Demonstration of Pm-147 GaN betavoltaic cells (postprint)

Authors: WANG Guan-Quan, LI Hao, LEI Yi-Song, ZHAO Wen-Bo, YANG Yu-Qing, LUO Shun-Zhong

Date: 2023-06-18T00:00:00+00:00

Abstract

Two GaN p-(i)-n diodes were designed and fabricated, and their electrical performances with 63Ni and 147Pm plate sources were compared. The results showed that the diodes with 147Pm had better electrical performances, with a short-circuit current (Isc) of 59 nA, an open-circuit voltage (Voc) of 1.4 V, and a maximum power (Pmax) of 49.4 nW. The ways to improve the electrical performances are discussed, including appropriate increase of the i-GaN thickness.

Full Text

Preamble

ChinaXiv Cooperative Journal, NUCLEAR SCIENCE AND TECHNIQUES 25, 020403 (2014)

Demonstration of Pm-147 GaN Betavoltaic Cells

WANG Guan-Quan,[1],* LI Hao,[1] LEI Yi-Song,[1] ZHAO Wen-Bo,[2] YANG Yu-Qing,[1] and LUO Shun-Zhong[1]
[1]Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang 621900, China
[2]No.44 Institute, China Electronics Technology Group Corporation, Chongqing 400060, China

(Received October 27, 2013; accepted in revised form November 27, 2013; published online March 20, 2014)

Two GaN p-(i)-n diodes were designed and fabricated, and their electrical performance with ^{63}Ni and ^{147}Pm plate sources was compared. The results showed that the diodes with ^{147}Pm exhibited superior electrical performance, achieving a short-circuit current (Isc) of 59 nA, an open-circuit voltage (Voc) of 1.4

V, and a maximum power (Pmax) of 49.4 nW. Methods to improve electrical performance are discussed, including appropriate increases in i-GaN thickness.

Keywords: Betavoltaic, GaN, Pm-147
DOI: 10.13538/j.1001-8042/nst.25.020403

Introduction

Advances in micro-electromechanical systems (MEMS) technology demand autonomous power sources [1–3]. Radioisotope batteries, which harvest energy from radioactive decay, operate without refueling and offer significant advantages over traditional micro-batteries for MEMS applications due to their high energy density and long operational lifetime. Among these, betavoltaic cells are particularly promising because of their compact size, maintenance-free operation, high energy conversion efficiency, and ease of integration, although research in this area remains in its infancy with relatively limited power output.

Considerable effort has been devoted to improving the electrical performance of betavoltaic cells. In addition to single-crystal silicon—the most mature semiconductor material—various other materials have been investigated for energy conversion devices, including amorphous silicon, InGaP, SiC, and GaN [4–8]. These studies have revealed a significant relationship between material bandgap width and the theoretical energy conversion efficiency ( ) of betavoltaic cells [9]. Generally, correlates positively with bandgap width, meaning that wide-bandgap materials yield better output performance.

Gallium nitride (GaN), with its wide bandgap of 3.4 eV, is well-suited for use as an energy conversion device in betavoltaic cells [10, 11]. In 2010, Cheng et al. [12] fabricated a GaN p-n junction device for a ^{63}Ni betavoltaic cell, achieving a short-circuit current (Isc) of 2.0 nA and an open-circuit voltage (Voc) of 0.025 V. The following year, they improved the device, obtaining an Isc of 0.64 nA and a Voc of 1.62 V [13]. Also in 2011, Lu et al. [14] created a GaN Schottky diode irradiated by ^{63}Ni, achieving an Isc of 0.012 nA and Voc of 0.10 V, and in 2012 they fabricated a GaN p-n junction device with Isc of 0.7 nA and Voc of 0.14 V [15]. Among these GaN betavoltaic cell results, Cheng et al. achieved notable success in Voc but not in Isc. However, all these results lag far behind those of single-crystal silicon devices and remain distant from theoretical values, indicating substantial room for improvement in developing GaN betavoltaic cells with practical performance levels.

The poor Isc of GaN betavoltaic cells may be attributed to small device area limiting collection of emitted particles and insufficient total energy from the radiation sources. Beta-emitting isotopes are excellent candidates for betavoltaic cell sources. For single-crystal silicon conversion units, low-energy β-emitters such as tritium (^{3}H) and ^{63}Ni are typically used as primary source isotopes to minimize radiation damage to the semiconductor.

In this respect, GaN offers superior radiation resistance compared to Si [11], enabling GaN conversion units to utilize higher-energy β-emitting radioisotopes than ^{63}Ni, thereby enhancing output power. Promethium-147 (^{147}Pm) is a suitable isotope for this purpose. Table 1 summarizes the key properties of these three β isotopes.

In this work, two large-area GaN p-n junction devices with different i-GaN thicknesses were fabricated and irradiated by a ^{147}Pm plate source. Their output performance was compared with that obtained using a ^{63}Ni plate source.

Experiment and Results

Two GaN p-n junction devices were designed, with the main fabrication flow chart shown in Fig. 1 [Figure 1: see original paper]. The structural quality of the epitaxial layer was assessed by measuring the full width at half maximum (FWHM) of the symmetric (002) low-angle diffraction peaks from the rocking curve (ω-scan), as depicted in Fig. 2 [Figure 2: see original paper]. Since dislocation density decreases with narrower XRD FWHM, the observed narrow FWHM of 112 arcsec indicates excellent crystalline quality of the GaN epilayer.

Device structural parameters are listed in Table 2 . The diodes measured 1.0 cm in diameter, with Ni (3 nm)/Au (3 nm) metal layers deposited across the entire top surface of the p-GaN to form Ohmic contact. The two devices were identical in structure except for their i-GaN thickness: 1.5 µm for device No. 2 and 1.0 µm for device No. 1. Dark I-V characteristics without irradiation were measured using a Keithley 2635 sourcemeter (Fig. 3 [Figure 3: see original paper]). The devices were irradiated using 10 mm diameter plate sources of ^{63}Ni (2.96×10^8 Bq) and ^{147}Pm (1.13×10^9 Bq). The experimental setup with ^{147}Pm source is shown in Fig. 4 [Figure 4: see original paper]. Output performance was measured using the Keithley 2635 after 240 hours of continuous irradiation of both diodes by the ^{63}Ni and ^{147}Pm sources, with results presented in Table 3 and scanning I-V curves shown in Figs. 5 and 6 [Figure 5: see original paper] [Figure 6: see original paper].

Discussion

The dark characteristics in Fig. 3 [Figure 3: see original paper] demonstrate that both GaN devices exhibit good p-n junction performance. Device No. 1 showed currents of 7.3×10^{-10} A at -10 mV and 4.0×10^{-9} A at -1.0 V, while device No. 2 exhibited currents of 1.9×10^{-11} A at -10 mV and 1.7×10^{-10} A at -1.0 V. The diode turn-on voltages exceed 2.0 V. These low leakage currents and high turn-on voltages are characteristic of wide-bandgap semiconductor p-n diodes.

The irradiation results reveal that ^{147}Pm-irradiated diodes significantly outperformed those irradiated by ^{63}Ni, achieving an Isc of 59 nA, Voc of 1.4 V, and Pmax of 49.4 nW. These represent the best Isc and Pmax values ever reported for a single GaN conversion unit, with Pmax being the key parameter for overall electrical capability.

This superior performance can be attributed to three main factors. First, the Voc of GaN devices exceeds that of traditional single-crystal Si devices because the built-in potentials of the GaN devices reach 3.26 V, compared to less than 1.0 V for typical Si devices. Second, ^{147}Pm possesses the highest power density among the three commonly used β isotopes in betavoltaic cells, as shown in Table 1 . Although the mass-specific activity of ^{3}H exceeds that of ^{147}Pm, the volume-specific activity of ^{147}Pm surpasses that of gaseous ^{3}H, enabling a ^{147}Pm source to deliver greater radioactivity per unit area than both ^{3}H and ^{63}Ni, resulting in higher β-particle emission power. Third, large diode area facilitates β-particle collection, while large source area supports higher radioactivity loading. Additionally, metal electrodes covering the entire top surface provide better charge collection efficiency due to the short diffusion length in GaN.

The test results after 240 hours of continuous irradiation showed minimal difference from pre-irradiation values, demonstrating stable operation of both GaN devices under ^{63}Ni and ^{147}Pm irradiation for at least 240 hours.

Under both ^{63}Ni and ^{147}Pm irradiation, device No. 2 exhibited superior output compared to device No. 1, with the only difference being i-GaN thickness. The mean penetration ranges of β particles in GaN were calculated to be 2.1 µm and 20 µm for ^{63}Ni and ^{147}Pm, respectively, based on their β energy spectra. Both values exceed the actual thicknesses of the two GaN diodes (p-GaN + i-GaN + n^{+}-GaN), which were 1.4 µm and 1.9 µm. When GaN material thickness is less than the β particle penetration range, thicker GaN can absorb more β-particle energy, leading to increased electron-hole pair generation and consequently higher Isc and Pmax.

A model dividing 2.0 µm of GaN into 20 equal steps was established [16] to calculate the energy deposition ratio for β particles from ^{63}Ni and ^{147}Pm (Fig. 7 [Figure 7: see original paper]). The deposition energy ratio decreases progressively, with the highest ratio occurring in the first step. While increasing i-GaN thickness enhances betavoltaic performance, the improvement is not proportional to the thickness increase.

Currently, defects persist in GaN material growth. Radiation-induced electron-hole pairs are minority carriers in the semiconductor and must diffuse into the built-in field region to be separated and generate current. Defects in GaN materials result in short minority carrier lifetimes and diffusion lengths (<0.3 µm) [17], causing many electron-hole pairs to recombine before reaching the built-in field and thus preventing them from contributing to current generation. Therefore, GaN diodes must be fabricated with an appropriate thickness.

Conclusion

In summary, two GaN devices were fabricated and their performance with ^{63}Ni and ^{147}Pm sources was compared. The devices with ^{147}Pm achieved superior results: 59 nA Isc, 1.4 V Voc, and 49.4 nW Pmax, representing the best Isc and Pmax values ever reported for a single GaN conversion unit. The 240-hour continuous irradiation test results demonstrated the reliability of the GaN devices under both ^{63}Ni and ^{147}Pm. Appropriate i-GaN thickness can improve power output, though performance enhancement of GaN betavoltaic cells ultimately depends on advances in GaN material growth technology, device fabrication, and structural design.

References

[1] Wacharasindhu T, Kwon J W, Meier D E, et al. Appl Phys Lett, 2009, 95: 014103.
[2] Wang G, Hu R, Wei H, et al. Appl Radiat Isot, 2010, 68: 2214–2218.
[3] Sciuto A, D'Arrigo G, Roccaforte F, et al. IEEE Trans Elec Dev, 2011, 58: 593–599.
[4] Sun W, Kherani N P, Hirschman K D, et al. Adv Mater, 2005, 17: 1230–1233.
[5] Liu B, Chen K P, Kherani N P, et al. Appl Phys Lett, 2009, 95: 014103.
[6] Cress C D, Landi B J, Wilt D M, et al. J Appl Phys, 2006, 100: 124502.
[7] Liu Y, Hu R, Yang Y, et al. Appl Radiat Isot, 2012, 70: 438–441.
[8] Chandrashekhar M V S, Thomas C I, Li H, et al. Appl Phys Lett, 2006, 88: 033506.
[9] Bower K E, Barbanel Y A, Shreter Y G, et al. Polymers, Phosphors, and Voltaics for Radioisotope Microbatteries. Boca Raton, FL, CRC Press, 2002: 336.
[10] Honsberg C, Doolittle W A, Allen M, et al. GaN Betavoltaic Energy Converters. Proceedings of the 31st IEEE Photovoltaics Specialist Conference. Orlando Florida, USA, 2005.
[11] Granta J, Batesa R, Cunninghama W, et al. Nucl Instrum Meth A, 2007, 576: 60–65.
[12] Cheng Z, San H, Li Y, et al. The Design Optimization for GaN-based Betavoltaic Microbattery. Proceedings of the 2010 5th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Xiamen, China, 2010.
[13] Lu M, Zhang G, Fu K, et al. Conv Manag, 2011, 52: 1955–1958.
[14] Cheng Z, San H, Chen X, et al. Chin Phys Lett, 2011, 28: 016101.
[15] Lu M, Wang G, Yao C, Adv Mater Res, 2012, 343–344: 56–61.
[16] Li H, Liu Y, Hu R, et al. Appl Radiat Isot, 2012, 70: 2559–2562.
[17] Kumakura K, Makimoto T, Kobayashi N, et al. Appl Phys Lett, 2005, 86: 052105.

Note: Figure translations are in progress. See original paper for figures.