TCAD Study of VLD Termination in Large-Area Power Devices Featuring a DLC Passivation

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

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 (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 kWs 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 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:

$$N(x,y) = g(y)h(x)\,, \tag{1a}$$

$$g(y) = N_{\mathrm{peak}} e^{-\dfrac{(y-y_0)^2}{2\sigma^2}}\,, \tag{1b}$$

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

with N_{peak}, σ and y_0 the peak concentration, standard deviation and peak position of the Gaussian function, N_{drift} the doping concentration in the drift region (labelled as n^- in Fig. 1), L_{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 loosing any relevant dependence in the following analysis. The dose Q corresponding to the vertical profile is determined by

$$Q = \int_0^{\infty} g(y)dy\,. \tag{2}$$

In order to optimize the VLD profile for the diode under study, an ideal SiO_2 has been used as passivation layer on top of a

---

L. Balestra, S. Reggiani, A. Gnudi and E. Gnani are with the ARCES Research Center, University of Bologna, IT-40136 Bologna, Italy, and also with the DEI Department, University of Bologna, IT-40136 Bologna, Italy (e-mail: luigi.balestra5@unibo.it; susanna.reggiani@unibo.it; antonio.gnudi@unibo.it; elena.gnani@unibo.it).

J. Dobrzynska is with ABB Switzerland Ltd., Semiconductors, CH-5600 Lenzburg, Switzerland (e-mail: jagoda.dobrzynska@ch.abb.com).

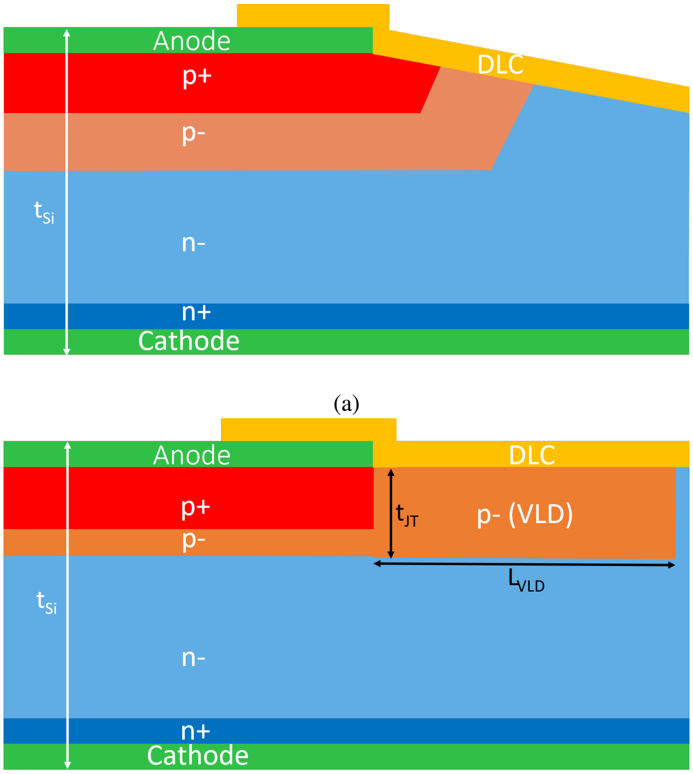
J. Vobecký is with ABB Switzerland Ltd., Semiconductors, CH-5600 Lenzburg, Switzerland, and also with the Microelectronics Department, Czech Technical University in Prague, CZ-166 27 Prague 6, Czech Republic (e-mail: vobecky@fel.cvut.cz).

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 $\mathrm{SiO_2}$ passivation, the maximum dose of the Gaussian profile providing the best performance in terms of V_BD has been obtained by changing N_peak and σ 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 $Q = 3.2175 \times 10^{12}$ 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 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.



(a)

(b)

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.

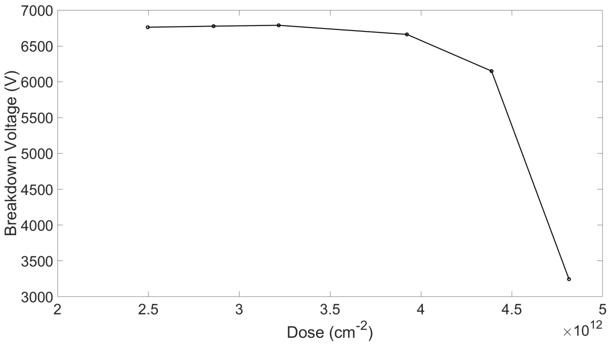
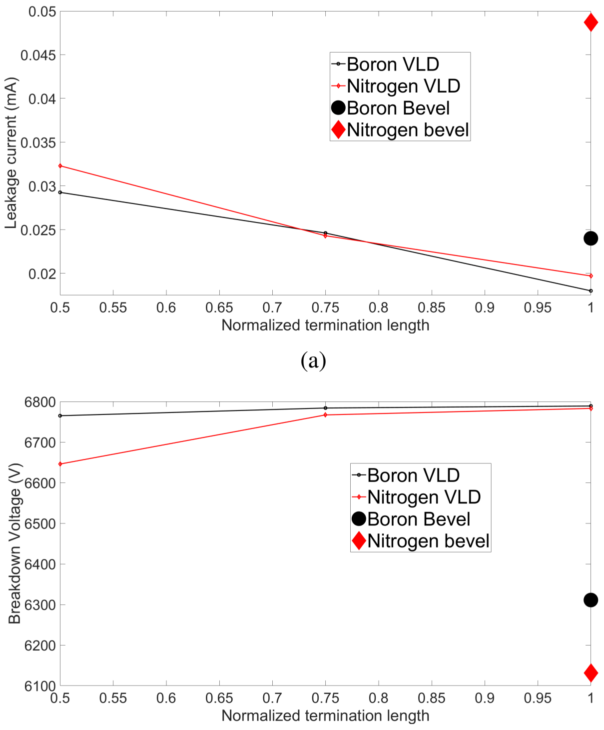


Fig. 2: Breakdown voltage of the power diode with VLD-JT as function of the JT dose. Passivation material: $\mathrm{SiO_2}$.



(a)

(b)

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

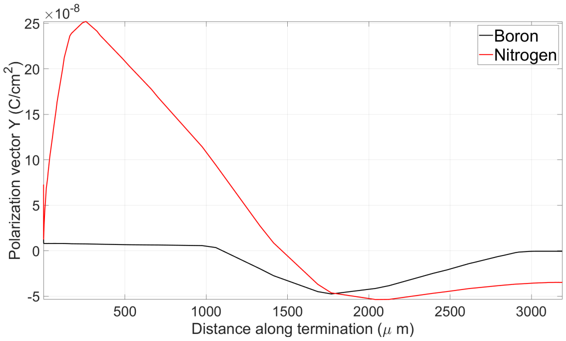
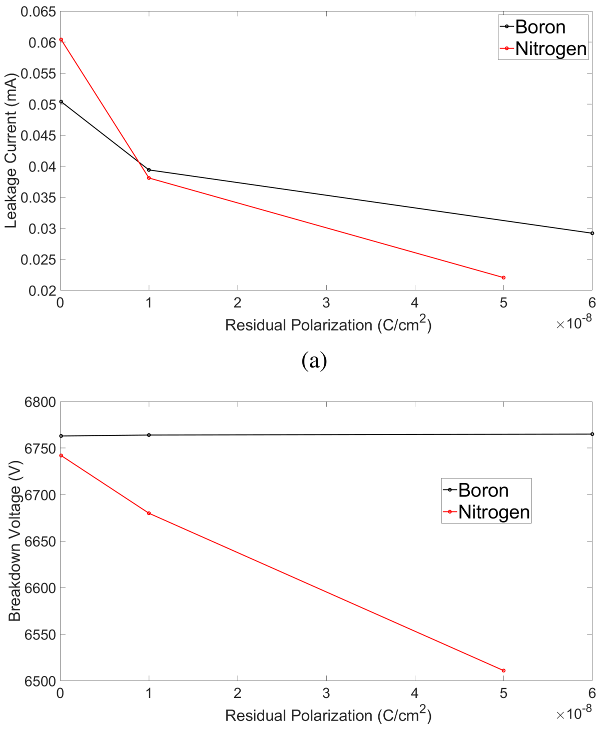


Fig. 4: Normal (y-axis) component of the polarization vector along the VL-JT.



(a)

(b)

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

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 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

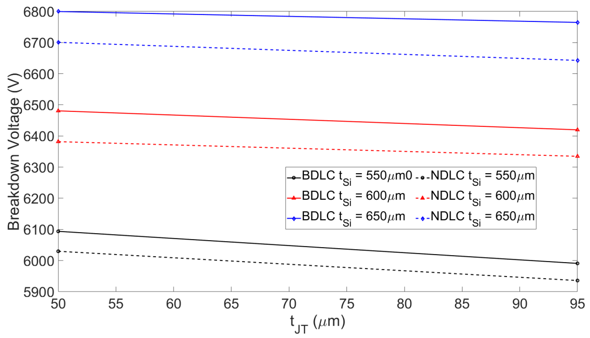


Fig. 6: Breakdown voltage as function of the junction depth (t_{JT}) for different values of t_{Si}.

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.

REFERENCES

[1] M. Rahimo, “Future trends in high-power bipolar metal-oxide semi-conductor controlled power semi-conductors”, Circuits Devices & Systems IET, vol. 8, no. 3, pp. 155–167, 2014.

[2] I. Nistor, M. Scheinert, T. Wikstrom and M. Luscher, “An IGCT chip set for 7.2 kV (RMS) VSI application,” in *Proc. ISPSD*, 2008, pp. 36–39.

[3] V. Jadhav, U. Schwarzer, S. Buchholz and W. Brekel, “Novel 550A/3300V module with IGBT4 and .XT Technology in XHPTM3 package to enhance power density and lifetime for next generation power converters,” in *PCIM Europe 2019*, Nuremberg, Germany, 2019, pp. 1–5.

[4] G. Schmidt et al., US 7,187,058 B2, 06.03.2007.

[5] S. Reggiani, C. Giordano, A. Gnudi, E. Gnani, G. Baccarani, J. Dobrzynska, J. Vobecky, M. Bellini, “TCAD-based investigation on transport properties of Diamond-like carbon coatings for HV-ICs,” in *Proc. IEDM*, 2016, p. 36.7.1.

[6] S. Reggiani, L. Balestra, A. Gnudi, E. Gnani, G. Baccarani, J. Dobrzynska, J. Vobecký, C. Tosi, “TCAD Investigation of Differently-Doped DLC Passivation for Large-Area High-Power Diodes,” in *IEEE J. Emerg. Sel. Topics Power Electron.*, Early Access (2019).

[7] R. Stengl, U. Gösele, C. Fellinger, M. Beyer, S. Walesch, “Variation of lateral doping as a field terminator for high power devices,” in *IEEE Trans. El. Dev.* 33, p. 426, 1986.

[8] E. Falck, H. -. Schulze, G. Schmidt, F. -. Niedernostheide and M. Pfaffenlehner, “Switching ruggedness of high-power diodes,” in *Proc. EPE*, 2005, p. 8.

[9] Synopsys Inc., Sentaurus Device User Guide M-2016.12, 2016.

[10] C. Ronsisvalle, V. Enea, “Improvement of high-voltage junction termination extension (JTE) by an optimized profile of lateral doping (VLD), ” in *Microelectron. Reliab.*, 50, pp. 1773–1777, 2010.

[11] J. R. Trost, R. S. Ridley, M. K. Khan, T. Grebs, H. Evans and S. Arthur, “The effect of charge in junction termination extension passivation dielectrics,” in *Proc. ISPSD*, 1999, pp. 189–192.

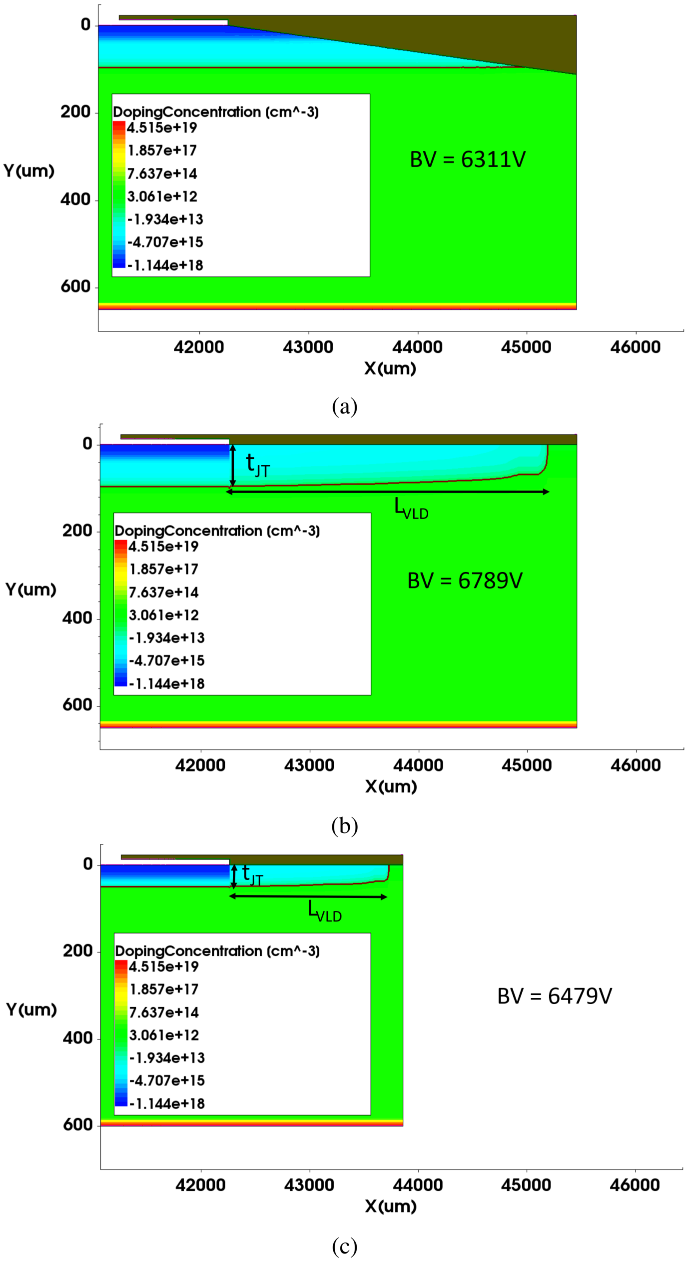


Fig. 7: Doping profile and structure of the diode terminations under study. (a) reference bevelled geometry; (b) VLD-JT realized with the same area and t_{JT} as the reference diode; (c) VLD-JT with optimized vertical and lateral thicknesses. Structures are not in scale. The additional encapsulation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