Preparation and characterization of CdZnTe particle detectors

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Abstract—CdZnTe detectors, as the most widely used X/γ ray detector in room temperature, has the advantages of high sensitivity, low noise, short pulse time and high detection efficiency. As the radiation category encountered in space environment is complex, research on the charged particle detection and particle discrimination capability of CdZnTe detector is conductive to expanding its application and providing solutions for special application scenarios in the space field. Therefore, this work mainly focused on the preparation of high resolution CdZnTe charge particle detectors. The main factors affecting charge particle detection resolution during the preparation of CdZnTe detectors were analyzed. The alpha/beta particle discrimination capability was verified using ²⁴¹Am and ⁹⁰Sr-⁹⁰Y radiation sources. Alpha particles and beta particles can be distinguished through the rise time of the pulse waveform according to the different incident depth in CdZnTe detectors.

1. INTRODUCTION

The ternary compound semiconductor CdZnTe detector has the advantages of room temperature, high sensitivity, low noise, wide response spectrum, short pulse time, high detection efficiency, large scale array integration, small volume and high stability, which is currently the most widely used X/γamma ray detector [1]. The detection of radiation in space environment can effectively reduce and avoid the radiation damage to spacecraft and astronauts, which is a hot topic in the space field [2, 3]. In the field of space exploration, CdZnTe detectors have been used in the small astronomical satellite project (SWIFT) of NASA [4], the High-energy X-ray Imaging Telescope project (EXIST) of European Space Agency [5], the ASTRO-H satellite project of Japan [6]and so on.

The radiation environment in the space is very complex, consisting mainly of charged particles (electrons, protons and other heavy ions), X-rays, gamma rays and neutral particles (neutrons, neutrinos) [7]. Therefore, CdZnTe detectors will be faced with multiple types of radiation, except X-rays and gamma rays. Researches on the charged particle detection performance and the particle distinguish properties of CdZnTe detector can further expand the application of CdZnTe detector, and provide solutions for the multiple particle composite detection in the space field.

The particle identification methods used in space environment mainly include pulse amplitude method, energy loss-total energy method, short pulse time and energy range method [8, 9]. Among them, the energy range method is widely applied and often used to measure solar high-energy particles and galactic cosmic rays, such as the MAST spectrometer on SAMPEX satellite [10].
In this work, α particle CdZnTe detectors were prepared by analyzing the factors that affect the energy resolution of CdZnTe detector in the detection of charged particles. The energy range method is used to analyze and compare the pulse waveform excited by α particles and β particles in the detector, to distinguish the types of particles.

2. MATERIAL AND METHODS
Cd$_{0.9}$Zn$_{0.1}$Te single crystal wafer with the dimension of 5×5×2 mm$^3$ was offered from Imdetek Ltd. The slice was polished mechanically with MgO suspension and then etched with 5% bromine-methanol (Br$_2$-MeOH) solution for 2 min to remove the damaged surface layer. Au contacts were prepared by vacuum evaporation. $^{241}$Am α particle source and $^{90}$Sr-$^{90}$Y β particle source were used to verify the detector performance. α particle detection systems consist of ORTEC 710 bias supply, ORTEC 142 charge sensitive pre-amplifier, ORTEC 570 shaping amplifier and a multi-channel analyser PS-MCA. The α particle energy spectrum is tested in vacuum to avoid scattering of α particles by air, as shown in Fig.1. The vacuum degree is 0.3 Pa, and the vacuum chamber also acts as an electromagnetic shield.

![Fig.1 Schematic diagram of energy spectrum equipment for α particle detection](image)

3. RESULTS AND DISCUSSION
3.1 Results and discussion
The cutting process of single crystal ingot will inevitably introduce a lot of scratches and other mechanical damage on the crystal surface, and the damage layer as the dead zone of detector will seriously affect the detection of charged particles. Therefore, a polishing process is used to remove the detector surface damage layer. Fig.2 shows the pulse height spectrum of the detectors to $^{241}$Am@5.48 MeV α particles after 2 min mechanical polishing, 30 min mechanical polishing and 2% chemical polishing of bromomethanol solution, respectively. The applied voltage is 200 V. Different polishing processes have great influence on the pulse height of the detector. 2 minutes of mechanical polishing is not enough to remove the damaged layer on the crystal surface. The energy of particles is basically deposited in the damaged layer on the surface. Therefore, the detector's pulse height is very small, requiring a gain of 100 times to reach 0.2 V. The 30 minute mechanical polishing greatly improved the pulse height of α particle detection to 0.38 V. The surface damage layer of CdZnTe crystal can be removed by chemical polishing process, and the pulse height is reached to 0.63 V.
As a semiconductor nuclear radiation detector, the preparation of ohmic electrodes on the surface of CdZnTe crystals is an essential process. According to Schottky-Mott theory, to form ohmic contact, the work function of metal must be larger than that of P-type semiconductor and smaller than that of N-type semiconductor. The work function of CdZnTe is related to the content of Zn. When the ratio of Zn to Cd is 0.1, the crystal work function is around 4.6 eV. The electrode materials commonly used in CdZnTe detectors are Au (4.7-5.2 eV), Pt (5.2-5.4 eV) and In (3.97 eV). Among them, Au's work function is the closest to CdZnTe crystal, and it is the most commonly used electrode material for CdZnTe detector. The energy loss of 5.5 MeV α particles in Au was calculated using SRIM software, as shown in Fig.3. The range of 5.5 MeV particles in Au is about 10 μm, and the energy loss ratio increases with incident depth. Fig.3 (b) shows the energy deposition of 5.5 MeV particles at different thickness of gold electrodes. The thickness of Au electrode prepared on the surface of CdZnTe crystal by vacuum evaporation is about 70 nm. Thus, the energy lose is approximately 30 keV when 5.5 MeV α particles passing through an Au electrode. According to (1), the influence of Au electrode on the energy resolution of 5.5 MeV α particle is about 0.5%.

\[
\eta = \frac{\Delta E}{E} \times 100\%
\]  

Fig.3 (a) Energy loss varies with the particle track of 5.5 MeV α particles in Au; (b) energy deposition of 5.5 MeV α particles at different thickness of Au electrodes
3.2 The detection performance of CdZnTe detectors for α particles

Fig. 4 shows the energy spectra of CdZnTe planar detector excited by $^{241}$Am@5.48 MeV α particles in the vacuum. The distance between the radioactive source and CdZnTe detector is 3 cm, the pre-amplifier signal is attenuated by 10 times, the main amplifier gain is 0.8×50 times, and the shaping time is 1 μs. The CdZnTe detector has an energy resolution of 0.68% for $^{241}$Am@5.48 MeV α particles. While, a phenomenon of low energy trailing is shown in Fig.4, which may be due to the energy absorption of the detector electrode to particles. However, the energy resolution of <1% is basically sufficient for the practical needs of α particle detection.

![Energy spectra of CdZnTe planar detectors excited by $^{241}$Am@5.48 MeV α particles in the vacuum](image)

3.3 The distinguish of α particles and β particles in CdZnTe detectors

Fig. 5 shows the range of α particles and β particles with different energies in CdZnTe crystals. The range of α particles is calculated using SRIM software and the range of β particles is calculated using (2) and (3) [11]. The range of α particles and β particles in CdZnTe crystals is quite different. Therefore, α particles and β particles can be distinguished by the difference in the detector pulse shape.

\[
R = \begin{cases} 
412E^{0.265-0.0054}\ln E & 0.01\text{MeV} \leq E \leq 2.5\text{MeV} \\
530E - 106 & E \geq 2.5\text{MeV}
\end{cases}
\]

(2)

\[
\frac{R_a}{R_b} = \left(\frac{Z/M}_a\rho_a\right)\left(\frac{Z/M}_b\rho_b\right)
\]

(3)
When electron-hole pairs are generated in the detector, the formed pulse shape is as follows[12].

\[ I_e(t) = -e \frac{X - x_0}{X} \exp\left(\frac{-t}{\tau}\right) \]  

\[ I_p(t) = -e \frac{X - x_0 \mu_p}{X \mu_n} \exp\left(-\frac{t \mu_p}{\tau \mu_n}\right) \]  

\[ Q_e(t) = -e \frac{(X - x_0)}{X} \left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \]  

\[ Q_p(t) = -e \frac{(X - x_0)}{X} \left[1 - \exp\left(-\frac{t \mu_p}{\tau \mu_n}\right)\right] \]

where (4) and (6) are electron induced current and induced charge respectively, and (5) and (7) are hole induced current and induced charge respectively. \( \tau \) is the dielectric relaxation time of CdZnTe, \( X \) is the depletion layer thickness, \( x_0 \) is the location of electron-hole pairs in the detector. \( \mu_n \) and \( \mu_p \) are the electron and hole mobility of CdZnTe respectively. When particles are passing through the depletion layer of detectors,

\[ Q_e(t) = -\frac{1}{2} Ne \left(2 - \frac{R}{X}\right) \left[1 - \exp\left(-\frac{t \mu_p}{\tau \mu_n}\right)\right] \]  

\[ Q_p(t) = -\frac{1}{2} NeX \left[1 - \exp\left(-\frac{t \mu_p}{\tau \mu_n}\right)\right] \]

\[ -(1 - \frac{R}{X}) \left[\exp\left(-\frac{t \mu_p}{\tau \mu_n}\right) - 1\right] \]

\( R \) is the particle range, \( N \) is the total number of ionized electron hole pairs. It can be seen from (8) and (9) that the pulse shape of the detector depends on the range of particles. Considering the influence of the back-end circuit, the current signal and voltage signal of the detector are as shown in (10), (11) and (12) [13].

\[ I(t) = \frac{Q}{\tau + R_d C_d} \exp\left(-\frac{t}{\tau + R_d C_d}\right) \]  

\[ V(t) = \frac{Q C_a}{C_a + C_d} \exp\left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \]  

\[ \tau = \frac{1}{\tau + \frac{R_d C_a}{C_a + C_d}} \]

where \( R_d \) and \( C_d \) are resistance and capacitance of the detector depletion layer, \( R_a \) and \( C_a \) are resistance and capacitance of the undepleted volume material, \( R_a \) and \( C_a \) are resistance and capacitance of the back-end circuit. When the detector is completely depleted, \( \tau_1 = \tau \), therefore the rise time of the signal pulse is determined only by the carrier collection mechanism, reflecting the difference in radiation particles.

Fig.6 shows the average value of 1000 pulses generated by \( \alpha \) particles and \( \beta \) particles in the detector, respectively. The detector is biased at 200 V, and the particles are incident at the cathode. The incident range of \( \alpha \) particles is relatively short, therefore, electron-hole pairs generate close to the cathode and the signal pulse is mainly contributed by electron drift. The incident range of \( \beta \) particles is deep, therefore, electron-hole pairs generate throughout the path. The signal pulse is the joint effect of electron and hole drift. Since the electron mobility of
CdZnTe crystals (1000 cm²·V⁻¹·s⁻¹) is much greater than that of holes (50 cm²·V⁻¹·s⁻¹), the signal rise time of β particles is greater than that of α particles.

![Fig.6 α and β particle pulse waveforms produced by the preamplifier in CdZnTe detector](image)

Fig.6 α and β particle pulse waveforms produced by the preamplifier in CdZnTe detector

Fig.7 shows the pulse signals generated by α particles and β particles in the detector under different bias voltage. When the voltage is greater than 50 V, the signal rise time of α particles is less than that of β particles. Therefore the rise time can be used to distinguish particle types. But when the voltage is low (< 30 V), the signal rise time of α particles is greater than that of β particles, this may be due to that the charge density of α particle ionization is higher, when the detector at low voltages, the internal electric field was weaken by electron clouds leading to delay of charge collection. Therefore, sufficient voltage should be applied in the detector to make the pulse shape reflect the particle type without interference from other factors.

![Fig.7 the pulse signal for CdZnTe detector biased at different voltages with (a) α particle and (b) β particle](image)

Fig.7 the pulse signal for CdZnTe detector biased at different voltages with (a) α particle and (b) β particle

4. CONCLUSIONS

The influence factors of CdZnTe detector used for charged particle detection are studied. The results show that the damaged layer of CdZnTe crystal can be removed by chemical polishing with bromomethanol solution. The influence of Au electrode on the energy resolution of 5.5 MeV α particle is estimated to be 0.5% by SRIM software. The energy resolution of CdZnTe detector to $^{241}$Am@5.48 MeV α particle is 0.68% in vacuum, but there is the low energy trailing phenomenon. The incident range of α particle and β particle with the same energy is different greatly in CdZnTe detector, so the charge collection time is different, which will eventually be reflected in the pulse shape. This can be used for particle identification.
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