Variable Temperature Testing and Parameter Annealing Behavior of Space-Grade High-Precision Photometric CMOS Image Sensors After Proton Irradiation

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Abstract

Exoplanet survey telescopes utilize high-precision CMOS image sensors operating at 233K for planetary detection; however, proton irradiation and temperature fluctuations in the space environment can induce sensor performance degradation, seriously threatening the on-orbit performance and service life of the telescope. This study aims to reveal the effects of different temperatures on key parameters of CMOS image sensors after proton irradiation, providing a theoretical basis for evaluating device radiation damage. By conducting 60 MeV proton irradiation experiments with a fluence of 6.71$×$10^{10} p/cm^2, we systematically tested the variation patterns of core parameters such as dark current and noise at different temperatures, combined pixel tracking methods to quantify the activation energy of hot pixels, conducted annealing experiments to analyze the degree of parameter recovery, and performed mechanism analysis based on semiconductor device physics and radiation damage theory. Experimental results demonstrate that with increasing temperature, dark current and its non-uniformity increase exponentially, while fixed pattern noise, temporal noise, and the number of hot pixels increase linearly; the Gaussian mean of the dark current distribution shifts rightward, the activation energy of hot pixels (0.627 eV) is lower than that of normal pixels (0.726 eV), and cluster defects dominate hot pixel generation. After annealing, dark current exhibits significant recovery, but fixed pattern noise shows no obvious recovery. Combined with pixel structure analysis, bulk defects induced by proton displacement damage are identified as the fundamental cause of sensitive parameter degradation. The research results provide critical experimental data and theoretical support for the on-orbit operation of high-precision CMOS sensors in space.

Full Text

Preamble

Study on Variable-Temperature Testing and Parameter Annealing Characteristics of High-Precision Space Photometric CMOS Image Sensors After Proton Irradiation

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Abstract

The exoplanet survey telescope employs a high-precision CMOS image sensor operating at 233 K for planetary detection. However, proton irradiation and temperature fluctuations in the space environment can degrade sensor performance, posing a significant threat to the telescope’ s on-orbit functionality and operational lifespan. This study aims to elucidate the effects of different temperatures on the key parameters of CMOS image sensors following proton irradiation, thereby providing a theoretical basis for assessing radiation-induced damage to these devices. A 60 MeV proton irradiation experiment was conducted at a fluence of 6.71×10^{10} p/cm^2 to systematically examine variations in key parameters, such as dark current and noise, across different temperatures. Additionally, the activation energy of hot pixels was quantified using a pixel tracking method. Annealing experiments were performed to assess the extent of parameter recovery, and a mechanism analysis was carried out based on semiconductor device physics and radiation damage theory. Experimental results indicate that as temperature increases, both dark current and its non-uniformity exhibit exponential growth. In contrast, fixed pattern noise, temporal noise, and the number of hot pixels increase linearly. Additionally, the Gaussian mean of the dark current distribution shifts to the right. The activation energy of hot pixels (0.627 eV) is lower than that of regular pixels (0.726 eV), suggesting that clustered defects predominantly contribute to hot pixel formation. After annealing, a significant recovery in dark current is observed, whereas fixed pattern noise does not show a marked recovery. Through an analysis of pixel structure, it is concluded that bulk defects induced by proton displacement damage are the fundamental cause of the degradation of sensitive parameters. The research findings provide critical experimental data and theoretical support for the on-orbit operation of high-precision CMOS sensors in space.

Keywords: CMOS image sensor; Proton irradiation; Displacement damage effect; Temperature effect

Introduction

High-precision CMOS image sensors play a critical role in aerospace applications such as sky surveys, star trackers, and space imaging due to their high integration and low power consumption. However, displacement damage effects caused by high-energy protons in the space radiation environment introduce defects into the sensor, leading to surges in dark current, abnormal hot pixels, and even device functional failure. Furthermore, temperature fluctuations experienced by spacecraft during on-orbit operation alter the thermodynamic characteristics of defects, such as activation energy and defect generation rates, creating discrepancies between traditional room-temperature test results and actual operational conditions. Therefore, investigating the degradation patterns of sensor parameters such as dark current and fixed pattern noise at different temperatures post-irradiation becomes particularly crucial. In recent years, scholars have conducted extensive research on the radiation effects in CMOS image sensors. Goiffon et al. studied the impact of displacement damage on dark current in CMOS image sensors, demonstrating that displacement damage introduces bulk defects within the space charge region, resulting in a hot pixel tail in the dark current distribution. Cai et al. investigated the dark signal distribution and generation mechanism in proton-irradiated CMOS image sensors, revealing that proton irradiation causes the dark signal to exhibit a Gaussian distribution accompanied by numerous dark signal spikes. Ma et al. analyzed the effects of proton irradiation on fixed pattern noise, noting that displacement defects increase dark signal non-uniformity, thereby increasing fixed pattern noise. However, these studies were all conducted under constant temperature conditions (typically 300 K), where the test environment differs from the dynamic thermal environment of spacecraft, leaving the extent of radiation damage uncertain. Consequently, there is a need to reveal the evolution patterns of parameters such as dark current and fixed pattern noise under variable temperature conditions.

To overcome the limitations of traditional evaluation methods, this study conducted post-irradiation variable-temperature testing. First, based on analysis of the proton differential energy spectrum in typical satellite orbits, 60 MeV protons were selected for the irradiation experiment. Second, gradient temperature testing was designed within the temperature range of 233 K to 273 K to analyze the response of parameters including dark current and fixed pattern noise, thereby establishing a relationship between device performance degradation and temperature. Simultaneously, annealing experiments were performed to assess the recovery of dark current and fixed pattern noise. Through systematic testing of temperature effects on the performance parameters of proton-irradiated CMOS image sensors, this study aims to reveal their evolution patterns under different temperature conditions, providing more accurate radiation damage assessment criteria for space optical detectors and thereby enhancing detector reliability and stability in extreme environments.

1 Experimental Content

The irradiation sample used in this experiment was a back-illuminated CMOS image sensor fabricated using 0.18 m CMOS process technology with a 4T-PPD pixel structure. The pixel size was 10 m × 10 m, and the readout noise was 5.45 e^-. Since the high-precision image sensor was designed to operate at 233 K, five temperature test points were established to investigate the effects of different operating temperatures on radiation-sensitive parameters following proton irradiation: 233 K, 243 K, 253 K, 263 K, and 273 K. Testing was conducted on a temperature-controllable system based on a refrigeration plate and vacuum dewar. The device was placed in the temperature control system and cooled, with each test performed after temperature stabilization for 30 minutes to ensure temperature fluctuations remained within $±$0.01 K.

Proton irradiation experiments on the high-precision CMOS image sensor were conducted at the Institute of Physics and Chemistry Technology, Chinese Academy of Sciences. The irradiation proton energy was 60 MeV, with a cumulative fluence of 6.71×10^{10} p/cm^2. Following irradiation, annealing was performed at 0 °C, 30 °C, and 50 °C for 96 hours at each temperature, with testing conducted every 48 hours. After annealing completion, the device was cooled to 233 K for final testing. The experimental and testing site is shown in [Figure 1: see original paper].

2 Results and Discussion

Proton irradiation induces both displacement damage and total ionizing dose damage in high-precision CMOS image sensors. Displacement damage arises from nuclear elastic and inelastic collisions between protons and silicon lattice atoms. This study primarily examines the temperature-dependent variation patterns of core parameters including dark signal, dark signal non-uniformity (DSNU), dark current, dark current non-uniformity (DCNU), temporal noise, and fixed pattern noise (FPN) following proton irradiation. The underlying damage mechanisms at different temperatures were investigated, and annealing experiments at 30 °C and 50 °C were conducted to characterize the recovery patterns of the high-precision CMOS image sensor.

The basic structure of a 4T pixel is illustrated in [Figure 2: see original paper]. When protons traverse semiconductor materials, they cause Rutherford (Coulomb) scattering, transferring energy to electrons outside atomic nuclei and exciting them—this is termed direct proton ionization. Protons also collide with atomic nuclei, generating primary recoil atoms that can displace lattice atoms and produce ionization effects. However, compared to direct proton ionization, the ionization effect of recoil atoms is negligible. When proton irradiation occurs in pixel units, oxide trap charges and interface states are generated at the STI isolation oxide interface, leading to increased dark current. Protons interact with silicon atoms through elastic and inelastic processes. Elastic interactions include Coulomb scattering and nuclear elastic scattering. When proton energy exceeds several MeV, inelastic nuclear reactions become particularly significant in proton-silicon interactions. Once lattice atoms acquire energy exceeding the displacement threshold, they leave their original positions, creating vacancy-interstitial pairs that form Frenkel defects. Following proton irradiation, point defects (such as Frenkel pairs) are generated in the silicon bandgap of CMOS image sensors. These point defects migrate and aggregate to form bulk defects, which create new generation-recombination centers and cause dark signal increase in CMOS image sensors. This process primarily occurs in the space charge region.

2.1 Response of Radiation-Sensitive Parameters at 233K-273K

Proton radiation damage significantly affects the response of high-precision CMOS image sensors (CIS), with temperature being another critical factor influencing performance. This section focuses on investigating the temperature response of proton radiation damage in high-precision CMOS image sensors. As shown in [Figure 3: see original paper] and [Figure 4: see original paper], the average dark current, average dark signal, DSNU, and DCNU increase exponentially with temperature. The distributions of dark signal and dark current for the high-precision CMOS image sensor at different operating temperatures post-irradiation are presented in [Figure 5: see original paper] and [Figure 6: see original paper], respectively. Both dark current and dark signal distributions exhibit a combination of a Gaussian distribution and an exponential tail with numerous hot pixels. Proton interaction types include inelastic collisions with atomic electrons, Coulomb elastic scattering, and elastic and inelastic nuclear scattering with atomic nuclei. Except for inelastic collisions with electrons, the remaining three interaction mechanisms all contribute to displacement damage generation. Total dose effects occur at the Si/SiO_2 interface in every pixel, jointly influencing parameter responses alongside displacement damage. Image analysis reveals that numerous pixels reside at the lower-valued Gaussian peak, attributed to the influence of Coulomb elastic scattering across the entire pixel array. This observation aligns with the characteristics of Coulomb elastic scattering—large cross-section and small damage energy—where a larger scattering cross-section implies greater occurrence probability. Conversely, the minority of pixels with high dark current levels (hot pixels) located in the exponential distribution tail result primarily from displacement damage, as nuclear elastic and inelastic scattering feature small cross-sections and large damage energy.

The generation rate of defects in the CMOS image sensor depletion region can be expressed as:

$$G = \frac{\sigma_n \sigma_p v_{th} n_i N_t}{\sigma_n n + \sigma_p p} \exp\left(-\frac{|E_t - E_i|}{kT}\right)$$

In this equation, σ_n and σ_p represent the capture cross-sections for electrons and holes, respectively; v_{th} denotes the carrier thermal velocity; n_i is the intrinsic carrier concentration; N_t is the defect density per unit volume; E_i is the intrinsic Fermi level; E_t represents the defect energy level; k is the Boltzmann constant; and T is temperature. Consequently, the defect generation rate is influenced by temperature, defect energy level, and the capture cross-sections for electrons and holes. It can be concluded that the carrier generation rate increases exponentially with temperature, thereby causing dark current and dark signal to increase with rising temperature.

Furthermore, the increase in dark current and dark signal, along with the rightward shift of their distributions, results from increased carrier concentration in the semiconductor at elevated temperatures. The electron-hole pairs generated by defect energy levels introduced through irradiation increase dramatically, and the density of defects in thermally excited states rises, leading to increased surface recombination current and diffusion current. This sensitivity primarily stems from ionization damage and displacement damage caused by proton irradiation. At low temperatures, the probability of carrier generation, capture, and mobility reduction decreases, and the dark current and dark signal generated by ionization and displacement damage are far less significant than at room temperature. Consequently, the Gaussian mean and exponential distribution tail are smaller at low temperatures.

Fixed pattern noise (FPN) and temporal noise increase linearly with temperature, as shown in [Figure 7: see original paper]. The non-uniformity in pixel spatial response arises from the non-uniform distribution of displacement damage energy across the pixel array. Displacement damage energy is deposited through elastic Coulomb scattering, nuclear elastic scattering, and inelastic nuclear scattering. Coulomb scattering and nuclear elastic scattering feature high occurrence probability and low deposited energy, while inelastic scattering exhibits low occurrence probability and high deposited energy. Most pixels are affected by displacement damage, and as temperature increases, the defect energy level generation process intensifies, causing FPN to increase. Temporal noise originates from source follower 1/f noise, whose behavior is closely related to device operating temperature. When temperature rises, the capture and release frequency of carriers by interface defects increases, thereby increasing temporal noise. These results demonstrate that average dark current, DCNU, average dark signal, DSNU, FPN, and temporal noise are all highly sensitive to temperature variations.

2.2 Hot Pixels at 233K-273K

High-precision CMOS detectors exhibit significant differences in dark current values when tested at various temperatures post-irradiation, generating numerous hot pixels that appear as bright spots or white patches in images under dark field or low-illumination conditions, thereby degrading imaging quality. Activation energy serves as a crucial method for characterizing defect energy levels. By introducing the Arrhenius equation, the dark current activation energy $E_a(T)$ can be obtained, where A is the pre-exponential constant factor:

$$I = A \cdot \exp\left(-\frac{E_a}{kT}\right)$$

Using a pixel tracking method to statistically analyze the average activation energy of hot pixels and normal pixels, the activation energies were determined to be 0.627 eV and 0.726 eV, respectively. The lower activation energy of hot pixels indicates that their defect energy levels are closer to the mid-gap, primarily composed of various cluster defects, whereas normal pixel defect energy levels are farther from the mid-gap and consist of both point defects and cluster defects.

As shown in [Figure 8: see original paper], the number of hot pixels increases significantly with temperature. Following proton irradiation, bulk defects generated in the pixel space charge region act as carrier generation-recombination centers, causing some electrons to transition from higher to lower energy levels and release energy, resulting in increased pixel output that creates hot pixels. Typically, hot pixels are defined as those with dark signals two to four times greater than normal pixels. We selected pixels with dark current exceeding four times the average as the hot pixel threshold and statistically analyzed their count, revealing the relationship between hot pixel number and temperature: as temperature rises, the number of hot pixels increases approximately linearly, reaching 31.9% at the highest temperature compared to only 7.1% at 233 K, as shown in [Figure 9: see original paper]. The hot pixel count exhibits strong temperature dependence, and low-temperature operating environments can effectively suppress hot pixel generation.

2.3 Annealing Characteristics of Radiation-Sensitive Parameters

Following proton irradiation, both total ionizing dose effects and displacement effects simultaneously impact device performance. Ionizing total dose effects generate oxide trap charges in gate oxides and isolation oxides, as well as interface state trap charges at the SiO_2/Si interface. Displacement effects form bulk defects in the silicon bulk. After room-temperature annealing, some displacement damage defects and ionization-induced defects are annealed out, eliminating their contribution to device parameter degradation. However, most interface state trap charges and displacement damage defects continue to affect device performance, as bulk defects formed by displacement damage are relatively stable and require higher temperatures for annealing.

In post-irradiation annealing experiments, the high-precision CMOS image sensor underwent annealing treatments at 0 °C, 30 °C, and 50 °C for 96 hours at each temperature, with testing performed every 48 hours. Experimental results demonstrate that dark current exhibits a clear annealing trend at 30 °C, while the annealing effect is not significant at 50 °C. The elevated temperature annealing at 30 °C shows remarkable effectiveness in restoring dark current in the image sensor. At 30 °C, most oxide trap charges and some displacement damage defects affecting dark current have been annealed out, while interface state trap charges, divacancies, and vacancy-interstitial defects continue to cause dark current degradation. After the 50 °C annealing process, the remaining dark current is primarily caused by bulk defects formed by protons in the silicon bulk.

Following proton irradiation, the fixed pattern noise of the back-illuminated CMOS image sensor increased significantly. However, after annealing treatments at 0 °C, 30 °C, and 50 °C, the fixed pattern noise did not recover substantially, as shown in [Figure 11: see original paper]. This noise reflects performance variations between pixels. During proton irradiation, the ionizing total dose effect impacts the entire pixel array uniformly, with oxide trap charges affecting each pixel similarly, thus contributing negligibly to fixed pattern noise. Interface state trap charge formation is closely related to Si/SiO_2 interface defects from the manufacturing process. Since interface states differ between pixels during fabrication, non-uniform readout circuit degradation occurs, which represents the primary mechanism by which interface state trap charges affect fixed pattern noise post-irradiation. Typically, pre-irradiation fixed pattern noise arises from readout circuit process variations. At the shortest integration time, the signal originates from the floating diffusion structure, and post-irradiation fixed pattern noise results from bulk defects acting as generation-recombination centers within this structure’ s bandgap. Displacement effects manifest primarily through elastic Coulomb scattering and inelastic nuclear scattering. Elastic Coulomb scattering features a large collision cross-section and relatively uniform impact on the pixel array, whereas inelastic nuclear scattering has a small collision cross-section, causing displacement defects to appear only in a minority of pixel units and significantly affecting imaging uniformity across the pixel array. Consequently, the impact of displacement damage on fixed pattern noise is mainly caused by bulk defects resulting from inelastic nuclear scattering of protons in some pixels. Therefore, below 50 °C, a large number of defects related to interface states and inelastic nuclear scattering do not undergo annealing, and fixed pattern noise shows no significant change.

Conclusion

This study employed a 4T-CMOS image sensor for 60 MeV proton irradiation experiments, followed by variable-temperature testing from 233 K to 273 K. The relationship between radiation-sensitive parameters and temperature was established: average dark current and DCNU increase exponentially with temperature, while fixed pattern noise, temporal noise, and hot pixels increase linearly. Hot pixels originate from cluster defects, as evidenced by their different activation energies—hot pixel activation energy is closer to the mid-gap, resulting in higher dark current than normal pixels. Experimental results demonstrate that lowering temperature can effectively reduce hot pixel count. After annealing at 0 °C, 30 °C, and 50 °C, dark current recovery was observed, with significant annealing occurring at 30 °C as some displacement damage defects and ionization-induced defects were annealed out. However, fixed pattern noise did not recover significantly after elevated temperature annealing because below 50 °C, a large number of defects related to interface states and inelastic nuclear scattering did not undergo annealing. This research provides experimental and theoretical support for evaluating proton radiation damage effects and temperature-dependent responses in high-precision CMOS image sensors. Future work will summarize parameter degradation patterns following low-temperature irradiation and investigate defect generation and evolution mechanisms at cryogenic temperatures.

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Note: Figure translations are in progress. See original paper for figures.