A 1000A 6.5kV Power Module Enabled by Reverse-Conducting Trench-IGBT-Technology

Dorothea Werber[1], Thomas Hunger[2], Matthias Wissen[2], Thomas Schütze[2],
Matthias Lassmann[2], Burkhard Stemmer[2], Volodymyr Komarnitskyy[3], Frank Pfirsch[1]
[1] Infineon Technologies AG, Am Campeon 1-12, D-85579 Neubiberg, Germany
[2] Infineon Technologies AG, Max-Planck-Str. 5, D-59581 Warstein, Germany
[3] Infineon Technologies Austria AG, Siemensstraße 2, A-9500 Villach, Austria

Abstract

A reverse conducting IGBT module based on the well-established high insulation 6.5kV-package platform for single switches is presented. The function of the IGBT-switch and the freewheeling diode is integrated into a single die enabling the higher current rating of 1000A. The maximum allowed junction temperature remains at 125°C as for the existing 6.5kV module portfolio. The ampacity enhancement is enabled by the significantly improved thermal resistance due to the increased effective silicon area for both operation in IGBT- and diode-mode. Additional benefit results from a reduction of the switching losses by proper gate control schemes during diode operation. The ampacity increase towards 1000A is therefore done without any cutbacks of the power cycling reliability, yet an increase of the effectiveness.

1. Introduction

High-voltage (HV-) IGBT-modules usually consist of two species of chips, IGBT-dies to offer the transistor and diode-dies the freewheeling functionality. A chip which combines both functions in one single die is called reverse conducting IGBT (RC-IGBT). Modules with these devices exhibit a lower thermal resistance compared to an IGBT module of same footprint because the number of active dies effectively increases. While the maximum junction temperature remains on the same level more current can be handled accordingly.

This paper reports on latest progress of developing an RC-IGBT-module designed for hard switching applications. The gate terminal of the device can be used during diode mode to control its characteristics. This is the reason for naming the new RC-IGBT Reverse Conducting IGBT with Diode Control (RCDC) [1]. The RCDC characteristics of the forward conduction (IGBT) mode remain similar to the trench-fieldstop technology of IGBT3 [2]. The controllability during the reverse conduction (diode) mode by dedicated gate drive schemes allows for additional minimization of the dynamic losses both during IGBT turn on and diode turn off.

2. Reverse Conducting Trench-IGBT-Technology

2.1. Chip Design

Infineon’s commercially available 6.5kV IGBT3 trench technology is modified to incorporate the diode function into the IGBT-chip. *N*-short regions are locally added at the backside of the 6.5kV IGBT3 die to enable current flow in reverse direction (diode conducting mode) (fig. 1a). Chip area exhibiting *p*-emitter portions on the backside serves as “IGBT” area, since the electrons injected through the open MOS-channel cause electron–hole plasma during IGBT mode. The chip area exhibiting *n*-emitter on the backside serves as “diode” area since holes

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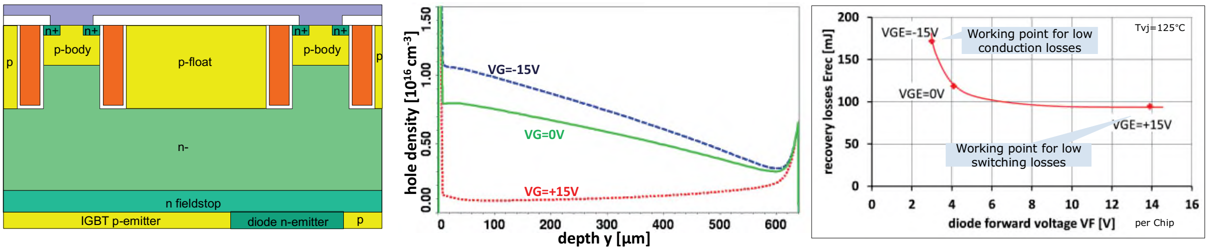
injected from the front side *p*-doped silicon areas cause electron injection from the backside *n*-emitter regions. If the pitch of the alternating *p*- and *n*-emitter areas on the backside is sufficiently small with respect to the vertical dimensions of the device, one silicon volume serves both as diode and IGBT regions depending of the current flow direction in the RCDC chip. While the complete silicon area present is used in IGBT mode, only part of it is used during diode mode. Additional continuous *p*-emitter areas on the backside overcome sufficiently the snap-back-behavior of the IGBT output characteristic discussed in the literature [3].

The front side *p*-doped silicon areas are designed with a minimum amount of highly doped anti-latch-up regions (maintaining the excellent overcurrent turn-off capability of IGBT3) in order to ensure a balanced carrier concentration and reverse recovery charge in diode mode without the usage of any charge carrier lifetime control means.

2.2. Gate-controllability during diode mode

During the reverse conduction mode the applied gate voltage V_{GE} causes a varying *p*-emitter efficiency which is reflected in the slope of the diode forward characteristics. For gate voltages above the IGBT threshold the front side *p*-emitter areas are bypassed by the open MOS electron channels. The current flowing is of a “quasi-unipolar” manner. An accumulation of holes in the drift region close to the gate trench occurs for negative gate voltages. The accumulated holes themselves and the optionally connected floating *p*-regions act as an additional hole source and thus increase the *p*-emitter efficiency. The resulting electron-hole plasma during diode mode is assessed by device simulation for the gate voltages V_{GE}=-15, 0, +15V (fig. 1b). For gate voltage below the IGBT threshold the RCDC device is capable of forward blocking. Therefore such a gate voltage can be used continuously during reverse conduction and blocking.

In fig. 1c the trade-off curve of the RCDC chip in diode mode is depicted: The free parameter of this trade-off curve is the voltage at the RCDC gate terminal. The diode can be driven into different working points: By applying a low gate voltage low conduction losses can be enforced. By raising the gate voltage to +15V, the diode can be prepared for turn-off with low switching losses. To combine both low on-state and low switching losses a smart gate voltage pattern can be applied.

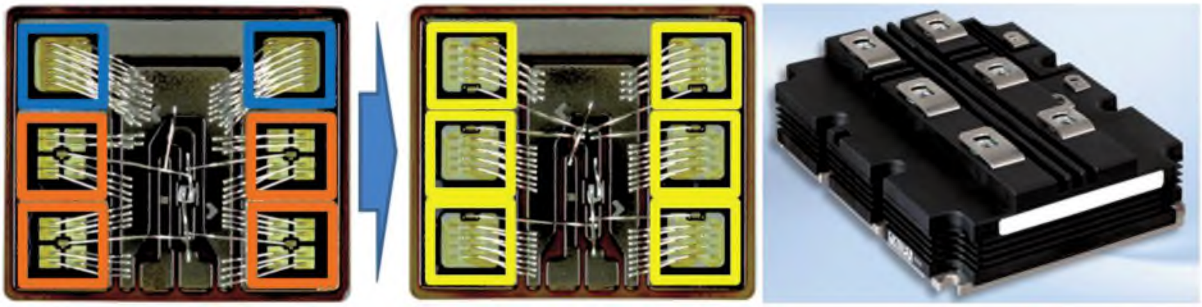


(a) (b) (c)

Fig. 1: (a) Schematic of the RCDC device; (b) Simulated carrier concentration of the RCDC in diode conduction mode along a vertical cut through a backside region with n-emitter for different gate voltages at 125°C; (c) Trade-off curve of the RCDC chip in diode mode with operation points for low conduction or low switching losses.

3. Module Design and Thermal Behavior

The HV-IGBT modules usually offer a ratio of silicon areas for IGBT and diode dies as 2:1 (fig. 2a). The substitution of the spatially separated IGBT and diode dies by the RCDC chip allows for the integration of the RCDC technology into the well-established industrial packages without changing the pinning of the module. This approach increases the silicon area used in IGBT mode by 50% while remaining at the same footprints as shown in fig. 2b. Moreover, the effective diode area is increased roughly by a factor 2 because each die acts during freewheeling state. The new RCDC-module with a footprint of 140×190mm² (FZ1000R65KR3) is rated at a nominal current of 1000A (fig. 2c).



(a) (b) (c)

Fig. 2: Comparison of commonly used IGBT (marked orange) and diode (blue) die combination (a) with RCDC (yellow) assembly (b) of same substrate layout used in the well-established 190×140mm² industrial housing having high insulation capability (c).

A general description of the module thermal behavior is well described by a matrix representation according to [4]

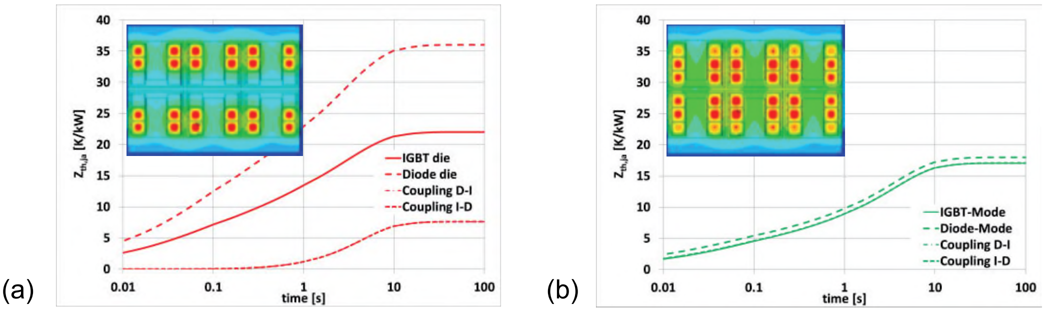
$$\begin{pmatrix} T_{vj}^{I} \\ T_{vj}^{D} \end{pmatrix} = \begin{pmatrix} \widehat{Z_{th,ja}^{I}} & \widehat{Z_{th,ja}^{I\leftarrow D}} \\ \widehat{Z_{th,ja}^{D\leftarrow I}} & \widehat{Z_{th,ja}^{D}} \end{pmatrix} \begin{pmatrix} P_I(t) \\ P_D(t) \end{pmatrix} + \begin{pmatrix} T_a \\ T_a \end{pmatrix}, \text{ with } \widehat{Z_{th,ja}}P(t) = \int_{-\infty}^{t} \dot{Z}_{th,ja}(t-\tau)P(\tau)\mathrm{d}\tau \; . \qquad (1)$$

A common IGBT module supplies a combination of spatially separated IGBT- and diode dies on one base plate. The structure of the constituting $Z_{th,ja}$ curves of the main diagonals representing the direct heat paths are different than the coupling terms (off-diagonals) to the their time-lagging (fig. 3a). Contrary, the structure and the absolute values of all $Z_{th,ja}$ curves are similar for an RCDC module due to fact that the heat loss is generated in the same piece of silicon which does not offer time delays in the cross coupling as shown in fig. 3b. A further simplification is possible for the RCDC module dealing with only one virtual junction temperature T_{vj} for transistor and diode action in one die. The matrix representation of eq. (1) can be reduced to

$$T_{vj}^{RCDC} = \widehat{Z_{th,ja}^{RCDC}}\left(P_I(t) + P_D(t)\right) + T_a \qquad (2)$$

when appropriately averaging the single $Z_{th,ja}$ curves. This simplification appears to have an acceptable accuracy due to the fact, that the temperature distribution inside a module as well as even on a single chip [5] might exceed the calculated differences by far.

The location of the virtual junction in an RCDC has to be carefully discussed. The RCDC-diode has its virtual temperature relevant *pn*-junction at the front side as it is the case of a standard diode.



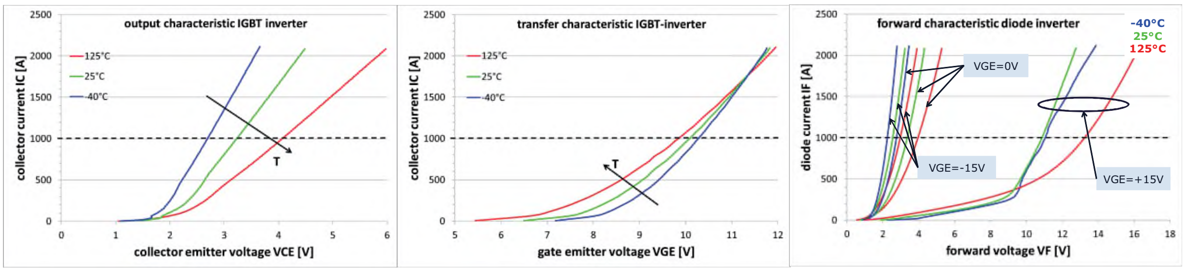
(a) (b)

Fig. 3: $Z_{th,ja}$ for the different heat paths including the thermal cross-coupling. (a): standard IGBT module. (b): RCDC. Insets: simulated temperature distribution in the RCDC as well as IGBT module having the heat loss applied to the IGBTs. Model heat sink: 65µm thermal grease with thermal conductivity of 1W/mK, 3mm Aluminum heat sink with a heat transfer coefficient of 8000W/m²K.

In a standard IGBT the backside *pn*-junction offers the temperature dependent diffusion voltage used for sensing T_{vj}. But, for an RCDC-chip this *pn*-junctions is locally shortened by the additionally introduced *n*-short regions. The presented Z_{th} curves for IGBT and diode mode of the RCDC refer to the die's front side temperature due to the fact of heating the same pieces of silicon. When seriously comparing the benefits of the RCDC-technology this has to be taken into account, especially when considering the IGBT operation mode. However, when calculating the power cycling capability no differences are expected because the assembly technology is not changed and the PC reliability curves are valid for the common diode dies having the *pn*-junction at their front side.

4. Electrical Behavior

The IGBT output and transfer characteristics are depicted in fig. 4a, b. The diode characteristic depends on the gate voltage actually applied to the module and can be seen in fig. 4c. This is a remarkable feature of the RCDC as it allows controlling the on-state voltage but requires dedicated current direction detection during inverter operation.



(a) (b) (c)

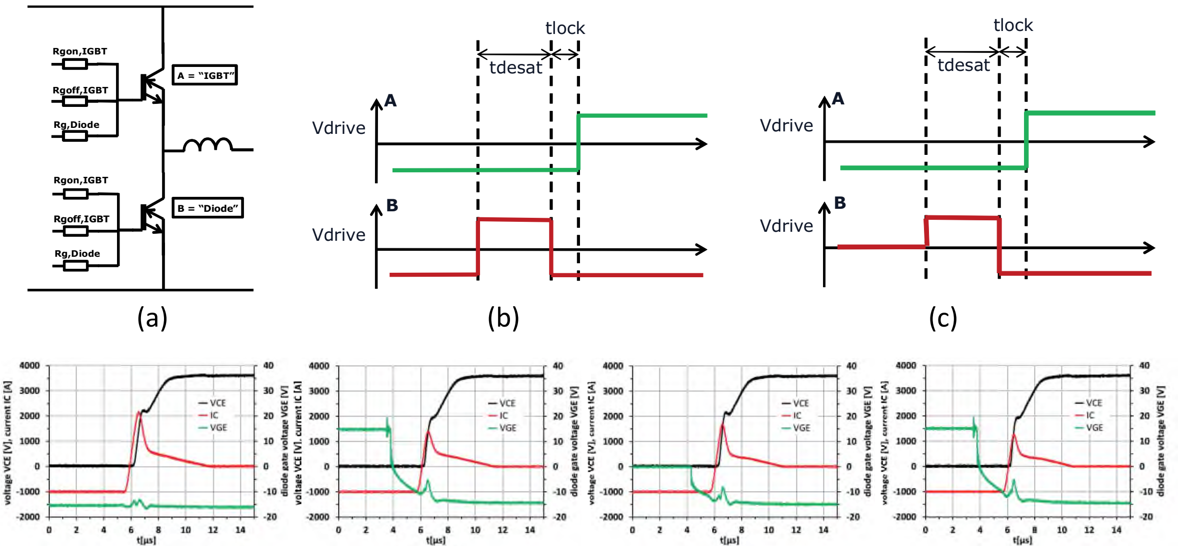
Fig. 4: Measured characteristics of the FZ1000R65KR3: a) output characteristics in IGBT mode; b) transfer characteristics in IGBT mode; c) forward characteristics in diode mode.

4.1. Gate-control of the RCDC

A schematic of a gate control pattern for the combination of lowest on-state and switching losses for a given half-bridge configuration is shown in fig. 5b. Applying a gate voltage step to the RCDC in diode conduction mode short before commutation reduces the switching losses by sweeping out the stored charge carriers just before the turn on of the according IGBT. This is referred to as the desaturation of the RCDC in diode mode. By this approach the reverse recovery current peak and therefore the switching losses can be significantly reduced (figs. 5d, e). Essential parameters of the desaturation are the desaturation duration t_{desat} and the locking time t_{lock}, which avoids the occurrence of a phase leg short circuit. Figs. 5c, f, g show a variant of the gate control pattern: The RCDC-diode conducts in a "pre-desaturated" stage at an applied gate-voltage of zero volts; to achieve similar dynamic losses the necessary desaturation time is shortened by this measure. Further details on how to drive the RCDC will be given in [6].

In general, four operation modes for the RCDC in diode mode are specified.

1) V_{GE}=-15V, no desaturation pulse: lowest conduction losses, but high switching losses due to highly saturated diode
2) V_{GE}=-15V, with desaturation pulse: low conduction losses and low switching losses due to desaturation of the diode by t_{desat} before recovery (see fig 5b). This desaturation mode is refered to as type 1 desaturation.
3) V_{GE}= 0V, no desaturation pulse: higher conduction losses but lower switching losses compared to 1) due to less saturation of the diode
4) V_{GE}= 0V, with desaturation pulse: Due to 0V control, less charge has to be removed during desaturation time leading to shortest possible t_{desat} pulses (see fig 5c). This desaturation mode is refered to as type 2 desaturation.



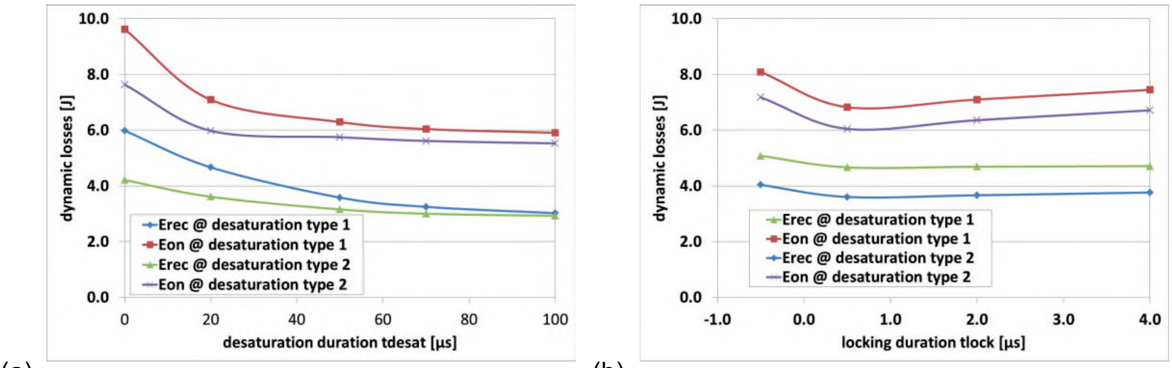
(a) (b) (c)

(d) (e) (f) (g)

Fig. 5: (a) Half-bridge configuration with two FZ1000R65KR3 modules: Module "A" in IGBT and module "B" in diode mode; (b) Gate control pattern with desaturation pulse applied to module "B" in diode mode; (c) Variant of a gate control pattern with a pre-desaturated module in diode mode; (d)-(g): Voltage V_{CE}, current I_C and gate voltage V_{GE} of the RCDC "B" in diode mode during commutation (V_{CC}=3.6kV and I_C=1000A) according to the operation mode 1-4 with, t_{desat}=20µs, t_{lock}=0.5µs where applicable.

4.2. Dynamic losses with diode control

In fig. 6 the reduction of the diode recovery losses and the IGBT turn-on losses in dependency of the desaturation duration t_{desat} and the locking duration t_{lock} are given. For longer t_{desat} and a fixed t_{lock} the dynamic losses are decreasing (fig. 6a). In order to end up with the same switching losses the t_{desat} for a type 2 desaturation mode can be decreased by several 10µs. For instance, to end up with turn-on losses of E_{on}=6J a t_{desat} =70µs has to be applied in case of a type 1 desaturation, whereas for a type 2 desaturation mode t_{desat}=20µs are sufficient. The second parameter to be optimized in terms of switching loss reduction is the locking duration t_{lock}. In contrast to the desaturation duration the locking duration shows a minimum of switching losses that is independent of the type of desaturation (fig. 6b).



(a) (b)

Fig. 6: E_{rec} and E_{on} for desaturation mode type 1 (V_{GE}=-15V) and type 2 (V_{GE}=0V) at V_{CC}=3,6kV, I_C=1000A and T_{vj}=125°C; (a) as a function of desaturation duration for a fixed t_{lock}=0.5µs; (b) as a function of locking duration at a fixed t_{desat}=20µs.

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The minimum t_{lock} duration applicable, when the dynamic losses are minimized, is defined by the respective gate resistors, i.e. the R_g of the RCDC in diode mode and the $R_{g,on}$ of the RCDC in IGBT mode as well as the parasitic turn-on of the MOS channel in diode mode. For locking durations shorter than a certain value the dynamic losses significantly raises. Fig. 6b is based on a $R_{g,on}$=0.9Ω for the IGBT and a R_g=0.5Ω for the diode. In this case the minimum switching losses are obtained at t_{lock}=0.5µs. A major advantage compared to the previously presented reverse conducting module in the field of 6.5kV applications [3] is the improved impact of the desaturation pulse with respect to loss reduction at even shortened desaturation durations.

4.3. Softness

The softness of the RCDC in diode and IGBT mode is investigated. Typical waveforms at low currents of a saturated diode and a desaturated diode are shown in fig. 7a. The RCDC diode reveals an excellent softness independently of the charge carrier concentration due to the fact that holes are injected from the *p*-emitter areas at the chip backside during diode commutation. In IGBT mode the RCDC reveals an excellent softness, too (fig. 7b). Turning off twice the nominal current is possible without any constraints regarding oscillations. Even in case of higher DC link voltages and further increased negative d*v*/d*t*, snapping of the tail current and therefore oscillations within the safe operation area are prevented.

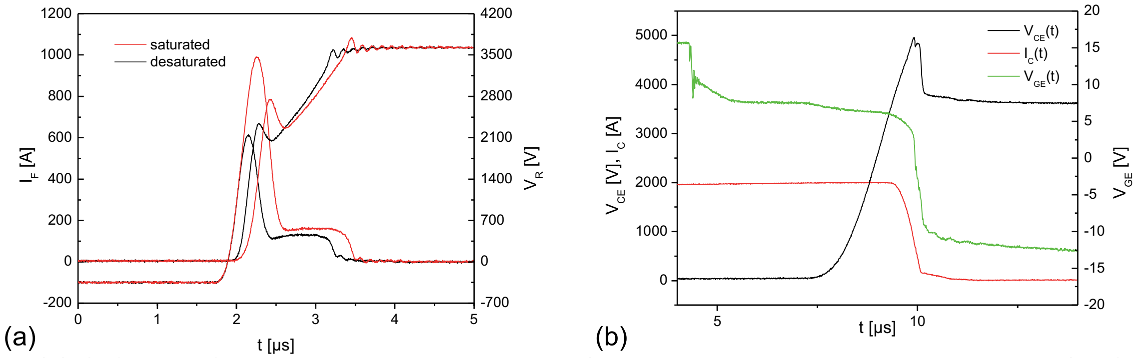


Fig 7: (a) Softness of a saturated and desaturated (type 2, t_{lock}=0,5µs, t_{desat}=20µs, R_g=0.5Ω) RCDC diode for I_F=100A and (b) RCDC IGBT for I_C=2000A, both at V_{CC}=3600V, T_{vj}=25°C, $R_{g,on}$=0.9Ω and $R_{g,off}$=3.9Ω, respectively.

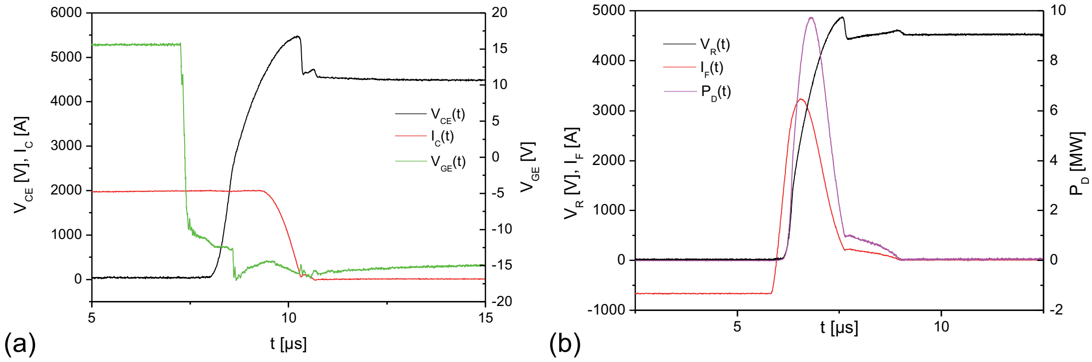
4.4. Robustness verification

1 RBSOA und SOA

In order to validate the robustness modules with a nominal rated current of I_C=660A, i.e. 2/3 of the 1000A module, have been switched off in IGBT mode without any failures at conditions exceeding the safe operating area. Fig. 8a shows a waveform where the turn-off current exceeds 3-times nominal current and the maximum d*v*/d*t* is in the range of 6.8kV/µs. Under such severe test conditions dynamic avalanche cannot be prevented. Such conditions are very far beyond the specified safe operating area. However, the RCDC robustness in IGBT mode is ensured. In diode mode the RCDC robustness up to a maximum peak power of P_{max}~9.8MW has been proven for a saturated diode at a constant gate voltage of V_{GE}=-15V (fig. 8b). This overstress for the diode can be achieved by a fast switching auxiliary RCDC IGBT resulting in an enormous d*i*/d*t* of approx. 8kA/µs.

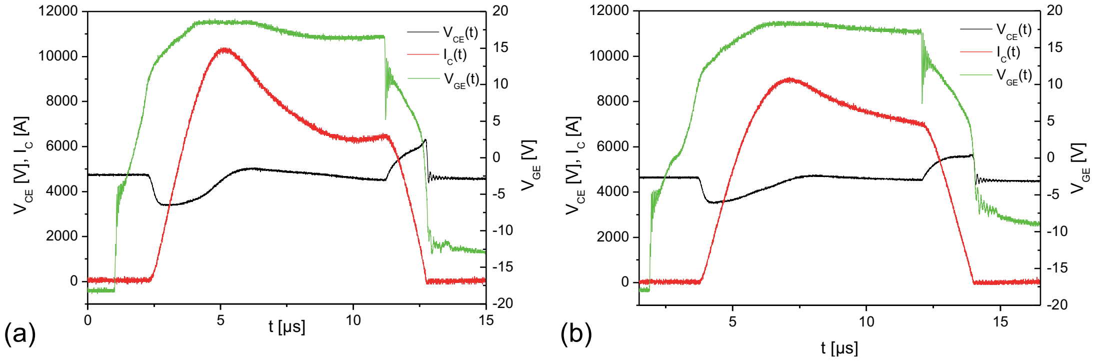
2 Short-circuit ruggedness

Short-circuit type 1 (SC) tests have been performed in order to confirm the robustness of the RCDC in IGBT mode. Fig. 9a and b show the waveforms of the RCDC and of a reference module prepared with 36 chips of the regular 6.5kV IGBT3 chip. The nominal rated current of this module formally would be I_C=1125A. In order to provoke overstress to the RCDC IGBT the gate voltage has been raised up to V_{GE}=17V. A TVS diode has been mounted at the auxiliary terminals of the module limiting the external gate voltage to values V_{GE}≤18V. The short circuit duration in these tests were kept constant at t_{SC}=10µs. For the same DC link set up and $R_{g,on}$ the SC currents appears different. The d*i*/d*t* is higher and thus leads to a higher maximum SC current: ~10.4-times nominal current for the RCDC module and 8.1-times nominal current for the IGBT3 module. After reaching its maximum the current of the IGBT3 module shows a monotonically decay due to the increase of chip temperature throughout the SC pulse. The RCDC module shows a slight current increase at the end of the SC pulse due to an increase of V_{GE} caused by a different internal gate wiring. However, considering both effects the resulting increase in deposited energy of approx. 7% does not lead to any thermal or current destruction of the RCDC module.



(a) (b)

Fig. 8: Robustness validation of IGBT and diode mode of a I_C=660A rated RCDC module (130×140mm²). (a) RBSOA test: I_C=2000A~3×I_{nom}, V_{CC}=4500V, d*v*/d*t*$|_{max}$~6,8kV/µs, T_{vj}=125°C; (b) SOA test: I_F=660A; V_{CC}=4500V, d*i*/d*t*$|_{max}$~8kA/µs, P_{max}~9.8MW



(a) (b)

Fig. 9: Comparison of short circuit type 1 waveforms of a (a) 1000A RCDC module ($I_{SC,max}$=10380A) and (b) a 1125A IGBT3 module ($I_{SC,max}$=9080A~8×Inom) at V_{CC}=4500V, V_{GE}=17V, T_{vj}=125°C and t_{SC}=10µs.

5. Loss comparison and output current benefit

Fig. 10a and b compare the sources for electrical losses in an RCDC module to an appropriate reference, here Infineon's FZ750R65KE3 rated at I_C=1000A. A reduction of the static as well as dynamic losses is obviously possible if using the diode control patterns. The reduced losses together with the better heat spreading in a RCDC module results in an increased inverter output power while using the same heat sink. The RCDC also benefits from the reduced T_{vj} ripple as discussed in [7]. The calculations shown in fig. 10c predict the benefit for an operation at f_0=50Hz and V_{CC}=3600V for the four discussed operation modes and a maximum junction temperature set to $T_{vj,max}$=125°C.

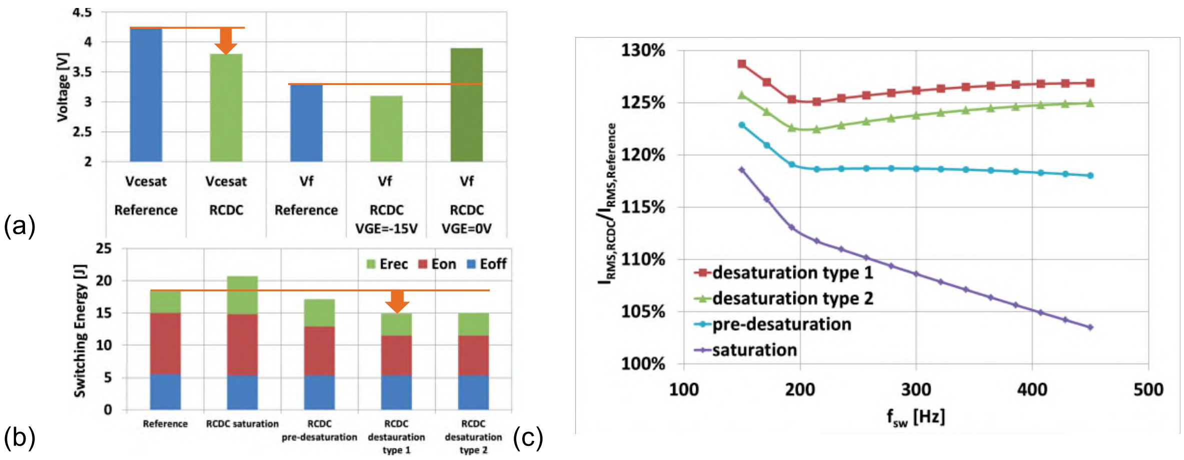


Fig. 10: (a) and (b) Comparison of static losses (described by forward voltage drops at I_C=1000A) and dynamic losses at T_{vj}=125°. The reference module is Infineon's FZ750R65KE3; (c) inverter gain by replacing the reference by a RCDC module taking into account the different operation modes of the diode.

6. Summary

The paper presents a 1000A hard switching reverse conducting IGBT module dedicated for the voltage class 6.5kV. It allows for an increased output power of inverters having the same footprint and maximum rated junction temperature 125°C as the standard IGBT module. The concept of the RCDC-modules takes advantage both of the thermal resistance reduction and the dynamic loss reduction by the diode control schemes. An increase of the output current for inverter applications with water cooling up to 30% is reached. The power cycling capability remains on the same level as standard IGBT module. No cutbacks concerning ruggedness or softness were observed.

7. Acknowledgments

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