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On-Orbit Performance of Pd/4H-SiC Schottky UV Detectors in a Low-Earth Orbit

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The monitoring of solar ultraviolet radiation from a space platform is now considered essential for a wide range of fields including solar physics, atmospheric science and astrobiology. 4H-Silicon Carbide (4H-SiC) is a superior alternative to conventional materials like silicon for the fabrication of UV detectors for adverse space conditions due to its inherent radiation hardness and visible-blind nature. This paper describes the space qualification and deployment of indigenously developed Pd/4H-SiC Schottky UV detectors in a low-earth orbit (LEO) and their on-board performance. Two SiC UV detectors were flown as a rad-hard sun detection sensor in the nanosatellite INS-2TD. The sensor has carried out solar UV flux observations continuously since its launch in February 2022 and the data gathered during the first seven months of flight is discussed in this paper.

Keywords: 4H-SiC UV detectors; LEO; Space qualification; Solar UV measurements

1 Introduction

Ultraviolet (UV) radiation from the Sun, despite comprising less than 8% of the total solar irradiance[1], has a significant impact on the structure and dynamics of planetary atmospheres[2]. Therefore, accurate and reliable knowledge on the amount of solar UV flux reaching Earth is of utmost importance. The monitoring of UV radiation falling on Earth is also necessary from a biological point-of-view as excessive exposure to UV can be fatal for life on Earth[3]. UV at wavelengths above 300 nm can cause skin cancer and cataracts in humans and lower-wavelength UV fluxes are capable of dissociating biological molecules like nucleic acids and proteins. The study of electromagnetic radiation in the UV wavelength regime contributes significantly to the field of astrophysics as well[4]. Moreover, UV observations augment studies of the solar corona and transient activity on the surface of the Sun[5].

On the path to develop highly reliable UV detectors for future space instrumentation, 4H-SiC semiconductor material has emerged as an excellent alternative to the conventional silicon based detector material. Its wide bandgap makes it intrinsically blind to visible and IR radiation, eliminating the need for external filters thereby decreasing the weight and complexity of the instrument. 4H-SiC offers outstanding long-term stability even when operated under high-intensity UV radiation[6] (up to 1000 Wm^{-2}) and at high operating temperature (up to 973 K), thermal conductivity (450 $Wm^{-1}K^{-1}$), high displacement threshold energy (22-35 eV), strong anti-radiation ability (1000 kGy of Gamma dose), high detectivity $10^{16} cmHz^{-1/2}W^{-1}$, and low dark current densities[7,8] $10^{-16} Acm^{-2}$. Due to these desirable features, 4H-SiC detectors are now being employed in space-based instruments for measuring UV irradiance at the Martian surface[9], for active dosimetry[10], space weather and ultraviolet solar variability studies[11], and astrobiological experiments[12], as well as for missile plume[13] and flame detection applications[14].

Laboratory for Electro-Optic Systems (LEOS) has indigenously developed technology for realization of Pd/4H-SiC based Schottky detectors operating in 220 – 365 nm wavelength region[15]. The salient objectives behind the development of the detectors were their deployment in UV instruments and sensors for future deep-space science missions, as active radiation monitors for manned space flights and as albedo-free sun attitude sensors with prolonged lifetime. To ensure the quality and reliability of the fabricated 4H-SiC UV detectors for space applications, a rigorous space qualification campaign was carried out. The qualification programme is detailed in Section 2. As a part of on-board calibration

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of these detectors, and to study the time dependent performance variations in harsh space conditions, these detectors were deployed in the nanosatellite mission INS-2TD. Details of the UV sensor flown in INS-2TD and the results of on-board data from the first seven months in orbit is given in Section 3.

2 Space Qualification

Before deploying the in-house developed Pd/4H-SiC UV detectors in various space instruments and sensors, the detector must pass a set of stringent space qualification and screening procedures. This ensures that the detectors operate optimally while being compatible with environmental conditions experienced during both launch and in-orbit operations (radiation environment, thermal and vacuum conditions, mechanical stresses, and electromagnetic compatibility). The space qualification tests were chosen in accordance with MIL standards (MIL-STD 883, MIL-PRF 38535) and ISRO's Environmental Test Level Specifications (ETLS) documents. From the lot of 30 batch fabricated 4H-SiC detectors, randomly chosen 18 4H-SiC Schottky detectors of pixel size 1mm^2 packaged in TO-5 header and 6 detectors of active area 25mm^2 packaged in DIP-8 package with fused silica window have undergone Screening Tests as per the flow chart mentioned in Fig 1(a).

A fine leak test was performed on all the 24 devices to determine the hermeticity of the sealed detector. After the leak test, devices were examined visually for any sign of degradation such as cracks, patches, discoloration and peeling. Post Visual inspection, screening tests including burn-in and thermo-vacuum cycling are carried out to weed out devices in view of infant mortality and choose devices suitable for space environmental conditions. Detector performance assessment tests are carried out after each environmental test to estimate the detector's electro-optical performance. Electro optical characterization involves the evaluation of parameters like responsivity, dark current, capacitance, series resistance and NEP (Noise Equivalent Power) of 4H-SiC detectors as mentioned in Table 1. Details on electro optical characterization can be found in our earlier report[15]. None of the devices failed the screening tests, and the observed variance in performance parameters was within stipulated range.

Further to examine the space worthiness of detectors, 12 randomly chosen screened devices were subjected to qualification tests using the test matrix shown in Fig 1(b). The qualification test matrix

Table 1 — Electro-Optical Test Parameters of Pd/4H-SiC UV detector

Sl. No.	Detector Parameter	Value
1	Responsivity at 280 nm	≥ 100 mA/W
2	Detector Leakage Current at -10V bias	≤ 50 pA
3	Junction Capacitance at -10V bias	≤ 1 nF
4	Series Resistance	≤ 25 kΩ
5	Noise Equivalent Power at 280 nm	≤ 1 nW

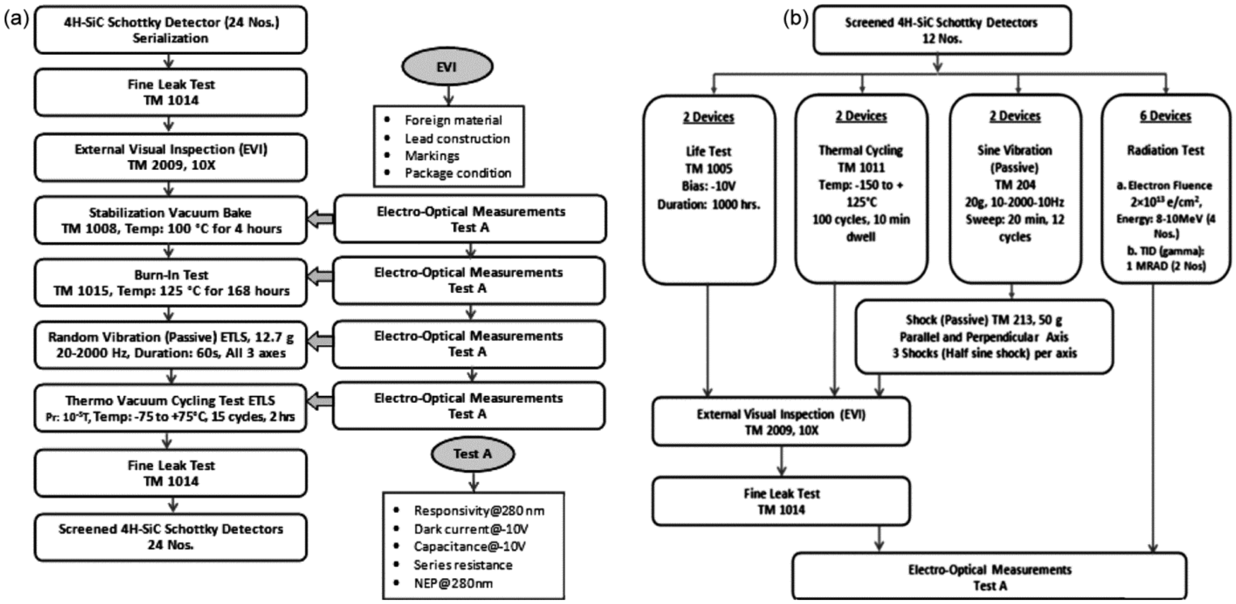

Fig. 1 — (a) Screening test matrix (b) Qualification test matrix.

includes Life test, thermal vacuum cycling at extreme temperatures, mechanical and radiation tests that simulate space environment. To determine the actual life expectancy of the detector, a continuous life test at a reverse bias of 10 V is carried out for 1000 hrs. Thermal cycling test is designed to evaluate the effect of the extreme temperature variations from -150 to 125 °C likely to be experienced by detectors on Mars and Venus environments. 4H-SiC devices are subjected to mechanical environmental tests that replicate dynamic circumstances such as shock, vibration, and acceleration. To investigate performance deterioration under radiation environments, four detectors were exposed to electron irradiation of 10 MeV energy at a fluence of 2×10^{13} e/cm^2 equivalent to a Total Ionizing Dose (TID) of 4.7 Mrad and two detectors to gamma irradiation of 1 Mrad. Degradation in responsivity of 4H-SiC detectors after subjecting to gamma irradiation is observed to be 15.8% and 14% after electron irradiation (TID:1 Mrad). Effect of electron irradiation at dose level 1 Mrad is deduced from the standard relationships[16]. These dosage specifications correspond to worst case scenario for GEO/LEO missions and results indicate End-of-Life performance for 10 years mission period. 4H-SiC detectors were proved to be highly radiation tolerant as they sustained up to a radiation dose of 6 Mrad as reported earlier[17].

All the 12 devices (4H-SiC detectors) have successfully undergone qualification tests as per test matrix Fig 1(b) and their EO parameters are confirmed to meet the original specifications. None of the devices showed any degradation in terms of electro-optical performance or cosmetic aspects and hermetic properties. This demonstrates the reliability, quality, and resilience of the 4H-SiC devices after undergoing extensive space qualification tests making it appropriate for their onboard use in GEO, LEO and interplanetary missions.

3 Flight Experience in INS-2TD

3.1 Mission Overview

After the successful completion of batch screening and qualification, two detectors were proposed for deployment onboard the nanosatellite INS-2TD as rad-hard sun sensors. INS-2TD is a technology demonstrator nanosatellite project launched by the Indian Space Research Organisation (ISRO) on 14th February 2022. The satellite was placed in a sun-synchronous polar orbit of altitude 524.87 km and inclination 97.51 degrees by ISRO's Polar Satellite Launch Vehicle (PSLV) - C52. The satellite was designed for a mission life of 6 months.

3.2 Instrument Description and Ground Calibration

Two detectors each with an active area of 5mm × 5mm were mounted on to a single PCB as shown in Fig 2 and the photo current output of the detectors were processed by attitude sensor processing card. With a trans impedance gain of 10k, and 12-bit Analog to Digital Converter (ADC) with 3.3 V reference, the Least Significant Bit (LSB) resolution of the processing electronics is 80 nA. The integrated 4H-SiC sun sensor has undergone environmental tests as per mission requirement. High Power UV LED stimuli was mounted onto the 4H-SiC sensor to verify its performance after each environmental test.

The indigenously developed detectors were calibrated in ground using NIST Calibrated UV detectors from UTD™. Deuterium arc lamp (LOT Oriel 63161), and Xe arc lamp (Oriel LCS-100) were used as light source for short and long wavelengths respectively. A set of narrow band pass UV filters (FWHM<10 nm) were used for spectral responsivity measurement at various wavelengths. Solar UV flux was estimated from standard reference data (ASTM E490[18]) and further weighted spectral response graph was generated by multiplying the solar spectral irradiance with detector responsivity as shown in Fig 3. On integrating the spectral response over the wavelength range of 220-365 nm, a total photocurrent of 93.86 μA was predicted which in turn corresponds to 1173 counts.

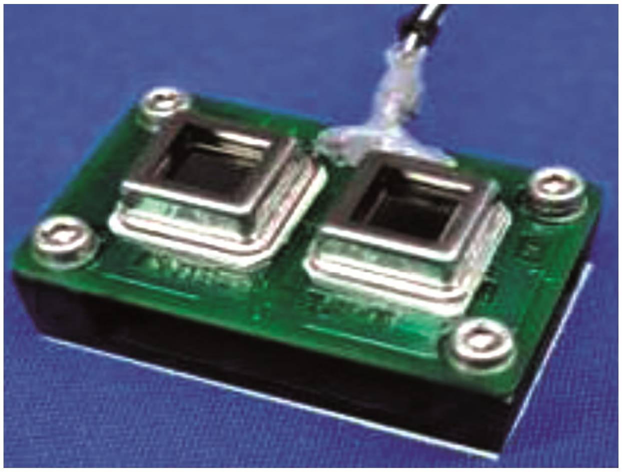

Fig. 2 — Flight model 4H-SiC UV sensor after completion of Test & Evaluation (T&E).

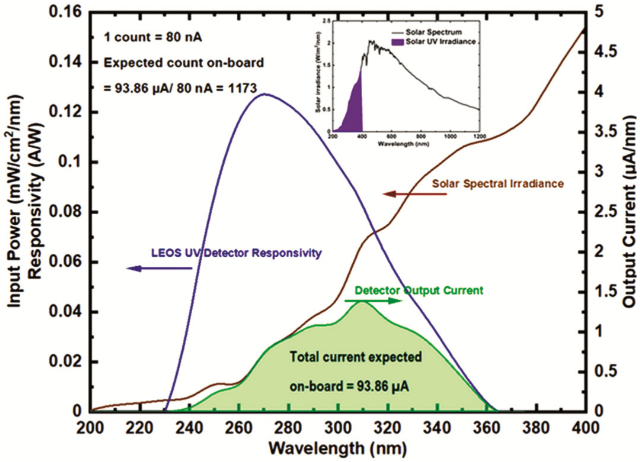

Fig. 3 — Estimation of the sensor output. Inset shows standard solar flux data (ASTM E490).

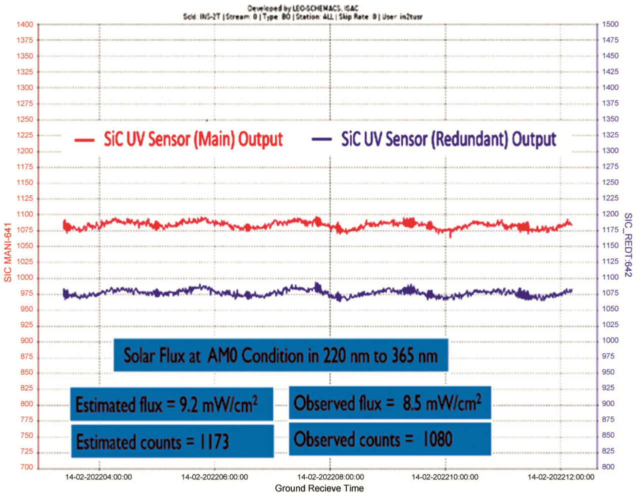

Fig. 4 — On-board telemetry data of the SiC UV sensor for the 3rd to 8th orbit of the spacecraft.

3.3 On-board Results

The on-board output was received in the form of counts at the ground. Fig 4 shows the telemetry data of the SiC UV sensor for the 3rd to 8th orbit of the space-craft. An average value of 1080 counts is observed with extremely good stability. The 3-sigma variation in the observed counts was less than 5 counts which corresponds to a noise equivalent power of 10 µW. From the observed counts, the solar flux at AM0 condition in the 220 nm to 365 nm wavelength region is calculated to be 8.5 mW/cm^2. This is 7.6 % lower than the flux estimated in Section 3.2 (9.2 mW/cm^2). This deviation could be due to errors in the laboratory calibration of the SiC detectors or due to the extrapolated responsivity values of the LEOS SiC detector for λ<240 nm.

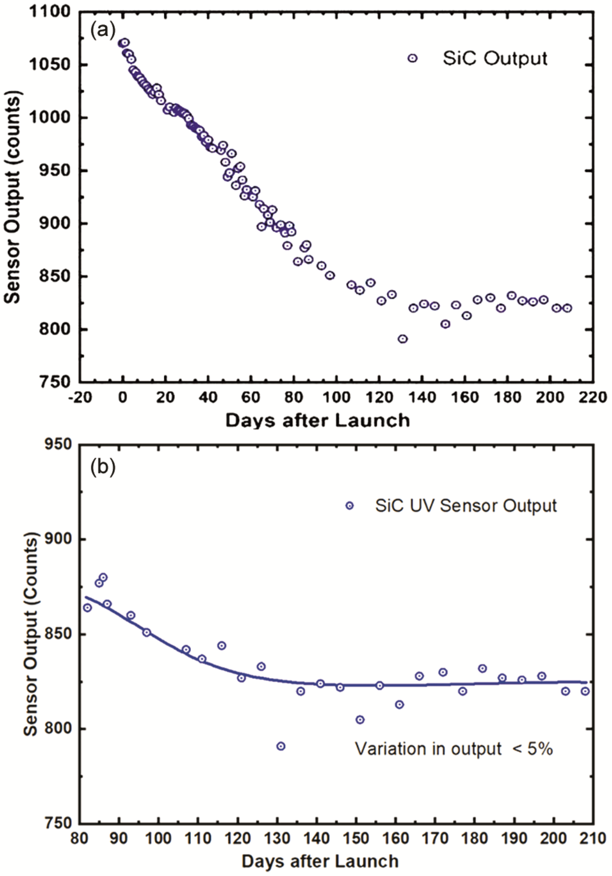

Fig. 5 — (a) SiC UV Sensor Onboard Output for the first seven months of flight (b) SiC UV Sensor Stabilized Onboard Output after 120 days.

Subsequently, the onboard performance was periodically monitored for seven months. Fig 5(a) shows the sensor output in counts for the first seven months in orbit. The data shows an initial decrease in output of ~20% followed by a stabilization after 120 days in orbit as observed in Fig 5(b). A possible explanation for the observed reduction in the sensor counts can be the change in transmittance of the fused silica top window due to radiation damage. Satellites in high-inclination low-Earth orbits experience dose rates of 1-10 krad (Si)/year[19]. Ionizing radiation in LEO is dominated by protons either trapped in the van Allen radiation belts or generated during solar particle events[20-22]. The flux of protons and electrons in lower Earth orbit varies between 10^3 and 10^8 cm^{-2}s^{-1}, with energies of 100 keV and 1 MeV respectively[23].

Further it is substantiated by the observation previously, the MOEMS sun sensors based on Silicon photodetectors developed in LEOS have undergone space qualification tests wherein the radiation effect was studied by proton irradiation. The results indicate that at AM0 condition, a degradation of 19.5% in the photocurrent response (in the wavelength region 400-1100 nm) of silicon detector pixel of the MOEMS sun sensor was observed, after exposure to proton irradiation of energy 10-20 MeV and fluence of 8.7×10^{10} p/cm^2 with no change in detector's dark current characteristics. Hence, the performance degradation is attributed to change in optical properties of glass window. Also, the electron and gamma irradiation results of 4H-SiC detectors during qualification tests have shown maximum degradation of less than 1.6% in its UV response (220-365 nm) for 100 krad[16]. Hence, it is evident that the on-board degradation of ~20% may be attributed to quartz window degradation as supported by other reports[24,25]. The reported observations follow a similar trend with a rapid initial change in optical density, which then saturates with increasing absorption dose. This degradation is attributed to darkening of the quartz window due to the formation of color centres. The exact nature of degradation and its quantification due to particle irradiation experienced onboard will be studied in subsequent space flights.

4 Conclusions

This paper provides an overview of the space qualification of indigenously developed 4H-SiC detectors and their successful deployment in the nanosatellite INS-2TD. Indigenous 4H-SiC UV detectors successfully passed a set of stringent space qualification tests while meeting the electro-optical specifications for space use. The on-orbit 4H-SiC UV sensor output is monitored for the first seven months of flight. A maximum degradation of ~20% is observed in the sensor output, which stabilizes after 120 days. This onboard performance has given enough confidence to develop SiC-based dosimeter for manned missions.

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