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Preparation and Characterization of β -Ga₂O₃-based Photodetectors for UV Detection Applications

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Summary: Compact photodetectors with a significant response in the UVC spectral band (100–280 nm) present a growing interest since their potential applications to “New Space” nanosatellite constellation missions. Gallium oxide, with an already intrinsic ultra wide bandgap of 4.9 eV at 253 nm, can be engineered further into the ultraviolet (UV) by alloying it with Al. This next generation of MUV (200–300 nm) photodetectors is uniquely suitable for solar radiation from Space, and specifically the Herzberg continuum (200–242nm) that plays an important role in regional climate change through interactions with stratospheric ozone. This work presents the photolithographic, packaging and characterization of β -Ga₂O₃-based photodetectors destined to study and improve our understanding of the solar UV impact on the Earth's climate. Different tests are used to confirm the final selection of protoflight detectors, such as photo-electric performance, photo-response time and thermal cycle studies. These detectors are then projected to be integrated on a nanosatellite (INSPIRE-Sat 7, a "2U" cubesat) to be launched in early 2023 to monitor the absolute solar spectral irradiance and variability in the Herzberg continuum to better understand the stratospheric ozone response to solar UV irradiance changes. Results suggest that β -Ga₂O₃-based photodetectors may certainly be a promising candidate for optoelectronic applications in the UV-detection for its high responsivity and low dark current, "solar-blindness above 250 nm" and radiation hard properties. Thermal influence, photo-responsivity and response time are reported.

Keywords: β -Ga₂O₃-based photodetectors, UV detection, Nanosatellite, Photo-detector performance, Thermal tests.

1. Introduction

Novel multifunctional solid state ultraviolet photodetectors in the MUV wavelenghts range (200–300 nm), have gained increasing attention over recent years. In the case of this study, the key characteristic of the photodetectors is their potential for selectively distinguishing weak MUV signals in a background of UV, visible and infrared signals which are orders of magnitude more intense (i.e. the case of space-based observation of the solar spectrum from the near-Earth stratosphere).

In order to construct suitable high performance photodetectors, the selection of appropriate light absorption materials is primordial. UV sensors in use require filters, to reduce unwanted visible and infrared radiation, that reduce significantly their responsivity [1]. β -Ga₂O₃ is an emerging semiconductor material with a distinctly tuneable ultrawide bandgap which makes it a natural choice for use as a light absorbing material in MUV photodetectors [2, 3]. Other key assets of β -Ga₂O₃ detectors for space applications are their intrinsic radiation hardness (longer lifetime), and

their high potential gain that allows operation at lower voltages (several hundreds mA/W at -5 V).

This work is an innovative development with an ambitious science goal: monitoring the Solar Spectral Irradiance (SSI) around 215/220 nm (Herzberg solar continuum: 200–242 nm) with an accuracy better than 0.5% (5 times better than previous measurements in Space, noticeably with the SOLAR/SOLSPEC experiment [4, 5]).

The Herzberg continuum corresponds to a spectral region (200–242 nm) where atmospheric absorption is relatively low and, hence, solar UV radiation penetrates deeply in the atmosphere, down to the lower stratosphere, where it converts molecular oxygen (O₂) by photolysis to produce ozone (O₃).

Furthermore, and since UV observations are to be performed in Space, these innovative detectors will be qualified to TRL 9 (Technology Readiness Level 9: "flight proven"), as they are to be on the next nanosatellite of LATMOS (INSPIRE-Sat 7, a "2U" cubesat) in the first quarter of 2023.

This paper presents the performances evaluation and qualification tests of new β -Ga₂O₃-based photodetectors developed for New Space observations in the UVC/MUV spectral band (Herzberg continuum, 200–242 nm).

2. Method

Metal-Semiconductor-Metal (MSM) devices were formed by making two “back-to-back” Schottky diodes in the form of interdigitated fingers (having widths and spacings of 2 μ m, as shown in Fig.1).

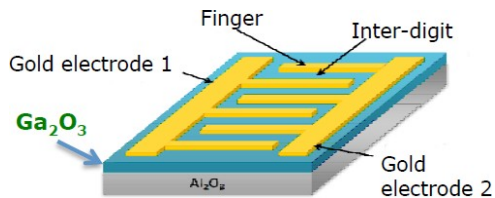


Fig.1. Schematic of MSN Inter-Digitated-Transducer (IDT) structures with the corresponding circuit diagram and a band structure representation.

Fig.2 shows the process flow for the development of an MSM photodetector (PD). This figure presents the principal main steps to achieve a final packaged PD.

In the first step, lightly doped n-type β -Ga₂O₃ films were deposited on Al₂O₃ substrates by Pulsed Laser Deposition (PLD) [6]. MSM devices were then formed by negative photolithography and Au/Ni contact deposition. Die singulation was then performed with a diamond saw. The singulated device die was soldered onto a TO can (TO-39) base and wires were wedge bonded to the MSM gold contact pads. The finished device was then encapsulated in dry nitrogen with a sapphire window cap. Back illumination adds performance.

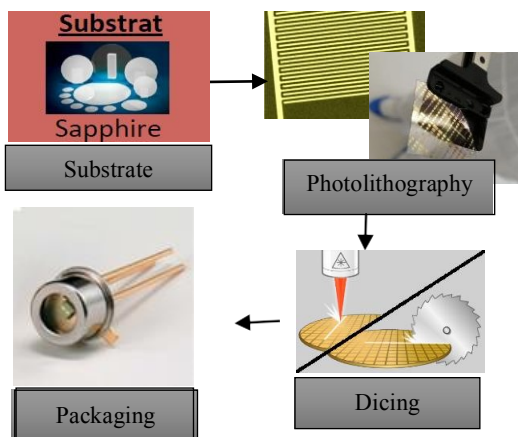


Fig.2. Process flow for the creation of an MSM photodetector.

Time response measurements were measured with broad band square wave light pulses generated using an optical chopper. Thermal cycling tests were made in a climatic chamber (Material Physico-Chimique “MPC AN80”). The objective of the test was to measure the

impact of temperature changes on the photo-current generated by polychromatic UV light. Tests were made between -30 and +50 degrees Celsius, which corresponds to their temperature environment for use in Space. The sensors were installed on a “breadboard” and biased at -5V (the maximum voltage available on the power limited nanosatellite).

3. Results and Discussion

3.1 Selection Rationale

For low radiation flux detection between 200 and 242 nm, a very large signal-to-noise ratio is essential. Furthermore, the spectral response of the detector should be selective for the 200–242 nm range, centered at 215–220 nm, with a low full width at half maximum of the order of 35 nm and an excellent rejection so that the visible spectrum, which is much more intense, does not affect the measurement. In previous work [6] the authors showed that β -Ga₂O₃-based sensors can be engineered to combine both a spectral response peak in the 200–242 nm range and a very large rejection ratio of the visible solar spectrum. Thus, with the β -Ga₂O₃, we can simultaneously obtain the desired maximum response at 215–220 nm, a very high rejection ratio (> 1000 compared to the peak of sensitivity) at wavelengths \geq 245–250 nm, and thereby achieve an excellent signal-to-noise ratio (dark current is very low: \leq 1 pA). In practice these detectors are “solar blind above 250 nm” (since insensitive to visible and infrared light, “visible blindness”). Other key properties of detectors are their intrinsic radiation hardness (durable long term performances) and their wide operating temperature range (no need for cooling below 0, neither -20° or -40°).

Such detectors were realized right through from the wafer to the final packaged sensors (including device architecture development, photolithography, singulation, contacting, packaging and testing).

3.2 Photo-response Time

We investigated the electrical conductivity and the time response performance of the β -Ga₂O₃ based PD. With a bias of -5.0 V, the 200–250 nm UV illumination was turned-on to measure the time-dependent photo-response of the device. The light absorption layer of the oxide thin film is an important factor of the high response in our β -Ga₂O₃-based PD.

Fig. 3 shows that the photoresponse of the device to 10 minutes of illumination for various wavelengths of monochromatic illumination in the UV Band (220-250nm). The Figure shows that the switching and photoreponse of the device are rapid and stable, respectively.

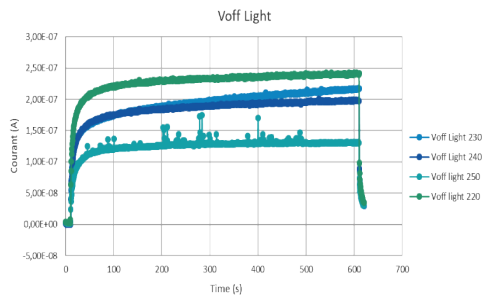
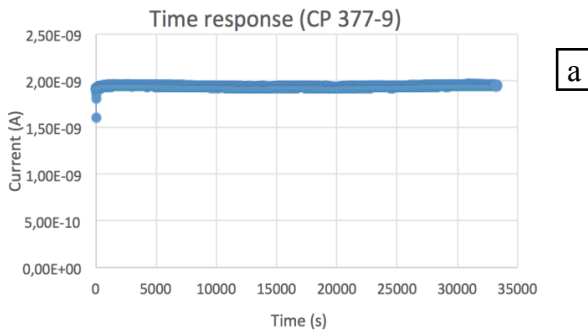
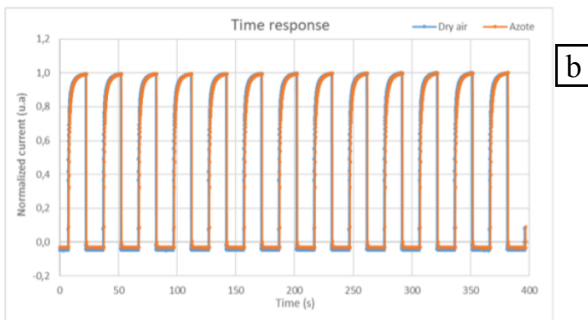


Fig.3. Photo-response time of a MSM photodetector (CP730C) for various monochromatic illuminations.

Fig. 4 shows the response time and dynamics. Current is stable in time (<1%, mainly from measurements uncertainty) during a 10 hours test (Fig.4 (a)).



a



b

Fig.4. Illustrative photo-response time and dynamics of a MSM photodetector (CP377-9).

We are investigating ways to improve rise time (ideally < 1s) but it should be noted that the measurements reported were made using a prober, and should be improved with the much better contacts provided by wire soldering.

3.3 Spectral Response

Fig.5 shows electric responsivities as function of wavelengths for selected β -Ga₂O₃ MSM devices. Two Groups with best sensitivity are considered for the DEVINS program (a): CP 707A and (b): CP 399 A. 2 x 4 different MSM devices that were selected based on their suitability for Herzberg continuum (200-242 nm) observations are displayed showing very comparable spectral responsivities.

Responsivities were measured at less than 10 mA/W (lower than expected but before packaging; investigations are pursued to improve them but a factor 5 to 10 should be gained with the better contacts in the packaged detectors); centering at 215-220 nm was

achieved with FWHM of 35 nm; and rejection at 250 nm ("solar blindness above 250 nm") is better than expected (> 1000).

With these characteristics, the Herzberg continuum spectral band is well covered and detectors ready for flight in 2023 on the INSPIRE-Sat 7 nanosatellite mission. Several groups of 4 detectors with similar response have been properly identified for the mission (this corresponds to the need of 2 flight components and 2 spare components for two different configurations of the detectors). These detectors correspond to the pre-defined criteria of sensitivity, centering and rejection.

3.4 Thermal Cycling Tests

The objective of the test is to measure the photocurrent generated under the effect of polychromatic UV light and temperature changes on the photodetector performance. Photodetectors are designed to operate between -30 and +50 degrees Celsius that correspond to their temperature condition in Space. These sensors should therefore be tested accordingly. The sensors are placed in a climatic chamber during the measurements. They are installed on a "breadboard" on which they are applied a bias voltage of -5V (power is limited by the nanosatellite). Fig. 6 shows one of the thermal cycles used, and Fig. 7 shows the thermal cycles and the corresponding photoresponse of the PD.

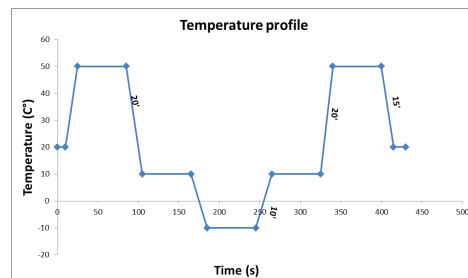


Fig.6. Temperature cycle applied on an MSM photodetector (CP 377-9).

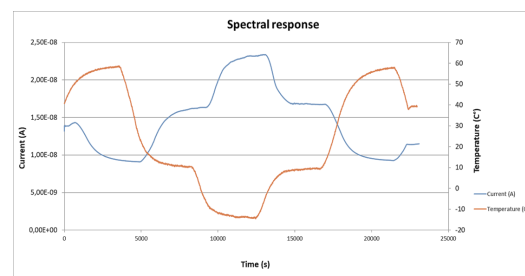


Fig.7. Temperature and PD photocurrent evolution (polychromatic UV illumination and -5V bias) as function of the time.

Fig. 7 shows that the trends in photocurrent are a faithful mirror image of the variations in temperature. This is very promising for use of the β -Ga₂O₃ detectors in the harsh temperature environment of low Earth orbit.

4. Conclusions

This study evidenced that β -Ga₂O₃ photodetectors can be extremely robust and show excellent detection performance with high responsivity and short photo-response, along with a remarkably high rejection of visible and near UV wavelengths ("solar-blind property above 250 nm"). Hence, these detectors are very promising and are now ready for intensive calibrations (in the BIRA-IASB facilities in Brussels) before deployment on the upcoming nanosatellite of LATMOS, INSPIRE-Sat 7 (launch planned in 2023). In the near future, these detectors are projected for large solar and climate satellite constellation ventures.

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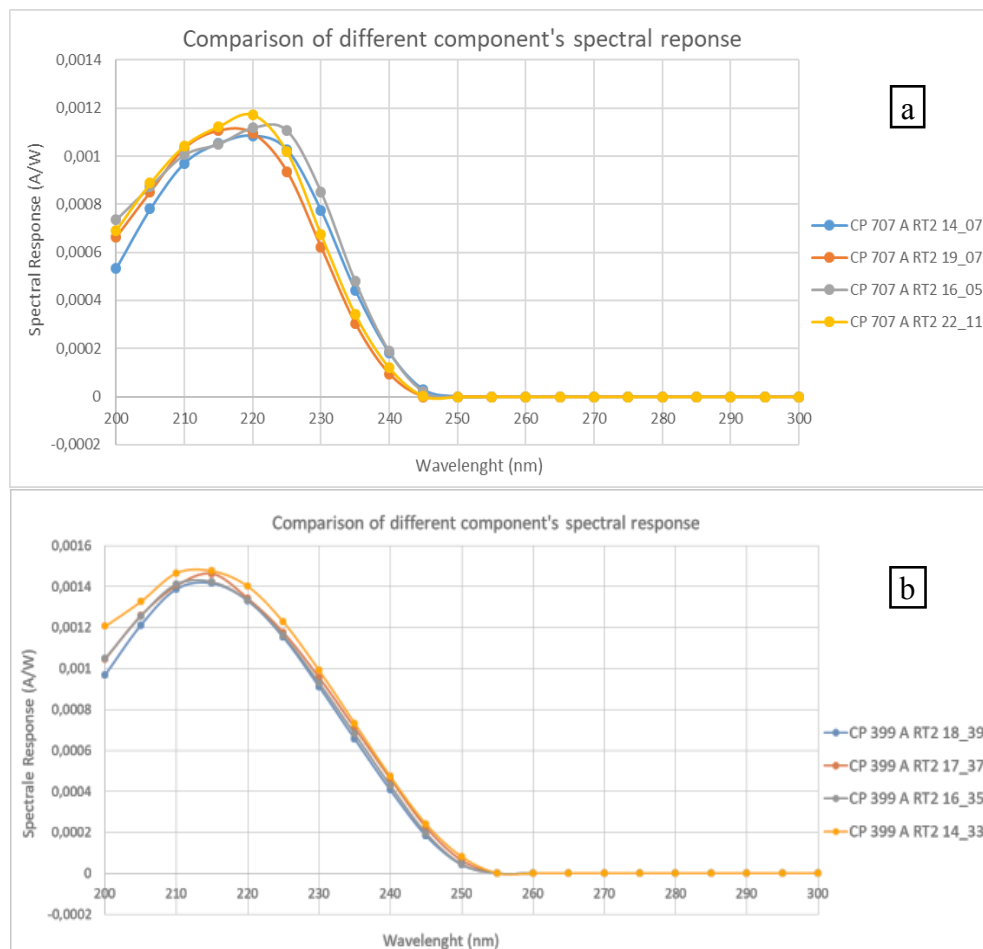


Fig.5. 2-Groups ((a): CP 707; (b): CP 399) of 4 β -Ga₂O₃ DEVINS components selected for the Nanosatellite INSPIRE-Sat 7 and presenting excellent rejection (solar blind for $\lambda > 250$ nm), centering (peak between 215–220 nm) and FWHM (~35 nm).