A 3.3 kV/800 A Ultra-High Power Density SiC Power Module

Takashi Ishigaki, Seiichi Hayakawa, Tatsunori Murata, Toshihito Tabata, Katsuyuki Asaka, Koyo Kinoshita, Tetsuo Oda, Kan Yasui, Toshiaki Morita, Daisuke Kawase, Yuji Takayanagi, Renichi Yamada, and Katsuaki Saito, Hitachi Power Semiconductor Device Ltd., Japan, takashi.ishigaki.ug@hitachi.com
Toru Masuda, Hiroshi Miki, Masakazu Sagawa, Hidekatsu Onose, Kumiko Konishi, Ryusei Fujita, Hiroyuki Matsushima, Shintaroh Sato, and Akio Shima, Research & Development Group, Hitachi Ltd., Japan

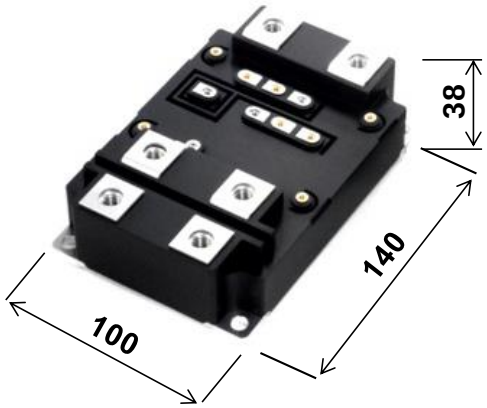
Abstract

A 3.3 kV/800 A diode-less (D-less) SiC power module has been developed adopting the next High Power Density Dual (nHPD^2) package. The ultra-high power density value of 37.7 kVA/cm^2 is realized by fulfilment with only SiC-MOSFETs. Furthermore, as a countermeasure for “bipolar degradation” issues related to body diodes in the SiC-MOSFET structure, a high throughput screening process is deployed. The low loss and high reliability characteristics of the D-less SiC module are set out herein.

1. Introduction

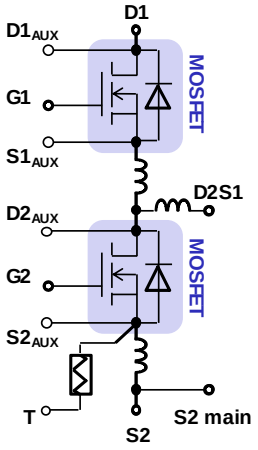
Performance, efficiency and the miniaturization of railway traction systems have been improved by advances in power semiconductor devices. High power density is one of the most important factors for the traction converter/inverters because the equipment shall be deployed within the limited space volume of the rolling stock, minimizing weight and increasing the opportunity to allocate space for increased passenger numbers. Silicon carbide (SiC) power modules are expected to meet these challenges due to low loss, high speed switching and high temperature operation features. Hitachi Power Semiconductor Device Ltd. developed a 3.3 kV/450 A “full SiC” power module (MSM450FS33A), consisting of both SiC-MOSFET and SiC-Schottky barrier diode (SBD), using the next high power density dual (nHPD^2) package [1]. The phase leg package is suitable for SiC deployment owing to its small footprint of 100 mm x 140 mm and perhaps more importantly, a low inductance value, less than 10 nH [2]. The switching loss of the module was reduced to one-fourth of a conventional 3.3 kV/450 A Si-IGBT module without unwanted switching oscillations. However, high output current density is strongly desired for system miniaturization and cost reduction. In conventional power modules, both transistor and diode are necessary to function satisfactorily. This requirement results in limiting both power density and cost.

In this work, a 3.3 kV/800 A diode-less (“D-less”) SiC power module with nHPD^2 package (MSM800FS33AL) was developed, offering the highest power density of 37.7 kVA/cm^2 among high voltage power modules (at the time of publication). The D-less SiC power module is constructed using only SiC-MOSFET, which drastically reduces its cost per Ampere. Mindful of well-known “bipolar degradation” issues when using the body diodes of SiC-MOSEFT [3], the authors have solved this problem by the deploying of a new high throughput screening process. Furthermore, the characteristics of the D-less SiC power module and the system level benefits by application of the module are discussed.



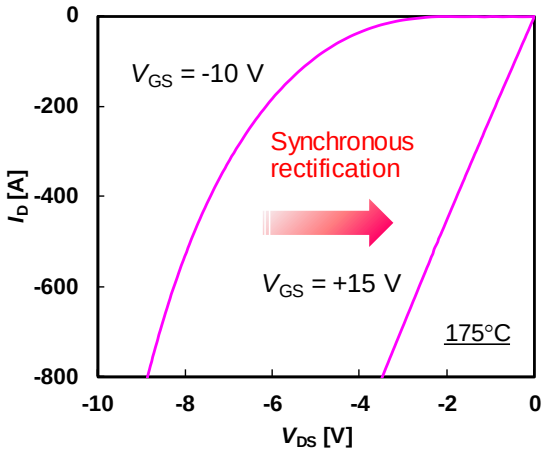
(a) nHPD^2 package

ISBN 978-3-8007-4646-0



(b) Circuit diagram

Fig. 1 3.3 kV/800 A D-less SiC power module (MSM800FS33AL)



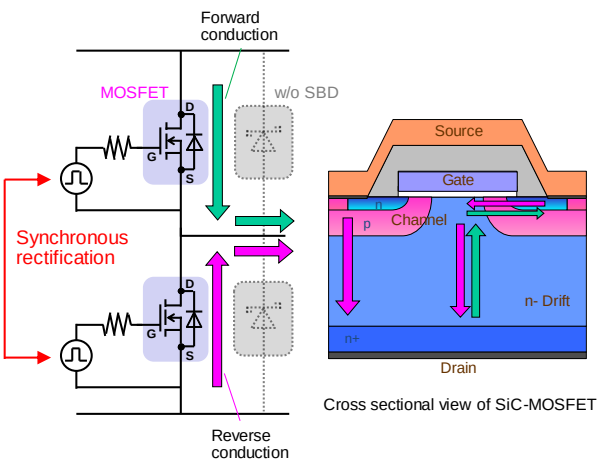
(b) Reverse conduction characteristics

Fig. 2 Conduction features of D-less SiC power module

2. High power density technology

2.1. D-less SiC power module

Since SiC-MOSFET have the capability of reverse conduction, freewheeling diodes (SiC-SBD) were not mounted in the module. Though body diodes of SiC-MOSFET have a high voltage drop (V_f) due to SiC's wide-bandgap, low conduction loss can be achieved by synchronous rectification, in which an on-gate voltage is also applied to the MOSFET for its reverse conduction, as shown in Fig. 2. This technique can limit body-diode conduction to the dead-time period only. Therefore, the influence of the large V_f on inverter operations can be considered negligible.



(a) Current flow in D-less SiC power module

2.1. Screening process for bipolar degradation issues

Bipolar operation of the body diode may lead to stacking fault expansion from pre-existing basal plane dislocations in SiC material by electron-hole recombination. The stacking faults increase not only the V_f of the body diode but also the on-resistance of channel conduction in SiC-MOSFET. This bipolar degradation is serious, especially in high voltage like to 3.3 kV class. A low doping density of the epi-layer lead to a long hole lifetime, and the thick epi-layer is susceptible to large stacking fault areas. In order to combat this problem, the authors developed a high throughput screening process technology, which is based on an accurate modeling of the degradation [4]. Figure 3 shows the probabilities of degraded SiC-MOSFET chips by application of the screening test. The degradation was evaluated by ΔV_{on}, i.e. the difference of forward on-voltage before and after the test. The tested samples were made using only high-quality wafers and were optimally designed to have a high-level immunity against the degradation. Consequently, over 90% of chips showed no V_{on} shift. However, it should be noted that there were small number of large ΔV_{on} chips. These degraded chips were screened out by this technology.

ISBN 978-3-8007-4646-0

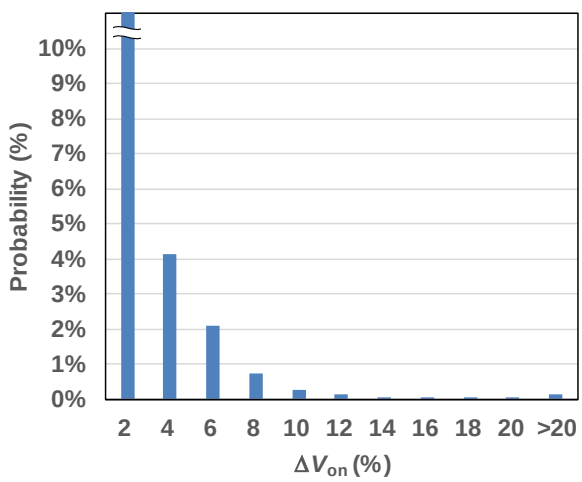


Fig. 3 Probabilities of "bipolar degradation" chip. The ΔV_{on} is a difference of forward on-voltage before and after the screening test.

3. Characteristics of D-less SiC power module

Figure 4 shows the forward I_D-V_{DS} characteristics of the 3.3 kV/800 A D-less SiC power module (MSM800FS33AL) and a previously reported 3.3 kV/450 A full SiC power module (MSM450FS33A) [1]. A low V_{on} value of MSM800FS33AL at 175°C was achieved, and a vast improvement compared to the MSM450FS33A measured at 150°C. This difference was due to an improved SiC-MOSFET die design and a highly integrated circuit within the module.

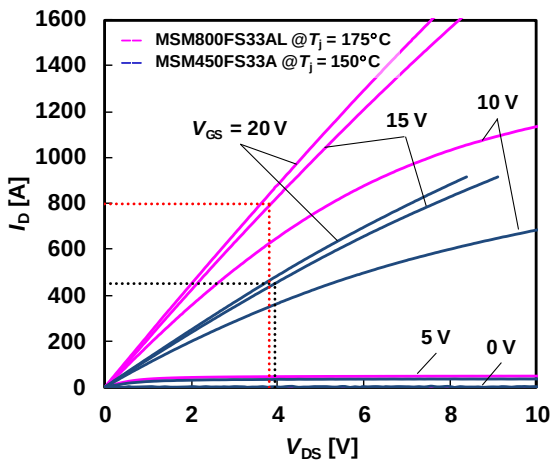
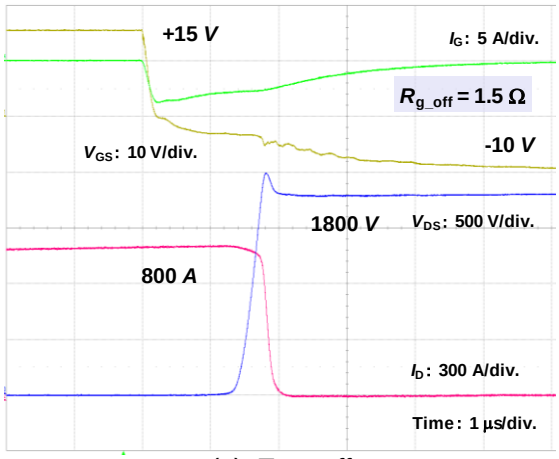
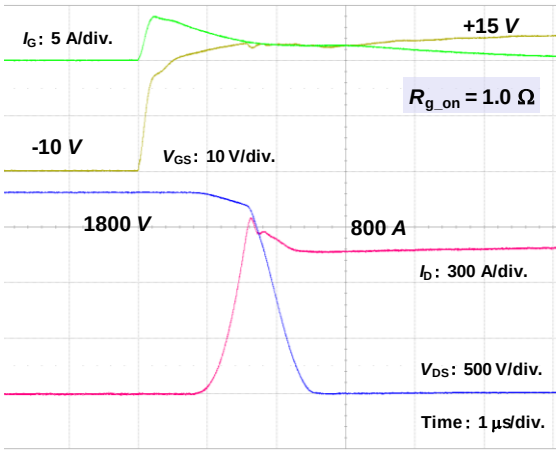


Fig. 4 Forward output characteristics of 3.3 kV/800 A D-less SiC (MSM800FS33AL) and 3.3 kV/450 A full SiC (MSM450FS33A) power modules with the same nHPD² package.

Figure 5 shows switching waveforms of a D-less SiC power module at 1800 V, 800 A and T_j 175°C. Gate-drive conditions were set to V_{GS} = +15/-10 V and gate resistances R_g(on/off) = 1.0/1.5 Ω. Due to the low internal inductance of nHPD² package, oscillations during the switching operation were successfully avoided. A unipolar operation without tail current in SiC-MOSFET reduced a turn-off loss significantly. Although a recovery current of the body diode was slightly larger in comparison to the full SiC power module [1], low losses in turn-on and reverse recovery switchings were also achieved in the D-less SiC power module. Additionally, a small recovery current was validated, whilst turning off twice the rated current under a recovery safe operation area (SOA) testing, at 175°C, as shown in Figure 6.

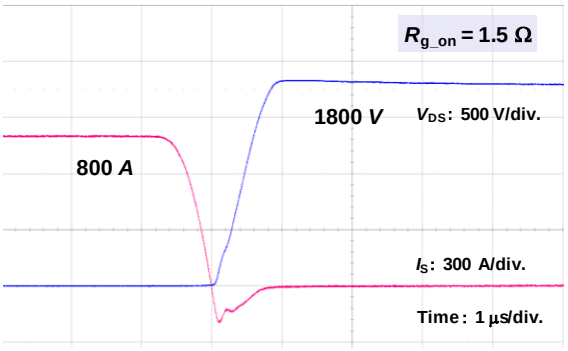


(a) Turn-off



(b) Turn-on

ISBN 978-3-8007-4646-0



(c) Reverse recovery

Fig. 5 Switching waveforms of MSM800FS33AL. Measurement conditions: V_{DS} = 1800 V, I_D or I_R = 800 A, T_j = 175°C, R_G(on/off) = 1.0/1.5 Ω, V_{GS} = +15/-10 V, L_s = 40 nH.

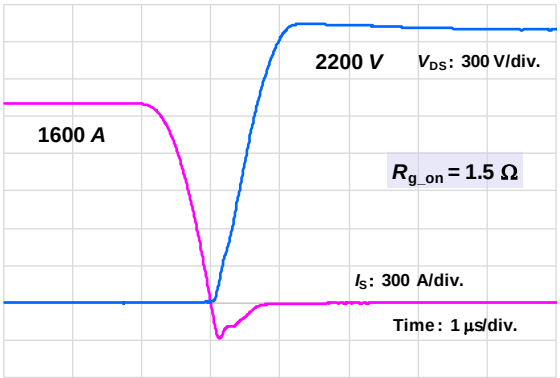


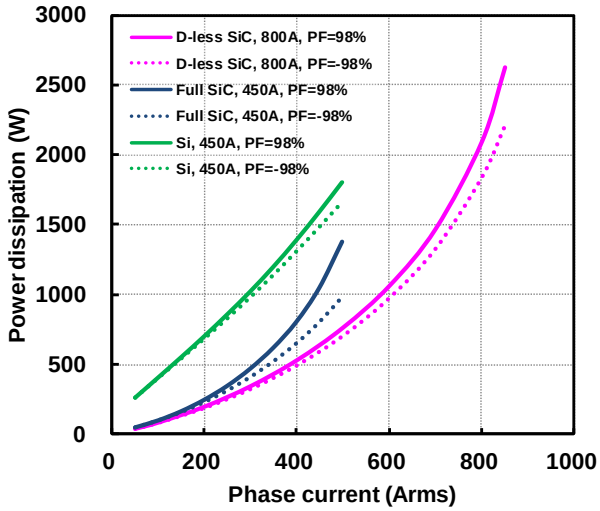
Fig. 6 Reverse recovery SOA test.

Conditions: V_{DS} = 2200 V, I_R = 1600 A, T_j = 175°C, R_G(on) = 1.5 Ω, V_{GS} = +15/-10 V, L_s = 40 nH.

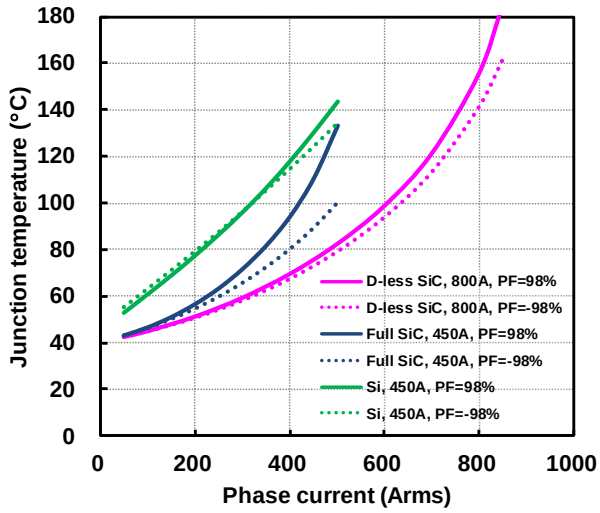
4. System level consideration

Power dissipations of 3.3 kV/800 A D-less SiC, 3.3 kV/450 A full SiC [1] and 3.3 kV/450 A Si-IGBT (MBM450FS33F) [5] nHPD^2 power modules were simulated and compared. For traction inverters it is very important to recognize the strong temperature dependency of on-voltage in SiC power modules, because the dependency is quite large especially in the 3.3kV class. In this simulation, the junction temperature (T_j) dependency of on-voltage and the T_j difference between MOSFET and SBD in SiC power modules are both taken into account [1]. The calculated example considers traction inverters with a 1 kHz carrier frequency at 1800 V DC-link voltage. Other conditions are as follows: modulation ratio 90%, ambient temperature (T_a) 40°C and thermal resistance between case to ambient (R_{th}(c-a)) 0.03 K/W.

Figure 7 shows the simulation results. In SiC power modules, loss curves are found to be quadratic. This is due to the T_j dependency of on-voltage in SiC. With increasing phase current, the losses of the power modules increase. This results in a T_j increase, and this rise of T_j leads to the increase of on-voltage. This feedforward feature, combined with no-offset on-voltage of SiC power modules, can reduce power dissipation drastically, particularly in low phase current ranges compared to Si-IGBT power modules.



(a) Power dissipations



(b) Junction temperatures

Fig. 7 Inverter simulation with differential output current. Motoring and regenerative braking railcar conditions: Power factor (PF) +98% & -98% respectively. DC-link 1800 V, carrier frequency 1 kHz, ambient temperature 40°C, and thermal resistance (R_{th}(c-a)) 0.03 K/W. Higher T_j of either transistor or diode in one module is plotted in (b).

ISBN 978-3-8007-4646-0

During actual traction inverter operation, high current operation is typically limited to emergency use. Due to this, SiC power modules can avoid larger energy losses during normal operation. At a phase current of 200 Arms, the energy savings by adoption of the D-less SiC module are 71.6% and 72.3% in motoring (power factor +98.5%) and regenerative braking (power factor -98.5%) respectively, when compared to the Si-IGBT module. Below 400 Arms, the savings are over 60% in both operational modes. Furthermore, the quadratic T_j curves of D-less SiC module as shown in Fig. 7 (b) indicate that the module operates with a low ΔT_j for most of the time. This contributes to an improvement of power cycle durability.

5. Conclusion

A 3.3 kV/800 A D-less SiC power module, which was constructed with only SiC-MOSFETs, featured in the nHPD^2 package was developed. An ultra-high power density of 37.7kA/cm^2 was achieved delivering smooth oscillation free switching. A high throughput screening process technology was also applied as a countermeasure against SiC's bipolar degradation issues. A low on-state voltage and low switching losses of the module were obtained even at 175°C. Reverse recovery SOA was confirmed to be durable for field application. These characteristics offer large energy saving potential by 60 – 80% in comparison with a conventional Si-IGBT power module and high reliability for actual traction inverter operations.

6. References

[1] T. Ishigaki et. al., "3.3 kV/450 A Full-SiC nHPD^2 (next High Power Density Dual) with smooth switching", PCIM Europe 2017, pp. 33-38, (2017).

[2] D. Kawase, M. Inaba, K. Horiuchi, and K. Saito, "High voltage module with low internal inductance for next chip generation - next High Power Density Dual (nHPD^2) -", PCIM Europe 2015, pp. 217-223, (2015).

[3] T. Kimoto et al., "Understanding and Reduction of Degradation Phenomena in SiC Power Devices", IRPS 2017, pp. 2A-1.1-1.7, (2017).

[4] K. Konishi, R. Fujita, A. Shima, and Y. Shimamoto, "Modeling of Stacking Fault Expansion Velocity of Body Diode in 4H-SiC MOSFET", ECSCRM 2016, (2016).

[5] http://www.hitachi-power-semiconductor-device.co.jp/products/igbt/nHPD2/index.html

