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Circuit models for quasi-3D spice simulation of turn-on transients in four-layer power bipolar devices

R. Quintero*, A. Cerdeira

Sección de Electrónica del Estado Sólido, Dep. de Ingeniería Eléctrica, CINVESTAV, Av. IPN 2508, México DF, CP 07300, Mexico

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Abstract

Improved transport models for quasi-3D circuit-based simulation (Q3DSim) of four-layer devices such as thyristors and transient over-voltage protectors (TOVPs) are presented. Q3DSim is an attractive alternative to full 3D transport equations based simulations (3D-TES), since it is much faster and requires less computer power. In Q3DSim, the thyristor is divided into four-layered square prisms, and a 1D PNP–NPN transistor pair model is associated to each of them in the anode to cathode direction. The PNP–NPN elements are interconnected through two transversal grid planes of circuit elements. The resulting equivalent circuit is simulated with Spice. Plasma-spreading velocity, used here as a benchmark, depends strongly on the current-dependent transport properties in the anode to cathode path given by the transistor gains, and on the transversal transport properties of both transistor bases.

The new circuital models reported here, based on the quasi-static approximation, add drift and diffusion current components to Q3DSim transversal base planes. The circuit version of the base model was implemented with finite differences in Spice. The PNP transistor of the PNP–NPN basic model was complemented with a second PNP transistor that simulates the transport enhancement in the N-base due to the ohmic effect. All the required parameters are extracted from static TES. The power of the method was demonstrated by comparing 2D-TES plasma spreading velocity simulations with Q3DSim simulations. Both simulations were very close to each other in the 50–1200 A/cm^2 anode current density range. Moreover, the Q3DSim current wave front shapes were very close to 2D-TESs in the same current density range, showing the validity of the presented models.

Keywords: 3D; 2D; Simulation; Power device; Thyristor; Four-layer; TOVP; Plasma spreading

1. Introduction

The simulation of the transient behavior of PNPN structures such as thyristors and TOVP's is of interest for device design purposes. The progress of a 2D-TES anode current density wave front, 37 μs after a short current pulse was applied to the gate, is shown in Fig. 1. Such simulations are practical [1,2], if time consuming, when the device can be reduced to two dimensions, such as when shorting dots are not present in four-layer devices. When a device cannot be reduced to 2D, as in the case of thyristors and TOVPs with shorting dots, 3D simulations become essential. If a 2D-TES consisting of $n \times n$ nodes takes a time t_{2D}, a 3D one of $n \times n \times n$ nodes takes about $t_{2D}n^{1.5}$ [3]. It can then be estimated that if a 2D-TES with $n = 50$ nodes takes 5 h, the 3D one will take about 350 h, and the required computer memory will be much larger. In such cases, a circuit approach is called for.

El-Saba et al. [4] report a chain of 20 1D cells, with which plasma-spreading velocity is simulated. The 1D cells simulate anode to cathode current transport, where the transport equation is solved by a shooting method for the wide base, and equivalent circuits are used for the rest of the anode to cathode path and for the transversal path.

Hung et al. [5] make use of a spline technique to calibrate a three-junction 1D equivalent circuit against 2D-TES, and a second dimension is added by connecting in parallel identical 1D elements. They report 2D electrothermal simulations of a light bulb dimmer, by means of a chain

* Corresponding author. Tel.: +52 55 5061 3786; fax: +52 55 5747 7114.
E-mail address: rquinter@cinvestav.mx (R. Quintero).

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Nomenclature

2D-TES	two-dimensional transport equations based simulation
Q3DSim	quasi-3D simulation
TOVP	transient over-voltage protector
BN	N-type base plane
BP	P-type base plane
q	electron charge
V_T	thermal voltage
τ	life time; subindexes no, low level electrons; po, low level holes; HL, high level
τ_F	transit time of Gummel–Poon model
R	recombination rate
p	hole concentration; subindex s, specific (cm^{-2}); i, intrinsic
n	electron concentration; subindex s, specific (cm^{-2}); i, intrinsic
J	current density; subindex A, anode; C, collector
E	electric field; subindex x, transversal
N	impurity concentration; subindex A, acceptor; D, donor
μ	mobility; subindex p, hole; n, electron
D	diffusion coefficient; subindex p, holes; n, electrons
L	diffusion length; subindex A, ambipolar
α	bipolar transistor common base current gain; subindex F, forward
J_{pxAS}	current density; x, transversal; p, hole; A, drift; S, for specific (A/cm)
J_{nxDS}	current density; n, electron; D, diffusion; S, specific (A/cm)
$\bar{E}$	electric field, average
W	width; subindex BP, P-base; BN, N-base; T, total; E emitter
y_e	position of emitter-base junction
y_c	position of collector-base junction
ps_{ij}	specific hole concentration between nodes i and j (cm^{-2})
$\overline{Ex}_{i,j}$	average electric field between nodes i and j
$\overline{\mu p}_{i,j}$	hole mobility, averaged over nodes i and j
$\overline{\mu_p}$	average mobility; subindex p, holes; n, electrons
Vb_i	base voltage at node i
Jp_x	transversal hole current
Jp_s	transversal specific hole (A/cm)
JpS_{ij}	specific hole current between nodes i and j
Vb_j	voltage at node j (N-base or P-base)
Δx	distance between adjacent PNPN nodes
v_s	plasma velocity
α_p	transmission line propagation constant
Δw	plasma wave span (10–90% of its amplitude)
2d	I region length of PIN diode (Fig. 9)
V_i	junction i voltage of PIN diode (Fig. 9)
GP	Gummel–Poon

of 20 1D PNPN elements. A third dimension cannot be added, according to the authors, because 3D-TES would have been required for the spline calibration.

In Schröder et al. [6], 1D PNPN cells are modeled by means of a simplified finite difference scheme. Through a chain of five 1D PNPN cells, each representing a ring in the anode plane of a GTO, and including magnetic induction, transient anode current density and voltage distributions in the anode plane are simulated, under the assumption of cylindrical symmetry.

Common to [4–6] is the use of a reduced number of cells, connected in 1D. The connection of a much larger number of cells in a 2D grid can render important information. According the method published previously by the authors of the present article [7], a thyristor is divided into four-layered square prisms, and a 1D PNP–NPN transistor pair model is associated to each of them, as shown in Fig. 2. The transistors are represented with the Gummel–Poon model. Fig. 3 shows an example of such simulations. It is the transient response to an anode to cathode current pulse of a TOVP. The set of 18 shorting dots of the simulated device are slightly shifted from its symmetric position and, as a result, conduction starts at the front-left corner where current density is at the instant of turn on very high, as shown in the first frame of Fig. 3. In the second frame, the current density has spread somewhat, and in the third one, the device has almost turned off.

The PNPN cells in [4–7] are interconnected with fixed value resistive elements, neglecting conductivity modulation and the lateral diffusion currents. The transient simulation of the thyristor in Fig. 1 shows a strong current density gradient in the x-direction that gives rise to a lateral diffusion current. Fig. 4 shows a 2D-TES simulated anode current density wave front, and Fig. 5 shows that the associated lateral drift and diffusion current components in the N-type base (BN) have comparable amplitudes. The drift and diffusion components are also similar in the PB. Therefore, the simple resistive coupling is not a sufficiently good approximation.

Since a transport model that is valid from very low to very high current densities is required, those based on the ambipolar diffusion equation are not applicable [8]. Models based on a few finite difference grid points in the anode to cathode direction [6] are not applicable, either, because they would fail to describe the very low current density range.

In the present article, the Gummel–Poon 1D PNP–NPN cells of [7] are kept, but an improved conductivity modulation model and a diffusion component were added to the cell-to-cell connections. Further, to simulate the current dependence of the transport factor of the N-base, due to the ohmic effect, a second transistor was added to the PNP