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Development of 8-inch Key Processes for Insulated-Gate Bipolar Transistor

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ABSTRACT Based on the construction of the 8-inch fabrication line, advanced process technology of 8-inch wafer, as well as the fourth-generation high-voltage double-diffused metal-oxide semiconductor (DMOS+) insulated-gate bipolar transistor (IGBT) technology and the fifth-generation trench gate IGBT technology, have been developed, realizing a great-leap forward technological development for the manufacturing of high-voltage IGBT from 6-inch to 8-inch. The 1600 A/1.7 kV and 1500 A/3.3 kV IGBT modules have been successfully fabricated, qualified, and applied in rail transportation traction system.

KEYWORDS insulated-gate bipolar transistor (IGBT), high power density, trench gate, 8-inch, rail transportation

1 Introduction

Since the 1950s, the semiconductor industry has made great progress in both integrated circuit (IC)-based microelectronics and power semiconductor devices [1]. In the application, microelectronics act as the brain to control huge information flows while power semiconductor devices act as the heart to manage intensive energy flows. Their effective cooperation allows high efficiency energy utilization. With rapid development and maturity of both semiconductor materials and microelectronics process technologies, the third-generation power chips, represented by insulated-gate bipolar transistor (IGBT), has opened up a new area in the power semiconductor field [2].

The IGBT has become a popular choice of power semiconductor device for a wide range of industrial power-conversion applications due to technological advancement such as rugged switching characteristics, low losses, and simple gate drives. As an advanced power semiconductor device, the IGBT with high power capacity has been widely applied in most strategic emerging industries such as high speed rail transportation, electric vehicles, smart grid, and renewable energy [3–7]. The IGBT chip and its related technology has been monopolized by several giant companies possessing competitive technologies and applications for a long time, thus more than 95% IGBT products had to be imported. The situation can be attributed to two reasons. Firstly, the IGBT business chain is imperfect in China, and due to the fact that little attention was paid to the importance of IGBT technology in the earlier 1980s, domestic IGBT companies are normally 20–30 years younger than other major IGBT players. Secondly, the academic investigation and innovation on IGBT technology in China is lagging behind that of the advanced international institute, which results in poor intellectual property accumulation on IGBT chip design and process.

The development trends and key characteristics of IGBT chip technology were summarized in this paper. Besides, the new 8-inch fabrication line dedicated to IGBT in China Railway Rolling Stock Corporation (CRRC) Zhuzhou Electric Locomotive Institute Co., Ltd. was introduced, and the advanced IGBT processes and key technologies were also highlighted. Finally, the high power density IGBT modules with 1.7 kV and 3.3 kV IGBT and fast recovery diode (FRD) chipsets based on the new-generation 8-inch fabrication line were fabricated, qualified, and successfully applied in rail transportation traction system.

2 Development of IGBT technology

With regard to the device basic structure, an IGBT is a kind of compound power semiconductor device combined with a bipolar junction transistor (BJT) and a metal-oxide-semiconductor field effect transistor (MOSFET). An N-channel IGBT is basically a vertical power MOSFET constructed on a layer doped by *p*-type impurity, as illustrated in Figure 1 [8, 9]. Once a positive voltage is applied from the gate to the emitter, inversion electrons are generated underneath the gate in the P-base region. If the gate-emitter voltage is above the threshold voltage, enough electrons are generated to form a conductive channel across the body region, supplying a base current

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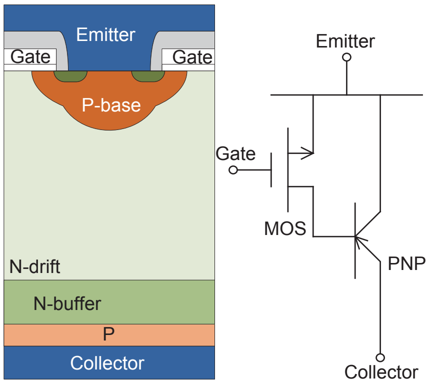


Figure 1. IGBT cross-section and equivalent circuit.

for the positive-negative-positive (PNP) transistor and allowing current to flow from the collector to the emitter. With the combination of an easily driven metal-oxide-semiconductor (MOS) gate and low conduction loss, IGBTs quickly replaced power bipolar transistors as the device of choice for high-current and high-voltage applications.

Basically, the performance of IGBT device is judged by static characteristics, dynamic characteristics, and reliability. The static characteristics consist of on-state voltage drop, gate threshold voltage, forward blocking voltage, and leakage current. The dynamic characteristics include switching losses and switching times, which are related to the dynamic losses and operation frequency. Finally, the reliability is mainly comprised of the reverse bias safe operating area (RBSOA) and the short circuit safe operating area (SCSOA). Normally, IGBTs have a significantly lower on-state voltage drop compared to that of unipolar devices in medium and high power classes. However, this is at the expense of increased turn-off time and loss. Besides, high current density and fast turn off speed prone to inducing narrow RBSOA and SCSOA. The ways to balance the trade-off among on-state voltage, turn-off energy and safe operating area (SOA) can be summarized as follows: refining fine pattern cell structure at the emitter side and tailoring the hole injection efficiency at the collector side, both are fully developed within the process evolvement of IGBT.

Figure 2 shows the key technologies during the development of IGBT technology since its invention. As we can see, the technologies on both sides of emitter and collector developed alternately and coordinately. At the early age, the collector region employed punch-through (PT) structure based on epitaxial wafer, while the cell on the emitter side used planar gate technology with large critical dimension. This kind of IGBT had poor anti-latch-up ability, high conduction voltage drop, and high turn-off energy. Besides, utilization of epitaxial wafer in PT-IGBT not only resulted in high cost of silicon material but also restricted its highest blocking voltage to be below 2 kV. The lately appeared non punch-through (NPT)-IGBT solved these problem by employing float-zone (FZ) wafer, laying the foundations for forwarding the IGBT to high-voltage field and reducing the cost significantly. Comparing with PT-IGBT, NPT-IGBT has dramatically reduced tail time owing to its lower injection efficiency of collector. In the meantime, improvement of refining cell pattern of planar IGBT and employing trench gate structure were realized on the emitter side for lower on-state voltage drop and more extensive SOA [10].

However, since the drift region of the NPT-IGBT was too wide, the reduction of the on-state voltage and turn-off loss was constrained. Aiming to solve this problem, the laser annealing and thin wafer processing technologies were introduced into the formation of field stop (FS) structure around the year of 2000, meanwhile the trench process based on advanced plasma etch technology was introduced on the emitter side [11, 12]. These two improvements not only significantly cut down the on-state voltage drop and turn-off losses, but also effectively improved the safe operation performance. In recent years, several new technologies were promoted to further improve the performance of the FS-IGBT. On the emitter side, the electron injection enhancement technology represented by the carrier storage technology significantly reduces the conduction voltage drop [13]. While on the collector side, the multi buffer structure and variable doping structure were developed to further optimize the injection efficiency of the collector [14]. In the future the trench gate technology will further develop toward the medium and high-voltage field and extend the boundary of power density of IGBTs [15, 16]. On the collector side, backside aligning and implantation will be introduced to further optimize the collector structure or integrate the free-wheeling diode on the backside [17, 18]. As is shown,

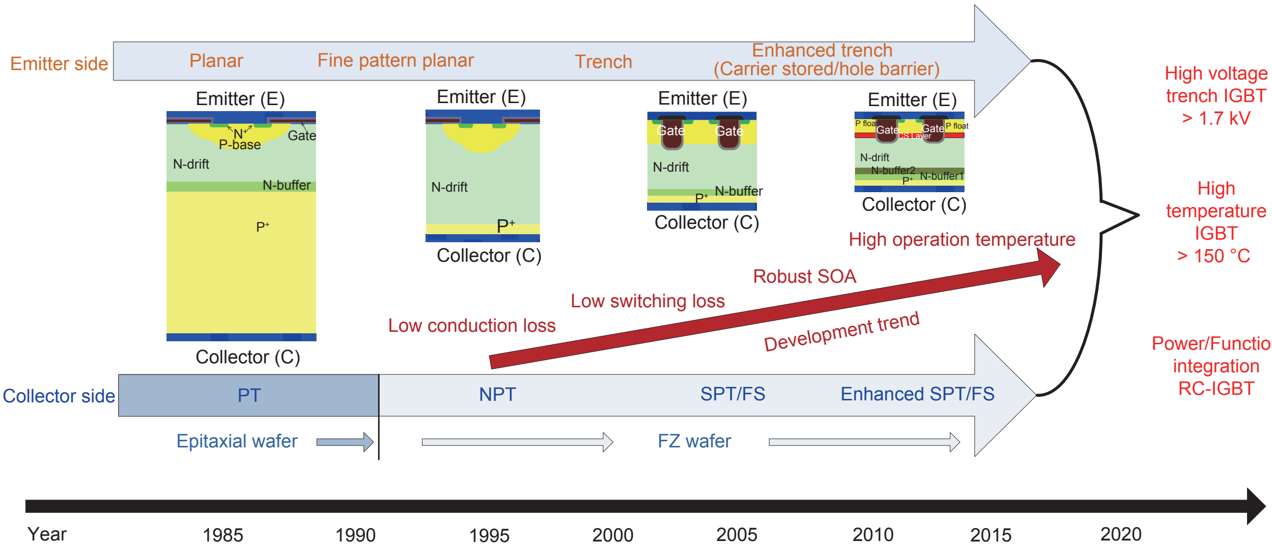


Figure 2. IGBT technology history and its trends.

the upgrade of IGBT technology should be supported by the advanced process technologies, and the advanced process technologies push the IGBT technology forward endlessly. On the other hand, wafer size of IGBT fabrication technology platform has been upgraded from 4-inch to the existing 8-inch and even 12-inch to control the processing cost according to the laws of Scaling Economics.

3 8-inch IGBT fabrication line and its technologies

3.1 8-inch IGBT process platform

Currently, most of the IGBT process platforms in China are based on IC foundry lines, which are hardly compatible with the IGBT processes, especially for the high-end IGBTs. And this will inevitably lead to the low-end IGBT products in China which are non-competitive with the other players all over the world.

Therefore, a new 8-inch fabrication line dedicated to IGBT was built in 2013 by CRRC Zhuzhou Electric Locomotive Institute Co., Ltd., with both planar and trench IGBT technologies, in addition to its experience in rail transportation traction system and industrial converters for decades. Figure 3(a) and (b) show the process platform and the module Assembly/Test line, respectively. The IGBT chips fabricated in this line feature a microelectronics processes with critical dimension of 0.35 μm, with the current density improved while the forward voltage drop maintained the same [19]. In addition, the decent plasma-etching process available in this line plays a very important part in process solution for current mainstream and next generation trench gate IGBTs, which to some extent depends on ideal trench profiles. Moreover, the ultrathin silicon wafers down to 50 μm in thickness can be processed in this line as well, resulting in the decrease of both conduction voltage drop and switching losses. Meanwhile, thin wafer handling with low breakage rate in back processes including laser annealing is realized by suppressing the deformation or breakage of the silicon wafer due to the thermo-mechanical stress during the fabrication process.


(a) (b)

Figure 3. New 8-inch IGBT product line in CRRC. (a) A corner of 8-inch process platform; (b) a corner of Assembly/Test line.

Besides, there are some other significant considerations, including module assembly in which vulnerable interconnections and interfaces should be strengthened for devices' long-term reliability, and module test on which intensive study should be made to bridge device characteristics and applications [20]. Some advanced interconnection technologies were adopted to improve the capability of power cycling, vibration tolerance, and thermal shocking of IGBT power modules, such as copper wire bonding and ultrasonic welding (USW) processes in the new 8-inch automatic Assembly/Test line.

3.2 The fourth-generation DMOS+ IGBT technology

Based on our standard high-voltage DMOS technology platform, some technologies were employed in the DMOS+ high-voltage IGBT, such as carrier storage, junction field effect transistor (JFET) resistor control, and vertical carrier control. These technologies reduced the conduction voltage drop considerably, and also ensured a good blocking capability. Figure 4 shows the schematic diagram of a DMOS+ high-voltage IGBT. The JFET injection layer is distributed on the surface, while the hole barrier layer is distributed at the outer of P-base region [13, 16]. In order to optimize the IGBT gate layout, a terrace gate structure is introduced into DMOS+ IGBT technology to improve the trade-off between the gate capacitance and threshold voltage [21]. It is clear in Figure 4 that the oxidation thickness of terrace gate at the channel area keeps normal while it is much thicker at non-channel area, which reduces the gate capacitance while maintains a reasonable threshold voltage.

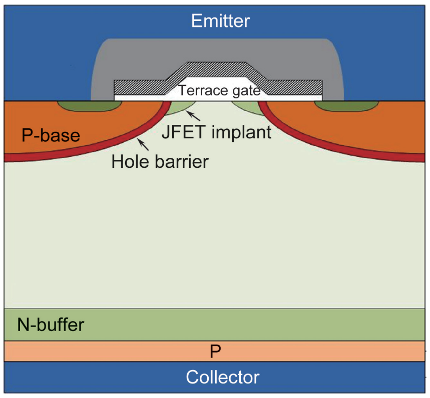


Figure 4. Cell of DMOS+ high-voltage IGBT.

3.3 The fifth-generation trench gate IGBT technology

The fifth-generation trench gate IGBT was developed successfully in this line, as shown in Figure 5. Figure 6 schematically shows the cross section of the trench gate IGBT. In this device, the carrier storage and the FS technologies are combined with the advanced fine geometry trench technology to achieve competitive comprehensive device performance. In order to improve breakdown voltage and dynamic robustness of trench gate IGBT, dummy trenches with carefully chosen trench space, dummy ratio, and dummy gate connection area are integrated [22]. At the same time, the employment of laser annealing apparently tailors the collector hole injection efficiency, which achieves enhanced coordination between conduction loss and turn-off loss. In the near future, based on the fifth-generation trench gate IGBT technology, more and more IGBT products with a

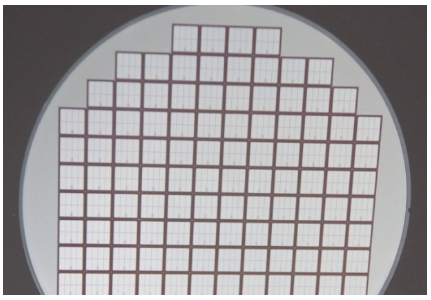


Figure 5. The fifth-generation trench IGBT wafer in CRRC.

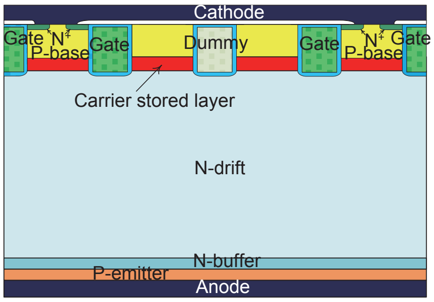


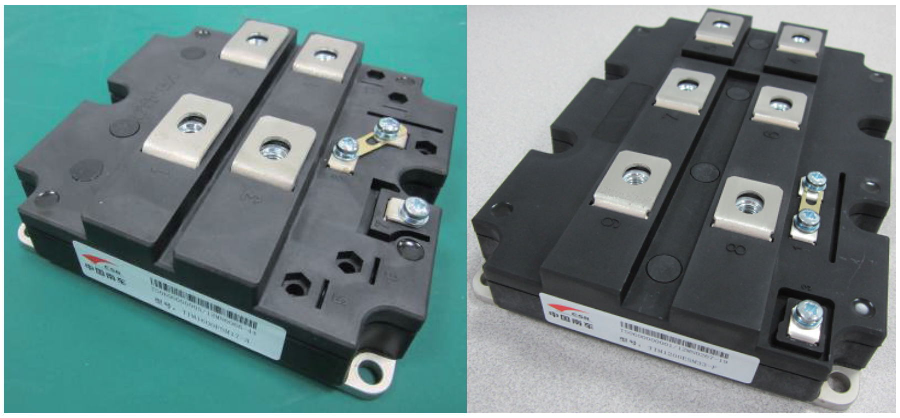
Figure 6. Trench cell of the fifth-generation IGBT technology.

range of ratings from 650 V to 6.5 kV will be released as planned.

4 IGBT for locomotive traction

Currently, IGBT has become the first choice of power semiconductor devices for motor control and power converter applications which are widely used in the rail traction systems. Compared with other applications, the IGBTs used in traction system are required to withstand a variety of harsh operating conditions. Thus, special static and dynamic characteristics and reliability are accordingly required and hence careful consideration in designing and processing of 63 A/3.3 kV IGBT as well as 100 A/1.7 kV chips which are candidates of power semiconductor devices in traction converters is implemented. The 1500 A/3.3 kV and 1600 A/1.7 kV IGBT modules with the said chipsets are manufactured and qualified on the Assembly/Test line, and successfully applied in rail traction systems.

Taking the 1500 A/3.3 kV IGBT module shown in Figure 7 as an example, the IGBT module is comprised of twenty-four 63 A/3.3 kV IGBT chips and twelve 125 A/3.3 kV FRD chips. Table 1 compares this module with similar products from several major players. It is obvious that the comprehensive performance of the CRRC module can benchmark the products of other manufacturers, though different modules may show their advantages in some certain aspects.



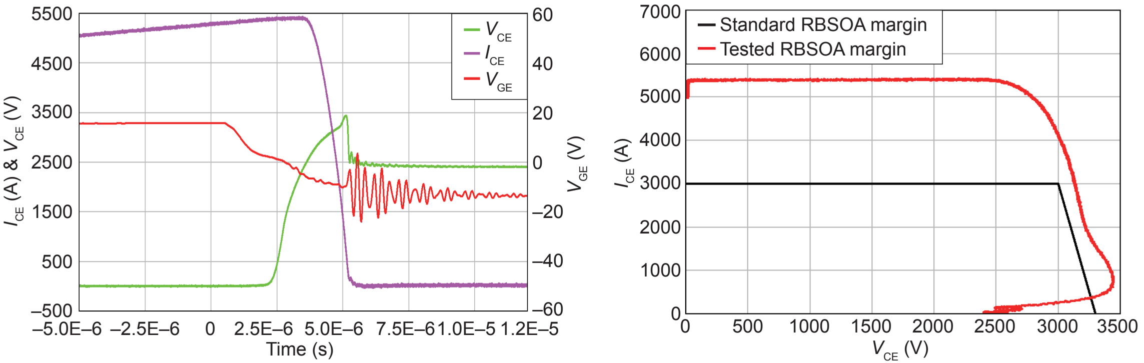
(a) (b)

Figure 7. IGBT modules with wide SOA. (a) 1600 A/1.7 kV IGBT module; (b) 1500 A/3.3 kV IGBT module.

Table 1. Comparison of the main electrical parameters of four 1500 A/3.3 kV IGBT modules.

Module	$V_{CE\text{-}sat}$ (V)	V_F (V)	E_{ON} (mJ)	E_{OFF} (mJ)	E_{REC} (mJ)	E_{TOT} (mJ)
Test condition	T_j = 125 °C		T_j = 125 °C, V_{LINE} = 1.8 kV, V_{GE} = ± 15 V, L_S = 150 nH (R_G and C_G were chosen referring to the data sheet for each module)			
CRRC module	3.1	2.7	2480	3030	1830	7340
Module A	3.0	2.4	3880	2370	1470	7720
Module B	2.9	2.1	2370	2630	2300	7300
Module C	3.1	3.0	2100	3270	3800	9170

Figure 8 shows the RBSOA of the 1500 A/3.3 kV IGBT modules. The second turn-off waveform of the double-pulse test is shown in Figure 8(a), in which the IGBT collector current is over 3 times of the rated current (4500 A). The result indicates IGBT can be switched off successfully on a condition which is a lot more severe than real application. As can be seen in Figure 8(b), the RBSOA boundary can fully cover standard RBSOA with a considerable margin which is very helpful for the converters to survive in some extreme conditions.



(a) (b)

Figure 8. RBSOA of 1500 A/3.3 kV IGBT modules. (a) Time order wavefoam; (b) dynemic curves. $R_{G(ON)}$ = $R_{G(OFF)}$ = 1.5 Ω, C_{GE} = 330 nf, V_{CC} = 2.4 kV, T_j = 150 °C, V_{GE} = 15 V)

Figure 9 shows the SCSOA results of the 1500 A/3.3 kV IGBT modules, accounting for a complete pulse of the IGBT from turn-on to turn-off with the gate voltage of 18 V and temperature of 150 °C. The results show that IGBT module can withstand such short-circuit conditions with the current over 7000 A and the voltage of 2 kV for a duration of 20 μs.

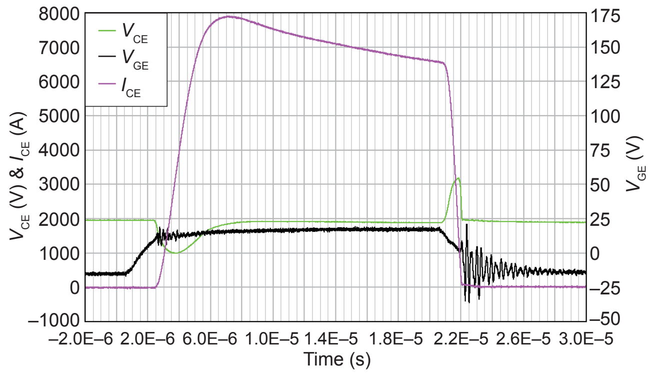


Figure 9. SCSOA of 1500 A/3.3 kV IGBT modules. $R_{G(ON)} = R_{G(OFF)} = 1.5\ \Omega$, $C_{GE} = 330$ nf, $V_{CC} = 2$ kV, $T_j = 150$ °C, $V_{GE} = 18$ V.

In the same way, Figure 10 illustrates the RBSOA results of the 1600 A/1.7 kV IGBT modules. The tested switching-off trajectory curve of 1600 A/1.7 kV IGBT module is wider than that of the standard RBSOA boundary. It is clear that there is a sufficient RBSOA margin for the 1600 A/1.7 kV IGBT module. Figure 11 gives the SCSOA result of the 1600 A/1.7 kV IGBT module, showing the complete switching waveform under an extreme test condition with $V_{GE} = 22$ V and $T_j = 150$ °C. Experimental results show that the IGBT module can withstand the extreme conditions for more than 12 μs.

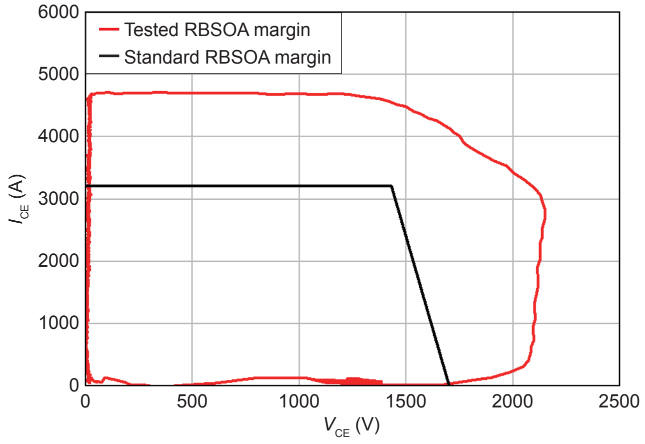


Figure 10. RBSOA of 1600 A/1.7 kV IGBT modules. $T_j = 150$ °C, $V_{LINE} = 1.3$ kV, $V_{GE} = \pm 15$ V, $R_{G(ON)} = R_{G(OFF)} = 1.5\ \Omega$.

5 Conclusions

An 8-inch IGBT chip fabrication line and automatic module Assembly/Test line are constructed by CRRC Zhuzhou Electric Locomotive Institute Co., Ltd. Key chip processes and packaging technologies are developed for the manufacturing of cutting-edge IGBTs with voltage rating from 650 V to 6.5 kV. Based on this process platform, the fourth-generation high-voltage enhanced DMOS (DMOS+) IGBT and the fifth-generation trench gate IGBT have been developed initially. Test results show that the 1500 A/3.3 kV and 1600 A/1.7 kV IGBT modules manufactured are equipped with robustness and competitive electrical characteristics.

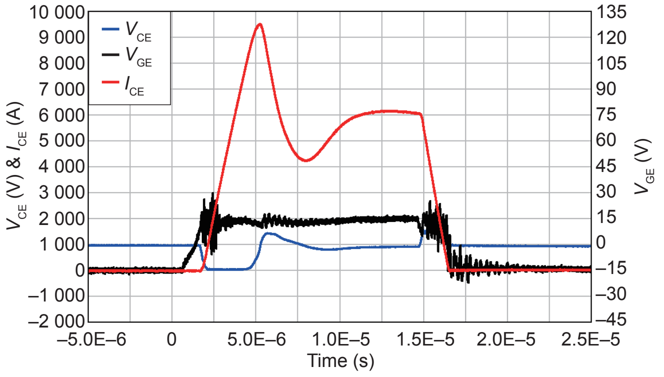


Figure 11. SCSOA of 1600 A/1.7 kV IGBT modules. $T_j = 150$ °C, $V_{LINE} = V_{CC} = 1$ kV, $V_{GE(ON)} = 22$ V, $R_{G(ON)} = R_{G(OFF)} = 1.5\ \Omega$.

In the near future, the development of IGBT chipsets and modules with a variety of voltage and current will be rolled out, constructing a strong point of "IGBT chips–power modules–power assembly–systems" business chain. In addition, based on the existing process platform and the 6-inch SiC fabrication line which is in construction, intensive effort will also be made on next-generation power semiconductor devices with novel structures, high intelligence, new materials, and advanced processes.

Compliance with ethics guidelines

Guoyou Liu, Rongjun Ding, and Haihui Luo declare that they have no conflict of interest or financial conflicts to disclose.

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