ESA-QCA00139-R93

STUDY OF SEUs GENERATED BY HIGH ENERGY IONS

J. Dreute, H. Röcher, and W. Heinrich
Universität-GH-Siegen, Fachbereich Physik, 57068 Siegen, Germany
R. Harboe-Sørensen and L. Adams
ESA-ESTEC, 2200 AG Noordwijk, The Netherlands
D. Schardt
Gesellschaft für Schwerionenforschung mbH, 64220 Darmstadt, Germany

Abstract

Using 1 GeV/nucleon ions SEUs have been studied in two types of CMOS-SRAMs with respect to tilt angle and tilt direction. Tracks of upset bits, which have been observed under large tilt angles, were used to determine the charge collection depth in these devices.

I. Exposure Conditions

A. Beams

We have continued our work [1] studying radiation effects of heavy ions in microelectronic devices at GSI Darmstadt (Germany). The activities have been concentrated on two different experimental facilities. On the one side, at the UNILAC, a 20 MeV/nucleon accelerator, a microprobe has been installed. It allows irradiation of devices by single ions with a local precision of a few μm. First results of experiments using the microprobe are reported by S. Metzger et al. [2] in a late paper contribution to this conference. On the other side, ions of the SIS with energies up to 1000 MeV/nucleon have been used in several experiments. Results of SEU testing using SIS beams are presented in this paper.

Particles with energies of several hundred MeV/nucleon represent the most abundant cosmic ray nuclei in space. They allow realistic simulations of cosmic ray effects on semiconductors in ground based experiments. These ions have ranges in material exceeding a few centimeters. Unopened devices can be exposed to particles penetrating the sensitive parts from all possible directions of incidence. At these high energies the LET remains almost constant inside the die.

Our experiments have been performed in several runs at cave A of the SIS. At this experimental area an exposure site with a beam diagnostic system has been installed to perform experiments in radiation biology. We have participated in different irradiations during the test phase and first radiobiological experiments. Special beams dedicated to our experiments have not been available. The main goal of our experiments has been to study SEUs at large tilt angles.

B. Devices tested

The devices tested are 2kx8 (MHS 65162) and 8kx8 (MHS 65664) Matra Harris SRAMs, for which information on device structure has been supported by the producer. These memories were designed using standard six transistor cells with four transistors for the flip-flop and two transitors for readout. The NMOS transistors are built in p-substrate and the PMOS transistors in an n-well. The 2kx8 is an epilayer device grown with a thickness of about $10\mu m$. Based on the device-structure the NMOS transistor is expected to be more sensitive than the PMOS transistor. The drain areas have a size of about $37\mu m^2$ for the NMOS transistor and about $30\mu m^2$ for the PMOS transistor, respectively. The total area of one cell is about $700\mu m^2$. From the LET dependent cross section curve [1] for this device a saturation cross section of about $150\mu m^2$ per bit can be derived which significantly exceeds the geometric dimensions of the drains. This observation underlines the importance of charge collection processes for SEU generation.

II. Cross sections for tilted devices

SEU cross sections σ as a function of LET generally are measured using low energy beams and devices tilted by an angle φ against the beam direction to get an effective LET increased by a factor of $\sec\varphi$. The validity of this concept has been questioned by T.L.Criswell et al. [3]. Using ions of the Berkeley BEVALAC with energies of several hundred MeV/nucleon they have shown that for the AMD 27LS00 bipolar device SEU cross sections depend on ion species and do not scale with $\sec\varphi$, whereas the concept of effective LET holds for another device (Fairchild 93L422). Additionally, they have observed that cross sections for the 27LS00 differ by three orders of magnitude for upsets generated by 30 MeV/nucleon Ne and 450 MeV/nucleon Fe ions, i.e. for ions having the same LET but different charge and velocity. This effect was not observed for the 93L422 device.

0-7803-1793-9/$4.00©1994IEEE

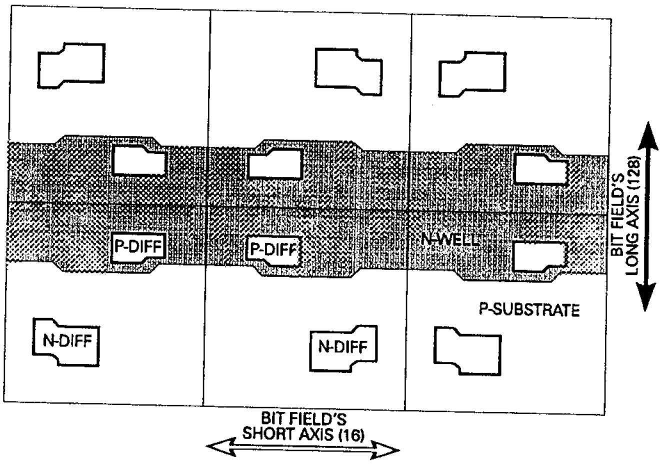

Figure 1: Location of the sensitive drain diffusions in six adjacent cells. Every cell contains the same binary information. The insensitive transistors of the flip-flop (in the on-state) are not drawn.

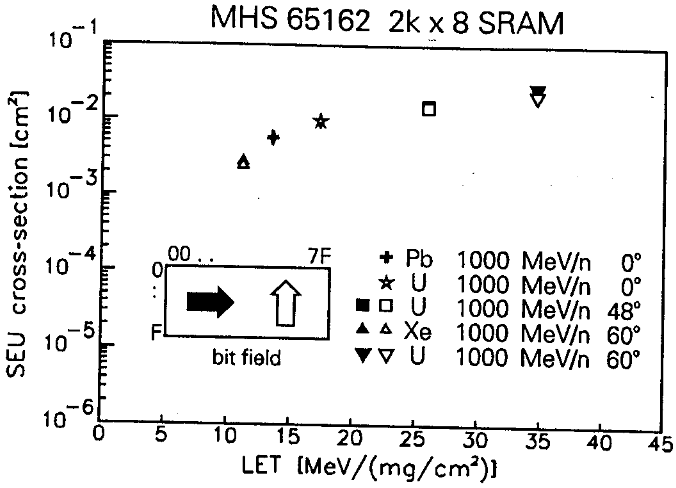

Figure 2: Device cross section of the 2kx8 SRAM measured for ions of different energy impinging with different orientation to the bit field. LET is given inside the die. For tilted devices LET$\cdot \sec \varphi$ is plotted. Closed symbols are used for devices exposed in direction of the long axis of the bit field and open symbols for the short axis, respectively.

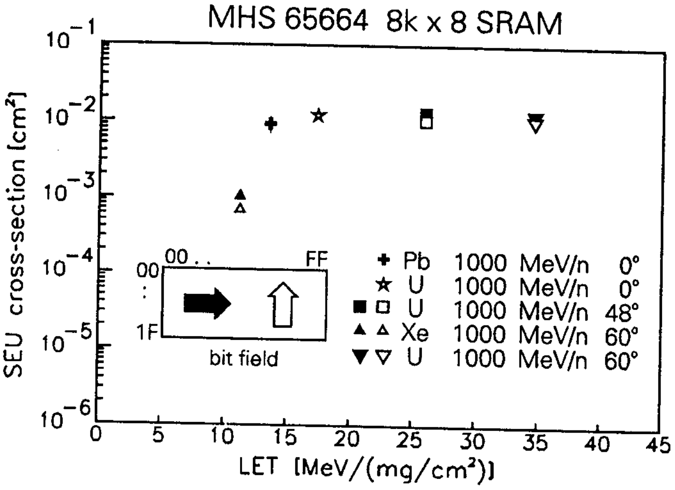

Figure 3: Device cross sections of the 8kx8 SRAM. For details see figure 2.

A. *Experimental Details*

In our experiments we have used Xe, Pb and U ions with an energy of 1000 MeV/nucleon to investigate special effects of high energy ions. We have restricted the experiment to well defined exposure conditions. The ions penetrated only a beam pipe window of $156 mg/cm^2$ thickness, followed by about one meter of air, and less than $200 mg/cm^2$ material of beam diagnostic detectors. No degraders have been used to get beams with different energy and LET. The main experimental uncertainties of measured cross sections arise from beam non-uniformities and fluctuations in flux. To overcome this problem we have used CR-39 plastic nuclear track detector foils, which have been slid into the beam line in front of the device during the exposure. Each particle impinging on the device also penetrates the detector foil and generates a radiation damage along its path. This damage can be made visible under an optical microscope after etching the foils in NaOH. For individual tracks the positions and the track size, which corresponds to LET, are measured using a completely computerized microscope [4]. Contamination of the beam by fragments produced in the CR-39 detectors can be neglected since the thickness of the detectors is only $0.6 mm$.

B. *Results*

Devices tilted in two different directions with respect to the bit field have been exposed. For the 2kx8 the location of single RAM cells inside the bit field is given in figure 1. Only the drain diffusions of those transistors sensitive for upset are drawn. Device cross sections measured for the 2kx8 SRAM are shown in figure 2 as a function of LET inside the die. The errors of the data points, including SEU counting statistics, flux and beam profile fluctuations, and uncertainties of calculated LET, in all cases are smaller than the symbols used in the plot. The data of figure 2 for the three different ions, different tilt angles, and tilt directions follow a common curve. No dependence on tilt direction and no difference between tilted and untilted devices which exceed three standard deviations significance can be observed.

Figure 3 shows the cross sections for the 8kx8 SRAM. These data show no large differences of measured cross sections for tilted and untilted devices and for different tilt directions, either. Comparing the data of devices tilted around different axes in figures 2 and 3 some systematics

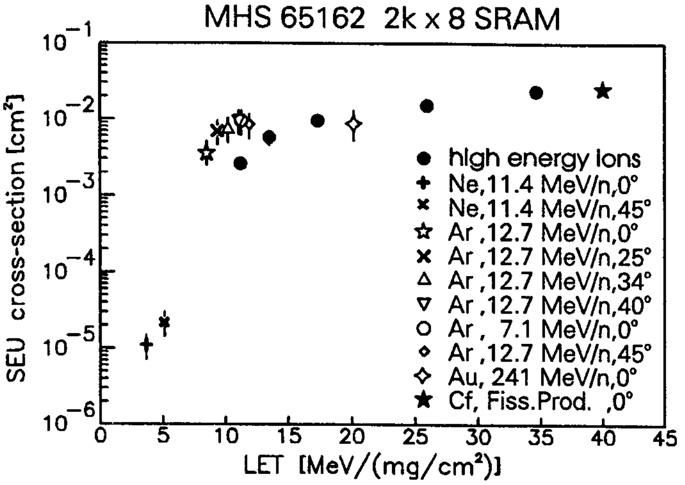

Figure 4: Comparison of device cross sections measured for the 2kx8 SRAM for high energy ions (data of figure 2) with results of earlier measurements [1].

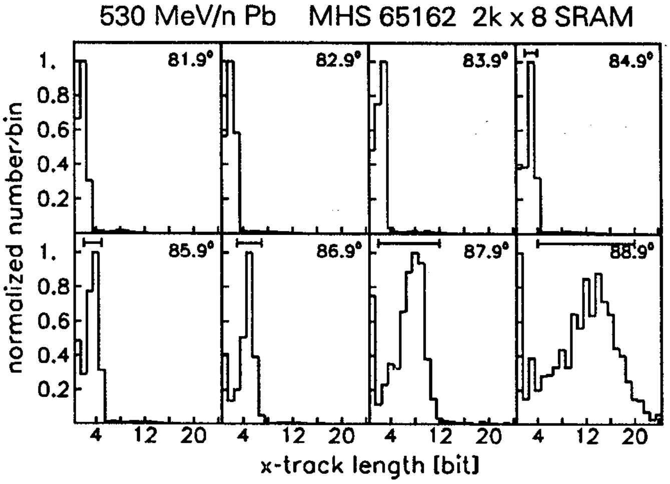

Figure 5: Track length distributions for the 2kx8 SRAM at different tilt angles for Pb ions. Total track numbers ranging from 3575 at 84.9° to 1366 at 88.9°.

are indicated. The results of all exposures show that for tilted devices in case of rotation around the short axis of the memory plane the cross sections are smaller than for a rotation around the long axis. An influence of tilt angle and direction on the measured cross sections cannot be excluded.

The 8kx8 SRAM has a design similar to that one of the 2kx8 but a cell size reduced by a factor of 0.5, i.e. the geometric size of one bit is reduced by a factor of 0.25 whereas the number of bits is increased by a factor of four. This explains that absolut values of cross sections within the platau region are comparable for both devices.

In figure 4 we compare the data of figure 2 with cross sections which we have measured before for the 2kx8 device [1]. The data point measured before for Cf fission products agrees well with results of relativistic U ions at large tilt angles. This observation underlines the importance of the simple and inexpensive method of Cf testing to determine asymptotic cross sections.

For LETs below 15 MeV/(mg/cm^2) in our earlier experiments low energy ions of the UNILAC have been used. For these particles beam flux has also been monitored using CR-39 detectors. However, due to the short range of these ions, the detectors could not be exposed together with the devices but either before or after SEU testing. This implies larger uncertainties of measured cross sections which dominate the error bars of these data. Differences up to a factor of three in measured cross sections for particles of same LET but different velocity can be observed in figure 4 for small LETs. These differences, which may be caused by track structure effects, are small compared to the three orders of magnitude which have been observed by Criswell et al. [3] for the 27LS00 device.

III. TRACKS OF UPSET BITS

Tracks of upset bits should be observed if a high energy ion with large penetration power moves almost parallel through the memory plane of a device. Observations of such tracks have been reported before [5, 3, 1]. For tilt angles greater than approximately 70° we have observed clusters of bits upset by a single ion. These clusters grow in length with increasing angle and become tracks. The maximum track length occurs with the beam almost parallel to the device. Especially tracks following the direction of the bit field's long axis have been studied in detail. We have reconstructed these tracks based on the bitmaps of the memories. Tracks which intersect the physical end of the memory ($x = 0$ and $x = 127$) have been excluded. Since the alignment of the device axis is never perfectly parallel to the beam direction a crossing-over of a track from one bit line to the next one with a gap in the data is possible. Therefore we allowed a maximum gap length of six bits in the track reconstruction procedure.

Figure 5 shows results for an exposure of the 2kx8 device to a 530 MeV/nucleon Pb beam. Distributions of observed track lengths for different angles of tilt are shown. These distributions give the differential probability to observe a certain track length. Since the absolute number of tracks is reduced considerably for angles close to 90° all plots have been normalized to one for the maximum of the histogram. Events with only one single upset bit (track length one) are observed with a high probability for all angles of tilt. For track length ≥ 2 the probability follows a function with an asymmetric broadening towards smaller track lengths. In all cases long tracks are observed with a small probability. Certainly some details of beam divergence are reflected by these distributions, however, they depend significantly on tilt angle.

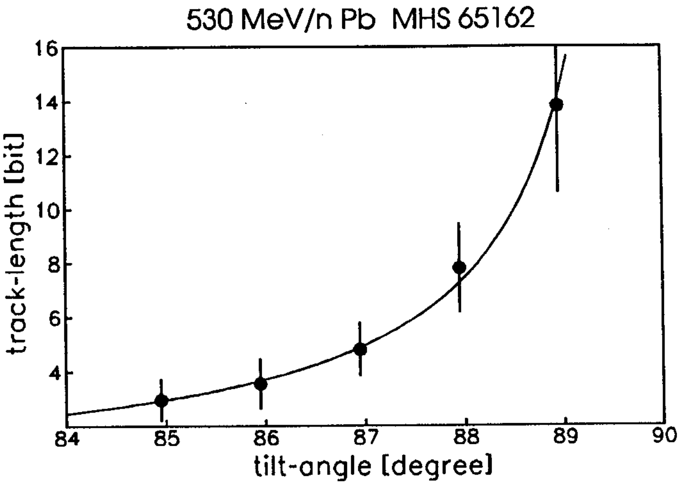

Figure 6: Mean track length as a function of tilt angle for the histograms shown in figure 5. The curve has been fitted based on a tan φ dependence (see text).

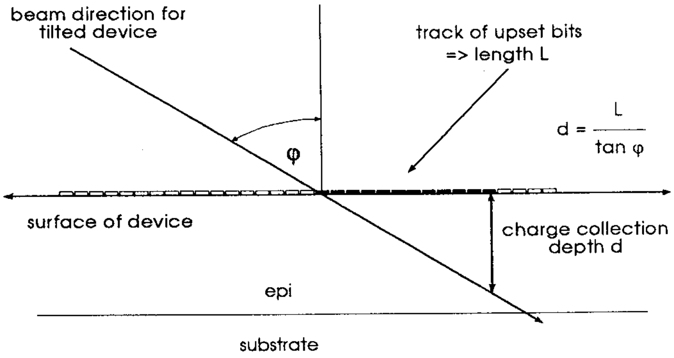

Figure 7: Relation between track length L and charge collection depth d.

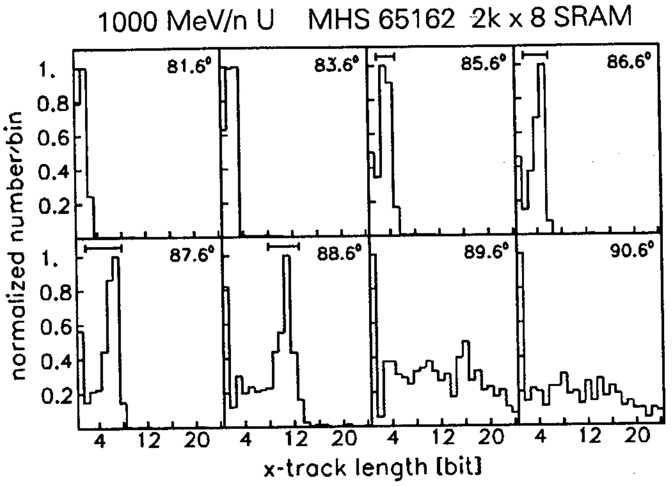

Figure 8: Track length distributions for the 2kx8 SRAM at different tilt angles for U ions. Total track numbers ranging from 2729 at 85.6° to 940 at 88.6°.

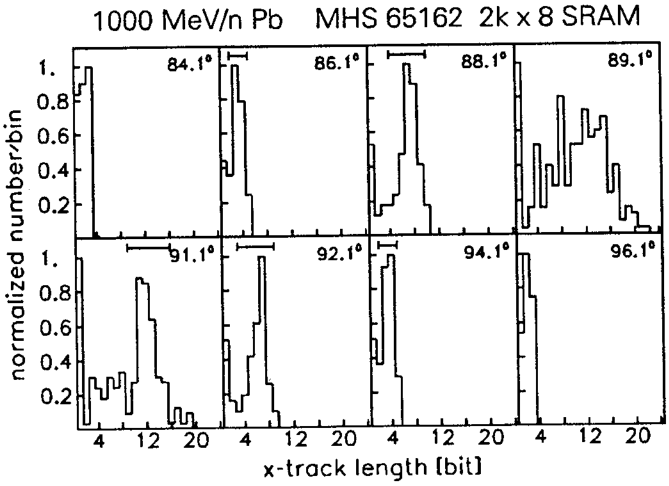

Figure 9: Track length distributions for the 2kx8 SRAM at different tilt angles for Pb ions. Total track numbers ranging from 205 at 91.1° to 71 at 88.1°.

A. Charge Collection

To investigate the mechanism of track formation in more detail we have determined an average track length for each histogram. For this purpose only those parts of the histograms marked by the bar on the top have been considered. Figure 6 shows the mean track length determined as a function of tilt angle. Errors of mean track length resulting from the data of the histograms are also included.

The curve in figure 6 is a fit to the experimental data based on a simple model of track formation, which is schematically shown in figure 7. For an ion penetrating a device under a tilt angle φ only those bits are upset which can collect sufficient charge from the layer below. A mean track length L corresponds to a mean charge collection depth d. These are related by $L = d \tan \varphi$. Based on this idea the data points shown in figure 6 should follow a $\tan \varphi$ curve. Due to alignment problems the absolute value of the tilt angle is known only with an offset φ_0 (typically less than one degree) which is constant within one experiment. Therefore we have fitted a curve $L = d \tan(\varphi + \varphi_0)$ to the data. The φ-values shown in figure 6 and the tilt angles given for individual histograms in figure 5 have already been corrected for φ_0. As a result we find d =0.26 bit. To determine an absolute value of d we use the distance between two bit cells of $\approx 27 \mu m$. As a result we finally get $d \approx 7 \mu m$.

B. LET Dependence

We have repeated this experiment for the 2kx8 device for U, Pb and Xe ions with an energy of 1000 MeV/nucleon to investigate the dependence of track formation on LET. The track length distributions for these ions are presented in figures 8 to 10. These data have been analyzed as described above. As a result we get d depending on the LET of the

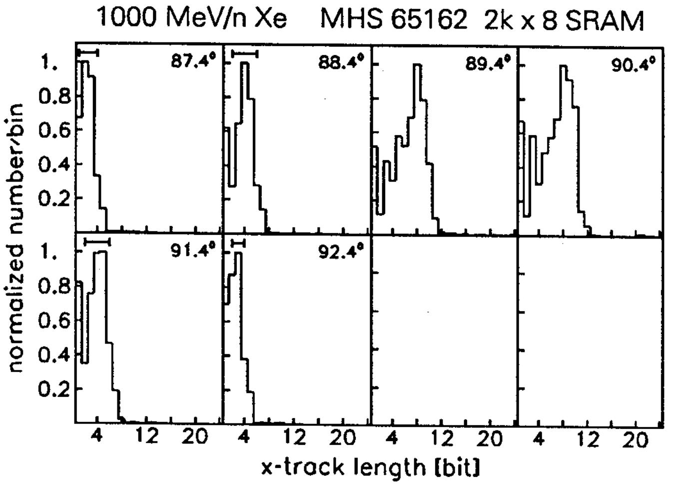

Figure 10: Track length distributions for the 2kx8 SRAM at different tilt angles for Xe ions. Total track numbers ranging from 3409 at 88.4° to 4883 at 92.4°.

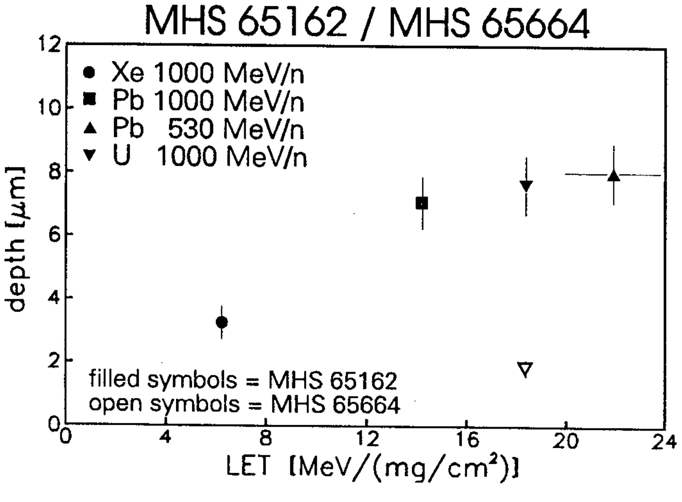

Figure 11: Mean charge collection depth as a function of LET for the 2kx8 and the 8kx8 SRAM.

ions inside the device. For each beam the energy of the ions after penetration of the device's package was calculated and the LET inside the memory plane was determined. These data are shown in figure 11. Within the errors of the three data points at high LET ($\geq 14 MeV/(mg/cm^2)$) the charge collection depth is constant and extends nearly down to the depth of the epilayer.

The results for 1000 MeV/nucleon Xe ions are of particular interest. These ions have an LET of $6.2 MeV/(mg/cm^2)$ inside the memory. Since this value is close to the threshold of the σ(LET) curve only few upsets for zero degree tilt angle are observed. However, for about 90° tilt angle tracks of upset bits with a considerable length as shown in figure 10 are formed. This increase of the cross section for single bit upsets under large tilt angles near the threshold has been observed before by Criswell et. al. [3]. The charge collection depth determined from these data does not extend down to the depth of the epilayer.

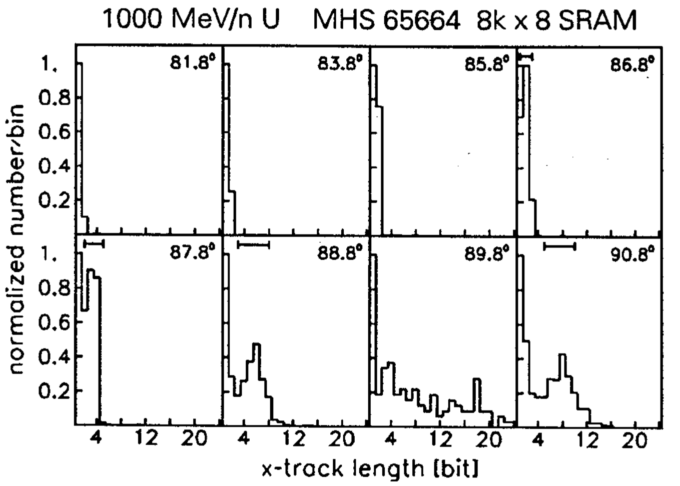

Figure 12: Track length distributions for the 8kx8 SRAM at different tilt angles for U ions. Total track numbers ranging from 1542 at 81.8° to 695 at 90.8°.

Some conclusions can be drawn about the dependence of the track formation process on the device's structure from data which have been taken for the 8kx8 SRAM (MHS 65664) at high LETs. Figure 12 shows track length distributions for a 1000 MeV/nucleon U beam. It must be considered that the bit geometry of the 8kx8 device is reduced in comparison to the 2kx8 device. The mean charge collection depth determined from the data of figure 12 is $1.9 \mu m$. This is only about half the depth of the epilayer ($5 \mu m$ for this device), however, the difference of $3 \mu m$ was also observed for the 2kx8 device. This may be caused by doping profiles at the interface between wafer and epilayer. Based on this idea we assume that the epilayer prevents measurement of possibly larger charge collection depths at high LET values.

An LET dependence which is not reflected by track length but by track width has been observed. For all LET values in general a track width of a single bit is observed. For tracks crossing-over two bit lines, however, the structure of the transition depends on LET. For small LETs gaps between the parts of the tracks are observed. These gaps decrease in length for increased LET. Finally, at large LETs, even bits set up in both involved bit lines have been observed.

IV. SUMMARY AND CONCLUSIONS

The SEU sensitivity of two SRAMs manufactured with comparable technology but different cell size and depth of epilayer has been investigated by exposure to ions under tilt angles. Our results for $\varphi \leq 60°$ only show small deviations from a scaling of cross sections with the secant of tilt angle. The dependence of the cross sections on tilt direction is small, too. The plateau cross section for the 2kx8 device measured before with Cf fission products has been confirmed with 1000 MeV/nucleon U ions at larger tilt angles. Differences in cross sections for particles of the same LET but different charge and energy observed in our experiments do not exceed a factor of three. We conclude that the $\sigma(LET)$ determined with low energy ions under different tilt angles and californium testing are a valid approximation to estimate cosmic ray effects for particles impinging under angles below 60°.

Tracks of upset bits for exposures at about 90° tilt angle were used to investigate the mechanism of charge collection by the sensitive volume. At high LETs, in both devices the charge is collected from a depth extending almost down to the depth of the epilayer. The remaining difference of 2 to $3\mu m$ is likely to result from the doping profile. For LET values below the threshold of the σ(LET) curve still sufficient charge is collected to form long tracks of upset bits. However, as observed for the 2kx8 device, the collection depth is restricted to smaller distances than the epilayer's thickness.

The behaviour of the tested devices for large tilt angles underlines the problems involved in SEU rate predictions for space missions with a 4π exposure geometry. Multiple upset bits or even tracks of upset bits are formed in a wide angular interval of $70° < \varphi < 90°$. However, the device's design parameters like cell size and depth of epilayer determine the track lengths. Therefore it should be possible to model cluster and track effects if the structure is known. Efforts in this direction must be included in SEU prediction work.

V. ACKNOWLEDGEMENTS

We are grateful for support by the GSI staff during our experiments. MHS has supported us with technical details of the tested devices. We especially thank T. Bion and T. Corbière who were very cooperating. The Siegen group acknowledges financial support by ESA/ESTEC.

REFERENCES

[1] J. Dreute, W.Heinrich, H. Röcher, R. Harboe-Sørensen, L. Adams, D. Schardt, and J. Vetter. "Investigation of Single Event Effects of High Energetic Heavy Ions". In *Proceedings of RADECS 91, La Grande-Motte, France, IEEE Cat. No. 91th0400-2*, pages 505–508, 9 1991.

[2] S. Metzger, J. Dreute, W. Heinrich, H. Röcher, B. E. Fischer, R. Harboe-Sørensen, and L. Adams. "Heavy Ion Microscopy of Single Event Upsets in CMOS SRAMS". In *Proceedings of RADECS 93*, 9 1993.

[3] T.L. Criswell, D.L. Oberg, J.S. West, P.R. Measel, and W.E. Wilson. "Measurements of SEU Thresholds and Cross Sections at Fixed Angles". *IEEE Trans. Nucl. Sci.*, NS-34, No. 6, 12 1987.

[4] W. Trakowski, B. Schöfer, J. Dreute, S. Sonntag, C. Brechtmann, J. Beer, H. Drechsel, and W. Heinrich. "An Automatic Measuring System for Particle Tracks in Plastic Detectors". *Nuclear Instruments and Methods in Physics Research*, 225:92–100, 1984.

[5] T.L. Criswell, P.R. Measel, and K.L. Wahlin. "Single Event Upset Testing With Relativistic Heavy Ions". *IEEE Trans. Nucl. Sci.*, NS-31:1559–1561, 1984.