Research Article

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Radiation dosimeter and charge detector onboard BeiDou navigation satellites in MEO

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Abstract: The orbit of BeiDou satellite system is a very ideal space environment monitoring area. The radiation dosimeters are present on this series of navigation satellites, and they are respectively installed in the x, y and z positions. A charge detector installed in the satellite cabin is used for monitoring satellite deep charging potential. Radiation dosimeters select the 100 nm P-channel metal oxide semiconductor (PMOS) sensors, whose monitoring range can reach 2×10^6 rad (Si). In the circuit design part, the "zero temperature coefficient" current of the PMOS is used as the constant current source for measuring, which effectively reduces the influence of temperature effect. Three radiation dosimeters realize the daily dose change monitoring during the satellite's operation, and the detection accuracy is high. The deep charging potential sensor adopts the equivalent capacitor design which is composed of the outer optical quartz glass and the inner circular gold-plate. The two kinds of detection instruments have the characteristics of small volume, low power consumption and high detection accuracy. The detection results show that they have important application value for space environment prediction and guarantee.

Keywords: radiation dosimeters, charge detector, space environment detection

1 Introduction

BeiDou satellite system operates in MEO orbit. Satellites in this orbit will encounter a variety of space particle radiation environments. The impact of space charged particles on satellites is serious (Tian *et al.* 2015, Chang *et al.* 2017). Charged particles mainly include radiation belt particles, solar proton events and galactic cosmic ray particles. These charged particles affect the safety of satellites through radiation dose effect, charge discharge effect and so on. Radiation dose effect means that radiation particles enter the materials and devices of spacecraft, ionize with their atoms and molecules, and transfer energy to the irradiated materials, thus affecting the performance of materials and devices. As early as 1996, many scientists have carried out monitoring research on satellite radiation environment (Dyer *et al.* 1996, Buhler *et al.* 1996, Mackay *et al.* 1997). In recent years, the research on total radiation dose has played an important role (Bhat *et al.* 2005, Bogorad *et al.* 2010). China has developed P-channel metal oxide semiconductor (PMOS) total dose detection technology for more than 20 years. The detection function has been continuously improved, and the detection indicators have been greatly improved. Spacecraft charging effects include surface charging and deep charging. The surface charging detector is generally installed outside the cabin to detect the satellite surface charging potential mainly caused by plasma (Anderson 2001, Tian *et al.* 2021). Deep charging is mainly caused by the high-energy

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electrons. High-energy electrons can pass through the surface of spacecraft, and deposit in the materials, which leads to deep charging Huang and Chen (2004), (Yu *et al.* 2012). Considering the serious impact of satellite charge and discharge, in recent 10 years, more and more satellites at home and abroad carried charge detectors to obtain the potential data of satellite, so as to provide monitoring information for spacecraft fault analysis and operation safety guarantee (Iucci *et al.* 2005)

The MEO orbit of BeiDou navigation satellite passes through the magnetosphere and the central region of the outer radiation zone. This is an ideal area for space environment monitoring. BeiDou navigation satellites are equipped with six radiation dosimeters and an inside charge detector to obtain the total radiation dose data and satellite's deep charging potential data in orbit, so as to provide support for the satellite in orbit and subsequent satellite engineering design. At the same time, it has a very good application value for building global space environment prediction and guarantee system.

2 Task requirement analysis

The space environment of MEO orbit is extremely complex. Solar activity makes the particle radiation environment in MEO extremely unstable and violently disturbed. They cause disastrous space environmental effects such as single particle events, radiation dose damage and deep charge and discharge of aerospace equipment, which seriously threaten the safe operation of spacecraft platform and payload in orbit (Dorman *et al.* 2005).

First, it is the requirement of space environment detection for long life and high reliable operation of satellites. In recent years, there are still many satellite anomalies and faults caused by the radiation environmental effect. Understanding the mechanism, characteristics and laws of radiation environment and effects, carrying out targeted engineering design, ground test verification and on-orbit verification, and finally forming design specifications and protection design evaluation specifications can effectively ensure the high reliability and long-life operation of spacecraft.

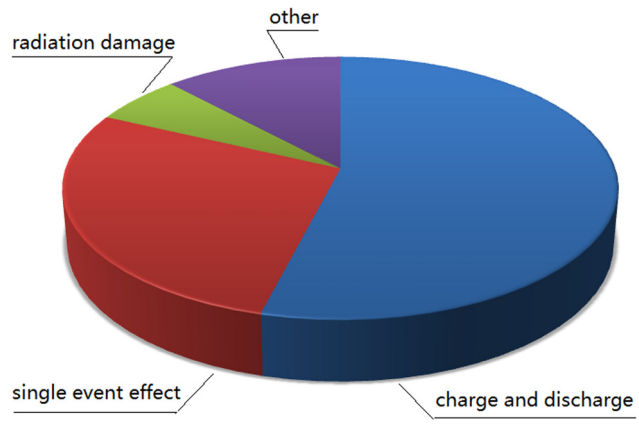

Figure 1: Satellite fault classification.

Second, it is the requirement of auxiliary fault zeroing location for spacecraft. Compared to LEO satellites, the environmental effect of medium and high earth orbit satellites is more complex. The satellites will encounter the particles from earth's radiation belt and cosmic ray. From Figure 1, we can see that the charging-discharging effect and radiation dose effect of the satellite are prominent; however, we have less detection data for them. So, the understanding is obviously insufficient.

3 Functional indexes of radiation dosimeter and charge detector

Based on the needs of the detection mission, the navigation satellites of BeiDou are both equipped with radiation dosimeters and charge detector. The service life of detectors is more than 8 years. During the in-orbit operation of the navigation series satellites, we can obtain the data of total dose and deep charging potential, which can provide a guarantee for the safe and reliable operation of the satellite.

Table 1 displays the main technical indexes of radiation dosimeter and charge detector. In order to reach the

Table 1: Main technical indexes of detectors

Technical indicators	Radiation dosimeter	Charge detector
Measuring range	$\geq 2 \times 10^6$ rad (Si)	−2.5 kV–0 kV
Detection sensitivity	79 rad (Si)	50 V
Measurement accuracy	Better than 20%	Better than 20%
Space coverage	3 detection directions	1 detection directions

task requirement, the appropriate sensors are selected for detectors. The required detection function can be obtained by debugging the parameters such as electronic magnification. Of course, all detector functional indicators have been checked by the ground calibration tests.

4 Design of radiation dosimeter

The radiation dosimeter is composed of PMOS sensor, electronic circuit and mechanical structural parts. Three similar radiation dosimeters are installed at different positions of the satellite to measure the radiation dose of the satellite. Figure 2 shows the structure diagram of the dosimeter.

4.1 Detection index analysis

The satellite operates in MEO orbit with a design life of 10 years. The total radiation dose mainly comes from the radiation band electrons, followed by bremsstrahlung. Total radiation dose of each component are shown in Figure 3.

Generally, we use SHIELDOSE-2 model to calculate the total dose. When calculating the index of total dose, we considered the front of PMOS and the rear of PMOS. Because the shielding thickness is different, the dose results in the two conditions are different.

There is no obstruction in front of the PMOS sensor, the shielding thickness is the thickness of satellite skin (usually 1 mm). According to the simulation calculation results, the omnidirectional total irradiation dose in 10 years under this shielding thickness is from 3.6×10^6 rad (Si) to 4.5×10^6 rad (Si). In the rear of PMOS, the shell thickness is 5 mm plus the satellite skin thickness, thus, the total shielding thickness at the back of the sensor is 6 mm. Under this shielding thickness, the total omnidirectional irradiation dose for 10 years is from 1.2×10^4 rad (Si) to 1.5×10^4 rad (Si).

The total dose received by the PMOS is the average of the total dose under above two conditions, so the total radiation dose range is from about 1.8×10^6 rad (Si) to 2.2×10^6 rad (Si). Therefore, we believe that the average value of total dose calculation results is 2×10^6 rad (Si), which can meet the requirements of total radiation dose monitoring inside the satellite within the service life.

4.2 Working principle

The dosimeter sensor is a radiation sensitive field effect transistor device developed by special technology (Kelleher *et al.* 1995, Schwank *et al.* 1996). The field effect transistor in the sensor is similar to the insulated gate field effect transistor. After irradiation, the induced charge and interface state in its insulating layer cause the change in surface potential, that is, the change in gate voltage. According to the corresponding relationship between the grid voltage and radiation dose, the radiation dose can be obtained by measuring the grid voltage August and Circle (1984). The relationship between the grid voltage and radiation dose needs to be given by ground calibration. The working principle diagram of radiation dosimeter sensor is shown in Figure 4.

In order to achieve the measurement of 2×10^6 rad (Si) total radiation dose, a new 100 nm radiation sensing

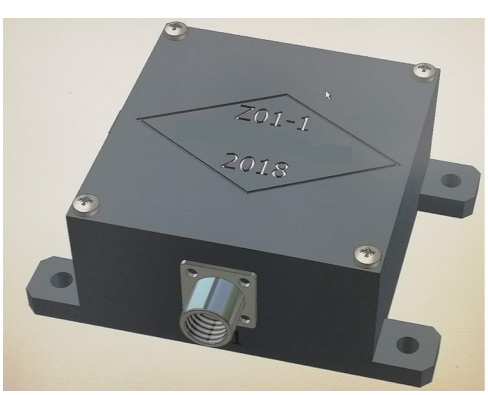

Figure 2: The structure diagram of the dosimeter.

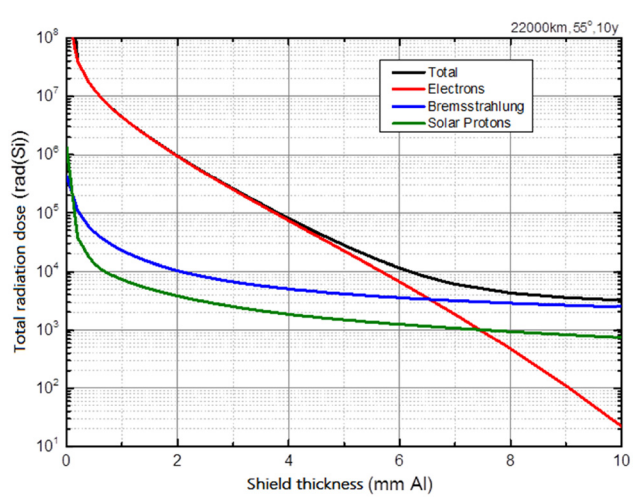

Figure 3: Total radiation dose of each component.

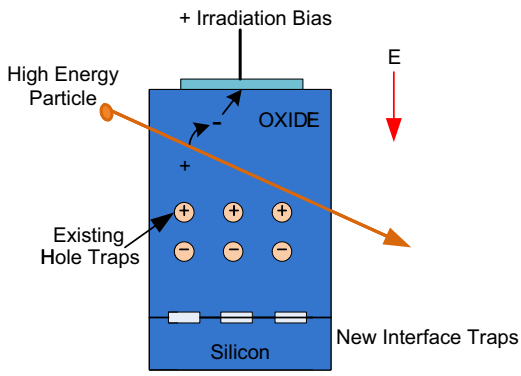

Figure 4: Schematic diagram of working principle of radiation dosimeter.

field effect transistor (RADFET) sensor is selected. The sensor has been calibrated in the national standard metrology laboratory, the irradiation source is ^{60}Co(γ) standard source, and the test dose rate is about 40 rad (Si) per second. The results are shown in Figure 5. In the figure, the abscissa is the total dose received by the sensor, and the ordinate is the voltage output by the sensor. Two PMOS sensors were used in the experiment. The experimental results show that the maximum measuring range of the sensor can reach 5×10^6 rad (Si), meeting the instrument design requirements.

4.3 Electronic circuit design

The electronic circuit of radiation dosimeter is mainly composed of constant current source circuit, sampling and temperature compensation circuit, output circuit, secondary power protection circuit, *etc.* The circuit principle block diagram of radiation dosimeter is shown in Figure 6.

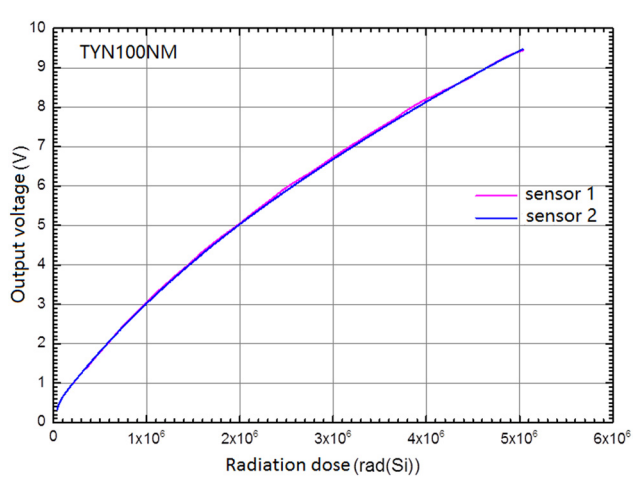

Figure 5: Calibration results of 100 nm RADFET.

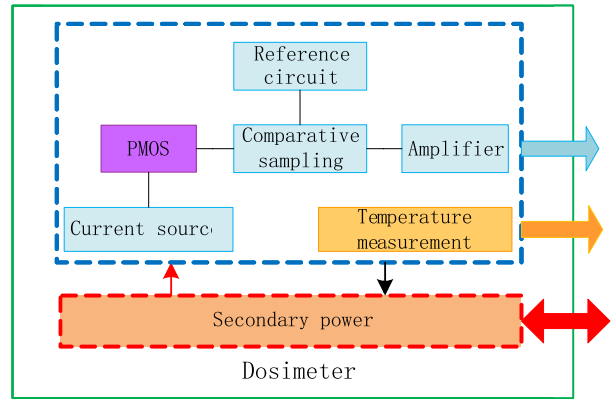

Figure 6: Working principle block diagram of single radiation dosimeter.

The reference circuit provides a stable reference voltage for the comparison sampling circuit, so as to ensure that the comparison sampling circuit can accurately measure the change in sensor output voltage. After comparing the change in sensor output voltage measured by the sampling circuit, the voltage signal can be output by the amplifying output circuit.

PMOS sensor is a p-channel enhanced MOS transistor, in which many parameters such as threshold voltage and carrier mobility are greatly affected by temperature (Hofman *et al.* 2017), Haran and Jaksic (2003). In order to overcome the influence of temperature, the zero temperature coefficient (ZTC) is used to realize the temperature compensation, that is, the ZTC current is used as the constant current source for the measuring circuit (Carbonetto *et al.* 2011, Martinez-Garcia *et al.* 2015, Hofman *et al.* 2015).

Normally, there is a cross section in the transfer characteristic curve cluster. The leakage current at this intersection has a temperature coefficient of approximately zero, and the change in the corresponding grid voltage with temperature is very small, we call it the ZTC point, as shown in Figure 7. The experimental results show that the compensation effect is obvious when the current at the ZTC point is used as the working current of PMOS transistor.

5 Design of charge detector

5.1 Working principle

The deep charging potential sensor adopts the equivalent capacitor design which is composed of the outer optical

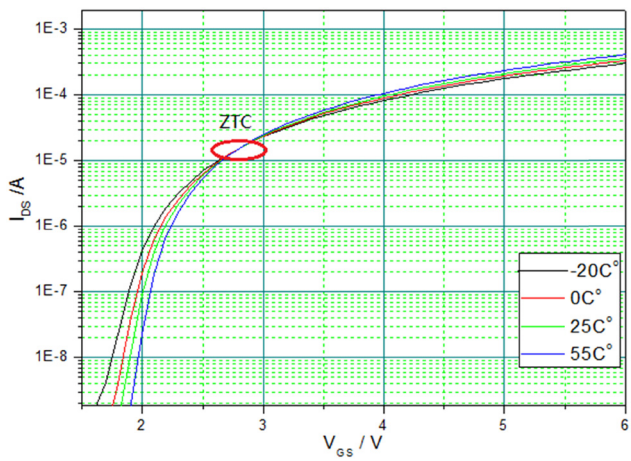

Figure 7: Schematic diagram of *I–V* curve cluster and ZTC point of PMOS at different temperatures.

quartz glass and the inner circular gold-plate. When charged particles are incident on the front glass surface of the sensor, the surface of the sensor is charged. Since the circular gold-plated area of the inner glass layer forms a capacitor with the surface of the sensor, the charging potential of the surface will enter the gold-plated area of the sensor by induction, so as to be output to the signal processing unit for measurement through the outgoing line of the sensor. The working principle of charge detector is shown in Figure 8.

5.2 Design of deep charging sensor

There is no electronic circuit inside the potential sensor, and its signal is output to the electronic box for processing and acquisition. The outer layer of the sensor is composed of optical quartz glass. The inner layer is a circular gold-plated area, which is led out through the

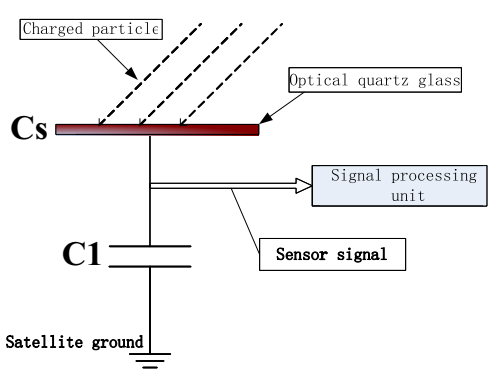

Figure 8: Working principle of the charge detector.

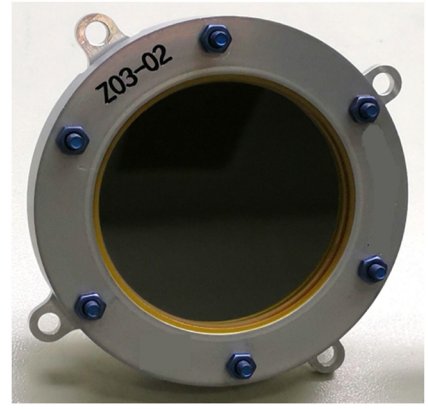

Figure 9: Structural diagram of deep charging potential sensor.

core wire. The outer and inner layers of the glass sheet are equivalent to capacitors to form the sensor. Figure 9 is a structural diagram of the sensor.

5.3 Electronic circuit design

The electronic circuit of charge detector is mainly composed of input following, amplification and output interface circuits. The power supply and data acquisition part are in the electronics box, as shown in Figure 10.

6 On-orbit detection results

Since the navigation series of BeiDou have been launched into the space, the space environment effect detection instruments have worked normally, and a large number of detection data have been obtained.

Figure 11 shows the total dose growth of the radiation dose detector in MEO from July 2020 to November 2021. The detection results show that the total dose growth

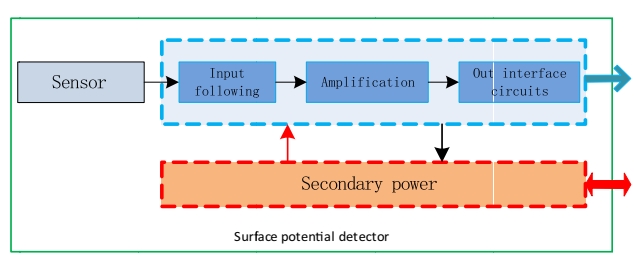

Figure 10: Schematic block diagram of internal circuit of charge detector.

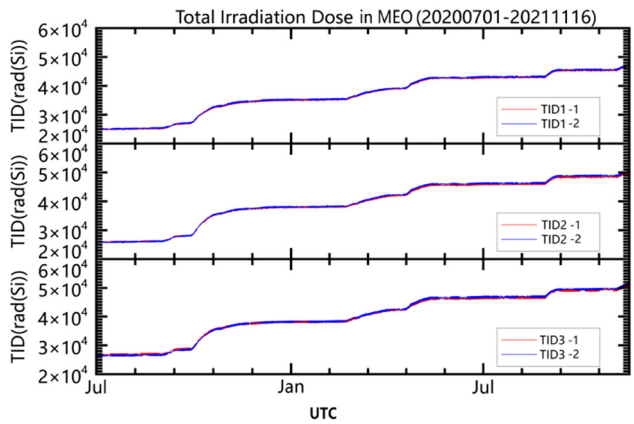

Figure 11: Total radiation dose in three directions in navigation satellite cabin.

trend in the three directions is consistent, and the dose detector can detect the daily dose change in the satellite. In the quiet period, the daily growth rate of satellite total dose is 5–13 rad (Si) per day. However, during the high-energy electron storm event, the daily growth rate of total dose increases significantly, which can reach the daily growth rate of tens of rad (Si) or even hundreds of rad (Si).

The PMOS chip is DIP14 packaged, and the front of the chip is a copper packaging structure with a thickness of 0.4 mm. In addition, the equivalent thickness of the satellite skin is 1 mm Al, the field of view is 180°, and the duration time is 503 days, the total dose calculated by the model is about 50 krad (Si). Due to the blocking around PMOS, the actual field of view is limited to 100°. Therefore, according to the actual field of view, the total dose calculated by the model should be 27 krad (Si), which is almost equal to the detection result of the radiation dose detector.

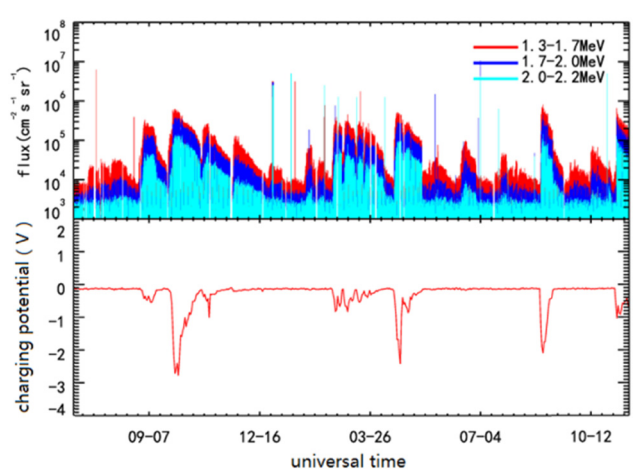

Figure 12: The monitoring results of satellite deep charging potential.

Figure 12 shows the detecting results of satellite deep charging potential and high-energy electron flux from July 2020 to November 2021.We can see that when the electron flux of 1.3–1.7 MeV exceeds $10^5/cm^2$ s.sr, deep charging will occur. Moreover, the charging potential is positively correlated with the duration when the electron flux exceeds $10^5/cm^2$ s.sr. The detection results show that the charge detector can accurately acquire the fluctuation of deep charging potential of navigation satellite caused by the change in high-energy electronic environment in orbit space.

7 Conclusion

On-orbit monitoring of space environment plays an important role in analysis of satellite anomaly. The detection of total radiation dose and deep charge level much guarantee the normal operation of the satellite. The detection data show that they have important application value for space environment prediction and guarantee. They are also beneficial to the fault location and analysis of the satellite load.

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