The Effects of Elevated Temperature on Pulsed-laser-induced Single Event Transients in Analog Devices

Dakai Chen *IEEE Member*, Stephen P. Buchner *IEEE Member*, Anthony M. Phan, Hak S. Kim, Andrew L. Sternberg *IEEE Member*, Dale McMorrow *IEEE Member*, and Kenneth A. LaBel *IEEE Member*

Abstract—We present results of laser-induced analog SETs at elevated temperatures. We found increasing pulse widths with increasing temperature for the LM124. We also observed increasing pulse amplitudes with increasing temperature for several sensitive transistors in the LM139. However the response from the input transistor of the LM139 was a rapidly shrinking SET, suggesting that the SET threshold increases at elevated temperatures for the input stage transistors. In addition we observed increases in the SET leading edge fall times with increasing temperature for the LM139 that are consistent with independently measured slew rates. Simulations revealed that the dominant mechanism is bipolar current gain enhancement at elevated temperatures. These temperature-induced changes to the SET characteristics may have critical implications for radiation hardness assurance.

Index Terms—Single event transients, lasers, elevated temperature effects, analog integrated circuits, bipolar circuits, radiation hardness assurance.

I. INTRODUCTION

Microelectronic components onboard spacecrafts are exposed to various types of radiation. Consequently the electronic circuits and devices are susceptible to a wide range of radiation-degradation phenomena. Single event transients (SETs) are caused by a single particle strike to a sensitive region of a device, such as the reversed biased p-n junction. The resulting voltage perturbation can propagate through the system’s circuitry and trigger functional errors. Several incidences of spacecraft functional glitches were caused by SETs [1]. For example, on a 2001 NASA flight mission, ionizing radiation initiated a processor reset on the Microwave Anisotropy Probe (MAP) [2]. Such instances of functional disruptions not only cost money but also leads to the loss of valuable scientific data.

SETs can differ drastically in pulse characteristics depending on the ion energy, strike location, bias configuration, and device circuitry [1], [3]-[5]. Since the devices onboard satellites often operate over a wide range of temperatures, it is also necessary to understand the effects of temperature on SETs. Heavy-ion microbeam-induced current transients in p-n diodes were shown to decrease in amplitude but increase in pulse width with increasing temperature [6], [7]. The changes to the SET shapes are dominated by variations in charge collection from drift and diffusion components at high temperatures [6], [7]. The temperature-induced effects on the SETs from simple p-n diode structures can also lead to changes in the SET sensitivity of more complex devices and circuits. Simulations on CMOS inverter chains showed that the linear energy transfer (LET) threshold for SETs can be reduced by up to 12% as temperature is increased from 300 K to 418 K [8]. These findings reveal that elevated temperature can substantially influence the SET characteristics in semiconductor structures and devices, which may also lead to increased SET sensitivity in modern analog integrated circuits.

Pulsed-laser testing is widely accepted as a reliable and cost-effective test method for measuring SETs [5], [9], [10]. Here we investigate laser-light-induced SETs in the LM124 operational amplifier and the LM139 voltage comparator at temperatures ranging from 300 K to 393 K. The LM124 and LM139 have exhibited sensitivity to SETs from pulsed-laser light previously [3], [5], [10]-[13]. In particular the SET characteristics, including the amplitude, width, and slope, varied for devices that were exposed to total ionizing dose (TID) due to degradations to the bipolar gain [11]-[13]. Our results show significant increases in the SET pulse widths for the LM124, and increases in the SET amplitudes for the LM139 at elevated temperatures.

II. EXPERIMENTAL DETAILS

The devices in this experiment include the LM124 operational amplifier from National Semiconductor (Lot Date Code (LDC): 036AD) and the LM139 voltage comparator from Texas Instruments (LDC: 0535F). Figures 1 and 2 show the circuit schematic diagrams of the LM124 and LM139, respectively. The laser testing was performed at the Naval Research Laboratory. The laser system details have been described in a previous publication [9].

The experiments here utilize a focused laser beam with a diameter of 1.7 µm, wavelength of 590 nm, and a penetration depth of 2 µm. The laser absorption coefficient has negligible temperature dependency for the wavelength used during the experiments [14]. Therefore temperature-dependent variations in charge collection are insignificant.
As the laser beam scans across the device to identify sensitive regions, an oscilloscope attached to the output captures all transients. The elevated temperature test setup employs a thermal pad that is attached to the bottom of the dual-inline-package (DIP) via thermal glue. The thermal pad is heated as voltage is applied through a power supply. A thermistor is attached to the top of the DIP via thermal glue to monitor the temperature of the device. A software program controls the temperature to within 0.5°C accuracy. The temperature is kept constant while the SETs are being captured. Then the temperature is increased, and after the temperature stabilizes, the new set of SETs is captured.

III. RESULTS

A. LM124 operational amplifier

The LM124 was biased with $V_{CC+} = 5$ V, $V_{CC-} = -5$ V, and $V_{IN} = -0.13$ V. The temperature varied from 300K (27°C) to 393K (120°C). We irradiated transistors from different stages of the operational amplifier (input, amplification, and output stage) to provide a comprehensive representation of the device’s SEE performance. Figures 3 – 6 show the SET pulse characteristics for transistors Q9, Q11, Q19 and resistor R1 (a bipolar transistor with a floating base), with the operational amplifier in the voltage follower configuration. Figures 7 – 9 show the SET pulse characteristics for transistors Q9, Q14, and resistor R1, with the operational amplifier configured as an inverter with gain of 10. In general the transients consisted of two components. The initial charge generation from the pulsed-laser produces the sharp negative dip at the output. The second component with a more gradual recovery rate is due to the feedback from the LM124’s output that is amplified on its passage through the amplifier. The SET pulse characteristics are similar to those observed from earlier studies [10]-[12].

Figure 1. Circuit schematic diagram of the LM124 operational amplifier (After[12]).

Figure 2. Circuit schematic diagram of the LM139 voltage comparator (After[13]).

Figure 3. SETs at temperatures ranging from 300 K (27°C) to 373 K (100°C) for transistor Q9 of the LM124 in voltage follower configuration.

Figure 4. SETs at temperatures ranging from 300 K (27°C) to 373 K (100°C) for transistor Q19 of the LM124 in voltage follower configuration.

Figure 5. SETs at temperatures ranging from 300 K (27°C) to 373 K (100°C) for transistor Q11 of the LM124 in voltage follower configuration.
With increasing temperature, we observed broadening of SET pulse widths for transistors Q9, Q19 and Q14. The SET characterization method is demonstrated in Figure 10. We linearly extrapolate the recovery edge to the leading edge, where the intercept was taken as the maximum amplitude to determine the Full-Width-Half-Maximum (FWHM) widths.

The pulse amplitude of the initial negative peak does not change significantly with temperature. However the amplitude of the recovery component increases with increasing temperature, resulting in the pulse broadening. The initial narrow negative spike is due to charge collection from drift and diffusion current components, while the recovery pulse represents the feedback response of the circuit. Degradations to the drive of the current source can increase the recovery time, which reduces the slew rate [12]. However the slew rate is unaffected here as reflected by the constant slope of the trailing edge. Furthermore degradations to the bipolar current gain can suppress the SET amplitude [12]. Our results illustrate the opposite effect, with the amplitude from the recovery component of the pulse increasing with increasing temperature. Therefore enhanced bipolar current gain is an important mechanism which causes the pulse broadening, as explained in more detail in a later section.

The response from R1 differs drastically in the inverter and voltage follower configurations. In the inverter configuration, the pulse amplitude of R1 decreases significantly with increasing temperature, as shown in Figure 9. The SET also exhibits bipolar characteristics, with a secondary negative-going component, which also decreases in magnitude with increasing temperature. On the other hand the SETs from R1 in the voltage follower configuration are relatively unaffected by temperature. There is a slight hump on the trailing edge of the transient, which becomes more prominent with increasing temperature. The hump is likely due to charges collected from the feedback response, similar to the perturbation that appears following the initial spike in other transistors.

The device configuration (inverter and voltage follower) did not influence the magnitude of the temperature dependence of the SETs. On the other hand the strike location...
affected both the magnitude of the SET response as well as the magnitude of the temperature dependence. SETs originating from Q14 showed the greatest change, while Q11 was relatively insensitive to temperature changes. The pulse broadening is particularly significant for transistors in Darlington structures, which are designed for current amplification. The amplification from the Darlington structure is further magnified as the current gain is enhanced at elevated temperatures. The effect leads to the increased sensitivity observed in Q14, which is the first stage of a Darlington pair.

Figure 11 summarizes the increase in pulse widths with increasing temperature for various transistors in the voltage follower and inverter configurations. The increase in the FWHM pulse widths were approximately 1 µs for Q9 and Q19 in both the voltage follower and inverter configurations. The pulse broadening was most significant for Q14 in the inverter configuration with an increase of ~ 2.5 µs (45%).

![Figure 10](image1.png)

**Figure 10.** SET pulse characterization method for extrapolating the FWHM pulse widths.

![Figure 11](image2.png)

**Figure 11.** SET pulse widths vs. temperature for various transistors in the LM124 with voltage follower and inverter with gain configurations.

B. **LM139 voltage comparator**

The LM139 was configured with \(V_{CC+} = 5 \text{ V}, V_{CC-} = 0 \text{ V}, V_{IN+} = 0.1 \text{ V and } V_{IN-} = 0 \text{ V or } V_{IN+} = 0 \text{ V and } V_{IN-} = 0.1 \text{ V for high and low output states, respectively. The laser intensity was kept constant when examining the change in SET amplitudes. We observed increasing SET amplitude with increasing temperature for most of the transistors, except for Q1. Figure 12 shows the case of increasing temperature at the higher temperatures to become saturated due to supply voltage limits. The increase in the SET amplitudes is also consistent with enhanced bipolar gains at elevated temperature.

In contrast the SET amplitudes for Q1 rapidly decreased when the temperature is increased to approximately 358 K (85°C), as shown in Figure 13. In fact the transients disappear (not observable on the oscilloscope with same trigger settings) as the temperature is increased further. SETs reappear if the laser intensity is increased. The behavior is consistent with a higher SET threshold at higher temperatures.

![Figure 12](image3.png)

**Figure 12.** SETs at temperatures ranging from 300 K (27°C) to 393 K (120°C) for transistor Q5 of the LM139 with high output state.

![Figure 13](image4.png)

**Figure 13.** SETs at 300 K (27°C) and 358 K (85°C) for Q1 of the LM139 with high output state.

The results also showed that the SET fall times – leading edge for high output and trailing edge for low output – consistently increased with increasing temperature. Accordingly, the slope decreases with increasing temperature, which is consistent with independent slew rate measurements as a function of temperature. Here the slew rate corresponds to how fast the device discharges from a high to low state. Figure
14 shows the decreasing slope of the SET falling edge (increasing slew rate degradations) for Q6. Figure 15 summarizes the change in slew rate with temperature for various transistors in the LM139. The decrease in slew rate varied from 30% to 50% as the temperature increased from 300 K (27°C) to 393 K (120°C).

We observed a similar response to the slope of the falling edge at elevated temperature pre-irradiation. A function generator produces a square wave to the positive input ($V_{IN+}$). We monitor the output waveform on an oscilloscope. As temperature increases, we found that the slope of the falling edge also increases, similar to the SETs. The magnitudes of change in the slew rate from 300 K (27°C) to 393 K (120°C) are also similar to those observed in the SETs. The results are included in Figure 15.

IV. SIMULATIONS

In order to better understand our results, we have performed simulations on various transistors in the LM124 at different temperatures. The circuit model is based on detailed analysis of photomicrographs of the LM124 [15]. Simulations of laser-induced SETs have been shown to accurately model experimental results [15]. Figure 16 shows the simulated SET response of transistor Q9. Simulation data reveal similar behaviors as temperature is varied relative to experimental results. In particular the SET pulse width of Q9 broadens with increasing temperature, while the slope of the recovering edge remains relatively constant. The SET amplitude increases slightly with temperature. However the different magnitudes of change in the SET amplitudes and widths between simulation and experimental results are not a concern for this study. The purpose of the simulation is to examine qualitatively how SETs are affected by temperature, instead of an attempt to replicate the experimental results.

We further investigated the behaviors of the transient for Q9, while varying the bipolar gains of all the transistors in the LM124, as would occur in a device at elevated temperatures. Figure 17 shows SETs for Q9 with different values of $\beta_{DC}$ (bipolar gain). The pulse width increases with increasing $\beta_{DC}$, while the slope of the recovering pulse edge remained relatively constant. The results are comparable to Figure 16 where temperature is varied. Thus increasing the temperature and increasing the bipolar gains affect the SETs similarly. The simulation results suggest that the dominant temperature-dependent mechanism is the enhanced bipolar gains at elevated temperatures.
The increase in the SET amplitude for the LM139 is consistent with the enhanced current gains. However previous studies have revealed that slew rate degradations in the LM139 can be caused by degradations to the current sources [13]. The slew rate is proportional to the ratio of the saturation current (current source) and the parasitic capacitance at the output [13]. Since the current sources are unlikely to be degraded at elevated temperatures, we investigate the effects of varying the output parasitic capacitance with P-Spice simulations. Figure 18 shows a simulated voltage transient with various parasitic capacitance values at the base-collector junction of transistor Q8. The results show that slight increases in the capacitance can impact the slew rate substantially. The simulation results are also consistent with the pre-irradiation characteristics when temperature is varied, and suggest that the change in the slew rate is purely a temperature effect, independent of pulsed-laser charge deposition. Nevertheless the effect influences the radiation response as it can increase the recovery time from an SET.

![Figure 18. P-Spice simulated current pulse with various output parasitic capacitance values for the LM139.](image)

**V. DISCUSSIONS**

Temperature influences a multitude of semiconductor device parameters. Notably the carrier mobility decreases with increasing temperature, due to lattice scattering. The energy band gap becomes slightly narrower at high temperatures, due to electron interactions with the conduction and valence bands [16]. So less energy is needed to produce electron-hole pairs. However the increase in charge generation from band gap narrowing is negligible. Heavy-ion microbeam testing on p-n diode structures showed that SET current pulses decrease in peak amplitude but increase in pulse width with increasing temperature, due to the reduced mobility and the increased ratio of the diffusion constant and mobility at elevated temperatures [6]. The same mechanisms may partially contribute to the pulse broadening observed in the more complex integrated circuits here. However charge diffusion from an SET pulse lasts for only several nanoseconds, while the pulse widths increase by several hundred nanoseconds to microseconds in our results for the LM124. Therefore the results here are likely caused by other more dominant mechanisms.

Studies have shown that the bipolar transistor current gain is enhanced at elevated temperatures [17]-[19]. Studies have attributed the improved current gain to band gap narrowing effects. The energy band gap is also a function of doping, in addition to temperature. Heavy doping, often applied to the emitter of a bipolar transistor, can cause lattice deformations and dislocations, which lead to band gap degradations. The temperature dependence of the current gain is further magnified for higher emitter doping densities [18]. While the enhanced current gain has minor effect on the initial transient, as the charges propagate through the circuitry, the feed-back signal is amplified. Evidently the amplitude and width of the recovering pulse component grow with increasing temperature. The response is in contrast to laser irradiation results on TID-irradiated LM124 [11], [12]. The TID-induced degradations to the transistor current gain resulted in decreased SET pulse amplitude and width in [11], [12], whereas elevated temperature enhances the bipolar gains here, thereby increasing the SET amplitude and width.

We observed several anomalies in the LM139. The increasing SET amplitudes with increasing temperature are consistent with the enhanced bipolar gains. However the amplitudes of transients from Q1 decreased rapidly as the temperature increased. The transients drop out abruptly as temperature is increased further. Transistor Q1 is located in the positive input stage, and is originally biased off for the high output condition. A laser pulse on Q1 at room temperature briefly turns on the positive input, and drops the output low. At higher temperatures, the enhanced current gains of transistors in the negative input stage prevent the conducting path from switching to the positive input transistors, thus maintaining the high output state. Therefore the SET threshold for the input transistors increases as temperature increases.

The slew rate degradations are most likely caused by modifications to the output parasitic capacitance at higher temperatures. The parasitic capacitance consists of the depletion and diffusion elements. The diffusion capacitance is given as:

$$C_{\text{diffusion}} = \tau_F g_m$$  \hspace{1cm} (1)

where \(\tau_F\) is proportional to the ratio of the base quasi-neutral region width and the minority carrier diffusion coefficient, and \(g_m\) is proportional to the collector current and the thermal voltage. So as the current gain improves with temperature, the diffusion capacitance also increases slightly. As illustrated by P-Spice simulations in Figure 16 small increases to the parasitic capacitance can lead to degradations in the slew rate.

Although the LM124 and LM139 are based on similar linear bipolar technologies, our results have shown that temperature can affect these analog devices very differently, depending on the device functionality and transistor layout.

**VI. CONCLUSION**
We have examined the effects of elevated temperature on laser-induced SETs for the LM124 operational amplifier and the LM139 voltage comparator. We found increasing SET pulse width with increasing temperature for transistors in the LM124. With additional simulations, we determined that the most dominant mechanism was the bipolar gain enhancement at elevated temperatures. The most significant pulse broadening was approximately 2.5 µs (45%) as the temperature increased from 300 K (27°C) to 393 (120°C).

In the LM139 the most significant temperature dependent effect was the increase in SET amplitudes. We also observed an increase in the SET threshold at elevated temperatures for transistors in the input stage. Finally the slope of the leading edge of the SETs, also given as the slew rate of the LM139, showed increased degradations with increasing temperature, which increases the recovery time from SETs.

The pulse broadening observed in the LM124 and the increasing of pulse amplitudes in the LM139 may have critical impact on radiation hardness assurance, depending on application. The results also indicate that the nature and significance of the temperature effects on SETs depend strongly on the relative locations of sensitive transistors as well as the type of device. Therefore the SEE response of microelectronic components at elevated temperatures is potentially an important aspect of radiation performance evaluations for space applications.

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VIII. REFERENCES


