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The effect of thermal diffusion on the electrical response of MSM photodetector

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ABSTRACT

A self-adjoint formulation of the Energy transport model for semiconductor devices is used to simulate the electron transport in a MSM photodetector. This model consists of a set of continuity equations for the density and energy together with constitutive relations for carriers and energy fluxes which is to be solved self consistently with Poisson equation. This formulation used semi Slothboom variables instead of carrier concentrations and temperatures. We use the finite difference discretization which leads to set of coupled nonlinear equations. These equations has been solved by Gummel approach. The carrier concentrations, carrier temperatures and electrostatic potential in each mesh points are achieved. Finally the thermal diffusion, current density and the response of the MSM photodetector are investigated. The numerical results confirm that high carrier gradients cause effective thermal diffusions which should be considered in device simulation.

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INTRODUCTION

Numerical simulation of semiconductor devices is one of the important processes in developing semiconductor devices. Metal Semiconductor Metal Photo Detector (MSM_PD) as a semiconductor device has been simulated several times by numerical solution of classical Drift-Diffusion Model. Numerical methods for the fundamental semiconductor equations play a significant role in this development. For most practical device structures, this model which yields electrostatic potential and carrier concentrations looks good but in other side carrier temperatures exhibit extreme layers or peaks, particularly in the neighborhood of p-n junctions and the oxide (Chen, R.C., J.L. Liu, 2003). Presence of this kind of singular phenomena forces us to use a model which includes these variables. Energy Transport model is used as a force majeure model.

A global iterative method is used to solve a self_adjoint formulation of energy transport model which has been introduced in (Chen, R.C., J.L. Liu, 2003). This formulation is purely mathematical rather than physical and is motivated by the transformation of carrier densities to the Slotboom variables. It leads to symmetric and monotonic properties of the resulting system of nonlinear algebraic equations from finite difference approximation (Chen, R.C., J.L. Liu, 2003; Chen, R.C., J.L. Liu, 2005).

In this paper we solved the Energy Transport model for a MSM photodetector to show the effects of carrier temperature gradients on carrier concentrations and potential profile through the device.

This paper is organized as follows: A self-adjoint formulation of energy transport model is presented. Next, finite difference discretization and global algorithm for the numerical simulation of the model is considered. The model is applied to the MSM photodetector and the results are discussed.

1. *Energy Transport Model:*

Different types of energy transport models have been used in simulation of semiconductor devices. Chen and Liu introduced a new formulation by defining new variables (Chen, R.C., J.L. Liu, 2003). In this formulation new Slothboom variables are defined instead of carrier concentrations (Mashayekhi, H.M., 1999). A same method is used to define the new variables instead of carrier's temperature. These new variables are defined to achieve a self-adjoint formulation. In particular, the model is edited in (Chen, R.C., J.L. Liu, 2003) and the following self-adjoint system in terms of the new variables is presented.

$$\nabla^2\varphi = F\left(\varphi, u, v\right) \quad (1)$$

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$$\frac{1}{q}\nabla\cdot\vec{J}_n = R(\varphi,u,v) \tag{2}$$

$$\frac{1}{q}\nabla\cdot\vec{J}_p = -R(\varphi,u,v) \tag{3}$$

$$\nabla\cdot G_n = R_n(g_n) \tag{4}$$

$$\nabla\cdot G_p = R_p(g_p) \tag{5}$$

These physical variables are tightly coupled together with the following auxiliary relationships:

$$F(\varphi,u,v) = \frac{qn_i}{\varepsilon_s}\left[u\exp\left(\frac{\varphi}{V_T}\right) - v\exp\left(\frac{-\varphi}{V_T}\right)\right] + q\frac{\left(N_A^- - N_D^+\right)}{\varepsilon_s} \tag{6}$$

$$\vec{J}_n = qD_n n_i \exp\left(\frac{\varphi}{V_T}\right)\vec{\nabla}u\,,\ \vec{J}_p = -qD_p n_i \exp\left(\frac{-\varphi}{V_T}\right)\vec{\nabla}v \tag{7}$$

$$R(\varphi,u,v) = \frac{n_i^2\left[uv-1\right]}{\tau_n^0\left[n_i v\exp\left(\frac{-\varphi}{V_T}\right)+P_T\right]+\tau_p^0\left[n_i u\exp\left(\frac{\varphi}{V_T}\right)+n_T\right]} \tag{8}$$

$$G_n = \kappa_n \exp\left(\frac{5\varphi_n}{4V_T}\right)\nabla g_n \quad G_p = \kappa_p \exp\left(\frac{-5\varphi_p}{4V_T}\right)\nabla g_p \tag{9}$$

$$R_n(g_n) = n\left(\frac{\omega_n-\omega_0}{\tau_{n\omega}}\right) - \mathbf{J}_n\cdot\mathbf{E} - \frac{1}{q}\nabla\cdot\left(\frac{1}{2}m_n^*\frac{\left|\mathbf{J}_n\right|^2}{q^2n^2}\mathbf{J}_n\right) \tag{10}$$

$$R_p(g_p) = p\left(\frac{\omega_p-\omega_0}{\tau_{p\omega}}\right) - \mathbf{J}_p\cdot\mathbf{E} + \frac{1}{q}\nabla\cdot\left(\frac{1}{2}m_p^*\frac{\left|\mathbf{J}_p\right|^2}{q^2p^2}\mathbf{J}_p\right) \tag{11}$$

In which the new variables are related to the carrier concentrations and temperatures as (Eq. 12~15)

$$u = \exp\left(\frac{-\varphi_n}{V_T}\right), \qquad v = \exp\left(\frac{\varphi_p}{V_T}\right) \tag{12}$$

$$n = n_i\exp\left(\frac{\varphi-\varphi_n}{V_T}\right), \quad p = n_i\exp\left(\frac{\varphi_p-\varphi}{V_T}\right) \tag{13}$$

$$T_n = g_n\exp\left(\frac{5\varphi_n}{4V_T}\right), \qquad T_p = g_p\exp\left(-\frac{5\varphi_p}{4V_T}\right) \tag{14}$$

where φ is the electrostatic potential, n and p are the electron and hole concentrations, q is the elementary charge, ε_s is the permittivity constant of semiconductor, N_A^- and N_D^+ are the densities of ionized impurities, J_n and J_p are the current densities, R is the function describing the balance of generation and recombination of electrons and holes, E is the electric field, $\tau_{n\omega}$ and $\tau_{p\omega}$ are the carrier energy relaxation times, ω_0 is the thermal energy, ω_n and ω_p are the carrier average energies, k_B is Boltzmann's constant, T_n, T_p, and T_L are the electron, hole and lattice temperatures, μ_n and μ_p are the field-dependent electron and hole mobilities, D_n and D_p are the electron and hole diffusion coefficients expressed by the Einstein relation with the mobilities, m_*^n and m_*^p are the electron and hole effective masses, v_n and v_p are the electron and hole velocities, κ_n and κ_p are the electron and hole heat conductivities, and (Eq.8) is the Shockley-Read-Hall generation-recombination model with n_i being the intrinsic carrier concentration, τ_{0n} and τ_{0p} the electron and hole lifetimes, and p_T and n_T the electron and hole densities associated with energy levels of the traps.

2. *Finite Difference discretization:*

The main ingredients of the algorithm solving the ET model are finite difference approximation of partial differential equations (PDEs) via set of coupled nonlinear algebraic equations. Node-by-node and monotone iterative solution of the resulting nonlinear algebraic systems, and Gummel's iteration consecutively on the PDEs are described for the ET model. Here, we use the Gummel's for outer iteration algorithm and monotone for inner iteration.

We use the five point finite difference method for discretization of ET model in 2Dimension. The following equations achieved for the (Eq.1~5)

$$a_{i,j}\varphi_{i-1,j}+b_{i,j}\varphi_{i+1,j}+c_{i,j}\varphi_{i,j}+d_{i,j}\varphi_{i,j-1}+e_{i,j}\varphi_{i,j+1}=F(\varphi,u,v)\Big|_{i,j}=$$
$$=\frac{qn_i}{\varepsilon_s}\left[u_{i,j}\exp\left(\frac{\varphi_{i,j}}{V_T}\right)-v_{i.j}\exp\left(\frac{-\varphi_{i,j}}{V_T}\right)\right]+q\frac{\left(N_A^- - N_D^+\right)_{i,j}}{\varepsilon_s} \tag{15}$$
$$\nabla\cdot\vec{J}_n\Big|_{i,j}=an_{i,j}u_{i-1,j}+bn_{i,j}u_{i+1,j}+cn_{i,j}u_{i,j}+dn_{i,j}u_{i,j-1}+en_{i,j}u_{i,j+1}=$$
$$=qR\Big|_{i,j} \tag{16}$$
$$\nabla\cdot\vec{J}_p\Big|_{i,j}=ap_{i,j}v_{i-1,j}+bp_{i,j}v_{i+1,j}+cp_{i,j}v_{i,j}+dp_{i,j}v_{i,j-1}+ep_{i,j}v_{i,j+1}=$$
$$=-qR\Big|_{i,j} \tag{17}$$
$$\nabla\cdot\vec{G}_n=R_n\left(g_n\right)=\nabla\cdot\vec{G}_n\Big|_{i,j}=$$
$$=ga_{i,j}g_{ni-1,j}+gbn_{i,j}g_{ni+1,j}+gcn_{i,j}g_{ni,j}+gdn_{i,j}g_{ni,j-1}+gen_{i,j}g_{ni,j+1}=R_n\Big|_{i,j} \tag{18}$$
$$\nabla\cdot\vec{G}_p=R_p\left(g_p\right)=\nabla\cdot\vec{G}_p\Big|_{i,j}=$$
$$gap_{i,j}g_{pi-1,j}+gbp_{i,j}g_{pi+1,j}+gcp_{i,j}g_{pi,j}+gdp_{i,j}g_{pi,j-1}+gep_{i,j}g_{pi,j+1}=R_p\Big|_{i,j} \tag{19}$$

Where the coefficients are:

$$a_{i,j}=\frac{2}{h_{i-1,j}\left(h_{i,j}+h_{i-1,j}\right)}\quad,\quad b_{i,j}=\frac{2}{h_{i,j}\left(h_{i,j}+h_{i-1,j}\right)},c_{i,j}=-\left(a_{i,j}+b_{i,j}+d_{i,j}+e_{i,j}\right)$$
$$d_{i,j}=\frac{2}{k_{i,j-1}\left(k_{i,j}+k_{i,j-1}\right)},\quad e_{i,j}=\frac{2}{k_{i,j}\left(k_{i,j}+k_{i,j-1}\right)} \tag{20}$$

The (Eqs. 15~19) are to be solved numerically using global Gummel iteration algorithm.

4. *Steady State Simulation of MSM Photodetector:*

The modeling of the electrostatic potential of externally biased metal semiconductor metal, MSM, photodetectors will be presented. The external voltage can be applied to the top contacts. The applied voltage to the top contact produces an electric field, which drifts photo-carriers towards contacts of opposite polarity. Applying a voltage to the top contact will change the electrostatic potential profile of the device which can be considered as one driving force for the carriers to move through the device because the electric field is proportional to the negative of the potential gradient. Of course, the other driving force is due to the gradient in the carrier concentration and carrier temperature which results in the diffusion of carriers and energy fluxes. So that the Energy Transport model for semiconductor devices is solved for the MSM photodetector and the electrostatic potential, carrier concentration and temperature of the device in 2D is presented which help us to describe the behavior of the device to an optical power.

The model is solved for the MSM PD that its 2-d profile can be seen in Fig. 1 :

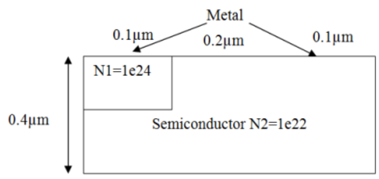

Fig. 1:

and in the following conditions:

Table 1:

	M1	M2
Applied voltage	1 volt	0

5. *Numerical Results:*

The numerical results of simulation are presented in this section for the MSM photodetector. The electrostatic potential profile of the device in 2D is shown in (fig. 2).

Fig.1 shows rapid changes in electric field in Ohmic contacts and a potential gradient which drifts the electrons to the contacts. Another important parameter which has important role in carrier transport is carrier concentration which cause carrier diffusion (fig. 3)

Rapid changes in the electron and hole temperatures especially in contacts (figs.4~5) cause a temporal diffusion in which influence on the electron transport in the device. So that, this flux of energies which causes from rapid changes in carrier temperature influence on the response of the MSM photodetector. These effects on the response of the photodetector can be seen by solving the ET model in dynamic condition.

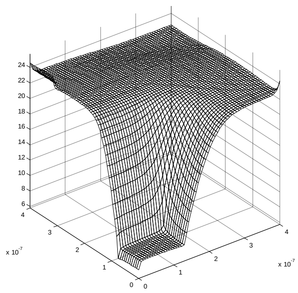

Fig. 2: Electrostatic Potential (v).

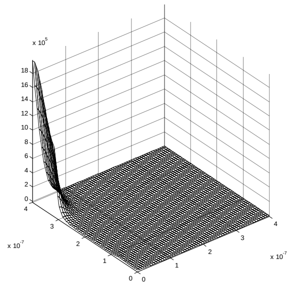

Fig. 3: The holes temperature profile through the device (K^0).

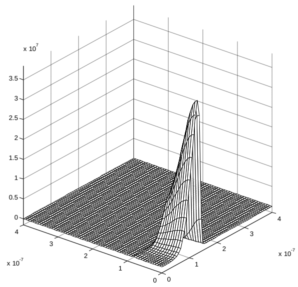

Fig. 4: The electrons temperature profile.

6. Conclusions:

A self-adjoint formulation of Energy transport model is used for simulation of a typical MSM-PD. An iterative method is developed for the solution of the resulting nonlinear algebraic equations of the model from adaptive finite difference approximation. This self-adjoint formulation of the Energy transport model of semiconductor devices is used to simulate the photodetector. This model consists of a set of continuity equations for the density and energy together with constitutive relations for the particle and energy fluxes. The carrier concentrations, carrier temperatures and electrostatic potential in each mesh points are achieved in a steady state conditions. Rapid variation of carrier temperatures through the device can be seen especially in contacts and junctions. This variations cause a high gradients of temperature through the device which create an effective thermal diffusion. It can be predicted that this thermal diffusion will change the electric current density and response of device. The results shows that gradients of carrier temperature will change the profile of potential through the device. It seems for a good approximation of a MSM photodetector behavior, the ET model is closer to the experiment especially for higher applied biases.

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