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Study on GaN-based epitaxial structures for betavoltaic battery

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1. Introduction

Radioisotope-based betavoltaic battery is one of the nuclear batteries, which directly convert the power of nuclear radiation into electric power. Recently, betavoltaic is promising as micro-scale power sources of micro-electromechanical system (MEMS) used in biomedical devices, military applications, wireless networks, and sensors in harsh environment, due to a small volume, high energy density, long lifetime, and insensitivity to environment [1]. Tritium (H-3), Ni-63, and Pm-147 are considered as sources in betavoltaic battery. Among them, Ni-63 is the more suitable as the energy source of micro-batteries due to relatively low beta particle energies and long-term half-life.

Gallium nitride (GaN), as a wide-band gap (E_g = 3.4 eV) semiconductor material, is attractive for betavoltaic battery because not only the power conversion efficiency of betavoltaic increases with increase of the band gap of semiconductor (based on theoretical analysis [2]), but also the radiation resistance from radioisotope is higher. Several groups reported the experimental results of GaN-based betavoltaic batteries [3-5], however, the reported results are significantly far from the theoretical values. This may be due to an inadequate design of epitaxial and device structures for GaN-based betavoltaic.

In this work, we studied the epitaxial structure of the previously reported GaN-based betavoltaic batteries by using simulation tools and proposed the advanced epitaxial structure that can be expected the enhanced performance.

2. Study on epitaxial structures of betavoltaic

GaN-based betavoltaic is generally demonstrated on epitaxial layers grown by using metal-organic chemical vapor deposition (MOCVD). The generated electron-hole pairs (EHPs) by beta particles are collected in depletion region, so if the depletion region is widened, collection rate of EHPs will be increased. For wider depletion region, the doping concentration of the GaN layer and the design of p-(i)-n structure are important, leading to performance improvement of betavoltaic.

Fig. 1 shows the schematic of conventional GaN-based betavoltaic and the simulated conduction band diagram of epitaxial structures (sample A-C) of betavoltaic in literatures [3-5]. The conduction band diagram was simulated by 1D poisson solver. The information of epitaxial structure and electrical characteristics were summarized in Table I. The open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and power conversion efficiency (PCE) are important parameters to determine the performance of betavoltaic battery. The simulated beta particle absorption profile in GaN layer was shown in Fig. 2, which indicates that the most of absorption in GaN layer was occurred near surface of structure (Ni-63 positioned on surface). The depletion width of sample B and C was similar as ~260 nm, but sample C has thicker depletion region with ~1900 nm. This is dependent on the doping concentration of p-(i)-n-GaN layer, respectively. Also, the doping concentration of each layer influences the

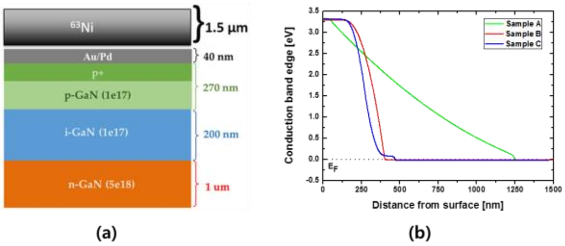


Fig. 1. (a) schematic of GaN-based betavoltaic structure [5] and (b) conduction band diagram of epitaxial structures reported in [3-5].

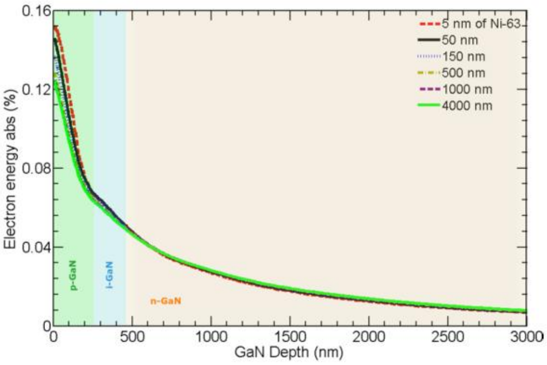
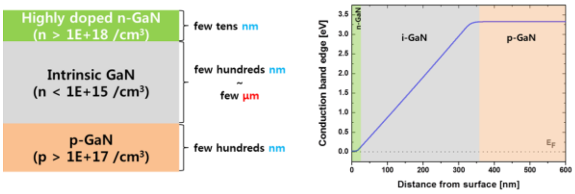


Fig. 2. Beta particle absorption profiles of Ni-63 according to GaN depth [5].

Table I: Summary of information of GaN-based betavoltaic batteries reported in [3-5].

	Sample A	Sample B	Sample C
Structures	p-i-n junction	p-n junction	p-i-n junction
V_{oc} [V]	1.62	0.25	0.79
I_{sc} [nA]	0.64	2.0	1.4
PCE [%]	1.13	< 1	0.016



(a) (b)

Fig. 3. (a) schematic of epitaxial structure and (b) conduction band diagram for proposed GaN-based betavoltaic battery.

V_{oc} and I_{sc} of betavoltaic. Sample B and C have higher I_{SC} than that of sample A, which is attributed to the formation of depletion region relatively near **the** surface (more closer to energy source as Ni-63). However, sample A has higher collection rate of EHPs due to wider depletion region, resulting the highest PCE among samples. Therefore, the position and width of depletion region are considered to design the advanced structure of GaN-based betavoltaic battery.

3. Design of advanced structure of betavoltaic

To more improve V_{oc} and I_{sc}, the deposition energy of the injected electrons emitted from Ni-63 must be increased. The deposition energy is decreased due to the absorption and back-scattering of the dead layer like metal contact and thick p-GaN layer. Hence, the thinning of the dead layer is also important.

We proposed the advanced epitaxial structure for GaN-based betavoltaic battery with enhanced performance, based on the study in this work. Fig. 3 shows the advanced structure and the simulated conduction band diagram. The top layer is a highly-doped n-GaN layer, instead of p-GaN layer, which can thin the dead layer and place the depletion region near the surface, due to relatively higher doping concentration than that of p-GaN. And the p-GaN of bottom layer can act as a very high back-barrier, which may block the leakage current path to bottom layers [6]. The i-GaN layer with low electron concentration can also help to widen the depletion region. The detailed conditions of each layer must be optimized to realize the improved performance. Also, other parameters related to the performance of betavoltaic, such as the crystalline quality of GaN layer, thickness and activity of Ni-63, and so on, will be studied in future works.

4. Conclusions

GaN-based betavoltaic batteries were studied and the important parameters related to performance were considered. Among parameters, the position and width of depletion region can significantly influence the performance improvement of betavoltaic. Based on this study, we proposed the advanced epitaxial structure for GaN-based betavoltaic battery, which can lead to more enhanced performance.

5. Acknowledgments

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