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Empirical Model of Phonon-Limited Electron Mobility for Ultra-Thin Body SOI MOSFET

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1. Introduction

The two-fluid density-gradient (2FDG) model has made it possible to obtain electron density in the two-fold and four-fold valleys without solving the Schrödinger equation [1]. However, to express the precise drain current (I_d) of MOSFETs more simply in device simulations, empirical mobility models for each valley are needed.

As the first step, we model phonon-limited electron mobility because electron-phonon interaction is a dominant scattering mechanism in a wide range of effective electric fields (E_{eff}) at room temperature; the scattering processes stemming from surface roughness (SR) or interface charges should be taken account of only at either very high or very low fields. As the SOI-layer thickness (T_{SOI}) decreases, the phonon-limited electron mobility (μ_{ph}) significantly varies [2, 3]. Calculations indicate that the variation is due to, in part, the quantum effect. Based on those results, we introduce an empirical model that involves a function of T_{SOI} and E_{eff}.

2. Device structure and simulations

The device structure assumed is the single-gate (SG) n-channel SOI MOSFET shown in Fig. 1. As shown in Fig. 1, gate oxide thickness is 3 [nm] and buried oxide thickness is 200 [nm]. Impurity concentrations (N_A) in the SOI-layer and Si substrate are taken to be 5×10^{15} [cm^{-3}].

This article simulates the phonon-limited electron mobility in the (100) and (111) Si inversion layers in such ultra-thin body SOI MOSFETs at 300K using a relaxation time approximation based on 1-D self-consistent calculations. The physical parameters used in the calculation are listed in Tables 1 and 2.

3. Results and Discussions

We propose empirical models of phonon-limited mobility in the two-fold valley ($\mu_{ph,2fold}$) and in the four-fold valley ($\mu_{ph,4fold}$). Mobility model for (111) surface is not shown below to save description space.

3.1 Empirical Model of Phonon-Scattering-Limited Electron Mobility in the Two-Fold Valley: (001) surface

$$m_{ph,2fold} = AE_{eff}^{2} - BE_{eff} + C \quad , \qquad (1)$$

$$A=\frac{a_1 b_1}{a_1+b_1},\quad B=\frac{a_2 b_2}{a_2+b_2},\quad C=\frac{a_3 b_3}{a_3+b_3},\qquad (2a),(2b),(2c)$$

$$a_1 = 1.15\exp\left[\frac{3(T_{SOI}+4)}{4}\right]+17 \quad , \qquad (3a)$$

$$b_1 = -0.250875\times T_{SOI}+215.5 \quad , \qquad (3b)$$

$$a_2 = 1.54\exp(T_{SOI}+3.5)+19.0\ ,\quad b_2 = 704.2 \qquad (4a),(4b)$$

$$a_3 = 1.6\exp[1.23(T_{SOI}+3.5)]+150.0\ ,\quad b_3 = 1108\ , \qquad (5a),(5b)$$

3.2 Empirical Model of Phonon-Scattering-Limited Electron Mobility in the Four-Fold Valley: (001) surface

$$m_{ph,4fold} = DE_{eff}^{E} \quad , \qquad (6)$$

$$D=\frac{a_4 b_4}{a_4+b_4},\ E=\frac{abc}{ab+bc+ca}, \qquad (7a),(7b)$$

$$a_4 = 1.15\exp\left[\frac{(T_{SOI}+3.3)}{1.1}\right]+90\ ,\ b_4 = 414.14\ , \qquad (8a),(8b)$$

$$a = -0.02546\times T_{SOI}+0.1,\quad b = -0.113\ , \qquad (9a),(9b)$$

$$c = 0.0000028\exp(2.3T_{SOI}), \qquad (9c)$$

We draw the simulation results of phonon-limited electron mobility in the two-fold valley ($\mu_{ph,2fold}$) and in the four-fold valley ($\mu_{ph,4fold}$) and empirical models, which are shown with parameter of T_{SOI} in Fig. 2 and Fig. 3, respectively. In Fig. 4, we show T_{SOI} dependencies of phonon-limited electron mobility models of (001) and (111) surfaces for comparison. Empirical models for (001) and (111) surfaces accurately reproduce the simulation results such as E_{eff} dependence and T_{SOI} dependence.

When electric field along the channel is assumed to be uniform, drive current (I_d) is approximately expressed by the following equation (10).

$$I_d \approx \frac{W}{L}V_d\left(qm_{2fold}N_{2fold}+qm_{4fold}N_{4fold}\right), \qquad (10)$$

where W is the channel width, L is the channel length, μ is the electron mobility, and N is the surface electron density; the subscripts "*2fold*" and "*4fold*" represent the two-fold valley and four-fold valley, respectively.

Using the electron density obtained from the 2FDG model and the empirical models (equations (1) and (6)), calculated I_d curves for (001) and (111) surfaces vs. gate voltage (V_g) is shown in Fig. 5 for T_{SOI} = 5 [nm]; here a metal gate is assumed. As shown in Fig. 5, entire I_d-V_g characteristics are successfully represented. However, the models don't reproduce TCAD simulation result [4], which suggests that the SR model must be included [3].

References

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[2] M. Shoji and S. Horiguchi, *J. Appl. Phys.*, vol. 82, p. 6096, 1997.
[3] S. Takagi et al., in *IEEE IEDM Tech. Dig.*, p. 219, 1997.
[4] TCAD/DESSIS operation manual, ver. 7.5, Synopsis.

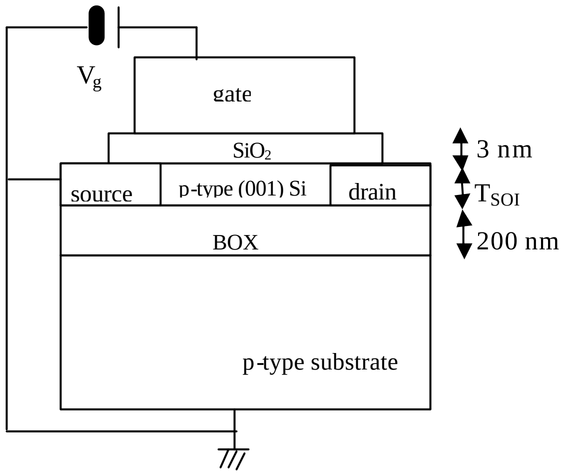

Fig. 1. Device structure considered.

Table. 1. Physical parameters used in the present calculations.

Parameters		Values [unit]
m_0	free electron mass	9.11×10^{-31} [kg]
m_l	longitudinal effective mass	$0.98m_0$
m_t	transverse effective mass	$0.19m_0$
m_{d2}	density-of-state mass in two-fold valley	$0.19m_0$
m_{d4}	density-of-state mass in four-fold valley	$0.43m_0$
m_{c2}	conductivity mass in twofold valley	$0.19m_0$
m_{c4}	conductivity mass in fourfold valley	$0.32m_0$
ρ	crystal density	2329 [kgm^{-3}]
S_l	sound velocity	9037 [ms^{-1}]
D_{ac}	acoustic deformation potential	12.0 [eV]

Table. 2. Parameters for inter-valley phonon scattering models.

Type of inter-valley Scattering	phonon energy E_k [meV]	deformation potential D_k [$x10^8$ $eVcm^{-1}$]
f	19.0	0.3
f	47.4	2.0
f	59.0	2.0
g	12.1	0.5
g	18.5	0.8
g	62.0	11.0

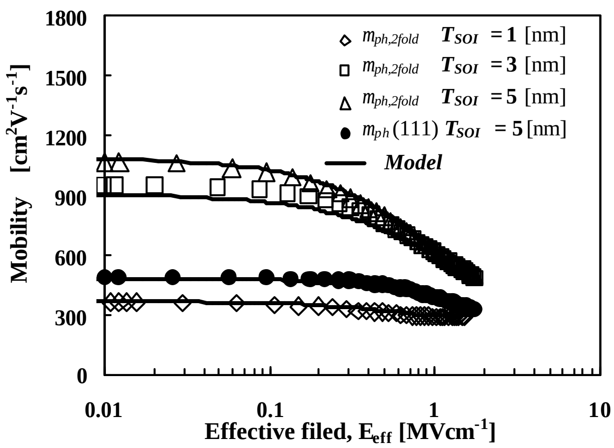

Fig. 2. E_{eff} dependence of phonon-limited electron mobility in the two-fold valley and in inversion layer on (111) surface.

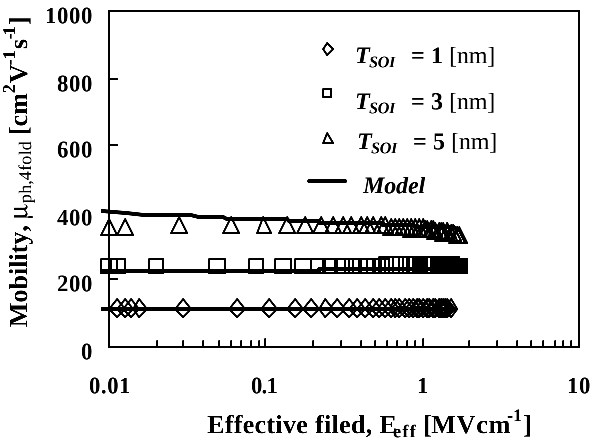

Fig. 3. E_{eff} dependence of phonon-limited electron mobility in the four-fold valley.

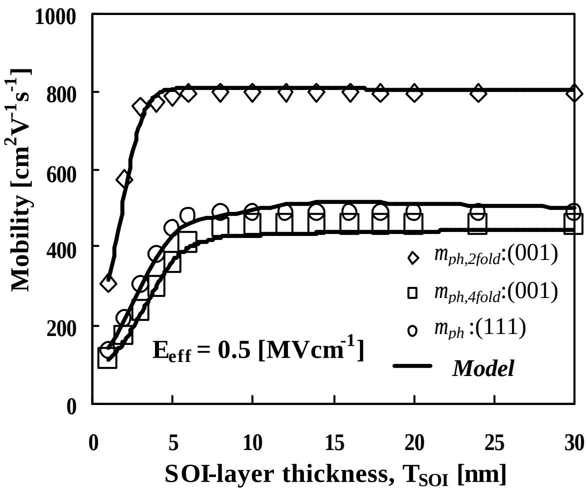

Fig. 4. T_{SOI} dependencies of phonon-limited electron mobility for (001) or (111) surface.

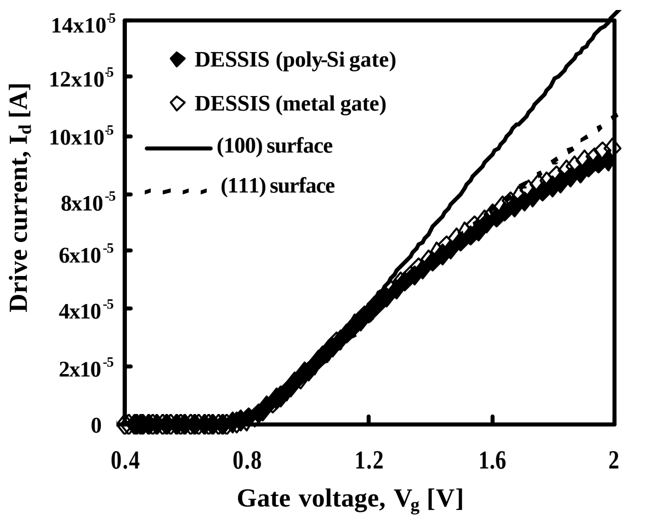

Fig. 5. Calculated I_d versus V_g in SOI MOSFETs with 20-nm thick SOI-layer. L = 500 [nm], W = 1 [μm], V_d =0.1 [V]