Fast Recovery Performance of Vertical Schottky Barrier Diodes on Low Dislocation Density Freestanding GaN Substrates

Susumu YOSHIMOTO*, Masaya OKADA, Fuminori MITSUHASHI, Takashi ISHIZUKA and Masaki UENO

For the realization of a "low-carbon society," there is an increasing demand for high efficiency power conversion. Gallium Nitride (GaN) is highly anticipated as a semiconductor with high potential for power devices. We developed vertical GaN Schottky barrier diodes on free-standing GaN substrates and demonstrated their high breakdown voltage and low on-resistance. In this paper, we demonstrated the advantage of GaN SBDs in terms of switching characteristics and long-time reliability.

Keywords: GaN, Schottky barrier diodes, reverse recovery

1. Introduction

The importance of the effective use of limited resources is increasing and technologies for energy-saving are in great demand. We need to consume generated energy efficiently, but also to convert it efficiently. The ultra-high voltages generated at power plants need to be converted into commercial voltages and every commercial voltage is certainly converted to a required value in devices. Therefore, high-efficiency power conversion plays a very important role. Nowadays, power conversion modules are used everywhere from power conditioners to AC adapters, hence miniaturization is also demanded.

Gallium Nitride (GaN) has been focused on as one of the most anticipated materials for power devices(1). The property values of GaN are shown in **Table 1**. GaN has about a 3-times larger bandgap, about a 10-times higher electric breakdown voltage, and about a 2.5-times higher electron saturation velocity than Silicon (Si). Baliga's figure of merit (FOM) can be calculated with these values, and we find that GaN has about a 1,000-times larger Baliga's FOM (low frequency) and about a 100-times larger Baliga's FOM (high frequency) than Si. This means GaN can improve power conversion efficiency. Furthermore, operating at higher frequency can miniaturize the whole circuit size because passive devices such as resistors, inductors, capacitors can be downsized.

GaN devices on other substrates such as Si, Silicon Carbide (SiC), sapphire, have started development earlier. Due to poor interfaces between GaN and those substrates, lateral structures were inevitably employed. However, lateral structures have problems in device characteristics such as blocking voltage and maximum current. Thus we developed and manufactured free standing GaN substrates with low dislocation density(2) and applied them to vertical structures with high crystal quality and homogeneous interfaces. Vertical structures are expected to be superior to lateral ones for power devices because they enable simpler packaging design, larger current density and higher breakdown voltage due to higher area efficiency.

In order to demonstrate the advantages of vertical GaN devices on GaN substrates, we fabricated and evaluated Schottky barrier diodes (SBDs)(3),(4). In this paper, we evaluate the reverse recovery characteristics to investigate the potential when operating at high frequency. GaN SBDs showed the fastest reverse recovery times compared to SiC and Si diodes. Moreover, we also demonstrate the lowest diode loss for the 30-MHz rectifying circuit and stable long-time reliability for 1,000 hours at 150°C.

Table 1. The property value of Si, SiC and GaN

	Si	SiC	GaN
Bandgap, E_g(eV)	1.1	3.3	3.4
Electric Breakdown field, E_c(10^6V/cm)	0.3	2.3	3.3
Electron Saturation velocity, v_{sat}(10^7cm/s)	1.0	2.0	2.5
Baliga's figure of merit (low frequency), $\epsilon\mu E_c^3$ (figure for Si as 1)	1	565	957
Baliga's figure of merit (high frequency), μE_c^2 (figure for Si as 1)	1	31	104

2. Device Fabrication and Characterization

2-1 Device structures

A vertical GaN SBD structure was fabricated using an n-type GaN substrate. **Figure 1** shows the schematic cross section of the GaN SBDs. GaN substrates were produced by hydride-vapor-phase epitaxy, and their threading dislocation densities were less than $1 \times 10^6 cm^{-2}$. A Si-doped 1-µm-thick n^+-GaN epitaxial layer was grown by metalorganic chemical vapor deposition, followed by a 7-µm-thick n-GaN epitaxial layer.

Nickel (Ni) / Gold (Au) Schottky contacts and an Aluminium (Al) pad layer were formed on the front side by a conventional deposition method. Electrodes were patterned into 1.1 × 1.1 mm square shapes by a conventional photo-lithography technique. To reduce the electric field concentration at the edges of the electrodes, we employed a field-plate structure. SiN was deposited as a field plate insulation layer. As ohmic contacts, Titan (Ti) / Al / Ti / Au were formed on the reverse.

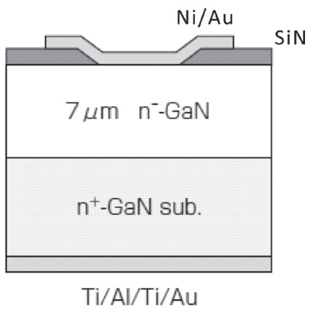

Fig. 1. Schematic cross-section of the vertical GaN SBD

GaN SBDs were separated into chips and molded with resins. In order to reduce the parasitic inductance for high frequency operation, we employed a newly designed surface mount type package with less parasitic inductance, instead of the conventional TO-220 package. **Photo 1** shows our GaN SBD (3.8 × 1.2 × 2.0 mm).

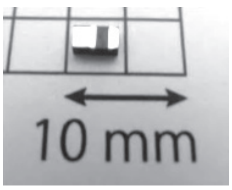

Photo 1. Appearance of the GaN SBD

2-2 Characterization of GaN SBDs

As efficient power converters, switched mode power supplies (SMPSs) are used in a commercial way. SMPSs convert input electric power to desired value by controlling switching frequency and duty cycles. Higher switching frequency gives rise to the reduction of passive circuit elements in size and the miniaturization of the whole circuit size. The breakdown voltage of power devices need to be more than 600 V in general since the world wide input voltage for SMPSs is 85–264 V.

The losses of SMPS consist of the conduction ones and the switching ones. The conduction losses are generated in the on-state, while the switching losses are generated at the time of switching-on and -off. Switching losses are proportional to the numbers of switching, namely the switching frequency. This means that switching losses depend on frequency. Therefore, low switching loss devices can realize higher frequency operation and miniaturization of SMPSs.

As switching losses by diodes in SMPSs are mainly attributed to a reverse recovery current. The reverse recovery current flows after switching diodes off due to accumulated electrons in diodes. The time that the reverse recovery current decreases to 90% of the peak value and the totally flowed charges in that time are called the reverse recovery time (T_{RR}) and the capacitive charge (Q_{RR}), respectively. This reverse recovery phenomenon induces losses in switching devices such as field effect transistors (FETs) by the current flow inversely into on-state FETs. In this study, we focus on these characteristics as parameters that reflect devices suitability for operation at higher frequency.

Figure 2 shows the schematic of a test circuit to measure the reverse recovery characteristics, and **Fig. 3** shows a timing chart of this measurement. For the observation of reverse recovery characteristics, double pulses were introduced into the circuit. (1) Magnetic energy was accumulated in the coil, and then (2) current flowed into the diodes by forming closed circuits. (3) The supply voltage V_{RR} was reapplied to the diodes. At this time, reverse recovery phenomena could be observed.

Reverse recovery characteristics are influenced by the forward current I_F and transition time di/dt shown in **Fig. 3**. Therefore, the same I_F and di/dt were employed in the following experiments.

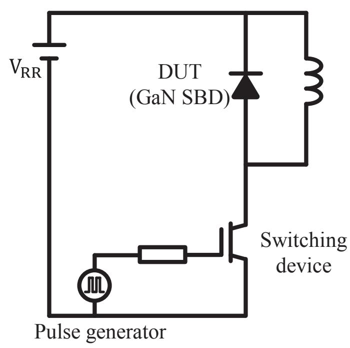

Fig. 2. Schematic circuit diagram for the reverse recovery measurement

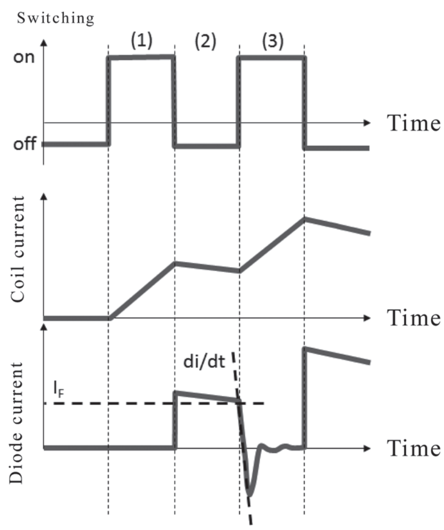

Fig. 3. Timing chart of evaluation

3. Results and Discussion

Figures 4 and 5 show the static forward and reverse current-voltage characteristics, respectively. The forward voltage drop was 1.48 V at 5 A (pulse) and the reverse leakage current was 3.1 μA at 600 V.

The reverse recovery characteristics of the GaN SBD, the SiC SBD, and the Si diode were measured under the same conditions of IF = 5 A, V_{RR} = 380 V, di/dt = 3.4 kA/μsec and were compared as shown in **Fig. 6** and **Table 2**.

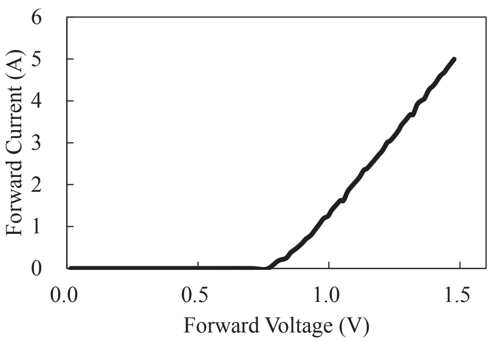

Fig. 4. Forward current-voltage characteristics

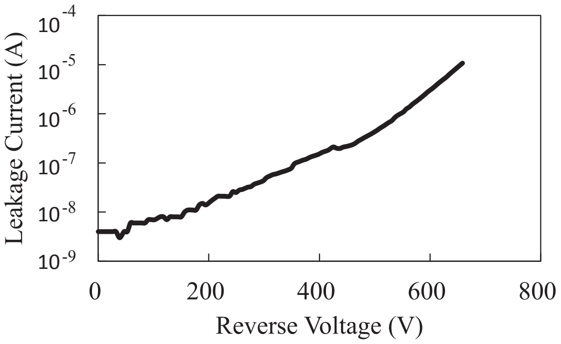

Fig. 5. Reverse current-voltage characteristics

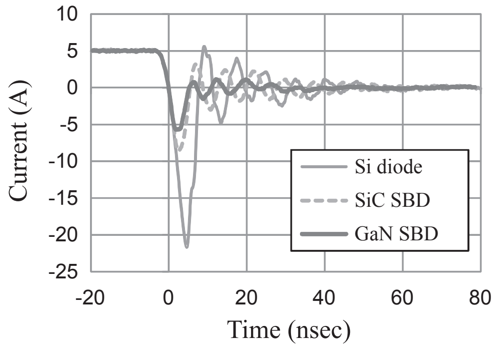

Fig. 6. Reverse recovery characteristics

Table 2. Comparison of reverse recovery

	T_{RR} (nsec)	Q_{RR} (nC)	Loss(μJ)
GaN SBD	5.2	19.4	0.11
SiC SBD	5.5	29.6	0.25
Si diode	7.6	91.0	0.62

The current drop of the GaN SBD was less than those of the other diodes. Compared to the SiC SBDs, the current drop of the GaN SBD was converged to zero faster while the peak value of the currents was slightly smaller. This means that the GaN SBD can reduce noises and losses in whole circuit, as compared with the others. Furthermore, **Table 2** shows that the Q_{RR} of the GaN SBDs was one-fourth of the Si diodes and two-thirds of the SiC SBDs.

The reverse recovery current could flow backward into the circuit and could be the causes of the switching losses. Therefore, the GaN SBDs are more suitable for operations at high frequencies among these diodes.

4. Evaluation with 30-MHz Rectifier Circuits

This section discusses the results of an evaluation with high frequency rectifying circuits(6).

The schematic of an evaluation circuit is shown in **Fig. 7**. A GaN SBD, a SiC SBD and a Si diode were

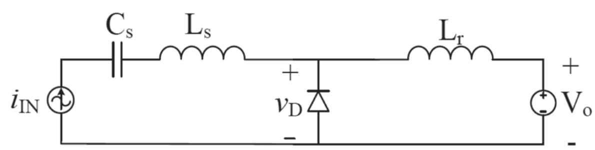

Fig. 7. Evaluation circuit for 30MHz rectifier

employed and frequency of input was set to 30 MHz. In order to estimate losses of diodes themselves, temperatures of diode's surface were measured. Power dissipations were calculated by relations between temperatures of diode's surface and power dissipations which were obtained in advance.

Figure 8 shows the dependency between output power and power dissipations of diodes. Power dissipations of diodes are described as a percentage of output power. The GaN SBD and the SiC SBD operated over the whole output range, while the Si diode did not work when output power was increased. This means that the Si diode could not operate at 30 MHz in this circuit. The GaN SBD operated with less loss, as compared with the SiC SBD. At 60 W output, the loss of the GaN SBD was two-thirds or less of the SiC SBD.

These results demonstrated that GaN SBDs have the advantage to operate at high frequency.

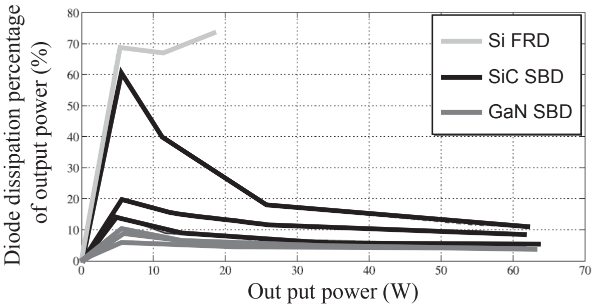

Fig. 8. Diode dissipation on the 30 MHz rectifier

5. Long-time Reliability

For practical use, long-time reliability is one of the most important characteristics. This section discusses the operating reliability under high temperature. **Figure 9 (a) and (b)** show the results of reliability tests for forward and reverse bias. Both were performed for 1,000 hours at a junction temperature of 150˚C.

The forward voltages were stable for the entire duration. The leak currents were also stable although they slightly increased up to the 100-hour marks. These results indicate that GaN SBDs have sufficient reliability under the high temperature and long-time operation.

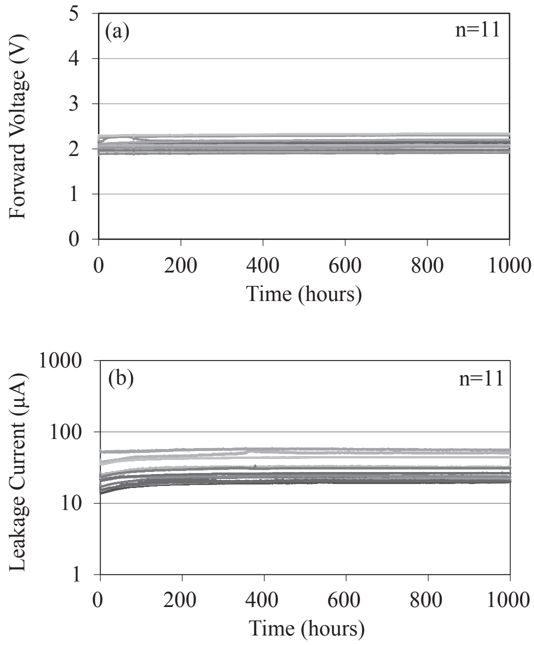

Fig. 9. Results of long-time reliability of GaN SBDs at 150˚C.
(a) forward voltage at forward current of 5 A,
(b) leakage current at reverse voltage of 600 V

6. Conclusion

The physical property of GaN is superior to those of most semiconductors as power devices in terms of high breakdown voltage, low on-resistance and high frequency operations. However, the intrinsic potentials may still not be derived. We fabricated and investigated vertical GaN SBDs on free-standing GaN substrates with low dislocation density. The GaN SBDs exhibited faster reverse recovery times and smaller capacitive charges with less loss than other prepared diodes. Also, the demonstration of the 30 MHz rectifying circuit revealed that the losses of the GaN SBDs were less than that of the SiC SBD. We also conducted long-time reliability tests, which convinced us that GaN SBDs had sufficient reliability. These results show that GaN SBDs are suitable for miniaturized switched mode power supplies that are operated at high frequency.

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