Resolving Design Trade-offs with the BIGT Concept

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Abstract

The Bi-mode Insulated Gate Transistor BIGT is a single chip reverse conducting IGBT concept, which is foreseen to replace the standard IGBT / Diode two chip approach in many high power semiconductor applications. Therefore, it is necessary to understand in detail the design challenges and performance trade-offs faced when optimizing the BIGT for different application requirements. In this paper, we present the main conflicting design trade-offs for achieving the overall electrical and thermal performance targets. We will demonstrate experimentally how on one hand, the BIGT provides improved design features which overcome the restrictions of the current state of the art IGBT/diode concepts, while on the other hand, a new set of tailoring parameters arise for an optimum BIGT behavior.

1. Introduction

Modern IGBT structures based on the Soft Punch Through or Field Stop lowly doped buffer concepts combined with low injection efficiency p-type anodes have provided very low on-state and switching losses when compared to previous generations [1]. However, this design approach was hindered to deliver optimum overall performance due to the difficulty to control the bipolar gain of the IGBT. The bipolar gain has a critical dependency on the finely controlled design parameters of the buffer and anode especially when compared to typical Non-Punch-Through NPT devices. It was also clear that these design restrictions become even more challenging for IGBTs with higher voltage ratings [2]. The main requirements affected by the Soft Punch Through (SPT) IGBT structure are illustrated in Fig. 1 and listed below [3]:

1. Reverse blocking leakage current which is critical for device stability during high

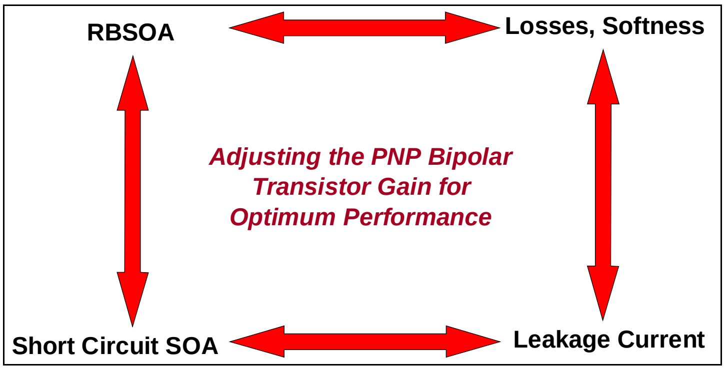

Fig. 1. The art of SPT-IGBT design

temperature operation
2. Short Circuit withstand capability at low temperatures and high gate emitter voltages
3. Turn-off softness under high inductance, low currents and temperatures
4. Safe operating area under dynamic avalanche and Switching-Self-Clamping-Mode SSCM
5. Static and dynamic losses trade-off point selection due to (1-4) restrictions

The recently introduced Bi-mode-Insulated-Gate-Transistor BIGT concept [4] shown in Fig. 2 is also based on the Soft Punch Through buffer design. Compared to the state of the art SPT IGBTs, the key BIGT feature has been the introduction of the anode shorts for the diode integration. The BIGT design in principle brings forth a new trade-off relationship in terms of IGBT mode versus diode mode losses optimization and also the requirements for providing good current uniformity and minimizing the IGBT mode on-state snap-back phenomenon. Nevertheless, on the other hand, the design approach has also a strong impact for the optimization of the buffer doping profile and anode injection efficiency which enable improved performance for points (1-4) above while allowing a wider range of options for the optimization of the losses on the device technology curve. It has been shown that the above performance and associated design trade-offs are strongly minimized by the introduction of the shorts. Thus, the anode shorts not only enable diode conduction but also are fundamental for the functionality of the whole device concept.

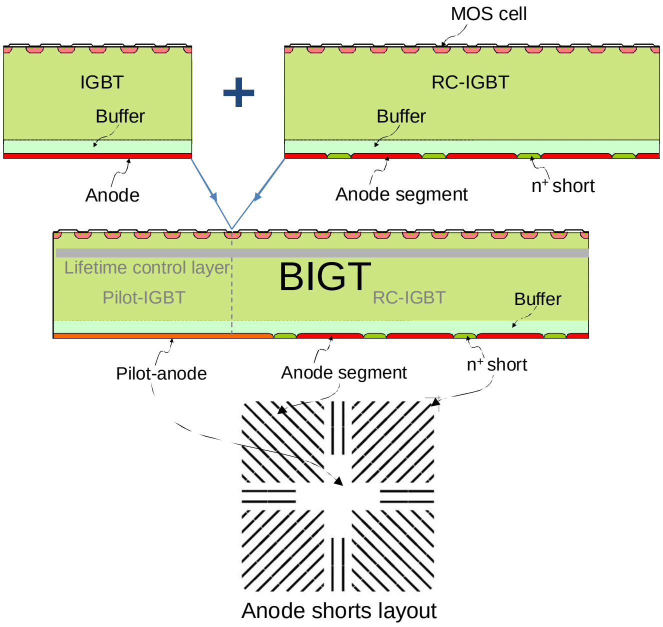

Fig. 2. Cross section of the BIGT

2. BIGT Trade-off Improvements over the IGBT / Diode

2.1. Leakage current and high temperature operation

The presence of the n-type shorts in the BIGT has a large impact on lowering the leakage current. The n-type areas provide a direct path for electrons during reverse blocking conditions, therefore no or very little hole injection occurs. Fig. 3 shows thermal stability comparisons at different temperatures for 6.5kV rated IGBTs and BIGT with two anode designs. The BIGT clearly demonstrate improved thermal stability at higher temperatures when compared to the IGBT even with very high anode injection efficiencies [5]. The anode shorts remove the influence of the bipolar gain on the leakage current to a large extent. As a result, the leakage current is suppressed and the increase with the temperature is reduced. In addition, the anode strength does not influence the leakage current in the BiGT in contrast to an IGBT structure. However, it can still occur that holes are injected due to the lateral voltage drop when a high leakage current is flowing over large/wide p-doped anode areas, but this was not observed in practical designs even with a pilot IGBT region occupying around 20% of the collector area.

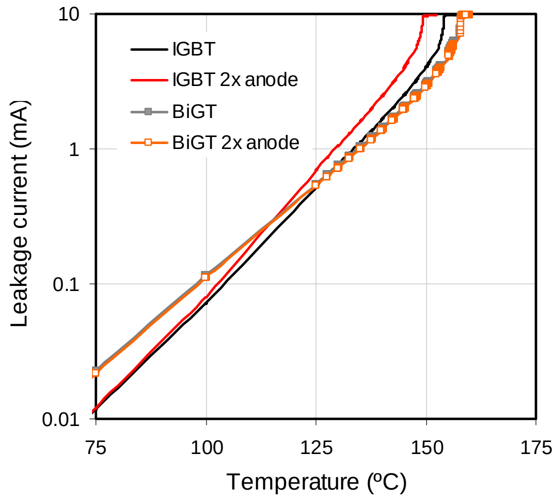

Fig. 3. 6.5kV BIGT and IGBT thermal stability curves.

2.2. IGBT mode and Diode mode Turn-off softness

With regard to the BIGT softness in both IGBT and diode modes, an inherent effect [6] in the BIGT similar to the Field Charge Extraction FCE diode has ensured soft performance under all operating conditions. Fig. 4 shows the IGBT mode turn-off for 6.5kV devices. The BIGT exhibits clearly a soft tail with no abrupt drop in the current during the later stages of the turn-off event as for the IGBT. As a typical example, this approach means that stronger anode injection is not anymore required to provide only for softer performance at the expense of higher losses, higher leakage currents and strong dynamic avalanche conditions as is the

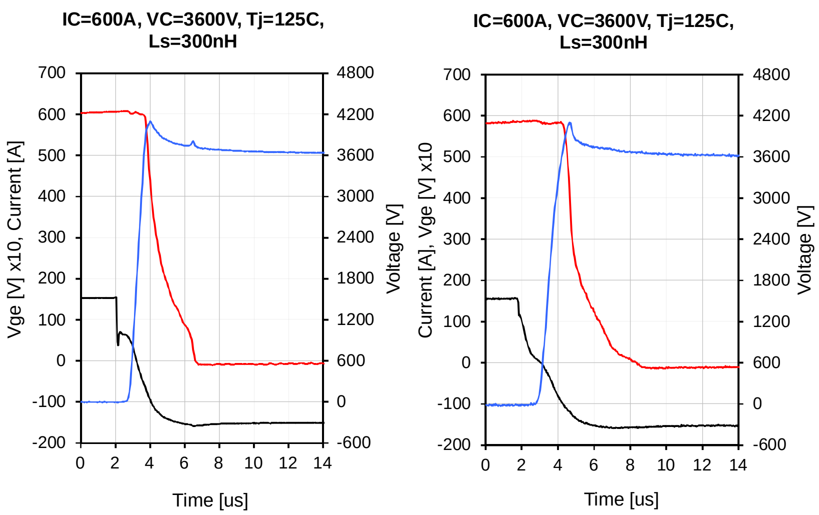

Fig. 4. 6.5kV/600A IGBT (left) and BIGT (right) turn-off waveforms under nominal conditions.

case with IGBTs.

The same effect brings a two-fold advantage for the Switching Self Clamping Mode SSCM robustness; first it reduces the possibility to enter into SSCM mode due to the continuous presence of holes during device turn-off; and second, SSCM capability is very similar to the short circuit dependency described later, and hence the BIGT also benefits for safe performance if it experiences this mode of operation. Therefore, the elimination of these aspects has brought about more freedom for losses trade-off selection to suit a given application and its frequency and circuit requirements.

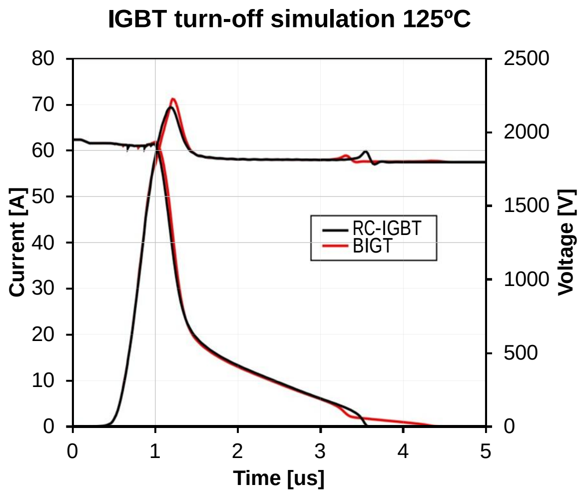

Fig. 5. Simulated turn-off waveforms of 3300V BIGT with and without pilot IGBT region.

Turn-off analysis using device simulation shows that the small current tail at the very end of the turn-off is caused by the injection from the pilot-IGBT region. Fig. 5 shows a comparison of the simulated turn-off waveforms of two reverse conducting devices with the same size of the anode shorts. The black curve corresponds to a RC IGBT without any pilot-IGBT region, which exhibits a better softness compared to an IGBT, but still experiences an abrupt current decay causing inductive voltage overshoot. The red curve is simulated on the same structure with a 640 um wide pilot-IGBT region added. The lateral current flowing above the large pilot-IGBT area forward biases the p-n junction and additional hole injection produces a small tail current providing the required softness and causing only minimal increase of the switching losses.

The same effect is also present in the diode mode. Here it is of more importance due to the fact that n-base region design of the BIGT is similar to IGBT and is not optimized for diode operation. A standard diode using IGBT n-base region design with low punch through voltage would be very susceptible to snappiness even under nominal conditions. Because of the FCE effect induced by the anode shorts, the diode is turning off softly and without any visible snap-off. Fig. 6 shows diode turn-off waveforms at the most critical conditions for softness at low current and low temperature (-40ºC).

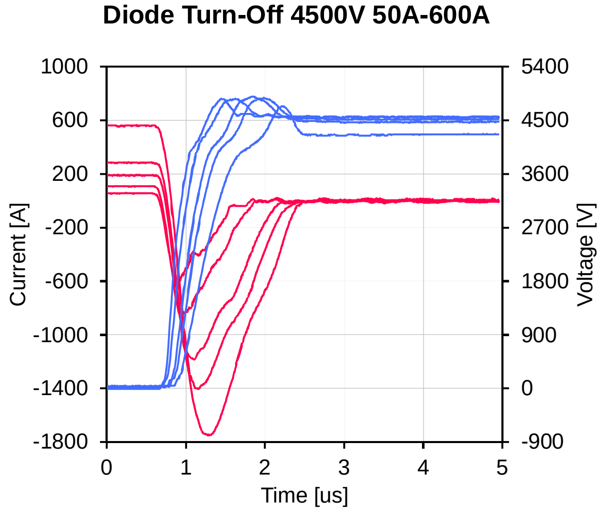

Fig. 6. 6.5kV/600A BIGT diode-mode turn-off waveforms at critical low current conditions at -40ºC.

2.3. Short circuit ruggedness

In addition, the BIGT shows that the high local anode injection levels needed with the presence of n-types shorts have brought about improvements on the short circuit SOA capability [4]. The BIGT will normally require higher anode p-region doping concentrations compared to an IGBT anode for obtaining the same over-all injection efficiency and hence on-state voltage drop and turn-off losses. During short circuit, an important current dependent failure mode occurs during the short circuit current pulse in SPT designs which is mainly dependent on the charge compensation effect near the buffer region of the IGBT which in turn is dependent on the anode and buffer design [7]. Under high gate-emitter voltage and/or lower operating temperatures, the resulting higher short circuit current will limit the short circuit SOA (SCSOA). In a BIGT, the higher anode p-region doping provide improved charge compensation and hence higher SCSOA. Fig. 7 shows the short circuit test of a 3300V/50A BIGT and reference IGBT chips at 25°C, and a gate voltage of 18V. Both devices are designed for the MOS cell, anode and buffer to have similar short circuit current

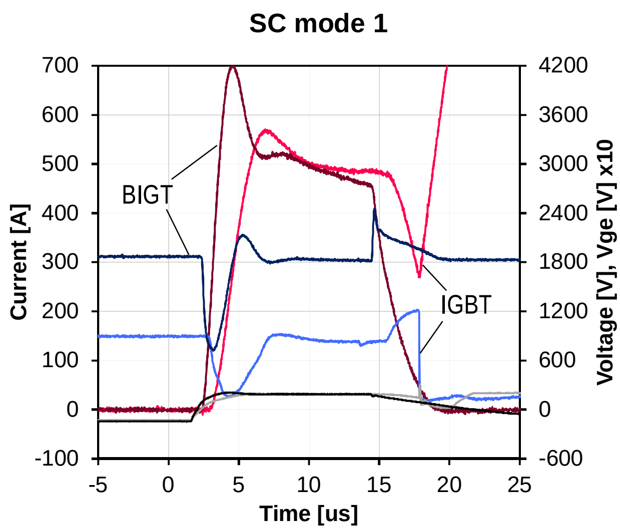

Fig. 7. 3.3kV IGBT and BIGT single chip Short Circuit type 1 waveforms at room temperature

and turn-off losses. While the BIGT has a faster turn-on behavior resulting in a higher overshoot current, it is still capable of withstanding this test at a DC-link voltage of 1800V compared to the IGBT which fails already at 900V. The BIGT chip is also capable of passing the test for higher gate voltages up to 19.5V. In addition to the advantages discussed previously, this feature in the BIGT design provides further flexibility for design trade-offs required to tailor the BIGT for improved overall performance.

3. BIGT Trade-off Challenges

Conventionally, the realization of the BIGT or RC-IGBT for high voltage and mainstream hard switching applications has always been hindered by design and process issues resulting in a number of performance drawbacks and trade-offs summarized below:

- Snap-back in the IGBT on-state I-V characteristics (the shorting effect)
- IGBT versus diode softness trade-off (the silicon design effect)
- IGBT on-state versus diode reverse recovery losses trade-off (the plasma shaping effect)
- Safe Operating Area SOA (the charge uniformity effect)

In the past few years, development efforts aimed at tackling the above issues.

3.1. Snap-back

Despite the fact that the n-type shorting regions have contributed to many advantages as explained earlier, its major drawback is related to the snap-back effect in the forward I-V characteristics. Nevertheless, this effect has been minimized strongly with the BIGT hybrid design and radial shorting layout [8] as shown in Fig. 8.

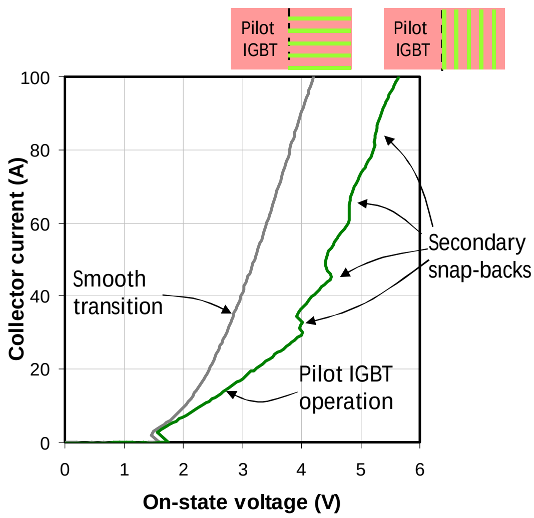

Fig. 8. Reducing the snap-back with the BIGT hybrid design and radial shorting layout

3.2. IGBT vs. Diode trade-off

The diode softness challenge due to the fact that generally the diode silicon does not match the IGBT silicon for obtaining soft recovery performance. Thus, such conflicting requirements could result in diode mode snappy behavior in an integrated structure. However, as discussed in the previous section, with the Charge Extraction technique, the diode softness issue is not only resolved, but snap-less behavior is granted under all operating conditions for both the transistor and diode.

For the BIGT loss optimization, the main challenge was to enable low diode mode recovery losses while not having a considerable effect on the transistor mode on-state losses. A three step approach is utilized to achieve this target. The first step is the fine control of the doping profiles of the emitter p-well cells and collector/short regions. As shown in Fig. 2, the enhanced planar cell technology exhibits low injection levels and a compensation effect due to the enhancement n-layer. These two features provide the BIGT with a fine pattern p-well profile for obtaining low injection efficiency for a better diode performance. The second optimization step employs a Local p-well Lifetime (LpL) control technique utilizing a self-aligned and well-defined particle implantation which further reduces the diode recovery without degrading the transistor losses trade-off curve and blocking characteristics. Final adjustment of the reverse recovery losses is achieved with a uniform local lifetime control employing proton irradiation. Further reductions in diode recovery losses can be obtained by applying a MOS Control during Diode-mode conduction and switching [9].

3.3. Charge uniformity

The structured collector of a BIGT with p+ and n+ areas introduces un-uniformities in lateral charge distribution which have been studied with the aid of device simulation. While the fine patterning of the RC-IGBT region (see Fig. 2) does not bring much changes to the overall charge distribution, the pilot-IGBT region significantly modifies the BIGT charge and current distribution compared to an IGBT. During the IGBT mode conduction, the pilot acts as a large non-shorted region of very strong anode injection, therefore the electron-hole plasma and the current density is the highest in the pilot region, see Fig. 9. The junction temperature distribution is also affected by this and is highest in the region of the pilot-IGBT, which is placed in the middle of the device for this reason. Conversely, the pilot region has the lowest carrier plasma density during diode conduction.

During the IGBT mode turn-off, the high plasma concentration in the pilot region triggers early dynamic avalanche at the MOS cells located above the same region, as shown in Fig. 9. The described charge inhomogeneity is mainly pronounced at lower temperature and low device currents [10]. At the critical SOA conditions, the difference between the RC-IGBT and Pilot-IGBT regions is reduced which results in a similar dynamic avalanche behavior as of the corresponding IGBT.

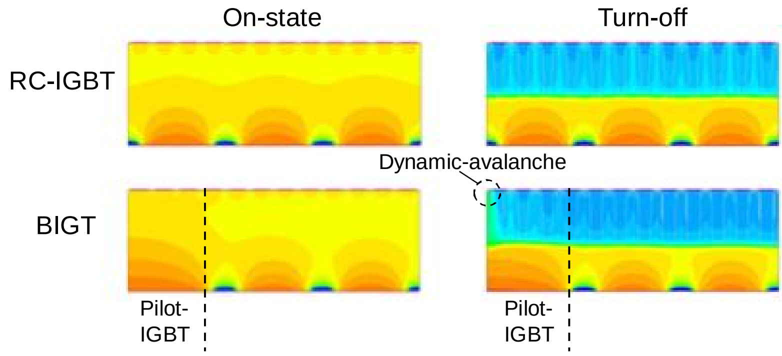

Fig. 9. Hole density during IGBT on-state conduction and turn-off of a Reverse-conducting IGBT compared to BIGT, showing the effect of carrier plasma un-uniformity and the occurrence of dynamic avalanche

4. Conclusions

The BIGT concept is foreseen to play an important role in many future power electronics applications. Hence, it is important to understand the design trade-off improvements and challenges presented by the new device concept when compared to state of the art IGBTs and diodes. This paper has presented a comprehensive review of these design aspects based on published and newly obtained results for a high voltage BIGT.

5. References

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