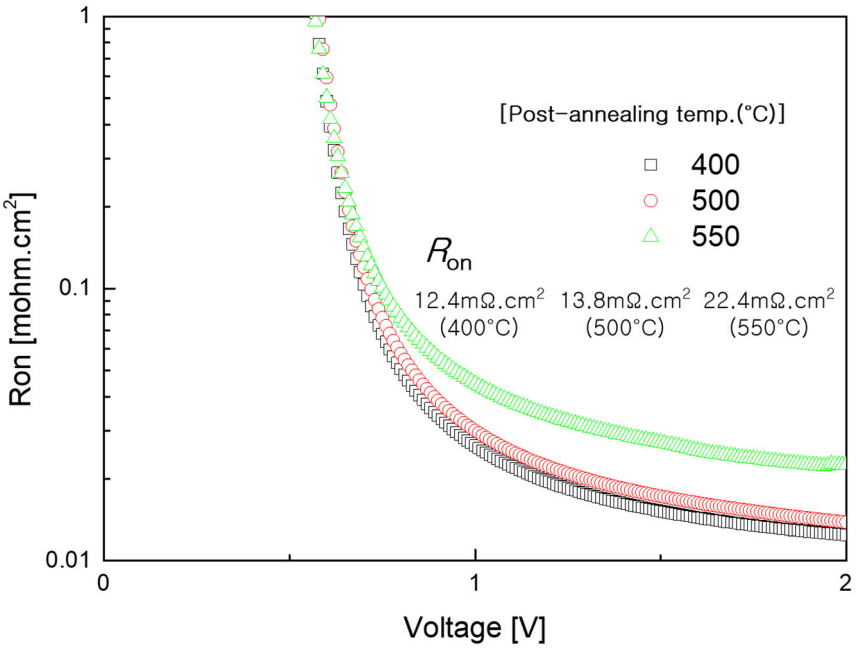


Figure 5. Electrical parameters of Mo/β-Ga_2O_3 SBDs as a function of post-annealing temperature.

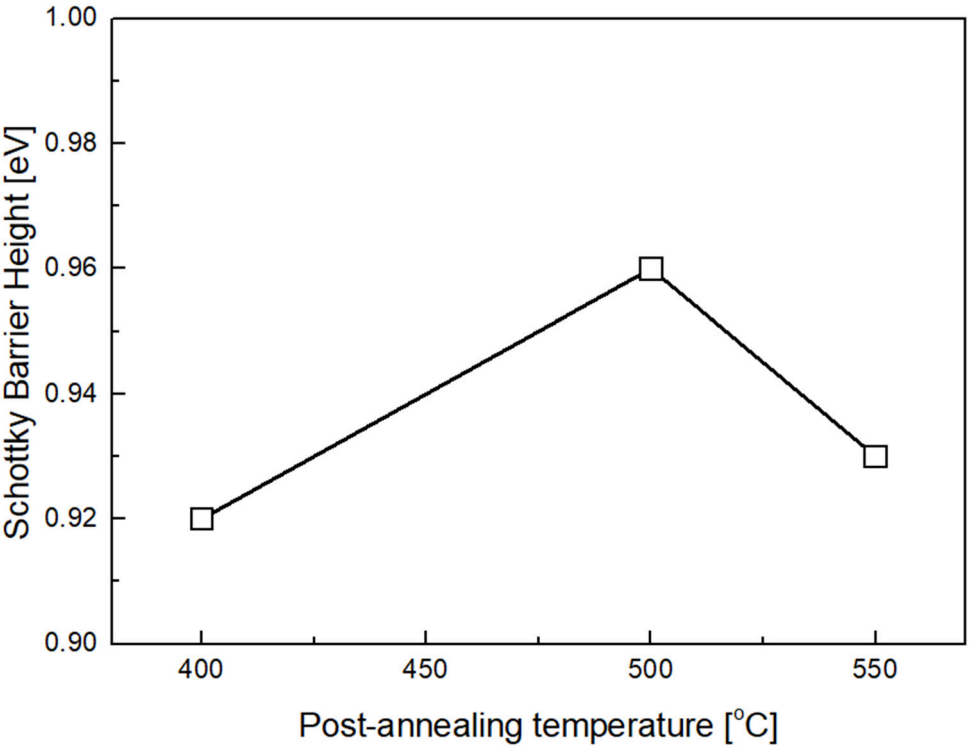


Figure 6. Schottky barrier height (SBH) of Mo/β-Ga_2O_3 SBDs annealed at 400 °C, 500 °C, and 550 °C.

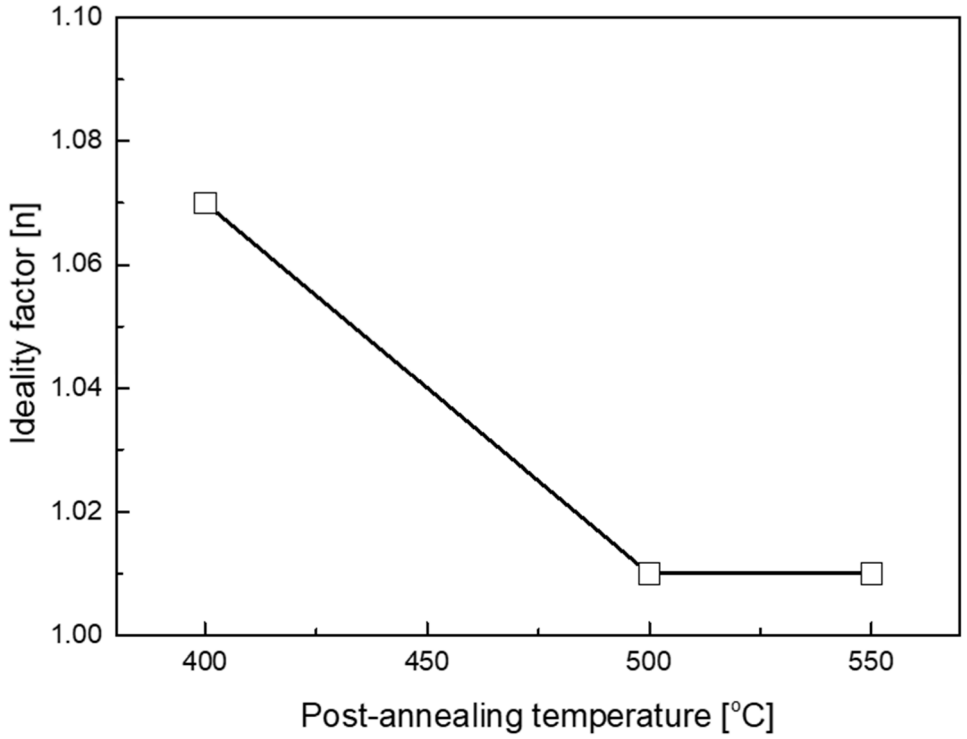


Figure 7. Specific on-resistance (R_{on}, sp) of Mo/β-Ga_2O_3 SBDs annealed at 400 °C, 500 °C, and 550 °C.

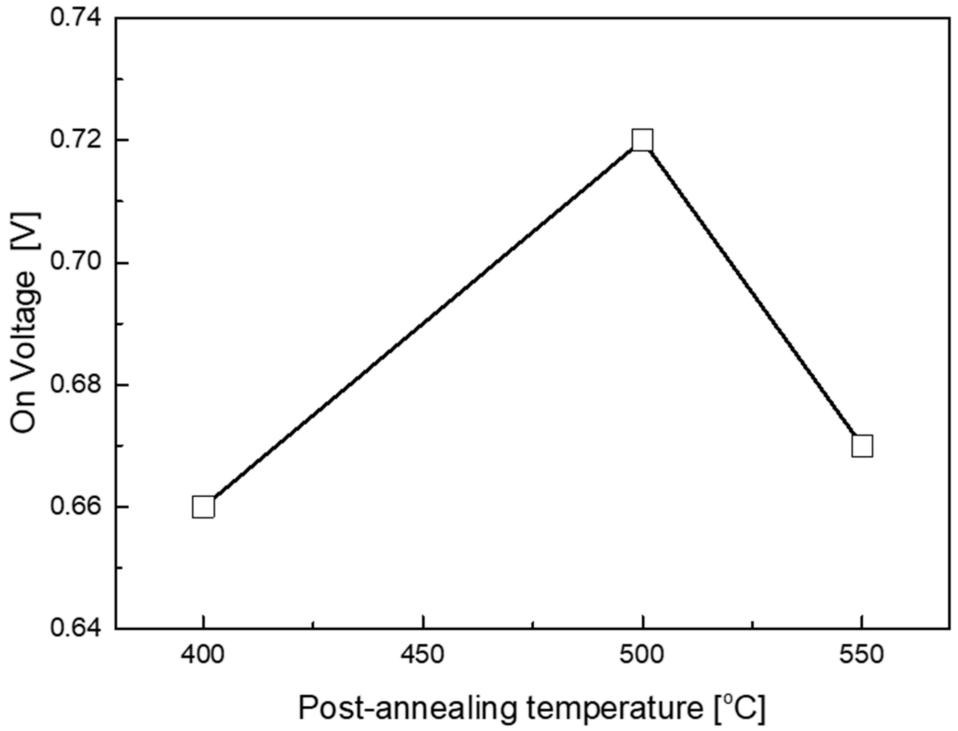


Figure 8. Ideality factor (n) of Mo/β-Ga_2O_3 SBDs annealed at 400 °C, 500 °C, and 550 °C.

3.2. C–V and 1/C²–V Analysis

In this study, C–V measurements were performed at a frequency of 100 kHz. The C–V characteristics showed a tendency for capacitance to decrease with increasing reverse bias, consistent with the depletion behavior of the Schottky junction in which the depletion region extends into the lightly doped drift layer. In the reverse-bias section, the $1/C^2$ vs. V (Mott–Schottky) plot exhibited excellent linearity, confirming uniform doping of the drift layer and successful formation of the Schottky junction [11,12]. As shown in Figure 9,

the built-in potential (V_{bi}) was extracted from the x-intercept of the $1/C^2$–V plot. V_{bi} exhibited 0.946 V at 500 °C and 0.916 V at 550 °C. As shown in Figure 10, the depletion layer thickness was calculated from the C–V measurement results. The relative dielectric constant of β-Ga_2O_3 along the (001) direction (ε_r = 12.4) was reported by Fiedler et al. [19] was applied in the calculation,

$$W(\text{width}) = \frac{\varepsilon_r \varepsilon_0}{C_{\text{density}}}$$

where the depletion layer thickness under the zero-bias condition (V = 0 V) was 0.150 μm and 0.153 μm, at 500 °C and 550 °C, respectively.

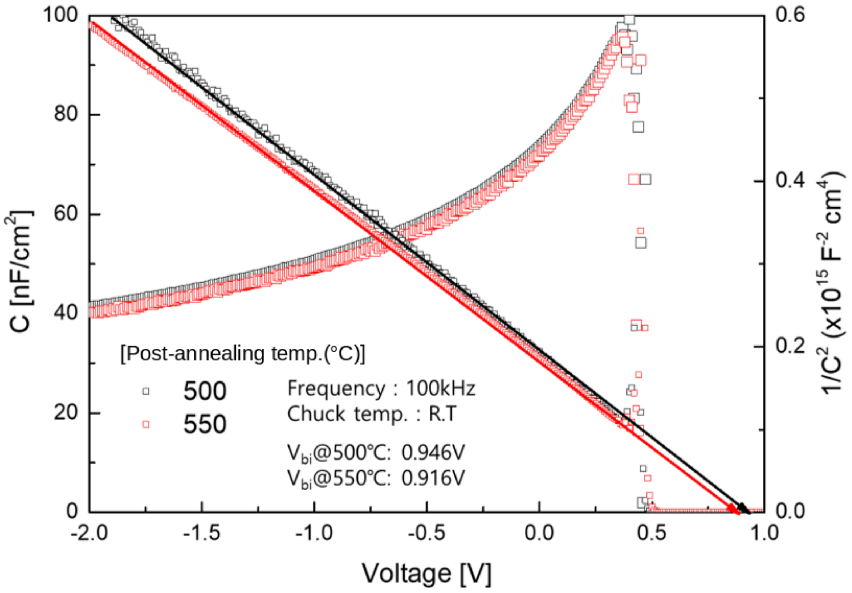


Figure 9. C–V characteristics and Mott–Schottky ($1/C^2$ vs. V) plots of Mo/β-Ga_2O_3 SBDs measured at 100 kHz at room temperature.

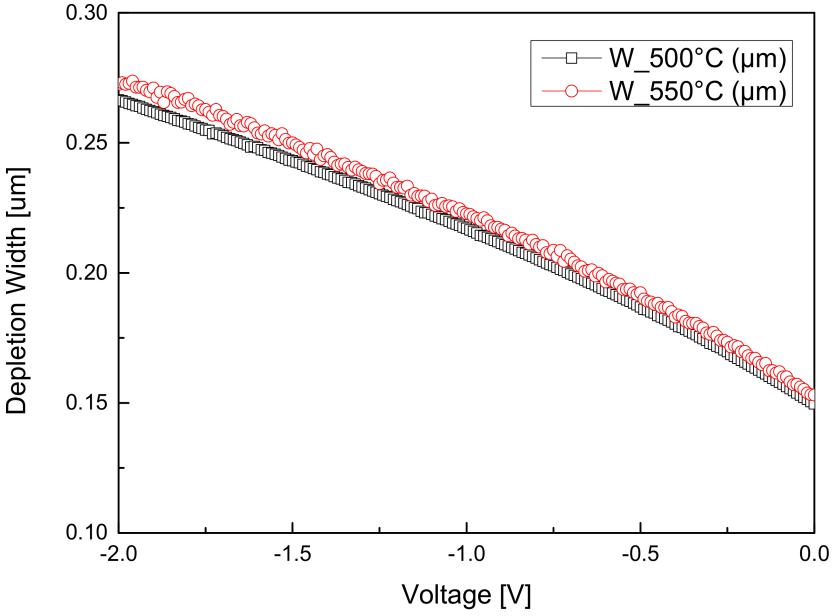


Figure 10. Depletion width as a function of applied voltage for Mo/β-Ga_2O_3 SBDs measured at 100 kHz at room temperature.

3.3. Temperature-Dependent Electrical Characteristics

To evaluate the thermal stability of the Mo/β-Ga_2O_3 SBD, temperature-dependent current-voltage (I–V) characteristics were measured for devices at 500 °C and 550 °C. As shown in Figures 11a,b and 12a,b, I–V characteristics were measured under each post-annealing temperature condition while the chuck temperature was increased gradually from room temperature (~25 °C) to 100 °C. For both post-annealing treatment conditions, it was observed that the reverse leakage current tended to increase as the chuck temperature increased, consistent with the thermionic emission (TE) model, which predicts that the reverse saturation current density increases exponentially with temperature [11–13]. A comparison of the two post-annealing treatment conditions showed that the device at 500 °C maintained superior electrical characteristics over the entire measurement temperature range. Specifically, the 500 °C device exhibited a higher SBH and lower reverse leakage current than the 550 °C device at all chuck temperatures, indicating relatively better thermal stability. It is judged that this is because the Mo/β-Ga_2O_3 interface is more clearly defined in the 500 °C post-annealing treatment condition, and a spatially uniform distribution is formed. On the other hand, it is determined that excessive heat treatment at 550 °C causes interfacial degradation or generation of additional defects, thereby lowering the stability of the device. This temperature dependence of SBH is a phenomenon commonly reported in Schottky diodes and is due to the following complex mechanism. First, the height of the effective barrier detected by the carrier changes due to the temperature-dependent activation of the interface state near the Schottky barrier. Second, the effect of image-force lowering is strengthened by increasing the interface electric field according to the increase in the reverse bias. Third, due to the spatial non-uniformity of the barrier distribution across the entire metal-semiconductor junction, the thermally activated carrier selectively passes through the low barrier region, and as a result, the apparent SBH extracted from the I–V analysis tends to decrease with increasing temperature [11,12,20]. Figures 13 and 14 and Table 3 exhibit the Schottky barrier height (SBH) and ideality factor (n) of the Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C as a function of the measurement (chuck) temperature. Figure 15 exhibits Arrhenius plots of the reverse leakage current density (ln J versus 1000/T) at −50 V for the Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C. The reverse leakage of the 500 °C device is thermally activated, whereas that of the 550 °C device is nearly temperature-independent at a high field, indicating a change from thermionic emission to tunneling-dominated conduction [21].

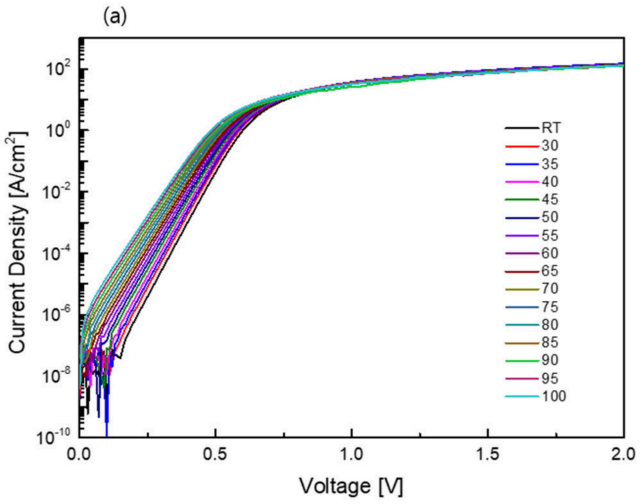


Figure 11. *Cont.*

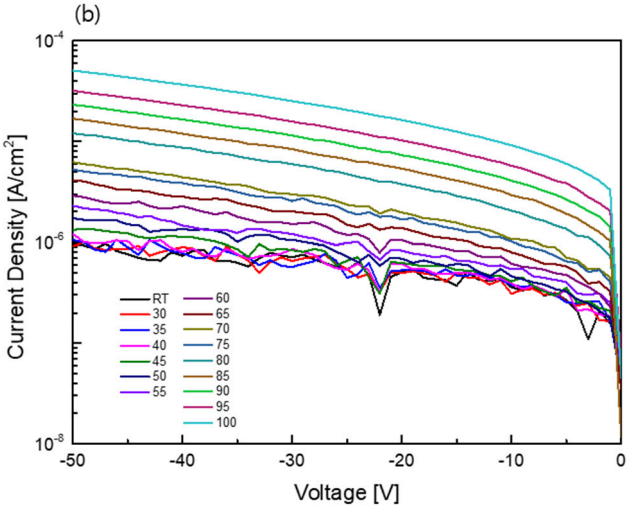


Figure 11. Temperature-dependent I–V characteristics of Mo/β-Ga_2O_3 SBDs annealed at 500 °C: (**a**) forward and (**b**) reverse bias.

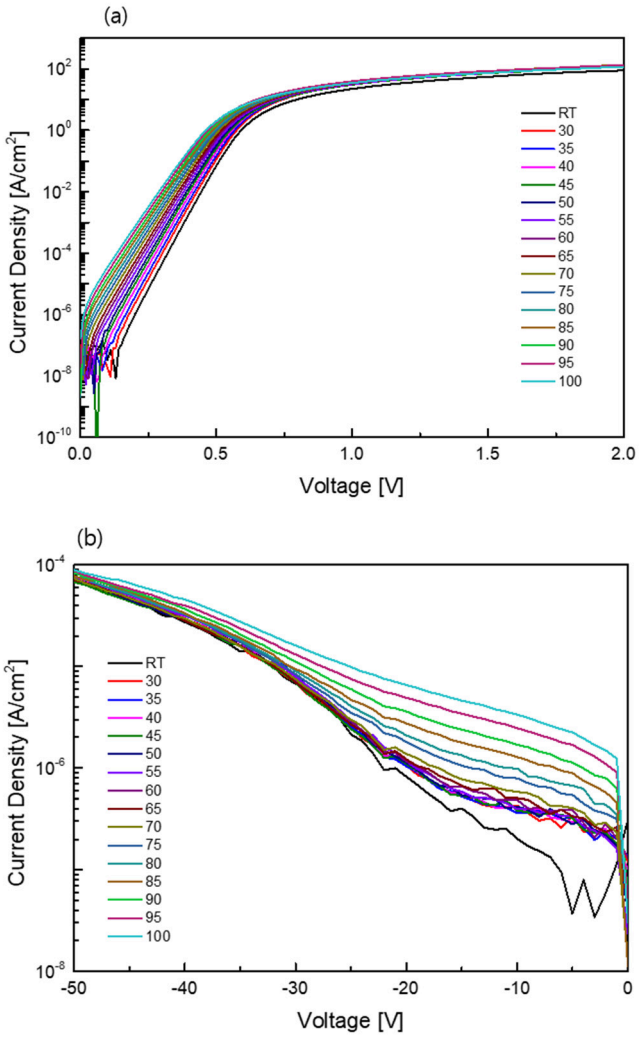


Figure 12. Temperature-dependent I–V characteristics of Mo/β-Ga_2O_3 SBDs annealed at 550 °C: (**a**) forward and (**b**) reverse bias.

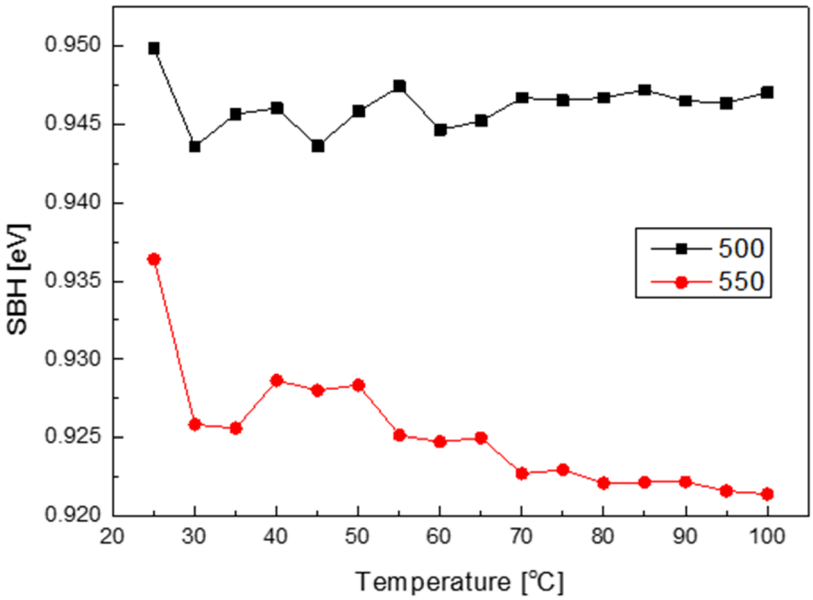


Figure 13. Schottky barrier height (SBH) of the Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C as a function of the measurement (chuck) temperature.

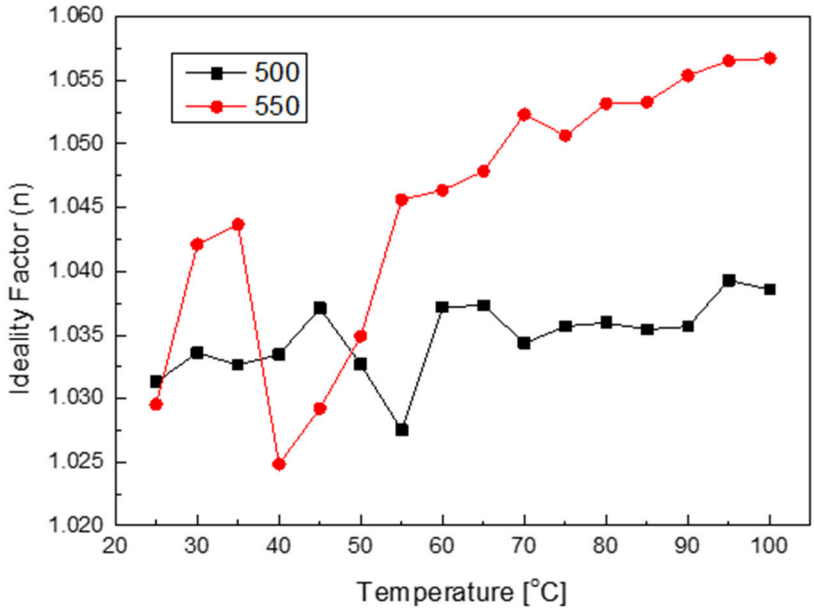


Figure 14. Ideality factor (*n*) of the Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C as a function of the measurement (chuck) temperature.

Table 3. Schottky barrier height (SBH) and ideality factor (*n*) of the Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C, extracted at different measurement temperatures.

Temp. [°C]	500 [°C], SBH	500 [°C], *n*	550 [°C], SBH	550 [°C], *n*
25	0.950	1.031	0.936	1.030
50	0.946	1.033	0.928	1.035
75	0.947	1.036	0.923	1.051
100	0.947	1.039	0.921	1.057

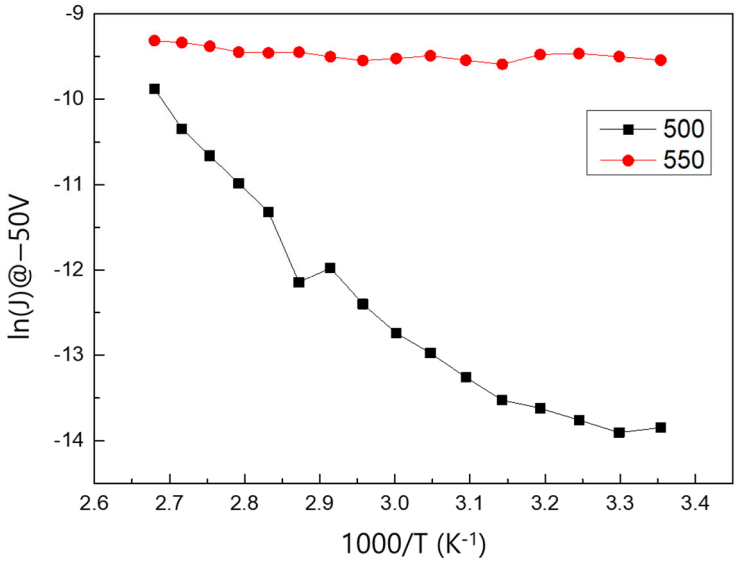


Figure 15. Arrhenius plots of the reverse leakage current density (ln J versus 1000/T) at −50 V for the Mo/β-Ga_2O_3 SBDs annealed at 500 °C and 550 °C [21].

3.4. Power Device Performance Evaluation

The breakdown voltage (BV) is the maximum reverse voltage that the device can withstand and is one of the key performance indicators for power devices. The 500 °C post-annealing treatment device achieved BV = −474 V, which was improved by about 13% compared to −419 V for the 550 °C device, indicating superior reverse-blocking characteristics (Table 4). The Power figure-of-merit (PFOM = BV^2/R_{on}) is a widely used indicator for evaluating the performance of unipolar power rectification devices [2,5,8]. For the 500 °C post-annealing treatment device, it was calculated as PFOM = $(474)^2/(13.8 \times 10^{-3}\ \Omega{\cdot}cm^2) \approx 16.3\ MW/cm^2$ without an edge termination structure, suggesting that there is room for performance improvement when introducing the termination structure [22–25].

Table 4. Comparison of the device performance of the Mo/β-Ga_2O_3 vertical SBD in this work with a previously reported β-Ga_2O_3 vertical Schottky rectifier [26].

Parameter	This Work	[High BV (−201) β-Ga_2O_3 Schottky Rectifiers] [26]
Schottky metal	Sputtered Mo	Ni by E-beam evaporator
Structure	Vertical SBD, no edge termination	Vertical SBD, no edge termination
R_{on} (mΩ·cm^2)	13.8	25
BV (V)	474	1600
On/off Ratio	~10^9	2.5×10^6~3×10^7
PFOM (MW/cm^2)	16.3	~102

4. Conclusions

In this study, Mo Schottky metal was deposited on β-Ga_2O_3 epitaxial layer using sputtering equipment. A Mo/β-Ga_2O_3 vertical Schottky barrier diode (SBD) was fabricated by rapid thermal annealing (RTA) in an Ar gas atmosphere. Electrical characteristics including I–V, C–V, breakdown voltage (BV), and temperature-dependent characteristics were evaluated. The As-deposited Mo/β-Ga_2O_3 SBD did not exhibit Schottky rectification characteristics, and a Schottky junction was formed after annealing at 400, 500, 550 °C. The device at 500 °C showed SBH = 0.96 eV, n = 1.01, V_{on} = 0.72 V, R_{on} = 13.8 mΩ·cm^2, on/off

current ratio = 10^9, and breakdown voltage BV = −474 V, indicating the best performance among post-annealing treatment conditions. It was confirmed that a high-quality Schottky junction was formed under the conditions by showing a value close to the ideality factor close to unity. On the other hand, excessive annealing treatment at 550 °C caused excessive Mo diffusion, increasing R_{on} to 22.4 mΩ·cm^2, reducing the on/off current ratio to 10^8, and lowering the BV to −419 V. As a result of temperature-dependent I–V measurements, the reverse leakage current systematically increased and SBH decreased with increasing chuck temperature in both 500 and 550 °C post-annealing treatments. The 500 °C annealed device exhibited a higher SBH and lower leakage current over the entire measurement temperature range, and better thermal stability compared to the 550 °C device. The power-figure of merit (PFOM = BV^2/R_{on}) of the 500 °C annealed device was calculated as about 16.3 MW/cm^2, demonstrating competitive performance for a β-Ga_2O_3 vertical SBD even without edge termination or passivation. These results confirm that the Mo metal deposited by the sputtering is a suitable Schottky junction material for the β-Ga_2O_3-based SBD and clearly suggest that a 500 °C with an Ar atmosphere condition is a post-annealing treatment condition that optimizes device performance.

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