Angular dependence of multiple-bit upset response in static random access memories under heavy ion irradiation*

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Experimental evidence is presented relevant to the angular dependences of multiple-bit upset (MBU) rates and patterns in static random access memories (SRAMs) under heavy ion irradiation. The single event upset (SEU) cross sections under tilted ion strikes are overestimated by 23.9%−84.6%, compared with under normally incident ion with the equivalent linear energy transfer (LET) value of ∼ 41 MeV/(mg/cm^2), which can be partially explained by the fact that the MBU rate for tilted ions of 30° is 8.5%–9.8% higher than for normally incident ions. While at a lower LET of ∼ 9.5 MeV/(mg/cm^2), no clear discrepancy is observed. Moreover, since the ion trajectories at normal and tilted incidences are different, the predominant double-bit upset (DBU) patterns measured are different in both conditions. Those differences depend on the LET values of heavy ions and devices under test. Thus, effective LET method should be used carefully in ground-based testing of single event effects (SEE) sensitivity, especially in MBU-sensitive devices.

Keywords: single event effects, effective LET method, multiple-bit upset, upset cross section

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1. Introduction

As complementary metal–oxide–semiconductor (CMOS) technology scales down, single event effects (SEEs) are becoming critical reliability threats for electronic devices used in a radiation environment.[1–3] Earth-based testing is thus of primary importance to guarantee the reliability of integrated circuits (IC) for space missions.[4] During laboratory testing at accelerators, angled ion strikes are often used to achieve higher effective linear energy transfer (LET) values conveniently by

$$\mathrm{LET_{eff}} = \mathrm{LET_0}/\cos(\theta), \tag{1}$$

where $\mathrm{LET_{eff}}$ means the effective LET for tilted ions incident at an angle of θ and $\mathrm{LET_0}$ denotes the initial LET for normally incident ions.[5,6] Under the assumption of thin rectangular parallelepiped (RPP) shaped sensitive volume, the path length of tilted ion in the sensitive volume is increased by a factor of $1/\cos(\theta)$, in comparison with that of normally incident ion. Thus, tilted ion creates $1/\cos(\theta)$ more charges in the sensitive volume and then has effective LET increased by a factor of $1/\cos(\theta)$. This approach has been extensively used in the past decades.

However, many experimental results have shown the inherent failings of this effective LET method.[4,7–9] Previous studies mainly focused on the failing mechanisms and corrections of this approach in terms of the breakdown of thin RPP assumption for small-geometry devices,[10–12] or the angle-invariant funneling and diffusion charge collection processes.[5,10,13–15] In addition, device-orientation effects[16–18] has also received increasing attention recently. Tilted ion strikes are usually performed at a single device-orientation (chosen randomly) which may miss the worst case SEE response and cannot evaluate the device sensitivity accurately. But, few data have been published considering the angular dependence of multiple-bit upsets (MBU).[19] As an ion injects into a chip at a tilted angle, more cells might be affected by the single oblique trajectory passing through several sensitive volumes, especially in advanced technologies with reduced spacing between adjacent cells.

The major focus of this paper is to investigate the angular dependence of MBU response in static random access memory (SRAM) devices. The single event upset (SEU) and MBU responses of SRAM devices to ions at normal and tilted incidences, with equivalent effective LET, are directly compared. The energy of normally incident ion at the die surface is degraded to match with that of tilted ion at the same LET value. Heavy ion experimental results show that the SEU cross section and MBU response exhibit a strong dependence on angle.

The experimental setup is presented in Section 2, including devices under test, beam information and test system and so on. In Section 3 the experimental results and analyses are presented, and some conclusions are drawn in Section 4.

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2. Experimental setup

In this work, two military-level bulk silicon SRAM devices from integrated device technology (IDT) company, i.e. IDT7164 (64 kb) and IDT71256 (256 kb) were irradiated. The test devices were de-capped before exposure so that heavy ions could reach the sensitive regions. The IDT SRAMs contained polyimide layers of about 60 μm on the top of the die, which were considered in the calculations of ion range and LET.

The heavy ion testing was carried out at the Heavy Ion Research Facility in Lanzhou (HIRFL) cyclotrons, using argon and krypton ions each with an initial energy of 25 MeV/nucleon. Irradiations were performed in air with heavy ions passing through a vacuum/air transition foil with a thickness of 30 μm. The aim of the experiment is to compare the SEE responses of SRAM devices to heavy ions with the same effective LET values, but at normal and tilted incidences as shown in Fig. 1. To change the ion LET at normal incidence, aluminum foils as energy degraders were inserted into the beam line. The thickness of degraders and tilt angles were chosen precisely to make the vertical ions and tilted ions match at the same effective LET points. The experimental parameters are reported in Table 1. Two types of ions with different LET values were used to investigate the ion species dependence. The maximum tilt angle that can be used for this purpose is determined by

$$\theta_{\max} = \arccos\left(\frac{\mathrm{LET}_0}{\mathrm{LET}_{\mathrm{BP}}}\right), \tag{2}$$

where LET_0 means the initial ion LET at the surface of the die and $\mathrm{LET}_{\mathrm{BP}}$ is the ion LET at Bragg peak, the maximum LET for vertical ions. During the experiment, other factors, such as the preset values of test devices, mode of test system, beam flux, etc, are kept constant.

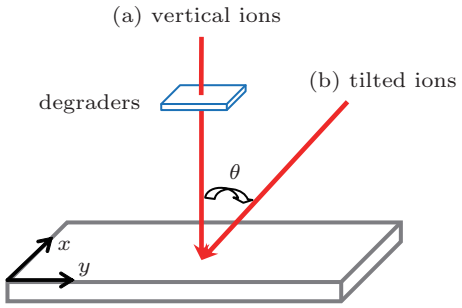


Fig. 1. (color online) Schematic diagram of the experimental setup. Degraders are used to degrade the energy, thus adjusts the LET of (a) vertical ions, in order to match with (b) tilted ions at the same LET point. Tilt angle θ is the angle between the incident beam and the normal to the surface plane of the device. Note that tilted ions are incident along the y axis of the test device (single device-orientation).

Table 1. Experimental parameters of heavy ions.

Ions	Degrader or angle	Energy/(MeV/u)	Range/μm	$\mathrm{LET}_{\mathrm{eff}}$/[MeV/(mg/cm^2)]
^{40}Ar	0°, 80 μm Al	10.6	139.9	9.5
	33°	14.5	183.2	9.3
^{86}Kr	0°, 40 μm Al	3.0	33.9	40.7
	30°	7.0	63.4	41.0

Tests were performed in dynamic mode with checker board patterns input at room temperature. The memories were scanned continuously by a field programmable gate array (FPGA) based tester. Once one bit-error is detected, several steps will be performed automatically by the tester: a) reading the bit again for confirmation, b) recording the bit-error information including error address, error data and time interval with the previous error for MBU judgment, c) correcting the erroneous bit, and d) reading the bit again to confirm the correction. The steps are finished in less than 2 μs (depending on the preset access time), then the scan process will continue at the next logical address. The device current was also monitored to protect the devices from burning out due to single event latchup (SEL). Once the current exceeds the preset threshold value, the power supply will be shut down automatically and the device will be reset.

For MBU identification, the logical error addresses are transformed into physical addresses based on the physical arrangement of the memories.[20] One error cluster is treated as an MBU based on the following rules: (i) the errors are physically adjacent; (ii) the error data are the same due to the interleaving architecture of the test devices, and (iii) the time intervals are less than the loop time to make sure that the errors in the cluster were detected in the same scanning loop. Few special cases which cannot be identified by previous rules are judged carefully during the identification process.

The validity of this identification rule can be estimated in the following. The probability of double adjacent bit-flips caused by two ions within the same scanning loop is

$$P = \frac{8}{N_{\mathrm{b}}}\left(T_{\mathrm{loop}}R\right)^2, \tag{3}$$

where N_{b} is the number of bits in the test device, T_{loop} the time of a scanning loop, and R the bit-error rate (errors/s) while irradiating, which can be controlled by the beam flux. Taking the IDT71256 device for example, $N_{\mathrm{b}} = 262144$ bits, $T_{\mathrm{loop}} = 6.6$ ms, and $R = 10$ errors/s. Then, the failure probability equals 1.3×10^{-7} per loop. In fact, for the entire about 10^4 bit-errors accumulated during the total SEU testing, there is only about 2% of probability that an erroneous judgment

happens. Low beam flux and high scanning speed are necessary to make the identification rules valid.

3. Experimental results and analysis

The experimental results are presented below in the following order. First, the SEU cross sections for heavy ions at vertical and tilted incidences, with the equivalent LET values, are reported and compared. Then, all kinds of MBUs induced by vertical ions and tilted ions are identified and the rates for those MBU types are shown for comparison. Finally, the MBU patterns are analyzed to find the predominant one.

3.1. SEU cross sections

SEU cross sections are calculated by

$$\sigma = \frac{\sum_i i \cdot N_{i-\mathrm{bit}}}{F \cdot N_{\mathrm{b}} \cdot \cos(\theta)}, \quad i = 1,2,3,4, \tag{4}$$

where $N_{i-\mathrm{bit}}$ is the number of MBU events involving i bits and F means the beam fluence. MBUs are counted separately as several errors in this calculation. In the following plots of SEU cross section versus effective LET, F and LET are both corrected for tilt angle. Up to 1000 bit-errors are cumulated in each test condition to obtain sufficient statistics.

The SEU cross sections of IDT SRAMs are reported in Table 2 for two LET values. Standard deviations of SEU cross sections are also presented. At LET value about 9.5 MeV/(mg/cm^2), the SEU cross section varies little with tilt angle. While at LET value about 41 MeV/(mg/cm^2), variations from 23.9% to 84.6% are shown, depending on the test devices, with the increase of SEU cross section at tilted incidence. Thus, tilted ion strikes may overestimate the device sensitivity in a higher LET region. In addition, the SEU cross sections of IDT SRAMs are not saturated, i.e., they still increase with effective LET increasing.

Table 2. The SEU cross sections of IDT7164 and IDT71256 SRAM devices under irradiations at vertical and tilted incidences, with the equivalent effective LET.

Ions	LET$_{\mathrm{eff}}$/[MeV/(mg/cm^2)]	Devices	Vertical or tilted	σ_{SEU}/(cm^2/bit)	$\Delta\sigma$/(cm^2/bit)
^{40}Ar	$\sim$9.5	IDT71256	vertical	4.82×10^{-8}	1.53×10^{-9}
			tilted	4.44×10^{-8}	3.03×10^{-9}
^{86}Kr	$\sim$41	IDT7164	vertical	7.32×10^{-7}	1.02×10^{-7}
			tilted	1.13×10^{-6}	5.78×10^{-8}
		IDT71256	vertical	5.15×10^{-7}	7.46×10^{-8}
			tilted	6.38×10^{-7}	9.45×10^{-8}

3.2. MBU rates

Although the effective LET values of vertical ions and tilted ions are the same, the ion trajectories through the test device are different which may lead to obvious discrepancy in the MBU response.

In the case of Ar ions with lower LET value about 9.5 MeV/(mg/cm^2), single-bit upset (SBU) is the predominant upset type for both vertical and tilted incidences. Only few double-bit upsets (DBUs) are observed. No clear discrepancy is observed between the MBU responses to vertical ion and tilted ions.

While for Kr ions with higher LET value about 41 MeV/(mg/cm^2), more upset types are identified with higher probabilities. Figure 2 shows the rates of SBU, DBU, triple-bit upset (TBU), and quadruple-bit upset (QDBU) for ions at vertical and tilted incidences in IDT7164 and IDT71256 SRAM devices. $R_{i-\mathrm{bit}}$ means the rate of MBU involving i bits

$$R_{i-\mathrm{bit}} = \frac{N_{i-\mathrm{bit}}}{\sum_i N_{i-\mathrm{bit}}}, \quad i = 1,2,3,4. \tag{5}$$

It is clearly shown that the tilted ions exhibit higher total MBU rate than the vertical ions in both IDT SRAMs, although the effective LETs are the same. Discrepancies from 8.5% to 9.8% of the SBU rate are shown, depending on the test devices. These results can partially explain the increased SEU cross section for tilted ions since MBUs are counted separately in the calculation of SEU cross section. Moreover, the total MBU rate increases 28%–29.3% with the packing density increasing, owing to reduced spacing between adjacent cells. Single particle induced MBU is typically attributed to charge sharing through diffusion and parasitic bipolar conduction.[21] Although the energies deposited in the struck-sensitive volume by vertical ions and tilted ions, with the equivalent LET, are the same, electron–hole pairs created outside the struck-sensitive volume by tilted ions are more likely to be collected

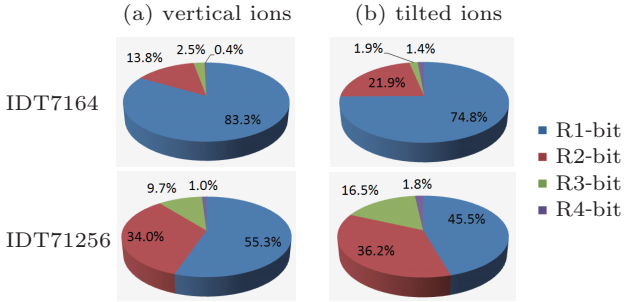


Fig. 2. (color online) MBU rates for (a) vertical ions and (b) tilted ions with the equivalent effective LET in IDT7164 (first row) and IDT71256 (second row) SRAM devices.

by neighboring sensitive nodes by charge diffusion due to the oblique trajectories. Thus, enough charges are collected in the nearby cells and may still induce upsets resulting in the higher MBU rates for tilted ions.

3.3. MBU patterns

To gain further insight into the MBU difference, the MBU patterns induced by ions at normal and tilted incidences, are investigated in more details. MBU pattern means the physical arrangement of the flipped-bits in an MBU event.

All the DBU patterns induced by vertical ions and tilted ions are reported in Table 3 for comparison. Three kinds of DBU patterns are identified: along x axis, along y axis, and diagonal configurations (see the axes in Fig. 1). For vertical ions, along x-axis pattern is the predominant DBU pattern which indicates that the test device is anisotropic in MBU response. This phenomenon results from the rectangular parallelepiped (RPP) shaped-sensitive volumes of the test device and different spacing between sensitive nodes along the x-axis and y-axis directions.[20] Moreover, although their effective LETs are the same, tilted ions create more DBUs with the along-y-axis pattern than vertical ions and the along-y-axis pattern may become the predominant pattern for tilted incidence. Note that the tilted ions are incident along the y axis of the test device as shown in Fig. 1.

The detected TBU patterns are also shown in Table 4. Unlike the different predominant DBU patterns induced by vertical and tilted ions with the same effective LET, L-shaped configuration is the predominant TBU pattern for both cases. QDBUs involve more patterns than other MBU types and square-shaped configuration turns out to be the predominant one.

Table 3. Cumulative DBU patterns for Kr ions at normal and tilted incidences for IDT71256 1# and 2# devices.

Device	Vertical or tilted	DBU patterns		
		Along-x-axis	Along-y-axis	Diagonal
1#	vertical	163	81	21
	tilted	161	144	41
2#	vertical	91	66	19
	tilted	40	87	25

Table 4. Cumulative TBU patterns for Kr ions at normal and tilted incidences for IDT71256 1# and 2# devices.

Device	Vertical or tilted	TBU patterns		
		L-shaped	Along-x-axis	Along-y-axis
1#	vertical	76	0	0
	tilted	156	1	1
2#	vertical	66	2	0
	tilted	107	0	0

4. Discussion

As shown above, the discrepancies in the SEU cross section and MBU responses to normally and angularly incident ions, with the equivalent effective LET, depend on the ion LET value and test device. At lower LET value, both normally incident ions and tilted ion strikes cannot create enough charges diffusing to upset nearby cells. Since the effective LETs of ions at normal and tilted incidences are the same, identical amounts of energy are deposited in the struck-sensitive volume. Therefore, no differences in SEU cross section and MBU feature are observed, which indicates the validation of effective LET method in this LET region. While at a higher LET value of about 41 MeV/(mg/cm^2), obvious differences are observed with tilted ions exhibiting increased SEU cross section, high MBU rate, and different predominant DBU patterns in comparison with the scenario of ions at normal incidence. In ground-based testing, the effective LET method should be used carefully in MBU-sensitive devices.

In this work, the tilt angle used for comparison is $\sim 30^\circ$ due to the limitation of formula (2). It can be seen in Fig. 3 that as tilt angle increases, the rate of SBU decreases dramatically, the rate of DBU keeps relatively constant while the rates of TBU, QDBU, and quintuple-bit upset (QTBU) increase with tilt angle increasing. Based on those results, larger discrepancy can be expected between the SEE responses to normally incident ions and tilted ions with higher angles of incidence, although their effective LETs are the same.

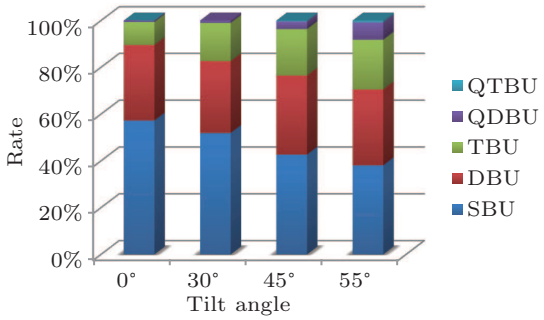


Fig. 3. (color online) MBU rates each as a function of tilt angle in IDT71256 SRAM device, with an ion LET value of 31.8 MeV/(mg/cm^2) at normal incidence.

Device-orientation effects have been receiving widespread concern recently.[4,16] If the device under test is anisotropic topologically, tilted ion strikes performed at different device-orientations may induce quite different SEE results. As shown in Table 3 of Section 3, preferable DBU pattern is observed for normally incident ions, which suggests that the MBU features for along-x-axis direction and along-y-axis direction of this anisotropic device can be different. Additionally, DBU patterns induced by tilted ion strikes (incident along the y axis of the test device) indicate that beam direction in relation to the device layout has a great influence on the resulting MBU patterns. Consequently, tilted ions incident at other

device-orientations are expected to exhibit different MBU responses. However, while using tilted ion strikes in ground-based testing, irradiations are usually performed at one single device-orientation which may miss the worst case of SEE responses and cannot evaluate the device sensitivity accurately. Actually, the SEU cross section for tilted ion strikes should be measured at several typical device-orientations and then integrated together, especially in anisotropic devices.

5. Conclusions

Experimental results are reported revealing clear discrepancies in SEU cross section, MBU rate, and MBU pattern of SRAM devices under both ion incident conditions, i.e., normal and tilt angles, with the same effective LET value. The difference is also observed as a function of LET value.

The SEU cross section is calculated counting MBU as several errors. At a lower LET value (about 9.5 MeV/(mg/cm^2)), no clear discrepancy is observed. While at a higher LET value (about 41 MeV/(mg/cm^2)), the SEU cross sections, MBU rates, and MBU patterns show a strong dependence on the tilt angle. In comparison with ions at normal incidence, SEU cross section for tilted incidence is observed to increase 23.9%–84.6%, which can be partially explained by the fact that the MBU rate for tilted ions of 30° is 8.5%–9.8% higher than that for ions at normal incidence, depending on the test device.

MBU patterns are further investigated. Although with the same effective LET, the ion trajectories of tilted ions are distinct from that of normally incident ions. In the anisotropic test devices, along-x-axis pattern is the main DBU pattern for ions at normal incidence. While tilted ions incident along the y axis of the test device create more DBUs with the along-y-axis pattern than ions at normal incidence, this pattern may become the predominant pattern for tilted incidence. Unlike the observed DBU patterns, the predominant TBU and QDBU patterns for ions at normal and tilted incidences are unexpectedly the same, i.e., L-shaped and square-shaped configurations, respectively.

Therefore, the effective LET method of single event effects may overestimate the SEE sensitivity, especially in MBU-sensitive SRAM devices. The applicability of this method depends on the ion LET value and test device. Future work will include heavy ion testing of SRAM device built in more advanced technologies at different device-orientations.

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