

# Total Dose Effects on Single Event Transients in Linear Bipolar Systems

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## I. INTRODUCTION

Single Event Transients (SETs) originating in linear bipolar integrated circuits are known to undermine the reliability of electronic systems operating in the radiation environment of space [1].

Ionizing particle radiation produces a variety of SETs in linear bipolar circuits. The extent to which these SETs threaten system reliability depends on both their shapes (amplitude and width) and their threshold energies. In general, SETs with large amplitudes and widths are the most likely to propagate from a bipolar circuit's output through a subsystem. The danger these SET pose is that, if they become latched in a follow-on circuit, they could cause an erroneous system response.

Long-term exposure of linear bipolar circuits to particle radiation produces total ionizing dose (TID) and/or displacement damage dose (DDD) effects that are characterized by a gradual degradation in some of the circuit's electrical parameters. For example, an operational amplifier's gain-bandwidth product is reduced by exposure to ionizing radiation, and it is this reduction that contributes to the distortion of the SET shapes.

Previous work found that the SET threshold in a linear bipolar circuit (LM119) changes with exposure to particle radiation [2]. Measurements with a pulsed laser indicated a monotonic increase in the SET threshold energy with particle fluence, suggesting that SETs become less of a threat following radiation exposure.

A recent paper presents a detailed analysis of the effects that TID can have on the shapes and sensitivities of SETs in a simple voltage comparator (LM139) [3]. For the case where the output is "high", TID causes the slope of the leading edge of the SET (determined by the comparator's slew rate) to decrease, resulting in SETs with reduced amplitudes. As a consequence, the expected SET rate in space should decrease with dose.

SETs in operational amplifiers, such as the LM124, have a much greater variety of shapes and sizes than do simple voltage comparators, making the LM124 an ideal device for gaining a better understanding of how TID exposure affects SETs [1]. A number of factors, such as supply voltage, feedback, gain, configuration and particle LET, are known to affect the shapes of SETs, but there are no published reports on how SETs are affected by TID/DDD.

In this paper, we compare SETs produced in a pristine LM124 operational amplifier with those produced in one exposed to ionizing radiation for three different operating configurations – voltage follower (VF), inverter with gain (IWG), and non-inverter with gain (NIWG). Each configuration produces a unique set of transient shapes that change following exposure to ionizing radiation. An important finding is that the changes depend on operating configuration; some SETs decrease in amplitude, some remain relatively unchanged, some become narrower and some become broader.

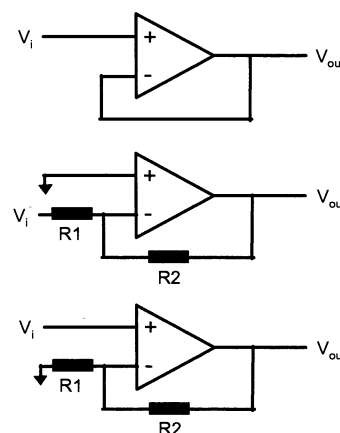


Fig. 1. Three operating configurations tested for the LM124. The top shows a voltage follower, the middle shows an inverter with gain, and the bottom shows a non-inverter with gain. The values of the resistors are  $R1 = 1 \text{ k}\Omega$  and  $R2 = 10 \text{ k}\Omega$ . The gains are 1, -10 and 11, respectively.

## II. DEVICE DESCRIPTION.

The device tested was a National Semiconductor LM124 quad operational amplifier in a dual in-line package (DIP) with a metal lid. Three of the four amplifiers in the package were tested, each in a different configuration – VF, IWG and NIWG. The fourth one was not connected. Fig. 1 shows the configurations.

Fig. 2 is a circuit diagram of the LM124. Many of the transistors in the circuit are SET sensitive and their identities have previously been established using the pulsed laser [4]. During accelerator testing, the entire chip is exposed to a beam of heavy ions whose arrival times and strike locations are random. As a result, each run contains SETs with a variety of shapes. The number of each type of SET captured depends on the threshold energy and cross-section for each sensitive transistor.

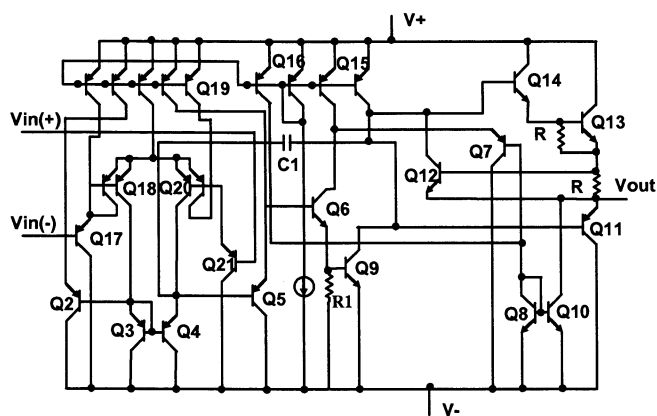


Fig. 2. Circuit diagram of the LM124.

### III. TEST METHOD.

An LM124 was mounted in a socket on a test board and exposed to gamma radiation in the NASA/GSFC Co<sup>60</sup> cell. During exposure, the same electrical bias was applied to all the devices, i.e.,  $V_{in} = 1$  V and  $V_{dd} = 5$  V and  $V_{ss} = -5$  V. Outputs were left floating.

The part was irradiated at a high dose rate of 5 krad(Si)/hour to a total dose of 150 krad(Si). Although the LM124 is known to have enhanced low dose rate sensitivity, a high dose rate was chosen because of time constraints. The large total dose ensured that radiation-induced changes in electrical parameters, specifically gain and transistor current drive, would be sufficient to noticeably distort the SETs.

The irradiated device and a pristine device from the same lot/date code were tested for SETs using pulsed laser light and heavy ions. All SET testing was done with  $V_{in}$  set to 0.13 V, so that  $V_{out}$  was 0.13V for the VF, 1.43V for the NIWG, and -1.3V for the IWG.

#### A. Pulsed-Laser Testing

Testing with pulsed-laser light was performed at the Naval Research Laboratory. The laser generates 1 ps pulses at a wavelength of 590 nm and a repetition rate of 1 kHz. The light is focused to a spot with a full-width-at-half-maximum diameter of 1.1  $\mu$ m and directed at transistor areas exhibiting sensitivity to SETs. Transients from the same areas in the pristine and irradiated chips were generated using constant laser pulse energy (4.3 pJ). A high-speed oscilloscope probe (capacitance of 8 pF) was attached directly to the op-amp output. SETs were captured on a digital oscilloscope and stored for later analysis.

#### B. Heavy-Ion Testing

Heavy-ion testing was conducted at Texas A&M Cyclotron Facility using the 15 MeV/amu energy tune. In order to capture both positive and negative transients, two oscilloscope probes were attached to an output and connected to two separate oscilloscope channels. One channel was set to trigger on a positive voltage deviation of +50 mV and the other on a negative deviation of -50 mV.

### A. Pulsed-Laser Results

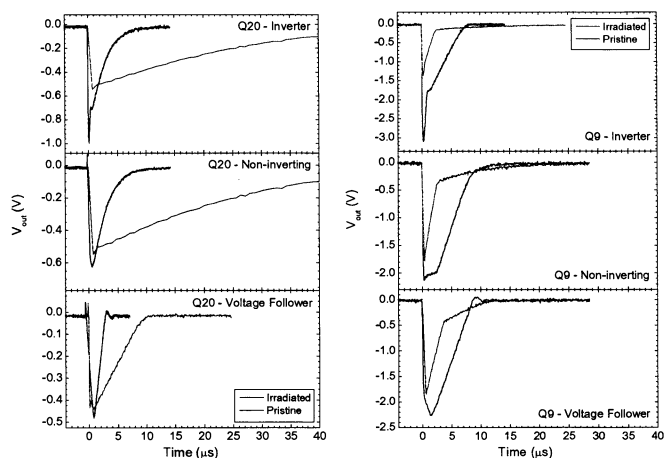


Fig. 3. SETs obtained for the LM124 in three different operating configurations for a pristine and an irradiated device. The left panel is for transistor Q20 and the right panel is for transistor Q9. (With the oscilloscope in AC mode, the baseline is at 0V).

It is possible, with focused laser light, to identify transistors responsible for producing particular SET shapes. Some SETs are positive, some are negative, and some have bipolar structure. In this work, we focus on transistors Q9 and Q20, both of which produce negative-going SETs in all three configurations. Transistor Q20 is part of the differential input circuit and Q9 is in the intermediate stage.

Fig. 3 compares SETs generated when the laser is focused on transistor Q20 (left panel) and transistor Q9 (right panel). The figure shows modest pre-rad differences in shape for SETs generated at transistor Q20 in each of the three different configurations. All three SETs have widths (FWHM) of between 2 and 3  $\mu$ s. Following exposure to ionizing radiation, SET widths for IWG and NIWG configurations increase from 2  $\mu$ s to 19  $\mu$ s. This may be contrasted with SETs for the VF configuration, for which the width increases from 2  $\mu$ s to 5  $\mu$ s.

The results for Q9 are very different in that following irradiation they become smaller and narrower.

#### B. Heavy-Ion Results

SETs were captured for all three operating configurations and for a number of different ion effective LETs. The electrical conditions are identical to those used for pulsed-laser testing, i.e.,  $V_{dd} = 5$  V,  $V_{ss} = -5$  V and  $V_{in} = 0.13$  V. Fig. 5 compares SETs for the pristine part (left panel) and irradiated part (right panel) for an LET of 54.8 MeV.cm<sup>2</sup>/mg. Of the numerous data sets, only those obtained with ions having an LET of 54.8 MeV.cm<sup>2</sup>/mg are presented in Fig. 5 because they best illustrate the variety of possible SET shapes and sizes.

The graphs reveal a number of interesting characteristics. First, the shapes of SETs in pristine devices depend strongly on the operating configuration. Whereas all the SETs in the IWG are bipolar, those in the other two configurations have a

variety of shapes and sizes, including positive, negative and bipolar.

Second, the fact that all the SETs in the IWG have the same bipolar shape strongly suggests that all originate from a single location.

Third, comparison of the left and right panels in Fig. 5 reveal dramatic change in the SET shapes observed for all three configurations following irradiation. The bipolar SETs observed for the IWG are almost completely absent in the irradiated part, having been replaced by unipolar positive and negative transients with significantly greater widths. In the VF, not only are the negative SETs largely absent following irradiation, but they generally have smaller amplitudes and are wider by a factor of about two. For the NIWG, the presence of both positive and negative SETs does not change appreciably following TID. However, the SET widths become considerably broader.

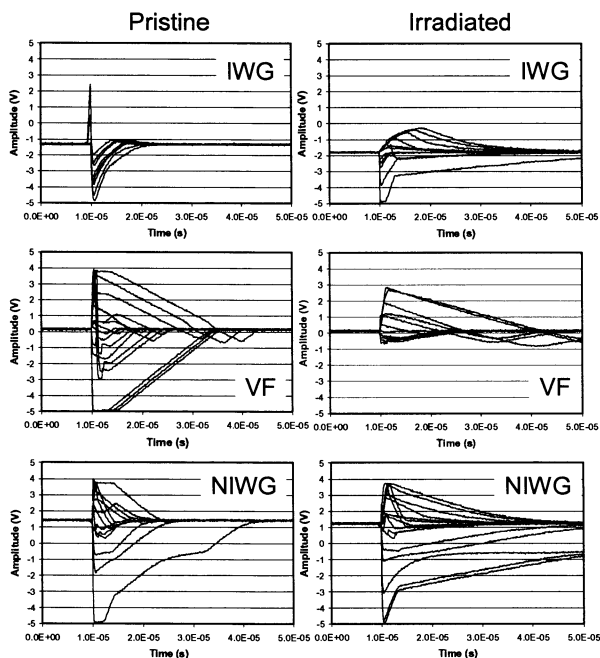


Fig. 5. Heavy-ion induced SETs for pristine (left panel) and irradiated (right panel) devices for IWG (top), VF (middle) and NIWG (bottom) at LET=54.8 MeV.cm<sup>2</sup>/mg.

### C. Slew Rate Measurements

Exposing an unhardened device to a TID of 150 krad(Si) raises the questions as to whether the device is still operational. Fig. 6 shows the responses of the devices to a square wave input with a frequency of 1 MHz. The results show that the rise time (slew rate) increases from 4.8 μs to 18 μs following irradiation for the VF, and from 10 ns to 48 ns for the IWG, but the devices are still operational.

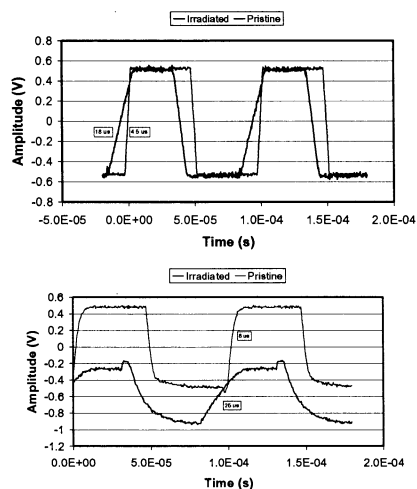


Fig. 6. Output signal of the LM124 in the VF configuration (top) and IWG configuration (bottom) before and after irradiation.

The output signal is more distorted following irradiation for the IWG than for the VF case. In addition, the signal never becomes positive in the irradiated part. To illustrate that this is at least partially due to the different bias conditions during irradiation, we configured all three devices in the VF configuration and compared the output signals. Fig. 7 shows that the IWG signal is more distorted than for the other two cases. Given that all conditions are identical except for the bias conditions during irradiation, one can partially attribute the greater distortion in the output signal to the different bias conditions during irradiation.

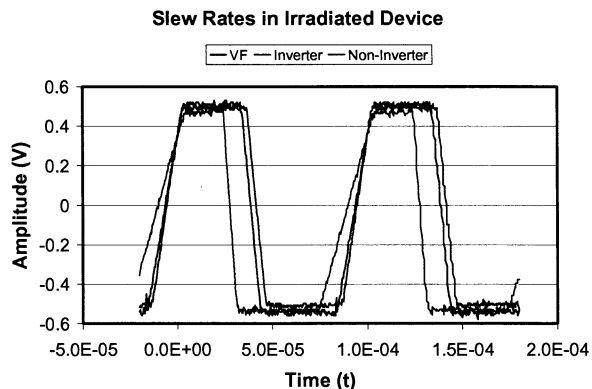


Fig. 7. Comparison of the output signals for the three different configurations. The differences in the rise times are attributable to the different bias conditions during irradiation.

## V. DISCUSSION

### A. Pulsed-Laser Results

Fig. 3 perfectly illustrates the oft-stated fact that SET pulse shapes differ among different operating conditions for the same bipolar circuit, i.e., whereas SETs in the VF and IWG are similar in shape, those for the NIWG are narrower and larger.

Radiation-induced distortions in the shapes of SETs can be explained by invoking known TID effects in bipolar transistors, together with simple circuit analysis. TID causes a

reduction in a bipolar transistor's gain as well as its drive capacity. Combining that information with circuit analysis makes it possible to explain radiation-induced changes in SET shapes in the LM124. The full paper will include an explanation for the changes in SET shapes.

### B. Heavy-Ion Results

During accelerator testing, the entire op-amp is exposed to heavy ions. SETs can originate in any transistor and the distribution of SET shapes and sizes reflects the sensitivities and cross-sections of the contributing transistors.

The significant differences in SET shapes among the three configurations are more evident in the data shown in Fig. 5 than in the data shown in Fig. 3, for which the results for only two transistors are presented. The point has been made previously, that SET shapes are dependent on configuration; the accelerator results presented here underscore this point.

The differences in transient shapes between the different configurations provide a good example of why it is important to test in the same configuration as the intended application. The positive components of the bipolar SETs in the IWG configuration are much narrower than the positive transients in the other two configurations. For example, the positive components in the IWG configuration have widths on the order of 1  $\mu$ s, whereas those in the VF are on the order of 30  $\mu$ s. Therefore, to qualify the LM124 included in a system in which only positive SETs will ultimately be latched, one cannot use the data for the IWG configuration if the intended application is either the NIWG or the VG.

### C. Significance for Error Rate Determination

It has become standard practice to display SETs in a less cluttered format than shown in Fig. 5 by plotting their amplitudes as a function of their widths (FWHM) [5]. Fig. 8 contains plots of amplitude versus width for the pristine and irradiated devices in the NIWG configuration and for ions with a LET of 2.8 MeV.cm<sup>2</sup>/mg. The plots illustrate clearly how total dose modifies SET shapes. In particular, the maximum SETs have amplitudes greater than 2 V in the pristine device but less than 1 V in the irradiated device, and there is a general increase in width by a factor of approximately two.

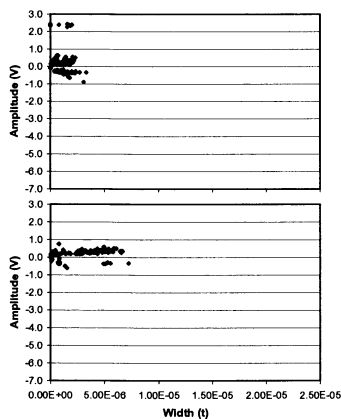


Fig. 8. Amplitude versus width for SETs in the pristine part (top) and the irradiated part (bottom) in the NIWG configuration for ions with LET = 2.8 MeV.cm<sup>2</sup>/mg.

This same procedure can be applied to SETs in all the different configurations and for all LETs. Then, only those SETs that will contribute to system errors need be counted. Including only those relevant SETs will have an effect on the SET cross-section, which can either increase or decrease, depending on the application. An example illustrating how the SET rate increases following irradiation will be presented in the final presentation and paper.

An important consequence of this work is that if bipolar parts that are not radiation-hardened are selected for use in space, they should be tested for both TID and SET sensitivity in the configuration in which they will operate.

## VI. CONCLUSION

The results presented in this paper clearly show that SETs originating in an operation amplifier have shapes that depend on the operating configuration. Furthermore, following irradiation, the SETs are distorted by TID such that some become wider and others become narrower. The physical locations of the SETs can be established with the aid of a pulsed laser microprobe. That information can then be used to explain the effects. The results reveal that the SET error rate associated with a linear part can either *decrease* or *increase* following TID exposure. These results reveal the necessity of considering the TID dependence of SET transients on linear devices, a result that may have significant hardness assurance implications.

## REFERENCES

- [1] S. Buchner and D. McMorrow, "Single-Event Transients in Bipolar Integrated Circuits," IEEE Trans. Nucl. Sci. NS53, pp. 3079-3102, December 2006.
- [2] S. Buchner, D. McMorrow and M. Maher, Characterizing Single-Event Transients in a Voltage Comparator (LM119) Presented at HEART, San Antonio, TX, March 2001.
- [3] M. Bernard, L. Dusseau, S. Buchner, D. McMorrow, R. Ecoffet, J. Boch, J.-R. Vaile, R. Schrimpf and K. LaBel, "Impact of TID Effect on Analog SET Sensitivity of Linear Bipolar Integrated Circuits," IEEE Trans. Nucl. Sci., (Submitted for publication).
- [4] S. Buchner, D. McMorrow, C. Poivey, J. W. Howard, R. L. Pease, M. Savage, L. W. Massengill, and Y. Boulghassoul, "Comparison of single event transients in an operational amplifier (LM124) by pulsed laser light and a broad beam of heavy ions," IEEE Trans. Nucl. Sci., vol. 51, no. 5, pp. 2776-2781, Oct. 2004.
- [5] P. Adell, R. D. Schrimpf, H. J. Barnaby, R. Marec, C. Chatry, P. Calvel, C. Barillot, and O. Mion, "Analysis of single event transients in analog circuits," IEEE. Trans. Nucl. Sci., vol. 47, no. 6, pp. 2616-2623, Dec. 2000.



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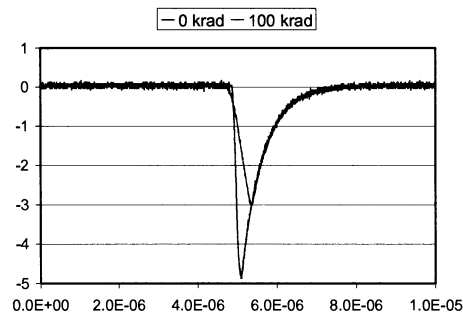
1. *PSGS/NASA-GSFC, USA*
2. *Naval Research Laboratory, USA*
3. *University of Montpellier, France*

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1

## Introduction

- Analog SETs (ASETs) can propagate through a system and cause a malfunction.
- Following radiation exposure, ASETs in LM139 become smaller → System error rate decreases.



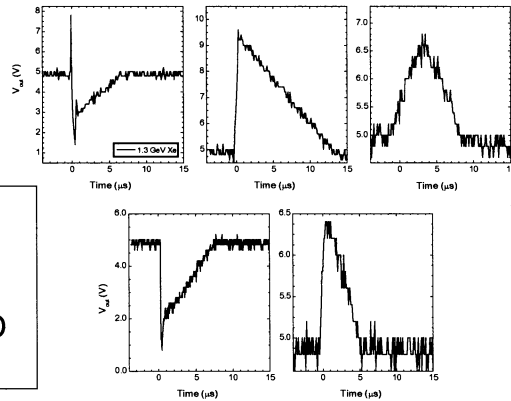
LM139  
Voltage Comparator

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2

# Introduction

- LM124 is an op-amp with a much larger variety of SETs.



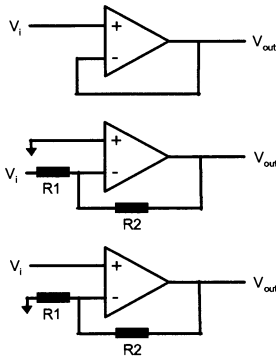
What happens to the SETs following TID irradiation?

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3

# LM124 Configuration

- LM124 is a quad op-amp. Configured in three ways: Voltage follower, Inverter, Non-Inverter.
- Irradiated to 150 krad(Si) under bias, i.e.,  $V_{in} = 1V$ .



Radiation causes a reduction in transistor gain and a loss of transistor current drive.

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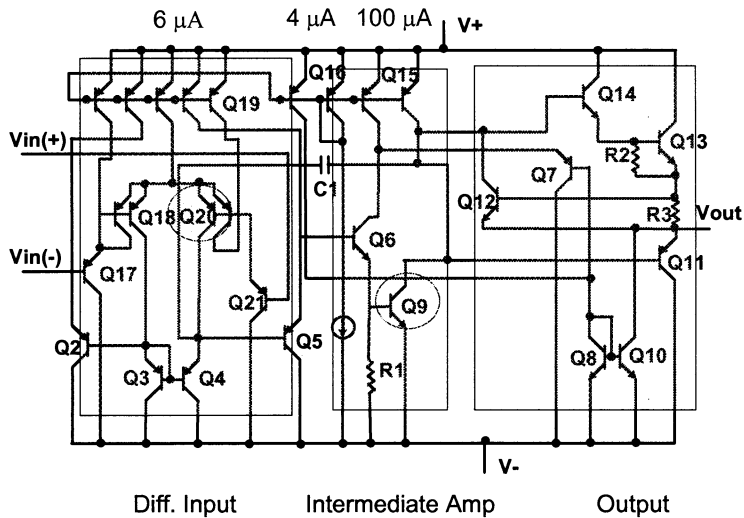
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# Pulsed Laser Data

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5

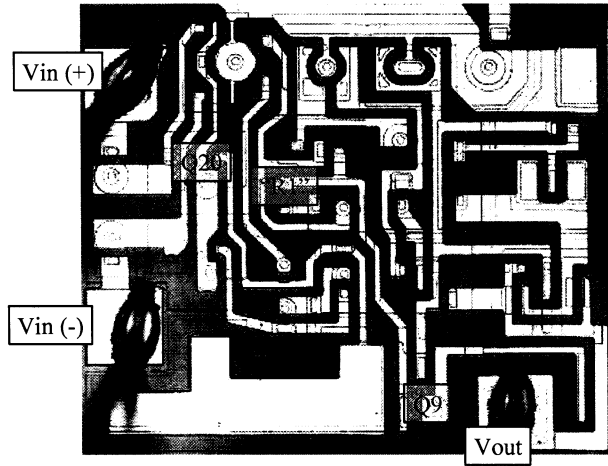
# LM124 Circuit



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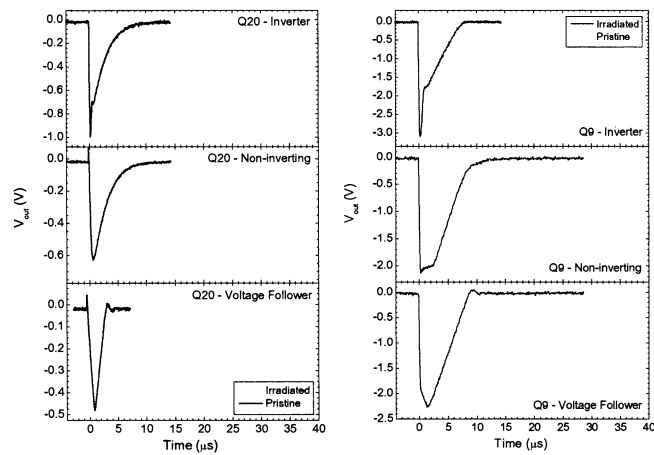
# LM124 Photomicrograph



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# SETs in Pristine Device

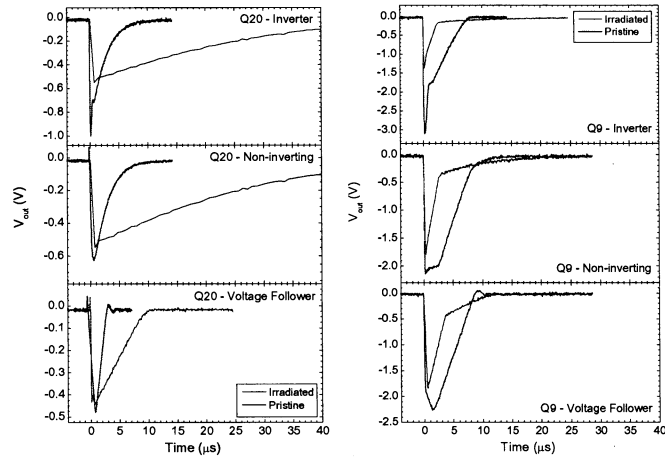


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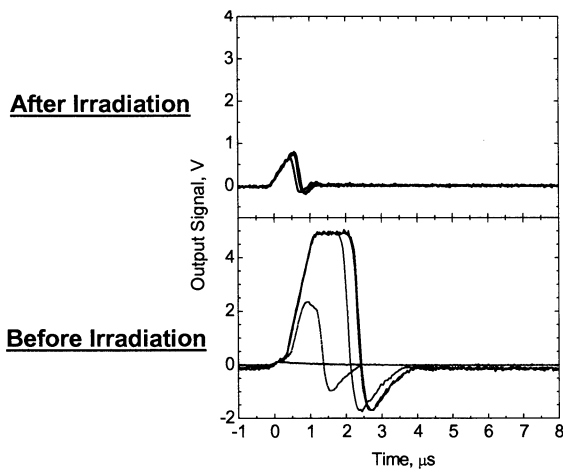
# SETs Before and After Irradiation



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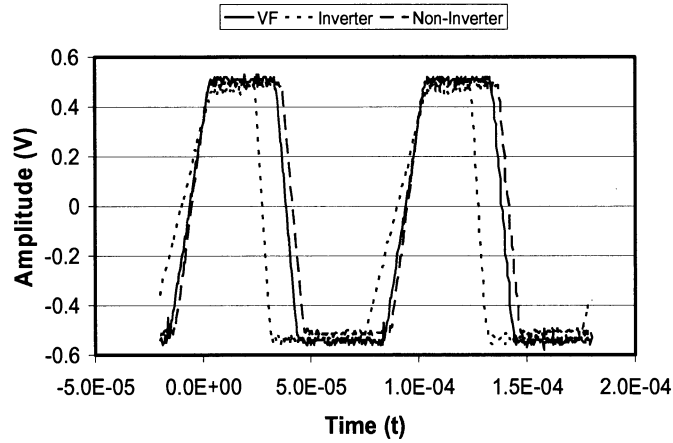
# SETs in R1



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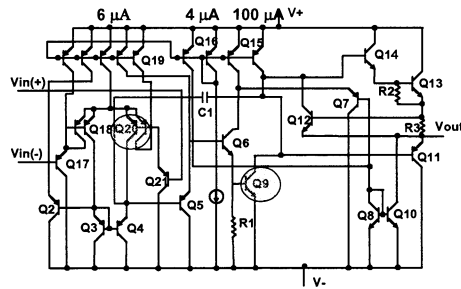
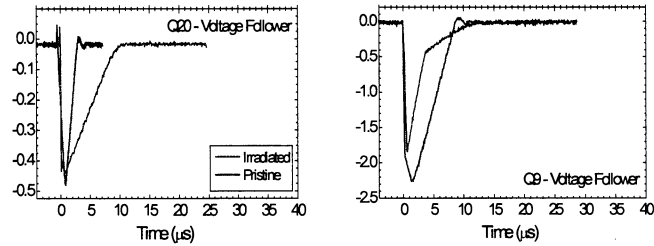
# Slew Rate



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# Explanation for SETs on Q20 & Q9



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# Heavy Ion Data

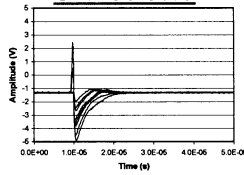
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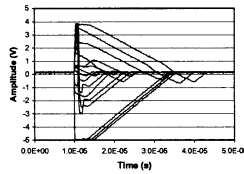
## LET=54.8 MeV.cm<sup>2</sup>/mg

### Unirradiated

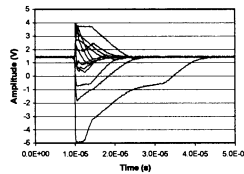
Inverter



Voltage Follower



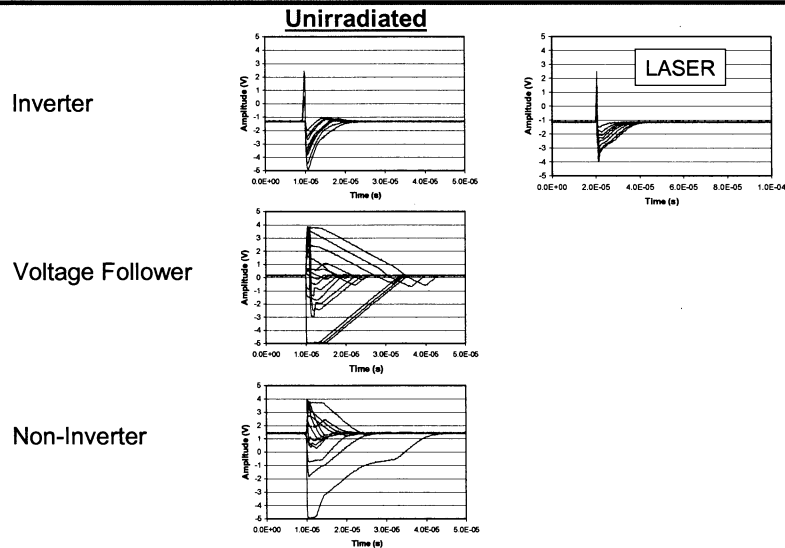
Non-Inverter



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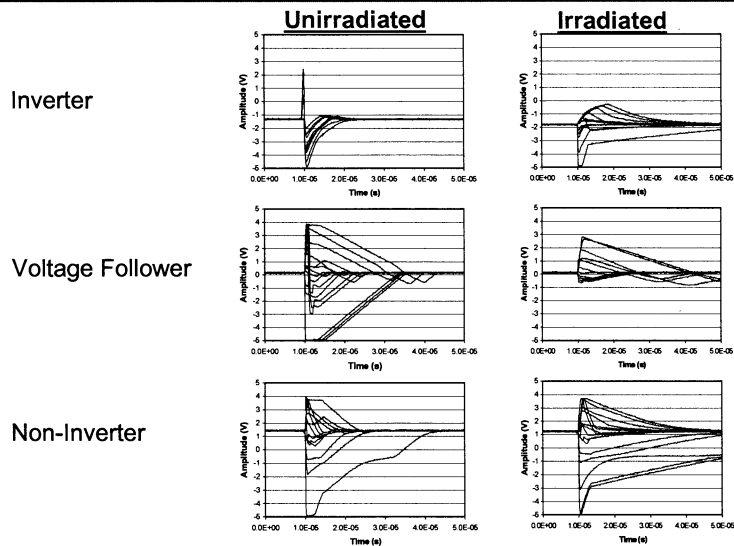
# LET=54.8 MeV.cm<sup>2</sup>/mg



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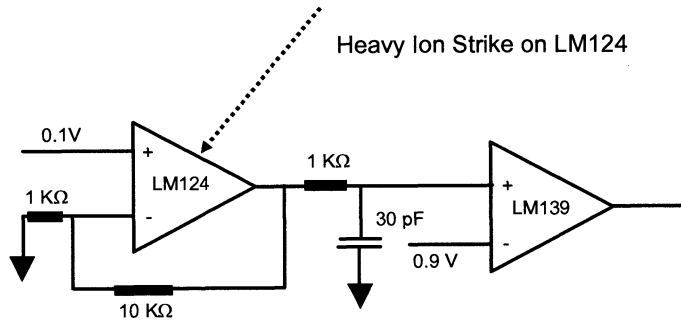
# LET=54.8 MeV.cm<sup>2</sup>/mg



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# Application

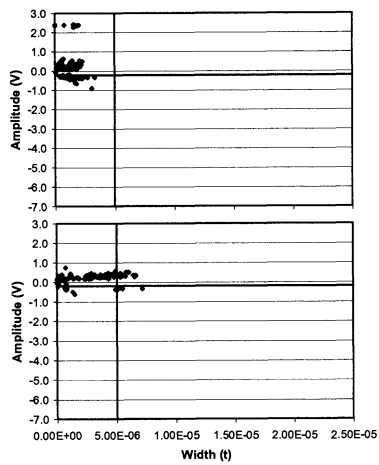


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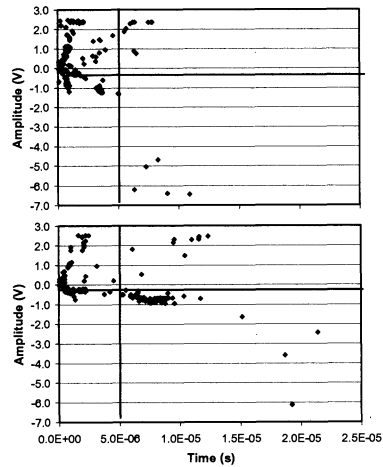
17

# Plots of SET Amplitude vs Width

## Non-Inverter



LET=2.8 MeV.cm<sup>2</sup>/mg

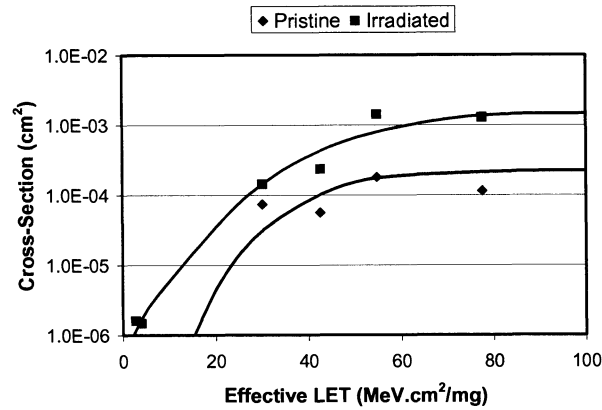


LET=54.8 MeV.cm<sup>2</sup>/mg

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18

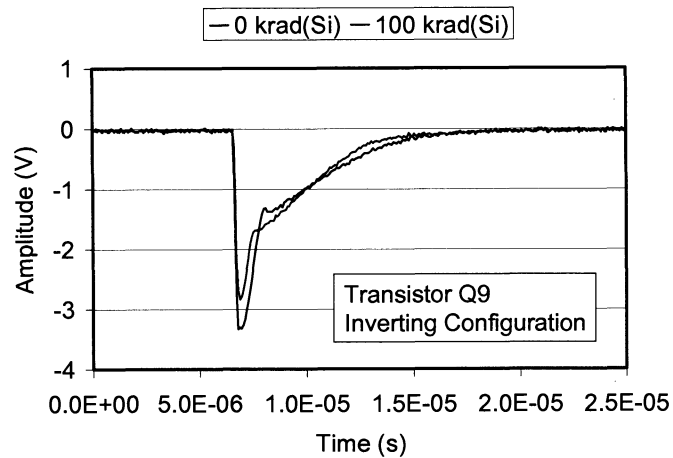
## LM124 Laser Induced Transients



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## RM124 Laser Induced Transients



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## Conclusions

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- SET shapes depend on:
  - Configuration – different transistors sensitive
  - Radiation exposure – degrades gain and current drive
- Understanding of how TID affects transistor operation together with simple circuit analysis can explain changes in SET shapes with dose.
- Depending on origin, SET widths can increase or decrease following exposure.
- System SET rate can change with radiation exposure.
- Hardness assurance implications.