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Radioluminescent nuclear batteries with different phosphor layers

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ABSTRACT

A radioluminescent nuclear battery based on the beta radioluminescence of phosphors is presented, and which consists of ^{147}Pm radioisotope, phosphor layers, and GaAs photovoltaic cell. ZnS:Cu and Y_2O_2S:Eu phosphor layers for various thickness were fabricated. To investigate the effect of phosphor layer parameters on the battery, the electrical properties were measured. Results indicate that the optimal thickness ranges for the ZnS:Cu and Y_2O_2S:Eu phosphor layers are 12 mg cm^{-2} to 14 mg cm^{-2} and 17 mg cm^{-2} to 21 mg cm^{-2}, respectively. ZnS:Cu phosphor layer exhibits higher fluorescence efficiency compared with the Y_2O_2S:Eu phosphor layer. Its spectrum properly matches the spectral response of GaAs photovoltaic cell. As a result, the battery with ZnS:Cu phosphor layer indicates higher energy conversion efficiency than that with Y_2O_2S:Eu phosphor layer. Additionally, the mechanism of the phosphor layer parameters that influence the output performance of the battery is discussed through the Monte Carlo method and transmissivity test.

1. Introduction

Microelectromechanical systems (MEMS) have undergone great development in recent decades. However, the small size and limited application of MEMS set stringent the requirements for its power supply. Traditional batteries, such as fuel and solar cells, cannot satisfy the power requirements of MEMS devices due to their large volume, short lifetime, and poor environmental adaptability. A nuclear microbattery, which is used to transform the decay energy of radioisotopes into electrical energy, is a potential candidate as an energy supply for MEMS [1]. Among the numerous competing types of nuclear microbatteries, betavoltaic microbatteries have been extensively examined [2–7]. The development of miniature satellites resulted in higher density requirements for the power supply, motivating the exploration of high-energy radioactive isotopes, such as ^{147}Pm and ^{241}Am. However, irradiation damage of the photovoltaic material under high-energy ray is very serious. To address this limitation, the radioluminescent nuclear battery is an awesome choice.

A radioluminescent nuclear battery utilizes radioactive decay to produce fluorescence in the phosphor material through the photoelectric effect of photovoltaic cells to generate electric current, as shown in Fig. 1. The development of photovoltaic materials and technology facilitated the use of III–V photovoltaic cells in the radioluminescent nuclear battery since III–V photovoltaic cells have many advantages: direct band gap structures, large light absorption coefficient, and small leakage current [8]. Sychov et al. [9] fabricated an indirect-conversion radioisotope battery based on ^{238}Pu/ZnS/AlGaAs with 21 μW power output. Prelas et al. [10,11] investigated optoelectronic betavoltaic cells based on ^{85}Kr and diamond, and this work indicated that the using of wide bandgap photovoltaics in nuclear energy was a promising application. Walko et al. [12] designed radioluminescent photoelectric power sources based on ^{3}H/ZnS aerogel composite light source and different photovoltaic cells. The study showed that III–V photovoltaic cell design was smaller than hydrogenated amorphous silicon design in the volume of battery. Sims et al. [13] reported the GaP power conversion in ZnS:Ag light source and demonstrated that GaP had 23.54% and 14.59% conversion efficiencies in 968 and 2.85 μW cm^{-2} blue light, respectively. Hong et al. [14] optimized the parameters of a beta radioluminescence nuclear battery and obtained a 2.5% energy conversion efficiency theoretically. Fluorescence efficiency, transparency and the thickness of phosphor layer will influence the fluorescence intensity of phosphor layer. Moreover, the match between the spectrum of layer and the spectral response of photovoltaic cells will affect the photoelectric efficiency of photovoltaic cells. Therefore, the selection of phosphor layer and optimization of thickness can effectively improve the output performance and energy conversion efficiency.

This paper presents a radioluminescent nuclear battery based on ^{147}Pm/phosphor layer/GaAs and reports the best thickness ranges of phosphor layers and output performance of the battery. The influence mechanism of the phosphor layer on energy

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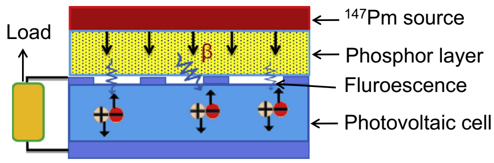

Fig. 1. Schematic of a radioluminescent nuclear battery.

conversion efficiency of the battery is discussed through the Monte Carlo method and transmissivity test.

2. Experimental

2.1. Battery prototype

β particles in substances usually range from a few tens of microns to hundreds of microns so that the phosphor layers can easily absorb the kinetic energy of the particles. As a result, the shielding of beta radioluminescent nuclear battery is easy to handle, and the size of the battery can become greatly miniaturized due to its relatively short ranges. Moreover, the battery will perform more stably since the irradiation damage of the phosphor materials is minimal. ^{147}Pm radioisotope with the specific (per unit area) activity of 5 mCi cm^{-2} was applied to the battery in this study.

As two kinds of typical phosphors, ZnS:Cu and Y_2O_2S:Eu were used to fabricate phosphor layer, and these parameters of which are given in Table 1. There are many ways to prepare phosphor layer: physical settlement method [15], photographic paste method, and electrophoresis method. The photographic paste method is costly, whereas the electrophoresis method produces unstable phosphor layers. The physical settlement method is more advantageous than the two aforementioned methods: easy operation and controllable thickness. In this paper, phosphor was deposited on quartz glass substrate by physical settlement method to prepare the phosphor layer, as shown in Fig. 2(b).

The fluorescence intensity of phosphor layer excited by the ^{147}Pm radioisotope is very weak, and GaAs photovoltaic cell with small leakage current can utilize and collect the weak fluorescence. The radioluminescent nuclear battery comprises ^{147}Pm radioisotope, phosphor layer, and GaAs photovoltaic cell with an area of 5×5 mm^2 (Fig. 2(d)).

Table 1
Phosphor parameters.

Phosphor (chemical composition)	Luminescence color	Grain diameter (μm)
Y_2O_2S:Eu	Red	6.8
ZnS:Cu	Green	7.4

2.2. Optical and electrical test

The radioluminescence spectrum and fluorescence efficiency of phosphor layer which are determined by the kind of phosphor, would influence the photoelectric response of the GaAs photovoltaic cell and fluorescence intensity of the phosphor layer, respectively.

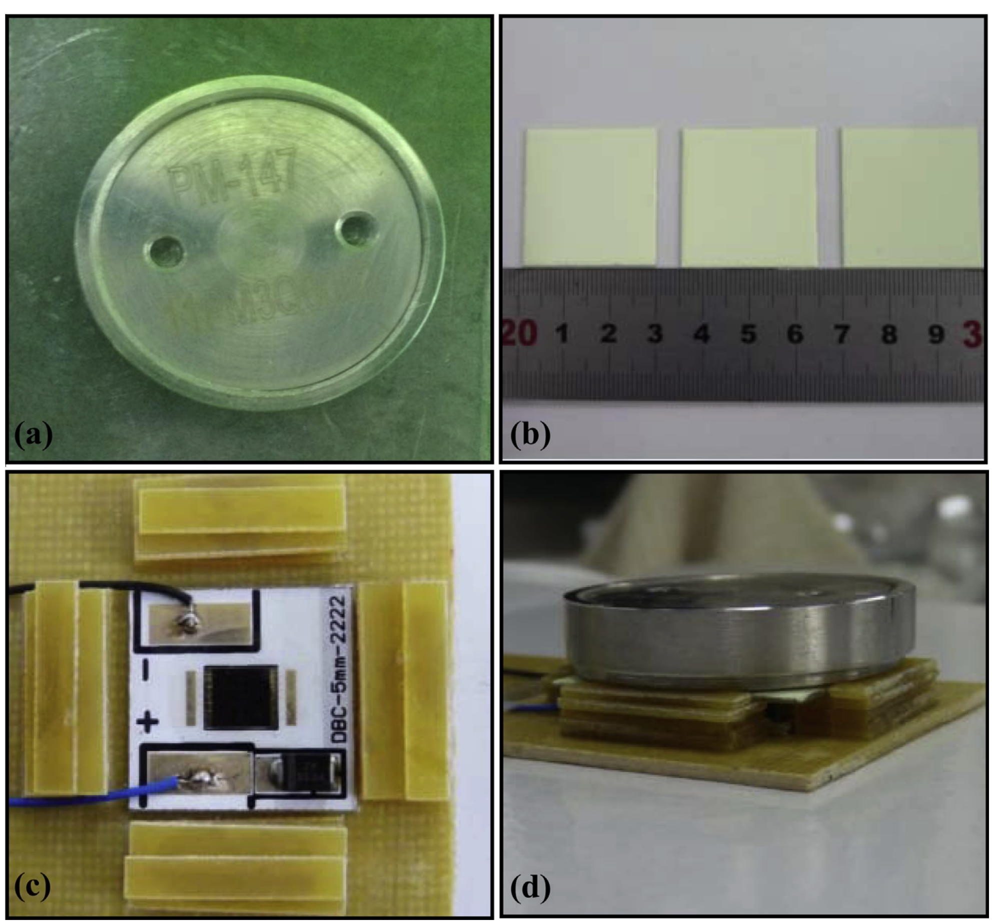

Fig. 2. (a) ^{147}Pm source, (b) phosphor layers, (c) GaAs photovoltaic cell, and (d) battery prototype setup.