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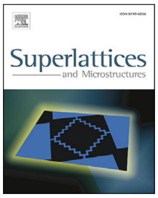

Improved Metal Oxide Semiconductor Field Effect Transistor models with wide temperature range including cryogenic temperature

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A B S T R A C T

The analytical Metal Oxide Semiconductor Field Effect Transistor (MOSFET) models with wide temperature range including cryogenic temperature have been presented in this paper. Based on the Berkeley Short-channel IGFET Model (BSIM) core, the mobility model, the threshold voltage model, the velocity saturation model and the parasitic resistance model have been updated and added to precisely describe the characteristics of MOSFETs at wide temperature range. The presented models have been verified by different MOSFETs and a capacitor charge-discharge circuit at regular and cryogenic temperatures. The measurement and simulation results have demonstrated the considerable accuracy and general applicability of the proposed models.

1. Instruction

The operation of MOSFETs at cryogenic temperature (such as −200 °C) has exhibited excellent performances: larger carrier mobility and saturation velocity, smaller sub-threshold slope and lower noise. All of these advantages will make Complementary Metal Oxide Semiconductor (CMOS) circuit own better on-state characteristics, faster switching speed, higher gain, lower power dissipation and higher integration density [1–3]. Consequently, the application of the MOSFETs at cryogenic temperature has become significant, such as the infrared and far-infrared optical detectors, the quantum computing and the electronics for outer space applications [4–7].

The simulation program with integrated circuit emphasis (SPICE) model is the link between the physical world and the design world of the semiconductor industry. However, the BSIM models, as the classical MOSFET models widely accepted in the industry, can not describe the electrical characteristics of a MOSFET at cryogenic temperature properly, because the temperature-dependence of the key parameters in the standard BSIM models will deviate from the linear relationship, resulting in the fitting errors for characteristics of a MOSFET at cryogenic temperatures. Therefore, it is necessary to realize the exact SPICE models of the MOSFET for a wide temperature range including cryogenic temperature. Although many papers have reported this topic [8–12], in which the presented models are physical, numerical or sub-circuit ones, the models which can be based on universal BSIM models and widely used in the SPICE simulator have been few documented.

In this paper, the analytical MOSFET models with wide temperature including cryogenic temperature have been developed basing on the BSIM model core, and the presented models can fit the electrical characteristics precisely both at

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regular and cryogenic temperatures. Moreover, a kind of capacitor charge-discharge circuit has already been designed and fabricated. Both at 25°Cand −200 °C, the measurement and simulation data of the circuit have been acquired and made a detailed comparative analysis, which have verified the considerable accuracy and general applicability of the presented SPICE models.

2. MOSFET models with wide temperature range

Based on the BSIM core, the mobility model, the threshold voltage model, the velocity saturation model and the parasitic resistance model have been revised and added to describe the characteristics of the MOSFET in a wide temperature range.

2.1. The mobility model

The scattering mechanisms responsible for the carrier mobility include the ionized impurity scattering, the phonons scattering and the surface roughness scattering [13]. For a MOSFET with regular channel doping and good interface quality, the phonons scattering is the dominant scattering mechanism. In BSIM model core, the equation of the carrier mobility can be given by Eq. (1) [14],

$$\mu_{eff} = \frac{\mu_0}{1 + \left(U_a + U_c \cdot V_{bseff}\right) \cdot \left(\frac{V_{gsteff} + 2V_{th}}{T_{ox}}\right) + U_b \cdot \left(\frac{V_{gsteff} + 2V_{th}}{T_{ox}}\right)^2} \tag{1}$$

$$V_{gsteff} = V_{gs} - V_{th} \tag{2}$$

where μ_0 is constant and represents the carrier mobility without any vertical electrical field affection, V_{bseff} is the effective substrate bias voltage, V_{gseff} is defined as Eq. (2), V_{th} is the threshold voltage, T_{ox} is the gate oxide thickness, U_a is the first-order mobility degradation coefficient, U_b is the second-order mobility degradation coefficient, U_c is the mobility degradation coefficient considering the body-effect.

However, the above carrier mobility model can be only used in the regular temperature range but not at the cryogenic temperature. As the temperature decreases, the lattice thermal motion of the atoms will be weakened. As a result, the phonons scattering is reduced and the carrier mobility increases. Therefore, for the mobility model with a wide temperature range, the temperature affection should be considered. Based on Eq. (1), the parameters μ_0, U_a, U_b and U_c have been updated,

$$\mu_0(T) = \mu_0 \left(\frac{T}{300}\right)^{ute} \tag{3}$$

$$U_a(T) = U_a + U_{a1}\left(\frac{T}{300} - 1\right) + U_{a2}\left(\frac{T}{300} - 1\right)^2 \tag{4}$$

$$U_b(T) = U_b + U_{b1}\left(\frac{T}{300} - 1\right) + U_{b2}\left(\frac{T}{300} - 1\right)^2 \tag{5}$$

$$U_c(T) = U_c + U_{c1}\left(\frac{T}{300} - 1\right) + U_{c2}\left(\frac{T}{300} - 1\right)^2 \tag{6}$$

where ute is the mobility temperature exponent, U_a, U_{a1} and U_{a2} are temperature coefficients for U_a(T), U_b, U_{b1} and U_{b2} are temperature coefficients for U_b(T), and U_c, U_{c1} and U_{c2} are temperature coefficients for U_c(T).

2.2. The threshod-voltage model

With the decreasing of the temperature, the Fermi level will move towards the conduction band. Accordingly, the channel surface potential responsible for the inversion layer thickness of threshold voltage will increase, and the threshold voltage will increase finally. Moreover, the presented threshold voltage model has also considered the temperature sensitivities of the short-channel effect, the narrow-channel effect and the substrate bias effect. The equation of the threshold voltage with a wide temperature range is expressed by

$$V_{th}(\mathrm{T}) = V_{th} + \left(K_{t1} + \frac{K_{t1l}}{L_{eff}^{K_{t1lp}}} + \frac{K_{t1w}}{W_{eff}^{K_{t1wp}}} + K_{tb} \cdot V_{bseff}\right)\left(\frac{T}{300} - 1\right) + \left(K_{t2} + \frac{K_{t2l}}{L_{eff}^{K_{t2lp}}} + \frac{K_{t2w}}{W_{eff}^{K_{t2wp}}} + K_{tb} \cdot V_{bseff}\right)\left(\frac{T}{300} - 1\right)^2 \tag{7}$$