Simulation of Semiconductor Processes and Devices 2016
Edited by E. Bär, J. Lorenz, and P. Pichler

Comparative Study of Contact Topographies of 4.5kV SiC MPS Diodes for Optimizing the Forward Characteristics

Yaren Huang+, Gerhard Wachutka
Technical University of Munich, Arcisstrasse 21, 80290 Munich, Germany
+Email: huang@tep.ei.tum.de

***Abstract*—The forward characteristics of MPS diodes is composed of two branches: the first one is determined by unipolar conductivity originating from the Schottky contact, while the second one arises from hole injection by the Ohmic contact. A high ratio W_s/W_o of the Schottky contact area W_s to the Ohmic contact area W_o results in high unipolar conductivity and, thus, less heat dissipation under normal operation condition. But the bipolar injection efficiency is too low to support a high surge current capability. We attempt to give some guidelines how these two complementary functional principles can be combined with a view to finding optimum trade-offs for given customer-defined specifications, such as blocking voltage, nominal forward current, and surge current capability. In this work, several novel contact topographies are investigated using comprehensive 2D and 3D computer simulation to analyze consecutive improvements of the trade-off between regular (nominal) operation and surge mode, These TCAD simulations provide a physical understanding of the inner electronic device behavior of each topography considered and lead us eventually to novel concepts.**

I. Introduction

MPS (Merged PiN Schottky) diodes consist of two functional parts: A Schottky diode (Schottky contact) connected in parallel with a PiN diode (Ohmic contact) (Fig.1). Combining the inherent advantages of each of them, MPS diodes are able to exhibit, at the same time, a low threshold voltage and a high surge current capability in forward direction as well as a high breakdown voltage and low leakage current in the reverse direction, and all of this at fast switching speed [1]. In this work, we focus on the forward characteristics of SiC MPS diodes, targeting at low threshold voltage (unipolar operation) and high surge current capability (bipolar operation). The forward characteristics of MPS diodes can be divided into two regims: unipolar conductivity at relative low forward voltage, and bipolar conductivity at high forward voltage. When the anode voltage reaches the threshold voltage of the Schottky contact, which is primarily determined by the Schottky barrier, a current of majority carriers starts flowing through the device. When the anode voltage is further increased beyond a certain value, the inherent $p^+ - n^-$ junction will be triggered to inject minority carriers and, thus, a plasma of electrons and holes will cause a significant resistance modulation in the bulk of MPS diodes. This bipolar operation mode gives MPS diodes a much higher thermal stability than JBS diodes [2].

978-1-5090-0818-6/16/$31.00

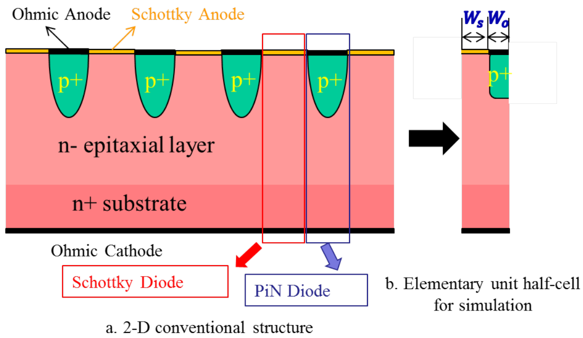

Fig. 1. a: 2D cross section of a conventional device structure of a SiC MPS diode; b: Elementary half-cell used as simulation domain.

As demonstrator we considered a 4.5 kV SiC MPS diode that is currently under development [3]. The relatively large resistance of the long drift layer due to the high blocking voltage, and the wide band gap of SiC material result in a high voltage V_{turn} triggering the bipolar mode. But a too high V_{turn} can cause premature overheating and lead to thermal runaway like it is known from Schottky diodes. Modifications of the device structure can reduce V_{turn}, but also result in a lower value of the nominal operation current density $J_{F,nom}$. Due to the electro-thermal coupling between the Schottky part and the PiN part, there exits a trade-off between V_{turn} and $J_{F,nom}$.

As a consequence of the required high blocking voltage, there is not much room in design space to modify the device structure, except for the contact topographies of the Schottky contact and the Ohmic contact. Detailed investigations, such as early work on Si JBS diodes [4] and 600V SiC MPS diodes [5], have revealed that the ratio of Ohmic contact area (W_o) to Schottky contact area (W_s) is a decisive parameter that controls the operational behaviour of MPS diodes. However, these studies focus on the nominal ratio of contact area only and do not consider alternative variants of contact topography, as it is attempted in our work. We discuss several new layout variants with a view to optimizing the forward characteristics of 4.5kV SiC MPS diodes.

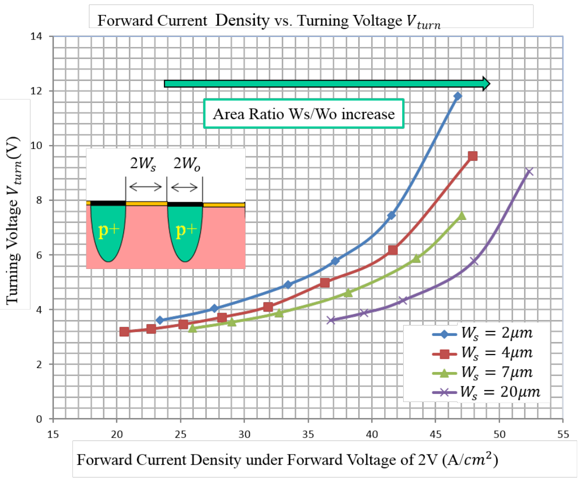

Fig. 2. By varying the area ratio (W_s/W_o) different trade-off curves between V_{turn} and $J_{F,nom} = J_{(U=2V)}$ are obtained. Larger unit cells show a better trade-off.

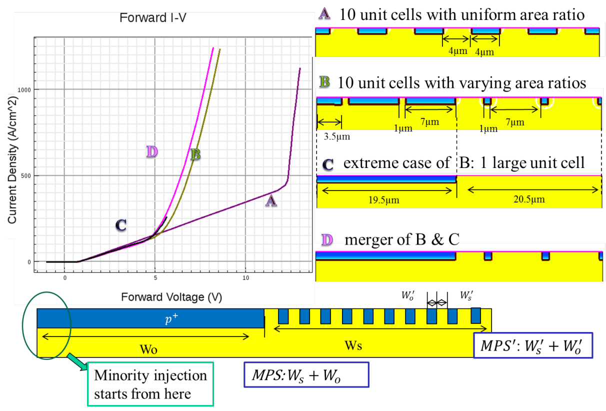

Fig. 3. Four different device structures with different contact topography are compared. These I-V curves already show that structures C and D are superior. Taking into account the requirements of the reverse characteristics leads us to proposing novel structure shown at the bottom.

II. Simulation Strategy

The operation of the forward biased MPS diodes has been analyzed by means of physical device simulation using Sentaurus TCAD. Fig.1 shows a conventional (strip) layout of MPS diodes together with an elementary unit cell used for 2D physical device simulation. Two issues show to be crucial for the reliable simulation of such structures:

A. Decoupling of the two contact models

Although the anode contact of a real MPS diode consists of one continuous metallization layer, we split this layer in the simulation into two separate regions and use an Ohmic contact model and a Schottky contact model individually for each of them (Fig.1). In order to avoid numerical convergence problems caused by the rapid variation of the electric field between these two kinds of contact, it is necessary to introduce an artificial contact gap placed between the Schottky contact model and the Ohmic contact model. This gap should be as small as possible to avoid any artefact in the simulation results. Furthermore, the Schottky contact model should not only cover the n^--region but in addition a small part of the p^+-region, which means the contact gap would be placed on the top of the p^+-regions, and not above the p^+-n^- junction. This is because the lateral under-diffusion of the p^+-islands in the adjacent areas aside results in a low doped p^--region where the Schottky contact model has to be employed.

B. Additional resistance for the simulation of the snap-back characteristics

The second point is to introduce an additional ohmic resistance between the MPS diodes and the voltage/current source. This is because there may be a strong snap-back behaviour in the forward characteristic of SiC MPS diodes, originating from the strong modulation of the bulk resistance due to minority carrier injection. The additional resistance can be added either as a contact resistance to the cathode contact of the MPS diode, or as an external resistor between MPS diode and voltage/current source. Following the first option, the contact resistance should not be attached to the anode contact, because this will cause different terminal potentials of the Schottky contact and the Ohmic contact. Using the second option, a circuit (mixed- mode) approach must be employed in the simulation mode.

III. Comparison of Different Contact Topographies

The nominal forward current density $J_{F,nom}$, the triggering voltage V_{turn} of bipolar operation, and the surge current density J_{surge} are the three key parameters of the forward characteristics of SiC MPS diodes. The multi-target optimization consists in achieving high $J_{F,nom}$ and, concurrently, low V_{turn} in order to avoid premature overheating, and maximum J_{surge}. The impact of contact topography on V_{turn} and J_{surge} is similar, because these two quantities are related to the pin substructure of a SiC MPS diode. In the case that the pin part is dominating in the whole device, V_{turn} is small while J_{surge} is large. Besides J_{surge} shows a strong dependence on the minority carrier lifetime in the epitaxial layer. In order to quantize the trade-off between nominal operation (unipolar) and surge current operation (bipolar), we plot V_{turn} versus $J_{F,nom}$ (so called trade-off relation) (Fig.2), and use this quantity as measure for assessing the performance of a given contact topography in the sequel.

A. Large sized unit cell

It should be noticed that even for the same area ratio W_s/W_o, the trade-off relations for different W_s and W_o are yet different. This means that the area ratio is not the only parameter that determines the trade-off relation. Fig.2 shows the simulation results for structures with $W_s = 2\mu m, 4\mu m, 7\mu m, 20\mu m$. By varying the area ratio

Simulation of Semiconductor Processes and Devices 2016
Edited by E. Bär, J. Lorenz, and P. Pichler

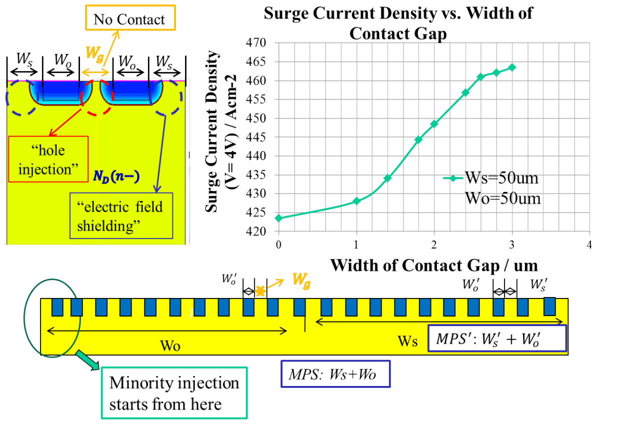

Fig. 4. A small unit cell realizing the new concept of "contact gap" is shown at the left upper corner. The chart illustrates the relationship between the increment of surge current density and the width of the "contact gap". The proposed novel structure is sketched below.

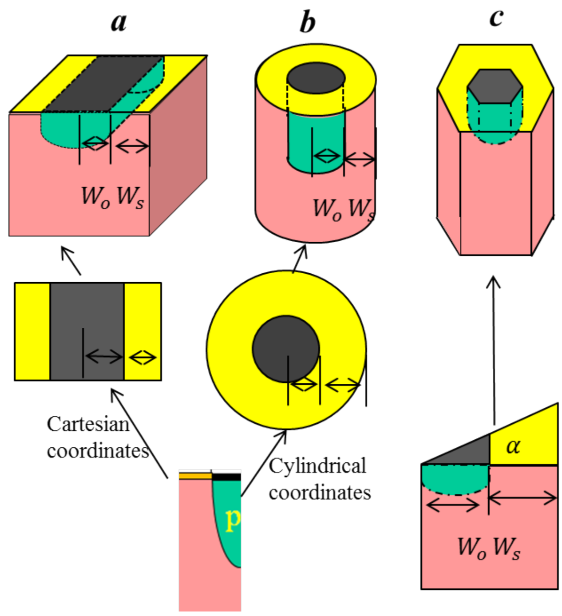

Fig. 5. Three 3D-structures of MPS diodes and their respective simulation domains.

W_s/W_o, several trade-off relations between $J_{F,nom}$ and V_{turn} are obtained, which reveal that, for the same $J_{F,nom}$, the SiC MPS diode with $W_s = 20\mu m$ has the lowest V_{turn}. This indicates that increasing W_s (i.e. a larger unit cells), will lead to a better trade-off relation.

This is corroborated by the comparison of four different contact topographies with the same total contact area and area ratio W_s/W_o (cf. Fig.3). The operational behavior of these four contact topographies (A to C) can be explained in a consecutive way. The first topography A, the one with uniform area ratio, is the same as in the conventional MPS structure. It exhibit highest V_{turn} and a negligibly better value of $J_{F,nom}$. When we split the uniform W_s/W_o into two different values of W_s/W_o but maintaining the same total value of W_s/W_o, we obtain topography B with two different unit cells placed on the anode contact. Eventually bipolar injection sets on at a much lower value of V_{turn} at the left corner of B, and the minority carriers diffuse from the left top corner down to the right of this structure. This process facilitates the triggering of the bipolar mode in the right half part of the p^+-n^- junction, thus dramatically reducing V_{turn} for the whole device. As an extreme case of topography B, we arrive at topography C by connecting the left half part (low W_s/W_o) to a complete large p^+-region ($W_s/W_o = 0$) and the right half part (high W_s/W_o) to a complete n^--region ($W_s/W_o = 1$). The trade-off relation on the left side shows that topography C has almost the same $J_{F,nom}$ as B and a slightly reduced V_{turn}. Eventually, topography C has to be enhanced to topography D, because a high density of p^+-islands is required to provide electric field shielding in the blocking state to reduce the leakage current caused by Schottky barrier lowering. And topography D may also interpreted as an array of large unit cells containing an embedded array of small unit cells, where the lager unit cells are ensuring optimum forward characteristics, while the small unit cells keep the leakage current low in blocking direction.

B. New concept with "contact gap"

Inspired by the fact that the trade-off between V_{turn} and $J_{F,nom}$ originates from the strong interdependence between Schottky contact and Ohmic contact, we proposed a novel contact topography with "contact gap", as shown in Fig. 4. The basic idea is the electrical decoupling of the PiN structure from the Schottky structure, thus minimizing the interaction between them, so that the bipolar operation mode can be easier triggered. The "contact gap" essentially serves the same purpose as enlarging W_o or p^+-region with a view to reducing V_{turn}. But it has an additional advantage that, at the same time, the surge current capability can be enhanced even further due to the increment of the effective area for minority carrier injection and the enhancement of the emitter efficiency. In comparison with the conventional structure with only one p^+- region, having a smooth and flat effective area of carrier injection, this novel structure has a rugged and coarse effective area. Combining the idea proposed in Fig.3 and the idea of "contact gap" leads to the topography shown at the bottom of Fig. 4. In order to study the dependence of the increase of the surge current density on the width of the "contact gap", a series of simulations have been implemented taking $W_s = 50\mu m$, $W_o = 50\mu m$, $W'_o = 2\mu m$ and W'_s as the width of the "contact gap". With the growing W'_s, the surge current density first rises, reaches a peak value at $3.75\mu m$, and then degrades. This value can be estimated by summing up W'_o and the double of the horizontal diffusion extension of p^+-regions, and it brings the maximum ruggedness along the anode topography. It should be noted that in the case that the large unit cell itself without "contact gap" already has a high surge current capability, the additional improvement brought

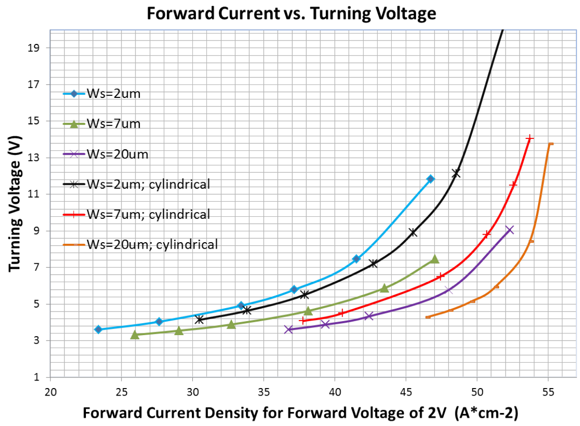

Fig. 6. Cylindrical structures feature a better trade-off between V_{turn} and $J_{F,nom} = J_{(U=2V)}$ than stripe-shaped structures.

by the "contact gap" will be more significant. For example, if W_s decreases from $50\mu m$ to $30\mu m$, the increase of the surge current density due to the wider "contact gap" will become larger.

C. 3D sturctures

So far, we considered stripe-shape MPS diodes only, which are properly modelled using 2D cross-sections and Cartesian coordinates (Fig.5a). With the same cross-section, but using cylindrical coordinates, we extended our the trade-off study to a 3D elementary cell of cylindrical structure (Fig.5b). In order to compare the stripe-shaped structures with the cylindrical structures, trade-off relations with different fixed value of W_s as curve parameter are shown in Fig.6. It shows that cylindrical structures outperform the stripe-shaped arrays. This finding has the following explanation. We define the location of the starting point for minority carrier injection as S. The direct linear distance between S and the edge of Schottky contact is the same in cylindrical structures and in strip structures (the same cross-section), but the effective area for unipolar conductivity is much larger in cylindrical structures, since the Schottky contact is the outer ring of the unit cell.

However, in a practical realization, hexagonal cells (Fig. 5c) should be preferred, because they feature the highest package density of unit cells in a 2D plane and at the same time own the similarity of cylindrical structures. For example, commercial 600V SiC MPS diodes manufactured by Infineon Technologies, exhibit a hexigonal cell array topography[6].

IV. Conclusion

Currently, SiC MPS diodes, as strongly competitive candidates for freewheeling diodes in the high voltage and high temperature application, are being designed to sustain even 10kV blocking voltage [7]. However, the progressively high blocking voltage and the wide bandgap of SiC will lead to a more aggressive trade-off between V_{turn} and $J_{F,nom}$. The optimization of contact topography optimization is the most direct and effective approach towards the goal of combining such extreme blocking voltage with acceptable forward characteristics including high surge current capability at affordable cost. Our work illustrates this trade-off by comprehensive case studies on contact topographies using 2D and 3D simulations. All proposed optimized structures of SiC MPS diodes are based on a unified concept, namely that the location S, the starting point injecting minority carriers, should be as far away as possible from the Schottky contact, while the Schottky area should be kept as large as possible. In the first study case of a larger unit cell, the distance between S and the Schottky contact region is maximized in a lateral direction, whereas in the case of the "contact gap" structures, additional distance is gained in vertical direction. In cylindrical structures, the effective Schottky area is enlarged, while the same distance between S and Schottky contact is maintained. Apart from that, since the p^+-regions have the additional function of shielding the Schottky contact from the electric field in the reverse bias in order to reduce the leakage current, two different kinds of p^+-regions serving the two different purposes should be implemented.

Acknowledgment

The study was funded by the European Commission within the FP7 project SPEED (Silicon Carbide Power Electronics Technology for Energy Efficient Devices).

References

[1] R. Rupp, M. Treu, S. Voss, F. Bjork, T. Reimann,2nd Generation SiC Schottky diodes: A new Benchmark in SiC device ruggedness, Proc. of the ISPSD, Naples, Italy, June 2006, pp.1-4.

[2] S. Fichtner, J.Lutz, T.Basler, R.Rupp, R. Gerlach, Electro-Thermal Simulations and Experimental Results on the Surge Current Capability of 1200V SiC MPS Diodes, Proc. of the CIPS, Nuremberg, Feb. 2014, pp.1-6.

[3] Y. Huang, T. Erlbacher, J. Buettner, G. Wachutka, "A Trade-off between Nominal Forward Current Density and Surge Current Capability for 4.5kV SiC MPS Diodes," Proc. of ISPSD, Prague, Czech Republic, June 2016, pp.63-66.

[4] S. Sawant and B. J. Baliga, "4 kV merged PiN Schottky (MPS) rectifiers," Proc. of ISPSD, Kyoto, Japan, 1988, pp. 297-300.

[5] V. d'Alessandro et al., "Influence of Layout Geometries on the Behavior of 4H-SiC 600V Merged PiN Schottky (MPS) Rectifiers," Proc. of ISPSD, Naples, June 2006, pp. 1-4.

[6] R. Rupp, R. Gerlach, A. Kabakow, "Current Distribution in the various functional area of a 600V SiC MPS diode in forward operation", Mater.Sci.Forum.

[7] Y. Jiang, W. Sung, X. Song, H. Ke, S. Liu, B. J. Baliga, A. Q. Huang et al., "10kV SiC MPS Diodes for High Temperature Application"Proc. of ISPSD, Prague, Czech Republic, June 2016.