Simulation of Gate Switching Characteristics of a Miniaturized MOSFET based on a Non-Isothermal Non-Equilibrium Transport Model

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Abstract— Our device simulator is developed for the analysis of a MOSFET based on Thermally Coupled Energy Transport Model(TCETM). The simulator has the ability to calculate not only steady-state characteristics but also transient characteristics of a MOSFET. It solves basic semiconductor devices equations including Poisson equation, current continuity equations for electrons and holes, energy balance equation for electrons and heat flow equation, using finite difference method.

I. INTRODUCTION

This paper follows a previous preliminary study [1] of the transient response of a miniaturized MOSFET based on the non-isothermal model (NIM). This latter model is adopted to compensate for the neglect of the thermal effect by the drift-diffusion model (DDM). Furthermore, in the TCETM, the energy balance equation is also considered to account for the localized effect of energy balance. This model has been also successfully used in a previous simulation of the steady-state case [2].

At this time we mainly report the transient characteristics based on TCETM. And for completeness, representative results obtained previously by the steady-state study will be retrieved here.

II. BASIC EQUATIONS

Basic equations for two-dimensional transient simulation, consisting of Poisson equation (1), current continuity equations for electrons (2) and holes (3), energy transport equation for electrons (4) and heat flow equation (5), are given as follow.

$$\text{div}(\ \varepsilon\ \text{grad}\ \psi) = -q(\ N_D - N_A + p - n) \tag{1}$$

$$\frac{\partial n}{\partial t} = \text{div}\ (\frac{J_n}{q}) + U \tag{2}$$

$$\frac{\partial p}{\partial t} = -\text{div}\ (\frac{J_p}{q}) + U \tag{3}$$

$$\frac{\partial (n\xi_n)}{\partial t} + \text{div}\ S_n = J_n \cdot E - nC_n + \xi_n U \tag{4}$$

$$\rho C \frac{\partial T_L}{\partial t} - \text{div}\ (k_L\ \text{grad}\ T_L) = Q_L \tag{5}$$

where ε, ψ, n, p, N_A, N_D and U represent permittivity, electric potential, electron density, hole density, acceptor doping concentration, donor doping concentration, and generation-recombination of carriers, respectively. J_n and J_p are electron and hole current densities. E is electric field. S_n and C_n are energy flux and mean energy loss rate for electron. ξ_n is electron mean energy. ρ, C, k_L, Q_L and T_L stand for density, specific heat capacity, thermal conductivity, lattice heat generation rate and lattice temperature, respectively. Note that equations (1)-(3) form what is conventionally called the drift-diffusion model, equation (4) is the energy balance equation for electrons and equation (5) is the heat flow equation which have been added here to account for the non-isothermal and non-equilibrium conditions. As for the energy balance equation, we consider electrons only, and assume that the hole and lattice temperatures are equal.

The electron mean energy ξ_n is assumed to be totally thermal, since thermal energy is much larger than the average kinetic energy in most cases. Here, the mean energy loss rate C_n is given as follows.

$$C_n = \frac{\xi_n - \xi_L}{\tau_{wn}} = \frac{3}{2} k_B \frac{T_n - T_L}{\tau_{wn}} \tag{6}$$

where τ_{wn} is energy relaxation time for electrons, T_n is electron temperature and ξ_L is lattice energy. Variables n, p, J_n, J_p are interrelated with each others by following auxiliary equations.

$$n = n_i \exp \frac{q(\psi - \phi_n)}{k_B T_L} \qquad (7)$$

$$p = n_i \exp \frac{q(\phi_p - \psi)}{k_B T_L} \qquad (8)$$

$$J_n = qD_n \, \text{grad} \, n - q\mu_n nE + k_B n a_n \mu_n \, \text{grad} \, T_n \qquad (9)$$

$$J_p = -qD_p \, \text{grad} \, p - q\mu_p pE - k_B p a_p \mu_p \, \text{grad} \, T_p \qquad (10)$$

$$S_n = -k_n \, \text{grad} \, T_n - (\xi_n + k_B T_n) \qquad (11)$$

Furthermore, the thermal energy is related to the total current as follows.

$$J = J_n + J_p + J_{disp} \qquad (12)$$

$$Q_L = E \cdot J - E_g U \qquad (13)$$

with

$$J_{disp} = -\varepsilon \frac{\partial}{\partial t} \, \text{grad} \, \psi \qquad (14)$$

where T_p, n_i, k_n and k_B are hole temperature, intrinsic carrier density, thermal conductivity for electron and Boltzmann constant. ϕ_n, ϕ_p, μ_n, μ_p, D_n and D_p represent quasi-Fermi potentials, mobilities and diffusion constants for electrons and holes, respectively. a_n and a_n are transport coefficients for electrons and holes. J is total current and J_{disp} is displacement current.

Note that all other physical parameters are identical with those in Ref.[3].

III. NUMERICAL METHOD

Equations (1)-(14) are now numerically solved self-consistently. We used a modified Scharfetter-Gummel formula by Tang[4], and the backward time differencing by Mock[5].

A simplified algorithm of the simulation is shown in Fig.1. This algorithm is composed of four computing loops, namely drift diffusion loop, energy transport loop, heat flow loop for solving the governing equations and the last transient loop for controlling the time flow.

First of all, structure parameters of the MOSFET are calculated as initial settings. Then the terminal voltage are increased until a given bias, e.g. 3.0[V]. After setting time t, equations (1)-(3), (7)-(10) are solved first by means of a coupled method for ψ, n, p. Equations (4), (5) and (11), (13) are solved next using the just-obtained ψ, n, p. This process is reiterated until convergence is achieved for each time step. The time is now renewed to $t + \Delta t$ and the whole thing is repeated until the prescribed simulation time is exhausted.

IV. SIMULATION STRUCTURE

A gate transient simulation is performed on a MOSFET structure shown in Fig.2, with channel length $L_{eff} = 0.2[\mu\text{ m}]$, oxide thickness $t_{ox} = 8[\text{nm}]$, junction depth $x_j = 0.08[\mu\text{ m}]$,

substrate density $N_{sub} = 3.9 \times 10^{17}[\text{ atoms/cm }^{-3}]$. Both drain and gate biases are initially fixed at 3.0[V], substrate bias at 0[V]. Then a gate bias ramp of various time lengths (e.g.50,25[ps]) is applied. Terminal currents are taken positive in their outward direction.

V. SIMULATION RESULTS

A. Steady-State conditions

Fig.3 shows the electron velocity along at the Si/SiO2 interface. We found that the velocity overshoot is much more pronounced than that of DDM case. Fig. 4 and 5 are the stereoplots showing the distribution of electron temperature and lattice temperature, respectively.
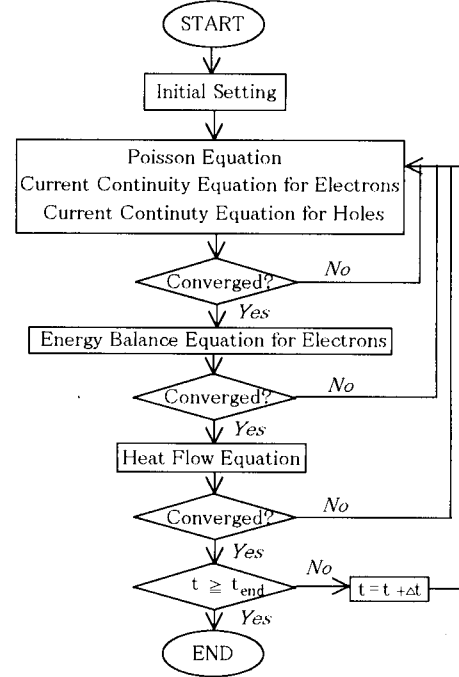

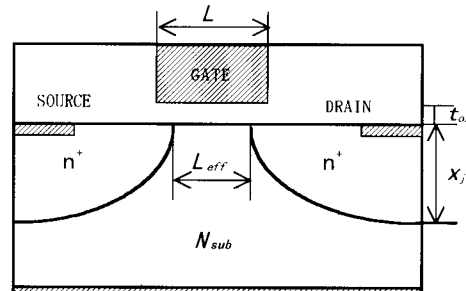Fig.1. The algorithm of the simulation
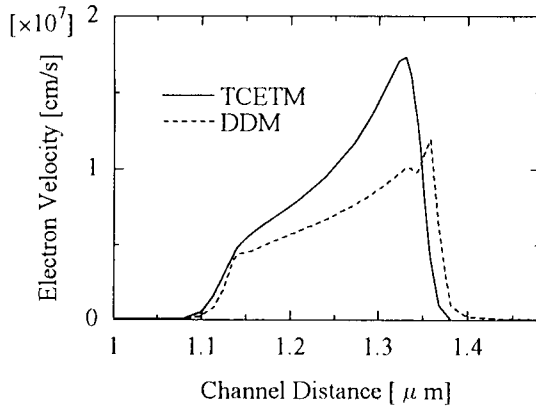

Fig. 2. Geometry of a n-channel MOSFET structure

Fig. 3. Electron velocity along at the Si/SiO2 interface
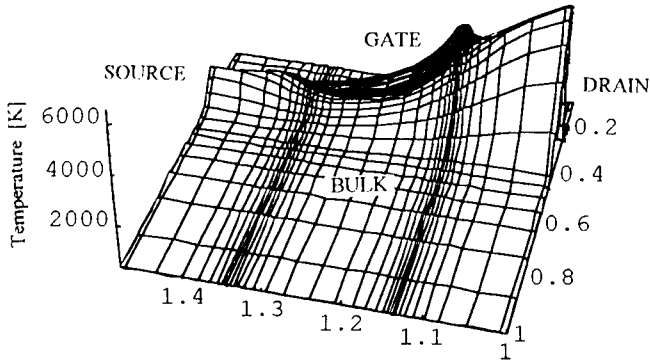

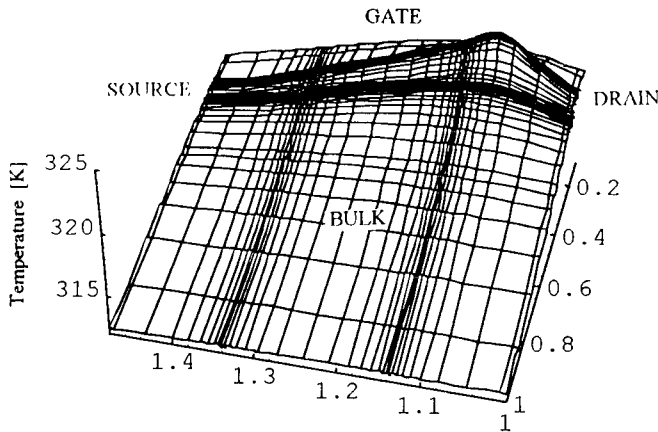Fig. 4. Distribution of the electron temperature

Fig. 5. Distribution of the lattice temperature

B. Transient Conditions

Fig. 6 shows a delay lattice temperature to fall even after the gate bias has decreased to zero.

Fig.7 and Fig.8 show the difference between DDM and TCETM in terms of the source and the drain terminal currents. It can be seen that the drain and the source currents based on the equilibrium model (DDM) is underestimated, due to the neglect of the carrier velocity overshoot effect shown in Fig. 3.

Fig.9 shows the gate current for two cases of different ramp times. The difference in gate currents between DDM and TCETM becomes bigger with shorter ramp time. Also note that, contrary to the case of source and drain currents, DDM yields a larger current than TCETM. This overestimation can be attributed to the difference in carrier profiles which the two models produce as shown in Fig. 10. Actually Fig. 10 shows steady-state distributions of electron density in depth direction at the middle of the channel. While the carrier density is concentrated at channel surface in DDM, the profile based on TCETM shows a broad penetration in the depth of the substrate. The distributions of electron in transient operation are shown in Fig. 11. Fig. 12 represents the electric field at the middle of channel. The slope of the electric field corresponds to the displacement current which is the gate current. Consequently, the overestimation is due to the difference in terms of the electric field distribution between DDM and TCETM.
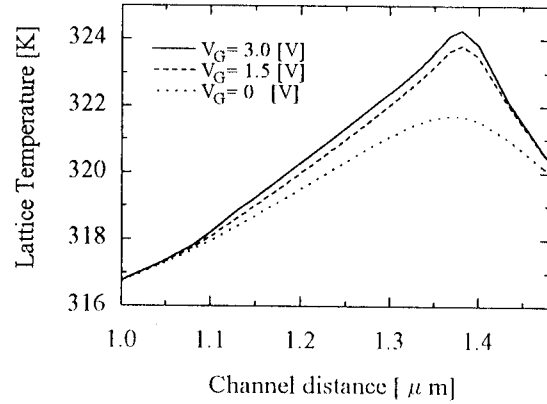

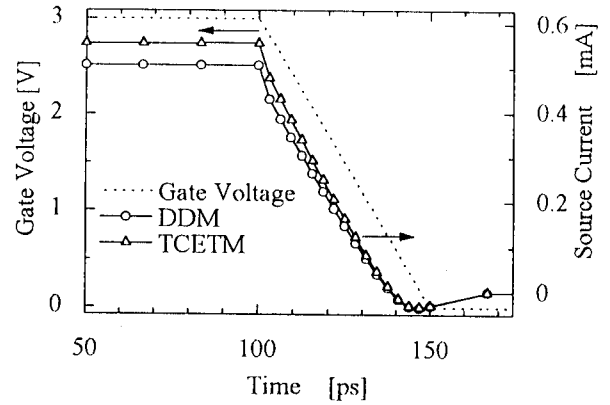Fig .6. Lattice temperature in transient conditions
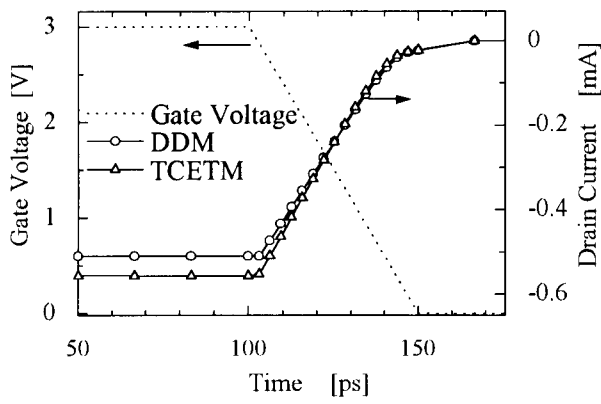

Fig. 7. Characteristics of the source current

Fig. 8. Characteristics of the drain current
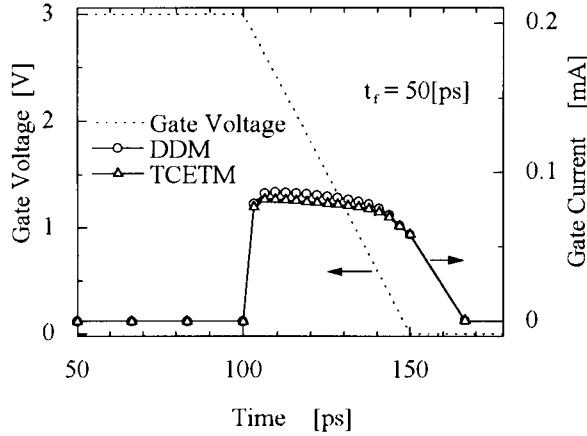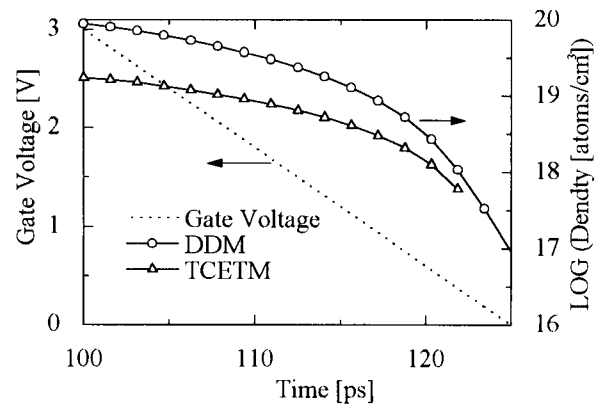

Fig. 11. Electron density on transient conditions
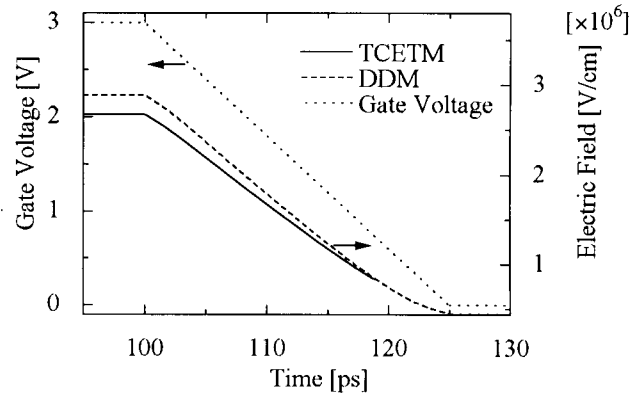

$t_f = 50[ps]$

Fig. 12. Electric field on transient conditions

VI. CONCLUSION

A detailed transient simulation of the gate switching characteristics of a miniaturized MOSFET based on a non-isothermal non-equilibrium transport model has been described. We found that the simulation accuracy depends on the model, when the channel length is short and/or gate oxide thickness thin. Non-isothermal non-equilibrium transport model (TCETM) shows better accuracy than isothermal equilibrium transport model (DDM). Therefore it is necessary to adopt this model when simulating a deep submicron MOSFET not only in stationary but also in nonstationary operations.

$t_f = 25[ps]$

Fig. 9. Characteristics of the gate current

SURFACE

Fig. 10. Distributions of electron density

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