Abstract—A Schottky barrier rectifier was fabricated with a 
(100)-oriented $\beta$-Ga$_2$O$_3$ substrate grown by the edge-defined 
film-fed method. The Sn-doped $\beta$-Ga$_2$O$_3$ substrate had an effective 
donor concentration of approximately $2 \times 10^{17}$ cm$^{-3}$. High 
performance parameters were obtained, such as a high forward 
current (421 A/cm$^2$ at 2 V), low ON-resistance (2.9 m$\Omega$ cm$^2$), and 
short reverse recovery time (20 ns). Furthermore, the dynamic 
behavior of the device is characterized through test on the 
half-wave rectification of AC voltages at different frequency. The 
diode worked well at 100 kHz. In the end of the article, how can 
Ga$_2$O$_3$ Schottky rectifier operating at high frequency are 
discussed.

Index Terms—(100) $\beta$-Ga$_2$O$_3$, Schottky barrier rectifier, 
Rectification characteristics.

I. INTRODUCTION

Currently, the rapid development of power electronics is 
promoting wide-bandgap semiconductor materials to 
apply into high power devices [1-4]. The rapid development of 
ultra-wide-bandgap $\beta$-Ga$_2$O$_3$ semiconductor is attracting 
focused interest [5]. $\beta$-Ga$_2$O$_3$ has advantages in unipolar 
deVICES with GaN due to its more desirable 
material properties [6]. For instance, these semiconductors 
have an extremely large bandgap ($E_g$) of 4.5 - 4.9 eV [7-9]. 
Their breakdown electric field strength ($E_b$) is estimated to be 
as high as 6 - 8 MV/cm [10]. The Baliga’s figure-of-merit 
(BFOM = $e\mu E_g^3$, where $e$ is a relative dielectric constant and $\mu$ 
is electron mobility), which is the parameter used to evaluate 
the appropriateness of a material for a power device [1], of 
ultra-wide-bandgap $\beta$-Ga$_2$O$_3$ is four times larger than that of 
SiC and GaN [11-13]. The conventional low-cost melt methods, 
such as Czochralski, floating zone (FZ) and edge-defined 
film-fed growth (EFG), can be used to grow large high-quality 
single-crystal $\beta$-Ga$_2$O$_3$ wafers [10,14-16], significantly 
reducing the cost of device production. Notably, many studies 
on $\beta$-Ga$_2$O$_3$ Schottky barrier diodes (SBDs), which constitute 
very important discrete and integral power devices, have been 
reported [17-23]. In these studies, the device structures are 
usually simple, but the device performance is adequate with 
respect to forward current, ON-resistance, and reverse 
breakdown voltage based on DC electrical measurements. However, the dynamic behavior of Ga$_2$O$_3$ SBDs (especially the 
rectifying modulation on the AC signal) has not been 
investigated in depth. The dynamic behavior of the diode is 
commonly evaluated for switching operations induced by 
rectification in an AC-DC converter circuit [24]. Furthermore, the $\beta$-Ga$_2$O$_3$ crystals used in SBD typically have (001), (\text{\bar{2}}01) and (001) orientations [17-22], but the (100)-oriented crystal is 
rarely used in SBD. In our previous work [23], we fabricated 
and characterized a simple SBD with (100) $\beta$-Ga$_2$O$_3$ that shows 
acceptable device performance. In this work, we optimized 
crystal growth parameters and improved the Sn doping 
concentration. The new device shows markedly improved 
performance, including forward current density ($I_{@2V}$), 
ON-state resistance ($R_{ON}$), and a reverse breakdown property, 
and the rectification ability for AC signals under different 
frequencies was also demonstrated.

II. EXPERIMENTS

The (100)-oriented $\beta$-Ga$_2$O$_3$ substrates grown by the EFG 
method [14] are rectangular blocks smaller than 10 mm $\times$ 10 
mm with thickness of about 480 nm, as shown in Fig. 1(a). The 
quality of the crystal was also improved in this work by 
obtaining the thermal field and seeding process during the 
growth [14]. SnO$_2$ powder was intentionally added into the raw
material, which makes the n-type carrier concentration reaches $2\times10^{17}$ cm$^{-3}$, as obtained by the Hall test and capacitance voltage ($C - V$) test. A high surface quality with root-mean-square (RMS) roughness of about 0.1 nm was obtained after mechanical exfoliation [16]. The schematic structure of the Schottky barrier diode is shown in Fig. 1(b), which is composed of a Pt/$\beta$-Ga$_2$O$_3$ Schottky contact and a Ti/$\beta$-Ga$_2$O$_3$ Ohmic contact. The fabrication method of this device is similar to that in our previous work [23]. The Au (40 nm)/Ti (10 nm)/Pt (30 nm) anode and Ti (20 nm)/Au (40 nm) cathode metal films were both deposited by magnetron sputtering. The 400 °C oxygen plasma treatment were applied prior to sputtering cathode to optimize ohmic contact. The circular Schottky electrodes have a diameter of 150 μm. The current density-voltage ($J - V$) and $C - V$ curves were measured by a semiconductor device analyzer (Agilent B1500A, Agilent Technologies, Santa Clara, CA, USA) and a semiconductor characterization system (Keithley 4200A-SCS, Tektronix Inc., Beaverton, OR, USA). A pulse generator unit (Agilent B1530A, Agilent Technologies, Santa Clara, CA, USA) was used to test the reverse recovery time of the SBD. A rectification circuit was configured (Fig. 4(a)), and by applying AC signals generated by an arbitrary function generator (AFG3102, Tektronix Inc., Beaverton, OR, USA), the waveforms during the rectification process were monitored by an oscilloscope (MSO9404A, Agilent Technologies, Santa Clara, CA, USA).

![Fig. 1. (a) (100) $\beta$-Ga$_2$O$_3$ substrates used for Schottky barrier diode (SBD) fabrication. (b) Schematic structure and equivalent circuit [24,25] of the Pt/(100)$\beta$-Ga$_2$O$_3$ SBD.](image)

### III. RESULTS AND DISCUSSION

We first characterized the DC $J - V$ and AC $C - V$ curves of the Pt/(100)$\beta$-Ga$_2$O$_3$/Ti SBD. Fig. 2(a) shows the semi-log and linear forward $J - V$ characteristics of the SBD measured at room temperature (RT). For comparison, the curve obtained in our previous work is also plotted in this figure. The device shows a high forward current density, reaching 421 A/cm$^2$ at the applied voltage of 2 V ($J_{2V}$), which is 7 times that in our previous work [23]. The ON-state resistance ($R_{ON}$) was significantly reduced to 2.9 mΩ·cm$^2$, much lower than the value of 12.5 mΩ·cm$^2$ reported in our previous work [23]. Fig. 2(b) shows the reverse $I - V$ characteristics of the Ga$_2$O$_3$ SBD. The device still does not breakdown under a 200 V reverse bias voltage. Due to the limitations of the instrument and probe station, we cannot further strengthen the voltage. However, from the current value ($2.3\times10^{-4}$ A at 200 V), we can estimate that the breakdown voltage is larger than this test value. The leakage current is larger than that in our previous work [23], mainly caused by the lower barrier height that is influenced by the higher doping concentration of the wafer [26]. Device structures with epi-layer [19,21], field plate [20], field ring [27], and trench [22] are good ways to solve this problem.

![Fig. 2. (a) Liner and semi-logarithmic plot of the forward $J - V$ curve of the Pt/(100)$\beta$-Ga$_2$O$_3$ SBD in this work (red lines) and in our previous work (black lines) [23]. (b) Reverse $I - V$ curve of Pt/(100)$\beta$-Ga$_2$O$_3$ SBD compared with previous work [23].](image)

Fig. 3(a) shows the $C - V$ and $1/C^2 - V$ plot for the SBD at 10 kHz and 1 MHz at RT. The linear relationship between $1/C^2$ and $V$ indicates the uniform doping of the substrate, and the difference between the two lines appears to be very slight, showing that few deep level impurities exist in the Ga$_2$O$_3$ semiconductor [28]. From the linear fitting results, the value of the threshold voltage or built-in potential ($V_{th}$) is 0.63 V, lower than the value of 1.07 V in the literature [23], mainly due to the increased carrier concentration.

A diode is usually a rectifier in a circuit and must work at different frequencies. To investigate whether our diode has rectification ability when working at high frequency, we first tested the reverse recovery time (RRT) of the SBD, with the testing result shown in Fig. 3(b). The diode was switched with the applied bias voltage abruptly decreasing from forward to reverse with peak to peak value ($V_{pp}$) from 4 V to 10 V. The result shows that the RRT is approximately 20 ns, which is a very short time and does not change with increasing amplitude of the signal, indicating that the fabricated SBD has the potential to switch at high frequency.

![Fig. 3. (a) $C - V$ and $1/C^2 - V$ characteristics of the SBD measured at 10 kHz (red circles) and 1 MHz (gray triangles). The blue straight line is the fitting result. (b) Reverse recovery time of the SBD measured under $V_{pp}$ from 4 V to 10 V.](image)

Next, we tested the rectification characteristics of the diode under the AC frequency $\geq 10$ kHz. First, we built a simple rectifier and filter circuit, as shown in Fig. 4(a). The circuit consists of a Pt/(100)$\beta$-Ga$_2$O$_3$ rectifying diode (D), including its junction capacitance ($C_J$) and series resistance ($R_S$), framed in the red dotted box, in series with a load resistance ($R_L$) representing the load of the eventual circuit. The parasitic
effects from the probe station were almost completely eliminated, by disconnecting its chuck. On the other hand, the parasitic effects from the cable can also be obviously weakened by shortening its length, and its remnant parasitic effects especially under high frequency can be described by using the transmission line model, as shown in the blue dotted box in Fig. 4(a). $R_P$, $L_P$, and $C_P$ are the parasitic resistance, inductance and capacitance in the testing circuit, respectively.

The input AC signal with 20 V peak-peak value was generated by the signal generator, and the input ($V_{in}$) and output ($V_L$) waveforms were measured by the oscilloscope. The black curves in Figs. 4(b) to 4(e) are the original sine waveform input signals $V_{in}$ under different frequency $f$, and the red curves show the output signal $V_L$. Half sine waveforms of the output $V_L$ similar to that of the input $V_{in}$ are presented, which is just led by the rectifying effect of the rectifier. From Figs. 4(b) to 4(e), we can also see that the amplitudes of the rectifying effect of the rectifier. From Figs. 4(b) to 4(e), we can also see that the amplitudes of $V_L$ keep constant under different frequencies and are just half those of $V_{in}$, which is determined by that the value of $R_L$ was kept constant and just equivalent to that of the cable and $R_L$. The slight phase delay of the output waveform when the rectifier operates over 500 kHz is caused by the inductance in the cable. In general, Fig. 4 shows that the diode still does not lose the rectification capability even in a frequency of 1 MHz. However, we can see a small amount of negative current in Fig. 4(e). This phenomenon is originated from the more and more obvious reverse recovery characteristic of our device under higher frequency that is influenced by the junction capacitance.

![Fig. 4. (a) Rectification circuit. Rectification characteristics of the SBD measured under (b) $f = 10$ kHz, (c) $f = 100$ kHz, (d) $f = 500$ kHz, and (e) $f = 1$ MHz. The load resistance $R_L = 100 \ \Omega$, $C_P$, $R_P$ and $L_P$ are the parasitic capacitance, resistance and inductance from the cable, respectively.](image)

Lissajous curve of the applied AC frequency. Lissajous pattern is a method for analyzing residual charges in diodes [24]. It shows that the $I - V$ characteristics of the SBD are ideal when operating at a frequency of up to 100 kHz.

![Fig. 5. Lissajous plot as $I - V$ characteristics for rectification operation of the SBD form 1 kHz to 1 MHz.](image)

All these results indicate that the rectifier based on (100) $\beta$-Ga$_2$O$_3$ has the ideal rectification ability working under 100 kHz. To investigate the possibility of improving operation frequency, let’s analyze the possible role of the barrier capacitance ($C_J$) of our SBD through its equivalent circuit as shown in both Fig. 1(b) and Fig. 4(a). As $C_J$ is in parallel with the Schottky junction, its impedance $(\omega C_J)^{-1}$ reduces with increasing frequency. Thus in high frequency, the Schottky junction will be shorted, resulting in the reduction or even loss of the rectification capacity. Therefore, for high frequency operation and application, low junction capacitance of the device is needed, which can be achieved by introducing epitaxy layer with low doping concentration or using ultra-thin wafer with low doping concentration.

### IV. Conclusion

In this study, a Schottky rectifier was fabricated with a (100) $\beta$-Ga$_2$O$_3$ single-crystal substrate with a comparatively high doping concentration. The device, which has a simple structure, shows good forward electrical characteristics, such as low on-resistance ($R_{on}$), low threshold voltage ($V_{th}$), high on-state current density ($J_{on}$), which are good enough compared to other works on Ga$_2$O$_3$ [17-22], SiC [29-31] and GaN [32-34]. Our device also shows good reverse electrical characteristics, including a very short reverse recovery time comparable to the reported value [21], and a breakdown voltage of about 200 V which is higher than that of other Ga$_2$O$_3$ wafer based devices [17]. The dynamic behavior was tested by using a half-wave rectification circuit. The result indicates that the device has the ideal working frequency of 100 kHz, which is equivalent to that of SiC [24]. These results indicate that Ga$_2$O$_3$ semiconductor has a good potential for power device application.

### REFERENCES

