Letters

Self-Reverse-Blocking Control of Dual-Gate Monolithic Bidirectional GaN Switch With Quasi-Ohmic ON-State Characteristic

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***Abstract*—Converter topologies such as current-source rectifiers and inverters require switching devices with bipolar voltage blocking and unidirectional current conduction capability. Recently available dual-gate GaN monolithic bidirectional switches (MBDSs) can mimic such self-reverse-blocking (SRB) behavior if the MBDS' two gates are controlled accordingly, but thus need twice the number of gate signals and gate drive circuits. Therefore, we propose cascode-diode control (i.e., without additional sensing or gate drive circuitry) of one MBDS gate using a cascode configuration with a low-voltage silicon Schottky diode. The resulting SRB-MBDS features quasi-ohmic conduction characteristic and single-gate control. We provide static and dynamic measurements of a discrete proof-of-concept realization (600-V, 190-mΩ GaN MBDS; 40-V, 10-A silicon Schottky diode) that demonstrate the proposed SRB-MBDS' feasibility.**

***Index Terms*—Bipolar voltage blocking, dual-gate GaN monolithic bidirectional switch, quasi-ohmic conduction characteristics, self-reverse-blocking.**

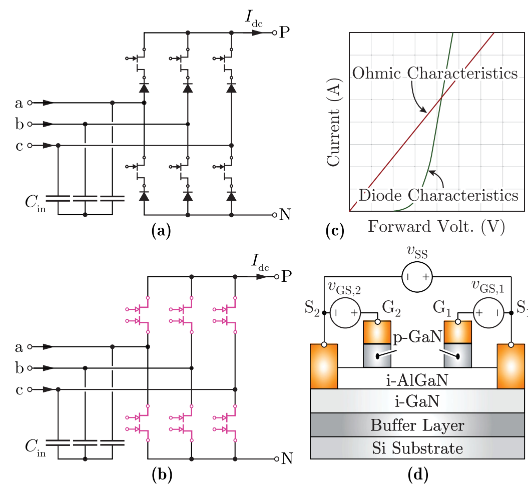

Fig. 1. CSR topology with unidirectional dc-link current that requires switching devices with bipolar voltage blocking and unidirectional current conduction capability, realized in (a) by a series connection of a GaN FET and a HV diode and in (b) with MBDs that feature favorable ohmic conduction characteristics [see (c)], but require two gate control signals per device. (d) Cross section of a dual-gate normally-OFF GaN MBDS with a shared drain-gate region for blocking either voltage polarity.

I. Introduction

VARIOUS power electronic converter topologies such as current-source rectifiers [CSR, see Fig. 1(a)] and inverters (CSI) [1], current-fed converters [2], inverting-link matrix converters [3], resonant inverters, and others [4] require switching devices capable of bipolar voltage blocking but only unidirectional current conduction. Silicon devices such as reverse-blocking insulated gate bipolar transistor (RB-IGBTs) [4] achieve an integrated realization of this functionality. However, in case wide-bandgap (WBG) power semiconductors should be used, e.g., to achieve higher switching frequencies and hence more compact converter realizations, a series connection of a transistor and a diode with *the same voltage rating*, i.e., a high-voltage (HV) diode, is required instead [1]. This series connection shows a diode-like (threshold voltage) conduction characteristic [see Fig. 1(c)]. Similarly, two power field effect transistor (FETs) could be connected in anti-series to realize a four-quadrant switch (i.e., with bidirectional conduction capability), resulting in an ohmic conduction characteristic but still in increased conduction losses as a consequence of effectively providing twice the blocking voltage than actually needed. Instead, novel dual-gate *monolithic* bidirectional GaN transistors [5], [6] use the same chip region for blocking either voltage polarity [see Fig. 1(b) and (d)], resulting in a (bidirectional) ohmic conduction characteristic similar to that of a single transistor. However, each such monolithic bidirectional switch (MBDS) requires *two* external gate control signals, even when employed in a topology with a fixed current direction, for which a reduced reverse-blocking functionality [see Fig. 2(a)]—controllable by a single gate signal—would suffice.

Therefore, in Section II, we discuss concepts for realizing self-reverse-blocking MBDSs (SRB-MBDSs) that combine an MBDS' favorable ohmic conduction characteristics with single-gate control and can be realized without additional sensing effort. We then provide a proof-of-concept of the proposed approach based on a cascode arrangement of a first-generation 600-V GaN MBDS and a low-voltage (LV) silicon Schottky diode in Section III.

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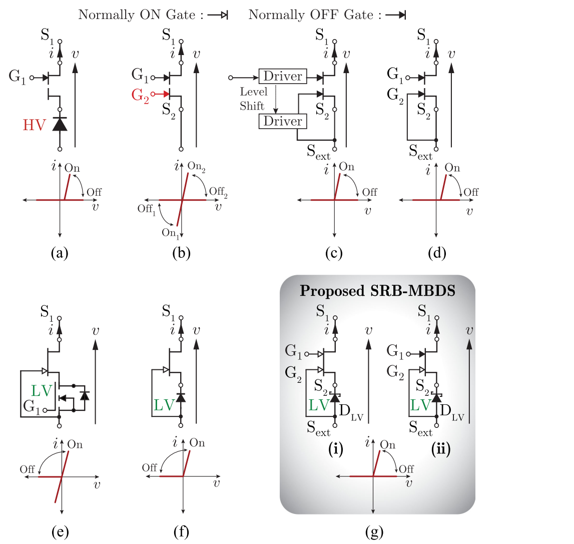

Fig. 2. Configuration and v-i characteristics of (a) a series connection of a HV diode and a FET that realizes the desired [see Fig. 1(a)] bipolar voltage blocking and unidirectional current conduction functionality. The normally-OFF MBDS in (b) provides bidirectional conduction capability but needs a second gate control signal. SRB-MBDS realization with (c) integrated *active* synchronous rectification and (d) simple *self*-control of one gate of a normally-OFF MBDS, suffering however from high ON-state losses. (e) and (f) show known cascode configurations that realize HV switch [7] or HV diode [8] functionality, respectively. (g)(i) Proposed cascode configuration of a normally-ON MBDS and a LV silicon Schottky diode D_{LV}, which realizes the same functionality as (a) without any active circuitry, and, advantageously, shows a quasi-ohmic conduction characteristic dominated by the MBDS; (g)(ii) shows a realization with normally-OFF characteristics of the externally accessible MBDS gate terminal.

II. RB-MBDS Concepts

A dual-gate GaN MBDS is a four-terminal device with an internal common drain region and two external gate and two external source terminals [see Fig. 1(d)]. Each gate individually controls the blocking of one of the two possible polarities of the voltage v applied between the source terminals [see Fig. 2(b)]. Therefore, the desired reverse-blocking behavior can be achieved if one of the two gates is *automatically* controlled according to the polarity of v.

Correspondingly, *active* "self-switching" concepts have been proposed earlier [9]; an advanced local gate drive and control unit senses the applied voltage and/or the device current, processes this information and controls the two gates of two antiseries connected MOSFETs to mimic the (programmable) behavior of an arbitrary switching device, e.g., that of a diode. Similarly, the desired SRB-MBDS could be realized by controlling one gate by a local active synchronous rectification logic [see Fig. 2(c)]. Whereas this approach facilitates lowest conduction losses (MBDS channel resistance only for both current directions), it requires additional active circuitry.

Instead, we propose *automatic self-switching* of one of the MBDS' two gate terminals. In the simplest case, automatic control of a normally-OFF gate to achieve diode-like behavior is realised by directly connecting it to the corresponding source terminal, thus enforcing a gate-source voltage $v_{G2,S2} = 0\,V$ [see Fig. 2(d)]. This ensures blocking of a negative polarity source–source voltage ($v \leq 0\,V$). The other gate terminal, G_1, enables active (external) control of the other blocking polarity ($v \geq 0\,V$). However, a current flow from S_2 to S_1 will incur a forward voltage drop consisting of the MBDS' channel resistance *plus* a contribution caused by the turned-OFF gate G_2; in case of GaN FETs, this corresponds to the threshold voltage which typically is in the range of 1 to 1.5 V—i.e., higher than that of a HV SiC Schottky diode (see also the measurement results presented in Section III-A).

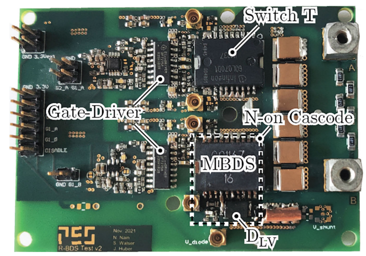

Fig. 3. Hardware implementation of the proposed SRB-MBDS configuration of Fig. 2(g) with a first generation normally-ON 600-V, 190-mΩ GaN MBDS, and a 40-V, 10-A silicon Schottky diode D_{LV} (Diodes Inc., PDS1040) along with a high-side unidirectional GaN FET, T [see Fig. 6(a) and (d)].

Cascode configurations of normally-ON HV WBG devices (such as junction-gate field effect transistor (JFETs)) and LV silicon devices such as MOSFETs [7] [see Fig. 2(e)] or diodes [8] [see Fig. 2(f)] to realize HV switches or HV diodes, respectively, with improved characteristics have been proposed earlier. Inspired by the latter, we propose the cascode configuration of a normally-ON MBDS and an LV silicon Schottky diode to realize an SRB-MBDS as shown in Fig. 2(g)(i). The proposed cascode configuration is capable of blocking bipolar voltages; for negative polarity of $v \leq 0$, the share of this voltage applied across the LV diode appears as a negative gate-source voltage at the normally-ON gate G_2 of the MBDS, ultimately turning it OFF. The blocking state of the other voltage polarity, $v \geq 0$, can be controlled by the external gate terminal G_1. A current flow in forward direction from terminal S_{ext} to S_1 now incurs an ON-state voltage consisting of the MBDS' channel resistance plus the additional forward-voltage drop of the LV silicon Schottky diode D_{LV}. Being an LV diode, this voltage drop is relatively small and typically in the range of 0.3–0.5 V only, facilitating a quasi-ohmic conduction characteristic of the proposed SRB-MBDS.

Note that it is in principle possible to manufacture asymmetric dual-gate GaN MBDSs with one normally-ON and one normally-OFF gate, as the essential structural difference resulting in the two different gate characteristics is the absence (normally-ON) or presence (normally-OFF) of, e.g., a p-GaN layer beneath the gate contact (monolithic integration of D- and E-mode GaN transistors has accordingly been demonstrated for logic-level devices, e.g., in [10]). Advantageously, asymmetric dual-gate GaN MBDSs facilitate the realization of a cascode-based SRB-MBDS having an external gate with normally-OFF characteristic as shown in Fig. 2(g)(ii); the manufacturing of such samples is ongoing and will be the subject of a future publication.

III. Experimental Proof-of-Concept

We demonstrate the feasibility of the cascode-based SRB-MBDS [see Fig. 2(g)] using a discrete proof-of-concept realization (see Fig. 3) with Infineon's first-generation normally-ON 600-V, 190-mΩ GaN MBDS and a 40-V, 10-A silicion Schottky diode (Diodes Inc., PDS1040).

A. Conduction Characteristics

Fig. 4 shows the measured[1] conduction characteristics of the proposed SRB-MBDS as well as that of the alternative realization

[1] Voltages measured with Agilent A34410A precision multimeters, current measured using a high-precision 0.5-Ω shunt resistor (SSDN-50) and an Agilent A34410A precision multimeter; measurements were taken immediately after the transient of an externally applied voltage pulse had subsided (to limit self-heating). In all experiments, the device under test (DUT) has been heated with a heat plate from below and the temperature has been measured with a negative temperature coefficient (NTC) (Littlefuse PS104J2) glued to the top of the semiconductor packages.

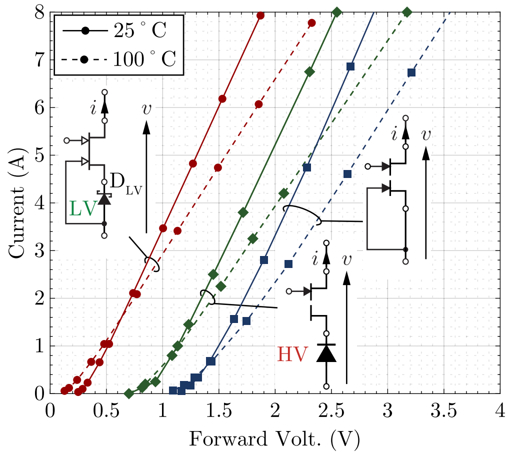

Fig. 4. Measured conduction characteristics of the proposed SRB-MBDS configuration [see Fig. 2(g)] using a normally-ON 600-V, 190-mΩ GaN MBDS and a 40-V, 10-A silicon Schottky diode (Diodes Inc., PDS1040); of the conventional approach, i.e., a series connection of a unidirectional GaN FET (with equal ON-state resistance as measured for the MBDS) and a 650-V, 10-A SiC Schottky diode (ST STPSC10065); and of the alternative SRB approach based on a normally-OFF 600-V, 190-mΩ GaN MBDS [see Fig. 2(d)], which shows higher ON-state losses.

(normally-OFF MBDS with one gate shorted to the corresponding source). For reference, we also show the conduction characteristics of a series combination of a 650-V, 10-A SiC Schottky diode (ST STPSC10065-Y) and a (hypothetical) unidirectional GaN FET with the same ON-state resistance ($R_{ds,on}$) as measured for the MBDS.[2] The proposed SRB-MBDS concept presents quasi-ohmic conduction characteristics with a significantly lower voltage drop compared to the default approach (unidirectional FET and HV diode).

B. Blocking Characteristics

Fig. 5(a) shows the measured[3] leakage current of the normally-ON MBDS (without cascode diode) at a blocking voltage of 400 V in dependence of its gate-source voltage. In the cascode SRB-MBDS, this gate-source voltage corresponds to the blocking voltage of the LV diode, while the same leakage current flows through the MBDS and the diode (series connection). Therefore, a steady-state operating point can be identified graphically by intersecting the MBDS' leakage current versus gate voltage characteristic at the desired blocking voltage with the diode's reverse-blocking characteristic (from the datasheet), which is also shown in Fig. 5(a).

Fig. 5(b) shows the measured leakage current of the cascode SRB-MBDS in dependence of the applied blocking voltage. The externally controlled gate terminal G_1 is turned-ON, which highlights the reverse-blocking capability of the proposed SRB-MBDS concept. As the diode's leakage current is approximately constant for minor variations of its reverse voltage [see Fig. 5(a)], a reduction of the MBDS' leakage current for lower blocking voltages [11] is prevented by a slight increase of the MBDS' gate voltage [and hence of the diode's reverse voltage, as can be seen in Fig. 5(a)]. The overall SRB-MBDS' leakage current is thus almost independent of the blocking voltage and it is ultimately defined by the LV diode's reverse characteristic. Its selection/design is thus subject to a tradeoff between a lower leakage current and a lower forward-voltage drop of the cascode combination, as also mentioned in [8] for realizing a HV diode with low ON-state voltage drop.

[2]This implies approximately equal GaN chip area for both solutions.

[3]Voltages and current (via a calibrated 132-kΩ shunt for 25 °C and a 996-Ω shunt for 100 °C) measured with Agilent A34410 A precision multimeters.

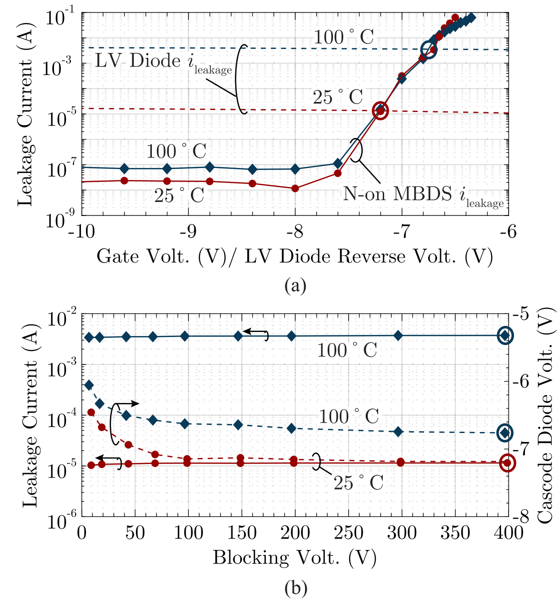

Fig. 5. Blocking characteristics. (a) Measured leakage current of the normally-ON 600-V, 190-mΩ GaN MBDS at 400-V blocking voltage, intersected with the 40-V, 10-A LV silicon Schottky diode's (Diodes Inc., PDS1040) reverse characteristic (datasheet) to identify the steady-state operating points. (b) Measured leakage current of the proposed cascode SRB-MBDS [see Fig. 2(g)] and the voltage across D_{LV} in dependence of the applied blocking voltage; note that the externally accessible gate G_1 is turned-ON.

C. Switching Characteristics

A double-pulse setup has been realized to demonstrate the proposed SRB-MBDS' switching operation for both blocking voltage polarities (see Fig. 6; note the different polarities of the dc voltage as well as of the unipolar GaN FET used as the high-side switch in Fig. 6(a) and (d), respectively). The SRB-MBDS cascode has been complemented by a transient voltage suppressor (TVS) diode (for transient overvoltage protection during testing only) and a 1.5-nF capacitor connected in parallel to the LV Schottky diode, D_{LV}, a gate resistor of 6.8 Ω, and a gate-source capacitance of 100 pF. These snubber elements prevent self-sustained turn-OFF oscillations that can appear in cascode devices—Xue and Iannuzzo [12] provide a comprehensive analysis—especially in case of relatively large gate-loop inductances that could not be avoided in the discrete proof-of-concept realization.

The measurements shown in Fig. 6, which have been taken at dc voltages of $\pm 400\,V$, a load current of 6 A, and junction temperatures of 100 °C and 25 °C (not shown for reasons of space), demonstrate the feasibility of the proposed SRB-MBDS concept, even using discrete components. Note that the presence of the snubber elements may slow down the switching transients and hence lead to increased switching losses. However, minimizing the parasitics, e.g., by copackaging the devices, generally enables improved performance of cascode structures [13] and specifically may obviate the need for the snubber elements [12] and the associated undesired effects.

IV. Conclusion

Switching devices with bipolar blocking and unidirectional current conduction capability are typically realized as a series connection of a transistor and a diode with equal voltage rating, leading to high ON-state losses. Instead, we propose a cascode arrangement of a novel dual-gate GaN MBDS and a LV silicon Schottky diode. This SRB-MBDS configuration achieves lower ON-state losses and still requires only one external gate control signal, as the MBDS' second gate is controlled via

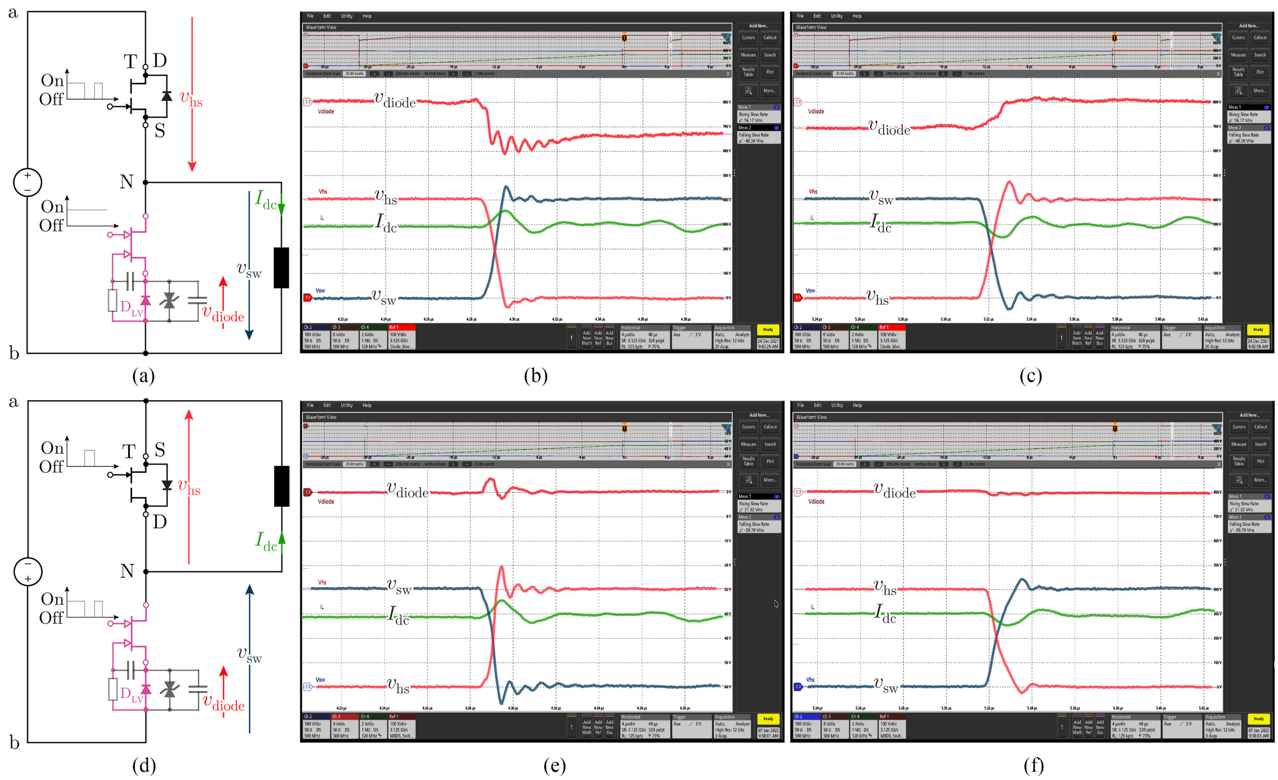

Fig. 6. Double-pulse test bench circuits for testing (a) the reverse-blocking behavior of the cascode SRB-MBDS, i.e., with the high-side transistor, T, being actively switched; (b) shows the SRB-MBDS' turn-OFF and (c) the turn-ON transition. Note that the high-side switch, T, is realized with a unipolar GaN FET. Similarly, (d) shows the test circuit, (e) the turn-ON, and (f) the turn-OFF transition for the other blocking voltage direction, which can be controlled by the SRB-MBDS' externally accessible single gate. All transitions are shown for 400-V DC voltage, 6-A load current, and 100 °C junction temperature. Time division: 20 ns/div; diode voltage, v_{diode}: 8 V/div (Tektronix IsoVu TIVH08); switch-node voltage, v_{sw}, and high-side drain-source voltage, v_{hs}: 100 V/div (PMK Bumblebee 500-MHz differential probe); load current, I_{dc}: 2 A/div.

the voltage occuring across a cascode-connected diode; there is no need for additional active sensing and gate drive circuitry. We demonstrate a proof-of-concept realized with discrete components, most prominently Infineon's fist-generation 600-V, 190-mΩ GaN MBDS. However, an *integration* of the LV diode and the GaN MBDS into the same package and careful fine-tuning of the device properties on the semiconductor level would be necessary to fully explore the proposed concept's performance limit.

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