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NEW GENERATION OF 3.3 KV IGBTS WITH MONOLITICALLY INTEGRATED VOLTAGE AND CURRENT SENSORS

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Abstract. *Although IGBT modules are widely used as power semiconductor switch in many high power applications, there are still reliability problems related to the current unbalance between paralleled IGBTs that may destroy the whole module and, eventually, the power system. Indeed, short-circuit and overvoltage events can also destroy some of the IGBTs of the power module. In this sense, the instantaneous monitoring of the anode current and voltage values and the use of a more intelligent gate driver able to work with the signals of each particular IGBT of the module would enhance its operating lifetime. In this sense, the paper describes the design, optimization, fabrication and basic performances of 3.3 kV – 50 A punch-through IGBTs for traction and tap changer applications where anode current and voltage sensors are monolithically integrated within the IGBT core.*

Key words: *IGBT, voltage sensor, current sensor, overvoltage, overcurrent*

1. INTRODUCTION

IGBTs [1,2] are the most widely used power semiconductor device in low, medium and high voltage applications. IGBTs with voltage capability ranging from 600 to 6500 V delivering up to 2500 A are commercially available as discrete devices or as power modules. Low voltage discrete IGBTs are manly addressed to automotive applications, where low losses and high reliability are the most critical challenges [3], while medium voltage IGBT modules are basically designed for traction applications and wind generation with short-circuit capability [4]. Finally, high voltage IGBT modules for applications operating at an output power in excess of 100 KVA are addressed to high speed trains, high power industrial drives, VAR compensation and flexible AC transmission [5]. Although the IGBT technology

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is mature, the reliable operation of a module is still under optimization since the safe operation of the power module is one of the most critical issues of a power system.

Short-circuit events and overcurrent transient peaks inherent to inductive load switching may destroy one or several IGBT chips packaged into the power module with the eventual subsequent destruction of the whole power system due to explosion or overcurrent burn-out. Therefore, the direct measure of the instantaneous anode voltage and current levels during an undesired destructive event would improve the lifetime of each discrete power semiconductor device included into the power module. In this sense, the current distribution between the different IGBTs may become unbalanced as a consequence of non-uniform thermal distribution or a local thermal resistance increase derived from delamination problems [6-8]. Hence, the current increase in one of the IGBTs may drive it out of its safe operating area [9]. The Implementation of integrated current sensors in the IGBT core, which is not commonly done in the IGBTs of commercial power modules for traction applications, would significantly increase their safe operation. Average current sensing is the most common technique using current mirrors with shunt resistors and a reference voltage [10]. Current sensors are usually implemented in large area discrete IGBTs, where a certain number of cathode cells are connected to an auxiliary cathode electrode, leading to a low current value proportional to the cathode current value.

Overvoltage or short-circuit events can also be destructive since the IGBT may be driven to avalanche or to high power dissipation, with local temperature increase and thermal destruction. If an anode voltage sensor is implemented, the undesired anode voltage increase can be quickly detected and the gate drive can safely turn-off the entire IGBT before destruction. However, the anode electrode is placed at the backside of the die and the anode voltage value is too high to be used in a logic circuit. Therefore, the anode voltage sensor has to be placed on top of the die with a voltage level compatible with the gate drive electronics. The first anode voltage sensors were successfully developed for 600 V applications based on the voltage mirror concept [11].

This paper describes the design and fabrication of smart IGBTs for 3.3 kV applications where current and anode voltage sensors are monolithically integrated within the core region. Two target applications are envisaged: traction modules with a large number of paralleled IGBTs delivering high anode currents and on-load tap changers for smart grid distribution transformers, where the transformer ratio has to be changed as a function of the active and passive connected loads if a stable and safe AC voltage waveform has to be delivered to end users. Commercial tap changers are based on the mechanical adding or subtraction of small inductances connected in series with the primary inductor [12]. However, the increasing demand of electrical energy with large fluctuations of the connected loads requires remote operation of tap changers and this can only be achieved by substituting the mechanical switches by the solid-state counterparts. The implementation of anode voltage sensors is crucial to avoid the destruction of the solid-state switch due to the eventual short circuits both at the high and low sides of the transformer.

2. ANODE VOLTAGE SENSOR

The design and optimization of the anode sensor structure is based on a 3.3 kV IGBT punch-through technology with terraced gate design [13] to prevent a premature breakdown between adjacent core cells at the curvature of the P-body diffusion. A cross-section of the last IGBT core cell and the sensor structure is plotted in Fig. 1, where the main design parameter; distance between adjacent deep P^+ sinkers (L), is highlighted. The layout of the core region cells is striped and the corresponding metal gate runners are also included to minimize the gate resistance and prevent possible delays in the turn-on process of the farthest cells with the subsequent current focalization. The process technology is based on the standard 8 mask IGBT technology available at the IMB-CNM clean room, including a back-side deep N-type diffusion to create the N-buffer layer inherent to the punch-through structures. An optimized multiple floating guard ring edge termination with 22 rings has been used to provide the required voltage capability for 3.3 kV applications, using the same deep P^+ sinker diffusion of the core cells. Each ring is covered by a metal line to ensure a uniform bias distribution along the ring, once it becomes biased due to the depletion region extension. Rings have to be wide enough to avoid a metal overlay that would lead to a field plate effect, degrading the effectiveness of the edge termination.

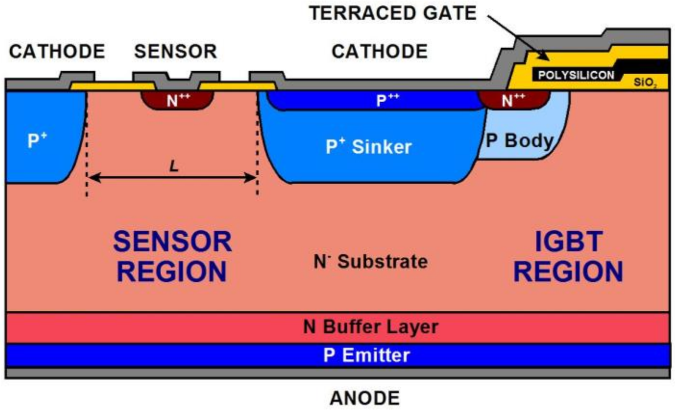

Fig. 1 Cross-section of the last IGBT core cell and the sensor region

The concept and the operation mode of the anode voltage sensor structure was initially demonstrated on a 600 V IGBT technology by integrating stripped and cellular sensor structures with the suitable edge termination selected IGBT structure [11]. The sensor consists of two deep P^+ diffusions connected to the grounded cathode electrode separated a certain distance with an additional shallow N^+ diffusion in between to provide an ohmic contact to the N^- substrate for the additional sensor electrode. When a positive bias is applied to the anode electrode, the two P^+N^- junctions of the sensor become reverse biased, leading to a self-shielding effect. Hence, the bias at the sensor electrode (V_{sense}) proportionally increases with the applied anode voltage in a range compatible with the gate driver electronics. In case of short-circuit or overvoltage, the V_{sense} value will exceed a pre-defined threshold value and the gate driver will directly turn-off the entire IGBT or reduce the anode current to a safe value. The V_{sense} value obtained in stripped sensor design is higher than that of the cellular counterpart but the most critical parameter is the resistive load connected to the sensor electrode.

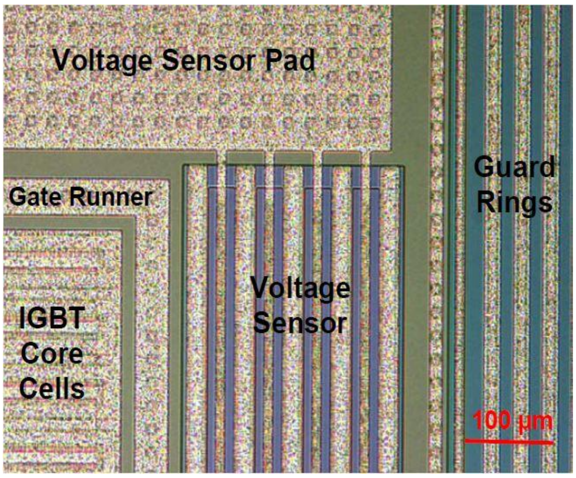

Fig. 2 Detailed view of the stripped anode voltage sensor and its monolithic integration within the core IGBT

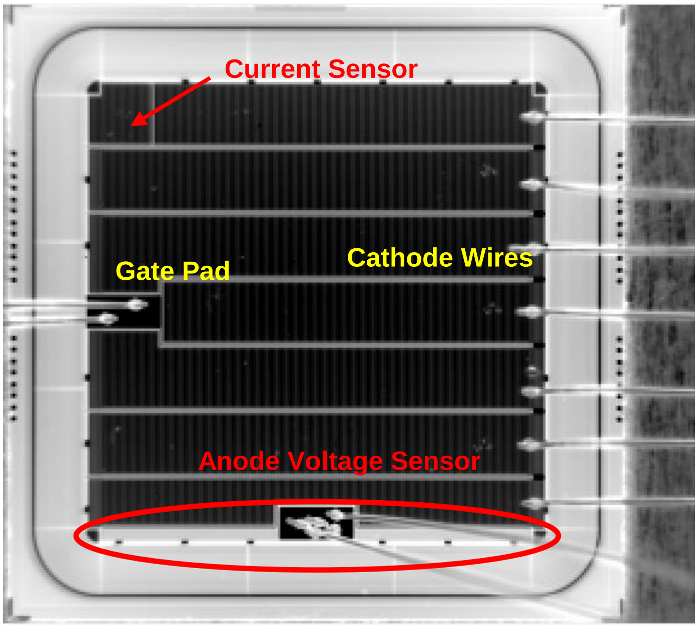

Fig. 3 Top view of a fabricated 3.3 kV – 50 A IGBT packaged for anode voltage sensor test

The final goal is to get 10 V at the sensor electrode at an anode voltage of 50 V for a 3.3 kV punch-through IGBT technology. In this sense, a stripped anode voltage sensor structure (see Fig. 2) has been placed within the core of the IGBT (see Fig. 3), consuming a 3% of the total active area. The anode voltage sensor electrode is placed at the edge of the IGBT core cells, being the stripes of the sensor orthogonal to those of the IGBT. The current sensor is placed at the opposite side of the chip. A gate runner is placed between the IGBT cells and the anode voltage sensor to minimize their mutual interaction. In this sense, the current flowlines simulated with Sentaurus [14] TCAD of the last IGBT core cell together with the first anode voltage sensor stripe are plotted in Fig. 4. A small fraction of the current is collected through the sensor P^+ diffusions with the inherent slight on-state resistance increase. Moreover, these P^+ diffusions helps in collecting holes during the IGBT turn-off process in a similar way than the peripheral P^+ diffusion connected to the cathode potential.

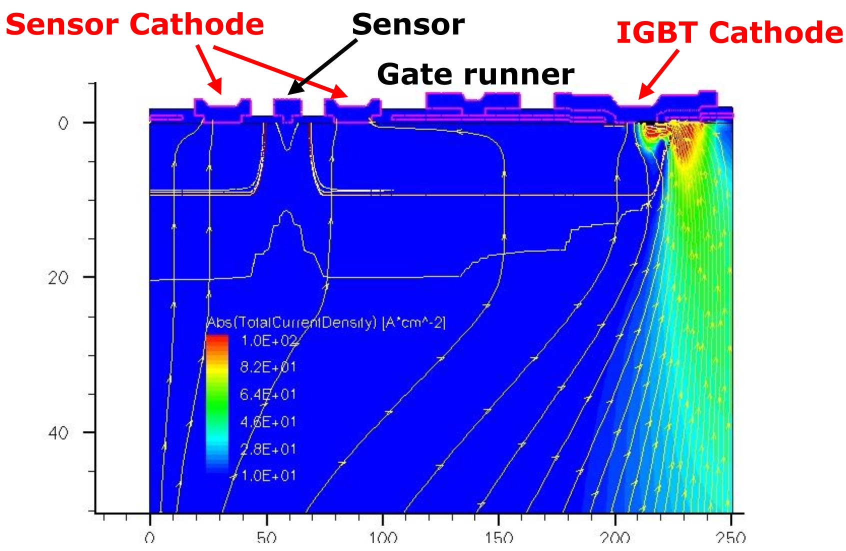

Fig. 4 Current flowlines at a gate bias of 15 V in the last IGBT core cell and the first anode voltage sensor strip

3. Fabrication of Intelligent 3.3 kV IGBTs

3.3 kV IGBTs have been fabricated with a total chip area of 1.3×1.3 cm² for a nominal current of 50 A. The real current capability is shown in Fig. 5 where more than 100 A are reached at a gate voltage of 15 V, being the gate threshold voltage in the range of 5 V. The feasibility anode voltage sensor has been experimentally measured with a V_{sene} = 8 V at an anode voltage of 50 V, as inferred from Fig. 6. In order to check the compatibility of the designed anode voltage sensor structure with a wide range of gate driver architectures, simulations of the V_{sense} evolution when different resistive loads (100, 200, 500 and 1000 Ω) are connected to the sensor electrode is also included in Fig. 6. Although the V_{sense} value at an anode voltage of 50 V slightly decreases when the load resistance increases, it can also be used as an input signal for the gate control driver.

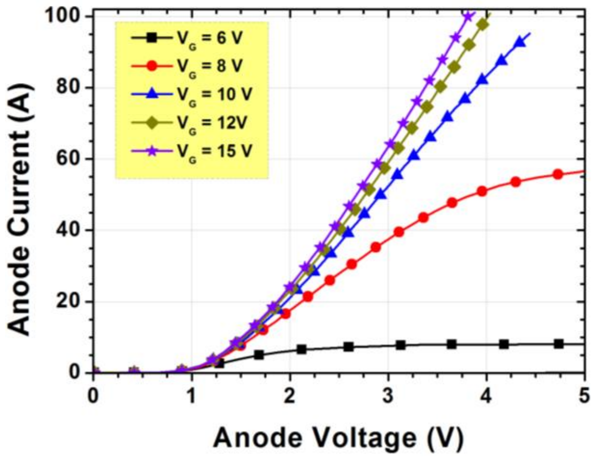

Fig. 5 Experimental I(V) curves of the 3.3 kV IGBT

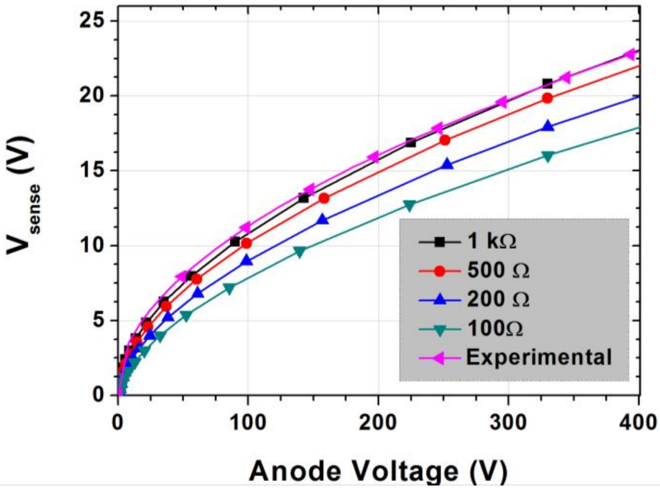

Fig. 6 Simulated and experimental evolution of the voltage sensor value as a function of the resistive load of the control electronics

4. Transient Analysis of the Anode Voltage Sensor

Up to now, the V_{sense} evolution has been simulated or measured by increasing the anode voltage from 0 to the desired value with the gate electrode grounded. Hence, the current flowing through the entire IGBT is the leakage range with no heating effects. In contrast, IGBT modules operating in traction or on-load tap changers applications are far from the described ideal conditions [15]. Pulse-width-modulation schemes are typical in traction applications to supply the sinusoidal current for the train speed control. Therefore, 2D

TCAD simulations have been carried out to determine the turn-off performance of the IGBT with an anode voltage sensor based on the typical turn-off test circuit plotted in Fig. 7 (left). $IGBT_1$ accounts for the designed 3.3 kV IGBT with anode voltage sensor while $IGBT_2$ is a conventional 3.3 kV IGBT with the corresponding area factor to deliver a nominal current of 50 A. $IGBT_1$ is dimensioned to take into account that the total anode voltage sensor length corresponds to one of the laterals of the active IGBT area and has also to deliver a nominal current of 50 A.

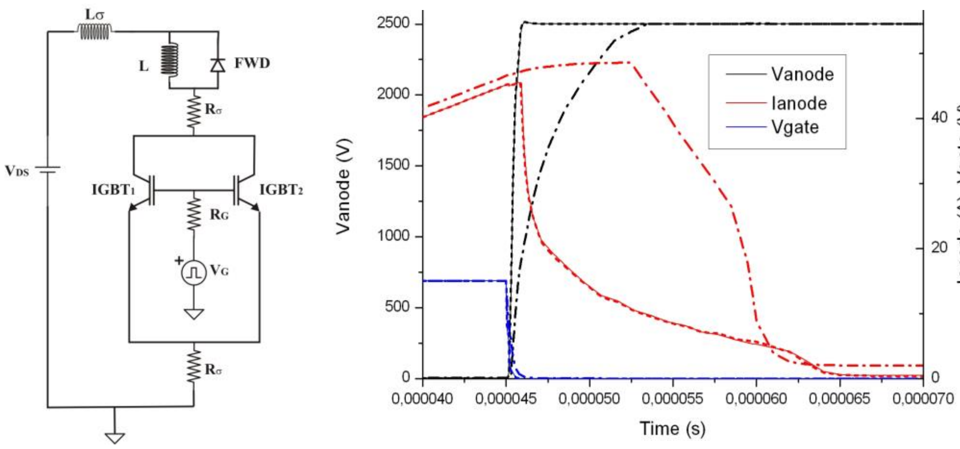

Fig. 7 Test circuit for the inverter switching simulation (left) and simulated turn-off waveforms of the different considered structures

Three different cases have been considered by properly selecting the way the two IGBTs are connected, assuming that they share the anode electrode. The first case is $IGBT_1$ connected and $IGBT_2$ not connected. Hence, information about the interaction between sensor and core cells can be directly derived. The second case is $IGBT_1$ not connected and $IGBT_2$ connected, leading to the transient simulation of a real 3.3 kV – 50 A PT-IGBT without anode voltage sensor. Finally, the third case corresponds to both devices connected in a mixed-mode way, accounting for the fabricated IGBT with anode voltage sensor.

The current at the inductor increases with a certain di/dt when a constant V_{DS} voltage is applied to the circuit up to the desired level. When the gate voltage is ramped to 0V, the IGBTs are turned-off and the inductor current is forced to flow through the freewheeling diode (FWD). The inverter test circuit has been designed in accordance to the standard 2.5 kV DC line, where 3.3 kV IGBTs are used. In this sense, V_{DS}, L, L_o and R_G are set at 2500 V, 2.5 mH, 285 nH and 3.7 Ω, respectively. As a consequence, the maximum achievable current is in the 50 A range, which corresponds to the limit of the Reverse Blocking Safe Operating Area (RBSOA).

The turn-off waveforms plotted in Fig. 7 reveals that a significant interaction between the sensor and the core cells can be expected (dash-dot line) with the subsequent turn-off delay and enhanced heat generation in the vicinity of the anode voltage sensor cells due to the increase of the parasitic capacitances. Nevertheless, when realistic area factors are used (solid line) to emulate the fabricated IGBT with anode voltage sensor, the turn-off performance approaches the one corresponding to the conventional PT-IGBT counterpart (dashed line). In conclusion, the monolithic integration of the anode voltage sensor within the core area of the 3.3 kV IGBT is feasible since the interaction between the sensor and the adjacent core cells has not a deep impact on the transient performance.

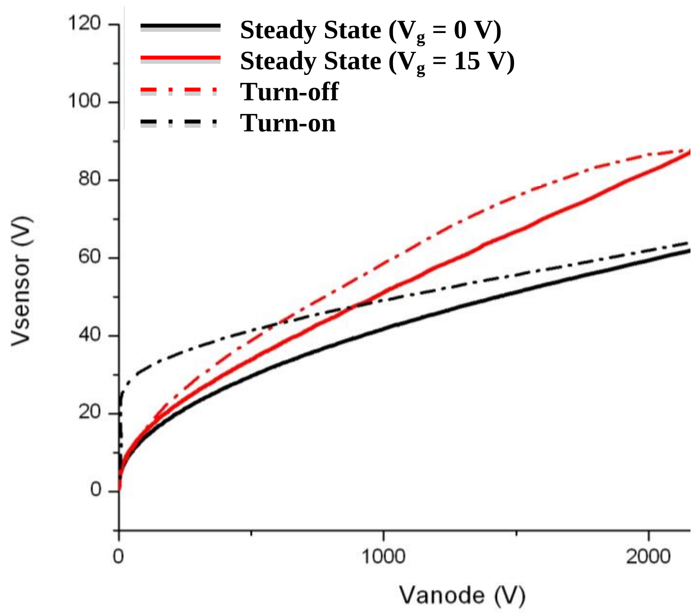

Fig. 8 Steady and transient simulation of the anode voltage sensor level as a function of the applied anode voltage

The last step in demonstrating the suitable operation of the fabricated intelligent IGBT with integrated sensors ($IGBT_1$ + $IGBT_2$) is the transient simulation of the anode voltage sensor at turn-on and turn-of processes and its comparison with the steady-state case. The turn-on and turn-off curves are extracted form transient simulations where the anode voltage is ramped down from 2500 V to 0 V (turn-on) and vice-versa (turn-off). The steady state simulations with the gate biased at 0 and 15 V exhibit a mismatch at high anode voltage values, far from real operation. Nevertheless, the simulation at high anode voltage with the gate at 15 V is included since these conditions will happen at the beginning of the turn-off process with a high current density flowing through the IGBT core cells. As a consequence, the carrier concentrations and the electric field distribution will be modified in the anode voltage sensor structure.

Assuming that the anode voltage sensor structure is included in the active IGBT area to mainly protect it from an unexpected fast increase of the anode voltage as a consequence of short-circuit event or when the energy of an inductor is dumped to the semiconductor, the fast increase of the anode voltage sensor value at turn-on ensures the protection capability since the threshold voltage level at which the gate driver will turn-off the intelligent IGBT will be reached even earlier than in the ideal steady state case.

5. CONCLUSIONS

The basic design aspects and the expected evolution of an intelligent 3.3 kV – 50 A IGBT with integrated anode voltage and current sensors is reported in this paper. The operation of the new anode voltage sensor structure is analyzed with the aid of TCAD simulations, including its interaction with the adjacent IGBT core cells. The experimental evolution of the anode voltage sensor level as a function of the applied anode voltage has corroborated the feasibility of the fabricated devices. Finally, transient simulations have been carried out to demonstrate the protection capability of the anode voltage sensor.

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