X-ray Detection Performance of Vertical Schottky Photodiodes Based on a Bulk $\beta$-Ga$_2$O$_3$ Substrate Grown by an EFG Method

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In this study, we investigated the X-ray detection capabilities of vertical $\beta$-Ga$_2$O$_3$ Schottky photodiodes on a bulk (100) $\beta$-Ga$_2$O$_3$ substrate that was grown by an edge-defined film-fed growth (EFG) method. Both the static and transient responses of the fabricated detectors to X-ray illumination were characterized, and a strong trap-related photoconductive effect was observed in addition to the photovoltaic mechanism. The responsivity of the detectors was calculated to be $1.8 \mu$A/Gy at a reverse bias of $-25.8$ V. The response time was studied though fitting the transient photocurrent using the exponential decay functions. Associated with material characterizations, it was revealed that the existence of oxygen vacancies within the $\beta$-Ga$_2$O$_3$ substrate weakened the performances of the X-ray detectors, mainly their sensitivity and response speed.

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Gallium oxide (Ga$_2$O$_3$) has an ultra-wide direct bandgap of $\sim 4.8$ eV, which possesses a large breakdown electric field and high transparency in visible to ultraviolet (UV) spectrum region. As a result, Ga$_2$O$_3$ has been extensively studied for power electronics$^{1-3}$ and solar-blind deep-UV detectors.$^{4-6}$ On the other hand, owing to its high atom density, low intrinsic carrier concentration and excellent chemical and thermal stability, Ga$_2$O$_3$ shows great potential for radiation detection in the aerospace and nuclear industries.$^{7,8}$ Different from UV detection, the radiation detector usually requires a much thicker sensitive region to collect the high-energy radiation photons and charged particles, since they usually have large penetration depths into the device. Figure 1 compares the linear attenuation coefficients between Ga$_2$O$_3$ and other wide bandgap semiconductors as a function of the X-ray photon energy in the range from 2 keV to 433 keV.$^9$ To achieve a good absorption of the X-ray photons, bulk materials with a sufficient thickness are always required for fabricating high performance X-ray detectors. Recently, large-diameter single crystal $\beta$-Ga$_2$O$_3$ bulk substrates have been successfully developed using melt growth techniques,$^{10,11}$ which enables the development of $\beta$-Ga$_2$O$_3$-based vertical X-ray detectors.

In this study, we demonstrated vertical Schottky X-ray detectors based on a (100) $\beta$-Ga$_2$O$_3$ bulk substrate that was grown by an edge-defined film-fed growth (EFG) method. Associated with material and electrical characterizations, the X-ray detection properties of the fabricated devices were investigated and discussed.

**Experimental**

A $\beta$-Ga$_2$O$_3$ bulk crystal was prepared using an EFG method and then cut into pieces along the (100) plane to form the 1 mm thick substrates. In order to obtain a better crystalline quality, the substrates were annealed at $1500 \, ^\circ\text{C}$ in an air atmosphere for 48 hours. After double-side chemical mechanical polishing (CMP) process, the transmittance of the prepared (100) $\beta$-Ga$_2$O$_3$ substrates was measured by a spectrometer (PE Lambda950). Cathodoluminescence (CL) analysis was also performed with a 30 keV and 100 nA electron beam (MonoCL3+) to evaluate the crystalline quality of the $\beta$-Ga$_2$O$_3$ substrates.

The fabrication of the vertical $\beta$-Ga$_2$O$_3$ Schottky barrier diodes (SBDs) started with the formation of cathode electrode. After substrate cleaning using acetone, isopropanol and DI water rinse, a Ti/Au (50 nm/250 nm) metal stack was deposited on the back side of the sample by E-beam evaporation and followed by a rapid thermal annealing (RTA) at $850 \, ^\circ\text{C}$ for 30 s in a N$_2$ ambient to obtain a good ohmic contact. Then, the Pt/Au (50 nm/150 nm) Schottky metal was deposited on the front side of the sample and patterned into circular shape by a lift-off process, serving as the anode electrodes. Figure 2a shows the cross sectional schematic of the fabricated SBDs. The diameter of the circular anode electrode was $400 \, \mu\text{m}$ and no passivation was employed for the devices.

After the conventional on-wafer capacitance-voltage (C-V) and current-voltage (I-V) characterizations, the sample was cut into small pieces and packaged onto a holder for the X-ray detection measurements. The X-ray source used in this study was a miniature X-ray tube with a tungsten anode (60 kV, 12W X-ray source, Moxtek, USA),

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Linear attenuation coefficient of wide bandgap semiconductors (ZnO (5.676 g cm$^{-3}$), GaN (6.15 g cm$^{-3}$), SiC (3.16 g cm$^{-3}$), Diamond (3.52 g cm$^{-3}$) and Ga$_2$O$_3$ (6.44 g cm$^{-3}$)) as a function of X-ray photon energy.
which can provide a wide continuous spectrum of X-ray beam with a radiation angle of 48°. The X-ray peak photon energy was at around 24 keV when the X-ray tube accelerating voltage is set at 30 kV. The X-ray dose rate was calibrated to be 383 mGy/s at a distance of 2 cm from the source when the tube current was set at 100 μA. In all the measurements, the β-Ga₂O₃ SBD detectors were illuminated from the front side perpendicularly, as illustrated in Figure 2b. The response currents of the devices under X-ray illumination were recorded by a source/measurement meter (B2902A, Agilent).

Results and Discussion

The measured transmittance spectrum of the (100) β-Ga₂O₃ substrate is shown in Figure 3. A sharp band-edge absorption at 258 nm can be observed, corresponding to the bandgap of β-Ga₂O₃ (4.80 eV). However, at longer wavelengths beyond 350 nm the substrate showed a relatively low transmittance (~60%), which might be due to the reflectance at the sample surface and the existence of defects within the material. As shown in the CL spectra in Figure 4, the UV emission at 370 nm (3.35 eV) is independent of the dopant and growth conditions, and has been attributed to self-trapped excitations. The peak at around 415 nm (2.98 eV) is associated with the recombination of a trapped electron in a donor with a trapped hole in an acceptor. The clear presence of a blue emission at 450 nm (2.75 eV) has been attributed to a donor-acceptor transition, between neutral oxygen vacancies (V₀) as donor, and oxygen-gallium vacancy pairs (V₀, V Ga) as acceptor. Such oxygen vacancies were inevitably generated in the β-Ga₂O₃ bulk during the growth and annealing process.

Figure 5 shows the C-V curve of the fabricated β-Ga₂O₃ SBDs measured at 1 MHz. From the 1/C² plot versus reverse bias voltage in the inset of Figure 5, the effective carrier concentration (N_D – N_A) of the β-Ga₂O₃ substrate used in this study was extracted to be ~4.2 x 10¹⁷ cm⁻³. Besides for the Si impurity, the high-density oxygen vacancies within the β-Ga₂O₃ bulk that discovered by the CL measurement were believed to be one of the major donor sources. With such a high carrier concentration, when biased at ~25 V the depletion width and the maximum electric field in the space charge region for the devices were calculated to be ~257 nm and ~1 MV/cm, respectively. According to the I-V measurements, most of the fabricated β-Ga₂O₃ SBDs exhibited typical I-V curves with a good rectification behavior, as shown in Figure 6, suggesting a high fabrication yield in the experiments and a good Schottky interface quality between Pt and β-Ga₂O₃. The inset of Figure 6 plots the reverse current of the devices in a semi-log scale. When biased at below ~20 V the SBDs exhibited a low leakage current of around 10⁻⁸ A, while a rapid increase of the leakage current appeared when the reverse bias voltage went beyond ~20 V. We believe that such a sudden increase of the reverse current at a relatively low electric field (~1 MV/cm at ~20 V in this case, when considering the β-Ga₂O₃’s critical electric field of 8 MV/cm) should be mainly attributed to the compromised crystalline quality.
The inset shows the reverse leakage current in semi-log scale. Of the β-Ga2O3 substrate, for example the oxygen vacancy-induced traps, as discussed in the CL analysis.24

The response current of the β-Ga2O3 SBD to X-ray illumination ($I_{x-ray}$) was compared to its dark current ($I_{dark}$) in Figure 7 as a function of reverse bias voltage, where the incident X-ray dose rate that reached to the detector was 1.149 Gy/s. The inset plots the two curves in a semi-log scale. It can be seen that the response of the β-Ga2O3 detector to the X-ray illumination was obvious. With the increase of the reverse bias voltage, the response current of the detector increased markedly, suggesting the existence of a photoconductive gain for the β-Ga2O3 SBD detectors in addition to the photovoltaic mode. The photoconductive mechanism is believed to be related to the deep level traps within the material,25-28 which can trap/detrap carriers that are excited by the X-ray photons to produce extra photocurrent. On the other hand, due to the rapid increase of the dark current at high reverse bias voltage was $\sim -20$ V, the photo-to-dark current ration started to decrease, as shown in the inset of Figure 7.

To quantitatively evaluate the X-ray detection performances of the fabricated β-Ga2O3 SBD detectors, we further calculated the responsivity ($R$) and the noise-equivalent dose rate ($NED$). The responsivity is defined as the ratio between the net photocurrent ($I_{x-ray} - I_{dark}$) and the incident X-ray dose rate reaching to the detector ($D$)

$$R = \frac{I_{x-ray} - I_{dark}}{D} \hspace{1cm} [1]$$

The noise-equivalent dose rate is defined as the incident X-ray dose rate that gives a signal-to-noise ratio of one in a 1-Hz bandwidth, which is a measure of the sensitivity of the detector and can be described by the following equation

$$NED = D \frac{\sqrt{2}\epsilon I_{dark}}{I_{x-ray} - I_{dark}} \hspace{1cm} [2]$$

Figure 8 plots the responsivity and noise-equivalent dose rate versus reverse bias voltage for the fabricated β-Ga2O3 SBD detectors. The responsivity keeps increasing with the increase of reverse bias voltage and reaches to 1.8 μGy/s at $\sim -25$ V. However, the noise-equivalent dose rate trends to get saturated when the bias voltage is beyond $-20$ V, which is due to the rapid increase of the dark current at high reverse bias. Thus, better material crystalline quality and lower carrier concentration are essential for further improving the detector’s performance.

Figure 9 shows the transient response of the β-Ga2O3 X-ray detectors to the switching of X-ray illumination at biases of 0 V and $-25$ V. The detectors exhibit stable transient responses to the switching of X-ray illumination when biased at both $-10$ V and 0 V. In the photoconductive mode, the capture and release of the photo-generated carriers by the deep level traps have a certain lifetime, leading to a relatively long response time. In order to study the trap-related time constant ($\tau$) of the β-Ga2O3 SBD detectors, curve fitting was performed for the photocurrent when biased at $-10$ V using exponential decay functions.

$$I(t) = I_0 + \sum I_n \exp\left[-(t - t_0)/\tau_n\right] \hspace{1cm} [3]$$

Figure 6. 1-V characteristic of the fabricated β-Ga2O3 SBD in dark condition. The inset shows the reverse leakage current in semi-log scale.

Figure 7. Comparison of the photocurrent ($I_{x-ray}$) and dark current ($I_{dark}$) of the β-Ga2O3 X-ray detector as a function of reverse bias voltage. The inset shows the plot in a semi-log scale.

Figure 8. The responsivity and noise-equivalent dose rate of the β-Ga2O3 X-ray detectors at reverse bias.

Figure 9. The transient response of the β-Ga2O3 X-ray detectors to the switching of X-ray illumination at biases of 0 V and $-10$ V.
Two different time constants are obtained for the photocurrent rising process ($\tau_{\text{rise}} = 13.8 \text{ s}$ and $\tau_{\text{rise}} = 1.4 \text{ s}$), while during the photocurrent decaying process the two time constants are $\tau_{\text{decay}} = 17.1 \text{ s}$ and $\tau_{\text{decay}} = 4.0 \text{ s}$. On the contrary, when biased at 0 V the response time of the β-Ga2O3 SBD detector is very short. The fast response of an unbiased SBD detector corresponds to a photovoltaic mechanism, where the photo-generated carriers in the space-charge region are swept out rapidly by the build-in electric filed. To further improve the detectors’ response speed, the trap-relasted photocductive mode has to be suppressed.

**Conclusions**

In conclusion, we fabricated vertical β-Ga2O3 Schottky photodiodes based on a bulk (100) β-Ga2O3 substrate and investigated their X-ray detection performances. The β-Ga2O3 single crystal was grown by an EFG method and the existence of oxygen vacancies within the material was revealed by the CL analysis. The fabricated β-Ga2O3 SBDs exhibited an obvious response to the X-ray illumination with a relatively high responsivity of 1.8 µC/Gy at a reverse bias of −25.8 V, while the sensitivity of the detectors was limited by the rapid increase of the dark current at high reverse bias => −20 V. Though fitting the transient photocurrent of the detectors by the exponential decay functions, the response time was calculated to be in the order of ten seconds. The continuous increase of the response current with the reverse bias voltage and its relatively slow response suggested the existence of a strong photocductive effect for the fabricated β-Ga2O3 X-ray detectors, which is believed to be related to the deep level traps induced by the oxygen vacancies within the material.

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