第23卷 第10期
2010年10月

传感技术学报
CHINESE JOURNAL OF SENSORS AND ACTUATORS

Vol. 23 No. 10
Oct. 2010

4H-SiC Schottky Alphavoltaic Nuclear Battery*

YAO Xianwang, YUAN Weizheng, QIAO Dayong, ZANG Bo*

(*Micro and Nano Electromechanical Systems Laboratory, Northwestern Polytechnical University, Xi' an* 710072, *China*)

Abstract: A 4H-SiC Schottky alphavoltaic nuclear battery is presented. It uses a Schottky barrier in place of the commonly used p-n diode, along with ^{241}Am as the radioactive source. Some of the critical steps in process integration for fabricating Silicon carbide-based Schottky diode were addressed. Under illumination of ^{241}Am with activity of 0.025 mCi/cm^2, an open circuit voltage(V_{OC}) of 0.25 V and a short circuit current density(J_{SC}) of 7.64 nA/cm^2 are measured. The maximum output power density(P_{max}) of 1.12 nW/cm^2 is obtained. And using XRD to analyse the composition of ohmic contact, the XRD analysis result shows that binary alloy phase Ni_2Si is demonstrated. The study results indicate that careful design and fabrication process without impurities of the Schottky diode structure should be carried out to prevent bringing about an increased density of interface states, resulting in an increased dark current. 4H-SiC Schottky diodes were fabricated, taking into consideration all the important aspects discussed in this paper, and the performance of this battery is expected to be significantly improved by using larger activity and more efficient collection and optimizing the design and processing technology of the battery.

Key words: silicon carbide; schottky; alphavoltaic battery; ^{241}Am; 4H-SiC

EEACC: **2500** **doi**: **10.3969/j. issn. 1004 -1699. 2010. 10. 008**

4H-SiC 肖特基结式 Alpha 效应微型核电池*

姚贤旺,苑伟政*,乔大勇,臧　博

(西北工业大学微/纳米陕西省重点实验室,西北工业大学,西安 710072)

摘　要:阐述了一种 4H-SiC 肖特基结式 Alpha 效应微型核电池。利用 Schottky 结取代常用的 p-n 结,在活度为 0.025 mCi/cm^2 的^{241}Am 源辐照下进行测试,得到了开路电压 V_{OC}为 0.25 V、短路电流密度 J_{SC}为 7.64 nA/cm^2 和输出功率密度 P_{max}为 1.12 nW/cm^2。在对 4H-SiC 肖特基结研制过程中的一些关键工艺进行研究之后,采用 XRD 法对欧姆接触成分进行了分析,结果表明形成了二元合金相 Ni_2Si。为了防止界面态密度的提高而导致漏电流增大,肖特基结的设计和加工过程都要严格控制污染源。考虑了所讨论的几个重要影响因素之外,可通过更换大活度放射源、高效地收集方式和提高工艺质量等方式来提高电池的性能。

关键词:碳化硅;肖特基;Alpha 效应电池;^{241}Am 源;4H-SiC

中图分类号:**TN305** **文献标识码**:**A** **文章编号**:**1004 -1699(2010)10 -1403 -05**

Certain electrical applications require power sources with long life and high output voltage. This can be accomplished with an alphavoltaic nuclear battery. This type of battery will convert the decay energy from alpha particles released by an alpha-emitting radioactive material into electrical energy. When compared with a conventional battery, due to the long half-life of the radioisotope and low leakage current, a battery like this is well-suited to applications such as undersea exploration, implantable medical devices and distributed sensors network.

The concept of an alphavoltaic battery was proposed in 1954 by W. G. Pfann and W. van Roosbroeck for silicon and germanium cells.[1] However, as

---

项目来源:This project is supported by National Hi-tech Research and Development Program of China(863 Program, Grant No. 2009AA04Z318)

收稿日期:2010 -06 -10 **修改日期**:2010 -07 -20

the energy of the alpha particles emitted from radioactive materials is very high, certain semiconductors will be seriously damaged; the radiation damage threshold for silicon ranges from 200 ~ 250 keV.[2] Therefore, the wide band-gap semiconductor materials, such as Gallium nitride(GaN), Zinc oxide(ZnO) and Silicon carbide(SiC), have been introduced to the research of alphavoltaic batteries. Due to advancement in crystal growth and manufacturing technology, and the material's characteristics of particularly high radiation resistant, the wide bandgap(4H-SiC 3.2eV), high critical breakdown voltage, high saturated drift velocity, high thermal conductivity and chemical stability, SiC is especially suitable for manufacturing high frequency, high efficiency, and radioprotective electronic devices.[3-5]

A p^+n SiC alphavoltaic battery was presented by George Rybicki et al[6]. Briefly, this battery is composed of a p-type SiC substrate with an aluminum doped p-type epitaxial layer and nitrogen doped n-type emitter. It needs to form ohmic contacts on both sides of p-n diode. With forming ohmic contact on p-type SiC and ion implantation accompanied by high temperature annealing(1 400 ~ 1 700 ℃) in which surface seal must be employed [7], the process difficulty and cost are expected to be increased.

In this paper, we have utilized n-type 4H-SiC substrate to fabricate a prototype of 4H-SiC Schottky alphavoltaic nuclear battery. To simulate the operation of an alphavoltaic battery, 4H-SiC Schottky diode was irradiated with 5.5MeV alpha particles from the radioisotope Americium(^{241}Am). This radioisotope is inexpensive and widely available enough to be used in household smoke detectors, and has a long half-life of 458 years.[6] The operation of the 4H-SiC Schottky alphavoltaic nuclear battery is analogous to a solar cell with the exception of high energy particles impinging on the cell rather than light. Highly radiation resistant SiC semiconductor materials and diodes with very low leakage currents when combined with the short range of an alpha particle in the diodes may make large performance increases in radioisotope batteries possible.

1 Operating Principle

The operating principle of 4H-SiC Schottky alphavoltaic nuclear battery is similar with the solar cell. As shown in Fig.1, in the neutral N-type region, minority carriers diffuse to the depletion region and are swept to the metal region by the build-in electric field, and the electron-hole pairs generated in depletion region are separated and swept to neutral N-type region and metal-region, respectively, then potential is produced.

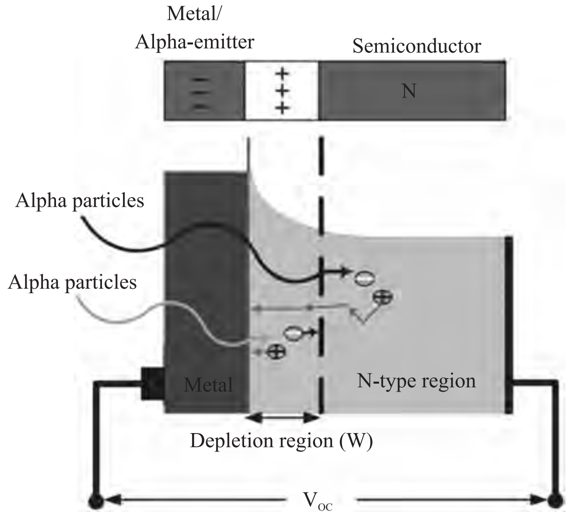

Fig.1 Schematic of alphavoltaic effect

2 Fabrication Process

Without forming ohmic contact on p-type SiC and ion implantation accompanied by high temperature annealing(1 400 ~ 1 700 ℃) in which surface seal must be employed, 4H-SiC Schottky diodes were fabricated on n-type 4H-SiC substrate by using conventional silicon processes, including photolithography, oxidation, and metal sputter deposition. Fig.2 illustrates the typical structure of the fabricated diodes. A round-shaped device structure was chosen to prevent the generation of cusp discharge.

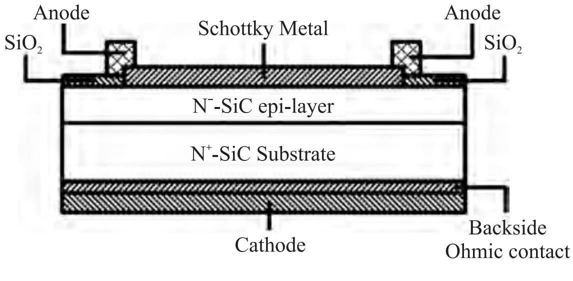

Fig.2 Typical structure of 4H-SiC Schottky diodes

Schematics of the fabrication process integration for 4H-SiC Schottky diodes are shown in Fig.3. SiC wafers with 10μm lightly doped(5×10^{15} cm^{-3}) n-type epi-layer grown on highly doped(5×10^{18} cm^{-3})

n^+-type 4H-SiC <0001> substrate cut 8° off-axis purchased from Cree Inc were used in this study. After epitaxial growth of the epi-layer, a relatively thick SiO_2 for dielectrics layer was deposited on front-side by using a tetraethylorthosilicate (TEOS) low-pressure chemical vapor deposition (LPCVD) system. The temperature at the center zone was maintained at 685 ℃ and the vacuum during deposition at 250 mTorr. Then a backside contact consisting of Ni/Ti/Au was evaporated and then annealed at 1050 ℃ by 2-min rapid thermal annealing (RTA) in N_2 ambient to form ohmic contact. E-beam evaporation was utilized to deposit 400nm Ni as the Schottky metal. To facilitate wire bonding and probe test, the Schottky electrode thus formed has a circular geometry, with a radius of 1mm.

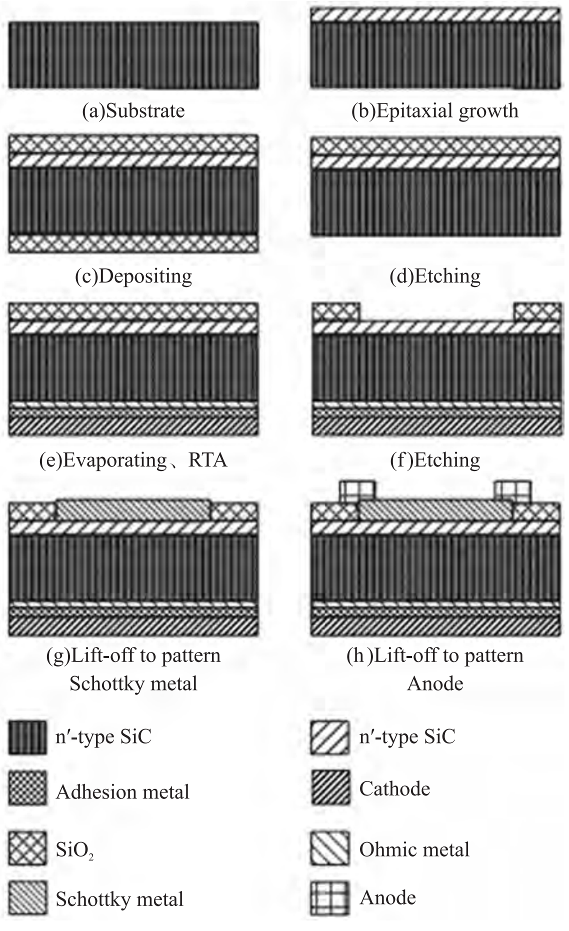

Fig. 3　Schematics of the fabrication process integration

Under illumination of a thin roundness ^{241}Am source with an activity of 0.025 mCi/cm^2, the electrical characteristics of 4H-SiC Schottky diodes were measured with Keithley 4 200 Semiconductor Parameter Analyzer equipment at a wafer probe station.

3　Results and Discussions

Table 1 shows the parameters of 4H-SiC Schottky alphavoltaic battery obtained from measurement. An open circuit voltage (V_{OC}) of 0.25 V and a short circuit current density (J_{SC}) of 7.64 nA/cm^2 are measured. And the peak power density (P_{max}) of the device was 1.12 nW/cm^2 at $J_p = 5.8$ nA/cm^2 and $V_p = 0.192$ V, leading to a fill factor (FF) of 0.59 as shown in Fig. 4. And the reverse saturation current density and ideal factor were extracted from forward dark *I-V* characteristic from Fig. 5, the reverse saturation current density was 1.71×10^{-15} A/cm^2 with an ideality factor n of 1.33.

Table 1　Parameters of the alphavoltaic battery

Parameter	V_{OC}/V	J_{SC}/(nA·cm^{-2})	P_{max}/(nW·cm^{-2})	FF
Measure	0.25	7.64	1.12	0.59

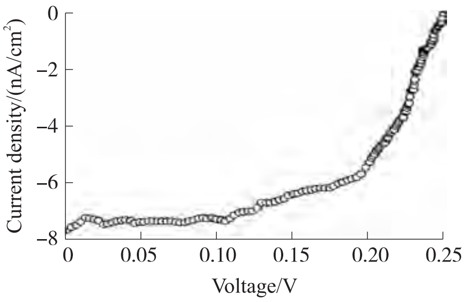

Fig. 4　I-V Characteristics of 4H-SiC Schottky Diode under ^{241}Am Illumination

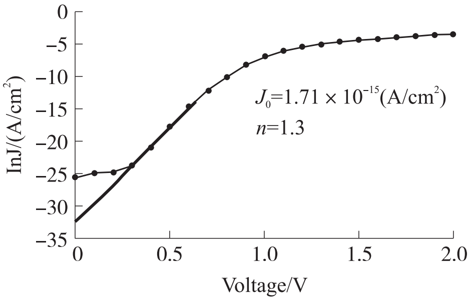

Fig. 5　Dark I-V Characteristic of 4H-SiC Schottky Diode

Using Philips x' PERT X-ray diffraction (XRD) to analyse the composition of ohmic contact, the XRD analysis result after alloy annealing is shown in Fig. 6. The XRD analysis result shows that the binary alloy phase Ni_2Si is demonstrated, but deficiency of the metal Ti, the XRD result does not show clearly[8].

For ^{241}Am source, the electrical output power density ($P_{^{241}Am}$) can be determined by

$$P_{^{241}Am} = 2\times3.7\times10^{10} e\Phi E_{avg} \quad (1)$$

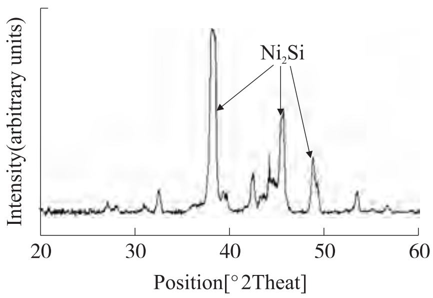

Fig. 6 XRD Analysis Result after Alloy Annealing

Where E_{avg} is 5.5 MeV, the average radiation energy of ^{241}Am, and e is electric charge(1.6×10^{-19}C). Under an activity (Φ) of 0.025 mCi/cm^2, the output power density ($P_{^{241}Am}$) of the ^{241}Am sources is 1 628 nW/cm^2.

The power conversion efficiency η can be calculated from.

$$\eta = FF\frac{V_{OC}J_{SC}}{P_{^{241}Am}} = \frac{V_pJ_p}{P_{^{241}Am}} \qquad (2)$$

Using the extracted V_p and J_p, the conversion efficiency was obtained. A maximum efficiency of 0.07% with a peak power density of 1.12nW/cm^2 and a fill factor below 0.6 were achieved.

Alphavoltaic effect of the diodes was not ideal owing to the low fill factor and low conversion efficiency. The performance of this battery is limited by 4 factors:

(1) Imperfect design occurred at the phase of epitaxial growth;

(2) The impurity in the fabrication process, such as oxidation, lithography and sputtering;

(3) Low shunt resistance. Shunt resistance is caused by current leakage from the surface or edge in the circuit, so shunt resistance is significant to the open circuit voltage in the "low illumination" circumstance[9-10], and higher shunt resistance may improve the open circuit voltage;

(4) Average ohmic contact. The internal series resistance of the battery can reduce the short circuit current and fill factor[11-13], but a good ohmic contact can reduce the series resistance. So forming a good ohmic contact is the key factor in the fabrication process.

4 Conclusion

In this paper, a 4H-SiC Schottky alphavoltaic nuclear battery is demonstrated. Under illumination of ^{241}Am with activity of 0.025 mCi/cm^2, an open circuit voltage(V_{OC}) of 0.25V and a short circuit current density(J_{SC}) of 7.64nA/cm^2 are measured. The maximum output power density (P_{max}) of 1.12 nW/cm^2 is obtained. And the XRD analysis result shows that binary alloy phase Ni$_2$Si is demonstrated. However, the performance of the battery is limited by imperfect design, the impurity in the processing, low shunt resistance, average ohmic contact and the low activity of radioactive sources, duo to the highly radiation resistant SiC semiconductor materials and diodes with very low leakage currents when combined with the short range of an alpha particle in the diodes, the Schottky barrier diode is proven to be a feasible approach to achieve practical beatvoltaics. Moreover, by using greater activity and efficient collector and optimizing the design and processing technology, the performance of the battery will be significantly improved.

References:

[1] Pfann W G, van Roosbroeck W. Radioactive and Photoelectric p-n Diode Power Sources[J]. Journal of Applied Physics, 1954, 25(11): 1422-1434.

[2] Rappaport P, Loferski J J. Thresholds for Electrons Bombardment Induced Lattice Displacements in Si and Ge[J]. Phys. Rev, 1955, 100: 1261-6.

[3] Francesco Moscatelli. Silicon Carbide for UV, Alpha, Beta and X-Ray Detectors: Results and Perspectives[J]. Nuclear Instruments and Methods in Physics Research A, 2007, 583: 157-161.

[4] Zhang Bo, Deng Xiaochuan, Zhang Yourun. Recent Development and Future Perspective of Silicon Carbide Power Devices Opportunity and Challenge[J]. Journal of CAEIT, 2009, 4(2): 111-118.

[5] Chandrashekhar Mvs. Demonstration of A 4H SiC Betavoltaic Cell [D], Cornell University, New York, USA, 2007: 10-63.

[6] George Rybicki, Carlos Vargas-Aburto, Roberto Uribe. Silicon Carbide Alphavoltaic Battery [C]//Proceedings of the 25th. IEEE, 13-17.

[7] Qiao Da-Yong, Yuan Wei-Zheng, Yao Xian-wang, et al. Demonstration of a 4H SiC Betavoltaic Nuclear Battery Based on Schottky Barrier Diode[J]. CHIN. PHYS. LETT, 2008, 25(10): 3798-3800.

[8] Guo hui. Theoretical and Experimental Study on Ohmic Contacts to Silicon Carbide[D]. Xidian University, Xi'an, China, 2007: 45-47.

[9] Liu Zuming, Wang Yichuan, Zhang Zhongwen, et al. The Open-Circuit Voltage of Crystalline Silicon Solar Cells at Weak Illumination[J]. Journal of Yunnan Normal University, 2000, 20(3): 149-153.

[10] Gao Peng, Li Xiao-Ying, Yao Xian-Wang, et al. 4H-SiC Schottky Betavoltaic Micro Battery[J]. Micronanoelectronic Technology, 2010, 47(3): 157 - 162.

[11] Goesmann F, Schmid-Fetzer R. Metals on 6H-SiC: Contact Formation From the Materials Science Point of View[M]. Mater. Sci. and Eng. B, 1997, 46(1 - 3): 357 - 362.

[12] Guo Hui, Zhang Yi-men, Zhang Yu-ming, et al. Investigation of Ni-Based Ohmic Contacts to N-Type SiC[J]. Chinese Journal Electron Devices, 2007, 30(2): 356 - 360.

[13] An Qilin, Cao Guochen, Li Guoxin, et al. Principle and Process of Solar Cells[M]. Shanghai: Shanghai Science and Technology Press, 1984: 105 - 120.

YAO Xianwang(1984 -), is currently a master candidate in Micro and Nano Electromechanical Systems Laboratory, Northwestern Polytechnical University, China. He received his bachelor degree from Northwestern Polytechnical University, China, in 2007. His research interests include micro-energy MEMS and Micro and Nano manufacturing technology, beyondyaoxianwang@126.com;

QIAO Dayong(1977 -), is currently an associate professor in Northwestern Polytechnical University, China. He received his PhD degree from Northwestern Polytechnical University, China, in 2008. His research interests include integrated design method for MEMS, Micro and Nano manufacturing technology, optical MEMS, micro-energy MEMS and etc, dyqiao@nwpu.edu.cn;

YUAN Weizheng(1961 -), is currently a professor in Northwestern Polytechnical University, and is also a distinguished professor in the program of Changjiang scholars awarded by Ministry of Education in China. His research interests include the fields of MEMS, NEMS, precise manufacturing technologies, and etc, yuanwz@nwpu.edu.cn;

ZANG Bo(1987 -), is currently a master candidate in Micro and Nano Electromechanical Systems Laboratory, Northwestern Polytechnical University, China. He received his Bachelor of Engineering degree from Northwestern Polytechnical University, China, in 2007. His research interests include micro-energy MEMS and Micro and Nano manufacturing technology, zangbobo@gmail.com.