SCIENCE CHINA
Technological Sciences

March 2012 Vol.55 No.3: 659–664
doi: 10.1007/s11431-011-4739-8

Optimization design of GaN betavoltaic microbattery

TANG XiaoBin, LIU YunPeng, DING Ding & CHEN Da*

Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Received October 30, 2011; accepted December 26, 2011; published online January 20, 2012

Betavoltaic radioisotope microbatteries have gradually become the research direction of micro-power sources because of their several advantages, including small scale, stable output performance, long service life, high energy density, strong anti-jamming capability, and so on. Based on the theory of semiconductor physics, the current paper presented a design scheme of isotope microbattery with wide-gap semiconductor material GaN and isotope ^{147}Pm. In consideration of the isotope's self-absorption effect, the current paper studied and analyzed the optimization thickness of semiconductor and isotope source, junction depth, depletion region thickness, doping concentration, and the generation and collection of electron hole pairs with simulation of transport process of beta particles in semiconductor material using Monte Carlo simulation program MCNP. In the proposed design scheme, for a single decay, an average energy of 28.2 keV was deposited in the GaN, and the short circuit current density, open circuit voltage, and efficiency of a single device were 1.636 μA/cm^2, 3.16 V, and 13.4%, respectively.

GaN, semiconductor, isotope battery

Citation: Tang X B, Liu Y P, Ding D, et al. Optimization design of GaN betavoltaic microbattery. Sci China Tech Sci, 2012, 55: 659–664, doi: 10.1007/s11431-011-4739-8

With the development of micro-electromechanical system (MEMS), micro power sources have gradually become a bottleneck in MEMS applications. Several reported kinds of miniaturized power source, such as solar cells and micro fuel cells, cannot satisfy the demands of MEMS devices for energy because of their restrictions in terms of volume, service lifetime, ability to adapt to the environment, and other aspects. Betavoltaic microbattery, with easy integration, stable output performance, long service lifetime, high energy density, strong anti-jamming, and so on, has become one of the most important research directions of the micro power source and is expected to become the best choice of MEMS.

Previous studies indicated that the theoretical value of energy conversion for betavoltaic batteries based on a p-n junction device can reach 40% [1]. This value can reach more than 20% for a GaN energy converter if the self-absorption of emitted particles is not considered [2]. Hang Guo Research Group of Xiamen University developed ^{147}Pm-GaN batteries with a 0.767% conversion efficiency [3]. Min Lu Research Group of Suzhou Institute of Nano-Tech and Nano-bionics developed ^{63}Ni-GaN batteries with a 1.6% conversion efficiency [4]. LU XuYuan Research Group of Pen-Tung Sah Lab of Xiamen University developed ^{63}Ni-GaN batteries with a 2.7% conversion efficiency [5]. Bower et al. [1] developed ^{3}H-GaN batteries with 3.24% to 7.65% conversion efficiencies. Big differences were observed among these researches with the ideal value. These differences can be attributed to the optimization for parameters of the energy conversion unit, aside from the limit of semiconductor device fabrication technology and loading methods of radioisotope sources.

In the current paper, a kind of micro betavoltaic battery based on the wide-band semiconductor GaN and the radioisotope ^{147}Pm is designed. The optimization of physical parameters for the battery is also discussed. Parameters, such

---

*Corresponding author (email: dachen@nuaa.edu.cn) as micro sensor, micro-mechanical device, and optical device, among others, are important in the development and application of micro-power sources required by MEMS.

1 Selection of semiconductor materials and isotope sources

1.1 Selection of semiconductor materials

Semiconductors with a wide band gap can help improve the conversion efficiency and output performance of batteries. Semiconductors, such as Si, GaAs, SiC, GaN, and so on, are mainly used for betavoltaic batteries. The theoretical energy conversion efficiency of the most widely used semiconductor Si, with a band gap of 1.12 eV, is only 14%. The radiation hardness of Si is also not desirable at 200 keV to 250 keV threshold energy because high energetic particles cause unrecoverable structural damage. However, the generation-III semiconductor GaN, with 440 keV threshold energy of radiation hardness [6] and 3.4 eV band gap, can satisfy the requirement of long-term application in extreme environments, such as high temperature and strong radiation, among others. In addition, it can also gain a higher open-circuit voltage and energy conversion efficiency than Si betavoltaic batteries. It has great application potential in the field of betavoltaic batteries because of its wide band gap and low leakage current of the p-n junction device. Therefore, the semiconductor GaN is selected as the subject in the current paper.

1.2 Selection of isotope source

Beta isotope source is commonly used in betavoltaic batteries because α isotope source with high-energy emissions may cause serious radiation damage to the p-n junction device. In addition, the penetrability of the γ source ray is strong, and a protective coating is required; hence, realizing miniaturization is not easy. The common beta isotope sources are shown in Table 1. The transduction device will be damaged by radiation because the particle energy decayed and released by ^{90}Sr and ^{137}Cs is excessively high. However, the particle energy decayed and released by ^{3}H and ^{63}Ni is low, which affects the output performance of a battery. The half-life of ^{35}S is only 87.44 d; thus, the requirement of MEMS for micro-power sources could not be achieved. The partial energy decayed and released by ^{147}Pm is moderate, and the highest is 225 keV. Therefore, the GaN material is subjected to small radiation damages. Moreover, the half-life of ^{147}Pm is 2.6 years; hence, the requirements of long-life micro-power sources could be satisfied. Therefore, ^{147}Pm is selected as the energy source of energy conversion unit in the current paper.

Table 1 Characteristics of conventional beta isotope sources

Radioisotope	Half-life time	Beta maximum energy (keV)	Average energy (keV)
^{3}H	12.3 (a)	18.6	5.7
^{35}S	87.44 (d)	167.5	48.8
^{63}Ni	100.2 (a)	66.7	17.4
^{147}Pm	2.6 (a)	225	62
^{90}Sr	28.8 (a)	546	195.8
^{137}Cs	30.1 (a)	1176	188.4

2 Optimization design of isotope battery

The analog computation of beta particle in GaN material during transport is conducted using the radioactive particle transport program MCNP based on the Monte Carlo method. Factors affecting the battery performance are analyzed and discussed to provide theoretical support and basis for furnishing an optimal design scheme.

The Monte Carlo program MCNP, a general Monte Carlo n-particle transport code developed by the American Los Alamos National Laboratory, can simulate the transport process [7] of neutrons, photons, and electrons in almost all energy ranges. A comparison between the ^{147}Pm beta energy spectrum data calculated via MCNP and the data obtained in the current experiment is shown in Figure 1 [8]. As shown in Figure 1, the computation value is nearly identical to the measured value; thus, the accuracy in the follow-up calculation is ensured.

Nowadays, betavoltaic batteries using generation-III semiconductor materials usually have a single planar energy conversion cell, of which the β utilization is less than 50%. However, in the current study, the β utilization could be increased to nearly 100%, with a stacked construction shown in Figure 2.

2.1 Optimization design of isotope source and semiconductor material thickness

2.1.1 *The self-absorption effect in isotope source*

Higher isotope source activity results in better output per-

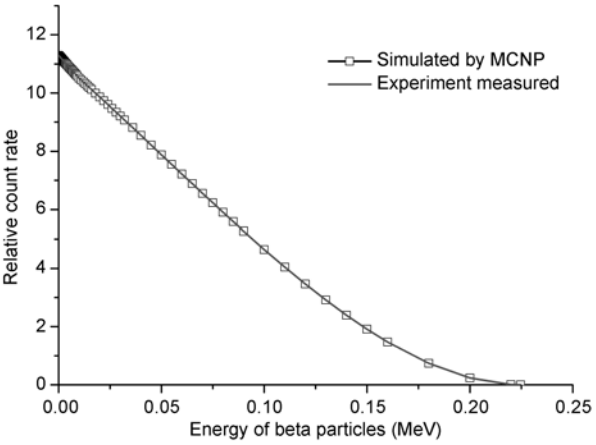

Figure 1 Simulated and measured beta spectra of ^{147}Pm.

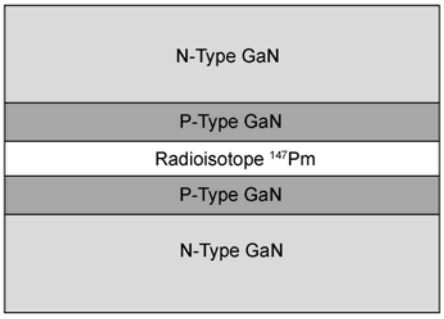

Figure 2 Structure of the GaN betavoltaic battery.

formance of the isotope battery. However, the surface activity of the source surface will not increase infinitely because of the scattering effect of peripheral materials and self-absorption effect in the isotope source. Previous studies did not discuss this factor in their theoretical research on isotope battery. The relationship between the mass thickness of ^{147}Pm source and surface activity of the source surface is calculated in the current study. As shown in Figure 3, the surface activity of the source surface increases with increasing mass thickness of source. However, the surface activity remains constant after a certain value.

2.1.2 *Beta particle stopping range*

The maximum and average energy of beta particles emitted by ^{147}Pm decay is 224.7 and 62 keV, respectively. By calculating the energy loss of mono energetic electrons in the unit length along the GaN depth direction using the MCNP program, the stopping ranges of the beta particles with energies of 30, 62, 100, 150, and 224.7 keV are 4, 11.8, 26.5, 53, and 100 μm, respectively (Figure 4). Simultaneously, according to the beta particle stopping range correction empirical equation of Katz and Penfld [9], the stopping ranges of the electrons of 62 and 224.7 keV in GaN are 9.5 and 81.9 μm, respectively. This result is identical to the calculation results of MCNP. However, when only the stopping range of beta particles is considered, the thickness of semiconductor material GaN should be greater than the stopping range of the particles, namely 100 μm.

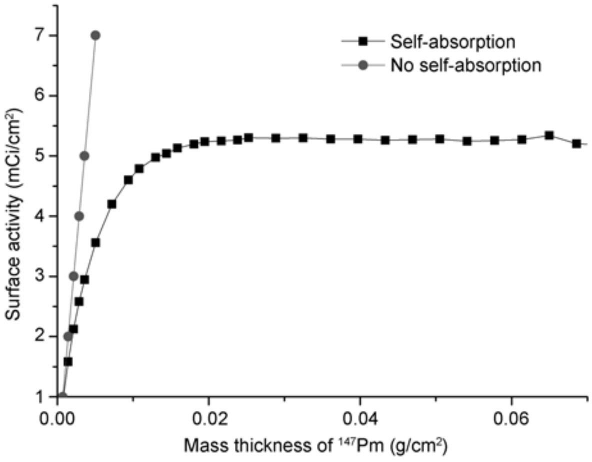

Figure 3 Self-absorption curves of ^{147}Pm.

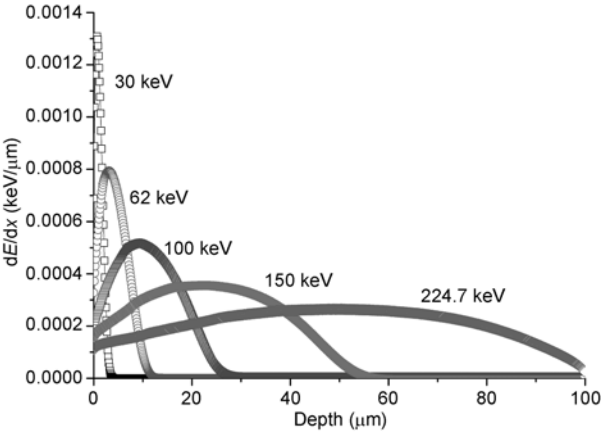

Figure 4 Energy losses per unit length of several single energy beta particles along GaN depth direction.

The energy loss of ^{147}Pm source beta particle in unit length along the GaN depth direction is also calculated in the current paper (Figure 5). When the thickness of GaN is greater than 40 μm, the energy loss will nearly become zero with continuously increasing thickness. That is, the output performance of battery will be affected, which indicates that the selected thickness of GaN should not be greater than 40 μm.

By changing the thickness of radioactive ^{147}Pm and GaN conversion units, the relationship between both conversion units and available power of isotope battery is calculated, which is shown in Figure 6. When the thickness of ^{147}Pm is 25 μm, the available power of battery will reach its maximum. However, the available power will not increase further with continuously increasing thickness. This result can be attributed to the self-absorption of the isotope source and the scattering effect of the peripheral semiconductor. When the thickness of GaN is 40 μm, the available power of the

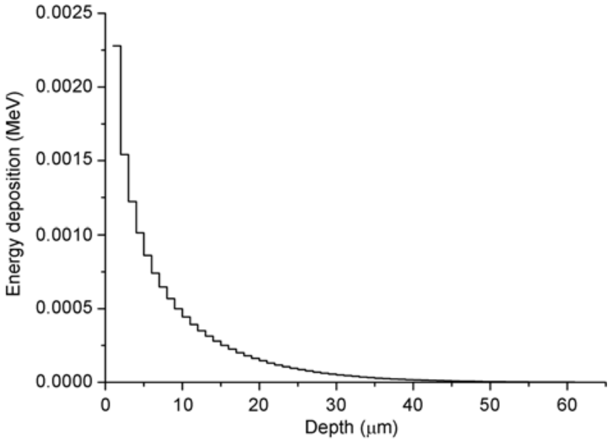

Figure 5 Energy loss per unit length of beta particles emitted from ^{147}Pm along the GaN depth direction.

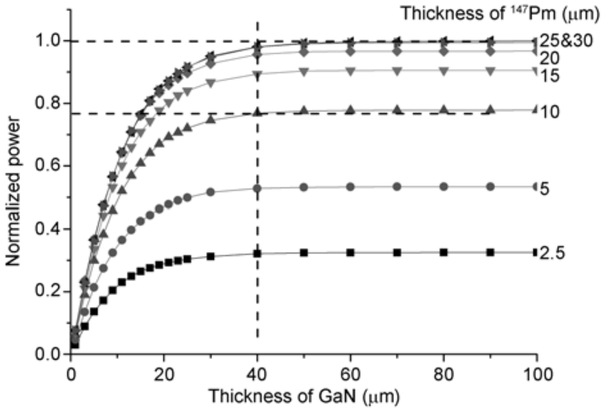

Figure 6 Available power as a function of the thickness of the ^{147}Pm and GaN layers.

battery will reach its maximum. If the thickness is increased continuously, the available power nearly remains unchanged. In addition, when the thickness of ^{147}Pm is decreased to 10 μm (a 60% decrease), the available power of battery will only be decreased by approximately 20%.

Based on the above analysis, the parameters of conversion unit thickness are determined. The selected thicknesses of ^{147}Pm and GaN are 10 and 40 μm, respectively.

2.2 Optimization design of doping concentration

The doping concentration of the p-type and n-type regions decides the depletion region width and the intensity of built-in field. To stimulate more electron hole pairs in the depletion region, the energy of external beta particles should be released in this region as far as possible. The designed depletion region width should match with the penetration depth of beta particle to realize the maximization of energy utilization. For example, the depletion region in a p-n junction based on n-type substrate is mainly distributed in the n-type region. If the junction depth is too deep, the energy loss of many beta particles will be generated before entry into the depletion region; otherwise, the formation of the abrupt junction will be affected. A 0.2 μm junction depth is selected, the doping concentration N_A in the p-type region is 3×10^{19}/cm^3, and the corresponding minority carrier diffusion length is 0.22 μm [10], which is greater than the junction depth and meets the design requirement

The built-in potential of the p-n junction can be expressed as follows:

$$V_{\mathrm{bi}}=\frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right), \tag{1}$$

where k indicates the Boltzmann's constant, T indicates the absolute temperature and q indicates the quantity of electric charge (C) by electron, N_A indicates the doping concentration (cm^3) of the acceptor p-type region, N_D indicates the doping concentration of the donor n-type region, and n_i indicates the intrinsic carrier concentration of semiconductor. For GaN, n_i is 4.6×10^{-11}/cm^3.

The width of the depletion region is expressed as

$$W=\sqrt{\frac{2\varepsilon_s\varepsilon_0}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)V_{\mathrm{bi}}}, \tag{2}$$

where ε_s is the dielectric constant of GaN, and ε_0 is the vacuum dielectric constant.

From eqs. (1) and (2), the relationships among the width of the depletion region, built-in potential, and n-type substrate doping concentration are plotted in Figure 7. As shown in Figure 7, the width W of the depletion region is inversely proportional to the substrate doping concentration, whereas the built-in potential increases with increasing doping concentration. Improving the output performance of isotope battery is necessary to increase the collection ratio of high electron hole pair. Within the stopping range of beta particle, the width W of the depletion region should be large as far as possible. As aforementioned, the optimal thickness of GaN is 40 μm, and the stopping range of the beta particle of ^{147}Pm maximum energy is 81.9 μm. Therefore, the width W of the depletion region should be 40 μm, and the corresponding substrate doping concentration is 2.3×10^{12}/cm^3. The built-in potential V_{bi} is the theoretical extreme value of the open-circuit voltage V_{oc}. The open-circuit voltage will also increase if the built-in potential is enhanced. The built-in potential will be increased with increasing substrate doping concentration. However, if the substrate doping concentration is very large, the built-in potential will not increase but decrease within heavy doping effects. However, no great changes are observed in the numerical value of the built-in potential (Figure 7). That is, the built-in potential decreases from 3.6 to 3.1 V when the doping concentration is in the range of 1×10^{20}/cm^3 to 1×10^{12}/cm^3. Therefore, a low substrate doping concentration is rational to select.

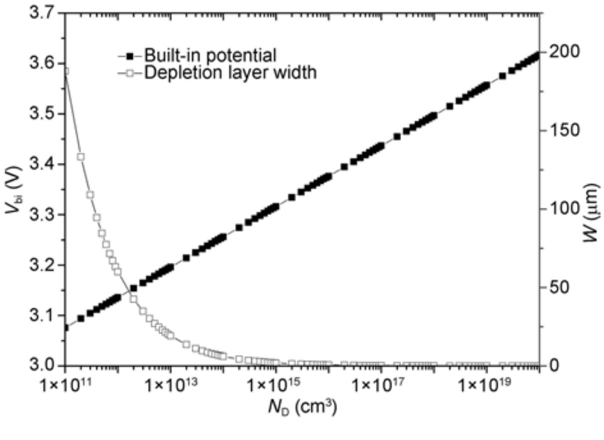

Figure 7 Relation curves of the depletion layer width, built-in potential, and doping concentration of n-type substrate.

3 Analysis on the electrical property of isotope battery

3.1 Computational physical structure model

As shown in Figure 8, the computational model of the electrical property of the isotope micro battery-sandwich structure is established through MCNP. The thicknesses of the upper layer of GaN, radioactive isotope ^{147}Pm, and lower layer of GaN are 40, 10, and 40, respectively. The cross sectional area of the isotope battery is 0.1 cm × 0.1 cm. The computation step length of each layer of GaN is 0.1 μm. Through calculation, an average energy of 28.2 keV is deposited in GaN for a single decay.

3.2 Calculation and analysis of electrical properties

3.2.1 Short-circuit current density

The collection ratio equation of electron hole pairs can be represented as follows[2]:

$$CE(n) = 1 - \tanh(x_n/L), \tag{3}$$

where $CE(n)$ is the collection ratio of the electron hole pairs of the nth layer of semiconductor in the computation model, L is the minority carrier diffusion length (μm); x_n is the distance between the position of the nth layer of GaN and the depletion region (μm). If the collection ratio of the electron hole pairs in the depletion region is 100%, then the expression of the short-circuit current deducted theoretically is

$$I_{sc} = \frac{Aq}{E_{\text{ehp}}} \sum_{n=1}^{n} CE(n) \times E(n), \tag{4}$$

where A is the activity of radioactive isotope (Bq/s), E_{ehp} is the average energy needed to generate an electron hole pair (MeV), as for GaN, it is 10.3 eV [11], and $E(n)$ is the energy of the beta particle deposited in the nth layer of GaN (MeV).

If the activity of ^{147}Pm is 1 mCi, then the short-circuit currents of the upper and lower layer's energy conversion cells are 8.19 and 8.17 nA, respectively. When the overlap mode is adopted to connect both, the total short-circuit current is 16.36 nA. That is, the current density is 1.636 μA/cm^2.

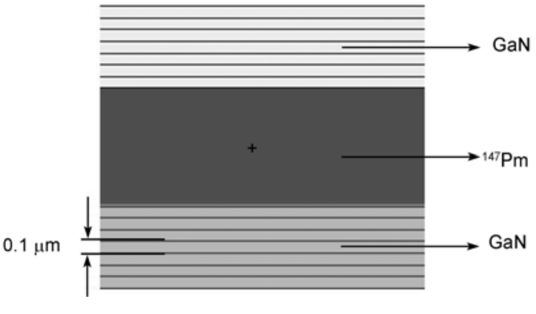

Figure 8 Calculation model of GaN betavoltaic battery.

3.2.2 Open-circuit voltage

Built-in potential is the theoretical extreme value of the open-circuit voltage. The ideal open-circuit voltage can be assumed to be equal to the built-in potential. That is, the ideal open-circuit voltage can be represented by

$$V_{\text{oc}} = V_{\text{bi}} = \frac{kT}{q}\left(\ln\frac{N_A N_D}{n_i^2}\right). \tag{5}$$

3.2.3 Filling factor and output power

Filling factor (*FF*), one of the important parameters for the evaluation of the output performance of a battery, is the specific value of the maximum output power and the product of short-circuit current and open-circuit voltage. *FF* can be expressed as follows:

$$FF = \frac{P_m}{V_{\text{oc}} I_{\text{sc}}} = \frac{V_m I_m}{V_{\text{oc}} I_{\text{sc}}}. \tag{6}$$

According to the empirical equation, the filling factor also could be given by

$$FF = \frac{v_{\text{oc}} - \ln(v_{\text{oc}} + 0.72)}{v_{\text{oc}} + 1}, \tag{7}$$

where v_{oc} is the normalized open-circuit voltage, namely $V_{\text{oc}} / (nkT/q)$. The calculated *FF* is 95.3%.

Then the maximum output power is

$$P_m = FF \times V_{\text{oc}} \times I_{\text{sc}}. \tag{8}$$

The calculated result is 49.27 nW.

3.2.4 Conversion efficiency

The energy conversion efficiency, the standard for the quality of energy conversion cell of the isotope battery, is given by

$$\eta = P_m / AqE_{\text{av}}, \tag{9}$$

where E_{av} is the average energy of the beta particles caused by ^{147}Pm decay, namely 62 keV. The calculated energy conversion efficiency η is 13.4%. When the self-absorption effect of isotope source is not considered, the energy conversion efficiency can reach 28%. The self-absorption effect of isotope source is an intrinsic phenomenon. Therefore, the actual energy conversion efficiency cannot reach 28%, which should be further explained.

4 Conclusion

A design scheme for the isotope microbattery with a wide band gap semiconductor GaN and radioactive isotope ^{147}Pm was proposed in the present study based on the semiconductor physical theory. In view of the self-absorption effect of isotope source, the current paper studied and analyzed the optimization thicknesses of semiconductor and isotope source, junction depth, thickness of depletion region, doping concentration, and the generation and collection of electron hole pairs by the Monte Carlo simulation program MCNP that can simulate the transport process of beta particles in a semiconductor material. In the proposed design scheme, for a single decay, an average energy of 28.2 keV was deposited in the GaN, and the short circuit current density, open circuit voltage, and efficiency of a single device were 1.636 μA/cm^2, 3.16 V, and 13.4%, respectively. The results of the current paper can provide significant technical parameters for MEMS, such as micro sensors, micro-mechanical devices, and optical devices, which require micro power source.

This work was supported by the China Postdoctoral Science Foundation Funded Project (Grant No. 20100481140) and the Nanjing University of Aeronautics and Astronautics Basic Research Funded Project (Grant No. Y1065-063).

1 Bower K E, Barbanel Y A, Shreter Y G, et al. Polymeres Phosphors and Voltaics for Radioisotope Microbatteries. Florida: CRC Press, 2002. 3–10

2 Honsberg C, Doolittle W A, Allen M, et al. GaN betavoltaic energy converters. Proceedings of the 31st IEEE Photovoltaics Specialist Conference, USA Orbando Florida, 2005. 102–105

3 Guo H, Yang H, Zhang Y. Betavoltaic micro batteries using porous silicon. Proceedings of the 20th IEEE Micro Electro Mechanical Systems, Japan Kobe, 2007. 867–870

4 Lu M, Wang G, Yao C S. Gallium nitride for nuclear batteries. Adv Mater Res, 2011, 343-344: 56–61

5 Cheng Z J, San H S, Feng Z H, et al. High open-circuit voltage betavoltaic cell based on GaN pin homojunction. Electron Lett, 2011, 47(12): 720–722

6 Ionascut-Nedelcescu A, Carlone C, Houdayer A, et al. Radiation hardness of gallium nitride. IEEE T Null Sci, 2002, 49(6): 2733–2738

7 X-5 Monte Carlo Team. MCNP—A general monte carlo n-particle transport code, Version 5. LA-CP-03-0245. 2003

8 Cross W G, Ing H, Freedman N. A short atlas of beta-ray spectra. Phys Med Biol, 1983, 28(11): 1251–1260

9 Liu Q C, Jia B S, Wan J. Overview of Nuclear Science. Harbin: Harbin Industrial University Press, 1988. 32–33

10 Kumakura K, Makimoto T, Kobayashi N, et al. Minority carrier diffusion length in GaN: Dislocation density and doping concentration dependence. Appl Phys Lett, 2005, 86(5): 052105

11 Klein C A. Bandgap dependence and related features of radiation ionization energies in semiconductors. J Appl Phys, 1968, 39(4): 2029–2038