Proceedings Paper:

Sheikhan, A. orcid.org/0000-0002-2207-1593 and Sankara Narayanan, E.M. orcid.org/0000-0001-6832-1300 (2024) Evaluation of a hybrid power switch based on trench clustered IGBT and SiC MOSFET. In: PCIM Europe 2024; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management. PCIM Europe 2024; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 11-13 Jun 2024, Nürnberg, Germany. VDE VERLAG GMBH , pp. 2601-2606. ISBN 9783800762620

https://doi.org/10.30420/566262364

Evaluation of a Hybrid Power Switch Based on Trench Clustered IGBT and SiC MOSFET

Alireza Sheikhan[1], E. M. Sankara Narayanan[1]

[1] The University of Sheffield, United Kingdom

Corresponding author: Alireza Sheikhan, asheikhan1@sheffield.ac.uk
Speaker: Alireza Sheikhan, asheikhan1@sheffield.ac.uk

Abstract

This paper reports performance of a hybrid power switch (HPS) based on parallel arrangement of a 1.2 kV silicon (Si) field stop trench clustered IGBT (FS-TCIGBT) and a 4H-Silicon Carbide (SiC) MOSFET of equivalent rating. The device is aimed to deliver optimum performance over a wide range of load conditions in terms of static and dynamic power losses while maintaining a low cost-to-performance ratio. The HPS can operate in unipolar or bipolar regime depending on load current and operating temperature which enables the device to offer a low on-state losses regardless of load condition. The results show that the HPS effectively combines high current capability of TCIGBT and switching performance of SiC in a single package.

1 Introduction

Motor drives require robust power semiconductors capable of delivering maximum efficiency over a wide range of load conditions. This is particularly important as the source of energy is limited. Wide bandgap semiconductors such as SiC are promising in terms of switching performance and power losses which is attributed to their superior material properties. The drift region, which is the main contributor to the on-state resistance in high voltage devices, can be made thinner than that of Si due to the high critical electric field strength and wide bandgap nature of 4H-SiC. Wide bandgap FETs also have extremely fast switching transitions due to the absence of bipolar charge carriers which results in lower switching energy than silicon MOS-bipolar counterparts [1,2]. However, despite advancements in manufacturing and fabrication technologies, the associated costs are still significantly higher when compared with Si counterparts. These costs increase non-linearly with higher current requirements. Si insulated gate bipolar transistors (IGBTs), on the other hand, have long established domination in high power applications. IGBTs are significantly cheaper than SiC and inherently suitable for high current operations due to their low voltage drop achieved through conductivity modulation. IGBTs offer superior cost-to-performance ratio, which is due to the availability of low-cost Si wafers. Despite the clear advantage of IGBTs in high current applications, their low current performance is hindered by a 0.7 V p-n junction voltage drop at RT. The switching performances of IGBTs are also limited because of the injected carriers due to the bipolar action. The injected carriers which reduce the drift region resistance, need to be removed or recombined in order for the device to turn-off. The removal process of these excess carriers causes a tail current. IGBTs also suffer from dynamic avalanche, which limit high current density operation [3,4]. Therefore, the development trend in IGBTs has been focused toward improving these trade-off issues. One of the recent innovations in this area is the introduction of the field stop (FS) trench clustered IGBT (TCIGBT), which is shown in Fig. 1 [5,6]. TCIGBT is aimed as a more efficient chip-for-chip replacement of IGBTs. One of the key features of TCIGBT is the utilization of thyristor mode of conduction to reduce the on-state voltage drop. The addition of a highly conducting N well region over a floating P well layer in an IGBT creates a MOS controlled thyristor action. The resulting PNP transistor involving (P well/N well and P base), is designed in such a way that the N well layer is punched through at a certain anode voltage and the voltage across the gate is therefore clamped [7]. This mechanism protects the trench gate from high electric fields. The design also includes a PMOS formed by the p base-N-well-p well along the side walls of the gates to enable efficient hole diversion and removal of DA effects. The PMOS is turned on with increase in the N well potential, which is akin to applying a negative gate bias to the PMOS gate.

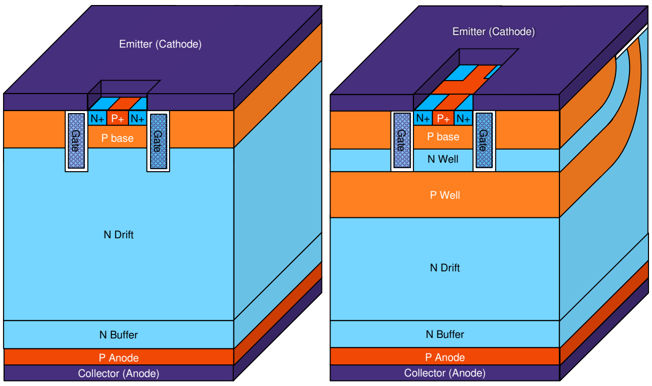

Fig. 1 Cross-sectional view of the trench IGBT (left) and trench CIGBT (right).

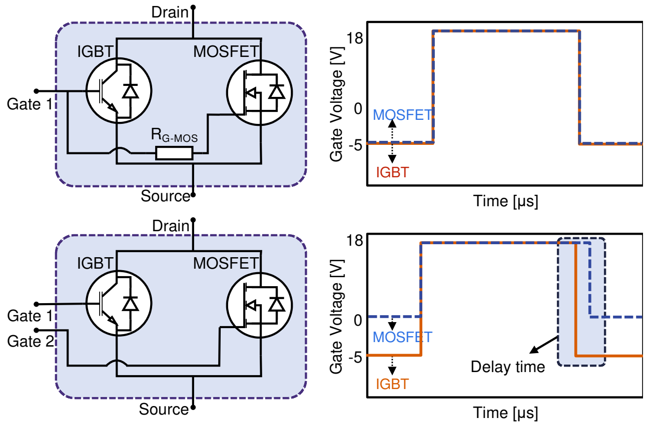

Fig. 2 Hybrid power switch configurations (left) and optimal gate drive approach (right).

Consequently, holes are extracted by the electric field and dynamic avalanche issues are avoided, which hinders high dV/dt and high current density operation in conventional IGBTs [4]. To take advantage of both SiC and Si, most electric vehicles (EVs) utilize a combination of both technologies. A remedy for high cost of SiC is to use less chip area at the expense of higher conduction losses, inferior thermal conductivity, and less current handling capability. Another approach is to use a hybrid power switch (HPS) that can fit for a wide range of load demand without compromising conduction losses or switching performance. In this paper, a hybrid power switch based on the latest TCIGBT and SiC MOSFET technologies is presented for the first time. The device characteristics, working mechanism and switching performance are experimentally demonstrated and analyzed. Additionally, a comparison of characteristics between the TCIGBT and IGBT is presented.

1.1 Hybrid Power Switch Concept

One of the early reports on hybrid combinational transistors is given in [8]. Several studies to this date have reported various hybrid device configurations using IGBTs and MOSFETs [1][9-12]. HPS's are formed by a parallel combination of unipolar and bipolar devices as shown in Fig. 2. HPS have a unique bi-mode operation that enables them to maintain a low conduction loss profile over a wide range of load currents. Under low load conditions, the device operates in unipolar mode and the load is entirely handled by the MOSFET. Meanwhile, under high load conditions, the HPS switches to bipolar mode which diverts excess current to the IGBT. The boundary between bipolar and unipolar mode is determined by the on-state resistance of the MOSFET and bipolar on-set voltage. There are two HPS gate configurations; (1) single gate, where the IGBT and MOSFET gates are connected. (2) dual gate, where gates are separated and independently controlled. This is because IGBTs generally have longer switching delay times than MOSFETs which is particularly troublesome during the turn-off as it results in higher switching losses in a single gate arrangement. However, with an intelligent control, a turn-off delay can be added in such a way that the MOSFET turns off after the IGBT in the dual gate mode. The benefit of this approach is that the load current is switched under the unipolar mode with the minimum switching losses. In this mode, the IGBT experiences a zero-voltage switching and does not contribute to switching losses. A turn-on delay is not always necessary as the MOSFET switches on first.

2 Experimental Setup

A 1200 V FS TCIGBT and a 1200 V SiC MOSFET (IMW120R030M1H – CoolSiC – Infineon [13]) with a current rating of 50 A each were selected for the HPS. For comparison purposes, a FS IGBT (IKW50N120CS7 – IGBT7 – Infineon [14]) with similar rating is also selected. The static characteristics of individual devices were measured using a curve tracer. The switching performance of the HPS were analyzed using an inductive switching test bench as shown in Fig. 3. The load inductor (L_{Load}) is 240 µH with 1200 V freewheeling SiC Schottky diode (D_{FWD}). The turn-on and turn-off switching performances were evaluated at V_{DC} of 600 V and I_{Load} of 50 A at different gate resistances R_{G1} to analyze the dV/dt controllability. The positive gate bias is set at 18 V. A turn-off gate bias of 0 V and -5 V are applied to the MOSFET and IGBT respectively.

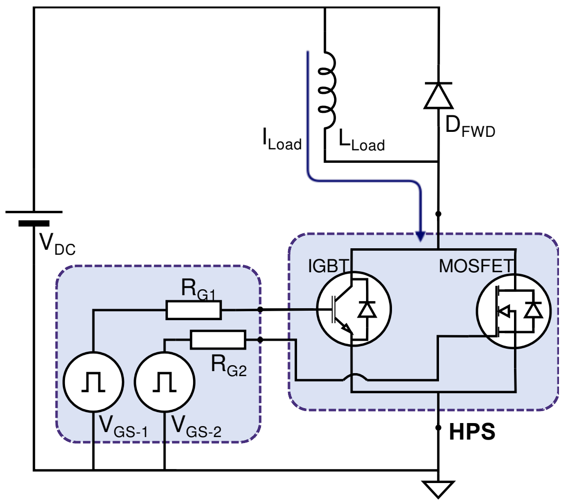

Fig. 3 Inductive switching test setup.

The switching losses were extracted from the measured data by integrating the dissipated power over switching periods as given by Eq. (1).

$$E_{SWT} = E_{On} + E_{Off} = \int V_{Drain} . I_{Drain}\, dt \qquad (1)$$

3 Device Characteristics

3.1 On-State Characteristics.

The on-state output I-V characteristics of the HPS were measured under pulse mode to prevent self-heating as shown in Fig. 4 and Fig. 5.

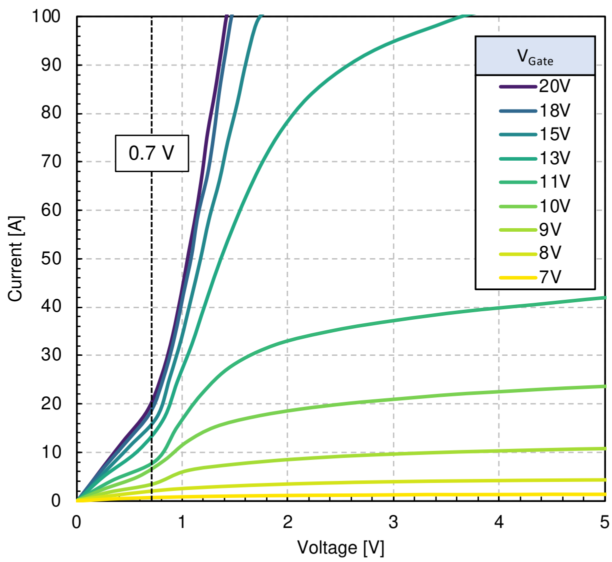

Fig. 4 Measured output IV characteristics of the HPS at different gate voltages and 25˚C. The pulse width is 250 µs.

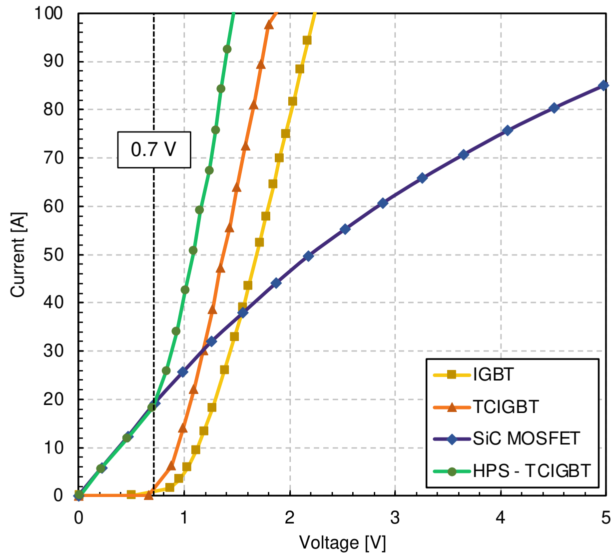

Fig. 5 Comparison of measured output IV curves at V_{GS} of 18 V and at 25˚C.

In this HPS configuration the boundary between bipolar and unipolar mode is ~20 A at RT. Below this boundary, the entire load current is conducted in unipolar mode through the MOSFET. The excess current above 20 A is handled by the TCIGBT as the voltage drop across the device is high enough to overcome the bipolar on-set voltage of 0.7 V at RT. With the increase in temperature, the boundary condition also changes because the bipolar on-set voltage decreases allowing more current to be diverted to the TCIGBT.

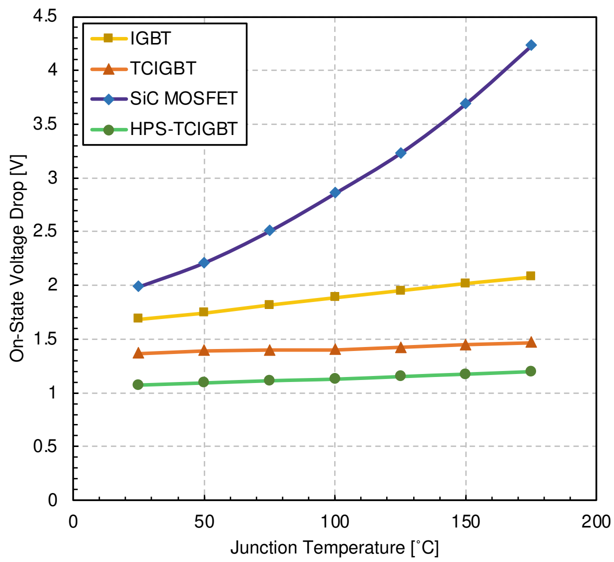

Fig. 6 Measured on-state voltage drop as a function of junction temperature at 50 A. The gate voltage is 18 V.

This mechanism allows the HPS to maintain low on-state losses under high temperature/current conditions. It is important to note that the TCIGBT achieves lower on-state voltage drop compared with the IGBT for the same given power rating and active area making it highly suitable for the HPS. The on-state voltage of the HPS and its constituent components were extracted at different junction temperatures as shown in Fig. 6.

The HPS exhibits a mild positive temperature coefficient of on-state voltage drop similar to the TCIGBT. In contrast, the on-state voltage of the SiC MOSFET increases rapidly with the temperature in such a way that the on-state voltage is twice as high as RT. Therefore, a pure SiC solution will result in significant power losses at elevated operating temperatures while conducting its nominal current.

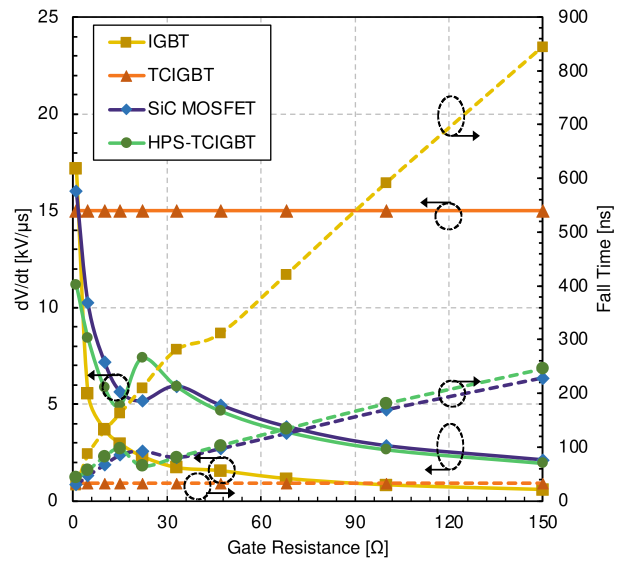

Fig. 8 Measured turn-on dV/dt and voltage fall time as function of gate resistance at 25˚C.

4 Switching Performance

4.1 Turn-On Switching

Figure 7 shows the turn-on switching waveforms of the HPS at different gate resistances at RT. In this experiment, no delay is added and both gate signals are applied at the same time. The MOSFET naturally turns-on first before the IGBT and thus the turn-on transition is handled in unipolar mode. The turn-on dV/dt and voltage fall time are presented in Fig. 8. As it can be seen the HPS offers a similar dV/dt and fall time figures to the SiC MOSFET which confirms the unipolar turn-on.

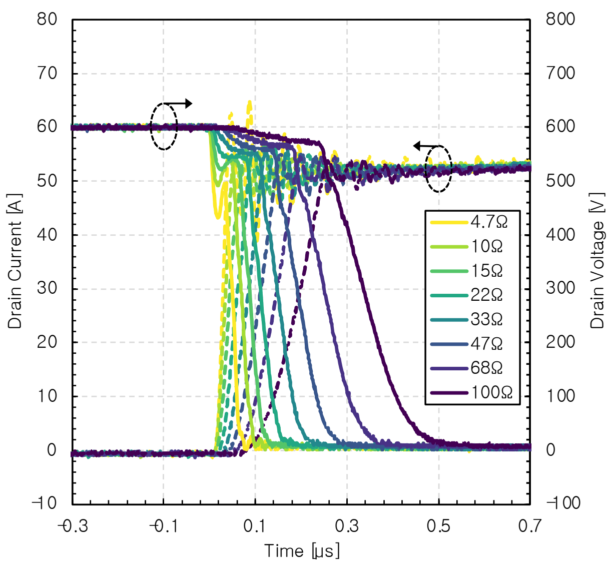

Fig. 7 Measured turn-on switching waveforms of the HPS at different gate resistances and 25˚C.

As previously stated, in TCIGBTs, the turn-on is governed by its inherent thyristor action. The current gain of the thyristor constituents determine the turn-on performance and the influence of the gate resistance is nominal which explains the flat dV/dt response. A more detailed analysis of the TCIGBT turn-on behavior is explained in [15].

The turn-on losses were extracted from the measured switching waveforms as illustrated in Fig. 9. Similar to the turn-off, the turn-on power losses are

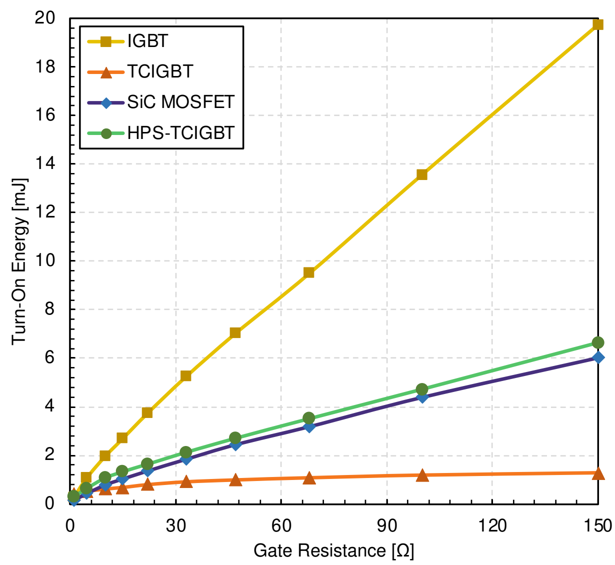

Fig. 9 Measured turn-on energy losses at different gate resistances and 25˚C.

comparable to the SiC MOSFET because of the unipolar switching transition. The IGBT exhibits higher turn-on losses due to its slower dV/dt. Meanwhile, the switching energy in TCIGBT is almost constant regardless of the gate resistance.

4.2 Turn-Off Switching

The turn-off switching performance of the HPS is evaluated at different gate resistances at RT as shown in Fig. 10. In this test a delay of 2 µs is added to the MOSFET to ensure that it turns-off after the TCIGBT.

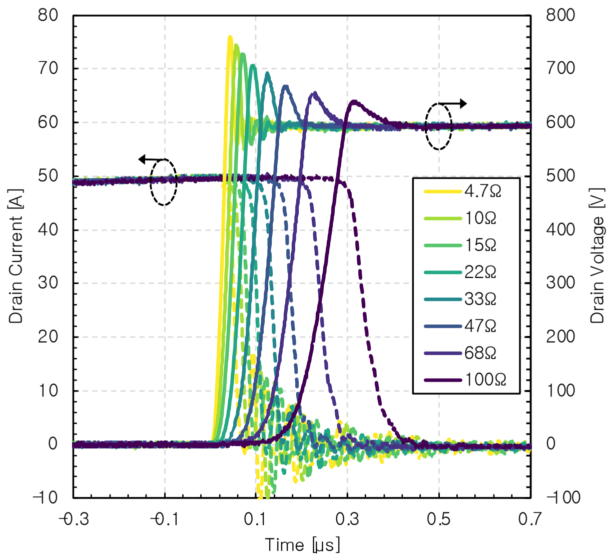

Fig. 10 Measured turn-off switching waveforms of the HPS at different gate resistances and 25˚C.

In the turn-off, no tail current can be observed which indicates a unipolar switching. Therefore, a higher switching speed can be achieved which results in lower losses. In several applications such as variable speed drive the dV/dt need to be limited to meet the application requirements and adhere to electromagnetic interference (EMI) requirements [16]. The turn-off dV/dt and voltage rise time were extracted for each device as shown in Fig. 11. The dV/dt can be effectively controlled by the gate resistor to fulfil various application requirements such as motor drives. At low gate resistance a plateau can be observed in dV/dt of the IGBT. This plateau is caused by the occurrence of a dynamic avalanche which limits the high-speed operation. The corresponding turn-off losses were extracted from the measured switching waveforms as shown in Fig. 12. Since the HPS switches in unipolar mode, the switching losses are similar to the SiC MOSFET. Meanwhile the HPS offers double the current handling capacity than the MOSFET. It is worth pointing out

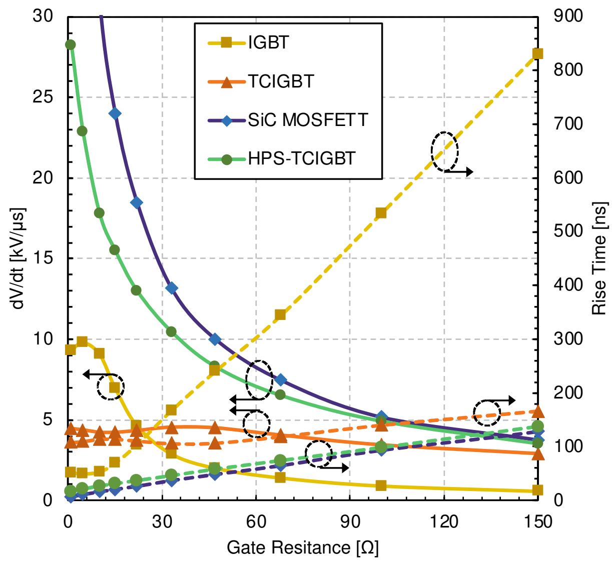

Fig. 11 Measured turn-off dV/dt and voltage rise time as function of gate resistance at 25˚C.

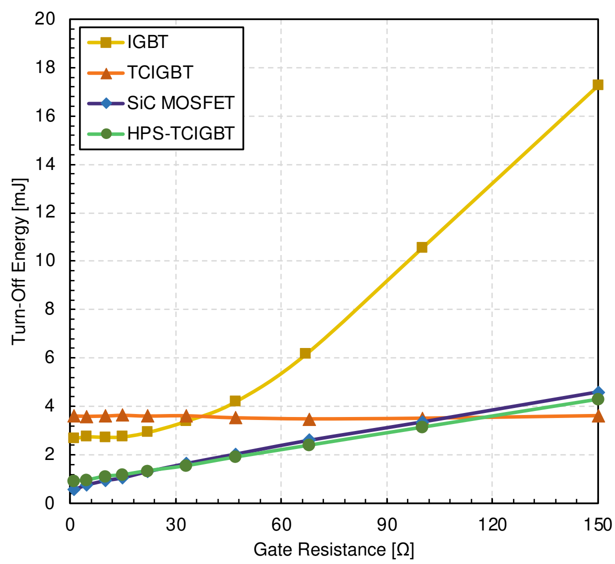

Fig. 12 Measured turn-off energy losses at different gate resistances and 25˚C.

that the TCIGBT power losses do not change with the gate resistor because of its nearly flat dV/dt. This is because of effective use of PMOS.

5 Conclusion

In this paper, a hybrid power switch using a FS-TCIGBT and SiC MOSFET have been evaluated experimentally. The device characteristics, operating principle and switching performance were analyzed. Based on the results, the HPS offers low switching losses similar to a SiC MOSFET while offering almost double the current handling capability. The bi-mode characteristics of the HPS allows the device to maintain a low power loss profile over a wide range of load current and operating temperatures. The results also show that the utilization of thyristor mode in TCIGBT contribute to improved on-state characteristics compared with the IGBT. Additionally, the unique self-clamping mechanism protect the gates from high electric fields and enables the device to operate high current densities without the risk of dynamic avalanche. Such characteristics makes this HPS configuration a highly suitable candidate for power electronic applications requiring flexibility and optimal performance particularly in the form of intelligent power modules for a wide range of applications, including drives.

6 Acknowledgements

The authors thank Eco semiconductors Limited for providing 1.2 kV FS-TCIGBT samples to undertake this study.

References

[1] A. Sheikhan and E. M. S Narayanan, “Evaluation of Characteristics and Turn-off dV/dt Controllability of 1.2 kV SiC Si Hybrid Power Switch,” in *International Seminar on Power Semiconductors*, Prague, 2023.

[2] A. Sheikhan, E. M. S. Narayanan, H. Kawai, S. Yagi and H. Narui, “Evaluation of turn-off dV/dt controllability and switching characteristics of 1.2 kV GaN polarisation superjunction heterostructure field-effect transistors,” *Japanese Journal of Applied Physics,* vol. 62, p. 064502, 2023.

[3] J. Lutz and R. Baburske, “Dynamic avalanche in bipolar power devices,” *Microelectronics Reliability,* vol. 52, no. 3, pp. 475-481, 2012.

[4] P. Luo, S. N. E. Madathil, S.-I. Nishizawa and W. Saito, “Evaluation of Dynamic Avalanche Performance in 1.2-kV MOS-Bipolar Devices,” *IEEE Transactions on Electron Devices,* vol. 67, no. 9, pp. 3691-3697, 2020.

[5] H. Y. Long, M. R. Sweet, M. M. D. Souza and E. M. S. Narayanan, “Next Generation 1200V Trench CIGBT for High Voltage Applications,” in *International Symposium on Power Semiconductor Devices & IC's*, Hong Kong, 2015.

[6] K. Vershinin, M. Sweet, L. Ngwendson, J. Thomson, P. Waind, J. Bruce and E. M. S. Narayanan, “Experimental Demonstration of a 1.2kV Trench Clustered Insulated Gate Bipolar Transistor in Non Punch Through Technology,” in *2006 IEEE International Symposium on Power Semiconductor Devices and IC's*, Naples, 2006.

[7] O. Spulber, M. Sweet, K. Vershinin, C. Ngw, L. Ngwendson, J. Bose, M. M. D. Souza and E. M. S. Narayanan, “A novel trench clustered insulated gate bipolar transistor (TCIGBT),” *IEEE Electron Device Letters,* vol. 21, no. 12, pp. 613-615, 2000.

[8] D. Y. Chen and S. A. Chin, “Bipolar-FET Combinational Power Transistors for Power Conversion Applications,” in *Fifth International Telecommunications Energy Conference*, Tokyo, 1983.

[9] M. Rahimo, F. Canales, R. A. Minamisawa, C. Papadopoulos, U. Vemulapati, A. Mihaila, S. Kicin and U. Drofenik, “Characterization of a Silicon IGBT and Silicon Carbide MOSFET Cross-Switch Hybrid,” *IEEE Transactions on Power Electronics,* vol. 30, no. 9, pp. 4638 - 4642, 2015.

[10] G. Ortiz, C. Gammeter, J. W. Kolar and O. Apeldoorn, “Mixed MOSFET-IGBT bridge for high-efficient Medium-Frequency Dual-Active-Bridge converter in Solid State Transformers,” in *Workshop on Control and Modeling for Power Electronics*, Salt Lake City, 2013.

[11] P. Luo, H. Y. Long, M. R. Sweet, M. M. D. Souza and E. M. S. Narayanan, “Analysis of a Clustered IGBT and Silicon Carbide MOSFET Hybrid Switch,” in *26th International Symposium on Industrial Electronics*, Edinburgh, 2017.

[12] C. R. Mueller, “Design and Analysis of a Low-Inductive Power-Semiconductor Module with SiC T-MOSFET and Si IGBT in Parallel Operation,” in *PCIM Europe*, Nuremberg, 2017.

[13] Infineon, “Datasheet: IMW120R030M1H,” Infineon, 2020.

[14] Infineon, “Datasheet: IKW50N120CS7,” Infineon, 2021.

[15] S. N. E. Madathil, P. Luo, W. Saito and S.-I. Nishizawa, “Performance Comparison of Scaled IGBTs and CIGBTs,” in *Solid State Devices and Materials conference*, 2021.

[16] H. Akagi, “Influence of high dv/dt switching on a motor drive system: a practical solution to EMI issues,” in *International Symposium on Power Semiconductor Devices and ICs*, Kitakyushu, 2004.