High Power 3-phase to 3-phase Matrix Converter Using Dual-gate GaN Bidirectional Switches

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***Abstract*— Highly efficient three-phase to three-phase matrix converters using Gallium nitride (GaN) bidirectional switches with both high current and high breakdown voltage are demonstrated. The GaN switch with dual gates works as a bidirectional switch by a single device, while a conventional bidirectional switch consists of four devices by two Insulated Gate Bipolar Transistors (IGBTs) and two diodes. In addition, the GaN bidirectional switch is also free from the voltage offsets for the current conduction so that the GaN-based matrix converter enables small size and highly efficient AC/AC conversion. Improvement of the device performance including the introduction of the recessed gate enables the low on-state resistance with stable operation free from current collapse. The maximum drain current reaches 100 A together with the breakdown voltage of 1340 V. The fabricated three-phase to three-phase matrix converter exhibits the maximum conversion efficiency of 98% at 1 kW output power with the expectation that the maximum output power can reach 10 kW or more by the high current device.**

Keywords—GaN; bidirectional switch; matrix converter;

I. INTRODUCTION

Matrix converters have been expected as the most efficient topology of AC/AC conversion because the single-stage conversion could reduce various operation losses in conventional double-stage AC/DC/AC conversion [1]. The most critical component in a matrix converter is a bidirectional switch that had been composed of the series and anti-parallel connection of two Insulated Gate Bipolar Transistors (IGBTs) and Fast Recovery Diodes (FRDs). In the conventional bidirectional switch, the total size of the multiple devices are larger as well as the forward and reverse conduction suffer from the on-state voltage offset. These disadvantages result in the limitation of the reduction of the system size and the operating loss. Gallium nitride (GaN)-based bidirectional switch with dual gates has been proposed as a viable solution for the above issues [2]. So far, monolithic integration of multiple bidirectional switches packaged with isolated gate-drivers has been also proposed targeting at very compact matrix converters [3]. However, the device can only handle low current in a small chip so that the achievable output power remains small and the integrated device is not suited for the practical use.

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In this paper, highly efficient operation of three-phase to three-phase (3×3) matrix converters is demonstrated using GaN bidirectional switches with the high maximum drain current (I_{max}) of 100 A and the breakdown voltage of 1340 V. The on-state resistance (R_{on}) is reduced down to 42 mΩ. The GaN-based matrix converter can achieve the output power over 10 kW or more by the high-current device and thus very promising for future compact and highly efficient AC/AC conversion systems.

II. GAN BIDIRECTIONAL SWICTH WITH HIGH CURRENT AND HIGH BREAKDOWN VOLTAGE

Fig. 1 shows the circuit diagram of a 3×3 matrix converter in which nine bidirectional switches are used. The detailed configuration of the components for a bidirectional switch is also shown in Fig. 2. The bidirectional switch is enabled by only a single GaN device with dual gates, while total four devices by two IGBTs and two FRDs are required for the conventional one. The dual-gate configuration reduces the total length between the two source terminals by sharing the length between the two gates as the channel distance for both directions, which leads to successful reduction of the on-state resistances [2]. Fig. 3 shows a schematic cross section of the

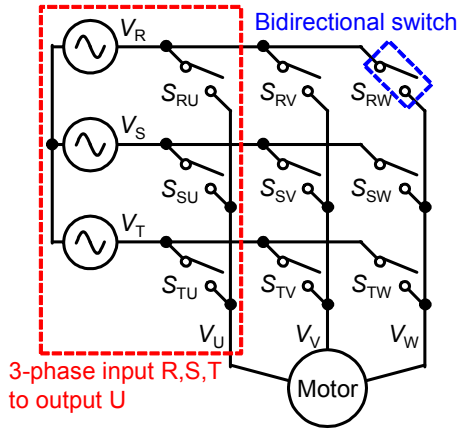

Fig. 1. Circuit diagram of 3×3 matrix converter with nine bidirectional switches.

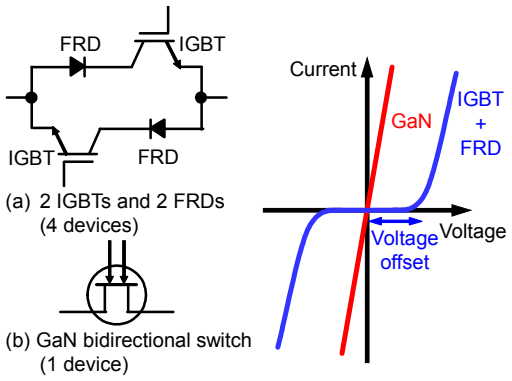

Fig. 2. Configurations and *I-V* characteristics of GaN and IGBT-based bidirectional switches.

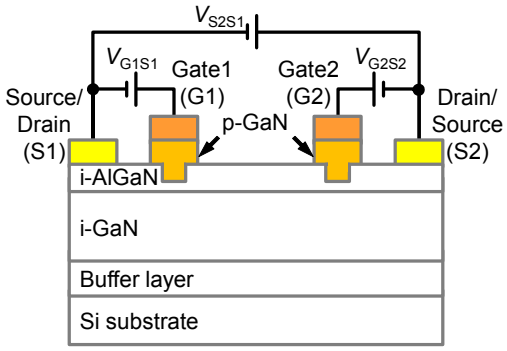

Fig. 3. A schematic cross-sections of GaN bidirectional switch with dual-gate structure.

fabricated GaN bidirectional switch. Recessed gates formed by p-GaN/i-AlGaN regrowth technique are introduced in order to reduce the on-state resistances and variation of the threshold voltages over the large wafer [4-5]. Fig. 4 shows the current-voltage (*I-V*) characteristics of the GaN switch for three sets of the gate biasing conditions. The three *I-V* curves represent the required operation modes for 3×3 matrix converters. The R_{on} is reduced down to 42 mΩ together with the I_{max} of 100 A as shown in Fig. 4 (a). The breakdown voltage is increased to 1340 V by increasing the buffer thickness on Si substrate as shown in Fig. 4 (b). Here, the breakdown voltage is fully increased to stand the increased input voltage and the unexpected overvoltage between the terminals caused by the inductive load operation. Operation of the switch as if a diode with reverse blocking capability is required as a part of the commutation sequence as shown in Fig. 4 (c). It is also noted that the current collapse in which the R_{on} is increased after the application of high operation voltage is fully eliminated in the fabricated GaN switch by the improvement of device structure and the processing [4-5].

III. HIGHPOWER GAN 3×3 MATRIX CONVERTER

The commutation sequence of the gate control needs to be carefully designed in the GaN 3×3 matrix converter to avoid the undesired open/short circuits between the switches. The current commutation strategy for the GaN matrix converter is summarized in Fig. 5. Three switches are a single set for a single phase output, where only one switch needs to be on-state. In order to change the on-state switch to the other, reverse blocking diode mode needs to be inserted as shown in Fig. 5. As shown in Fig. 4 (b), turning on only a single gate of the GaN switch enables the reverse blocking diode mode that is required for the commutation. Simultaneous turn-on and turn-off for the both gates of the GaN bidirectional switch enable the on-state and the off-state in the strategy, respectively. As a result, the commutation strategy is implemented by setting the sequences of gate control with the commutation step of 1 μs. Fig. 6 shows a photograph of the fabricated GaN 3×3 matrix converter, where nine sets of GaN bidirectional switches and gate driving circuits are mounted on

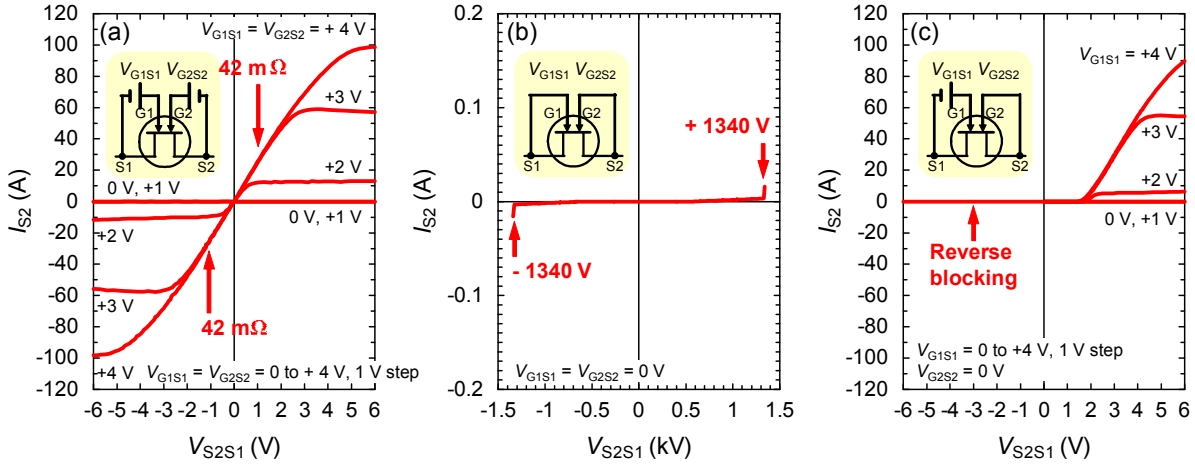

Fig. 4. *I-V* characteristics of the fabricated GaN bidirectional switch for three operation modes for (a) ON state, (b) OFF state and (c) Diode mode, respectively.

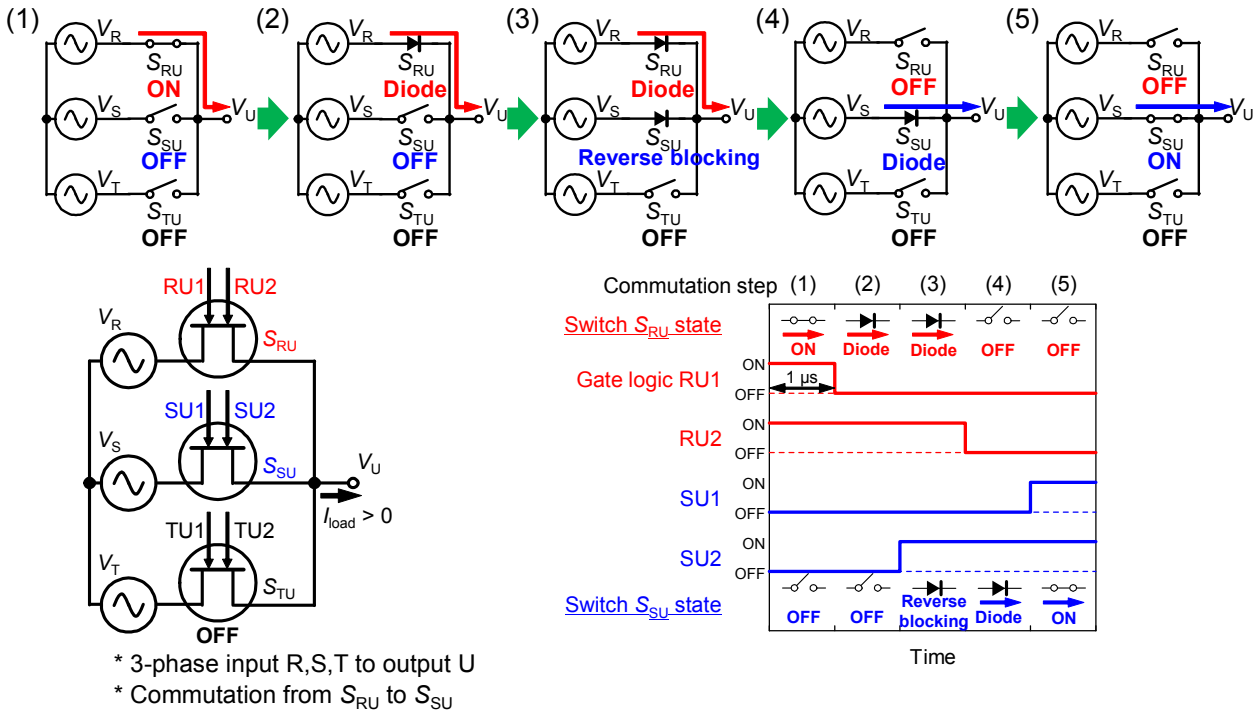

Fig. 5. Control sequences of current commutation for GaN bidirectional switches.

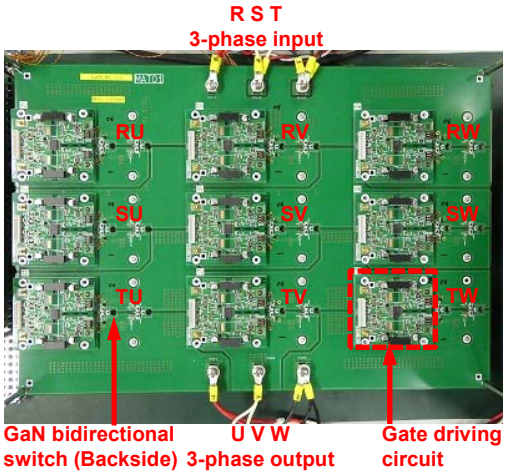

Fig. 6. Fabricated GaN 3×3 matrix converter with nine GaN bidirectional switches and gate driving circuits.

a single circuit board. A three-phase, 200-V, 50-Hz AC voltage is applied to the matrix converter connected to resistive-inductive (RL) load of 5 - 45 Ω and 1.1 mH with the output frequency and the carrier frequency of 50 Hz and 10 kHz, respectively. The operating waveforms, measured operating efficiencies and losses for various output power are summarized in Fig. 7 and Fig. 8, respectively. Here, maximum conversion efficiency reaches 98% at the output power of 1 kW that is significantly higher than that by IGBT-based matrix converter. Figure 9 shows the detailed analysis of the operating loss for both GaN-based and IGBT-based matrix converters. The resultant operating loss is reduced almost by half in the GaN-based matrix converter from the IGBT-based one, in which the conduction loss is dramatically reduced by the reduction of on-state resistance and the elimination of forward voltage offset by the GaN devices. Although the employed GaN switches with the R_{on} of 42 mΩ, the I_{max} of 100 A and the breakdown voltage of 1340 V would demonstrate the 3×3 matrix converter with higher output power in the range of 10 kW or more, the measurements are just up to 2 kW because of the limitation of the measurement set-up.

IV. Conclusions

In this paper, successful operation of 3×3 matrix converters using GaN bidirectional switches is demonstrated. The GaN switch with dual gates enables bidirectional operation with low R_{on} together with the operation of reverse blocking diode mode. The I_{max} reaches 100 A together with the breakdown voltage of 1340 V by the improvement of the device structure and processing. The fabricated GaN 3×3 matrix converter exhibits the maximum operating efficiency of 98% at 1 kW output power. The GaN switches with high current have capability to achieve high output power in the range of 10 kW, of which the experimental confirmation remains as a future work. This indicates that GaN bidirectional

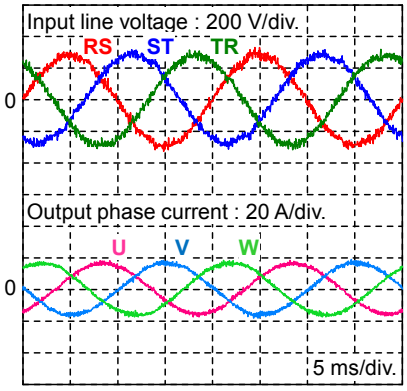

Fig. 7. Operating waveforms of the fabricated GaN matrix converter at the output power of 2 kW.

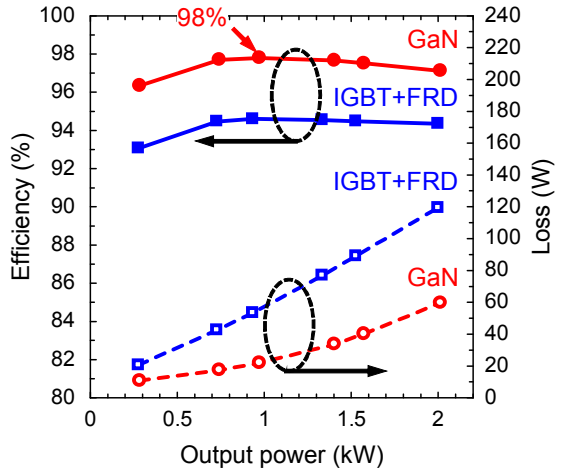

Fig. 8. Measured conversion efficiencies and losses for various output power.

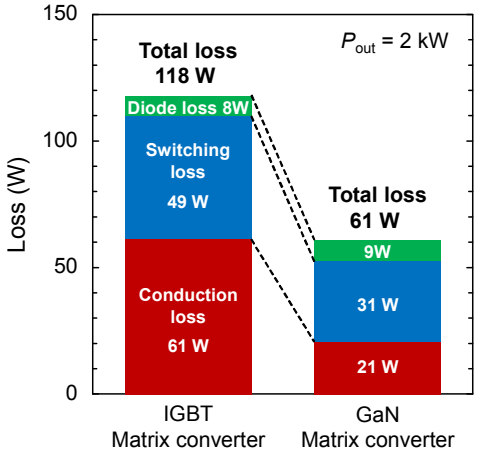

Fig. 9. Detailed analysis of the operating loss for GaN-based and IGBT-based matrix converters at the output power of 2 kW.

switches are very promising for compact and efficient AC/AC conversion.

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REFERENCES

[1] P. W. Wheeler, J. Rodriguez, J. C. Clare, L. Empringham, and A. Weinstein, "Matrix converters: a technology review," IEEE Trans. Ind. Electron., vol. 49, no. 2, pp. 276–288, 2002.

[2] T. Morita, M. Yanagihara, H. Ishida, M. Ishida, K. Kaibara, H. Matsuo, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, "650 V, 3.1 mΩcm^2 GaN-based monolithic bidirectional switch using normally-off gate injection transistor," in Int. Electron Devices Meeting (IEDM), pp. 865-868, 2007.

[3] S. Nagai, Y. Yamada, N. Negoro, H. Handa, Y. Kudoh, H. Ueno, M. Ishida, N. Otsuka, and D. Ueda, "A GaN 3×3 matrix converter chipset with Drive-by-Microwave technologies," in Int. Solid-State Circuits Conference (ISSCC), pp. 15-17, 2014.

[4] S. Kaneko, M. Kuroda, M. Yanagihara, A. Ikoshi, H. Okita, T. Morita, K. Tanaka, M. Hikita, Y. Uemoto, S. Takahashi, and T. Ueda, "Current-collapse-free operations up to 850 V by GaN-GIT utilizing hole injection from drain," in Int. Symp. on Power Semiconductor Devices and ICs (ISPSD), pp. 41-44, 2015.

[5] H. Okita, M. Hikita, A. Nishio, T. Sato, K. Matsunaga, H. Matsuo, M. Mannoh, and Y. Uemoto, "Through recessed and regrowth gate technology for realizing process stability of GaN-GITs," in Int. Symp. on Power Semiconductor Devices and ICs (ISPSD), pp. 23-26, 2016.