

Radiation Effects of Advanced Electronic Devices and Circuits

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1. Introduction

Research on the effects of radiation on advanced electronic devices and integrated circuits has experienced rapid growth over the last few years, resulting in many approaches being developed for the modeling of radiation's effects and the design of advanced radiation-hardened electronic devices and integrated circuits [1–10]. With the progressive scaling of integrated circuit technologies and the growing complexity of electronic devices, their susceptibility to radiation's effects has presented many exciting challenges that are expected to propel research in the coming decade [11–14]. Additionally, regarding single-event effects (SEEs), continued scaling has drastically introduced new challenges, resulting in multiple-cell upsets, multipulse propagations, and other complex effects [15–22]. These issues necessitate the development of new solutions to assess and mitigate radiation sensitivity in advanced devices and integrated circuits.

The first edition of “Radiation Effects of Advanced Electronic Devices and Circuits” features nineteen high-quality submissions that showcase emerging applications and address recent breakthroughs. One key focus is the exploration of materials and device architectures designed to enhance radiation tolerance. This Special Issue also studies the development of advanced simulation tools and modeling techniques for accurately predicting the behavior of electronic devices exposed to radiation. These efforts encompass the refinement of existing simulation methodologies and the development of new computational approaches to better capture the complex interactions between radiation particles and basic materials. Additionally, this Special Issue addresses the growing importance of testing and validation methodologies for assessing the radiation hardness of integrated circuits and electronic systems. Researchers are exploring innovative testing protocols to ensure the reliability and robustness of electronic components in radiation environments, highlighting recent advancements in the field of radiation-tolerant electronics for space applications. Overall, this Special Issue serves as a comprehensive platform for researchers to showcase their latest findings and advancements in the effects of radiation on advanced electronic devices and circuits. By addressing a wide array of topics spanning from fundamental mechanisms to practical applications, this first Special Issue aims to foster collaboration and innovation within the radiation effects community and to contribute to the ongoing advancement of radiation-hardened electronics technology.

2. Highlighting Key Contributions

The nineteen articles in this Special Issue focus on not only systematic evaluation methods such as technology computer-aided design (TCAD), geometry and tracking (GEANT4), and novel numerical computation techniques but also the basic mechanisms and hardening results regarding the radiation performance of key components or devices such as sensors,



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FinFET, silicon-on-insulator (SOI), system-on-chip (SoC), direct current (DC)–DC converters, SiC, heterojunction bipolar transistors (HBTs), and carbon nanotubes (Contribution 1–19).

With the development of integrated circuit technology, radiation's effects such as total ionizing dose (TID) effects, the high-dose-rate transient ionizing radiation response, and the single-event upset (SEU) of electron devices under advanced SOI CMOS processes have attracted considerable attention. Three articles provide recent and relevant research on the effects of radiation on SOI technology. The detailed TID effects and SEU features for SOI static random-access memories (SRAMs) with different layout structures were explored by Zhao, P. et al. (Contribution 1). The experimental results indicate that the SEU cross-sections are not only influenced by TID irradiation but also closely related to the layout structure of the memory cells. Li, T. et al. (Contribution 13) conducted an experimental and simulation study on the high-dose-rate transient ionizing radiation response and factors influencing fully depleted SOI (FDSOI) D flip-flop (DFF) circuits. The results demonstrate that the number of errors in DFFs nonlinearly increases with increasing dose rate, and the increasing supply voltage leads to an increase in data errors due to increased charge collection efficiency. Lin, L. et al. (Contribution 15) investigated the effect of hot-carrier injection (HCI) on γ -ray-irradiated partially depleted (PD) SOI n-MOSFETs with a T-shaped gate structure. The results indicate that the HCI has a recovery effect on the long-term reliability of n-MOSFETs when applied to a space environment.

Bulk silicon complementary metal oxide semiconductor (CMOS) devices encounter distinct single event latch-up (SEL) problems in aerospace. The traditional method fails to release devices from the latch-up state due to the narrow resistance range. Therefore, Xin, J. et al. (Contribution 2) developed an improved design for the resistor in front of the DC–DC buck converter, which increases the resistance range according to the input characteristics of the DC–DC buck converter. The method enhances the latch-up hardness performance by expanding the resistance range in comparison with that of the conventional design.

Some studies focused on the basic radiation effects of transistors or diodes have been published in our Special Issue. Pan, X. et al. (Contribution 3) investigated the inflection point of a single-event transient in a SiGe HBT. The collector's transient inflection point is jointly determined by the transient current of the emitter, substrate, and base, and the characteristics of the transient peaks widely vary among electrodes. Additionally, the contributors proposed a method to introduce the initial ionized EHPs' distribution of the Geant4 simulation to a TCAD simulation, thereby increasing the simulation accuracy and efficiency of the heavy-ion-induced SEE. To understand the microphysical mechanism of SEEs in SiGe HBTs, the effects of the heavy-ion striking location, incident angle, LET value, projected range, ambient temperature, and bias state were investigated by Zhang, Z. et al. (Contribution 5). The results indicate that the current transient peak value increases with the LET and the projected range of the heavy ions and decreases with the ambient temperature. The SEEs of SiGe HBTs are influenced not only by heavy-ion irradiation parameters such as the incident angle, LET value, and projected range but also by the striking location, ambient temperature, and bias state. In addition, the effects of proton irradiation on CMOS single-photon avalanche diodes with and without shallow trench isolation were examined by Xun, M. et al. (Contribution 19). The I–V characteristics, dark count rate, and photon detection probability of the diodes were measured under proton irradiation, contributing to meeting the dramatically increasing demands for satellite-to-ground quantum communication and space environment detection. Furthermore, semiconductor devices have entered the post-Moore era, where new materials and new technology have emerged. The excellent performance and radiation-hardness potential of carbon nanotube field-effect transistors (CNTFETs) have widely attracted attention. Ding, H. et al. (Contribution 4) investigated the TID effect of top-gate structure CNTFETs and the influence of the substrate on top-gate during irradiation. Studies regarding the influence mechanism of trapped charge introduced by TID irradiation on the characteristics of the top-gate CNTFETs are urgently needed for the design of CNT-based devices.

SiC power devices require resistance to both SEEs and TIDs in a space radiation environment, and several articles in our Special Issue present detailed results on simulation or irradiation experiments. Li, X. et al. (Contribution 6) investigated the impact mechanism and regularity of using the split-gate-enhanced process to determine the radiation resistance and long-term reliability of SiC vertically diffused MOS (VDMOS). The split-gate-enhanced VDMOSFET process can effectively enhance the radiation resistance of SiC VDMOS but impacts on the gate oxide reliability of SiC VDMOSs. Feng, H. et al. (Contribution 9) investigated the impact mechanism and regularity of using the SGE process to determine reliability of SiC VDMOS under radiation conditions. The use of the new process leads to more defects in the oxide layer, reducing the long-term reliability of the device, but its stability recovers after accelerated high-temperature annealing. Liang, X. et al. (Contribution 12) experimentally studied heavy-ion irradiation with different particle LETs, gate biases, and drain biases. The experimental results, along with those of TCAD simulations, suggest that the latent damage induced by irradiation in gate oxide is closely related to the peak electric field in the gate oxide at the time of particle incidence. The peak electric field, determined via the potential difference between the two sides of the gate oxide, is affected by the particle LETs, gate biases, and drain biases together. The leakage current is the most critical parameter for characterizing heavy-ion radiation damage in SiC MOSFETs. Moreover, an accurate and refined analysis of the source and generation process of leakage current is the key to revealing the failure mechanism. Xiang, Y. et al. (Contribution 16) finely tested the online and postirradiation leakage changes in and leakage pathways of SiC MOSFETs caused by heavy-ion irradiation, reverse-analyzed the damaged location of the device, and discussed the mechanism of leakage generation. The experimental results further confirm that an increase in the leakage current of a device during heavy-ion irradiation is positively correlated with the applied voltage of the drain, but the leakage path is indirect from the drain to the source. This study provides a theoretical basis for the radiation resistance reinforcement of SiC power devices.

Star sensors are widely used on satellites owing to their precise pointing accuracy. However, space radiation environments will cause cumulative effects and single-event transients (SETs) in the imaging systems of star sensors, which can affect their star map recognition success rate. In this Special Issue, three articles illustrate the radiation effects on sensors. Cui, Y. et al. (Contribution 7) individually analyzed the influence of the decrease in the number of stars to be identified caused by proton irradiation, hot pixels, and SET spots on the success rate of different star map recognition algorithms. The findings of this study provide theoretical and technical bases for the improvement in star map recognition algorithms for long-term on-orbit star sensors. In addition, Feng, J. et al. (Contribution 10) conducted gamma-ray TID radiation experiments on CMOS image sensors and camera systems, and they thoroughly analyzed the impact mechanisms of dark current, full well capacity, and quantum efficiency of CMOS image sensors on camera resolution. Yang, Z. et al. (Contribution 11) investigated the relationship between the variation in SET bright spots under different conditions by conducting heavy-ion irradiation of image sensors. The authors propose identifying and classifying SEUs using the characteristics of set bright spots. They established a fast identification method to analyze SEU patterns and sensitive areas based on transient bright spot size, background gray value, and other parameters. These studies provide theoretical bases for the evaluation of the radiation resistance of sensors in radiation environments and the development of radiation-resistant cameras.

The reliability of nanoscale electronic systems is crucial in various applications. Current research has confirmed that atmospheric neutrons can induce single-event effects in advanced relay protection devices as well. Yang, W. et al. (Contribution 8) investigated a Xilinx Zynq-7000 SoC manufactured with 28 nm CMOS technology using two rounds of spallation neutron irradiation. They conducted spallation neutron irradiation and analyzed the results in combination with those of Monte Carlo simulation to explore the impact of atmospheric neutrons on the SEEs of the target system-on-chip. Zhou, H. et al. (Contribution 18) preliminarily assessed the SEEs on relay protection devices using neutron-based analysis

and provide valuable insights for evaluating the reliability of advanced technology relay protection devices.

Several novel evaluation methods for radiation effects have been developed. Based on the illustrations of Liu, M. et al. (Contribution 14), depending on the particle energy, the areal density aluminum equivalent method may over- or underestimate the absorbed dose in a shielded silicon detector, especially for the ionization total-dose shielding effect of low-energy electrons. For integrated circuits used in space applications, the soft errors caused by transient pulses must first be evaluated, and the conventional evaluation approaches are limited to the circuit scale. Additionally, Song, R. et al. (Contribution 17) developed an approach for evaluating the soft error rate using machine learning technology. A back propagation neural network is implemented in the proposed approach. The proposed approach helps with determining the probability of transient pulse propagation. Compared with the conventional soft-error-rate evaluation results, the proposed approach strong correlations in both trend and magnitude.

3. The Future

The space radiation environment strongly impacts electronic devices, thereby seriously affecting the service life of spacecraft on-orbit electronic equipment. Consequently, the need is critical to thoroughly investigate the basis of radiation effects and develop innovative strategies to enhance the radiation resistance of electronic devices. The diverse array of articles featured in this Special Issue underscore the breadth of research in the field of the effects of radiation on advanced electronic devices and circuits. These articles span from cutting-edge advancements in nuclear and solid-state physics to sophisticated device and circuit-level modeling techniques as well as innovative hardening design methodologies. Moreover, these researchers have explored the application of progressive algorithms and deep learning methodologies to optimize system performance across various radiation environments. Together, these articles represent a collective leap forward in the pursuit of understanding radiation's effects and devising efficient methods for assessing the reliability and responses of novel electronic devices under radiation conditions.

In addition to the aforementioned areas of focus, the second edition of "Radiation Effects of Advanced Electronic Devices and Circuits" will delve deeper into several key aspects of radiation effects on electronic systems. This includes exploring the impact of radiation on emerging technologies such as quantum computing, neuromorphic computing, photonic devices, etc. The second edition will feature research on the development of radiation-hardened sensors and actuators, as well as advances in fault-tolerant computing architectures designed to mitigate the effects of radiation-induced errors. Moreover, given the push toward miniaturization and the complexity of electronic systems, the second edition will highlight research on radiation's effects at the nanoscale level. This will encompass investigations into the susceptibility of advanced electronic devices, such as carbon nanotubes, graphene-based transistors, and nanostructured materials, to radiation-induced degradation and failure mechanisms. Furthermore, the second edition will address the growing importance of system-level approaches to radiation hardening, including the integration of redundant components, fault-tolerant algorithms, and adaptive error correction techniques. Additionally, the next Special Issue will include articles exploring the role of machine learning and artificial intelligence in enhancing the resilience of electronic systems to radiation's effects, particularly in autonomous spacecraft, low-orbit commercial satellites, and space station systems. Overall, the second edition aims to provide a comprehensive overview of the latest advancements in radiation effects research and their implications for the design and operation of advanced electronic devices and circuits in space applications. These insights are expected to drive innovation and development in the field, paving the way for the creation of more robust and reliable electronic systems for future space missions.

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Issue. Y.C. and C.C. drafted this manuscript. Y.C., C.C. and L.C. reviewed, edited, and finalized the manuscript. All authors have read and agreed to the published version of the manuscript.

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