Gamma Irradiation Effect on Performance of β-Ga2O3 Metal-Semiconductor-Metal Solar-Blind Photodetectors for Space Applications

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The radiation hardness of Ni/Ga2O3/Ni metal-semiconductor-metal (MSM) solar blind photodetectors has been investigated under the exposure of 60Co γ-source. It was observed that the metal contacts were not degraded and the dark current of photodetector was slightly improved from 3.27 × 10−7 A to 1.88 × 10−7 A. The photo to dark current ratio (PDCR) was observed to increase from 5.1 to 14.1 with increasing γ-radiation exposure. The apparent Schottky barrier height (SBH) evaluated from current-voltage characteristics were found to increase with irradiation. The increased SBH was explained using image force induced barrier lowering. The obtained results reveal that the Ga2O3 solar blind photodetectors are relatively less susceptible to radiation environment.

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Solar blind photodetectors with superior thermal and chemical stability as well as to withstand in radiation hard atmosphere are required inevitably for operation in harsh environment.1 These photodetectors have large applications of defense, environmental monitoring, UV astronomy, space communications, water treatment, insect disinfection in crops, sterilization etc.2–4 For space applications, the detectors must have tolerance to radiation environment up to 100 kilo-Gray (kGy) for reliable operation of solar-blind photodetectors under harsh environment.5,7–9 The gamma-irradiation on the materials may exhibit profound effects on photodetector performance. Radiation-matter interaction induces long-lived defects such as increased defect concentrations, decreased carrier concentration and carrier lifetime etc. and transient defects such as rapid annealing of minority carriers in the semiconductors.5,6 Therefore, radiation hard materials are necessary for the reliable operation of solar-blind photodetectors under harsh environment.

The wide bandgap semiconductors such as SiC and GaN possess intrinsic radiation hardness due to high chemical stability.5,7–9 These semiconductors were found to immune to the radiation exposures due to high displacement energy. The displacement energy is a measure of bond strength in the material. An empirical relationship between displacement energy and inverse of lattice parameters have been reported7 which showed that a low lattice constant material such as β-Ga2O3 is expected to possess high radiation hardness. Recently, research based on β-Ga2O3 deep UV photodetectors steeply up surged due to large bandgap of 4.5–5.0 eV, and high chemical and thermal stability.10,11 The intrinsic solar blindness of Ga2O3 provides additional advantage of reduced packaging and cooling systems than conventional Si based photodetectors which is the demanding thrust for satellite or space-borne applications.12 Recently, M. H. Wong et al. reported excellent radiation hardness of bulk Ga2O3 single crystal MOSFET toward gamma rays.13 However, the effect of gamma irradiation on the performance of solar blind photodetectors based on Ga2O3 has not been investigated till now.

In this article, the effect of γ-rays irradiation on the metal-semiconductor-metal (MSM) solar-blind photodetectors based on β-Ga2O3 thin films deposited by pulsed laser deposition (PLD) is reported. The obtained photodetector performance parameters are impressive and paves the way for practical application of Ga2O3 solar-blind photodetectors in radiation harsh environments.

Experimental

The gallium oxide thin films (201) were deposited using PLD technique on c-plane sapphire. The deposition was carried out at 0.5 mTorr oxygen pressure and 800°C substrate temperature. Further information about the material growth can be found in our earlier report.10 The structural measurements were performed using X-ray diffraction system (Philips Xpert Pro) with Cu Kα (λ = 1.54 Å) source. The surface topology was analyzed by Atomic Force Microscopy (Dimension ICON, Bruker). The photoluminescence (PL) spectra were measured at room temperature using (Horiba Jobin Yvon Lab RAM, HR 800 Evolution). The PL measurements were recorded using 325 nm He-Cd laser excitation source and 1800 lines/mm grating.

The interdigitated electrodes on Ga2O3 thin film were patterned in class 100 clean room using maskless lithography system (Intelligent micropatterning, SF-100). These electrodes were 1000 μm long and 100 μm wide with figure spacing of 100 μm. The metal contacts of Ni (30 nm)/ Au (40 nm) was deposited using thermal evaporation system. The schematic of fabricated MSM structure of photodetector is shown in Figure 1. Nitrogen purged Xenon lamp (75W) source combined with computer interfaced monochromator (Bentham TMC-300V) was used for the spectral responsivity measurements. An optical UV Fiber (PCU-1000) was used to direct monochromatic beam over the device under test (DUT) placed on a dc probe station (Ever-Being International Corporation, EB 6). The power spectrum of Xenon lamp was

Figure 1. Schematic of the fabricated β-Ga2O3 based Ni/Au/Ni metal-semiconductor-metal photodetector.
acquired using Thorlabs power meter (PM-100D) and calibrated Si-photodiode (S-130VC). Keithley semiconductor parameter analyzer (SCS-4200) was also connected for external biasing of DUT.

The photodetector was irradiated with $^{60}$Co $\gamma$-ray source in the radiation shielded gamma chamber with cumulative total dose of 15 kGy and 100 kGy. The irradiations were carried out in dark conditions with $\gamma$-ray dose rate of 3 kGy/hr at room temperature. The photodetection measurements were performed after completion of each dose.

Results and Discussion

The X-ray diffraction (XRD) 2$\theta$-scan of pulsed laser deposited Ga$_2$O$_3$ thin film is depicted in Figure 2a. The XRD results showed that the $\beta$-Ga$_2$O$_3$ thin film having monoclinic crystal structure was epitaxially grown in (201) orientation. The inset of Figure 2a depicted with the full width at half maximum (FWHM) of rocking curve of (201) plane. The FWHM of 2° was obtained for (201) plane of Ga$_2$O$_3$ thin film. The topography of as grown thin film on 2 $\mu$m × 2 $\mu$m scale is shown in Figure 2b. The RMS roughness of about 3.0 nm was obtained using Nanoscope software analysis.

The current-voltage characteristics under dark condition and 245 nm wavelength UV light illumination with different radiation exposures were measured as depicted in Figures 3a and 3b respectively. The dark current was observed to decrease as the $\gamma$-irradiation dose increased up to 100 kGy. The decrease in dark current has been reported due to decreased bulk carrier concentration upon $\gamma$-irradiation. However, photocurrent was almost constant with $\gamma$-irradiation. Further, photo to dark current ratio was calculated at 10 V applied bias. The PDCR is defined as:

$$PDCR = \frac{I_p - I_d}{I_d}$$  \[1\]

Where $I_p$ and $I_d$ is photocurrent and dark current of the device. For better performance of photodetectors, a high PDCR value is desired. The PDCR of 5.1 was observed for the as-fabricated device, and it further increased to 14.1 at 100 kGy $\gamma$-radiation exposure, which is depicted in Figure 4a. The PDCR values were calculated at 10 V applied bias with 30 $\mu$W/cm$^2$ power density of 245 nm UV light. The enhancement in PDCR values were obtained due to reduced dark current. Figure 4b showed the peak responsivity at 10 V bias under 245 nm UV illumination. The responsivity of photodetector is defined as:

$$R = \frac{I_p - I_d}{P \cdot S}$$  \[2\]

Where S is the effective device area and P is the optical power density of incident wavelength. The peak responsivity of 5.6 A/W was observed at 10 V bias. It increased to 7.1 A/W after 100 kGy irradiation of $\gamma$-rays. Further, spectral responsivity at 10 V were plotted with increasing radiation dose as shown in Figure 5. It was observed that fabricated photodetectors performed in solar blind regime with peak responsivity at 245 nm wavelength.

Further, the scanning electron microscope (SEM) images of unexposed and after 100 kGy $\gamma$-ray irradiation dose of Ni/Ga$_2$O$_3$ metal-semiconductor-metal (MSM) photodetector is shown in Figures 6a and 6b. It was observed that Ni/Au metal contacts were not much degraded. Although some dark spots were observed in the SEM image.
Figure 4. (a) Photo to dark current ratio (PDCR) and (b) peak responsivity at 10 V of fabricated photodetector with radiation dose under 245 nm illumination.

density of device after 100 kGy exposure, which might be coming due to some contamination due to handling of the devices during irradiation.

The thermionic emission model was used to analyze the current-voltage characteristics of MSM photodetector in the dark condition. The thermionic emission equation is given as:

\[ I = I_0 \exp \left( \frac{eV}{nkT} \right) \left[ 1 - \exp \left( -\frac{eV}{kT} \right) \right] \]  \[ \text{[3]} \]

For \( V > 3kT/e \), above equation simplifies as:

\[ \ln \left[ I \exp \left( \frac{eV}{kT} \right) \right] = \ln I_0 + \frac{eV}{nkT} \]  \[ \text{[4]} \]

Where,

\[ I_0 = A^* T^2 \exp \left( -\frac{q\phi_{ap}}{kT} \right), \]  \[ \text{[5]} \]

\[ \phi_{ap} = kT \left[ \ln \left( A^* T^2 \right) - \ln I_0 \right] \]  \[ \text{[6]} \]

Where \( I_0 \) is saturation current, \( A \) is the device area, \( A^* \) is Richardson constant, \( \phi_{ap} \) is apparent barrier height and other symbols have usual meanings. The value of \( A^* \) is taken as 41 A/cm² K² for Ga₂O₃.\(^{18}\) The barrier height values were calculated from the intercept plot \( \ln[I\exp(eV/kT)] \) vs \( V \) curve which is shown in Figure 7. The apparent Schottky barrier height (SBH) of 0.69 eV was obtained from Equations 4 and 6 at 295 K for forward characteristics of MSM structure. It further increased up to 0.71 eV after 100 kGy exposure of device in \( \gamma \)-ray chamber. The improvement in SBH and decrease in dark current of MSM photodetector with \( \gamma \)-ray irradiation is shown in Figure 8. The increase in SBH have also been reported in the GaN Schottky diodes under \( \gamma \)-ray irradiation.\(^{19}\) They reported the increase of about 20 meV in the barrier height calculated by current-voltage characteristics after the 21 Mrad (equal to 210 kGy) irradiation of \( \gamma \)-rays. The image force barrier lowering induced by formation of negative charges at the Ni/GaN interface was responsible for the SBH enhancement. The apparent barrier height is defined as: \(^{20}\)

\[ \phi_{ap} = \phi_b - \phi_{if}, \]  \[ \text{[7]} \]

Here, \( \phi_b \) is barrier height and \( \phi_{if} \) is the image force induced barrier lowering. The image force induced barrier lowering depends on the donor concentration \( (N_d) \) of semiconductor material as:\(^{21}\)

\[ \phi_{if} \propto N_d^{1/4} \]

In this report, it was observed that the dark current was reduced with increasing \( \gamma \)-irradiation. The reduction in dark current indicated the decrease in carrier concentrations of Ga₂O₃ which led to smaller barrier height lowering (\( \phi_{if} \)). The decrease in donor concentration \( (N_d) \) can be explain by increased trapped centers due to \( \gamma \)-irradiation. The photoluminescence (PL) spectra were recorded prior and after the \( \gamma \)-ray exposures of the Ga₂O₃ which is shown in Figure 9. In Ga₂O₃, various emission bands UV, blue, green and red were observed. The origin of UV and blue emissions was ascribed to transition in self-trapped holes and donor-acceptor levels.\(^{21,22}\) The red emission in Ga₂O₃ was reported due to transition in the energy level generated by nitrogen doping. Song et. al observed that the nitrogen doping generates acceptor levels in Ga₂O₃.\(^{23}\) However, the appearance of green emission was reported due to various impurities such as Be, Li, Sn, Si, Ge, Zr.

Figure 5. Spectral responsivity of photodetector with \( \gamma \)-ray irradiation at 10 V bias.

Figure 6. SEM images of MSM photodetectors (a) pristine (b) after 100 kGy irradiation.
The enhancement in the green emission band was also reported due to the presence of increasing oxygen content during the growth or annealing in the oxygen atmosphere and air.\textsuperscript{24,25} The excess oxygen was also reported as the acceptor defect in Ga$_2$O$_3$.\textsuperscript{25} It was observed that the intensity of defect bands corresponding to UV, green and red emissions were increased after irradiation. However blue band was not affected by irradiation. Hence, the self-trapped holes and various acceptors such as excess oxygen and nitrogen doping act as trap centers for the charge carriers which resulted in the decreased carrier density (Nd). Similar analogy of SBH improvement was also reported for the Ag$^{+11}$ ion irradiated Ni/GaN Schottky barrier diodes.\textsuperscript{20}

**Conclusions**

The effect of $\gamma$-ray irradiation on Ni/Ga$_2$O$_3$ MSM photodetectors has been studied. The dark current of photodetector observed to decrease under the $\gamma$-ray exposure up to 100 kGy. However, peak responsivity and PDCR with 245 nm wavelength illumination were observed to increase as the radiation dose increased cumulatively. The apparent SBH was also found to increase slightly with $\gamma$-irradiation due to decreased image force Schottky barrier lowering. The obtained results showed the potential application of Ni/Ga$_2$O$_3$ solar blind photodetectors for harsh radiation atmosphere.

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