Single Event Transient (SET) Response of National Semiconductor's ELDRS-Free LM139 Quad Comparator

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***Abstract*— Heavy ion and pulsed laser Single Event Transient (SET) data are presented for National Semiconductor's LM139AxLQMLV (5692R9673802VxA). The SET signatures for this part are compared to older versions of the part. The results confirm complications in performing SET testing on bipolar analog products reported by others plus raise new considerations when evaluating SET test results.**

I. INTRODUCTION

In a space environment, a single event transient (SET) on a comparator output is of major concern. There has been a documented incident where a spacecraft went into a hold mode, which took several days to correct, due to an output transient from an LM139 caused by an ionizing particle strike from a solar event [1]. The LM139 (Fig.1) has been used in space applications for many decades and has been manufactured by a number of different suppliers. Each supplier may have used a number of different product layouts, manufacturing locations and processes to produce these products over the years. Previous SET testing on different versions of the LM139 has shown that the SET response can depend upon the product's manufacturing origin, such as manufacturer and wafer fabrication facility (fab) [2]-[4].

National Semiconductor introduced the LM139 in 1972 and has manufactured it in many different fab locations, using different wafer fabrication processes. National has long been a supplier of a QMLV version of the product, manufactured according to the requirement of MIL-PRF-38535 [5]-[7]. Most single event studies on National's LM139 have been performed on material manufactured prior to 1999. In 2000, the LM139 went through a die shrink and a manufacturing transfer to National's Arlington, Texas wafer fab. A difference in SET response has been seen between die manufactured in National's Santa Clara or UK wafer fabs, using the original die layout and die manufactured in the Texas wafer fab, using the shrunk die layout [2]. Since then, National moved the QMLV version of the LM139 to its Greenock, Scotland (UK) 6" wafer fab, resulting in additional process and layout changes. This new QMLV version of the LM139 went through total ionizing dose (TID) testing, has been rated to 100 krad(Si) and found not to exhibit enhanced low dose rate sensitivity (ELDRS) [8].

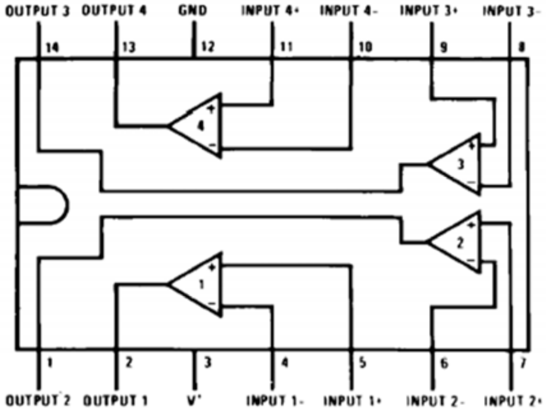

Fig. 1 LM139 pinout in dual inline package (DIP) [6]

The ELDRS-free version of the LM139 has been put through heavy ion and pulsed laser testing. In addition, an older version of the LM139, manufactured before the die shrink, was put through pulsed laser testing to determine if the die shrink had any impact on the SET signatures (Table I). The results of these tests are presented, along with an analysis of the impact of supply and input voltages and unit to unit variation on SET response. The data are compared to published data on other versions of the LM139. This study confirms the complications of SET testing of bipolar analog products reported by others plus brings up new considerations that should be taken into account when evaluating SET results.

TABLE I
PRODUCTS TESTED

Product	Radiaiton Level	Wafer Fab	Die Shrink?
LM139AJRLQMLV	100 krad(Si) ELDRS-free	UK 6"	Yes
LM139AJ	None	UK 4"	No

Manuscript received July 30, 2009

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II. PRODUCT DESCRIPTION

The main focus of this study is National Semiconductor's ELDRS-free LM139 (LM139AxRLQMLV, where x is the variable for the package identifier), produced in the UK 6" wafer fab [6][7]. The units were assembled and put through burn-in per the V process flow of MIL-PRF-38535 [5]. Also going through the pulsed laser testing was an LM139Ax unit manufactured in the UK 4" wafer fab (Table I). This version of the LM139 did not receive the die shrink and the die is 25% larger than the LM139AxRLQMLV. It was assembled to the standard commercial manufacturing flow and did not receive burn-in. All units tested were assembled in the 14 lead ceramic dual inline package (cerdip), package identifier "J", and delidded to expose the surface of the die to the beam.

III. TEST METHOD

Unless otherwise indicated, Channel 2 was connected as shown in Fig. 2. For some tests, the output pull-up resistor was connected to a separate power supply from the V+ power supply. The other three channels were left floating. For the pulse laser testing, the output pull-up resistor was 5.6 kΩ, while a 470 Ω resistor was used during the heavy ion testing.

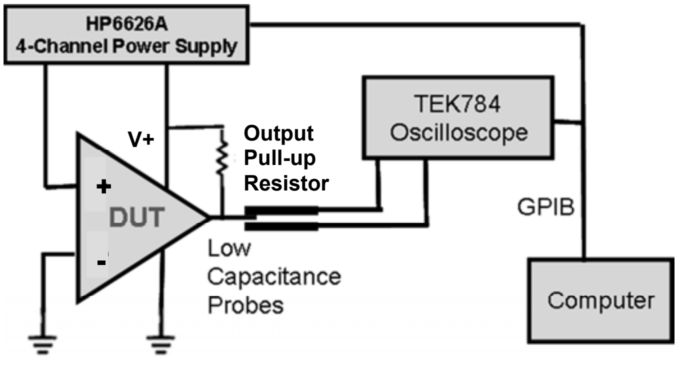

Fig. 2 Test setup for SET testing. Only Channel 2 was connected and the other 3 channels were left floating. The output pull-up resistor was 5.6 kΩ for the pulsed laser testing and 470 Ω for the heavy ion testing.

Various supply voltages (Vcc) and input voltages (Vin) were used (Table II). Under these conditions, the output should be high and very close to the supply voltage. For the heavy ion testing, the output was monitored for both negative and positive going transients. The trigger threshold was set at ±15 mV. The supply current was monitored for spikes that would indicate a single event latch-up (SEL). Only the output was monitored for negative-going transients during the pulsed laser testing. The scope trigger level was adjusted depending upon the test conditions.

Heavy ion testing was conducted at the Radiation Effects Facility at the Texas A & M University Cyclotron Institute. The 25 A MeV beam was used for the testing [9]. Ion runs were done with neon and krypton. Effective linear energy transfer (LETeff), angle, and penetration depth are shown in Table II. The ion beam was run until the fluence reached 1×10^7 ions/cm^2 or 400 transients were seen, which ever came first. The 400 error count was chosen for a ± 5% error level. All combinations of supply and input voltages and ions were run on device under test (DUT) 1. Due to time limitations, only a few conditions were run on DUTs 2 and 3.

Pulsed laser testing was conducted at the Naval Research Laboratory, using a 590 nm wavelength that resulted in a penetration (1/e) depth of 2µm. The pulsed laser allows for controlled and repeatable charge injection, allowing the study of the effect of other variables on the SET pulses [10][11]. The beam was focused in the field area of the negative input transistor epi tub (Fig. 3). Pulsed laser testing was performed on DUT 4, an LM139AJRLQMLV, and DUT 5, an LM139AJ.

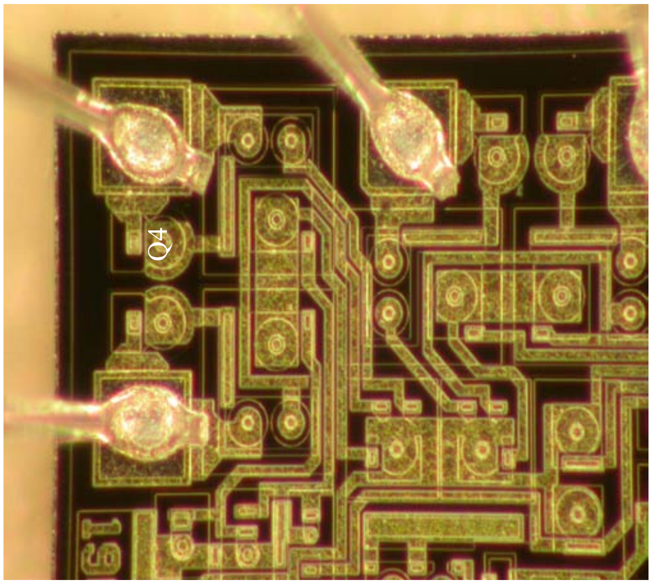

Fig. 3 Photograph of the LM139AJRLQMLV. The pulsed laser beam was focused on the field area of the epi tub of Q4, the negative input transistor.

IV. SEL AND OTHER DESTRUCTIVE EFFECTS

No evidence of (SEL) or any other destructive single event effects was seen during any of the testing. There were no spikes in the supply current. Transients were seen, but the part would recover to normal operation within 3 µs.

V. SET CROSS SECTIONS

The results of the heavy ion testing on LM139AJRLQMLV are summarized in Table II. The cross section, which indicates the relative probability of an SET, is calculated by dividing the number of SETs by the fluence in an ion run.

A. Impact of Output Trigger Level

In most applications, it is only important that the output of the comparator is either high or low. A small magnitude output transient may not cause an upset to the whole system. The number of upsets per ion run was recounted using a 50% trigger level (2.5 V for the 5 V supply conditions and 7.5 V for the 15 V conditions). It was found that over 60% of the transients had magnitudes of less than 50% of the nominal output voltage (Table II). SET cross sections with the trigger limits set at 15 mV and 2.5 V for Vcc=5 V and Vin=50 mV are plotted in Fig. 4.

TABLE II
HEAVY ION TESTING SET RESULTS FOR LM139AJGRLQMLV

Run#	**DUT**	**Vcc** (V)	**Vin** (mV)	**Ion**	**angle**	**LETeff** (MeV-cm^2/mg)	**Range** (μm)	**Fluence** (ions/cm^2)	**#SETs** ±15 mV	**#SETs** 50% Trigger	**σ** (cm)^2 ±15mV Trigger	**σ** (cm)^2 50% Trigger
2	1	5	50	Ne	0	1.8	799	1.00E+07	38	6	3.80E-06	6.00E-07
9	1	5	50	Ne	45	2.5	799	1.00E+07	77	2	7.70E-06	2.00E-07
33	1	5	50	Kr	0	20.3	332	6.76E+05	404	154	5.98E-04	2.28E-04
32	1	5	50	Kr	45	28.6	332	5.23E+05	400	113	7.65E-04	2.16E-04
40	1	5	50	Kr	60	40.6	332	4.19E+06	408	151	9.74E-05	3.60E-05
5	1	5	100	Ne	0	1.8	799	1.00E+07	11	6	1.10E-06	6.00E-07
6	1	5	100	Ne	45	2.5	799	1.00E+07	40	4	4.00E-06	4.00E-07
36	1	5	100	Kr	0	20.3	332	7.62E+05	410	183	5.38E-04	2.40E-04
29	1	5	100	Kr	45	28.6	332	5.64E+05	415	111	7.36E-04	1.97E-04
37	1	5	100	Kr	60	40.6	332	4.02E+05	403	130	1.00E-03	3.23E-04
28	1	5	1000	Kr	45	28.6	332	8.40E+05	560		6.67E-04	
3	1	15	50	Ne	0	1.8	799	1.00E+07	34	8	3.40E-06	8.00E-07
8	1	15	50	Ne	45	2.5	799	1.00E+07	14	2	1.40E-06	2.00E-07
34	1	15	50	Kr	0	20.3	332	1.82E+06	402	187	2.21E-04	1.03E-04
31	1	15	50	Kr	45	28.6	332	1.57E+06	408	109	2.60E-04	6.94E-05
39	1	15	50	Kr	60	40.6	332	1.84E+06	200	132	1.09E-04	7.17E-05
4	1	15	100	Ne	0	1.8	799	1.00E+07	6	6	6.00E-07	6.00E-07
7	1	15	100	Ne	45	2.5	799	1.00E+07	16	2	1.60E-06	2.00E-07
35	1	15	100	Kr	0	20.3	332	2.09E+06	401	173	1.92E-04	8.28E-05
30	1	15	100	Kr	45	28.6	332	1.84E+06	405	135	2.20E-04	7.34E-05
38	1	15	100	Kr	60	40.6	332	1.41E+06	200	126	1.42E-04	8.94E-05
10	2	5	50	Ne	0	1.8	799	1.00E+07	34		3.40E-06	
11	2	5	50	Ne	45	2.5	799	1.00E+07	94		9.40E-06	
12	3	5	50	Ne	0	1.8	799	1.00E+07	44		4.40E-06	
13	3	5	50	Ne	45	2.5	799	1.00E+07	96		9.60E-06	

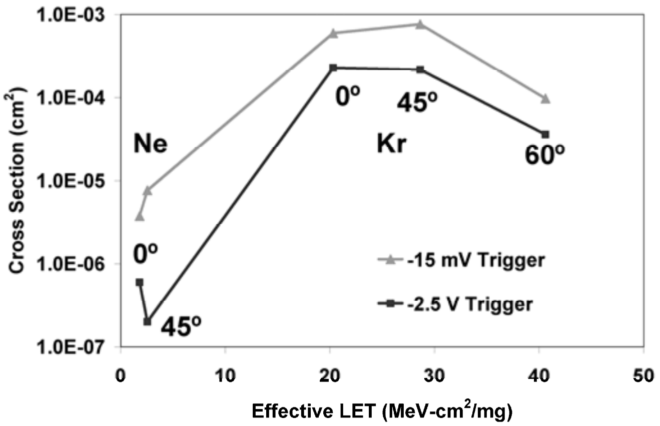

Fig. 4 SET cross section vs. effective LET at Vcc=5 V and Vin=50 mV for DUT 1, using different trigger levels. The data points are labeled with the ion and beam incident angle used.

B. Impact of Ion Beam Angles

Fig. 4 is a plot of the SET cross section vs. LETeff for Vcc=5 V and Vin = 50 mV for the -15 mV and -2.5 V trigger levels. For the 2.5 V trigger level, anomalies can be seen where the cross section can be lower as the LETeff increases. The cases where the cross section is lower with LETeff are where an incident beam angle other than 0º was used to achieve a higher LETeff. It has been postulated that carriers generated by an ion strike as deep as 30 to 100 μm can be collected at the surface of the die and that ion strikes that deep may be required to cause an SET at lower LETs, in the range of 1 to 2 MeV-cm^2/mg [12]. The minimum width of an epi tub on the LM139AJRLQMLV is 37 μm. The maximum distance an ion could travel directly below the surface of an epi tub at a 60º angle would be 43 μm and it will be less if the ion strikes the in the middle of the epi tub. These shorter distances of ion travel below the epi tub surface may not be enough to generate enough carriers to cause an SET. This indicates that it is not valid to simply use beam angles to calculate LETeff for a traditional bipolar product. If the sensitive depth is less than the width of the epi tub, it is possible to fit the data, or make corrections to the LETeff. If the sensitive depth is greater than the epi tub width, as may be the case for the LM139 for some of the epi tubs, LETeff is no longer a useful concept [13]. For SET rate predictions, the geometry of the sensitive volume needs to be taken into consideration.

C. Impact of Input Voltage

The SET threshold LET (LETth) is the lowest LET where an SET is seen. It has been reported that for the older version of the LM139, before the die shrink, the LETth is highly dependent upon the difference in the input voltages (ΔVin), with a larger ΔVin resulting in a higher LETth. With Vcc at 13 V, and a ΔVin of 0.91 V, SETs were seen at an LET of 6 MeV-cm^2/mg, while with a ΔVin of 1.17 V, the LETth was somewhere between 14 and 30 MeV-cm^2/mg [14]. It was further shown that for an LM139 produced in the Texas wafer fab, using the shrunk die layout, the ΔVin did not have as much of an effect on LETth with LETth being below 6 MeV-cm^2/mg for ΔVin up to 2.5 V [15]. The heavy ion testing in these studies was conducted at the Lawrence Berkeley National Laboratory 88" cyclotron, using the 4.5 MeV/nucleon beam. For this beam energy, the ion penetration is between 41 to 67 µm into the silicon [16]. Some of the lack of SET sensitivity perceived may be due to the reduced beam penetration. However, since in real applications, ion strikes will occur at multiple angles, these are important phenomena to consider.

The LM139AJRLQMLV SET cross sections vs. LET at the different Vcc and Vin settings are plotted in Fig. 5 for the ion runs at 0° incident angle. It can be seen at the lower LET that the SET cross section does have some dependence upon Vin, while there is no difference at the higher LET.

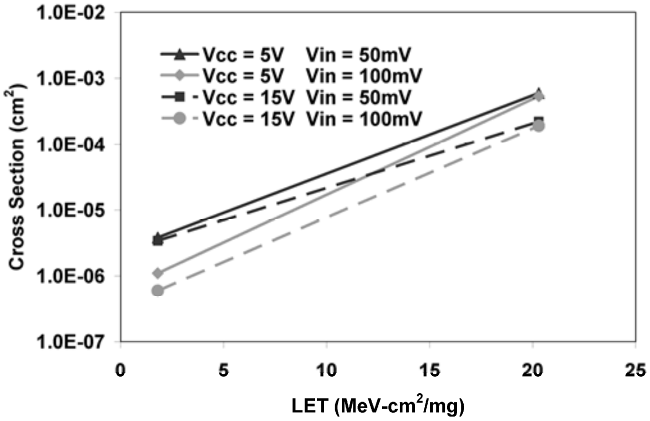

Fig. 5 SET cross section vs. LET for DUT 1 for all conditions at 0° beam incident angle. Trigger level is ±15 mV.

D. *Impact of SupplyVoltage*

For the LM139AJRLQMLV, at 20.3 MeV-cm^2/mg, the SET cross section with Vcc=5V is about two times greater than that with Vcc=15 V (Fig 5 and Table II).

E. *Unit to Unit Variability*

DUT 1, 2 and 3 were tested with effective LETs of 1.8 and 2.5 MeV-cm^2/mg. The SET cross sections are plotted in Fig. 6 and the SET cross section averages and standard deviations shown in Table III.

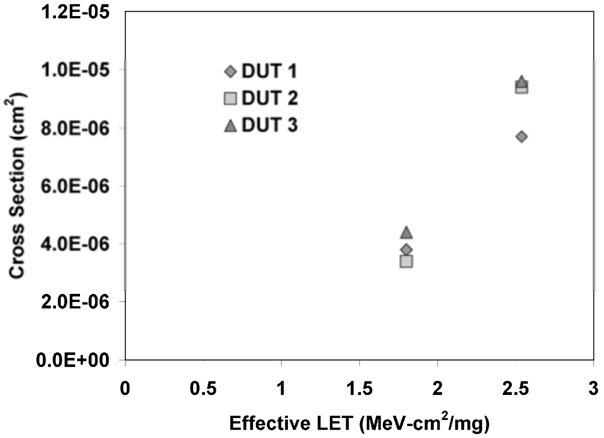

Fig. 6 SET cross section vs. effective LET for DUT 1, 2 and 3. Vcc=5 V, Vin=50 mV, trigger level=±15 mV. The cross section is plotted on a linear scale to allow the differences in the unit cross sections to be discerned.

TABLE III
AVERAGE AND STANDARD DEVIATION OF THE SET CROSS SECTION FOR LM139AJRLQMLV DUT 1, 2 AND 3 FOR THE NE ION RUNS

		SET Cross Section	
Incident Angle	LETeff (MeV-cm^2/mg)	Average (cm^2)	Standard Deviation (cm^2)
0°	1.8	3.87E-06	5.03E-07
45°	2.5	8.90E-06	1.04E-06

VI. SET SIGNATURES

Most of the SETs detected during heavy ion testing and all SETs created through pulsed laser testing had the same signatures. With the output high, the SETs are negative-going and the fall times match the switching speed of the part. For some SETs, the output will hit the bottom rail of the supply voltage and remain there before recovering (Fig. 7 and 8). The length of the transient times varied, but the maximum time seen was under 3 µs before the output would begin to recover (Fig. 7). These SET signatures are similar to those reported on other versions of the LM139 [2][4].

During the heavy ion testing some positive-going transients were detected. These were less than 1% of the total number of transients recorded, were less than 0.5 V in amplitude and lasted less than 40 ns (Fig. 8).

A. *Impact of Output Pull-Up Resistor*

As reported by others, the SET recovery of an LM139 is dependent upon the output pull-up resistor [2][17]. In Fig. 8, the recovery times for the heavy ion and the pulsed laser testing are different because different output pull-up resistors were used during the testing. Fig. 9 shows pulsed laser testing on the LM139AJRLQMLV using different output pull-up resistors.

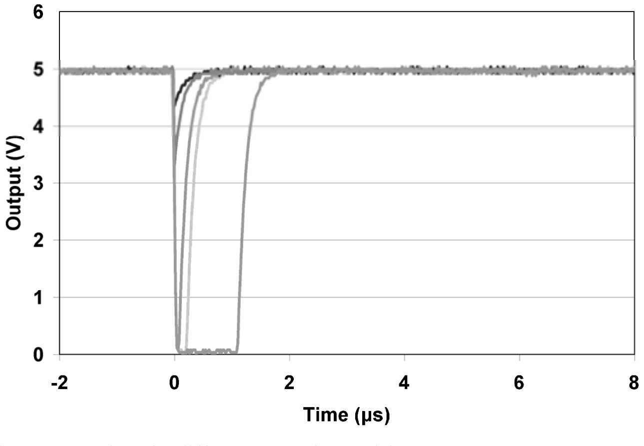

Fig. 7 Examples of 5 different SETs detected for LM139AJRLQMLV DUT 1 during heavy ion testing. Vcc=5 V, Vin=50 mV.

B. *Impact of Input Voltage*

Pulsed laser testing was used to study the impact of input voltage on SET pulse width. As the input voltage increased, the SET pulse width decreased (Fig. 10) until no transients were observed when the input voltage was set to 2 V. Only the input transistor was probed during the pulsed laser testing. If other areas of the circuit were probed, other sensitivities might be seen.

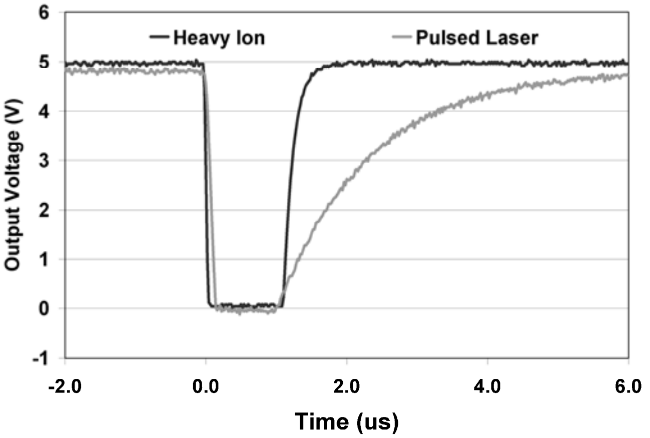

Fig. 8 Examples of SETs from heavy ion testing on DUT 1 and pulsed laser testing on DUT 4. The recovery times are different because different output pull-up resistors were used for the two different methods.

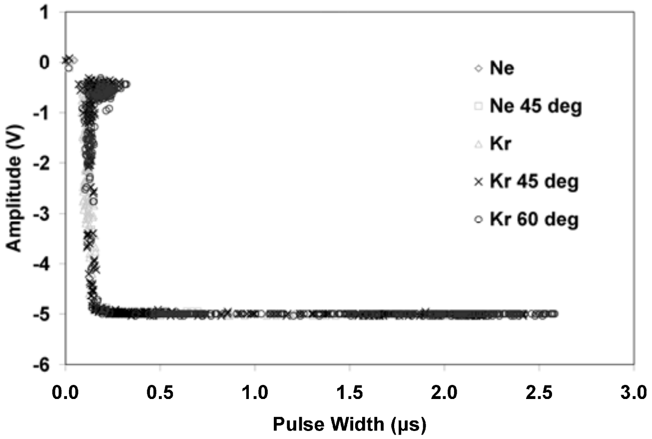

Fig. 9 SET amplitude vs. pulse width for all ion runs on DUT 1 with Vcc=5 V and Vcc=50m V. Trigger limits were set at ±15 mV around the nominal output.

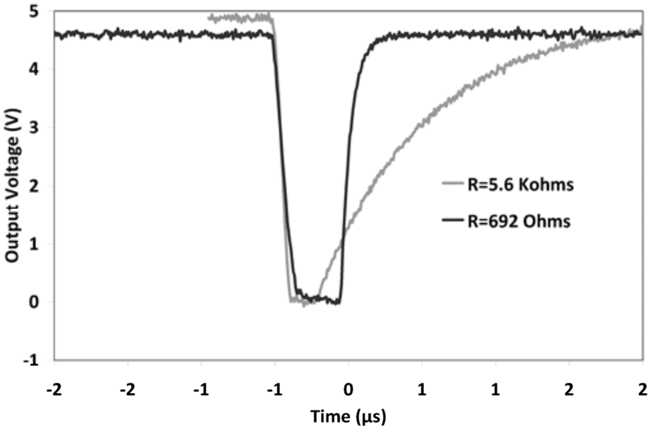

Fig. 10 SETs for different values of output pull-up resistors. This is from pulsed laser testing on DUT 4 with Vcc=5 V and Vin = 50 mV.

C. *Impact of Supply Voltage*

The supply voltage had very little impact on the SET pulse amplitudes and widths under pulsed laser testing. With the output connected to a 5 V supply through a 5.6 kΩ pull-up resistor and Vin at 50 mV, the SET pulses are almost identical with Vcc at 5 and 25 V. With Vin at 1 V, the amplitude of the SET is a 0.5 V larger with Vcc at 5 V than at 25 V (Fig. 12).

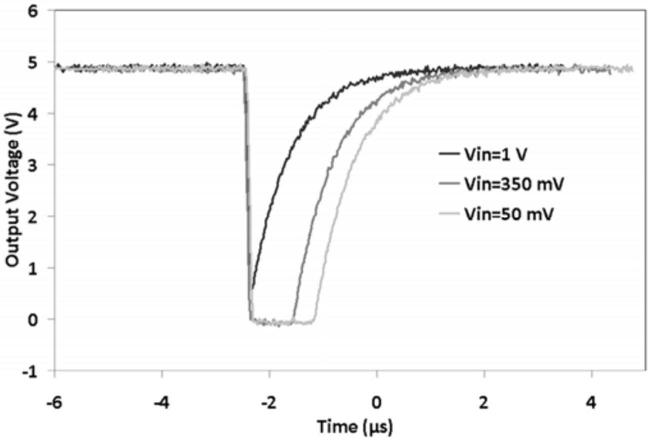

Fig. 11 SETs for different input voltages. This is from pulsed laser testing on DUT 4 with Vcc=5 V.

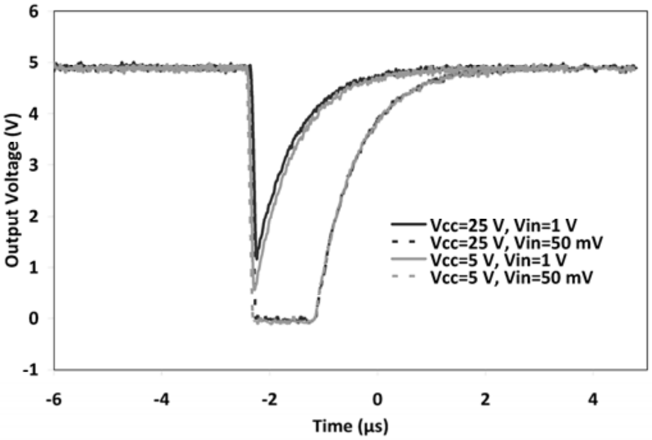

Fig. 12 SETs for different supply voltages. This is from pulsed laser testing on DUT 4 with the output pin pulled up to 5V through a 5.6 kΩ resistor.

D. *Comparison to Old LM139 before Die Shrink*

The pulsed laser induced SET pulses for the ELDRS-free LM139AJRLQMLV (DUT 4) were compared to those from DUT 5, an "old" version of the LM139 (Fig. 13). DUT 5 was processed through the wafer fab before 2000 and it does not have the die shrink. With Vin at 50 mV the two parts behaved the same. When Vin was increased to 350 mV, the SET amplitude and width for DUT 5 was less than that for DUT4. With Vin at 2 V, no transients were seen on either part. These data confirm that, as previously reported [15], a major change in die layout, such as a die shrink that reduces the surface area of an epi tub, can impact the SET response. The pulsed laser is an effective tool for determining the impact of an epi tub shrink under different operating conditions. It does not give an indication of what impact the die shrink would have on the SET cross sections, since only one area of the circuit was probed, the depth (1/e) of the pulsed laser into the silicon was only 2 µm and does not comprehend the overall impact of the different die sizes. The 25% larger die size of the old part would be expected to have a similar impact on SET cross section.

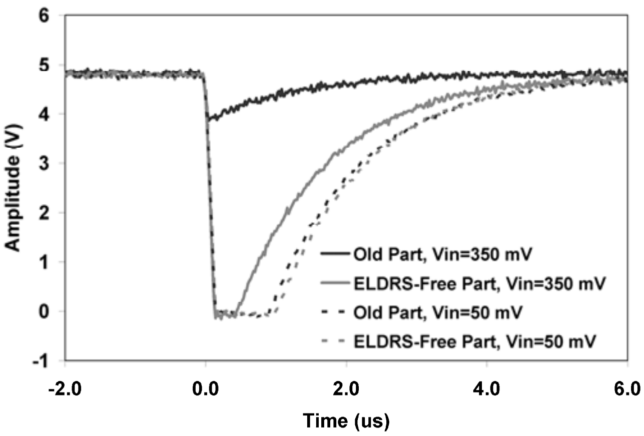

Fig. 13 SETs for different versions of the LM139 from pulsed laser testing of the input transistor. The "Old Part" is DUT 5 which is an LM139AJ manufactured before 2000 and that does not have the die shrink. The ELDRS-free part is DUT 4, an LM139AJRLQMLV. Vcc=5 V.

VII. Conclusion and Additional Testing

The SET response of the LM139 is dependent upon many factors, including test facility, operating condition, and product version and revision.

Because the sensitive area resulting in an SET extends deep into the silicon, test conditions such as beam penetration and beam angle must be carefully considered. Beam energies with relatively shallow beam penetration, and beam incident angles other than 0° can result in a lower SET cross section being determined. Using beam angles for effective LET may not be valid for a classic bipolar product such as the LM139. However, testing at a 0^o incident angle may result in an overly conservative cross section, since in a space application, ion strikes can happen at any angle. The geometry of the sensitive volume should be taken into consideration for SET rate predictions.

Operating conditions such as input voltage and supply voltage can impact the SET amplitude, pulse width and cross section.

The die used in one product version or revision can be significantly different from that used in another product version or revision. In the case of the LM139, the product went through a die shrink after the majority of SET testing was done [2]-[4], [11]-[14], [17]. The different die revisions have been shown to have some differences in SET sensitivities and those sensitivities can vary with operating conditions. The die shrink, resulting in a smaller die area, should see a similar reduction in SET cross section. However, some of that may be offset by a higher sensitivity of some of the cells.

All of the individual variables that affect SET response can have complex interactions that further complicate trying to predict or model SET response. It is not possible to directly compare the results of much of the testing that was done as different test conditions have been used. To fully understand how the product will perform in a system, it would be necessary to test the product under the operating conditions of that system.

VIII. References

[1] S. Buchner, D. McMorrow, "Single Event Transients in Linear Integrated Circuits", *2005 IEEE Nuclear and Space Radiation Effects Conference Short Course*, Seattle Wa, June 11, 2005

[2] S. D. LaLumondiere, R. Koga, P. Yu, M. C. Maher, S. C. Moss, "Laser-induced and heavy ion-induced single-event transient sensitivity measurements on 139-type comparators", *IEEE Trans. Nucl. Sci*., vol. 49, no. 6, pp. 3121-3128, Dec. 2002

[3] R. Koga, S. H. Crain, K. B. Crawford, S. C. Moss, S. D. LaLumondeire, J. W. Howard, Jr., "Single event transient (SET) sensitivity of radiation hardened and COTS voltage comparators", *2005 IEEE Radiation Effects Data Workshop Record*, pp. 53-60

[4] D. K. Nichols, J. R. Coss, T. F. Miyahira, H. R. Schwartz, "Heavy ion and proton induced single event transients in comparators", *IEEE Trans. Nucl. Sci.*, Vol. 43, No. 6. pp. 2960-2967, Dec. 1996

[5] MIL-PRF-38535 Integrated Circuits (Microcircuits) Manufacturing, General Specification for, Department of Defense, Defense Supply Center Columbus, Columbus, OH, Mar 16, 2007 http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-PRF-38535/prf38535.pdf

[6] "LM139A/LM139QML Low Power Low Offset Voltage Quad Comparators", National Semiconductor, Apr. 2, 2008, http://www.national.com/ds/LM/LM139A.pdf

[7] "Standard Microcircuit Drawing 5962-96738 Microcircuit, Linear, Radiation Hardened, Quad Voltage Comparator Silicon", Defense Supply Center Columbus, Columbus, OH 43128, Nov. 6, 2008

[8] K. Kruckmeyer, L. McGee, B. Brown, D. Hughart, "Low dose rate test results of National Semiconductor's ELDRS-free amplifier LM124 and comparators LM139 and LM193", *2008 IEEE Radiation Effects Data Workshop Record*, pp. 110-117

[9] Radiation Effects Facility, The Cyclotron Institute, Texas A&M University, http://cyclotron.tamu.edu/ref/

[10] J. S. Melinger, S. Buchner, D. McMorrow, W. J. Stapor, T. R. Weatherford, A. B. Campbell, H. Eisen, "Critical evaluation of the pulsed laser method for single event effects testing and fundamental studies", *IEEE Trans. Nucl. Sci.*, vol. 41, no. 6, pp 2574-2584, Dec. 1994

[11] S. Buchner, J. Howard, Jr., C. Poivey, D. McMorrow, R. Pease, "Pulsed-laser testing methodology for single event transients in linear devices", *IEEE Trans. Nucl. Sci.*, vol. 31, no. 6, pp 3716-3722, Dec. 2004

[12] R. L. Pease, A. Sternberg, L. Massengill, R. Schrimpf, S. Buchner, M. Savage, J. Titus, T. Turflinger, "Critical charge for single-event transients (SETs) in bipolar linear integrated circuits", *IEEE Trans. Nucl. Sci.*, vol. 48, no. 6, pp 1966-1972, Dec. 2001

[13] E. L. Petersen, "Single-event data analysis", *IEEE Trans. Nucl. Sci.*, no. 55, vol. 6, pp 2819-2841, Dec. 2008

[14] R. Koga, S. H. Crawford, W. R. Crain, S. C. Moss, S. D. Pinkerton, S. D. LaLunondiere, M. C. Maher, "Single event upset (SEU) sensitivity dependence of linear integrated circuits (ICs) on bias conditions", *IEEE Trans. Nucl. Sci*, vol. 44, no. 6, pp 2325-2332, Dec. 1997

[15] R. Koga, S. Crain, S. George, S. LaLunondiere, K. Crawford, P. Yu, V. Tran, "Variability in measured SEE sensitivity associated with design and fabrication iterations", *2003 IEEE Radiation Effects Data Workshop Record,* pp 77-82

[16] M. B. Johnson, M. A. McMahan, M. Galloway, D. Leitner, J. R. Morel, T. L. Gimpel, B. F. Ninemire, R. Siero, R. K. Thatcher, 'Super' cocktails for heavy ion testing," *2007 IEEE Radiation Effects Data Workshop Record*, pp. 34–37

[17] C. Poivey, S. Buchner, J. Howard, K. Label, "Testing Guidelines for Single Event Transient (SET) Testing of Linear Devices", NASA NEPP and ERC, DTRA, June 30, 2003, http://radhome.gsfc.nasa.gov/radhome/papers/2003_Linear.pdf