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Analog Single Event Transient Susceptibility of an SOI Operational Amplifier for Use in Low-Temperature Radiation Environments

Jamie S. Laird[1], Leif Scheik[1], Testuo Miyahira[1], Mohammad M Mojarradi[1], Benjamin Blalock[2], Robert Greenwell[2], Gyorgy Vizkelethy[3], Philippe C Adell[1], Farokh Irom[1] and Barney Doyle[3]

Abstract— **The next generations of Martian rovers are to examine the polar regions where temperatures are extremely low and the absence of an earth-like atmosphere results in a plethora of radiation issues including Analogue Single Event Transients. To this end, a radiation-hardened, temperature compensated CMOS Silicon-On-Insulator operational amplifier was designed and fabricated using Honeywell's SOI V process. Broad beam heavy-ion tests at the University of Texas A&M were performed to ascertain the duration and severity of any SET's for low and high gain application. Ambiguity regarding the location of transient formation required the use of an ion microbeam to confirm a region of major concern in the internal bias circuitry.**

I. INTRODUCTION

For the next generation of rovers designed to explore the polar regions of Mars, the absence of an atmosphere results in some radiation issues at ground level although the lack of a magnetic belt does reduce issues related to total ionizing dose (TID). High-energy heavy ions can still lead to Single Event Effects (SEE) such as analog transients, which if occurring in a critical component such as an Operation Amplifiers (OA) being used as an encoders for Rover arm positioning, can have potentially disastrous results. Furthermore, the use of an OA as an optical encoder providing feedback on mechanical positioning close to the external body may also require reliability at low-temperatures. Generally speaking, Silicon On Insulator (SOI) technologies are known to be both (a) reliable at low-temperatures and (b) have greatly reduced device susceptibility to SEE by simply truncating charge collection with an insulating oxide layer just below the active Si region. SOI has been shown to be vastly superior to bulk and epilayer structures. Furthermore, isolation of device wells all but removes any lateral parasitic paths largely eliminating Single Event Latchup (SEL). However, high LET ions can still result in Analog Single Event Transients (SET) which lead to a plethora of problems for microelectronics used in space exploration [1]. Indeed. previous studies in linear technologies amplifiers (OA) [2-5] and comparators [6] have shown them to be particularly susceptible to Analog SET. Limiting charge collection leading to voltage disturbance on internal transistors can aid in reducing SET amplitudes.

[1] Jet Propulsion Laboratory, California Institute of Technology. Pasadena, CA 91109, US
[2] Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, Tennessee 37996-2100
[3]Sandia National Laboratories (SNL), Albuquque, New Mexico USA

In this work, broad beam and microbeam based Single Event Transient (SET) tests were performed on a Quad Operational Amplifier (OA) designed for the Mars mission by Blalock and Greenwell et al. from the University of Tennessee [7] and fabricated by Honeywell using the 0.35μm SOI RICMOS V process [8]. Two types of devices were fabricated; (a) a SLOW part with CrSiN thin-film resistors in place and (b) a FAST part where these resistors had been removed from the circuit using a Focused Ion Beam. Spice simulations on an earlier design of the device concluded that several stages of the amplifier were likely to be extremely sensitive to SET with voltage swings as high as the supply rail. This triggered the need for laboratory confirmation on the newer design.

Broad beam high-energy heavy-ion tests were performed with the cyclotron at Texas A&M University (TAMU) for a range of ions with varying Linear Energy Transfer (LET). Transient signatures collected there appeared to suggest a complex interaction involving a struck region initiating a response at other points in the circuit. Attempts were made to locate regions of sensitivity using a focused laser beam. An apparent electromagnetic (EM) shield proved difficult to remove and laser tests were abandoned. The Time-Resolved Ion Beam Induced Current (TRIBIC) [9] system on the heavy-ion microbeam at the Sandia National Laboratory (SNL) proved extremely useful in locating and confirming specific regions primarily responsible for the bulk of the cross-section observed with a broad beam.

II. EXPERIMENTAL

A. Device Structure and Fabrication

The SOI QOA can be segregated into two basic regions; bias circuitry and current reference which is common to all quad OA's as well as the amplifiers themselves as shown in Figure 1. According to the manufacturer, the device has 4-layers of metallization over an active Si layer of approximately 0.2μm [8]. A 0.4μm thick SOI BOX resides below this region. An optical shield of a patterned Al alloy (used to meet metal fill density requirements) covered the entire active region, over which a passivation layer exists. Secondary Electron Microscopy (SEM) based EDS analyses confirmed a top SiN_x passivation layer of approximately 2μm. Attempts to remove the optical shield for laser testing using Reactive Ion Etching proved too difficult. SET position dependence information required the use of a MeV ion microbeam as already indicated.

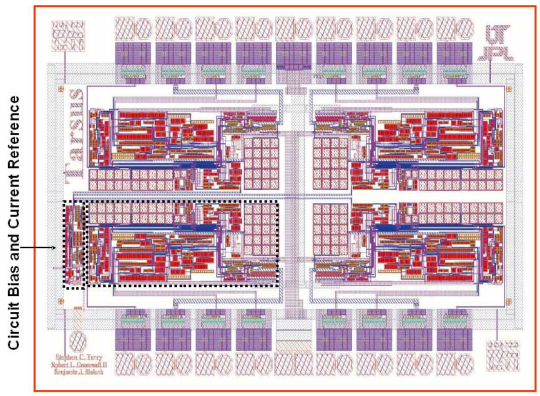

Figure 1: Overall layout the OA under test indicating both the circuit bias and current reference region and the remaining area for a single OA in the bottom left of the figure.

B. Device Configuration for Testing

For all tests, V_{cc} was clamped at +5V and V_{ss} was grounded. The two circuit applications tested for the slow and fast device are shown in Figure 2. Configuration (U1A) corresponds to a unity gain (UG) amplifier in which the single input V_1 was adjusted (0.0, 1.0, 2,5) and SET data collected. Configuration (U1B) corresponds to the “comparator” like circuit in which the input differential $\Delta V=V_1-V_2$ was maintained at a constant 0.1V and its DC offset varied (1.0, 1.1 to 2.5, 2.6). For broad beams tests both configurations were tested on the SLOW and FAST device. A buffer circuit (gain of 1/2) on the test board isolates the response of the DUT and drives the length of cable required to pass the signal from the beam line into the 50Ω load of the digital storage oscilloscope (DSO) (a TDS784 1GHz BW). The buffer supply was ±12V to ensure output transients remained in the linear regime. The buffer bandwidth was also considerably higher than that of the DUT. The effect of OA load on the SET could be adjusted by a relay for including an additional pre-buffer load of 680Ω. Due to the signals being quite small, the DSO was AC coupled (1MΩ input impedance) to remove any DC offset. A trigger level, typically ±5mV was set to collect transients above or below a threshold set just above background noise. Together with the applied fluence an SET trigger-level dependent cross-section and its LET dependence can be assessed. For microbeam tests only the U1A configuration was examined on the SLOW part since it proved to have the largest SET sensitivity in broad beam measurements. For this reason only UG results on the high-speed device will be shown here. Furthermore, only a small subset of these results will be displayed; those pertinent to a comparison of broad and microbeam data.

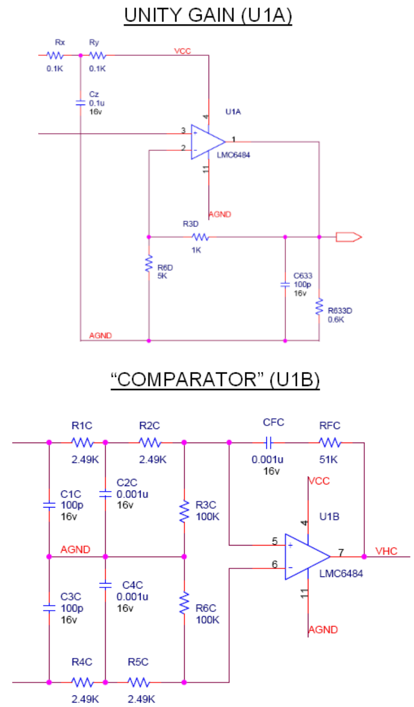

Figure 2: The block diagram of the test circuit configurations UA1 and UB1. The buffer circuit for driving a higher impedance load is not shown.

C. Broad Beam Heavy Ion Tests

Prior to heavy-ion testing, devices were mounted onto daughter board representations of both the U1A and U1B configuration and preliminary in-house system checks were performed. Laser, flash-lamp and alpha particle irradiation using a ^{241}Am source all failed to induce an SET response for all nodes in the test matrix i.e. with and without load for all bias configurations. Attenuation in the SiN_x passivation layer and an optical shield were deemed responsible i.e. the ion end-of-range and absorption length are too short. SET measurements could be made with a ^{256}Cf source to check board functionality. Broad beam tests were performed in air using 2.1GeV Kr and 3.297GeV Xe with surface LETs of 19.2 and 37.9MeV/mg cm^{-2}, respectively. The respective ranges in Si are well beyond that required to pass through passivation and the SOI BOX layers. Although it is quite common in SEE testing to use long ranging ions to turn on parasitic structures or charge collection from deep in the device, here it is likely unnecessary. A comparison of the energy-loss in the near-surface region is shown in Figure 3 assuming hypothetical Al and SiO_2 thicknesses of 2μm.

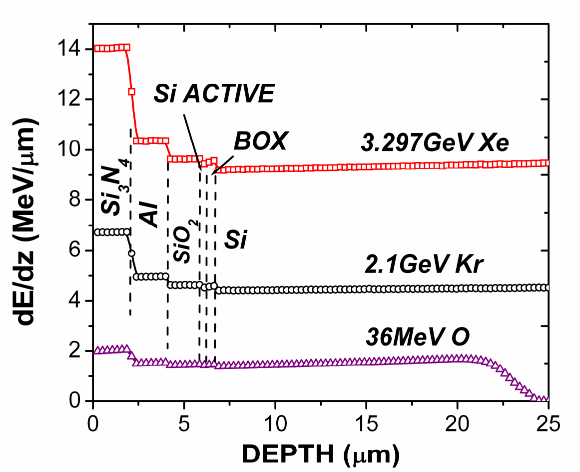

Figure 3: SRIM calculated dE/dz profiles near the surface region. Below the BOX region little charge will be collected besides that from a displacement current induced across the BOX during the ambipolar duration of charge transport in the substrate [10]. The charge initiating the SET is approximately that generated in the 0.2µm active Si

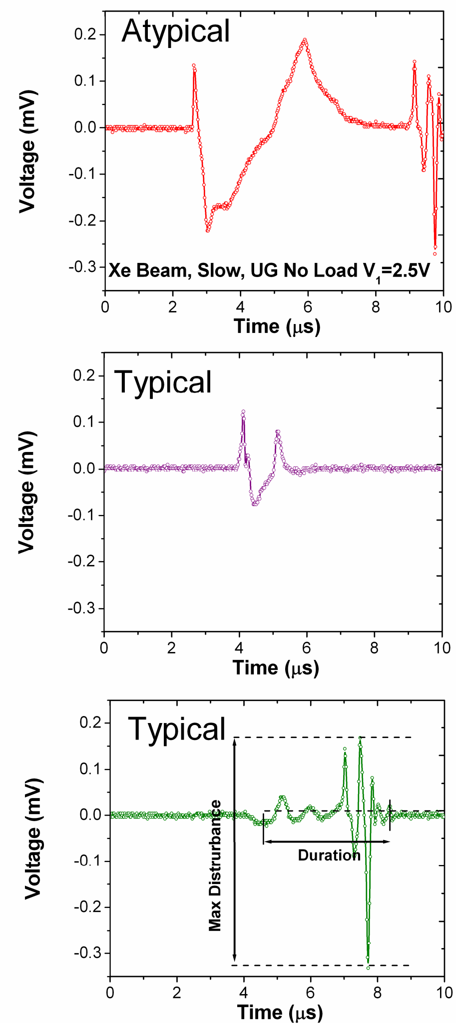

Figure 4: An example of two typical SET waveforms (bottom) and an atypical response (top) for the slow part configured as described in the UG configuration with zero load.

Also shown is the energy-loss profile for 36MeV O used for the microbeam experiments. The LET in the active Si region is about a factor of 2 higher for Xe than for Kr and almost 5 times lower than Xe for 36 MeV O. Please note that due to time constraints most TAMU time was spent on the more exotic faster part to be used in the MSL mission. The accumulated beam fluence applied over all runs was limited to reduce TID and displacement damage effects being convolved with the SET response. Typical beam fluxes ranged between 10^4-10^6 cm^{-2}/s depending on the SET cross-section in the different load and circuit configurations. After estimating an approximate cross-section for SET formation, the beam flux chosen for remaining measurements was set to minimize beam use whilst not running into dead time issues such as multiple SET pile-up. Most measurements were made in beam fluence increments of around 10^7 cm^{-2}. TID effects were monitored by looking for any change in input offset voltage, V_{io} on the SLOW part in the U1A configuration; it was 40mV before and after irradiation. The RICMOS V process is apparently hard to between 300krad and 1Mrad and TID effects are of little concern here.

Shown in Figure 4 are several typical SET's and an atypical one measured for the Xe beam on a slow part with zero load in the UG configuration. The SET signature is complex and represents the worst case of all configurations examined and therefore the most troublesome for mission assurance. Due to the statistical nature of the struck position, histograms are typically generated showing SET characteristics for various input voltages and loads as shown in Figure 5 for the same case of Xe. Since the slower DUT is noticeably more sensitive than its faster counterpart, this part was chosen for microbeam investigation.

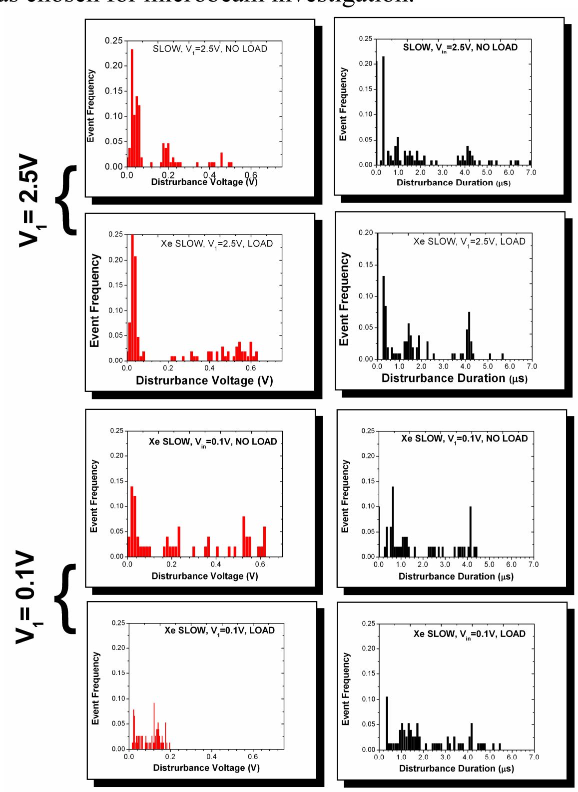

Figure 5: Comparison of the SET histograms for the case of Xe irradiation on the "slow" part configured for U1A with an input bias V_1 of 2.5V (top) and 0.1V (bottom), with and without the additional serial load of 680Ω.

D. Heavy Ion Microbeam Results

For microbeam analysis at the Sandia National Laboratories (SNL), a 36MeV O^{6+} beam was focused to about 1µm and scanned over the slow part in the UG configuration using the Time Resolved Ion Beam RIBIC system [9] and a 4GHz digital storage oscilloscope (DSO). The input bias V_1 was set at 1.0V as done in the TAMU tests. Unlike the TAMU tests however, these tests were performed under vacuum at nominal room temperature. Due to a maximum scan size of $130\times140(\mu m)^2$, the DUT was mechanically scanned to locate regions of sensitivity. The only region exhibiting an SET sensitivity above the trigger level was found in the bias circuitry. Within this region three areas were observed to trigger SETs; the main one being a $20\times20(\mu m)^2$ region comprising 4 smaller strips marked R1 shown in Figure 6. Smaller regions were also observed above and below R2 (not shown here) with considerably small cross-sections. The total cross-section including the two smaller strips was ~$6\times10^{-6}cm^{-2}$ which is the same order of magnitude as that estimated from broad beam runs. The exact location could be correlated with the gerber file of the device die by noting key fiducial markings on the die; primarily distinctive metallization strips. Note that the microbeam stage was not automatically controlled to completely ensure 100% ion coverage of the complete die quadrant and the possibility exists that some regions were not identified. However, the cross-sections calculated using the TAMU results approximately agree with the actual sensitive area mapped using the microbeam (~ $5\times10^{-6}cm^{-2}$). Typical SETs measured in R1 and R2 are shown in Figure 7 for a negative trigger level. The trigger condition was set to capture the larger negative transient, which interestingly has the same form in both R1 and R2 with some delay separating the two.

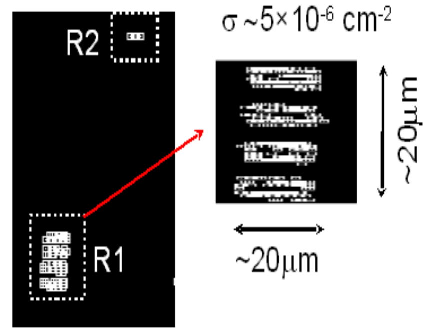

Figure 6: Microbeam bitmap image of the region exhibiting by far the highest cross-section across the die. Shown on the right hand is a zoomed region of R1 indicating 4 narrow strips comprising the bulk of the SET cross-section.

III. Discussion

Although not shown here, difference in SET amplitudes measured with Kr and Xe were not proportional to the energy deposited in the top active Si layer to within 20% or so. The SET signatures and estimate of cross-section estimated from the TRIBIC scans are qualitatively similar to those observed with the higher LET's at TAMU. In particular, the presence of two discernible events with an approximate separation of 4µs is common to both experiments. The additional energy deposited by the Kr (factor of 5) and Xe (factor of 3) results in the same characteristic signature in the UG configuration with an initial pulse generated by a hit to the CMOS MOSFET noted in Figure 8. Sometime later, this pulse propagates causing a more violent disturbance, the cause and location of which requires detailed circuit modeling to comprehend.

Furthermore, the difference in SET amplitudes between the (Xe, Kr) and O data of about 2-3 indicates that charge collection is being truncated close to the surface; most probably by the SOI layer. If not, the difference in amplitudes would be more considerable given the enormous energy differences. The microbeam with high LET ions but short range is therefore a reasonable means for simulating high LET ion with long ranges since range isn't really an issue. Importantly, these microbeam results indicate that SET's generated in the common bias circuitry will simultaneously affect the functionality of all quad devices, meaning the DUT cannot support multiple redundancies as a means of SET mitigation.

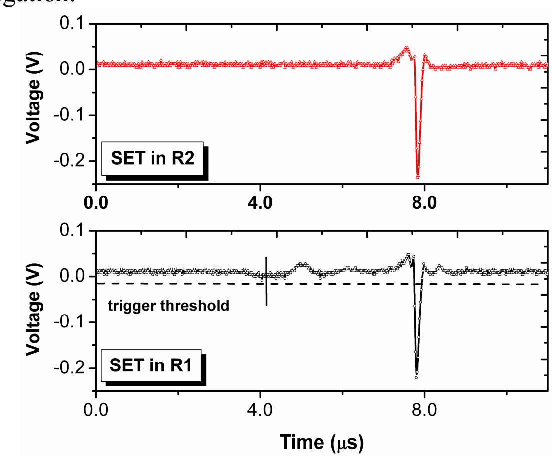

Figure 7: Representative SET in the regions R1 and R2 indicating the DSO trigger level and apparent delay between events in R1 initiating an event in R2, based on the uncanny similarities between the large spike regions.

Furthermore; no SET's at all were expected in the bias circuitry of the device. Upon investigation, engineers noted a design flaw which has since been remedied and was the subject of further microbeam investigation which indicated no SET response from the same region after repair.

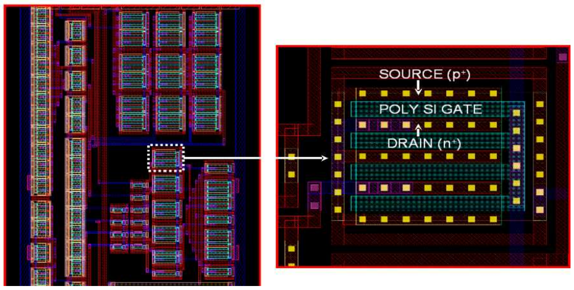

Figure 8: Circuit layout in the bias circuit/current reference region which microbeam imaging shown in Figure 6 indicates has the largest SET cross-section across the die.

In general: Operating the device with a higher bandwidth (lower gain) appears to *generally* result in higher peak ASET voltages which are relatively short in duration compared to other OA previously studied such as the LM124 [2, 3, 5, 11-13]. The unity gain U1A configuration with the widest bandwidth (gain bandwidth product is conserved) is therefore more sensitive to SET with respect to its voltage swing. Clearly the use of the SLOW op-amp in "comparator" U1B mode with a higher gain results in a much reduced SET peak disturbance. However, the disturbance can persist for up to hundreds of microseconds; typically 10-20 times that encountered for the SLOW U1A configuration. The comparator mode will experience a correspondingly smaller BW, resulting in much smaller transients over longer durations. This presumes the response to be generated in the input stage before any gain and circuit elements process the response. In fact, if transients are primarily due to strikes in the bias circuitry and current reference, as noted in the microbeam results, these may propagate onto the input stage thereby causing the relationship noted above.

IV. CONCLUSION

A heavy ion microbeam has been used to: (a) verify its ability to simulate long ranging high LET ions in SOI devices where charge collection from below the BOX limiting range effects typically important for most SEE studies such as latchup etc, and (b) locate a region of SET susceptibility in the common bias circuitry of the OA. Locating the sensitive node in the bias region confirmed certain qualms engineers had about design in that region. The SOI OA was found to be largely insensitive to SET and is predicted to perform well in the Martian environment.

V. ACKNOWLEDGEMENT

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