

## Postprint: Pulsed Laser Rapid Evaluation of SET Hardening Effects in Linear Devices

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### Abstract

SET effects have become a significant factor threatening spacecraft reliability. This study investigates the influencing factors of laser-induced SET effects and corresponding hardening methodologies. Experiments were conducted to measure the impact of different irradiation positions, laser energies, and laser focal depths on SET pulses. Based on the worst-case scenario, Hspice circuit-level simulations were performed to investigate the mitigation effectiveness of mitigation circuits with various parameters on SET pulses. Finally, experimental verification was carried out to validate the hardening effectiveness of the mitigation circuit.

### Full Text

#### Research on Rapid Evaluation of Linear Device SET Hardening Effects Using Pulsed Laser

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**Abstract:** The Single Event Transient (SET) effect has become a critical factor threatening spacecraft reliability. This paper investigates the influencing factors of laser-induced SET effects and corresponding mitigation approaches. We experimentally measured how SET pulses are affected by different irradiation positions, laser energies, and laser focusing depths. Based on the worst-case scenario, Hspice circuit-level simulations were conducted to study the mitigation effectiveness of filter circuits with various parameters. Finally, the hardening effectiveness of the mitigation circuit was experimentally verified.

**Keywords:** SET effect, pulsed laser, mitigation circuit, Hspice

**Classification:** P353

## Characteristics of Electron Distribution Functions in Magnetic Cloud Boundary Layers

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**Abstract:** SET effect has become an important factor threatening the reliability of spacecraft. In this paper, the effects of different irradiation positions, different laser energy, and different laser focusing depth on SET pulse are measured. According to the worst case, Hspice circuit-level simulation is carried out to study the effect of different parameters on the SET pulse. In the end, the effect of the Suppressor is verified.

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## 0 Introduction

Soft errors in CMOS integrated circuits for space applications represent a major reliability concern, with Single Event Transient (SET) effects being among the primary causes. SET refers to the instantaneous voltage signal appearing at a circuit's output when a single high-energy particle strikes a sensitive node under specific bias conditions. The SET characteristics and hazards of operational amplifier circuits have garnered significant international attention, as studies show that SET-induced disturbances can severely impact downstream digital circuits, potentially causing entire spacecraft electronic systems to fail. Consequently, SET effects have become both a critical threat to spacecraft reliability and a prominent research focus in recent years.

While international studies have examined SET pulse width distributions in CMOS devices of different process nodes under various heavy-ion LET values, this work employs pulsed laser irradiation to generate SET pulses for measuring their width distribution. Pulsed laser offers distinct advantages for such research due to its continuously adjustable energy range and precise positioning capabilities.

Hardening techniques for single-event effects fall into two categories: hardware and software approaches. Common methods include resistor hardening, triple modular redundancy, error correction coding, and DICE-structure-based techniques. Domestic research on SET mitigation has primarily focused on layout

design for different process devices and circuit design for typical components. However, these approaches impose requirements during the circuit design phase, making them impractical for commercial-grade devices used in satellites—a growing trend driven by cost considerations. This paper investigates an easily applicable and more cost-effective SET pulse mitigation method.

We selected the LM124 operational amplifier as a representative test vehicle. First, we studied SET pulse influencing factors through pulsed laser simulation of SET transients. Subsequently, we designed a backend filter based on SET waveform characteristics, calculated optimal filter parameters, and employed Hspice circuit-level simulation to evaluate the mitigation effectiveness under various SET conditions. Finally, we experimentally validated the feasibility of this protection method.

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## 1 Experimental Setup

### 1.1 Pulsed Laser Single-Event Effect Simulation System

The pulsed laser test system, illustrated in [Figure 2: see original paper], comprises five main components: (1) a pulsed laser source, (2) laser detection and adjustment system, (3) focusing control system, (4) positioning and imaging system, and (5) DC power supply and digital oscilloscope. The laser source generates pulsed beams for device irradiation, while the detection and adjustment system monitors and regulates laser energy. The focusing control system minimizes the laser spot size for enhanced precision, and the imaging system provides real-time monitoring of irradiation positions. The DC power supply biases the device under test, and the oscilloscope captures output pulse characteristics.

[Figure 1: see original paper] Diagram of pulse laser test device

### 1.2 Device Under Test and Experimental Conditions

The test vehicle is the LM124 quad operational amplifier manufactured by National Semiconductor. The test circuit configures the op-amp in a  $20\times$  inverting amplifier mode, where  $\text{gain} = -20$ ,  $V_{CC} = 6\text{ V}$ ,  $V_{EE} = -6\text{ V}$ , and input  $V_{in} = -60\text{ mV}$ . Under normal operation, the op-amp works in its linear region with  $V_{out} = 1.15\text{ V}$ .

Accurate data collection requires precise laser focusing on the chip's sensitive region—specifically, the depth range corresponding to the active area. The device was decapsulated to expose the circuit for front-side irradiation. During laser exposure, the beam must remain perpendicular to the surface and avoid metal interconnects.

## 2 Test Methodology

The experimental setup integrates a test sample, circuit board, objective lens, nanosecond pulsed laser, three-dimensional positioning stage, optical path, charge measurement and collection system, nanosecond pulsed laser single-event effect apparatus, CCD monitoring, power supplies (VCC, GND), shutter control, and computer control system. The circuit configuration provides a -60 mV input with  $\pm 6$  V supplies, 1 k $\Omega$  and 20 k $\Omega$  resistors, and monitors the output.

Since laser penetrates to a certain depth within the chip, and considering that PNP transistors in amplification mode operate with forward-biased emitter junctions and reverse-biased collector junctions, this study focuses on pulse laser simulation of SET transient influencing factors for specific transistors within the device. For the LM124, the most sensitive region is the base-emitter junction of transistor Q9, making it the primary target for investigation.

The test matrix covers three key parameters: 1. **Terminal-specific irradiation:** Two device lots were tested by positioning the laser on identical transistors and irradiating the base, collector, and emitter terminals separately to observe output variations. Additional tests examined effects of irradiating different positions on the same terminal. 2. **Laser energy variation:** Using a second device lot, we validated pulse polarity independence by testing another transistor under varying laser energies. 3. **Focusing depth variation:** One device lot was tested at different laser focusing depths to characterize the resulting SET pulse variations.

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## 3 Experimental Results

### 3.1 Terminal-Specific and Positional Effects

In transistor operation, the emitter injects electrons into the base where they diffuse and recombine while the collector gathers free electrons. For both NPN and PNP transistors in amplification mode, the emitter junction must be forward-biased and the collector junction reverse-biased. When laser irradiates different terminals, SET pulses exhibit distinct characteristics, with emitter irradiation producing the maximum pulse amplitude, as shown in the experimental data. This contradicts the previous conclusion that reverse-biased PN junctions generate larger charge collection, warranting further investigation.

[Micrograph of LM124 layout structure]

Output pulses for base injection at 110 pJ laser energy and emitter injection at 110 pJ laser energy demonstrate these positional dependencies.

### 3.2 Laser Energy Effects

Validation tests on the second device lot confirm that irradiating transistor Q9' s emitter terminal with increasing laser energy progressively enlarges both pulse duration and amplitude, reaching a maximum at approximately 380 pJ. The pulse characteristics across different energy levels are illustrated in the experimental figures.

Further validation using transistor Q4' s emitter terminal produces positive-polarity SET pulses consistent with previous findings: increasing laser energy enhances pulse duration and amplitude. These results confirm the energy-dependent trends observed in the initial tests.

### 3.3 Focusing Depth Effects

For front-side decapsulated devices, the relationship between focusing depth and output waveform characteristics reveals that maximum response occurs when the laser focuses near the chip surface. The experimental data show that pulse width and height vary with position, being larger near the emitter region.

Based on these results, we establish the worst-case scenario: laser irradiation on the transistor emitter, focused at the chip surface, with sufficient energy to produce the maximum SET response.

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## 4 Circuit Mitigation Analysis and Verification

### 4.1 Simulation Analysis

Even under worst-case SET conditions, the resulting pulses remain extremely narrow, corresponding to very high frequencies. The LM124 in inverting amplifier configuration operates in DC mode (zero input signal frequency), making filter-based SET mitigation feasible for downstream circuits.

We employed Hspice circuit-level simulation to determine optimal filter parameters. Two approaches exist for obtaining filter input signals: (1) direct oscilloscope data sampling, which provides accuracy but complicates parameter adjustment for varying irradiation conditions, and (2) simulation using single-event current models combined with the LM124 circuit model. While the latter requires more expertise, it offers superior flexibility when irradiation conditions or positions change. We adopted the second approach.

When laser irradiates the active region, the transient current can be approximated by a double-exponential function:

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})$$

where  $I_0$  is the peak current,  $1/\alpha$  is the charge collection time constant, and  $1/\beta$  is the ion track establishment time constant. Under different charge injection

conditions, the simulated SET waveforms match the experimentally determined worst-case results.

We implemented an RC low-pass filter to attenuate SET effects. The circuit structure includes a load resistor  $R_L$  (1 k $\Omega$ ) representing downstream circuitry. The filter's upper cutoff frequency is  $f_H = 1/(2\pi RC)$ . For the worst-case SET pulse width of approximately 20 ns, we approximate it as a single-frequency sinusoidal pulse at 50 kHz (though other frequency components exist). This yields a time constant of approximately  $3.2 \times 10^{-6}$  s. Simulation verification indicates that amplifying this time constant by about 10 $\times$  provides effective mitigation, as the signal contains additional frequency components.

Considering standard laboratory component values, we selected  $R = 50 \Omega$  and  $C = 1 \mu\text{F}$ , giving a time constant of  $5 \times 10^{-5}$  s. The filter's frequency response is:

$$H(\omega) = \frac{1}{1 + j\omega RC}$$

Simulation results for this configuration demonstrate excellent SET pulse suppression with minimal voltage amplitude variation.

However, filter parameter selection involves critical trade-offs. When the RC time constant is too small (e.g.,  $R = 50 \Omega$ ,  $C = 1 \text{ mF}$ ), the passband shifts to higher frequencies, allowing SET pulses to pass through and interfere with downstream circuits. Conversely, excessively large time constants shift the passband lower, causing signal tail pile-up where the output fails to recover before the next laser pulse arrives. For instance, with  $R = 50 \Omega$ ,  $C = 1 \text{ mF}$ , significant pulse remnants persist.

Additionally, large resistor values cause excessive voltage division. With  $R = 100 \text{ k}\Omega$  and  $C = 1 \mu\text{F}$ , the output voltage deviates substantially from the original signal, potentially causing downstream circuits to misinterpret it as invalid.

The primary limitation of this first-order RC filter is its gradual roll-off characteristics. Higher-order filters provide steeper attenuation but introduce phase shift and stability concerns. Another drawback is poor load-driving capability, which could be addressed with active filters, though this increases circuit complexity and may introduce new SET vulnerabilities.

It is important to note that this mitigation approach is only suitable for non-high-frequency analog applications. For high-frequency circuits, SET protection must be addressed through process technology, layout design, and internal circuit architecture.

## 4.2 Experimental Verification

Combining simulation results with commonly available laboratory components, we determined that  $R = 50 \Omega$  and  $C = 1 \mu\text{F}$  represent optimal values for miti-

gating SET pulses around 50 ns in width. Experimental verification confirmed the simulation predictions, demonstrating effective SET pulse suppression under worst-case conditions.

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