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Effect of Anode Structure on Performance of GaN PIN Betavoltaic Cells

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1. Introduction

Semiconductor-based betavoltaic cells are the one of nuclear batteries, which directly convert the nuclear energy released by beta-emitting radioisotopes into electrical power through a semiconductor junction [1]. Because the conversion mechanism depends solely on nuclear decay rather than external environmental conditions, betavoltaic cells operate independently of illumination, temperature, and atmospheric pressure and require no replacement or periodic maintenance [2].

Gallium nitride (GaN) has a wide bandgap energy of 3.4 eV, enabling higher theoretical output voltage and energy-conversion efficiency compared with narrow-bandgap semiconductor like Si. The relatively large bandgap also allows a greater fraction of beta-induced electron–hole pairs to contribute to useful electrical power rather than being lost through recombination or thermalisation processes. As a result, when carrier-collection conditions are properly optimized, GaN-based betavoltaic cells are expected to deliver higher open-circuit voltage and improved conversion efficiency [3]. In our previous study [4], GaN PIN betavoltaic cells showed the excellent power performance with power conversion efficiency of 4.5% under electron beam (e-beam) evaluation.

In this work, the GaN PIN betavoltaic cells with different anode structure were fabricated and the power performance was evaluated by using electron beam irradiation. The difference in device performance depending on anode structures were analyzed through the extraction of series resistance.

2. Experiments

Two types of GaN PIN betavoltaic cell with different anode configurations were fabricated as shown in Figure 1. Sample A is betavoltaic cell with fully-covered anode on p^{++}-GaN layer and Sample B is device with partially-covered anode.

The fabrication process began with a cleaning procedure of epitaxial structure to remove organic contaminants and surface residues. To enable a quasi-vertical current flow by exposing the n-GaN layer for cathode formation, GaN mesa etching was carried out using an oxide/photoresist bilayer hard mask. After removing hard mask, the cathode contact with Ti/Al/Ni/Au metal stack (30/100/30/100 nm) was formed on n-GaN using e-beam evaporator and then annealed using rapid thermal annealing (RTA) at 850 ℃ for 30 s in an N_2 ambient to achieve ohmic contact on n-type GaN. Finally, the anode contact was deposited on the p-GaN using e-beam evaporator. A Pd/Ni/Au metal stack (10/20/50 nm) was selected to form ohmic contact to p-type GaN, followed by RTA at 600 ℃ for 2 min in air ambient to activate the contact interface and stabilize the metallization [5]. Sample A and B was only difference in anode size. All fabrication processes were proceeded at Electronics and Telecommunications Research Institute (ETRI). Figure 2 showed the optical microscopy images of fabricated betavoltaic cells.

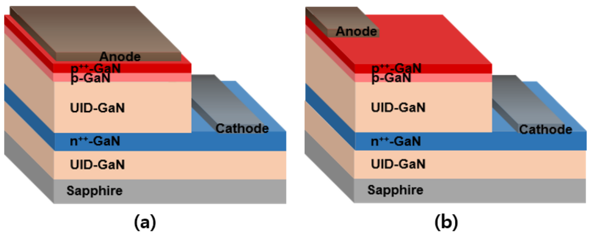

Figure 1. Cross-sectional schematics of fabricated betavoltaic cells: (a) Sample A and (b) Sample B

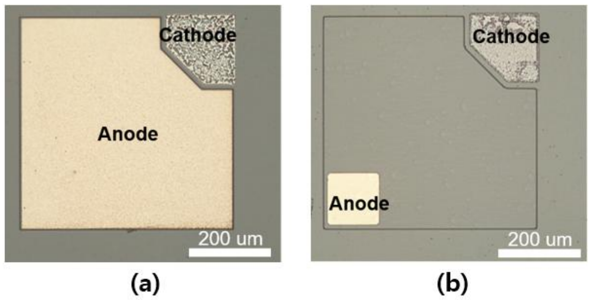

Figure 2. Optical microscopy images of fabricated betavoltaic cells: (a) Sample A and (b) Sample B

3. Results & Discussion

The I-V characteristic of two cells was evaluated under dark conditions and 17 keV e-beam irradiation, respectively, as shown in Figure 3. A 17 keV of e-beam energy is corresponding to the mean β-decay energy of

Ni-63 [4]. Both devices exhibited the current generation under e-beam irradiation, which means the operation of betavoltaic cell. And the Sample A showed the more large and stable current generation compared to Sample B.

To understand this phenomena, the series resistance of the two cells was quantitatively extracted by using dV/dlnI – I method [6]. The Sample A exhibited a series resistance of 14.5 Ω, whereas the Sample B had 49.8 Ω that is three times higher value. This is because the generated holes in depletion region can directly move to anode in Sample A, leading to the lower series resistance. While in Sample B, the moving path of generated holes was more longer than that of Sample A, resulting in the larger series resistance. Figure 4 illustrated the relationship between the anode structure and series resistance of GaN PIN betavoltaic cell.

The key parameters of betavoltaic cell were extracted from I-V characteristics, such as the short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), and power conversion efficiency (PCE), respectively. Sample A had 5.54 μA of I_{SC} and 2.39 V of V_{OC}, which resulted in the approximately 5.85% of PCE. This value was significantly higher than Sample B (1.24%) and the highest PCE of GaN betavoltaic cells among the values evaluated using e-beam irradiation. It may be resulted from the optimized betavoltaic cell structure and improved anode and cathode contact characteristics.

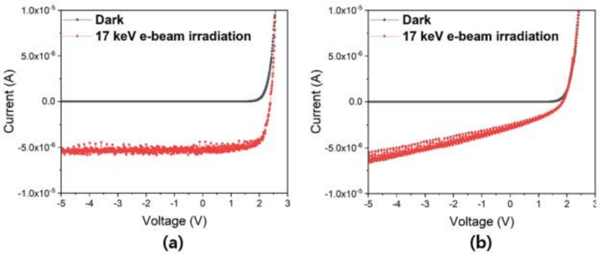

Figure 3. I-V characteristics of (a) Sample A and (b) Sample B

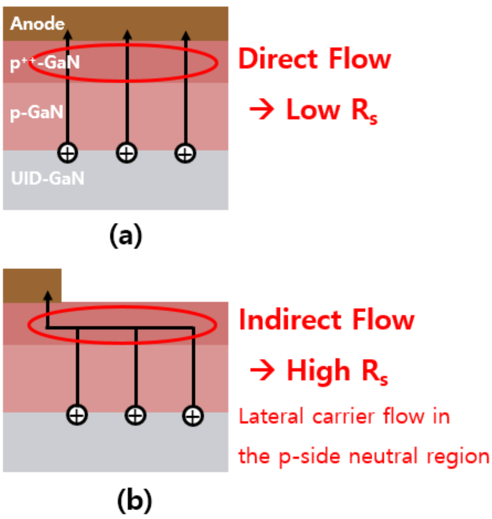

Figure 4. Illustration of relationship between the anode structure and hole current flow: (a) Sample A and (b) Sample B

4. Conclusions

We investigated the effect of anode structure on the performance of GaN PIN betavoltaic cells. The device with fully-covered anode structure showed the excellent power performance compared to device with partially-covered structure. This performance enhancement was analyzed in terms of series resistance. It demonstrated that the optimized structure of betavoltaic cell can improve the power performance.

ACKNOWLEGMENTS

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