Electrical characterisation of β-Ga_2O_3 Schottky diode for deep UV sensor applications

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Abstract**—** β-Ga_2O_3 is a promising semiconductor for electronic devices. In the present work we have demonstrated a novel method for manufacturing a β-Ga_2O_3 Schottky diode, in which the same electrode material is used for both contacts. The device is tested it for its applicability in deep UV sensing. Devices were manufactured directly onto **β**-Ga_2O_3 (010) wafer material. From the perspective of diode performance, a high rectification ratio of 1.5x10^7 and high forward current of 17.58 mA/cm^2 at -5 V bias was obtained. A responsivity of 12.5 mA/W was recorded when irradiated with light possessing a wavelength of 254 nm. Importantly, detailed analysis is conducted in order to evaluate the performance of the Schottky diode using Cheung's and Norde's methods allowing for accurate calculation of the Schottky barrier height in this device.

Keywords—Schottky diode, β-Ga_2O_3, deep UV, planar diode.

I. INTRODUCTION

β-Ga_2O_3 is a promising semiconductor with a wide bandgap of 4.9 eV [1], which is of great interest for applications in deep UV sensors [2]. For this application, Schottky diodes are often used and the literature contains many examples of different devices architectures and contact types to β-Ga_2O_3 diodes in order to enhance the performance. As an example, Khan, *et al*. demonstrated vertical Schottky diodes using β-Ga_2O_3, which presents lower on-resistance although planar Schottky diode can withstand much higher breakdown voltage [3]. A planar device is normally preferred for Schottky diode UV sensors to maximize the light capture.

In recent years, there has been a growing interest to manufacture β-Ga_2O_3 films from alterative deposition approaches and films have been obtained by several techniques such as evaporation of Ga_2O_3 powder [4], spray pyrolysis from water-based solutions [5], edge-defined film-fed growth (EFG) [6] and pulsed laser deposition (PLD) [7]. Each technique has an individual appeal, for example, EFG is one of the most attractive because it allows to obtain wafers from melt grown Ga_2O_3 bulk single crystals, which enable large-size, high quality and low-cost mass production of β-Ga_2O_3 which is needed to meet the demand of high power devices that will come in a near future [8], [9]. Previous work indicates that β-Ga_2O_3 Schottky diode obtained by EFG with (010) orientation shows the best performance [10]. For the commercialization of devices with this material as an active layer, further investigations in regards to the semiconductor-metal junction are needed. In this work we investigate a planar Schottky diode using Ti/Au contacts on β-Ga_2O_3, studying this device by analysis of diode parameters in current and capacitance voltage curves, and evaluating its potential for deep UV sensing.

II. EXPERIMENTAL

The β-Ga_2O_3 (010) face polishing wafer obtained by EFG method was purchased from Tamura Corporation®. Samples were spin coated at 3000 rpm with 2% PMMA 950 K (EM Resists Ltd.), exposed using electron beam lithography (EBL) at an acceleration voltage of 30 kV then developed using 1:3 MIBK:IPA. Physical vapor deposition (PVD) was used to deposit the Ti/Au (20/100 nm) electrodes, each pad size was 200 μm x 200 μm with gap of 200 μm between each pad. After removal of the PMMA resist, the sample was submitted for rapid thermal annealing (RTA) at 400 ºC for 1 min in a N_2 atmosphere at a pressure of approximately 1 mbar. Generally. the large bandgap and the interface states lead to difficulty in obtaining consistent ohmic contacts at the β-Ga_2O_3 surface; however, this inconsistency allows for fabrication of a mixture of ohmic and Schottky contacts on the same substrate using the same materials and deposition processes. The possibility of obtaining ohmic or Schottky contacts to β-Ga_2O_3 using Ti has already known in the state-of-the-art devices [11]. The configuration used for the diode in this work was a planar architecture. An Agilent B2912A unit connected to a probe station was used for DC characterization and a Solartron SI 1260 with 1296 dielectric interface was used for AC characterization of the Schottky diode. A deep UV source based on an 18W fluorescent lamp with a wavelength of 254 was used to perform the photodetector measurements.

III. RESULTS AND DISCUSSION

For Schottky diodes the current-voltage (I-V) behavior is governed by the follow equation:

$$I = AA^{*}T^{2}\left[exp\left(\frac{-q\phi_{b}}{kT}\right)\right]\left[exp\left(\frac{qV_{D}}{\mathrm{n}kT}\right)-1\right] \quad (1)$$

where q is electron charge, ϕ_b is Schottky barrier height, V_D is applied voltage, k is Boltzmann constant, T is temperature, n is the ideality factor, A is effective area and A^* is effective Richardson constant. **Fig. 1** presents the I-V characteristics for the β-Ga_2O_3 Schottky diode. This device has a high forward current of 0.36 mA and very low dark current of 24 pA at -5 V bias voltage which results in a very high rectification ratio of $1.5\text{x}10^7$. Given the area of the photodetector has a 0.02048cm^2 area, this corresponds to a current density of 17.58mA/cm^2.

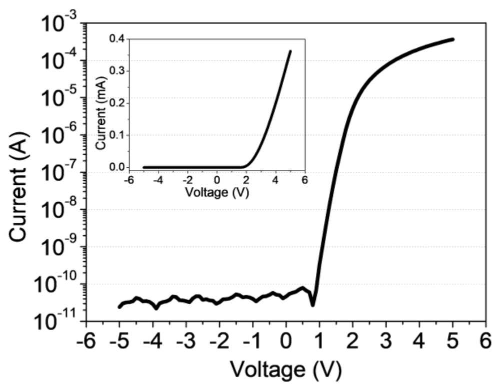

Fig. 1. I-V curves of the β-Ga_2O_3 Schottky diode in semi-log scale. Inset: the same curve in linear scale.

In Schottky diodes, ideally the series resistance (R_s) is low and the shunt resistance (R_{sh}) is high. In our case, the diode series and shunt resistance was determined as 6.4 kΩ and 2.9 $G\Omega$, respectively, using dynamic resistance - voltage ($R_D - V$) curve, as shown in **Fig. 2**. In comparison to the literature, the shunt resistance is very high and, the series resistance is compatible with some results, as ~7.0 kΩ reported by Shen, Y. *et al* [12]. However, some references present really small series resistance, as 28.96 Ω reported by Reddy, P. *et al* [13]. Although high series resistance is not surprising for a planar device architecture.

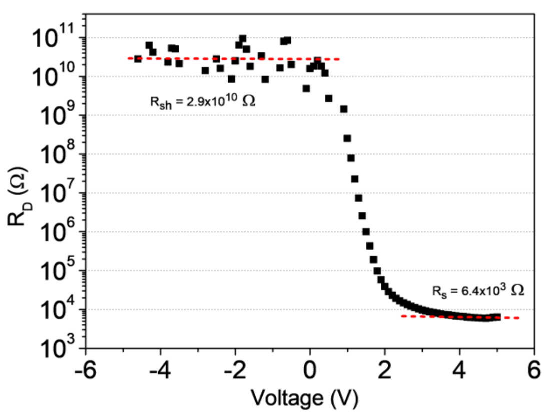

Fig. 2. Dynamic resistance versus voltage of the β-Ga_2O_3 Schottky diode.

Subsequently, Cheung's [14] and Norde [15] methods have been used for parameter extraction from the I-V characteristics of the Schottky diodes, in particular for the Schottky barrier height, ϕ_b and ideality factor, n. The Cheung's method uses of the follow equations:

$$\frac{dV}{dlnI} = IR_s + \frac{nkT}{q} \quad (2)$$

$$H(V) = V - \frac{nkT}{q}ln\left(\frac{I_o}{AA^{*}T^{2}}\right) = IR_s + n\phi_b \quad (3)$$

Likewise, Norde's method applies the following equation for parameter extraction:

$$F(V) = \frac{V}{\alpha} - \frac{kT}{q}ln\left(\frac{I}{AA^{*}T^{2}}\right) \quad (4)$$

where F(V) is the Norde function and α is an arbitrary constant greater than n. By the F(V)-V plot we can get the values of Schottky barrier height from the minimum point in the curve (V_o), being the ϕ_b given by:

$$\phi_b = F(V_0, \alpha) + \left(\frac{\alpha - n}{n}\right)\left(\frac{V_0}{\alpha} - \frac{kT}{q}\right) \quad (5)$$

and series resistance by:

$$R_s = \frac{(\alpha - n)kt}{qI_0} \quad (6)$$

Tab. I summarize all the parameter values that have been extracted. The resistance of both methods are in a good agreement with that one founded by dynamic resistance plot (all around ~$10^3\Omega$). Also, the Schottky barrier height is in a good agreement of 0.75 ± 0.01 eV which demonstrates the consistency of both methods. The diode presents a high-value ideality factor associated with a high R_s, which are frequently related to the presence of imperfections at the interface. We believe that high values for these parameters are expected due to the nature of the Schottky and ohmic contact formation in this diode. This high ideality factor suggests that the transport through the junction is no longer due to thermionic emission [16], it may be through trap-assisted tunneling or for a high density of defect states that makes the conductivity be governed by hopping conduction [17].

TABLE I. β-Ga_2O_3 SCHOTTKY DIODE PARAMETERS EXTRACTED BY CHEUNG'S AND NORDE METHOD.

Method	R_s *(kΩ)*	n	$q\phi_b$ *(eV)*
Cheung	7.5-7.6	7.5	0.76 eV
Norde generalized	2.5	-	0.74 eV

The capacitance-voltage (C-V) behaviour of the Schottky diode is governed by the following equation:

$$C = A\sqrt{\frac{q\varepsilon_s N_d}{2(V_{bi} - V - kT/q)}} \quad (7)$$

where N_d is the carrier density, V_{bi} is the built-in voltage and ε_s is the dielectric constant. **Fig. 3** presents the C-V and 1/C^2-V curves for the β-Ga_2O_3 Schottky diode for the frequency of 100 Hz. The built-in potential (qV_{bi}) was determined as 0.89 eV by linear extrapolation of the inverse square capacitance curve using the follow equation:

$$\frac{1}{C^2} = \frac{2}{q\varepsilon_s N_d A^2}\left(V_{bi} - V - \frac{kT}{q}\right) \quad (8)$$

The Schottky barrier height can be also determined from the capacitance curves, once

$$\phi_b = V_{bi} + (E_C - E_F) + \frac{kT}{q} \qquad (9)$$

where, $E_C - E_F$ have being reported as ~ 0.1 eV [3], [18]. Using eq. 9 it was founded Schottky barrier height of 1.01 eV. We can note that the ϕ_b from C-V is ~0.25 eV higher than that founded by I-V curve. When the device behaves in a non-ideal way, it is common that C-V characteristics determine higher values, particularly due to the presence of barrier inhomogeneity [19]. We emphasize that it was not taken into consideration the potential barrier lowering due to the image charge effect.

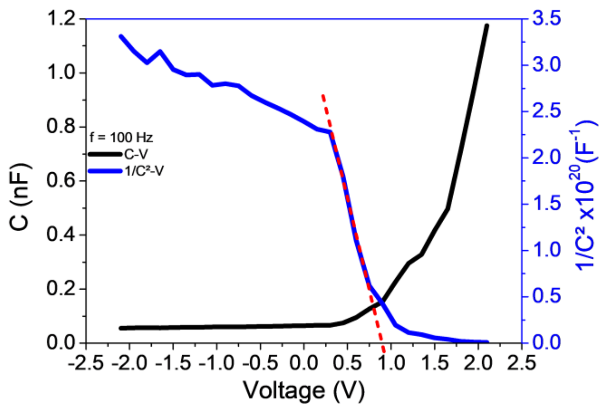

Fig. 3. C–V and $1/C^2$–V curves of the β-Ga_2O_3 Schottky diode.

Finally, the Schottky diode was tested for operation as a deep UV photodetector. **Fig. 4** presents the I-V curve in the dark and under UV light. When the UV light was incident onto the diode, it is clear that the current changes mainly in reverse-bias condition, which increases as the reverse voltage is increased. The UV/dark ratio increases also, being around ~10^3 at -5 V bias. This indicates that our device works as well as a photodiode.

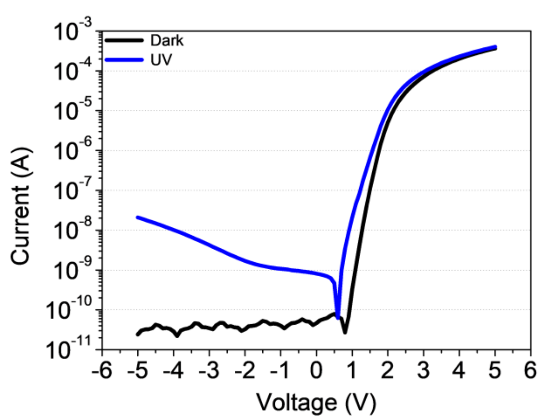

Fig. 4. I-V curves of the β-Ga_2O_3 Schottky diode in semi-log scale in the dark and under deep UV.

In order to evaluate the photodetector performance, the responsivity and EQE were calculated using the follow equations:

$$R_\lambda = \frac{I_{ph}}{A_d P_d} \qquad (10)$$

$$EQE = \frac{R_\lambda hc}{q\lambda} x100 \qquad (11)$$

being I_{ph} being the photocurrent, A_d the detection area, P_d the power density, h the Planck's constant, c the speed of light and λ the wavelength. The calculated values of responsivity and EQE, at -5 V, were 12.5 mA/W and 6.12 %, respectively.

Fig. 5 shows the current-time (I-t) characteristics for the β-Ga_2O_3 Schottky diode with -5 V bias, with the UV externally triggered to switch off and on in order to characterise the responsivity using the approach reported in [20,21]. The response time defined as the time required to reach 90% of the current, under illumination is 24 s, with UV/dark ratio of ~10^2. The time for the current to return to its value in the dark is also 24s. The on and off cycles shows that this photodetection is reversible and has reproducibility, reaching the maximum/minimum of currents with similar rise and decay times, respectively.

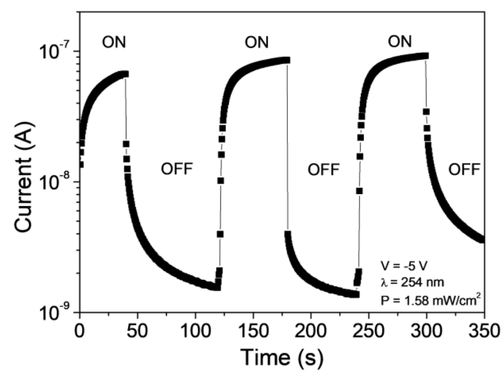

Fig. 5. I-t curve of the β-Ga_2O_3 Schottky diode in semi-log scale, turning the UV light off and on.

IV. Conclusion

The performance of the planar β-Ga_2O_3 Schottky diode with Ti/Au electrodes was characterized using I-V and C-V measurements, achieving a high rectification ratio of 1.5x10^7, forward current of 17.58mA/cm^2 at -5 V bias and high shunt resistance of 2.9 $G\Omega$. The Schottky height has been calculated as ~0.75 eV from Cheung and Norde method and 1.01 eV from capacitance curve. The device presented promising properties for application as a photodetector of deep UV radiation with good reversibility and reproducibility and is much simpler to manufacture than conventional deep-UV photodetectors. Responsivity and EQE of 12.5 mA/W and 6.12 %, respectively as achieved. The response time was 24 s to both rise and decay, with UV/dark ratio of ~10^2.

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