# Side Gate HiGT That Realizes the High Power Density of IGBT Modules

**Yujiro Takeuchi [1) ]Masayuki Kamikawa [2) ]Yukihiro Kumagai [2) ]Takashi Wada [2)]**
**Toshiki Tanimura [2) ]Takayuki Ouchi [1) ]Hisayuki Tsuruoka [2) ]Seiichi Hayakawa [2)]**
**Takayuki Kushima [2) ]Yutaka Kato [2) ]Masaki Shiraishi [2) ]Tetsuo Oda [2)]**

*1) Hitachi, Ltd., Research & Development Group, Hitachi, Ibaraki, Japan*

*E-mail: yujiro.takeuchi.bx@hitachi.com*

*2) Hitachi Power Semiconductor Device, Ltd., Hitachi, Ibaraki, Japan*

**ABSTRACT**: This paper describes a developed high power density 750 V/800 A 6-in-1 IGBT module suitable for xEV application. The developed module has features of the copper lead structure for reduction of thermal resistance and the epoxy resin encapsulation for improving thermal stress reliability. In order to reduce power loss, side gate HiGTs and U-SFDs were installed to achieve both low switching loss and low noise. Furthermore, side gate HiGTs have a superior feature of a wide RBSOA necessary for the latest high power density IGBT modules. By integrating the above technologies, the developed module can achieve a −29% smaller footprint and a −27% lighter weight while keeping the same output current as our conventional IGBT module. Consequently, the developed module can realize a +70% higher power density than the conventional one.

**KEY WORDS**: electric vehicle, power module, power semiconductor device, IGBT, side gate structure, RBSOA

## 1. INTRODUCTION

Vehicle electrification has become one of the key trends and is rapidly being promoted to reduce $CO_2$ emissions recently. The role of IGBT modules in vehicle electrification is essential, and a further reduction in loss and size, that is, higher power density, is required. In addition, the AQG324, a qualification guideline for power modules used in motor vehicles prepared by the international working group, is becoming popular, and it is required that future IGBT modules conform to this standard. With these backgrounds in mind, we have developed a new high power density, 750 V/800 A 6-in-1 IGBT module enabling acceleration of vehicle electrification (Fig. 1).

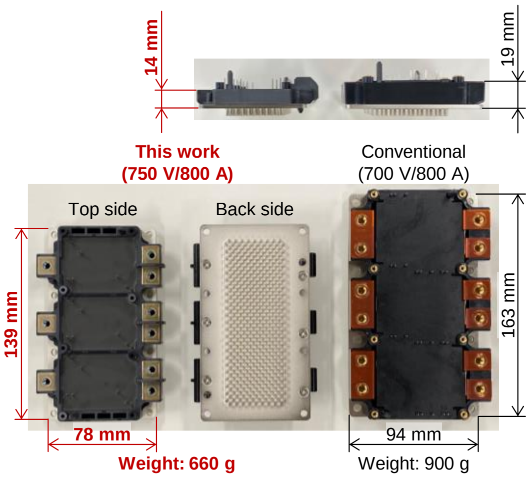



Fig. 1 Developed 750 V/800 A 6-in-1 IGBT module.

The developed module has various features to achieve high power density, some of which have been described in the previous paper mainly from the viewpoint of package design.(1) For example, the Cu lead structure was applied for downsizing and improving thermal resistance.(2) Another is that epoxy resin encapsulation was adopted to advance mechanical vibration resistance and thermal stress reliability.(3)

Reducing the loss of IGBT and diode chips is significant to achieve a high power density. In order to reduce loss, side gate HiGTs (high conductivity IGBT) and U-SFDs (ultra-soft & fast recovery diode) were installed in the developed module (Fig. 2). In addition, to increase power density, the current density of the chip must be increased, which means it requires a wider RBSOA (reverse bias safe operating area). This paper describes design concepts and measurement data, primarily focusing on that point.

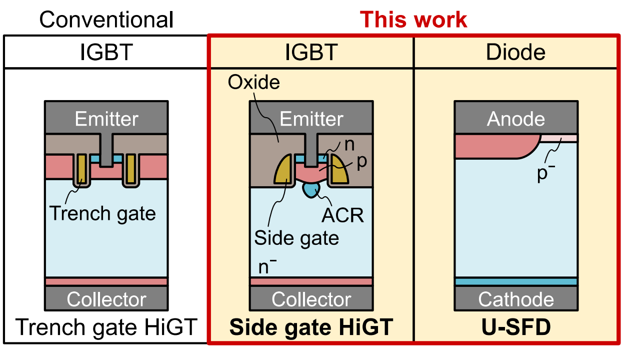
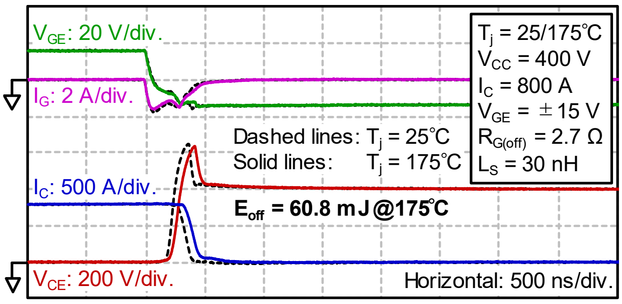



Fig. 2 Cross-section diagrams of side gate HiGTs and U-SFDs.

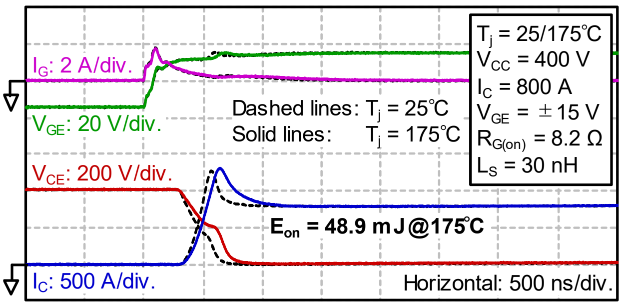
## 2. SIDE GATE HIGT AND U-SFD

### 2.1. Structure and features of side gate HiGTs and U-SFDs

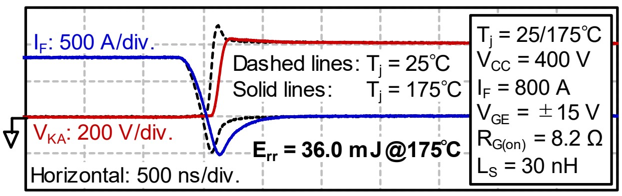
Side gate HiGTs, which have a side-wall gate surrounded by a thick oxide layer, realize a feature of low reverse transfer capacitance.(4), (5) Because of this unique feature, they have superior controllability of switching speed with varying gate resistance and can realize both low switching loss and low noise. Furthermore, they also have small input capacitance, which is the advantage of reducing the output capability of gate drivers. The developed 750 V/800 A side gate HiGT chip has an input capacitance of 13.4 nF (at the conditions of $T_j = 25$°C, $V_{CE} = 10$ V, $V_{GE} = 0$ V, $f = 100$ kHz), which is about the one-fifth value compared to the conventional trench gate HiGT. U-SFDs, which have a composite structure of deep pn junctions and shallow $p^-$-type Schottky junctions, achieved a smaller peak and a more extended period of reverse recovery current.(6)(7) This feature suits U-SFDs as anti-parallel diodes for recent high-speed IGBTs, such as side gate HiGTs. The developed 750 V/800 A side gate HiGT and U-SFD chips were fabricated and confirmed their low loss and low noise switching characteristics through actual measurement (Fig. 3).




(a) Turn-off waveforms.




(b) Turn-on waveforms.




(c) Reverse recovery waveforms.

Fig. 3 Measured switching waveforms of the developed 750 V/800 A side gate HiGT and U-SFD chips.

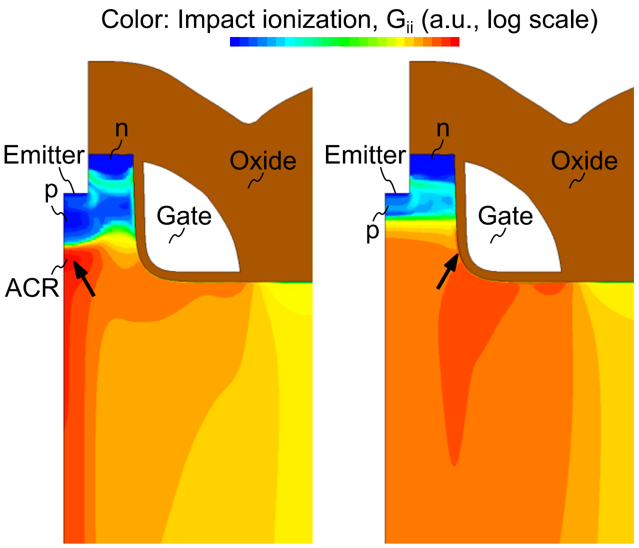
These new IGBTs and diodes were designed not only for loss reduction but also for reliability issues. The termination structure with the combination of FLRs (field limiting ring) and field plates was optimized to a 750 V class and applied for both IGBTs and diodes. This new termination structure provides robust electric field distribution against external charged ions, and the chips successfully passed HTRB (high-temperature reverse bias) and $H^3$TRB (high-humidity, high-temperature reverse bias) tests regulated in the AQG324. It is remarkable that the chips with the new termination structure passed the $H^3$TRB test not only with 80 V biased but also 0.8 × $V_{CE,max}$ (600 V) biased.

### 2.2. Wide RBSOA concept of side gate HiGTs

When using IGBTs at a high current density to increase power density, there is often a problem in ensuring sufficient RBSOA. In the case of the conventional trench HiGTs, a dynamic avalanche phenomenon generates a large number of charge carriers near the bottom of deep trench gates by a high electric field strength during turn-off switching. The turn-off current, including the generated carriers, then flows along the surface of trench gates, leading to a forward bias of the pn junctions on the chip emitter side, i.e., latch-up occurs.

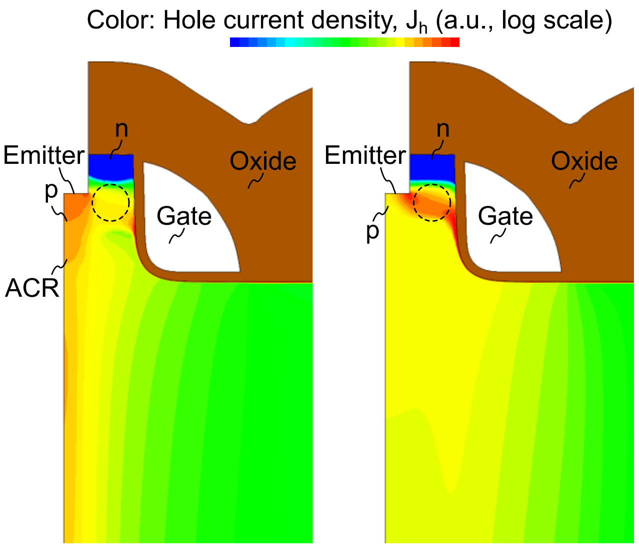
On the other hand, the side gate HiGTs can break through this limitation with their unique features. Since the trench depth of the side gate HiGTs is shallower than that of the trench gate HiGTs, the electric field strength applied to the bottom of the trench gate is essentially relaxed. In addition, an ACR (avalanche control region, see Fig. 2) provided under the $pn^-$ junction of the side gate HiGT plays an important role in realizing a wide RBSOA. The ACR is an n-type layer with a slightly higher impurity concentration than the $n^-$ body layer, which induces the peak point of electric field strength onto the center of its pn junction from the bottom of the trench gate. Due to this function of the ACR, the generated carriers are directly swept out to the emitter electrode so that the side gate HiGTs can prevent latch-up.

Figure 3 shows the TCAD simulation results of impact ionization of the side gate HiGTs with and without the ACR. It shows the moment of maximum power dissipation when turn-off twice the rated current, and the arrows in the figure indicate the peak position. As can be seen from the figure, without ACR, impact ionization occurs at the surface of the gate oxide. However, with ACR, the peak position of impact ionization can be moved to the center of a pn junction as intended. Figure 4 shows the simulation results of hole current density at the same time as Fig. 3. In the case without the ACR, hole currents flowing along the gate oxide




(a) With ACR (b) Without ACR

Fig. 4 TCAD simulation results of impact ionization of the side gate HiGTs with the ACR.




(a) With ACR (b) Without ACR

Fig. 5 TCAD simulation results of hole current density of the side gate HiGTs with the ACR.

surface separate from the interface, traverse under the n-emitter layer (dashed circled area), and flow out to the emitter electrode. On the other hand, with the ACR, the function of the ACR increases the components of hole currents that flow directly from the center of the pn junction to the emitter electrode, forming a current path that is less likely to occur latch-up.

Figure 6 shows the measured RBSOA waveforms of the developed 750 V/800 A side gate HiGT chip. As shown by the figure, the side gate HiGT turn-off safely even with severe high voltage and high current conditions due to the function of the ACR, and demonstrated that it has a wide RBSOA. As a result, the side gate

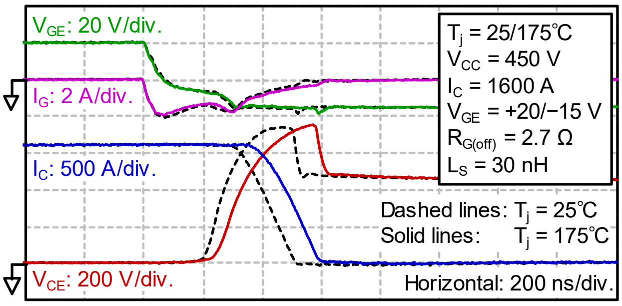



Fig. 6 Measured RBSOA waveforms of the developed 750 V/800 A side gate HiGT.

HiGTs have succeeded in increasing the rated current density by +22% compared to the conventional trench gate HiGT.

## 3. INVERTER LOSS CALUCULATION

Inverter loss calculation was performed based on the measured conduction loss, switching loss, and thermal resistance of the developed module. Figure 7 shows the estimated output phase current of the three-phase inverter using the developed module compared with the case of the conventional one while varying a carrier frequency. The maximum junction temperature is limited to 165°C for maintaining a safety margin because this calculation considers averaged chip temperature. As shown in the figure, the developed module can handle almost the same phase current as the conventional one, even though it has a −29% smaller footprint. Furthermore, the developed module has a well-balanced output phase current between motoring and generating inverter operation.

The output power density of the developed module under various junction temperature conditions was calculated by dividing the effective output power of an inverter at a carrier frequency of

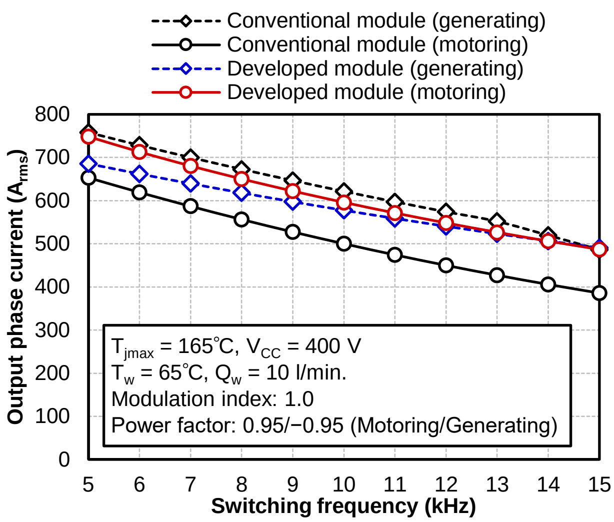



Fig. 7 Estimated output phase current with varying a carrier frequency.

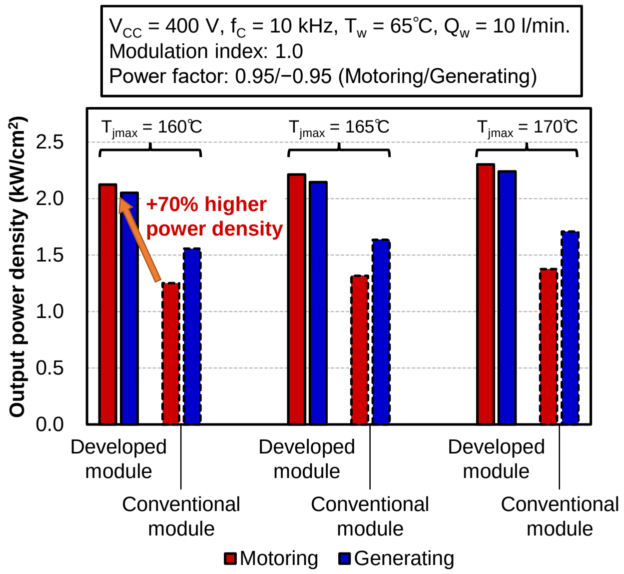



Fig. 8 Output power density of the developed module in comparison with the conventional one.

10 kHz by the module footprint (Fig. 8). It is revealed that the developed module can achieve a +70% higher output power density than the conventional one.

## 4. CONCLUSION

In this paper, a high power density 750 V/800 A 6-in-1 IGBT module enabling vehicle electrification was discussed. In order to reduce semiconductor loss, side gate HiGTs and U-SFDs were installed. The side gate HiGTs with the ACR exhibit a wide RBSOA and realize +22% higher rated current density than the conventional trench gate HiGT. The Cu lead structure was applied for downsizing and improvement of thermal resistance. Epoxy resin encapsulation contributes to the advance of mechanical vibration resistance and thermal stress reliability.

By integrating the above technologies, the developed module can achieve a −29% smaller footprint and a −27% lighter weight while keeping the same output current as our conventional IGBT module. Consequently, the developed module can realize a +70% higher power density than the conventional one.

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