Evaluation of the Breakdown Behavior of 4H-SiC Schottky Diodes with a p-Guardring Junction Termination

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ABSTRACT

We have investigated the reverse behavior of 4H Silicon Carbide (SiC) Schottky diodes with a p-guardring junction termination (Fig. 1). The breakdown behavior was analyzed with respect to the doping concentration of the epi-layer underneath the Schottky contact. Furthermore we examined the influence of the effective surface charge of the p-guardring on the breakdown characteristics. Two different methods for determining the breakdown voltage by device simulation were considered to evaluate their ability of predicting the real reverse behavior.

Keywords: Silicon Carbide, high power electronics, Schottky diode, breakdown behavior, device simulation.

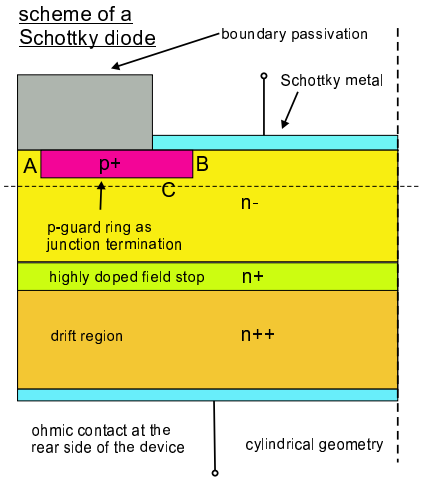

Figure 1: Cross section of the analyzed structure

1 INTRODUCTION

Silicon carbide (SiC) power devices receive increasing attention in application fields of high-voltage engineering and power transmission. Meanwhile, SiC Schottky diodes are available as industrial product and replace the traditional silicon diodes in converters and other components. Due to the physical properties, namely a critical field strength 10 times larger than Si, with a band gap of about 2.5-3 times larger than that of Si, a heat conductivity better than copper and large saturation velocities for electrons and holes, SiC offers best qualities for high power devices. Therefore, SiC Schottky diodes exploit the attractive features of SiC as electronic material: Robust operation under high temperature, very high blocking capability under reverse bias conditions, fast switching speed and a significant reduction of switching losses [2].
Among all of that, the optimization of the blocking capability is one of the most important objectives of the design. To this end, we evaluated the electric breakdown behavior of industrial 4H-SiC Schottky diodes by means of numerical device simulation. The device structure investigated (Fig. 1) features a highly doped p+ guardring at the lateral boundary of the Schottky contact, serving as junction termination in order to avoid a local enhancement of the electric field at this location, and a dielectric boundary passivation layer. The aim was to find the doping concentration and penetration depth of the guardring at various doping levels of the epi-layer which yield the maximum breakdown voltage.

2 DEVICE SIMULATION

The design study was performed using the multi-dimensional device simulator $Dessis_{ISE}$ which is based on a rigorous thermodynamic model of the device behavior comprising the coupled system of Poisson's equation together with the electron continuity and hole continuity equations. The device simulator is based on calibrated models which account for the specific properties of SiC [1]. The reverse behavior, in particular the effect of the junction termination, is characterized by relating the breakdown voltage to the effective surface charge density of the p-guardring. This quantity is defined as $N_A \cdot d_D$ (see Fig. 2), where N_A is the acceptor concentration and d_D the doping depth of the p-guardring. The influence of the epi-layer doping underneath the Schottky contact is quantitatively expressed by the relation bet-

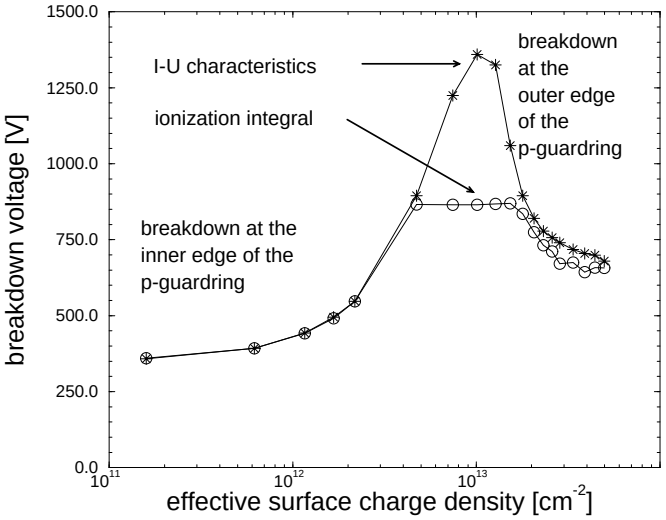

Figure 2: Breakdown voltage versus effective surface charge of the p-guardring defined by the ionization integral method and the evaluation of the I-U characteristics

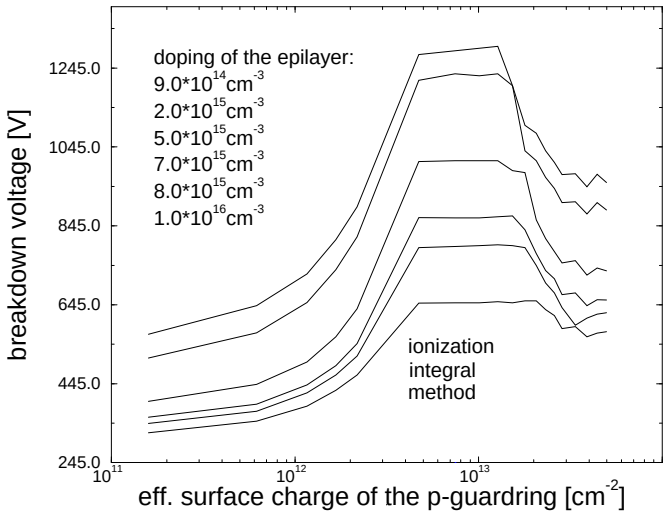

Figure 3: Breakdown voltage versus effective surface charge of the p-guardring for different values of the epi-layer doping defined by the ionization integral method

ween breakdown voltage and the epi-layer doping. The thickness of the n^- epi-layer is assumed as $9\mu m$. In the numerical analysis the Schottky diode was treated as a 2-dimensional structure and the results were achieved by quasistationary simulations at reverse bias conditions.

2.1 P-GUARDRING JUNCTION TERMINATION

In accordance with earlier work [5] we find that, dependent on the Al concentration of the p-guardring, different locations can be identified where avalanche breakdown occurs. High doping leads to critical peaks of the electric field at the outer edge (A) of the p-guardring (see Fig. 1), whereas low doping concentration makes this peak move to the interface underneath the Schottky contact (B). The maximum breakdown voltage is attained if the region with the maximum electric field is situated at a point along the edge of the p-implantation, i.e. in a certain depth inside the bulk (C). So it is obviously the doping concentration of the p-guardring which controls the breakdown voltage and determines the location where avalanche breakdown takes place (Figs. 1 and 2).

2.2 IONIZATION INTEGRAL METHOD AND I-U CHARACTERISTICS

In Fig. 2, two different methods to determine the breakdown voltage are shown. They obviously provide different results and must therefore be compared with respect to the ability of predicting the real reverse characteristics.

The first method uses as criterion for attaining breakdown conditions that the so-called ionization integral becomes equal to one, which indicates that the carrier multiplication factor caused by impact ionization is becoming infinite. Hence, the onset of avalanche breakdown can be detected by inspecting the ionization integrals

$$I_n = \int_0^W \alpha_n(x) \cdot e^{-\int_x^W \alpha_n(x') - \alpha_p(x')dx'} dx \qquad (1)$$

$$I_p = \int_0^W \alpha_p(x) \cdot e^{-\int_0^x \alpha_p(x') - \alpha_n(x')dx'} dx \qquad (2)$$

where $\alpha_{n,p}$ are the impact ionization coefficients for electrons and holes, respectively, and W is the width of the depletion zone. The integrations are performed along field lines through the depletion zone. Equation (1) describes electron multiplication and Equation (2) describes hole multiplication [4]. The evaluation of the ionization integrals leads to a dependence of the breakdown voltage on the doping concentrations of guardring and epi-layer as displayed in Fig. 3. A lower doping of the epi-layer results in an increase of the breakdown voltage. The second method extracts the breakdown voltage directly from the reverse I-U characteristics, tak-

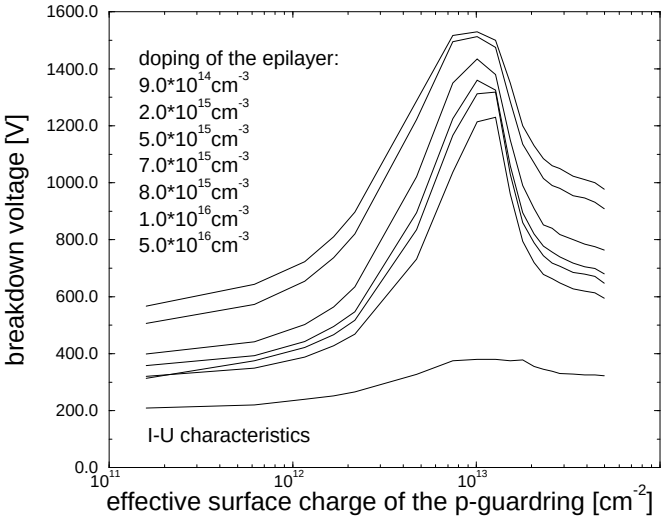

Figure 4: Breakdown voltage versus effective surface charge of the p-guardring for different values of the epi-layer doping defined by the evaluation of the I-U characteristics

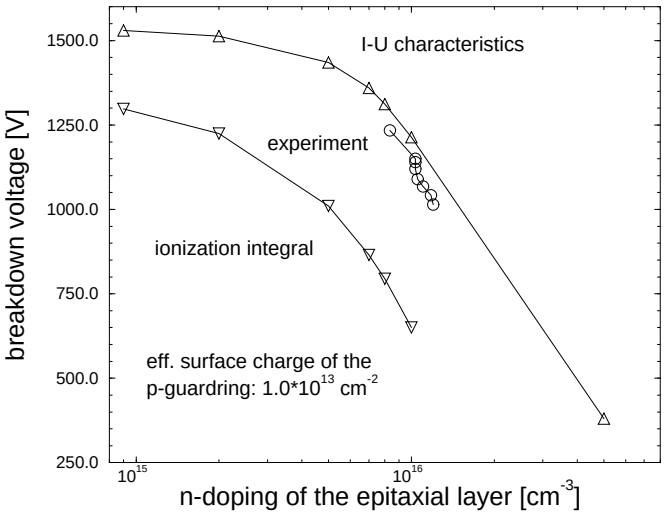

Figure 5: Breakdown voltage versus doping of the epi-layer and an effective surface charge of the p-guardring of $1.0 * 10^{13} cm^{-2}$. Comparison of the ionization integral method and the I-U characteristics with experimental data from *R. Rupp et.al.* [3]

ing the point where the reverse current starts rising to infinity. The breakdown curves obtained by this approach (see Fig. 4) resemble those of Fig. 3, but differ in the values of the maximum attainable breakdown voltage and show a sharper maximum than the curves obtained by the ionization integral method. Comparing the two methods in the special case of an epi-doping of $7.0 * 10^{13} cm^{-3}$ (Fig. 2) the difference in the attainable breakdown voltage amounts to 500V.

2.3 DISCUSSION OF THE SIMULATION RESULTS

In order to clarify the situation, we compared the results of the two extraction methods with experimental data [3] (marked by circles in Figs. 5 and 6). Fig. 5 shows the breakdown voltage versus the doping level of the n-epitaxial layer at a fixed doping of the p-guardring, which is known from the technological process parameters. It becomes evident that the ionization integral method predicts too low breakdown voltages, whereas the evaluation of the I-U characteristics gives a much better estimate of the real breakdown characteristics. Hence, the later method was employed for all further investigations. These are summarized in Fig. 6 showing a family of breakdown curves (breakdown voltage versus epi-doping), where the effective surface charge density of the p-guardring was varied in the range from $1.0 * 10^{13} cm^{-2}$ to $2.5 * 10^{13} cm^{-2}$. The steep decrease of the breakdown voltage with increasing guardring doping corresponds to the right-sided slope of the breakdown curves in Fig. 2. We also find that the experimental data points coincide with the simulated breakdown curve which attains the maximum breakdown voltage. Hence we can confirm that the design of the junction termination is very close to the optimum, leaving very little space for further improvements. However, varying the n-doping of the epi-layer underneath the Schottky contact and the p-guardring doping can be helpful to adapt the device geometry to special switching requests. So, for instance, in special applications a lower breakdown voltage may be sufficient, whereas the on-resistance correlated to the doping of the epi-layer could be reduced.

2.4 SUMMARY AND CONCLUSIONS

The principal effects of a p-guardring junction termination on the breakdown behavior of a 4H-SiC Schottky diode have been investigated by numerical simulation. Two different methods to determine the breakdown voltage were compared with respect to the ability of predicting the real reverse behavior. We find that the evaluation of the I-U characteristics reproduces the experimental data and, therefore, is the better method for examining the breakdown behavior of SiC power devices.

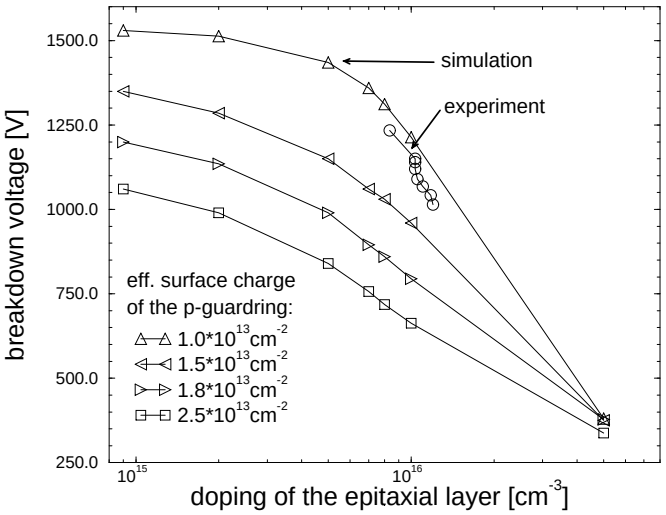

Figure 6: Breakdown voltage versus doping of the epilayer for different dopings of the p-guardring defined by the I-U characteristics, experimental data from *R. Rupp et.al.* [3]

3 ACKNOWLEDGEMENTS

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