Research on β-ray Radiation Effects and Detection Methods of CMOS Active Pixel Sensors

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Abstract

This paper presents research on β-ray detection methods based on complementary metal-oxide-semiconductor (CMOS) active pixel sensors (APS), analyzes the mechanisms and characteristics of β-radiation response and damage, discusses the nonlinear characteristics of annealing effects on sensor damage, proposes a gain optimization method based on double-threshold constraints, and develops a noise suppression technique utilizing temporal differences. Additionally, a β-ray detection model correlating visual imaging with radiation absorption dose is established. Through 63Ni β radioactive source irradiation experiments and Geant4 Monte Carlo simulations, the characteristics of β-ray radiation response events in CMOS APS at different gains, the average pixel values of dark images at different integration times, energy deposition, damage modes, and room-temperature annealing effects are investigated. Experimental results demonstrate that the β-radiation response event is characterized by near-saturation of a single pixel' s value and induces a sharp increase in the values of a very small number of surrounding pixels. The optimal gain for β-ray measurement was determined to be 43dB through the double-threshold constraint gain optimization method. When the gain is below 43dB, the sensor inadequately amplifies the charge signal generated by β-rays, resulting in weak effective signal intensity. When the gain exceeds 43dB, the response signal becomes distorted due to charge overflow. With increasing irradiation time, the damage to CMOS APS continues to intensify. The room-temperature annealing effect leads to nonlinear variation in its damage trend. During the annealing process, the reduction in dark signal count is partly due to the sensor' s self-recovery to the pedestal noise level and partly due to intermittent pixel failure, which temporarily loses charge collection ability, manifested as a pixel value of 0. The temporal difference filtering method effectively removes noise while preserving β response events, achieving a retention rate of 99.75% and improving the signal-to-noise ratio by a factor of 5.17 compared to that before noise reduction. When the sensor operates in the low-integration-time region below 5.625ms, the calculated energy deposition shows relatively high agreement with the simulated energy deposition. However, in the high-integration-time region above 5.625ms, charge saturation effects occur in the sensor pixels, and the error increases significantly. The gray value-dose detection model based on piecewise exponential attenuation correction enables quantification of β-ray absorbed dose.

Full Text

Research on β-Ray Radiation Effects and Detection Methods of CMOS Active Pixel Sensors

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This paper investigates β-ray detection methods based on complementary metal-oxide-semiconductor (CMOS) active pixel sensors (APS), analyzing the mechanisms and characteristics of β-radiation response and damage, discussing the nonlinear influence of annealing effects on sensor degradation, and proposing a gain optimization method based on double-threshold constraints along with a noise suppression technique utilizing temporal differences. Additionally, it establishes a β-ray detection model correlating visual imaging with radiation absorption dose. Through irradiation experiments using a ^{63}Ni β radioactive source and Geant4 Monte Carlo simulations, this study examines the characteristics of β-ray radiation response events in CMOS APS at different gains, the average pixel values of dark images at various integration times, energy deposition, damage modes, and room-temperature annealing effects. Experimental results demonstrate that β-radiation response events are characterized by near-saturation pixel values in single pixels, affecting a sharp increase in a very small number of surrounding pixels. The optimal gain for β-ray measurement was determined to be 43 dB through the double-threshold constrained gain optimization method. When the gain is below 43 dB, the sensor inadequately amplifies the charge signal generated by β-rays, resulting in weak effective signal intensity. When the gain exceeds 43 dB, the response signal becomes distorted due to charge overflow. As irradiation time increases, damage to the CMOS APS continues to intensify, with room-temperature annealing effects leading to nonlinear changes in the damage trend. During the annealing process, the reduction in dark signals is partly attributable to the sensor’ s self-recovery to the pedestal noise level, and partly due to intermittent pixel failure that temporarily loses charge collection capability, manifested as pixel values of 0. The temporal difference filtering method effectively removes noise while preserving β response events, achieving a retention rate of 99.75% and increasing the signal-to-noise ratio by 5.17 times compared to pre-noise reduction levels. When the sensor operates in the low-integration-time region below 5.625 ms, the calculated energy deposition shows relatively high agreement with simulated energy deposition. However, in the high-integration-time region above 5.625 ms, charge saturation effects occur in sensor pixels, and errors increase significantly. The gray value–dose detection model based on piecewise exponential attenuation correction enables quantification of β-ray absorbed dose.

Keywords: β-ray detection method; active pixel sensor; radiation response; noise compensation method; annealing at room temperature

INTRODUCTION

β particles serve as key tracer particles in nuclear facility operations, radioactive waste treatment, and environmental radiation monitoring, particularly ^{14}N applied in primary circuit monitoring of reactors [1]. Precise detection technology is directly related to the accuracy of nuclide identification, radiation dose assessment, and nuclear safety assurance capabilities [2–4]. Although current mainstream scintillator detectors and gas detectors can meet basic detection requirements, they generally face bottlenecks such as heavy volume, insufficient radiation resistance performance, and large energy deposition quantification errors when monitoring high-fluence-rate β fields in nuclear reactors [5] and radioactive contamination sites [6, 7], which restricts the development of real-time dynamic reconstruction technology for nuclear radiation fields. Achieving precise detection of β particles requires radiation detectors to not only capture them efficiently but also accurately measure energy deposition in sensitive media [8]. In recent years, radiation detectors based on semiconductor materials [9] have become a research hotspot due to their high sensitivity and rapid response characteristics [10, 11].

Among these, the CMOS Active Pixel Sensor (CMOS APS) represents an advanced device integrating signal detection, processing, and readout functions [12–15]. Its unique pixel-level signal processing capability enables high resolution, low noise, and rapid imaging [16, 17], demonstrating unique potential in space radiation dose monitoring [18–20] and real-time nuclear medicine imaging [21]. However, most existing studies focus on interaction mechanisms between γ rays and radiation sources such as protons [22–24], lacking systematic understanding of β-particle energy deposition in silicon-sensitive layers and resulting radiation damage [25]. Moreover, image noise generated by radiation damage also limits β-ray detection accuracy. While traditional noise reduction algorithms such as statistical models, machine learning, transform domains, and image processing [26–28] can address noise recognition and compensation to some extent, they significantly impact radiation information extraction. Current studies mostly focus on comprehensive response characteristics of β rays and α rays, yet a significant gap remains in systematic research on the independent action mechanism of β rays. There is a lack of a full-chain research system specifically targeting β rays, covering particle response, dynamic evolution of radiation damage, annealing process optimization, and noise suppression strategies. This limits the application reliability of CMOS APS in core nuclear science scenarios such as nuclide activity analysis [29], β radioactive contamination localization [30, 31], and primary circuit monitoring of nuclear reactors [32-34]. Therefore, research on β-particle radiation detection methods using CMOS APS will facilitate the development of digitization, intelligence, and chip-scale integration for β-particle detection [32–34].

This paper systematically investigates β-ray action mechanisms, radiation damage characterization and annealing effects, and noise suppression methods based on CMOS APS. Irradiation experiments were conducted using ^{63}Ni β radioactive sources to study the effect patterns of β rays on active pixel sensors, analyzing the influences of integration time and gain on β response events. A double-threshold constrained gain optimization method was proposed to determine the optimal sensor gain and improve detection accuracy. The variation patterns of sensor radiation damage under different irradiation times were discussed, and the influence of room-temperature annealing on radiation damage was analyzed. A temporal difference noise filtering method was proposed to suppress noise generated by β radiation and reduce its impact on detection. By extracting image response events, energy deposition at each integration time was analyzed, verified through Geant4 Monte Carlo simulation, and systematic errors were corrected. Finally, a measurement model correlating image gray values with absorbed dose was constructed to further improve β-ray detection capability of active pixel sensors and provide important technical and data support for enhanced nuclear detection capabilities.

II. EXPERIMENTAL SCHEME FOR β-RAY RADIATION RESPONSE AND DAMAGE CHARACTERIZATION

A. Experimental Samples and Conditions

This study selected the MT9P031 CMOS active pixel sensor produced by Aptina Imaging Company as the experimental sample. The sensor features an effective pixel array of 2592H$×$1944V with an effective pixel area measuring 5.70 mm (H) × 4.28 mm (V). Each individual pixel measures 2.2 µm × 2.2 µm and outputs an 8-bit digital frame image. Based on the EMVA 1288 standard [35], the conversion gain K (the increment in output image gray value per effective photoelectron) for this sensor model was measured to be 0.0224 DN/e$^-$. The output events of the CMOS active pixel sensor are collected and transmitted using the iCamera motherboard, with data transmitted to a PC for processing through the USB communication protocol. During the experiment, functions such as automatic white balance, automatic black balance calibration, noise reduction, and exposure compensation were disabled, with gain and integration time manually set.

The experiment utilized a ^{63}Ni β radioactive surface source to irradiate the sensor. The source activity was 7.4×10^{7} Bq, with an average β-ray energy of 17.425 keV, at an ambient temperature of approximately 25°C ($\pm$0.5°C). The β-ray fluence rate was calibrated using a gold-silicon surface barrier detector, yielding a surface fluence rate of 3.03×10^{8} cm^{-2}s^{-1} at the sensor. During the experiment, β rays released by the ^{63}Ni source were incident perpendicularly on the sensor surface. The glass protective layer above the sensor was removed to allow β rays to directly strike the sensor target surface. Throughout the entire experiment, the sensor and radioactive source were housed in a vacuum dark box to isolate visible light interference, enabling the experiment to be conducted in a vacuum and dark environment. The experimental samples and modules are shown in Fig. 1 [Figure 1: see original paper].

B. Experimental Scheme

The experimental scheme and parameter settings are shown in Table 1 . Before the irradiation experiment, pedestal noise data of the sensor were measured and stored. During the irradiation experiment, dark image data under different integration time and gain parameter settings were collected every three hours. After each set of radiation response data was collected, the radioactive source was removed to collect radiation damage data. Following 30 hours of irradiation, the radioactive source was removed, and the sensor was kept powered on at room temperature for 60 hours of annealing while collecting annealing data. The data storage format was BMP file format, with a frame sampling rate of one frame per second, and the number of frames collected was set according to the experimental purpose.

Table 1. Experimental Scheme and Parameter Settings

Serial Number	No. 1	No. 2	No. 3
Parameter	Pedestal noise	Dark image during irradiation	Dark image after natural annealing
Gain Setting (dB)	from 0 to 64 dB	from 0 to 64 dB	16 dB, 43 dB, 56 dB
Irradiation Time (h)	from 0 to 30 (collected every 3 hours)	from 0 to 30 (collected every 3 hours)	from 31 to 90 (collected every 6 hours)
Integration Time Setting	from 0 to 45 ms	from 0 to 45 ms	22.5 ms & 45 ms

C. Experimental Data Processing Method

In this paper, the signal-to-noise ratio (SNR) serves as the core indicator for measuring β-ray response signal quality in CMOS APS, defined as the ratio of effective signal to pedestal noise. Higher SNR indicates better signal quality. The SNR calculation formula is shown in Eq. (1):

$$SNR = 10\log_{10}\left(\frac{\sigma_{sn}^2 - \sigma_n^2}{\sigma_n^2}\right)$$

where σ_{sn} is the standard deviation of pixel values in images containing both response events and pedestal noise, σ_n is the standard deviation of pixel values in images containing only pedestal noise, and N is the total number of frames in the dark image ($N = 100$).

The standard deviation calculation formula for pixel values is shown in Eq. (2):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{H}\sum_{j=1}^{V}(F(i,j) - \mu)^2}{H \times V}}$$

where H and V represent the horizontal and vertical pixel counts of the image, respectively. For captured images in this paper, M and N are 1920 and 1080, respectively. $F(i,j)$ denotes the pixel value at coordinate (i,j), and μ denotes the average pixel value in the frame image.

The incremental calculation of pixel values in the K-th frame image is shown in Eq. (3):

$$\Delta I_K = \sum_{i=1}^{n}(I_{i,t} - I_{i,h})$$

where $I_{i,t}$ represents the pixel value of the i-th pixel at irradiation time t, $I_{i,h}$ is the pedestal pixel value of the i-th pixel stored without irradiation, and n is the number of pixels.

III. ANALYSIS OF β-RAY RADIATION RESPONSE

A. β Response Event Characteristics

Fig. 2 [Figure 2: see original paper] shows the heat map of pixel value distribution for typical β radiation response events on a dark image. The radiation response events caused by β radiation exhibit pixel values greater than 15 in two or more adjacent pixels, presenting irregular shape features. Their position changes with the frame image, and the magnitude of response events is similar to that of γ-ray radiation response events [36]. This similarity occurs because γ-ray radiation response signals are caused by secondary electrons generated through the Compton scattering effect, which shares the same ionizing radiation mechanism as β rays. From the pixel value perspective, β-ray radiation response events are primarily manifested as a sharp increase in single-pixel values approaching 255, affecting a very small number of surrounding pixel values to change sharply within a short period. In β-radiation response events, three situations can be classified: unsaturated, just-saturated, and oversaturated. An unsaturated event refers to no pixel reaching a value of 255 in the response event. A just-saturated event occurs when only one pixel' s value reaches 255. An oversaturated event refers to multiple pixels reaching values of 255 in the response event.

B. Influence of Parameters on β Response Events

Fig. 3 [Figure 3: see original paper] shows the relationship curves between pixel values and integration time under gain conditions of 16 dB, 43 dB, and 56 dB. As integration time extends, the average pixel value of frame image pixels increases, demonstrating a good linear relationship. This occurs because ^{63}Ni β rays undergo ionization effects when passing through pixels, generating electron-hole pairs. When these ionized charges are captured by the space charge region within pixels, they appear as white bright spots with peaks near saturation. During the experiment, the fluence of the β radioactive source remained unchanged. Extended integration time leads to capture of more ionized charges, thus increasing the average pixel value. Gain directly affects the amplification ratio of the response signal, manifested in the relationship curve graph as the slope of high-gain fitting curves being greater than that of low-gain curves. Therefore, both gain and integration time parameters impact β response event extraction based on CMOS APS detection.

Based on the analysis of β response event characteristics in Fig. 2, this paper adopts the connected region method to count typical response events generated by β rays in frame images. The connected region threshold was set to 2, with threshold segmentation and binarization processing based on pixel values. Pixels with values greater than 15 were determined as 1, and those below 15 as 0. The specific determination formula is shown in Eq. (6):

$$g(x,y) = \begin{cases} 0, & f(x,y) \le 15 \\ 1, & f(x,y) > 15 \end{cases}$$

where $f(x,y)$ is the pixel value at coordinates (x,y).

Fig. 6 [Figure 6: see original paper] shows the number of β response events under three gain settings statistically analyzed using the connected region method. Green circles represent unsaturated response events, red represents just-saturated events, and blue represents oversaturated events. Fig. 6(a) shows that when gain is lower than 43 dB, the sensor inadequately amplifies the charge signal generated by β rays, resulting in weak effective signal strength and causing 88.74% of response events to be in an unsaturated state. Fig. 6(b) shows that when gain exceeds 43 dB, response signal distortion occurs due to charge overflow, resulting in 90.37% of response events being in an oversaturated state. Fig. 6(c) shows that at 43 dB gain, the number of just-saturated response events is maximized, while some oversaturated and unsaturated events also exist.

Fig. 7 [Figure 7: see original paper] shows the image signal-to-noise ratio under different gains. As gain increases, the signal-to-noise ratio increases, reaching a peak of 23.30 at 43 dB, after which it decreases. It can be concluded that the optimal gain obtained through the double-threshold constrained gain optimization method enables the signal-to-noise ratio to reach its peak, thereby achieving more precise ray detection.

IV. ANALYSIS OF THE RESULTS OF RADIATION DAMAGE EXPERIMENTS

Fig. 8 [Figure 8: see original paper] shows the pedestal noise distribution of the sensor at different stages. At various stages, pixel values of most pixels in the sensor array are within the 0–15 range, conforming to Poisson distribution. In the non-irradiation stage, the proportion of pixels with values exceeding 15 is less than 0.01% of the total. Therefore, this paper sets the pedestal noise threshold I_{th} to 15 to eliminate pedestal noise influence on experimental results.

Fig. 9 [Figure 9: see original paper] presents the logical block diagram for dark signal quantity statistics. Due to sensor pedestal noise, its influence must be deducted when conducting dark signal statistics. Here, $(i, j)_n$ represents the pixel value at point (i, j) in the N-th frame image, and N_{rd} is the number of dark signals.

Fig. 10 [Figure 10: see original paper] shows the heat map of dark signal quantity N_d distribution under different irradiation times. The "A" area indicates pixel gray values generally within the 0–15 range, where pedestal noise dominates. The "B" area indicates pixel gray values more within the 16–255 range. At fixed irradiation time, as integration time or gain increases, the proportion of pixels with values exceeding 15 continuously increases. This occurs because increased integration time causes CMOS APS to accumulate more thermal noise and dark current-generated noise, raising image gray value levels. Increased gain significantly amplifies signals collected by the sensor, intensifying irradiation-induced noise. Moreover, the noise increase rate accelerates accordingly, and gray values become higher. With fixed integration time and gain, as irradiation time increases, pixel damage intensifies, manifested as the peak value of the base noise region gradually decreasing, its proportion gradually decreasing, and more pixels falling within the 15–255 gray range. This occurs because when the sensor is irradiated by β rays, defects form in the semiconductor device' s oxide layer and at the oxide-silicon interface, generating trap charges. These trap charges further form dark currents and produce dark signals. With increased irradiation time, the sensor' s accumulated absorbed dose increases, creating more defects, which appears in the image as a continuous increase in pixels exceeding the pedestal noise threshold.

Fig. 11 [Figure 11: see original paper] shows the relationship curve between dark image pixel value increment and irradiation time. As irradiation time increases, image pixel value increments show an overall upward trend, but with sudden decreases at the 12th and 27th hours. This indicates that sensor radiation damage has a nonlinear relationship with total radiation dose, possibly due to certain mechanisms during the radiation damage process. However, under short-term irradiation, pedestal noise variation in individual pixels within consecutive frames remains below 1 unit. This indicates that gray value changes caused by radiation-generated noise constitute a long-term cumulative process, with changes within consecutive frames at 22.5 ms intervals being almost negligible.

Fig. 12 [Figure 12: see original paper] shows variation curves of dark signal quantity and noise pixel values during the 60-hour room-temperature annealing process. Based on the above findings, β-ray radiation damage in the sensor exhibits natural annealing repair capability, with room-temperature annealing effects occurring during the radiation damage process. Relevant studies have confirmed this phenomenon: most vacancies and gaps (over 90%) caused by displacement damage are not permanent, and the silicon lattice can self-repair. This paper studies the radiation damage annealing effect after β-ray irradiation. Fig. 12 shows dark image data collected under parameters of 43 dB gain and 45 ms integration time, with statistics on dark signal quantity and image noise pixel value changes. Dark signal quantity refers to the number of pixels within a frame image with values exceeding the pedestal noise threshold of 15. Noise pixel value change refers to the sum of pixel value changes for each pixel within the frame image in the annealed state compared to the non-irradiated frame image. Before 42 hours of room-temperature annealing, the sensor' s dark signal quantity and image noise pixel values generally show a downward trend. The reduction in dark signal quantity may be caused by two reasons: some pixels return to normal state through sensor self-repair, with pixel values at pedestal noise level; other pixels are completely damaged and lose charge collection capability, manifested as pixel values of 0. After 42 hours of annealing, the sensor exhibited reverse annealing, with dark signal quantity rebounding significantly. This reverse annealing may occur because transistor leakage current and subthreshold leakage current caused by oxide trap charges have basically disappeared, while numerous interface states remain in the SiO_2 around the surface boundary of the photodiode P-N junction and the N^+/P^- substrate junction at the reset transistor source end [37]. The results show that β radiation damage to the sensor is not permanent and can be repaired after a certain period, causing the sensor to exhibit nonlinear growth during the damage process.

Fig. 13 [Figure 13: see original paper] shows the distribution map of radiation damage and annealing effects on pedestal noise. When the sensor is not irradiated, most pixels concentrate at values of 9, 10, and 11, while pixels with value 0 are negligible. After 30 hours of irradiation (annealing for 0 hours), pixels with value 0 account for 71% of pedestal noise, far exceeding pixels with values 1–15. This indicates that pixels with value 0 in this state are not in pedestal noise state but in intermittent failure state. During room-temperature annealing, pixels in transient failure state self-recover. However, due to sensor crystal defects, they do not fully return to normal undamaged levels. Moreover, this repair process is random and unstable. Therefore, dark signals generated by radiation damage are transformed from pixels with value 0 that are temporarily failed and submerged in pedestal noise.

V. β-RADIATION DAMAGE COMPENSATION FOR CMOS APS

Based on the conclusion that under short-duration irradiation, pedestal noise variation of individual pixels in consecutive frames remains below 1 unit while radiation-responsive pixel values change over time, this paper proposes a noise filtering method based on temporal differences to achieve noise suppression, with its logical block diagram presented in Fig. 14 [Figure 14: see original paper]. The method first extracts gray matrices from three consecutive frames, then selects pixel $(i,j)_n$ from the nth frame and compares its corresponding values $(i,j)_{n-1}$ and $(i,j)_{n+1}$ in preceding and subsequent frames. If a pixel's gray value remains unchanged across three consecutive frames, it is identified as radiated noise and reset to pedestal noise level.

Fig. 15 [Figure 15: see original paper] compares noise suppression effects on frame images after 24 hours of irradiation using the temporal difference filtering method. Images processed by this method clearly retain β-radiation response events while effectively suppressing radiation noise. Therefore, this method can compensate for radiated noise without affecting response signals. The temporal difference filtering method adopted in this paper was compared with several commonly used noise suppression methods including median filtering, mean filtering, and interpolation filtering. The noise suppression effects are shown in Table 2 . Median filtering and mean filtering not only reduce noise but also remove radiation response events that need to be retained. The temporal difference filtering method effectively removes noise while retaining β response events, achieving a retention rate of 99.75% and increasing the signal-to-noise ratio by 5.17 times compared to pre-suppression levels.

Table 2. Comparison of Denoising Methods for β Radiation Response Events

Denoising Method	β Response Events (No Damage)	β Events After Noise Suppression (24h)	Event Retention Rate	SNR (Before)	SNR (After)
Median Filtering	50.25%	-	-	-	-
Mean Filtering	25.62%	-	-	-	-

Denoising Method	β Response Events (No Damage)	β Events After Noise Suppression (24h)	Event Retention Rate	SNR (Before)	SNR (After)
Interpolation Filtering	68.04%	-	-	-	-
Temporal Difference Filtering	99.75%	-	-	-	5.17× improvement

VI. β RADIATION DETECTION METHOD BASED ON CMOS APS

Fig. 16 [Figure 16: see original paper] presents the logical block diagram of the CMOS APS β-ray detection algorithm. This method detects and corrects β rays from both experimental and simulation perspectives. In the radiation experiment portion, frame images are collected and analyzed to set the pedestal noise threshold I_{th}. β-ray response events are extracted using the temporal difference filtering method. The total gray value G_{rt} of response events is counted, and the energy deposition E_{real} corresponding to image gray values is calculated. In the simulation portion, with ^{63}Ni as the radioactive source, parameters such as CMOS APS material properties, position, and distance are set. The number of emitted particles N under different integration times is simulated. The energy deposition rate dE/dx of single particles in the detector is calculated, and the total energy deposition Q_{dep} of β particles is obtained. After comparing and verifying experimental E_{real} with simulation results, systematic errors are corrected. Finally, the measurement model correlating image gray values with absorbed dose is constructed.

The calculation formula for the total gray value of response events is shown in Eq. (7):

$$G_{rt} = \sum_{(x,y)\in(H\times V)} [f(x,y)] - (H \times V) \cdot I_{th}$$

The energy E_{pair} required to generate an electron-hole pair in silicon is approximately 3.6 eV [38]. Combined with the conversion gain K of the MT9P031 sensor, the energy deposition E_{real} of the sensor in radiation experiments can be calculated as shown in Eq. (8):

$$E_{real} = Q_e \cdot E_{pair} = \left(\frac{G_{rt}}{K}\right) \cdot 3.6$$

Based on energy spectrum data for ^{63}Ni β radioactive sources provided by the International Atomic Energy Agency (IAEA), this paper establishes a β particle irradiation simulation model. The experimental MT9P031 CMOS APS has a wafer thickness of 300 µm. The charge collection area proportion within a single pixel exceeds 90%. The bottom of adjacent pixels is electrically connected through metal interconnections, with lateral isolation achieved by a shallow trench isolation (STI) structure. Process analysis indicates the gate oxide layer thickness is less than 10 nm, total gate thickness approximately 200 nm, and semiconductor doping concentration below 1\$×10ˆ{18}\$ atoms/cm^3. Since the doping concentration is only 1/50,000 of the intrinsic silicon atomic density of 5\$×10ˆ{22}\$ atoms/cm^3, the pixel array can be approximately simplified as a periodic arrangement of rectangular units composed of intrinsic silicon. Energy deposition calculations are based on these geometric parameters and material assumptions, with detailed structure and size distribution shown in Fig. 17 [Figure 17: see original paper].

The number of particle emissions at different integration times is shown in Eq. (9):

$$N = 3.03 \times 10^{8} \times T$$

During interaction between β particles and CMOS APS, the energy deposition process is modeled by Continuous Slowing Down Approximation (CSDA). Based on the ^{63}Ni radioactive source energy spectrum and sensor material properties, the linear energy transfer of a single β particle in silicon material is calculated as shown in Eq. (10):

$$\frac{dE}{dx} = \left(\frac{4\pi r_e^2 m_e c^2 N_A Z_{eff}}{A\beta^2}\right) \cdot \left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right) - 2\beta^2 - \delta\right]$$

where $Z_{eff} = 14$ and $A = 28.09$ g/mol are the equivalent atomic number and molar mass of silicon, respectively; $\rho = 2.329$ g/cm^3 represents silicon density; N_A is Avogadro' s number; T_{max} represents the maximum energy transfer of the β particle; $I = 173$ eV is the average ionization energy of silicon; and δ is the density effect correction term.

Since the sensor' s doping concentration is much lower than the intrinsic silicon atomic density and the influence of impurity atoms on energy deposition is negligible, the pixel array is simplified to a uniform silicon medium. The total deposition energy Q_{dep} within a single pixel can be obtained through integration of the energy spectrum $S(E)$, with the calculation formula shown in Eq. (11):

$$Q_{dep} = \int_0^{E_{max}} S(E) \cdot \left[1 - e^{-\mu(E)\cdot L_z}\right] \cdot L_x \cdot L_y \cdot dE$$

where $\mu(E)$ represents the mass attenuation coefficient of silicon for β particles.

Fig. 18 [Figure 18: see original paper] presents a comparative analysis of computational simulation and experimental measurement results for β particle energy deposition by CMOS APS under different integration time conditions. Based on Eq. (8), the gray value of response signals extracted from experiments is transformed into β particle energy deposition, plotted as a blue dot graph showing the relationship between experimental energy deposition and gray value. Based on Eq. (9) and Eq. (10), the β particle energy deposition simulation model for CMOS APS is established, plotted as a red dot graph showing the calculated relationship between energy deposition and gray values. When the sensor operates in the low integration time region below 5.625 ms, the matching degree between calculated and simulated energy deposition is relatively high. However, in the high integration time region above 5.625 ms, as integration time increases, error also increases significantly. This is primarily because at high integration times, charge saturation effects occur in image sensor pixels. When cumulative charge generated by incident particles exceeds the full well capacity (FWC) [39], pixels enter the nonlinear response region, resulting in signal compression or cutoff that cannot be effectively recorded. This nonlinear process causes the experimental gray value growth rate to be lower than simulation predictions.

For deviations between experimental and simulated data caused by charge saturation effects under high integration time conditions (>5.625 ms), a nonlinear correction model is established to compensate experimental energy deposition. Signal compression caused by full well capacity limits constitutes a systematic error requiring correction of actual recorded calculated energy deposition and further conversion to β particle absorbed dose D, as shown in Eq. (12). This paper adopts a piecewise exponential attenuation model to correct experimental gray values. For the CMOS APS samples used, a linear relationship is maintained when integration time is less than or equal to 5.625 ms, with exponential attenuation compensation applied for times greater than 5.625 ms.

Fig. 19 [Figure 19: see original paper] shows the relationship between CMOS APS gray values and absorbed dose. By analyzing gray values of β response events in images, β-ray absorbed dose can be well quantified and represented, thereby meeting practical detection requirements.

$$D = \begin{cases} \frac{E_{real}}{1.602\times10^{-12}G}, & T \leq 5.625 \text{ ms} \\ \frac{E_{real}}{1.602\times10^{-12}G} \cdot \left(1 - e^{-1.397\times10^{10}\cdot(T-5.625)}\right) \times 2 - 3.225 \times 10^{-6}, & T > 5.625 \text{ ms} \end{cases}$$

VII. CONCLUSION

This paper studies β-ray detection methods based on complementary metal-oxide-semiconductor (CMOS) active pixel sensors (APS), analyzing the mechanisms and characteristics of β-radiation response and damage, exploring the nonlinear influence characteristics of annealing effects on sensor damage, and proposing a gain optimization method based on double-threshold constraints and a noise suppression method based on temporal differences. Finally, a β-ray detection model correlating visual imaging with ray absorption dose is obtained. The main conclusions are as follows:

1. **β-radiation response events** are manifested as near-saturation of single-pixel values approaching 255, affecting a sharp increase in a very small number of surrounding pixel values. The optimal gain for β-ray measurement was determined as 43 dB through the double-threshold constrained gain optimization method. When gain is below 43 dB, the sensor inadequately amplifies the charge signal generated by β rays, resulting in weak effective signal intensity. When gain exceeds 43 dB, response signals become distorted due to charge overflow.

2. **As irradiation time increases**, damage to CMOS APS continues to intensify. Room-temperature annealing effects lead to nonlinear changes in damage trends. During annealing, the reduction in dark signals is partly due to sensor self-recovery to pedestal noise level, and partly due to intermittent pixel failure that temporarily loses charge collection capability, manifested as pixel values of 0. The temporal difference filtering method effectively removes noise while retaining β response events, achieving 99.75% β-event retention and 5.17-fold SNR enhancement over raw data.

3. **When the sensor operates** in the low-integration-time region below 5.625 ms, the matching degree between energy deposition calculated from experimental data and simulated energy deposition is relatively high. However, in the high-integration-time region above 5.625 ms, charge saturation effects occur in sensor pixels, and errors increase significantly. The gray value–dose detection model based on piecewise exponential attenuation correction can quantify β-ray absorbed dose and achieve effective measurement.

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