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Modelling and performance analysis of a GaN-based n/p junction betavoltaic cell

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ABSTRACT

In this work, we optimized the performance of a gallium nitride (*GaN*)-based *n/p* junction betavoltaic cell irradiated by the radioisotope nickel-63 (Ni^{63}). In particular, we developed a lab-made software starting from an analytical model that takes into account a set of fundamental physical parameters for the cell structure. The simulations reveal that, by using a Ni^{63} radioisotope source with a 25 mCi/cm^2 activity density emitting a flux of beta-particles with an average energy of 17.1 KeV, the cell performs a conversion efficiency (η) in excess of 26%, thus approaching the theoretical limit for a *GaN*-based device. The other electrical parameters of the cell, namely the short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), and maximum electrical power density (P_{max}) are 240nA/cm^2, 2.87 V, and 660 nW/cm^2, respectively. The presented analysis can turn useful for understanding the theoretical background needed to better face *GaN*-based betavoltaic cell design problems.

1. Introduction

With the continuous development in technology and human lifestyle, the interest in long-life power batteries has significantly increased in recent years. Nowadays, based on their energy source, batteries can be divided into three major groups, namely chemical, solar, and nuclear. After rigorous theoretical and experimental studies, it was clear that the possibilities of the first and second categories are limited in many applications with respect to the enormous and attractive potential of the nuclear approach. For example, we can consider all the applications where battery replacement is inconvenient or impossible such as implantable prosthetic devices, automatic weather stations in the arctic, deep-sea explorations, space missions, and so on.

Nuclear batteries converts the kinetic energy of alpha- or beta-particles, which is emitted from a radioactive isotope source, into electrical energy across semiconductor materials similarly to the solar cell working principle. Accordingly, they are called alphavoltaic or betavoltaic cells. The right choice of the radioactive source, as well as the absorbing semiconductor material, depends on many factors among which we can quote the radioisotope half-life fitting the task duration, decay type, and energy content. At the same time, the semiconductor material must have both good radiation resistance and high conversion efficiency. In this context, by considering the high penetration ability of beta-particles and the less radiation damage that attains the device structure if compared to the use of alpha-particle, the development and exploitation of betavoltaic cells have gained a great attention.

The concept of nuclear batteries was suggested by *Mosely* in 1913 and the first betavoltaic design based on silicon *p/n* junctions was investigated by *Rappaport* in the '50s [1,2]. Since 1989, the development of betavoltaic batteries has involved the use of alternative semiconductor compounds such as gallium arsenide (*GaAs*) [3,4], silicon carbide (*SiC*) [5–8], gallium nitride (*GaN*) [9–11], aluminium gallium arsenide (*AlGaAs*) [12,13], and indium gallium phosphide (*InGaP*) [14,15]. Different devices based in turn on *p/n*, *p-i-n*, and *Schottky* structures were designed to exploit the advantages of radioisotopes that emit beta-particles [16–22]. Also, a great improvement in performance has been achieved thanks to the efforts in theoretical research based on analytical and/or numerical simulations, which contribute significantly in gaining time and limiting the financing required for experimental tasks involving relatively dangerous and expensive materials [23–28].

Within this framework, considering the need for more understanding how different physical and geometrical parameters of a wide bandgap material like *GaN* affect the performance of a nuclear battery, we have developed a comprehensive analytical model and compiled a lab-made software that allows an exhaustive analysis of a *GaN*-based *n/p* junction betavoltaic cell irradiated by the radioisotope nickel-63 (Ni^{63}). In more detail, by using a set of reference parameters for simulations, in this paper we have investigated the effects of the doping concentration, surface recombination velocity, junction depth, reflection coefficient, and Ni^{63} radioactivity density in determining the

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