

Avalanche Breakdown in IGBT Corners with VLD Termination: Quantitative 3D TCAD Investigation

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Abstract—This work presents a quantitative and comprehensive three-dimensional (3D) Technology Computer-Aided Design (TCAD) investigation of avalanche breakdown in Insulated Gate Bipolar Transistor (IGBT) featuring a Variation of Lateral Doping (VLD) corner. First of all, by correctly capturing corner-induced electric field crowding in the presence of VLD termination, the 3D simulation results are shown to carefully reproduce the measured trend of the Breakdown Voltage (BV) vs. implant dose of the device. Then, the benefits of the VLD against the Junction Termination Extension (JTE) corner design are clearly quantified in terms of higher optimal BV and stronger process robustness. Finally, a Front-End-Of-Line (FEOL) – Back-End-Of-Line (BEOL) interaction limiting the device BV is pointed out and an architectural solution to mitigate it is proposed. These results provide a strong guidance for the development of next-generation IGBT technologies.

Index Terms—IGBT, VLD Edge Termination, 3D TCAD, Avalanche Breakdown

I. INTRODUCTION

The Insulated Gate Bipolar Transistor (IGBT) remains the backbone device for multi kV power conversion [1]. With application driven device scaling pushing both blocking capability and ruggedness requirements, accurate prediction and optimization of edge termination breakdown — often the weakest point of industry-level dice — critically depend on the choice and design of device periphery and on correct electrostatic modeling of three-dimensional (3D) corners [2]. Several termination options such as floating rings (FRs), Junction Termination Extension (JTE), and field plates (FPs) are currently adopted by semiconductor manufacturers [3], but the Variation of Lateral Doping (VLD) termination [4] has been demonstrated superior in terms of breakdown performance. In particular, VLD termination has a reduced implant dose sensitivity and improved dynamic ruggedness in the case of Si power devices, enabling high termination efficiency [3], [5], [6]. Reported VLD implementations in IGBTs and diodes show extremely high Breakdown Voltage (BV), provided the lateral dose profile is well controlled [7]. However, 3D and geometry-driven effects play a significant role in this context: sharp or low radius corners locally amplify the electric field and can dominate avalanche onset if not properly mitigated. Although 3D Technology Computer-Aided Design (TCAD) is fundamentally required to resolve the inherently 3D nature of

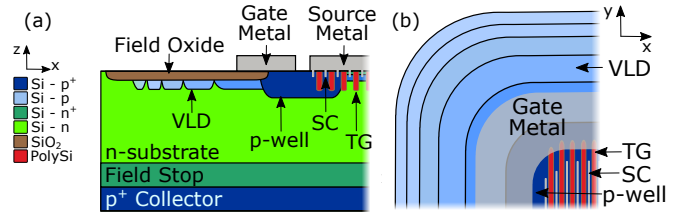


Fig. 1. Device schematics: (a) Cross-section of the edge termination of a trench-gate, field-stop IGBT with VLD, deep p-well, and Field Oxide; (b) plan view of the device corner showing VLD rings and gate-metal ring placement.

peripheral breakdown in power devices, its use in industrial design flows remains limited, due to the significant computational burden and meshing complexity associated with full corner simulations [7], [8].

In this work, by exploiting our previously introduced large domain 3D TCAD methodology for device corners [9], we carry out a quantitative and systematic investigation of the breakdown physics of VLD terminations across all relevant implantation dose regimes — namely the low dose, optimal dose, and high dose conditions. In particular we: (i) conduct a quantitative analysis of the BV as a function of the VLD ring dose, establishing that accurate agreement with experimental data is attainable exclusively through 3D simulation; (ii) compare VLD and JTE terminations, within a full 3D corner resolved framework, explaining the physical origin of the superior robustness of VLD termination to process-induced dose variations in the high dose regime; and (iii) uncover the FEOL–BEOL coupling mechanism responsible for the BV degradation at low VLD dose, and propose a layout-level correction that fully mitigates this limitation while keeping unchanged the fabrication process flow.

II. SIMULATED DEVICE CORNER

Fig. 1 schematically shows the reference simulated device structure, which is the corner of a commercially available trench-gate, field-stop IGBT. The edge termination of the device consists of multiple *p*-type laterally graded rings that implement the VLD approach. These rings start at the outer edge of a deep and heavily doped *p*-well wrapping the outermost source contacts (SCs) and polysilicon trench-gates (TGs).

A thick Field Oxide overlies the VLD region. Above it sits a gate-metal ring whose inner edge is vertically overlapped with the p -well and whose outer edge lies above the first VLD ring.

To compare the BV performance of the VLD-terminated device with that of a JTE-terminated device, the p -type graded rings in the structure of Fig. 1 were replaced with a continuous p -type region running over the same lateral distance. Both the implantation dose of this region and that of the graded rings were arbitrarily varied over a wide interval of values to explore the sensitivity of the BV of the two terminations to process tolerances.

III. 3D TCAD FRAMEWORK

To accurately address avalanche breakdown with affordable computational burdens, we adopted the 3D TCAD simulation approach introduced in our previous work [9] and recalled in Fig. 2(a)-(b). The 3D simulated device is built by combining the vertical structure obtained from 2D process simulations with the planar morphology from the process masks, while merging the central TGs into a single polysilicon plate and trimming the active-region boundary to minimize the simulation domain. This strategy avoids the need for computationally expensive full 3D process simulations while preserving the key geometrical features governing the breakdown behavior. The adopted approximations and domain shaping enable an accurate yet computationally affordable description of the breakdown voltage and of the avalanche current distribution. This approach is here applied to both VLD and JTE edge terminations, as shown in Fig. 2(c). In the analysis, the same 3D modeling framework was adopted for the two structures, comparing simulation results with the experimental findings.

IV. SIMULATION RESULTS AND DISCUSSION

A. VLD Dose Investigation

Figure 3 shows the trend of the BV of the VLD-terminated device with the implantation dose of the VLD rings, as resulting from 2D and 3D TCAD simulations and experimental data. Across the entire dose sweep, the 2D TCAD curve (purple) is systematically higher than the 3D TCAD curve (orange), because 2D simulations cannot correctly reproduce the 3D field crowding that develops at device corners. In this regard, the 3D TCAD results closely track the experimental data (orange box-plots). This validates our 3D TCAD approach and confirms the breakdown-limiting hot spots reside at the device corners and are intrinsically three-dimensional. This quantitative agreement underscores that determining practical termination dose windows at device corners requires a full 3D treatment, whereas 2D planar slices provide, at best, qualitative guidance.

By combining planar and vertical cross-sections, Fig. 4 highlights the 3D electric-field maps at breakdown for three representative VLD termination doses. These doses are labeled as low, high and optimal and correspond, respectively, to the minimum and maximum explored dose and to the dose resulting in the highest BV (see the vertical dashed lines in Fig. 3). At low dose, the termination charge is

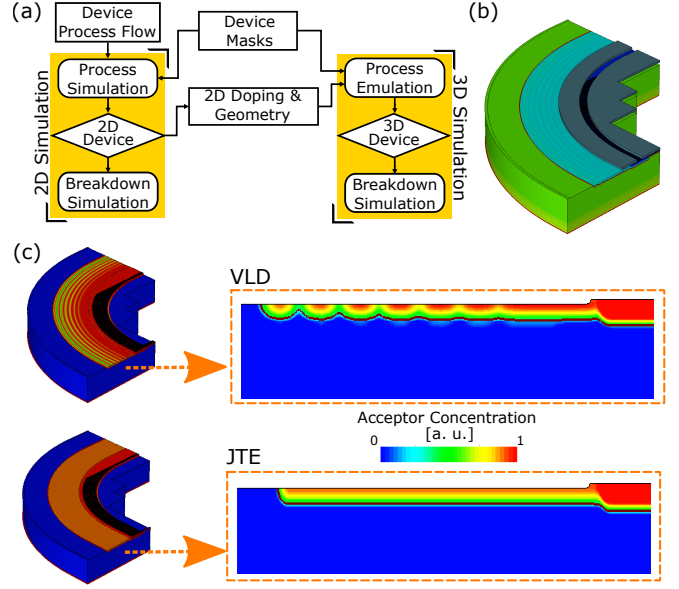


Fig. 2. (a) Simulation flow [9]; (b) 3D simulation domain; (c) p -type doping concentration in a representative example of VLD-terminated device and JTE-terminated device (a bird's eye view and a cross-sections of the two devices are provided).

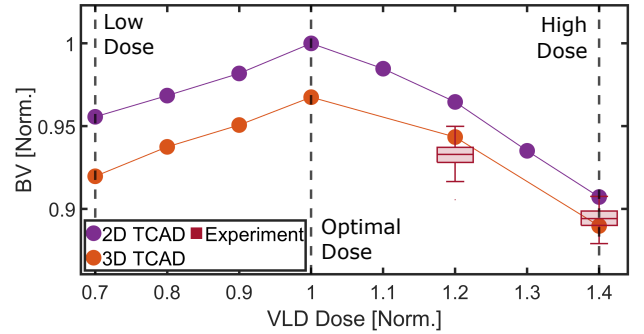


Fig. 3. BV vs. dose curves resulting from 2D and 3D TCAD simulations of IGBT with VLD edge termination. Experimental results are also shown for comparison.

insufficient to effectively spread the electric field away from the p -well corner, resulting in field crowding and premature breakdown. At the optimal dose, the termination charge most effectively redistributes the electric field across the VLD rings. This results in an electric field profile that is more gradual than with the low implant dose, with moderate peaks appearing at the positions corresponding to the VLD rings. At high dose, the termination charge drives the electric-field distribution excessively toward the outer rings; in this case the peak field remains divided among more than one ring, leading to a modest degradation of BV. In summary, Fig. 4 demonstrates that the optimal value for the VLD dose from the BV standpoint corresponds to an electrostatic condition where the field intensification is shared across the largest number of

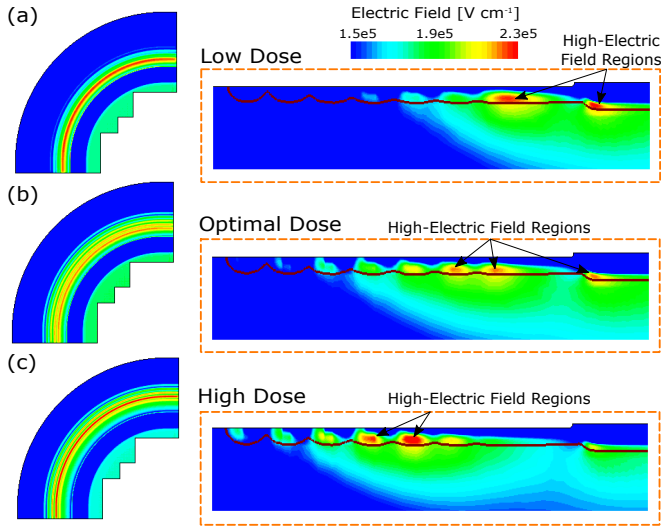


Fig. 4. Planar and vertical cross-sections showing electric-field maps at the BV for (a) low, (b) optimal, and (c) high VLD implantation dose.

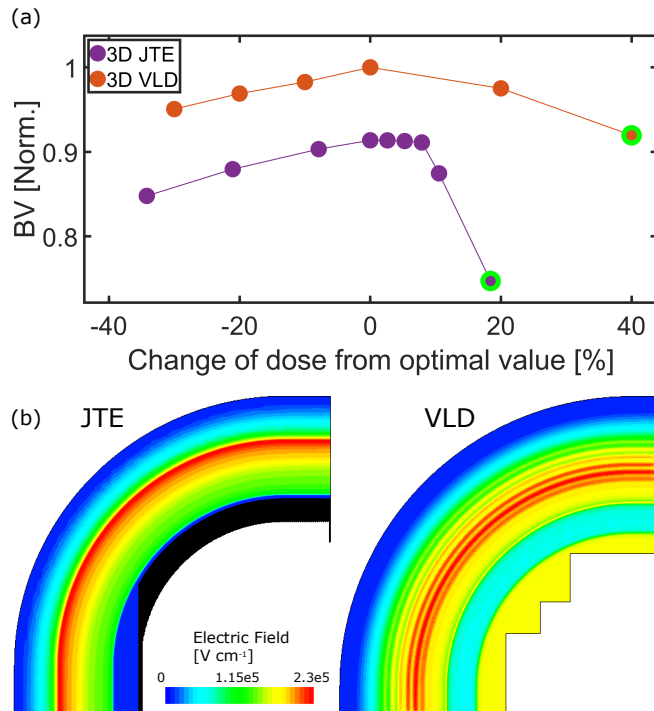


Fig. 5. (a) BV vs. dose curves of VLD and JTE terminations; (b) high dose field maps at BV (green circles in (a)), showing VLD multi-ring sharing.

VLD rings.

Figure 5(a) reports the BV as a function of the implant dose of the VLD and JTE terminations. The comparison reveals, first of all, that VLD termination achieves a higher maximum BV than JTE termination at their respective optima. This is the result of the more gradual electric field profile achievable with the VLD region than with the JTE region. In addition to that,

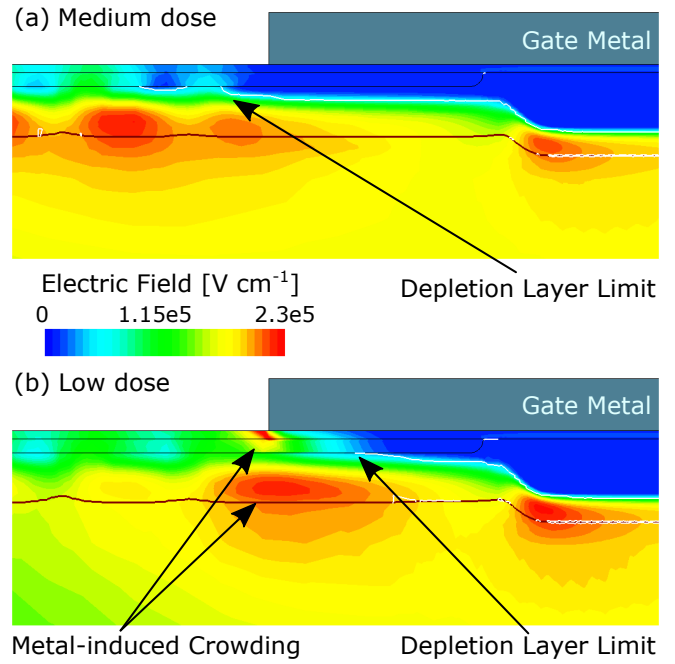


Fig. 6. Electric field maps at BV for (a) medium and (b) low VLD doping dose, highlighting electric field crowding near the gate-metal edge in the latter case.

the drop of the BV from its maximum value is more gradual with the VLD termination than with the JTE termination, especially at high implant doses. When increasing the implant dose above the optimal value, in fact, the JTE termination introduces an excess termination charge that shifts the electric-field distribution up to the outer edge of the termination. Due to the high acceptor concentration in this region and the small curvature radius of the termination outer edge, the electric field rapidly intensifies at that position when the implant dose is increased, as clearly visible in Fig. 5(b). This compromises the BV. By contrast, Fig. 5(b) reveals that in the case of the VLD termination the multi-ring sharing preserves field partitioning over a broader dose range; the peak field remains distributed among several rings rather than collapsing into a single hot spot, so BV degrades only modestly. To conclude, the simulations highlight that VLD inherently broadens the acceptable dose window, making it markedly less sensitive to dosing errors and, consequently, substantially more robust to process variability than JTE.

B. Metal Gate Induced Electric Field Crowding

Figure 6 highlights a critical phenomenon appearing for low VLD implant doses and remained unnoticed so far in the analysis of device breakdown: in this regime, the depletion layer at the edge of the p-region reaches the silicon surface under the Field Oxide and intersects the outer edge of the gate-metal ring above the VLD. The sharp metal corner, then, gives rise to relevant electric field intensification close to it, creating an additional breakdown path. This behavior

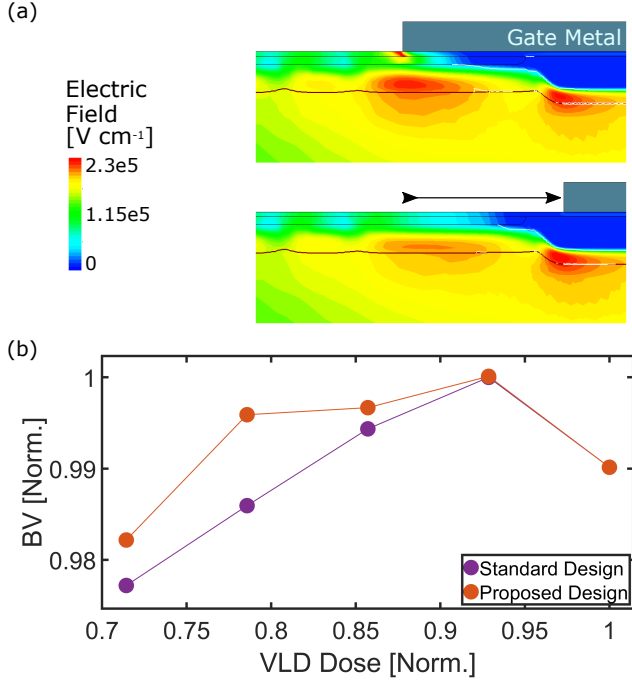


Fig. 7. (a) Original device design (upper figure) vs. proposed design solution (lower figure) to mitigate electric field crowding near the outer metal-gate edge; (b) BV-versus-dose curves comparing the two designs showing low-dose BV recovery, flatter low-dose dependence, and overall upward shift.

represents a reliability issue arising from the coupling of the FEOL-BEOL design of the device. In this dose window, the local electrostatic is no longer determined solely by VLD dose balancing; instead, it is driven by additional design choices—notably Field Oxide thickness and gate-metal placement/alignment—so that a sharp metal corner above the electric field oxide crowds the field and depresses BV.

Starting from the insight provided by our 3D simulations, we propose a design modification that aims to mitigate the low-dose BV loss. The outer corner of the gate-metal ring is rerouted towards more central regions of the device so that it lies above the deep, heavily doped internal p-well rather than above the VLD/Field Oxide stack (Fig. 7(a)). Because this p-well is not depleted under blocking conditions, the metal corner cannot contribute to electric field intensification. As a result, Fig. 7(b) demonstrates that a relevant improvement in the BV at low implant doses can be achieved. Along with the increase in magnitude, the curve becomes distinctly flatter on the low-dose side, indicating reduced sensitivity to dose variations and therefore a broader process window. The upward shift of the BV trend further confirms that the limiting factor in this regime was not the intrinsic VLD dose balancing but the FEOL-BEOL coupling created by the gate-metal corner and that removing that surface hot spot restores the underlying termination performance. To conclude, all these substantial improvements are obtained through a layout-only modification without any change in the fabrication process flow or additional process steps.

V. CONCLUSIONS

We presented a comprehensive analysis of avalanche breakdown in VLD terminated IGBTs. Results revealed that a 3D TCAD simulation is indispensable to capture the breakdown physics of VLD terminations across the complete implantation-dose space. Using our wide-area methodology, we quantitatively reproduced the measured BV vs. dose dependence, proving that 2D analyses systematically overestimate blocking capability when corner crowding dominates. Within the same 3D framework, we confirmed the physical origin of the superior robustness of VLD to process variability over JTE in the high dose regime. Besides, we identified a previously unnoticed reliability issue coming from a FEOL-BEOL design interaction in the low-dose regime. Finally, we proposed a layout-level correction that relocates that metal corner above the internal deep p-well, thus removing the surface hot spot and flattening the BV-dose curve, while fully maintaining the existing fabrication process flow. These findings provide actionable guidance for termination design and a practical path to improved blocking capability and broader process windows for the next generation power devices.

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