2.5kV-6.5kV Industry Standard IGBT Modules Setting a New Benchmark in SOA Capability

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Abstract:
In this paper, we introduce our new high voltage IGBT HiPak module line-up with voltage ratings ranging from 2.5kV up to 6.5kV. We demonstrate for the first time the performance of our HV-HiPak modules employing ABB's newly developed high voltage SPT- IGBTs and diodes. The new devices show excellent over all electrical performance and are capable of withstanding extreme conditions during device turn-off and short circuit operation. Therefore, setting new standards in SOA capability for the given voltage class.

1. Introduction

Trends for the development of IGBTs and diodes aimed for wide SOA limits are fuelled by many requirements in applications operating under hard-switching conditions such as traction, industrial drives, and HVDC. Compared to the low and medium voltage class devices rated below 2000V, previous experience has clearly shown that the SOA performance for higher voltage devices degrades significantly. This trend is due physical constraints in the device structure and the high stress operating conditions mainly in terms of higher dc link voltages. Furthermore, a significant trade-off relationship between the optimisation of the overall losses and the SOA capability has imposed further restrictions in the design window of high voltage devices.

In order to ensure that high voltage devices do not exceed their SOA limits, device manufacturers and system designers have resolved into setting many limits in device operation in the data sheets and circuit designs accordingly. In addition, an increase in component count is needed for the protection and control schemes employed. The added complexity has usually resulted in sacrificing many optimisation parameters in terms of performance, size and cost of high power electronic systems.

In this paper, we introduce our new HiPak module line-up (1) with voltage ratings up to 6.5kV and current ratings up to 1200A. The new HV-HiPak module shown in figure (1) employ ABB's newly developed high voltage SPT- IGBTs and diodes. The new high voltage chip-sets exhibit low losses, soft switching waveforms and excellent overall electrical properties. Furthermore, the new chip design platforms have a unique capability of achieving a square SOA performance, resulting in a clear breakthrough in SOA capability especially for higher voltage devices rated above 2.5kV.

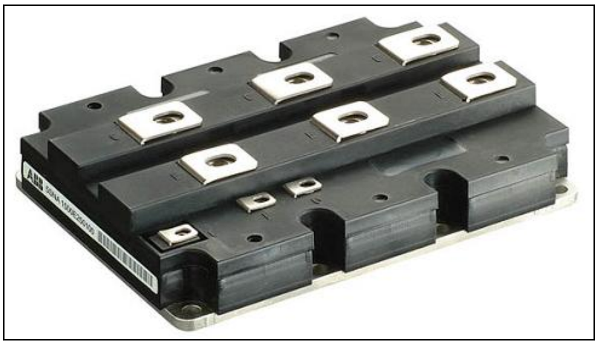


Figure 1: The new HiPak industry standard package with 2500V-3300V SPT-IGBT and diode technology.

The performance of the new HiPak module range is discussed here and results will be presented with particular reference to the excellent SOA performance and its impact on the optimisation of system designs. The presented new benchmark in SOA capability will provide a new outlook for system designers enabling a far more optimum performance for high-voltage applications.

2. High Voltage Chip-Set Technology

In order to achieve excellent static and dynamic characteristics for the IGBT and diode, the latest IGBT and diode technologies employ the Soft-Punch-Through concept. This approach has helped us to take a considerable leap in reducing the over-all losses of the device when compared to older designs (2).

The addition of a low doped and deep SPT buffer region realises a reduction of 20% of the total device thickness when compared to an NPT design. However, this approach demands a higher resistivity starting material with lower punch-through voltages to achieve the required blocking voltage and low cosmic ray failure rates. The SPT buffer then ensures that such a device maintains soft turn-off characteristics. This approach becomes even more critical when the chips are employed in very high current modules such as the HiPak, because the overshoot voltage peak in this case can reach critical values during the IGBT turn-off, resulting in large oscillations and increased EMI levels. In addition to these advantages, we demonstrate here that by further optimisation of the SPT design, major benefits will result in improving the SOA performance of both the IGBT and the diode. Furthermore, the new HV-IGBT design platform utilises an advanced and extremely rugged planar cell design. The new technology was developed mainly for substantially increasing the cell latch-up immunity for a wide SOA performance.

In addition, the input capacitance of the SPT-IGBT has also been optimised to provide good controllability of the turn-on di/dt with respect to varying the gate resistance while eliminating any need for the use of an external capacitance across the gate-emitter terminals. Faster voltage decays for the IGBT were also obtained, hence reducing the IGBT turn-on losses substantially.

Also, new high voltage fast and soft recovery SPT diodes were developed to add to the advantages of the SPT-IGBTs. The superior SOA performance of the new HV-diodes was reached by applying the following design features. Firstly, a highly doped P+ anode was employed; thus, resulting in an extremely rugged performance when compared to low P anode diodes. This is due to a reach-through effect during reverse recovery when the device is tested under extreme dynamic avalanche conditions. The higher P+ doped anode has also aided in developing a robust junction termination design to eliminate any possible drawbacks in terms of device ruggedness due to high fields and current crowding at the anode periphery during reverse recovery. Furthermore, by using a combination of local and homogenous lifetime control methods, the electron-hole plasma can be shaped in an optimal way for tailoring the electrical parameters and improve the SOA performance. Finally, a positive temperature coefficient during on-state for both the IGBT and diode was obtained to ensure good current sharing of the paralleled die operating in the high current module.

3. The HiPak Module Range

The HiPak module range takes full advantage of the exceptional characteristics of the high voltage SPT-IGBT and diode chip-sets, to offer a whole range of standard configurations at different voltage and current ratings. Typical nominal condition losses are outlined in table (1) for the (140mm x 190mm) single IGBT HiPaK module configuration. The newly developed modules utilise state-of-the-art AlSiC base-plates for high power cycling capability and AlN substrates for allowing a low overall thermal resistance.

Proprietary internal wiring and layout designs were also employed to ensure that the die and substrates were optimised in order to minimise any oscillations or current mismatch that might occur between the chips.

All the relevant reliability tests (HTRB, HTGB THB and TC) were conducted successfully for the chip-sets and module.

Table (1)

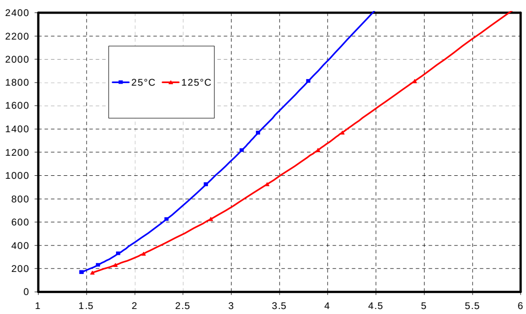
Voltage	Current	Type	Part Number	V_{ce} 125°C	V_F 125°C	Eoff 125°C	Eon 125°C	Vdc
2500V	1200A	Single	5SNA 1200E250100	3.1V	1.8V	1.25J	1.1J	1250V
3300V	1200A	Single	5SNA 1200E330100	3.8V	2.35V	1.9J	2.0J	1800V
6500V	600A	Single	5SNA 0600G650100	4.7V	4.0V	3.5J	4.0J	3600V

4. 3300V/1200A HiPak Performance

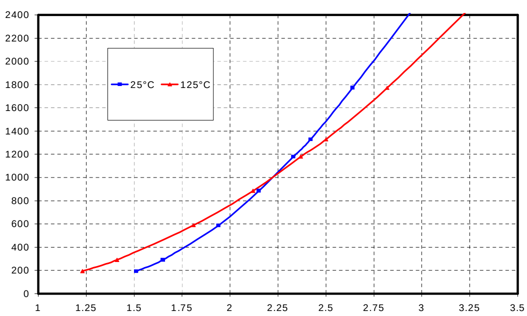
The 3300V/1200A HiPak modules have been evaluated and tested confirming the electrical performance advantages achieved by employing the 3300V SPT-IGBT and diode chip set. The modules were tested for the static and dynamic characteristics, and Safe Operating Area (SOA) during turn-on, turn-off and short circuit.

a) Static Performance:

Due to the large reduction in the base region thickness and optimised emitter of the 3300V SPT-IGBT chip, 20% less on-state losses were obtained compared to an equivalent NPT structure. Figure (2) shows the on-state characteristics of the 3300V/1200A HiPak module. The IGBT has an on-state voltage of 3.1V at 25°C and 3.8V at 125°C at rated current as shown in figure (2:a). The curves also exhibit a strong positive temperature coefficient even at low current levels to prevent current mismatch during parallel device operation due to thermal imbalance. The diodes also maintain low on-state voltages and a slightly positive temperature coefficient having 2.3V at 25°C and 2.35V at 125°C at rated current as shown in figure (2:b).



(a) IGBT on-state voltage against collector current



(b) Diode voltage against forward current

Figure 2: 3300V/1200A HiPak module on-state characteristics for both (a) SPT-IGBT and (b) diode at 25°C and 125°C, measured at the power terminals.

Both the SPT-IGBT and diode have typical blocking voltages close to 4000V to ensure a sufficient margin for the required voltage of 3300V at low temperatures (e.g. -40°C).

b) Switching Performance:

Figures (3) and (4) show the switching characteristics of the 3300V/1200A HiPak module during turn-off and turn-on respectively. The tests were carried out at rated current and a DC link voltage of 1800V. It can be observed that the turn-off current switching transients of the 3300V SPT-IGBT are very smooth.

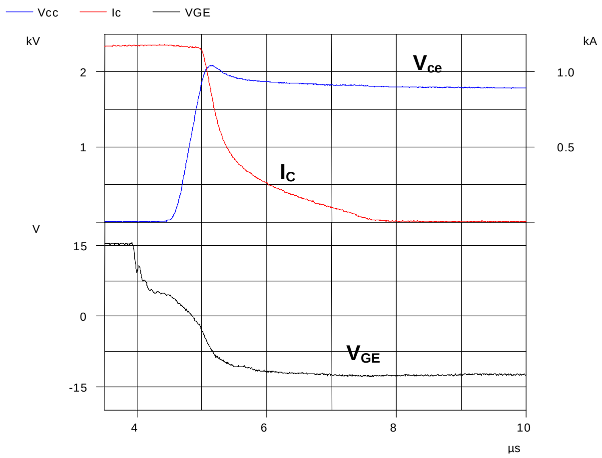


Figure 3: 3300V/1200A HiPak IGBT turn-off waveforms at V_{CC}=1800V, I_C=1200A, V_{GE}=15V, R_G =1.5Ω, L_s=100nH, T_j =125^{o}C, No clamps applied.

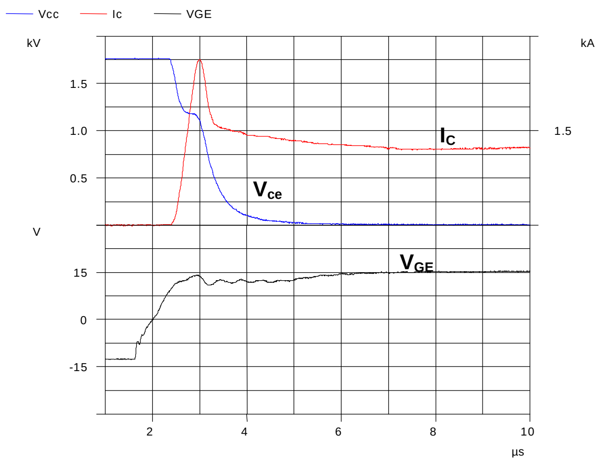


Figure 4: 3300V/1200A HiPak IGBT turn-on waveforms at V_{CC}=1800V, I_C=1200A, V_{GE}=15V, R_G =1.5Ω, L_s=100nH, T_j =125^{o}C

Figure (4) shows the switching waveforms during turn-on. Thanks to an optimized IGBT capacitance and a low loss diode, the IGBT turn-on losses were reduced by 30% when compared to older generation devices. The turn-on losses have typical values of 2.0J under nominal conditions and 125^{o}C.

c) SOA Performance:

The new 3.3kV IGBT has set a new benchmark in terms of turn-off RBSOA performance. This can be clearly seen in the RBSOA waveforms shown in figure (5) when operating under extreme conditions. No active clamps or snubbers were employed in the test set-up. The devices were tested at twice rated current of 2400A and DC rail voltage of 2500V at 125°C. In addition, a larger stray inductance of 170nH was employed in the test.

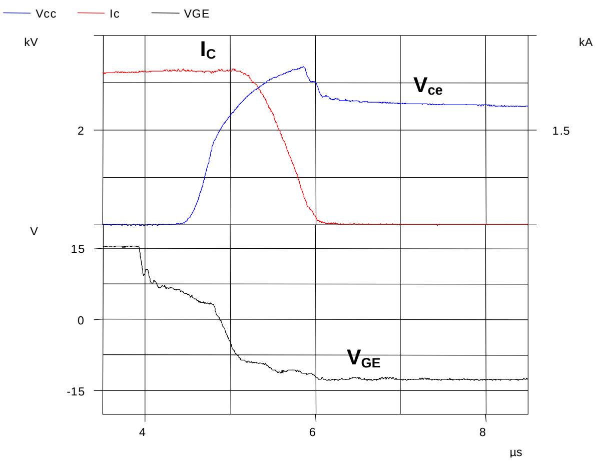


Figure 5: 3300V/1200A HiPak IGBT RBSOA switching characteristics during turn-off at V_{CC}=2500V, I_C=2400A, V_{GE}=15V, R_G=1.5Ω, L_s=170nH, T_j =125^{o}C, no clamps.

In order to demonstrate the modules world-class ruggedness and the real capability of the new devices, the IGBT was then tested under much more severe conditions as shown in figure (6). It is remarkably clear that the IGBT is capable of turning off higher than 4 times its rated current (5000A) under extreme conditions using a very large inductance and high DC link voltage. One also can observe the module experiencing two modes of operations during turn-off. First, the IGBT is capable of withstanding dynamic avalanche conditions and then it enters a self-clamping mode at 4000V. This is the first time where a high voltage IGBT is capable of surviving such conditions especially at these elevated current levels and temperatures. The total energy dissipated during turn-off is 20 Joules including 5 Joules dissipated during the Self-Clamping period. The peak power during this turn-off transit reached 14MW.

Figure (7) shows the 3300V/1200A HiPak module diode reverse recovery under extreme SOA conditions with a large stray inductance and a very low gate resistance value in order to achieve a high commutating di/dt. The diode dynamic behaviour ensures soft recovery, ruggedness and reliable performance under all operating conditions especially at low current levels and low temperatures as shown in figure (8) for –40°C.

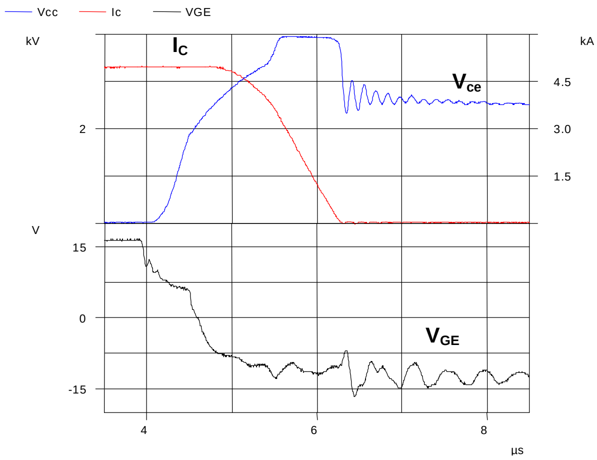


Figure 6: 3300V/1200A HiPak IGBT RBSOA switching characteristics during turn-off at V_{CC}=2600V, I_C=5000A, V_{GE}=15V, R_G=1.5Ω, L_s=280nH, T_j =125^{o}C, no clamps.

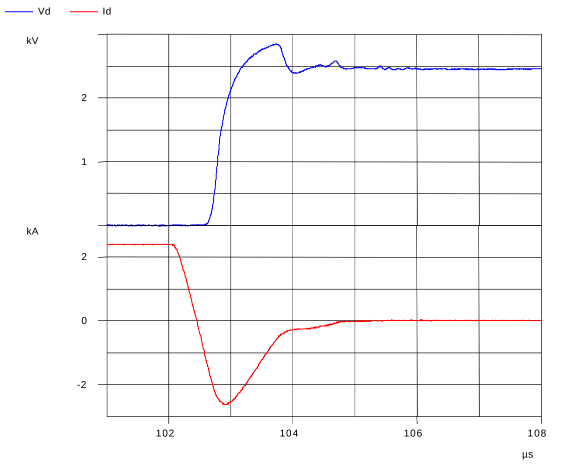


Figure 7: 3300V/1200A HiPak diode RBSOA switching characteristics at V_{CC}=2500V, I_C=2400A, R_G=0.27Ω, L_s=280nH, T_j =125^{o}C

The waveforms in figure (9) and (10), show the 3.3kV HiPak module in short circuit mode with soft turn-off at a DC rail voltage of 2600V at 125°C and -40°C respectively for a current pulse of 10µsec.

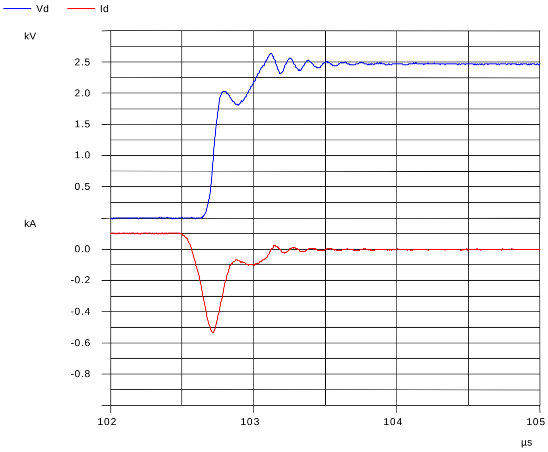


Figure 8: 3300V/1200A HiPak diode non-snappy switching characteristics at V_{cc}=2500V, I_c=100A, R_G=1.5Ω, L_s=140nH, T_j =-40^{o}C

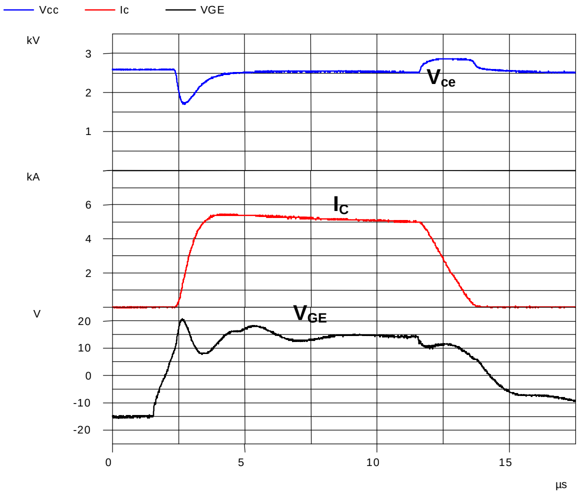


Figure 9: 3300V/1200A HiPak SCSOA characteristics at V_{cc}=2500V, R_G=1.5Ω, V_{GE}=15V, T_j =125^{o}C

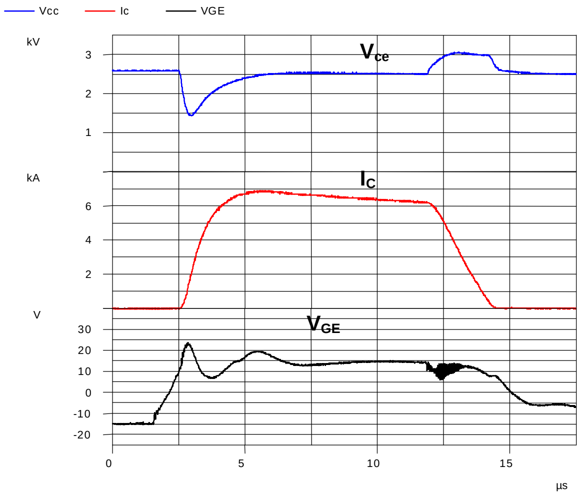


Figure 10: 3300V/1200A HiPak SCSOA characteristics at V_{cc}=2500V, R_G=1.5Ω, V_{GE}=15V, T_j =-40^{o}C

5. New 6500V/600A HiPak Performance

One of the many advantages of an extremely rugged IGBT is the possibility of operating the device with lower gate resistance (R_G) values, thus, resulting in much lower losses and shorter delay times during device turn-off. The conventional technology would require a significantly higher gate resistance value to achieve the required turn-off current capability when compared to the new technology. The new 6.5kV/600A HiPak module takes full advantage of this feature being the first ever 6.5kV module capable of operating robustly in a similar mode to lower voltage devices. No dv/dt or peak voltage restrictions are imposed in order to enhance the device turn-off capability.

Figures (11) and (12) show the switching characteristics of the 6500V/600A HiPak module during turn-off and turn-on respectively. The tests were carried out at rated current and a DC bus voltage of 3600V. The IGBT was then tested under much more severe conditions as shown in figure (13). Due to the severe dynamic avalanche conditions, the peak voltage only reaches up to 5kV. However, the IGBT is capable of exceeding voltages well above 6kV during turn-off. The waveforms in figures (14) and (15) show the 6.5kV HiPak module in short circuit mode with soft turn-off at a DC rail voltage of 4500V at 125°C and 25°C respectively. The module is also capable of withstanding short circuit with the application of high gate voltages above 17V.

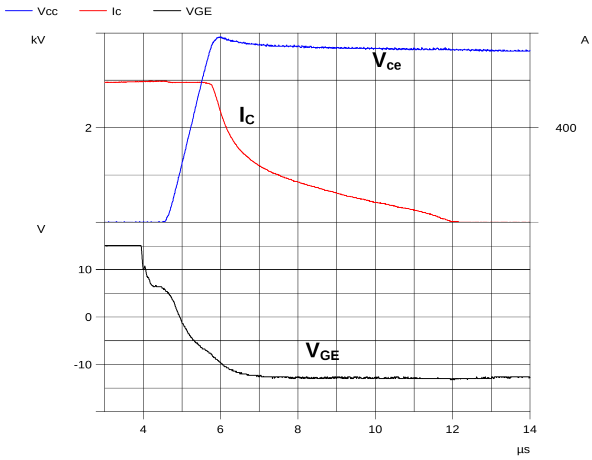


Figure 11: 6500V/600A HiPak IGBT Turn-off waveforms at V_{cc}=3600V, I_c=600A, V_{GE}=15V, R_G=2.7Ω, L_s=280nH, T_j =125^{o}C

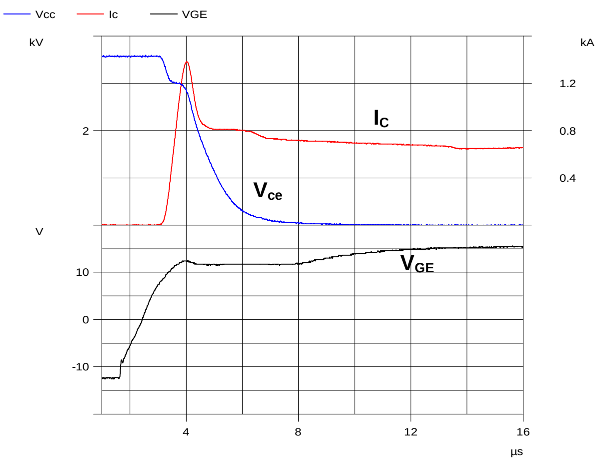


Figure 12: 6500V/600A HiPak IGBT Turn-on waveforms at V_{CC}=3600V, I_c=600A, V_{GE}=15V, R_G=5.6Ω, L_s=280nH, T_j =125^{o}C

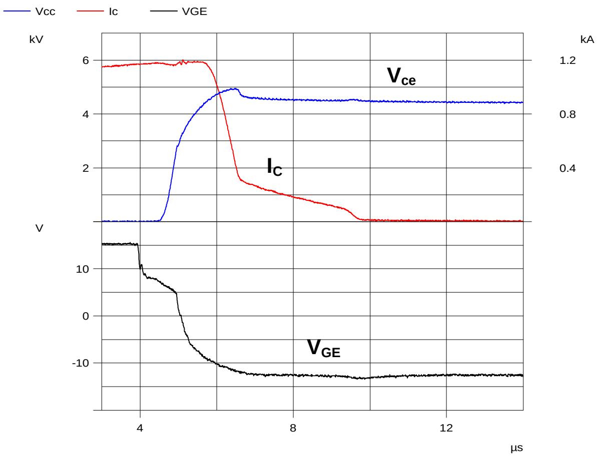


Figure 13: 6500V/600A HiPak IGBT RBSOA switching characteristics during turn-off at V_{CC}=4400V, I_c=1200A, V_{GE}=15V, R_G=2.7Ω, L_s=280nH, T_j =125^{o}C, no clamps.

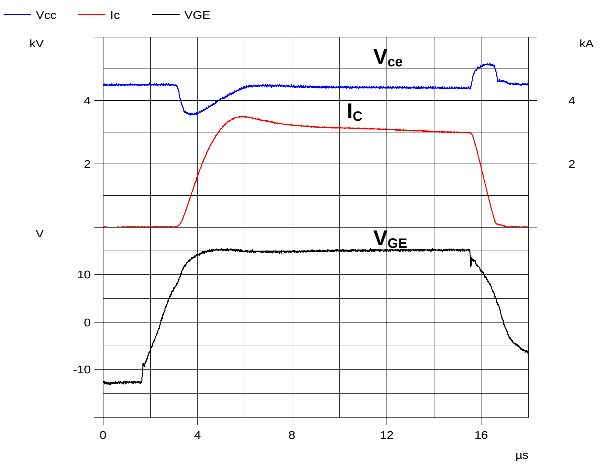


Figure 14: 6500V/600A HiPak SCSOA characteristics at V_{CC}=4500V, R_G=5.6Ω, V_{GE}=15V, T_j =125^{o}C

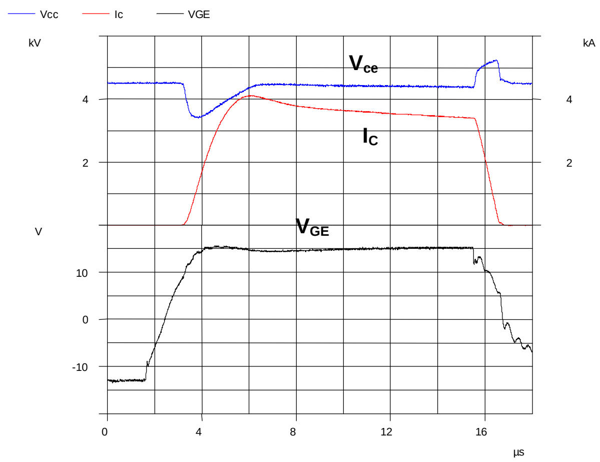


Figure 15: 6500V/600A HiPak SCSOA characteristics at V_{CC}=4500V, R_G=5.6Ω, V_{GE}=15V, T_j =25^{o}C

6. Conclusions

The new high voltage HiPak industry standard module range utilising the newly developed high voltage SPT-IGBT and diode chip-sets have been introduced. The employed chip technology has resulted in a clear breakthrough in SOA performance especially for higher voltage devices rated up to 6.5kV. Both IGBTs and diodes were designed to exhibit very wide SOA limits even under extreme test conditions, while still maintaining lower conduction and switching losses when compared to older generation devices. The presented new benchmark in SOA performance will provide a new outlook for system designers, enabling a far more optimum performance of high voltage power electronics applications.

References

1. M. Rahimo et al., “High-Power Modules with Soft-Punch-Through IGBT Technology for Traction Applications” Proc. PCIM’03, NURNBERG, GERMANY, 2003.
2. M. Rahimo et al., “Novel Soft-Punch-Through (SPT) 1700V IGBT Sets Benchmark on Technology Curve” Proc. PCIM’01, NURNBERG, GERMANY, 2001.