고전력 사이리스터 제작을 위한 PNPN 실리콘/질화갈륨 이형접합 개발

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Development of PNPN Si/GaN Heterostructures for High Power Thyristors

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ABSTRACT

The demand for power devices has been increased for decades due to the development of power electronics including smart grids, electric vehicles, and drones. In this work, the PNPN Si/GaN heterostructures were constructed for development of thyristors where the wide bandgap material can enhance the breakdown capability compared to that of conventional thyristors. The PNPN heterostructures were achieved by junction bonding technique. The enhanced switching speed in addition to the breakdown capability of the Si/GaN thyristors was expected.

1. Introduction

Increases in the power density and breakdown field are the important aspects for the development of next-generation power semiconductor devices. Due to the existence of wide bandgap, high critical breakdown field, and higher carrier velocity, the GaN-based electronic devices are used in high power amplification and switching (table 1).[1] Because of wide bandgap and higher carrier velocity compared to those of Si, the GaN-based electronic devices can perform improved power handing capability in terms of high breakdown field and switching speed.

Thyristor is the choice for the application where the low on-state voltage drop during current handling is top priority with the easiness of control.[2] The thyristor maintains a significant market share for some decades since the PNPN device structure was first produced by Si alloying and diffusion techniques in 1956.[3] One method to enhance reliability and performance of Thyristors with improved safe operating area is to use wide bandgap semiconductors.[4]

In this work, PNPN Si/GaN heterostructures were formed by junction bonding technique for the high power thyristors and the electrical characteristics were exhibited to demonstrate the bipolar junction properties. The enhanced power capability and switching speed would be expected from the Si/GaN-based thyristors.

Table 1 Semiconductor materials properties.

	Si	SiC	GaN
Bandgap(eV)	1.12	3.26	3.40
Breakdown field (MV/cm)	0.3	3.0	3.3
Electron mobility (cm^2/Vs)	1500	1000	2000
Electron saturation velocity (cm/s)	1×10^7	2×10^7	2.5×10^7
Dielectric constant	11.9	10	8.9
Johnson figure of merit	1	400	760
Baliga figure of merit	1	11	39

2. Results and Discussion

2.1 Experimental

The PNPN Si/GaN heterostructures were achieved by membrane junction bonding technique.[5] The n-GaN wafers were grown by metal-organic-chemical vapor deposition. The Si membranes were obtained from silicon-on-insulator wafers after the reactive-ion-etching and undercut in HF solution. The p-, n-, p-Si membranes were individually transfer printed on the GaN substrates, leading to the PNPN Si/GaN heterostructures for high power thyristors.[6] The PNPN bipolar heterostructures then went through junction bonding with rapid thermal annealing. The metal contacts for anode, cathode, and gate were deposited by e-beam evaporator, separately (Fig. 1).

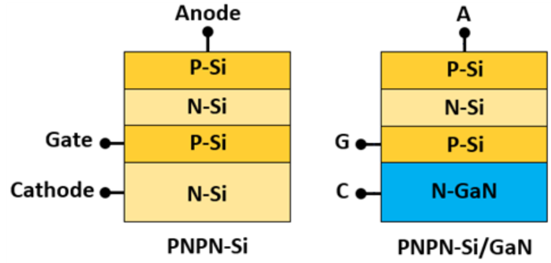

Fig.1 Thyristors comprised with PNPN Si and Si/GaN heterostructures. The Si/GaN heterostructures were formed by membrane junction bonding process.

2.2 Electrical characteristics

The conduction properties of Si/Si and Si/GaN diodes were investigated using semiconductor parameter analyzer. The electrical characteristics demonstrate that the Si/Si and Si/GaN diodes exhibit rectifying behaviors, separately, which indicates that the Si/GaN heterostructures formed by junction bonding method possess PNPN bipolar polarity that is for thyristor structure (Fig. 2).

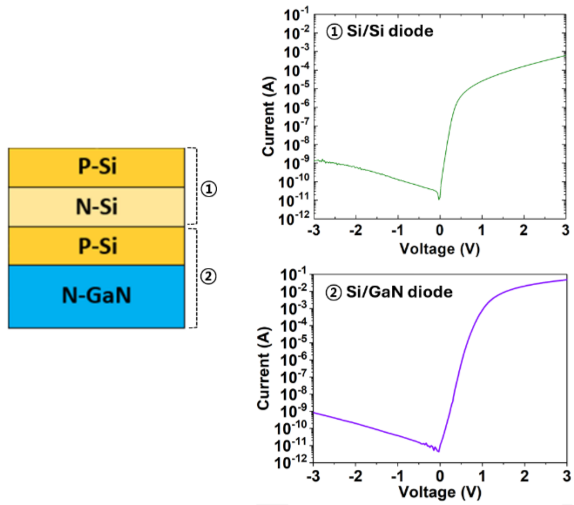

Fig.2 Electrical characteristics of PNPN Si/GaN heterostructures: Si/Si and Si/GaN diodes.

3. Conclusions

In conclusion, the PNPN Si/GaN heterostructures were fabricated through membrane junction bonding technique for high power thyristors. The wide bandgap GaN substrate can improve the breakdown voltage compared to that of the thyristors with Si substrate. The method to construct heterostructures with wide bandgap materials can be applicable to the achievement in the bipolar power semiconductor devices with improved current handling capability and safe operation area.

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References

[1] Trupti Ranjan Lenka et al., HEMT Technology and Applications. Springer, 2023.
[2] J. Vobecky et al., "Silicon Thyristors for Ultrahigh Power Applications", IEEE Trans. Electron Devices, Vol. 64, pp. 760-768, 2017, Mar.
[3] J. L. Moll et al., "P-N-P-N Transistor Switch", Proc. IRE, Vol. 44, pp. 1174-1182, 1956, Sept.
[4] K. Lawson et al., "Safe Operating Area and Long-Term Reliability of 9-kV Silicon Carbide PNPN Super Gate Turn-Off Thyristors", IEEE Electron Device Lett., Vol. 35, pp. 862-864, 2014, Aug.
[5] K. Kim et al., "Negative Differential Resistance in Si/GaAs Tunnel Junction Formed by Single Crystalline Nanomembrane Transfer Method", Results Phys., Vol. 25, pp. 104279, 2021, June.
[6] Y. Zhang et al., "Multidimensional Device Architectures for Efficient Power Electronics", Nat. Electron., Vol. 5, pp. 723-734, 2022, Nov.