Heavy ion microscopy of single event upsets in CMOS SRAMs

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Abstract

The single event upset (SEU) imaging has been applied at the GSI heavy ion microprobe to determine the sensitivity of integrated circuits (IC) to heavy ion irradiation. This method offers the possibility to directly image those parts of an IC which are sensitive to ion-induced malfunctions. By a 3-dimensional simulation of charge collection across p-n micro-junctions we can predict SEU cross-sections.

For a MHS65162 2k x 8bit CMOS SRAM we found two regions per bit with different sensitivity and measured a total cross-section of $(71 \pm 18)\mu m^2$ for a bitflip per cell and simulated $60\mu m^2$ with an argon beam of $1.4 MeV_{\text{mol}}$ (LET of $19.7 MeV_{\text{mg/cm^2}}$).

I. INTRODUCTION

Heavy ion microprobes utilize electromagnetic lenses to focus ion beams to $\mu m$ dimensions and magnetic beam steers to scan the microbeam over a sample to produce high resolution images. By adding a fast beam shutter to an ordinary microprobe and detecting the hit of a heavy ion by detecting the emitted secondary electron cloud, it is possible to irradiate targets with single heavy ions [1, 2]. The high spatial resolution and position control of a microprobe can also be used to study SEU in ICs. When used in an upset mapping mode, the malfunction of the irradiated IC is detected and mapped. The resulting images can be used to directly measure the cross-section for an upset per cell.

II. THE MICROPROBE AT GSI

In principle a scanning heavy ion microprobe can be an instrument as simple as the setup shown in fig. 1. The wide ion beam coming from the UNILAC (universal linear accelerator), which can deliver all ions from carbon to uranium with energies between 1.4 and $20 MeV_{\text{mol}}$, is reduced to a narrow beamlet of a few $\mu m$ diameter by a set of two micro slits. The micro beam is focused onto the target by an ion optic lens. Because the focusing procedure requires intense beams, only beams of carbon, oxygen, neon, argon, calcium, nickel, krypton and xenon can be used. With these ions and energies LETs from 0.7 to $70 MeV_{\text{mg/cm^2}}$ and ranges of 15 to $500\mu m$ in silicon are available. The image of the target is built up on the display by sweeping the focused ion beam over the target where it releases various reaction products (electrons, X-rays, ions, light, etc.). The intensity of these products determines the brightness of the electron beam spot moving synchronously over the display screen. The design details of the GSI heavy ion microprobe are described elsewhere [1-3].

Figure 1: Minimum setup for a scanning ion microprobe

III. SEU IMAGING

We use ion-beams with low flux, typically less than $10^3 s^{-1}$. For single-particle techniques ions hitting onto the target must be detected reliably so that the beam can be switched off to prevent further particles from hitting the same target position. For this reason we use the detection of the emitted secondary electron cloud with a channel electron detector. With this type of detector we can clearly distinguish...
detector can also be used to produce ion induced secondary electron images of the target.

Beam positioning is normally done by scanning the microbeam over the area of interest and looking for a known "fingerprint" of the desired position. However, in SEU ima-

![Beam positioning](image)

When a hit of a single heavy ion has been detected by measuring the secondary electron cloud the following procedure starts: 1. the electrostatic beam switch is activated and the beam is switched off within 200ns, 2. an external computer scans the SRAM searching for bitflips, 3. if a bit-flip has been found a signal and the logical address of the SEU are sent to the data acquisition computer, 4. the actual beam coordinates of the microprobe at which the bit-flip occurred is set in the upset image, 5. if the scan through the SRAM is finished the beam is switched on and scanning is continued.

The upset images shown were measured while scanning a focused beam of \(^{40}\text{Ar}\) ions of 1.4 \(\text{MeV} \div \text{mg/cm}^2\) (LET of 19.7 \(\text{MeV} \div \text{mg/cm}^2\) and range of 15\(\mu\)m in Si) with a diameter of about 1\(\mu\)m across a MHS65162 2k x 8bit SRAM, which is fabricated in a \(N\)-well on \(P^+\)-epitaxial layer 1.5\(\mu\)m CMOS process with six transistor static RAM cells, consisting of two cross-coupled CMOS inverters and two n-channel pass transistors.

![SEU image](image)

In fig. 3 those beam coordinates of the microprobe are plotted, where upsets have been found after irradiating these positions with single \(^{40}\text{Ar}\) ions. The scatter plot shows the existence of two parts per cell with different sensitivity. Looking at the IC at the same magnification and comparing the SEU image to the cell design one finds another remarkable fact: the changing of the upset sensitive regions after altering the logical level from logic low to high. In fig.4 SEU images and cell design are drawn at the same magnification. From the SEU image it can be seen that the highest probability for an upset is found at the drain region of the n-channel transistor which is in the "off"-state ("N"-hit). But also at the
change their logical state at that LET. These results are in good agreement with earlier experiments which used wide ion beams to irradiate the whole IC [4].

IV. SIMULATIONS

Predictions of error rates for a given device require knowledge of the physical mechanism of charge generation along the particle track, the amount of charge collected across the SEU-sensitive microjunction and the response of the circuit to the current pulse.

When a charged particle traverses an IC there are depending on the position two ways of collecting the generated charges: 1. if the particle hits the drain area the total charge generated within the depletion and funneling region is collected by drift. 2. from outside or underneath the drain area charges can only be collected by diffusion. Expressions for the thickness of the depletion layer for given dopant concentrations and applied bias can be found in text books on semiconductor physics, e.g. [5]. According to McNulty et al. we assume that the probability for charges to be collected by diffusion is given by the solid angle $\Omega$ of a cubic junction at a distance from the point of charge generation [6]. The lateral dimensions of the SEU-sensitive junction are the same as those used for the SPICE simulations done by Twomey et al. [7]. The LET values have been taken from Hubert et al. [8]. We estimate the cross-sections for "N"- and "P"-hits by determining the area in our 3d-simulation in which the collected charge is above a threshold value. This so-called critical charge is calculated in a SPICE simulation [7] and gives for "N"-hits $0.3pC$ and $0.4pC$ for "P"-hits. These values were used to cut the contour plots of collected charge which are shown in fig. 5. The simulated sensitive areas are compared to the measured values in table 1. As can be seen the 3-dimensional charge collection model and the SPICE simulation fit the imaging of upset sensitive regions.

<table>
<thead>
<tr>
<th>critical charge for bit-flips</th>
<th>sensitive area simulated</th>
<th>sensitive area measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;N&quot;-hit 0.3</td>
<td>49</td>
<td>57 +/- 10</td>
</tr>
<tr>
<td>&quot;P&quot;-hit 0.4</td>
<td>11</td>
<td>14 +/- 8</td>
</tr>
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Table 1: Comparision of simulated and measured sensitive areas per cell in a MHS65162 CMOS SRAM after irradiating with $^{40}Ar$ of 1.4 MeV $\mu$A.

V. CONCLUSION

Scanned ion microbeams are widely used to study elemental compositions and are now increasingly used to investigate SEU in integrated circuits [9-11]. Using the heavy ion microprobe at GSI, we have been able to image the upset sensitive regions of a memory with $\mu$m resolution. From these images we can derive upset-cross-sections - usually statistically derived numbers - directly by measuring the area of the sensitive regions. In addition to this we can locate the sensitive
regions and measure the different sensitivities of elements within one memory cell.

The underlying physical process of generating and collecting charges can be simulated in a 3-dimensional model. This model is able to predict the upset-cross-sections, so that on the basis of this model predictions for other ions hitting the same SRAM should be possible.

VI. REFERENCES


