

New 4.5 kV IGBT and diode chip set for HVDC Transmission Applications

Josef Georg Bauer¹, Matthias Wissen², Thomas Gutt¹, Jürgen Biermann², Carsten Schäffer³, Gerhard Schmidt³, Frank Pfirsch¹

¹ Infineon Technologies, Am Campeon 1-12, D-85579 Neubiberg, Germany

email: josef-georg.bauer@infineon.com

² Infineon Technologies, Max-Planck-Str. 5, D-59581 Warstein, Germany

³ Infineon Technologies, Siemensstraße 2, A-9500 Villach, Austria

Abstract

In this paper, we present the development of a new 4.5 kV trench field stop IGBT and an emitter controlled EC diode for industry applications and especially for HVDC application in an IHM-B package.

The IGBT and diode performance is focused on very low on state voltages, fast turn on switching behavior of the IGBT especially for high voltage and high current beyond the standard conditions and simultaneously high robust short circuit performance. Furthermore an extremely high IGBT and diode robustness during over current turn-off is demonstrated. The new devices are designed for an operation temperature up to 150 °C. These features were realized by adaption of the trench cell design as well as the vertical structure of the 6.5 kV IGBT [1] for the 4.5 kV voltage class and improvement of the vertical structure of the IGBT and diode using HDR technology [2] for both devices.

1. Introduction

The newly launched 4,5kV trench field stop IGBT and field stop diode supplement the already existing high voltage classes of 3.3 kV and 6.5 kV. The 4.5 kV chip set will be available in two different housings:

First one in the highly insulated 6.5 kV module housing, offering 10.2 kV isolation capability and corresponding creepage distance and clearance distance as requested by the harsh environment of traction applications with DC link voltages in the range of 2500-3000V. This product is not in focus of this paper. The second chip set is designed for the IHM-B housing, the successor of the famous and world-wide applied IHM-A module. This module addresses industrial applications like medium voltage drives and the wide field of High Voltage Direct Current (HVDC) as well as flexible-AC-transmission-system (FACTS) applications. The module is shown in Fig. 1



Fig. 1: Package of the 4.5 kV module FZ1200R45HL3 for HVDC applications

These IGBT-based voltage source converters (VSC) will play an important role for future HVDC systems, in contrast to well-known thyristor-based grid-commutated high-voltage DC transmission. The main advantages of IGBT-based solutions are independent active- and reactive-current control due to the turn-on and turn-off capability of the IGBT as well as superior performance in case of AC-grid faults.

For high voltage applications a large number of semiconductors needed to be connected in series and simultaneous switching with high accuracy. Therefore a simple design of multi-level VSC for high voltage applications like HVDC and FACTS has been proposed [3] – the Modular Multilevel Converter (MMC). For these HVDC applications the switching frequency of individual IGBT modules can be reduced. Therefore low on-state losses are of special interest in order to reduce the overall power consumption.

For HVDC applications the use of a 3.3 kV IGBT module with low losses and a maximum operation temperature of 150 °C has been published [4]. In addition a 4.5 kV IGBT press-pack has been reported [5]. This paper presents a 4.5 kV IGBT module which is optimized to the needs of a HVDC application.

2. IGBT and diode structure

The IGBT trench technology provides low on state losses due to carrier accumulation effect between the cells together with an optimized cell pitch, and an optimized channel length as well as channel width designed for high blocking voltages. As a result the trench technology offers an easy possibility to influence the charge carrier concentration below the cell within a wide range compared to the standard planar technology. In Fig. 2 and Fig. 3 the schematic cross sections of the 4.5 kV diode / IGBT are shown. For the edge termination for both devices a VLD structure (varied lateral doping) has been applied which, in combination with the vertical HDR structure, leads to an extreme high turn-off robustness of the IGBT and commutation robustness of the diode, respectively, due to the reduction of dynamic avalanche phenomena during the switching sequence [2].

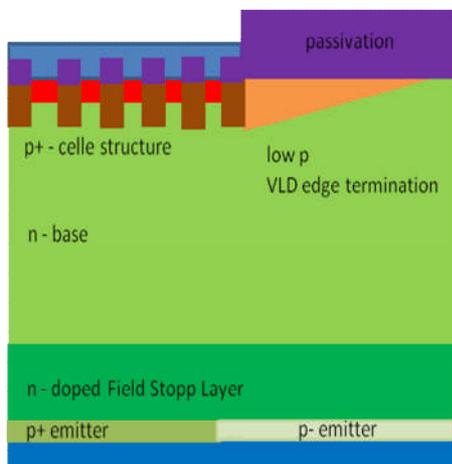


Fig. 2: Schematic cross section of the IGBT with HDR and VLD edge termination.

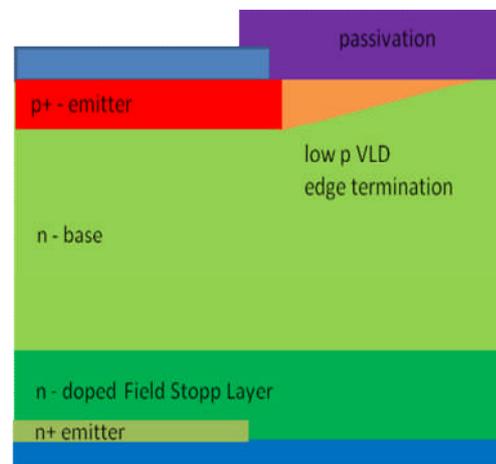


Fig. 3: Schematic cross section of the EC diode with HDR and VLD edge termination.

3. Electrical performance

3.1. Static characteristics

To realize low on-state voltages for the 4.5 kV IGBT our well known trench technology known from 6.5 kV device platform has been adapted using suitable base material, an adapted field stop and an optimized cell design that results in the best-in-class on-state characteristic for 4.5kV devices. In Fig. 4 the forward characteristic of the IGBT is shown for different temperatures. At $I_C=1200$ A, the nominal current of the FZ1200R45HL3 module, a typical $V_{CE(sat)}=2.35$ V at 25°C, $V_{CE(sat)}=2.9$ V at 125°C and $V_{CE(sat)}=3.0$ V at 150°C temperature is realized. Fig. 5 shows the forward characteristic of the EC diode. It exhibits a nearly neutral temperature coefficient at nominal current of $I = 1200$ A and a typical forward voltage drop in the range of $V_F \leq 2.5$ V in the temperature range of $25^\circ\text{C} \leq T \leq 150^\circ\text{C}$.

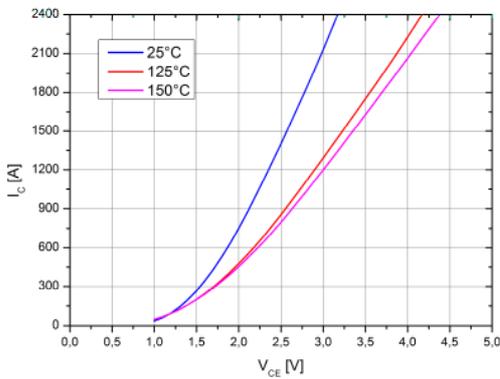


Fig. 4: Forward characteristics of the IGBT at 25 °C (blue), 125 °C (red) and 150 °C (pink).

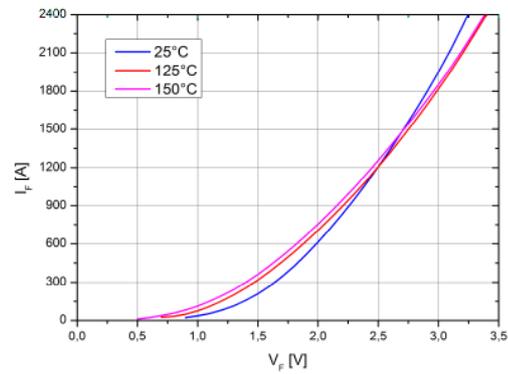


Fig. 5: Forward characteristics of the diode at 25 °C (blue), 125 °C (red) and 150 °C (pink).

3.2. Dynamic characteristics

3.2.1. Switching at nominal conditions

The dynamic characteristics of the IGBT are typically described by a trade-off curve where the turn-off losses E_{off} are plotted versus the forward voltage drop $V_{CE(sat)}$ (Fig. 6). The forward voltage $V_{CE(sat)}$ was changed by modification of the emitter efficiency. Within the desired $V_{CE(sat)}$ range the trade-off curve show a comparatively slight E_{off} dependence and it becomes even flatter for decreased dV/dt 's. The turn-off waveforms at nominal conditions, i.e. $V_{CE}=2.8$ kV and $I_C=1200$ A, at $T=150^\circ\text{C}$ for a $dV/dt=2.1$ kV/ μs are shown in Fig.7. Under these conditions the V_{CE} does not exceed 3.4 kV and a soft turn-off behavior is shown for a typical commutation inductance of 150 nH. Based on this optimized behavior also for harsher conditions, i.e. higher stray inductances and higher currents and operation temperatures down to $T=-40^\circ\text{C}$ a soft turn-off is ensured.

In Fig. 8 the IGBT turn-on waveforms at nominal conditions and 150°C for a $dI/dt=5.9$ kA/ μs are shown. The typical reverse recovery waveforms under these conditions are depicted in Fig. 9 and reveal a very smooth I_F tail gradient.

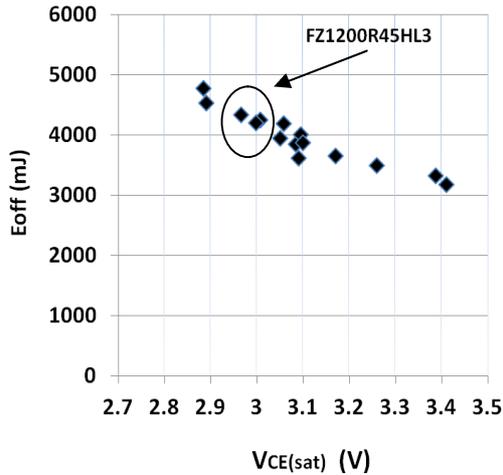


Fig. 6: Trade-off E_{off} versus $V_{CE(sat)}$ for the 4.5 kV trench IGBT at nominal conditions ($I_C=1200$ A, $V_{CE}=2800$ V), $L=150$ nH, 125 °C, $dV/dt=2.7$ kV/ μ s.

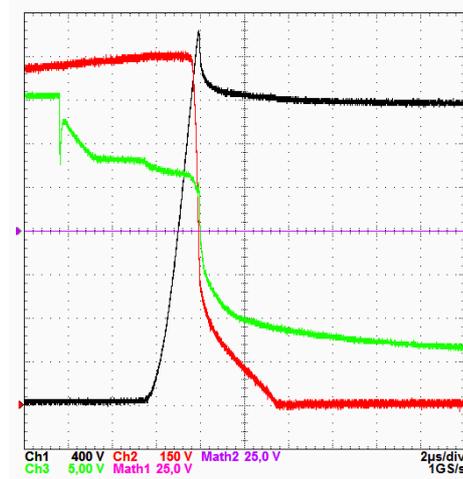


Fig. 7: Typical turn-off waveforms at $I_C=1200$ A, $V_{CE}=2800$ V $L = 150$ μ H, $T=150$ °C $dV/dt=2.1$ kV/ μ s. ($V_{CE}=400$ V/div, $I_C=150$ A/div, $V_{GE}=5$ V/div)

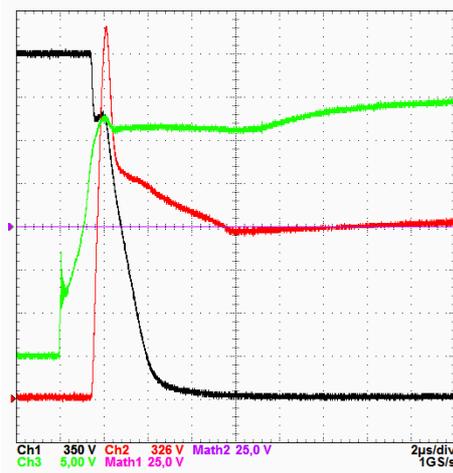


Fig. 8: Typical turn-on waveforms for $V_{CE}=2800$ V, $I_F=1200$ A, $dI/dt=5.9$ kA/ μ s, $L=150$ μ H, $T=150$ °C. ($V_{CE}=350$ V/div, $I_C=326$ A/div, $V_{GE}=5$ V/div)

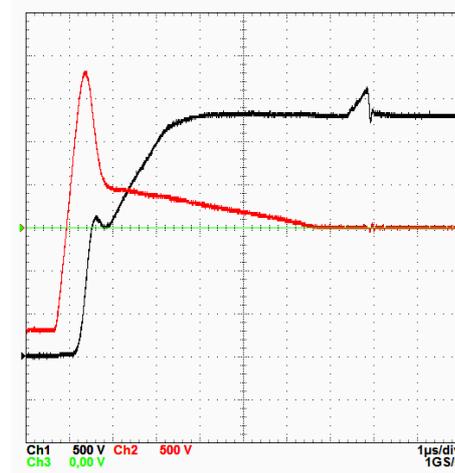


Fig. 9: Typical Reverse recovery waveforms for $V_{CE}=2800$ V, $I_C=1200$ A, $dI/dt=5.3$ kA/ μ s, $L = 150$ μ H, $T=150$ °C. ($V_{CE}=500$ V/div, $I_C=500$ A/div) (The increase of voltage after accomplished current commutation is due to the measurement set-up.)

3.2.2. Switching at high voltage and high current

For a HVDC application it is important that in a failure event the IGBT shows a rapid turn-on behavior at high voltage and high current in order to detect this faulty situation in time. The device ruggedness under such conditions beyond the RBSOA limits has been evaluated.

Amongst others, one possible IGBT parameter is its channel width to adapt the turn-on behavior to a predictable failure event. In Fig. 10 and Fig. 11 the turn-on waveforms for a module with 200 A nominal current and two different channel widths A and B and $A < B$, for $V_{CE}=3000\text{ V}$ and $I_C=550\text{ A}$ are shown. In case of an increased channel width (Fig. 11) a rapid turn-on performance can be achieved and results in a $V_{CE}\leq 200\text{ V}$ in less than $t=6.5\text{ }\mu\text{s}$ ($t=0 @ 0.9*V_{CE}$) whereas for less channel width (Fig. 10) a $V_{CE}\leq 200\text{ V}$ is achieved not before $t=9\text{ }\mu\text{s}$. But the same time an increased channel width is suffering from short circuit capability due to an increased short circuit current. Hence, a compromise between turn-on performance and short circuit capability has to be found or the vertical structure of the IGBT is further enhanced to fulfill all requirements.

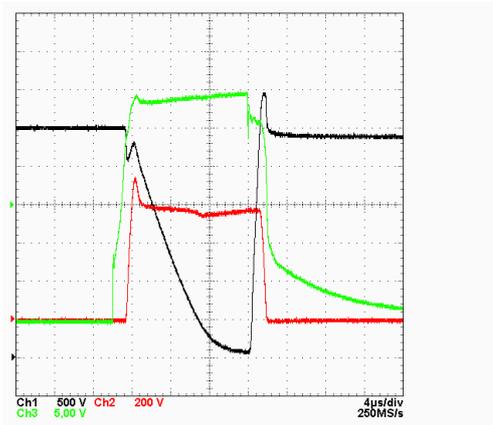


Fig. 10: Turn-on waveforms for $V_{CE}=3\text{ kV}$, $I_C=550\text{ A}$ (nominal current = 200 A), at $125\text{ }^\circ\text{C}$. ($V_{CE}=500\text{ V/div}$, $I_C=200\text{ A/div}$, $V_{GE}=5\text{ V/div}$) for channel width A

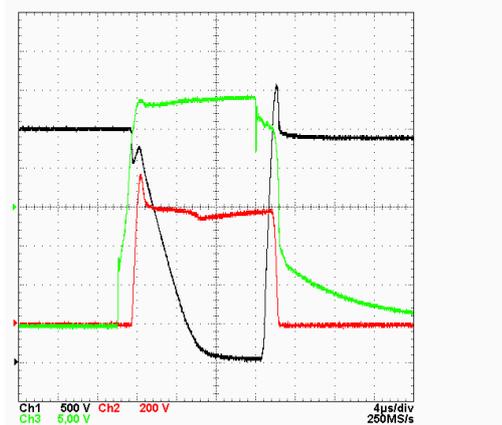


Fig. 11: Turn-on waveforms for $V_{CE}=3\text{ kV}$, $I_C=550\text{ A}$ (nominal current = 200A), at $125\text{ }^\circ\text{C}$. ($V_{CE}=500\text{ V/div}$, $I_C=200\text{ A/div}$, $V_{GE}=5\text{ V/div}$) for channel width B

3.3. Short circuit capability

To prove the short circuit (type 1) capability of the IGBT tough conditions such as $V_{CE}=2000\text{ V}$, $V_{GE}=17\text{ V}$ and $T=25\text{ }^\circ\text{C}$ have been applied. Here, an intermediate DC-link voltage was chosen due to a much higher sensitivity regarding current destruction in short circuit operation [6]. Fig. 12 shows such a current destruction after $6\text{ }\mu\text{s}$ short circuit duration for a non-optimized IGBT, where only an increased channel width B (Fig. 11) is applied.

Therefore the vertical IGBT structure has been optimized to prolong the lower limit of short-circuit time until device failure. In Fig. 13 the short circuit waveforms of an optimized 4.5 kV IGBT under the same tough conditions as before ($V_{GE}=17\text{ V}$, $V_{CE}=2\text{ kV}$, $T=25\text{ }^\circ\text{C}$) are shown. The short-circuit event can now be handled by the IGBT and a reliable turn-off is granted even after a short circuit duration of $10\text{ }\mu\text{s}$ for the FZ1200R45HL3 module.

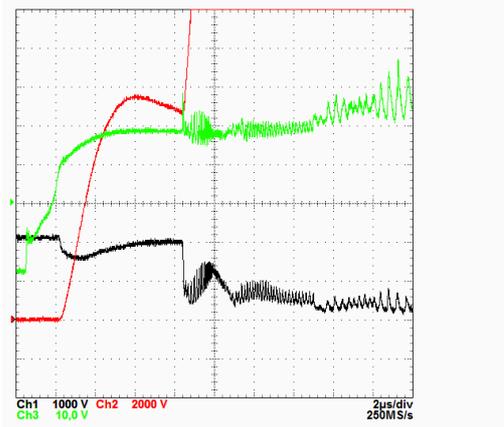


Abb. 12: Short circuit waveforms for $V_{CE}=2$ kV, $V_{GE}=17$ V at $T=25$ °C and a non-optimized IGBT ($V_{CE}=1000$ V/div, $I_C=2$ kA/div, $V_{GE}=10$ V/div)

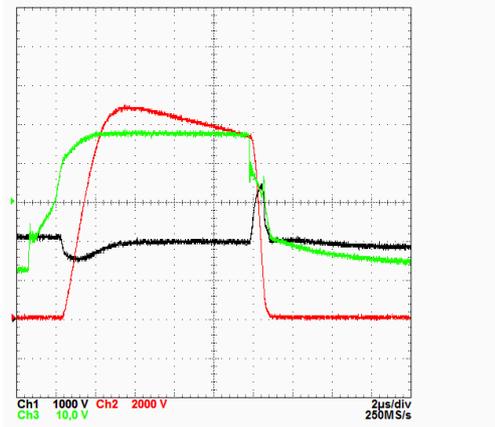


Abb. 13: Short circuit waveforms for $V_{CE}=2$ kV, $V_{GE}=17$ V at $T=25$ °C and an optimized IGBT ($V_{CE}=1000$ V/div, $I_C=2$ kA/div, $V_{GE}=10$ V/div)

3.4. Robustness of IGBT and diode

For HVDC applications as well as for traction applications a high over current turn-off capability for IGBT and diode is improving the systems reliability.

By applying the HDR concept the impact of the termination system on the IGBT robustness can be neglected and is therefore only limited by the cell design. The trench structure provides the possibility of a further reduction of the source length of the IGBT. Because the current density decreases inversely proportional to the source length, the latch-up immunity of the trench IGBT is effectively improved and excellent turn-off ruggedness is obtained [7]. This is demonstrated by the waveforms shown in Fig. 14, where the IGBT turns-off multiples of the nominal current without severe oscillation on neither current or voltage signals.

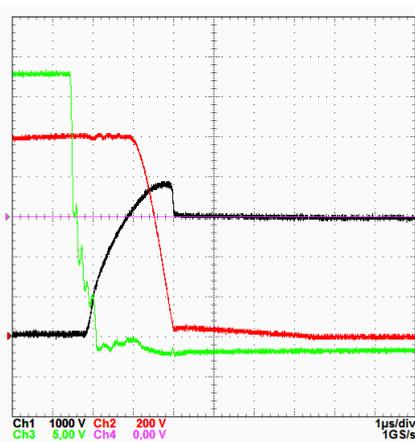


Fig. 14: IGBT robustness evaluation test at 5-times nominal current (i.e. $I_C=1000$ A) at $V_{CE}=3$ kV, $T=150$ °C, $dV/dt=3.5$ kV/ μ s, $V_{GE}=18$ V ($V_{CE}=1000$ V/div, $V_{GE}=5$ V/div, $I_C=200$ A/div)

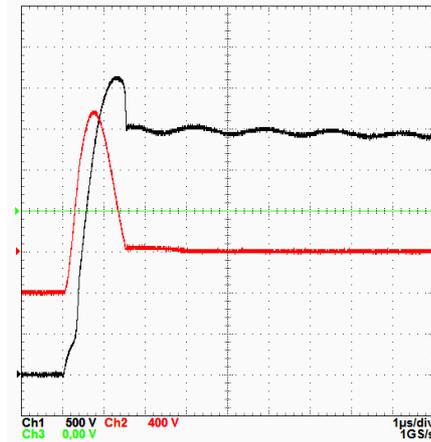


Fig. 15: Diode recovery waveforms at 2-times nominal current (i.e. $I_F=400$ A), $V_{CC}=3$ kV, $T=150$ °C, $P_{max}=4.1$ MW ($V_{CE}=500$ V/div, $I_C=400$ A/div)

In addition to a low on-state voltage V_F the new 4.5 kV emitter controlled (EC) diode reveals low dynamic power losses in combination with a very high robustness. Fig. 15 shows the diode recovery waveforms of a test set-up for $I_F=200$ A nominal current module tested with $P_{\max} \geq 4$ MW without destruction.

3.5. Surge Current capability

In an event of failure, e.g. short circuit in the power transmission line, fault conditions such as high surge currents can occur during diode operation. The ability to withstand high surge currents is an important criterion for the usability of the module. Fig. 16 proves the surge current capability that can be realized by an optimized vertical design resulting in a low V_F together with the HDR concept. A typical I_{FSM} value of about 2500A can be reached which corresponds to a I^2t of about 500 kA²s at 125°C temperature or 460 kA²s at 150°C for a module with $I_C=1200$ A nominal current.

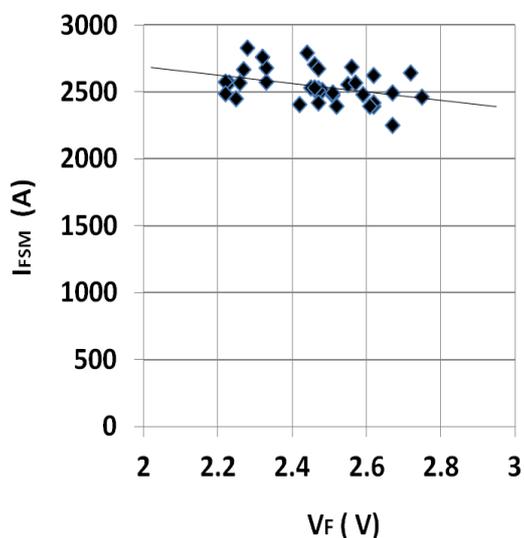


Fig. 16: Last good I_{FSM} values for 4.5 kV ($I_{nom} = 200$ A) EC3 diode for $t=10$ ms at $T=125^\circ\text{C}$.

3.6. Cosmic ray robustness

The 4.5 kV IGBT and emitter controlled diode is also designed for high robustness against cosmic radiation. The vertical device structure is designed for low electrical field at typical DC-link voltages. The typical FIT rates (FIT: number of failure for 10^9 h operation time) for the FZ1200R45HL3 module have been measured (Fig. 17). 100 FIT can be determined at ~ 3 kV DC-link voltage. In addition to the steady state situation during blocking the DC-link voltage also cosmic ray robustness under switching operation has to be considered. It has been verified by simulations that an additional dynamic FIT rate can be neglected for dV/dt 's up to $2\text{kV}/\mu\text{s}$ due to a limited electric field within the device [8].

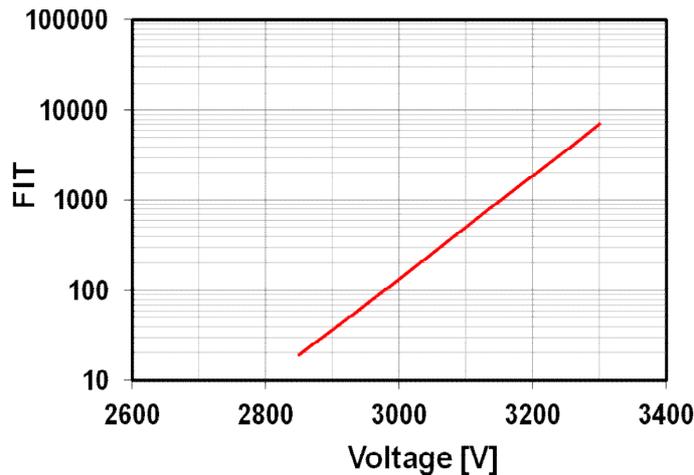


Fig. 17: Failure rates versus applied voltage obtained for 4.5 kV IGBT and diode measurements at 25°C, normalized for module FZ12000R45HL3 at sea level.

4. Conclusion

A new 4.5 kV IGBT diode chip set has been developed and optimized for HVDC application with very low on state voltage losses combined with fast turn on behavior for high current and voltage and high robust short circuits behavior. High robustness was demonstrated using HDR technologies for IGBT and diode.

5. References

- [1] J.G. Bauer , T. Duetemeyer, E. Falck, C. Schaeffer, G. Schmidt, H. Schulze, "Investigations on 6.5 kV Trench IGBT and adapted EmCon Diode," Proc. ISPSD, 2007, pp 5-8.
- [2] H.- J. Schulze, J. G. Bauer, E. Falck, F.- J. Niedernostheide, J. Biermann, T. Duetemeyer, O. Humbel, A. Schieber, " Increase of the Robustness of the Junction Terminations of Power Devices by a Lateral Variation of the Emitter Efficiency," Proc. ISPSD, 2013, pp. 257-260.
- [3] R. Marquardt, A. Lesnicar, "New Concept for High Voltage-Modular Multilevel Converter", Proc. PESC, 2004 Conference, Aachen, Germany
- [4] X. Gong, "A 3.3kV IGBT module and application in Modular Multilevel converter for HVDC," Proc. ISIE, Hongzhou, 2012, pp.1944-1949.
- [5] F. Dugal, E. Tsyplakov, A. Badchnagel, L. Strasta, T. Clausen, "IGBT Press-pack for the industrial market," Proc. PCIM Europe 2012, pp. 800-807.
- [6] A. Kopta, M. Rahimo, U. Schlapbach, N. Kaminski, D. Silber, " Limitation of the Short-Circuit Ruggedness of High-Voltage IGBTs," proc. ISPSD, 2009, pp. 33-36.
- [7] A. Müller-Dauch, F. Pfirsch, M. Pfaffenlehner, D. Silber, "Source Side Thermal Runaway of Trench IGBTs, Dependence on Design Aspects," Proc. ISPSD, 2006, pp 21-24.
- [8] A. Haertl, G. Soelkner, F. Pfirsch, W. Brekel, T. Duetemeyer, " Influence of dynamic switching on the robustness of power devices against cosmic radiation" Proc. ISPSD, 2012, pp. 353-356.