Renesas High Voltage GaN Bi-Directional Switches: Strong Performance, Simpler to Use

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The world is seeing an unprecedented surge in power demand. Personal devices, AI infrastructure, solar energy, battery systems, motors and automotive, all require higher power levels with greater efficiency in smaller system sizes. Gallium Nitride—with its superior semiconductor properties—is enabling the revolution. A true renaissance in power electronics is being fueled by the advent of the fastest and smallest power switches ever made.

GaN not only improves the efficiency of *conventional* topologies, widely used in today's power converters[1], but also unlocks the design of *new* topologies, with smaller part count and higher efficiency. That is possible with the high-voltage GaN bi-directional switch (BDS), a single device capable of conducting and blocking current in both directions.

GaN is the only semiconductor able to implement a *high-voltage* bi-directional blocking capability on the same chip. Due to its lateral architecture, GaN BDS has two opposing source terminals controlled by two

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[1] D. Bisi, A. Bhatt, A. Ekbote, Renesas white paper "D-mode GaN Remains a Natural Fit for High-Voltage Applications"

opposing gate terminals, blocking currents and holding high voltage in both polarities, within the same chip area in common drain.

If discrete, conventional uni-directional switches were to be connected back-to-back to achieve bi-directional current blocking capability, their combined chip-size would increase *four* times, resulting in significant cost, footprint and performance degradation (Figure 1 center). On the other hand, by integrating the common drain bi-directional functionality on the same GaN chip, the chip size penalty is negligible (figure 1, right).

This results in a significant reduction in part count, footprint, cost, parasitic capacitance and parasitic inductance, yielding smaller and more efficient converters at a lower cost.

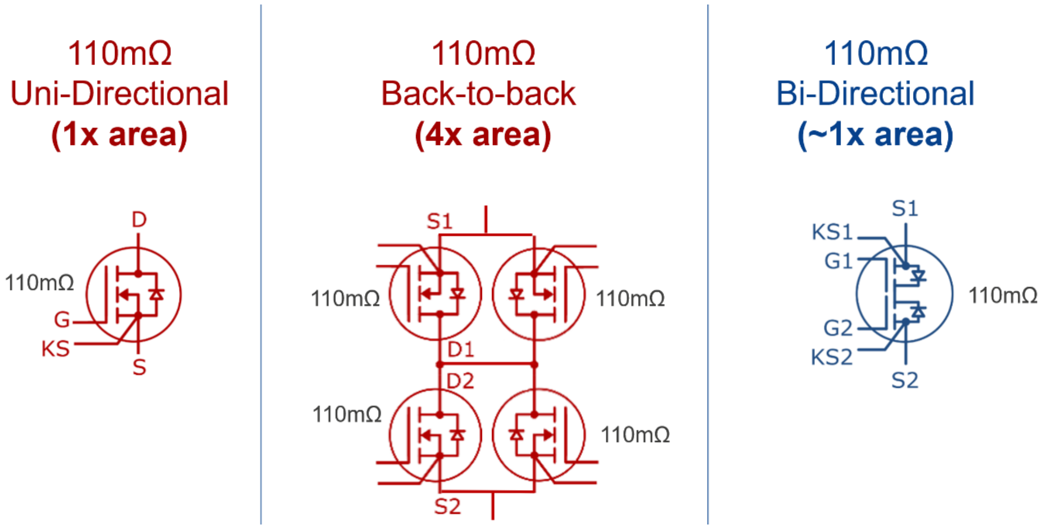

***Figure 1**. If discrete uni-directional devices were to be connected back-to-back to achieve bi-directional current blocking, they would result in a dramatic 4x increase in specific Ron, whereas if back-to-back connection is monolithically integrated using GaN, the specific Ron drops to almost 1x, a significant improvement not only in footprint and cost, but also in performance with lower parasitic capacitance and inductance.*

Single-stage topologies

Because of their small size and footprint along with high performance, GaN BDS enables a revolution in power electronics circuit topologies.

Up to now, AC/DC power converters typically consist of two stages. The first stage was an AC/DC rectifier with power factor correction connected to the grid. The second stage was a galvanically-isolated DC/DC converter connected to the load. Both were coupled using electrolytic DC-link capacitors (figure 2 top). This two-stage converter topology was born out of necessity, when uni-directional devices, such as silicon IGBTs or super junction MOSFETs, were the only options on the market. The two-stage converter has a simple, robust control scheme, but suffers from relatively high part count, including *three* active bridges, several transistors, lossy hard-switching and electrolytic DC-link capacitors which not only increase size and weight of the converter but also reduce its lifetime.

GaN bi-directional switches enable *single-stage* topologies, which have superior performance and lower system size and cost.

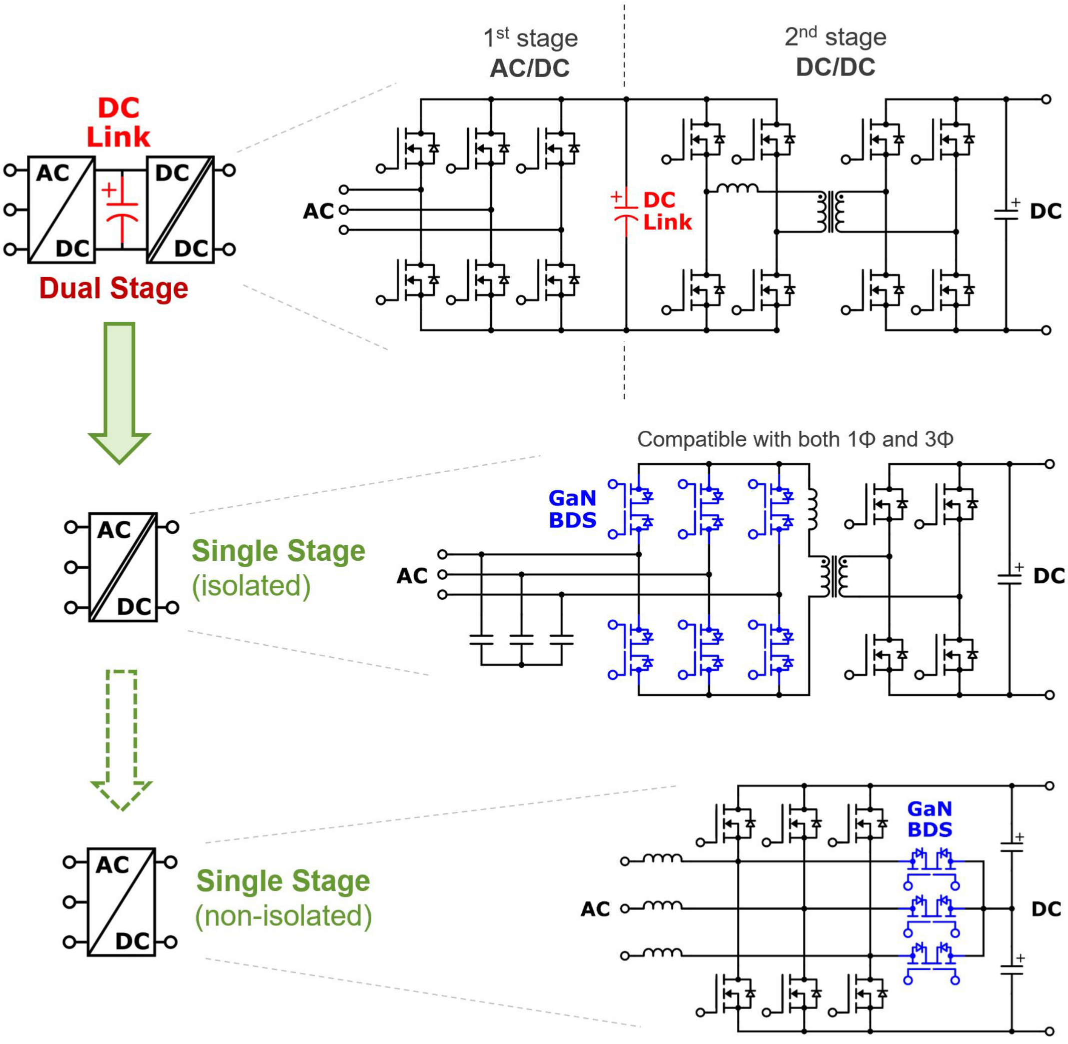

***Figure 2**. GaN BDS allow innovative topologies such as single-stage AC/DC converters, resulting in lower part count for smaller, lighter, more efficient power systems.*

In a single-stage topology, both the AC/DC rectification stage and the DC-link capacitor are eliminated while retaining unity power factor. The converter comprises only *two* active bridges separated by a transformer (figure 2 center). The bridge on the primary side faces the grid and employs GaN bi-directional switches to block current during both positive and negative AC half-cycles. The bridge on the secondary side faces the DC load and employs conventional GaN uni-directional devices. Both bridges are operated under soft-switching conditions, with no hard transitions. This topology is a win-win situation, with lower part count (win) and no hard-switching (win), resulting in record efficiency and power density. This is the perfect topology for higher efficiency battery systems and onboard chargers (figure 3 bottom).

In addition, the single-stage topology is capable of bi-directional energy flow, which means it can be used not only for AC/DC battery chargers or power supplies, but also as a single-stage DC/AC inverter, useful for example in a solar microinverters with smaller size, lower part count and fully resonant switching towards more efficient energy harvesting[2]. (figure 3 center).

A step further in single-stage converters is the implementation of non-isolated topologies, such as the multi-level T-type Neutral Point Clamp (T-NPC, figure 2 bottom), also known as a Vienna rectifier. In this topology, GaN BDS devices are employed on the “T-branch” facing AC voltage. Because of the lack of the transformer, the non-isolated topologies have an even smaller part count and lowest conduction losses, albeit hard switching could still be present under certain conditions and careful control of ground currents must be ensured for safety. Vienna rectifiers can be used in 3-phase AI infrastructure sidecar racks for highest efficiency and compatibility with 0-800V as well as ±400V bus[3] (figure 3 top). Similarly to the isolated topology, the T-type allows bi-directional energy flow and can be employed not only as an AC/DC rectifier but also as a DC/AC inverter, of particular interest for motor drives, where the multi-level nature of the T-NPC results in lower EMI and gentler transients on the motor windings.

Whether isolated or non-isolated, single-stage topologies using GaN BDS allow overall reduction in power converter size and weight, with lower transistor count and no DC link capacitors. GaN bi-directional switches are enabling the implementation of single-stage topologies, at low cost and low part count in addition to higher efficiency. In the following section, we’ll dive deeper into GaN BDS product architecture, performance and reliability.

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[2] Michael Harrison, “Monolithically Integrated GaN HEMT Bi-Directional Switch (BDS)” PCIM 2025 Keynote

[3] Pietro Scalia et al., Renesas white paper “Power Architecture Evolution in Data Centers”

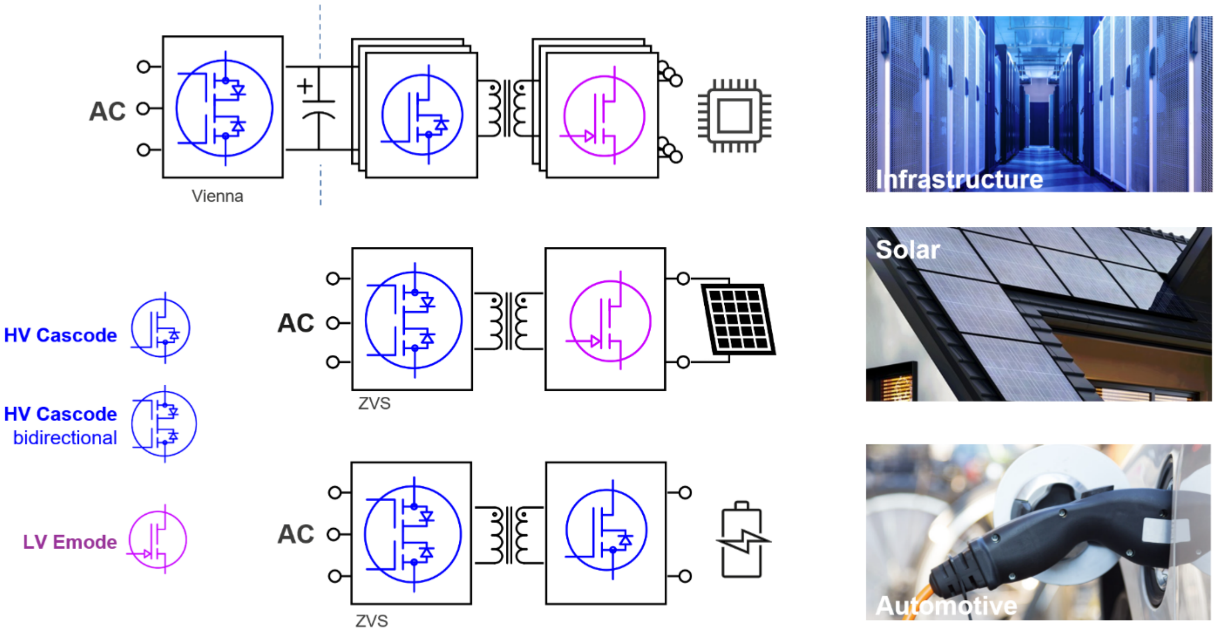

Figure 3. *Single-stage AC/DC converters reduce size and increase efficiency in solar microinverters, battery systems, onboard chargers and IT sidecar racks.*

GaN BDS Architecture

By nature, GaN transistors are normally on. The quest for fault-safe normally-off GaN power solutions has engaged the semiconductor industry for the last 20 years, culminating in the distillation of two main GaN device technologies. The first involves heterogeneous integration, where high-voltage, depletion-mode GaN is integrated with a low-voltage, normally-off silicon MOSFET to achieve normally-off operation (figure 4 right). The second is enhancement-mode GaN, where a p-type GaN layer is inserted underneath the gate metal to deplete charge in the channel, attaining normally-off operations with a single chip.

Both D-mode and E-mode GaN technologies are implemented on low-cost silicon substrates with high-volume manufacturing. The devices comprise of a few microns of engineered buffers to ensure mechanical integrity and low leakage, capped by an AlGaN/GaN heterointerface which generates the high-mobility, two-dimensional electron gas (2DEG), which is the high-performance channel making GaN switch at top speed. Both D-mode and E-mode technologies have source-connected field-plates (FP): metal structures designed to hold voltage and protect the gates from high electric fields. By design, the field-plates are connected to the source to minimize the gate-drain capacitance—a strategy adopted by most power devices. In bi-directional switches, the terminals are deployed with a mirror symmetry, holding voltage in both polarities and sharing the same drift region for smallest footprint (figure 4).

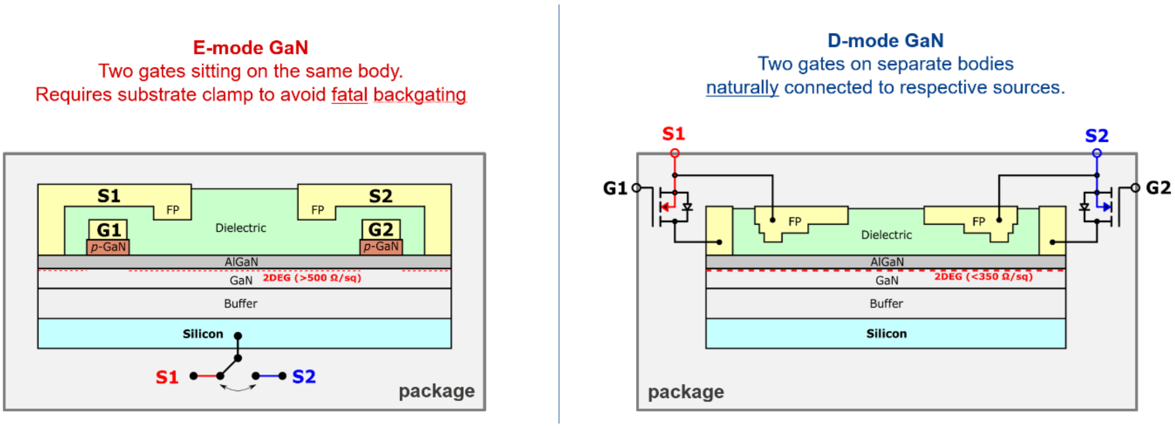

***Figure 4**. Normally-off GaN solutions: (left) single-chip E-mode with non-isolated gate ideal for low-voltage applications (device rating up to 200V), if single-chip E-mode is to be used in high-voltage applications (650-V rating), substrate bias is needed to ensure connection to lowest potential avoiding failures. (right) Heterogeneous solution using low-voltage Si-FET in cascode with high-voltage D-mode GaN, where no substrate switching is required as the threshold voltage of each MOSFET is referenced to physically separate bodies, always connected to their respective sources.*

Both E-mode and D-mode technologies have strengths and are penetrating different segments of the market. The choice of one or the other ultimately depends on voltage requirements.

E-mode GaN is recommended for low-voltage applications with bus voltages up to 48V-150V, where single chip architectures rated up to 200V enable die-level packaging with low parasitic resistance and inductance for ultra-low product resistance (sub 2mΩ). But E-mode GaN has a relatively low threshold (1.6 V) and a non-insulated gate with relatively low drive margin. While ideal for low voltages, it needs extra attention at high voltages. When switching at higher voltages—for example when connected directly to the AC grid—E-mode GaN requires special driving conditions to ensure no parasitic turn-on and no gate overvoltage. With E-mode GaN, extra components are required on the board to operate at high voltage: a negative gate drive supply, a Zener clamp and a series bypass capacitor 10 times larger than the actual input capacitance of the device itself, adding extra board area, BOM costs and gate driving losses (figure 5 left).

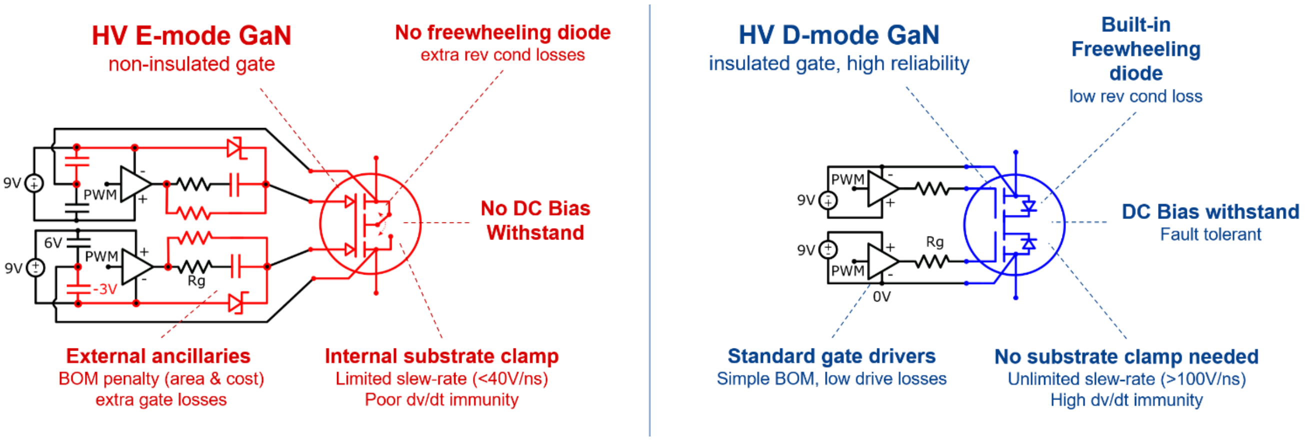

Figure 5. *D-mode GaN products (right) are ideal for high-voltage applications. They have insulated gates with high gate threshold and high gate robustness. For designers, driving D-mode GaN products is as simple as driving silicon MOSFETs, with standard drivers and simple gate resistors. Much simpler than driving E-mode GaN, which needs extra components adding board area penalty, BOM cost and drive losses.*

While showcasing very low gate charge on datasheets (Qg), high-voltage E-mode devices, especially GIT, experience significant gate current during switching. This current is needed first to charge and discharge the large bypass capacitor and then to maintain the non-insulated gate on. Despite low datasheet gate charge, gate drive losses in high-voltage E-mode devices are actually higher than high-voltage insulated D-mode GaN products (figure 6).

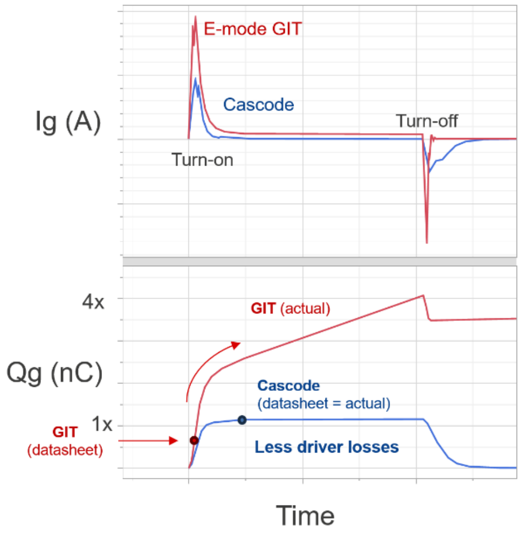

Figure 6. *D-mode GaN products (cascode) have insulated gates yielding very low drive losses, much lower than E-mode devices, especially GIT with no gate insulation at all, which experience significant gate current during switching.*

Last but not least, the two gates of E-mode GaN BDS devices are physically located on the same GaN buffer and the same substrate. At high voltage, this causes parasitic back-gating through the common substrate, resulting in severe threshold voltage instabilities. If left unchecked, backgating of E-mode GaN BDS causes them to turn on when they are supposed to be off and vice versa, triggering catastrophic parasitic turn-on events and/or severe increase of the on-state resistance. For this reason, high-voltage E-mode BDS needs additional circuitry to dynamically clamp the substate voltage to the low-potential source. This substrate clamp circuitry not only uses extra GaN chip area, but also lags during fast switching transients, limiting the dv/dt of high-voltage E-mode BDS products and preventing designers from reaping the benefits of low output capacitance and fast switching speed.

On the other hand, the threshold voltage of D-mode GaN products is set by two silicon MOSFETs with their own physically separate p-type body layers always connected to their respective sources. Therefore, regardless of the voltage polarity and level, no GaN substrate clamping circuitry is required. The silicon MOSFETs are immune to GaN back-gating, resulting in stable threshold voltage under high-voltage conditions, ensuring safe switching with low dynamic Ron and very high dv/dt immunity (>100V/ns). Thanks to the cascode architecture, BDS products with D-mode GaN are capable of both soft-switching and hard-switching with top performance.

Furthermore, D-mode GaN BDS products simplify the gate drive. While the D-mode GaN chip integrates the bi-directional, high-voltage blocking capability for smallest footprint and highest switching figure of merit, the low-voltage silicon MOSFETs ensure insulation, high gate threshold (3V) and high gate robustness. Both GaN chip and silicon MOSFETs are integrated in the same package and require no extra components on the board. For designers, driving D-mode GaN products is simple and efficient, with commercial drivers, simple gate loops and low driving losses. (figure 5 right).

Finally, D-mode GaN BDS products have built-in freewheeling diodes thanks to the body of the low-voltage silicon MOSFET. During deadtime, the body diode conducts current with a very small voltage drop (less than 2V), achieving highest reverse conduction efficiency. At high switching frequencies, where dead time constitutes a significant portion of the switching cycle, a low voltage drop improves efficiency compared to E-mode solutions where the lack of a body diode and the need for a negative drive causes a higher voltage drop (as high as 6V or more). When it comes to reverse recovery, the body diode of the silicon MOSFET doesn’t add any significant reverse recovery charge because the MOSFET is designed for low voltage (30V) with lowest charge and resistance. It is in fact the GaN chip, with low parasitic capacitance and no minority carries, that holds high voltage (650V and beyond) with no Qrr and minimal Qoss.

Renesas GaN BDS Products

D-mode GaN BDS products are packaged in top-side cooled surface mount packages for best thermal and switching performance (figure 7). The packages have gate, source and Kelvin source terminals, with a pinout compatible with that of other major suppliers, ensuring broad market adoption where second- and third-source compatibility is essential.

The GaN chips are made with Renesas GaN epitaxial layers with epi IP developed over more than 15 years, resulting in stable dynamic Ron and high breakdown voltage. Devices are fabricated in Renesas' own GaN fab, maintaining end-to-end control of process IP and know-how. Additionally, the substrate of the GaN chip is directly connected to the package tab for highest thermal performance.

TP65B110HRU, the first product in the Renesas high-voltage GaN BDS family, has a continuous voltage rating of 650V, a typical on-state resistance of 110mΩ and is suited for solar microinverters and other low-mid power applications up to 500W. Other products in the roadmap have a smaller on-state resistance down to 55, 25 and 15 mΩ to cater to higher power applications, such as AI infrastructure supplies, battery systems and automotive onboard chargers. The BDS family is designed to operate with ordinary single-phase systems (240Vrms) and three-phase systems line-to-neutral (277Vrms). All Renesas GaN BDS products have a transient voltage rating of 800V to survive extraordinary overvoltage events and line surge events. The gate threshold voltage has been engineered to be around 3V, the sweet-spot ensuring safe switching with no negative drive, and compatibility with E-mode drive in the 9V range for easy drop-in replacement. The low-voltage silicon MOSFETs are included in the package so no additional circuitry is needed on board. The product has an ESD immunity of 2 kV (Human Body Model and Charge Device Model), ensuring high manufacturing yield and preventing ESD field failures.

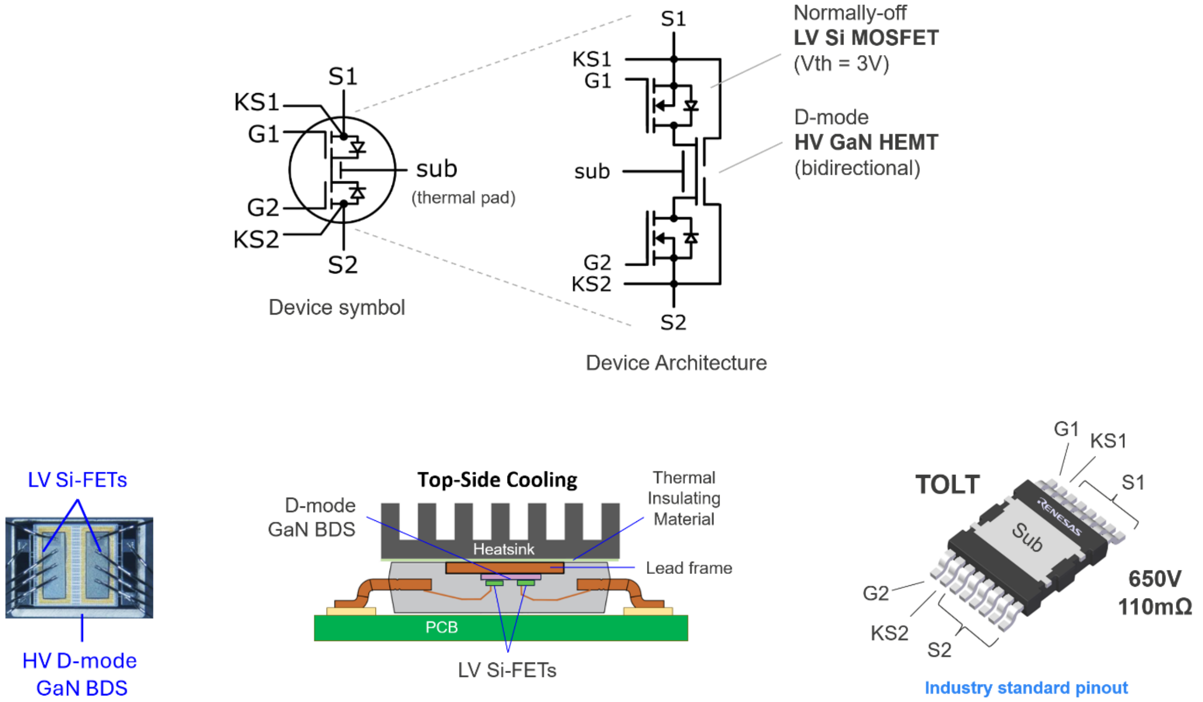

__Figure 7__. D-mode GaN BDS products are packaged in top-side cooled surface mount packages for best thermal performance and switching performance. The low-voltage silicon MOSFETs are included in the package. No additional circuitry to achieve safe normally-off operations is needed on board.

GaN BDS Modes of Operation

The GaN BDS products have three main modes of operation:

1. **Conduction:** When **both gates are on**, the device conducts current in both directions with the lowest on-state resistance (figure 8 left). This mode is commonly used during conduction time to ensure lowest conduction losses.
2. **Rectification:** When a **single gate is on**, the device rectifies, conducting current in one direction and blocking it in the other (figure 8 right). This mode is used during deadtime periods to ensure a free-wheeling path for inductive currents while preventing shoot-through.
3. **Bi-directional blocking:** When **both gates are off**, the device blocks current in both directions (figure 8 left). No free-wheeling path is available in either direction. This mode can be used to prevent short-circuits when the AC polarity may suddenly change, for example during ordinary AC zero-crossing points or during extraordinary overvoltage events, such as surge. This mode must be used with caution; unclamped inductive switching at high voltage may push the device beyond maximum ratings (800V). To prevent device failure, designers of single-stage topologies recommend auxiliary clamping circuitry on board.[4]

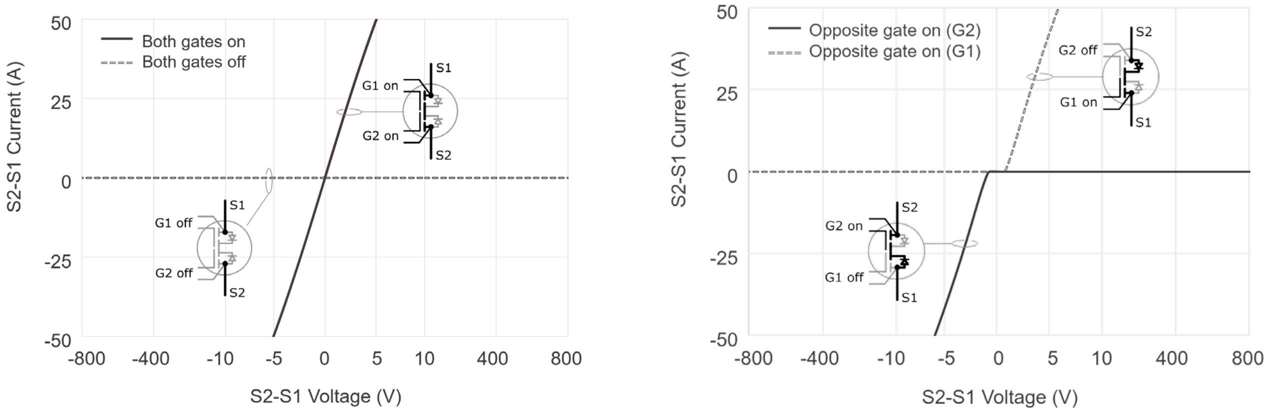

***Figure 8**. Thanks to a common drain configuration, GaN BDS products have three main modes of operation: conduction, when both gates are on for lowest conduction losses; rectification: when a single gate is on to ensure freewheeling during deadtime and bi-directional blocking: when both gates are off to prevent short-circuits when the AC line changes polarity.*

Renesas GaN BDS Performance

The switching behavior of the Renesas GaN BDS device was tested using a simple yet effective half-bridge configuration, specially designed to study bi-directional voltage blocking (figure 11). The half-bridge is connected to an AC source to study the bi-directional voltage blocking capability and is loaded with an LC tank to study zero-voltage switching (ZVS). The board allows the study of BDS behavior in relevant conditions, very similar to those found in single-stage converters with dual-active bridge (matrix) and the

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[4] Wheeler et al., DOI: 10.1109/41.993260, section VI.B

report is available to customers[5]. The AC source has a standard frequency of 60Hz and a peak voltage of 400V. The inductor current waveform is triangular, rising and falling at each ZVS switching cycle. Each gate is connected to an isolated gate driver with a standard supply of 9V. Waveforms are clean, with no ringing and no overshoot. Transients are fast, with turn-off delay and turn-off time in the range of 20ns each, making this device suited for high-frequency operations into the MHz regime.

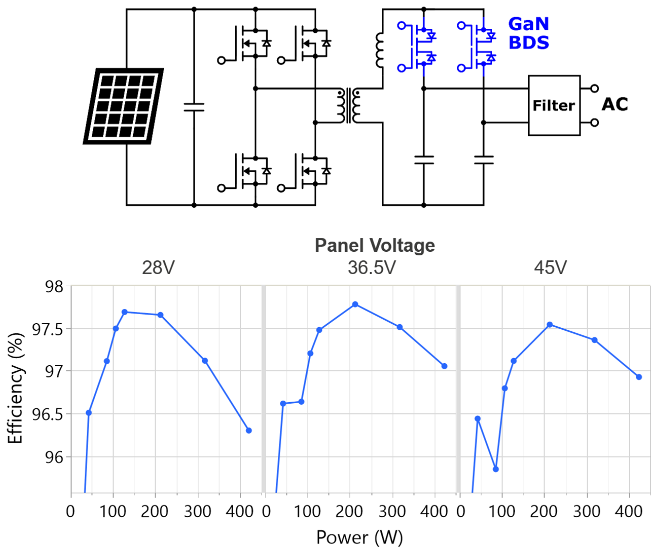

Figure 9. *GaN BDS implementation in solar microinverter application (top) and TP65B110HRU efficiency curves at different panel voltages, reaching 97.5% CeC efficiency (bottom).*

To prove the performance in a full converter, the 650V 110mΩ Renesas GaN BDS product was tested in a customer solar microinverter product, reaching 97.5% CeC efficiency with an output power of more than 400W (figure 9). These results testify to the top performance for the Renesas BDS product.

The devices were also tested under hard-switching conditions, which are relevant if using Vienna rectified topologies. Results show ultra-fast switching[6] with a turn-on speed above 100 V/ns, unmatched by the competition.

While D-mode GaN can switch fast, enabling designers to benefit from low switching losses, it also allows for slew-rate control to meet EMI targets. In hard-switching topologies, slew-rate can be controlled with the gate resistor[7]. In soft-switching topologies, the dv/dt can be further tuned by adding an external capacitor between the source terminals without dissipating additional energy[8].

Renesas GaN BDS Qualification and Reliability

Renesas GaN BDS products are qualified to JEDEC standards and beyond. Conventional JEDEC standard tests include electrostatic discharge (ESD), high temperature reverse-bias and gate-bias (HTRB and HTGB), accelerated humidity tests (HAST), temperature cycling (TC), package integrity and more. In addition, Renesas carries out further qualification tests targeted specifically to GaN. These tests include

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[5] RTDACHB0000RS-MF-1 Renesas Bi-directional GaN Evaluation Kit

[6] TP65B110HRU datasheet

[7] Bisi et al., D-mode GaN whitepaper “D-mode GaN Remains a Natural Fit for High-Voltage Applications”

[8] D. Bisi, GaN Bi-directional Switches: The Revolution is Here, IEEE

dynamic on-state resistance, switching reliability (DHTOL), overvoltage transient reliability and low-temperature reliability to ensure maximum device ratings are held across the full temperature range. These thoroughly designed tests ensure product robustness in all environmental conditions, not only for consumer and industrial but for automotive, as well.

Finally, while Renesas GaN BDS is qualified under AC bias relevant for ordinary field applications, it can also withstand DC bias, a feature not possible with GIT GaN competition. DC blocking capability is a plus, giving customers extra safety during DC fault conditions and extra flexibility during custom start-up or diagnostic sequences where AC bias may not always be available.

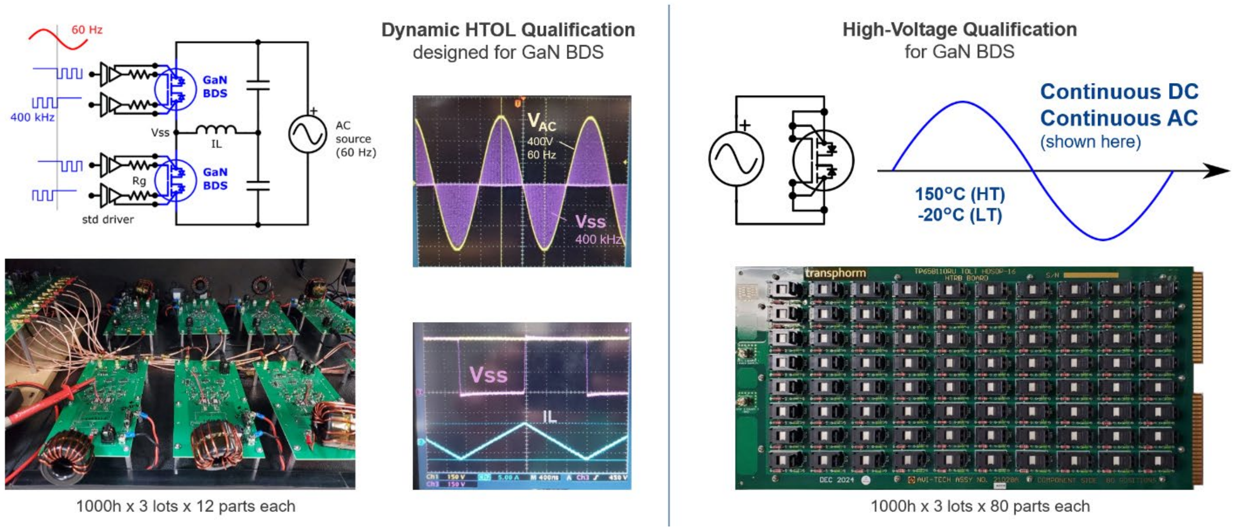

***Figure 10**. High-voltage qualification tests were designed to test bi-directional blocking capability, stressing the devices with an AC bias under both switching conditions (left) and idle conditions (right). Renesas GaN can also withstand DC conditions with no catastrophic failures, providing customers with extra flexibility and safety.*

Conclusion

High-voltage GaN Bi-Directional Switches enable the implementation of single-stage power converters by providing true bi-directional voltage blocking and current conduction within a single device. This capability significantly reduces component count, converter volume and system losses compared with conventional two-stage solutions based on uni-directional switches.

The Renesas Bi-Directional GaN cascode architecture combines the intrinsic advantages of GaN with insulated, robust gate control and compatibility with standard gate drivers and higher threshold voltage ensuring stable operation under both soft and hard switching conditions. Experimental and system level results demonstrate excellent switching performance, high efficiency under AC operation, and robust reliability. These results establish GaN bi-directional switches as a scalable and reliable technology platform for compact, high-efficiency, next-generation power conversion systems in solar inverters, AI infrastructure and automotive OBC applications. Further, the GaN BDS portfolio expansion is planned with lower on-state resistance with both industrial and automotive qualifications. GaN bi-directional switches are a true revolution, enabling smaller, more efficient and less expensive power converters for the benefit of human society, economy and ecology.

Visit renesas.com/GaN-BDS for more information and additional resources. Find more details on the half-bridge evaluation board at renesas.com/rtdachb0000rs-ms-1-kit.

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