[4] J. R. Schwank, M. R. Shaneyfelt, J. A. Felix,et al., IEEE Trans. Nucl. Sci., 53(2006)1772.

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5 - 21 Differences in MBUs Induced by High-energy and Medium-energy Heavy Ions in 28 nm FPGAs*

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The high performance and flexible configuration ability of static random-access memory (SRAM)-based field-programmable gate arrays (FPGAs) make them widely used in space missions[1]. However, they are sensitive to single event upsets (SEUs) caused by heavy ion incidence[2]. Moreover, as the feature size continues to shrink, the reduction of critical charges and the enhanced ment of charge sharing effects in FPGA lead to multiple-bit upsets (MBUs) occurring more frequently[3]. MBU occurs when a single particle deposits energy into several memory cells of the same words to simultaneously upset them. When MBUs occur in critical configuration RAMs (CRAMs) that are used to configure critical system functions, on-orbit FPGA systems will face serious failures[4]. Therefore, it is mandatory to conduct an MBU evaluation of CRAMs on advanced FPGAs before their application in aerospace.

In this study, we conducted high-energy and medium-energy heavy ion tests on 28 nm FPGAs. The effects of heavy ions with different energies on the MBUs were thoroughly investigated. High-energy ^{78}Kr and medium-energy ^{129}Xe heavy ion experiments were performed at the Heavy Ion Research Facility in Lanzhou (HIRFL) in the Institute of Modern Physics, Chinese Academy of Sciences. The irradiation experiments of ^{78}Kr ions with an initial energy of 60 MeV/u and ^{129}Xe ions with a initial energy of 19.5 MeV/u were compileted at the high-energy radiation effect terminal and terminal No.5, respectively.

The detailed MBUs induced by ^{78}Kr ions were extracted, as shown in Fig. 1(a). It can be seen that compared with the 1.0 V, the 0.9 V radiations induced a higher proportion of and larger scale MBUs. Additionally, we found that compared with 13.3 and 31.0 MeV·cm^2/mg, ^{78}Kr ions with an linear energy transfer (LET) of 20.8 MeV·cm^2/mg can cause higher percentages of greater-than-3-bit MBUs in vertical radiations at 0.9 and 1.0 V, and greater-than-4-bit MBUs in tilted radiations at the 0.9 V operation. This is related to the different influence ranges and abilities of the ionization tracks. Because the $(\theta=0°, \psi=30°)$ ion trajectories covered more cells, the largest 6-bit MBUs appeared even at the LET of 13.3 MeV·cm^2/mg, which identified the worst influences in this study.

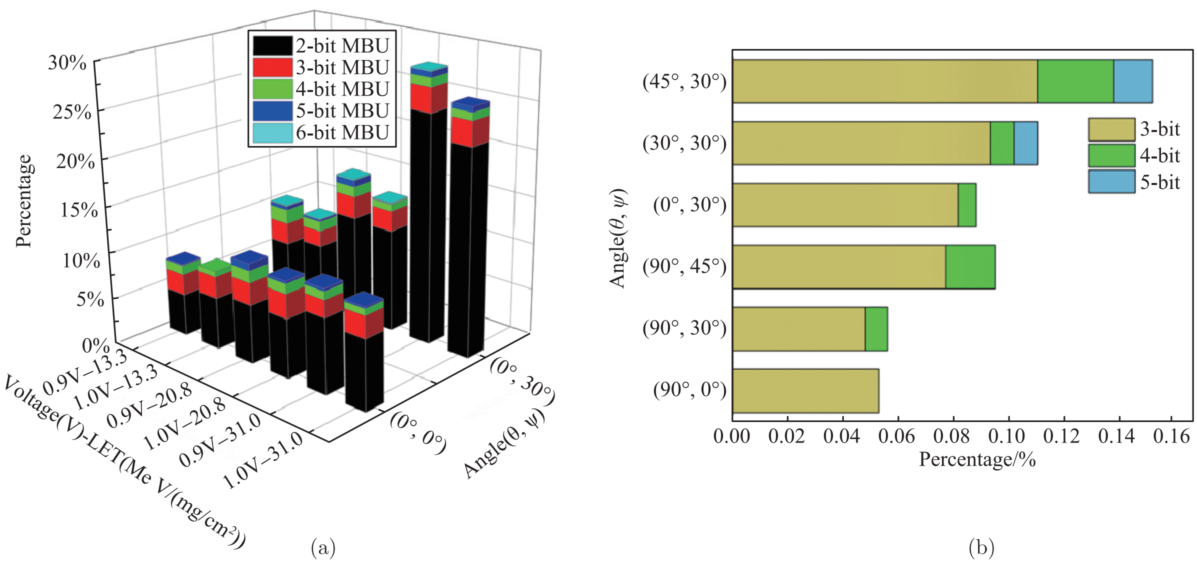

Fig. 1 (color online) Detailed percentages of different type MBUs induced by (a) ^{78}Kr and (b) ^{129}Xe ions at different conditions.

The detailed results of greater-than-2-bit MBUs induced by ^{129}Xe ions are shown in Fig. 1(b). Only the largest 3-bit MBUs were found at $(\theta=90°, \psi=0°)$. When setting $\theta=90°$ while rotating ψ, we captured MBUs no larger than

4-bit; however, for $\psi = 30°$ while changing θ, the largest 5-bit MBUs appeared six times, which helped us determine worse dimensional impacts. In addition, the percentages of 3-bit MBUs at $(\theta = 0°, \psi = 30°)$ were approximately twice as large as those at $(\theta = 90°, \psi = 30°)$, demonstrating that there are different sensitivities in the directions of either the word or between words in our device under test (DUT). We observed that large-scale upsets occurred between words in our DUT at $\theta = 90°$, but the largest number was four. When considering the largest 5-bit MBUs, we believed that the distances between word cells are closer than the cells between words.

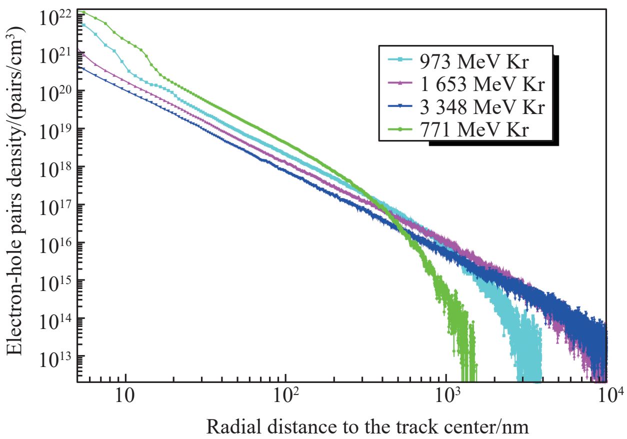

Fig. 2 (color online) Electron-hole pairs density changing as a function of the radial distance in silicon.

As mentioned above, although ^{78}Kr ions have a much lower LET, they can induce even larger MBUs. This appears to be caused by the different ionization track structures. Hence, using the Geant4 toolkit, we performed Monte Carlo simulations to investigate the track structures of the ^{78}Kr and ^{129}Xe ions used in our experiments. The results are shown in Fig. 2. It can be seen that ^{78}Kr ions have much wider tracks; particularly, the ^{78}Kr ions of 3 348 MeV were approximately five times wider than the ^{129}Xe ions. Large clustered MBUs occurred due to the large track radius. Besides, it can be seen that as ^{78}Kr ions with an energy of 1 653 MeV have a better trade-off between the wide ionization track radius and high electron-hole pair density, they caused higher percentages of large MBUs.

To reduce the failure risk of FPGA-based systems in actual space, comprehensive high-energy characterizations are necessary to prevent the underestimation of radiation reliability. SEU mitigation strategies depend on actual and accurate irradiation results. Therefore, radiation hardened designers should carefully consider the comprehensive factors mentioned in this paper to prevent wastage of the area, resources, power, and operation frequency of devices.

References

[1] van Harten LD, M. Mousavi, R. Jordans, et al., Microprocessors and Microsystems, 63(2018)1.
[2] M. Ceschia, M. Violante, M. S. Reorda, et al., IEEE Transactions on Nuclear Science, 50, 6(2003)2088.
[3] H. Quinn, P. Graham, J. Krone, et al. , IEEE Transactions on Nuclear Science, 52, 6(2005)2455.
[4] T. Li, H. Liu, H. Yang, IEEE Transactions on Very Large Scale Integration Systems, 27, 6(2019)1276.

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