Expert View

by Victor Veliadis

Monolithic Bidirectional WBG Switches Rekindle Power Electronics Technology

There are numerous mass volume power applications where it is necessary to control the flow of bidirectional power, including electric vehicles (vehicle to grid, vehicle to home, and vehicle to vehicle), distributed and grid-tie power systems using regenerated energy and/or energy storage components, and solid-state circuit breaker protection. Silicon carbide (SiC) and gallium nitride (GaN) based bidirectional power switches can enable these applications with their compelling advantages of high efficiency, high blocking voltage capability, and low system weight and volume. In particular, monolithic switches that allow for bidirectional symmetric conduction and voltage blocking with a chip area close to that of a similarly rated unidirectional switch are ideally suited to fuel a revolution in power electronics technology.

Today, monolithic bidirectional (MBD) power semiconductor switches are not commercially available. Instead, back-to-back connection schemes of unidirectional power MOSFETs or IGBTs are typically used, resulting in a 4X penalty in chip area and high cost. However, various types of SiC and GaN bidirectional concepts are being investigated including bonded-wafer bidirectional IGBTs, monolithic dual-gate bidirectional GaN switches, and MBD back-to-back connected SiC MOSFETs and JFETs.

GaN power devices are commercially available from multiple vendors in the high volume ~650 V range. They are of lateral configuration and the gate-to-drain spacing determines blocking voltage capability. A high mobility lateral 2-D electron gas conducts current, and the lack of a body diode facilitates symmetric bidirectional current flow. GaN power devices are typically designed with a large gate-to-drain spacing to withstand high voltage, and a smaller gate-to-source separation to accommodate the lower V_{GS} and save space on the wafer. This asymmetry only allows for unidirectional high voltage blocking. To enable symmetric bidirectional voltage blocking, equidistant source-gate and drain-gate spacings are required, which nearly doubles the size of the device. A more elegant MBD voltage blocking solution is the dual-gate structure of Figure 1 [1]. Sharing a common drain region reduces device cell pitch (lateral extent) and R_{on}, and only increases device area by about 1.2X compared to similarly rated commercial GaN unidirectional voltage blocking devices.

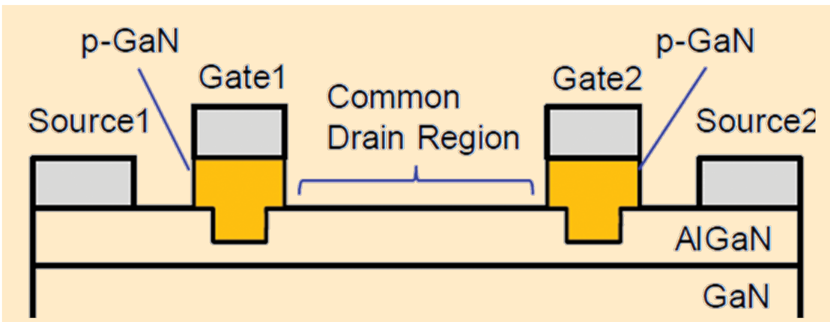

FIG 1 Monolithic bidirectional GaN switch with dual-gate structure. Sharing a common drain region reduces device cell pitch (lateral extent) and R_{on}.

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Recently, Panasonic demonstrated a prototype 1.1 kV, 100 A MBD GaN switch with dual-gate structure and R_{on} of 22 mΩ [2]. Infineon Technologies also demonstrated a similar monolithic dual-gate bidirectional GaN switch as part of their PowerAmerica project. Both Panasonic and Infineon have strong IP portfolios in this technology. Much like commercial lateral power GaN devices, their dual-gate bidirectional counterpart is fully silicon (Si) CMOS compatible and can be fabricated in volume fabs using mature node technology. This leverages existing Si economies of scale to reduce manufacturing cost.

Extending power device operation beyond 900 V might be impractical for GaN lateral devices as it necessitates larger lateral gate-to-drain separation, which reduces the total number of devices per wafer. It also requires growth of thick buffer layers, which can compromise thermal conductivity. Thus, for devices rated above 900 V, the vertical configuration is preferable as it optimizes space on the wafer. In vertical devices, blocking voltage is tailored by adjusting the doping and thickness of the vertical drift layer while the lateral device extent on the wafer remains approximately same (a small increase in device area with higher voltage rating is necessitated by the larger lateral extent of the edge termination). SiC power devices are vertical and the efficient choice for +900 V applications. They are commercially available to 3.3 kV from multiple vendors, with 6.5 and 10 kV MOSFETs having been demonstrated and inserted in engineering systems. Furthermore, SiC also competes effectively with GaN and Si IGBTs in the lucrative ~600 V EV and power supply applications space.

SiC MOSFETs and JFETs are capable of bidirectional symmetric current flow under appropriate biasing conditions. However, they only block voltage in the forward direction due to the gate and edge termination structures that are difficult to fabricate at both the device "bottom" and "top" to form a MBD switch with a single shared drift layer. In practice, bidirectional symmetric current-flow and voltage blocking have been demonstrated by connecting two SiC MOSFETs (or JFETs) in the anti-series (back-to-back) configuration schematically depicted in Figure 2. (See article in this issue "*The BiDFET Device and its Impact on Power Converters*" by B. Jayant Baliga, Douglas Hopkins, Subhashish Bhattacharya, Aditi Agarwal, Tzu-Hsuan Cheng, Ramandeep Narwal, Ajit Kanale, Suyash Shah, and Kijeong Han, *IEEE Power Electronics Magazine*, March 2023, p. 20)

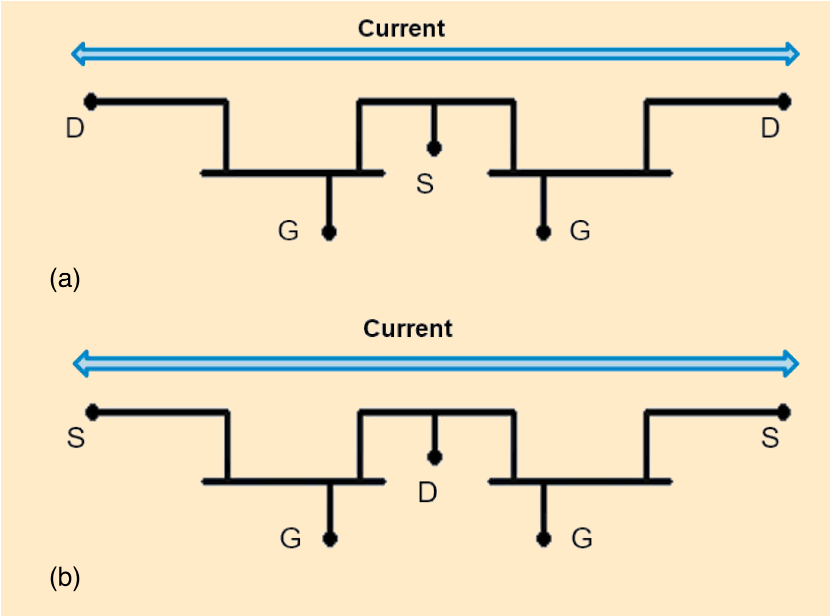

FIG 2 Back-to-back connected (a) common-source and (b) common-drain device configurations for symmetric bidirectional conduction and voltage blocking.

The common-source configuration of Figure 2(a) allows control of the bidirectional switch using a single synchronous drive signal to bias both gates [3]. Utilizing anti-series connected SiC JFETs, a bidirectional solid-state circuit breaker (BD-SSCB) with a single bipolar current actuated gate driver was demonstrated [4]. In no-fault circuit operation, current flows with all the JFET p-n junctions turned OFF. In a fault event, the reverse conducting JFET's gate-drain diode turns ON generating bipolar current that passes through the gate driver. The bipolar gate current was sensed in the driver to turn off the BD-SSCB. Despite being coupled with transient voltage suppression components to mitigate the fast SiC dV/dt, the BD-SSCB actuated three orders of magnitude faster than conventional mechanical circuit breakers and can provide dramatic improvements in reliability and operating life, resulting in superior system protection and reduced system maintenance and repair. The common drain bidirectional switch configuration of Figure 2(b) has recently been fabricated and tested in circuits [5]. The anti-series device configurations of Figure 2 can be monolithically integrated in a single chip on the wafer simplifying packaging and reducing parasitic inductances. SiC MBD fabrication utilizes the same processes of standard SiC switches, thereby exploiting that platform's volumes, yields, and performance metrics. Compared to similarly rated conventional unidirectional vertical MOSFETs/JFETs, the bidirectional "two anti-series connected devices" configuration doubles total resistance. This is in contrast to the lateral GaN dual-gate bidirectional solution, where the common shared drift layer minimizes resistance. Indeed, for the "two anti-series connected devices" bidirectional SiC switch to equal the resistance of a single unidirectional device, the chip area must increase by 4X.

MBD switches provide opportunities for dramatically improving key performance metrics of dc–ac and ac–ac power converters, including their power density, efficiency, EMI suppression, and eventually cost. Three types of three-phase ac–ac converter topologies that are advantageously realized (high efficiency, high power density, and low circuit complexity) with MBD switches are indirect matrix converters, direct matrix converters, and current-source converters. While the compelling advantages of matrix converters for direct ac–ac power conversion have long been recognized, the unavailability of MBD switches has prevented matrix converters using the baseline 3 × 3 matrix of ac switches from achieving wide commercial success. Another opportunity for MBD switches is their application in a T-Type switching cell topology that provides the basis for designing high-performance SiC/GaN-based multi-level voltage-source inverters that can achieve appealingly high power density and efficiency. MBD switches also enable current-source-inverter based integrated motor drives, which combine motors and drives into the same housing, allowing for major improvements including higher power density and efficiency, lower EMI, higher temperature operation, and enhanced fault protection in permanent magnet machine drives. (See article in this issue "*Monolithic Bidirectional Power Transistors: Opening New Horizons in Power Electronics*" by Jonas Huber and Johann W. Kolar, *IEEE Power Electronics Magazine*, March 2023, p. 28)

As SiC and GaN devices approach mass commercialization propelled by insertion in electric vehicles and consumer electronics, respectively, fabrication of SiC and GaN MBD switches is becoming economically viable enabling their wide adoption in key volume applications.

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