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New termination architecture for 1700 V diamond schottky diode

Houssam ARBESS[1,2], Karine ISOIRD[1,3], Saleem HAMADY[1,2,4]
[1]LAAS - CNRS, 7 avenue du colonel Roche, F-31400 Toulouse, France
[2]Univ de Toulouse, LAAS, F-31400 Toulouse, France
[2]Univ de Toulouse, UPS, LAAS, F-31400 Toulouse, France
[4]GET/LPE, Lebanese University, Hadath campus, Beirut, Lebanon
Tel : +33 / (5) 61 33 79 64
Fax : +33 / (5) -- 61 33 62 08
E-Mail : harbess@laas.fr, kisoird@laas.fr , shamady@laas.fr
URL : www.laas.fr, www.univ-tlse3.fr, www.ul.edu.lb

Keywords

«Diamond», «TCAD simulation», «Schottky diode», «Field plate architecture».

Abstract

New field plate architecture is applied to pseudo vertical diamond Schottky diode. Using several field plate architectures, a TCAD simulation is realized in order to reduce the electric field in the dielectric while maintaining high breakdown voltage. Firstly and after simple variations in the field plate architecture, the breakdown voltage was improved from 1632 V to 2141 V at 700 K. Concerning E_{max} in the dielectric, we obtained a decreasing of maximum electric field from 57 to 18 MV/cm.

Introduction

Diamond is a promising material for future high power and high temperature electronics applications, where its outstanding physical properties can be fully exploited. It exhibits an extremely high band gap, very high carrier motilities, high breakdown field strength and the highest thermal conductivity of any wide band gap material[1].

Since the N-type doping diamond is not yet optimized, we do not find diamond MOS transistor or PIN diode, most of the work is focused on the improvement of the Schottky diode.

With those first batches of components, we need to develop junction termination structures that will allow the diamond devices to reach their full potential, mainly in terms of breakdown voltage. Since diamond has a huge theoretical critical electric field, the junction termination structure is going to have a major impact on the performance of the power devices. Those structures will allow us to demonstrate the efficiency of such diamond diodes.

Context and Aim of the Study

Considering the specific case of diamond, many technological steps are not available, so the solution for the device protection is limited by the field plate [2–5]. The critical field of diamond is very strong which imposes severe constraints at the device termination. Since the critical field of the deposited dielectric material is less than that of diamond, we aim to find new architectures that reduce the electric field in the termination structure.

The previous structure studied at LAAS is a diamond pseudo vertical Schottky diode with Field plate as termination on the diamond surface (Fig. 1). This structure consists of two diamond layer, the first is a 7 µm P^+ doped diamond with a doping concentration of 3.10^{20} cm^{-3} and the other is a 7 µm P^- -doped diamond with doping concentration of 8.10^{15} cm^{-3}.To study the breakdown voltage of this

structure and to look the optimum desired values of different technological parameter, we use Sentaurus TCAD simulation .The physical model used to calculate the breakdown voltage is the default Van Oversteaten model [7].

Firstly we simulated an ideal schottky diode, that means one dimensional simulation and without limit condition. Fig. 2 presents the variation of the simulated breakdown voltage of one dimensional diamond schottky diode with the doping concentration of the P^- layer and the thickness of the last one. In our case (8.10^{15} cm^{-3} and 7 µm as P^- layer parameters), we obtain a breakdown voltage equal to 2288 V.

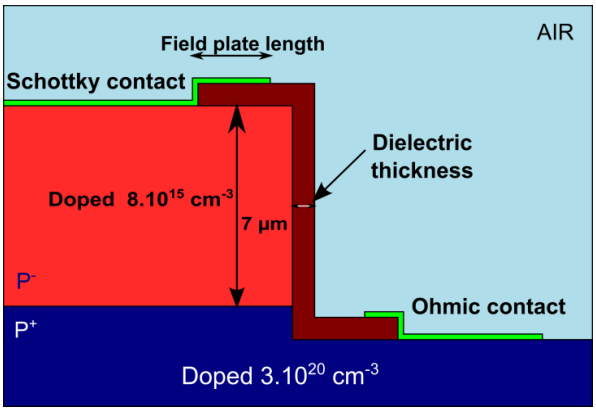

Fig. 1: Simulated pseudo vertical diamond Schottky diode

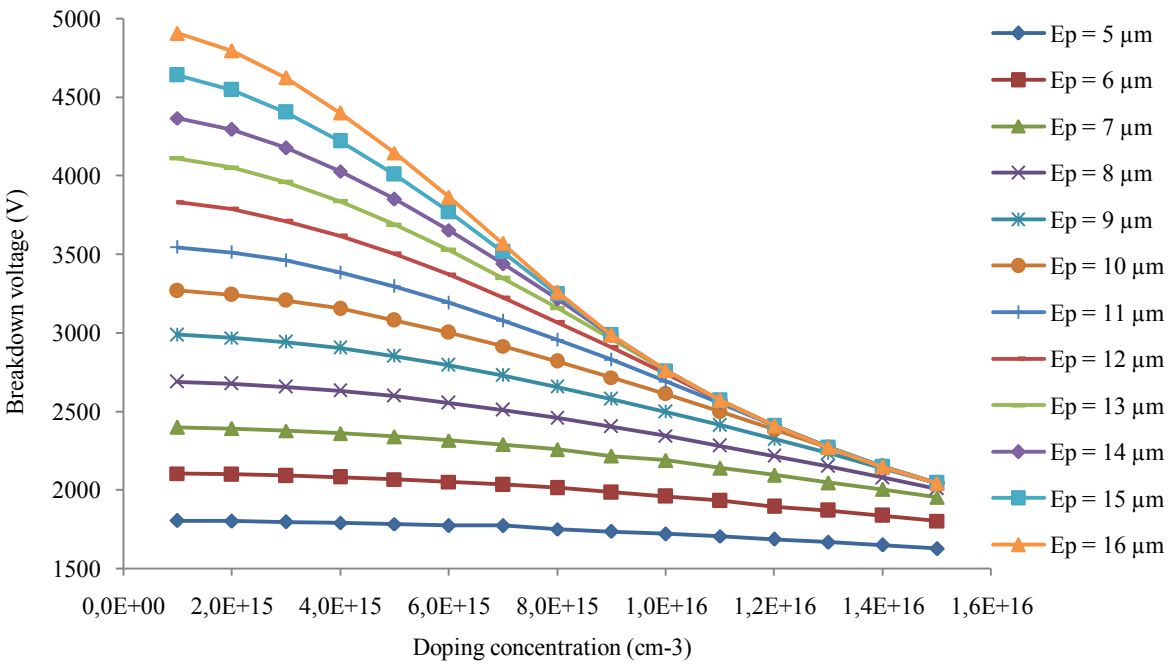

Fig. 2: Breakdown voltage for an ideal schottky diode (one dimensional simulation). Ep present the P- thickness layer of the diode.

The field plate was optimized for a length of 10 microns and dielectric thickness of 0.7 microns. The dielectric used in this optimization is the Silicon oxide SiO_2 [6]..With these parameters, we obtained 1638 V as a breakdown voltage. However the electric field reached at the end of Field plate is higher than 19.5 MV/cm at 700 K.

All results shown in this paper were extracted at 700 K due to simulation problems at low temperatures. Other simulations have been made in order to evaluate the variation of maximum

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electric field with temperature shown a negligible difference.

New Field plate architecture

A new idea has been proposed in order to increase the breakdown voltage. It is to keep the whole electrode flat, with no corners, and replace the diamond below the field plate region, with an optimized thickness of dielectric material (Fig. 3). Indeed, the presence of corners on the path of the potential strengthens the electric field. In the previous architecture, the dielectric is located on the diamond surface, creating a corner in the electrode. At this corner the electric field is stronger in the diamond and then the impact ionization is greater for the first structure than the second for the same external voltage. Consequently, the breakdown voltage in our structure is higher than the one previously proposed.

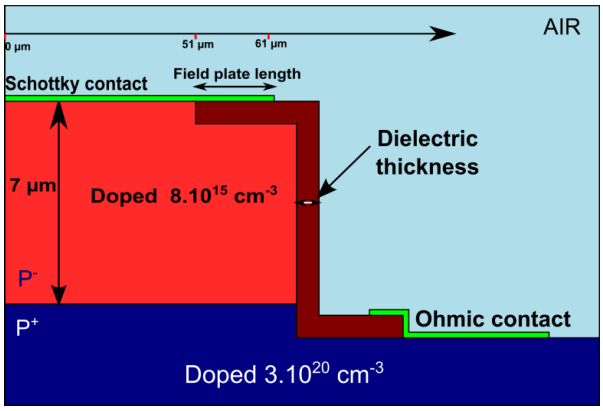

Fig. 3: New field plate architecture for diamond Schottky diode

Fig. 3 shows the new field plate architecture for the simulated structure with the same technological parameters as the initial one. The optimum positions and thickness of the dielectric are 51microns for begin field plate, 10 micron for the field plate length and 1 microns of thickness. With these parameters we obtain a breakdown voltage of 2141 V.

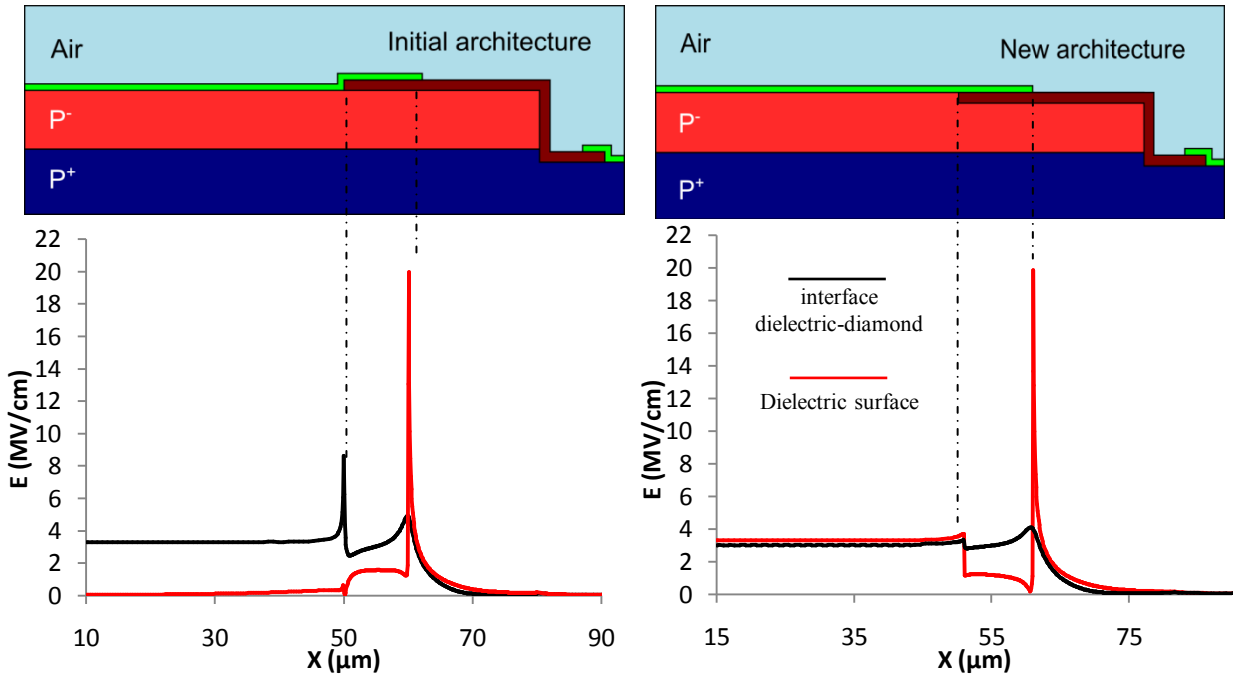

Fig. 4: Representation of the electric field distribution at 1700 V in the initial architecture (left) and the new one (right)

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Fig. 4 shows the difference between the electric field distribution in the two architectures where we have plotted the electric field variation along horizontal axis passing by the surface of the dielectric and another passes through the dielectric-diamond interface. The electric field focalization in the diamond for the first one (initial architecture) increases the impact ionization and as a result, the breakdown voltage decreases. In the graph at the left (old architecture), we have two peaks. The first one is in the diamond in the beginning of the field plate and the second is at the extremity of the field plate. The graph at the right shows one peak of the electric field at the extremity of the field plate.

The highest electric field at 1700 V is 19.9 MV/cm for the initial solution and 19.8 MV/cm for the new one. The high mesh refinement in the high electric field zone to 10 nm(node-to-node distance)shows an increase in the electric field to 49 MV/cm and 48.5 MV/cm for the initial and new architecture respectively. Assuming that the oxide we used has a high quality, the maximum electric field carried by the silicon oxide is 10 MV/cm and between 5 and 7 MV/cm for silicon nitride. In this case, the oxide will break before the voltage across the diode reaches the maximum value, and consequently the field plate doesn't play its desired role.

Electric field optimization

Looking at the experimental results, the average breakdown voltage was 400 V (Fig. 4) [6]. One of the reasons responsible for this failure may be the break of the dielectric. To improve the efficiency of the termination, we can change the dielectric as Ikeda [8], who used the Al_2O_3 as a dielectric for the field plate, but it's not enough. We aim to find a dielectric form for the field plate able to minimize the electric field as much as possible. Our idea is to change the form of field plate.
For all simulation, we used the silicon oxide as a dielectric with air above.

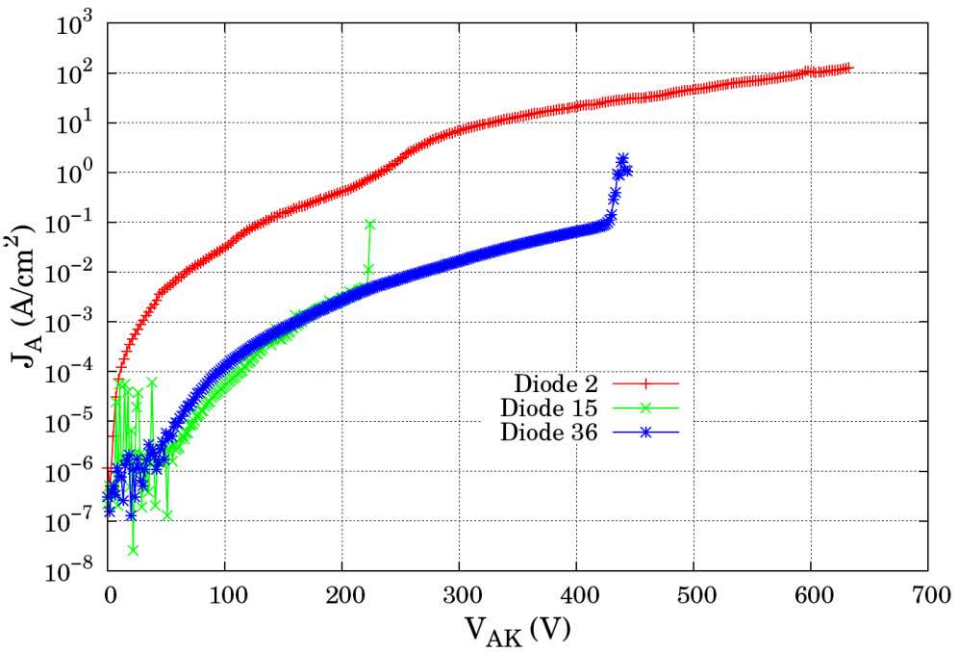

Fig. 5: Breakdown voltage for several diamond schottky diodes [6].

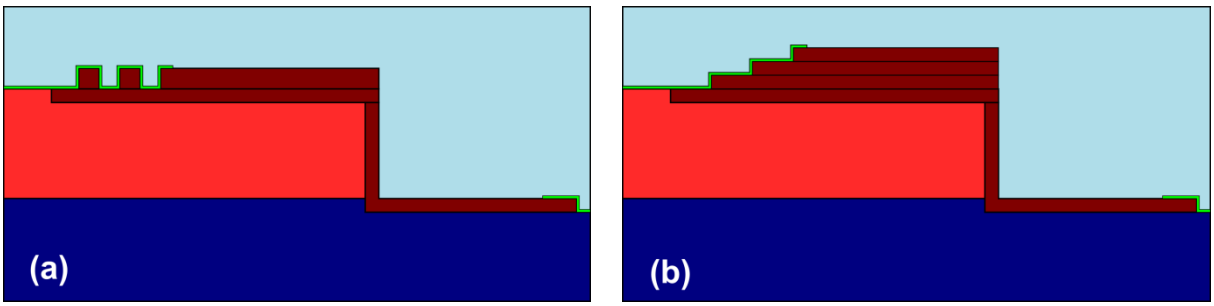

Fig. 6: Pillars oxide form (a), graduated oxide form (b)

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As we have already seen, the maximum electric field is at the corner. Thus, increasing the number of corners in the potential way, reduces the electric field value at the output of the field plate (distribution of peaks). Two architectures may be able to solve this problem.

a- The pillars dielectric form. That means, making the oxide in pillars form until the end of the electrode which increase the number of corners in the path of the potential Fig. 6 (a).
b- The graduated dielectric form Fig. 6 (b).

Pillars dielectric from

The termination efficiency depends on many parameters: the pillar height, the pillar width, number of pillar and finally the contact length on the last pillar (Fig. 7). Using this dielectric form we made constant the field plate length. The last oxide pillar attains a contact length of 1 micron.

Fig. 8 shows the variation of the maximum electric field as a function of the pillars height. Increasing the Pillars height from 0 to 1.6 microns decreases the breakdown voltage 25 V, but we have obtained a reduction in the maximum electric field to 20 MV/cm at 1700 V. The length of the field plate on the last pillar plays its role also. Passing from 1 micron as in the previous case to a value of 0.3 microns, the maximum electric field decreases from 37 MV/cm to 27 MV/cm. Fig. 9 shows the electric field variation at the oxide-oxide interface and the oxide surface for pillars height equal to 1.6 microns at 1700 V. We can remark the electric field peaks at the corners.

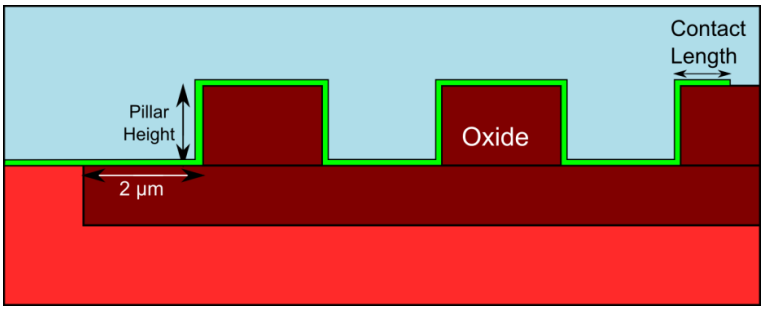

Fig. 7: Pillars oxide form

Now, we made a simulation of the same field plate form, but this time we reduce the width of the pillars (new width = 0.5 microns and 9 pillars), that's mean increase the corner number while keeping the length of the field plate on the last pillar to its optimal value (0.3 micron). Simulation results show that by reducing the width of the pillars, the electric field drops to 24 MV/cm. Note that, if we increase the pillar height over 1.6 microns, the effect of this increase becomes negligible

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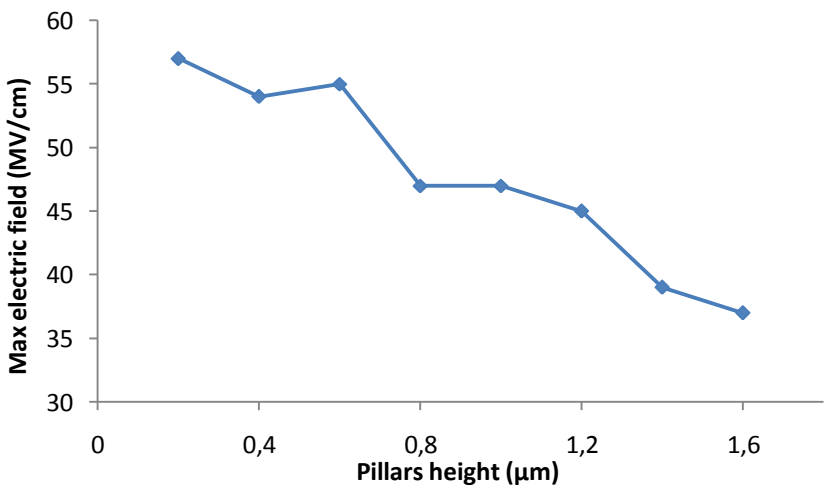

Fig. 8: Maximum electric field at 1700 V in terms of pillar height for the pillars field plate form

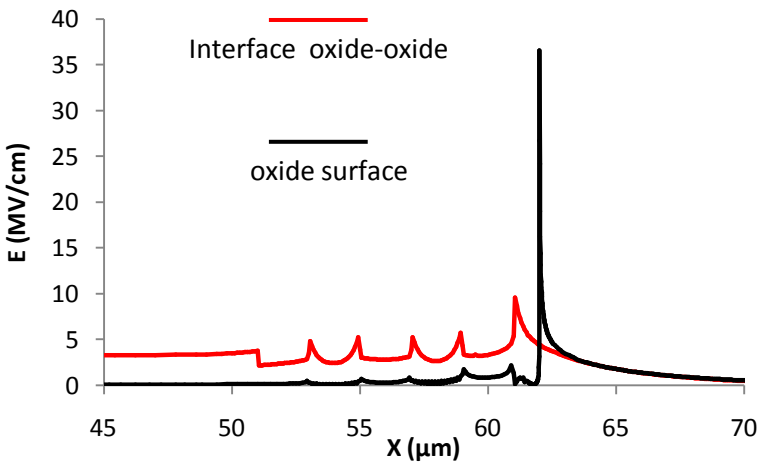

Fig. 9: Electric field values at the oxide-oxide interface and the oxide surface for height pillars equal to 1.6 microns at 1700 V

Graduated dielectric form

The second proposed field plate form is the graduated form, where the potential meets three corners before it exits the fourth one (Fig. 10). Three parameters play a role in optimizing the architecture: The step oxide height, the number of steps and the field plate length in the last step. Only three steps are made for the sake of reducing technology process. This oxide form was previously used by Brezeanu [9] to increase the breakdown voltage and not to minimize the maximum electric field in the dielectric.

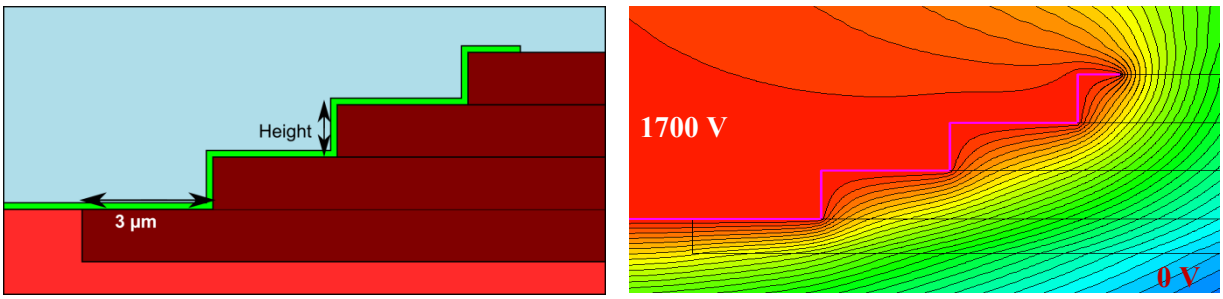

Fig. 10: Graduated oxide form (left), and presentation of the electrostatic potential in the structure in the dielectric structure (right).

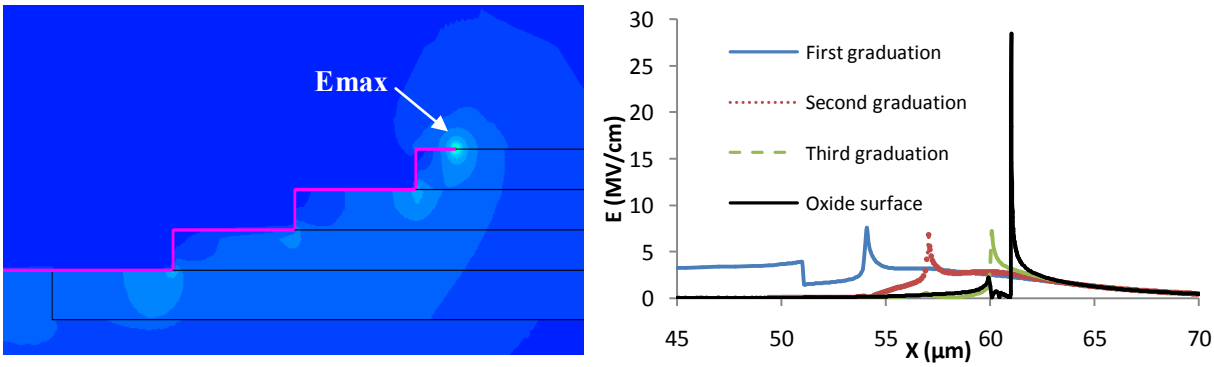

Fig. 11: electric field distribution in the structure at the protection oxide zone (field plate) (left) and cross sectional view of the electric field for each graduation and at the oxide surface (right).

Fig. 11 shows the electric field distribution in the structure at the protection oxide zone (field plate) and cross sectional view of the electric field for each graduation and at the oxide surface. We can see in this figure the electric field peaks at each corner.

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Fig. 12 shows the maximum electric field as a function of the step height. The decrease of the breakdown voltage is now greater since the total thickness of the oxide is greater than that of the first architecture (pillars oxide form). The breakdown voltage therefore decreases from 2320 to 2306 V. At 1700 V the maximum electric field decreases from 53 MV/cm to 33 MV/cm. Even this decrease is important, electric field does not achieve the required value of 10 MV/cm.

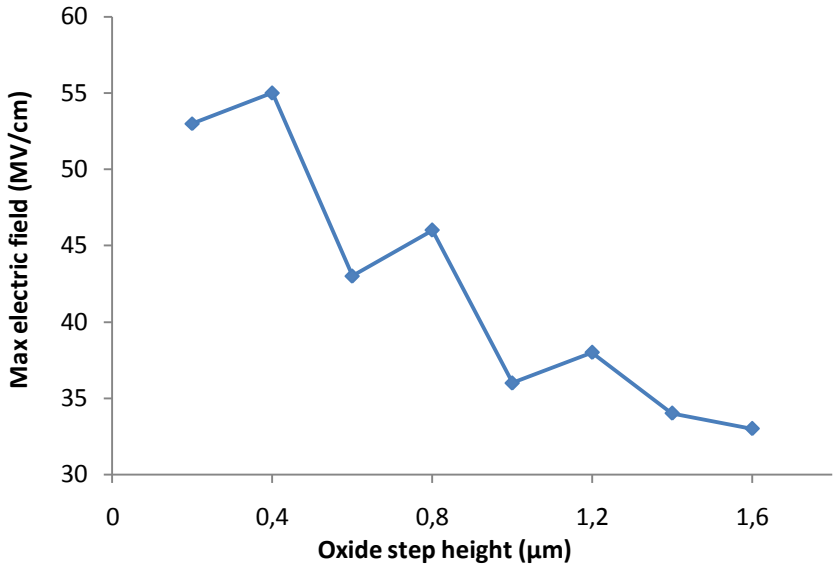

Fig. 12: Maximum electric field variation as a function of one step height.

Discussions

Each proposed solution allows to decrease the peak of electric field, but not in the target range. Also we must consider other ways.

Replacing the silicon oxide with another dielectric material with higher electric permittivity (such as silicon nitride Si_3N_4 or aluminum oxide Al_2O_3) reduces the value of the maximum electric field. However, the reached value remains above the requirement.

If we increase the total oxide thickness to over 7.5 microns when we using the silicon oxide e.g., the point of maximum electric field become at the first corner as a result of the dielectric thickness. In this paper we have given the results until 1.6 µm of dielectric thickness step. Indeed, in our clean room the maximum deposit film of silicon oxide equal to 1.6 µm.

Finally, an idea is to combine the two architectures into a new oxide form in order to obtain the maximum number of corners with minimal technological steps. With this idea, we obtained a maximum electric field equal to 18 MV/cm using the silicon oxide as field plate dielectric and 13 MV/cm using the aluminum oxide.

Conclusion

New field plate architecture for diamond Schottky diode was proposed which helps in increasing the breakdown voltage from 1632 V to 2141 V using the same technological parameters.
The maximum electric field in the field plate provokes a new problem since it is larger than the critical field of dielectric used. To resolve this problem, three solutions were proposed. The first is to make the field plate in a pillars form, the second is to change the field plate to graduated form and the last is making a mixed oxide form in order to increase the corners numbers. With the final solution and

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changing also the dielectric material (from silicon oxide to aluminum oxide) we obtained 13 MV/cm as maximum electric field.

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