High-Performance Ga$_2$O$_3$ Diode Based on Tin Oxide Schottky Contact

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Abstract—A high-performance Schottky diode based on a 600-μm-thick Cr-doped β-Ga$_2$O$_3$ single crystal has been fabricated using SnO$_x$ as the Schottky contact. The SnO$_x$ film was deposited in argon/oxygen mixture gas to ensure an oxygen-rich stoichiometry in Ga$_2$O$_3$ near the Schottky interface, thus reducing oxygen deficiency related interface state density. The SnO$_x$ film included three components: Sn, SnO, and SnO$_2$, as revealed by X-ray photoelectron spectroscopy characterization. The high quality Ga$_2$O$_3$ single crystal grown by an edge-defined film-fed method has a carrier concentration of $1.0 \times 10^{18}$ cm$^{-3}$ and an electron mobility of $90$ cm$^2$/Vs. Current density-voltage characteristics of the Schottky diode demonstrated high performance with a large barrier height of 1.17 eV, a close-to-unity ideality factor of 1.02, and a high rectification ratio beyond 10$^{10}$. Frequency-dependent capacitance and conductance analysis revealed that the maximum active interface state density is $5.92 \times 10^{13}$ at a frequency of 7 kHz.

Index Terms—Ga$_2$O$_3$, Schottky barrier diodes (SBDs), tin oxide (SnO$_x$).

I. INTRODUCTION

GALLIUM oxide, Ga$_2$O$_3$, has attracted extensive attention for the next generation power electronics and solar-blind optoelectronics due to its large breakdown electric field strength of 8 MV/cm and extremely wide bandgap of 4.5-4.9 eV [1]-[6]. Schottky contact quality is critical for Schottky diode power electronics, because it determines their key performances such as breakdown voltage, leakage current, and rectification ratio, $I_{on}/I_{off}$ [7]-[13]. Recently, many efforts have been made to improve Ga$_2$O$_3$ Schottky contact quality [7]-[11]. Konishi et al. demonstrated that fluoride ion treatment can realize a barrier height, $\phi_B$, increase of 0.3 eV of Ga$_2$O$_3$ Schottky barrier diodes, SBDs [9]. Sasaki et al. developed MOS-type Ga$_2$O$_3$ SBDs with improved $\phi_B$ of 1.07 eV but a slight deteriorated ideality factor, $n$ [10]. Most of the reported Ga$_2$O$_3$ Schottky contacts used high work function metals such as Pt, Pd, Ni, and Au, for achieving large $\phi_B$ [6], [7], [9], [10], [12], [13]. To the best of our knowledge, only Müller et al. demonstrated oxidized noble metal PtO$_x$ as Ga$_2$O$_3$ Schottky contacts, and the diodes showed an extremely large $\phi_B$ of 1.94 eV, an ideal $n$ of 1.09, and a high $I_{on}/I_{off}$ of $4.5 \times 10^9$ at ±2 V [11]. For ZnO and InGaZnO SBDs, it has been demonstrated that a series of oxides such as AgO$_x$ [14], PtO$_x$ [15], PdO$_x$ [16], and Ru-Si-O [17], [18], at Schottky interfaces can improve the Schottky contact quality due to reduction of oxygen deficiency related interface state density by ensuring oxygen-rich stoichiometry near the Schottky interface [14]-[18].

In contrast to the high work function metals such as Pt, Pd, Au, Ni, etc. which are usually expensive, Sn has a low work function and is inexpensive. In this work, we used reactively sputtered SnO$_x$ as Schottky contacts to achieve high performance Ga$_2$O$_3$ SBD, providing a new effective way to fabricate high quality Schottky contact on Ga$_2$O$_3$.

II. EXPERIMENTAL DETAILS

Cr-doped β-Ga$_2$O$_3$ single crystal was grown by edge-defined film-fed growth method, and the (100)-oriented β-Ga$_2$O$_3$ plate with a thickness of ~600 μm and a size of 2 mm × 10 mm was obtained by cleaving the bulk single crystal. To form cathode ohmic contact, firstly, one surface of the cleaved Ga$_2$O$_3$ plate was etched with inductively coupled plasma (ICP) technique using a mixture gas of BCl$_3$ (15 sccm) and Ar (5 sccm) for 2 min under the ICP/RF power of 150 W/15 W and a chamber pressure of 10 mTorr. Then, Ti/Au (40 nm/20 nm) was deposited by e-beam evaporation onto the etched Ga$_2$O$_3$ plate surface, and a rapid thermal annealing in N$_2$ gas at 350°C for 2 min was applied followed for improving the ohmic contact. A 200-nm-thick SnO$_x$ layer was deposited by reactive sputtering using a pure Sn target (99.9%, 3 inch in diameter) at room temperature with a sputtering power of 50 W. The working pressure and oxygen partial pressure, $P_O$, during the sputtering were ~ 5.7 mTorr and 3.1%, respectively. Finally, the SnO$_x$ film was capped with an e-beam evaporated Ti layer. The active area of the SBD is $7.1 \times 10^{-4}$ cm$^2$. 

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The surface morphology and roughness of the Ga2O3 plate were analyzed by an atomic force microscope (AFM, Dimension FastScanTM). The cross-sectional structure of Ti/SnOx/Ga2O3 was analyzed using a scanning electron microscope (SEM, FEI Nova 450). The microstructure of the Ga2O3 plate was elucidated by a Raman spectrometer (Renishaw in Via-Reflex) using a 532-nm wavelength laser at a power of 5 mW. The chemical composition of the SnOx film was characterized by X-ray photoelectron spectroscopy (XPS, ESCALAB 250Xi). The binding energy was calibrated by setting the C 1s signal at 284.6 eV. The current density-voltage, J-V, and capacitance-voltage, C-V, characteristics were measured using a semiconductor analyzer (Agilent 2902B) and an LCR meter (Agilent E4980A), respectively, at room temperature in dark.

### III. RESULTS AND DISCUSSION

The Ga2O3 exhibits high transmittance and a clear absorption edge at ~260 nm, as shown in Fig. 1(a), corresponding to a band gap of ~4.8 eV. AFM analysis indicates that the cleaved Ga2O3 surface is atomically flat with a root mean square roughness of 0.3 nm in an area of 1×1 µm², as shown in the inset of Fig. 1(a). The Ga2O3 plate shows ten sharp and narrow Raman active peaks located at 113, 146, 171, 201, 346, 418, 477, 630, 659, and 768 cm⁻¹, as shown in Fig. 1(b), illustrating high crystallinity of the plate. The peak at 201 cm⁻¹ correlates to the characteristic vibration and translation mode of Ga-O chains [19]. The peaks between 300 and 500 cm⁻¹ relate to deformation of Ga2O6 octahedra [20], and the peaks between 600 and 800 cm⁻¹ attribute to the stretching and bending of GaO4 tetrahedra [20].

To determine the composition of the SnOx film, an XPS measurement was carried, with the topmost native oxidized SnO2 layer on the SnOx film was sputtered away by low energy (3 keV) argon plasma bombardments to get rid of its contribution. The XPS results illustrate that three compositions of Sn, SnO, and SnO2 are included in the film, and the predominant composition is SnO. Figure 1(c) shows the Sn 3ds2 and 3dz2 spectra of with deconvoluted fittings (Gaussian + Lorentz (<30%)). The binding energy of the Sn 3dz2 and 3dz2 peaks centered at 484.4 and 492.8, 485.9 and 494.3, and 486.6 and 495.0 eV, corresponding to Sn+, Sn²+, and Sn³+, respectively [21].

The morphology and electrical properties of the SnOx/Ga2O3 SBD were investigated. Figure 2(a) shows the SEM image of the cross-sectional structure of Ti/SnOx/Ga2O3, which shows two clear and smooth interfaces: SnOx/Ga2O3 and Ti/SnOx. Using the Richardson constant of 41.1 Acm⁻²K⁻² for β-Ga2O3 [3], [22], by fitting the forward J-V curve in Fig. 2(b) with the thermionic emission theory [23], the n and ΦB,JV of the SBD are extracted as 1.02 and 1.17 eV, respectively. Here, the n and ΦB,JV is defined as the ΦB extracted by the J-V curve. The close-to-unity n indicates a very high quality Schottky interface between Ga2O3 and SnOx. Such high performance is mainly due to that the main composition SnO in the SnOx film usually contains a high density of tin vacancy defect states [24], [25]. Such tin vacancies induce oxygen dangling bonds which can compensate for oxygen vacancies in Ga2O3 at the Schottky interface. Thus, an insulating interfacial Ga2O3 layer with high oxygen stoichiometry at the SnOx/Ga2O3 interface can be formed, leading to the large barrier height and near unity ideality factor. The ideality of the contact was further supported by the very low reverse current below our detection limit.

![Fig. 1.](image1.png)

![Fig. 2.](image2.png)

The forward-bias current at V > 0.9 V is limited by the series resistance, Rs, of ~28 mΩcm² extracted from the slope of the J-V curve in linear scale in Fig. 2(b). The Rs of the SBD is larger than the resistance of the Ga2O3 layer, which is 4.2 mΩcm² given by $R = L/\mu_n n$. Here, $L$ is the thickness of the Ga2O3, $\mu_n$ is the mobility and is 90 cm²/Vs extracted by Hall effect measurement, and $n$ is the carrier concentration and is 1.0 × 10²² cm⁻³.
10\textsuperscript{18} \text{cm}^{-3} \text{ extracted by Hall effect measurement. The large } R_s \text{ of SBD is contributed by the resistance of the insulating interfacial Ga}_2\text{O}_3 \text{ layer. The SBD shows high performances such as a high } I_{\text{on/off}} \text{ of } > 10^{10}, \text{ a large } \Phi_{\text{b,yr}} \text{ of } 1.17 \text{ eV, and a close-to-unity } n \text{ of } 1.02, \text{ which are comparable and even better than the reported high performance Ga}_2\text{O}_3 \text{ SBDs with noble metal Schottky contacts [8], [10]-[12], [22], [26], [27].}

To better understand the high quality Schottky contact interface, \textit{C-V} measurement was performed and the results are plotted in Fig. 2(c) and (d). The built-in potential, \( V_{\text{bi}} \), of 1.25 V and the background doping density in the depletion region, \( N_{\text{d,dep}} \), of 1.69 \times 10\textsuperscript{18} \text{cm}^{-3} \text{ were obtained by linear fitting of the \textit{C-V} curve [23], as shown in Fig. 2(c) and Table I. This net donor concentration in the Ga}_2\text{O}_3 \text{ extracted from the \textit{C-V} characteristic is in reasonable agreement with the value of } 1.0 \times 10\textsuperscript{18} \text{ cm}^{-3}. \text{ The high doping limited the depletion region thickness to } 29 \text{ nm at } 0 \text{ V as shown in Fig. 2(d). The free charge density of the Ga}_2\text{O}_3 \text{ layer estimated from the } R_s \text{ value is } 1.47 \times 10\textsuperscript{17} \text{ cm}^{-3} \text{ by using an electron mobility of } 90 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} [28]. \text{ The } \text{SnO}_x/\text{Ga}_2\text{O}_3 \text{ SBD has a very low } N_{\text{d,dep}}/N_i \text{ ratio of } 11, \text{ indicating very low defect density, and this agrees well with the close-to-unity } n \text{ of } 1.02. \text{ The Schottky barrier extracted from the } \text{C-V} \text{ characteristic, } \Phi_{\text{b,CV}}, \text{ is } 1.34 \text{ eV by using } \Phi_{\text{b}} = qV_{\text{bi}} + kT/q \ln(N_i/N_d) [29], \text{ where the last term describing the energy gap between the conduction band and Fermi level is deduced to be } 0.09 \text{ eV, and the conduction band density of states } N_c \text{ is } 5.2 \times 10\textsuperscript{18} \text{ cm}^{-3} [29]. \text{ A close agreement of } \Phi_{\text{b,yr}} (1.17 \text{ eV}) \text{ and } \Phi_{\text{b,CV}} (1.34 \text{ eV}) \text{ indicates that the } \text{SnO}_x/\text{Ga}_2\text{O}_3 \text{ Schottky contact has relatively high uniformity.}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Frequency dependence of (a) \textit{C-V} and (b) \textit{G/\omega-V} characteristics of the SnO}_x/\text{Ga}_2\text{O}_3 \text{ SBD. (c) Partially enlarged view of \textit{G/\omega-V} curve. (d) Variation of } N_{\text{ss}} \text{ as a function of the frequency.}
\end{figure}

To evaluate the SnO}_x/\text{Ga}_2\text{O}_3 \text{ interface state density, the dependences of } \textit{C-V} \text{ and conductance-voltage (\textit{G/\omega-V}) characteristics of the diode on the applied frequencies (1, 3, 5, 7, 10, 30, 50, 70, 100, 300, 500, 700, 1000 kHz) were investigated, as shown in Fig. 3(a) - (c). Here, } \omega = 2\pi f \text{ is the angular frequency, and } G \text{ is the conductance. The value of } C \text{ increased slightly with increasing applied bias voltage firstly due to the decreasing depletion width, and then showed an anomalous peak at about 0.8 V due to the switching on of the diode, indicated also by Fig. 2(b) [30], [31]. This peak shows a decrease in value and a shift toward negative biases in position with increasing frequency. Such behavior is mainly due to the presence of interface states with various lifetimes [30], [31]. At low frequencies, the trap and de-trap of charges can follow the ac signal, and thus the charges at traps can contribute as excess capacitance to the measured capacitance (\( C_m \)). At high frequencies with voltage operation speed faster than the charge trap and de-trap speed, the charges at traps cannot contribute to the \( C_m \) any more. Figure 3(b) and (c) shows that under positive bias (-0.75-1 V), the conductance increases slowly down with the increase of frequency, indicating the existence of interface states with different response time, and this is in good coordinate with the frequency dependent \( C_m \).

\begin{table}[h]
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\begin{tabular}{|c|c|c|c|c|c|}
\hline
\( \Phi_{\text{b,yr}} \) & \( n \) & \( R_s \) & \( I_{\text{on/off}} \) & \( N_i \) & \( \Phi_{\text{b,CV}} \) \\
(eV) & (m\Omega \text{cm}^2) & (\text{mA}) & (\text{cm}^{-3}) & (\text{cm}^{-3}) & (\text{eV}) \\
\hline
1.17 & 1.02 & 28 & >10\textsuperscript{10} & 1.47 \times 10\textsuperscript{17} & 1.25 \times 10\textsuperscript{18} & 1.34 \text{ eV} \\
\hline
\end{tabular}
\caption{Characteristics of the SBD from \textit{J-V} and \textit{C-V} measurements}
\end{table}

In summary, a high performance \( \beta \)-Ga}_2\text{O}_3 \text{ Schottky diode was fabricated using SnO}_x \text{ as Schottky contact. The SnO}_x \text{ film contains three components: Sn, SnO}_x \text{, and SnO}_2 \text{, of which SnO}_x \text{ is the main component. The ultra-high quality Schottky contact interface was indicated by a near-unity ideality factor of } 1.02, \text{ a large barrier height of } 1.17 \text{ eV, and a high on/off ratio of } > 10\textsuperscript{10}. \text{ This was achieved by that tin vacancies with oxygen dangling bonds in SnO}_x \text{ compensate for oxygen vacancies in Ga}_2\text{O}_3 \text{ at the Schottky interface and reduce the interface state density. The maximum active interface state density obtained by Hill-Coleman method is } 5.92 \times 10\textsuperscript{13} \text{ eV}^{-1}\text{cm}^{-2}. \text{ The high-performance SnO}_x/\text{Ga}_2\text{O}_3 \text{ diode shows that SnO}_x \text{ film can be an excellent Schottky contact, which is inexpensive and convenient to deposit.}

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