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Influence of heavy ion flux on single event effect testing in memory devices

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A B S T R A C T

The natural space presents a particle flux variable environment and choosing a suitable flux value for ground-based single event experiments is an unresolved problem so far. In this work, various types of memory devices have been tested over the ion flux range from 10 to 10^5 ions/(cm^2·s) using different ions covering LET from 10.1 to 99.8 MeV·cm^2/mg. It was found that for most devices the error rates of single event upsets are affected by the applied flux value. And the effect involving flux becomes prominent as it is increased above 10^3 ions/(cm^2·s). Different devices behave differently as the flux is increased and the flux effect depends strongly on the LET of the impinging ions. The results concluded in this experiment are discussed in detail and recommendations for choosing appropriate experimental flux are given.

1. Introduction

Single event effects (SEEs) [1–3], resulting from energetic particles penetrating sensitive volumes in semiconductor devices, pose a fundamental threat to the microelectronics equipped in space borne vehicles. The natural space radiation environment is extremely complicated which is composed of various types of energetic particles at different flux levels [4,5]. Basically, according to the particle origin there are three radiation types: Galactic cosmic rays [6], solar particle events [7], and earth radiation belts [8]. Each of these types is of difference particle composition with different particle fluxes. Moreover, the particle fluxes of these types are not constant which is modulated by solar activities at a 11-year cycle [9]. Solar disturbances occasionally cause much larger fluxes of particles and the peak flux during a solar particle event (SPE) may be two to five orders of magnitude larger than the non-SPE radiation condition [10,11].

To evaluate whether or not the device is suitable for the space mission, ground-based test is introduced to simulate the space radiation environment. Spacecraft in different orbits experience different particle fluxes and the fluxes undulate during the whole mission span [12,13]. On the other hand, the flux for ground-based single event experiments is always set to a fixed value.

Furthermore, no test guidelines or test standards have indicated what specific flux to be applied during the experiments. ASTM F1192 [14] and ESA/SCC basic specification No. 25100 [15] only suggest the ion flux range of 10^2–10^5 ions/(cm^2·s). EIA/JEDEC57 [16] indicates that lower flux experiment is preferable which is more mimicking the natural radiation environment. In reality, sometimes much higher ion flux is used due to the time efficiency of the higher flux condition. Whether the experimental flux may adequately simulate the natural complex flux environment is an unresolved issue.

Until now, not too many studies have been done regarding the ion flux influence on the single event effect. Edmonds in his work [17] indicated that single event error rate of triple module redundancy (TMR) hardened device has flux dependence. Yu et al. reported the test result differences between high flux and low flux for various hardened devices and observed that the single event cross sections for some devices exhibited flux dependency while some did not [18].

To address this issue, the experiment work in this paper was set out to study the influence of ion flux on single event effect in the microelectronic devices. The ion flux influence was investigated among various types of devices including harden and unhardened ones. The difference between high flux and low flux was studied and the effect of ion beam at high flux level was explored whether it is appropriate to present the low flux level for it is more time efficient during the experiment. Recommendations for the selec-

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tion of appropriate ion flux in ground-based experiments are also given.

2. Experimental details

2.1. Devices under test (DUT)

Seven types of devices from different vendors were selected for the flux related single event effect test including bulk-Si and silicon-on-insulator (SOI) static random access memories (SRAMs), Flip-Flop, and programmable read-only memory (PROM). The complete specification of the devices under test is listed in Table 1. The devices from vendor A are SOI SRAMs with unhardened structure and the hardened structure obtained by implementing active delay element (ADE) [19]. In order to enhance test procedure efficiency, the different device structures from vendor C are fabricated on the same chip with each memory size of 16 kb. The hardened parts from vendor C include dual interlocked storage cell (DICE) [20], TMR, and TMR coupled with DICE. The technology nodes varied from 0.5 μm to 65 nm. All the samples were delidded before irradiation.

2.2. Experimental setup

The irradiation experiments were carried out at the Heavy Ion Research Facility in Lanzhou (HIRFL) in Institute of Modern Physics, Chinese Academy of Sciences by using three kinds of heavy ions: ^{58}Ni, ^{86}Kr, and ^{209}Bi. The ion fluence detector was placed in the vacuum chamber and the aluminum foil was placed in the air right behind the vacuum window working as a degrader. The DUT was placed along the beam line behind the aluminum degrader. To achieve different linear energy transfer (LET) [21], different combinations of aluminum thickness and air gap were applied. In the case of Kr ions, the DUT was also tilted against the beam line. Table 2 lists the LET at the surface of the device calculated by SRIM code [22] and the effective LET at the tilted angle was calculated by applying the cosine law [23]. The accumulated ion fluence for each test run was different. According to [24], we set out to test the devices to the same error count, mostly more than 300.

2.3. Beam condition and calibration

The original ion beam was tuned by the deflecting magnet at the entrance of the main accelerator (Separated Sector Cyclotron) by controlling the amount of the particles entering into the accelerator [25]. The ion flux can be varied from the lowest value of 10 ions/(cm^2·s) up to the detection limit of 10^5 ions/(cm^2·s) and be stabilized within 20% fluctuation. The beam arriving at the irradiation terminal was a round spot of about 5 mm in diameter. Then the beam was scanned over to a 3×3 cm^2 square region at the frequency of 200 Hz in horizontal direction and 77 Hz in vertical direction and the uniformity of the beam was within ±5%.

The ion fluence detector was calibrated by placing a membrane behind the detector and then comparing the counting result of ion tracks in the membrane. The ion beam passed through the detector and then irradiated at the membrane. The membrane was etched after the irradiation with each hole in the membrane represented an ion track. We calibrated the detector by irradiating at different fluxes from 10^2 to 10^5 ions/(cm^2·s). At each flux value the deviation between the counts of ion fluence detector and the membrane was within ±5%.

3. Experimental results and analysis

3.1. Impact of flux level

The devices were tested under different fluxes to study the flux impact on single event upset (SEU). Fig. 1 shows the test results of SEU cross sections for the SOI SRAMs irradiated with Bi ions at the LET of 99.8 MeV·cm^2/mg at different flux values. Note that the vertical scale of the SEU cross section was decimal and there was a break in the y-axis in order to exhibit the curve clearly. The horizontal coordinate was from 10 to 2×10^4 ions/(cm^2·s) and was scaled to denary logarithm. The errors at 10 ions/(cm^2·s) were accumulated to 100 and the errors above 10^2 ions/(cm^2·s) were more than 300 as the error bar shown at 10 ions/(cm^2·s) was the largest.

The DUT #3 was an ADE hardened device with SEU cross section much lower than its unhardened counterparts. The SEU cross sections for all SOI SRAMs exhibited the same trend as the flux was increased which showed that the cross sections did not alter too much when the ion flux was in the range 10–10^3 ions/(cm^2·s) and the cross sections increased steadily as the ion flux was increased above 10^3 ions/(cm^2·s). For DUT #3 the SEU cross section at 2×10^4 ions/(cm^2·s) was found 40% larger as compared to that at 10 ions/(cm^2·s).

The devices from vendor A were also tested with other LETs. Fig. 2 shows the SEU cross sections of SOI SRAMs irradiated with Kr ions at the LET of 37.6 MeV·cm^2/mg at different fluxes. The diagram is drawn according to the same rule as Fig. 1. The characteristics of the curves shown in Fig. 2 are much similar to Fig. 1, that the SEU cross section stayed the same within experimental error as the ion flux was below 10^3 ions/(cm^2·s), and began to increase as the flux was increased above 10^3 ions/(cm^2·s).

Other devices have been tested according to the same strategy. Fig. 3 shows the SEU test result of PROM with Kr ions at the LET of 30.1 MeV·cm^2/mg. The same SEU trend appeared as the test results of the SOI SRAMs. While the flux was below 10^3 ions/(cm^2·s) the cross section hardly changed, and as the flux was increased above 10^3 ions/(cm^2·s) the cross section started to increase. The experiment was tested to 10^5 ions/(cm^2·s) and as the flux reached 10^5 ions/(cm^2·s) the SEU cross section increased drastically extending the rising trend.

Table 1
Specification of the devices under test.

Vendor	Device Type	Fabrication Technology	Feature Size	Memory Size	Structure Feature	DUT No.
A	SRAM	SOI	0.5 μm	1 Mb	Unhardened	#1
			0.35 μm	1 Mb	Unhardened	#2
			0.18 μm	4 Mb	ADE hardened	#3
B	SRAM	Bulk-Si	90 nm	1 Mb	Unhardened	#4
			90 nm	512 kb	Unhardened	#5
C	D-Flip flop	Bulk-Si	65 nm	16 kb × 4	Unhardened, DICE, TMR, TMR coupled with DICE	#6
D	PROM	Bulk-Si (anti-fuse)	0.18 μm	256 kb	Hardened	#7

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