Nonlinear Conductivity of ZnO Materials Induced by X Ray

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Abstract. Due to high energy electron radiation in space, Spacecraft internal charging will occur, which will cause deep dielectric electrostatic discharge and cause the most serious anomalies, that is, those that have resulted in the loss of mission. Because spacecraft internal charging is accompanied with X-ray bremsstrahlung, it is possible to mitigate inner dielectric electrostatic discharge by using nonlinear conductivity material induced by X-ray radiation. It shows that the conductivity of ZnO materials increases with the increase of X-ray radiation dose rate. At low X-ray radiation dose rate, the conductivity of ZnO increases linearly with the increase of X-ray dose rate. At high X-ray radiation dose rate, the conductivity of ZnO is saturated gradually. The conductivity of ZnO with high original resistivity varies more widely with the dose rate of X-ray, which is more suitable for spacecraft internal charging protection.

1. Introduction
Spacecrafts will encounter various radiation environments in space, such as the earth radiation belt, solar high-energy particles, cosmic rays. Among them, space high-energy electrons will penetrate the surface structure of spacecrafts, chassis and other equipment shells, and deposit in dielectrics such as insulating cables and circuit boards. Because of the high resistivity of dielectrics, the electrons deposited would accumulate continuously and establish a high internal electric field in the dielectrics. When the electric field strength exceeds the dielectric breakdown field, discharge phenomenon would occur, which is called deep dielectric charging effect [1-3]. A large number of on-orbit experiments and theoretical analysis show that deep dielectric charging effect in the spacecrafts will cause serious anomalies [4,5]. So highly insulating materials should be avoided in spacecraft charging environments.

An effective way to mitigate deep dielectric charging effect in spacecrafts is that when deep dielectric charging effect in spacecraft occur, the conductivity of the dielectrics is nonlinear and can increase to release the accumulated charges, prevent the development of large electric fields internal to the dielectrics and thereby prevent them from developing electrostatic discharge pulses [6]. Because the process of high-energy electrons injecting into spacecraft will produce X-ray bremsstrahlung, it is possible to develop a dielectric with nonlinear conductivity induced by X-ray radiation to reduce the risk of deep dielectric charging effect.

ZnO is a wide band gap semiconductor material, which has important applications in ultraviolet photoelectric detection. In recent years, it has been found that ZnO materials also have a great response to X-rays [7-10]. It is possible to use ZnO materials as nonlinear conductivity dielectrics to mitigate deep dielectric charging effect. Here, the conductivity of zinc oxide semiconductor materials...
has been studied under different X-ray radiation conditions, which is very important to develop deep dielectric charging effect mitigation.

2. experimental
Three kinds of zinc oxide powders with different particle sizes of 20 nm, 30 nm and 1 micron were used respectively. The ZnO powders were characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD). The ZnO powders were pressed into thin flakes and each side of the thin flake was clamped with aluminum foil. The thickness of ZnO flake was about 1 mm. Aluminum foil acted as test electrode. The conductivity of zinc oxide flakes induced by X-ray was tested at National Institute of Metrology of China and Beijing Normal University, respectively. The schematic of the test process is shown in Figure 1. The current–voltage measurement was performed using Keithley 6517B, which can provide a maximum voltage of 1000V and a current measurement range of 1fA to 20mA.

3. result and discussion
The SEM images of ZnO powders with different particle sizes are shown in Figure 2. The diameters of the particles are 20 nm (Figure 2. a), 30 nm (Figure 2. b), and 1 µm (Figure 2. c) respectively. The particle sizes of ZnO are relatively uniform, and each particle has edges and corners.
Figure 2. SEM images of ZnO powders. (a) 20nm, (b) 30nm, (c) 1μm

Figure 3 shows the XRD pattern of the sample with particle size of 20nm. The XRD spectra are in agreement with the standard spectra. It shows that the samples obtained are pure wurtzite zinc oxide.

![XRD pattern of 20nm ZnO powder](image)

Figure 3. XRD pattern of 20nm ZnO powder

Table 1 shows the experimental results of the current of different particle size ZnO materials varying with X-ray radiation dose rate under the same voltage. Because the conductivity is proportional to the current under the same voltage, the change of conductivity can be reflected directly by measuring the current.

| X-ray dose rate (mGy) | Current of 20nm ZnO under 200V (μA) | Current of 30nm ZnO under 1000V (μA) | Current of 1μm ZnO under 500V (μA) |
|----------------------|-------------------------------------|-------------------------------------|-----------------------------------|
| 0                    | 208                                 | 41                                  | 115                               |
| 0.81                 | 207                                 | 38                                  | 126                               |
| 1.2                  | 208                                 | 40                                  | 131                               |
| 10                   | 209                                 | 43                                  | 170                               |
| 100                  | 205                                 | 42                                  | 214                               |
| 500                  | 209                                 | 41                                  | 243                               |

It shows that the nonlinear conductivity phenomenon induced by X-ray radiation only occurs in 1μm ZnO particles. When the dose rate reaches 500 mGy, the current of ZnO increases from 115 μA to 243 μA, which means that the conductive of ZnO can be doubled by X-ray radiation.
Figure 4 shows the curve of the current versus X-ray dose rate for 1μm ZnO particles. It shows that the current of ZnO tends to be stable when the X-ray dose rate is high enough.

\[ I_{1\mu m} = 243 - 78 \exp^{-r/78} - 50 \exp^{-r/3} \]  

(1)

Where \( I_{1\mu m} \) is the current of 1 μm ZnO flakes under applied voltage of 500 V, and \( r \) is X-ray radiation dose rate.

The variation of the current of ZnO with the radiation dose rate can be well fit with double exponential function. The current changing equation with radiation dose rate is in accordance with the following formulas:

It is presented that the change of radiation-induced nonlinearly conductivity of ZnO is gradually stable with the radiation dose rate. The mean reason is the saturation of electron hole pairs in ZnO. In semiconductors, electrons are concentrated in a very small energy gap near the bottom of the conduction band. Because the energy gap is very small, it can be simply considered that the energy levels are occupied by these electrons on the bottom of the conduction band \( (E_c) \). The number of them can be expressed by the effective density of states \( (N_c) \) at the bottom of the conduction band. So the electron concentration in the conduction band \( (n) \) is given by:

\[ n = N_c \cdot \exp\left(-\frac{E_c - E_F}{kT}\right) \]  

(2)

Where \( \exp\left(-\frac{E_c - E_F}{kT}\right) \) is the Boltzmann distribution representing the probability that electrons occupy the bottom of conduction band. \( E_F \) is Fermi level.

When ZnO semiconductor is in X-ray radiation environment, some electrons at the bottom of conduction band will jump to valence band, but the total amount of excited electrons is limited by \( N_c \). So the conductivity of ZnO will be saturated with the X-ray dose rate.

It seems that the change of conductivity induced by X-ray is related to the particle size of ZnO. More obvious change of radiation-induced conductivity can be obtained in ZnO with larger the particle size. So ZnO bulk material may present non-linear conductivity induced by X-ray much more clearly. Single crystal ZnO bulk material was fabricated by Sun Yat-sen University. Nonlinear conductivity induced of single crystal ZnO bulk material by X-ray was tested as shown in Figure 5.
Figure 5. The schematic of the ZnO bulk sample for testing

The voltage between the electrodes is 10 V. The results are shown in Figure 6. It shows that the current of single crystal ZnO bulk material is only about 0.2 nA when X-ray dose rate is zero. When the dose rate of X-ray reaches 370 mGy/s, the current reaches 1.9 nA, which means the conductivity of single crystal ZnO bulk material increases by 8.5 times. Nonlinear conductivity of single crystal ZnO bulk material induced by X-ray is more obvious than ZnO particles, and single crystal ZnO bulk material is more suitable for mitigating deep dielectric charging effect.

Figure 6. Current versus X-ray dose rate of single crystal ZnO bulk material

4. Conclusion
Non linear conductivity of ZnO semiconductor materials induced by X-ray will occurs changes under certain conditions. It seems that the phenomenon of radiation induced nonlinear conductivity of ZnO semiconductor materials is related to the particle size of ZnO. Radiation induced nonlinear conductivity of larger particle size ZnO or single crystal ZnO bulk material is more obvious. The variation of radiation-induced conductivity with X-ray dose rate can be described by exponential function, that is, there is a saturation value for the change of radiation-induced conductivity of ZnO. The conductivity of high-resistivity single crystal ZnO varies in a much larger range under the same X-ray radiation conditions and may be more suitable for deep dielectric charging effect mitigation.
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