4H-SiC Diode Avalanche Breakdown Voltage Estimation by Simulation and Junction Termination Extension Analysis

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Abstract. This paper presents and compares different avalanche breakdown voltage estimation methods in 4H-SiC (silicon carbide) using finite element simulation results on Schottky diode. 4H-SiC avalanche breakdown voltage and depletion width estimated with Baliga's equations have shown to be higher than other estimation techniques and simulation results, especially for voltages higher than 5kV. This paper discusses the impact of choosing different junction termination extension (JTE) structures on two-dimensional junction curvature effects and electric field crowding for Schottky diodes. Space-Modulated JTE (SMJTE) structure with optimum JTE dose and dimension could achieve up to 90% of the parallel plane breakdown voltage. For ultra high voltage devices (>15 kV) the SMJTE has significant improvement in terms of breakdown voltage. It also has a wider optimum JTE dose window. For 1 kV device there is not a significant difference in breakdown voltage between JTE and SMJTE structures.

Introduction

SiC semiconductor devices have been widely expected to replace silicon in power electronics systems due to its superior physical and electrical properties [1]. One of the requirements for designing a high voltage 4H-SiC power device is to accurately estimate the avalanche breakdown voltage in relation to the drift region doping concentration. Impact ionization coefficient is a key part to estimate the relationship between the breakdown voltage and doping concentration, but different power law approximation will result in different impact ionization coefficient values [2, 3]. Recent paper [2] has shown that the Baliga's power law approximation [4] for the impact ionization coefficients for 4H-SiC overestimates the avalanche breakdown voltage by up to 80%. Also, the breakdown voltage results from our simulation using SILVACO is about 20% lower than Baliga's equations.

In this paper, we present and compare different avalanche breakdown voltage estimation methods in 4H-SiC Schottky diode [1-3] with our simulation results. Results have shown that the 4H-SiC avalanche breakdown voltage estimated using Baliga's equations [4] is indeed higher than other estimation techniques. In practice we need to consider the three-dimensional junction curvature effects and electric field crowding near the edge of the junction for power devices. The unterminated planar devices will exhibit very low breakdown voltages as compared to the ideal one-dimensional device structures. Therefore a good junction termination is important to achieve a high breakdown voltage. Several JTE structures such as implanted JTE [5], mesa-combined JTE [6], and etched JTE [7], have been investigated as a promising structure in 4H-SiC. Since the JTE dose needs to be precisely controlled to achieve a high breakdown voltage for a conventional single-zone JTE, many different JTE structures such as space modulated JTE (SMJTE) [8], multiple-floating-zone JTE [9], etc. have been proposed. These different structures have a wider window for JTE dose. In this paper we have looked at and compared the different termination structures on Schottky diode, i.e. unterminated, single-zone and SMJTE.

Device structure and simulation

Fig.1 shows the schematic structure of parallel plane Schottky diode that used in SILVACO for breakdown voltage simulation. N+ substrate has a constant doping concentration of 1e+19 cm^{-3}, N- drift layer has various doping concentrations from 1e+15 cm^{-3} to 1e+17 cm^{-3}. The thickness of epilayer varies according to its doping concentration to avoid punch through in depletion region. The impact ionization model that SILVACO uses to calculate breakdown voltage and depletion width for 4H-SiC is a default anisotropic impact ionization model which is the same as in literature [10]. Parameters of electrons and holes impact ionization coefficients model are shown in Table 1. <0001> direction is used in our simulation. Fig.2 and Fig.3 show the breakdown voltage and maximum depletion width as a function of drift region doping concentration for different estimation methods.

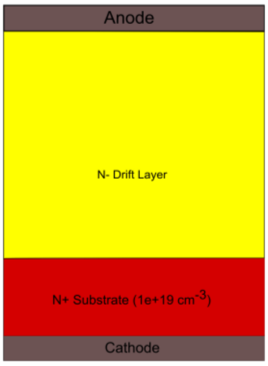

Fig.1. Schematic of paralell plane Schottky

Parameter	a_e	a_h	b_e	b_h
Unit	cm^{-1}		V/cm	
<0001>	1.76×10^{8}	3.41×10^{8}	3.30×10^{7}	2.50×10^{7}
<11$\bar{2}$0>	2.10×10^{7}	2.96×10^{7}	1.70×10^{7}	1.60×10^{7}

Table 1: Default Silvaco 4H-SiC parameters of electron and hole impact ionization coefficients model

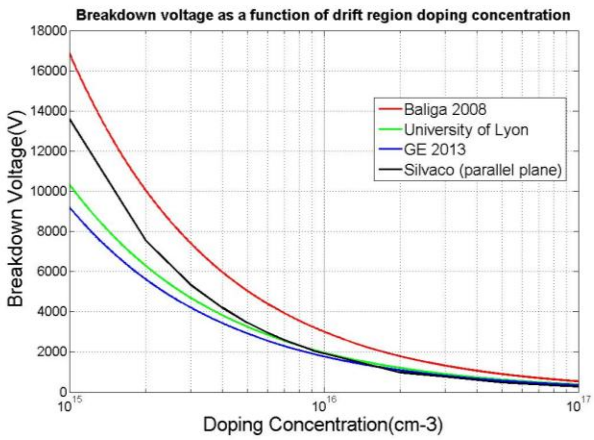

Fig.2. Breakdown voltage versus doping concentration of 4H-SiC for different

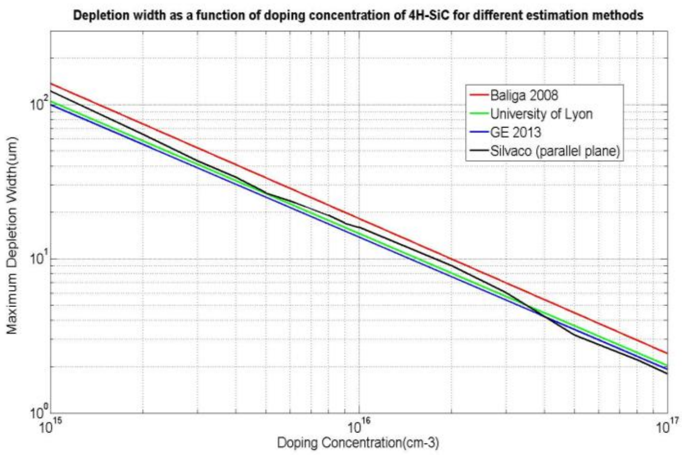

Fig.3. Depletion width versus doping concentration (both in log scale) of 4H-SiC for different estestimation methods.

Result and Discussion

Fig.4 shows the schematic structures of PiN diode with mesa edge single zone, space modulated JTEs (SMJTE) and space modulated two zones JTE (SM-MZ-JTE) and their respective breakdown electrical field plots. Breakdown voltage as a function of the JTE doping concentration is shown in Fig.5. The total length of the termination was fixed at 600um for all JTE structures. The spaces within SMJTE are followed by the mean does ratio in one period, $R = d_{ring} / (d_{space} + d_{ring})$, where R was varied with a tapered profile from 0.7 to 0.3 while keeping the number of spaces n = 5. The implant profile of JTE region was set as box profile with depth of 0.8 um. The diameter of the mesa is 300 um and the height of the mesa is 1 um. The ratio of the JTE dose in JTE1 and JTE2 for SM-MZ-JTE were fixed to 3:2.

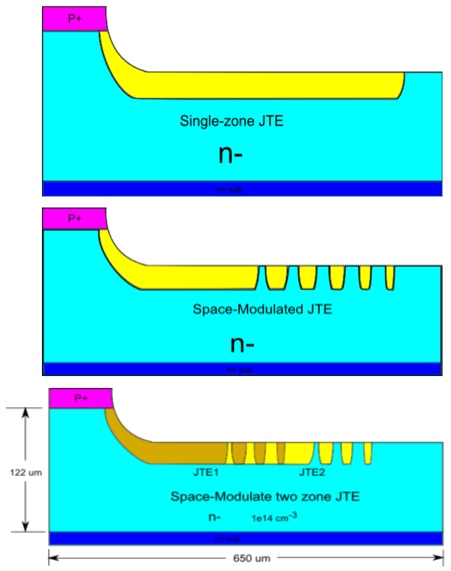

Fig.4. Schematics of the three different JTE structures of PiN

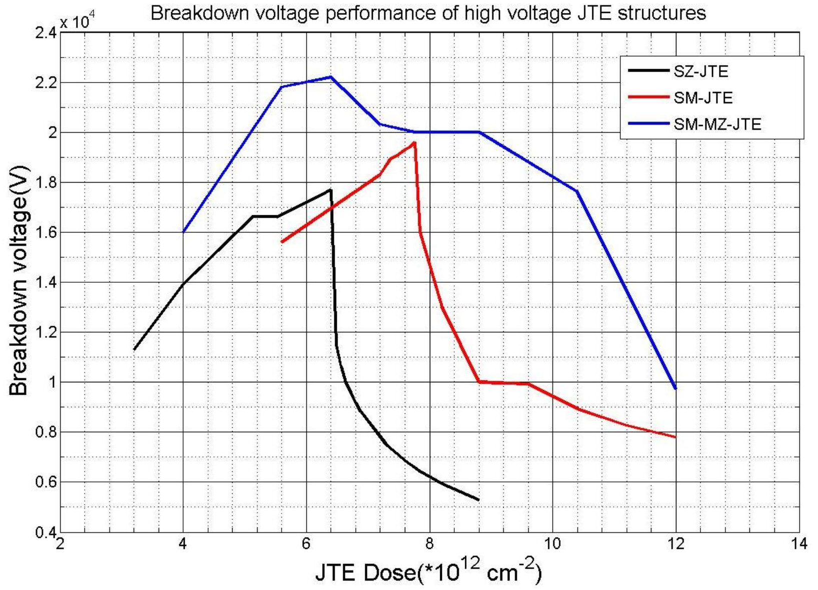

Fig.5. Simulated JTE dose dependence of breakdown voltage for 22.5 kV PiN diodes with different JTE structures.

Simulation results have shown that for the same doping concentration the SM two-zone JTE has the highest breakdown voltage. Maximum breakdown voltage of 22.2 kV was obtained in the SM two-zone JTE, which is about 98.6% of the ideal 1D parallel plane breakdown voltage (22.5 kV) obtained from 1D PiN diode simulation. The SM two-zone JTE also gives a wider optimum JTE doping window for breakdown voltage above 20 kV, which is advantageous when it comes to device fabrication. The drawback of the SM two-zones JTE is that it requires two separate implantations which require extra mask and higher cost. For 1 kV devices (drift region thickness of 10um and 2e16 cm^{-3} doping concentration) there is not much difference between JTE structures in terms of peak breakdown voltage as shown in Fig.6, but the SMJTE and SM-MZ-JTE still provide a wider optimum JTE doping window than single zone JTE.

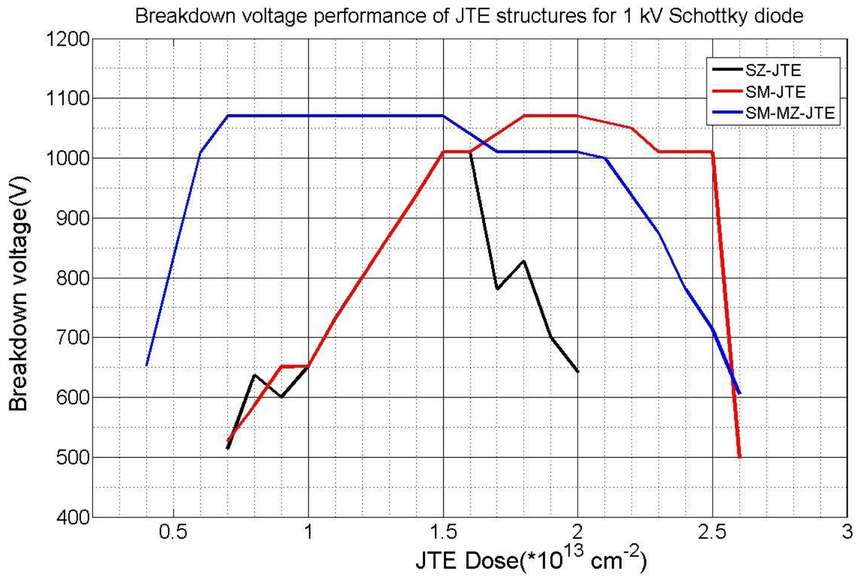

Fig.6. Simulated JTE dose dependence of breakdown voltage for 1kV Schottky diode with different JTE structures.

From Fig.6 it is seen that the peak breakdown voltage of 2D Schottky diode with the JTEs is 1070 V at JTE dose of around 1.5e+13 cm^{-2}, which is about 97% of the parallel plane breakdown voltage

(1110 V). Although the peak breakdown voltage is almost the same for all JTE structures, the SMJTE still shows better doping window than the single zone JTE. SM-MZ-JTE provides even wider optium doping window with peak breakdown voltage shift slightly towards the lower JTE dose range.

Summary

Different avalanche breakdown voltage estimation methods for the 4H-SiC has been investigated and compared with the SILVACO simulation results. It is found that the breakdown voltage estimated using Baliga's equations [4] is higher than others estimation methods especially for voltage greater than 5 kV. A mesa-SMJTE edge termination for 4H-SiC Schottky diode has also been investigated together with the conventional single zone JTE. SM two zones JTE could achieve up to 98% of the ideal parallel plane voltage and gives a wider optimum JTE doping window for ultra high voltage devices (20kV), but has disadvantage of more implantation steps and higher cost. For 1 kV Schottky diode there is no significant difference between the single zone JTE, SMJTE and SM two zones JTE in terms of peak breakdown voltage, but SMJTE still shows wider doping JTE doping window than single zone JTE. The peak breakdown voltage with SMJTE for the 1 kV Schottky diode could also achieve about 97% of the parallel plane breakdown voltage. Results have demonstrated that with the design of SMJTE or SM two zones JTE, breakdown voltage of up to 97% of ideal breakdown voltage can be achieved for wider range of JTE doses.

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