Conducted noise of GaN Schottky barrier diode in a DC–DC converter

Takaaki Ibuchi\textsuperscript{1a)}, Tsuyoshi Funaki\textsuperscript{1}, Shinji Ujita\textsuperscript{2}, Masahiro Ishida\textsuperscript{2}, and Tetsuzo Ueda\textsuperscript{2}

\textsuperscript{1} Osaka University, Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Suita, Osaka 565–0871, Japan
\textsuperscript{2} Panasonic Corporation, Green Autonomous Technology Development Center, Engineering Division, Automotive & Industrial Systems Company, Nagaokakyo, Kyoto 617–8520, Japan
\textsuperscript{a)} ibuchi@eei.eng.osaka-u.ac.jp

Abstract: Wide-bandgap power devices such as those made from silicon carbide (SiC) and gallium nitride (GaN) offer superior electrical performance over conventional silicon (Si) devices for high-voltage applications. Their fast switching operation and low switching losses help increase the efficiency of power conversion circuit. This study focuses on the switching characteristics of a GaN Schottky barrier diode (SBD) and investigates the conducted noise characteristics in a DC–DC boost converter by comparing a Si PiN diode and a SiC SBD.

Keywords: gallium nitride Schottky barrier diode, silicon carbide Schottky barrier diode, reverse recovery, DC–DC converter, conducted noise

Classification: Electron devices, circuits, and systems

References

1 Introduction

Gallium nitride (GaN) semiconductors have superior material properties (wide energy bandgap, large critical electric field, high electron mobility, and high thermal conductivity) as compared with conventional silicon (Si) semiconductors [1]. As a result, they are more attractive for high-frequency and high-temperature operating power electronic applications. Most published studies on GaN Schottky barrier diode (SBD) have focused on device structure [2, 3], substrate material, which allows high-quality GaN epilayer growth [4, 5], and recovery characteristics or converter efficiency, as compared with Si PiN diode (PiND) and Silicon Carbide (SiC) SBD [6]. However, the relationship between the dynamic characteristics of a GaN SBD and the electromagnetic interference (EMI) noise emissions in the power converter has not yet been properly investigated. Our previous study [7, 8] evaluated switching characteristics and the conducted noise levels of a Si PiND and a SiC SBD in a DC–DC converter. This study experimentally evaluates the turn-off characteristics as well as the conducted noise emissions of a GaN SBD in a continuous current mode (CCM) DC–DC boost converter, which are then compared against a Si PiND and a SiC SBD.

Section 2 shows the static characteristics of the studied GaN SBD (Panasonic, test sample), the Si PiND (Fairchild Semiconductor, RHRP860, 600 V, 8 A), and the SiC SBD (Infineon, IDH08SG60C, 600 V, 8 A). These devices were packaged in TO-220 package. In Section 3, we evaluate the switching characteristics and the conducted noise in a tested boost converter for each of three types of diode. Finally, we provide the conclusions in Section 4.

2 Static characteristics of diodes

Fig. 1(a) shows the measured forward I–V characteristics of the studied diodes at room temperature (25 °C) by means of a curve tracer (Agilent, B1505A). All samples yield similar voltage drops at 3–4 A of the conduction current level. Fig. 1(b) shows the C–V characteristics as measured by a curve tracer. The reverse bias voltage dependencies of terminal capacitance per unit area are calculated, and the results are shown in Fig. 1(c). The SiC SBD (chip size: 1.7 mm²) had larger junction capacitances than the Si PiND (chip size: 4 mm²) because of higher impurity concentrations in the drift region. The GaN SBD (chip size: 1 mm²) yields lower junction capacitances than the SiC SBD due to the smaller device area and lower impurity concentration, which can also be estimated from higher on-resistance, as shown in Fig. 1(a). Fig. 1(d) depicts the measured frequency characteristics of the diode’s impedance [Z] at the blocking state (V_r = 40 V) with a 100 mV AC measurement signal using an impedance analyzer (Keysight, E4991B).
The frequency responses of all samples corresponded with the characteristics of an RLC series equivalent circuit. The equivalent series inductances (ESLs) were almost identical (10 nH) due to the fact that the same TO-220 package type was used for each diode. The steep impedance change around 100–300 MHz corresponded to the series resonance for the respective diode’s junction capacitances and ESLs. The Si PiNd has a larger equivalent series resistance (ESR) than the SiC and GaN SBDs, which was identified from the minimum impedance at the series resonance frequency. Fig. 1(e) shows the reverse bias voltage dependency of the diodes’ ESR at $f = 100$ MHz. The ESR for respective diode corresponds approximately to the minimum impedance shown in Fig. 1(d).

![Diagram showing static characteristics of diodes](image-url)

**Fig. 1.** Static characteristics of diodes.
3 Switching characteristics and the conducted noise of the GaN SBD

Fig. 2(a) shows the circuit diagram of the tested CCM DC–DC boost converter. The MOSFET (Infineon, IPP60R099CP) was operated at a 100 kHz switching frequency with a 50% duty cycle for a 100 V DC output voltage and a 50 Ω load resistance. A 1.5 µA reverse leakage current flowed through the GaN SBD at room temperature (25°C) for $V_r = 100$ V. The measured current and voltage in the tested converter are depicted in Fig. 2(b). The conduction losses of each type of diode are comparable because the average inductor current was 4 A and the conduction drop voltages of each diode were similar, as shown in Fig. 1(a). The diode current behavior during the turn-on operation was almost unaffected by the diode type because it was dominated by the turn-off characteristics of the MOSFET [7]. The diode turns off with the turning on of the MOSFET and commutates the inductor current from the diode to the MOSFET. A PiN diode induces large reverse recovery currents during the turn-off operations because of the stored minority carriers, which results in large switching losses. In contrast, SBD is free from the reverse recovery phenomena because it operates with the majority carrier; thus, SBDs have...
lower switching losses as compared with the conventional Si PiND. This section evaluates the turn-off switching characteristics of the studied GaN SBD, Si PiND, and SiC SBD, and discusses the influence of the diode characteristics on the conducted noise emissions.

3.1 Diode and MOSFET switching characteristics

Fig. 3 shows the measured diode and MOSFET dynamic characteristics for the diode turn-off operation at room temperature (25°C). The diode type was given as the parameter. The measured current of the Si PiND shows the characteristics of a bipolar device with large peak reverse currents, as shown in Fig. 2(a), and also results in large current in the MOSFET, as shown in Fig. 3(b). A high di/dt of the recovery current in the Si PiND also leads to a large voltage overshoot, as shown in Fig. 3(c). The switching characteristics of the GaN and SiC SBDs during the diode turn-off operation are much better than for the Si PiND, and can reduce switching losses. The GaN SBD shows a slightly smaller reverse current peak and shorter recovery time than the SiC SBD, due to the lower impurity concentration and lower junction capacitances shown in Fig. 1(b). The current for both types of SBD during the turn-off operation exhibited high-frequency ringing oscillation and slower damping than that of the Si PiND. Prony analysis was applied to the measured time-domain data to evaluate the damping factor of the ringing oscillation mode [9]. The damping factor of the ringing oscillation was calculated as $1.40 \times 10^7/s$, $1.89 \times 10^7/s$, and $6.88 \times 10^7/s$ for the GaN SBD, SiC SBD, and Si PiND, respectively; the difference corresponds to the ESR in the diode blocking condition, as shown in Fig. 1(e). The lower ESR of the GaN SBD compared with that of the SiC SBD contributes to the slower damping. Prony analysis also extracted
dominant ringing oscillation frequencies of 95.5 MHz, 73.7 MHz, and 96.7 MHz in the diode turn-off currents for the GaN SBD, SiC SBD, and Si PiND, respectively. These ringing oscillations are due to the LC resonance between the diode junction capacitance and the circuit parasitic inductance. The differences in oscillation frequency correspond to the junction capacitance differences, with the same parasitic inductance provided by the TO-220 package. The larger capacitance of the SiC SBD results in a lower oscillation frequency than for the GaN SBD and Si PiND.

3.2 Conducted noise evaluation

This section presents the measured frequency spectrum in the terminal disturbance voltage of the active power line to the ground $v_d$. Line impedance stabilization network (9117-5-PJ-50-N, Solar Electronics Co., Ltd.) and a spectrum analyzer (Agilent, E4402B) with a peak-detection mode were used for measurement, as shown in Fig. 2(a). Fig. 4(a) shows the conducted noise in 0.15–30 MHz with a 9 kHz resolution bandwidth (RBW) according to CISPR 16-1-1 [10]. The spectrum peaks correspond to the theoretical harmonic components of the integral multiple of the switching frequency up to several megahertz. The Si PiND exhibits spectrum levels that are 3–5 dB higher than those of the SBDs up to 30 MHz because of its larger reverse recovery current peak and longer recovery time. The GaN SBD shows the lowest noise spectrum level of all because of its smallest reverse current peak and recovery time.

![Fig. 4. The measured frequency spectrum of conducted noise.](image)

Fig. 4(b) shows the spectrum of the conducted noise terminal voltage at higher frequencies (10–100 MHz). The RBW was 120 kHz. No significant differences were found in the spectrum level among the diodes at 50 MHz, which is dominated by the turn-off characteristics of the MOSFET. The SiC SBD exhibits spectrum peaks of around 70 MHz. A spectral peak was observed at around 100 MHz for the GaN SBD and the Si PiND. The differences in the frequencies and levels of the measured noise spectrum peaks for each diode agree with the frequencies extracted from the ringing oscillation and their damping factor of the diode currents during turn-off operations by Prony analysis. The results suggest that the ringing oscillation in the diode switching current has a significant influence on the conducted noise level and spectrum distribution above 50 MHz.
4 Conclusion

This study experimentally characterized the switching behavior and the conducted noise of a GaN SBD in a CCM DC–DC boost converter. The turn-off characteristics of the GaN SBD were found to be comparable to those of the SiC SBD. The small reverse recovery current peak and short recovery time of the GaN SBD led to lower line-conducted noises at frequencies of up to 30 MHz as compared with those of the Si PiND. The ringing oscillation in the diode switching current had a significant influence on the EMI noise levels above 50 MHz. The frequency and damping in the ringing oscillations of the diode currents during turn-off operations were dependent on the junction capacitance and ESR of the diode. The smaller ESR of the GaN SBD resulted in fewer damping characteristics than that of the Si PiND. The smaller capacitance of the GaN SBD led to a higher oscillation frequency than that of the SiC SBD. However, GaN SBD still faces many challenges related to the crystal quality and surface treatment. Significant improvement and design optimization of GaN power diodes are required before a comparison with the performance of SiC SBDs can be made.

Acknowledgments

This work was partially supported by the Ministry of the Environment, Government of Japan.