Verification for Protection Design of Single Event Lockup with Pulsed Laser

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Abstract

Pulsed laser testing is a simple, cost-effective, safe, and radiation-free method, offering flexible scheduling, adjustable energy levels, non-destructive testing, and easy operation. It has broad application prospects in simulating single event effects (SEE) in space and has become a mainstream method used domestically and internationally in the past decade, besides the heavy ion accelerator test method. With its ability to accurately target sensitive areas, pulsed laser testing has evolved into a valuable complement to heavy ion experiments, widely used in the performance evaluation of single event effect hardening designs of electronic devices. This paper investigates the single event lockup in image sensors and evaluates the effectiveness of protection strategies using pulsed laser experiments. The research focuses on CMOS APS image sensors, using a focused pulsed laser beam to simulate single event effects. By adjusting the laser' s energy and irradiation position, we simulate varying energies and incident angles of SEE, observing the sensor' s response. The study provides a detailed analysis of device lockup behavior and evaluates the actual effectiveness of protection methods. The results show that pulsed laser testing offers an effective means to assess the protection strategies against SEE lockup in image sensors. Through comparative experiments, the advantages and disadvantages of the protection strategies in resisting the single event lockup can be clearly seen, thus providing insights for improved designs in practical space applications.

Full Text

Verification of Protection Design Against Single Event Lockup Using Pulsed Laser

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Abstract

Pulsed laser testing has emerged as a simple, cost-effective, safe, and radiation-free method for simulating single event effects (SEE) in space applications. Offering flexible scheduling, adjustable energy levels, non-destructive testing, and straightforward operation, it has become a mainstream approach both domestically and internationally over the past decade, complementing traditional heavy ion accelerator testing. With its ability to accurately target sensitive areas, pulsed laser testing has evolved into a valuable tool for evaluating the performance of single event effect hardening designs in electronic devices. This paper investigates single event lockup (SEL) in image sensors and evaluates the effectiveness of protection strategies through pulsed laser experiments. Focusing on CMOS APS image sensors, we use a focused pulsed laser beam to simulate single event effects by adjusting the laser' s energy and irradiation position to replicate varying SEE energies and incident angles, observing the sensor' s response throughout. The study provides a detailed analysis of device lockup behavior and evaluates the actual effectiveness of protection methods. Results demonstrate that pulsed laser testing offers an effective means to assess protection strategies against SEL in image sensors. Through comparative experiments, the advantages and limitations of different protection strategies in resisting single event lockup become clearly evident, providing valuable insights for improved designs in practical space applications.

Keywords: Single Event Effects (SEEs), Single Event Lockup, Protection Design, Pulsed Laser, Effectiveness Verification

1. Introduction

Single Event Effects (SEEs) are radiation-induced phenomena caused by the interaction of high-energy particles with microelectronic devices. For example, electronic devices in satellites can be affected by single event effects during on-orbit operation in harsh radiation environments, impacting device functionality and potentially causing system failures. With the rapid advancement of space technology, image sensors are increasingly deployed in space exploration and remote sensing applications, making the understanding and mitigation of SEEs in these devices critically important.

In the space environment, image sensors are susceptible to high-energy particle radiation that leads to various single event effects, which can cause malfunctions or reduced performance. Among these effects, Single Event Lockup (SEL) is particularly critical, as it can cause certain circuits within the image sensor to enter a locked state for extended periods, severely affecting normal operation. Therefore, protecting image sensors from SEEs, especially SEL, is essential for ensuring their reliable operation in space environments. Current protection strategies include the use of current-limiting resistors and current-limiting low-dropout regulators, which have proven effective in limiting operating current and preventing excessive current flow that leads to circuit lockup. However, optimization of these protection strategies and the development of new materials and structures for enhanced protection remain important areas of ongoing research.

In China, several institutions—including Chongqing University, Lanzhou Institute of Physics, and Qian Xuesen Laboratory of Space Technology—have conducted significant work in this field, highlighting the effectiveness of pulsed laser testing in studying SEL and providing insights for improved designs. Globally, SEE research has been an active area of investigation for decades. While heavy ion accelerators have traditionally been the primary tool for SEE testing, pulsed laser testing has emerged as a simple, cost-effective, and safe alternative. Over the past decade, pulsed laser testing has become a mainstream approach for SEE testing worldwide, offering the advantage of accurate positioning of sensitive areas and gradually developing into a beneficial supplement to heavy ion experiments for performance evaluation of SEE-hardened designs in electronic devices. Researchers worldwide have demonstrated the potential of pulsed laser experiments in evaluating hardened designs, with particular advances in two-photon absorption laser testing enabling more accurate simulation of SEEs in semiconductor devices. Studies have shown that this technique can effectively induce SEL in SRAM cells, providing valuable insights into sensitive depths and failure mechanisms.

This paper examines the effects of SEL in image sensors using pulsed laser testing, analyzes the impact of single event lockup on sensor performance, and verifies the effectiveness of SEL protection strategies through experimental evaluation.

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2. Principle and Method

SEL occurs when a space radiation particle strikes an MOS device, generating a large current pulse that alters device performance. This study uses a focused pulsed laser beam to simulate SEE and conducts experimental research on the SEL effect in CMOS APS image sensors. The experimental setup primarily includes a pulsed laser, optical system, image sensor samples, and test circuits. By adjusting the laser' s energy and irradiation position, we simulate SEEs with different energy levels and observe the sensor' s response.

The photoelectric effect in silicon can be described by the Einstein equation, which relates the energy of the incident photon (E_{photon}) to the energy needed to create an electron-hole pair (E_{gap}) plus the kinetic energy (E_k) of the emitted electron:

$$E_{\text{photon}} = E_{\text{gap}} + E_k$$

The energy of a photon is given by the Planck-Einstein relation:

$$E_{\text{photon}} = h\nu$$

where h is Planck' s constant and ν is the photon frequency. For laser light with a wavelength of 1064 nm (used in our experiments), the photon energy can be calculated as:

$$E_{\text{photon}} = \frac{hc}{\lambda}$$

where $h = 6.626 \times 10^{-34}$ J, $c = 2.998 \times 10^{8}$ m/s, and $\lambda = 1064 \times 10^{-9}$ m. For 1064 nm, E_{photon} is approximately 1.85 eV. Since $E_{\text{photon}} > E_{\text{gap}}$, the photon has sufficient energy to excite an electron from the valence band to the conduction band, leaving behind a positively charged hole. The excess energy above the bandgap is converted into kinetic energy of the electron.

The probability of photon absorption (P_{abs}) in a semiconductor can be approximated using the Beer-Lambert law, which states that the intensity (I) of light decreases exponentially with the thickness (x) of the material:

$$I = I_0 e^{-\alpha x}$$

where I_0 is the incident intensity and α is the absorption coefficient of silicon at the laser wavelength. For silicon at 1064 nm, α is relatively small, indicating that a substantial fraction of the laser light can penetrate the material before being absorbed.

Upon absorption, electron-hole pairs are generated at a rate proportional to the absorbed photon flux. These charge carriers can then interact with the semiconductor lattice, causing local heating, ionization of neighboring atoms, and potentially leading to SEL in sensitive circuits. This process is called Single Photon Absorption (SPA), as shown in [Figure 1: see original paper]. However, for photon energies less than the semiconductor bandgap, a single photon cannot create an electron-hole pair, so multiphoton absorption may occur.

In our experiments, the focused pulsed laser beam simulates SEEs by precisely depositing energy into the silicon material, triggering the generation of electron-hole pairs and subsequent effects. By adjusting the laser's energy and irradiation position, we simulate varying energies and incident angles of SEE, observing the sensor' s response and evaluating the effectiveness of protection strategies.

3. Experimental Setup

3.1 Experimental Devices and Protective Circuit Design

The typical protection strategy for SEL involves adding current-limiting resistors and implementing a power-off restart mechanism. In this study, current-limiting resistors and current-limiting low-dropout regulators are integrated into the circuit to limit both operating current and output current, thereby preventing the occurrence of single event lockup effects. To verify the effectiveness of this protection strategy, experiments were conducted on image sensors equipped with these protective components, with SEE induced through pulsed laser irradiation.

Preliminary research revealed that the control circuit of the image sensor is particularly sensitive to SEL. Therefore, this design incorporates real-time current monitoring and an overcurrent power-off restart mechanism for protection, as illustrated in [Figure 2: see original paper]. The basic principle employs an independent power supply loop, with a voltage regulator featuring an enable control pin serving as the sensor' s main power supply. The FPGA' s built-in ADC module (12-bit resolution, 1 MS/s sampling rate) monitors the total current of the image sensor in real-time by measuring the voltage across a shunt resistor.

When the image sensor enters a lockup state, the supply current abnormally increases. The FPGA detects when the supply current exceeds a set threshold and maintains this condition for a specified duration, then controls the power supply enable pin to turn off the output of the total power voltage regulator (5V to 3.3V). After the voltage regulator cuts off the image sensor' s power supply for 1 second, the FPGA restores power following the correct sequence.

The experiments focused on three key aspects: (1) normal working current testing of the CMOS APS image sensor (CMV4000), (2) current testing when single event lockup occurs, and (3) verification of SEL protection effectiveness. The basic experimental setup is shown in [Figure 3: see original paper], where the power enable signal controls the activation and deactivation of the APS image sensor' s total power supply. The exposure end signal marks the completion of the sensor' s photo exposure, after which data is prepared for output. V_A represents the voltage at the high end of the shunt resistor (positive end of R203) and V_B represents the voltage at the low end (negative end of R203). The voltage difference between V_A and V_B directly indicates the working current of the image sensor, enabling real-time current monitoring.

3.2 Pulsed Laser Experiment System

The experimental pulsed laser has a wavelength of 1064 nm, pulse width of 25 ps, spot diameter of 2 m, pulse frequency of 10 Hz, and uses a 20× objective lens. The pulsed laser emission, XYZ displacement precision control, energy selection, energy testing, focused beam spot testing, and scanning positioning are all computer-controlled. The complete pulsed SEE experiment system is shown in [Figure 4: see original paper].

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4. Experimental Results

4.1 Sensor Normal Working State

The sensor' s maximum current occurs during image output through LVDS. The experiment measured the total supply current waveform of the APS image sensor by sending a capture command and using the exposure end signal as the trigger condition, as shown in [Figure 5: see original paper]. The waveforms from multiple measurements were consistent and repeatable.

Under normal operating conditions, the current waveform of the APS image sensor illustrates the changes during image data transfer. The real-time current monitoring mechanism ensures that the sensor's current remains within a stable range during normal operation. Calculations from the waveform diagram reveal that during data output, the sensor' s operating current significantly increases due to increased activity within the sensor' s internal circuits, aligning with the current monitoring and power supply control logic.

From the waveform in [Figure 5: see original paper], the following working parameters can be calculated: the working current during the camera' s data output process is 216 mV / 0.253 Ω = 854 mA, and the peak current during data output lasts approximately 288 s.

4.2 Single Event Lockup Current Test

Pulsed laser SEE experiments were performed on the APS image sensor selected for the mini camera using the PL-2250 (EKSPLA) system. The placement of the image sensor and test circuit is shown in [Figure 6: see original paper]. During SEL testing, by adjusting the pulsed laser energy and scanning sensitive regions of the image sensor, we successfully induced SEL phenomena. As shown in [Figure 6: see original paper] and [Figure 7: see original paper], when the laser energy reached 7 nJ and illuminated a specific location, the sensor' s operating current abruptly surged, as depicted in [Figure 8: see original paper]. This phenomenon confirms the occurrence of SEL and demonstrates the response capability of the protection circuit.

The test circuit was powered on, and commands were sent through the serial port to verify the device's operational state. The laser energy was adjusted from 0.1 nJ to 7 nJ, scanning three target areas. The experiment found that when a 7 nJ laser scanned the range (14338, 4206) −(27780, 5649) in area B, a sharp increase in supply current occurred, which was determined to be single event lockup. This lockup phenomenon could be reliably replicated. After lockup, the total supply current of the APS image sensor increased significantly to about twice the standby working current.

A laser energy of 7 nJ was used to repeatedly trigger SEL at the sensitive point (15488, 4891) to verify the effectiveness of the protection measures. The current and voltage waveforms collected from the shunt resistor terminals during multiple reproductions of the lockup phenomenon were consistent.

4.3 Single Event Lockup Protection Verification

During the protection strategy verification phase, repeated triggering of SEL events and observation of the protection circuit' s response validated the effectiveness of the protection measures. As depicted in [Figure 9: see original paper] and [Figure 10: see original paper], upon SEL occurrence, the abnormal increase in operating current is promptly detected by the FPGA through the AD conversion module, triggering the overcurrent protection mechanism. When the current exceeds the preset threshold, the FPGA controls the power enable signal to rise to a high level, cutting off the output of the total power LDO chip, thereby achieving rapid response and suppression of the SEL event. After a 1-second interval, power is restored and the sensor resumes normal operation. This process aligns perfectly with the overcurrent protection restart mechanism outlined in [Figure 2: see original paper].

Further analysis reveals that current-limiting resistors and current-limiting low-dropout linear regulators play pivotal roles in the protection circuit. The current-limiting resistors prevent circuit lockup by restricting operating current, while the current-limiting LDOs automatically adjust output current when it exceeds the maximum level, maintaining the output current within a safe range and effectively preventing SEL occurrence.

[Figure 11: see original paper] shows the power supply waveform during a single event lockup with a time scale of 2 ms. After the power supply is turned off for 1 second, the power enable signal drops to a low level, activating the total power LDO chip output. This results in a current overshoot pulse lasting approximately 1.5 ms, followed by a 5 ms stabilization in the voltage waveform. After this waveform collection, the APS image sensor was verified to be in a normal working state after being powered on again by sending a capture command.

The experiment demonstrates that single event lockup occurs when the CMOS APS image sensor is exposed to pulsed laser radiation above a certain energy threshold, causing some circuits to lock and producing abnormally high output signals. The results indicate that the image sensor with added current-limiting resistors and current-limiting low-dropout regulators shows superior performance in resisting SEL.

5. Conclusion and Future Prospects

This paper investigates single event lockup in image sensors and evaluates protection strategies through pulsed laser experiments. The results confirm that pulsed laser technology is an effective simulation tool for studying SEL and can inform practical protection designs. The study demonstrates that current-limiting resistors and current-limiting low-dropout regulators provide effective protection against single event lockup. Specifically, current-limiting resistors can effectively restrict operating current, preventing circuit lockup due to excessive current flow, though they are limited to integrated devices with small dynamic working currents and a large ratio of latch-up current to working current. In contrast, current-limiting low-dropout regulators offer greater flexibility by automatically maintaining the output current at a threshold value when exceeded, thereby effectively preventing SEL. However, the threshold value of the current-limiting LDO is usually fixed and difficult to perfectly match the lockup current of the protected device, which to some extent affects its protection effectiveness.

By comparing experimental data before and after implementing the protection strategies, the effectiveness of these approaches in suppressing SEL is evident. With the protection measures in place, the sensor promptly resumes normal operation even under high-energy laser exposure, ensuring system stability and reliability. The experimental results validate the efficacy and reliability of pulsed laser testing in assessing SEE protection strategies.

Future research could focus on: (1) exploring new types of protective materials and structures to improve protection effects, (2) developing more accurate pulsed laser simulation methods to better replicate actual single events in the space environment, (3) strengthening combination with practical applications, and (4) applying research results to the protection design of image sensors against single event effects in actual spacecraft to improve their reliability and stability in space.

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