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Effect of second-order temperature jump in Metal-Oxide-Semiconductor Field Effect Transistor with Dual-Phase-Lag model

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ABSTRACT

The present numerical investigation is concerned with the role of second-order temperature jump in a horizontal planar micro-channel heat transfer. We solve numerically Dual-Phase-Lag model in a two dimensional configuration coupled with a new jump boundary condition. The nanodevice of model consists of Metal-Oxide-Semiconductor Field Effect Transistor with either uniform or non-uniform heat generation. A new temperature jump boundary condition of first and second order is used especially in the oxide–semiconductor interface. The finite element method is used to bring forth the results for a 10 nm channel length of the transistor. Thermal properties of transistor device have been investigated for different orders of the temperature jump boundary condition. It has already been deduced that the increasing orders of temperature jump boundary condition lead to an increase of phonon-wall collisions. This new condition can lead to a significant increase in the heat flux and the calculated lattice temperature.

1. Introduction

The miniaturization of the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) has gained considerable attention in recent years. As the system size decreases the heat dissipation density increases rapidly and nanoscale heat conduction becomes an important issue. An analytical model for MOSFET based on Fourier law and which includes the effect of Robin boundary condition was developed by Romano and Rusakov [1]. They developed a macroscopic model which describes the electron transport in semiconductors and the electro-thermal characteristics of MOSFET with a 200 nm length channel. Sabry et al. [2] developed a lumped transient thermal model for self-heating in MOSFETs. They studied the self-heating related dynamic effect including Dirichlet boundary condition effect. Djelti et al. [3] used the Fourier law in the electro-thermal simulation to investigate the heat transfer effect in MOSFET with a 200 nm length channel.

Classical equation based calculations in this domain deviate from experimental. Several investigations have been carried out in nanoscale to simulate heat transfer in nanodevices [4–9].

Cattaneo [10] and Vernotti [11] proposed a new model with a single-phase-lag. This model assumes that the temperature gradient is the cause whereas the heat flux is the result. The time delay between them is generally called the relaxation time of the heat flux. Laroche and Taur [12] simulated the heat conduction in nanoMOSFET using the Ballistic Diffusive Equation (BDE) and the phonon Boltzmann equation (BTE). Tzou [13] proposes a new model for heat conduction in nanoscale devices given by the Dual-Phase-Lag model (DPL) in which the temperature gradient (cause) can precede the heat flux vector (effect) or inversely the heat flux vector (cause) can precede the temperature gradient (effect). Ghazanfarian and Abbassi [14] investigated numerically and analytically the DPL heat conduction equation with temperature jump boundary condition in nanoscale geometry by changing the Knudsen number. Ghazanfarian and Shomali [15] investigated numerically the DPL model in a simplified MOSFET device where the boundary phonon scattering is taken into account by employing a new mixed type boundary condition. The authors presented a two-dimensional numerical solution and found that the deviations among the DPL, BDE and BTE models are significant under the same operating conditions.

Chen and Weng [16] had presented numerically and analytically a second-order slip and jump model based on the Beskok–Karniadakis slip law [17] and found that the second-order condition played an important role in the developing region of a micro-channel.

Several forms of slip flow and temperature jump boundary conditions have been proposed. Although first-order models of slip flow can provide reasonable accuracy [18], the use of second-order

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models becomes necessary for high Knudsen numbers Kn in the slip regime, and for the transition regime [19].

The aim of the present work is to investigate the DPL model coupled with a new second-order jump boundary condition to assess the thermal properties in a 2D MOSFET for three cases bulk silicon with uniform and non-uniform heat generation. To enhance our model, the third case was devoted to the study of heat transfer in our MOSFET using the jump condition coupled with the Robin condition. The equations were solved numerically using the finite element method. The collisions in SiO_2/Si interface were considered by applying the second-order temperature jump boundary condition. The results were compared with those for the first-order case [15] and data obtained from Laroche and Taur [12].

2. Mathematical modeling

2.1. New DPL model, second order

In order to consider the effects of heat transfer in nanoscale devices, the DPL model was proposed [13]. This model reads

$$\vec{q}\,(t+\tau_q,\vec{r}\,) = -K\vec{\nabla}T(t+\tau_t,\vec{r}\,) \tag{1}$$

where T is the temperature, t is the time, K is the heat conductivity and $\boldsymbol{q}$ is the heat flux vector. τ_t is the phase lag of the temperature gradient, and τ_q is the phase lag of the heat flux.

First order in Taylor series of the Eq. (1) reads

$$\vec{q}+\tau_q\frac{\partial\vec{q}}{\partial t} = -K\cdot\left\{\vec{\nabla}T+\tau_t\frac{\partial}{\partial t}\vec{\nabla}T\right\} \tag{2}$$

The energy equation is

$$\nabla\vec{q} = -C\partial T/\partial t+Q \tag{3}$$

where C is the specific heat of the solid and Q is the volumetric heat generation.

Eq. (2) gives

$$\nabla\vec{q}+\tau_q\frac{\partial\nabla\vec{q}}{dt} = -K\left\{\Delta T+\tau_t\frac{\partial}{\partial t}\Delta T\right\} \tag{4}$$

The combination of Eq. (4) with the energy equation taking into account $K=(C|v|A)/3$ leads to the dual-phase-lag conduction equation (DPL model) that reads

$$\frac{\partial T}{\partial t}+\tau_q\frac{\partial^2T}{\partial t^2} = \frac{Q}{C}+\frac{\tau_q}{C}\frac{\partial Q}{\partial t}+\frac{K}{C}\Delta T+\tau_t\frac{k}{C}\frac{\partial}{\partial t}\Delta T \tag{5}$$

where $|v|$ is the heat carrier group velocity, and A is the phonon mean free path.

In the present work $\tau_q>\tau_t$, which means the temperature gradient precedes the heat flux vector. To calculate the temperature distribution in the MOSEFT, we use a temperature jump condition at the oxide–silicon interface. The following dimensionless variables are introduced to normalize Eq. (5):

$$T^* = (T-T_0)/T_0,\quad t^* = t/\tau_q,\quad Kn = A/L_c,\quad v = A/\tau_q$$

$$x^* = x/L_c,\quad y^* = y/L_c,\quad q^* = \frac{q}{CvT_0},\quad B = \tau_t/\tau_q$$

Eq. (5) can be rewritten as

$$\frac{\partial T^*}{\partial t^*}+\frac{\partial^2T^*}{\partial t^{*2}} = Q^*+\frac{\partial Q^*}{\partial t^*}+\frac{Kn^2}{3}\Delta^*T^*+B\frac{Kn^2}{3}\frac{\partial}{\partial t^*}\Delta^*T^* \tag{6}$$

Ghazanfarian and Abbassi [20] considered the temperature jump boundary condition at the first order as follows:

$$T^*-T_w^* = -d_1Kn\left(\frac{\partial T^*}{\partial n^*}\right)_{\Omega^*} \tag{7}$$

where T_w^* is the dimensionless boundary temperature of the wall, T^* is the dimensionless temperature, and d_1 is an adjustable coefficient. In this work, $d_1=0.06$ [15] and n is the direction of the outward normal vector of the boundaries. Eq. (7) represents the dimensionless temperature jump between the channel and the wall. We can take account of the highest orders terms when the Knudsen number is higher [21]. We also note that Deissler's result [22] for second-order temperature jump is based on approximate mean-free-path arguments.

Second order temperature jump boundary condition is expressed as follows [23,24]:

$$T^*-T_w^* = -d_1Kn\left(\frac{\partial T^*}{\partial n^*}\right)_{\Omega^*}+d_2\frac{Kn^2}{2}\left(\frac{\partial^2T^*}{\partial n^{*2}}\right)_{\Omega^*} \tag{8}$$

Eqs. (7) and (8) suggest that the temperature of the structure at the wall will not be the same as the wall temperature. The temperature jump condition in the first order is more equal to the temperature of the wall than the gradient of the temperature. This expression misses the term of diffusion of the temperature inside our structure. The new second term on the right of Eq. (8) represents the diffusive part in the second order of the jump temperature, where d_2 is the coefficient which determines the speed of the propagation of the heat in the structure and is given by [21] as

$$d_2 = \frac{\gamma^2}{Pr^2}\frac{k_0^2}{2}A^2 \tag{9}$$

where Pr is Prandtl number, γ is the specific heat ratio, K_0 is a coefficient close to unity and A is the mean free path of the molecules. d_1 [15,25] and d_2 [26], should be determined in a way that results of the DPL model with our new boundary condition coincide with the solution of the Boltzmann equation. It is worth noting that these equations stem from numerical results are appropriate for engineering applications [20]. Temperature jump condition is due to phonon reflection–absorption on the wall. d_2 is obtained when one makes Taylor series of the system temperature at the wall [19–23,24].

2.2. Geometry and boundary conditions

The geometry of the transistor used in the present survey given by $L=100$ nm, $l=50$ nm and 1 μm with the heat generation area of 10 nm × 10 nm shown in Fig. 1. In order to consider the geometry as a 2D transistor, the results are presented at time $t=50$ ps, since the third length direction (1 μm) is much longer than the phonon traveling length 30 nm in 10 ps [12].

Sverdrup et al. [27] declared that the peak temperature is located near the drain junction of the device and the heat generation also peaked in the limit of the channel at the drain side of the MOSEFT. Generally the Joule effect is given by [28]

$$Q = \vec{J}.\vec{E}+(R-G)(E_G+3K_BT) \tag{10}$$

where J is the current density, $(R-G)$ is the rate of non-radiative recombination, E_G is the band gap energy of semi-conductor and K_B is the Boltzmann constant.

In order to simplify our model, the Joule effect in this work is given by

$$Q = Q_{max}|X+Y-1| \tag{11}$$

where X and Y are given in Fig. 1b and $Q_{max}=10^{19}$ W/m^3.

In the first case shown in Fig. 1a, the bottom of the simulation domain is assumed to be at a uniform temperature of 300 K because after 50 ps, the temperature at this location remains almost constant. The SiO_2/Si interface is exposed to the temperature jump boundary condition in first and second-order. The two ending parts of the top surface of the transistor are exposed to the ambient. Finally, the left and the right boundaries are assumed to be adiabatic. This case is supposed to be similar to the case considered by Ghazanfarian and