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Realistic Simulations on Reverse Junction Characteristics of SiC and GaN Power Semiconductor Devices

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Abstract

This paper presents a practical methodology for realistic simulation on reverse characteristics of Wide Bandgap (WBG) SiC and GaN p-n junctions. The adjustment on certain physic-based model parameters, such as the trap density and photo-generation for SiC junction, and impact ionization coefficients and critical field for GaN junction are described. The adjusted parameters were used in Synopsys Medici simulation to obtain a realistic p-n junction avalanche breakdown voltage. The simulation results were verified through benchmarking against independent data reported by others.

Key Words: High voltage p-n junction, SiC/GaN diode simulation, WBG power semiconductor

I. Introduction

Wide bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), have received considerable attention in the research and development of future generation power semiconductor devices. Wide bandgap materials provide high critical electric field, which is suitable to sustain high breakdown voltage [1]–[4]. The maturing technology in the production of single crystal SiC substrates and its process technologies enable the successful fabrication of extremely high voltage SiC devices. On the other hand, the GaN-based high voltage devices offer the promise of great advantage in power density, efficiency and cost saving, without much problem of the channel mobility issue. All of these make the GaN power device the potential competitor.

In principle, ideal SiC and GaN devices can both be simulated in Synopsis Medici [5] with default models and parameters available. However, simulation of reverse characteristics of WBG p-n junction using Medici poses challenges as the ideal equilibrium minority carrier concentration is too low to yield meaningful result on impact ionization carrier generation. In the practical situation, the equilibrium minority carrier concentration is much higher than the default level due to traps caused by the inherent substrate defects or fabrication processes. This needs to be adequately addressed in simulation model in order to yield meaningful results.

In this paper, we report a practical methodology to simulate 4H-SiC and GaN p-n diodes with model parameter adjustment in Medici. Some discussions on defects, photo-generation, impact ionization coefficients and critical field parameters are made. The obtained results are compared with reported results to clearly establish predictive capability of the simulations. This study paves the way for simulation of other SiC and GaN devices in their reverse-bias state.

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II. Physical Parameters

A. SiC p-n Junction Diode[6]

The current state-of-the-art quality of SiC high power devices are still a distance away from the ideal state, partially due to the imperfect substrate quality and limited fabrication techniques. Moreover, the variety of defects in SiC wafers and their adverse influence on device performance needs to be captured adequately in simulators. The approach taken in this work along with a brief discussion on defects now follows.

The common defects found in SiC epi-layers can be classified into two types: surface defects and crystalline defects. The surface defects, such as small growth pits and scratches, mainly affect the shallow junction devices, such as Schottky diodes. As for the types of crystalline defects, such as micropipes, inclusions, and elementary screw dislocations are detrimental to p-n junctions and other buried layers. The density of elementary screw dislocations typically ranges from 10^3 cm^{-2} to 10^4 cm^{-2} [7] and is the largest. This high density makes it the most detrimental defect for SiC device. The breakdown voltage reduction owing to elementary screw dislocations ranges from 10% to 30% compared to the ideal.

Hence, it is important to include the influence of the elementary screw dislocations on the electrical characteristics

of SiC devices on the substrate containing such a defect. It is known that the SiC diode reverse characteristics are primarily varied by the enhanced impact ionization process due to the dislocation defects [8]. The presence of dislocations leads to the creation of trap states within the band gap leading to enhancement in carrier generation to participate in the impact ionization process. The device breakdown voltage and leakage current are to be influenced and determined by such an important parameter. The lowered breakdown voltage due to this mechanism should depend on the trap energy level and density. The dislocation levels are reported in [9] to be at (E_C - 0.3 eV) and (E_V + 0.4 eV). These levels are included in simulation to properly model the adverse effect of the defects on device reverse characteristics.

In SiC, the annealing process after ion-implantation is a major process challenge because the material is dense and stable with a short bond length (about 1.9Å) and a high binding energy. Consequently, intrinsic point defects are anticipated to exhibit a high thermal stability. In addition, for common dopants Al, B, N, and P, high-temperature post-implant annealing (1400–1800°C) is required to reach the activation energy level. However, still only limited defect annealing can be achieved after ion-implantation. The existence of defects forms traps in the bandgap, which enhances carrier generation.

To simulate the SiC p-n junction practically in Medici, it needs to take the effect of all the defects into account through the TRAP model. If the trap state is specified as CHARGED as in the case of donor state, then the following form of the Poisson equation can be used [6].

$$\varepsilon\nabla^2\psi = -q(p-n+N_D^+ - N_A^- - \sum_i N_{t_i}(f_i-1)) - \rho_s \qquad (1)$$

Where ψ is the intrinsic Fermi potential, p and n are hole and electron concentrations respectively, $N_D{}^+$ and $N_A{}^-$ are the ionized impurity concentrations, ρ_S is a surface charge or interface charge density and N_{ti} is the total number of traps for the i-th energy level. N_{ti} is calculated from the N.TOTAL parameter specified by the TRAPS statement and is also a function of energy and position. Thus the simulation results are able to capture the influence of defects on practical SiC device.

B. GaN p-n Junction Diode

The emphasis on GaN p-n junction breakdown simulation is instead on the selection of impact ionization coefficients of electrons and holes. Fig. 1 shows the calculated impact ionization coefficients as a function of inverse electric field for electrons and holes in both zincblende and wurtzite phase GaN [10]. It can be seen that, the impact ionization coefficients tend to merge within a zone between 5×10^4 and 3×10^5 per cm when the field is close to or larger than 4 MV/cm, knowing that the critical electric field is in the range of 3 to 6 MV/cm.

III. Simulation Results and Discussion

A. SiC p-n Diodes

One common difficulty in the SiC device breakdown simulation is the convergence problem due to very low intrinsic carrier concentration at room temperature. Such a low minority carrier concentration prohibits the impact ionization, hence a realistic numerical solution is not possible. One way to avoid this problem is by adding a photo-generation statement in Medici at around the SiC p-n junction to artificially increase minority carrier concentration. The photo-generation effect can be removed once the avalanche generation begins and a much larger number of electrons and holes exist to continue the impact ionization process for proper reverse bias behaviors.

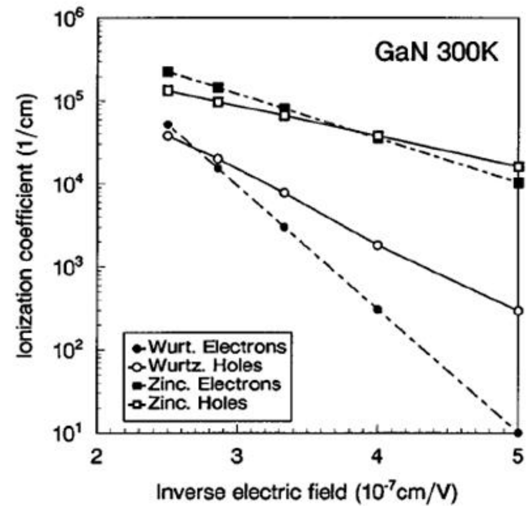

Fig. 1. Calculated impact ionization coefficients as a function of inverse electric field [10].

In MEDICI, the photo-generation model provides the steady-state and time-dependent injection of electrons and holes into the specific device area. For the ease of simulation, full complexity of this model is not required and by setting of a single constant parameter Al is sufficient. The value of parameter Al, which represents uniform carrier generation, will determine the carrier photo-generation rate, and thus raise up the carrier concentration within a device. According to previous study, A1 should be high enough to have a sizeable carrier concentration for the initialization of impact ionization and at the same time not causing the device breakdown by overwhelming large number of electrons and holes. When A1 is set in a suitable range between the lower limit and upper limit, the simulated result on breakdown voltage is independent of the photo-generation rate. A suitable value for A1 is to be 10% of the doping concentration of the drift layer.

Since most of the defects occur during SiC growth and dopant implantation damage, defect density should be a function of the parameters associated with these processes. Hence, we can expect that the trap density created by defects is related to drift layer concentration and thickness. Higher dose and hence higher dopant concentration of implantation will lead to a larger defect density. A thicker drift layer requires higher the implantation dose, depth and energy for doping adjustment, which will lead to larger defect density as well. Moreover, to grow a thicker drift layer, longer time for high temperature HTCVD growth is required when fabricating the original wafer, which will also lead to a larger defect density. Therefore, a linear relationship for trap density (cm^{-3}) in terms of the doping and the drift layer thickness is assumed

TABLE I
SiC P-N JUNCTION SIMULATION RESULTS FOR VERIFICATION

n-Layer Concentration (cm^{-3}) and Thickness (μm)		Reported breakdown Voltage (V)	Trap Density (cm^{-3})	Simulated breakdown voltage (V)	Simulated breakdown voltage without traps (V)
2×10^{14}[11]	100	8600	8.9432×10^{16}	9710.7	14272
3×10^{15}[12]	35	3500	3.1497×10^{16}	3346	3953.9
9.3×10^{15}[13]	13	1267	1.2245×10^{16}	1294.4	1682.1
1.3×10^{17}[14]	2	280	1.0466×10^{16}	270.5	270.7

to capture these effects as:

$$D_{trap} = \alpha \times N + \beta \times W \quad (2)$$

where N (cm^{-3}) is the drift layer doping concentration, W (μm) is the thickness of drift layer, α and β account for parameters of trap density induced by implantation and growth respectively. The value of these two parameters were obtained by matching the simulated data of reported devices to the experimental data. By adjusting trap concentrations and doing a linear least squares fit to the values, it arrived at the best values of α = 0.06675 and β = 0.89×10^{15}. To assess the validity of the parameters, the trap densities calculated from eq.(2) were applied to simulation of diodes reported in [11]–[14] and the results of breakdown voltages are compared to reported ones as shown in Table I.

The breakdown voltages simulated without traps show much difference from the reported data compared to those with trap density. It should be noted that the default Medici simulations are reasonably accurate for device with thin drift layer indicating marginal role played by traps. This confirms excellent utility of the trap model in Medici with eq.(2) to realistically simulate the SiC p-n junction. The dependence of breakdown voltage of p-n diodes against the trap density is depicted in Figs. 2 and 3 at different width W and doping concentration. It can be seen that, the influence on the trap density existence is more prominent at thick and lightly doped drift region.

Simulated leakage current curves with adjusted A1 to fit reported curves are shown in Figs. 4 and 5. The A1 values set for diodes of [15] and [16] with respective drift layer concentrations 9.7×10^{15} cm^{-3} and 3×10^{15} cm^{-3} are 2×10^{15} cm^{-3} and 1×10^{14} cm^{-3} respectively. As A1 set in the range between $1\times10^{13}cm^{-3}$ and $1\times10^{18}cm^{-3}$ does not vary breakdown voltage simulation, we can choose optimum value of A1 to be about 10% of drift layer doping concentration to find the reverse current.

However, this optimized A1 may vary depending on the SiC doping concentration, substrate quality and fabrication environment. If the substrate quality, and/or fabrication environment are relatively better, a slightly lower value below 10% of doping concentration can be picked up for simulation and vise versa.

Reported leakage current for diode [17] with drift layer concentration $1\times10^{15}cm^{-3}$ is simulated with the optimized A1 of 1×10^{14} cm^{-3}. Predictive capability for SiC p-n junction leakage current is verified through a good match of the simulated leakage current with reported experimental data as shown in Fig. 6.

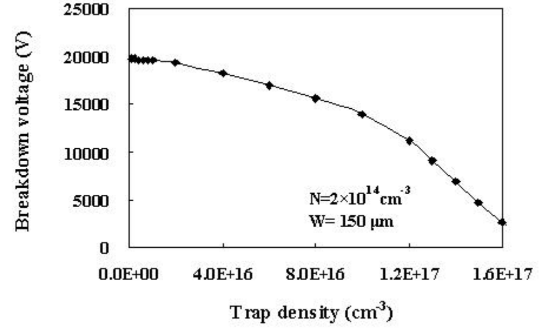

Fig. 2. Simulated breakdown voltage of SiC diode vs. trap density. Influence of trap density is very strong for thick low doped drift region.

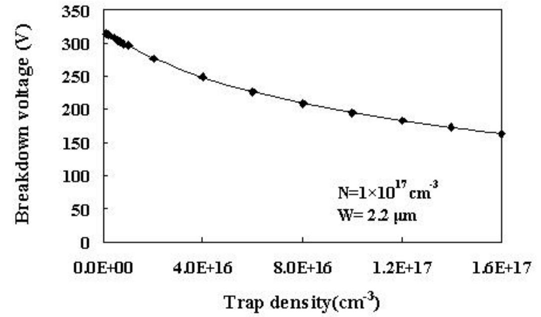

Fig. 3. Simulated breakdown voltage of SiC diode vs. trap density. The influence of heavily doped drift layer is not as strong as that of the lightly doped case.

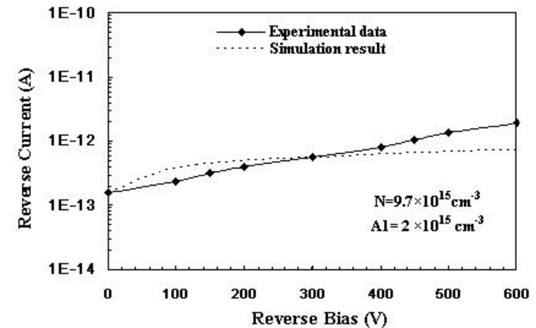

Fig. 4. Experimental and simulated reverse current characteristics of SiC p-n diodes [15].

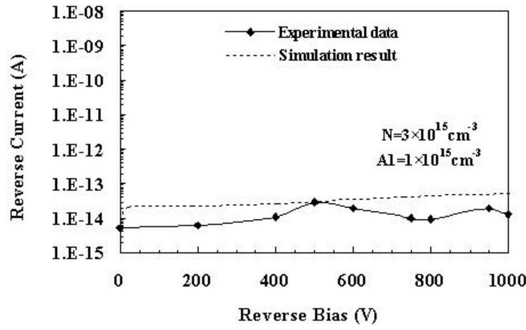

Fig. 5. Experimental and simulated reverse current characteristics of SiC p-n diodes [16].

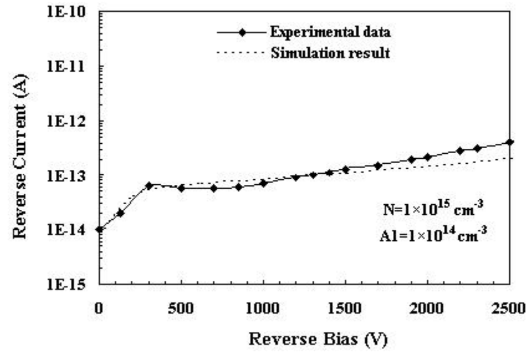

Fig. 6. Application of the methodology to predict reversed current characteristics of a reported SiC p-n diode [17].

B. GaN p-n Diode

As stated, the adjustment in impact ionization coefficients is made for the simulation for GaN p-n junction breakdown. The coefficients are listed in Table II for comparison. The critical field is set to be 5×10^6 V/cm for the coefficients (in wurtzite phase) to be in the specified region.

The simulation results on breakdown voltage is shown in Fig.7. The p-n junction has the profile of 5000Å p-GaN top layer at 10^{18} cm^{-3}, 4 μm undoped GaN drift region and 1.2 μm n$^+$-GaN at 3×10^{18} cm^{-3}.

From the figure, the adjusted coefficients within the specified zone give the breakdown voltage at 500 V, which is in close agreement with the device in [18]. If the default coefficient and critical field are used, the breakdown voltage is simulated at 1700 V. By adjusting critical field depending on GaN defect density (the higher the defect density, the lower the critical field number should be) and drift region thickness (the thicker the epi drift region, the lower the critical field number should be), the simulation methodology can be applied to other GaN devices. For the GaN vertical p-i-n diode of 2 μm drift region thickness in [19], the simulation was done with E_c = 6.8×10^6 V/cm to yield a similar breakdown voltage of 410 V.

Investigation has also been done on the dependency of critical electric field against the drift region doping concentration.

TABLE II
ADJUSTMENT IN IMPACT IONIZATION COEFFICIENTS

	α_n	α_p	E_c
Ideal (no defect)	2.5×10^8	8×10^5	3.4×10^7
Adjusted (with defect)	2.2×10^5	6×10^4	5×10^6

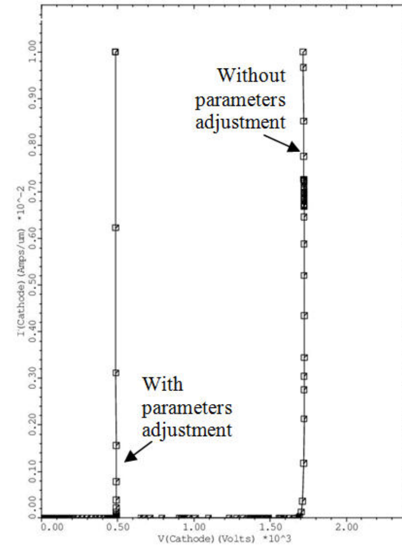

Fig. 7. Breakdown voltage of GaN p-n junction simulated with (breakdown at 500V) and without (breakdown at 1700 V) adjusted impact ionization coefficients.

Preliminary results gave the relationship

$$E_c = 3.97\times10^6 + 3.06\times10^{11}N \tag{3}$$

for the range between 10^{15} and 10^{18} cm^{-3}. Further investigations on quantitative expression of E_c against drift region thickness, doping concentration and defect density will be carried out.

IV. CONCLUSIONS

A practical methodology for SiC and GaN p-n junction breakdown simulation is reported. The approach to select optimum trap and carrier photo-generation density parameters based on the doping concentration and drift layer thickness, which are physically linked to the defect density, is described. With these two parameters properly chosen, both the breakdown voltage and leakage current of simulated SiC p-n diodes match the experimental data well. The methodology clearly shows that the influence of defects on junction breakdown characteristics can be properly captured. On the GaN p-n junction simulation, the impact ionization coefficients are adjusted within the specified critical field zone based on the physics calculated. Adjustments on the critical field and impact ionization coefficients were found necessary in order to obtain realistic simulation outcomes.

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