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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 possibilty 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 $1.4\frac{MeV}{nucl.}$ (LET of $19.7\frac{MeV}{mg/cm^2}$).

I. INTRODUCTION

Heavy ion microprobes utilize electromagnetic lenses to focus ion beams to µm dimensions and magnetic beam steerers 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 (<u>u</u>niversial <u>l</u>inear <u>acce</u>lerator), which can deliver all ions from carbon to uranium with energies between 1.4 and $20\frac{MeV}{nucl.}$, is reduced to a narrow beamlet of a few µm diameter by a set of two micro slits. The micro beam is focused onto the target by an ion optic lens. Because the focussing 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 $70\frac{MeV}{mg/cm^2}$ 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].

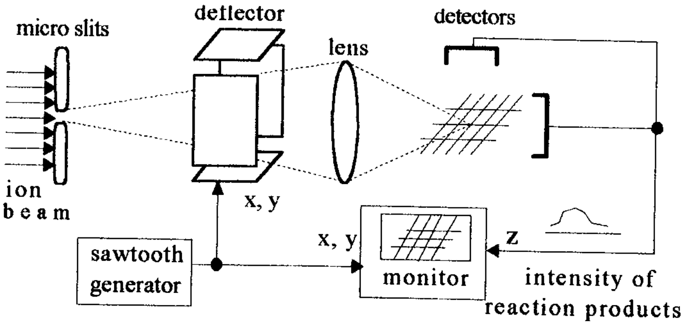

Figure 1: Minimum setup for a scanning ion microprobe

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

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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 imaging it is required that the area of interest must not be hit by energetic heavy ions before the experiment, and therefore an indirect positioning must be used. We accomplish the beam positioning in the following way: 1. imaging a special micro grid with ion induced secondary electrons (see fig. 2), 2. looking with a light microscope, which can be positioned with submicron accuracy, at the same target, 3. identifying the area in the secondary electron image with the light microscope (see fig. 2), 4. steering the micro beam so that the center of the secondary electron image coincides with the center of the optical image, 5. removing the micro grid and moving the area of interest of the IC into the center of the light microscope.

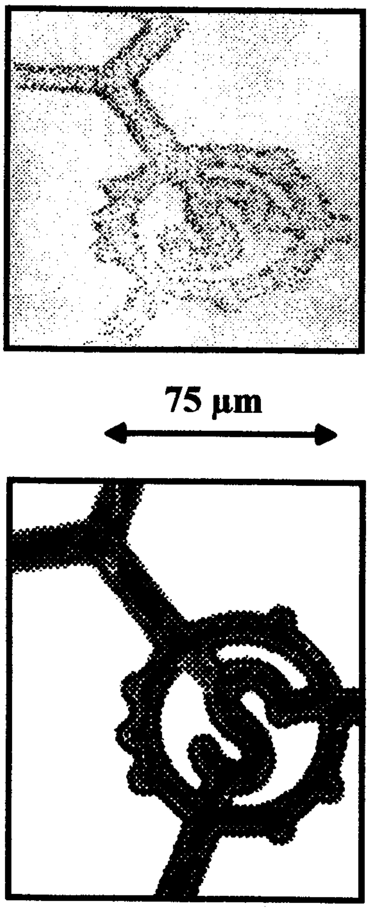

Figure 2: Beam positioning: ion induced secondary electron image (top) and light optical image (bottom) of a micro grid.

When single focused heavy ions are used to image SEU the impinging ion gives rise to two detected signals: 1. the emission of secondary electrons from the target (when the ion strikes the surface), 2. the change of the logical state in the target IC (resulting from the generation of charges within the chip as the ion penetrates the silicon).

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 occured 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}Ar ions of $1.4\frac{MeV}{nucl.}$ (LET of $19.7\frac{MeV}{mg/cm^2}$ and range of 15µm in Si) with a diameter of about 1µm across a $MHS65162$ $2k$ x $8bit$ SRAM, which is fabricated in a N-well on P^+-epitaxial layer 1.5µm CMOS process with six transistor static RAM cells, consisting of two cross-coupled CMOS inverters and two n-channel pass transistors.

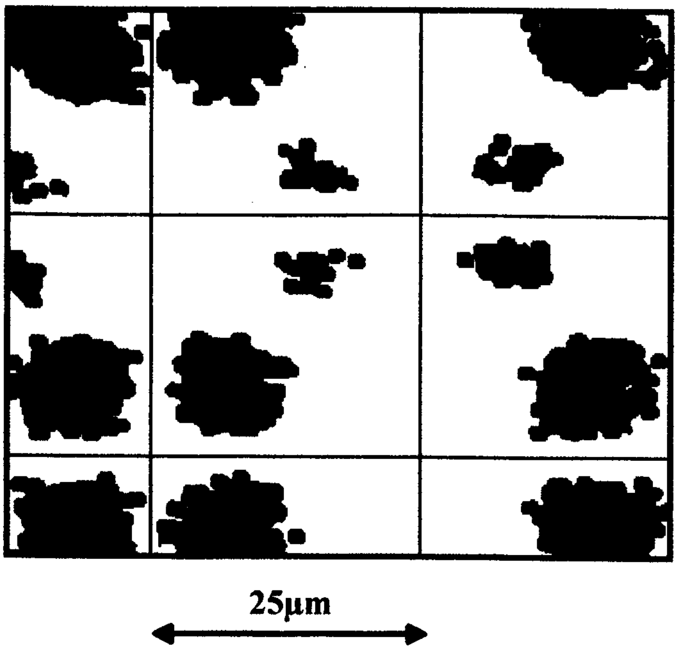

Figure 3: SEU image of a small part of a MHS65162 CMOS SRAM. Radiation induced bit-flips from "0" to "1" are shown. The cells are seperated by solid lines.

In fig. 3 those beam coordinates of the microprobe are plotted, where upsets have been found after irradiating these positions with single ^{40}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

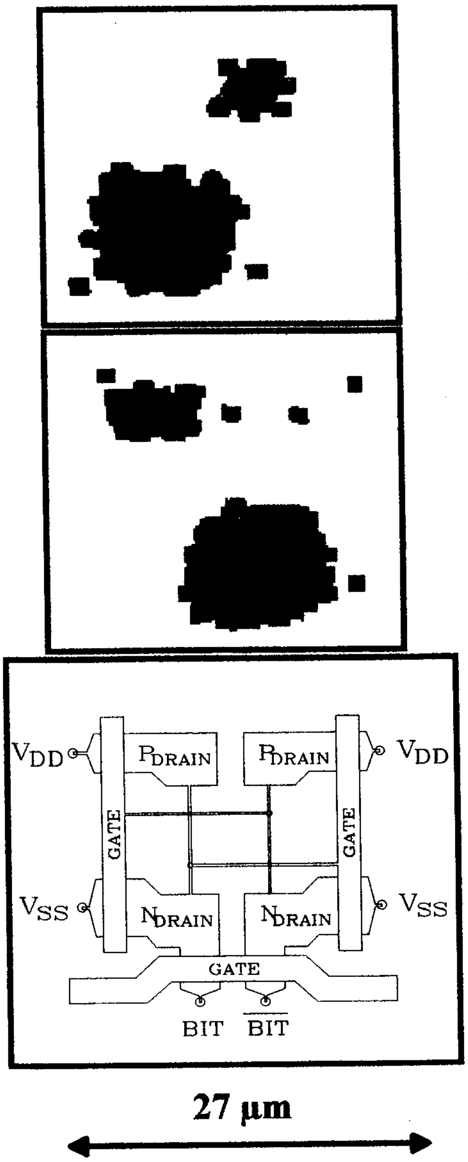

Figure 4: Comparison of SEU images and cell design of a memory cell. Bit-flips from "0" to "1" (top), "1" to "0" (middle) and cell design (bottom). In the image of the cell design only the drains are drawn as originally, the rest is modified to protect the owners proprietary rights.

drain region of the p-channel transistor in the "off"-state ("P"-hit) occur SEUs. These probabilities can be expressed by cross-sections which are the areas of the upset sensitive regions. Measuring the areas gives $(57 \pm 10)\mu m^2$ for "N"- and $(14 \pm 8)\mu m^2$ for "P"-hits and a total cross-section of $(71 \pm 18)\mu m^2$ per cell or $(1.16 \pm 0.30) x 10^{-2} cm^2$ per chip.

We get a similar result if we measure the cross-section in a more conventional way, that means dividing the total number of upsets (2232) by the total number of hits (19798) in fig. 3 which gives a probability of (0.11 ± 0.01) for a bit-flip. In other words 11% or $(81 \pm 7)\mu m^2$ of one cell or $(1.33 \pm 0.12) x 10^{-2} cm^2$ of the whole chip are sensitive to 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 reponse 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 Ω 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 determinating 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.

	critical charge for bit-flips [pC]	sensitive area simulated [µm²]	sensitive area measured [µm²]
"N"-hit	0.3	49	57 +/- 10
"P"-hit	0.4	11	14 +/- 8

Table 1: Comparision of simulated and measured sensitive areas per cell in a MHS65162 CMOS SRAM after irradiating with ^{40}Ar of $1.4\frac{MeV}{nucl.}$.

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 µm resolution. From these images we can derive upset-cross-sections - usually statisticly derived numbers - directly by measuring the area of the sensitive regions. In addition to this we can locate the sensitive

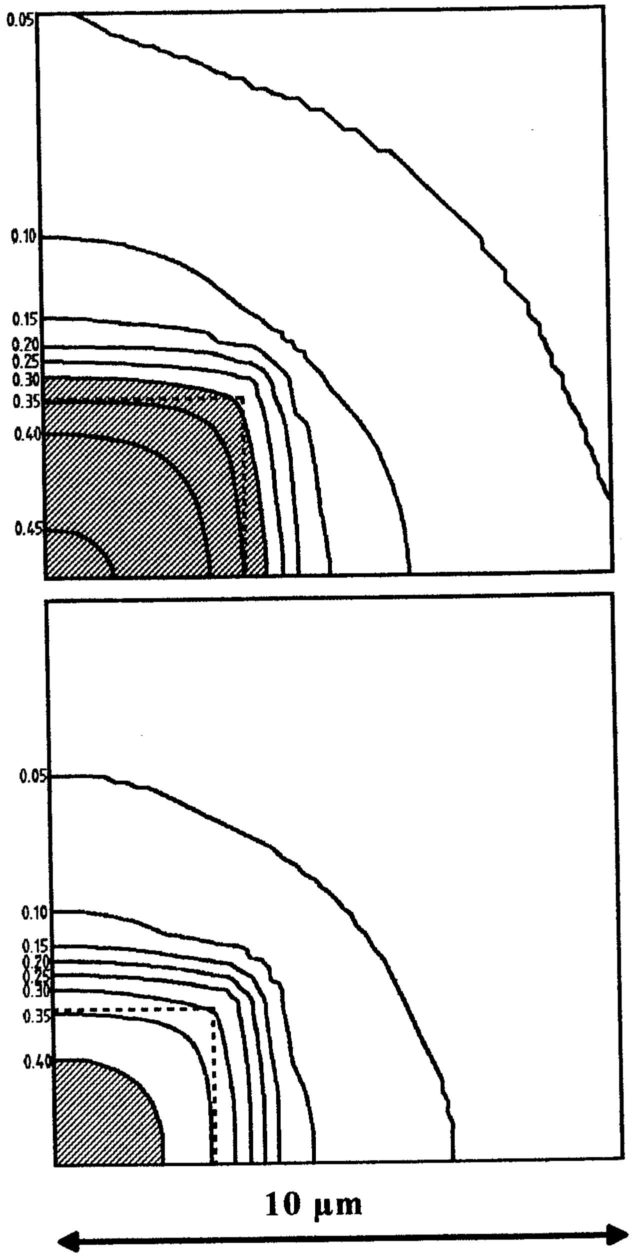

Figure 5: Contour plots of collected charge in the n-drain (top) and p-drain (bottom) in pC after hits with ^{40}Ar of $1.4\frac{MeV}{nucl.}$. Shown for one quadrant of a square shaped drain (within dashed lines). The areas of the drains are the same as those of a MHS65162 CMOS SRAM cell, only the shape is modified for simplicity. The sensitive area is hatched.

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

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