Research on Radiation Effects of CMOS Image Sensors

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Abstract. With technological advancements, chips have become a critical component of human life. CMOS image sensors (CIS), with advantages such as low power consumption, low cost, high integration, and high speed, are gradually replacing CCDs and becoming important devices in the aerospace field. However, the presence of space radiation limits their large-scale application in satellites. This paper focuses on the effects of heavy ion radiation, proton radiation, and transient dose rate effects on CMOS image sensors. Through circuit design and simulation models, key parameters and changing trends of the sensors before and after radiation are tested and analyzed, combined with physical theories to explore the mechanisms. The research results indicate that these three types of radiation can lead to pixel degradation and even sensor failure, but their mechanisms and degrees of impact differ. Nevertheless, these radiation effects are not entirely unavoidable and can be effectively mitigated through specific design methods or process optimization. In summary, this study provides important references and insights for research on radiation effects in CMOS image sensors.

Keywords: CMOS image sensors ((CIS), pixel degradation, radiation effects

1. Introduction

In recent years, artificial intelligence has entered a period of rapid development, placing higher demands on bandwidth. Complementary Metal-Oxide-Semiconductor (CMOS) technology has become a mainstream solution in chip design due to its advantages such as lower voltage operation, lower power consumption, on-chip functionality, and lower cost [1]. This type of integrated circuit is widely used in imaging technology, spectral analysis, quantum computing, and other fields. Particularly in aerospace applications, the CMOS image sensors could reduce the degree of noise at high frame rates [2]. Its notable advantages, including lightweight design, radiation resistance, and low power consumption, allow this technology to adapt to extreme environments.

In 2011, Canon pioneered a novel CMOS imaging sensor; in 2015, the European Union improved sensors to achieve hyper-spectral imaging monitoring; CMOSIS Company developed a high-resolution miniaturized sensor successfully applied in aerial surveying and mapping. In recent years, several advanced CMOS products and cameras have also been developed. Xu et al. investigated the detection effectiveness of CMOS image sensors for gamma-ray radiation doses, Magalotti et al. studied parameter variations of CMOS image sensors under different X-ray conditions [3]. Lee et al. designed a circuit based on CMOS image sensors to distinguish types of radiation particles [4]. Fossum et al. conducted experiments on CMOS image sensors using electrons, protons, and heavy ions of varying energies; Hopkinson et al. also carried out heavy ion irradiation experiments [5] [6].

However, this technology currently faces developmental bottlenecks: poor stability and temperature characteristics limit its practical value, and research on radiation has been largely confined to detection, with issues such as limited precision and excessive computational complexity in the research process. Although some measures have been taken to mitigate these problems to a certain extent, certain challenges remain unresolved. These issues will severely restrict in-depth research on radiation, making it imperative to break through these technical bottlenecks.

Based on the current state of CMOS image sensors, this study explores performance optimization pathways by integrating various technologies and algorithms: First, appropriate measurement methods or model structures are employed to analyze the data information or model states of the sensors in various radiation environments. Subsequently, physical theories and formulas are applied to computationally identify the mechanisms and sensitivity of different types of radiation effects on

CMOS image sensors. Finally, corresponding conclusions are drawn, and reasonable optimization solutions are proposed to enhance the performance of CMOS image sensors in satellite chips, thereby obtaining the optimal solution suitable for satellites or providing feasible ideas to alleviate the problems to a certain extent.

2. Research and Application of CMOS Image Sensors under Three Types of Radiation Conditions

2.1. Research on CMOS Image Sensors under Heavy Ion Radiation

CMOS circuits are widely used in imaging sensors, particularly in sensors mounted on satellites for monitoring Earth and space environments. However, these sensors exhibit radiation sensitivity, which can lead to parameter degradation and pixel defects [7]. Therefore, changes in the performance of CMOS sensors can be utilized to measure the dose of particles in radiation environments. The performance degradation, and even functional failure, of CMOS image sensors in radiation environments has drawn significant attention to their reliability and radiation detection capabilities [8]. Research on related sensors can provide data support for evaluating their detection efficacy [9]. CMOS image sensors can directly leverage existing photoelectric payloads, substantially reducing cost and power consumption, while their low error rates enhance the reliability of results. Currently, numerous researchers and teams worldwide have conducted radiation tests on CMOS sensors using high-energy charged particles, including protons, electrons, and heavy ions.

One experimental principle involves the CMOS image array, which consists of multiple pixel units. Under light conditions, the number of photo-electrons stored in a pixel unit reflects the light intensity. If heavy ion radiation is applied in the absence of light, ionized charges generated can be stored by the pixel units. These charges can also output dark signals in the absence of light, with the magnitude of the dark signal indicating the radiation intensity [7]. A second experimental principle employs a circuit, as illustrated in the figure below, where a master chip acts as the core controller. It processes signals from other modules (such as drive signals for the image sensor and data configuration timing) and issues subsequent instructions, ultimately completing data processing and transmission [8]. A third experimental approach utilizes Correlated Double Sampling (CDS) circuits and Analog-to-Digital Converter (ADC) circuits. After light stimulation, pixel units generate optical signals, which are sampled and processed by the CDS circuit to obtain effective photosensitive signals. These signals are then converted into binary digital signals via the ADC circuit, ultimately producing a net-list model to analyze circuit conditions under various radiation states [9].

Fig. 1 shows a schematic of the FPGA main control circuit, where the power module supplies energy to the irradiation board. After radiation effect testing, the sensor transmits digital signals to a DDR2 buffer chip. The data is buffered and stored in both the DDR2 cache module and the USB 2.0 module before being transmitted to a host computer via a serial interface for further analysis and processing.

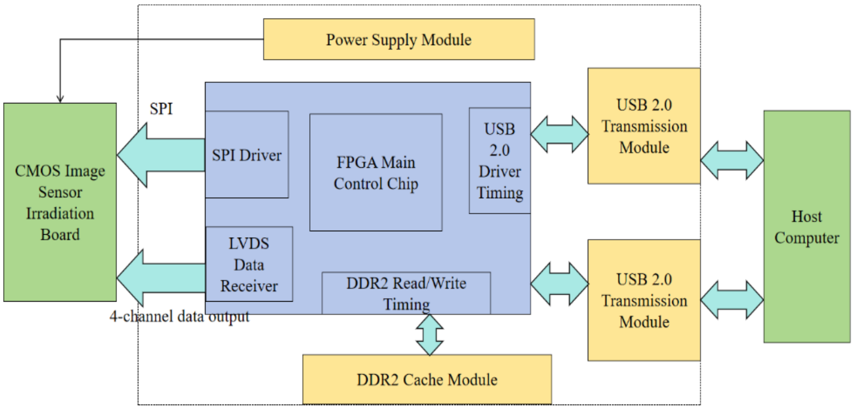

Figure 1. FPGA Main Control Circuit

Theoretically, compared to the latter two experiments, the first experiment offers stronger operability as it does not require overly complex circuits or auxiliary systems. The availability of data support also lends a certain degree of credibility to the experimental results. However, its working principle is more complex and requires additional technologies such as thermal imaging for precision. The second experiment involves manipulating the timing of digital circuits, while the third requires signal processors. Both demand higher technical support but enable multi-faceted analysis, leading to more accurate experimental results.

During the experimentation, the presence of radiation particles may affect the surrounding environment (e.g., temperature, light, etc.), and since the image sensor primarily relies on dark signal parameters, such environmental changes could impact the experimental outcomes. Additionally, the absence of noise suppression devices means that noise generated during particle movement may interfere with the sensor's input data, further affecting the accuracy of the results. As radiation intensity increases, the structure and performance of the sensor may also be significantly compromised.

In the measurement process based on CMOS image sensors, the dark signal, as a key parameter, is susceptible to environmental interference, thereby affecting measurement precision. In contrast, introducing alternative indicators such as the number of bright spots can mitigate the impact of environmental fluctuations to some extent and enhance the reliability of the results. Furthermore, particle movement introduces noise. To reduce its adverse effects on measurement outcomes, noise suppression devices can be installed on the sensor itself or in adjacent areas. On the other hand, if the sensor material inherently lacks sufficient radiation resistance, radiation exposure may lead to performance degradation or even damage. Therefore, selecting materials with radiation-resistant properties is of great significance. Table I summarizes the above content.

Table I. Effects on CMOS Image Sensors in Heavy Ion Radiation Environments and Corresponding Solutions

Problem	Solution
Radiation particles may alter environmental temperature, light, etc., introducing errors in test results.	In addition to dark signals, auxiliary parameters such as bright spot count can be used for supplementary analysis.
Lack of effective noise suppression capability.	Install appropriate noise suppression devices near the CMOS sensor.
Sensor performance gradually degrades as radiation intensity increases.	Use materials with enhanced radiation resistance properties.

2.2. Research on CMOS Image Sensors under Transient Dose Rate Effects

The radiation effects on CMOS image sensors have attracted significant attention, including cumulative radiation effects and transient radiation effects. The latter further comprises single-event effects and transient dose rate effects. Transient dose rate effects refer to a type of transient radiation phenomenon where high-dose-rate gamma rays generate electron-hole pairs within semiconductors, leading to the formation of photo-current. This photo-current can disrupt normal device operation or even cause device burnout [10]. As CMOS image sensors are increasingly deployed in extreme radiation environments, studying transient dose rate effects is crucial for improving their performance. However, research on transient dose rate effects remains relatively limited compared to single-event effects, primarily for two reasons. First, the high integration density of sensors makes it challenging to effectively shield peripheral circuits from radiation. Second, such studies are time-consuming, labor-intensive, and costly. Although institutions in the United States and Europe have proposed testing standards and specifications for electronic components, these guidelines only provide general references for this field of research [11].

Researchers often employ a combined simulation approach using TCAD (Technology Computer-Aided Design) device models and HSPICE (a simulation program for integrated circuits) device models to establish accurate simulations. Fig. 2 illustrates the corresponding HSPICE circuit model.

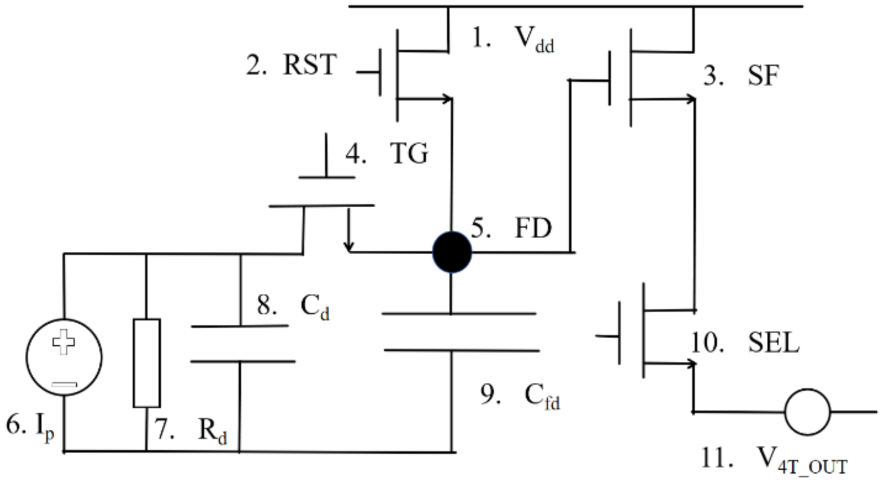

Figure 2. HSPICE Circuit Model

The TCAD model operates through four working stages. By controlling TG and RST to form a potential difference, the output signal is generated through subsequent circuits. Another HSPICE model operates simultaneously with the TCAD model, similarly controlling the charging and discharging of capacitors through TG and RST to form a continuous process, thereby obtaining the output signal. The output signals are then processed to establish a net-list model for analysis [10]. Another experimental approach involves directly using CMOS image sensors as the device under test (DUT), simulating a gamma-ray source, and conducting direct observation and corresponding parameter analysis of the sensors. This method includes step-by-step functional testing and sensitive parameter measurements [11].

In the first experiment, differences between the simulation model and actual devices exist, and not all types of CMOS image sensors are considered, leading to insufficient data support. As a result, the findings can only qualitatively analyze part of the mechanism of transient dose rate effects. In comparison, the second experiment can measure specific parameters and enable quantitative analysis. However, achieving ideal radiation conditions is challenging, improper operations can easily lead to sensor waste, and experimenters may face potential harm. During the experiments, the dose rate is continuously increased. However, excessively high dose rates can severely affect sampling signals, preventing normal readout of CMOS pixel signals. Additionally, frequent switching of capacitor states in the circuit consumes significant energy, making it difficult to achieve green and energy-efficient operation. In radiation environments, the photosensitive area of the device is exposed, making it susceptible to more external factors, and the CMOS chip is prone to damage.

To ensure the reliability and performance stability of CMOS image sensors, it is essential to minimize their long-term exposure to external environments, reducing adverse effects from factors such as humidity, temperature fluctuations, contaminants, and light on the device's structure and electrical characteristics. Simultaneously, maintaining a low radiation dose rate is critical for preserving the integrity and accuracy of pixel signals, effectively preventing signal attenuation and distortion, thereby improving image quality and data reliability. Furthermore, to reduce overall system energy consumption, optimizing the sensor's structure and material selection during the design and manufacturing stages is necessary. By adopting low-power device architectures, high-dielectric materials, or novel semiconductor materials, energy loss due to parasitic capacitance during circuit switching can be significantly reduced, enhancing conversion efficiency and extending device lifespan. Table II summarizes the above content, primarily focusing on the impacts of transient dose rate effects on CMOS image sensors and corresponding solutions.

Table 2. Impacts of Transient Dose Rate Effects on CMOS Image Sensors and Corresponding Solutions

Problem	**Solution**
Excessively high dose rates affect signal sampling and readout.	Control the radiation dose rate to a low level to ensure signal integrity.
Frequent capacitor switching consumes high energy.	Optimize device structure and materials to reduce parasitic capacitance and energy loss.
Exposed photosensitive area is susceptible to external environmental influences.	Minimize long-term exposure to external environments such as humidity, temperature, and contaminants.

2.3. Research on CMOS Image Sensors under Proton Irradiation

In the space radiation environment, high-energy particles can cause functional abnormalities or even failures in CMOS image sensors. Protons, as the primary component of such radiation, induce single-event effects that lead to functional errors in integrated circuits [12]. External manifestations of pixel performance degradation include a significant increase in dark current after irradiation, exhibiting random telegraph signals (RTS) [13]. Researchers worldwide have studied proton irradiation, primarily through experimental approaches focusing on dark current, noise, saturation output, and conversion gain. However, there is limited research on anti-radiation design and performance degradation related to full-well capacity [14]. Full-well capacity refers to the maximum charge that can be stored in a Pinned Photo-diode (PPD). Although some studies exist, simulation methods can more intuitively illustrate the relationship between full-well capacity and pixel process parameters, which is crucial for radiation damage assessment and hardening techniques. Various research teams have adopted different approaches, but most focus on analyzing the pixel units of CMOS image sensors.

The first pixel unit analysis method is based on the fundamental model of CMOS image sensor pixel units. Electrons and holes undergo drift-diffusion motion driven by electric fields, disrupting the internal equilibrium of the device and affecting its parameters. Results are derived by analyzing measured data using physical principles and formulas [14]. The second method utilizes the CMOS image sensor pixel unit, as shown in the figure below. After radiation testing, sampling and random telegraph signal (RTS) testing are conducted at different temperatures, and results are statistically analyzed using RTS pixel detection software [13]. The third method involves a control room operation, where an image acquisition calculator is used to control the circuit board's working status, power supply, and image capture. Results are obtained through image analysis [12].

Fig. 3 shows the structure of a CMOS image sensor pixel unit, which uses a four-transistor (4T) pixel architecture consisting of a photodiode and four transistors: transfer transistor (MTX), source follower (MSF), reset transistor (MRS), and row select transistor (MSEL). The photo-diode comprises, from top to bottom, a heavily doped P+ layer, an N-type buried layer, and a P-type substrate layer. The abundant holes in the P+ layer effectively suppress oxide interface states, thereby reducing surface dark current and dark noise. The photo-diode collects signal charges, the transfer transistor transfers signal charges, and the floating diffusion region performs charge-to-voltage conversion.

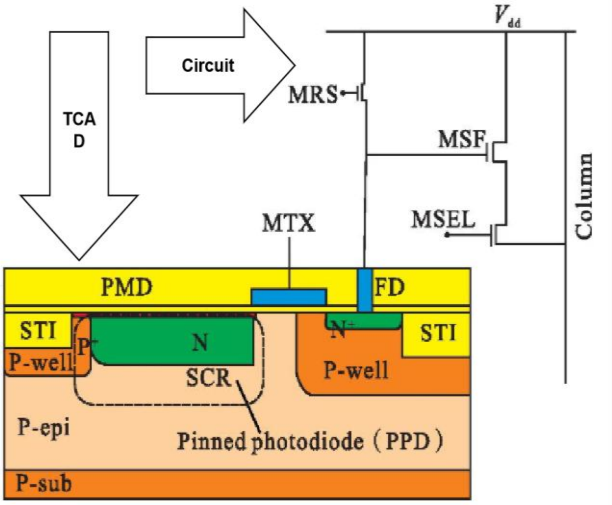

Figure 3. Structure of CMOS Image Sensor Pixel Unit

The first method enables quantitative parameter extraction but requires complex modeling and higher technical expertise. The second method yields richer information but involves a time-consuming testing process and demands advanced system capabilities. The third method is relatively simpler to operate but is highly comprehensive with less clear mechanistic insights. Through this research, it is evident that proton irradiation causes both ionization damage and displacement damage in CMOS image sensors. Ionization damage occurs when generated electron-hole pairs are trapped by the oxide layer, leading to threshold voltage drift, increased leakage current, and ultimately resulting in excessive power consumption or even device failure [12]. Displacement damage is the primary concern, where high-energy protons colliding with silicon atoms create lattice defects, significantly increasing dark current and reducing charge transfer efficiency. This results in diminished signal quantity and trapping of pixel signal charges.

To address proton radiation issues, thinner gate oxide layers or isolated transistors can be employed to reduce charge transfer efficiency and optimize pixel performance. Additionally, lowering the operating temperature of the sensor effectively suppresses dark current growth. Furthermore, radiation-hardened processes can minimize the generation of electron-hole pairs, thereby mitigating parameter drift.

Table 3 summarizes the above content, presenting the effects of proton radiation on CMOS image sensors and corresponding solutions.

Table 3. Effects of Proton Radiation on CMOS Image Sensors and Corresponding Solutions

Problem	Solution
Increased dark current	Low-temperature operation and calibration
Decreased charge transfer efficiency	Use of thinner gate oxide layers or isolated transistors
Parameter drift	Adoption of radiation-hardened processes

3. Conclusion

To address the impact of space radiation on CMOS image sensors in satellite applications, this study investigated the underlying mechanisms and damage caused by heavy ion radiation, gamma rays, and proton radiation from various perspectives. All three types of radiation induce both ionization damage and displacement damage in CMOS image sensors, leading to reduced charge and electron transfer efficiency, decreased pixel signal quality, and overall degradation of pixel performance. To mitigate these risks, it is necessary to optimize the sensors through multiple approaches, including improving manufacturing materials, adopting auxiliary technologies, and refining pixel design. These methods collectively contribute to enhancing sensor performance.

In summary, this research advances the study of radiation effects to some extent, providing significant insights into the understanding of CMOS image sensors and their applications in satellites. It also offers methodologies and perspectives for studying space radiation, facilitating the broader application of CMOS image sensors in various fields. However, the current research is limited by experimental conditions, which differ significantly from the actual space radiation environment, resulting in limited precision of the findings. Additionally, the experimental studies primarily focus on qualitative analysis, making it challenging to provide precise quantitative data on the effects of radiation on CMOS image sensors.

References

[1] M. Bigas, E. Cabruja, J. Forest and J. Salvi, “Review of CMOS Image Sensors”, *Microelectronics Journal*, vol. 37, no. 5, pp. 433-451, May 2006.

[2] P. Jerram and K. Stefanov, “CMOS and CCD image sensors for space applications”, *High Performance Silicon Imaging*, vol.9, pp. 255-287, Oct. 2020.

[3] D. Magalotti, L. Bissi, E. Conti, M. Paolucci, P. Placidi, A. Scorzoni and L. Servoli, “Performance of CMOS imager as sensing element for a Real-time Pixel Dosimeter for Interventional Radiology Procedures”, *Journal of Instrumentation*, vol.9, no. 1, Jan. 2014.

[4] J. H. Lee, S. H. Lee, “A study on radiation detection using CMOS image sensor”. *Journal of IKEEE*, vol. 19, no. 2, pp.193-200, 2015.

[5] E. R. Fossum, D. B. Hondongwa, “A review of the pinned photodiode for CCD and CMOS image sensors”. *IEEE Journal of the Electron Devices Society*, vol. 2, no. 3, pp.33-43, May 2014.

[6] G. R. Hopkinson, A. Mohammadzadeh, “Radiation effects on a radiation-tolerant CMOS active pixel sensor”. *Journal of Environmental Sciences*, vol. 51, no. 5, pp.2753-2762, Oct. 2004.

[7] X. Liu, L. Wen, Y. Li and Q. Guo, “Method and Error Analysis of Heavy-ion Radiation Detection Using CMOS Image Sensors”, *Atomic Energy Science and Technology*, Early Access, Apr. 2025 (in Chinese).

[8] Z. Wang, X. Nie, et al, “Test Circuit Design and Radiation Experiment Verification of CMOS Image Sensors”, *Semiconductor Optoelectronics*, vol.45, no.2, pp.226-221, Oct. 2023 (in Chinese).

[9] Y. Fu, Y. Wei, Y. Zuo, J. Zhu and S. Niu, “Simulation Study of Total Dose Radiation Effect on Readout Circuit of Typical CMOS Image Sensor”, *Modern Applied Physics*, vol.16, no.3, pp.145-152, Jul. 2024 (in Chinese).

[10] Z. Peng, Y. Fu, et al, “Simulation Method for Transient Dose Rate Effect of CMOS Image Sensors”, *Modern Applied Physics*, vol.16, no.3, pp.123-134, Sep. 2024 (in Chinese).

[11] Z. Wang, “Test Methods for Radiation Damage Effects on CMOS Image Sensors”, *Semiconductor Optoelectronics*, vol.46, no.1, pp.180-188, Dec. 2024 (in Chinese).

[12] Y. Li, L. Wen and Q. Guo, “Single Event Transient Effect of CMOS Image Sensor Irradiated by Protons with Different Energies”, Modern Applied Physics, vol.15, no.3, pp.114-121, Feb. 2024 (in Chinese).

[13] B. Liu, Y. Li, L. Wen, J. Feng, D. Zhou and Q. Guo, “Random Telegraph Signal Mechanism on CMOS Image Sensors After Proton Irradiation”, Modern Applied Physics, vol.15, no.4, pp.24-28+62, May 2024 (in Chinese).

[14] X. Yang, Z. Wang, A. Shang, Y. Huo, Y. Xue, T. Jia and Q. Jiao, “Simulation of Full Well Capacity Degradation of 4T CMOS Image Sensor Irradiated by Proton”, Modern Applied Physics, vol.12, no.3, pp.133-141, Apr. 2021 (in Chinese).