High-Temperature Operation of HPT+ IGCTs

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Abstract

A new 91 mm diameter 4.5 kV IGCT (Integrated Gate Commutated Thyristor) with extraordinary Safe Operating Area (SOA) at 140°C is presented. Moreover the turn-off losses are reduced compared to the current High Power Technology HPT-IGCT range. The improvements for the new HPT+ IGCT were achieved by optimising the HPT's corrugated p-base doping profiles.

In addition, the metallisation has been improved for higher thermo-mechanical wear resistance.

1. Introduction

1.1. The IGCT

The IGCT has established itself as the device of choice for high power applications such as medium voltage drives, interties and power-quality applications. This is due to its low losses, high load cycling capability and high power handling capability, especially high current turn-off capability [1].

The power ratings of converters are limited mainly by the on-state and turn-off losses of the IGCT compared to the cooling power on one hand, and the current turn-off capability (Safe Operating Area SOA) on the other hand. Furthermore, in line with recent trends, operating the semiconductor device at a higher temperature enables a higher power rating of the converters.

All three aspects are addressed in our newest developments: lowering losses, increasing SOA at high temperatures and increasing the maximum junction temperature.

1.2. The Corrugated P-Base in HPT IGCTs

The introduction of the corrugated p-base to the IGCT design was a large step to high current turn-off capability [2, 3]. The corrugation is formed by two different Al doping profiles: One underneath the cathode segments and a deeper profile between the segments. This led to the desired shaping of the current flow during turn-off: The current density underneath the finger is reduced and the current is more easily commutated to the gate. The biggest advantage of the corrugated P-base is the increase of SOA.

The corrugated base of the IGCT has been referred to as "High Power Technology" (HPT). We have developed a full IGCT range based on this technology for voltage classes between 4.5 kV and 10 kV [4].

2. Results

2.1. Doping Profiles

The starting point of the most recent HPT development is our current 4.5 kV IGCT with the corrugated p-base. In both cases, the conventional corrugation and the new one referred to here as HPT+, the corrugation is formed by masked Al implantations and subsequent diffusion steps (see figure 1). The shape of the p-base has been varied. The parameters used to tailor the turn-off behaviour have been

- Junction depth and Al doping profile underneath the gate
- Junction depth and Al doping profile underneath the finger

- Width of the implantation mask, thus the width of the bulge

These parameters have been varied by different Al implantation doses, diffusion times and photo masks. In addition to that, the anode strength was varied.

The main parameters to be optimised are

- Turn-off capability

  especially multiple turn-off events at 10 kHz (burst) at high temperatures, e.g. 140°C.
- Turn-off losses

The low 100 FIT failure rate caused by cosmic radiation is kept since the width and doping concentrations of the n^--region remains unchanged.

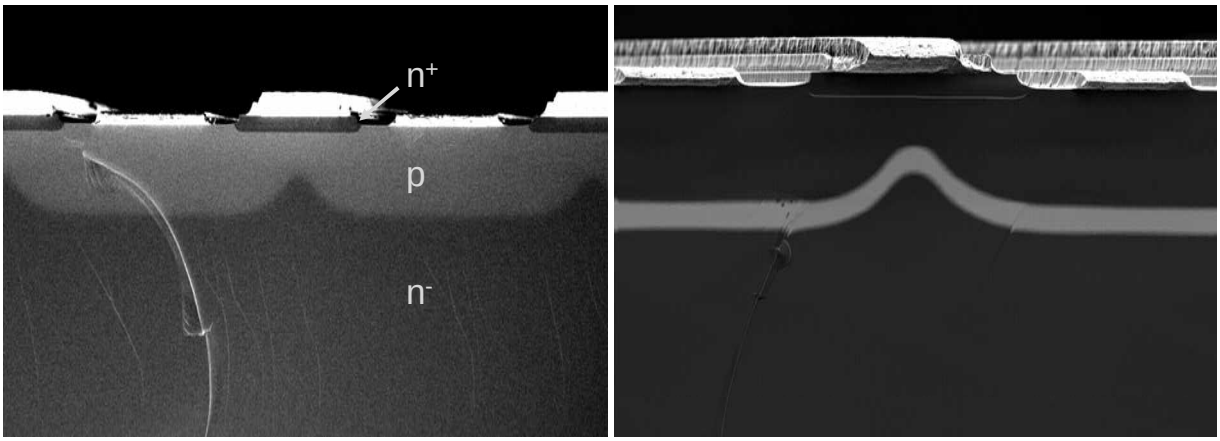

Fig. 1. SEM images of the corrugated P-base of an IGCT. Left: Doping contrast SEM. Right: Electron beam induced current image (EBIC).

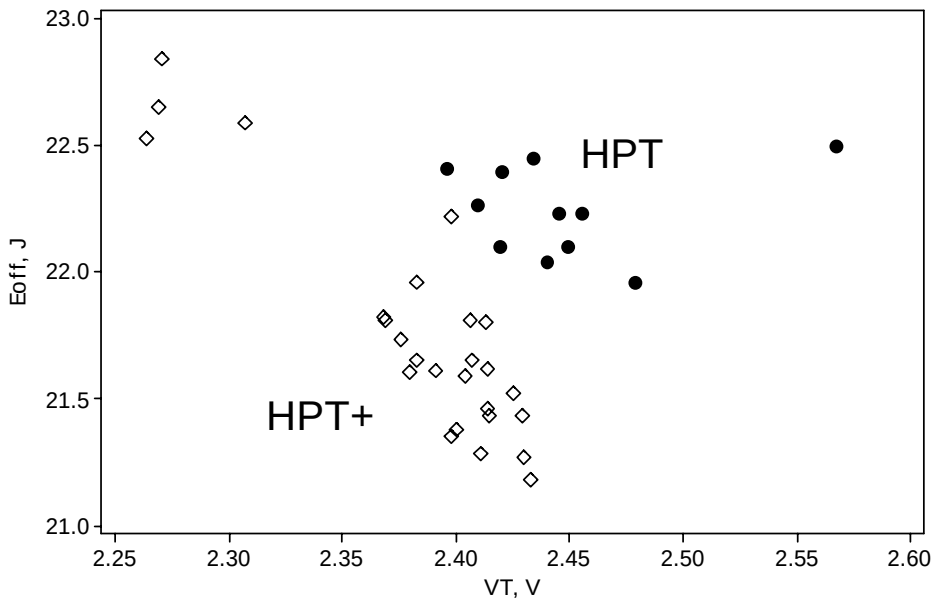

Fig. 2. Technology curve. On-state voltage VT (125°C, 4 kA) against turn-off losses E_{off} (125°C, 4 kA, 2.8 kV, circuit 1, see figure 5).
The HPT+ IGCT with the new corrugation has a clearly improved technology curve.

2.2. Electrical

Nominal Losses and Turn-off Waveforms

The optimised p-base in HPT+ technology leads to reduced turn-off losses resulting in an improved technology curve. The losses are reduced by 0.8 Ws at 125°C (4 kA against 2.8 kV, see figure 2. Circuit configuration 1, see figure 5). Note that operating the device at even higher temperatures, leads to higher turn-off losses.

The turn-off waveforms at 125°C in figure 3 show why the switching losses are lower in case of the optimised p-base. The main difference is the shorter duration of the tail current. The tail current is reduced by the interaction of the optimised p-base and the weaker anode.

Reducing the anode strength alone, without improving the p-base, results in undesired high overvoltages when switching at low temperatures, as shown in figure 4. In figure 4, the turn-off waveforms of the optimized doping profiles at 25°C are shown (4 kA against 2.8 kV). One feature of the HPT+ IGCT is the behaviour at the instant when the anode current is approaching zero. No extra overvoltage appears as in the conventional case. When switching off a current of 4 kA, the maximum voltage is 4.2 kV. This is below the clamp overvoltage at a 5 µs delay and below the specified blocking capability of 4.5 kV.

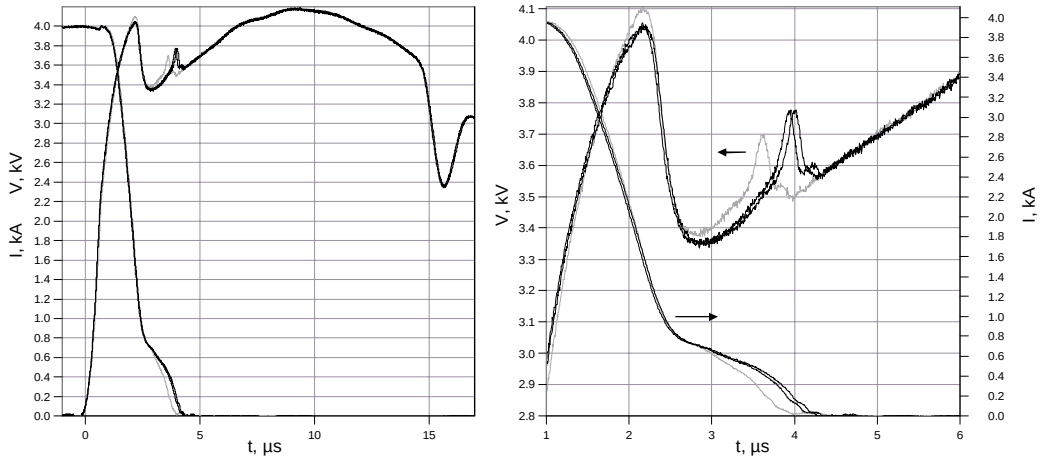

Fig. 3. Turn-off waveforms from 4.0 kA to 2.8 kV DC link voltage at 125°C.Conventional profiles (black) and optimised profiles (grey). Anode current and anode-cathode voltage. Left: whole curve; right: zoom to 1 to 6 µs, when the current reaches 0. Circuit configuration 1.

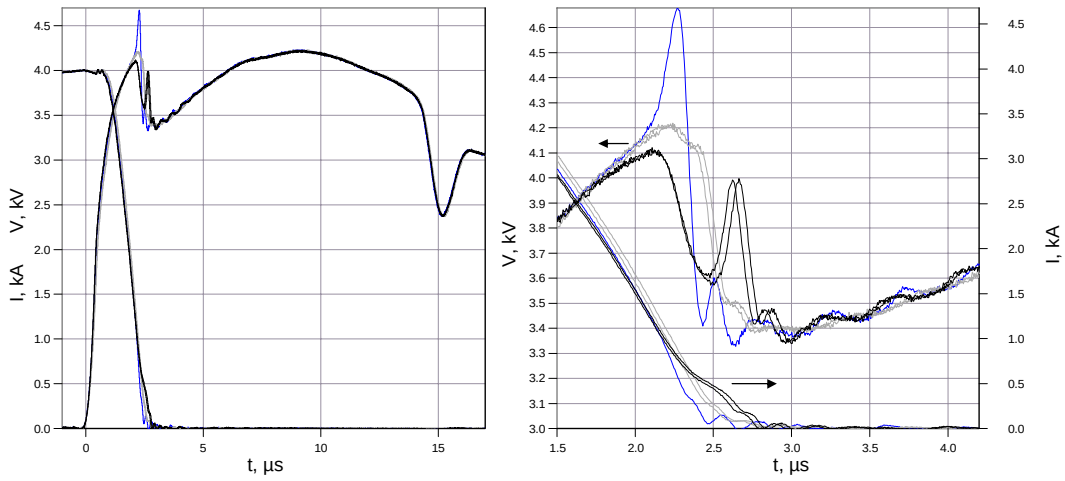

Fig. 4. Turn-off waveforms from 4.0 kA to 2.8 kV at 25°C. Conventional profiles (black), optimised profiles (grey) and experimental device with large overvoltage (blue). Anode current and anode-cathode voltage. Left: whole curve; right: zoom to 1.5 to 4.2 µs. Circuit configuration 1.

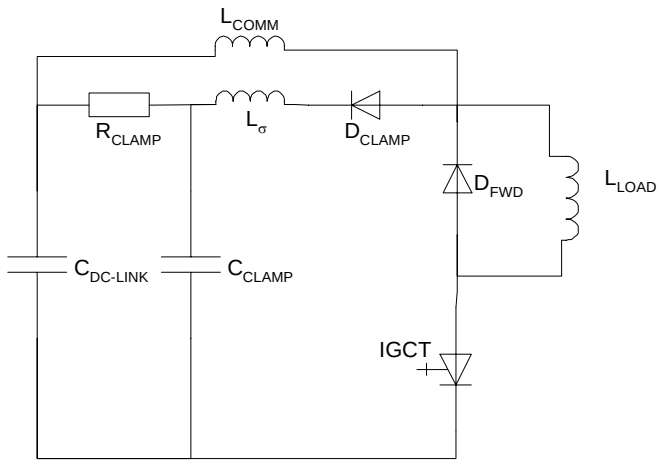

Fig. 5. The circuit used for turn-off measurements throughout this paper. L_{comm}= 3.2 µH
Configuration 1: C_{clamp} = 10 µF, R_{clamp} = 0.625 Ω, L_{σ} = 330 nH
Configuration 2: C_{clamp} = 20 µF, R_{clamp} = 0.37 Ω, L_{σ} = 325 nH

Turn-off SOA Capability

The turn-off capability of the new HPT+ IGCT is very high. For two subsequent turn-off events with a frequency of 10 kHz, it reaches around 6.0 kA against 2.8 kV DC-link voltage. A turn-off waveform at 140°C is shown in figure 6. A current of 6.1 kA is successfully turned off against a DC-link voltage of 2.8 kV.

The p-base profiles have been tailored for the highest snubberless turn-off capability at 140°C in a 10 kHz double pulse test. Under these conditions the optimised p-base corrugation leads to an SOA increase of around 800 A compared to the standard corrugation.

One part of the optimisation experiment is shown in figure 7. In this experiment the doping profile underneath the gate was kept constant while the corrugation amplitude was varied. Single turn-off SOA and double pulse SOA tests were carried out at 140°C. The investigation showed that there is an optimum corrugation amplitude where SOA is at its maximum. If the p-base profile is too flat (low amplitude), the desired shaping of the current distribution is lost. It has not yet been clarified, why the SOA goes down if the p-base underneath the cathode segment is weaker (high amplitude). One possible explanation is the disadvantageous localized heat generation.

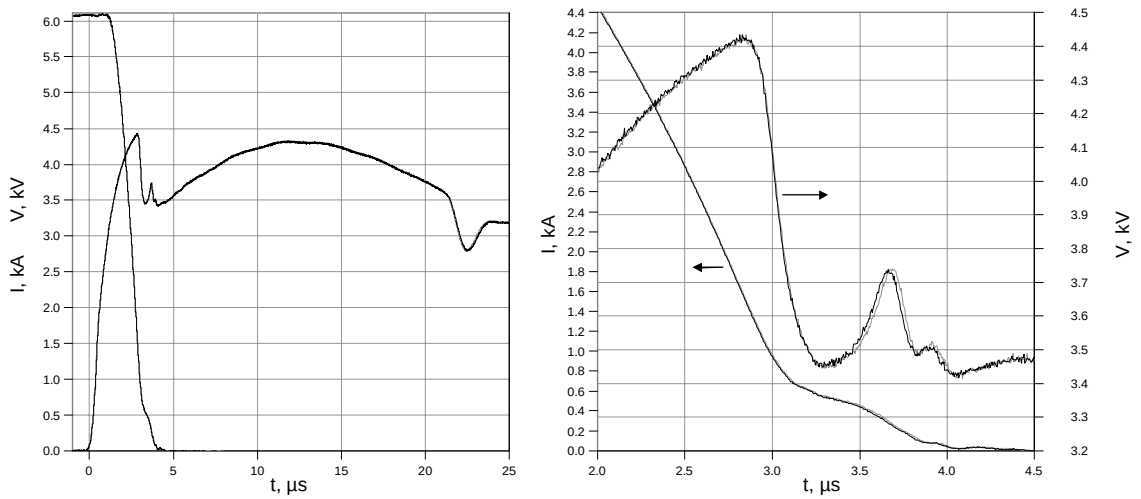

Fig. 6. Turn-off from 6.1 kA to 2.8 kV at 140°C. Anode current and anode-cathode voltage. Left: whole curve; right: zoom to 2 to 4.5 µs, when the current reaches 0. Circuit configuration 2.

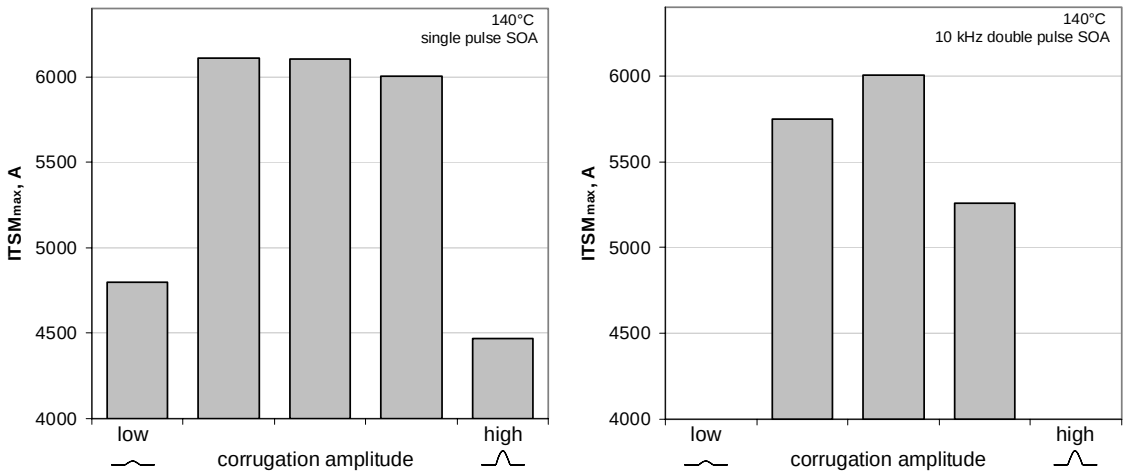

Fig. 7. Part of the optimization experiment. Testing the influence on SOA of the p-base corrugation amplitude at a constant profile underneath the gate.
Left: Influence on SOA at 140°C. Note that the test was stopped after passing 6.1 kA. Circuit 1
Right: Influence on 10 kHz double-pulse SOA at 140°C. Circuit 2.

2.3. Reliability

An increased maximum junction temperature of e.g. 140°C increases the reliability requirements, most importantly is the blocking stability and load cycling capabilities.

High Temperature Reverse Blocking

With an increased junction temperature, the leakage current increases. The 91 mm HPT+ IGCT under investigation have a leakage current below 10 mA at 3.2 kV at 140°C. Long term blocking stability (high temperature reverse blocking HTRB) is being qualified. Nevertheless, the used termination and passivation system with a negative bevel and diamond-like carbon passivation layer is qualified for temperatures up to 140°C for fast recovery snubber and freewheeling diodes.

IOL and Metallisation

Increasing the maximum junction temperature may lead to an aggravated power cycling stress in the application. This is due to the increased average temperature and by the larger temperature variation amplitude.

The main power cycling failure mechanisms for IGCTs are related to the thermo mechanical wear of the metallisation. We have improved the cathode metallisation and increased the contact area by up to 40%. This reduces the stress in the aluminium metallisation layer and therefore improves the thermo mechanical stability, as shown by 100 temperature cycles between -40°C and 140°C (see figure 8). Active load cycling is under investigation.

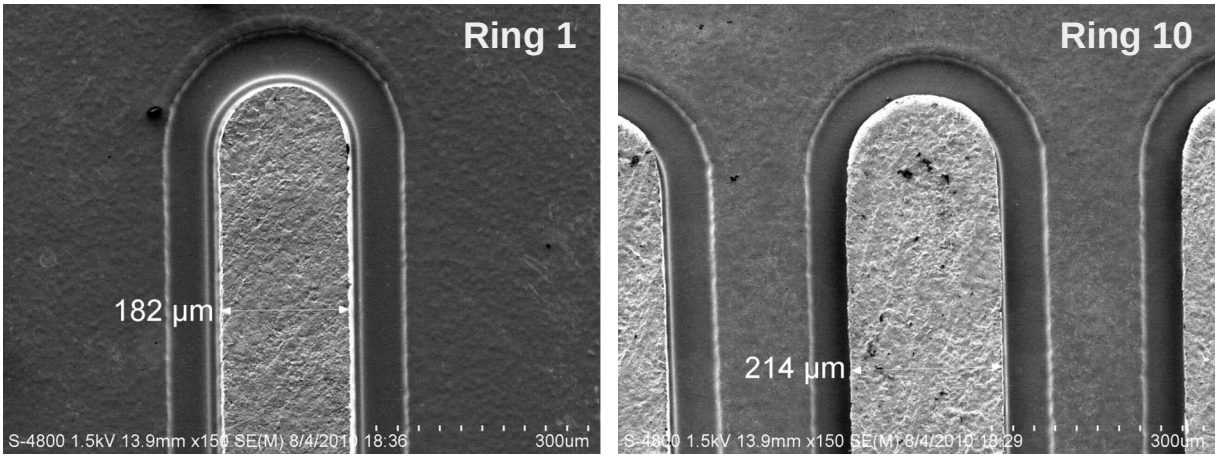

Fig. 8. IGCT cathode metallisation after temperature cycling (-40°C to 140°C, 103 cycles). The metallisation on the innermost ring 1 remains virtually unchanged. The one on the outermost ring 10 is widened by 32 µm. The former metallisation was widened by around 60 µm under the same conditions.

3. Summary

In order to increase the maximum output power of high power converters, IGCT are required with low losses, high turn-off capability at a high junction temperature. We have optimised the corrugated p-base doping profiles of the HPT IGCT to achieve these goals. For the resulting HPT+ IGCT design, the turn-off losses are reduced by 0.8 Ws without compromising the turn-off overvoltage. Furthermore, the turn-off capability in a 10 kHz double pulse test at 140°C has been improved by 800 A. Similar work has also been carried out for optimising the fast recovery diodes complementing the HPT+ IGCT range [5].

4. Literature

[1] S. Klaka, M. Frecker, H. Grüning, “The Integrated Gate-Commutated Thyristor: A New High-Efficiency, High-Power Switch for Series or Snubberless Operation”, PCIM, Nürnberg, Germany, 1997.

[2] T. Wikström, T. Stiasny, M. Rahimo, D. Cottet, and P. Streit, “The corrugated p-base – A new benchmark for large area SOA scaling”, Proc. ISPSD 2007, Jeju, Korea.

[3] US Patent 7,816,706 B2, October 19 2010

[4] Iulian Nistor, Maxi Scheinert, Tobias Wikström, Matthias Lüscher, “An IGCT chip set for 7.2 kV (RMS) VSI application“ ISPSD 2008, Orlando, USA.

[5] Jan Vobecky, R. Siegrist, M. Arnold, K. Tugan, “Large Area Fast Recovery Diode with Very High SOA Capability for IGCT Applications“, PCIM, Nürnberg, Germany, 2011.