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An Accurate High Frequency Full Wave Mathematical Model for Nanometric Silicon PIN Diode

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Abstract:
In recent, the effect of electromagnetic radiation on semiconductor active devices and the coupling effect, which occurs at high frequency between different circuit elements, become more and more important.
This paper presents a high frequency full wave model for Silicon PIN diode. Ended,we present a three dimensional solutions for the electromagnetic field equations (Maxwell's equations) considering finite difference time domain (FTDT) method to describe the circuit passive part. So, we include the electromagnetic effect by solving Maxwell's equations while taking into account the interaction between electromagnetic wave and the active device.
We propose, in this paper, a mathematical method to couple a three-dimension (3-D) Finite Difference Time Domain(FDTD) solution of Maxwell's equations to the Drift Diffusion Model (DDM) concerning the PIN diode. The coupling between the two models is established by introducing the Maxwell equations in a relation connecting the current circulating in the diode to the tension on its terminals.
The active device in the microwave circuits is typically very small in size . Then it can be modeled by its equivalent lumped device with a very high degree of accuracy. Thus, in the conventional lumped element-FDTD (LE-FDTD) approach.
Design and analysis of dynamic resistor of PIN diode coupled with a microstrip line are presented, the simulation result show that the critical frequency of the microwave circuit is 20 GHz.

Keywords: FTDT, Silicon PIN diode, Electromagnetic, Boundary conditions.

1 Introduction

The radiative effects on semiconductor devices become very important for the integrated circuit domain. So, to take into account this effect we applied the FDTD method which can be applied successfully on linear and nonlinear devices.
In this paper, we present a time-domain full-wave approach for modeling our circuit by coupling a three-dimensional time domain solution of Maxwell's equations with the proposed model of the PIN diode.
In a first part of this wok, we develop an accurate model for a nanometric PIN diode. For this we present an algorithm in order to solve the Drift Diffusion Model (DDM)equations, which provides the distribution of the electrostatic potential, carriers concentration, current for the PIN diode. We consider carrier's transport and Poisson equations and Shockley-Read-Hall (SRH) statistics for the determination of the generation-recombination rate . A Newton method is considered to solve the semiconductor equations.
In a second part of this paper, we present a three dimensional solutions for the Maxwell's equations considering finite-difference time domain (FTDT) method to describe the passive part of the considered circuit.
We chose a Gauss pulse source ,and we use the Uniaxial Perfectly Matched layer (UPML) and the perfectly electric conducting (PEC))conditions to model the microstrip line and the absorbing boundary effect. The extraction of the scattering parameters Sij of the circuit is obtained thanks to the Fast Fourier transform (FFT) technique at the transient wave source.Ended ,we consider our PIN diode as a lumped element because its dimensions are very small in size compared to the wavelength [1]-[2]. To simplify this modelisation we replace it by the dynamic resistance which extracted from the current -voltage curve.
In this work, the drift-diffusion model of PIN diode is achieved using the SILVACO-TCAD software and the EM model is implemented using MATLAB code simulator.
To confirm the validity of the proposed model for the microstrip line, we have compared it with obtained by other authors [2]-[3].

2 Mathematical model

For the active device, the drift diffusion model (DDM) is considered to model it. It consists on a set of a coupled equations [4]:

a- Poisson's equation:

$$\nabla^2 V = -\frac{q}{\epsilon}(p - n + Dop) \tag{1}$$

where n , p , V , Dop denote the electron density, hole density , electrostatic potential and net ionized impurity concentration respectively.

b- The charge conservation equations:

$$\frac{\partial n}{\partial t} - \frac{1}{q}\vec{\nabla}\vec{J_n} = -r_{SRH}, \tag{2}$$

$$\frac{\partial p}{\partial t} + \frac{1}{q}\vec{\nabla}\vec{J_p} = -r_{SRH} \tag{3}$$

where r_{SRH} correspond to the Shockley-Read-Hall recombination rate and q is the electronic charge.

c- Current densities:

$$\vec{J_n} = -qn\mu_n \vec{\nabla} V + qD_n \vec{\nabla} n, \tag{4}$$

$$\vec{J_p} = -qp\mu_p \vec{\nabla} V - qD_p \vec{\nabla} p \tag{5}$$

where μ_n, μ_p are the carrier's moblities and D_n, D_p their diffusion coefficients.
The Dirichlet boundary conditions are applied at the ohmic contacts and the Neumann boundary conditions at the free surface. The numerical solution of these equations, considering Newton method, gives us the density of the charge n and p , the potential and the current.

For the microstrip line, we consider the electromagnetic model (EM) which can be characterized by solving Maxwell's equations, given by [5]- [6]:

$$\vec{\nabla} \times \vec{H} = \epsilon\frac{\partial \vec{E}}{\partial t} + \overrightarrow{J}_{media}, \tag{6}$$

$$\vec{\nabla} \times \vec{E} = -\mu\frac{\partial \vec{H}}{\partial t}. \tag{7}$$

We apply the Perfect Electric Conductor conditions (PEC) to model the microstrip line effect by setting the tangential components of the electric field equal to zero [7], and we use the Uniaxial Perfectly Matched Layer boundary conditions (UPML) to define the borders of the field as being without reflection [8].

In order to analyze the hole circuit, we must consider the DDM model and its interaction with the electromagnetic model. In the Maxwell equations, and regarding the nanometric dimensions of the PIN diode in relation to the considered wave lengths, The diode will be replaced by its equivalent schema : its dynamic resistor. This later is evaluated by the DDM model.

So, we consider the Lumped-FDTD (LE-FDTD method) to couple between the $R_{dynamic}$ of the PIN diode and the electromagnetic model [9]. The discretisation and projecting of equation 7 along the z direction gives us:

$$E_z^{n+1}(i,j,k) = E_z^n(i,j,k) + \frac{\Delta t}{\epsilon.\Delta x}[H_y^n(i,j,k) - H_y^n(i-1,j,k)] - \frac{\Delta t}{\epsilon.\Delta y}\times$$
$$[H_x^n(i,j,k) - H_x^n(i,j-1,k)] - \frac{\Delta t}{2\epsilon}[J_{lumped,z}^{n+1}(i,j,k) + J_{lumped,z}^n(i,j,k)], \tag{8}$$

$$J_{lumped,z}^{n+1}(i,j,k) = \frac{\Delta z}{2.R_{dynamic}.\Delta x\Delta y}[E_z^{n+1}(i,j,k) + E_z^n(i,j,k)] \tag{9}$$

where $J_{lumped,z}$ is the current density through the PIN diode [10],[11], and the potential V is related to the electric field E_z by the relation:

$$V = -E_z(i,j,k).\Delta z. \tag{10}$$

By introducing the Maxwell equations in a relation connecting the current circulating in the element to the tension on its terminals we obtain the following relation: [12]- [13]- [14]

$$E_z^{n+1}(i,j,k) = \left[\frac{1 - \frac{dt.\Delta z}{2.R.\epsilon.\Delta x.\Delta y}}{1 + \frac{dt.\Delta z}{2.R.\epsilon.\Delta x.\Delta y}}\right].E_z^n(i,j,k) + \left[\frac{\frac{dt}{\epsilon}}{1 + \frac{dt.\Delta z}{2.R.\epsilon.\Delta x.\Delta y}}\right].\nabla \times H_z^{n+1}(i,j,k). \quad (11)$$

3 Results and Discussion

The active device is a Silicon PIN diode with an intrinsic length zone (W=0.1μm). The anode and the cathode junctions are doped with N_A= $N_D = 5.10^{17} cm^{-3}$.
The device length is 0.137 μm.
The applied voltage V_a = 0.8 V.

The density of the charge n and p , the potential and the current are presented on figures 1,2 and 3 respectively .

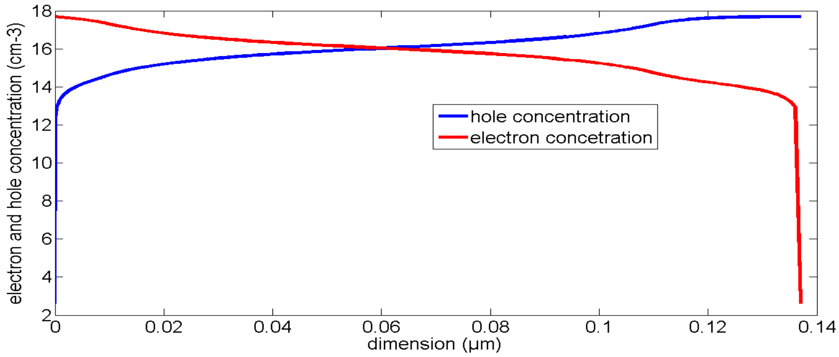

Fig. 1: Electron and hole density distribution.

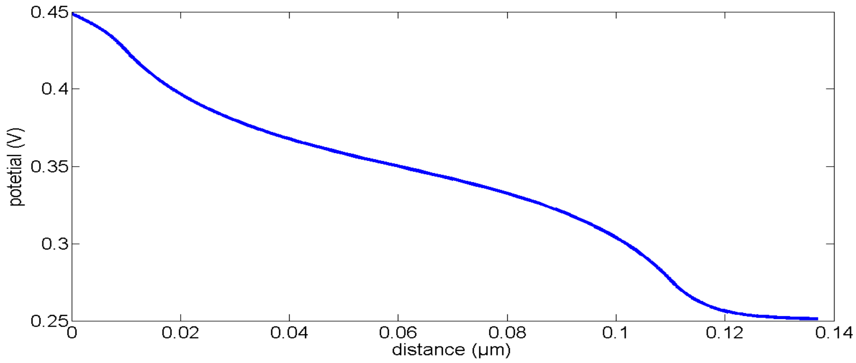

Fig. 2: 2D Calculated potential distribution.

From the figure 1 and 2 we can observe that the space charge area is practically extended over all the structure of PIN diode.

The figure 3 presents the current-tension characteristics of the nanometric PIN diode , from this curve we can extract the dynamic resistor by the following relation:

$$R_dynamic = \frac{\Delta V}{\Delta I} = 0.63 ohm \quad (12)$$

The FDTD simulation of the microstrip line is performed with uniform grids of space steps Δx = 0.389 mm, Δy = 0.4 mm and Δz = 0.265 mm. The computation domain of the microstrip line is divided into a grid of 80 $\times$ 120 $\times$ 23.The relative permittivity ϵ_r=2.2 [2].

The figure 4 shows the distribution of electric field E_z(x,y,z, t) at $1.57.10^{-11}$s. The Fast Fourier analysis (FFT) is performed in the inpout and the outpout characteristics in order to obtain scattering parameters presented in figure 5. We note that S_{11} is minimal at 8GHz and 30 Ghz and in the same time S_{21} is maximal, so at this frequencies we have good transmission. We note also, that with the evolution of the frequency we will have more reflexion because of the decreases of the capacity impedance of microstrip line.

The circuit considered in this paper is presented on figure 6.

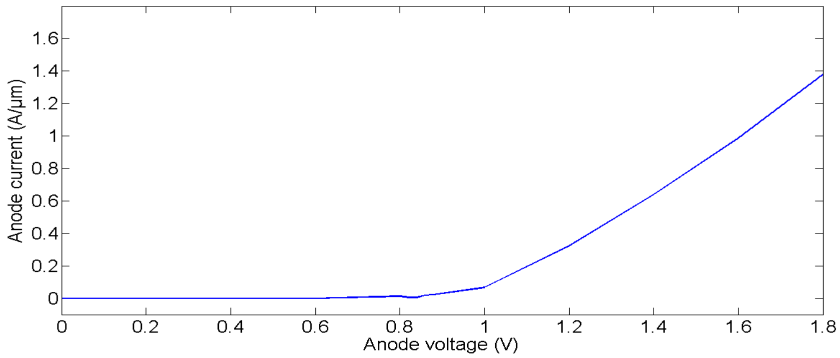

Fig. 3: I-V characteristics of the PIN diode.

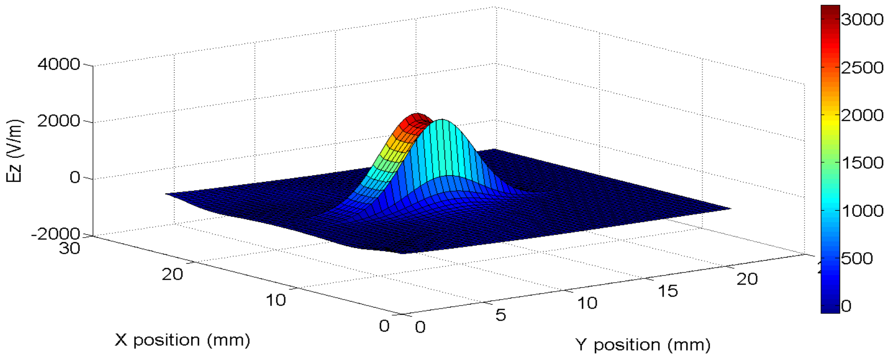

Fig. 4: distribution of electric field Ez.

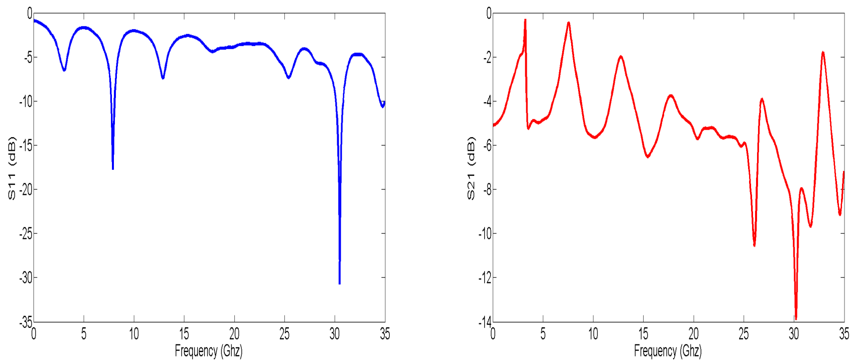

Fig. 5: S-parameters for the microstrip line .

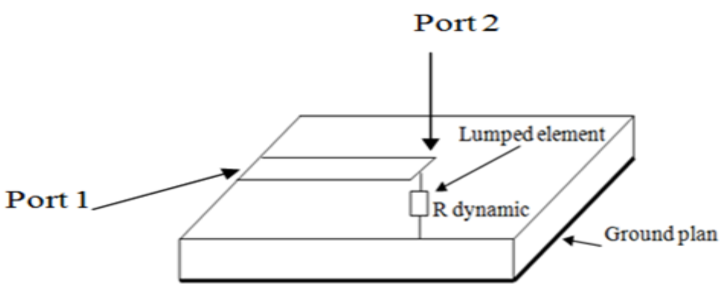

Fig. 6: The simulated structure.

The LE-FDTD method is applied to model the dynamic resistor which located inside the Yee cell [11]. We note on figure that a critical point frequency of the microwave circuit is observed at 20 GHz. So we conclude that the simulation confirm that the proposed device can be used at the high frequency domain .

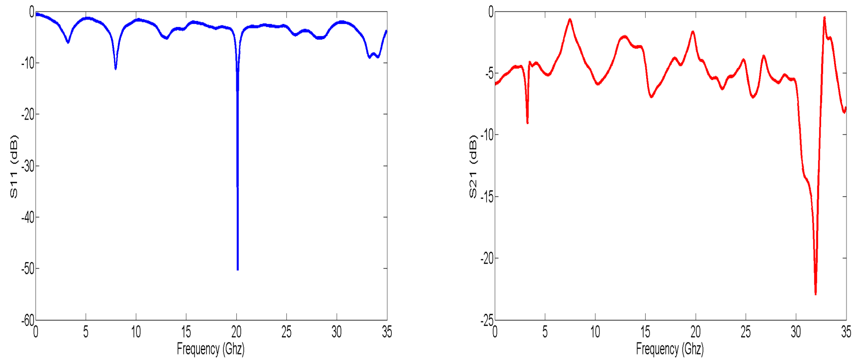

Fig. 7: S-parameters for the microstrip line .

4 Conclusions

We have presented in this paper the drift-diffusion model (DDM) of a PIN diode. The numerical solution of the set of its equations was achieved using the SILVACO-TCAD software. Newton method was adopted.
Considering the monolithic microwave integrated circuit (MMIC) concerned by this study, We have proposed a (FDTD) numerical method for full-wave simulation of microstrip line structure .
In addition, we have found that the variation of the electric and magnetic fields in this structure can easily be introduced in the proposed model (DDM) which allow the evaluation of the frequency performances of the device by introducing the lumped elements model to update the dynamic resistance voltages from the electric field. The critical point frequency of the microwave circuit is 20 Ghz. So the simulation confirms that the proposed active device can be used at the high frequency domain.

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