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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

Luigi Balestra, S.R. (2020). TCAD Study of VLD Termination in Large-Area Power Devices Featuring a DLC Passivation. IEEE TRANSACTIONS ON ELECTRON DEVICES, 67(11), 4645-4648 [10.1109/TED.2020.3013238].

*Availability:*

This version is available at: <https://hdl.handle.net/11585/793619> since: 2021-02-01

*Published:*

DOI: <http://doi.org/10.1109/TED.2020.3013238>

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# TCAD study of VLD termination in large-area power devices featuring a DLC passivation

L. Balestra, S. Reggiani, A. Gnudi, E. Gnani, J. Dobrzynska, J. Vobecký

**Abstract**—The sensitivity of discrete large-area power devices to the design aspects of the termination region and to the charging effects of the electroactive passivation layer on top is presented in this work. The junction termination featuring the variation of lateral doping (VLD) is revisited for such devices by focusing on the interaction with the passivation material on top. To this purpose, an ideal dielectric ( $\text{SiO}_2$ ) is compared with differently-doped diamond-like carbon (DLC) by incorporating the passivation layer in the TCAD setup. The simulation analysis rigorously explains the impact of the DLC material on the layout re-optimization of a specific reference diode.

**Index Terms**—Power Semiconductor Devices, Junction Termination (JT), Variation of Lateral Doping (VLD), Diamond-Like Carbon (DLC), TCAD modeling

## I. INTRODUCTION

Silicon-based discrete high-power devices continue to play an enabling role in modern high-power systems [1]. The majority of state-of-the-art converters reach power ratings ranging from few kW to beyond the 1 GW mark and devices need to be designed with optimal performance up to several thousand volts and amperes as single wafer components. To this purpose, a key element is the improvement of the junction termination (JT), which is usually realized with traditional positive and negative bevels invented well before their planar counterparts and which for several ten years constitute standard processing step in bipolar production lines. Recently, the design focused towards improved planar terminations resulting in finer junctions and profiles for optimum device performance has been reported [2]. In order to preserve the ideal blocking capability, high-quality semi-insulating surface passivation is also needed to compensate the charging effects at the silicon interface which might be experienced by simply using  $\text{SiO}_2$ . Among the newest passivation materials, diamond-like carbon (DLC) has been proved to be a good candidate due to its outstanding characteristics [3], [4], and it has been modelled in the framework of a TCAD setup suitable for design studies [5], [6].

Many different junction terminations have been studied based on the doping profile optimization. Among them, the variation

of lateral doping (VLD) technique can drastically reduce the JT area and might be an interesting option to the bevel approach [7], [8]. Anyway, the semi-insulating passivation is required to avoid defects, and investigations on the influence of the DLC layer on VLD-based JTs is still lacking.

In this brief, the effects of the transport properties of the DLC used as passivation material on the termination region of a reference power diode are rigorously investigated through TCAD simulations with special attention given to the comparison between bevelled structures and VLD-JTs.

## II. TCAD SETUP FOR LARGE-AREA POWER DIODES

Our reference diode is a circular device as schematically represented in Fig. 1. Due to the axial symmetry, transport equations are solved under cylindrical coordinates to obtain full 3D results [9]. The vertical doping profile and the TCAD setup adopted for the bevelled structure calibrated in [6] are used as a starting point (Fig. 1a). An additional encapsulation material, modelled as an ideal insulator, is assumed on the diode periphery on top of the passivation in order to account for its electrostatic effect on the overall performance of the diode (not drawn in the schematics). The bevel termination has been replaced by a planar JT doping profile following the VLD technique [10] as depicted in Fig. 1b. More specifically, a Gaussian function along the  $y$ -axis (Fig.1) is defined with a peak concentration linearly decreasing along the termination region. From an analytical point of view, it reads:

$$N(x, y) = g(y)h(x), \quad (1a)$$

$$g(y) = N_{\text{peak}} e^{-\frac{(y - y_0)^2}{2\sigma^2}}, \quad (1b)$$

$$h(x) = \left( \frac{N_{\text{drift}}}{N_{\text{peak}}} - b \right) \frac{x}{L_{\text{VLD}}} + b, \quad (1c)$$

with  $N_{\text{peak}}$ ,  $\sigma$  and  $y_0$  the peak concentration, standard deviation and peak position of the Gaussian function,  $N_{\text{drift}}$  the doping concentration in the drift region (labelled as  $n^-$  in Fig. 1),  $L_{\text{VLD}}$  the total length of the VLD profile and  $b$  a fitting coefficient of the linear variation along the  $x$ -axis. As a specific case study,  $y_0 = 0$  and  $b = 1$  have been fixed without losing any relevant dependence in the following analysis. The dose  $Q$  corresponding to the vertical profile is determined by

$$Q = \int_0^\infty g(y) dy. \quad (2)$$

In order to optimize the VLD profile for the diode under study, an ideal  $\text{SiO}_2$  has been used as passivation layer on top of a

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planar termination with total length  $L_T$  equal to the bevelled diode in [6]. The length  $L_{VLD}$  is optimized by reducing it with respect to  $L_T$ . In a second step, the passivation material has been replaced by Boron- and Nitrogen-doped DLC in order to check the role of doping, transport and polarization on the device performance. To this purpose the TCAD approaches in [6] have been adopted. Specifically, the dielectric polarization induced by the DLC disorder has been accounted for in the TCAD setup as calibrated for the bevelled structure in [6].

### III. RESULTS AND DISCUSSION

The optimization of the reference diode with the planar VLD-JT and different passivation layers has been monitored by checking the relative variations of the breakdown voltage at a fixed current of 15mA ( $V_{BD}$ ) and leakage current at a reverse bias of 4000 V ( $I_{OFF}$ ). Starting with an ideal  $\text{SiO}_2$  passivation, the maximum dose of the Gaussian profile providing the best performance in terms of  $V_{BD}$  has been obtained by changing  $N_{\text{peak}}$  and  $\sigma$  so to keep the depth of the pn junction unchanged. In Fig. 2,  $V_{BD}$  is reported as a function of  $Q$  showing an optimal value for  $Q = 3.2175 \times 10^{12} \text{ cm}^{-2}$ . As expected,  $V_{BD}$  is equal to 99% of the ideal one, outperforming the bevelled-diode case reaching only 80%. When the DLC material is considered, the electroactive behaviour of the layer can influence not only  $V_{BD}$  but also  $I_{OFF}$ . Previous analyses in the literature showed significant  $V_{BD}$  degradation with positive fixed charge on top of the lateral junction [11]. Differently from the previous results, the simultaneous presence of doping and free carriers in the DLC layers makes not only  $V_{BD}$  but also  $I_{OFF}$  almost independent of the doping type in the DLC layer, as shown in Fig. 3. In addition, since the depletion width in silicon is mostly controlled by the VLD-JT profile, the effect of additional charge on the top layer is very limited as confirmed by the  $I_{OFF}$  levels compared with the bevelled-diode cases reported in Fig. 3a. A small degradation of the diode performance in terms of  $V_{BD}$  is observed for  $L_{VLD}$  reduced to half of the original  $L_T$  (Fig. 3b).

By comparing the different doping types in the DLC, the largest degradation effect is observed for the Nitrogen-doped DLC and can be ascribed mostly to the highest dielectric polarization: the presence of electric dipoles at the Si/DLC interface affect the electric field distribution not only along the interface but also in the bulk silicon. Simulations clearly show that if a Nitrogen-doped DLC is used, the polarization vector at the Si/DLC interface is large and positive near the cathode and changes to negative values by moving towards the edge of the termination (Fig. 4), leading to additional positive charge near the cathode and to a consequent reduction of the interface electric field. However, it should be noted that in an optimized VLD-JT, the onset of avalanche is not correlated to the Si/DLC interface but to the hot spot located deeper into the bulk region where, vice-versa, the electric field is increased by the additional positive charge on top. In other words, polarization in a Nitrogen-doped passivation layer provides a significant reduction of the leakage current and breakdown voltage as shown in Fig. 5. Similar considerations can be applied to the Boron-doped DLC passivation, but the

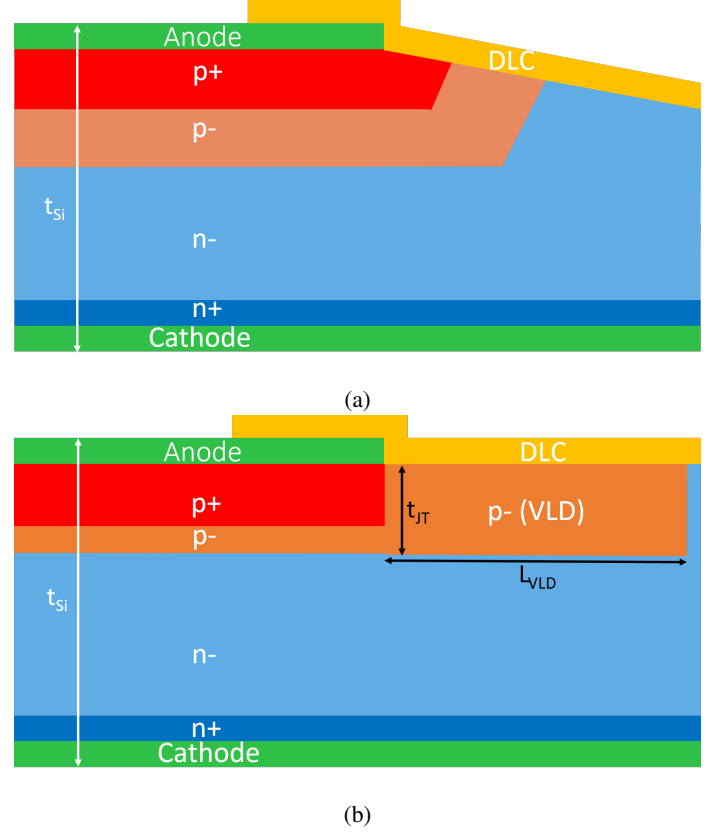


Fig. 1: Radial cross-section of a large-area diode with (a) a negative bevel termination and (b) a VLD-JT. Structures are not in scale. Thicknesses are referred to the  $y$  axis, lengths to the radial  $x$  axis.

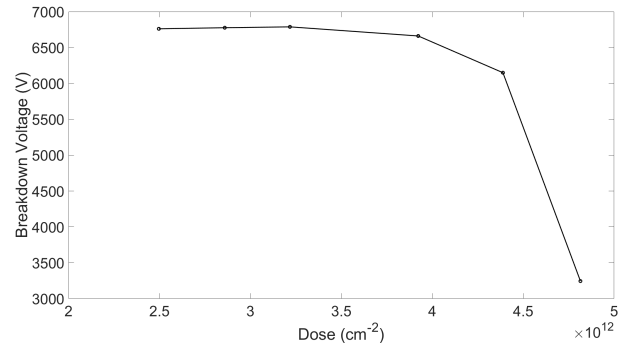


Fig. 2: Breakdown voltage of the power diode with VLD-JT as function of the JT dose. Passivation material:  $\text{SiO}_2$ .

polarization vector in this case causes a negligible variation to the vertical electric field, which is very close to the ideal condition, and no  $V_{BD}$  degradation is observed (Fig. 5b). On the other hand, the effects of the DLC polarization on  $I_{OFF}$  are quite independent of the DLC doping type (Fig. 5a) because in both cases the polarization at the Si/DLC interface provide an increase of the depletion region width. This means that carriers flow through a longer resistive path reducing  $I_{OFF}$ . The latter results clearly show that the VLD-JT can drastically reduce  $L_{VLD}$ , increasing the ON-state performance per area.

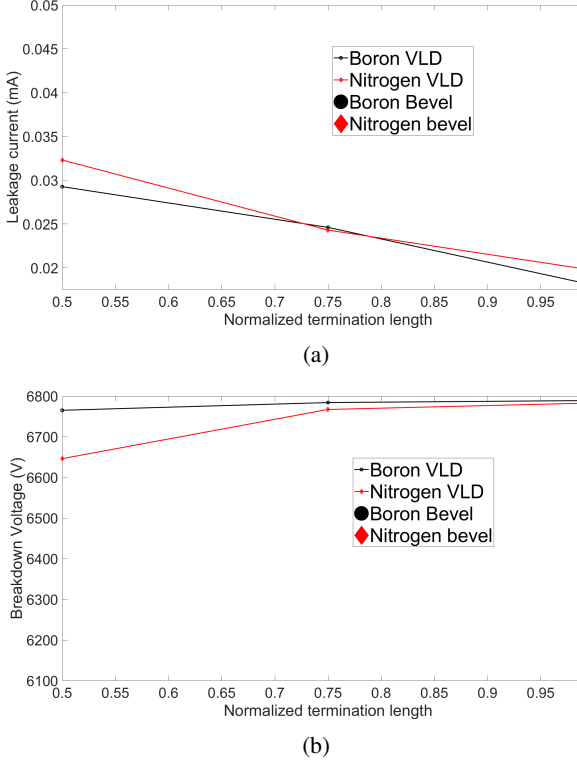


Fig. 3: (a) Leakage current and (b) breakdown voltage of the power diode with VLD-JT as a function of the normalized length  $L_{VLD}/L_T$  compared with the results previously obtained with a bevelled termination of length  $L_T$ . Two differently doped passivation layers are considered.

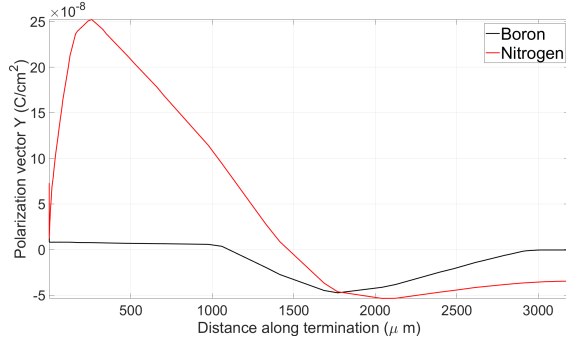


Fig. 4: Normal (y-axis) component of the polarization vector along the VL-JT.

The detailed understanding of the VLD-JT operation including charge transport and polarization in the passivation layer reported in the previous section is a key element for the investigation of the narrowing of the pn-junction depth in silicon. In general, the use of a negative bevel requires to drive the pn-junction deeper in silicon. This implies that an overall thicker structure is required for the discrete power devices with a practical trade-off as explained in [2]. The VLD-JT comes out to be an interesting approach to decouple the vertical thickness from the termination structure, giving the possibility to design a thinner pn-junction under the termination and

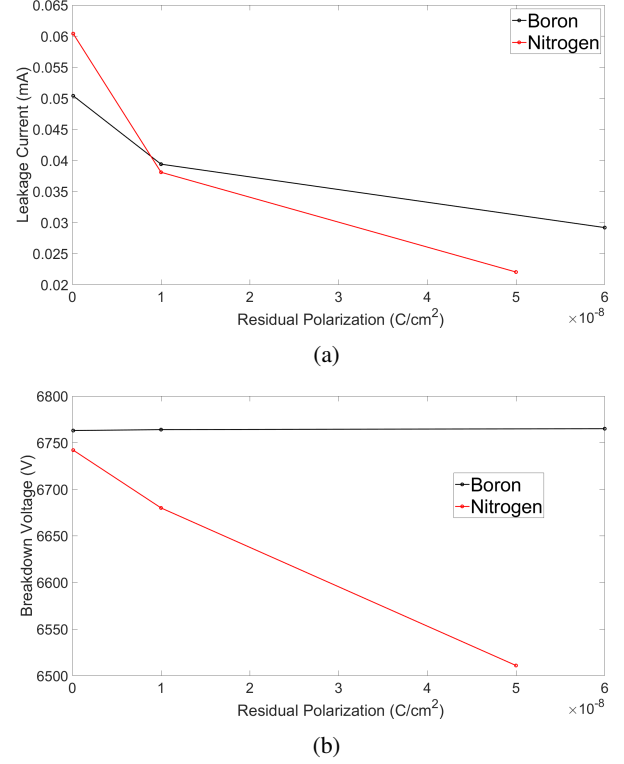


Fig. 5: (a) Leakage current and (b) breakdown voltage as a function of the residual polarization.

consequently the total thickness of the structure, namely,  $t_{JT}$  and  $t_{Si}$  as defined in Fig. 1b. Since  $V_{BD}$  is affected mainly by  $Q$  and  $L_{VLD}$ , optimized as illustrated above, it is possible to reduce  $t_{JT}$  to its minimum value by keeping them unchanged without compromising the blocking capability. This is confirmed by the  $V_{BD}$  analysis reported in Fig. 6, showing the limited variation with a significant reduction of  $t_{JT}$  for different  $t_{Si}$ . As expected, no significant dependence of  $V_{BD}$  on  $t_{JT}$  is found because  $V_{BD}$  is dominated entirely by the active region of the device, while it becomes to decrease at lower  $t_{Si}$  as the full volume of the device is affected by this variation. The effect of different doping in the DLC slightly reduces the performance of the diode when the Nitrogen-doped DLC is used, which can be ascribed to the positive fixed charge effect on the termination junction.

A good final compromise between losses and dimensions is obtained by reducing the silicon thickness and the termination length by 7.7% and 50% with respect to the reference bevelled structure as shown in Fig. 7. A small reduction of the  $V_{BD}$  is experienced, but a value still larger than the reference case is found, while a very similar  $I_{OFF}$  is obtained.

#### IV. CONCLUSION

In this brief, the effects of a semi-insulating material as the diamond-like carbon on a VLD termination have been analysed with the aim of increasing the performance of discrete power devices. TCAD simulations on a reference power diode show that the presence of free carriers in the passivation layer partially compensate the fixed-charge effect

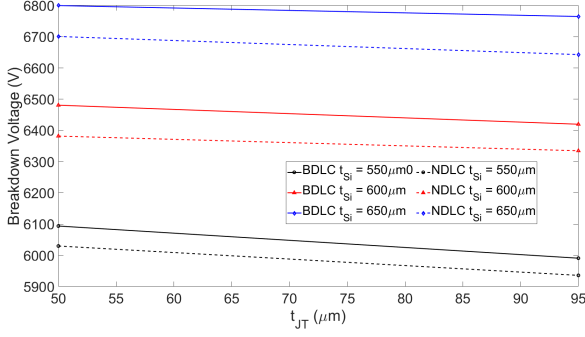


Fig. 6: Breakdown voltage as function of the junction depth ( $t_{JT}$ ) for different values of  $t_{Si}$ .

given by the doping. For this reason, the doped DLC does not show a significant reduction of the breakdown voltage as expected from the presence of positive ionized impurities. The role of polarization has been extensively discussed: it provides additional charge depending on the direction of the electric field at the Si/DLC interface. This feature is useful to reduce the surface electric field but can degrade  $V_{BD}$  clearly indicating differences between Nitrogen-doped and Boron-doped DLC, showing the latter as a better candidate. The proposed optimization of the structure also shows the effects of a reduction of vertical dimensions intended to minimize the on-state losses and to eventually improve other power devices which benefit from a thinning of the wafers.

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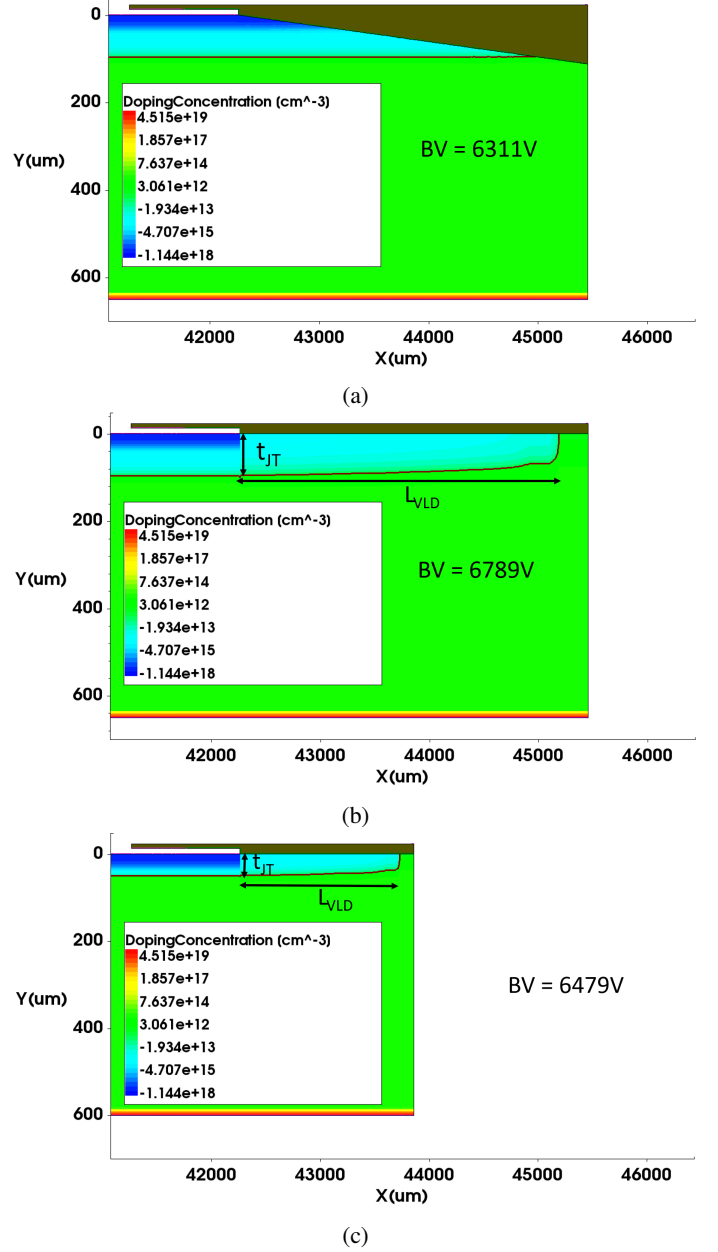


Fig. 7: Doping profile and structure of the diode terminations under study. (a) reference bevelled geometry; (b) VLD-JT realized with the same area and  $t_{JT}$  as the reference diode; (c) VLD-JT with optimized vertical and lateral thicknesses. Structures are not in scale. The additional encapsulation material is drawn in dark color on top.