

REPETITIVE SHORT CIRCUIT BEHAVIOUR OF TRENCH-/FIELD-STOP IGBTs

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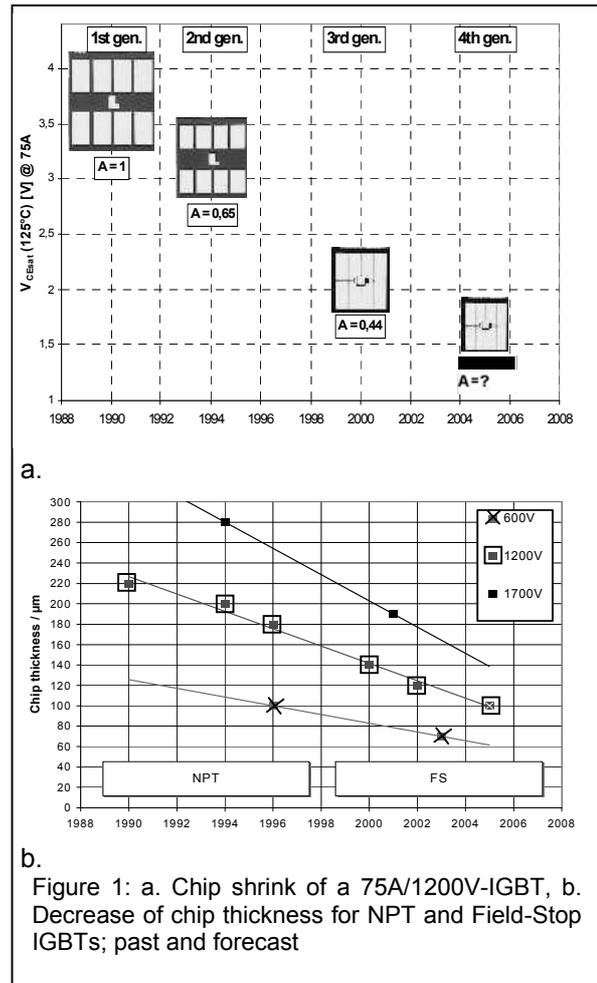
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Abstract: This paper has a focus on the short-circuit robustness of eupec modules with 1200V 3rd generation IGBT chip from Infineon. Short-circuit failure modes are described and measures with regard to an optimised and robust chip structure are presented. Measurements of repetitive short-circuit pulses based on the Trench/Field-Stop IGBT 3 show that the typical number of short circuit pulses until destruction depends exponentially on the maximum chip temperature reached within the pulse.

INTRODUCTION

For traditional 600V, 1200V and 1700V applications in the industrial drives segment an essential demand for short circuit capability of IGBTs exists. Among others this is one reason why the robust “Non Punch Through” IGBT technology with homogeneous base material dominated the original “Punch Through” concept based on Epitaxial technology. In the last two years a tendency towards a new vertical structure called “Field Stop” IGBT [1,2] can be observed, which is also known as “Soft Punch Through” [3] or “Light Punch Through” [4].

Because of economic reasons there is a strong demand for smaller chips. Figure 1 demonstrates the shrink of the IGBT chip size and the thickness over the last 15 years. For the 4th generation IGBT a further chip volume reduction can be expected as indicated in figure 1a. As a consequence of smaller chip sizes current densities are increased not only under nominal but also in short circuit condition. This results in a strong increase of power dissipation density in combination with smaller silicon heat capacity. It becomes obvious that short circuit robustness is a general challenge in the development process of modern IGBT technologies. Therefore it is no surprise, that many publications in the last years have already dealt in detail with the short circuit behaviour and specific physical device aspects



[5][6]. A recent publication by Otsuki et. al. [2] has even reported about critical short-circuit properties of the above mentioned new vertical structures.

In the first part of this paper different failure modes of an IGBT under short-circuit conditions are described and it is explained in short how these failures in the new vertical structure were avoided in Infineons latest 3rd generation IGBT 3 with an optimised Trench-cell and Field-Stop design.

In many industrial applications it is important not only to get experience about the robustness in case of just one short circuit event, but also about the number of short-circuit pulses a modern chip will withstand until its destruction. Therefore the second part of this paper will investigate the reliability of the IGBT chip based on the Trench and Field-Stop concept under repetitive short circuit conditions at various operation conditions.

FAILURE MODES AND OPTIMISED CHIP DESIGN

As is demonstrated in detail in [7] three failure modes can be observed during a typical 10 μ s short-circuit pulse:

1. Chip destruction many hundred microseconds after a successful short-circuit turn-off.
2. Chip destruction during short-circuit turn-off.
3. So called "Short-circuit destruction mode" appearing during the short circuit pulse itself.

By experiment it is found that failure modes 1 and 2 depend on the dissipated power during the short-circuit pulse. The third destruction mode is still under investigation. This failure occurs just after few microseconds in the short circuit pulse at moderate d.c.-link voltages and operation temperatures, but at high current densities. This mode seems to be independent of the dissipated power.

To handle the problems of over-temperature in failure mode 1 and 2 the cell structure of Infineons Trench/Field-Stop-IGBTs was efficiently optimised with regard to moderate short circuit current levels of about five times of the rated current. Furthermore compared to the NPT ("Non Punch Through") chip design the IGBT 3 has a more homogeneous distribution of heat generation inside the chip. This is due to the triangular electric field distribution in the vertical chip direction of the NPT concept where most of the heat is generated near the pn junction. As a consequence of this, in short circuit condition temperature distribution in the chip is inhomogeneous with a maximum at the pn junction. In the Trench/Field-Stop concept electric field and heat

generation is distributed more homogenous because of the trapezoidal electric field distribution and so temperature distribution is more homogeneous. Both effects, short circuit current limitation and trapezoidal field distribution, lead to a smaller temperature rise in the Trench/Field-Stop device despite smaller chip size, thickness and higher current densities. These statements are confirmed by simulation in [7]. A third helpful aspect concerning failure mode 1 and 2 is the design of a latch-up free cell geometry, which was realized by the introduction of a highly conductive p well near the chip emitter [7].

The investigation of the third failure mode appearing during the short circuit pulse and its physical mechanism is still ongoing. Experiments have shown that main parameters that influence the destruction condition are the doping profile of the Field-Stop layer and the backside emitter as well as the chip thickness. Especially the carrier concentration gradient in the neutral region near the backside emitter seems to influence this failure mode. Although the physics have not been fully understood, the phenomenological analysis lead to a short circuit rugged IGBT 3.

REPETITIVE SHORT CIRCUIT BEHAVIOUR

To investigate the robustness of the Trench/Field-Stop IGBT 3 chip two types of power modules for high and medium power applications which are based on this chip technology have been analysed (figure 2). Each of these power modules contains the biggest available 150A IGBT 3 chip which is arranged in parallel to realize nominal currents up to 3600A corresponding to short-circuit currents rated approximately 5 times the nominal current. The objective of these experiments is to answer the

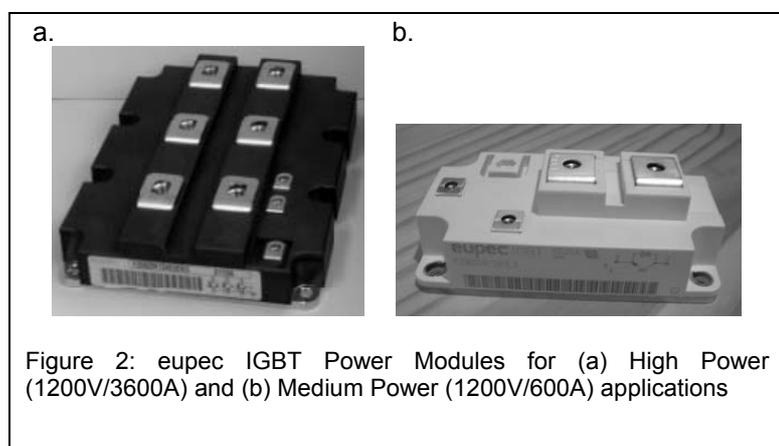
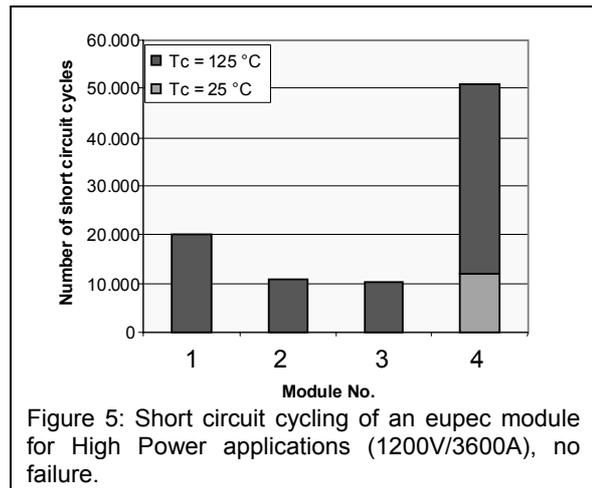
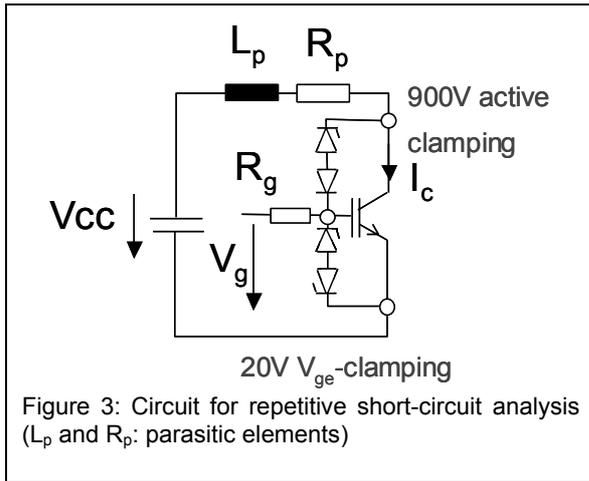


Figure 2: eupec IGBT Power Modules for (a) High Power (1200V/3600A) and (b) Medium Power (1200V/600A) applications



following questions:

1. How many repetitive short-circuit pulses under different operation conditions does a power module withstand until destruction of chip or module interconnects ?
2. Are there any aging effects observable ?
3. Is it possible to recognize any dependence on the operation conditions ?

Figure 3 shows the electrical circuit with parasitic elements for the repetitive short-circuit analysis. For the measurements an active clamping with zener diodes rated 900V and a gate-emitter clamping at 20V is included. In the IGBT High Power module 24 and in the IGBT Medium Power module 4 IGBT chips are arranged in parallel to realize the output power.

A typical short-circuit switching pulse at nominal condition (d.c.-link voltage $V_{cc}=600V$, gate voltage $V_g=15V$, module case temperature $T_c=125^\circ C$) for a pulse length of $10\mu s$ is shown in

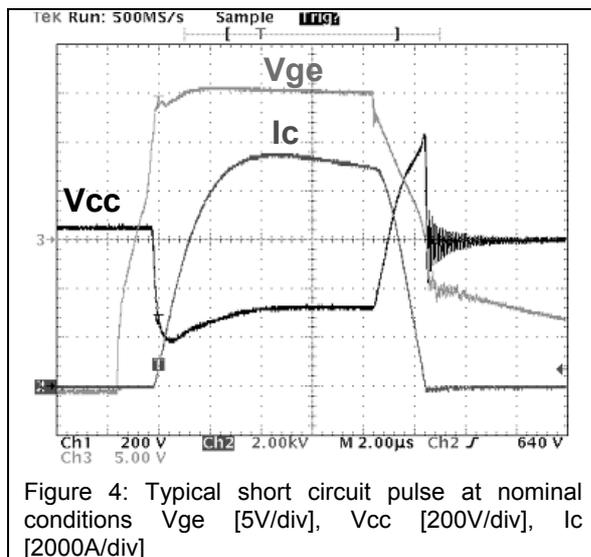
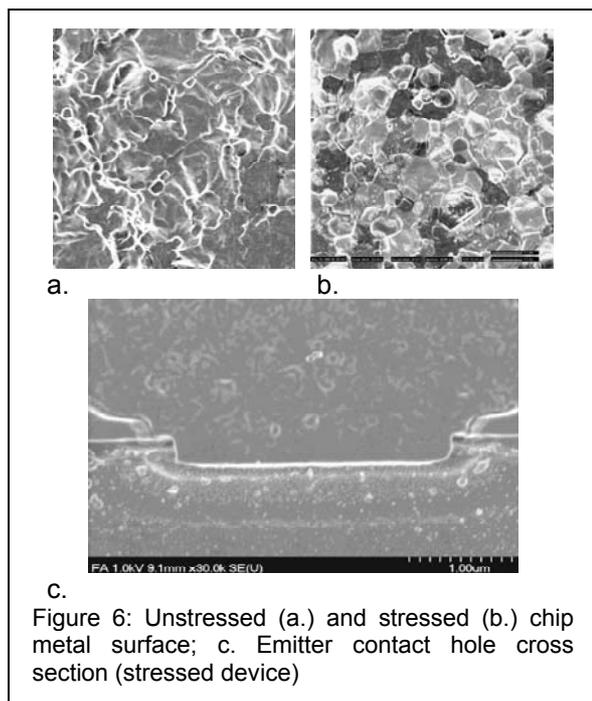


figure 4. The maximum transient dissipated power is about 3 MW and the cycling frequency for the repetitive short-circuit analysis is 1/3 Hz. Four modules have been stressed, each with a different number of short-circuit pulses. Figure 5 shows how the in all 90.000 cycles were split up between the 4 modules. No failure occurred and the maximum number of pulses applied to a module was 50.000. The most stressed device was analysed for aging effects. No differences in the electrical parameters like collector-emitter cut-off current, gate-emitter leakage current and device avalanche voltage were observed. Additionally, the output and transfer characteristic remain unchanged.

Concerning the power module mechanical properties the bond wire connections were analysed by pull- and shear test. All connections



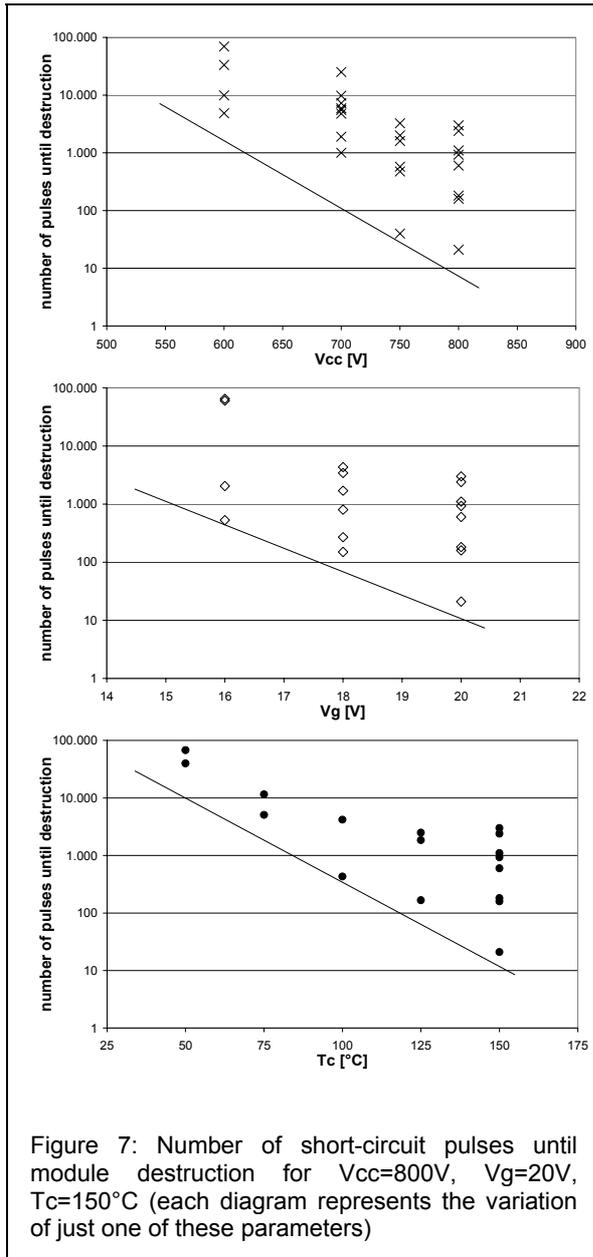


Figure 7: Number of short-circuit pulses until module destruction for $V_{cc}=800V$, $V_g=20V$, $T_c=150^{\circ}C$ (each diagram represents the variation of just one of these parameters)

remained in the production specifications. An ultrasonic analysis of the chip solder connections and a visual inspection of the chip and module interconnections do not show any signs of degradation phenomena.

For the IGBT the chip metal surface and the contact hole region between metal and silicon were analysed. The only changes observed are recrystallization effects of the top aluminium contact layer (Figure 6a/b). However these changes due to the high temperature load are known to be absolutely uncritical for the device performance. Additionally, there were no critical

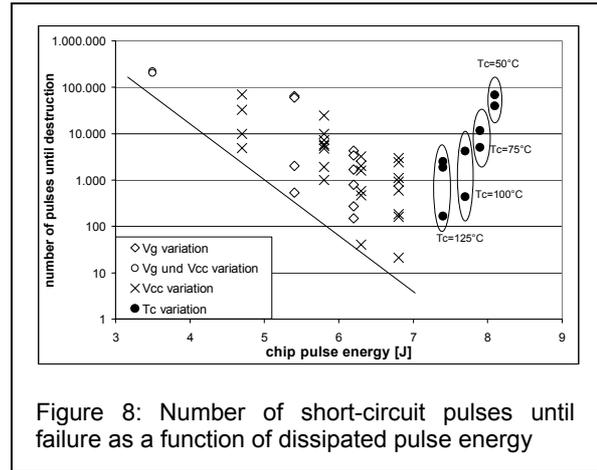
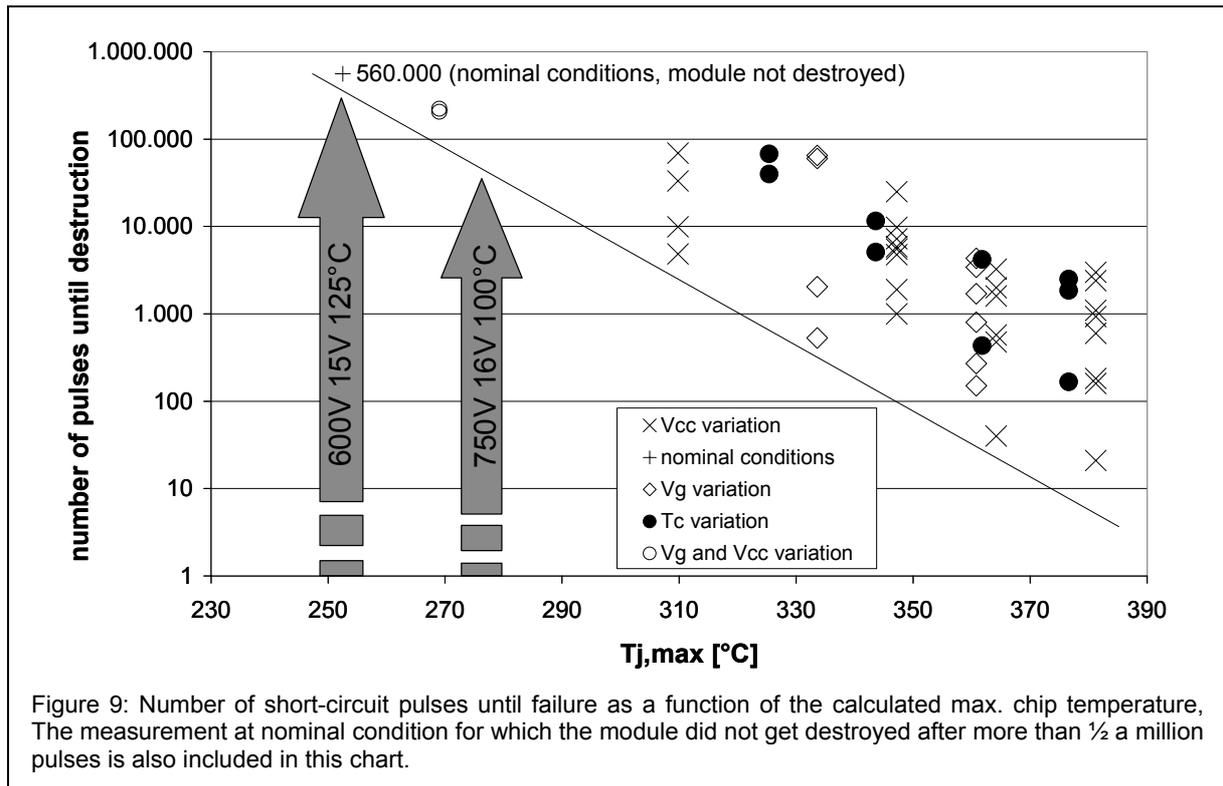


Figure 8: Number of short-circuit pulses until failure as a function of dissipated pulse energy

changes (e.g. melted areas due to a local over-temperature) in the contact hole region recognized (figure 6c).

The medium power module reached more than $\frac{1}{2}$ a million short-circuit pulses without module destruction. So measurements with intensified operation conditions were carried out to get an impression about the possibilities of the IGBT chip and the connection technology of the power module. Figure 7 shows the dependence of the number of reached short-circuit pulses until chip destruction on the d.c.-link voltage, the gate voltage (which influences the current levels according to the chip transfer characteristic), and the module case temperature. For all parameters there exists a strong exponential dependence. In the analysed parameter range the number of "survived" short circuits varies between 11 for very hard conditions and 560.000 for the nominal case (the nominal case is not included in the charts).

To combine all these measurements the dissipated pulse energy was calculated to put all measurements into one diagram (figure 8). For the d.c.-link and gate voltage this plot reveals a common exponential dependence on the short circuit pulse energy except for the measurements based on the temperature variation. In another approach the maximum chip temperature at the end of each pulse under consideration of the module case temperature was determined. As shown in figure 9 the maximum chip temperature within a short-circuit pulse can be identified as the decisive parameter for the expected number of short-circuit pulses a power module is capable to handle: For all parameter variations (V_{cc} , V_g , T_c) the same exponential dependence on $T_{j,max}$ is found.



CONCLUSION

Three different failure modes during short-circuit operation in modern IGBT chips are presented and design aspects with regard to a high degree of short-circuit capability for the Trench IGBT with Field-Stop concept are discussed. We have shown that IGBT 3 technology is designed for excellent short-circuit robustness and moreover module and chip technology are typically tolerant to a large number of short circuit pulses under relevant operation conditions. No signs of power module degradation and changes in electrical performance were observed. It is demonstrated by experiment that there exists an exponential dependence of the number of short circuit pulses on the maximum chip temperature at the end of each pulse. The investigations of the actual destruction mechanism after many short circuit pulses are ongoing.

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