Electrical Characterizations of Planar Ga$_2$O$_3$ Schottky Barrier Diodes

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Abstract: In this work, a Schottky barrier diode (SBD) is fabricated and demonstrated based on the edge-defined film-fed grown (EFG) Ga$_2$O$_3$ crystal substrate. At the current stage, for high resistance undoped Ga$_2$O$_3$ films and/or bulk substrates, the carrier concentration (and other electrical parameters) is difficult to be obtained by using the conventional Hall measurement. Therefore, we extracted the electrical parameters such as on-state resistance ($R_{on}$), Schottky barrier height ($\Phi_B$), the ideal factor ($n$), series resistance ($R_s$) and the carrier concentration ($N_d$) by analyzing the current-density–voltage (J–V) and capacitance–voltage (C–V) curves of the Ga$_2$O$_3$-based SBD, systematically. The detailed measurements and theoretical analysis are displayed in this paper.

Keywords: Ga$_2$O$_3$; Schottky diode; I–V; C–V

1. Introduction

Owing to the suitable energy band gap ($E_g$) of $\sim$4.9 eV, a high Baliga’s figure of merit (FOM) of more than 3200, a high Huang’s material FOM of 279, Johnson’s FOM of 2844, and a high theoretical breakdown field ($E_{BR}$) of $\sim$8 MV/cm, gallium oxide (Ga$_2$O$_3$) has been widely employed to construct optical detectors and power electronics along with low direct current losses and stable operations [1–3]. Till now, Ga$_2$O$_3$-based Schottky barrier diodes (SBDs) have achieved high breakdown voltages of 2300 V in a vertical edge-terminated SBD [4] and 3000 V in a lateral field-plated (FP) SBD [5], suggesting strong competitiveness superior to GaN and SiC. Owing to the low dark current and fast response speed [6], the Ga$_2$O$_3$-based Schottky diode photodetectors also have drawn much attention for high performances. For instance, the high photo responsivity (R), high external quantum efficiency (EQE), large specific detectivity ($D^*$), and short response time in Ni/β-Ga$_2$O$_3$ [7], Pt/ε-Ga$_2$O$_3$ [8], graphene/β-Ga$_2$O$_3$ [9], and MXenes/β-Ga$_2$O$_3$ [10] photodiodes are realized.

In electronic devices, the electrical parameters, such as carrier concentration, are key issues that affect the device design, construction, and operation. For doped Ga$_2$O$_3$ and/or the flakes exfoliated from the bulk single crystal, the electron concentrations are reported as $10^{18} - 10^{20}$ cm$^{-3}$ [11–14], while in fact, the un-doped Ga$_2$O$_3$ has a high resistance due to the large $E_g$, thus it is very hard to obtain some electrical parameters via the conventional...
Hall measurement. Additionally, a systematic and comprehensive study for electrical characterizations such as on-state resistance ($R_{\text{on}}$), Schottky barrier height ($\phi_B$), the ideal factor ($n$), series resistance ($R_s$) and the carrier concentration ($N_d$) of Ga$_2$O$_3$ Schottky devices is less reported. Therefore, to solve this problem, we fabricated a Ga$_2$O$_3$-based SBD, and then performed the electrical characterizations through the J–V, H(J)–J, and C–V characteristic curves.

2. Experimental Section

The Ga$_2$O$_3$ crystal substrate was grown by the edge-defined film-fed grown method, whose scale is 10 mm $\times$ 10 mm. For fabricating the Schottky diode, photolithography, lift-off, and electron beam vapor techniques were used to finish the Ni/Au (Schottky, 30 nm/100 nm) and Ti/Au (Ohmic, 30 nm/100 nm) electrode patterns as shown in Figure 1b. X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and scanning electron microscopy (SEM) were performed to verify the quality of the Ga$_2$O$_3$ crystal substrate. The electrical test was executed with Keithley 4200 analysis equipment in the air at room temperature. The area of the electrode pattern is $2.4 \times 10^{-3}$ cm$^2$. Figure 1a is the schematic of the planar Ga$_2$O$_3$ SBDs.

Figure 1. (a) The geometry of the Schottky diodes with Ni/$\beta$–Ga$_2$O$_3$/Ti structure. (b) Optical microscopy image of the fabricated Schottky diode.

3. Results and Discussion

As shown in Figure 2a, the XRD pattern of the edge-defined film-fed (EFG)-grown Ga$_2$O$_3$ substrate is displayed, showing (201), (400), (401), (402), and (601) orientations. The prepared Ga$_2$O$_3$ crystal is polycrystalline $\beta$-Ga$_2$O$_3$. The SEM image of the surface of the Ga$_2$O$_3$ substrate is portrayed in Figure 2a inset, suggesting a decent crystallization with well-defined boundaries and uniform claviform grains. In Figure 2b, the binding energies of Ga 2$p_{1/2}$, Ga 2$p_{3/2}$, and O 1$s$ are determined to be 1144.7 eV, 1117.9 eV, and 530.6 eV by XPS, they are similar to the reported values as shown in Table 1, verifying the formation of the Ga$_2$O$_3$ semiconductor.
Figure 2. (a) The X-ray diffraction (XRD) pattern and (b) the X-ray photoelectron spectroscopy (XPS) of the Ga$_2$O$_3$ substrate, of which the scanning electron microscope (SEM) image is shown in (a) inset.

Table 1. Comparison of the binding energies of Ga 2p$_{1/2}$, Ga 2p$_{3/2}$, and O 1s.

|       | Ga 2p$_{1/2}$ (eV) | Ga 2p$_{3/2}$ (eV) | O 1s (eV) | Reference |
|-------|-------------------|-------------------|----------|-----------|
|       | 1144.7            | 1117.9            | 530.6    | This work |
|       | 1145.18           | 1118.28           | 531.18   | [15]      |
|       | 1145              | 1120              | 530.7    | [16]      |
|       | 1145.5            | 1118.5            | 531.4    | [17]      |

In Figure 3a, current density–voltage (J–V) curves of the Ni/Ga$_2$O$_3$/Ti Schottky diode are shown in linear-scale and semi-log scale, respectively. The output current density is $3.04 \times 10^{-2}$ A/cm$^2$ and $1.25 \times 10^{-7}$ A/cm$^2$ at 2 V and −2 V, respectively, translating to a high rectifying ratio of $2.44 \times 10^5$; the fabricated device is on-state at forward voltages while off-state at reverse voltages. By extrapolating the linear region of the log-scaled J–V curve in Figure 3a (red line) to obtain its slope, the on-state resistance ($R_{on}$) is estimated to be 51.5 Ω cm$^2$. Furtherly, we use the thermionic emission (TE) model to describe the Ni/Ga$_2$O$_3$/Ti Schottky diode [18]:

$$J = J_s(e^{\frac{qV}{nKT}} - 1)$$  \hspace{1cm} (1)

$$J_s = A^*T^2e^{-\frac{\phi_B}{kT}}$$  \hspace{1cm} (2)

$$\phi_B = \frac{kT}{q}\ln\left(\frac{A^*T^2}{J_s}\right)$$  \hspace{1cm} (3)

and

$$A^* = \frac{qnm^*k^2}{2\pi^2\hbar^3}$$  \hspace{1cm} (4)

where $q$ is the electron charge, $V$ is the applied voltage, $J_s$ is the reverse saturation current, $n$ is the ideal factor, $k$ is the Boltzmann constant, $T$ is the thermodynamic temperature, $\phi_B$ is the Schottky barrier height, and $A^*$ is the Richardson constant. For Ga$_2$O$_3$, its effective electron mass $m^* = 0.342 m_0$, with $m_0$ the mass of the free electron, thus the $A^*$ of Ga$_2$O$_3$ is calculated to be 41.07 A/cm$^2$ K$^2$ [19].
As displayed in Figure 3b, with the TE model described in Equations (1)–(4), the \( n \), \( \phi_B \) and turn-on voltage \( (V_{\text{on}}) \) are determined to be 1.34, 0.93 eV, and 0.52 V, respectively. In Figure 3b inset, the \( J_s \) of the Schottky diode is \( 9.35 \times 10^{-10} \, \text{A/cm}^2 \). The \( n \) value between 1 and 2, nearer to 1, indicates a decent Schottky electrical behavior in the fabricated device. The \( V_{\text{on}} \) suggests a built-in potential difference \( (V_{\text{bi}}) \) of 0.52 eV. In fact, the work function of Ni \((W_m)\) is 5.15 eV [20], and the electron affinity of Ga\(_2\)O\(_3\) \((\chi_s)\) is 4.00 eV [21]. The Ni-Ga\(_2\)O\(_3\) energy band diagram before they make contact is shown in Figure 4a. According to the Schottky–Mott rule [22,23], the Ni-Ga\(_2\)O\(_3\) interface barrier is about 1.15 eV, i.e., the difference between \( W_m \) and \( \chi_s \). After they make contact, as given Figure 4b, the conduction and valence energy band edge \((E_c \text{ and } E_v)\) bend up, owing to the electron transferring to the electrode. The formation of the \( \phi_b \) indicates a barrier for electron transport in the device, thus the device has a \( V_{\text{on}} \) and rectifying effect.

![Figure 3](image1)

**Figure 3.** (a) The current density–voltage (I–V) curves of the Ni/Ga\(_2\)O\(_3\)/Ti Schottky diode, inset is the equivalent circuit diagram, (b) the \( n \), \( J_s \), and \( V_{\text{bi}} \) based on thermionic emission (TE) model.

![Figure 4](image2)

**Figure 4.** The energy band diagram of the Ni/Ga\(_2\)O\(_3\)/Ti Schottky diode (a) before and (b) after contact.

For the device, the series resistance \( (R_s) \) is a key parameter affecting the performances of the Schottky diode, modeled by a combination of a capacitance \( (C_j) \) and a resistor \( (R_j) \) as shown in Figure 2a inset. When the current flow is in the diode, it has a relationship with voltages applied on the device [24]:

\[
V_D = V - JAR_s
\]
where $V_D$ is the voltage on the two sides of the diode, $V$ is the applied voltage, and $A$ is the area of the electrode. Other than the homojunction device, in the Schottky junction similar to the heterojunction, the key role in determining the electrical behavior could not be told by diffusion current model. When $V_D > 3kT/e$, the current in diode could be described by the thermionic electron model:

$$J = J_s \exp\left(\frac{e(V - JAR_s)}{nkT}\right)$$

Thus,

$$V = AR_s J + n\phi_B + \frac{nkT}{e} \ln\left(\frac{J}{A^*T^2}\right)$$

$$dV/dlnJ = AR_s J + \frac{nkT}{e}$$

moreover, $H(J)$ is defined as

$$H(J) = V - \frac{e}{nkT} \ln\left(\frac{J}{A^*T^2}\right) = AR_s J + n\phi_B$$

based on Equation (8), through the linear fitting $(dV/dlnJ)$-$J$ curve shown in Figure 5a (blue dot-line curve), the $n$ and $R_s$ of the Schottky diode are estimated to be 1.67 and 45.5 $\Omega$ cm$^2$. Then, according to the Equation (9), $\phi_B$ and $R_s$ of the Schottky diode could be obtained as 0.86 eV and 46.6 $\Omega$ cm$^2$, by fitting the H(J)-J curve displayed in Figure 5a (green dot-line curve). In addition, according to the energy band diagram in Figure 3, $\phi_B$ can be demonstrated as $\phi_B = eV bi + (E_c - E_F)$ [18], where $E_c$ and $E_F$ are the conduction minimum and Fermi level of the Ga$_2$O$_3$. $E_c - E_F = kT \ln\left(\frac{N_c N_d}{N_a}\right)$, where $N_c$ is effective state density at conduction band, expressed as $N_c = \frac{2m^*kT^{3/2}}{h^2}$, thus the electron concentration of the Ga$_2$O$_3$ can be calculated to be $1.04 \times 10^{19}$ cm$^{-3}$ [25]. What’s more, based on the Norde’s method [26], a function $F(V)$ is defined as:

$$F(V) = \frac{V}{2} - \frac{kT}{e} \ln\left(\frac{J(V)}{A^*T^2}\right)$$

so, $\phi_B$ and $R_s$ could be expressed as:

$$\phi_B = F(V_0) + \frac{V_0}{2} - \frac{kT}{e}$$

and

$$R_s = \frac{kT}{e f(V_0) A}$$

where $V_0$ is the voltage at the rock bottom of this function, $F(V_0)$ and $J(V_0)$ are the corresponding functions of $V_0$. As shown in Figure 5b, the $V_0$ has been marked as 0.45 V. On the basis of Equations (10)–(12), $\phi_B$ and $R_s$ of the Schottky diode could be obtained as 1.04 eV and 112.1 $\Omega$ cm$^2$. 


The Schottky barrier region in a Schottky diode could be regarded as a planar capacitance, which can be shown as \( C = \frac{\varepsilon_s\varepsilon_0}{W} \) \[25,27\], where \( W \) is the width of the depletion, \( \varepsilon_s \) and \( \varepsilon_0 \) are the permittivity of Ga\(_2\)O\(_3\) (\( \varepsilon_s \approx 10 \)) and vacuum permittivity \((8.85 \times 10^{-12} \text{ F/m})\).

Based on Poisson’s equation, it can be described as:

\[
\frac{1}{C^2} = \frac{2}{qN_D \varepsilon_0 \varepsilon_s A^2} (V_{bi} - V - \frac{kT}{q})
\]  \( (13) \)

As shown in Figure 6a, the capacitance–voltage (C–V) and \( \frac{1}{C^2} \)-V curves are displayed with a frequency \( f \) of 100 kHz, and it can be clearly seen that the C decreases from \( 1.75 \times 10^{-10} \text{ F} \) to \( 1.27 \times 10^{-10} \text{ F} \), with a gradual slowing rate. With Equation (13), the \( N_D \) could be fitted through the \( \frac{1}{C^2} \)-V curve to be \( 4.36 \times 10^{17} \text{ cm}^{-3} \). In addition to Figure 6b, the C is almost unchanged with different frequencies, due to the fact that the current in a Schottky diode is caused by the entrance of a majority carrier into the metal side instead of the charge accumulation, i.e., there is no storage effect, thus no diffusion capacitance. Such characterization is beneficial in constructing high-frequency devices for Ga\(_2\)O\(_3\).
Table 2 lists and compares the basic electrical parameters of some Ga$_2$O$_3$ SBDs in the past two years. From the table, we comprehensively discussed and calculated the basic electrical parameters by different analysis methods of $J$–$V$ and $C$–$V$.

| Substrate | Anode | Metal | $V_{br}$ (V) | $I_{on}$ ($I_{off}$) | $n$ | $qV_{bi}$ (eV) | $q\phi_B$ (eV) | $N_d$ ($cm^{-3}$) | $R_{on}$ (mΩ·cm$^2$) | $R_s$ (mΩ·cm$^2$) | Ref |
|-----------|-------|-------|-------------|----------------|-----|---------------|---------------|-----------------|-----------------|----------------|------|
| Wafer (100) | Ni | - | $2.44 \times 10^5$ | - | - | 1.34 | 0.52 | 0.93 | $4.36 \times 10^{17}$ | 51.5 | 45.5 | This work |
| Epi layer (001) | Ni | 261 | - | - | - | 1.21 | 0.74 | - | $1.77 \times 10^{16}$ | 77.3 | - | [27] |
| Wafer (201) | Ni | 23 | $2 \times 10^{11}$ | - | - | 1.31–1.64 | 1.96 $\times 10^{18}$ | 1.54 | - | - | [28] |
| Film (100) | Mo | 260 | - | - | - | 1.55 | - | - | $2 \times 10^{17}$ | - | - | [29] |
| Wafer (201) | Ni/Pt | - | - | - | - | 1.37 | - | - | $1.45 \times 10^{18}$ | - | - | [30] |
| Epi layer (001) | Ni | - | $1 \times 10^{10}$ | - | - | 1.17 | - | 1.02 | $6.9 \times 10^{15}$ | 40 | - | [31] |

4. Conclusions

In this work, an EFG-grown Ni/Ga$_2$O$_3$/Ti Schottky diode is fabricated and characterized. By different analysis methods of $J$–$V$ and $C$–$V$, its electrical parameters such as on-state resistance ($R_{on}$), Schottky barrier height ($\phi_B$), the ideal factor ($n$), series resistance ($R_s$) and the carrier concentration ($N_d$) are obtained and discussed, systematically and comprehensively. The further investigation of Ga$_2$O$_3$ materials and devices is in inherent demand due to its excellent properties and the prospect of applications.

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