Variations in SET Pulse Shapes in the LM124A and LM111

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Abstract—We present a paper that shows remarkable variation in Single-Event Transient (SET) pulse signal shape of the LM124 Operational Amplifier, and the LM111 Voltage Comparator. Both the data and the test methods used are presented.

Keywords- Single Event Transient, SETs, Heavy Ion, LM124, LM111

I. INTRODUCTION

When a heavy ion deposits charge in a sensitive structure of a microelectronic device, this deposited charge can produce a spurious voltage on the closest circuit node. If this analog voltage deviation or pulse propagates to an output, it is known as a Single Event Transient (SET). These transient signals can propagate to downstream circuits, and result in system errors. An example given by R. Koga et al. is the disrupted output of an operational amplifier being erroneously counted by a digital counter that is set to count amplitudes above a certain threshold [1]. Just such an error was observed in NASA's TOPEX satellite in 1993 [2]. Transients can also lead to fatal errors, several of which have already been observed in flight [3]. The conditions that allow a SET to induce a system failure are dependant on transient pulse amplitude, as well as duration. This has led Adell et al. to analyze SET pulses in terms of SET duration versus pulse amplitude, in addition to measuring the conventional cross-section versus LET [4].

In this work, the SET response of the LM124A and LM111 is investigated, characterizing both the cross-section as well as the SET pulse duration and amplitude. Results show that the transient pulses exhibited variations in pulse shape from event to event in the LM124A. However these

variations were found to fall into four distinct classes. This result contrasts sharply with the LM111, which presents only one pulse shape. Finally a brief discussion will highlight the results of modeling, in which specific pulses are traced to specific junctions. Andrew Sternberg has detailed the results of this modeling in a separate paper [5].

II. EXPERIMENT

A. Test Circuit

The LM124A Op-Amp was irradiated as a closed loop non-inverting amplifier with a gain of 2, as shown in Fig. 1. In this experiment statistical variations were not studied, therefore sample size was limited to a single DUT. As an Op-Amp is free to respond to a positive or negative signal, the LM124A responded with both positive and negative going pulses. The SET response was evaluated at DC V_{in} inputs of 4.30 Volts, 0.65 Volts, -0.06 Volts, -0.65 Volts, and -4.30 Volts, with V_{cc} fixed at ± 6.5 Volts.

The LM111 comparator was biased open loop with resistor pull-up output as shown in Fig. 2. As with the LM124A, statistical variations were not studied and sample size was limited to a single DUT. Unlike the LM124, the LM111 is a referenced to ground, and only positive input voltages were applied, forcing the output high. This constrained the output and therefore the device's SET response was always a negative going pulse. The V_{in} was tested at two input voltages

Figure 1. Application of the LM124

Table 1: Ion and Energies Used

Ion	Energy (MeV)	LET (MeV cm ² /mg)	Range (μm)
Chlorine	210	11.50	62.91
Magnesium	150	6.25	76.53
Bromine	100	39.22	15.99
Carbon	50	2.28	20.53

Figure 2. Application of the LM111

0.05 Volts and 0.10 Volts, with V_{cc} always set at a nominal ± 15 Volts.

B. Test Setup

The test setup is shown in Fig. 3. The DUT was exposed to heavy ion radiation inside a vacuum chamber. A Tektronix P6243 FET probe was attached to the output of the device, and power was provided to the probe inside the vacuum chamber via a Tektronix 1103 tekprobe power supply. The output of the probe was then routed into a Tektronix TDS 784D digital phosphor oscilloscope set to trigger to pulses with amplitude above 250 mVolts for the LM124 and 1 Volt for the LM111. The entire experiment was controlled remotely using a PC. The experiment was performed at Brookhaven National Laboratory Tandem Van De Graaff facility. The ions and energies used in this test are given in Table 1. At specific LETs the ion angle was varied from 0° to 30° to 60° , which in turn varied the penetration depth as $d_p = R(E) \cos(\theta)$ from a minimum of $8 \mu\text{m}$ to a maximum of $76 \mu\text{m}$.

Figure 3. SET Test Setup

Figure 4. SET Cross-Section versus Effective LET of the LM124 at all Input Voltages Tested

III. EXPERIMENTAL RESULTS

A. Cross-section versus LET_{EFF}

1) LM124

In Fig. 4 the SET cross-section is plotted versus the effective LET, which is $LET_{EFF} = LET / \cos(\theta)$, for the LM124 at input voltages of 4.30, 0.65, -0.06, -0.65 and -4.30 Volts.

2) LM111

The cross-section curves for the LM111 at input voltages of 0.05 and 0.10 Volts are shown in Fig. 5.

B. Pulse Width versus Pulse Height.

1) LM124

Analysis of transient pulses reveal that the SET response is more detailed than can be shown by the cross-section curve alone because the characteristics of the SET response depend

Figure 5. Cross-Section versus Effective LET of the LM111 at all Voltages Tested

Figure 6. Pulse-Height versus Pulse-Width for the LM124 at an Input Voltage of 4.30 Volts

Figure 8. Pulse-Height versus Pulse-Width for the LM124 at an Input Voltage of -0.060 Volts

Figure 7. Pulse-Height versus Pulse-Width for the LM124 at an Input Voltage of 0.650 Volts

Figure 9. Pulse-Height versus Pulse-Width for the LM124 at an Input Voltage of -0.650 Volts

on many factors. One method to quantify this detail is to measure the pulse width (the length of time that the output signal is disrupted from its non disturbed state), versus peak amplitude of the transient signal called pulse height. This analytical approach was used by Adell et al. in the study of LM124 as a closed loop low power voltage regulation system and allows better insight into the LM124 SET response [4].

The pulse-height (V) versus pulse-width (μ s) for the LM124A at a V_{in} input of 4.30, 0.65, -0.06, -0.65 and -4.30 Volts is shown in Fig. 6, Fig. 7, Fig. 8, Fig. 9, and Fig. 10 respectively. For simplicity further analysis will concentrate on the 0.060 V input data set, however, these conclusions are applicable at all inputs.

2) LM111

The pulse-height (V) versus pulse-width (μ s) for the LM111 at input of 0.05 and 0.10 Volts are shown in Fig. 11

Figure 10. Pulse-Height versus Pulse-Width for the LM124 at an Input Voltage of -4.30 Volts

Figure 11. Pulse-Height versus Pulse-Width for the LM111 at an Input Bias of 0.050 Volts

Figure 12. Pulse-Height versus Pulse-Width for the LM111 at an Input Voltage of 0.100 Volts

and Fig 12. As before, for simplicity further analysis will concentrate on the lowest input voltage (0.020 V) data set. However, these conclusions are applicable at both test voltages, as the response of the device was unaffected by changes in the input voltage.

C. SET Pulse Shape Variations

1) LM124A

At ± 0.65 , and -0.06 Volts in the LM124A, there were three distinct families of curves within the data sets. These distinct functions are defined as subsets A, B, and C. Examples of subsets A and B are shown in Fig. 13, and of subset C in Fig. 14.

(1) Subsets A and B

Subsets A and B consist of low amplitude pulses with relatively slow recovery times. Family A consists of negative

Figure 13. a) Subset A and b) Subset B

Figure 14. Subset C

Figure 15. Location of Subsets A (Negative Going Pulses) and B (Positive Going Pulses)

Figure 16. Evolution of Subset C

Figure 18. LM111 Single Event Transient Pulse

Figure 17. Evolution of Subset C Continued

Figure 19. Penetration Depth dependence of Cross-Section

going transients and family B of positively going transients, shown in Fig. 13. In Fig. 15 the pulse amplitude versus pulse width of subsets A and B were plotted, with all 0.060-Volt data plotted for comparison. Clearly the two families of slow curves describe two similar linear trends that appear as mirror images of each other, reflected about the x-axis. The most notable difference between subsets A and B, is that A extends to larger pulse widths and amplitudes.

(2) Subsets C

Subset C was present as signals with small negative amplitude and large positive amplitude. These curves strongly resemble square waves in their “saturated form” as shown in Fig. 14. When the transient amplitudes are plotted versus SET duration the fast pulses exhibit a linear relationship until amplitude of 4.5 Volts is reached, at which point the pulse height saturates and is limited by power supply rails. Beyond that point, any increase in SET duration is not reflected by an

increase in amplitude, as shown in Fig. 16. Within this trend an evolution of transient pulse shapes of subset C was observed. At lower transient amplitudes (represented by D in Fig. 17) these fast pulses, resemble a sharp spike as shown by curve A in Fig. 16. As the amplitudes increase eventually this response rails at amplitude of 4.5 Volts (represented by B in Fig. 16 and Fig. 17), which is not the circuit rail and the amplitude is prevented from increasing further by an internal voltage drops. Transients presumed to be of an even greater charge then produced transients of this maximum saturation amplitude, but the transient duration lengthens (represented by D in Fig. 16 and Fig. 17).

2) LM111

The LM124A behavior contrasted sharply to the LM111 Data. Only one response revealed when pulse amplitude versus pulse width was plotted as shown in Fig. 18.

III. DISCUSSIONS

A. LM124A

In Fig. 19 the cross-section is found to be dependant with penetration depth. Fig. 19 suggests that there are at least two separate depths involved in the SET response, a small sensitive volume near the surface of the device, and a larger sensitive volume deeper in the microcircuit. The heavy ions with a penetration depth less than $21\text{ }\mu\text{m}$, penetrated the shallower sensitive volume, but failed to deposit charge in the deeper sensitive volume. The ions with a penetration depth greater than $21\text{ }\mu\text{m}$ cross both sensitive junctions, and since the deeper sensitive volume has the larger cross sectional area the deeper junction dominates the cross-section.

Vanderbilt University computer science department modeled the response of the LM124. They found that subset B is due to imbalances in the input stage current mirror transistors Q3 and Q4. These simulations also show that subset A are due to amplification stage transistors Q6 and Q9. The origin of subset C was found when the resistor R1 was examined by failure analysis at NAVSEA Crane. R1 proved to be a floating base NPN transistor, perhaps to be used as an over temperature and/or an over voltage shut down device shut down device to protect the circuits output [6]. Simulations also showed that strikes at the base/emitter junction and the base/collector or substrate junction produced the same output transient signal. Summing up the base/emitter and substrate junctions of the sensitive transistors we obtain two cross-sections which are shown in Fig. 19. Cross-sections of the die show that the base/emitter and the collector/substrate junctions are approximately $6\text{ }\mu\text{m}$ and $26\text{ }\mu\text{m}$ deep, further bolstering this hypothesis. However, there is still an unresolved difference between the cross-section

measured from heavy ion data and deduced from simulation.

B. LM111

Very similar behavior was seen in the LM111, which since the manufacturing process was similar is not unexpected. This could have profound implications for angular studies. As penetration depth is a function of angle, it is possible to have an ion penetrate the larger deeper junction at normal incidence, yet at an angle only penetrate the shallow junction. This would result in a decrease in the cross-section at higher effective LETs, due to this angle effect.

Overall the LM111 exhibits a far simpler SET response. Only one pattern is observed when the transient amplitude versus the SET duration response is examined. The two most obvious conclusions are that either there is only one sensitive node or there is considerable signal modification occurring. Since modeling suggests numerous sensitive node, we are led to the conclusion that the LM111 output is circuit limited.

III. CONCLUSION

In this work the SET response of the LM124A and LM111 was investigated. Both the cross-section as well as the SET pulse duration and amplitude of both devices was studied. Further investigation showed that the transient pulses exhibited variations in pulse shape from event to event in the LM124A. However, similar investigation showed that LM111 presented only one pulse shape. The pulse variations of the LM124A were not random, but fell into three distinct classes. In this work these pulses were detailed, and the three classes of LM124A waveforms were presented and described in detail. Finally the SET results of the LM124A and the LM111 were compared and contrasted.

Figure 20. Schematic of the LM124 [7]

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