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Gallium Nitride for nuclear batteries

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Abstract. Gallium Nitride (GaN) PIN betavoltaic nuclear batteries (GB) are demonstrated in our work for the first time. GaN films are grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD), and then GaN PIN diodes are fabricated by normal micro-fabrication process. Nickel with mass number of 63 (63Ni), which emits β particles, is loaded on the GaN PIN diodes to achieve GB. Current-Voltage (I-V) characteristics shows that the GaN PIN diodes have leakage current of 18 pA at -10V due to consummate fabrication processes, and the open circuit voltage of the GB is estimated about 0.14 V and the short circuit current density is 89.2nAcm^{-2} . The relative limited performance of the GB is due to thick dead layer and strong backscattering of β particles, Which lead to less energy deposition in GB. However, the conversion efficiency of 1.6% and charge collection efficiency (CCE) of 100% for the GB have been obtained. Therefore, the output power of the GB are expected to greatly increase with thin dead layer and structural surface weakening the backscattering.

Introduction

As a third generation semiconductor, GaN has been widely applied in the fields of photoelectron devices, such as light emission diodes (LED), laser diodes (LD) and ultraviolet (UV) detectors, and electronic devices, such as high electron mobility transistors (HEMT) and heterojunction bipolar transistors (HBT) [1-3]. It has been just several years to research GaN detectors for nuclear radiations, eg. X-ray, α particles and β particles, etc.[4-6]. For β particles detectors, it is reasonable to employ them as betavoltaic nuclear batteries. The advantage of the micro- electronic mechanical system(MEMS) is its micro scale, but the relative large scale MEMS chemical battery, which cannot be made into micro scale because of its low energy density, seriously hinder the application of MEMS. Many patient with pacemaker have died from the unexpected energy exhaustion of chemical pacemaker power, which has short lifetime. In space study, when space aerocraft faces the sun, solar power cells supply power for scientific apparatuses, and when the back of space aerocraft faces the sun, there should be addional batteries with high energy density , low mass and long lifetime, supplying power for scientific apparatuses. Batteries applied in remote site, such as polar region, deep seas and high mountains, should have the property of long lifetime and high relibility. Due to the high energy density, long lifetime(equal to half life of loaded isotope) and easily fabricating in small scale, nuclear batteries have been becoming the promising micro-power for MEMS power, medical application such as pacemaker power, and application in execrable ambient, such as space and polar region [7,8]. The silicon(Si) betavoltaic nuclear batteries were first patented by Rappaport at Radio Corporation of America in 1956, and several researchers have investigated betavoltaics with the materials of Si, gallium arsenic(GaAs), or gallium phosphor(GaP), in the years since. Comparing to narrow bandgap semiconductors (Si, GaAs, GaP), there are many more advantages of betavoltaic batteries with wide bandgap semiconductors (silicon carbon (SiC), GaN, zinc oxide (ZnO), diamond (C)), for example, high output voltage, high conversion efficiency and hard radiation resistant. SiC betavoltaiv nuclear batteries were investigated by some research groups, and some experimental resuts have been reported [9,10]. However, there have been few reports about GaN-based nuclear batteries besides some theoretic articles [11-14]. In this study, the first GB was demonstrated and its properties were examined.

Experiment

The GaN films using in our work were grown on Al_2O_3 (0001) substrates by MOCVD(Thmas swan corp., 6×2inch per batch).They were muli-layer films of p-GaN(200 nm)/ undoped GaN(8 μm)/ n-GaN(4 μm). The fabrication processes of the GaN PIN diodes are shown as below: depositing silicon oxide (SiO_2) film on GaN by plasma enhancement chemical vapor deposition(PECVD) (UK, Oxford plasmalab system 100) firstly, following patterning SiO_2 by lithography (Suss corp. in Germany, MA6-BA6) and reactive ion etching (RIE) (Tegal 903e), GaN etching by induced couple plasma(ICP) (UK, Oxford plasmalab system 100 RIE-ICP), layered metal of Titanium (Ti) (20 nm) /Aluminum (Al) (20 nm) /Ti (20 nm) / gold (Au) (300 nm) deposition for ohmic contact on n-GaN by sputter (ORION-8-UHV), layered metal of Nickel (Ni) (25 nm) /Au (25 nm) for ohmic contact p-GaN by electron beam evaporator(E-beam) (ULVAC, ei-5z), chip scribing by laser scriber (Newwave, Accuscribe Titan), and then chip adhereing to chip holder using Ag glue, finally Au line bonding for electrical testing by bonder (West bonder 747677E). ^{63}Ni with an apparent activity of 30μCimm^{-2} was employed as β particles emitter, whose average energy was about 17.4KeV. So the assumed lifetime of the GB is about 100 years. The ^{63}Ni plate was placed 1mm away from the schottky contact of the GaN diodes in order not to make short circuit. The I-V characteristics of the GB was measured by Keithley electrometer (keithley 6487), and the absorption property dependence of β particles energy in GaN films was calculated by the stopping and range of ions in matter (SRIM).

Results and discussion

Fig. 1 shows the investigated battery structure, which is similar to that of GaN PIN UV detectors [15].The depth between two ohmic contacs is 8.3 μm. The circle ohmic contact on n-GaN is with the inner radius of 550 μm and the outer radius of 700 μm, and the circular ohmic contact on p-GaN is with 500 μm radius. The device was mounted on a PCB die holder to I-V test (shown in Fig.2). We used Au ball bonding for connection to enhance the bonding reliability. There are twelve semilar PIN dioes in the holder, and only six of them have been wire bonded to the pins of PCB. Pin 2 is the common negative electrode of the batteries, which is connected with ohmic contacts on n-GaN, while the other pins connected with ohmic contacts on p-GaN, are positive electrode of the batteries. As shown in Fig.3, leakage current of GaN PIN diodes at room temperature without loading Ni^{63} have been obtained to be 18pA at -10V corresponding to a current density of 2.3 nAcm^{-2}. When the reverse voltage increases, leakage current increases, and reached only 0.16 nA at -20 V, which indicates that diodes are well cooled down and the leakage current is also well controlled due to consummate fabrication processes. The forward biased I-V relationship is exponential, which means the GaN diodes are successfully achieved. Fig.4 shows the change of I-V dependence between loading ^{63}Ni and unloading ^{63}Ni on GaN PIN diodes. The current with ^{63}Ni includes leakage current and ^{63}Ni producing current based on betavoltaic effect (shown in Fig.4a). Thus the net isotope producing current could be deduced from the current with ^{63}Ni and without ^{63}Ni (shown in Fig.4b), which is illustrated in Fig.4c. Both the current with ^{63}Ni and the net isotope producing current increase with the increase of bias voltage. It could be seen from Fig.4c that short circuit current of the battery is 0.7 nA (corresponding to a current density 89.2 n Acm^{-2}), and the open circuit voltage of the GB is estimated about 0.14 V. With and without concerning the influence of dead layers including p-contact layer of 25nm Ni/25nm Au, 200nm p-GaN and 1mm gap air, the relationship between the energy deposition of β particles with 17.4KeV in GB and the effective absorption thickness of GB in air, is shown in Fig.5a and Fig.5b. It could be seen from Fig.5a that the maximum absorption energy of 17.4KeV β particles in GB with 1.5 um or thicker GaN is 6.23 KeV due to the absorption (~1.652KeV) of dead layer and back scattering (~6.94KeV) of dead layer and GaN, and in our work 6.23 KeV has been deposited in GB because the effective absorption thickness in our GB is 8.137 um， which is composed of 8 um depleting layer and 137 nm diffusion layer calculated from the parameters of GaN films as grown, such as the concentration, mobility and lifetime of carriers. The beta to electric conversion efficiency η could be expressed as (supposing fill factor (FF) equal to 100%)

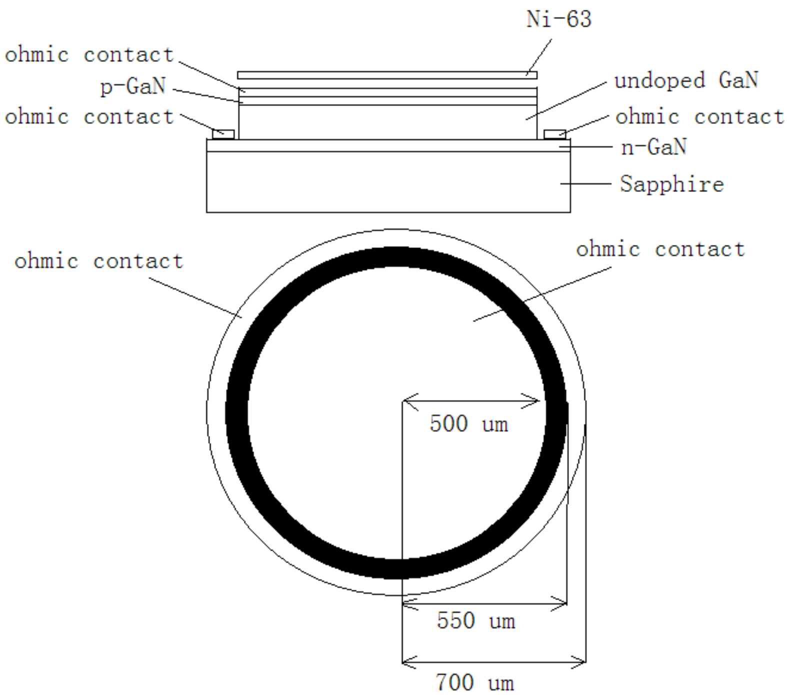

Fig.1. Schematic crossection and topview diagram of the GB.

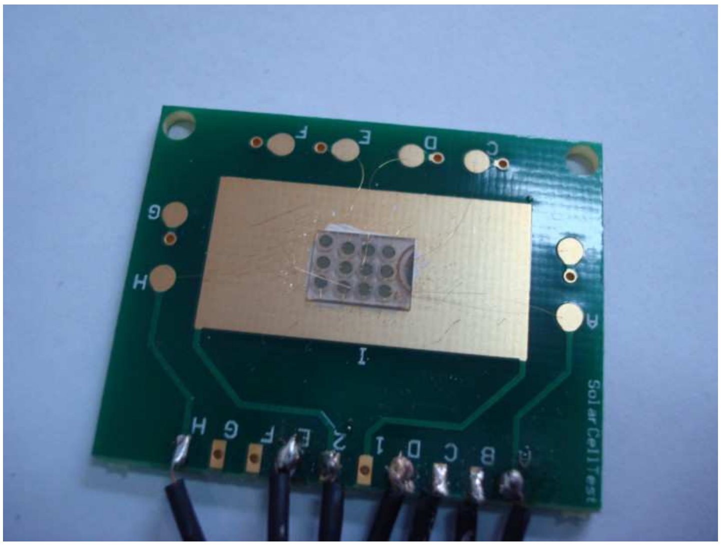

Fig.2. Photograph of the GaN PIN diodes mounted on a PCB die holder.

$$\eta = FF\frac{IV}{5.92CE} \qquad (1)$$

where I,V,C and E is short circuit current (nA), open circuit voltage (V), apparent activity (mCi) and deposited energy (KeV), respectively. From formula (1), the conversion efficiency of 11.3% could be calculated. Compared to the theoretical conversion efficiency about 26% [12], the conversion efficiency of our GB is lower. Therefore, many research works should be done to improve the GB characteristics. In addition, efficiency η could be also expressed as

$$\eta = FF\frac{eVCCE}{\varepsilon} \qquad (2)$$

where e, CCE and ε is electron charge, charge collecting efficiency and mean ionization energy

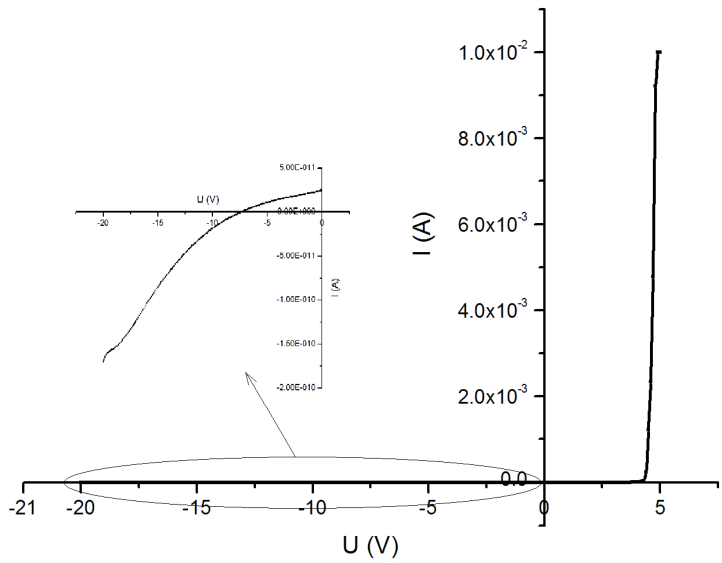

Fig.3. The I-V dependence for the GaN PIN diode unloading ^{63}Ni.

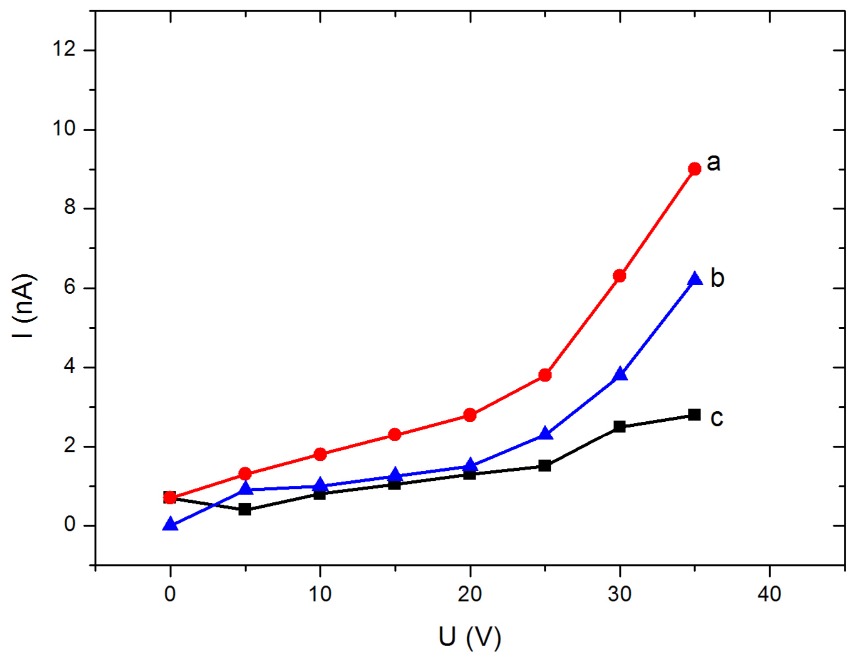

Fig.4. The I-V characteristics for the GaN schottky diodes (a)without ^{63}Ni, (b) with ^{63}Ni. (c) the net ^{63}Ni producing I -V.

(about 8.9eV for GaN), respectively. Thus CCE of our GB is estimated about 100%, and the FF is estimated about 14%. Then apply the FF of 14% in formula (1), the conversion efficiency will adjust to 1.6%. Moreover, when ignoring the influence of dead layer, the absorption energy of 1.3 μm or thicker GaN could reach the maximum of 10.6KeV, which is 70% larger than that of considering the dead layer (shown in Fig.5b). Conclusively, if we decrease the thickness of p-GaN and its contact layer, and employ structural surface of GB to restrain backscattering of β particles, the performance of the GB would be greatly improved.

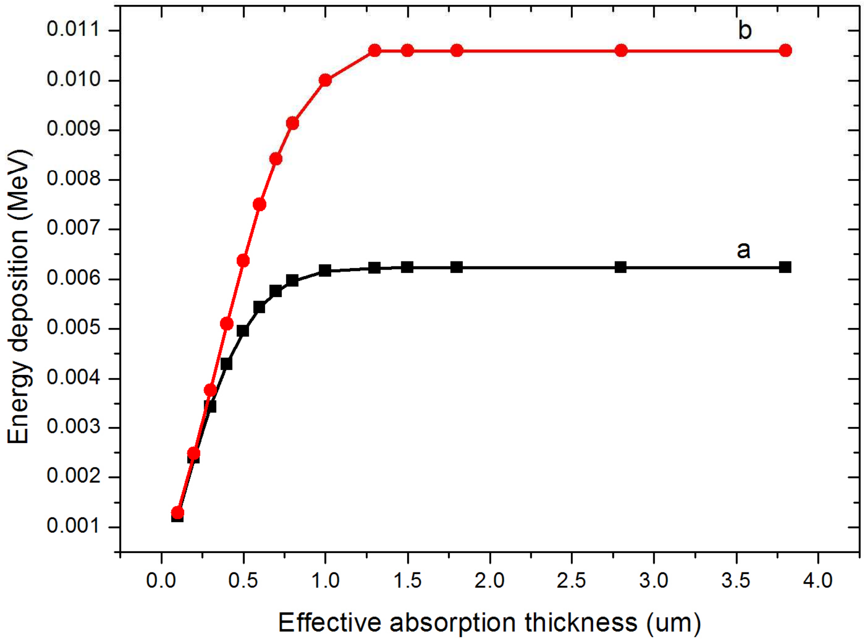

Fig.5. Plot of energy deposition of ^{63}Ni emitting β particles of 17.4KeV as a function of effective absorption thickness of GB with (a) and without (b) concerning the influence of dead layers.

Summary

As a conclusion, we have demonstrated that GaN PIN diodes can be used as betavoltaic nuclear batteries. GaN films were epitaxied by MOCVD. Through consummate fabrication process, GaN PIN diodes with the reverse leakage current of 0.16 nA at -20 V, were successfully fabricated. Loading ^{63}Ni, the conversion efficiency and CCE of the GB were estimated about 1.6% and 100%, respectively, and the short circuit current density was 89.6nAcm^{-2}. The main reason for the relative limted performance is the dead layer is thick and the backscattering of β particles is strong, thus growing high quality GaN films with low dislocation density and fabricating GB with thin dead layer and structural surface will be our next study for improving the batteries characteristics.

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