Postprint of Research on Irradiation Testing of Si-PIN Sensors for Space Particle Detection

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Abstract

Long-term high-energy electron irradiation can affect the detection performance of Si-PIN sensors. To assess the payload lifetime requirement specifications for over eight years in orbit, irradiation tests were conducted on semiconductor sensors using electron irradiation sources to simulate the space electron environment. The test results indicate that: when the sensor receives an irradiation dose of 7.64×1014, its energy response capability remains unchanged, while the counting efficiency decreases slightly; as the irradiation dose increases, although the sensor' s leakage current continues to increase, the noise level remains relatively stable, and the sensor performance does not affect the payload' s operational specifications.

Full Text

Research on Irradiation Test of Si-PIN Detectors for Space Particle Monitor

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Abstract

Long-term high-energy electron irradiation may affect the performance of Si-PIN semiconductor detectors (SSD). To assess the detector' s lifetime in the space radiation environment, electron irradiation sources were used to simulate the space electron environment, and irradiation experiments were carried out on the semiconductor detector. Experimental results show that under a radiation dose of 7.64×10^1 , the SSD's energy response capability had not changed, and the counting efficiency slightly decreased. As the radiation dose increased, although the leakage current of the SSD increased, the noise level remained relatively stable, and the detector' s performance did not affect the operational index of the payload.

Key words: high energy electron, semiconductor detector, irradiation, life, noise

0 Introduction

The FY-4 satellite is China' s new-generation geostationary meteorological satellite, which will carry a space high-energy particle detector. This instrument is an important monitoring device for charged particle disturbances in the geostationary orbit space environment and will provide first-hand data support for China' s space weather service and research. For space charged particle detection, semiconductor sensors are typically selected as the incident window for measured particles due to their high energy resolution, fast time response, good position resolution, wide linear range, small size, and low operating voltage compared with gas and scintillator detectors.

The new-generation high-energy particle detector on FY-4 employs novel ion-implanted P-N junction silicon semiconductor sensors, representing the first time an imported device has been selected for this orbit to ensure the instrument' s detection performance reaches internationally advanced levels. The FY-4 meteorological satellite has an on-orbit lifetime requirement of more than 8 years. The geosynchronous orbit contains a large number of relatively stable radiation belt high-energy electrons and high-energy protons from solar proton events. Long-term high-energy charged particle irradiation can cause damage to Si semiconductor sensors, reducing detection performance and operational lifetime. This work investigates the performance impact of space high-energy charged particles on this selected semiconductor sensor model by using radioactive electron beam sources to simulate the space radiation particle environment for long-term irradiation of the device under test, providing a basis for on-orbit performance evaluation of space high-energy particle detection instruments.

1 Si-PIN Semiconductor Sensors

Semiconductor sensor fabrication processes mainly include gold-silicon surface barrier type, Si(Li) drift type, and ion implantation type. Gold-silicon surface barrier sensors form a Schottky surface barrier by evaporating and depositing a very thin gold layer on the surface of N-type high-resistance silicon. These sensors have advantages such as a thin dead layer at the incident window and ease of fabrication, but also have disadvantages: (1) surface barrier sensors are susceptible to environmental influences and have high requirements for storage and use environments; (2) the Schottky surface cannot be touched or contacted, resulting in a short service life; (3) gold-silicon surface barrier sensors have poor reliability, consistency, stability, and repeatability. Lithium drift sensors drift lithium ions into the semiconductor under certain voltage and temperature conditions to compensate for P-type impurities, thereby obtaining silicon-lithium drift sensors with thicknesses up to several millimeters. Their outstanding characteristics include low background, high energy resolution, high detection efficiency, and fast speed, but this type of device has very strict storage environment and operating conditions, and improper operation can seriously affect device lifetime. The third type, the emerging ion-implanted Si semiconductor sensor in recent years, overcomes the shortcomings of the above two sensor types and can leverage integrated circuit fabrication processes and mature production lines, offering stable fabrication processes, convenient storage and use, and stable detection performance, significantly improving device lifetime compared with other sensor types.

The sensor used in the FY-4 high-energy particle detector is a British imported device, representing the first time this model has been selected for this orbit in China. The sensor has an effective diameter of Φ20 mm (large window) and an effective thickness of 1 mm. The multi-guard ring design effectively reduces the sensor’ s leakage current and noise. This type of sensor offers advantages such as a large detection window, low leakage current, low noise, and good energy resolution compared with similar domestic devices. The cross-section is shown in [Figure 1: see original paper].

2 Space Environment and Irradiation Test Setup

Based on the FY-4 satellite launch planned for 2016, as previously described, the space particle irradiation that the sensor will mainly encounter in the satellite orbit includes radiation belt electrons and protons from some solar proton events. Using the AE8Max model provided by the Spenvis website, the possible maximum integrated energy spectrum of the total space high-energy electron flux that the satellite will encounter during its expected 8-year on-orbit operation is shown in [Figure 2: see original paper]. The total flux density of electrons above 0.1 MeV is on the order of 2×10 /cm^2. Based on the sensor’ s sensitive area of Φ20 mm, the sensor will potentially encounter on the order of 6.28×10 space electron irradiations during the on-orbit operation phase.

The irradiation test equipment and experimental setup are schematically shown in [Figure 3: see original paper]. During the experiment, two integrated circuit boards were used: one to provide high-voltage power supply (130 V) to the sensor, and another to amplify the sensor’ s output signal and detect noise.

Two groups of electron radioactive sources were used throughout the test. Group I used a weak Sr/ Y source with an electron flux density of 10 /cm^2•s. Group II used a stronger Sr/ Y source array composed of 7 independent radioactive sources, with each of the 7 identical sources in Group II having an activity of 1.85×10 Bq, distributed evenly as shown in [Figure 4: see original paper]. The source intensity distribution is shown in a and b.

[Figure 5: see original paper] shows the irradiation test process with the Group II strong source array and the structural relationship between the source array and the sensor. The sensor was placed inside a test box, where d represents the horizontal distance from the sensor' s irradiation point to the radioactive source.

The test began on November 13, 2013, using the weak Group I source to irradiate the sensor for 984 hours. During irradiation, the source was placed directly against the sensor' s sensitive surface with no blocking layer in between. On January 2, 2014, irradiation with the strong Group II source began, with a total irradiation time of 743 hours. During irradiation with Group II, the distance between the strong source array and the sensor was 4.5 cm, with a 15 m thick blocking layer in front of the sensor. Before and after the irradiation test, detection tests were conducted using ^{2} Bi and $^{2\ 1}$Am radioactive sources, and a multi-channel spectrum analysis system was used to detect changes in the sensor' s energy response, detection efficiency, and leakage current. The high-voltage board and amplifier board connected to the sensor remained unchanged throughout the test. The total number of particles received by the sensor was 7.64×10^{1} .

3 Irradiation Test Results Analysis

3.1 Energy Spectrum Response

The test results for the $^{2\ 1}$Am energy spectrum response are shown in . Using the 976 keV energy point of ^{2} Bi as a reference, the test results for the sensor' s electron energy spectrum response to ^{2} Bi before, during, and after the test are summarized in .

Data analysis: Six tests were conducted on the sensor under test throughout the experiment. As shown in , the sensor' s response peak channel, peak count, and total count response to $^{2\ 1}$Am showed no significant change, indicating that the sensor' s response capability and particle counting efficiency for $^{2\ 1}$Am alpha particles remained essentially unchanged and the sensor performance was basically stable. The sensor' s response peak channel to ^{2} Bi (976 keV) remained constant, indicating stable response capability to ^{2} Bi (976 keV). The second and fourth test results showed lower peak counts and total count response values because these were test data obtained during the experiment and can be considered invalid data not for reference. The sensor' s counting response to the ^{2} Bi electron source showed a slight decreasing trend as the irradiation test progressed, indicating a slight decline in the sensor' s electron counting efficiency, but within 20%.

Due to objective factors such as statistical fluctuations in counting and peak drift, the test data have certain uncertainties. The following figures show the energy spectrum response test curves of the sensor under test for $^{2\ 1}$Am and ^{2} Bi.

[Figure 6: see original paper]-a shows the $^{2\ 1}$Am energy spectrum response before irradiation, [Figure 6: see original paper]-b shows the $^{2\ 1}$Am energy spectrum response after the test, [Figure 6: see original paper]-c shows the ^{2} Bi energy spectrum response before irradiation, and [Figure 6: see original paper]-d shows the ^{2} Bi energy spectrum response after the test.

3.2 Leakage Current and Noise

The leakage current test data are shown in , and the noise test data are shown in -a and -b. Data analysis: The sensor noise detection used a specialized ground test circuit developed by the Space Center of the Chinese Academy of Sciences. The leakage current and noise test data show that as the accumulated irradiation fluence increased, the leakage current of the sensor under test showed a clear upward trend. However, the sensor noise test results remained relatively stable. Although there was some increase before and after the test, it remained within the allowable background noise value range and would not cause significant impact on the detection payload' s performance. The experiment demonstrates that as the radiation dose increased, although the sensor' s leakage current continued to increase, the leakage current component that mainly contributes to the sensor noise index remained relatively stable, thus the noise level remained relatively stable.

Based on the electron irradiation test data, the total particle count received by the sensor reached 7.64×10^{1} . The main performance index test results of the sensor under test are as follows: (1) The energy response capability did not change, and the counting efficiency for ^{2} ^{1}Am alpha particles did not show significant change, but the electron counting efficiency decreased slightly, though within 20%; (2) As the irradiation fluence increased, although the sensor' s leakage current continued to increase, the noise level remained relatively stable, indicating that the leakage current component that mainly contributes to the sensor noise index remained relatively stable. These results demonstrate that under this radiation dose, the performance of the sensor under test did not change significantly, can ensure normal payload operation on orbit, and meets the performance requirement for an operational lifetime of more than 8 years.

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