New Test and Analysis Approaches for SEE Characterization

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Abstract: *As technology feature sizes decrease, single event upset (SEU), digital single event transient (DSET), and multiple bit upset (MBU) effects dominate the radiation response of microcircuits in space applications. Even in high-altitude and terrestrial applications, cosmic-ray neutron recoil byproducts can easily produce an unacceptable soft error rate (SER) in modern microcircuits. Process modifications and engineered substrate attempts have not provided significant levels of SEE (single event effect) mitigation. Circuit-level hardening approaches have, however, proven effective in mitigating all heavy-ion related effects. The size and speed penalties associated with these circuit hardening techniques often cannot be tolerated in commercial product designs. For this reason, experimental SEE characterization is necessary to identify dominant response mechanisms so that critical circuits can be identified and hardened with minimal impact on overall IC performance and permit the most effective trade-off between SER and the area/speed overhead. For complex designs, conventional broad-beam testing provides limited data to isolate the exact cause of observed errors and little insight into potential design improvements. We report on our new Milli-BeamĒ test hardware and associated data acquisition software that provides rapid SER raster scanning with spatial isolation as small as 10 microns to physically isolate dominant circuit susceptibilities of complex modern microcircuits.*

Keywords: Heavy-ion testing; Milli-Beam; Micro-Beam; SEE; Single Event Effects; SEU; Single Event Upset; SET; Single Event Transient; SER; Soft Error Rate. .

Introduction

Broad-beam heavy-ion testing, such as that performed at the Lawrence Berkeley Laboratory (LBL) 88-inch cyclotron [1], is primarily used to measure the SEE response of various ICs (integrated circuits). Characterization of SEE basic mechanisms is usually performed using specially designed test chips while qualification testing is often performed using large ICs containing complex designs. For complex designs, conventional broad-beam test data provides limited data to isolate the exact cause of observed errors and little insight into potential design improvements. New test methods are needed to address these issues and help isolate dominant circuit susceptibilities of complex modern microcircuits.

To address this problem, we have developed a new test capability, termed the Milli-Beam, to rapidly raster scan an IC with spatial isolation as small as 10 µm to physically isolate dominant circuit susceptibilities of complex modern microcircuits. The associated software automatically raster scans any device and provides the spatial location associated with each error during the test. Through post processing of the raster scan data, the software provides 3-dimensional surface plots showing the location of error counts over the entire area of an IC. While we presently use the Milli-Beam at the LBL 88-inch cyclotron facility, it can in principal be used at any heavy-ion test facility.

Milli-Beam System Description

Figure 1 shows a schematic of the Milli-Beam system as it currently exists for use at the LBL heavy-ion test facility. The critical component of the system is the primary aperture which defines both the beam size and position on the DUT (device under test). Other components of the system facilitate data acquisition and ensure data accuracy and quality.

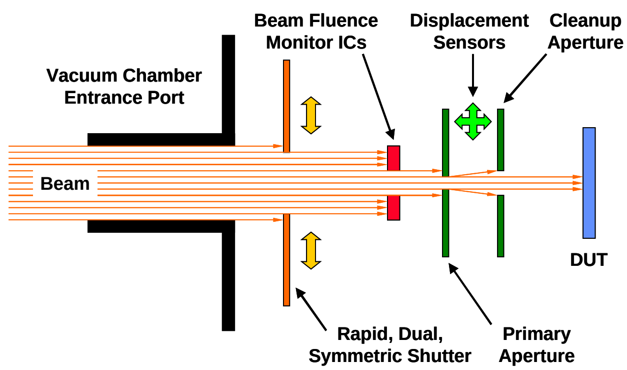

Figure 1. Milli-Beam hardware schematic diagram.

Two complete X-Y stages are mounted on a table attached to the Berkeley vacuum chamber wall directly downstream of the 4-inch beam line entrance port. Each stage holds a small square aperture. The first stage holds the primary aperture which defines, through collimation, the beam size and position. The second stage holds the cleanup aperture, slightly larger than the primary aperture, which can be used to prevent background ions scattered by the primary aperture from reaching the device under test. Each X-Y stage system is controlled by a LabVIEW [2] program which performs predetermined raster scanning of the beam over the DUT.

Given the angular divergence of the Berkeley beam, a 2 to 3 cm collimator separation appears to be ideal, with the cleanup collimator being only 1.5 µm to 2.0 µm larger than the primary collimator, provided that the DUT can be positioned within 1 cm of the final set of slits.

Each X-Y stage is constructed from two linear actuators which can be positioned to an accuracy of better than 1 µm [3]. The linear actuators controlling the horizontal (X) position are mounted directly on the mounting table while the vertical (Y) actuators are mounted on the X-actuators. The beam collimators are then mounted on their respective Y-actuators.

Beam collimators are formed by back-to-back horizontal and vertical slits constructed from steel feeler-gauge material. The slightly rounded honed edges of this material choice provide minimum degradation of the beam due to slit edge scattering. This approach enables square collimation (equal width and height), rectangular collimation (different width and height), or simple slits (either horizontal or vertical).

While developing the Milli-Beam system we made several preliminary measurements stepping over simple SRAM devices to calibrate the system. In the course of these measurements (which should display a uniform error cross section) we observed error rate variations well outside statistical uncertainties. These variations were easily attributed to beam flux variations. We have observed similar beam calibration problems in the past that can be attributed to the calorimetry technique used at Berkeley. Scintillators monitor the beam flux at the extreme edges (top, bottom, left, and right) and a periodic calibration establishes the intensity ratio between the beam center (as measured by a removable center scintillator) and the edge scintillators. This ratio can, however, be quite sensitive to the broad-beam profile and can change over time with variations in beam tuning and focusing. (We have in the past seen well over 10% variations in error cross sections made in back-to-back measurements presumably run for identical fluences.)

For this reason we now incorporate, as shown in Figure 1, an independent beam monitor as part of the Milli-Beam apparatus and control the run time at each raster step using this independent monitor. This monitor consists of four special low pin count chips placed upstream (and very close to) the Milli-Beam primary aperture. The chips, die attached to a simple lead frame having a hole in the center, are positioned symmetrically around (to the left, right, top, and bottom) of the primary aperture.

Figure 2 demonstrates the accuracy achievable using the four detector Milli-Beam fluence monitoring system. The data points with error bars represent beam monitor counts, proportional to the fluence, at the primary aperture location. The solid line labeled prediction is computed from the four curves labeled Monitor 1 through 4. These results indicate that for a total accumulated fluence of 10^7 cm^{-2} at each raster scan position, the fluence normalization will be accurate to 1.6%, based on the Poisson counting statistics in the four monitor chips.

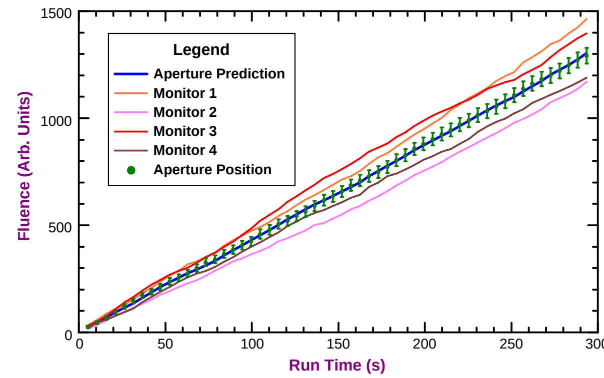

Figure 2. Accuracy of the Milli-Beam fluence monitor.

Finally, as shown above in Figure 1, we incorporate a rapid beam shutter as part of the Milli-Beam system. This shutter is controlled by the same LabVIEW software that controls the raster scanning. This LabVIEW program stops data acquisition at preset fluences as measured by a microprocessor controlling the beam monitor chips, steps the Milli-Beam aperture position, updates the FPGA test board with the new coordinate position, and resumes data acquisition. All raster scan data is contained a single ASCII data file, with each observed error having an X-Y position tag. Data reduction to extract position information is finally performed by Perl post-processing scripts.

If it proves necessary to jump over a sensitive circuit, such as a PLL (phase locked loop) or a control mode register, that could produce an undesired SEFI (single event functional interrupt) not relevant to the measurement being taken, then the software can additionally actuate the rapid beam shutter to block the beam during the raster scan step. It is desirable that the beam shutter traverse linearly through the beam (not in-out like the Berkeley shutter) so that all parts of the unblocked beam experience the same fluence.

We therefore incorporate a dual symmetric shutter. This shutter system first unblocks the beam by moving the left shutter out of the beam by moving to the left. The beam is subsequently blocked by moving the right shutter into beam, also moving to the left. For the next beam exposure, the right shutter then moves to the right out of the beam. This is followed by the left shutter moving to the right to finally block the beam, completing the cycle of two raster exposures.

Ion Beam Considerations

The finite emittance of the heavy-ion beam along with edge scattering from defining slits and collimators are the major factors that must be considered in constructing and using the Milli-Beam technique. Beam emittance is defined as the area an ellipse in Rθ phase space containing all particles in the beam at any given point along the beam axis where R is the radius of a particle in the beam, θ is the angle dR/dz of the particle trajectory, and z is the beam axis coordinate [4]. The emittance area is invariant as the beam is transported which means that particle trajectories become more parallel as the beam diameter is made larger. To ensure beam uniformity over the area of an IC, the beam diameter is made as large as possible (~10 cm) as it enters the chamber. This fortunately means that the angular spread of the beam particles in minimized since as θ will decrease inversely as R is increased to maintain a constant emittance ellipse area.

We measured the angular spread of the Berkeley 88-inch cyclotron beam as it enters the vacuum chamber and found a Gaussian distribution of angles with a sigma of 0.0025°. This angular spread means that for a defining collimator 40 cm before the DUT, all edges of beam will degrade on the order of 18 µm. Thus, a 10 µm diameter beam will blow up to ~46 µm by the time it reaches the IC and will not have well defined edges. This can be seen in Figure 3 as the rounded edges of the beam profile of a 100 µm square beam. By placing the DUT within 5 cm to the defining apertures, the edge degradation is reduced to less than 2 µm, as seen by the sharper edges of the profile in the plot of Figure 4.

The surface plots in Figures 3 and 4 were obtained by performing a least-squares fit to the errors produced in an SRAM positioned 40 cm and 4 cm, respectively, from the Milli-Beam primary aperture. The fitting function consisted of a 2-dimensional convolution of a Gaussian product Z(X)*Z(Y) with an box in X-Y-Z space. The X and Y dimensions represent the width and height of the Milli-Beam, respectively, and the Z dimension represents the number of observed errors. The parameters of the fitting function included total number of errors under the convolution integral, the Milli-Beam width and height (before edge washout by the Gaussian), the center location of the beam (the mean X and Y), and the edge washout parameters σ_x and σ_y (the sigma values for the Z(X) and Z(Y) Gaussians, respectively).

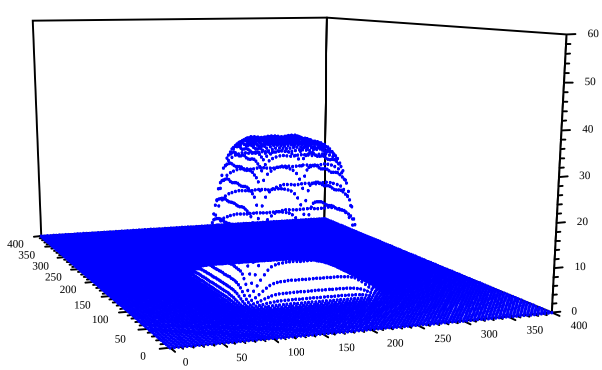

Figure 3. Milli-Beam profile 40 cm from the defining aperture.

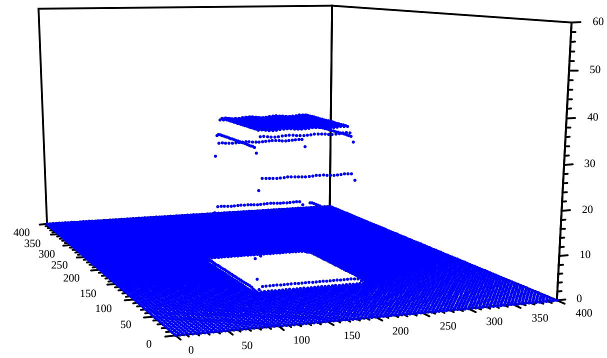

Figure 4. Milli-Beam profile 5 cm from the defining aperture.

While this edge degradation does not present many problems for larger beams (~100 µm to 200 µm diameter), it does mean that the defining apertures must be much nearer the IC for smaller beams (~10 µm to 20 µm diameter). Beam scattering from the edges of the defining apertures now presents new problems that must be addressed in constructing the Milli-Beam apparatus. For this reason we use the second cleanup aperture to remove these scattered particles so that heavy-ion strikes will not occur outside the targeted region on the DUT.

Raster Scanning Procedure

In any particular heavy-ion Milli-Beam test, the displacement and rotation of the DUT relative to a special calibration SRAM must be known from measurements of the test board made on the bench. These measurements must determine three parameters to describe the relative displacement (both X and Y) and the relative angle of rotation between the devices.

We make these measurements using a stationary high powered (150× objective) microscope with the DUT/SRAM test board mounted on an accurate (to 1 µm) X-Y stage. Supporting Perl scripts extract these parameters at each of four different test board rotations and subsequently combine the results so as to remove systematic errors associated with any non-orthogonality of the optical axis with the plane of X-Y stage. These Perl scripts give both values and expected uncertainties of the DUT and SRAM relative displacement vector as well as the angle of rotation of the DUT relative to the calibration SRAM.

As in any data reduction and error analysis effort, establishing estimates of final parameter variances is just as important as determining the final parameter values themselves. The expected uncertainties are computed using the standard error propagation formula,

$$\pm_y^2 = \pm_u^2 \left(\frac{\partial f}{\partial u}\right)^2 + \pm_v^2 \left(\frac{\partial f}{\partial v}\right)^2 + \Lambda \qquad (1)$$

where σ_y is the desired parameter uncertainty, σ_u and σ_u etc are the input value uncertainties, and the partial derivatives are obtained numerically using the parameter extraction function directly.

The calibration SRAM and DUT can be mounted on the same test board or can be mounted in separate packages that share the same socket on the test board. In the first case, measurements are made of the DUT relative to the SRAM. In the second case, each chip location is measured separately to obtain displacement and angle parameters relative to two known positions on the board. The extracted results for each chip are then subtracted to provide the final DUT to SRAM displacement vector and relative rotation angle.

Two additional matrix parameters then need to be extracted at the heavy-ion facility. The first of these is the angle between the calibration SRAM Y-axis and the Milli-Beam Y-axis. The second is the angular deviation from orthogonal of the Milli-Beam X and Y stages. (It should be noted that physical systems, such as right angle mounting brackets, cannot be machined with sufficient precision and must therefore be measured and accounted for in the various matrix transformation operations.)

This is done by making Milli-Beam ΔY steps with $\Delta X=0$ and extracting the relative angle (θ_y) of the Y stage with respect to the SRAM die. By holding $\Delta Y=0$ and making ΔX steps gives a measurement from which one can extract both the X stage angle with respect to the IC and determine the angle of non-orthogonality between the Y actuator and the X actuator ($\theta_\perp$). These values are subsequently used to, through the use of appropriate coordinate transformations, to target known positions on the DUT.

Using an SRAM rotation matrix transformation, a Milli-Beam axis skew transformation, a DUT displacement translation, and a final rotation of the DUT relative to the SRAM finally allows one to place the Milli-Beam over the coordinate system origin on the DUT itself. Using similar inverse matrix transformations, additional software then computes the Milli-Beam actuator positions needed to strike the specified X-Y locations on the DUT. This software also provides an estimate of the variance, again based on Equation 1, for each targeted DUT coordinate.

Summary

We have described a new test capability, termed the Milli-Beam, which compliments existing heavy-ion and laser test methods. By raster scanning complex designs with any beam presently available at the LBL cyclotron, the spatial location associated with each observed error can be determined. This provides detailed information that can be used to isolate the exact cause of each observed error as well as giving maximum insight into potential design improvements.

Acknowledgements

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