

# Evolution of Wide-Bandgap Semiconductors for Power Devices Expanding Fields of Application

Wide-bandgap semiconductors including silicon carbide (SiC) and gallium nitride (GaN) are currently attracting attention for use in next-generation power devices in view of their excellent characteristics offering higher energy efficiency.

In developing key technologies to improve the performance of SiC power devices, Toshiba Electronic Devices & Storage Corporation has focused on the reduction of wafer thickness and cell miniaturization, and has been continuously releasing a wide variety of SiC power devices. The application of SiC hybrid modules to traction inverters for rolling stock, for example, is contributing to reductions in the size and weight of such inverters. We are also developing GaN power devices capable of performing high-speed switching operations, including a quasi-normally-off GaN high-electron-mobility transistor (HEMT) and a GaN metal-oxide-semiconductor field-effect transistor (MOSFET).

## 1. Introduction

Power devices have achieved high efficiencies in recent decades because of improvement in the performance of power semiconductors, which are made of silicon (Si). However, Si power devices are approaching their theoretical limits of performance, and wide-bandgap semiconductors are expected to break through these limits.

In 2013, Toshiba Electronic Devices & Storage Corporation developed Schottky barrier diodes (SBD) made from silicon carbide (SiC), which is a wide-bandgap semiconductor. In 2014, we announced the launch of a SiC hybrid module, a device that assembles silicon injection-enhanced gate transistors (IEGTs) and SiC SBDs in a single integrated package. By developing SiC hybrid modules and applying them to inverters for electric railways, improved power conversion efficiencies and space savings are achieved<sup>(1)</sup>. Another promising wide-bandgap semiconductor, gallium nitride (GaN), excels in high-speed switching performance, leading the way toward more efficient solutions and miniaturization of power supply equipment.

Here, we describe the latest advances associated with these two new semiconductor materials and their future trends.

## 2. Expansion of applicable field of SiC devices

Unlike Si devices, SiC devices can achieve high breakdown voltage and low energy loss simultaneously. However, the materials are expensive and difficult to process, the need to minimize the defects in the crystals poses a challenge, and moreover, the manufacturing methods are quite different from those for traditional Si. These issues have hampered the widespread adoption of SiC.

### 2.1 SiC discrete products

In recent years, the progress of discrete products consisting of one chip in one package has been remarkable. As the quality of wafers improves and their diameter increases, these devices are finding uses not only for small industrial

apparatus (eg., power supplies for information and communication equipment, electric vehicle (EV) charging stations, solar light inverters, commercial air conditioners) but also for high-end consumer products (eg., organic electroluminescent TVs, audio-visual amplifiers).

The following is a description of the features of our company's SiC-based discrete SBD and MOSFET products.

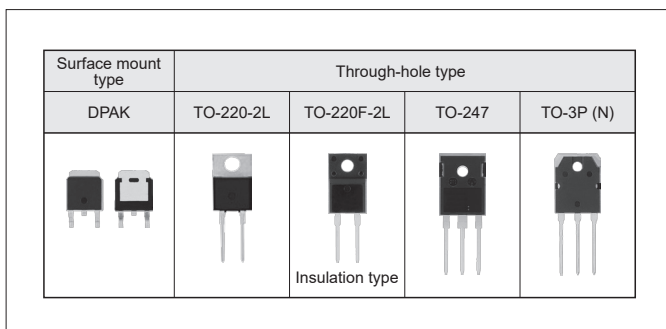
### 2.1.1 SiC SBD discrete products

Figure 1 shows examples of packages of our current products. These products have a breakdown voltage of either 650 V or 1,200 V, and the current rating can be selected within the range of 2 A to 24 A. They are used for power factor correction (PFC) circuits from the alternating current (AC) power supply.

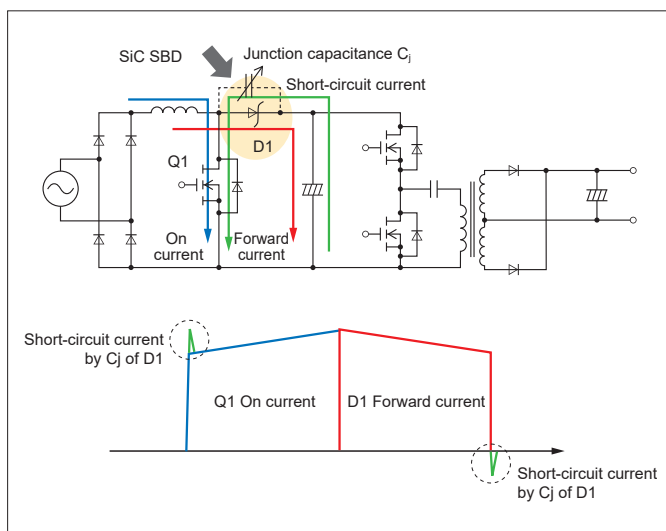
Figure 2 shows a PFC circuit using a SiC SBD, together with a schematic diagram and a sample waveform. In the PFC circuit, the turn-on of D1 (SiC SBD) is controlled by the switching device Q1. The energy loss of Q1 is affected by the characteristics of D1. When Q1 turns on, short-circuit current flows according to the total charge  $Q_c$  determined by the junction capacitance  $C_j$  of D1 and the reverse voltage  $V_R$ . This short-circuit current increases the turn-on loss of Q1, such that the smaller the  $Q_c$ , the smaller the turn-on loss.

On the other hand, the loss of D1 is due to charging/discharging of  $Q_c$  and on-loss from the forward voltage  $V_F$ . Using the same design rules, there is a trade-off between  $Q_c$  and  $V_F$  in that the smaller the efficiency performance index ( $V_F \cdot Q_c$ ), expressed as the product of  $V_F$  and  $Q_c$ , the higher the efficiency and the lower the loss.

Mass production of the first-generation SBDs began in 2013, and transitioned to the second-generation SBDs in 2017. The second-generation design combines an improved Schottky structure with a thin wafer. The efficiency performance index required for the PFC circuit is reduced to about two-thirds of that of the first generation, enabling a device with lower loss as well as an improved surge current tolerance  $I_{FSM}$  1.7 times larger than that of the first generation (Table 1).



(Figure 1) : Examples of packages for SiC Schottky barrier diodes (SBDs)



(Figure 2) : Application of SiC SBD to power factor correction (PFC) circuit and current waveforms

(Table 1) : Evolution of cross-sectional structure and performance of SiC SBDs

Generation	Basic Study 1	Basic Study 2	1st-gen. (Current)	2nd-gen. (New)	
Structure	SBD Structure	MPS Structure	JBS Structure	Improved JBS Structure	
Wafer Thickness (Relative Value)	1	1	1	1/3	
Sectional Structure					
Performance	Leak current $I_R$	×	△	◎	
	Improvement: Low Effect: Thermal runaway suppression	JBS Structure → Low $I_R$			
	Efficiency performance ( $V_F \cdot Q_c$ )	◎	○	△	○
	Improvement: Low Effect: Low loss	Thinner Wafer → Low $V_F$ at any current			
	Surge current $I_{FSM}$	×	◎	△	◎
Improvement: High Effect: High tolerance	Improved JBS Structure → Low $V_F$ at high current				

◎ : Very good   ○ : Good   △ : Fair   × : Poor  
MPS: Merged PN Schottky   N: N-type semiconductor   P: P-type semiconductor

### 2.1.2 SiC MOSFET Discrete Products

In 2017, we began to develop the second-generation SiC MOSFETs. The main features of this second generation are as follows:

- (1) MOSBD structure - By adopting the MOSBD structure in which the SBD and MOSFET are formed on one chip,  $V_F$  becomes 1/2 or less compared with that of the competition's MOSFET structure, and low-loss operation becomes possible for synchronous rectification and motor applications.
- (2) Threshold voltage  $V_{th}$  - Minimum of 3 V, reducing possibility of malfunctions.
- (3) Absolute maximum rating of gate-source voltage  $V_{GSS} - V_{GSS}$  is large and its allowed range is also wide at 35 V (-10 V to +25 V), which increases design freedom.

For SiC MOSFETs using these technologies, we are planning a product line with 650-V and 1,200-V breakdown voltages and an on-resistance range from 22 m $\Omega$  up to 350 m $\Omega$ .

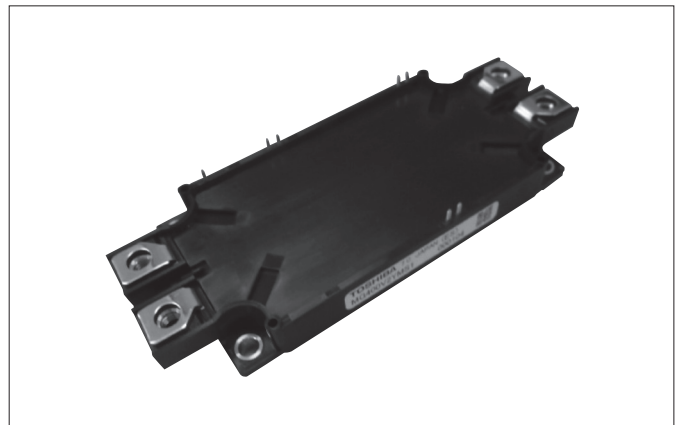
## 2.2 SiC module products

We developed the SiC hybrid module in 2014. The SiC hybrid module consists of a Si IEGT and a SiC SBD in one sealed package. Compared with a module in which both the IEGT and the diode are made of Si, the turn-on loss of IEGT is reduced by approximately 50% and the reverse recovery loss of the SBD is reduced by approximately 97%. The volume of the inverter for the railway cars using this SiC hybrid module was reduced by approximately 40% and the mass by approximately 50% compared with a conventional inverter<sup>(1)</sup>.

The SiC MOSFET module in which the switching device is SiC can further reduce loss by high-speed switching.

For that purpose, however, it is necessary to design a

package in which the parasitic inductance  $L_s$  is reduced to the limit. Our SiC MOSFET module package (Figure 3) has reduced the  $L_s$  to about 1/2 compared with the industry standard package of 1,700 V. We are working to achieve the early commercialization of 1,200- and 1,700-V-rated products using this package. In addition, we are developing a package optimized for applications that makes better use of SiC's features.

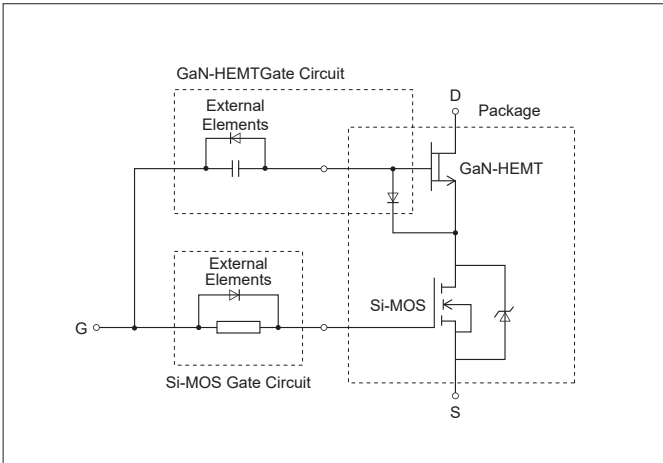


(Figure 3) : Package for SiC power module

## 3. Development status of GaN power devices

A power semiconductor using gallium nitride (GaN), whose breakdown electric field strength is about 10 times higher than that of Si, is expected to excel as a switching device with its low on-resistance similar to that of SiC. Currently available GaN power devices from various companies (some available as samples and others as production models) have laminated structures built by epitaxial growth of GaN and AlGaN layers on a Si substrate. Since the generated two-dimensional electron gas has a high electron mobility exceeding 1,000 cm<sup>2</sup>/(V·s), a device with low on-resistance and low switching loss can be realized. Therefore, the GaN power device can be used at a high switching frequency. Miniaturization of passive elements such as inductance and capacitance, as well as downsizing of the entire apparatus, becomes possible. For system applications, a normally-off solution is required, and two kinds of normally-off configurations are currently adopted. One consists of a combination of a depletion-mode (normally-on) GaN device and a low-voltage Si-MOSFET. The other is an enhancement-mode (normally-off) GaN device built with p-type GaN as the gate.

We have been studying a quasi-normally-off scheme that directly drives the gate of the GaN power device during



(Figure 4) : Quasi-normally-off circuit proposed by Toshiba Electronic Devices & Storage Corporation

switching (Figure 4). In this system, unlike the usual cascode-type quasi-normally-off arrangement, the Si-MOS is always on during the switching period, and only the GaN-HEMT (high-electron-mobility transistor) is switched. This is done because the time constant determined by the product of the resistance of the Si-MOS and the gate capacitance of the Si-MOS does not turn off the Si-MOS even if the voltage at the gate electrode goes off. In addition, it is possible to control the rise and fall times (i.e., slew rate) of the drain voltage and drain current of the GaN-HEMT.

We are also conducting research and development of next-generation MOS-type GaN power devices. As an example of such a power device under development, the cross-sectional structure (Figure 5) and the output characteristics (Figure 6) of the device<sup>(2)</sup> are shown. By removing the AlGaN layer using dry etching, the two-dimensional electron gas generated under the gate area is eliminated, thereby realizing normally-off device operation. Damage caused by the dry etching process is removed by thermal treatment in an ammonia atmosphere, which suppresses the issues of threshold voltage instability and degradation of channel mobility<sup>(2)(3)</sup>.

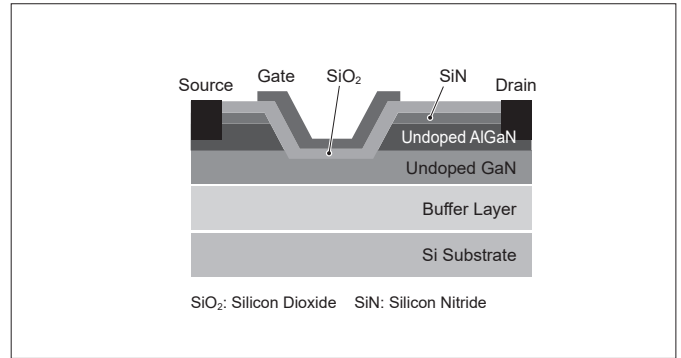
In order to commercialize MOS-type GaN power devices, it is necessary to improve the reliability of the devices. Along with the advances in the fabrication process techniques, the technology for improving the crystal quality of GaN on Si epitaxial wafers is also being addressed.

## 4. Conclusion

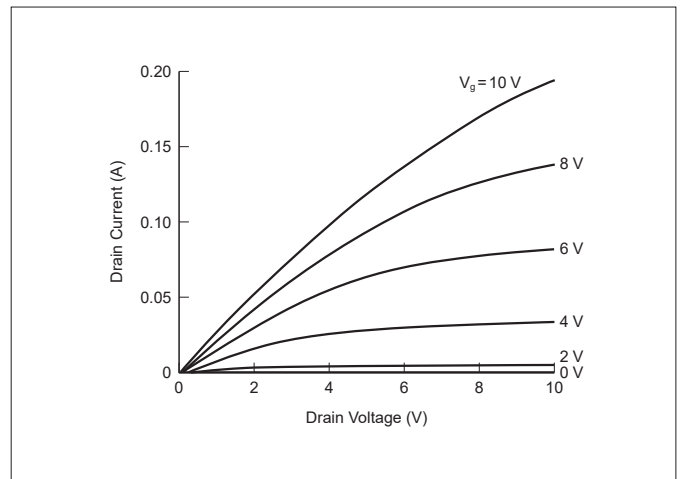
We have been developing power semiconductors that meet the demands for system miniaturization and high power density by utilizing such solutions as low-energy-loss, wide-bandgap SiC and GaN power devices as well as newly developed packaging. We will continue to develop innovative products that address the needs of the times while focusing on the basic underlying technologies that will be at the core of our products.

### References

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(Figure 5) : Cross-sectional structure of GaN MOS power device



(Figure 6) : Drain current ( $I_D$ )-drain source voltage ( $V_{DS}$ ) characteristics of GaN MOS power device