# Experimental Study on Pulsed Laser Testing for Single-Event Latch-Up Protection in Space

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## Abstract

Pulsed laser, as a simple, economical, safe, reliable, and non-radiation-damaging experimental method, offers advantages such as flexible beam time, continuously adjustable energy, non-destructive testing to devices under test, and convenient operation. It has broad application prospects in simulating space single-event effects and has become the mainstream method adopted domestically and internationally in recent decades, apart from heavy ion accelerators. With its capability for accurate localization of sensitive areas, it has gradually developed into a valuable complement to heavy ion single-event effect testing and has been widely applied in the performance evaluation of single-event effect hardening designs for electronic devices. This paper aims to investigate the single-event latchup effect in image sensors and validate the effectiveness of its protection strategies through pulsed laser experiments. The experimental study focuses on CMOS APS image sensors, employing focused pulsed laser beams to simulate single-event events. By adjusting the energy and irradiation position of the pulsed laser, single-event events of different energies and incident angles are simulated, and the response of the image sensor is observed and recorded. An in-depth study of the device's single-event latchup effect is conducted, and the practical effectiveness of the protection methods is analyzed. The results demonstrate that pulsed laser experiments provide an effective means for validating protection strategies against single-event latchup effects in image sensors. Through comparative experiments, the strengths and weaknesses of protection strategies in resisting single-event latchup effects can be clearly observed, thereby providing strong support for protection design in practical applications.

# Full Text

## Experimental Study on Pulsed Laser for Single Event Latchup Protection in Space

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### Abstract

As a simple, economical, safe, reliable, and radiation-damage-free testing method, pulsed laser offers broad application prospects for simulating space single event effects (SEE). Characterized by flexible scheduling, continuously adjustable energy, non-destructive testing of devices, and convenient operation, it has become a mainstream approach both domestically and internationally over the past decade, alongside heavy-ion accelerators. With advantages such as accurate positioning of sensitive regions, pulsed laser testing has gradually evolved into a powerful complement to heavy-ion single event effect experiments and is widely employed in evaluating the performance of radiation-hardened designs for electronic devices. This paper investigates the single event latchup (SEL) effect in image sensors and verifies the effectiveness of protection strategies through pulsed laser experiments. Using a CMOS active pixel sensor (APS) as the test vehicle, focused pulsed laser beams were employed to simulate single event occurrences. By adjusting the laser energy and irradiation position, we simulated single events with varying energies and incident angles, observing and recording the sensor's response to conduct an in-depth study of the device's SEL effect and analyze the practical effectiveness of protection methods. The results demonstrate that pulsed laser experiments provide an effective means for verifying SEL protection strategies for image sensors. Through comparative experiments, the relative merits of different protection strategies in resisting SEL can be clearly observed, providing strong support for protection design in practical applications.

**Keywords:** single event effect (SEE); single event latchup (SEL); protection design; pulsed laser; effectiveness verification

## 1 Introduction

Single event effects (SEE) are radiation effects produced by the interaction of individual high-energy particles with microelectronic devices. Electronic components in satellites during on-orbit operation and other harsh radiation environments are susceptible to single event effects that can impact device functionality.

With the rapid development of aerospace technology, image sensors are increasingly deployed in space exploration, satellite remote sensing, and related fields. However, in the space environment, image sensors are vulnerable to high-energy particle impacts that generate single event effects, leading to device functional failure or performance degradation. Single event latchup represents one of the most critical single event effects, causing portions of an image sensor's circuitry to remain in a latched state for extended periods, severely affecting normal operation. Therefore, investigating single event latchup effects and protection strategies for image sensors holds significant importance.

In recent years, pulsed laser has emerged as a simple, economical, safe, reliable, and radiation-damage-free testing method with broad application prospects for simulating single event effects. Offering flexible scheduling, continuously adjustable energy, non-destructive testing of devices, and convenient operation, it has become a mainstream approach both domestically and internationally over the past decade, complementing heavy-ion accelerators. With advantages such as accurate positioning of sensitive regions, pulsed laser testing has gradually developed into a valuable supplement to heavy-ion single event effect experiments and is widely applied in evaluating the performance of single event effect hardening designs for electronic devices. This paper employs pulsed laser technology to investigate single event effects in image sensors, analyze the impact of single event latchup on performance, and validate the effectiveness of SEL protection designs.

## 2 Principle and Methods

Single event latchup occurs when space radiation particles strike MOS devices, generating large current pulses within the device that cause performance degradation. If these high-current pulses persist for too long, they can seriously affect device performance or even destroy the device. This study employs focused pulsed laser beams to simulate single event occurrences and conducts experimental research on single event latchup effects in CMOS APS image sensors. The experimental setup primarily consists of a pulsed laser, optical system, image sensor sample, and test circuit. By adjusting the pulse laser energy and irradiation position, we simulate single event occurrences caused by particles with different energies and incident angles, observing and recording the image sensor's response.

Protection strategies for single event latchup typically involve adding current-limiting resistors and power-cycling restart mechanisms. Dynamic current-limiting resistor protection can be implemented through digital potentiometer-based dynamic current-limiting circuits or self-resetting fuse (PPTC) + MOSFET active power clamping circuits. The potentiometer-based dynamic current-limiting circuit uses a microcontroller unit (MCU) to real-time adjust the digital potentiometer resistance, achieving dynamic switching between "low-resistance state during normal operation and high-resistance state during SEL." The structural principle is shown in [Figure 1: see original paper].

The schematic employs a Hall effect sensor to detect load current and output an analog voltage to the MCU's ADC interface. During normal operation, the digital potentiometer is set to minimum resistance (e.g., 10Ω) to ensure low power consumption. When overcurrent is detected (e.g., current > 1A), the resistance is quickly increased via the SPI bus to the current-limiting threshold (e.g., 500Ω), restricting current within a safe range (e.g., < 500mA). This protection method achieves response speeds at the microsecond level and is suitable for scenarios requiring dynamic adjustment of current-limiting thresholds.

[Figure 1: see original paper] Dynamic Current Limiting Resistance Protection Principle Block Diagram

In the diagram above, Rcs is connected in series with the power supply loop to convert load current into a voltage signal. A differential amplifier amplifies the sampling voltage to match the MCU's ADC input range. A hysteresis comparator sets threshold voltages—when the sampling voltage exceeds the upper threshold, it outputs a high level, triggering the MCU to initiate current limiting; when it falls below the lower threshold, it returns to low level, and the MCU reduces the current-limiting resistance. The digital potentiometer communicates with the MCU via SPI bus. When the comparator outputs high, the MCU gradually increases resistance until the current sampling value meets the set requirements.

The self-resetting fuse (PPTC) + MOSFET active power clamping circuit achieves passive current limiting through the PPTC and rapid power disconnection through the MOSFET. The PPTC is selected with a rated current matching the load's normal operating current (e.g., for a normal load current of 0.5A, a 1A rated PPTC is chosen), with a resistance jump threshold triggered at 2-3 times the rated current. In the MOSFET drive circuit, a comparator continuously compares the current sampling signal (from the voltage drop across the PPTC) with a threshold voltage. During overcurrent events, the comparator outputs high, driving the MOSFET gate to turn it off and cut power (response time < 100ns). This protection method leverages the PPTC to suppress sustained large currents while the MOSFET rapidly cuts off transient spikes, making it suitable for monitoring and protecting against instantaneous currents triggered by single heavy-ion strikes (SEL events).

[Figure 2: see original paper] Block Diagram of Self-Resetting Fuse (PPTC) + MOSFET Active Power Clamping Circuit Principle

In the diagram above, current detection resistor Rds samples the MOSFET source current. The overcurrent comparator outputs an overcurrent signal that, when exceeding the threshold, triggers the enable signal to activate the drive circuit, thereby turning off the MOSFET.

This study designs current-limiting resistors and current-limiting low-dropout regulators within the circuit to restrict operating and output currents, preventing single event latchup effects. To verify the effectiveness of the protection strategy, pulsed laser irradiation was used to induce single event effects in image sensors equipped with current-limiting resistors and current-limiting low-dropout regulators.

## 3 Experimental Details

### 3.1 Test Devices and Protection Circuit Design

Preliminary research revealed that the control circuit portion of image sensors is particularly sensitive to single event latchup effects. Therefore, this design employs real-time current monitoring and overcurrent power-cycling restart mechanisms for device protection. The fundamental principle of the protection measures is illustrated in [Figure 3: see original paper].

[Figure 3: see original paper] Schematic Diagram of Single Event Latchup Protection

The design utilizes independent power supply loops and selects voltage regulators with enable control terminals as the sensor's main power supply. An FPGA's built-in ADC module continuously monitors the image sensor's total current. When the image sensor experiences latchup, the supply current increases abnormally. After the FPGA detects that the sensor supply current exceeds the limit and remains above threshold for a set duration, it shuts down the main regulator (5V to 3.3V) by controlling the power enable pin. After a 1-second shutdown period, the FPGA sequentially reapplies power to the image sensor.

The primary experiments and verifications include: normal operating current testing of the CMOS APS image sensor (CMV4000), current testing during single event latchup occurrence, and validation of single event latchup protection effectiveness. The basic test connections are shown in [Figure 4: see original paper].

[Figure 4: see original paper] Schematic Diagram of Basic Test Connections

In [Figure 4: see original paper], the power enable signal controls the APS image sensor's main power supply on/off state. The exposure end signal marks the completion of APS image sensor exposure and the beginning of data preparation. VA represents the voltage at the high side of the APS image sensor's current-sensing resistor (positive terminal of R203), while VB represents the voltage at the low side (negative terminal of R203). The voltage difference between VA and VB directly reflects the image sensor's operating current, enabling real-time monitoring of the sensor's working current through measurement of the voltage drop across the current-sensing resistor.

### 3.2 Pulsed Laser Test System

The pulsed laser used in the experiments has a wavelength of 1064nm, pulse width of 25ps, spot diameter of 2 m, pulse frequency of 10Hz, and objective lens magnification of 20X. Pulsed laser emission, XYZ displacement precision control platform movement, pulse laser energy selection, energy testing, focused beam spot testing, and scanning positioning are all computer-controlled. The pulsed single event effect test system is shown in [Figure 5: see original paper].

[Figure 5: see original paper] Pulsed Laser Single Event Effect Test Equipment

## 4 Results and Analysis

### 4.1 Normal Operating State of Sensor

The sensor's maximum current occurs during image data output via LVDS. By sending a capture command and using the exposure end signal as a trigger, we measured the APS image sensor's total supply current waveform, shown in [Figure 6: see original paper]. Multiple measurements yielded consistent, repeatable waveforms.

[Figure 6: see original paper] Voltage Waveform During Image Data Transmission Process

From the waveform in [Figure 6: see original paper], we can extract several operating parameters for the APS image sensor in the miniature camera. The camera's operating current is $44\text{mV}/0.253\Omega = 174\text{mA}$ when no data is being output. During data output, the operating current is $216\text{mV}/0.253\Omega = 854\text{mA}$, with the current peak lasting approximately 288 s.

### 4.2 Single Event Latchup Current Testing

Pulsed laser single event effect experiments were conducted on the APS image sensor selected for the miniature camera. The equipment model was PL-2250 (EKSPLA). The placement of the device under test and test circuits is shown in [Figure 7: see original paper].

[Figure 7: see original paper] Test Layout of DUT

The test chip was not decapped, retaining its original transparent glass protective window. During testing, the peripheral control circuits of the image sensor were divided into three regions—A, B, and C—as shown in [Figure 8: see original paper].

[Figure 8: see original paper] Schematic Diagram of Pulsed Laser Scanning Zoning

After powering up the test circuit and confirming normal operation via serial command, laser energy was adjusted from 0.1nJ to 7nJ to scan the three target regions. Experiments revealed that when 7nJ laser energy scanned the area within region B bounded by coordinates (14338, 4206)–(27780, 5649), a surge in supply current occurred, identified as a single event latchup event that was reproducible. After latchup, the APS image sensor's total supply current increased significantly. The voltage across the current-sensing resistor and current probe waveforms collected during multiple reproducible latchup events at position (15488, 4891) showed consistency, as depicted in [Figure 9: see original paper], with current increasing to approximately twice the standby operating current.

[Figure 9: see original paper] Voltage Difference Waveform Diagram Across Current-Sensing Resistor During SEL

### 4.3 Single Event Latchup Protection Verification

Based on the measured current during latchup events, the current protection threshold for the protection measures was set via command. Using the reproducible laser energy of 7nJ at the sensitive point (15488, 4891), SEL was repeatedly triggered to verify the effectiveness of the designed protection measures.

[Figure 10: see original paper] illustrates a complete protection action process (time scale: 150ms). When overcurrent is detected, the power enable signal outputs high level to shut down the main LDO regulator output. After a 1-second interval, the power enable signal outputs low level, reactivating the main LDO regulator output and repowering the APS image sensor.

[Figure 10: see original paper] Waveforms of the Whole Process of Single Event Latchup Protection

After the APS image sensor was repowered, a capture command was sent via serial interface to the test circuit controller to verify whether the sensor returned to normal operational status. With the APS image sensor's imaging window exposed to light, image capture and data readout were performed. As in normal operation, the read image data was all "0F FF," indicating saturated pixel output at maximum value. With the imaging window covered by a black shield, image capture and data readout were performed. As in normal operation, the read image data showed non-saturated output, consistent with the chip's photosensitive characteristics.

[Figure 11: see original paper] shows the power shutdown waveform during a single event latchup event (time scale: 2ms). When overcurrent is detected, the power enable signal outputs high level to shut down the main LDO regulator output, causing rapid voltage and current drop. After capturing this waveform, a capture command was sent again to verify that the APS image sensor returned to normal operation after repowering.

[Figure 11: see original paper] Waveform of Power Shutdown for Single Event Latchup Protection

[Figure 12: see original paper] shows the power re-energization waveform during a single event latchup event (time scale: 2ms). After a 1-second power-off period, the power enable signal outputs low level to activate the main LDO regulator output. The current exhibits an approximately 1.5ms overshoot pulse, while the voltage waveform shows a stabilization period of about 5ms. After capturing this waveform, a capture command was sent again to verify that the APS image sensor returned to normal operation after repowering.

[Figure 12: see original paper] Waveform of Power Re-energization for Single Event Latchup Protection

The experimental results demonstrate that CMOS APS image sensors indeed exhibit single event latchup effects when subjected to pulsed laser irradiation. When pulsed laser energy reaches a certain threshold, portions of the image sensor's circuitry latch, causing abnormal output signals. Additionally, experiments revealed that image sensors equipped with current-limiting resistors and current-limiting low-dropout regulators show improved performance in resisting single event latchup effects.

In summary, current-limiting resistors can effectively restrict operating current, preventing latchup due to excessive current. However, their application is limited to CMOS integrated devices with relatively small dynamic operating currents and large ratios between latchup current and operating current. In contrast, current-limiting low-dropout regulators offer greater flexibility, automatically maintaining output current at the threshold level when output current exceeds the limit, thereby effectively preventing single event latchup. Nevertheless, the threshold of current-limiting low-dropout regulators is typically fixed, making it difficult to perfectly match the latchup current of the protected device, which somewhat affects protection effectiveness.

## 5 Conclusion and Future Outlook

This paper investigated single event latchup effects in image sensors and the effectiveness of protection strategies through pulsed laser experiments. The results demonstrate that pulsed laser technology provides an effective simulation tool for studying single event latchup effects and offers strong support for protection design in practical applications.

The study shows that current-limiting resistors and current-limiting low-dropout regulators play a role in protecting against single event latchup effects. However, optimizing protection strategies to improve image sensor resistance to single event latchup in space environments remains a future research priority. Subsequent research may focus on several aspects: first, exploring novel protection materials and structures to enhance protection effectiveness; second, developing more accurate pulsed laser simulation methods to better replicate actual space environment single event occurrences; and finally, strengthening integration with practical applications to apply research findings to radiation-hardened design of image sensors in actual spacecraft, improving their reliability and stability in space environments.

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*Note: Figure translations are in progress. See original paper for figures.*