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Efficient Modeling of PIN Diode Switches Employing Time-Domain Electromagnetic-Physics-Based Simulators

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Abstract—**This paper presents an efficient full-wave time-domain simulator for accurate modeling of PIN diode switches. An equivalent circuit of the PIN diode is extracted under different bias conditions using a drift-diffusion physical model. Net recombination is modeled using a Shockley-Read-Hall process, while generation is assumed to be dominated by impact ionization. The device physics is coupled to Maxwell's equations using extended-FDTD formulism. A complete set of results is presented for the on and off states of the PIN switch. The results are validated through comparison with independent measurements, where good agreement is observed. Using this modeling approach, it is demonstrated that one can efficiently optimize PIN switches for better performance.**

***Index Terms*— Device transport physics, global modeling, Maxwell's equations, PIN diode switches.**

I. Introduction

Millimeter-wave PIN diode switches are extensively used in microwave systems, for example, in high resolution radars (HRR) employed for automotive collision at 77 GHz that require very high isolation and fast switching speeds [1]. Another application is in the generation of high-power through an array of PIN diode microwave switches [2]. Accordingly, it is indispensable to present analysis of PIN switches based on a coupled full-wave simulator. The possibility of achieving this type of modeling is addressed by global circuit modeling as has been demonstrated in [3]-[6]. Here, we present a fast electromagnetic (EM) simulator for efficient modeling and optimization of low-loss and high-isolation mm-wave PIN diode switches. To our knowledge, this the first time such a modeling approach has been used for this problem.

II. Problem Statement

The PIN diode model presented in the present work is a three-dimensional (3-D) full-wave model. The basic model couples Maxwell's equations for the electric and magnetic fields with the switch equivalent circuit extracted using a drift-diffusion model given by:

$$\frac{\partial n}{\partial t} - \frac{1}{q}\nabla\cdot\boldsymbol{J}_n = G - R \tag{1}$$

$$\frac{\partial p}{\partial t} + \frac{1}{q}\nabla\cdot\boldsymbol{J}_p = G - R \tag{2}$$

$$\boldsymbol{J}_n = -q\mu_n n\nabla U + qD_n\nabla n \tag{3}$$

$$\boldsymbol{J}_p = -q\mu_n p\nabla U - qD_p\nabla p. \tag{4}$$

Where n and p are the electron and hole densities, $\boldsymbol{J}_n$ and $\boldsymbol{J}_p$ are the electron and hole current densities, q is the electron charge, G is the extrinsic generation rate, R is the recombination rate, U is the electrostatic potential, D_n and D_p are the electron and hole diffusion coefficients. The net recombination rate is modeled using the Shockley-Read-Hall process, while extrinsic generation is assumed to be dominated by impact ionization [7].

Since it is only required to have two different modes of operation in a PIN diode switch, i.e. the on and off-state, it is not necessary to model the actual semiconductor physics during electromagnetic simulation. Thus, the drift-diffusion physical model can be used to estimate the on-state resistance R_{ON} and the off-state capacitance C_{OFF} of the diode switch, which is the accurate alternative for the analytic formula given by [8]:

$$R_{ON} = \frac{1}{I_F\tau}\frac{W_i^2}{4}\frac{\mu_n + \mu_p}{\mu_n\mu_p}, \tag{5}$$

where W_i is the thickness of the intrinsic region, μ_n is the electron mobility, μ_p is the hole mobility, I_F is the forward bias DC current, and τ is the effective carrier life-time in the intrinsic region. In our GaAs PIN diode case, μ_n and μ_p are 450 and 8000 cm^2/Vs. On the other hand, under reverse bias, another approximation that is used instead of running a drift-diffusion simulator is to assume a constant depletion capacitance [9]:

$$C_{OFF} = \varepsilon\frac{Area}{W_i}, \tag{6}$$

Here ϵ is the dielectric constant of the depletion layer material. In Fig. (1), W_i and the depletion area are 0.25 µm and 400 $(\mu m)^2$, respectively. This gives an approximate junction capacitance of 0.01 pF. The proposed full-wave coupling approach is carried out using extended FDTD formulism [10]. For example, for a PIN diode oriented in z-direction, the electric-field at cell (i,j,k) for the on and off states are given by Eqs. (7) and (8)

$$E_z\Big|_{i,j,k}^{n+1} = \left[\frac{1-\dfrac{\Delta t\Delta z}{2R_{ON}\varepsilon\Delta x\Delta y}}{1+\dfrac{\Delta t\Delta z}{2R_{ON}\varepsilon\Delta x\Delta y}}\right]E_z\Big|_{i,j,k}^{n} + \left[\frac{\dfrac{\Delta t}{\varepsilon}}{1+\dfrac{\Delta t\Delta z}{2R_{ON}\varepsilon\Delta x\Delta y}}\right]\nabla\times H\Big|_{i,j,k}^{n+1/2} \tag{7}$$

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$$E_z\Big|_{i,j,k}^{n+1} = E_z\Big|_{i,j,k}^{n} + \left[\frac{\frac{\Delta t}{\varepsilon}}{1+\frac{C_{OFF}\Delta z}{\varepsilon \Delta x \Delta y}} \right] \nabla\times H\Big|_{i,j,k}^{n+1/2}. \quad (8)$$

III. DC Simulation Results

DC simulation results are obtained by solving the drift-diffusion model in conjunction with Poisson's equation. Figure (1) shows a generic cross-section of the simulated PIN diode. Figure (2) shows the forward I-V characteristics of the PIN diode obtained using the drift-diffusion model. Figure (3) shows the RF resistance as a function of the DC bias current. It should be noted that the RF resistance is extracted using the I-V characteristics of the PIN diode. The DC results are consistent with those obtained from the literature and measurements where exponential relations are observed [11]. Reverse-bias modeling is carried out in a similar manner. Figures (4)-(5) show the net recombination rate as well as the generation rate by impact ionization @35 V reverse bias. Considering both figures, one notices that when the junction is reverse biased, generation by impact ionization dominates over net recombination, which is consistent with theory and literature. Finally, Fig. 6 shows the breakdown of the junction around -35V. The breakdown occurs due to carrier generation by impact ionization.

IV. Full-Wave simulation Results

Modeling of PIN diodes can be carried out through semiconductor simulation or experimental data obtained from design of experiments (DOE). Measurements are the most accurate technique to characterize PIN diodes at high-frequencies. Nevertheless, measurements do not allow for efficient device optimization since the iteration cycle is very long. On the other hand, semiconductor simulations provide the intrinsic parameters of the diode, which are insufficient by themselves to be used directly in RF design since they do not include full EM-wave effects such as air-bridge inductances and capacitances as well as attenuation and radiation. The modeling approach presented in this paper is based on simulating the entire diode using the Extended-FDTD approach by embedding the proper lumped elements and their values extracted at given bias conditions from the semiconductor simulator. It should be noted that the switch has only two states of real interest, i.e. on and off. Therefore, for small-signal modeling, it is not required to directly couple the semiconductor physics with Maxwell's equations during simulation, which would not be the case for nonlinear large-signal modeling [6]. Instead, in this preliminary work, the Extended-FDTD approach is used to model PIN diodes with a relatively good accuracy. The advantage of this approach is that it eliminates the time-step *dt* constraint set by the physical simulator when coupled directly with Maxwell's equations in an FDTD environment. Here, we assume that this approximation is valid, where wave-device interaction can be neglected. This approach will not only increase the accuracy because the structure is simulated as a whole, but will also enable the optimization of the diode structure for different parameters more efficiently. For example, matching of the capacitance of the diode in the off state with the air-bridge inductance can be efficiently carried out by this approach. Another example is the optimization of the diode area for minimum spreading resistance. The full-wave simulation results of the PIN switch are shown in Figs. (7)-(10). The proposed simulator is validated by modeling the configuration provided in [9], where the switch is realized using the CPW configuration with a shunt SPST GaAs PIN diode. The air-bridge is assumed to be 10 μm wide. Figures [7] and [8] show comparison with measurements for the insertion loss for the forward and reverse bias cases. It is worth noting that since doping profile and other semiconductor parameters were not provided in [9], we had to use Eqs. (5) and (6) instead of drift-diffusion simulation only for validation and comparison with the measurements presented in [9]. Considering Figs. (7)-(8), one notices very good agreement, emphasizing the accuracy and expediency of the developed simulator. The next configuration was realized using a shunt PIN diode mounted on a 50Ω microstrip line, where the diode terminals are connected between the ground plane and the stripline conductor. The simulated diode is shown in Fig. 1. The diode resistance in the on-state in this particular case is extracted using the drift-diffusion model instead of Eq. (5). Figure 9 shows the insertion loss as a function of the DC bias current. One notices the increase of isolation as the DC bias current increases. From Fig. 3, it is observed that as the current increases, the RF resistance of the shunt switch decreases. This results in a decreasing output voltage, hence increasing isolation. Further, the isolation is between 15 to 20 dB over the whole spectrum and it decreases with frequency. Hence, one can employ the developed simulator to efficiently design PIN diode switches by optimizing its parameters such as doping profile, air-bridge height and width, size and height of ground vias, and metallic contact shapes.

V. Conclusions

We presented an efficient time-domain full-wave simulator for modeling of PIN diode switches used for mm-wave applications. The modeling approach is based on coupling of the drift-diffusion model with Maxwell's equations via the extended FDTD formulism. The advantage of this approach is that it eliminates the time-step *dt* constraint set by the physical simulator when coupled directly with Maxwell's equations in an FDTD environment. This approach will not only increase the accuracy because the structure is simulated as a whole, but will also enable the optimization of the diode structure for different parameters more efficiently and easily.

ACKNOWLEDGMENT

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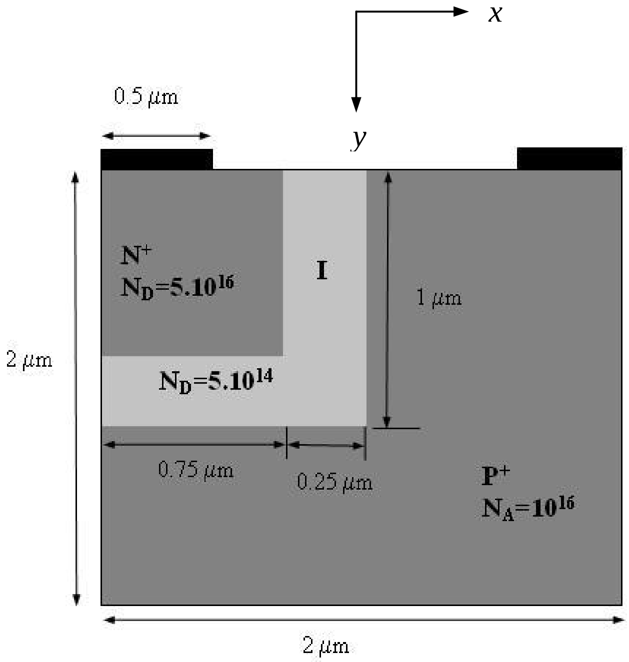

Fig. 1. Generic cross-section of the simulated PIN diode.

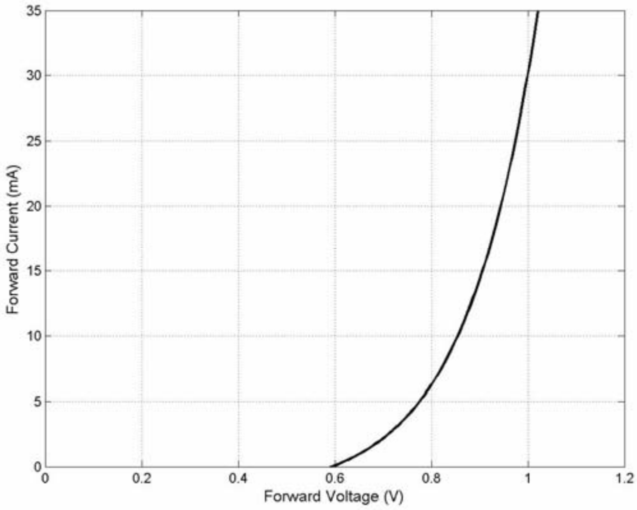

Fig. 2. IV-characteristics of the PIN diode**.**

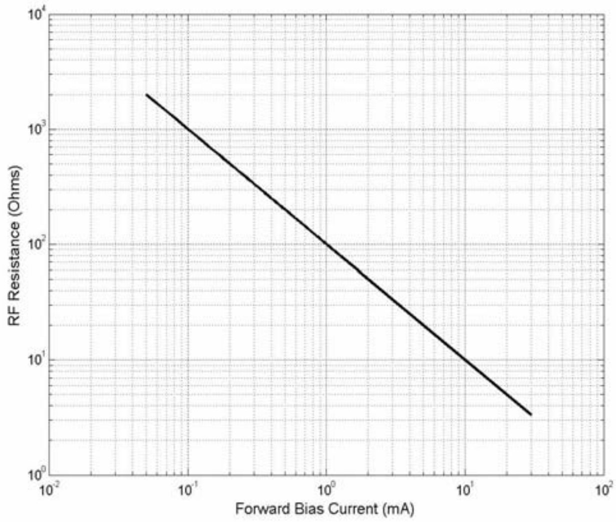

Fig. 3. RF resistance vs. forward bias current.

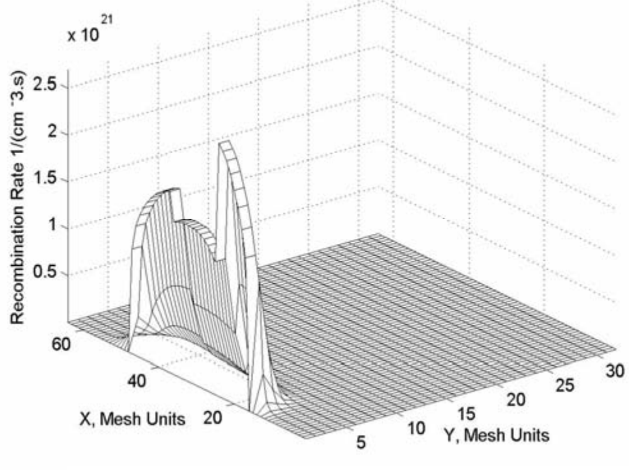

Fig. 4. Net recombination rate @35 V reverse bias.

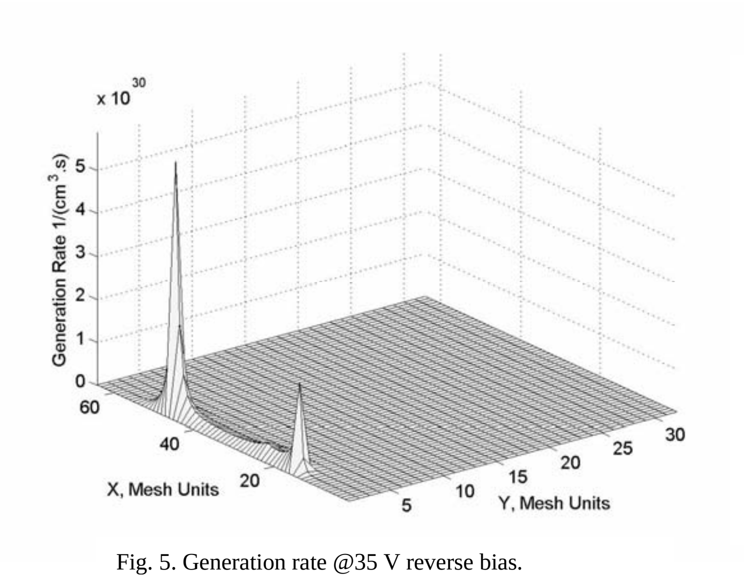

Fig. 5. Generation rate @35 V reverse bias.

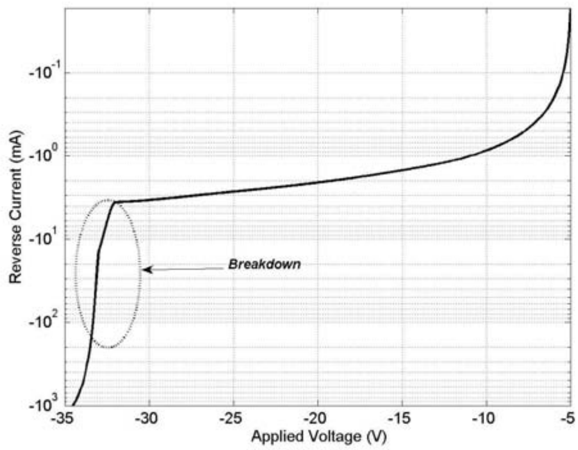

Fig. 6 Break-down modeling of the PIN diode.

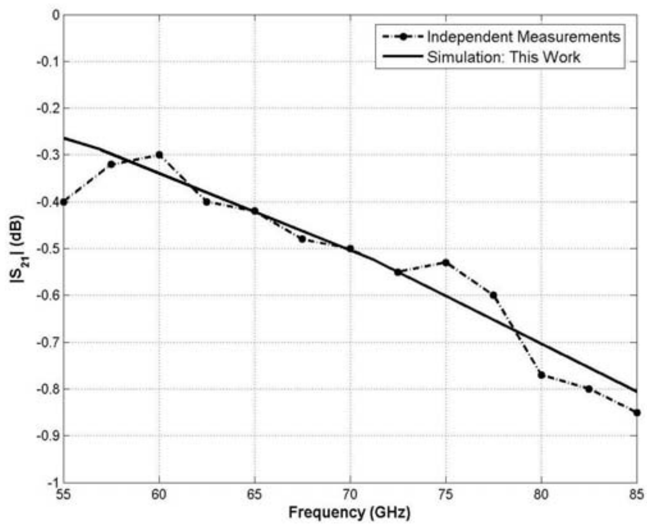

Fig. 7. Insertion loss (S_{21}) comparison with measurements provided by [9] of a shunt PIN switch under reverse bias condition**.**

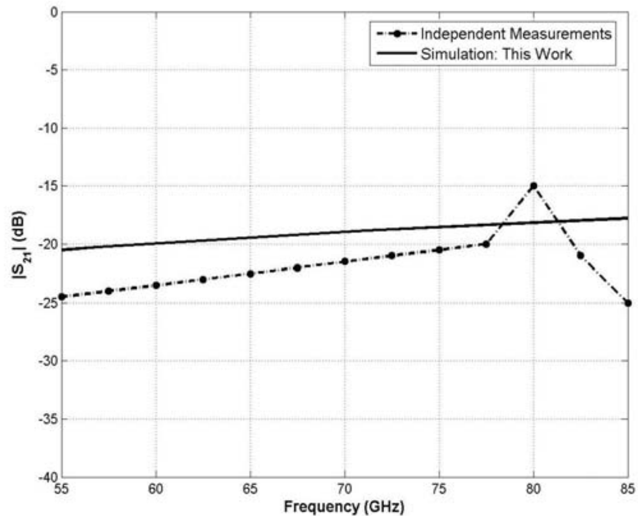

Fig. 8. Insertion loss (S_{21}) comparison with measurements provided by [9] of a shunt PIN switch under forward bias condition**.**

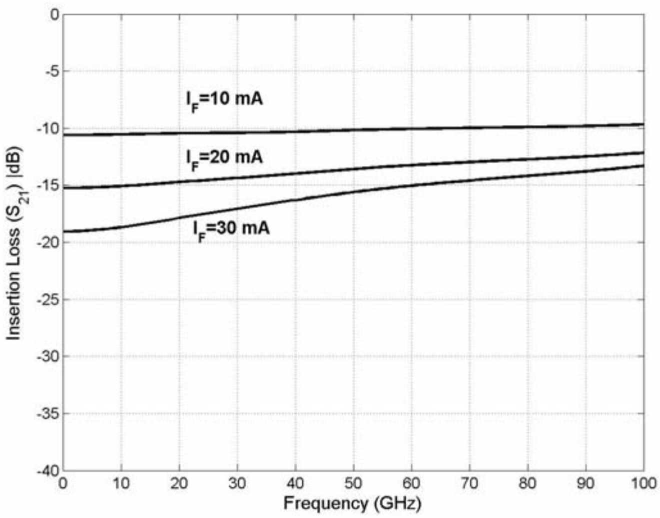

Fig. 9. Insertion loss (S_{21}) of the shunt PIN switch under different forward bias conditions.

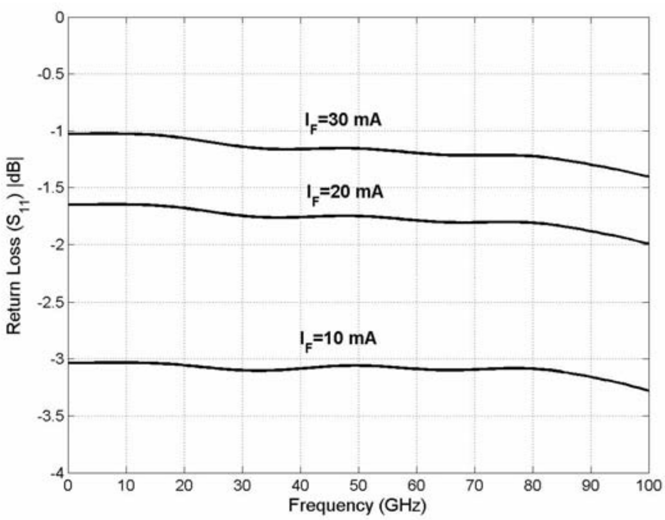

Fig. 10. Return loss (S_{11}) of the shunt PIN switch under different forward bias conditions**.**