Effect of Thermal Annealing on Ga$_2$O$_3$-Based Solar-Blind Photodetectors Prepared by Radio-Frequency Magnetron Sputter

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Abstract

The authors report on the solar-blind deep-ultraviolet (DUV) β-Ga$_2$O$_3$ based photodetectors and discuss its optical properties under varying thermal treatment. The β-Ga$_2$O$_3$ thin film was grown on sapphire substrate by Radio-Frequency Magnetron Sputter technique. The electrical and optical characteristics of the photodetector were studied. At an 10 V bias voltage, the device shows an extremely low dark current (~10 pA), a responsivity of 1.09 mA/W, and a high DUV-to-visible discrimination ratio up to 6412 upon 250 nm DUV illumination.

The variation in the electrical and photoresponse properties of solar-blind photodetector can be attributed to O vacancies effects at interface during the annealing process. The modulation of the photoresponse properties of a solar-blind photodetector by thermal annealing offers an efficient route toward the development of high-performance and low-cost DUV detectors.

EYWORDS: Ga$_2$O$_3$, solar-blind, photodetectors,

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I. Introduction

Monoclinic structured gallium oxide (\(\beta\)-Ga2O3) is a wide band gap (4.9 eV) semiconductor and has attracted interest as a material for gas sensors, phosphors, transparent conductors, and transparent electronic devices. In particular, it is a promising candidate for a deep-ultraviolet photodetector that is blind to wavelengths above 280 nm, the so-called solar-blind photodetector. This device would find application in a flame detector, which is useful in protecting from flame and in fire control areas.

So far, Ga2O3 photodetectors based on thin films grown by spray pyrolysis, sol–gel techniques, and molecular beam epitaxy have been realized. In this paper, we report the epitaxial growth of (201) oriented \(\beta\)-Ga2O3 thin films on sapphire substrates by RF sputter and demonstrate a DUV photodetector using comb electrodes with small dark current and high photoresponsivity. The strongest responsivity upon 250 nm DUV illumination indicates its potential application for solar-blind detectors.

II. Experiments

The samples used in this study was first prepared by depositing a 200-nm-thick Ga2O3 layer on sapphire substrate by Radio-Frequency Magnetron Sputter. The sapphire substrates were degreased in ultrasonically agitated organic solvents prior to film preparation. After the growth of \(\beta\)-Ga2O3 thin film the substrates were placed into an alumina boat. The boat was then loaded at the center of a quartz tube, which was inserted in a horizontal tube furnace. The furnace was heated under a working pressure and maintained at the temperature for 20 min injected with 50 sccm oxygen gas. The sputtering process was conducted in argon gas under a pressure of 10 mTorr. In this study, the rf powers (150 W) were employed for Ga2O3 target to produce Ga2O3 films. The thickness of the Ga2O3 films was kept at 200 nm. Deposited Ga2O3 films were then thermally annealed at different temperatures ranging from 400 to 1000°C in a quartz tube furnace. A detailed study on the relationship between the quality of the \(\beta\)-Ga2O3 thin film and these growth parameters will be reported later. Crystallographic property of the furnace oxidized
sample was characterized by a MAC MXP18 X-ray diffractometer (XRD). For the fabrication of PD, a thick Ti/Al (30/100 nm) film was deposited through an interdigitated shadow mask onto the furnace oxidized sample to serve as contact electrodes. We designed the size of interdigitated shadow mask size were 2 mm wide and 2.2 mm long with finger width of 0.1 mm and finger spacing of 0.2 mm (figure 1). Current-voltage (I-V) characteristics of the fabricated PD were then measured by an HP 4156 semiconductor parameter analyzer at room temperature. Spectral responsivity measurements of the PD were then performed by JOBIN-YVON SPEX System with a 300 W xenon arc lamp light source (PERKINELMER PE300BUV) and a standard synchronous detection scheme.

III. Results and Discussion

Figure 2 shows XRD spectrum measured from Ga2O3 grown on the sapphire substrate by rf sputter and annealed at various temperatures from 400 °C -1000 °C. The sharp XRD peaks observed in the spectrum can be indexed to (-102), (004), (202) and (217) of β-Ga2O3. Full width at half maximum (FWHM) of the (004) diffraction peak decreases with an increase of annealing temperature, indicating that crystal quality of the films could be improved by thermal annealing. A larger FWHM was attributed to the degradation of the crystal quality for Ga2O3. At the same time, the diffraction intensity of the annealed films indicate that the monoclinic structure of β-Ga2O3 could be obtained using the thermal annealing process.

Figure 3 shows the dark current versus gate bias of the photodetector annealed at 800 °C in linear-scale while the inset shows the current–voltage characteristics taken in dark and under illumination in log-scale. During photocurrent measurement, we illuminated the sample with 250-nm UV light by dispersing a 300-W xenon lamp with a monochromator. It was found that measured dark current increased linearly with the applied bias. Such an observation suggests that Ti/Al
electrodes formed ohmic contacts on the sputter Ga$_2$O$_3$ thin film. In addition, the photocurrent significantly increases as the forward bias voltage increases, as shown in the inset of Fig 3. From the figure 3, With 10-V applied bias, it was found that measured dark current was only $10^{-11}$A. The small dark current should be attributed to the highly resistive nature of the β-Ga$_2$O$_3$. With the same 10V applied bias, it was found that measured current increased to $10^{-8}$A as we turned on the UV illumination. In other words, detector current increased by more than three orders of magnitude upon UV illumination.

Figure 4 shows spectral responses of the photodetector annealed at various temperatures at bias of 10V. For the as-annealed photodetector, the peak responsivity was around 435mA/W but the contrast ratio was only 92 between 250 and 350 nm. According to the results of the measurements, the cut-off wavelength is not obvious because the as-annealed oxidized layer was amorphous β-Ga$_2$O$_3$ (Figure 1). It seems to suggest that the β-Ga$_2$O$_3$ thin film was full of defect. With photo-illumination, the intensity of incident light below the bandgap of Ga$_2$O$_3$ was also absorbed.

Clearly, the spectrum indicates the DUV response in the wavelength region below 260 nm was dramatically enhanced by annealing at 500 °C while achieved 2549 rejection ratio at 250 nm/350 nm. The cutoff wavelength of the photodetector occurs at 250 nm which corresponds to the band gap of the Ga$_2$O$_3$ films. These indicate that the device has high spectral selectivity.

As we increased the annealing temperature to 900 °C, it was found that measured responsivity decreased to 1.09mA/W. Moreover, it shows a significant difference between responsivities at 250 and 350 nm, with a rejection ratio of about $6.4\times10^3$ at 900 °C. Such a result suggest clearly that measured responsivity decreased while the blind-visible rejection ratio increasesd with increasing annealing temperature. The performance of the photodetector depending on varying temperature are listed in Table I. Such behavior can be explained by the presence of oxygen vacancy in
the photodetector. The trapping of photogenerated carriers by defect states at the interface was proposed to be responsible for shrinking of the responsivity during annealing. The oxygen vacancy decreased along with the increasing annealing temperature. To clarify our assumptions, XRD analyses were performed on the annealed β-Ga2O3 films which showed the annealed one have better crystal quality during the annealing process. The spectral response showed solar-blind sensitivity and it is an encouraging result toward the further optimization of solar-blind UV detection.

**IV. Conclusion**

In summary, we demonstrated high-performance β-Ga2O3 based visible-blind DUV photodetectors by RF sputter and postmetal deposition annealing. The detectors had a low dark current, high contrast ratio and excellent spectral response. The study reveals that the optical performance of the device, in general improves when the postmetal deposition annealing temperature is restricted up to 500 °C approximately. The device performance degrades dramatically when the annealing temperature is increased beyond 1000 °C. The trapping of photogenerated carriers by defect states at the interface was proposed to be responsible for shrinking of the responsivity during annealing. The outcome of the study will be useful for the design of β-Ga2O3 based UV detectors for deployment in temperature ranging from 500-900°C electronics.

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References


Figure 1 Schematic diagram
**Figure 2**  XRD spectrum of the furnace sample depending on varying different temperature.
Figure 3  measured I-V characteristics in log-scale of the fabricated \(\beta\text{-Ga}_2\text{O}_3\) PD. The inset shows measured dark current plotted in linear-scale.
Figure 3  Spectral responses measured from the fabricated $\beta$-Ga$_2$O$_3$ PD.
<table>
<thead>
<tr>
<th>Annealing Temp.</th>
<th>Responsivity @250nm (A/W)</th>
<th>Rejection ratio (R@250nm/350nm)</th>
<th>Rejection ratio (R@250nm/400nm)</th>
</tr>
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<tbody>
<tr>
<td>As-deposited</td>
<td>0.435</td>
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<td>82</td>
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<tr>
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<td>387</td>
<td>84</td>
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<tr>
<td>500°C</td>
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<td>469</td>
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<td>5347</td>
<td>570</td>
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<td>797</td>
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<td>1120</td>
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<td>1000°C</td>
<td>9.2x10^{-5}</td>
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Table 1