

Radiation characterization of an event-based asynchronous sun sensor

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ABSTRACT

This paper presents a comprehensive experimental characterization of the radiation tolerance of a novel event-based asynchronous CMOS sun sensor designed for spacecraft attitude determination. The sensor's robustness was evaluated through an extensive radiation test campaign, including total ionizing dose (TID) exposure up to 58.6 krad(Si) and heavy-ion irradiation with linear energy transfer (LET) values up to 62.5 MeV·cm²/mg. Key performance parameters – such as centroid accuracy under sun-simulated illumination, open-circuit voltage stability, global power consumption, and logical level integrity across multiple threshold voltage settings – were systematically monitored throughout the TID and single event effects tests. No significant degradation was observed in any parameter, and the sensor exhibited immunity to single event latch-up (SEL), single event upset (SEU), and single event functional interrupt (SEFI) under all tested conditions. The use of a calibrated sun simulator during irradiation enabled real-time assessment of sensor functionality under representative operational scenarios. Additionally, the impact of varying illumination and threshold settings on transient event susceptibility was investigated, demonstrating that any radiation-induced transients can be effectively mitigated at the system level without loss of pointing accuracy. These results validate the suitability of event-based asynchronous sun sensors for reliable, radiation-tolerant operation in demanding space environments.

Keywords: Image sensor, sun sensor, address event representation, total ionizing dose, single event effect, radiation characterization

1. INTRODUCTION

Sun sensors are critical components in spacecraft attitude determination systems, providing precise and reliable measurements of the Sun's position relative to the spacecraft.¹ Traditional sun sensors often employ frame-based active-pixel sensor (APS) architectures, which, while effective, are limited by their relatively high-power consumption, data throughput, and susceptibility to radiation-induced transients.²⁻⁵ These limitations are particularly relevant in the space environment, where radiation effects can compromise sensor performance and reliability.

Recent advances in event-based sensing have introduced a new paradigm for sun sensor design.⁶ Unlike conventional frame-based imagers, event-based sensors generate output asynchronously when local illumination variations exceed a programmable threshold. This operating principle enables high-speed, low-power sensing with update rates of several kilohertz and significantly reduced data rates. Gómez et al.⁷ introduced an asynchronous event-based sun sensor architecture that determines the Sun's position directly from the centroid of sparse event clusters, offering inherent advantages in power efficiency and temporal resolution.

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In addition to these electro-optical advantages, the event-driven sensing principle provides an inherent degree of radiation hardness. In particular, the asynchronous operation and threshold-triggered event generation can reduce the impact of transient disturbances compared with conventional frame-based architectures. However, the inherent radiation hardness of the sensing principle does not fully characterize the radiation response of the complete sensor. Quantitative characterization is required to determine the effects of irradiation on the sensor output, event generation, centroid accuracy, and overall functionality, as well as to establish its operational limits under radiation exposure.

This work presents an experimental radiation characterization of an asynchronous CMOS event-based Sun sensor operating in photovoltaic mode, with on-chip centroid computation and address-event representation output. The sensor was evaluated through total ionizing dose (TID) exposure up to 58.6 krad(Si) and heavy-ion irradiation with linear energy transfer (LET) values up to 62.5 MeV·cm²/mg. Centroid accuracy, open-circuit voltage, global power consumption, and logical-level integrity were monitored for different threshold-voltage settings. The sensor's single event effect (SEE) response, including single event latch-up (SEL), single event upset (SEU), and single event functional interrupt (SEFI), was also investigated, together with the influence of illumination and threshold settings on radiation-induced transient events. The results provide a quantitative assessment of the sensor's radiation response and demonstrate robust operation under the tested radiation conditions. The remainder of this paper is organized as follows: section II describes the sensor and experimental setup and methodology, section III presents and discusses the radiation-characterization results, and section IV summarizes the main conclusions.

2. EXPERIMENTAL

Sample description

Figure 1 shows the principle of operation of the asynchronous event-based sun sensor with on-chip centroid computation.⁷ The sensor is composed of 64 x 64 pixels with 19 μm pitch. Each pixel consists of a photodiode working in the photovoltaic regime and a compact analog frontend which converts the photocurrent into an open-circuit voltage V_{OC} followed by the local thresholding circuitry that compares this voltage against the reference voltage V_{th} . Every time local luminance variation is sufficient to cross the threshold, the pixel generates an event, and the corresponding pixel address is transmitted to the readout circuit. The readout circuit computes the centroid accumulating the row and column addresses of active pixels during a short observation window and dividing the accumulated sums by the total number of events. The resulting coordinates correspond directly to the Sun position on the sensor surface and can subsequently be converted into Sun angles and a Sun vector through a previously calibrated geometrical model. The combination of photovoltaic-mode operation, asynchronous event generation, and on-chip centroid computation results in a low-power sensor consuming approximately 63 μW while achieving update rates in the kilohertz range. The prototype provides a Sun-vector update rate of approximately 5 kHz with an angular resolution of 1.23° and accuracies of 2.38° in latitude (θ) and 5.82° in azimuth (ϕ). Detailed description of the sensor and its operation mode can be found in Ref. [7].

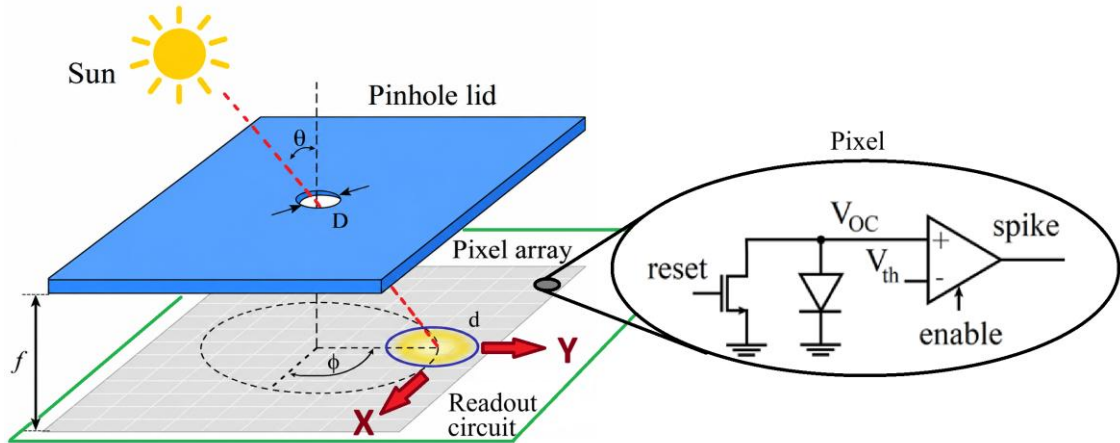


Figure 1. Scheme of the working principle of the asynchronous event-based image sensor.

Electro-optical measurements

Figure 2 shows the realization of the setup for electro-optical (EO) measurements. EO characterizations were performed in a laboratory environment prior to irradiation and at intermediate TID steps. The device under test (DUT) was mounted on a custom motherboard that provided access to the power rails, configuration interface, and digital event output. A broadband light source was used for optical characterization and neutral-density filters enabled controlled variation of the incident irradiance over several orders of magnitude. The DUT was powered using a low-noise external power supply, and the event-stream output was monitored with a digital oscilloscope and acquisition software. At each TID step, a set of electro-optical parameters representative of sensor functionality and event-driven performance was evaluated. First, the open-circuit voltage V_{OC} was measured in the function of illumination at 30°C to evaluate photodiode and front-end stability. Then global power consumption was determined by monitoring the supply currents of the asynchronous sensor. Due to the time constraints two other tests were performed as pass/fail criteria: centroid position under sunspot emulation, obtained from the on-chip centroid calculation logic and logical-level integrity, which was assessed by sweeping the pixel threshold V_{th} and verifying the sensor's response to desired illumination changes.



Figure 2. Setup for electro-optical measurements: 1 – power supply, 2 – motherboard with DUT mounted on top, 3 – light source with corresponding neutral filters for illumination level control, 4 – oscilloscope, 5 – thermometer.

Total ionizing dose setup

Total ionizing dose irradiation was performed at the RADLAB facility of the Centro Nacional de Aceleradores (CNA), Spain. Two devices under test (S1 and S2) were exposed to a ^{60}Co gamma-ray source under unbiased conditions at a dose rate of 197 rad/h, until a cumulative dose of 58.6 krad(Si) was achieved.

To assess radiation-induced degradation, characterization measurements were carried out at several intermediate dose levels during the irradiation campaign. At each interval, the DUTs were removed from the irradiation bunker and evaluated using the characterization procedure described in the previous subsection. This methodology allowed the evolution of photodiode sensitivity, threshold characteristics, power consumption, and centroiding performance to be tracked as a function of accumulated TID.

Single event effect setup

Heavy ion experiments were performed at the Heavy Ion Facility (HIF) of Université Catholique de Louvain (UCL), Belgium. Sensors S3 and S4 were irradiated under biased conditions using a range of ion species with linear LET values up to 62.5 MeV·cm²/mg. Since the ion beam diameter is 2.5 cm, only the image sensor was irradiated, while the surrounding electronics remained outside of the beam footprint. The parameters of the beam used in the experiment are listed in Table I.

SEE susceptibility was investigated for three sensor threshold settings, 79 mV, 163 mV (nominal operating point), and 264 mV, under controlled illumination conditions. A sunspot emulator was used to reproduce representative optical conditions, employing a 630 nm laser to approximate the solar spectral irradiance (see Figure 3).

Table 1. Heavy ions beam parameters.

Ion	Range ($\mu\text{m}(\text{Si})$)	LET ($\text{MeV}\cdot\text{cm}^2/\text{mg}$)	TID ($\text{krad}(\text{Si})$)
$^{58}\text{Ni}^{18+}$	100.5	20.4	3.26 a
$^{84}\text{Kr}^{25+}$	94.2	32.4	5.18 a
$^{103}\text{Rh}^{31+}$	87.3	46.1	7.38 a
$^{124}\text{Xe}^{35+}$	73.1	62.5	10.0 a

According to ASTM E490⁸, the expected irradiance at this wavelength is $1.65 \text{ W}/(\text{m}^2\cdot\text{nm})$, which corresponds to an optical power of $2.35 \mu\text{W}$ for a 20 nm FWHM laser and a $300 \mu\text{m}$ top-hat spot projected onto the sensor surface (Figure 3 and 4). Owing to the 1 mA resolution of the laser driver, the actual laser power was set to $2.75 \mu\text{W}$. Three illumination conditions were considered: Sun-equivalent irradiance, the minimum detectable irradiance for each V_{th} , and darkness. The threshold for each minimum detectable irradiance was:

- $V_{\text{th}} = 79 \text{ mV}$, $P_{\text{O}} = 0.019 \mu\text{W}$;
- $V_{\text{th}} = 163 \text{ mV}$, $P_{\text{O}} = 0.045 \mu\text{W}$;
- $V_{\text{th}} = 264 \text{ mV}$, $P_{\text{O}} = 45.0 \mu\text{W}$.

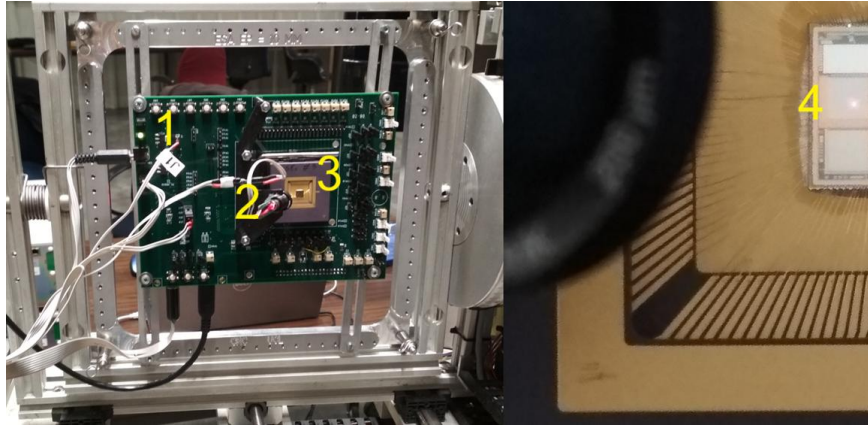


Figure 3. Setup for SEE test: 1 – motherboard with zero insertion force socket, 2 – laser sunspot emulator, 3 – DUT, 4 – sunspot on the sensor surface.

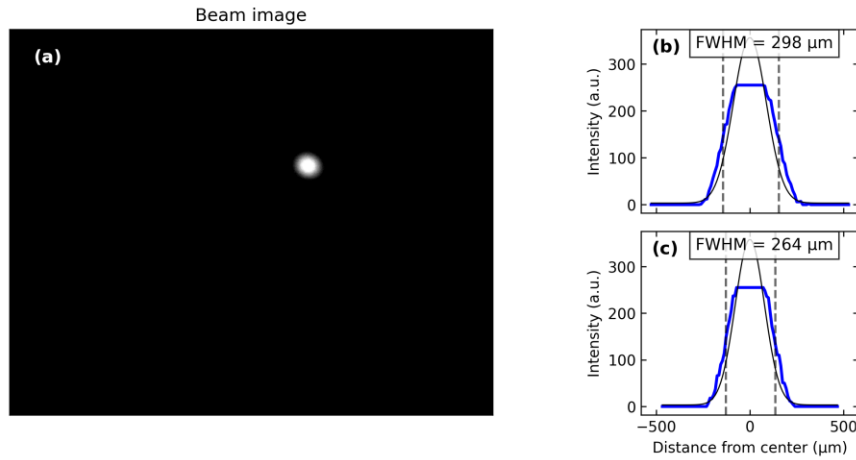


Figure 4. Characterization of the laser beam: (a) raw image of the beam, the profiles of the longer (b) and shorter (c) axis.

The SEE campaign considered three main failure mechanisms:

Single-Event Latch-up (SEL): SEL events were monitored through the supply currents of both the analog and digital power rails. The power supplies provided over-current protection, while the acquisition software continuously logged the current levels to identify abnormal current increases associated with latch-up.

Single-Event Upset (SEU): SEUs were identified from anomalous changes in the reported Sun centroid. During illumination, the centroid was expected to remain at the nominal sunspot position, whereas under dark conditions its nominal value was (0,0). A spontaneous displacement from the expected position was therefore considered indicative of a SEU.

Single-Event Functional Interrupt (SEFI): A SEFI was defined as a radiation-induced loss of sensor functionality in the absence of SEL. Events resulting in an unresponsive sensor, including those associated with corruption of configuration registers, were classified as SEFIs. Recovery from such events required a manual device restart.

3. RESULTS AND DISCUSSION

Total ionizing dose

Following ECSS 22900 standard⁹, intermediate characterizations were performed within two hours after each irradiation step in order to minimize the impact of room-temperature annealing. A subset of functional tests was used as pass/fail criteria, including centroid localization under sunspot-emulation conditions and verification of the output logical levels. Throughout the irradiation campaign, all tested devices remained fully functional and met the specified criteria. The overall supply current exhibited only a minor 5.9% increase, rising by approximately 2 mA relative to the initial consumption of 34 mA measured before irradiation. To assess the impact of ionizing radiation on the photodetection mechanism, particular attention was given to the open-circuit voltage V_{OC} . In the photovoltaic operating mode, V_{OC} represents the equilibrium voltage established across the photodiode under illumination when the net current through the junction becomes zero. This parameter is determined by the balance between photogenerated carriers, and the recombination and leakage processes occurring within the device and can therefore serve as a sensitive indicator of radiation-induced degradation. The open-circuit voltage is given by:¹⁰

$$V_{OC} = \frac{nkT}{q} \ln \left(\frac{I_{ph}}{I_0} + 1 \right), \quad (1)$$

where n , k , T , and q are the ideality factor, Boltzmann constant, temperature, and elementary charge, respectively. I_{ph} is the photocurrent generated under illumination, whereas I_0 denotes the dark saturation current, which is closely related to the recombination activity and leakage mechanisms of the photodiode. The evolution of $\Delta V_{OC} = V_{OC}(\text{TID}) - V_{OC}(0)$ with TID for different illumination levels is shown in Figure 5.

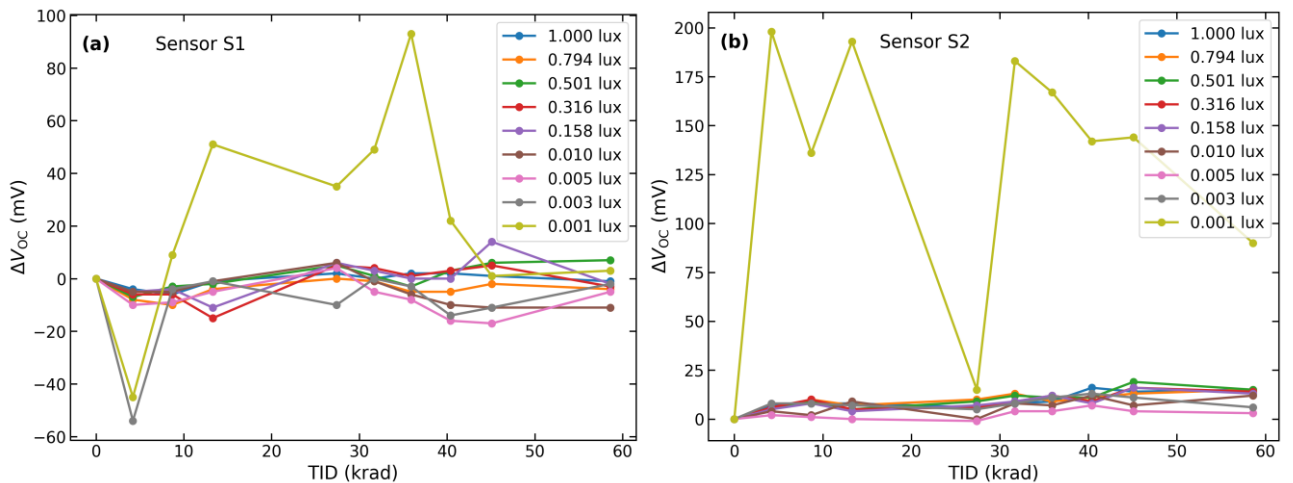


Figure 5. Dependence of the ΔV_{OC} in a function of TID for different illumination levels for sensor S1 (a) and sensor S2 (b).

At the lowest illumination level (0.001 lux), a noticeable dispersion of the measured values is observed for both sensors. This behavior is attributed primarily to the absence of active temperature stabilization during the measurements. Under extremely low illumination, the photocurrent becomes comparable to the dark current contribution, increasing the sensitivity of the extracted parameters to temperature fluctuations and low-frequency noise sources. Consequently, the associated measurement uncertainty becomes significantly larger than at higher illumination levels. For moderate and high illumination conditions, no systematic degradation attributable to TID is observed. The extracted parameters remain essentially stable throughout the irradiation campaign (within $\pm 4\%$), suggesting that the carrier generation and transport processes governing the photodiode response are largely preserved. In particular, no evidence of a substantial increase in recombination activity or leakage-related effects is detected within the experimental uncertainty.

Additional insight is obtained from the ideality factor analysis, presented in Fig. 6. For both sensor implementations, the extracted ideality factor remains close to unity over the entire investigated dose range, changing only marginally from 0.95 to 1.01 for sensor S1 and from 0.93 to 1.07 for sensor S2. Such values are characteristic of diffusion-dominated current transport¹¹ and indicate that the underlying recombination mechanism remains essentially unchanged after irradiation. The absence of a significant increase in the ideality factor further suggests that defect-assisted Shockley-Read-Hall recombination contributes only weakly to the device behavior under the investigated TID conditions.^{11, 12}

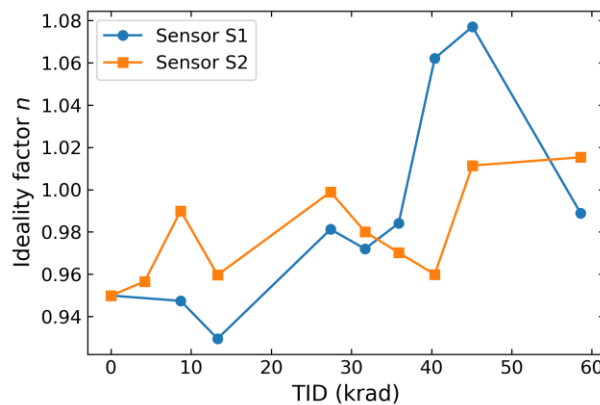


Figure 6. Dependence of the ideality factor in a function of TID.

Overall, the results indicate that the photodiode conversion mechanism exhibits a high degree of tolerance to ionizing radiation, with no measurable degradation of the parameters governing the event-generation process up to the maximum accumulated dose investigated in this work.

Single event effects

Single-event latch-up was monitored as a primary failure mechanism because of its potential to cause permanent damage to the device. Reliable SEL identification was particularly challenging for the investigated sensor because its supply currents vary significantly with the illumination and operating conditions. The analog supply current IDD18, ranged from approximately 9 mA in darkness to 45 mA under full-frame illumination. The digital supply current IDD_PERIPH, was close to zero in darkness but exhibited transient peaks of up to 28 mA during centroid computation, with durations below 1 ms. Similarly, the pixel-readout current IDD_PIX varied from approximately 0.8 mA to short-duration peaks of about 28 mA during pixel activity. To distinguish normal operating transients from radiation-induced latch-up, the analog and digital supply currents and voltages were continuously monitored by a watchdog system with a response time below 1 ms. Average values were additionally recorded at 5 s intervals for post-test analysis. Independent current limits were defined for each supply rail to provide appropriate SEL protection under the different operating conditions. No SEL event was detected for any of the tested ions or illumination configurations. The sensor therefore showed no evidence of latch-up up to the maximum tested LET of 62.5 MeV·cm²/mg.

SEU susceptibility was evaluated by monitoring deviations of the reported centroid from its expected position. A key observation of the SEE campaign was that no SEU events were detected under any of the tested illumination conditions. SEU events were observed only when the sensor was operated in darkness, indicating a strong dependence of the single-event response on the illumination state. Figure 7 presents the average SEU cross section as a function of LET for the different threshold-voltage settings under dark conditions. The reported values were obtained from sensors S3 and S4.

Events were only observed at the highest LET values, corresponding to the Rh and Xe ion irradiations, and the measured cross section exhibited a clear dependence on V_{th} . For Xe irradiation, increasing V_{th} from 79 mV to 264 mV reduced the average SEU cross section from approximately $7 \cdot 10^{-6}$ cm²/device to $1.2 \cdot 10^{-6}$ cm²/device.

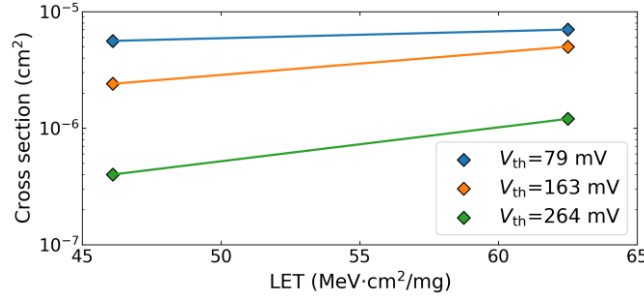


Figure 7. Averaged SEU cross section in the function of LET in the darkness for different threshold voltages.

No observed SEU resulted in SEFI. Throughout the heavy-ion campaign, the sensor remained responsive and did not require a recovery or power cycle following a SEU. The absence of SEUs under illuminated conditions, together with the lack of SEFIs, demonstrates the robustness of the complete sensing chain during normal Sun-sensing operation. Under dark conditions, where SEUs were observed only at the highest LET values, the resulting disturbances remained limited to transient centroid deviations and did not compromise sensor functionality.

Finally, the cumulative dose deposited during heavy-ion testing reached 70.7 krad(Si) for sensor S3 and 36.3 krad(Si) for sensor S4. No degradation of functionality was observed at these dose levels. Taken together, the results demonstrate that radiation robustness arises not only from the underlying CMOS implementation but also from the sensing architecture itself. The combination of threshold-based event generation, centroid-based processing, and temporal filtering provides an intrinsically resilient event-driven sensing approach suitable for spaceborne Sun-tracking applications.

4. SUMMARY AND CONCLUSIONS

This work presented an experimental radiation characterization of an asynchronous event-based CMOS sun sensor for spacecraft attitude determination. The sensor was evaluated under TID exposure up to 58.6 krad(Si) and heavy-ion irradiation up to an LET of 62.5 MeV·cm²/mg. Throughout the tests, centroid accuracy, open-circuit voltage, power consumption, and logical output levels were monitored under different operating conditions.

No significant degradation was observed during TID irradiation, and the sensor maintained its nominal functionality. During heavy-ion testing, no SEL or SEFI events were detected. No SEUs were observed under illuminated conditions, while SEUs occurred only in darkness and at the highest LET values. The measured SEU cross section decreased with increasing threshold voltage, and none of the observed events resulted in a loss of sensor functionality.

Overall, the results demonstrate robust operation of the investigated event-based Sun sensor under the tested radiation conditions. The absence of measurable performance degradation and the limited impact of single-event effects support its suitability for radiation-exposed spacecraft Sun-sensing applications. Future work will address improved angular performance and extended radiation characterization under additional operating and irradiation conditions.

ACKNOWLEDGEMENTS

This work was supported in part by the Spanish Ministry of Industry and Tourism as DIGISOLAR I (AEI-010500-2022b-2), National Project In part, by project ELIXIR (PID2023-147244OB-I00) funded by MICIU/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”; by Public Function through grant USECHIP (TSI-069100-2023-001) of PERTE Chip Chair program, funded by European Union – Next Generation EU, and by project INTFOT (DGP PIDI 2024 00388), funded by the program “Subvenciones para el desarrollo de proyectos de investigación aplicada y desarrollo experimental por los agentes del sistema andaluz del conocimiento 2024 - Línea 2.

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