Ga_2O_3 Schottky Barrier Diodes Fabricated by Using Single-Crystal β–Ga_2O_3 (010) Substrates

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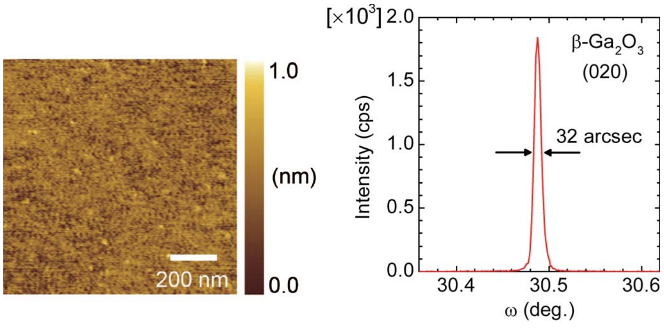
***Abstract*—We fabricated gallium oxide ($\mathbf{Ga_2O_3}$) Schottky barrier diodes using $\boldsymbol{\beta-Ga_2O_3}$ single-crystal substrates produced by the floating-zone method. The crystal quality of the substrates was excellent; the X-ray diffraction rocking curve peak had a full width at half-maximum of 32 arcsec, and the etch pit density was less than $\mathbf{1 \times 10^4}$ $\mathbf{cm^{-2}}$. The devices exhibited good characteristics, such as an ideality factor close to unity and a reasonably high reverse breakdown voltage of about 150 V. The Schottky barrier height of the $\mathbf{Pt/\boldsymbol{\beta}}$–$\mathbf{Ga_2O_3}$ interface was estimated to be 1.3–1.5 eV.**

***Index Terms*—Breakdown voltage, gallium oxide ($\mathbf{Ga_2O_3}$), Schottky barrier diode (SBD), single crystal.**

I. INTRODUCTION

THE SEMICONDUCTOR, i.e., gallium oxide (Ga_2O_3), will be useful in next-generation high-power devices because of its excellent material properties and ease of mass production. β–Ga_2O_3 has an extremely large band gap of 4.8–4.9 eV [1]. The breakdown electric field is expected to be 8 MV/cm, from the relation between the band gaps and the breakdown fields of other semiconductors [2]. This value is more than twice that of silicon carbide (SiC) or gallium nitride (GaN). The electron mobility is experimentally estimated to be 300 $cm^2/(V \cdot s)$ for the range of electron density from 10^{15} to 10^{16} cm^{-3}, which is a typical range used for the drift layer of vertical power devices [3]. Although this value is slightly low, Baliga's figure-of-merit [4], which is the basic parameter to show how suitable a material is for power devices, is four or more times larger than that of SiC or GaN. This is because Baliga's figure-of-merit is proportional to the cube of the breakdown electric field but only linearly proportional to the electron mobility. These estimates indicate that Ga_2O_3 power devices would outperform SiC and GaN ones. Another important feature is that large single-crystal substrates can be fabricated at atmospheric pressure with melt-growth methods, such as the floating zone (FZ) [5] or the edge-defined film-fed growth [6]. This fact would directly lead to an easy and low-cost means of mass production and is a big advantage over SiC, GaN, and diamond substrates.



(a) (b)

Fig. 1. (a) Surface atomic force microscope image after CMP and (b) X-ray diffraction rocking curve peak from (020) plane of the $\beta-Ga_2O_3$ (010) substrate.

Recently, we succeeded in fabricating Ga_2O_3 metal–semiconductor field-effect transistors on single-crystal β–Ga_2O_3 substrates [2]. The devices exhibited characteristics that were good enough for practical power device applications. In this letter, we report on Ga_2O_3 Schottky barrier diodes (SBDs) fabricated by using single-crystal β–Ga_2O_3 (010) substrates. The devices also showed good characteristics, such as an ideality factor close to 1.0 and a reasonably high reverse breakdown voltage V_{BR}.

II. EXPERIMENTAL PROCEDURE

We used unintentionally doped β–Ga_2O_3 (010) substrates prepared from a bulk crystal grown by the FZ method. The bulk crystal was cut into pieces along the (010) plane, and chemical mechanical polishing (CMP) was performed on both sides. Fig. 1(a) shows the surface morphology of the Ga_2O_3 substrate after CMP. The surface was atomically flat with a root mean square roughness of 0.11 nm in a 1×1 μm square. The substrate was about 10 mm in diameter and 600 μm in thickness. After CMP, we cleaned the substrate with organic solvent (acetone and methanol), acid [HF (46%) and $H_2SO_4 + H_2O_2$], and ultra pure water.

The crystal quality of the Ga_2O_3 substrate was excellent. The X-ray diffraction rocking curve peak from the (020) plane had a full width at half-maximum of 32 arcsec, as shown in Fig. 1(b). The etch pit density was less than 1×10^4 cm^{-2}. Note that we did the etching by using heated 85 wt.% H_3PO_4 at 135 °C [7].

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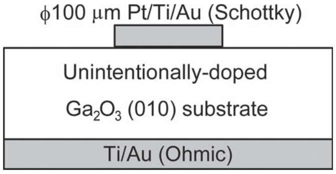

Fig. 2. Cross-sectional schematic illustration of Ga_2O_3 SBDs.

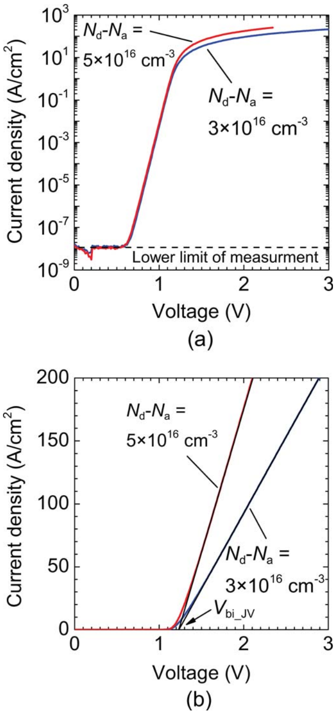

Fig. 3. Forward J–V characteristics of two different Ga_2O_3 SBDs in (a) single logarithmic and (b) linear plots.

The substrate exhibited n-type conductivity due to unintentional silicon doping from the high-purity Ga_2O_3 powder source (99.999%) for the melt growth. The effective donor concentration $N_d - N_a$ was uniform in the depth direction but distributed in the range of 0.3–1 $\times$ 10^{17} cm^{-3} in the in-plane direction. The distribution showed a decreasing tendency from the center of the substrate toward the edge.

Fig. 2 shows a cross-sectional schematic illustration of Ga_2O_3 SBDs fabricated in this letter. First, circular Schottky contacts with a diameter of 100 μm were fabricated on the front side of the substrate as anode electrodes using standard photolithography patterning, Pt (15 nm)/Ti (5 nm)/Au (250 nm) evaporation, and liftoff. Next, reactive ion etching (RIE) was performed on the back side using a mixture gas of BCl_3 (35 sccm) and Ar (5 sccm) for 5 min, followed by evaporation of Ti (20 nm)/Au (230 nm). The etching depth was about 100 nm. The RIE treatment changes the electrode properties from Schottky to ohmic and significantly decreases the contact resistance [2].

III. RESULTS AND DISCUSSION

Fig. 3(a) and (b) shows the forward current density–voltage (J–V) characteristics of two different Ga_2O_3 SBDs with $N_d - N_a = 3 \times 10^{16}$ and 5×10^{16} cm^{-3}, which were fabricated at different places on the same substrate. Note that the J value simply corresponds to the current divided by the electrode area. We were not able to measure J below 1×10^{-8} A/cm^2, due to the limitations of the measurement instrument. The ideality factors of the SBDs were estimated to be 1.04–1.06 from the subthreshold slopes in Fig. 3(a). These values are close to the ideal value of one (i.e., unity) and indicated the high crystal quality of the substrate and good Schottky interface properties. On the other hand, the ON-resistances were relatively high, at 7.85 and 4.30 m$\Omega \cdot$ cm^2, as determined from the slope of the linear regions in Fig. 3(b). These relatively high values are because of the low conductivity of the substrate due to the low electron density. Therefore, they can be improved simply by using a typical SBD structure consisting of an $n^- - Ga_2O_3$ epitaxial layer on an $n^+ - Ga_2O_3$ substrate.

TABLE I
SCHOTTKY BARRIER HEIGHTS OF Pt/β–Ga_2O_3 INTERFACE

N_d-N_a (cm^{-3})	from J-V				from C-V	
	J_s (A/cm^2)	$q\phi_{B\_Js}$ (eV)	qV_{bi_JV} (eV)	$q\phi_{B\_JV}$ (eV)	qV_{bi_CV} (eV)	$q\phi_{B\_CV}$ (eV)
3×10^{16}	6.5×10^{-19}	1.47	1.23	1.36	1.39	1.52
5×10^{16}	9.0×10^{-19}	1.46	1.23	1.35	1.40	1.52

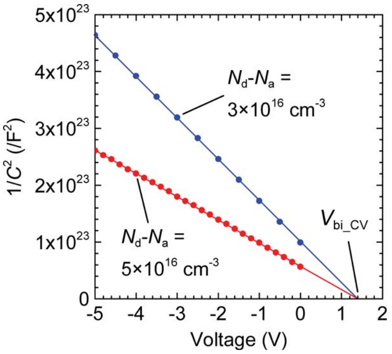

Fig. 4. $1/C^2 - V$ characteristics of Ga_2O_3 SBDs.

We estimated the Schottky barrier height ($q\phi_B$) of the Pt/β–Ga_2O_3 interface from the J–V and capacitance–voltage (C–V) characteristics. The results are summarized in Table I. Here, J_s is the saturation current density, and $V_{\mathrm{bi\_JV}}$ and $V_{\mathrm{bi\_CV}}$ are the built-in potentials extracted from the J–V and C–V characteristics, respectively. J_s was determined by the extrapolation of J to zero voltage in Fig. 3(a). $V_{\mathrm{bi\_JV}}$ was determined from the extrapolation of J to zero, as shown in Fig. 3(b). $V_{\mathrm{bi\_CV}}$ was determined from the $1/C^2 - V$ lines shown in Fig. 4, for 1/C^2 to zero. $q\phi_{B\_\mathrm{Js}}$ was calculated from the following formulas [8]:

$$q\phi_{B\_\mathrm{Js}} = kT \ln\left(\frac{A^* T^2}{J_s}\right) \tag{1}$$

$$A^* = \frac{4\pi q m^* k^2}{h^3} \tag{2}$$

where k, h, q, and T are the Boltzmann constant, the Plank constant, the elementary charge, and the temperature, respectively. A^* is the effective Richardson constant. By using the

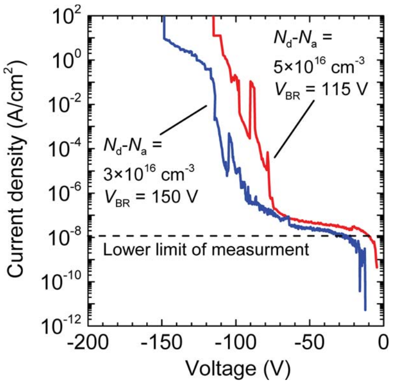

Fig. 5. Reverse J–V characteristics of Ga_2O_3 SBDs.

electron effective mass of β–Ga_2O_3 $m^* = 0.342\ m_0$ [9], A^* for β–Ga_2O_3 is calculated to be 41.1 A cm^{-2} · K^{-2} at room temperature. m_0 is the electron rest mass. $q\phi_{B\_\mathrm{JV}}$ and $q\phi_{B\_\mathrm{CV}}$ were calculated from the following formulas:

$$q\phi_{B\_\mathrm{JV}} = qV_{\mathrm{bi\_JV}} + (E_C - E_F) \tag{3}$$

$$q\phi_{B\_\mathrm{CV}} = qV_{\mathrm{bi\_CV}} + (E_C - E_F) \tag{4}$$

where E_c is the energy of the conduction-band edge, and E_F is the Fermi energy at thermal equilibrium. $E_C - E_F$ was calculated from the following formulas:

$$E_C - E_F = kT \ln\left(\frac{N_C}{n}\right) \tag{5}$$

$$N_C = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{\frac{3}{2}} \tag{6}$$

where N_c and n are the effective density of states of the conduction band and the electron density, respectively. We assumed that n was equal to $N_d - N_a$. Although there is some variation among the different measurement and calculation methods, these results indicate that the $q\phi_B$ of the Pt/β–Ga_2O_3 interface was about 1.3–1.5 eV.

We compared the results with the reported data for other typical widegap semiconductor materials. The following values were reported for SiC or GaN.

Pt/6H-SiC (0001) Si-face: 1.06–1.33 eV [10];

Pt/4H-SiC Si-face: 1.39 eV [11];

Pt/GaN: 1.11–1.27 eV [12].

The $q\phi_B$ value of Pt/β–Ga_2O_3 interface was comparable or a little larger than those of Pt/SiC and Pt/GaN.

Fig. 5 shows the reverse J–V characteristics. The reverse V_{BR} values were about 150 and 115 V for $N_d - N_a = 3 \times 10^{16}$ and 5×10^{16} cm^{-3}, respectively. We defined the voltage at which the device was permanently destroyed as V_{BR}. These values are reasonably high since the devices had a simple structure without passivation or edge termination. Note that the catastrophic breakdown always happened at the cathode electrode edge, i.e., it was not an intrinsic one limited by the breakdown field. Therefore, a further increase in V_{BR} can be expected just by using common high-voltage SBD structures with such as a field plate and a guard ring for avoiding the concentration of electric field at the edge.

IV. CONCLUSION

We have fabricated Ga_2O_3 SBDs by using single-crystal β–Ga_2O_3 (010) substrates. A good ideality factor close to 1.0 and reasonably high V_{BR} have been demonstrated by using the simple device structure and process technique. These results can be attributed to the high crystal quality of the Ga_2O_3 substrates and indicate the great potential of Ga_2O_3 power devices for future applications. It also includes the possibility of Ga_2O_3 heterostructures with Al_2O_3, In_2O_3, and their alloys, as is the case in other compound semiconductors.

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