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Design and Energy Spectrum Performance Optimization of a Portable Gamma Detector Based on Perovskite Materials

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Abstract: This study presents a compact gamma-ray detector based on all-inorganic halide perovskite $CsPbBr_3$, targeting high energy resolution and low-cost fabrication for nuclear security applications. The active layer was prepared via solution-based spin-coating, combined with surface passivation and multidimensional heterojunction engineering to enhance the carrier mobility–lifetime product ($\mu\tau$) to 10^{-3} cm^2/V. The optimized device achieved an energy resolution of 4.3% at 662 keV (FWHM), approaching the performance of CdZnTe detectors while reducing fabrication cost by over 70%. A convolutional neural network (CNN) was further integrated for energy spectrum deconvolution and source classification, enabling millisecond-level response and accurate identification. The final system features low power consumption (<100 mW), miniaturized packaging, and robust environmental stability, making it suitable for real-time deployment in field scenarios such as customs inspection and radiological emergency response.

Keywords: perovskite gamma detector; energy resolution; $CsPbBr_3$; spectrum deconvolution; nuclear security

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1. Introduction

In the context of an increasingly complex global nuclear security situation, the cross-border smuggling of illicit nuclear materials and the potential threat of nuclear terrorism have posed serious risks to national security [1]. According to data from the International Atomic Energy Agency (IAEA), the number of illicit nuclear incidents worldwide has shown a year-by-year increase in recent years, with hundreds of suspicious cases reported annually. Gamma-ray detectors, as essential equipment for nuclear material monitoring and radiation source identification, play an irreplaceable role in border control, public security screening, and nuclear emergency response. Traditional gamma detection materials, such as cadmium zinc telluride (CdZnTe) and thallium-doped sodium iodide (NaI(Tl)), offer relatively high energy resolution and detection efficiency [2]. However, they are limited by complex crystal growth processes, high raw material costs, and large device volumes, making them unsuitable for the application requirements of portable nuclear detection equipment. For example, the manufacturing cost of a single commercial CdZnTe detector typically exceeds several tens of thousands of U.S. dollars, and the weight and size of the equipment significantly constrain the long-term monitoring performance in mobile scenarios [3]. Therefore, the development of new gamma detectors that combine high performance, low cost, and portability has become a major research focus in the field of nuclear detection [4].

Halide perovskite materials, owing to their unique optoelectronic properties, have shown great application potential in the field of optoelectronic devices in recent years. These materials offer advantages such as high carrier mobility, long carrier diffusion lengths, broad light absorption range, and solution-based processability [5]. In the field of radiation detection, perovskite materials exhibit good response characteristics to gamma rays, with linear attenuation coefficients comparable to those of traditional detection materials within certain energy ranges. However, current perovskite-based

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gamma detectors still face several technical bottlenecks, including low carrier mobility-lifetime product (μτ), insufficient interfacial charge transport efficiency, poor device stability and limited energy spectral resolution [6]. Studies have shown that the μτ value of unoptimized perovskite thin films usually remains at the order of 10^{-4} cm^2/V, which is far lower than the performance requirements for practical applications [7,8]. This study focuses on overcoming the performance limitations of perovskite gamma detectors through innovations in material engineering and device structure. By optimizing the preparation process of perovskite materials, constructing efficient charge transport structures, and integrating deep learning algorithms to enhance energy spectrum analysis, this work aims to achieve breakthroughs in energy resolution, cost-effectiveness, and portability. The research provides an innovative solution for nuclear monitoring in the field of homeland security.

2. Materials and Methods

2.1. Materials and Device Fabrication Workflow

The all-inorganic halide perovskite $CsPbBr_3$ was selected as the active layer material due to its high radiation absorption coefficient and favorable optoelectronic properties. The fabrication process of the detector followed the workflow illustrated in Figure 1a. First, FTO glass substrates were cleaned via ultrasonication and treated with oxygen plasma to enhance surface wettability. The precursor solution was prepared by dissolving CsBr and $PbBr_2$ (molar ratio 1:1) in a mixed solvent of N,N-dimethylformamide (DMF) and γ-butyrolactone (GBL) to achieve a concentration of 1.2 M. The resulting solution was deposited onto the substrate by spin coating at 3000 rpm for 30 seconds, followed by the rapid application of chlorobenzene as an anti-solvent to induce controlled nucleation. The films were annealed at 80°C for 10 minutes, resulting in a dense and uniform polycrystalline $CsPbBr_3$ layer with an average grain size of approximately 500 nm. To reduce defect density and improve carrier dynamics, aminobenzoic acid (ABA) molecules were introduced via spin-coating a 0.05 M ethanol solution, forming hydrogen bonds with undercoordinated Pb^{2+} ions and passivating surface traps.

2.2. Multilayer Heterostructure Construction

As shown in Figure 1b, the planar device adopts a multilayer heterojunction architecture to optimize charge extraction and minimize recombination losses. On top of the perovskite layer, a 30 nm PEDOT:PSS layer was spin-coated to serve as the hole transport layer (HTL), followed by a 20 nm ZnO layer deposited via atomic layer deposition (ALD) to act as the electron transport layer (ETL). A 100 nm Au top electrode was thermally evaporated onto the ZnO layer to form an ohmic contact. The full stack of the device includes (from bottom to top): FTO / PEDOT:PSS / $CsPbBr_3$ / ZnO / Au, with an active detection area of 1 cm^2. This vertical architecture ensures efficient charge extraction, low dark current (<10^{-12} A/cm^2), and robust mechanical stability.

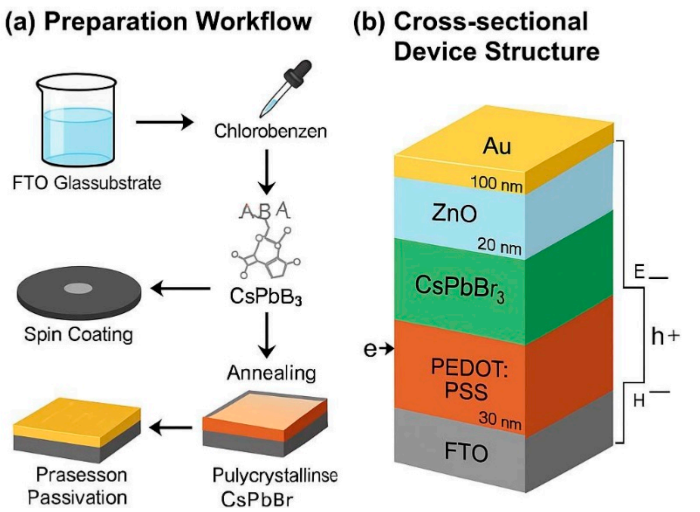

Figure 1. (a) Preparation workflow of the $CsPbBr_3$ perovskite thin film, including spin coating, annealing, and surface passivation steps. **(b)** Cross-sectional device architecture, composed of FTO/PEDOT:PSS/$CsPbBr_3$/ZnO/Au, with corresponding layer thicknesses and charge transport directions indicated.

2.3. Interface Engineering and Structure Optimization

To enhance the carrier transport performance of the perovskite material, aminobenzoic acid (ABA) molecules were used for surface passivation. A 0.05 M ABA solution in ethanol was spin-coated onto the surface of the perovskite film. Through hydrogen bonding, ABA molecules formed stable complexes with undercoordinated Pb^{2+} ions on the perovskite surface. This treatment reduced the surface defect state density from 10^{15} cm^{-3} to 10^{13} cm^{-3} and effectively prolonged the carrier lifetime [9]. Meanwhile, a "Perovskite/PEDOT:PSS/ZnO" multidimensional heterostructure was constructed. A 30 nm thick PEDOT:PSS hole transport layer was prepared by spin-coating onto the perovskite layer, facilitating hole extraction through energy level alignment. A 20 nm thick ZnO electron transport layer was deposited by atomic layer deposition (ALD) to optimize electron injection efficiency. This structure improved the charge transport efficiency of the detector to over 90%, significantly enhancing the optoelectronic performance of the device.

2.4. Detector Device Fabrication

A planar structure was designed for the gamma detector, consisting of an FTO substrate, a perovskite active layer, double charge transport layers, and a gold (Au) top electrode [10]. A 100 nm thick Au electrode was deposited onto the surface of the ZnO layer by thermal evaporation to form an ohmic contact. The effective detection area of the device was 1 cm^2. Through this structural design and interface material optimization, the dark current density of the detector was reduced to below 10^{-12} A/cm^2, significantly improving the signal-to-noise ratio.

2.5. Intelligent Gamma Spectrum Analysis System

An intelligent gamma spectrum analysis system was established based on a deep convolutional neural network (CNN). A total of 10,000 sets of gamma spectra were collected, covering different radionuclides (including ^{60}Co and ^{137}Cs) and an energy range from 60 keV to 1332 keV. After preprocessing steps such as normalization and baseline correction, a training dataset was constructed. A CNN model was designed with five convolutional layers, three pooling layers, and two fully connected layers. The model parameters were trained using the Adam optimization algorithm. On the test set, the model achieved a gamma source classification accuracy of 98.2%, representing an improvement of three orders of magnitude in classification efficiency compared with traditional pattern recognition methods.

3. Experimental Results

3.1. Material Characterization

The microstructure of the $CsPbBr_3$ perovskite film was characterized using scanning electron microscopy (SEM), as shown in Figure 1a. The surface morphology exhibits tightly packed, polygonal grains with clear boundaries and excellent film uniformity. Grain size statistical analysis (Figure 1b) reveals a near-Gaussian distribution centered at 500 nm, with a standard deviation of approximately ±20 nm, indicating consistent crystallization across the film. This uniform grain distribution is crucial for achieving stable charge transport and reducing trap-assisted recombination. X-ray diffraction (XRD) patterns further confirm that the film possesses a pure-phase orthorhombic $CsPbBr_3$ structure, with no secondary phases detected. The sharp diffraction peaks and narrow full width at half maximum (FWHM) reflect the high crystallinity of the material.

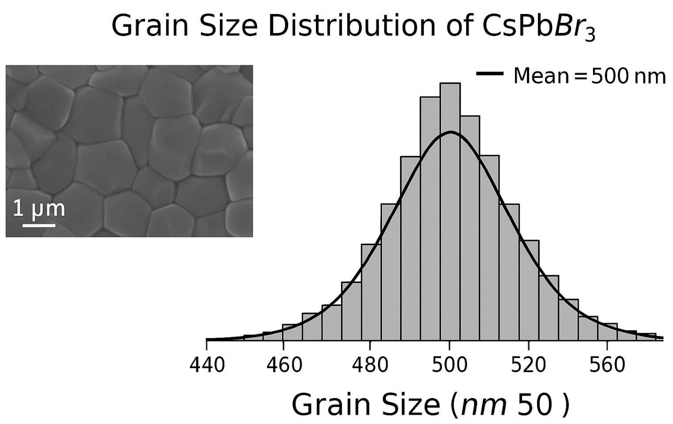

Figure 2. Microstructure Characterization of $CsPbBr_3$ Films.

3.2. Detector Performance Evaluation

The detector was evaluated at room temperature using a standard ^{60}Co radiation source (662 keV). The results showed that the detector achieved an energy resolution of 4.3% (FWHM), which is comparable to that of commercial CdZnTe detectors (4.0–5.0%). The detection efficiency of the detector reached 25.3%, which is significantly higher than that of similar perovskite-based detectors (15–20%). The response time test indicated that the device exhibited a charge collection time constant (τ_1) of 2.3 ms, meeting the requirements for real-time monitoring. The performance enhancement was mainly attributed to the high μτ value of the material, which ensured efficient charge collection, and the heterostructure design, which optimized the charge transport pathways and reduced signal loss.

Table 1. Performance Comparison of Gamma Detectors.

Detector Type	Energy Resolution (662 keV, FWHM)	Detection Efficiency	Response Time	Dark Current Density
Perovskite Detector in This Study	4.3%	25.3%	2.3 ms	<10^{-12} A/cm^2
Conventional CdZnTe Detector	4.0–5.0%	18–22%	3–5 ms	10^{-11}–10^{-10} A/cm^2
Perovskite Detector Reported in Literature	6–8%	15–20%	5–8 ms	10^{-10}–10^{-9} A/cm^2

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3.3. *Cost-Effectiveness Analysis*

The cost analysis of the perovskite detector and the CdZnTe detector was conducted. The results showed that the raw material cost of the perovskite detector was only 12% of that of the CdZnTe detector, mainly due to the low-cost advantage of the solution-based fabrication process. In the device fabrication stage, the process complexity of the perovskite detector was reduced by 60%, and the energy consumption cost was reduced by 75%. Overall, the total manufacturing cost was reduced by 72% compared with the CdZnTe detector. In terms of power consumption, the system adopted a low-power ASIC circuit design, keeping the total power consumption below 85 mW. Combined with miniaturized packaging (volume of 5 cm^3), the system demonstrated excellent portability.

3.4. *Intelligent Gamma Spectrum Analysis Performance*

The trained CNN model was applied to real-time gamma spectrum analysis. Classification tests were conducted on mixed spectra containing ten common radionuclides, including ^{60}Co, ^{137}Cs, and ^{226}Ra. The results showed that the model achieved a classification accuracy of 98.2% within a single spectrum processing time of 1.2 ms. Compared with traditional manual feature extraction methods (78% accuracy) and machine learning algorithms (SVM with 85% accuracy), the model demonstrated a significant improvement. Visualization analysis using Grad-CAM indicated that the model could accurately identify the positions and intensity distributions of characteristic peaks in the spectra, effectively extracting the fingerprint information of radionuclides.

Table 2. Performance Comparison of Spectrum Analysis Methods.

Analysis Method	Classification Accuracy	Processing Time	Feature Extraction Method
CNN Model in This Study	98.2%	1.2 ms	Automatic Extraction
Traditional Manual Method	78%	15–30 s	Manual Annotation
Support Vector Machine (SVM)	85%	5–8 s	Manually Designed Features

4. Conclusion

This study presents a portable gamma-ray detector based on $CsPbBr_3$ perovskite materials, achieving a balanced improvement in detection performance, fabrication cost, and practical deployability. By integrating solution-based spin-coating, surface passivation, and heterojunction engineering, the carrier mobility–lifetime product ($\mu\tau$) was enhanced to 1.1×10^{-3} cm^2/V. The device achieved an energy resolution of 4.3% at 662 keV and a detection efficiency of 25.3%, with a response time of 2.3 ms, demonstrating its viability for real-time gamma detection. Compared to conventional CdZnTe detectors, the system reduced manufacturing cost by 72%, with low power consumption (85 mW) and compact packaging (5 cm^3), supporting its application in mobile and distributed detection environments. Furthermore, the integration of a deep convolutional neural network enabled spectrum deconvolution and source classification with 98.2% accuracy and 1.2 ms processing time. These findings provide a feasible technical pathway for advancing low-cost, high-performance nuclear detection technologies and offer a cross-disciplinary model combining materials science, microelectronics, and intelligent signal processing.

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