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Demonstration of GaN Betavoltaics based on p-n junction

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1. Introduction

Betavoltaics based on radioisotope can directly convert the power of nuclear radiation into electric power. Betavoltaic battery is a promising as micro-scale power sources 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.

Gallium nitride (GaN), as a wide-band gap (E_g = 3.4 eV) semiconductor material, is promising candidate for betavoltaic battery, compared to Si- and SiC-based betavoltaic batteries, because not only the power conversion efficiency of betavoltaic can be increased by increasing the band gap energy, but also the radiation resistance from radioisotope is higher [1]. Several groups reported the experimental results of GaN-based betavoltaic batteries [3-5], however, the reported power conversion efficiencies are discrepant with the theoretical values [6]. This may be due to an inadequate design of epitaxial and device structures for GaN-based betavoltaics. In our previous work [1-2], we designed and grown the p-n junction based epitaxial structures. In addition, GaN-based p-(i)-n diodes were fabricated on epitaxial structures and current-voltage (*I-V*) characteristic was confirmed.

In this work, we demonstrated GaN betavoltaics based on p-n junction by confirming the output power characteristics using electron beam (e-beam) irradiation. The TCAD simulation for the fabricated device structures was performed to support the experimental results.

2. Experiments

GaN p-n junction based epitaxial structures for betavoltaics were grown on GaN/sapphire templates by using metal-organic chemical vapor deposition (MOCVD). Sample A is fabricated diode based on p-n junction and Sample B is based on p-i-n junction. Detailed information of epitaxial structures and fabrication processes were addressed in Ref. [1]. Fig. 1 shows the cross sectional schematic of the fabricated betavoltaics and Fig. 2 shows the secondary ion mass spectrometry (SIMS) result for p-i-n junction.

The e-beam was irradiated into the fabricated betavoltaics to measure the output power characteristics, using SEM with nano probe workstation (shown in Fig. 3). The energy of e-beam was selected as 17 kV that is the average energy of Ni-63 radioisotope. The current of e-beam was 3.57 nA, which means the activity of about 600 mCi.

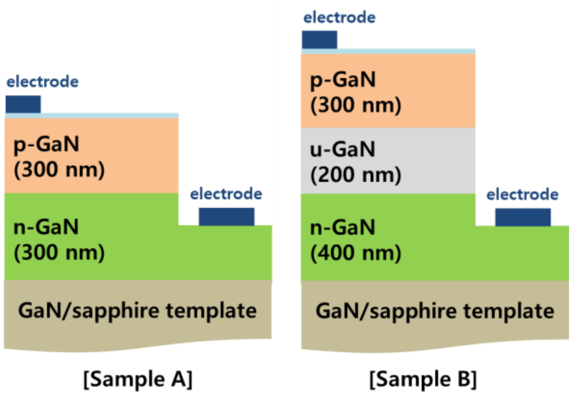

Fig. 1. Cross-sectional schematic of GaN betavoltaics fabricated on p-n (Sample A) and p-i-n junction (Sample B)

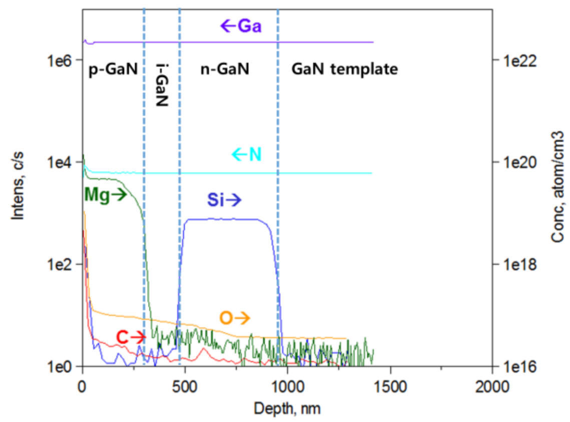

Fig. 2. SIMS results of p-i-n junction

The TCAD simulation (Silvaco ATLAS) for fabricated betavoltaics was performed to support the experimental results. The actual thickness and carrier concentration of each layer in experimental structures were used in the simulation, however, the size of devices in simulation is set as smaller than real devices to obtain results easily.

3. Results and Discussion

Fig. 4 shows the *I-V* characteristics without and with e-beam irradiation of Sample A and B. The open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) of Sample A were 1.87 V and 1.12 μA, while those of Sample B were 2.23 V and 1.86 μA, respectively. From these values, the output power (P_{out}) of Sample A and B was

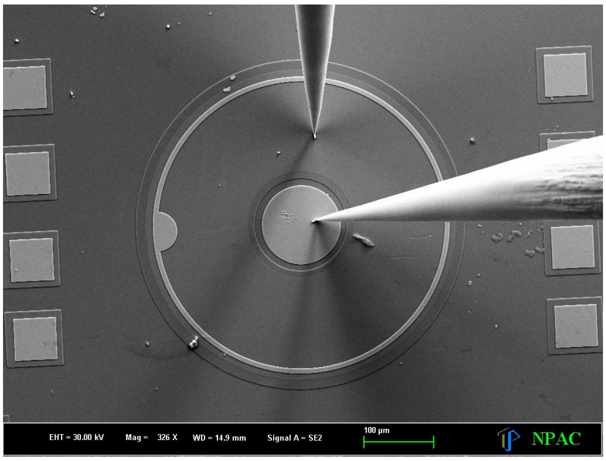

Fig. 3. SEM image of device measurement with e-beam irradiation using nano probe workstation

extracted as 2.74 μW and 1.88 μW, respectively. The power conversion efficiency (PCE) can be calculated using following equation:

$$PCE = P_{out} / P_{in}$$

where P_{in} is a input power and a 60.7 μW from e-beam irradiation. The calculated PCE of Sample B was ~4.5% that is higher than that of Sample A (~3.1%). It is attributed to the difference in epitaxial structure. In previous work [2], we studied about an epitaxial structures to achieve a high PCE of betavoltaic and found the position and width of depletion region between p-n junction is important factors related to PCE. Sample B has intrinsic(undoped) GaN layer between p-GaN and n-GaN layer and this additional i-GaN layer help to expand the depletion width of fabricated betavoltaic. Therefore, total depletion width of Sample B is wider than that of Sample A, resulting in higher PCE. Compared to similar research using e-beam irradiation [7], the PCE of Sample B is reasonable value.

The TCAD simulation results of devices based on p-n and p-i-n junction were shown in Fig. 5. The device based on p-i-n junction has larger V_{OC} and I_{SC} than those of p-n junction due to the existence of i-GaN layer, which indicates a similar trend as experiment. This means that the depletion width between junction is crucial factor of betavoltaic characteristics.

4. Summary

GaN betavoltaics based on p-n and p-i-n junction were demonstrated by measuring the output power characteristic using electron beam (e-beam) irradiation. The TCAD simulation for the fabricated device

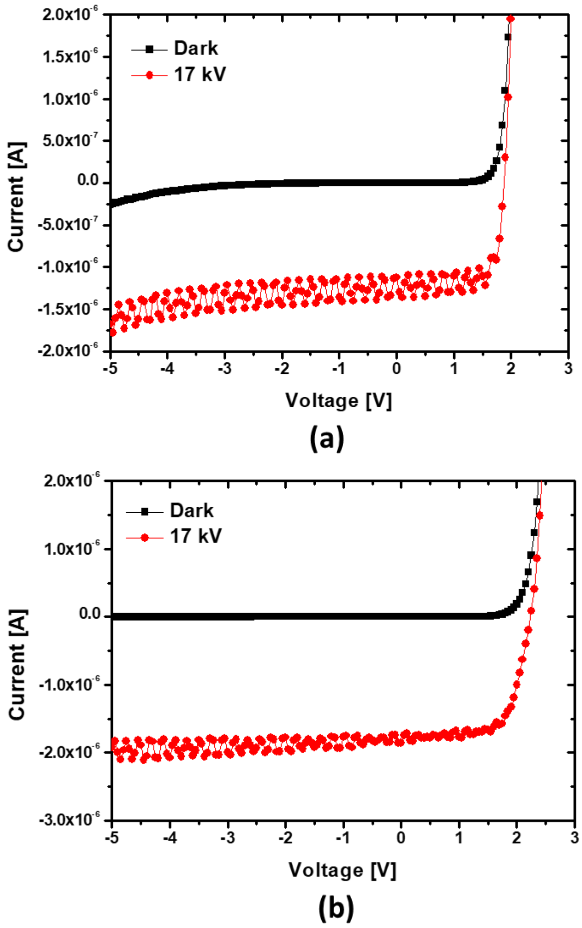

Fig. 4. *I-V* characteristics of Sample A(a) and B(b) w/ and w/o 17 kV e-beam irradiation

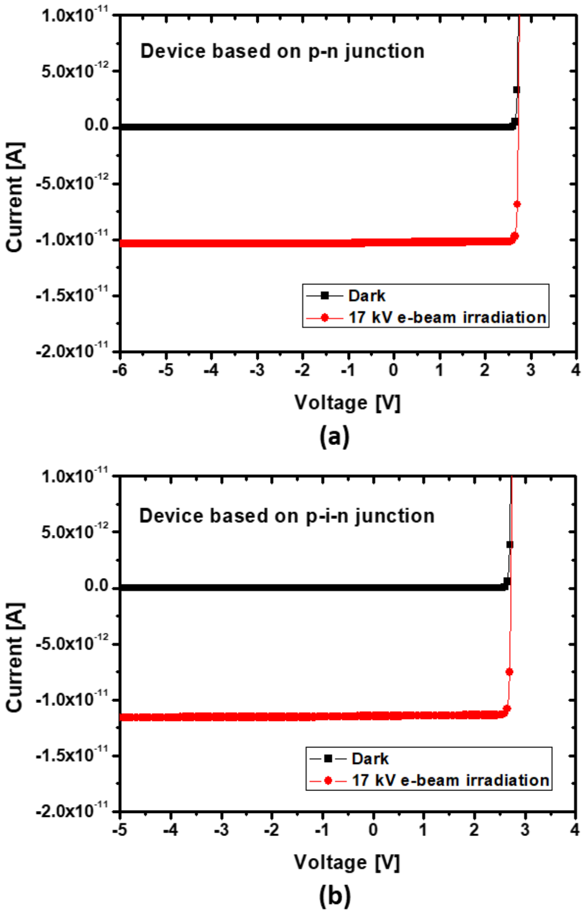

Fig. 5. Simulated I-V characteristics of devices based on p-n(a) and p-i-n junction(b)

structures was performed to support the experimental results. From simulation and experimental results, the depletion width between junction is main factor to determine the characteristics of betavoltaics.

5. Acknowledgments

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