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Demonstration of Pm-147 GaN betavoltaic cells

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

Keywords: Betavoltaic, GaN, Pm-147

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I. INTRODUCTION

The technology advancement in micro-electromechanical systems (MEMSs) requests attended power sources [1–3]. Radioisotope batteries using energy from a decaying radioisotope work without refueling, meeting the requirements of MEMSs due to their high energy density and long life, over traditional micro-batteries. Among this type of batteries, betavoltaic cells shall be advantageous in their nature of small volume, maintenance-free, high energy conversion efficiency, easy integration etc., though researches on betavoltaic cells are still in their infancy, with rather limited power outputs.

Great efforts have been made to improve the electrical capabilities of betavoltaic cells. On materials for energy conversion devices, amorphous silicon, InGaP, SiC, GaN etc. have been tried, in addition to single crystal silicon, the most mature semiconductor [4–8]. And what has been learned is a considerable relationship between the band gap width of the materials and the theoretical energy conversion efficiency (η) of betavoltaic cells [9]. Generally, the η and the band gap width are of positive correlation, so betavoltaic cells of wide band gap materials has better output performances.

Being a semiconductor of wide band gap (3.4 eV), GaN is suitable for energy conversion device of a betavoltaic cell with improved performance [10, 11]. In 2010, Cheng *et al.* [12] fabricated a GaN p-n junction device for energy conversion of a ^{63}Ni betavoltaic cell, with the short circuit current (I_{sc}) of 2.0 nA and the open circuit voltage (V_{oc}) of 0.025 V. Next year, they improved the GaN device and got an I_{sc} of 0.64 nA and V_{oc} of 1.62 V [13]. Also in 2011, Lu *et al.* [14] made a GaN Schottky diode irradiated by ^{63}Ni, getting an I_{sc} of 0.012 nA and V_{oc} of 0.10 V, and in 2012 they fabricated a GaN p-n junction device with I_{sc} of 0.7 nA and V_{oc} of 0.14 V [15]. Among these results of GaN betavoltaic cell research, Cheng *et al.* achived predominantly in the V_{oc}, but not the I_{sc}. The results, however, are far behind those of single crystal silicon's, and far away from the theoretical values, hence there is a long way to go in developing GaN betavoltaic cells of practical performances.

The poor I_{sc} of a GaN betavoltaic cell is possibly due to small device area for collecting enough the emitted particles and small total energy of the driving sources. The β isotopes are good candidates for betavoltaic cell driving sources. The single crystal silicon is a main base material of conversion unit with ^{3}H and ^{63}Ni which emit low energy β particales, as the main driving source isotopes, in consideration of radiation damage to the semiconductor. In this regard, GaN is better than Si [11]. A GaN conversion unit is able to use radioisotopes of higher energy β particales than ^{63}Ni-63, so as to enhance the outputs. ^{147}Pm is an appropriate isotope. Table 1 gives the main properties of the three β isotopes.

In this work, two big area GaN p-n junction devices of different thicknesses of i-GaN were fabricated and irradiated by a ^{147}Pm plate source. Their outputs were compared with that irradiated by a ^{63}Ni plate source.

II. EXPERIMENT AND RESULTS

Two GaN p-n junction devices were designed. Fig. 1 is the main fabrication flow chart. Structural quality of the epilayer was assessed by measuring the full width at half maximum (FWHM) of the symmetric (002) low angle diffraction peaks of the rocking curve (ω-scan), as shown in Fig. 2. As the dislocation density decreases with the XRD FWHM, the narrow FWHM of 112 arcsec indicates an excellent crystalline quality of the GaN epilayer.

Structure parameters of the devices are given in Table 2. The diodes were 1.0 cm in diameter. The metals of Ni (3 nm)/Au (3 nm) were layered on the whole top surface of P-GaN as Ohm contact. The two devices were of the same structure parameters except their thickness of i-GaN, being 1.5 μm for the No.2# device and 1.0 μm for No.1#. The dark I-V characteristics without irradiation were tested by Keithley 2635 (Fig. 3). The devices were irradiated by ϕ10 mm plate sources of ^{63}Ni (2.96×10^{8} Bq) and ^{147}Pm (1.13×10^{9} Bq). The devices with ^{147}Pm source are shown in Fig. 4. The outputs tested by Keithley 2635 are

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TABLE 1. Main properties of three β isotopes

Isotopes	Ave. energy (keV)	Max. energy (keV)	Mass specific activity (TBq/g)	Vol. specific activity (TBq/cm^3)	Specific power (W/g)	Half life (y)
H-3	5.70	18.6	357	1.60	0.326	12.3
Ni-63	17.4	66.9	2.10	18.5	0.00584	100
Pm-147	61.8	224	34.3	247	0.339	2.62

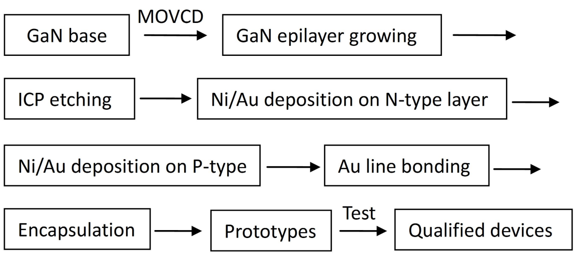

Fig. 1. The main fabricating flow chart.

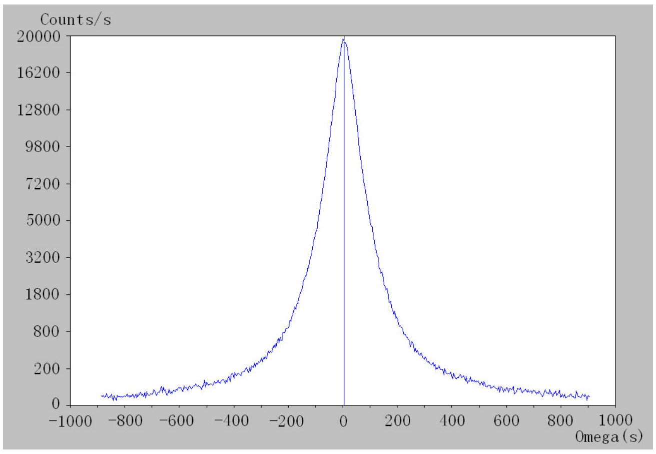

Fig. 2. (Color online) The symmetric (002) low angle diffraction peaks of the rocking curve for the GaN p-i-n epilayer.

TABLE 2. The configuration of GaN diodes

Type of layers	Thickness (μm)	Doping density (cm^{-3})
P-GaN	0.1	$> 1 \times 10^{18}$
i-GaN (N type)	1.0 (1#) 1.5 (2#)	$< 1 \times 10^{16}$
N$^+$-GaN	0.3	$> 2 \times 10^{18}$
u-GaN	> 7.0	–
GaN	–	–

given in Table 3, and scanning I-V curves are shown in Figs. 5 and 6. The outputs were tested after 240 h of continual irradiation on the two diodes by the ^{63}Ni and ^{147}Pm sources.

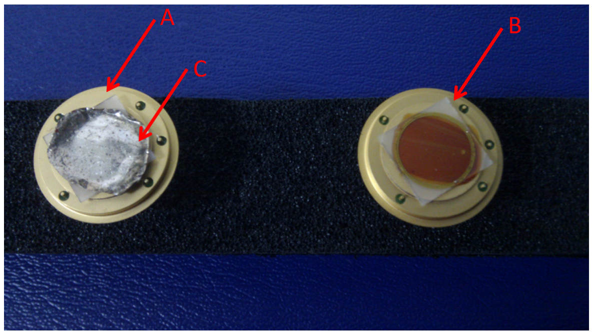

Fig. 4. (Color online) The devices with Pm-147 source.A, is device 1#, B, is device 2#, C, is Pm-147 source.

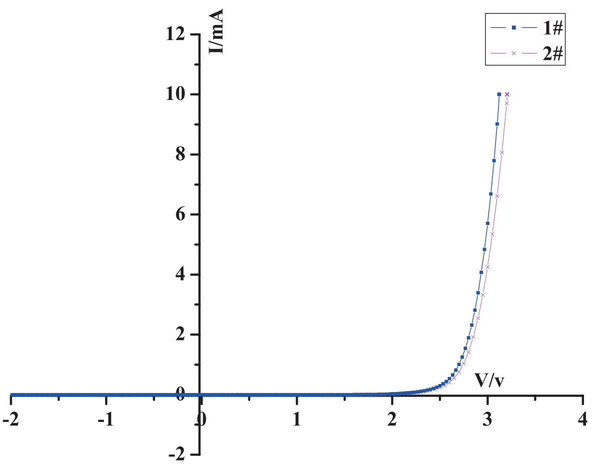

Fig. 3. (Color online) Dark characteristics of devices 1# and 2#.

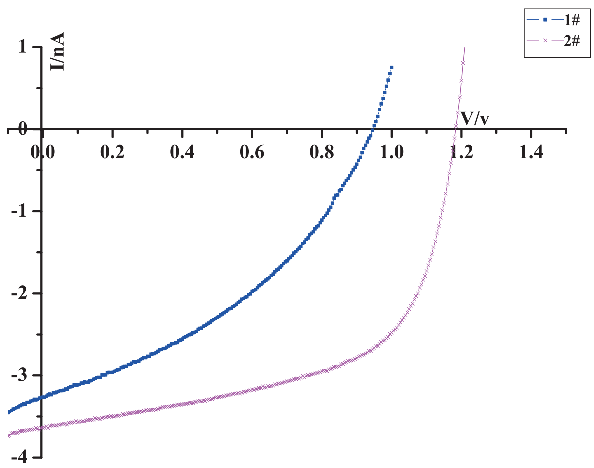

Fig. 5. (Color online) I-V curves of device 1# and 2# irradiated by Ni-63.

TABLE 3. The results of electrical performance

Device /No.[a]		^{147}Pm				^{63}Ni			
		I_{sc1} (nA)	V_{oc1} (V)	P_{max1} (nw)	η_1 (%)	I_{sc2} (nA)	V_{oc2} (V)	P_{max2} (nw)	η_2 (%)
1#	Before irradiation	51.5	1.32	38.2	0.341	3.28	0.940	1.19	0.144
	After irradiation	51.1	1.31	38.1	0.340	3.27	0.940	1.19	0.144
2#	Before irradiation	59.2	1.43	49.4	0.441	3.70	1.190	2.54	0.308
	After irradiation	59.0	1.43	49.4	0.441	3.69	1.190	2.54	0.308

[a] I: Before continual irradiation; II: After continual irradiation

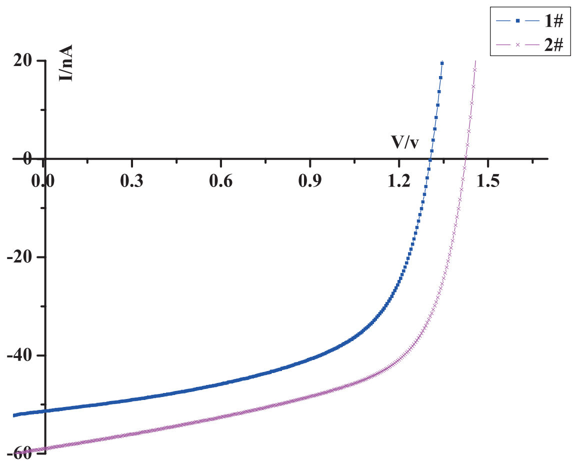

Fig. 6. (Color online) I-V curve of device 1# and 2# irradiated by ^{147}Pm.

III. DISCUSSION

From the dark characteristics of devices in Fig. 3, one sees that the two GaN devices are of good p-n junction performances. The currents of device 1# at -10 mV and -1.0 V are 7.3×10^{-10} A and 4.0×10^{-9} A, respectively, while the currents of device 2# at -10 mV and -1.0 V are 1.9×10^{-11} A and 1.7×10^{-10} A, respectively. The diode turn-on voltages are higher than 2.0 V. The low leakage currents and high turn-on voltages are typical for wide band gap semiconductor p-n diodes.

The results irradiation show that the ^{147}Pm-irradiated diodes out-performed the ^{63}Ni-irradiated, with an I_{sc} of 59 nA, V_{oc} of 1.4 V and P_{max} of 49.4 nw. These are the best results ever reported in I_{sc} and P_{max} with a single GaN conversion unit. And P_{max} is just the parameter to total electrical capability.

These may due to the following three reasons:

(1) The V_{oc} of the GaN devices is higher than traditional single crystal Si devices. This is because that the build-in potentials of the two GaN devices are 3.26 V, rather than less than 1.0 V for normal Si devices.

(2) The power density of ^{147}Pm is the highest of all the three β isotopes commonly used in betavoltaic cells as shown in Table 1. Although the mass specific activity of ^{3}H is higher than that of ^{147}Pm, the volume specific activity of ^{147}Pm is higher than that of ^{3}H in its gas phase. A ^{147}Pm source has more quantities of radioactivity in the same area than ^{3}H and ^{63}Ni, hence the higher β particle-emitting power.

(3) Big diode area is in favor of the β particle-collection and the big source area in favor of the radioactivity load. Also, the metal electrodes covering the whole top surface have better collection efficiency of electric charges due to short diffuse length in GaN.

The test results after continual irradiation for 240 h continual irradiation differed little from the results before the continual irradiation, indicating a stability of at least 240 h with the two GaN devices irradiated by ^{63}Ni and ^{147}Pm.

Irradiated by ^{63}Ni and ^{147}Pm, the No.2 device is better in outputs than No.1 device. They differ from each other only in the thickness of i-GaN. The mean ranges of β particles penetrating in GaN are 2.1 μm and 20 μm calculated respectively with β energy spectra of ^{63}Ni and ^{147}Pm. Both are greater than the actual thickness (1.4 μm and 1.9 μm) of the two GaN diodes (P-GaN + i-GaN + N^{+}-GaN). When the thickness of GaN materials is thinner than the β particles penetrating range, a thicker GaN can deposit more energy of β particles, hence the increased generation of electron-holes, and increased I_{sc} and P_{max}.

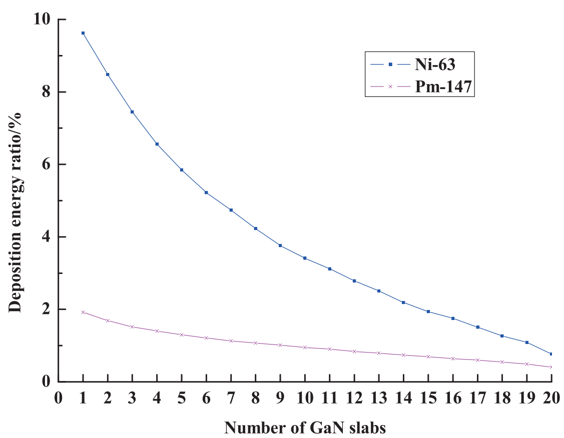

Fig. 7. (Color online) The deposition energy ratio of β particles of ^{63}Ni and ^{147}Pm in GaN.

A model with GaN of 2.0 μm divided into 20 equal step-lengths was established [16]. The deposition energy ratio in this model was calculated with β particles of ^{63}Ni and ^{147}Pm

(Fig. 7). The deposition energy ratio decreases step by step, with the biggest ration in the first step. The increase in i-GaN thickness enhances the performance of betavoltaic, but the performance enhancement is not proportional to thickness increase.

At present, there are defects in growing the GaN materials. The radiation-induced electron-holes are minorities in semiconductor and they must diffuse into built-in field to separate and generate current. The defects in GaN materials lead to short life and diffuse length ($<0.3\,\mu$m) of minorities [17]. It makes many electron-holes recombine before they diffuse into built-in field being no longer of use for current generation. So the GaN diodes must be fabricated at an appropriate thickness.

IV. CONCLUSION

In conclusion, two GaN devices were fabricated and their performances with ^{63}Ni and ^{147}Pm were compared. The devices with ^{147}Pm had better results: $59\,$nA in $I_{\rm sc}$, $1.4\,$V in $V_{\rm oc}$, and $49.4\,$nw in $P_{\rm max}$, which are the best results ever reported in $I_{\rm sc}$ and $P_{\rm max}$ with single GaN conversion unit. The test results after $240\,$h continual irradiation by ^{63}Ni and ^{147}Pm showed the GaN devices were reliable. The appropriate thickness of i-GaN could improve the power outputs. The performance enhancement of GaN betavoltaic cells shall base on technological advancment of GaN materials growth, device fabrication and configuration design.

[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**: 2214–2217.

[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**: 233112.

[6] Cress C D, Landi B J, Wilt D M, *et al*. J Appl Phys, 2006, **100**: 114519.

[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**: 078401.

[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**: 2559–2563.

[17] Kumakura K, Makimoto T, Kobayashi N, *et al*. Appl Phys Lett, 2005, **86**: 052105.