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ANALYTICAL MODELS FOR CHANNEL POTENTIAL, DRAIN CURRENT, AND SUBTHRESHOLD SWING OF SHORT-CHANNEL TRIPLE-GATE FinFETs

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Abstract

An analytical model for channel potential, subthreshold drain current, and subthreshold swing of the short-channel fin-shaped field-effect transistor (FinFET) is obtained. The analytical model results are verified against simulations, good agreement is observed. The explicit expressions for drain current and subthreshold swing make the model suitable to be embedded in circuit simulation and design tools.

I. Introduction

As the channel length of metal-oxide-semiconductor field-effect transistors (MOSFETs) continues to scale down, short channel effects (SCEs) and carrier mobility degradation will be serious [1]. To solve these
problems, a MOSFET with a triple-gate has been proposed, fabricated and studied to some extent [2-7], and this new device is considered to be one of the best candidates for deca-nanometer scaling of MOSFETs. To facilitate the applications of the device in integrated circuits, analytical models for channel potential, drain current, subthreshold swing, and threshold voltage are urgently needed.

Yang et al. established the scaling theory of FinFETs by solving Poisson’s equation (PE) through the superposition method [3]. Ritzenthaler et al. obtained the model of subthreshold characteristics of FinFETs [4], they solved the Laplace’s equation instead of Poisson’s, which made their model only applicable to the device where the channel is lightly doped. The authors of [5] and [6] explored the lightly doped short-channel triple-gate MOSFETs, and presented a compact drain-current model, respectively. Hamid et al. obtained the subthreshold swing model for undoped trigate FinFETs [7].

Most of the aforementioned research works dealt with undoped or lightly doped devices. In this work, we focus our research on the FinFETs with evenly doped channel. We solve the three dimensional Poisson’s equation analytically, and obtain the electric potential in the channel region. Based on the potential model, we present the expressions for subthreshold drain current and subthreshold swing.

II. Analytical Model

The bird’s eye view and the cross section view of the device are shown in Figures 1(a) and 1(b). $x$, $y$ and $z$ are along the channel length, width and height directions, respectively. The channel of the device is an evenly doped silicon body, which is surrounded with a very thin layer of oxide, and the oxide is enclosed with a fin-shaped gate, whose material can either be a metal or a heavily doped polysilicon.

The Poisson’s equation in the silicon body is

$$
\frac{\partial^2 \phi(x, y, z)}{\partial x^2} + \frac{\partial^2 \phi(x, y, z)}{\partial y^2} + \frac{\partial^2 \phi(x, y, z)}{\partial z^2} = \frac{qN_A}{\varepsilon_{si}},
$$

(1)
where $\phi$ is electric potential, $q$ is the electronic charge, $N_A$ is the doping density, and $\varepsilon_{si}$ is the permittivity of silicon.

**Figure 1(a).** Bird’s eye view of a FinFET.

**Figure 1(b).** Cross section view of a FinFET.

1. Electric potential

Similar to the treatment used in research works [2, 3], we simplify the boundary conditions of the device. There are altogether six boundary conditions set by the source, the drain, the front gate, the back gate, the top
gate, and the bottom, respectively. The bottom is always thick enough that the electric field there can be ignored. The whole region is now approximated as homogeneous silicon with effective thickness \( T_{\text{eff}} \) and effective height \( H_{\text{eff}} \) \[2, 3\]. These two parameters are defined as \[2, 3\],

\[
T_{\text{eff}} = \sqrt{T_{\text{fin}} \left( T_{\text{fin}} + 4T_{\text{ox1}} \varepsilon_{\text{Si}} / \varepsilon_{\text{ox}} \right)},
\]

\[
H_{\text{eff}} = \sqrt{H_{\text{fin}} \left( H_{\text{fin}} + 2T_{\text{ox1}} \varepsilon_{\text{Si}} / \varepsilon_{\text{ox}} \right)},
\]

where \( T_{\text{ox1}} \) and \( T_{\text{ox2}} \) are the oxide thicknesses shown in Figure 1(b). \( H_{\text{fin}} \) and \( T_{\text{fin}} \) are the channel height and channel thickness, respectively. \( \varepsilon_{\text{ox}} \) is the permittivity of the oxide.

Then, the six boundary conditions are:

\[
\phi(0, y, z) = V_{\text{bi}},
\]

\[
\phi(L, y, z) = V_{\text{bi}} + V_{\text{ds}},
\]

\[
\phi(x, T_{\text{eff}} / 2, z) = V_{\text{gs}} - V_{\text{fb}},
\]

\[
\phi(x, -T_{\text{eff}} / 2, z) = V_{\text{gs}} - V_{\text{fb}},
\]

\[
\phi(x, y, H_{\text{eff}}) = V_{\text{gs}} - V_{\text{fb}},
\]

\[
\frac{\partial \phi}{\partial z} \bigg|_{z=0} = 0,
\]

where \( V_{\text{bi}} \) is the S/D build-in voltage, \( V_{\text{ds}} \) is the drain bias, \( V_{\text{gs}} \) is the gate bias, \( V_{\text{fb}} \) is the flat-band voltage, and \( L \) is the channel length. With \( 4f \), the bottom boundary condition could be replaced with the following equation \[3\]:

\[
\phi(x, y, -H_{\text{eff}}) = V_{\text{gs}} - V_{\text{fb}}.
\]

Similar to our previous works \[8, 9\], with boundary conditions \( 4a \) and
(4b), we assume that the electric potential along the channel length direction \((x)\) can be described by a summation of series, then, analytical solution for (1) can be obtained as the following:

\[
\phi(x, y, z) = V_{bi} + \frac{V_{ds}}{L} x + \sum_{n=1}^{\infty} A_n(y, z) \sin\left(\frac{n\pi}{L} x\right). \tag{5}
\]

Substituting (5) into (1), we find \(A_n(y, z)\) is determined by

\[
\sum_{n=1}^{\infty} \left[ \frac{\partial^2 A_n(y, z)}{\partial y^2} + \frac{\partial^2 A_n(y, z)}{\partial z^2} - k_n^2 A_n(y, z) \right] \sin\left(\frac{n\pi}{L} x\right) = \frac{qN_A}{\varepsilon_{si}}, \tag{6}
\]

with the use of the rest of the boundary conditions, \(A_n(y, z)\) can be obtained by solving (6). At last, an analytical expression for channel potential is achieved

\[
\phi(x, y, z) = V_{bi} + \frac{V_{ds}}{L} x + \sum_{n=1}^{\infty} \left[ B_n(y, z) + \varphi_n \right] \sin\left(\frac{n\pi}{L} x\right), \tag{7}
\]

where

\[
B_n(y, z) = \sum_m \sum_l b_{ml}(n) \cos\left[ \frac{(m - 0.5)\pi}{l} y \right] \cos\left[ \frac{(l - 0.5)\pi}{h} z \right],
\]

\[
b_{ml}(n) = \frac{(-1)^{m+l+1} 4(d_n + k_n^2 \varphi_n)}{(m - 0.5)(l - 0.5)\pi^4 \left[ \frac{(m - 0.5)^2}{t^2} + \frac{(l - 0.5)^2}{h^2} + n^2 / L^2 \right]},
\]

\[
\varphi_n = \frac{2}{n\pi} \left\{ (V_{gs} - V_{fb} - V_{bi}) [1 - (-1)^n] + V_{ds}(-1)^n \right\}, \quad k_n = n\pi / L,
\]

\[
d_n = \frac{2qN_A}{n\pi\varepsilon_{si}} \left[ 1 - (-1)^n \right], \quad t = T_{eff} / 2, \quad h = H_{eff}, \quad m, \quad n, \quad \text{and} \quad l \text{are all integers}.
\]

2. Subthreshold drain current

The position of the minimum potential value along the \(x\) axis can be approximated as [2, 4]:

\[
\]
\[
\frac{x_c}{2} = \frac{L}{2} - \frac{1}{2\pi} \left( \frac{1}{T_{\text{eff}}^2} + \frac{0.5}{H_{\text{eff}}^2} \right)^{-1/2} \ln\left(1 + \frac{V_{\text{ds}}}{\Phi_{ms}}\right),
\]

where \( \Phi_{ms} \) is the gate work function difference of the S/D to the channel, and in this work its value equals to the built-in voltage, \( V_{bi} \).

Using drift-diffusion transport model and the most leaky path approach [7], the current flowing from the drain to the source can be expressed as

\[
I_{ds} = \frac{q n_i \mu V_t}{L} \left(1 - e^{-V_{\text{ds}}/V_t}\right) \int_0^{T_{\text{fin}}} \int_0^{H_{\text{fin}}} e^{\phi(x_c, y, z)/V_t} dy \, dz,
\]

where \( \mu \) is the mobility, \( n_i \) is the intrinsic carrier concentration, and \( V_t = k_B T / q \) is the thermal voltage.

### 3. Subthreshold swing

The definition of subthreshold swing, \( S \), is:

\[
S = \frac{\partial V_{gs}}{\partial \log_{10} I_{ds}}.
\]

With the use of equation (9), one obtains:

\[
S = 2.3 V_t \left[ \frac{\partial \phi(x_c, y, z)}{\partial V_{gs}} \right]^{-1}.
\]

Since the electric currents are mainly from the center of the channel, the electric potential at the location of \( (x_c, 0, H_{\text{fin}}/2) \) is used to obtain the subthreshold swing

\[
S = 2.3 V_t \left[ \frac{\partial \phi(x_c, 0, H_{\text{fin}}/2)}{\partial V_{gs}} \right]^{-1}.
\]

### III. Verification and Results

We verify our model against a simulation tool, Sentaurus [11]. In the simulation, a heavily doped \( p^+ \) polysilicon is chosen for the gates, \( V_{bi} = 0.8 \, V \), and \( \mu = 300 \, \text{cm}^2 / \text{V} \cdot \text{s} \) are assumed. Symbols are model results, and lines are simulation results, excellent agreement between the model results and the simulated results is observed.
Figure 2 shows the electric potential along the channel length direction. We notice that the potential reaches to a minimum near the middle of the channel length, which is consistent with equation (8). Figure 3 presents the electric potential along the channel width direction.

Figures 4 and 5 demonstrate the subthreshold drain current versus gate bias for the devices with a different channel length or with a different channel width, respectively. It is obvious that the subthreshold drain current will be larger for the device with a shorter channel, and/or for the device with a larger channel width.

Figures 6 and 7 characterize the subthreshold swing behaviors of the device. It is noted that, subthreshold swing will get worse with the reduction of channel length, and/or with the increase of channel width, and/or with the increase of the gate oxide thickness. As the channel length reduces, short channel effect will deteriorate the subthreshold swing. When increase the channel width, or increase the gate oxide thickness, it will be more difficult for the gates to control the channel, therefore, the subthreshold swing of the device get worse.

IV. Conclusion

An analytic model for channel potential, subthreshold drain current, and subthreshold swing is obtained. The proposed model has been verified against the commercial device simulator. The explicit expressions for the subthreshold drain current and subthreshold swing make the model suitable to be implemented in circuit simulation and design tools.
Figure 2. Electric potential distribution (in the channel center, $y = 0, z = H_{fin}/2$) along the channel length direction.

Figure 3. Electric potential in the channel (in the position $x = x_c, z = H_{fin}/2$) along the width direction.

Figure 4. Subthreshold drain current versus $V_{gs}$, for the FinFETs with different $L$. 
Figure 5. Subthreshold drain current versus $V_{gs}$, for the FinFETs with different channel width, $T_{fin}$.

Figure 6. Subthreshold swing versus channel length, $L$, for the FinFETs with different channel width, $T_{fin}$.

Figure 7. Subthreshold swing versus $T_{ox1}$ and $T_{ox2}$, for the FinFETs with different channel length, $L$. 
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