Simulation of Dynamic Ionization Effects in 6H-SiC Devices

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Abstract

A numerically robust and physically consistent implementation of the rate equations describing the dynamics of discrete impurity states (deep traps) in the band gap has been accomplished within the framework of an advanced drift-diffusion model. Conceiving the dopants in SiC as such energy states, the impact of long ionization time constants on the device operation has been demonstrated.

1. Introduction

In the recent decade, silicon carbide (SiC) has received more and more attention for high-power, high-temperature, and high-frequency device applications [1]. Due to its wide band gap and the corresponding large ionization energies of the dopants, quasi-static and dynamic incomplete ionization effects can very sensitively affect the device characteristics. Additional balance equations accounting for these effects have been added to the drift-diffusion model implemented in the multi-dimensional device simulator DESSIS_ISE [2]. We applied this extended model to analyze the dynamic response of 6H-SiC pn-junctions to different transient bias conditions such as a reverse bias pulse and the switch-off behavior of a power diode. A comparison between the quasi-static approximation usually applied and the complete dynamic model will be given.

2. Modeling

Within the framework of phenomenological transport theory [3], each energy state tp ($tp \in Traps$) situated in the band gap contributes to the isothermal drift-diffusion equations by an additional rate equation (5) which couples to the Poisson and continuity equations (1) - (3):

$$\vec{\nabla}(\tilde{\varepsilon}\vec{\nabla})\,\Psi = q\,[n - p + N_A^- - N_D^+ - \sum_{tp} N_{tp}(z_{emp}^{tp}(1-f_{tp}) + z_{occ}^{tp} f_{tp})] \tag{1}$$

$$\frac{\partial n}{\partial t} - \frac{1}{q}\vec{\nabla}\,\vec{J}_n = -R + \frac{\partial N_D^+}{\partial t} + \sum_{tp}(N_{tp}[e_n^{tp} f_{tp} - c_n^{tp} n(1-f_{tp})]) \tag{2}$$

$$\frac{\partial p}{\partial t} + \frac{1}{q}\vec{\nabla}\,\vec{J}_p = -R + \frac{\partial N_A^-}{\partial t} + \sum_{tp} (N_{tp}[e_p^{tp}(1 - f_{tp}) - c_p^{tp} p f_{tp}]) \tag{3}$$

$$\vec{J}_\alpha = q\,\alpha\,\tilde{\mu}_\alpha\,\vec{\nabla}\phi_\alpha,\ (\alpha = n,\,p) \tag{4}$$

$$\frac{\partial f_{tp}}{\partial t} = -(e_n^{tp} + e_p^{tp} + c_n^{tp} n + c_p^{tp} p) f_{tp} + e_p^{tp} + c_n^{tp} n. \tag{5}$$

This system of mixed differential equations has to be solved for the electrostatic potential Ψ, for the occupation probabilities f_{tp} of the impurity states, and for the electron and hole densities n and p, respectively.

Due to the anisotropic material properties of 6H-SiC, the current relations (4) are tensor equations just as eqn. (1) with the static dielectric tensor $\tilde{\varepsilon}$ and the tensors of the carrier mobilities $\tilde{\mu}_\alpha$ for electrons and holes, respectively [5]. Here, q denotes the elementary charge, while $\vec{J}_\alpha$ are the current densities and ϕ_α are the quasi-Fermi potential of the electrons and holes, respectively. The carrier recombination rate R is modeled by field-enhanced Shockley-Read-Hall (SRH) statistics [4].

In this work, we want to focus on the dopant dynamics by conceiving them as acceptor or donor-like impurities with nearly vanishing coupling to the conduction or the valence band. The influence of other impurity states such as deep traps, which act in addition to the dopants, will be neglected in the following.

(i) Quasi-static approximation: In this case, the incomplete ionization of the dopants can be described by Gibbs distributions which read in the case of acceptors, for instance, as follows:

$$N_A^-(\phi_p, T) = \frac{N_A}{1 + \frac{1}{g_A}\exp(\frac{E_A - q\Phi_p}{kT})}. \tag{6}$$

Here N_A denotes the total acceptor concentration, N_A^- the ionized portion of this concentration which occurs in equations (1) - (3), E_A the ionization energy, and g_A the degeneracy factor. This approximation is valid as long as the transient charging and discharging processes of the dopants can be considered as very fast compared to all other electrical and thermal time constants. However, the time derivative in eqn. (3) has to be included, because N_A^- is a function of the quasi-Fermi potential ϕ_p [7]. Incomplete ionization reduces the concentration of free carriers in field effect transistor channels as well as in forward biased pn-junctions according to the type and concentration of the dopants and the device temperature.

(ii) Dynamic ionization: With increasing depth of the energy levels of the dopants, the time constants for ionization and neutralization may rise in such a way that the correct dynamical operation of the device must be described in the same way as deep impurities characterized by emission and capture coefficients

$$c_\alpha^{tp} = \sigma_\alpha^{tp} v_{th} \tag{7}$$

$$e_\alpha^{tp} = \sigma_\alpha^{tp} v_{th} N_\alpha g_{tp}^{-1} exp[\frac{-E_{tp}}{kT}] \tag{8}$$

Here, σ_α^{tp} are the capture cross sections for electrons and holes, respectively, N_α are the corresponding effective densities of states and E_{tp} the ionization energies with respect to the pertinent band edge. Thus N_A^- and N_D^+ have to be replaced by equivalent trap densities N_{tp} $(tp = A, D)$ with charge numbers $z_{emp}^{tp} = z_{emp}^{D} = 1$ and $z_{occ}^{tp} = 0$ for donors, and $z_{occ}^{tp} = z_{occ}^{A} = -1$ and $z_{emp}^{tp} = 0$ for acceptors. Conservation of electric charge implies that the increase of free carriers per time due to impurity ionization is given by the sums in equations (2) and (3).

3. Results

Depending on the emission and capture rates of the dopants and the temperature, the dynamic response of the incompletely ionized dopants in a SiC device may sensitively influence the dynamic device behavior. In Fig. 1, the transient evolution of the space charge region around a pin-junction during a reverse switch-off pulse with a rise time of 10 ns is compared for two different cases. The dotted lines are the result of the quasi-static approximation, with aluminum as acceptors in the low doped region at room temperature. For an exact simulation of the dynamic behavior of aluminum, the doping of the low doped region is excluded from eqs. (1) - (3) and replaced by an appropriate trap level (5) instead. The emission and capture rates are adapted from admittance measurements [6]. In consequence of the slower response time $\tau_B \approx 1/e_p$ of aluminum, the maximum extension of the space charge region is dynamically larger than in the quasi-static case. As the voltage rises, first only that portion of acceptors which is ionized at thermal equilibrium (about 65% in this case) is able to contribute to the space charge required for sustaining the bias voltage ($1ns$). Subsequently, we observe the gradual ionization of the still unionized aluminum with the response time τ_B in an increasing vicinity of the pn-junction ($10ns$). Finally, this leads to the same extension of the space charge region as in the quasi-static case ($30ns$).

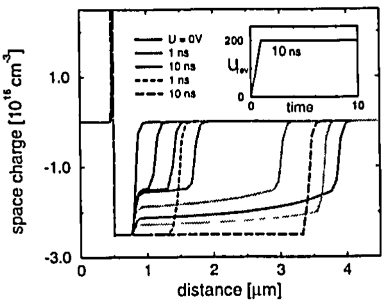

Figure 1: Dynamic evolution of the space charge at a pn-junction during a reverse bias pulse.

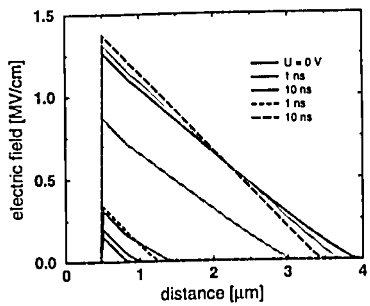

Figure 2: Electric field distribution at a pn-junction during a reverse bias pulse.

In Fig.2, the corresponding distribution of the electric field is plotted. The dynamically inhomogeneous space charge region leads to a varying gradient of the electric field. The maximum electric field at the pn-junction is reached not before $30ns$. The different punch-through behavior caused by these effects has to be accounted for in the design of power devices.

To demonstrate the practicability of numerical simulations with the static doping concentration substituted by additional rate equations, the switch-off characteristics of a SiC PIN high-power diode have been simulated (Fig. 3). Due to the higher electrical breakdown field of SiC, the low doped regions of power devices can be designed much smaller compared to silicon devices with the same maximum blocking voltage. Because of the reduced storage charge, we also find a significant reduction of the switching losses.

In Fig. 4, the electric field distribution during switch-off including the complete dynamic model is compared to the quasi-static approximation for boron as acceptors. The larger ionization time of boron [6] results in a significantly larger depletion region overshoot compared to Fig. 2. A reverse voltage of 100 V is obtained at 40 ns accounting for this effect and at 55 ns using the quasi-static approximation. We obtain a nearly homogeneous electric field distribution in the low doped region and a smaller maximum electric field at the pn-junction. Thus the influence of a dynamic avalanche would be reduced by this effect.

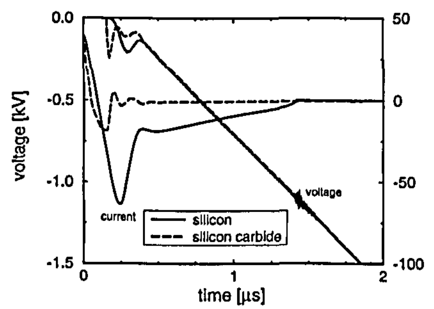

Figure 3: Comparison of the switch-off characteristics of a Si and a 6H-SiC PIN diode.

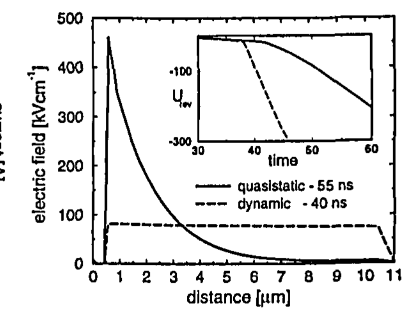

Figure 4: Field distribution in the low doped region during switch-off.

4. Conclusion

The transient incomplete ionization of dopants in wide band gap semiconductor devices such as a SiC PIN high-power diode has been modeled by conceiving them as deep energy states described by additional rate equations which have been added to an advanced drift-diffusion model. The quasi-static approach usually applied to model such devices cannot be applied within a wide operation range.

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