Bipolar Transistor Gain Influence on the High Temperature Thermal Stability of HV-BiGTs

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ISPSD, June 2012, Bruges, Belgium

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***Abstract*— In this paper we present the detailed investigation of the influence of the internal bipolar PNP transistor gain on the thermal stability of high voltage IGBTs and BiGTs. The bipolar gain is controlled by means of anode and buffer design and by the introduction of anode shorts. The influence of the different buffer and anode doping profiles and the different layouts in the case of anode-shorted designs are analyzed. Temperature dependent leakage current measurements confirm that the lowering of the leakage current and its subsequent weak temperature dependency can be achieved by buffer and anode engineering albeit with certain design trade-off restrictions. Nevertheless, another effective approach for suppressing the leakage current and its dependency on temperature is achieved by the introduction of anode shorts as demonstrated in reverse conducting IGBT or BiGT structures. Such designs eliminate to a large extent the internal bipolar transistor action in the BiGT anode shorted designs while allowing different anode and buffer doping profiles for the design trade-offs. Despite the fact that the lifetime control in the BiGT drift region causes the leakage current to increase, the temperature coefficient remains unchanged, hence, making the hard switched BiGT suitable for high temperature operation.**

Keywords-Reverse-conducting IGBT; Anode shorts, Thermal Stability; Leakage current

I. Introduction

Increasing the operating temperatures of power semiconductors represents an important trend for achieving higher power densities of future devices. Hence, recent development trends have shifted the focus on lowering the leakage current of power devices especially at higher temperatures. Operating junction temperatures of 175°C and 150°C are already commercially available for up to 1700V and 3300V IGBTs and diodes respectively.

In power devices, three separate design aspects contribute to the leakage current during reverse blocking as listed below:

1. The PN Junction and bulk design
2. Termination / Passivation design
3. Lifetime Control

In addition for bipolar structures with an internal bipolar transistor (Fig. 1) such as IGBTs and Thyristors, the inherent

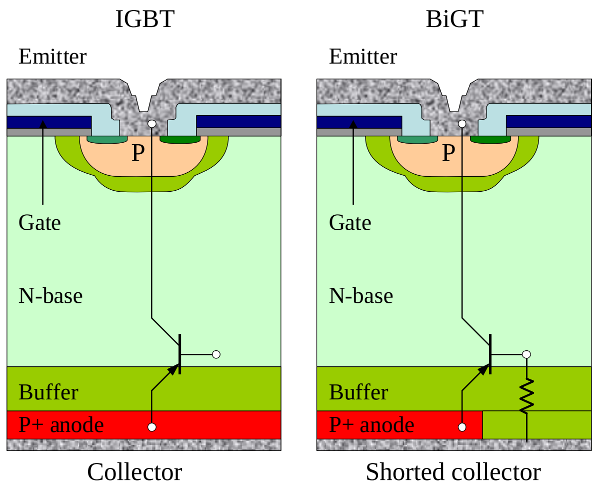

Figure 1. IGBT and BiGT structures showing the internal PNP transistor

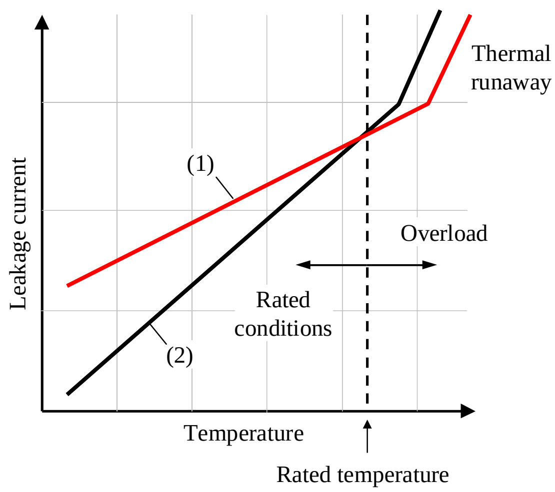

Figure 2. Characteristic temperature dependence of the leakage current for differently optimized devices

bipolar gain increases the leakage current due to amplification of the above three mechanisms [1]. It is important to point out that the transistor bipolar gain also plays an important role for determining the device losses and robustness in terms of turn-off and short circuit withstand capability [2].

It is clear that all these contributions can be minimized by advanced termination and carried lifetime control design [3,4]. However, we observed that high temperature reverse bias stability in IGBTs with "field-stop/soft punch through" buffer type structures is mainly dependent on the bipolar gain of the internal PNP transistor due to its critical temperature dependency behavior. Due to the positive temperature coefficient of the PNP transistor gain, the leakage current temperature dependent slope is increased and hence becoming the main factor for determining the thermal stability of the device, in particular under overload conditions (Fig. 2) [1]: devices with lower leakage currents and weak temperature dependency are therefore preferred for this purpose (see curve 1 in Fig. 2). The bipolar gain required to achieve a lower leakage current and reduced slope can be adjusted to a limited extent by choosing different combinations of the buffer layer design and anode strength. However, such adjustments might have a negative influence on other IGBT parameters such as the short circuit safe operating area (SCSOA) and the breakdown voltage of the buffer-anode junction.

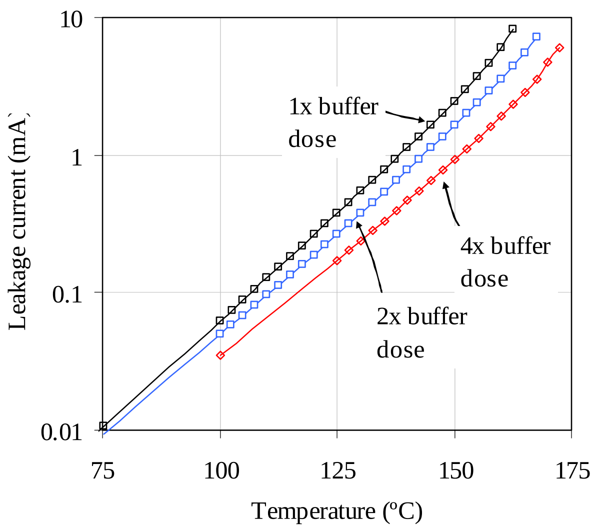

Figure 3. Temperature dependence of the leakage current in 3300V IGBTs with different buffer doses

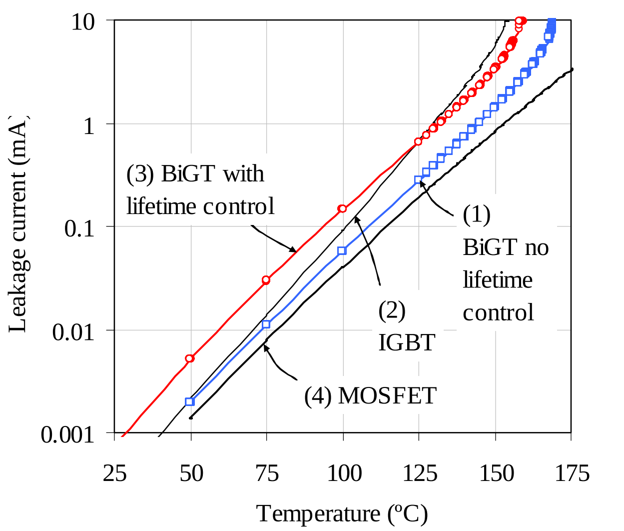

Figure 4. Comparison between temperature dependence of the leakage current in 4500V IGBT, BiGT and MOSFET

In reverse conducting IGBTs and BiGTs, the anode, which also acts as emitter of the internal PNP transistor, is shorted to the base (Fig. 1) [5]. The leakage current can therefore flow to the anode shorts without initiating hole injection (MOSFET mode). Accordingly, the leakage current is expected to be much lower than for a corresponding IGBT. In this paper we analyze in detail how in a BiGT structure, the influence of the bipolar PNP transistor gain can be eliminated with an optimum anode short design to enable stable thermal performance above 150°C for high voltage devices rated at 4500V and 6500V.

II. Experiment Setup

The temperature dependence of the leakage current was analyzed in 3.3kV, 4.5kV and 6.5kV IGBTs and BiGTs at nominal voltage. The MOS cell design and layout and the VLD termination design were identical for both the IGBTs and BIGTs, which allowed fair comparison of different collector design concepts. The devices were mounted on a large heater with controlled temperature, and the leakage current was measured at different temperatures under constant voltage stress. The thermal resistance between the device and the heat sink as well as the thermal capacity of the heater was kept the same for all tested devices. For each temperature, reverse bias was applied for 5 minutes, during which the leakage current was recorded. The test was stopped when the leakage current reached 10mA/cm^2.

III. Results and Discussion

A. *Bipolar gain adjustment in IGBT*

To obtain a comparison between IGBTs and BiGTs, we first analyzed the possibilities of bipolar gain optimization to obtain low leakage current in IGBTs. When the IGBT is in the blocking state, the electrons generated in the space charge region are leaving through the anode (collector contact), causing an injection of holes defined by the anode P layer injection efficiency. The p-body, n-base/field stop buffer and the anode of an IGBT form an internal PNP bipolar transistor, therefore the leakage current is amplified and has the temperature dependency determined by the temperature dependency of the bipolar gain of the internal PNP transistor.

The bipolar transistor gain β_{pnp} can be expressed by

$$\beta_{pnp} = \frac{D_{pB}}{D_{nC}} \frac{L_{nC}}{W_B} \frac{N_A}{N_D} \left(\frac{n_{ieB}^2}{n_{ieC}^2} \right) \tag{1}$$

which is dependent on the un-depleted base width in the buffer W_B at voltages above the punch-through value. The N_D and N_A

represent the background doping of the un-depleted buffer and the IGBT anode respectively. Also, D_{pB} and D_{nC} are the minority carrier diffusion coefficients in the un-depleted buffer and anode respectively. Finally, L_{nC} is the diffusion length of electrons in the anode. As a result, the bipolar gain can be adjusted by the anode doping concentration and field-stop layer width. Figure 3 shows the measured temperature dependency of the leakage current of 3.3kV IGBTs with different buffer doping profiles. The anode injection efficiency was maintained constant for all designs through the adjustment of the doping level of the anode, which resulted in all the analyzed IGBTs to have the same on-state and switching losses. The 4 times increased buffer doping effectively reduces the bipolar gain and a decrease of the leakage current by a factor of 2 can be reached. At the same time, the slope of the curves and thus the sensitivity to the thermal overload is slightly improved. However, following this approach further for the reduction of the IGBT leakage current would compromise the breakdown voltage of the anode-buffer junction. This junction prevents injection of holes into the IGBT base during the forward recovery phase of the antiparallel diode [6]. Failure to do so will result an increased turn-on losses. In addition, low bipolar gain designs suffer from low SCSOA and SSCM capability.

B. *Leakage current in BiGT: comparison to IGBT*

Figure 4 shows a comparison between temperature dependency of leakage currents in different device concepts. The BiGTs confirm inherently lower leakage currents and better temperature stability when compared to an IGBT. Curve (2) shows the leakage current temperature dependence of a standard 4500V IGBT. Compared to curve (1) showing the 4500V BiGT with the same on-state and turn-off losses, the leakage current is effectively reduced by a factor of 4 at 150ºC, and the leakage current increase with temperature is less steep due to the anode shorting. A comparison with a 4500V MOSFET (IGBT without anode) curve (4) reveals that the BiGT curve (1) has the same slope and similar leakage levels. This finding confirms that all the leakage current is flowing through the anode shorts (n regions), which completely eliminates the leakage current amplification up to 150ºC. Curve (3) shows the temperature dependence of the leakage current in an optimized hard switching BiGT with lifetime control in the n-base region for lowering the diode mode reverse recovery losses. In this case, the leakage current is increased by carrier generation in the space charge region, but the rate of the growth with temperature remains the same as for the un-irradiated BiGT. As a result, the irradiated BiGT leakage current coincides with the IGBT curve at 125ºC, but increases at a slower rate. Therefore, offering additional margin for the high temperature operation and for providing good tolerances for overload conditions despite the higher leakage current at room temperature.

C. *Leakage current in BiGT: Influence of Pilot-IGBT size*

The leakage current flowing to the anode shorts has to make a lateral path above the anode segments. The widest segment in the BiGT is the so called pilot-IGBT, designed to obtain smooth on-state characteristics. Lateral current induces a voltage drop across the p-region and, when sufficiently high, may forward bias the anode junction and start injecting the holes, as illustrated in Figure 5. The mechanism is similar to the one which allows avoiding snap-back in the on-state mode of the BiGT [7], but now it has a negative impact of introducing charge into the n-base during blocking. However, it is visible only for very large pilot-IGBT areas at relatively high currents. In Figure 6 the comparison of the temperature dependence curves for 4500V BiGTs with different pilot-IGBT area sizes is presented. At low temperature, where the leakage current is still below 0.1 mA/cm^2, the increase of the pilot-IGBT size from 20% to 60% does not affect the leakage current and the temperature dependence slope significantly. However, above 125ºC, the leakage current slope gets steeper rapidly for designs with large pilot-IGBTs, causing worse temperature stability. Therefore for optimum performance, the

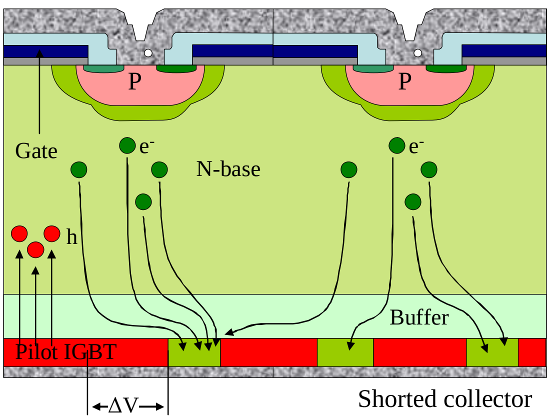

Figure 5. Leakage current flow in a BiGT with large pilot-IGBT area

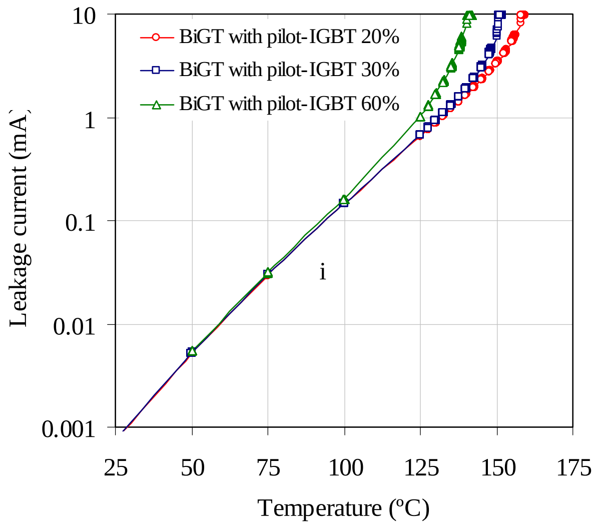

Figure 6. Comparison between temperature dependence of the leakage current in 4500V BiGTs with different pilot-IGBT areas

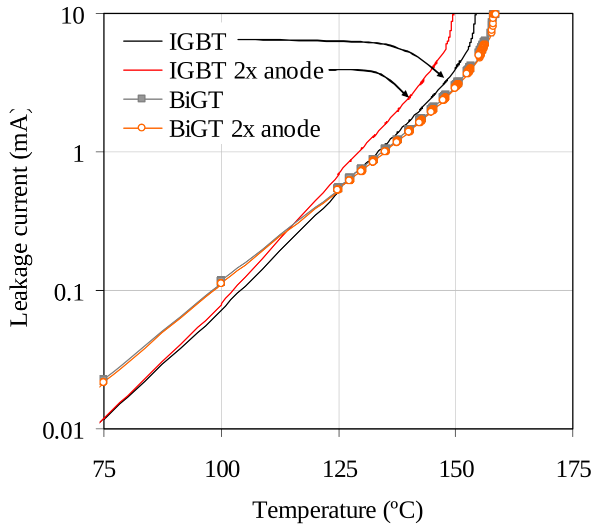

Figure 7. Comparison between temperature dependence of the leakage current in 6500V IGBTs and BiGTs with different anode implantations

pilot size has to be kept relatively small, which is also important for temperature distribution in the chip during on-state conduction.

D. Leakage current in BiGT: Influence of anode strength

From the argumentation and the results presented above it is clear that the leakage current in a BiGT structure is independent of the anode doping and the arrangement of anode shorts, as long as the anode segments are sufficiently narrow to prevent hole injection. This behavior is significantly different from the IGBT, where strong anodes lead to increased leakage currents and loss of thermal stability. Figure 7 shows a comparison between 6500V IGBT and BiGT chips with a factor of 2 difference in anode dose. The change of anode dose causes an increase of leakage current by 50% in the IGBT at 125ºC, whereas the BiGT chips prove to be insensitive to the anode dose and outperform the IGBT chips with weak anodes. Even at temperatures above 150ºC no difference between leakage current in BiGTs with different anodes can be detected, which confirms complete elimination of the bipolar transistor gain. This removes the important design trade-off of the IGBT and opens a lot of new possibilities for the BiGT design optimization in terms of static and dynamic losses, robustness and leakage current.

IV. Conclusions

We have presented the investigation of the influence of the internal bipolar PNP transistor gain to the thermal stability of high voltage IGBTs and BiGTs. The investigation shows that the leakage current and the temperature dependency of the leakage current can be controlled to a limited extent in IGBTs by the means of anode and buffer design, the parameters which also strongly affect device ruggedness. In the case of BiGT, the anode shorts introduced for reverse conduction 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 slowed down. In addition, the anode strength does not influence the leakage current in the BiGT in contrast to IGBT. On the other hand, it has been shown that the over-expansion of the non-shorted area (Pilot-IGBT) dimensions in the BiGT reduces the thermal stability at high temperatures. The carrier lifetime control in the BiGT drift region for the diode mode reverse recovery optimization causes higher leakage currents at room temperature, but the temperature coefficient remains low, making BiGT leakage levels still lower than for the IGBT at high temperatures above 125ºC. With an optimum design of anode shorts, stable thermal performance above 150°C for high voltage devices rated at 4500V can be achieved.

Acknowledgment

The authors wish to acknowledge the help of R. Jabrany and K. Ruef with device processing.

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