Effects of Ion Damage on IBICC and SEU Imaging

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Abstract

The effect of displacement and ionizing dose damage on ion-beam-induced-charge-collection (IBICC) and single-event-upset (SEU) imaging are explored. IBICC imaging is not affected by ionizing dose damage, and its dependence on displacement damage is a complex function of the structure of the samples used in this study. Degradation of the IBICC signal is controlled by displacement damage that occurs at different rates in the heavily doped substrate and lightly doped epitaxial silicon layer, leading to a non-linear dependence of inverse degradation versus ion fluence. The effect of ion exposure on the electrical performance of complementary metal-oxide-semiconductor (CMOS) static random access memories (SRAMs) is solely related to ionizing dose effects in the transistor oxides. With SEU imaging, we found that an additional region became sensitive to upset with ion fluence probably as a result of ionizing dose effects on the restoring transistors. Finally, SEU during IBICC imaging resulted in charge collection from both p-drains of a memory cell. Implications of damage on the use of these microbeam techniques are discussed.

I. INTRODUCTION

Since the first observation of upset in near-earth satellites [1], heavy-ion microbeams have been shown to be useful tools for investigating SEU mechanisms in integrated circuits (ICs). Upset can result from charge collection processes in both n-type and p-type regions of an IC. Different circuit elements within the IC can have different sensitivities as well. With broad-beam techniques it is difficult, if not impossible, to separate these effects and gain insight into the mechanisms contributing to upset.

Magnetically-focused scanned heavy-ion microbeams have been used in recent years to study SEU in ICs. Magnetically-focused microprobe systems can achieve beam dimensions less than 1.0 μm. In fact, spot sizes as small as 0.05 μm have been reported [2]. SEU imaging provides a raster-scanned image of those portions of an IC that are sensitive to upset. For example, SEU imaging of the Sandia TA670 16k-bit SRAM with a 1.0-μm microbeam determined that upset occurred primarily in the n-drain regions [3] of each memory cell. Studies by Metzger et al. [4] yielded images of two sensitive regions per memory cell in an MHS65162 16k-bit CMOS SRAM.

IBICC is a complimentary microbeam technique that generates images of charge collection in pn junctions of an IC [5-8]. This technique images all the collected charge following a heavy-ion strike, not just the charge contributing to upset. Images of the TA670 16k SRAM, for example, showed photocurrent collection in the reverse-biased p-drain regions of the memory cell, and current amplification in n-drain regions that were biased “on” [7]. The same technique has been used by Breese et al. [5] as a failure analysis technique to image charge collecting regions of an IC through overlaying metal and insulating layers.

In order to use these techniques most effectively and to derive results that are applicable to SEU, it is important to understand how the ion beam itself affects the device response. Previous charge collection studies by Breese [8] have related the change in pulse height with ion fluence to a change in minority carrier diffusion length due to displacement damage. Nashiyama et al. [9] explored the effect of ion damage on current transients in test structures and related the observed change in amplitude to displacement damage effects through the concept of non-ionizing energy loss (NIEL). These previous studies on displacement damage used simple diode structures.

In this paper, we address ion microbeam damage effects on SEU and IBICC imaging in more complicated integrated circuits. First, we assess the impact of ion dose on IBICC image quality and explore whether the observed effect can be attributed to ionizing energy loss as well as non-ionizing energy loss within the semiconductor device. We consider whether ionizing dose may change an IBICC image through the effects of trapped charge on transistor threshold voltage and drive current in devices connected to the struck node. Effects on IC performance are also measured using conventional electrical techniques and recently developed techniques that are much more sensitive to changes in device response. We also examine how upset affects IBICC imaging by using ions with sufficiently high linear-energy-transfer
(LET) to cause upset compared to ions with lower LET. Then, we study the effect of ion dose on SEU imaging. A better understanding of radiation damage resulting from these techniques has been developed in these studies. This work also has implications for the effects of both ion damage and total ionizing dose effects on device response in space radiation environments.

II. EXPERIMENTAL DETAILS

IBICC imaging is accomplished by raster scanning a micron-resolution heavy-ion beam over a region of an IC while the charge resulting from each ion strike is recorded. Charge is measured by connecting a charge-sensitive pre-amplifier to either the power or ground pin of the device under test while the part is under nominal bias. The beam position is recorded as a 64x64 array of pixels, while the analog charge signal is converted to a 64-channel pulse height spectrum associated with each pixel. Thus, the charge collection information from one exposure consists of a 64x64x64 data cube. This data is reduced to a 2-D representation of charge by median filtering the spectral data and applying a color spectrum to the resulting median charge collected at each pixel. This technique has been described in more detail previously [6].

To measure IBICC dependence on ion fluence, IBICC images were taken of a region of the IC before and after exposure to an ion fluence that gave a predetermined total-ionizing-dose level. The effect of ion fluence was determined by comparing the pre- and post-irradiation IBICC images. A fresh region of the IC was measured for each level. The effect of ion fluence on device performance was determined by measuring the read access time and bit-flip voltage [8], two measurements that are sensitive to ionizing dose. Bit-flip voltage is the power supply voltage at which the information stored in a memory bit changes after a fixed time interval. A pattern is written to the memory array at the nominal power supply voltage. Then, the power supply voltage is reduced to a predetermined level for 40 s, and then it is returned to its nominal value. The memory contents are read, and any changes in the stored pattern indicate that bit-flip has occurred. The usefulness of these techniques in monitoring displacement damage effects on electrical response is not yet known. Pre- and post-irradiation electrical measurements were performed to determine the degradation of device response. For both experiments, ion flux was measured before and after the series of exposures using a p-i-n diode. Fluence was determined from the exposure time.

To separate the effects of displacement damage and ionizing dose on IBICC imaging, different regions of an IC were exposed to different levels of ionizing dose in a 10-keV x-ray source at a dose rate of 1.8 rad(SiO2/s). IBICC and electrical measurements were performed in these regions before and after irradiation.

SEU imaging is accomplished by scanning a micron-resolution heavy-ion beam over a region of an IC while the part is exercised with computer controlled test equipment. The position of the beam is recorded when an upset occurs, yielding a 2-D spatial map of those regions sensitive to upset. This technique has been described in detail previously [3]. For this study, a single region of the device was exposed to increasing levels of ion fluence. After each step, an SEU image was taken of the region.

The test device in this study was the Sandia TA670 16k-bit radiation-hardened CMOS SRAM. This device has 2-μm feature sizes and is fabricated in the AT&T 1.25-μm twin-well radiation-hardened technology [11]. One level of polysilicon and two levels of metal are used for interconnections in this 6-transistor memory cell design. Two versions of this IC were used in this study. For the IBICC-imaging studies, parts with feedback resistors were used, while for the SEU-imaging studies, parts without feedback resistors were used so that upset could be achieved with the beams available on the Sandia microbeam system.

III. RESULTS

A. Effects of Ion Fluence on IBICC Images

In Figure 1, we show IBICC images of several regions of the memory array of the TA670 as a function of ion fluence. Also shown is the total ionizing dose impinging on the device surface as calculated from the ion fluence. The color scale for these images matches the visible spectrum, with red indicating the highest collected charge and blue the lowest collected charge. A 2.5-MeV helium beam was scanned over a 90x90-μm area at a flux of 7200 ions/sec. At this rate, only 0.3 ions are deposited per pixel on average in one scan (163 ms). Therefore, 100 scans were necessary to give sufficient statistics to ensure a clear IBICC image. The equivalent total ionizing dose per scan is 217 rad(Si) for an average dose rate of 1.3 krad(Si)/s. At each region on the IC, an initial IBICC image was obtained with 100 scans. A subsequent exposure was performed by scanning the ion beam until the specified dose was accumulated, followed by a second IBICC image of 100 scans to obtain a post-irradiation image. In Figure 1, we note a marked decrease in the signal arising from the p-drain regions of the device (outlined in white), until at a fluence of 6700 ions/μm² (10 Mrad(Si)) these regions can barely be discerned.
from the background. The n-type diffusions within the p-well also showed a marked decrease in charge collection (outlined in black), but at 6700 ions/μm² (10 Mrad(Si)) continue to produce a signal sufficiently above background to allow imaging. From earlier work, the p-drain regions were shown to be in an "off" bias, while the n-drain regions were in an "on" bias [7].

The loss of image contrast is directly attributable to a loss of signal-to-noise ratio with decreasing pulse height in a given region. This is shown in Figure 2, where we plot median pulse height for the p-type (circles) and n-type (triangles) diffusions, respectively, as a function of ion fluence (ionizing dose is shown on the top axis). The data are averaged over all drain regions of the given type visible in a scan. Error bars indicate one standard deviation in the data. Variation of the p-drain data is smaller than the plot symbol. In this study, both regions show a logarithmic decrease in pulse height with increasing fluence. The n-drain degradation saturates after a fluence of 1000 ions/μm² while the p-drain degradation begins to saturate at a higher fluence of 3000 ions/μm². Note that the absolute value of pulse height depends on experiment factors that can vary from one experiment to the next, such as amplifier gain settings, and is therefore shown as arbitrary units in this and subsequent plots.

Change in address access time, Δtac, and bit-flip voltage, ΔVbf, are shown in Figure 3 as a function of increasing ion fluence. Here we plot the average change in response for the group of cells in each scanned region. Error bars denote one standard deviation in the data. The top axis shows the equivalent ionizing dose. Each curve has been normalized to its maximum shift. Initial τac was 130.8±1.5 ns and its shift at 10⁷ rad(Si) was 2.1 ns. Address access time (triangles) showed no change until a fluence of 1350 ions/μm² (5 Mrad(Si)) was accumulated in a given region. This was not unexpected for a device such as the TA670 that has a demonstrated radiation hardness to 10 Mrad(Si) [11]. Note that Δtac is sensitive to changes in transistor drive in both the memory cell and sense amplifier circuitry, primarily through an increase in threshold voltage and decrease in channel mobility [12]. In contrast, bit-flip voltage (squares) increased slightly by the first dose level and showed a near logarithmic increase above 120 ions/μm² (200 krad(Si)). Its response has the same logarithmic dependence (but opposite) as the decrease in pulse height shown in Figure 2. Bit-flip voltage is a measure of the upset sensitivity of...
Figure 3: Change in device response as a function of ion fluence. Equivalent ionizing dose accumulated during the ion exposure is shown on the top axis. The memory cells only and is sensitive to changes in threshold voltage and mobility degradation induced by ionizing radiation [10]. Differences between access time and bit-flip voltage may be due to the masking effects of peripheral circuitry, such as decode and sense-amp circuits. Both techniques are sensitive to changes in both the n- and p-channel transistors. Further study of these techniques is warranted to understand these differences.

The logarithmic dependence of pulse height and bit-flip voltage with fluence suggests that both responses arise from the same damage mechanism. The question arises: is the change in IBICC contrast due solely to displacement damage effects, or does the change in transistor response with ionizing dose also affect the collected charge? To answer this question, a TA670 was irradiated with a 10-keV x-ray source so that only ionizing dose related mechanisms could affect device response. The x-rays were collimated with an aperture so that only one quadrant of the memory was exposed at a time. Each region was exposed to a different level of total dose: dose levels were 0.5, 1, 2, and 5 Mrad(SiO₂). The device's electrical response was measured, and IBICC images were taken before and after irradiation.

The average electrical response from each region is plotted in Figure 4. Data are normalized to the maximum response at 5 Mrad(SiO₂). Here, the behavior of ΔVbf with ionizing dose (squares) is similar to that observed in Figure 3 exhibiting a logarithmic increase with dose, while address access time, Δtac, shows a more gradual change with dose than was observed with 2.5-MeV He ions (triangles). We note that if the data of Figure 3 is normalized to 5 Mrad(Si) (not shown), all the response curves would fall slightly below the x-ray response curves. This is consistent with earlier work by Oldham et al. [13] that showed a lower charge production efficiency for heavy ions compared to energetic photons, such as x-rays. Less charge escapes the initial recombination processes due to the higher charge density of the ion track for the case of heavy ions.

Median pulse heights from IBICC images of the same four regions of the memory array that were exposed to x-ray irradiation are shown in Figure 5. Unlike the response observed with ion fluence, little or no change in pulse height was observed with increasing x-ray dose. This is a clear indication that, for these devices, IBICC is not sensitive to ionizing dose and that the degradation in IBICC signal with ion fluence shown in Figure 1 and 2 is due entirely to displacement damage effects.

B. Effect of Upset on IBICC Images

In Figure 6, we compare IBICC images obtained with and without upset. The IBICC image on the left was made with 30-MeV Cu, while the image on the right was made with 2.5-MeV He ions. For the IC with no feedback resistor, the memory cells upset with Cu ions (LET ~ 27 MeV-cm²/mg), but do not upset with He ions (LET ~ 1.2 MeV-cm²/mg). In the He image where upset...
C. Effect of Ion Fluence on SEU-Imaging

The effect of ion damage on SEU imaging is seen in Figure 7, where we plot upset maps as a function of fluence for the TA670 during exposure to 30-MeV Cu ions (LET ~ 27 MeV-cm²/mg). The upset threshold for this part with no feedback resistors was determined to be about 18 MeV-cm²/mg from SEU tests at the Berkeley cyclotron. Each image is a result of 2 scans of an 80x80-μm area of the memory array. The outlines in the large image on the left show the location of p-drains and n-drains as a reference for the upset images. In the initial image, upsets only occur in the p-drain region. As dose increases to about 110 ions/μm² (~5 Mrad(Si)), we begin to observe upsets in the n-drain region, also. With further exposure, n-drain upsets

![Figure 6: IBICC images are shown for 30-MeV Cu (left) and 2.5-MeV He (right). With higher LET Cu, the memory cell upsets and charge is collected from both p-drain regions. Charge is collected from only one drain region when the memory cell does not upset (right). The p-drain regions are outlined in white at the top of each image.](image)

![Figure 7: SEU images as a function of total ionizing dose. The sketch on the left shows the registry of the upset images with the memory cell elements. At megarad doses, upsets begin to occur in the n-drain region, in addition to the p-drain region.](image)
strengthen and saturate at a fluence of about 1200 ions/\mu m^2 (~52 Mrad(Si)).

IV. DISCUSSION

A. IBICC-Imaging

The fact that we observed no change in the IBICC pulse height with x-ray exposure indicates that ionizing dose effects are not significantly affecting the IBICC contrast, and that the observed loss of contrast must be explained by displacement effects alone. The data of Figure 2 do not follow an inverse linear dependence as we would expect if the classic damage factor model applies. This model predicts a response of

$$\frac{1}{Q} = \frac{1}{Q_0} + K\Phi,$$

where $Q_0$ is the initial response, $\Phi$ is the fluence, and $K$ is the damage factor [15]. The absence of an inverse linear dependence is linked to the structure of this IC.

This technology has a complex vertical structure with a lightly doped epitaxial silicon region ($\sim 10^{15} \text{cm}^{-3}$, 2-\mu m thick) on top of a heavily doped substrate ($\sim 10^{18} \text{cm}^{-3}$). In Figure 8, we show displacement damage and electronic stopping power as a function of depth into the silicon. The depths of the sources and drains and the epitaxial-substrate interface are indicated. From previous studies of this part, we know that charge collection occurs in both the epi and substrate regions [7]. Those studies indicated a charge collection depth of $4.8 \pm 0.4$ \mu m for p-drain hits, therefore a significant portion of charge came from the heavily doped substrate. We also observed that charge amplification occurred in the drains of n-channel transistors biased "on." This was attributed to either a bipolar gain or shunt mechanism. We point out that these experiments measured all the charge being collected, not just that portion that contributes to upset.

The data of Figure 2 can be explained by a model that has two regions of charge collection, one in the depletion region (which, in this case, extends to the epitaxial-substrate interface) and a second in the heavily doped substrate. Charge generated in the first region is rapidly swept out by the electric field in the depletion region and is not dependent on displacement damage. In the second region, charge collection is modified by the effect of damage on minority carrier lifetime. This model has the form

$$Q = Q_0 \left[ (1 - F) + \left( \frac{F}{1 + K\Phi FQ_0} \right) \right],$$

where $Q_0$ is the initial charge, $F$ is the fraction of charge in the damage sensitive region, and $K$ is the damage factor, as in Eq. (1). $Q_0$ is determined by the initial charge, and $F$ is constrained by the saturation level of the data, so this is essentially a one-parameter fit through the $K$ factor. The predictions of this model are plotted against the data in Figure 9 (solid lines). The model shows an excellent fit to both the p- and n-drain data. Parameter values for these fits are shown in Table 1. For the p-drain fit, an $F$ value of 0.42 indicates that nearly half the charge comes from substrate region, initially. The same is true for the n-drain, indicating that charge collection here is due to a minority-carrier lifetime-based mechanism, such

![Figure 8: TRIM92 calculation of electronic stopping (LET) and displacement damage vs. depth of a 2.5-MeV He ion beam into silicon taking into account the energy loss in the overlayers. Charge is collected from the lightly-doped epi layer and heavily-doped substrate.](image)

![Figure 9: Pulse height data from Figure 2 are compared to model predictions (solid lines) of Equation (2).](image)
as bipolar gain. The damage factor is the same for both regions, as we would expect.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>P-Drain</th>
<th>N-Drain</th>
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<tr>
<td>Q0 (pC)</td>
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</tr>
<tr>
<td>F</td>
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<td>0.36</td>
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<tr>
<td>K (cm²/pC)</td>
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**Table 1: Parameters for damage model of equation (2) vs. type of region.**

**B. SEU-Imaging**

For the SEU images of Figure 7, the appearance of an additional region sensitive to upset will increase the saturation cross section observed in a broad-beam exposure. Increasing ionizing dose as the part is exposed will degrade the current drive of the restoring transistor, thereby reducing critical charge and making the device more sensitive to upset. As critical charge decreases, ion strikes in regions where less charge is collected can then become sensitive to upset. Supporting this argument, n-drain upsets are occurring at the same dose level (5Mrad(Si)) at which address access time begins to increase in Figure 3. An increase in saturation cross section with ionizing dose has been noted previously [17-19]. SEU images of an NEC 64k-bit SRAM showed changing cross section with dose, with sensitive area increasing in the p-drain and decreasing in the n-drain region [19]. In their work, however, the device power supply voltage had to be reduced to 0.4 V to observe an upset. In this work, we were able to image upsets at the nominal supply voltage of 5.0 V, since our facility can focus higher-Z ions.

**V. CONCLUSIONS**

In this work, we have shown that IBICC imaging is degraded by displacement damage effects alone in ICs. A model was developed that explained the degradation in terms of two regions of charge collection: one that is insensitive to damage in the depletion region, and one that is sensitive to damage beyond the depletion region. For the hardened circuits used in this study, adequate contrast could be obtained before degradation occurred. Only 100 to 200 scans were required to obtain good images for these devices; therefore, displacement damage does not impose a serious limitation on the use of the technique. In SEU imaging, we found that new regions can become sensitive to upset with dose. If ICs used in space systems accumulate sufficient dose for this effect to occur, the error rate may increase significantly. We note that these are very high doses and are not likely to be obtained in any realistic scenario. It is important to note, however, that the same effects may occur in commercial radiation-soft devices at much lower doses. We also note that microbeams provide a convenient way to study SEU with controlled radiation doses.

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**References**


