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Commentary

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GaN HEMT Technology Enables Smaller, Smarter Bidirectional Power Switches

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At the end of the 1960s and beginning of the 1970s electromechanical (EM) switches started to be replaced by solid-state switches in a variety of power-related applications, thanks to the rapid development of the semiconductor industry. Bipolar junction transistors (BJTs), MOSFETs and thyristors became convenient altenatives to the electromechanical switches, offering key advantages. A solid-state switch is fast switching, and has no moving parts, hence no contacts to wear out, longer life and no audible noise.

While there were some early applications of EM switches in switched-mode power conversion,[1,2] this field really took off with the introduction of solid-state switches, particularly MOSFETs and later IGBTs. In general, BJTs are suitable overall for low current and voltage applications, MOSFETs for medium current and voltage power applications, and thyristors for high current and voltage. Solid-state switches can replace the electromechanical ones both in dc and ac applications, so they can be unidirectional or bidirectional.

With the development of transistors based on wide-bandgap materials in recent years, a new class of monolithic bidirectional solid-state switches is emerging. Just as the early transistors replaced many EM switches, the new bidirectional power switches may replace many of their unidirectional predecessors. In this article our focus is on the bidirectional switches as their use relates to SMPS designs.

Bidirectional Solid State Power Switches

A solid-state bidirectional power switch (BPS) is an active device which allows a bidirectional flow of current when powered on, and blocks a bidirectional flow of voltage when powered off. A solid-state bidirectional power switch is defined as a four-quadrant switch having the ability to conduct positive or negative current in the on-state (Fig. 1a), and also blocking positive or negative current in the off-state, regardless of the polarity of the voltage or the waveform. (Fig. 1b).

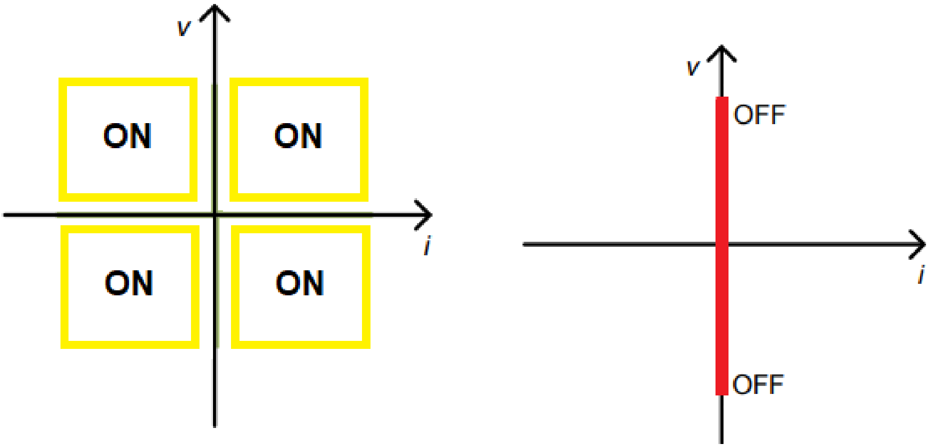

Fig. 1. Characteristics of a bidirectional power switch in the on-state (a) and the off-state (b).

A solid-state bidirectional power switch has been generally realized using discrete MOSFETs (p-channel or n-channel) configured with common sources or with common drains, but also with IGBTs in back-to-back configuration or with thyristors.

In Fig. 2 schematics of two MOSFETs connected in common-drain configuration are shown. Let's see what happens when applying the positive voltage in D1 and the negative voltage in D2 (Fig. 2a). In this case the gate voltage of the MOSFET on the left is on so the current can circulate through it and the forward-biased body diode of the adjacent MOSFET.

When the voltage polarity is reversed, the positions are inverted as shown in Fig. 2b. In this case, the gate voltage of the MOSFET on the right is on and the current can circulate through it, so that the BPS switches on along with the internal body diode of the left-side MOSFET, to enable the conduction in the reverse direction.

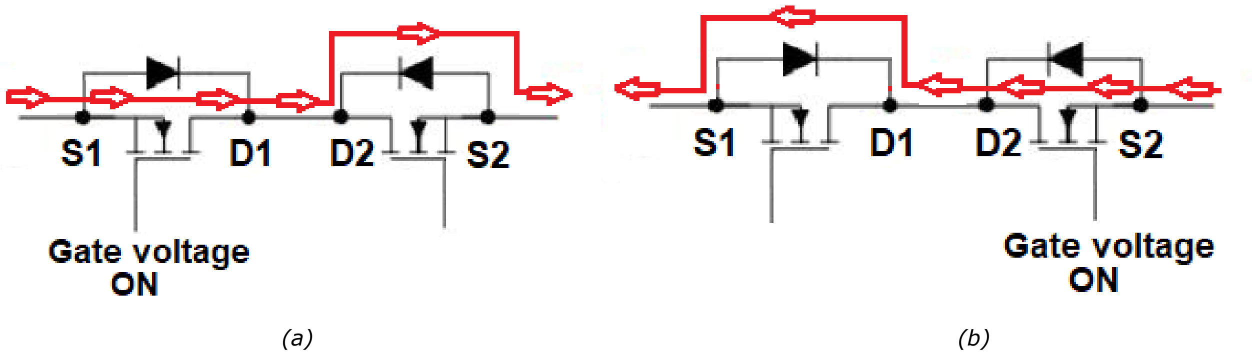

Fig. 2. Current conduction during positive wave (a) and during negative wave (b) of two n-channel MOSFETS connected with common sources.

BPS Applications

Nowadays there are many applications where the solid-state bidirectional power switches are requested, both in low-to-medium voltage and in high-voltage electronic systems. As mentioned before, in low-to-medium voltage applications BPSs are implemented with MOSFETs while in high-voltage applications IGBTs or thyristors are the chosen devices but facing strong competition lately from a new class of wide-bandgap (WBG) devices—SiC MOSFETs.

The main power applications where bidirectional switches are today particularly useful are:

- electric vehicles (EVs)
- renewable energy generation and energy storage
- datacenters
- solid-state circuit breakers

In photovoltaic generation, for instance, thanks to the solid-state bidirectional power switch the dc-ac conversion has been optimized in the microinverter. Each PV panel has a microinverter connected in parallel, so that the dc-ac conversion is done in the single module.

The main advantage with respect to a central inverter is that if one PV panel is out of order for whatever reason, it does not impact the whole energy production. An MPPT device is installed in the single module so that the optimum working point is searched independently from the other modules. The final stage of the microinverter is a cycloconverter where the legs are bidirectional switches.

BPS With Power GaN HEMT Devices

In the past decade new wide-bandgap devices (WBGs) have been heavily commercialized and they are going to successfully replace silicon devices in several applications. We are talking about SiC MOSFETs and GaN HEMTs (high electron mobility transistors). While power transistors based on other materials are being investigated, at present SiC MOSFETs and GaN HEMTs are the most promising WBG power devices. Herewith we will focus on the GaN HEMTs.

Thanks to their specific advantageous characteristics GaN HEMT devices are able to cover different fields of applications in low and medium power and very high frequency environments. They can replace both the silicon components and the SiC MOSFETs. A GaN HEMT device is inherently a d-mode device and therefore normally on. But for proper operation, in switched-mode circuits normally off devices are preferred.

As shown in Fig. 3, a common approach to obtaining a normally off GaN HEMT device is to insert a p-doped GaN layer underneath the gate. Clearly the figure is showing a lateral GaN HEMT technology, and this is the preferred fabrication process because it is compatible with high-volume silicon device manufacturing.

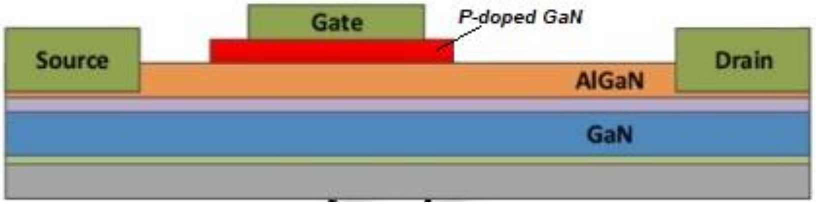

Fig. 3. Cross section of a p-doped GaN device.

Bidirectional Power GaN HEMTs

A BPS GaN HEMT can be built using two discrete devices as shown in Fig. 2 where two MOSFETs are represented. This can be done in a common-drain configuration as in Fig. 2 or in a common-source configuration.

Using the GaN HEMT instead of MOSFETs, the body diodes typical of MOSFETs are absent, allowing the possibility of current flowing from the drain to the source and vice versa much more easily. The switch in on-state supports a current flow in any direction, while when it is turned off the switch is capable of blocking positive or negative voltages. The reverse conduction is done by means of the gate command signals.

Using GaN HEMT devices fabricated with a lateral structure on a silicon substrate, with a heterostructure of an AlGaN/GaN layer and a p-GaN layer under the metal gate, as shown in Fig. 3, it is possible to integrate a dual-gate structure on chip obtaining a whole BSP in a single device as depicted in Fig. 4.

The main advantage of the GaN HEMT with respect to the other devices—Si or SiC MOSFET, IGBT, and thyristor—is in fact the use of a single device instead of two, with a drastic reduction in size and with very low voltage drop in the two directions of current conduction.

The common-drain configuration is the preferred one. Monolithic GaN bidirectional switches realized with a common-drain structure rather than a common-source configuration minimize on-resistance and chip area because they share a single drift region between two GaN transistors. This eliminates the need for two separate devices in series, which would double the resistance and require more silicon area.

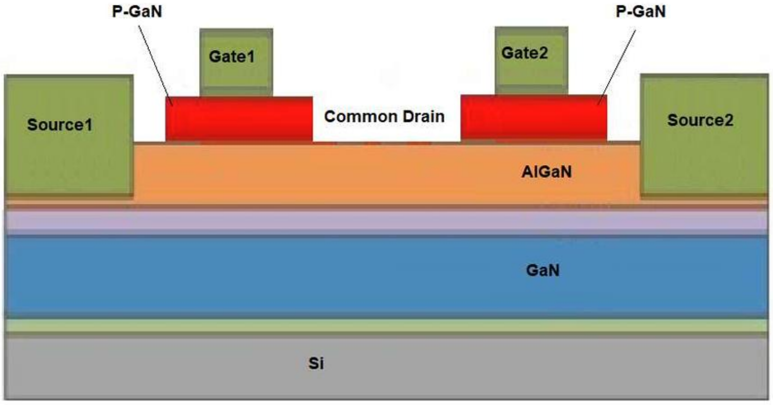

Fig. 4. Cross section of a dual-gate BPS structure.

In Fig. 4, when a high voltage is coming at Source2, Gate1 will be used, and the common drain region blocks the high voltage keeping the source to gate extent small. Similarly, if the high voltage comes at Source1, Gate2 will control the device. However the real problem of implementing a common-drain configuration instead of a common source one is the floating drain substrate, that will generate uncontrolled substrate potentials.

To solve this problem of uncontrolled potentials the manufacturers that are offering bidirectional GaN HEMT devices use specific patented circuitry to realize a substrate dynamic voltage control on chip. In this way the drain substrate is dynamically connected to the source with the lowest potential (Fig. 5).

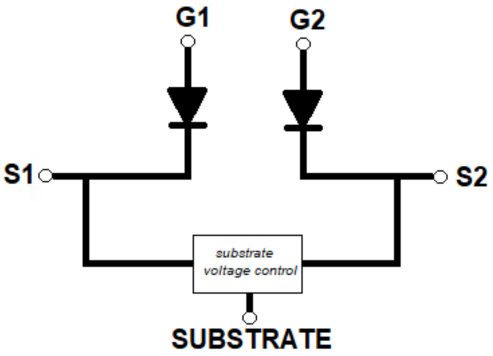

Fig. 5. Floating-drain substrate with dynamic voltage control circuit integrated on chip.

Conclusions

Gallium nitride makes it is possible to increase the power efficiency of a 600- to 650-V BPS, as well as reducing the chip size and therefore the space occupied by the device on the PCB. The technology of the GaN HEMT on silicon in fact allows the fabrication of lateral GaN HEMT transistors applying the same rules used for a smart power chip in BCD technology.

Several key semiconductor manufacturers are actually offering HV (650-V to 700-V typical breakdown voltage) and LV (30-V to 120-V typical breakdown voltage) bidirectional GaN HEMTs solutions for compact power conversion. Just to mention some with higher volume: Infineon, Navitas, and Innoscience. But there are many others.

It is likely that all the big semiconductor players are going to add bidirectional GaN HEMTs to their present range of products. Now that a whole BPS with circuitry integrated on chip and housed in standard power packages is available, engineers can unleash their design creativity.

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Now retired, Giuseppe Di Stefano is a former technical marketing manager in the Industrial & Power Conversion Business Unit of STMicroelectronics. He is based in Catania, Italy. Giuseppe joined the company in 1982 and covered different roles inside ST: application engineer for small-signal and medium-power transistors, hardware development engineer for advanced testing, marketing engineer for automotive smartpower devices, and finally technical marketing manager for intelligent power switches (IPSs) for industrial. He is the author of several technical articles concerning smartpower devices, presented in international conferences and technical magazines, and holds a B. Eng. in industrial engineering. You can reach Giuseppe at giodiste62@gmail.com.