Single Event Transient Analysis of an SOI Operational Amplifier for Use in Low-Temperature Martian Exploration

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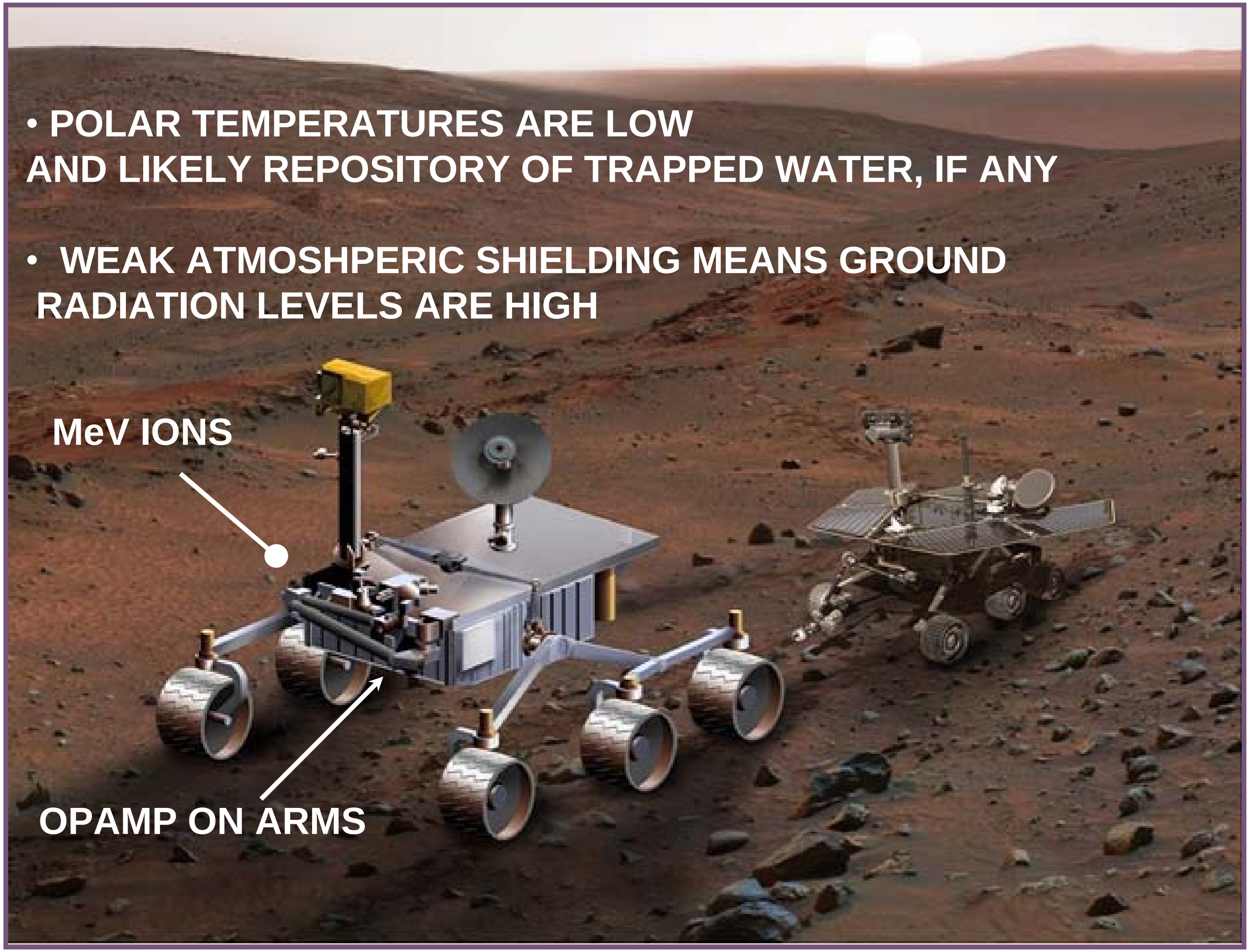
Abstract:

The next generation of Martian rover’s to be launched by JPL are to examine polar regions where temperatures are extremely low and the absence of an earth-like atmosphere results in high levels of cosmic radiation at ground level. Cosmic rays lead to a plethora of radiation effects including Single Event Transients which can severely degrade microelectronic functionality. As such, a radiation-hardened, temperature compensated CMOS Single-On-Insulator (SOI) Operational Amplifier has been designed for JPL by the University of Tennessee and fabricated by Honeywell using the SOI V process. SOI technology has been shown to be far less sensitive to transient effects than both bulk and epilayer Si. Broad beam heavy-ion tests at the University of Texas A&M using Kr and Xe beams of energy 25MeV/amu were performed to ascertain the duration and severity of the SET for the op-amp configured for a low and high gain application. However, some ambiguity regarding the location of transient formation required the use of a focused MeV ion microbeam. A 36MeV O^{6+} microbeam at the Sandia National Laboratory (SNL) was used to image and verify regions of particular concern

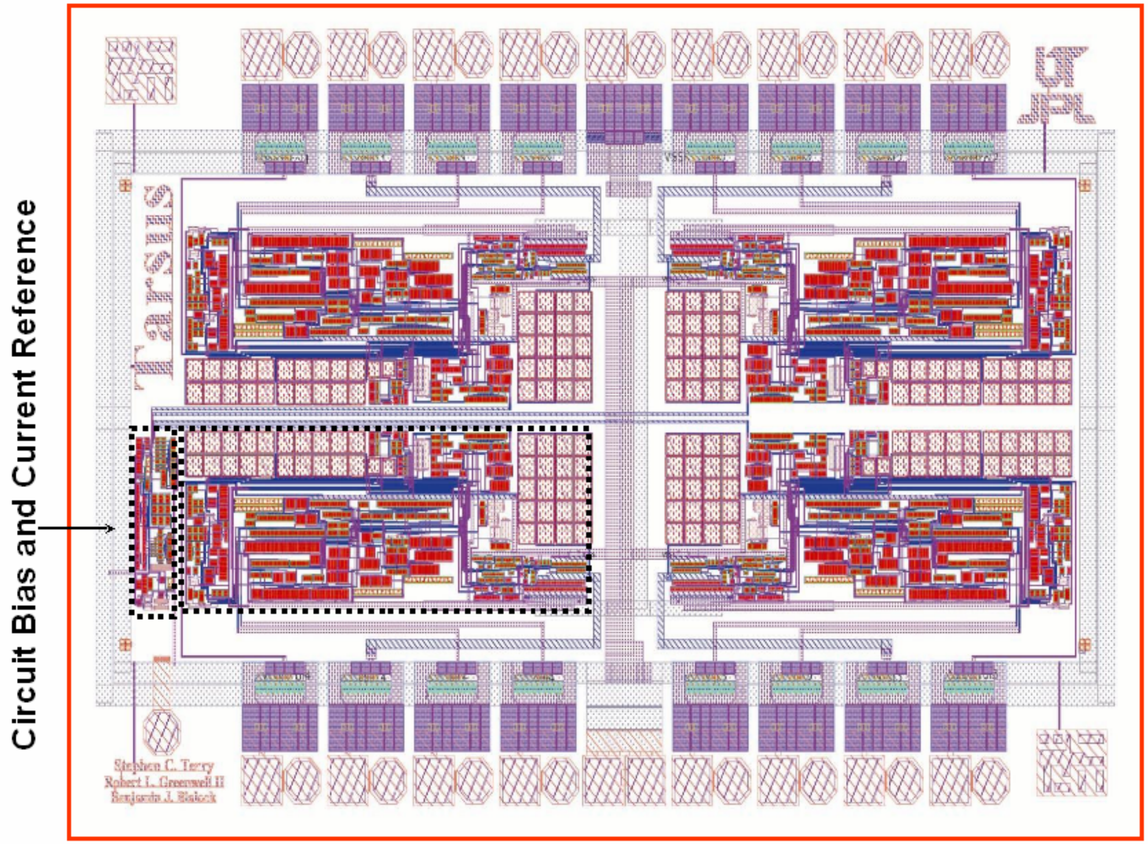
LOW-TEMPERATURE MARTIAN CLIMATE AND RADIATION HARDNESS



OPERATIONAL AMPLIFIER SUFFER FROM SINGLE EVENT TRANSIENTS (SET)

SILICON-ON-INSULATOR (SOI) QUAD OPERATIONAL AMPLIFIER

- SOI Operational Amplifier designed by the University of Tennessee to withstand the low-temperature environment and fabricated for MSL by Honeywell using the SOI RICMOS V process. The device contains 4 OA's and a common bias circuit and current reference for temperature compensation.

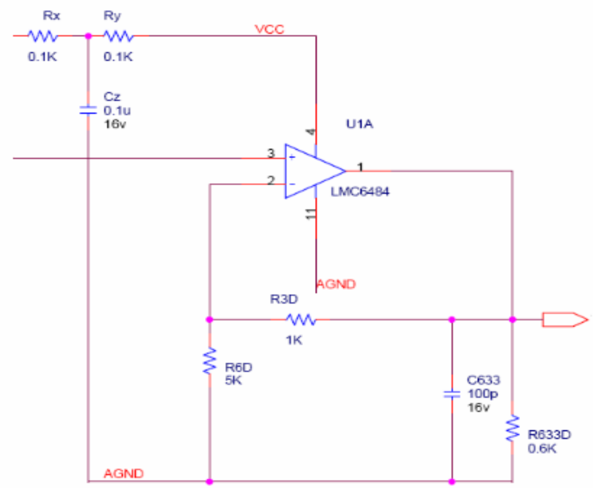


OPERATIONAL AMPLIFIER CONFIGURATION

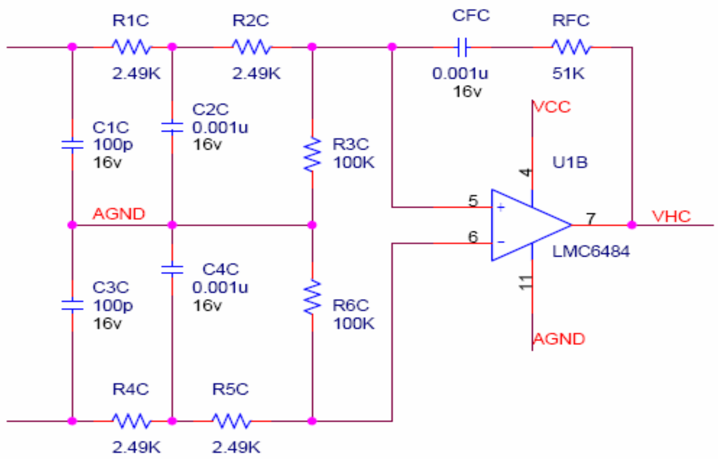
- The OA was tested in two standard configurations known as the unity gain (U1A circuit) and the comparator configuration (U1B) as shown in the schematics aside. Besides the application configuration SET sensitivity in OA's is known to also depend on the output load and input voltage (or differential in the U1B mode).

- For this work we only illustrate results taken with the U1A configuration since broad beam results indicated it to be the more sensitive of the two.

UNITY GAIN (U1A)



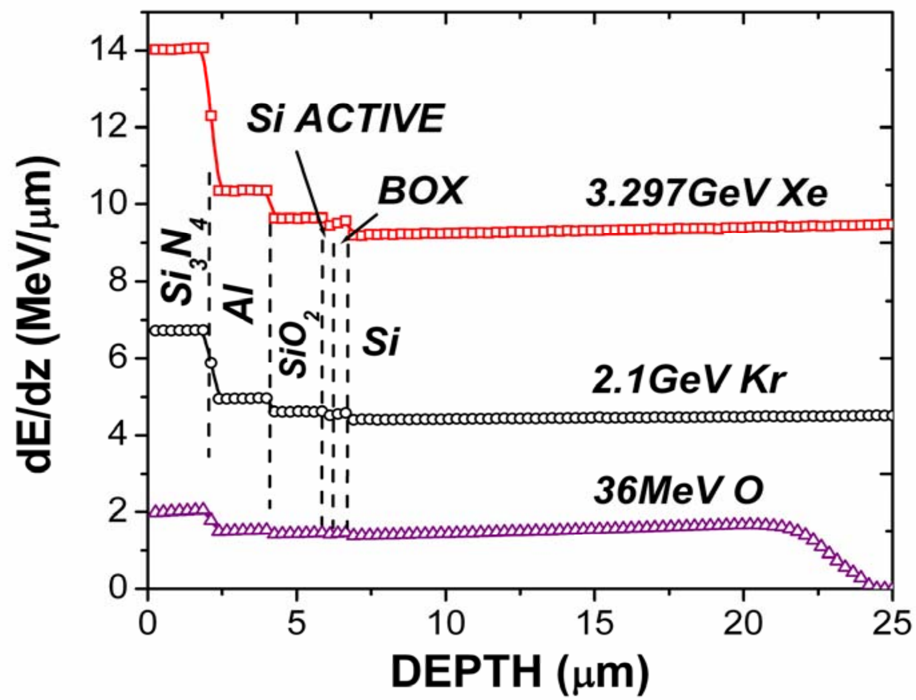
"COMPARATOR" (U1B)



OPERATIONAL AMPLIFIER CROSS-SECTION

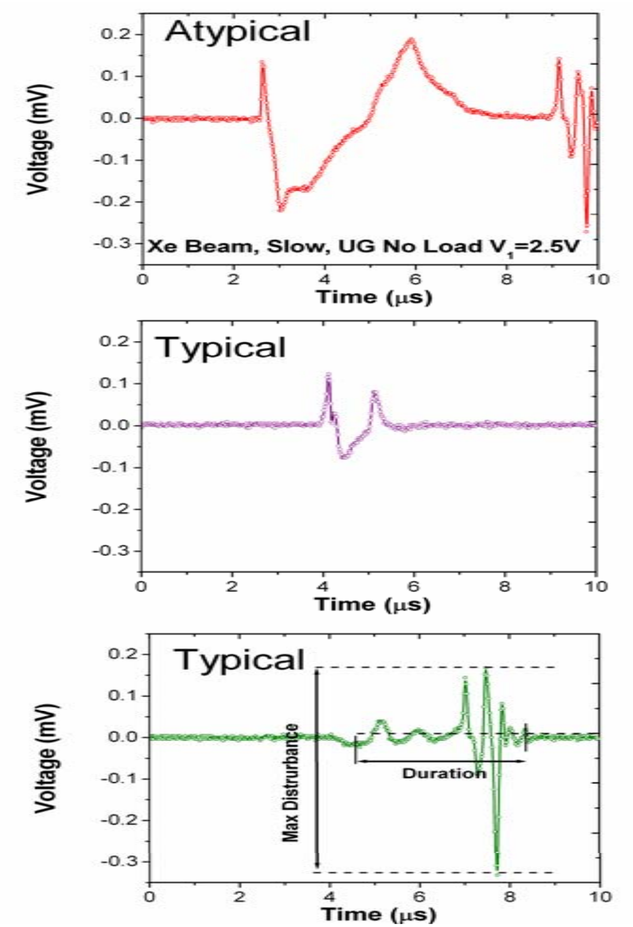
- Three ion beams were to be applied to the DUT to examine SET sensitivity in the U1A and U1B configuration. Broad beams at Texas A&M University were 2.1GeV Kr and 3.3GeV Xe. These both have high surface LET's of XXX with ranges long enough to examine any long range effects typical in latch-up etc. In this SOI device the oxide at a depth of around 5μm is likely to truncate most charge generated below it.

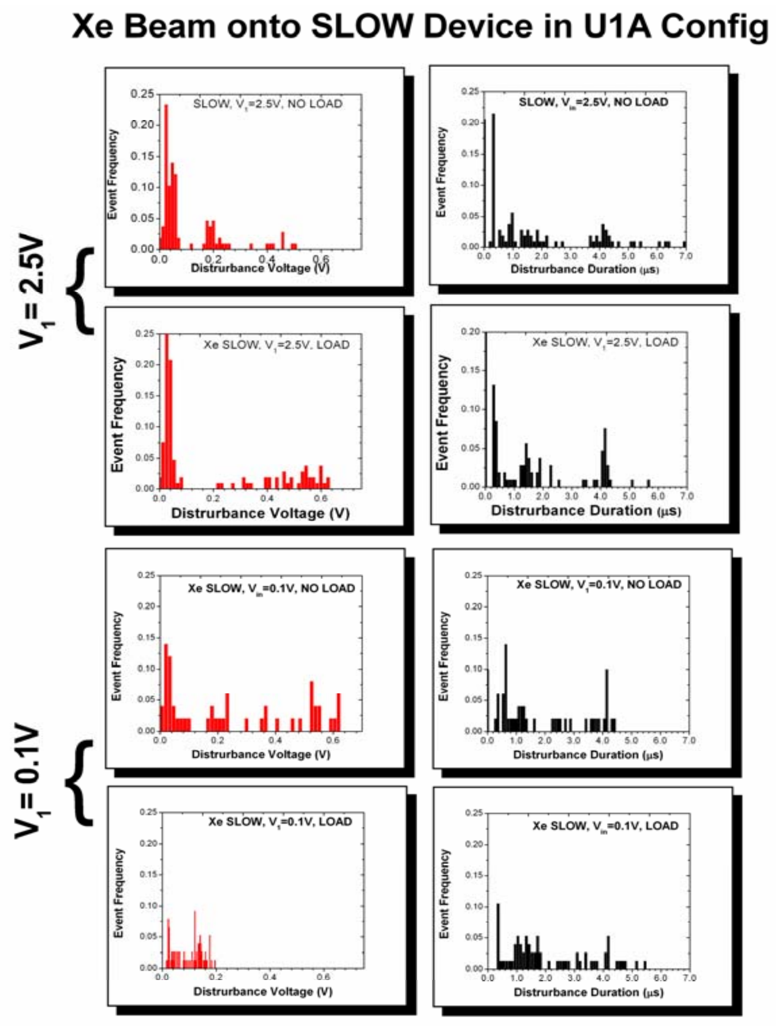
- Cross-sectional SEM and EDS gave approximate layered information which was used in SRIM to examine the ion LET (MeV/mm) in the near-surface region of the OA.



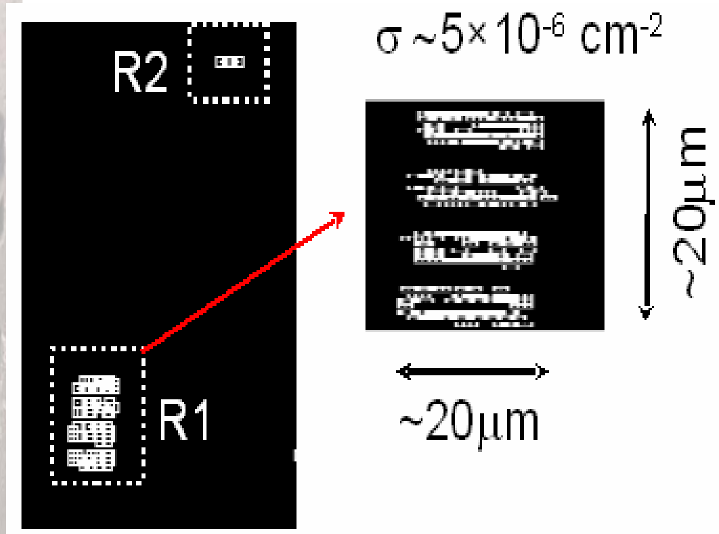
Although the range is significantly different, the surface LET for the 36MeV O beam is less than an order of magnitude smaller than that of 2.1GeV Kr and 3.297GeV Xe.

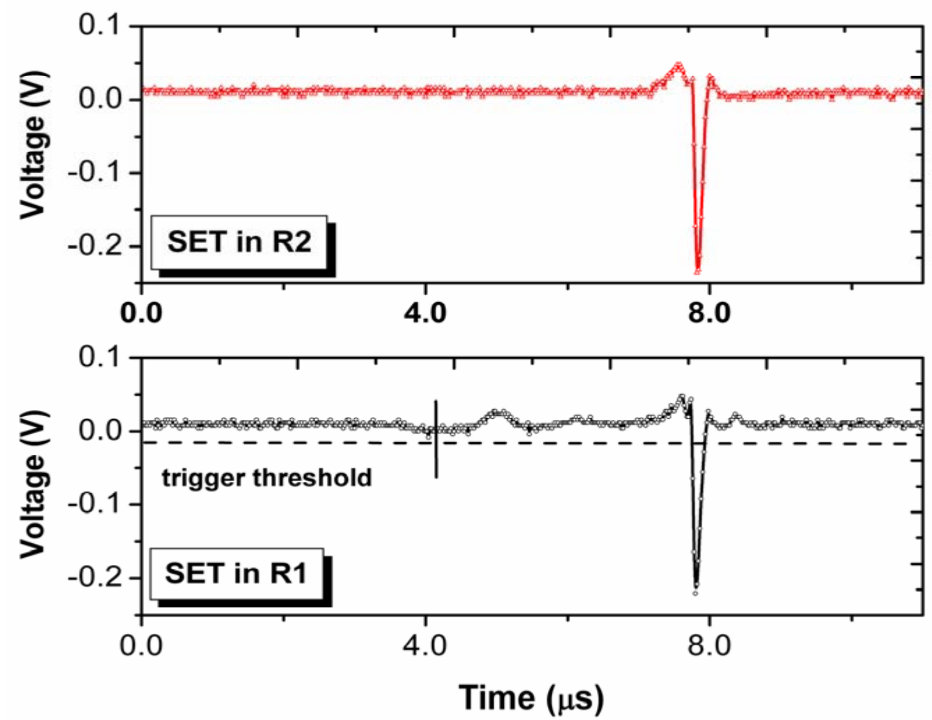
HIGH-ENERGY BROAD BEAM (CYCLOTRON) RESULTS





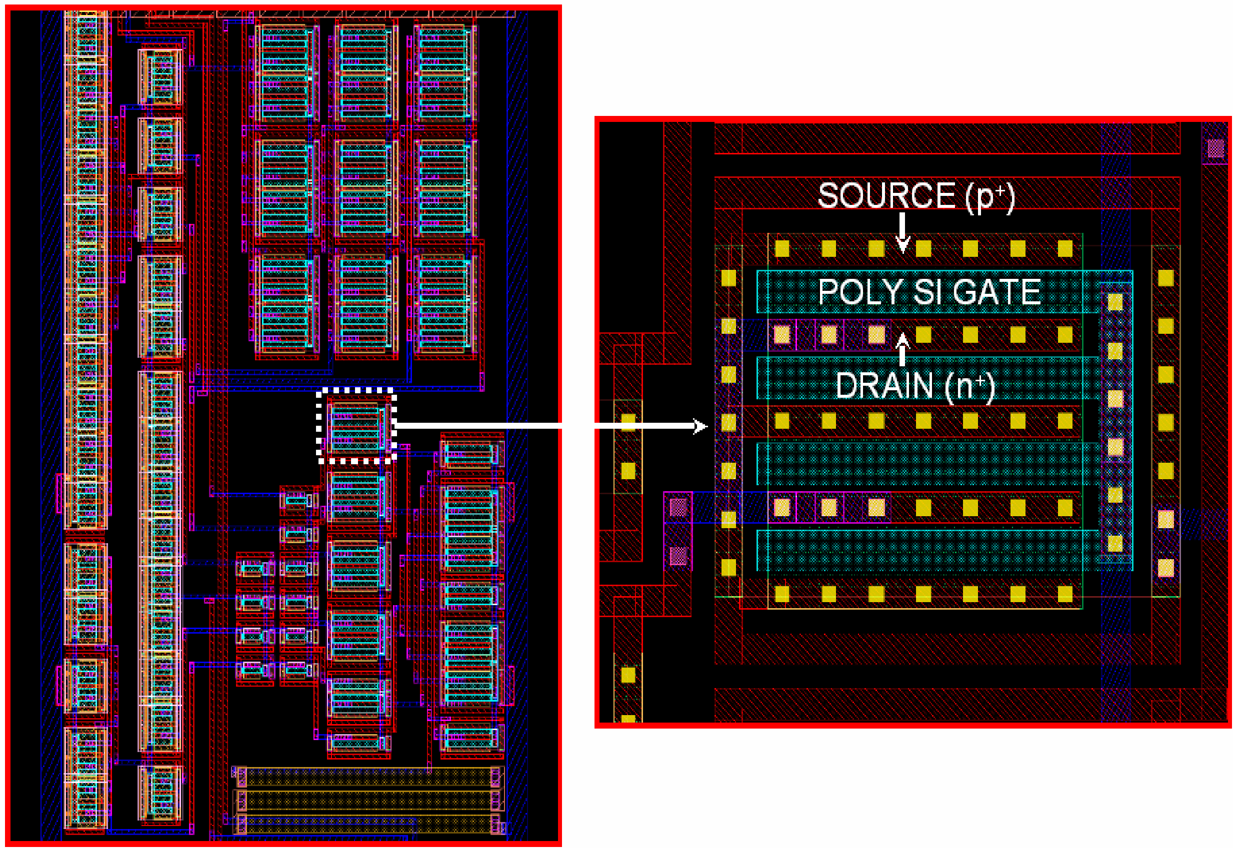
SNL HEAVY ION SINGLE EVENT TRANSIENT DATA





SNL HEAVY ION SINGLE EVENT TRANSIENT DATA

BIAS CIRCUIT/ CURRENT REFERENCE



CONCLUSION

CONCLUSION AND FUTURE MICROBEAM WORK

- SOI Operational Amplifier designed by the University of Tennessee to withstand the low-temperature environment and fabricated for MSL by Honeywell using the SOI RICMOS V process. The device contains 4 OA’s and a common bias circuit and current reference for temperature compensation.

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- ***Abstract:***
- The next generation of Martian rover's to be launched by JPL are to examine polar regions where temperatures are extremely low and the absence of an earth-like atmosphere results in high levels of cosmic radiation at ground level. Cosmic rays lead to a plethora of radiation effects including Single Event Transients which can severely degrade microelectronic functionality. As such, a radiation-hardened, temperature compensated CMOS Single-On-Insulator (SOI) Operational Amplifier has been designed for JPL by the University of Tennessee and fabricated by Honeywell using the SOI V process. SOI technology has been shown to be far less sensitive to transient effects than both bulk and epilayer Si. Broad beam heavy-ion tests at the University of Texas A&M using Kr and Xe beams of energy 25MeV/amu were performed to ascertain the duration and severity of the SET for the op-amp configured for a low and high gain application. However, some ambiguity regarding the location of transient formation required the use of a focused MeV ion microbeam. A 36MeV O6+ microbeam at the Sandia National Laboratory (SNL) was used to image and verify regions of particular concern.

- **Keywords:** Silcon On Insulator, Operational amplifier, Single Event Transient

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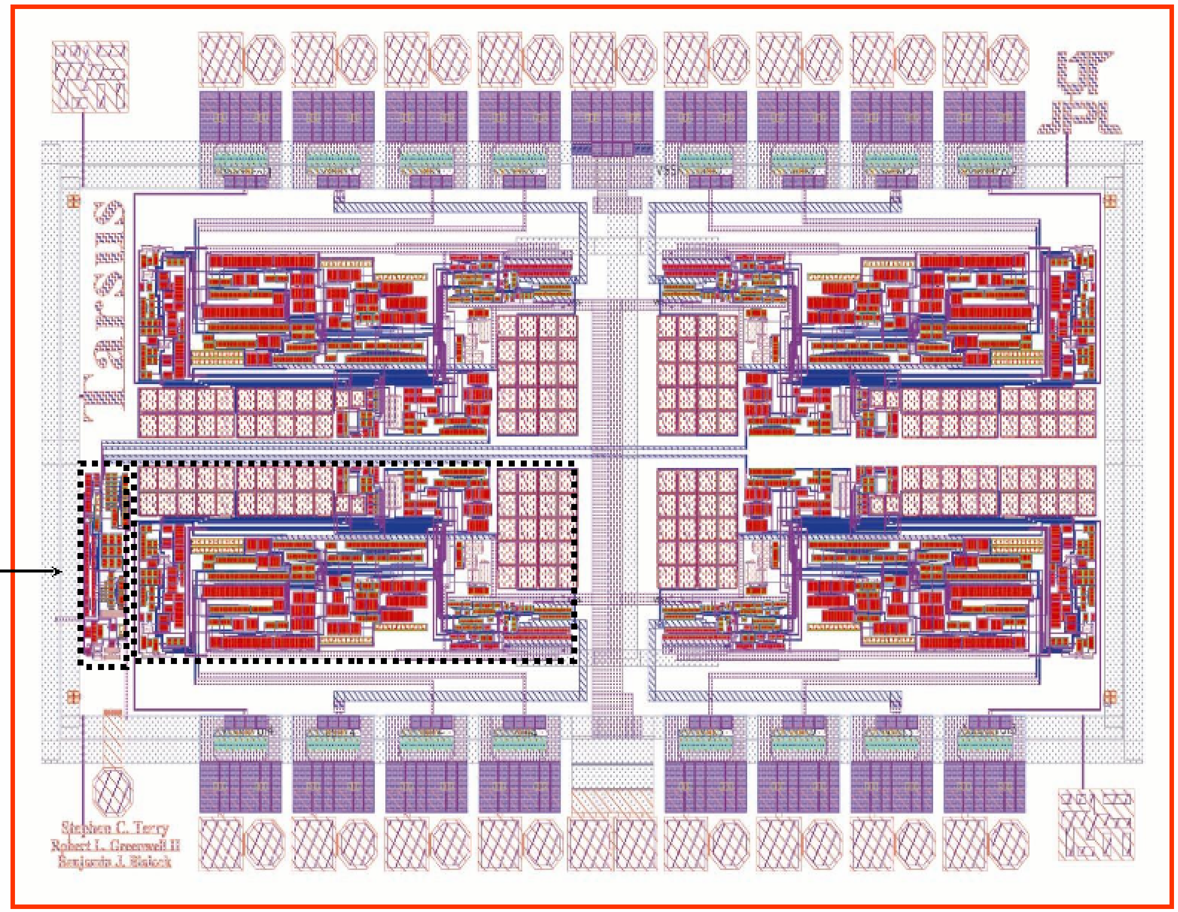
- **1. Introduction**
- Single Event Transients generated by high-energy cosmic radiation lead to a plethora of problems for microelectronics used in space exploration [1]. For the next generation of Martian rovers (MSL) to examine the polar orbits the low-temperatures and absence of an atmosphere capable of suppressing high radiation levels makes radiation issues of paramount importance. Operational amplifiers (OA) are particularly susceptible and have been well studied in the past. In recent years however, Silicon On Insulator (SOI) technology has improved the susceptibility to Single Event Effects (SEE) by simply truncating charge collection by the existence of an insulating layer just below the active Si region. SOI has been shown to be vastly superior to bulk and epilayer Si structures[jpl1] .
- In this work, broad beam and microbeam based Single Event Transient (SET) tests have been performed on a Quad Operational Amplifier (OA) chip designed for MSL by the University of Tennessee, and fabricated by Honeywell using the SOI RICMOS V process. Two types of devices were fabricated; a slower part with CrSiN thin-film resistors in place and a high-speed part where these resistors had been surgically cut using an Focused Ion Beam (FIB). Spice simulations on an earlier deisgn of the device performed at Vanderbilt University[jpl2] , concluded that several stages of the amplifier were extremely sensitive to SET with transient swings as large as the supply rail; triggering the need for laboratory confirmation on the newer design.
- Radiation testing was performed at three locations; initial tests were performed using an in-house Cf source to confirm device configuration and test board operation. Broad beam high-energy heavy-ion tests were performed at the cyclotron facility at the Texas A & M for ions with combined high Linear Energy Transfer (LET) and long range. Transient signatures collected there appeared to suggest a more complex interaction involving the struck region initiating a response further along in the circuit (this conclusion will be discussed later). Attempts were therefore made to locate regions of sensitivity using a focused laser beam. However, due to a heavy passivation layer and a metallic optical shield, removal proved difficult and laser transients could not be generated. In light of this, the best method for investigating such matters is with a focused MeV ion microbeam where specific regions can be pin-point irradiated with single ions. This final test was performed using the Time-Resolved Iob Beam Induced Current (TRIBIC)[2] system on the heavy-ion microbeam at the Sandia National Laboratory (SNL).
- [jpl1]Need a few refernces etc.
- [jpl2]Can I refer to an internal report made by ISDE for JPL.

- **2. Experimental**
- **2.1 Device Structure and Fabrication**
- The OA under question can be segregated into basic two regions; one containing the bias circuitry and current reference which is common to all quad OA’s, and the other any remaining circuitry as shown in Figure 1. According to the manufacturer, the device has 4-layers of metallization over an active Si layer of approximately 0.2mm. The SOI BOX under this region is 0.4mm thick. An optical shield of a patterned Al alloy (used to meet metal fill density requirements) covered the entire active region, over which an approximate 2mm SiNx passivation layer is grown. Secondary Electron Microscopy (SEM) based EDS analysis confirmed a top SiNx passivation layer of approximately 2mm (manufacturers statement was 0.9mm).This layer was investigated with an SEM (in EDS mode) and removed using Reactive Ion Etching (RIE) for possible laser tests. However, removal of the optical shield proved too difficult and front-side laser testing was abandoned. SET position dependence information required the use of a MeV ion microbeam as already indicated. Since the elements of high sensitivity in the ISDE report could not be correlated with position on the actual die, no comparisons between simulation and measurement, beyond commenting on general tendencies, could be made.
- **2.2 Circuit Configuration**
- For all tests, Vcc was clamped at +5V and Vss 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 V1 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 DV=V1-V2 was maintained at a constant differential of 0.1V and its DC offset varied (1.0, 1.1) and (2.5, 2.6). For broad beams tests both configurations were tested on both devices. A buffer circuit (gain of 0.5) 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 cyclotron control room and onto the low-impedance load of the digital storage oscilloscope (DSO). The effect of OA load on the SET could be adjusted by a relay which includes, or not, additional serial load of 680W prior to the buffer. 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 output of the buffer is then passed to a DSO (TDS 784 1GHz BW) and recorded for a given device condition, beam energy, and fluence. Due to the signals being quite small, the DSO was used in AC mode (1MW input impedance) to remove any DC offset from the output. In DC mode the transients cannot be viewed with any reasonable vertical resolution. A trigger level, typically ±5mV was set to collect transients above or below a threshold. 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 since this part proved to have the largest SET sensitivity in the broad beam measurements. For this reason only UG results on the high-speed device will be shown here. Furthermore, only a small subet of these results will be displayed; those pertinent to a comparison of broad and microbeam data. The full dataset will be published elsewhere [7].

- **2.3 Broad Beam Heavy Ion Tests:**
- Prior to heavy-ion tests, 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 241Am 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 SiNx passivation layer and optical shield were deemed responsible i.e both the ion end-of-range (EOR) and absorption coefficient are too short. However, SET measurements were made with a 256CCf source which emits a spectrum of alpha's particles and heavy ion fission fragments; as such it really fulfills a gross measurement.
- Broad beam heavy-ion tests were performed in air (approximately 6cm from vacuum window to DUT) with two beams both of 25MeV/amu; a 2.1GeV Kr and 3.297GeV Xe beam with a surface LET of 19.2 and 37.9MeV/gcm-2, respectively. The respective ranges in Si are well beyond that required to pass through the passivation and SOI BOX documented above. It is quite common in SEE testing to use ion LET's with long ranges due to the ability to turn on parasitic structures deep in a sample. As expected that is not the case here due to the role of the BOX. One additional test using a beam degrader on the Kr beam gave an additional LET point, at the expense of some additional energy straggle. A comparison of the energy-loss in the near-surface region is shown in Figure 3 assuming hypothetical Al and SiO2 thicknesses of 2mm. 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 consecutive runs was limited to reduce total-dose and displacement damage effects being convolved with the SET response. Typical beam fluxes ranged between 104 to 106 cm-2/s depending on the effective cross-section of the DUT 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 107 cm-2. According to a report issued by the Arizona State University on total doses effects in this part, the input offset voltage, defined as the output offset when both inputs are tied to ground, provides a reasonable measure of total does effects. The voltage *Vio* was measured on the slow part in the U1A configuration to be the same 40mV before and after irradiation. Total dose effects are assumed to be of little concern at these doses[jpl1] .
- Shown in **Figure 4** is an atypical and several typical SET's measured using the Xe beam on the slow part with zero load in the UG configuration. The SET signature is quite complex and represents the worse 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 characterstuics for various input voltages and loads as shown in Figure 5 for the same case of Xe.
- **2.6 Preliminary Heavy Ion Microbeam Results**
- Since the slower DUT is noticeably more sensitive to SET than its faster counterpart, this part was chosen for initial microbeam investigation at the SNL. For microbeam analysis a 36MeV O6+ beam was focused to about 1mm and scanned over the slow part in the unity gain configuration using the Sandia Time Resolved Ion Beam Induced Current (TRIBIC) system [2]. The test board was configured with 0.1mF capacitors for transient suppression on the power rails. The input bias V1 was set at 1.0V as done in the TAMU tests. Unlike the TAMU tests, these tests were performed under vacuum at nominal room temperature. As the maximum scan size was 130×140(mm)2, the DUT was mechanically scanned to locate regions of sensitivity. The only region exhibiting SET was found to be in the bias circuitry/current reference region which supplies all four quadrants of the device. Within the region mechanically scanned, three regions within the bias circuit/current reference region were observed to trigger SET's; the main one being a 20×20(mm) 2 region comprising 4 smaller strips marked R1 shown in **Figure 6**. Smaller separate regions were also observed above (R2) and below (not shown here) with considerably small cross-sections. The total cross-sectional area including the two smaller strips above and below the main region is approximately 6×10-6 cm-2 which was the same order of magnitude as that estimated from the broad beam runs. The exact location could be correlated with the gerber file of the device die by noting key fuducial 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 with the actual sensitive area mapped using the microbeam (approximately 5×10-6cm-2). Typical SET's 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 appears to be of the same form in both R1 and R2 with some delay separating the two.
- [jpl1]**2.4 General Comments on Pulse Shape**
- Pulse Shape Analysis (PSA) is typically used to quantify in previous reports on OA's, a simple peak height and duration were extracted to form histogram representations from which conclusions are drawn [3-6]. For the SOI OA examined here however, the added complexity of an SOI structure has led to a menagerie of waveform shapes which requires a different analytical approach. It proved very difficult to define a single Pulse Shape Analysis (PSA) routine which returned attributes which completely characterize SET shape for all configurations and device types.
- For each device and configuration examined we therefore give representations of a "likely" response so the reader can witness the complexity, and examples of any SETs deemed important for mission assurance i.e. those with larger peak and durations than the mean of the distribution. Also note that several long duration oscillation-like responses were also collected during the TAMU tests; these appeared to be correlated with beam but are not necessarily due to beam hitting the DUT. These events were not noted in the microbeam results and were rejected in all analyses as they (a) introduce error into SET histogram calculations and (b), artificially raise the cross-section, in some cases by as much as 20%.
- PSA routines were written to filter and reject all spurious noise-like events using a peak detection algorithm and culling the SET if the number of peaks is significantly higher than typical. After considerable thought, three algorithms were chosen for histogram generation. The first denoted as MaxDist, estimates the magnitude of the disturbance and is defined as the maximum point in the SET plus the modulus of the minimum i.e. the maximum vertical span of the SET. The second is the length of the disturbance defined as the time between the occurrence of the first and last peak/trough in the SET (denote henceforth as Peak-2-Peak Duration). This underestimates the duration by the sum of half the first and last peak/trough. Since this is much less than typical durations (except in the case of the faster device), errors are minimal. For the faster part the Peak-2-Peak Duration algorithm introduced errors as discussed later and a simpler pulse Full Width at Half Maximum (FWHM) was applied. This is denoted as Simple FWHM. All analysis routines were written with the Labview 7.1.

- **3. Discussion of Results**
- Although not shown here, difference in SET amplitudes measured with the Kr and Xe beam did follow the expected total 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 speration of 4ms is common to both experiment.
- 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**. Somtime later this pulse propagates downstream causing a more violent disturbance, the cause of which requires detailed SPICE modeling to ascertain. Furthermore, the difference in SET amplitudes between the (Xe,Kr) and O data of about 2-3 indicates that charge collection is indeed 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 difference factor of around 100 or so. The microbeam with high LET ions but short range is therefore a reasonable means for simulating the high LET and long range ions typically employed for SEE analysis, in SOI devices.
- In addition, the microbeam results are extremely useful; SET's generated in the power supply circuitry will affect the functionality of all 4 devices simultaneously, meaning the DUT cannot support multiple redundancies as a means of SET mitigation. 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 remedid and will be the subject of further microbeam investigation. Further work will also examine OA SET susceptibility at low-temperatures common at the Martian poles.
- **4. 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 has confirmed certain qualms enginners had about the design of that region. The SOI OA was found to be largely insensitve to SET and is predicted to perform well in the Martian environment.

Circuit Bias and Current Reference



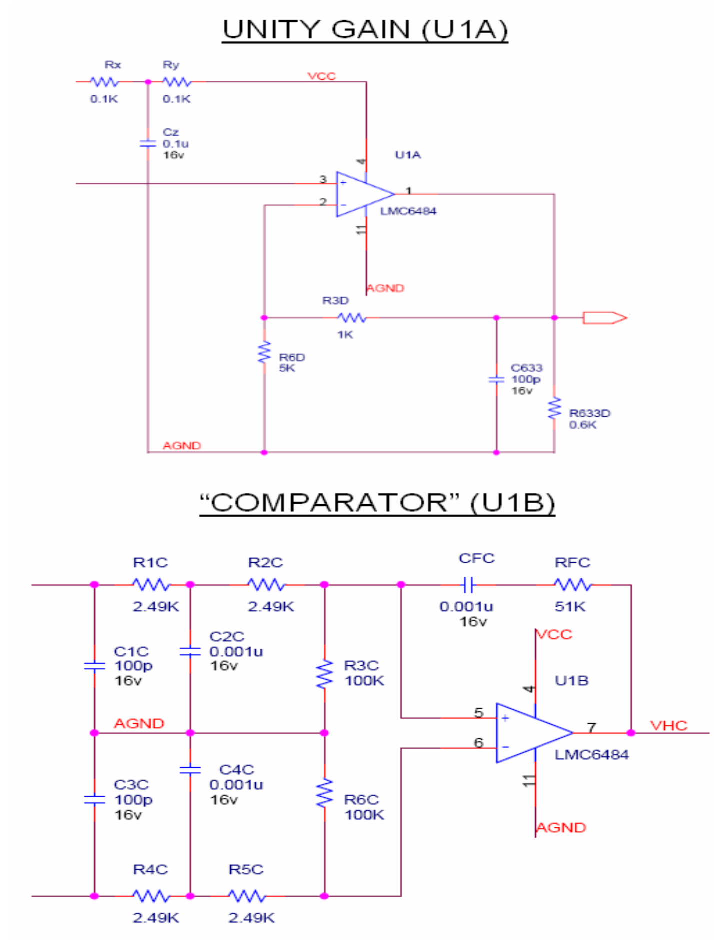


Figure 2: The block diagram of the test circuit configurations UA1 and UB1. The buffer circuit for driving a higher impedance load is not shown.

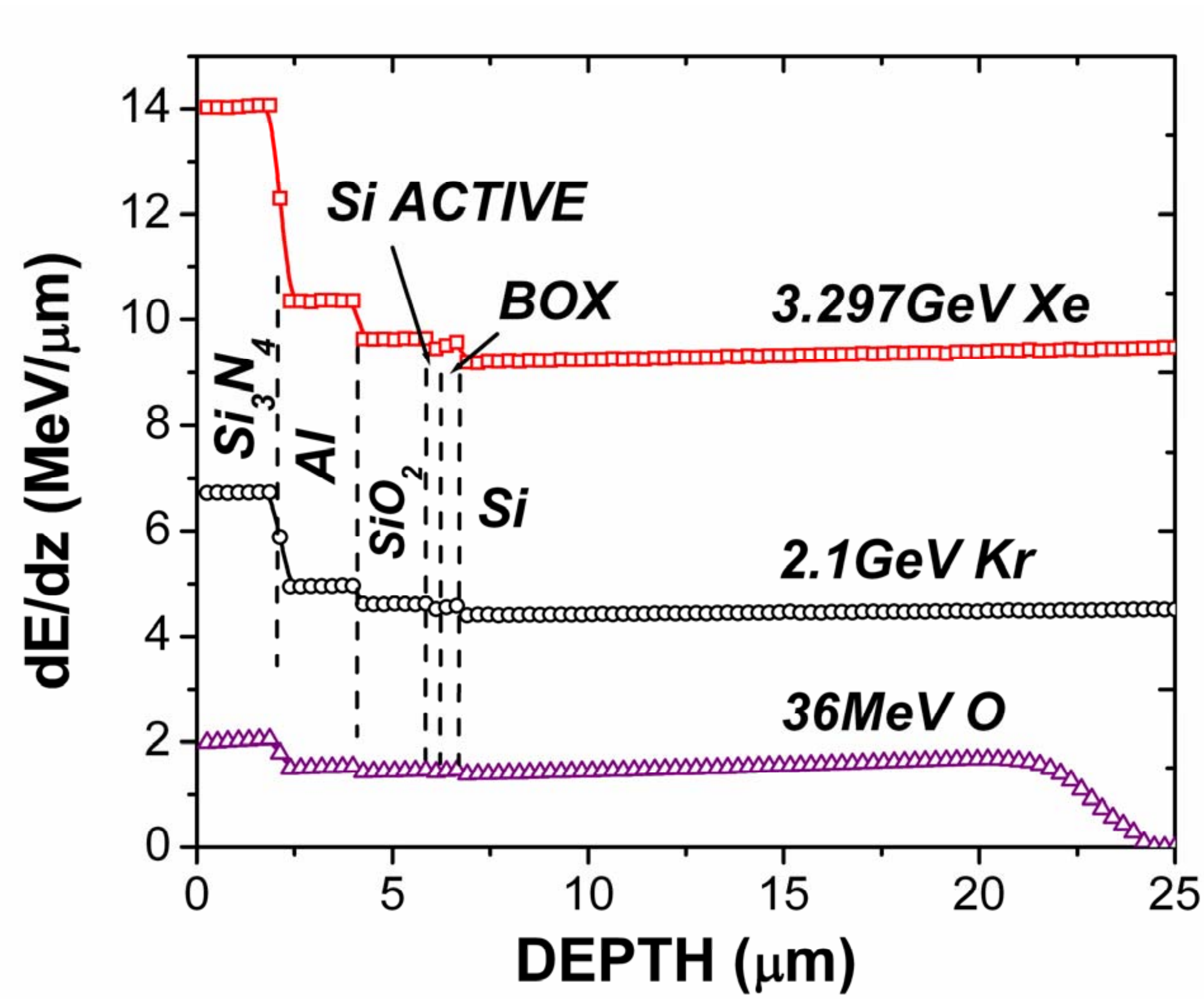


Figure 3: SRIM calculated dE/dz profiles near the surface region. Below the BOX region little charge will be collected besides that from a displacement current induced across the BOX during the ambipolar duration of charge transport in the substrate [8]. The charge initiating the SET is approximately that generated in the 0.2mm active Si

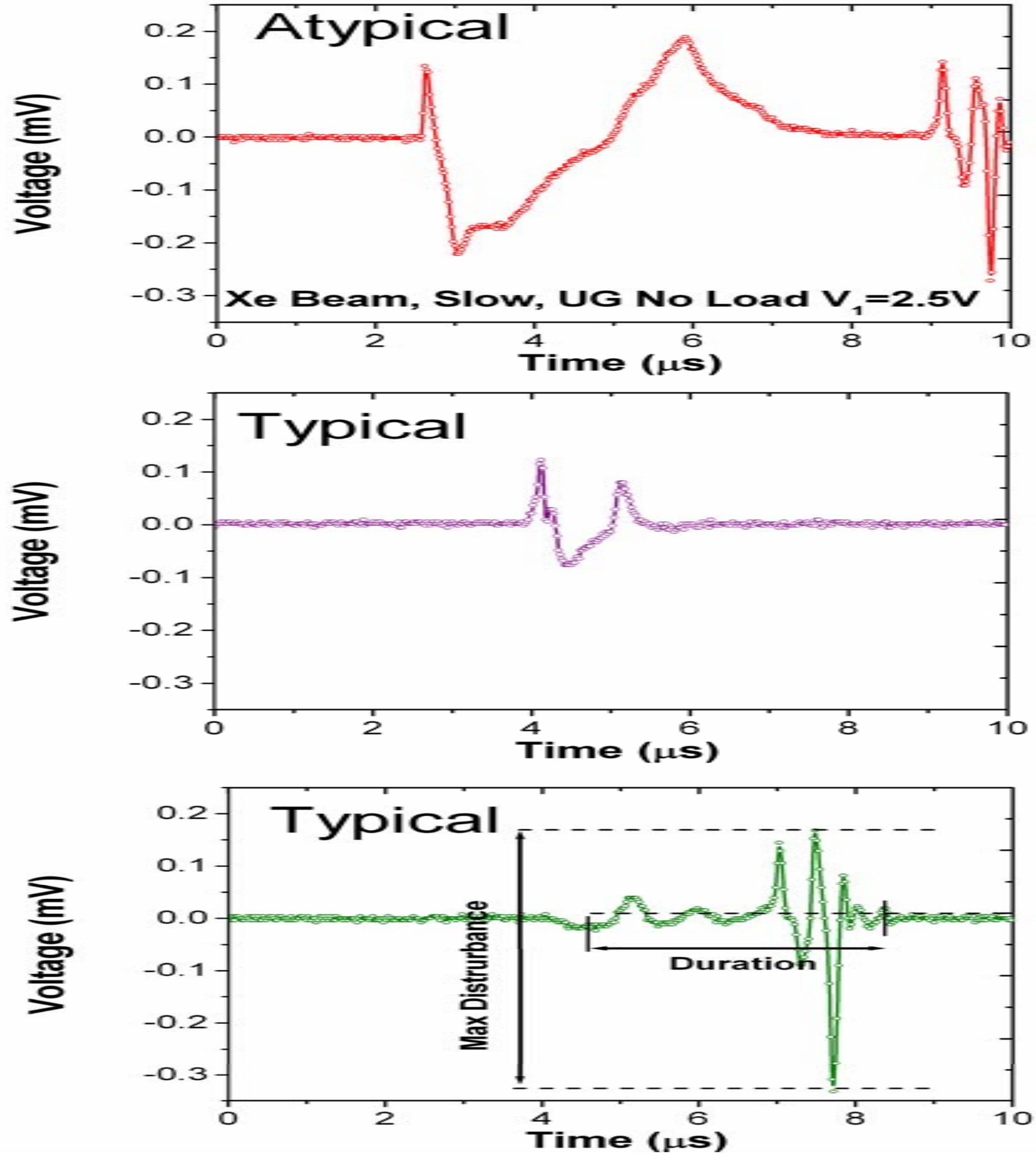


Figure 4: An example of two typical SET waveforms (bottom) and an atypical response (top) for the slow part configured as described in the top of the figure. The returning parameters of the algorithms (MaxDist and Peak-2-Peak Duration) are shown on the bottom figure.

Xe Beam onto SLOW Device in U1A Config

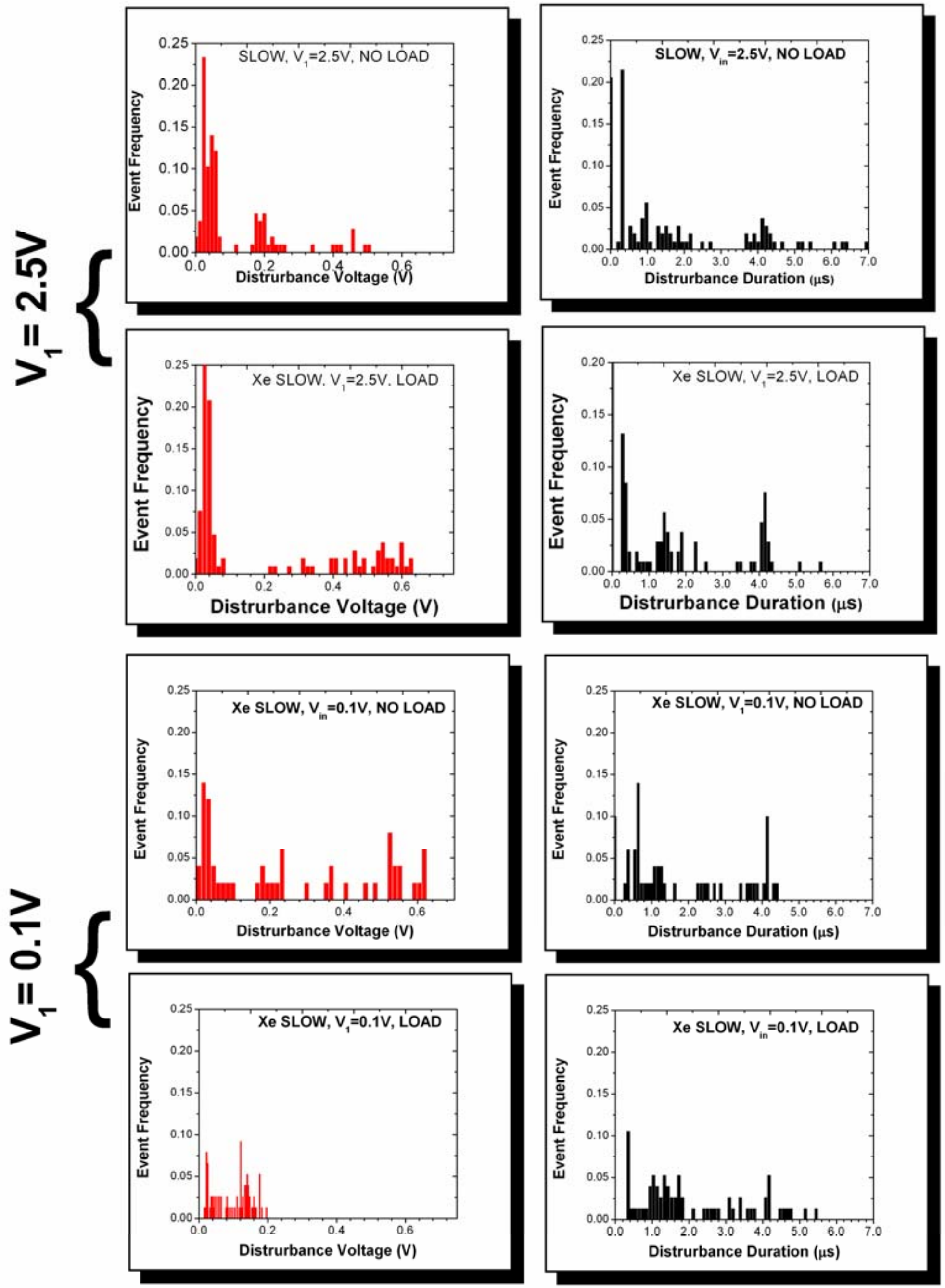


Figure 5: Comparison of the SET histograms for the case of Xe irradiation on the “slow” part configured for U1A with an input bias V1 of 2.5V (top) and 0.1V (bottom), with and without the additional serial load of 680W.

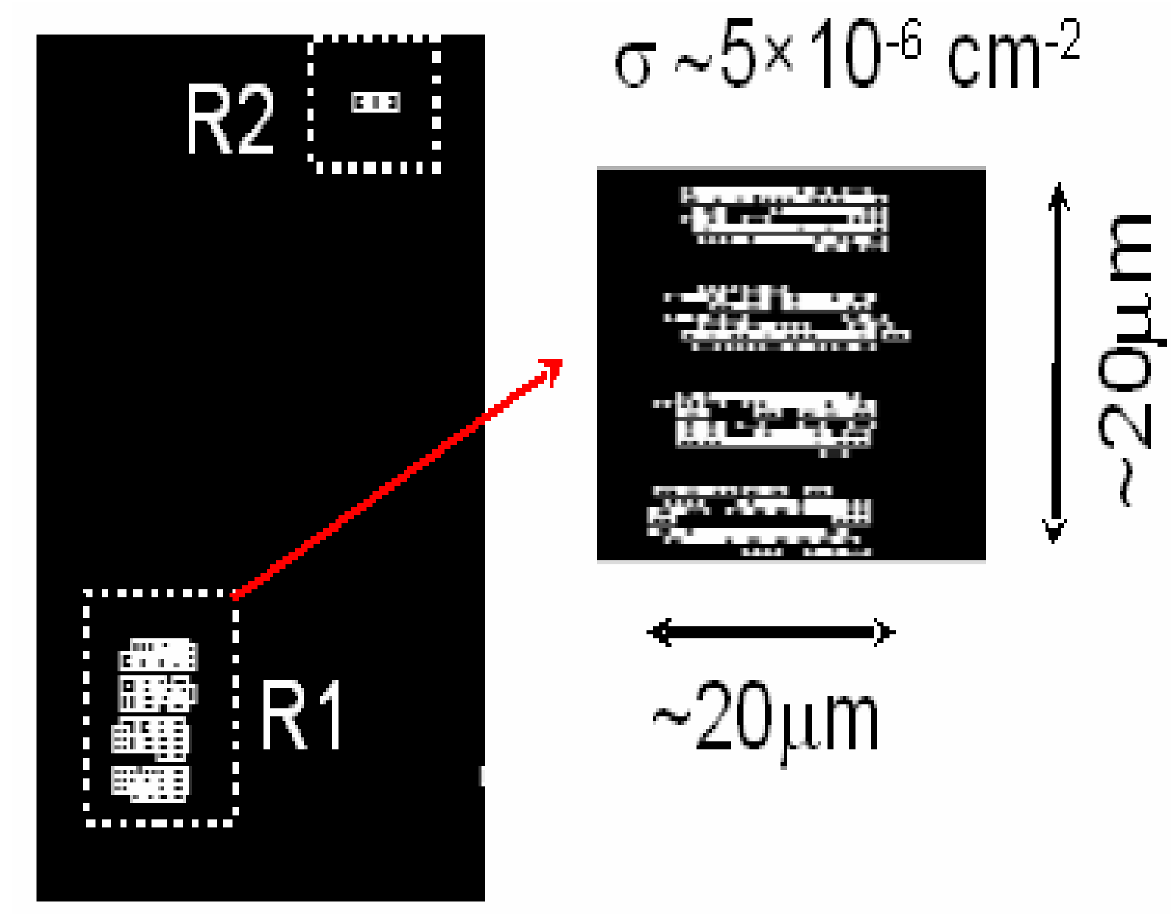


Figure 6: Microbeam bitmap image of the region exhibiting by far the highest cross-section across the die.

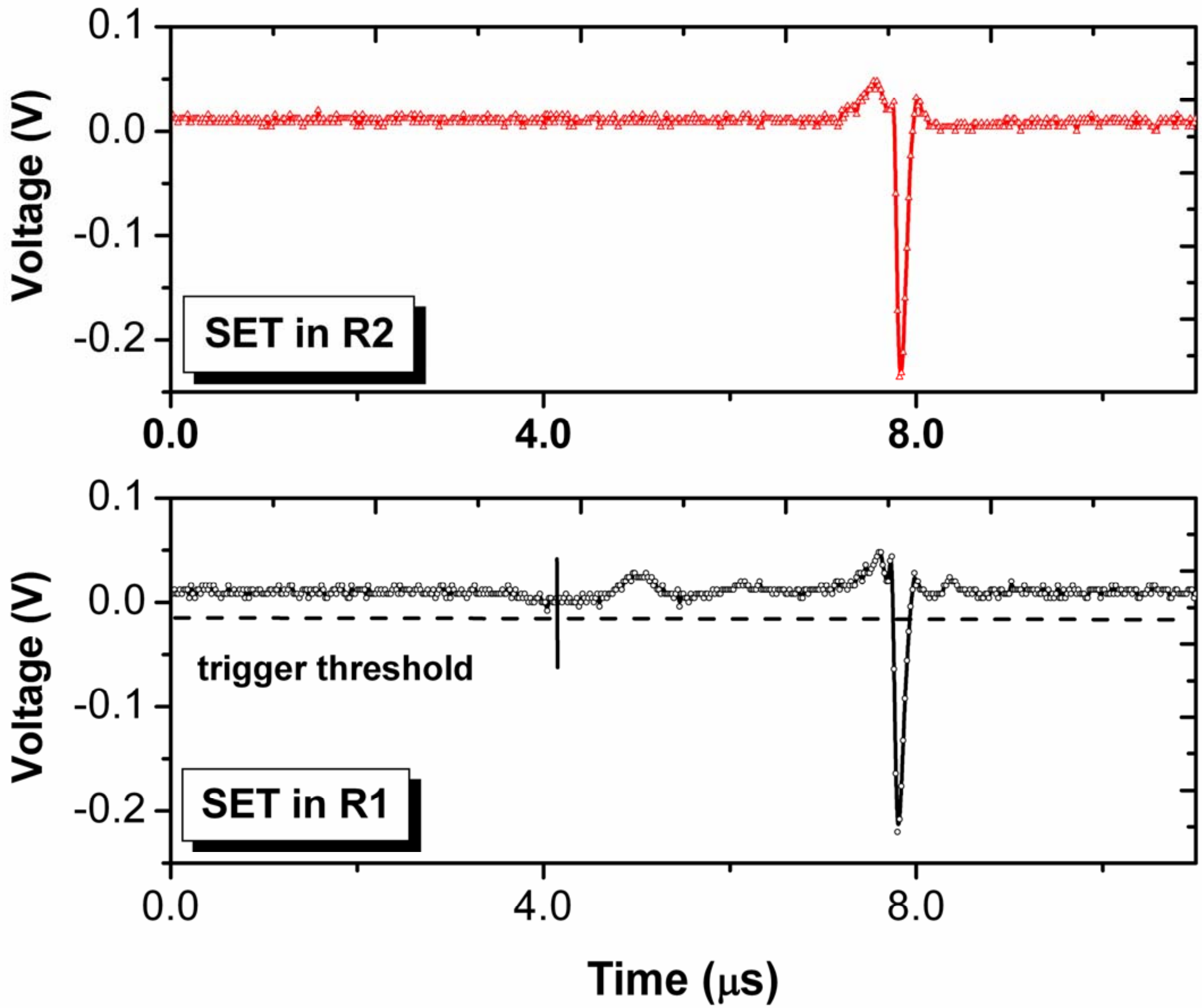


Figure 7: Representative SET in the regions R1 and R2 indicating the DSO trigger level and apparent delay between an event in R1 initiating the possible event in R2, based on the uncanny similarities between the large spike region.

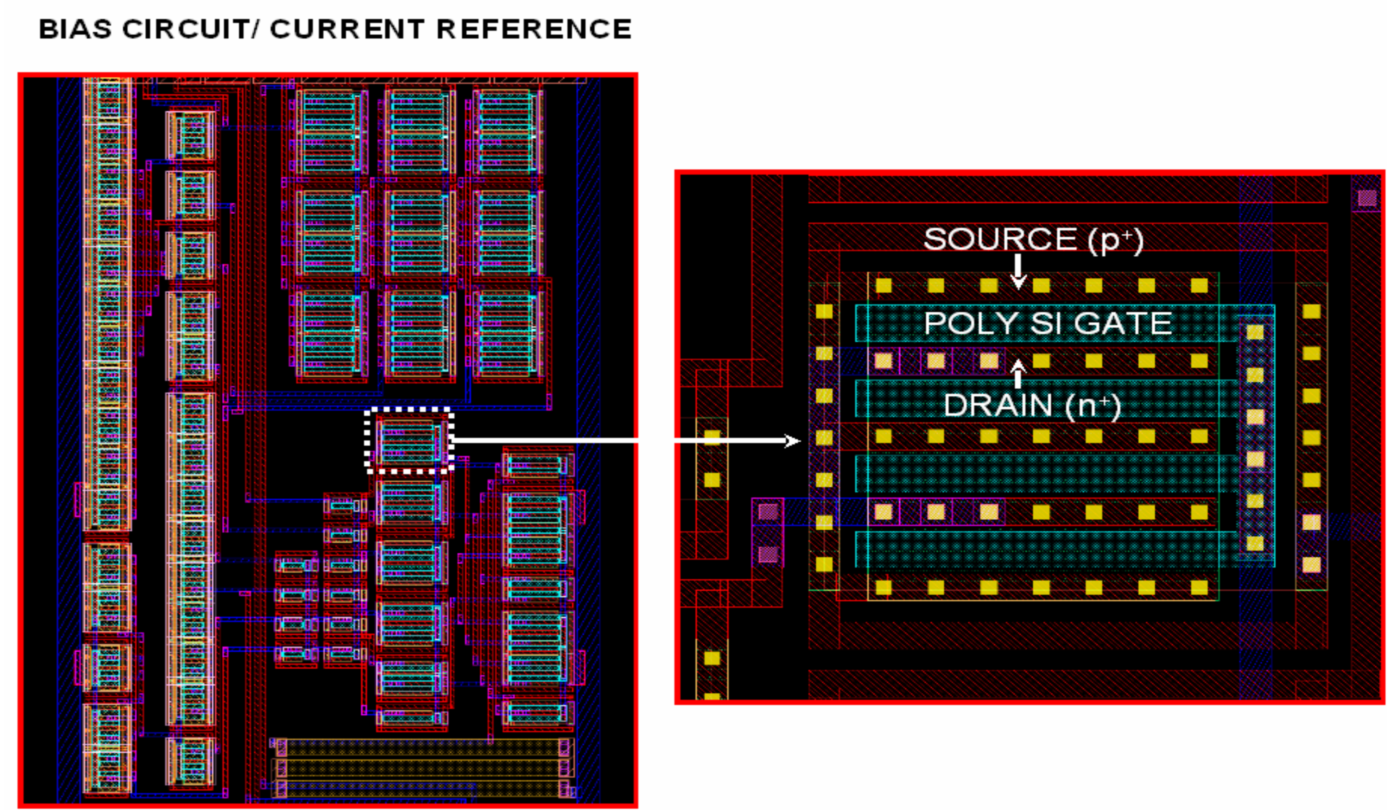


Figure 8: Circuit layout in the bias circuit/current reference region which microbeam imaging shown in Figure 6 indicates has the largest SET cross-section across the die.

5. References

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