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Self-Reverse-Blocking Normally-On/Off-Dual-Gate Monolithic Bidirectional GaN Transistor

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***Abstract*—Current-source rectifiers and similar topologies require switches with bipolar voltage blocking and unidirectional current conduction capability. The traditional combination of a transistor and a diode of equal voltage rating results in high conduction losses. GaN dual-gate monolithic bidirectional switches (MBDSs) can mimic the functionality but require twice the number of gate signals. Advantageously, self-reverse-blocking (SRB) functionality can be realized with normally-on MBDSs in a cascode configuration with a low-voltage (LV) Schottky diode, resulting in favorable quasi-ohmic conduction characteristic. Here, we introduce a new hybrid normally-on/off dual-gate GaN MBDS (H-MBDS) to realize an SRB-H-MBDS with a single external normally-off gate and present static and dynamic experimental characterization using a 650-V, 140-mΩ H-MBDS and a 60-V, 20-A LV diode.**

***Keywords*—Monolithic bidirectional GaN switch, self-reverse-blocking, hybrid D/E-mode dual-gate.**

I. Introduction

Current-source rectifiers (CSRs) or inverters (CSIs) [1], [2] and similar power converter topologies [3]–[5] require switching devices that can block bipolar voltages and conduct unidirectional currents. Historically, symmetric GTOs [6], reverse-blocking (RB) IGCTs [7], and then RB IGBTs [3] have been employed in (pulse-width-modulated) CSR/CSI systems. However, in order to minimize the size of magnetic components like the dc-link inductor via higher switching frequencies, in modern systems, wide-bandgap (WBG) devices i.e., conventionally, a combination of a high-voltage (HV) MOSFET and a HV diode with the same voltage rating as shown in **Fig. 1a** should be used [1]. But, this results in high conduction losses due to the HV diode threshold voltage, see **Fig. 2a**. Recently, dual-gate GaN monolithic bidirectional switches (MBDSs) [8]–[10] have become available, which use a single drift region to block both voltage polarities and hence show low, purely ohmic conduction losses. However, as each MBDS features two gates (one for controlling each direction of current flow), the number of gate drivers and signals, and the control complexity (e.g., due to multi-step commutation sequences [11]) increase. Alternatively, the required RB behavior can be realized by an advanced gate drive that controls one gate directly based on sensed device voltage and/or current [12]. This retains the favorable ohmic conduction characteristic of the MBDS, but requires a relatively complicated gate drive and sensing circuitry.

Therefore, based on well-known cascode configurations of a HV transistor with a low-voltage (LV) transistor [13] or with an LV diode [14], we have demonstrated a *self-reverse-blocking* (SRB) MBDS in [15], i.e., a 600-V/190-mΩ GaN MBDS with two normally-on gates, one of which has been controlled via a cascode connection of an LV 40-V/10-A Schottky diode, similar to **Figs. 1bd**. If a voltage $v < 0$ is applied between S_{ext} and S_1, a small share (a few volts) across the LV diode appears as $v_{G2S2} < 0$ and thus turns off the normally-on gate of the MBDS, which then blocks the major share of the applied voltage. Advantageously, the LV diode contributes only a comparably small threshold voltage and hence overall favorable quasi-ohmic conduction characteristics result. However, if a depletion-mode (D-mode i.e. a normally-on) MBDS is used as in [15], the external gate G_1 used to control the blocking of $v > 0$ shows a normally-on characteristic, too. Whereas this can be beneficial in certain topologies[1], full functional equivalence with the standard approach (HV transistor in series with an HV diode) regarding control and modulation implementation would require

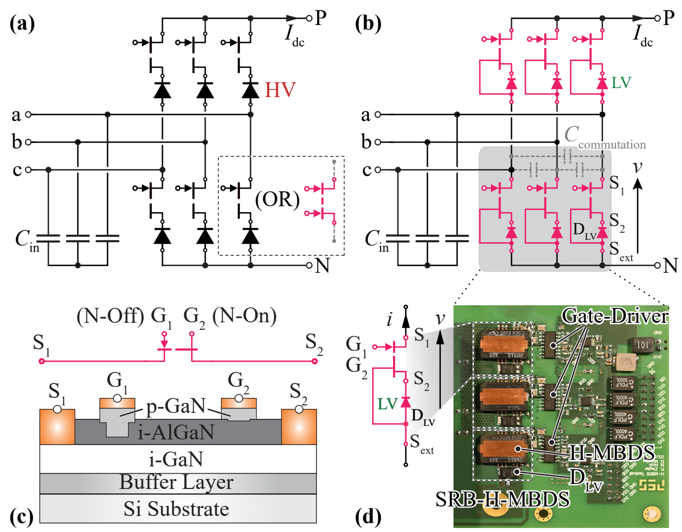

Fig. 1. **(a)** Three-phase current-source rectifier (CSR) with switching elements featuring bipolar voltage blocking and unidirectional current conduction capability, i.e., an HV MOSFET in series with an HV diode; alternatively, dual-gate MBDSs could be employed but require twice the number of gate signals. **(b)** CSR with the proposed SRB-H-MBDSs using an LV diode in a cascode configuration with a normally-on MBDS gate, and **(c)** conceptual cross section of a novel hybrid GaN MBDS with one normally-off and one normally-on gate; the key difference is the presence (normally-off) or absence (normally-on) of a threshold modulation layer (e.g., a p-GaN layer) underneath the gate contact. **(d)** Test PCB with one SRB-H-MBDS-based CSR commutation cell.

[1]For example, in CSRs or CSIs, in case of a gate drive power supply failure a freewheeling path for the dc-link current would naturally establish, while the SRB feature would prevent short-circuiting the ac-side capacitors.

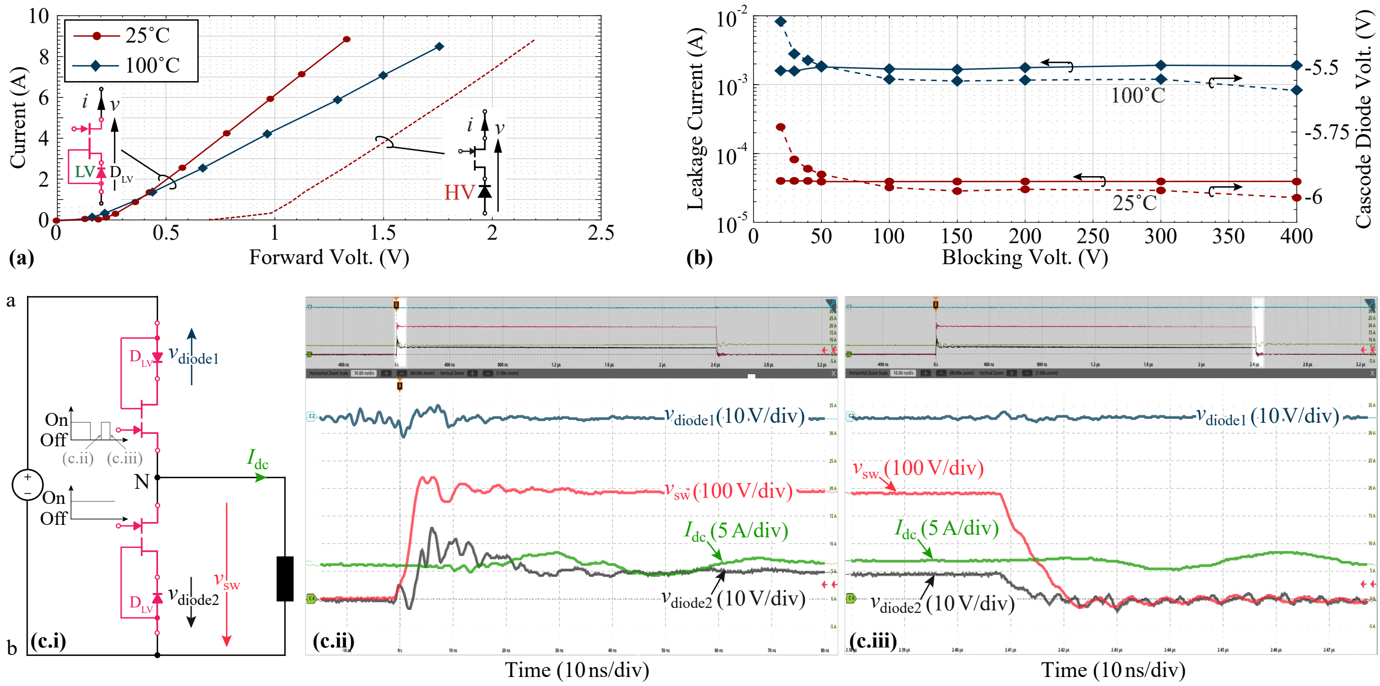

Fig. 2. Characterization of the SRB-H-MBDS based on a 650-V, 140-mΩ H-MBDS and a 60-V, 20-A LV diode (Diodes Inc., SBRT20U60SP5-13). **(a)** Measured forward characteristics (calculated curve for series connection of a 140-mΩ transistor and a 650-V, 10-A SiC diode (ST STPSC10065) at 25 °C shown for reference). **(b)** Measured reverse blocking characteristics with external normally-off gate turned on. **(c.i)** Double-pulse test setup and measured key waveforms for **(c.ii)** hard turn-off and **(c.iii)** soft turn-on transitions of the low-side SRB-H-MBDS at 25 °C and 400 V, 6 A.

an external gate with normally-off characteristic—i.e., an asymmetric/hybrid normally-on/off dual-gate GaN MBDS (H-MBDS) as shown in **Fig. 1c**. Whereas such devices have been demonstrated for logic-level signals [16] before, we demonstrate here, for the first time, a 650-V/140-mΩ GaN H-MBDS[2] and characterize the corresponding SRB implementation (SRB-H-MBDS), whose externally controlled gate is now, in contrast to our earlier work from [15], of the normally-off type.

II. SRB-H-MBDS Experimental Characterization

Fig. 1d shows the realized test PCB with a CSR commutation cell consisting of three SRB-H-MBDSs. Each is realized using a 650-V, 140-mΩ H-MBDS sample from Infineon and a 60-V, 20-A LV diode arranged in a cascode configuration to control the H-MBDS normally-on gate. Note that a TVS diode is placed in parallel to the LV diode for protection purposes, but, in contrast to [15], no additional snubber elements were needed in the cascode circuitry; this is possibly owed to the better commutation cell layout enabled by the top-cooled packages of the H-MBDS samples (compared to the bottom-cooled packages of the MBDSs used previously in [15]).

Fig. 2a shows the measured conduction characteristics[3] and **Fig. 2b** the leakage current of the SRB-H-MBDS and the voltage across the LV diode in the blocking state. It should be noted that the SRB-H-MBDS cascode configuration's leakage current is determined by the LV diode's blocking characteristics, where a trade-off exists between low leakage current and low forward voltage drop of the diode [15]. **Fig. 2c** verifies the SRB-H-MBDS switching behavior in a half-bridge formed by two of the commutation cell's three devices (the third is present and exposed to the dv/dt of the switching transitions without actively taking part, see [10]). Whereas in [15], the SRB-MBDS has been commutated against a normal GaN FET, here we use a symmetric arrangement of two SRB-H-MBDSs. Due to the symmetry, it is sufficient to show the results for only one voltage polarity, even though both have been successfully tested and symmetric behavior has been verified. Clearly, the cascode works as expected, turning off the normally-on gate when the SRB-H-MBDS should block $v_{sw} > 0$; also, the cascode diode voltage of the high-side SRB-H-MBDS is stable during the switching transitions.

III. Conclusion

A new hybrid normally-on/off dual-gate GaN MBDS enables a new variant of an SRB-MBDS whose external gate is of the normally-off type. This new SRB-H-MBDS is thus functionally equivalent (current conduction and voltage blocking capability; single gate control signal) to a series connection of an HV transistor and a diode of equal voltage ratings as conventionally used in topologies like CSRs and CSIs, but shows favorable quasi-ohmic conduction characteristics due to the cascode configuration of the H-MBDS' second, normally-on gate with a LV diode. The concept is verified by static and dynamic measurements using 650-V, 140-mΩ H-MBDS samples. Future work should address the loss characterization and possibly the integration/co-packaging of the H-MBDS and the cascode LV diode.

[2] 140 mΩ max. at 25 °C, typically 110 mΩ.

[3] Measurements were taken with a sufficiently short current pulse to limit self-heating. DUT heated to 100 °C with temperature-controlled heating plate.

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