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On the avalanche ruggedness of optimized termination structure for 600 V punch-through IGBTs

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ABSTRACT

In this paper, the current paths in avalanche conditions of a Floating Field Ring (FFR) termination for a Punch-Through (PT) Insulated Gate Bipolar Transistor (IGBT) are analyzed. The design of the termination region is achieved with two different optimization techniques, and both static and dynamic electrical behavior are analyzed by means of 2D TCAD simulations, up to high current density levels. A comprehensive analysis of the Unclamped Inductive Switching (UIS) operation of the proposed terminations is carried-out with electro-thermal simulations. Although the behavior of both structures at low current levels is different, results show the same current crowding effect at the main junction for high current levels, resulting in a reduced conduction area of the overall termination, hence, of the avalanche reliability. Finally, experimental confirmation of filamentary current conduction during UIS test are detected on 600 V commercial devices by means of transient infrared thermography.

1. Introduction

IGBTs are widely adopted in most of the power switching applications, where high current capability and low on-state voltage drop are required. Although the IGBTs are typically employed in application where freewheeling diode are present, in applications with inductive loads, such as automotive, avalanche robustness has become a harsh requirement to achieve high reliability. The UIS test is commonly used for the IGBT design validation in terms of avalanche robustness [1]. The standard UIS test is aimed to evaluate the maximum energy that a device can handle before its catastrophic failure during avalanche conduction, depending on the load value, the supply voltage and operative temperature. Several papers report uneven devices behavior during UIS transient with a reduced energy capability addressed to a not uniform current conduction [2,3]. The most critical scenario occurs when a filamentary current conduction takes place, whit a drastic energy capability reduction [4–6]. Furthermore, depending on the overall device design, at the breakdown voltage the current can flow either in the active region or in a portion of the termination area, exacerbating the avalanche energy capability decrease [7,8]. Since the actual trend for the design of power semiconductor devices is the demand of high current density to reduce the overall die area, a higher reliability of the termination area is also required. Usually, the Breakdown Voltage (BV) value at low current levels is the only main objective for the termination design and many techniques were proposed to improve the blocking capability such as Floating Field Ring (FFR).

In [9–12] analytical and numerical analysis of the FFR structure optimization techniques were carried out considering the termination behavior only at Low Current Levels (LCL); while the beneficial influence of buffer layer on the avalanche robustness of device with FFR termination was investigated in [13,14]. However, it has been proved in [15] that the analysis at High Current Level (HCL) is of a paramount importance to evaluate the Reverse Bias Safe Operation Area (RBSOA), where the correlation between Negative Differential Resistance (NDR) in the I-V curve and current filamentation problem was also highlighted. Electro-thermal analysis to study the current filamentation problem in the termination region of power diode was carried out in [16] for different termination typologies. Correlation between transient and static avalanche behavior was studied in [17], even if the study was performed on the Junction Termination Extension (JTE) and the Variation of Lateral Doping (VLD) structures.

In this work the avalanche capability of a FFR termination, designed for a 600 V PT-IGBT, is investigated focusing on both HDL dynamics, the local electric field – charge interactions, and the presence of a NDR region in the forward blocking I-V curve. Two FFR terminations were realized by means of two different techniques of optimization at LCL [9,10]. A comparative analysis aimed to highlight the differences between the two designs at LCL and HCL, in both static and dynamic conditions is performed and, for the first time, the current path at HCL is investigated. Starting from the optimized structures, a preliminary set of isothermal 2D TCAD simulations is carried out to trace the avalanche I-V curve of the structures, allowing the evaluation of the carrier paths distribution

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without thermal effects. Subsequently, the dynamic investigation is focused on the UIS test, where the static avalanche occurs.

In the second section, the self-heating effect on the termination region is evaluated by means of transient electro-thermal TCAD simulations by applying an idealized UIS test to the structures. Firstly, the influence of thermal effects on the current paths distribution is analyzed in Positive Differential Region (PDR) conditions. Finally, an analysis on the maximum sustainable energy in NDR condition are performed for different design solutions. Experimental proof of the theoretical results and current filamentation evidences are finally reported, by means of infrared thermal analysis.

2. Termination structures

The FFR technique allows to increase the blocking capability of the termination region. Several parameters can be managed in order to maximize the termination efficiency as the distance among the rings and their width, the ring doping concentration and junction depth. In this work, only the former two parameters have been considered to optimize the structures, adopting doping profiles typical of a PT-IGBT with a blocking voltage of 600 V (See Fig. 1).

In particular two methodologies [9,10], both aiming to maximize BV by appropriately spacing the distances among the rings (d1, d2 and d3), were analyzed. The structure whose design was achieved from [9] was named M1; while that achieved from [10] was named M2. The width of rings was fixed at 10 μm since it represents a good trade-off to minimize the overall dimensions. Three rings were used, since they allow to achieve a BV beyond the rated voltage of 600 V. In general, the hookup ring region is adopted as an interface between the active area and the edge termination [18], therefore, the main junction is here addressed as the hookup ring region, which is connected to the Emitter terminal. The Drift region has doping concentration of $1\text{x}10^{14}$ cm^{-3} and thickness of 56 μm. The Buffer region has doping concentration and thickness of $1\text{x}10^{17}$ cm^{-3} and 15 μm, respectively, while the collector concentration is $5\text{x}10^{18}$ cm^{-3}. Usually, lifetime killing techniques are adopted in the PT-IGBT technology and this was kept into account with a reduction of the lifetime in the structure with an electron lifetime and hole lifetime of 1 μs and 300 ns, respectively. Finally, the results refer to terminations designed for a square active device of 1 cm^2.

3. Static analysis

The two optimization procedures adopted have produced the two set of distances among the rings reported in Table 1.

The avalanche I-V curves of the two optimized terminations are reported in Fig. 2 for T = 300 K. It is visible that for a current level of 10 μA the M1 structure reaches a BV 15 V higher than M2 case; while for I > 10A they exhibit similar NDR branches with ΔV and ΔI of 180 V and 950A, respectively.

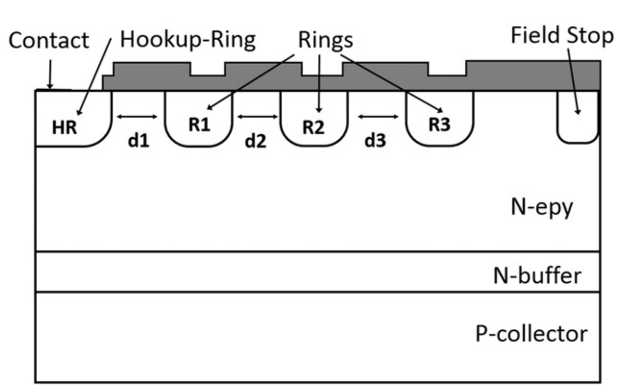

Fig. 1. FFR structure schematic.

Table 1
Rings spacing values for M1 and M2.

Technique	d1[μm]	d2[μm]	d3[μm]
M1	17	21	26
M2	18	21.7	27.5

The weak difference between the two sets of ring distances does not significantly influences the maximum BV achievement, however it affects the electric field distribution which generates different local impact ionization rates. Contrary to [9,10] where the optimization techniques leaded to a uniform electric field peaks on each ring junction and a consequent uniform distribution of current density at LCL, in this work, the electric field peaks are unevenly distributed. This is because in [9,10] a Diode structure was analyzed, while in the PT-IGBT structure the current gain of the vertical *pnp* regulates the carriers flows ratio together with the impact generation rate in a more complex distribution. Non uniformity of the generated carriers are reported at I = 10 μA in Fig. 3(a), (b).

This is highlighted in Fig. 4(a), (b), where the carrier density of the two structures is depicted in for a same current. The current density of M1 design has a peak placed at the edge of the first ring, while M2 presents a current peak located at the edge of the hookup ring.

The passage from LCL to HCL is defined in the following. The electric field can be redistributed according to Poisson law:

$$\frac{dE}{dx} = \frac{q(N_D + p - n)}{\varepsilon} \tag{1}$$

From (1) it is possible to define a threshold current density J_{Th}:

$$J_{Th} = qN_D v_{sat} \tag{2}$$

The doping concentration of the analyzed structure gives a $J_{Th} \approx 10^2$ A/cm^2 and the device operates in HCL when the local current density exceeds this value. Because of the complexity of the phenomena that regulate the termination behavior, it can happen that the condition is verified locally in a portion of the structure, even if the overall forced current density is lower than the J_{Th} current density level. In Fig. 3(c), (d) it is visible that at HCL (I = 500A) the high holes injection from the P-Collector into the depletion region warps the electric field distribution and an electric field peak $E_{peak} = 3.37\text{x}10^5[\text{V}\cdot\text{cm}^{-1}]$ is achieved at the edge of the hookup ring, where the impact ionization shows a peak. Indeed, in the investigated structures, the local HCL condition is

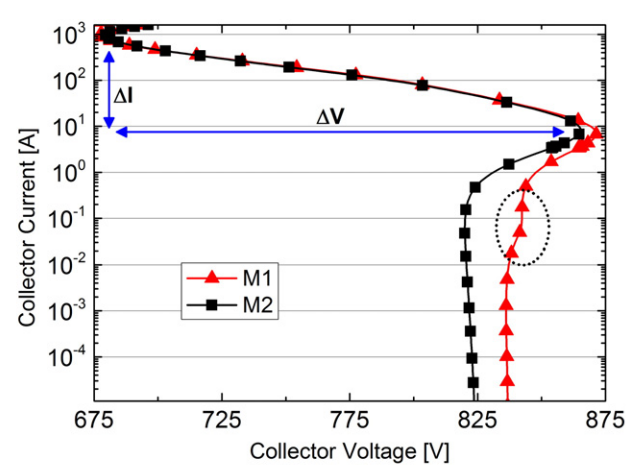

Fig. 2. Avalanche curves relative to the structures optimized by the techniques M1 and M2.