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TCAD Analysis of Short-Circuit Oscillations in IGBTs

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Abstract—Insulated-Gate Bipolar Transistors (IGBTs) exhibit a gate-voltage oscillation phenomenon during short-circuit, which can result in a gate-oxide breakdown. The oscillations have been investigated through device simulations and experimental investigations of a 3.3-kV IGBT. It has been found that the oscillations are more likely to occur at low DC-link voltages, high gate voltages and low temperatures due to a charge-storage effect at the surface of the IGBT. Based on this insight, the charge-storage effect can be explained with a reduction in carrier velocity due to the electric field shape rotation during short circuit.

I. INTRODUCTION

The Insulated-Gate Bipolar Transistor (IGBT) is clearly the dominating device in the range of a few kW to several MW in the power electronics industry [1]. However, it has also been said that it is the weakest component according to a survey based on field experiences from power electronics manufacturers [2]. One of the instabilities observed in IGBTs is due to gate-voltage oscillations taking place in short-circuit conditions [3], [4].

The oscillation mechanism has been studied over the years [5] showing that, under adverse combinations of large circuit stray inductance under certain operating conditions, it is likely that IGBTs exhibit high-frequency oscillations, whose excessive amplitude causes the gate-oxide breakdown. Several experimental evidence of such phenomenon can be found in [6]–[9] and, recently, also for trench-gate, field-stop IGBTs [4], [10]. The root cause of the oscillation mechanism has not been well understood, but what is even more important is that such oscillations still limit nowadays IGBT’s reliability.

The complex behaviour of the IGBT is better tackled with both circuit and device analysis, as presented in [11], e.g. for the diode snappy recovery. This approach is also adopted in this work to find the interaction between the capacitive behaviour of the IGBT and the main circuit parameters. A planar IGBT cell has been used for the simulations. As it is demonstrated in this paper, the investigated mechanism does not depend on the cell structure design (i.e., planar or trench), but on the IGBT inherent characteristics. IGBTs have pretty low n-base doping and high-level carrier injection features which favours Kirk effect’s occurrence.

In this paper, a sensitivity analysis on the oscillating behaviour’s dependence reveals which conditions are the key enabling factors. This result has been achieved by using a combination of finite-element device simulations and experimental investigations of 3.3-kV planar IGBTs. The main outcome of this work is the deep understanding of the physical mechanisms behind short circuit oscillations, enabling countermeasures at device design level.

Fig. 1. Short-circuit tests of a SPT (Soft-Punch Through) 3.3-kV planar IGBT: (a) at different DC-link voltages, (b) at different gate voltages, and (c) at different temperatures. (\(R_{g,on} = 2.2 \Omega\) and \(L_{\sigma} = 580 \text{nH}\).)
II. SHORT-CIRCUIT EXPERIMENTS ON A SINGLE CHIP IGBT

This section presents the experimental results on the short-circuit capability of a Soft Punch Through (SPT) 3.3-kV planar IGBT. The driving factors for the occurrence of the short-circuit oscillations are investigated through the variation of the operating conditions, such as, DC-link voltage, gate-emitter voltage and temperature. The outcome of these results is of particular importance to later justify through finite-element device simulations the root cause of such oscillations.

Fig. 1a shows the short-circuit performance of a 3.3-kV planar IGBT tested under two DC-link voltages of 1 kV and 1.9 kV. While the gate oscillations are observed at 1 kV DC-link voltage, the oscillations disappear at higher DC-link voltages of 1.9 kV. The amplitude of the oscillation rapidly increases in a few microseconds for both gate and collector voltage waveforms, however, the oscillation is not observed in the collector current waveform.

To investigate any correlation between the current density value and the onset of the oscillation phenomenon, the IGBT is also tested at different gate voltages. Fig. 1b shows that driving the IGBT with a lower gate voltage of 13 V seems to be beneficial to mitigate the instability. Although the results in Fig. 1 show no sign of collector current decrease during the short-circuit pulse length, in some other cases e.g. [4], the self-heating of the device is quite obvious and oscillations tend to converge with decreasing collector current.

The 3.3-kV IGBT chip has also been tested under two initial junction temperatures of 25 ºC and 100 ºC. Fig. 1c demonstrates that a higher amplification is observed at lower temperatures in contrast with the results at higher temperatures. It is worth to point out that the self-heating of a single IGBT under the short-circuit condition is not as strong as the one observed in multi-chip IGBT modules [4]. As a consequence, the amplification mechanism for a single IGBT chip is not attenuated with increasing short-circuit time, in contrast with the results for multi-chip modules in [4].

Fig. 2. (a) Circuit used for short-circuit finite-element simulations, and (b) the 3.3-kV planar IGBT half-cell. The vertical cut position used in the following figures is illustrated.

III. SENSITIVITY ANALYSIS OF SHORT-CIRCUIT GATE OSCILLATIONS

Finite-element simulations have been carried out, including the external circuit of Fig. 2a. Fig. 2b shows the SPT 3.3-kV IGBT half-cell, used for the short-circuit simulations. The model has been calibrated to fit the characteristics of the IGBT experimentally tested in the previous section. The vertical carrier profiles, which will be shown in the following, have been taken along the cut shown in Fig. 2b.

Fig. 3 shows the simulated voltage and current waveforms of the 3.3-kV IGBT, resulting from varying different operating
conditions such as DC-link voltage (Fig. 3a), gate voltage (Fig. 3b) and temperature (Fig. 3c). Through these simulations, the oscillation mechanism has been reproduced, demonstrating that the trends are similar as the ones observed by the experiments. From both experiment and simulation results, the collector current can be assumed to be constant, whereas the collector voltage and gate voltage oscillate. In order to understand the physical mechanisms, taking place inside the IGBT, the electric field and the carrier distribution will be evaluated for each testing condition. To do so, the parameters have been evaluated along a vertical cut as shown in Fig. 2. Figs. 4, 5 and 6 show the comparison between the electric field shape and carrier distribution in respect to DC-link voltage, gate voltage and temperature, respectively. It can be noted that the operating conditions strongly affect the amount and position of the electrons and holes in the n-base, and therefore, the shape of the electric field is remarkably affected. Several mechanisms can be observed, which are summarized here:

- The IGBT during short-circuit presents a rotated-field (Kirk Effect) because the effective charge $N_{eff}$ becomes negative ($N_{eff} = N_D + h - e$) (i.e., the amount of electrons prevail over the sum of holes and the background doping concentration).

- An electron storage-charge effect at the surface of the IGBT is observed for the operating conditions at which the IGBT oscillates. For instance, in Fig. 4, the amount of electrons reaching the surface of the IGBT (or emitter side) is larger at low DC-link voltages, where oscillations can be seen. This trend is also noted in Figs. 5 and 6. The larger the accumulation of electrons, the more chances to observe oscillations. The electron charge-store effect can be better compared in Figs. 7a and b for $1 \text{kV}$ and $2 \text{kV}$ DC-link voltages, respectively.

- The low electric field at the surface of the IGBT is associated with low electron velocities, as confirmed in Fig. 7, where the electron velocity is much lower at the surface of the IGBT for a collector voltage of $1 \text{kV}$. Since the collector current is assumed to be constant and the electron density is given as $J_n = qn \mu n$, the low electron velocity at the surface of the IGBT leads to a carrier concentration increase.

### IV. Capacitive Effects Under Short Circuit

In order to demonstrate the IGBT capacitive effects resulting from both charge and electric field distributions, the instantaneous input capacitance is calculated. From the experimental results shown in Fig. 3a at different DC-link voltages, Fig. 8 shows the time-zoom instantaneous capacitance during the short-circuit turn on.

The input capacitance has been calculated from $i_g$ and $V_{GE}$ waveforms through the formula, $C_i = i_g \times dt/dV_{GE}$. Fig. 8 compares the capacitance values for both DC-link voltages of $1 \text{kV}$ (oscillatory mode) and $2 \text{kV}$ (non-oscillatory mode). Here it is observed that the instantaneous capacitance value for both operating conditions is within the same range, however, one behaves as a time-varying capacitance while the other has a constant characteristic. This is in agreement with previous works about varying capacitances during oscillations [7]. Based on this observation, the circuit oscillates not because the IGBT cell is behaving as an amplifier but rather because there is a part of the system whose parameters are changing with time, in this case, the gate capacitance. This type of behaviour can be recognized as a parametric oscillation [12].

In order to prevent the short-circuit oscillations, one should avoid, as much as possible, the low electron velocity at the surface of the IGBT, which it is function of the electric field...
amplitude. The electric field shape during short circuit rotates due to the Kirk Effect, which in turn leads to weak fields at the emitter. Therefore one should guarantee that the electric field is strong enough at the emitter, in order to avoid the low electron velocities causing electron accumulation effects. This is further confirmed in in Figs. 4, 5, and 6, where higher electric fields at the surface are associated with a more robust short-circuit operation without oscillations.

V. CONCLUSIONS

The short-circuit oscillation mechanism in IGBTs has been investigated through a sensitivity analysis on different parameters, in order to observe the oscillation dependency behaviour. The factors which help to minimize the oscillations can be identified based on the results from experiments and device simulations: high collector-emitter voltage, low gate-emitter voltage and high temperature. In this work, it has been found that the oscillations can only occur when the electric field at the emitter of the IGBT becomes weak. The analysis presented here through both circuit and device simulations, confirms that the oscillations can be explained with focus on the device charge-storage effect resulting from both electric field and carrier velocity variations. It has been demonstrated that the proposed hypothesis is in agreement with the input capacitance variation formerly presented in the literature.

REFERENCES