A Two Dimensional Nonlinear Ambipolar Diffusion Equation Model of an IGBT and its Numerical Solution Methodology

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To consider the nonlinear and the two-dimensional characteristics of the carries and holes in the draft region of a planar-gate insulated gate bipolar transistor (IGBT), which are not properly modeled in the existing physics-based models, a two dimensional Ambipolar Diffusion Equation model is proposed and solved using the finite element method. Moreover, a numerically iterative procedure is introduced to simply and efficiently solve the nonlinear finite element equations. The numerical results of the transient performances obtained using the proposed model and solution methodology show good agreement with those of the corresponding experiment, validating the high accuracy and feasibility of the proposed model and method.

***Index Terms*—Ambipolar diffusion equation, insulated gate bipolar transistor, transient behavior.**

I. A TWO DIMENSIONAL AMBIPOLAR DIFFUSION EQUATION MODEL AND ITS SOLUTION METHODOLOGY

DUE to the high power density and low loss, the insulated gate bipolar transistor (IGBT) has played an ever-increasing important role in large power electronics devices. The model and method to compute precisely the performances, especially the transient one, of an IGBT, is thus the most topical issue in recent power electronics studies [1]-[3]. Nevertheless, the development of the advanced physics based IGBT model and method is lagging the advancement of the device. For example, the inherent nonlinearity and the two dimensional inhomogeneous characteristics of the electromagnetic phenomenon are not approximately modelled in the existing studies [1-6]. Also, the transients of the carrier are simplified to a steady or quasi-steady description [7]-[9]. In this regard, a two-dimensional (2D) Ambipolar Diffusion Equation (ADE) model of an IGBT and its numerical solution methodology are proposed.

In the forward (on-state) operation of an IGBT, the behavior of carriers at the MOS end is shown in Fig. 1. Between the p-well and the drift region, there is a reverse-biased junction in the IGBT on-state process. Therefore, around the p-well, a depletion layer appears, forcing the excess carrier density around the p-well to be approximately zero [9]. Close to the depletion layer, there is an accumulation layer under the MOS gate, which is a very thin highly concentrated source of electrons, and holes are attracted to this layer. Therefore close to the accumulation layer, the carrier concentration is maximum in the intercell region [9]. However, most of the existing physics-based IGBT model assume one dimensional distribution of the carriers in the N- drift region.

In the drift region of an IGBT, the freedoms are the hole and electron current densities, as governed by the following 2D Ambipolar Diffusion Equation (ADE):

$$\boldsymbol{J}_{\mathrm{p}} = ep\mu_p \boldsymbol{E} - eD_p \nabla p \tag{1}$$

$$\boldsymbol{J}_{\mathrm{n}} = en\mu_n \boldsymbol{E} + eD_n \nabla n \tag{2}$$

where, n is the electron concentration, p is the hole concentration, μ_n is the electron mobility, μ_p is the hole mobility, D_p is the hole diffusivity, D_n is the electron diffusivity, and $\boldsymbol{E}$ is the electric field strength.

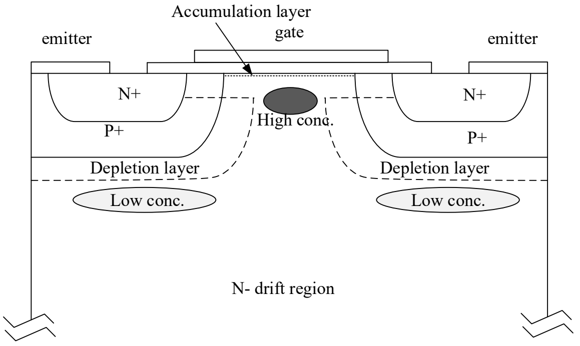

Fig. 1. Behavior of carriers in the P-well and intercell regions for IGBT. The high carrier concentrations are associated with the accumulation layer, while the low concentrations are associated with the depletion layer.

The total current density is the sum of the hole and electron current densities:

$$\boldsymbol{J} = en\mu_n \boldsymbol{E} + ep\mu_p \boldsymbol{E} + eD_n \nabla n - eD_p \nabla p \tag{3}$$

The continuity equations for hole and electron concentrations are:

$$\frac{\partial p}{\partial t} = -\nabla \cdot \boldsymbol{F}_p^+ - \frac{p}{\tau_p} + g_p \tag{4}$$

$$\frac{\partial \mathrm{n}}{\partial t} = -\nabla \cdot \boldsymbol{F}_n^- - \frac{n}{\tau_n} + g_n \tag{5}$$

where $\boldsymbol{F}_p^+$ is the hole-particle flow, $\boldsymbol{F}_n^-$ is the electron-particle flow, g_p and g_n are the generation rates of holes and electrons respectively, τ_p is the hole lifetime, and τ_n is the electron lifetime.

One divides the hole current density by (+*e*) and the electron current density by (-*e*), and obtains each particle flux:

$$\frac{\boldsymbol{J}_p}{+e} = \boldsymbol{F}_p^+ = \mu_p p \boldsymbol{E} - D_p \nabla p \tag{6}$$

$$\frac{\boldsymbol{J}_{\mathrm{n}}}{-e} = \boldsymbol{F}_n^- = -\mu_n \mathrm{n} \boldsymbol{E} - D_n \nabla n \tag{7}$$

Finally, the 2D ADE is derived as:

$$D(\nabla^2 \Delta p) + \mu(\boldsymbol{E} \cdot \nabla \Delta p) - \frac{\Delta p}{\tau} = \frac{\partial \Delta \mathrm{p}}{\partial \mathrm{t}} \tag{8}$$

where, $D = \frac{D_n D_p (n+p)}{nD_n + pD_p}$, $\mu = \frac{\mu_n \mu_p (n-p)}{n\mu_n + p\mu_p}$,

$\tau = \frac{n\mu_n + p\mu_p}{n\mu_n / \tau_n + p\mu_p / \tau_p}$, $\boldsymbol{E} = \frac{\boldsymbol{J} - eD_n \nabla n + eD_p \nabla p}{en\mu_n + ep\mu_p}$,

$\mathrm{n} = \Delta p + N_B$, $p = \Delta p + n_i^2 / N_B$, $\frac{\mu_n}{D_n} = \frac{\mu_p}{D_p} = \frac{e}{kT}$,

where, Δp is the excess hole concentration, Δn is the excess electron concentration, n_i is the intrinsic carrier concentration, N_B is the base doping concentration, k is the Boltzmann's constant, T is the Lattice temperature.

The relationship between the coefficients and Δp is nonlinear in (8). The ADE is thus a nonlinear partial differential equation. Moreover, the finite element method is employed to solve the 2D nonlinear ADE, and a sequentially iterative approach is proposed to solve finite element equations related to the nonlinear ADE, and will be explained in details in the full paper for space limitations.

II. NUMERICAL EXAMPLE AND CONCLUSION

To validate the proposed model and methodology, it is used to simulate the switching on and off transients of a prototype IGBT. Fig. 1 gives the meshes and the computed excess hole concentrations in a time instant of a typical switching process of the prototype IGBT system. Fig. 2 shows the calculated solutions of 2-D ADE in the MOS end at a typical time instant in the turn-on process. Obviously, the calculated excess holes distribution in the MOS end is very close to what it is qualitatively postulated in the theoretical analysis. Fig. 3 presents the simulated (sim) and the experimented (exp) results on the turn-on stages of the prototype IGBT. Compared to existing works, it is obvious that the computed results of this paper are extremely close to the experimental ones.

To sum up, these numerical results not only validate the high accuracy and feasibility of the proposed model and method but also imply that the proposed model can predict the internal behavior of an IGBT, which is very important for the safety study of an IGBT module.

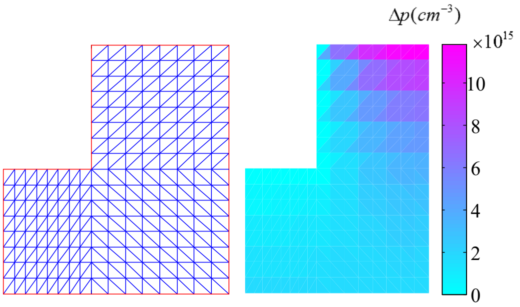

Fig. 1. Meshes and the finite element solutions of the ADE equation.

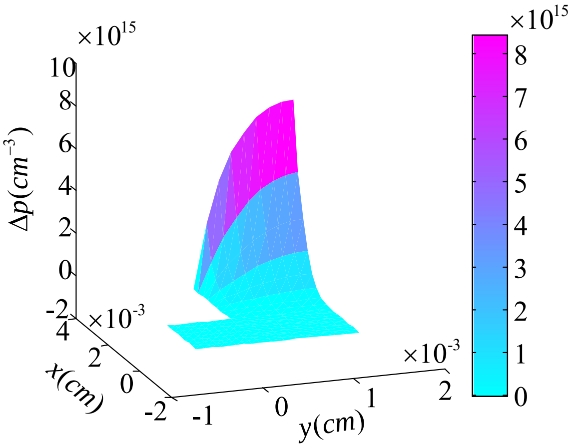

Fig. 2. The calculated 2-D excess holes distribution.

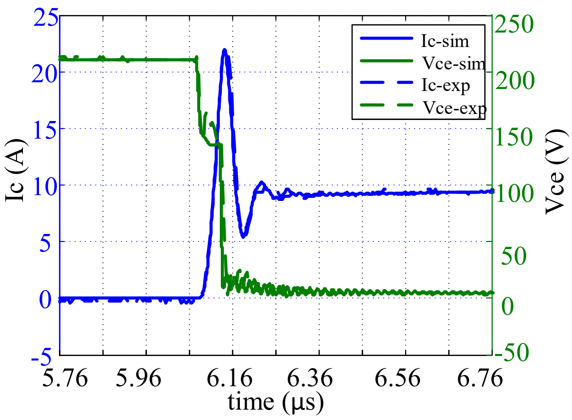

Fig. 3. Experimented and simulated results for a prototype IGBT turn-on transient.

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