Development of PSJGaN HEMT

Hironori Ito*

Abstract

A prototype device development was conducted with utilizing polarization super junction (PSJ) technology originally developed by Powdec Co., Ltd.

PSJGaN is expected to increase breakdown voltage and suppress current collapse because the simultaneous presence of positive and negative polarization charges confined in respective double heterojunction interfaces leads to a uniform distribution of the electric field.

To verify these effects, prototype fabrication and device evaluation were conducted. Comparative analysis with conventional GaN HEMTs (High Electron Mobility Transistors) revealed superior performance of breakdown voltage and current collapse characteristics. Furthermore, in cascode configuration, PSJGaN demonstrated better switching performance than SJMOS. Based on these results, development toward commercialization of integrated devices of PSJGaN, MOSFET, and control IC will be continued.

1. Introduction

Gallium nitride (GaN) has excellent material characteristics such as a wide bandgap, high electron mobility, and high breakdown electric field as shown in Table1. These characteristics offer significant improvements in power density and switching performance over conventional silicon (Si) devices.

In recent years, as the demand for higher efficiency and miniaturization of power conversion systems has increased, GaN HEMTs have gained significant traction as power semiconductor devices.

Nevertheless, achieving both high breakdown voltage and low on-resistance, which are inherently conflicting characteristics, is still a major challenge. Therefore, innovation of device structure is required. As a new approach to address this challenge, we have been developing PSJGaN, a GaN HEMT utilizing PSJ structure—an original technology of Powdec Co., Ltd. now merged with Sanken Electric Co., Ltd.

Table 1. Material Characteristics of Various Semiconductor Materials

	Si	4H-SiC	GaN
Band Gap (eV)	1.12	3.26	3.39
Electron Mobility (cm2/Vs)	1350	700	1500
Breakdown Electric Field (MV/cm)	0.3	3	3.3
Baliga's Figure of Merit	1	439	1128

PSJGaN utilizes the polarization properties unique to group III–V materials and leads to a uniform distribution of the electric field like the concept of super junction in Si devices, thereby it enables both low on-resistance and high breakdown voltage. Additionally, by using sapphire as the supporting substrate, it allows for the use of thin epitaxial layers and offers superior cost performance compared to GaN on Si. Moreover, higher breakdown voltage devices exceeding 1200V, which are difficult to achieve with GaN on Si, can be realized. On the other hand, because sapphire is an insulating substrate, there is concern that PSJGaN may suffer from current collapse.

Herein, the device performance and application prospects of the PSJGaN are studied through device design, processing, fabrication, and evaluation and its effectiveness for practical use.

* Engineering Development Headquarters, Process Engineering Division, GaN Device Development Department, GaN Device Development Section

2. Structure and Features of PSJGaN

As shown in Fig.1, when the PSJ structure, a GaN/AlGaN/GaN double heterostructure, is formed, a piezoelectric field is generated within the AlGaN layer due to piezoelectric polarization. This can lead to the formation of the high density, high mobility of electrons (2DEG) and holes (2DHG) at respective heterointerfaces [(1)].

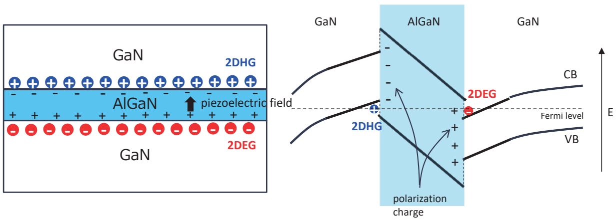


Figure 1. GaN/AlGaN/GaN Double Heterostructure and Energy Band Diagram

2DEG exhibits high charge density and high mobility, enabling the realization of devices with low specific on-resistance. Furthermore, by utilizing PSJ structure, high breakdown voltage devices can be achieved.

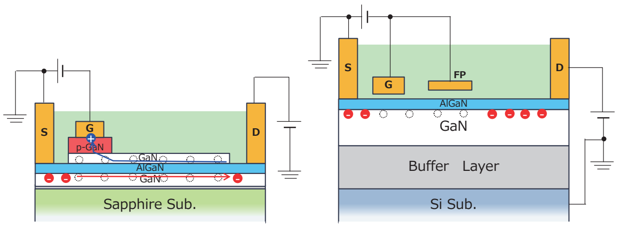
Fig.2 shows the device structures of PSJGaN and conventional GaN HEMTs during turn-off, respectively.

When a negative bias is applied to the gate of PSJGaN, 2DHG is depleted from the upper GaN region as shown in Fig.2(a). As a result, both 2DEG and 2DHG are depleted through respective terminals by charge balance.

This leads to a uniform distribution of the electric field at the PSJ structure, which enables the device to withstand high voltages.

However, a positive gate voltage is required to turn on the device because controlling 2DHG is necessitated for gate drive.

On the other hand, conventional GaN HEMTs use Si substrate (GaN on Si) and rely on field plate (FP) structures to prevent breakdown voltage degradation caused by electric field concentration at the gate edge as shown in Fig.2(b).



(a) PSJGaN (b) Conv. GaN HEMT

S: Source electrode, G: Gate electrode, D: Drain electrode

Figure 2. Device Structures and Carrier Distribution in the Off-State

However, considering the electric field between the drain electrode and the Si substrate, breakdown voltage is currently limited to below 800 V.

Additionally, conventional GaN HEMTs sometimes suffer from current collapse—a phenomenon where current flow is suppressed during switching operation, resulting in increased on-resistance. This phenomenon is caused by electrons trapped in the GaN layer or the interface between AlGaN and interlayer due to electric field concentration at the gate edge or the drain edge during turn-off, forming a virtual gate. As a countermeasure, FP structures are utilized to mitigate such electric field concentration.

Because PSJGaN can lead to a uniform distribution of the electric field, it is expected to suppress current collapse more effectively than conventional GaN HEMTs.

3. Evaluation Results of Prototype Devices

3.1 Breakdown Voltage Characteristics

Breakdown voltage characteristics were evaluated for the various length of the PSJ structure (L_{psj}) shown in Fig.3. A trend of increasing breakdown voltage with longer L_{psj} was obtained and the dependence of breakdown voltage on gate-drain distance (L_{gd}) is shown in Fig.4.

PSJGaN exhibited higher breakdown voltage at the same L_{gd} compared to the conventional GaN HEMTs, which suggests superior performance of PSJGaN.

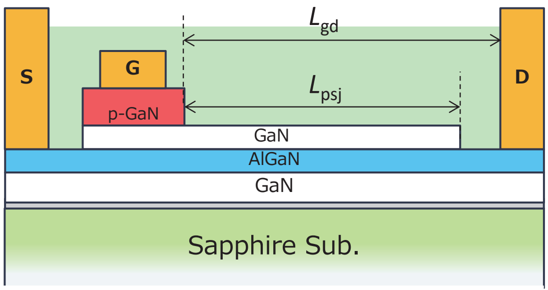


Figure 3. Cross-sectional View of PSJGaN

3.2 Current Collapse Characteristics

Current collapse characteristics were quantitatively evaluated using a pulse IV measurement method. A two-level(on/off) pulse signal was applied to the gate. The pulse width was 25 μs and drain current and voltage were measured 20 μs after turn-on.

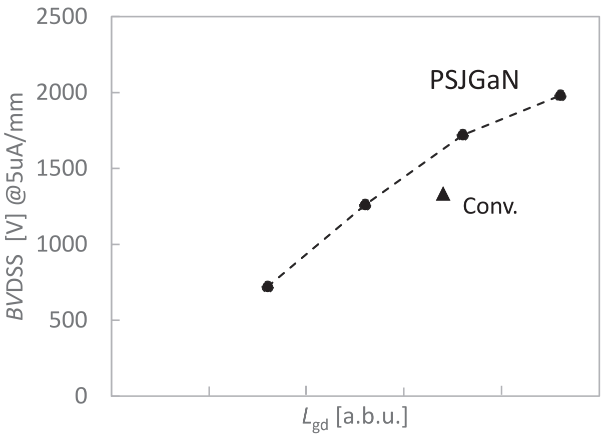


Figure 4. Breakdown Voltage Characteristics of PSJGaN with Varying *L*psj

The relative change of on-resistance during switching operation (R_{on} dynamic) compared to the initial on-resistance (R_0) was defined as the collapse ratio to evaluate current collapse quantitatively. If the value is close to 1, the impact of current collapse becomes almost negligible.

$$\{\text{collapse ratio}\} = R_{on}\ (\text{dynamic})\ /\ R_0$$

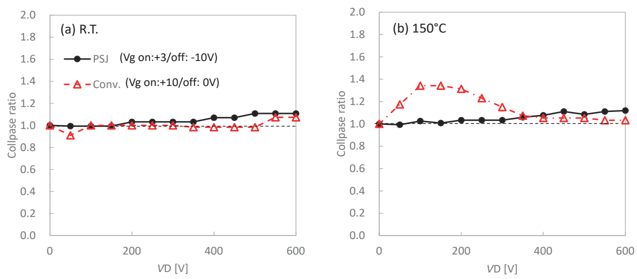


Figure 5. Current Collapse Characteristics of PSJGaN

Fig.5 shows the current collapse characteristics of PSJGaN and conventional GaN HEMTs, respectively.

PSJGaN achieved equal or better current collapse characteristics than conventional GaN HEMTs despite using a sapphire substrate. Therefore, it is confirmed that the PSJ structure is also effective for suppressing current collapse.

3.3 Dynamic Characteristics of Cascode Configuration

By applying a cascode configuration, a normally-on GaN HEMT is connected in series with a MOSFET, and the gate of the GaN HEMT is grounded. This allows the device to operate as a normally-off device, as shown in Fig. 6.

The transfer characteristics and output I-V characteristics for the case where a normally-on PSJGaN is applied

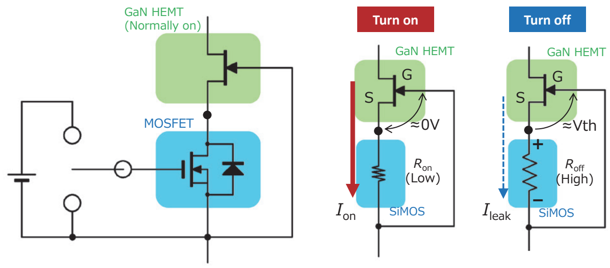


Figure 6. Cascode Connection of Normally-On GaN HEMT

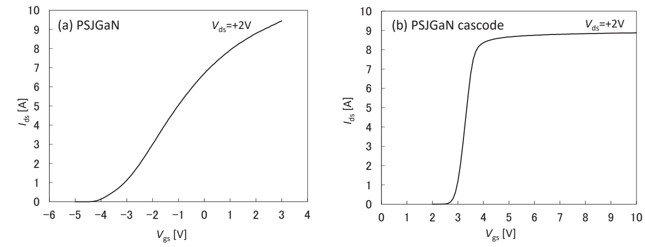


Figure 7. Transfer Characteristics

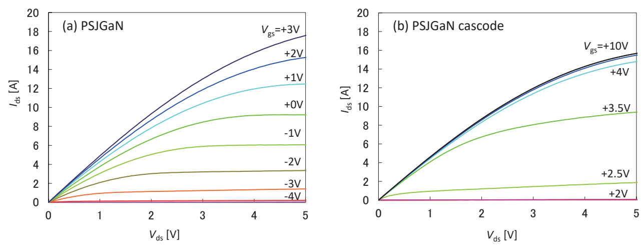


Figure 8. *I–V* Characteristics

in a cascode configuration (PSJGaN cascode) are shown in Fig. 7 and Fig. 8, respectively.

Because it is necessary to control not only the gate but also PSJ structure during the gate drive, the gate charge (Q_g) is larger than that of conventional GaN HEMTs. However, because the PSJGaN gate is grounded and the MOSFET gate is driven in a cascode configuration, it is expected to mitigate the impact on capacitance characteristics and switching speed.

Fig.9 shows the capacitance characteristics of PSJGaN cascode and Super Junction MOSFET (SJMOS), respectively. PSJGaN cascode showed lower C_{oss} and C_{rss} compared to SJMOS.

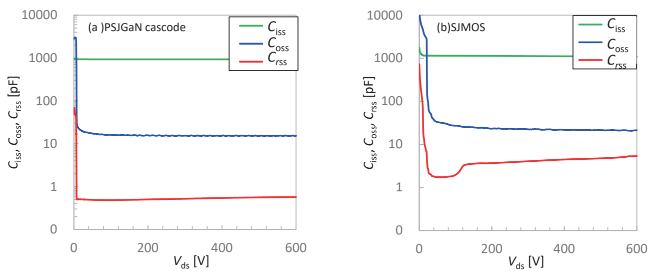
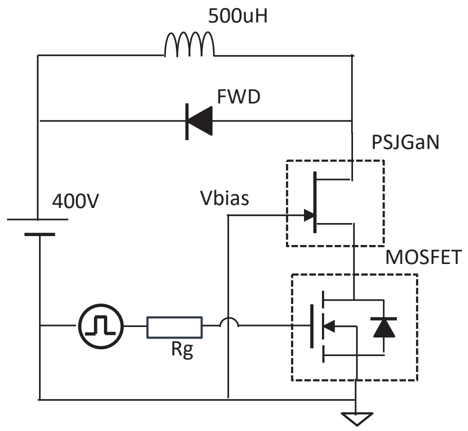


Figure 9. Capacitance Characteristics



	PSJGaN	MOSFET
V_{ds} max	600V	60V
R_{on}	200mΩ	20mΩ
V_{th}	-5V	+2.4V

Figure 10. Switching Evaluation Circuit of the PSJGaN Cascode

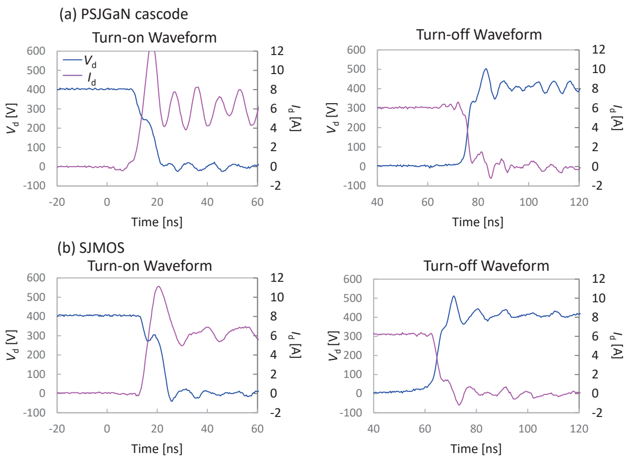


Figure 11. Switching Waveforms of (a) PSJGaN Cascode and (b) SJMOS

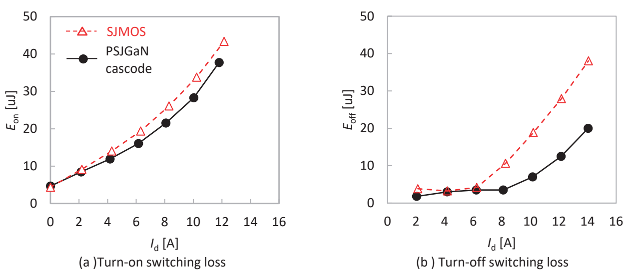


Figure 12. Switching Energy Loss of (a) PSJGaN Cascode and (b) SJMOS

Switching performance was also evaluated under hard switching conditions with an inductive load (Fig.10). Fig.11 shows the switching waveforms at 400V/6A operation.

Based on the results, the switching energy losses during turn-on and turn-off were extracted, as shown in Fig.12.

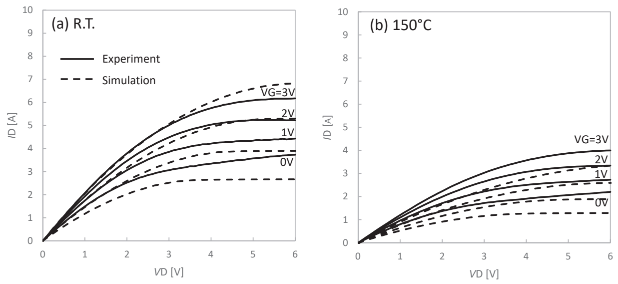


Figure 13. *I–V* Characteristics of PSJGaN

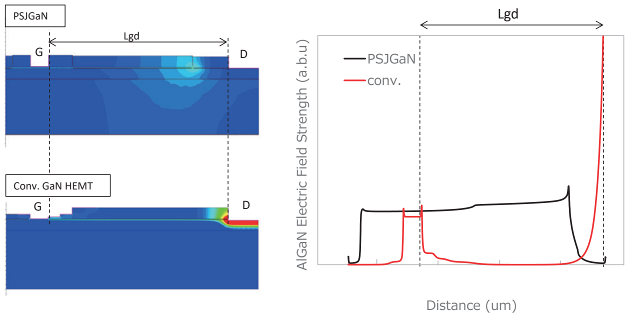


Figure 14. Simulation Results of Electric Field Strength Distribution under High Voltage in the Off-State

From these results, it is confirmed that PSJGaN cascode exhibited lower switching energy losses than SJMOS.

4. Challenges in Device Simulation

Device simulation of PSJGaN using TCAD is currently undertaken.

For output *I–V* characteristics, relatively good reproducibility was achieved at room temperature, but discrepancies remain at high temperatures as shown in Fig.13.

Moreover, simulation results of the distribution of electric field during turn-off are shown in Fig.14 for PSJGaN and conventional GaN HEMTs, respectively.

The results show that PSJGaN exhibits a more uniform distribution of electric field compared to conventional GaN HEMTs with FP structures.

This tool will support device design after validating the physical models and improving simulation accuracy.

5. Conclusion

This report introduced PSJGaN, a GaN-based device capable of achieving low power conversion loss and high efficiency.

Evaluation of prototype devices demonstrated that PSJGaN offers superior breakdown voltage and current collapse characteristics compared to conventional GaN

HEMTs. Additionally, PSJGaN cascode showed superior capacitance characteristics and switching performance compared to SJMOS.

The drive ICs which can control PSJGaN under optimal conditions will be also developed in conjunction with improvements in PSJGaN performance.

TCAD device simulation of PSJGaN is also undertaken and this tool will be useful for device design and accelerate the commercialization of such integrated devices.

References

1. Sato et al., "Toyota Gosei Technical Report," Vol. 63, pp. 41–45 (2021)