HiSIM-SOI: The First Surface-Potential-Based Fully-Depleted SOI-MOSFET Model for Circuit Simulation Development and Future Tasks

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Introduction

Recently, there has been an increasing production of Fully-Depleted (FD) SOI-MOSFET mainly because of its high speed and low power consumption. Other major advantages of FD SOI-MOSFET are

-Small junction capacitance
-Small sub-threshold swing
-Large saturation current.

To fully utilize these advantages, a FD SOI-MOSFET model for circuit simulation becomes an imperative requirement. Up to now, no FD SOI-MOSFET model with stable simulation exists. The common practice is to utilize bulk MOSFET model by fitting to FD SOI-MOSFET measurement data. However, this practice proves to be inaccurate and prediction of FD-SOI MOSFET characteristics is impossible.

This work aims to develop HiSIM-SOI, the first surface-potential based FD SOI-MOSFET model for circuit simulation. The model development is focused on the n-channel case.

Surface-Potential-Based Modeling

HiSIM-SOI (Hiroshima-university STARC IGFET Model) is developed based on surface potential in the same way with HiSIM, which is a bulk-MOSFET model for circuit simulation developed by Hiroshima university and STARC [HiSIM]. Surface-potential-based modeling realizes a self-consistent modeling among potential, charge and capacitance. Fig. 1 shows the structure of a SOI-MOSFET.

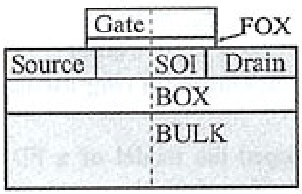

Fig. 1: Structure of SOI-MOSFET

SOI layer of FD SOI-MOSFET is always and entirely depleted under normal bias condition. There are 4 main requirements in developing HiSIM-SOI:

(1) Solution of the 1D-Poisson equation which is necessary for obtaining the surface potential.

(2) The relationship between potential and charge must be established. This relationship cannot be described analytically in SOI layer.

(3) Solution of the current-density equation to obtain the equation of channel current.

(4) An accurate method of extracting SOI-MOSFET's parameters should be established.

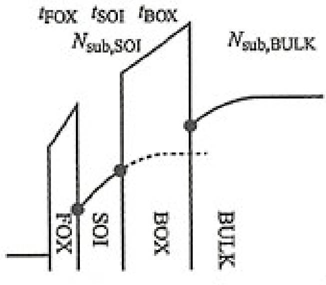

Fig. 2: Band diagram and parameters of SOI-MOSFET (along the dashed line of Fig. 1)

Approach in Developing HiSIM-SOI

(1) Surface potential

First, HiSIM calculates the surface potentials (ϕ_s) at the source and drain ends of the bulk-MOSFET channel. Using these potentials, the mobility, the channel current and other device quantities are calculated. In this calculation, an accuracy of 10^{-11}V is required for ϕ_s. In the case of bulk-MOSFET, it is enough to consider only the state at the Si surface. But in the case of SOI-MOSFET, the states at SOI-layer surface, SOI-layer back and BULK surface must be considered at the same time as described in Fig. 2 by solid circles. In principle the accumulation, depletion and inversion states are possible at each surface. In this work, the following simplifications under normal bias conditions are considered: (i) Depletion and inversion at SOI-layer surface, (ii) only depletion at SOI-layer back, and (iii) depletion and inversion at BULK surface. These simplifications enable analytical calculation of channel

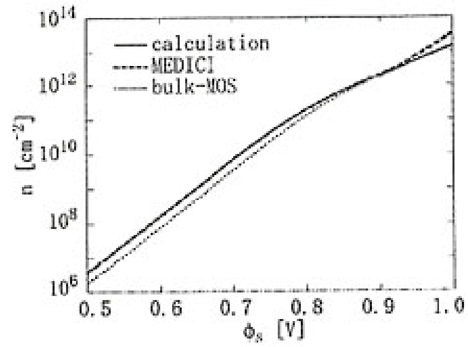

Fig. 3: The relationship between ϕ_s and n.

current and entire depletion charge.

(2) Charge-potential relationship

The relationship between electron concentration at SOI-layer surface and surface potential of SOI layer is needed to solve 1D Poisson equation. However the conventional relationship derived analytically cannot be applied at SOI layer. In this work, electron concentration is calculated by solving Eq. 1 under the triangle-potential approximation.

$$n = \int_0^\infty \frac{n_i^2}{N_{sub}} e^{\beta\varphi_s - E_s x} dx \quad (1)$$

(3) Channel current

In HiSIM, channel current is calculated by solving the current-density equation (Eq. 2) analytically under the charge-sheet approximation and the gradual-channel approximation.

$$\frac{\beta L}{\mu W} I = -\int_{\phi_{s0}}^{\phi_{sL}} \beta Q_n d\phi_s + \int_{Q_{n0}}^{Q_{nL}} dQ_n \quad (2)$$

In this work, the same approach was taken with additional simplifications.

(4) Parameter extraction

t_{SOI} (thickness of SOI layer), t_{BOX} (thickness of buried oxide) and other parameters are needed in the HiSIM-SOI calculation. They are unique parameters of SOI-MOSFET. In extracting the parameters, the calculated threshold voltages with the developed threshold voltage description are fitted to measurements. The threshold voltages in the range of V_{bs} ± 10V, 4 regions of operations are distinguished as shown in Fig. 4.

(1). Inversion at bulk surface, accumulation at SOI-layer surface
(2). Inversion at bulk surface, depletion at SOI-layer surface
(3). Depletion at bulk surface, depletion at SOI-layer surface
(4). Accumulation at bulk surface, inversion at SOI-layer surface

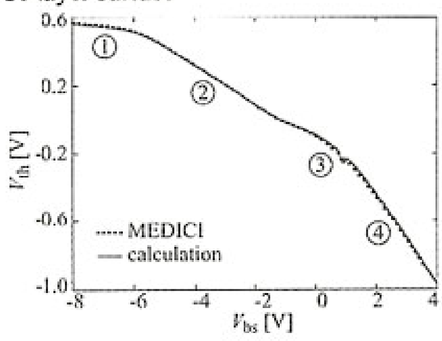

Fig. 4: V_{th}-V_{bs}

The gradient at region 2 is determined by t_{BOX}, and $N_{sub,BULK}$ determines the boundary between region 2 & 3.

In this way all essential parameters are extracted from individual region. The solid line in Fig. 4 is calculated V_{th} with the same parameters with MEDICI. It is possible to extract parameters because the same parameters result the same V_{th}.

Model Verification

We verify HiSIM-SOI by 2 aspects:

1. Reproducibility of DC current
2. Stability of transient simulation

Here verification is done for long channel transistors, because the short-channel effect in SOI-MOSFET is not included yet. Result of fitted DC current is shown in Fig. 5 in comparison with measurements. Simulation result of a ring-oscillator is shown in Fig. 6. The period of ring-oscillator is not verified because there are no available measured data of capacitances.

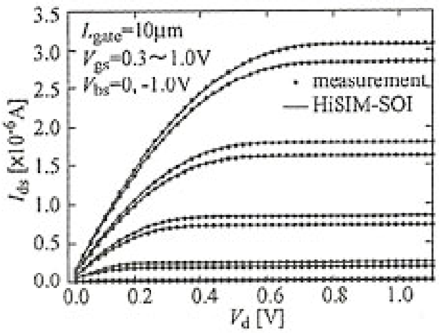

Fig. 5: Result of fitting.

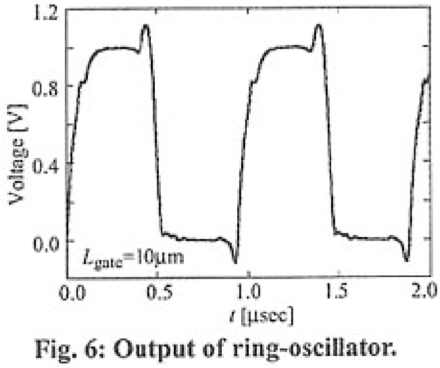

Fig. 6: Output of ring-oscillator.

Conclusion

We have developed the model of a FD SOI-MOSFET model (HiSIM-SOI) based on the surface-potential description for the first time in the world. HiSIM-SOI is verified to calculate DC current accurately and realizes stable circuit simulation.

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References

[1] HiSIM1.1 User's Manual (http://www.starc.or.jp/kaihatu/pdgr/hisim/)

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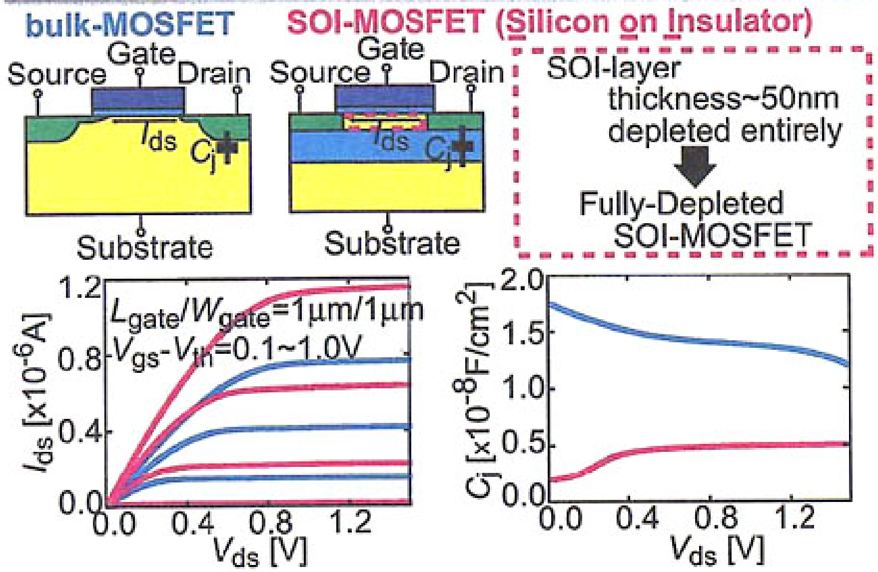
SOI-MOSFET



Background

Advantages
- large saturation current
- small capacitances
- small sub-threshold swing

eager to utilize

⇕

No Stable Model Exists
- difficult to do circuit simulation
- fitting of bulk-MOSFET model to SOI measurement

Purpose / Method

Purpose : Develop a Stable Fully-Depleted SOI-MOSFET Model

- based on Surface Potential (ϕ_s)
- consistency among Potential–Charge–Capacitance

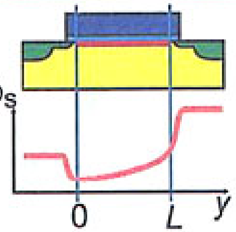
Method : Develop HiSIM-SOI based on HiSIM framework

HiSIM

Surface Potential (ϕ_s)
iteration : accuracy of 10^{-11}V

current-density equation / Poisson equation integration

Current — Charge — derivative — Capacitance



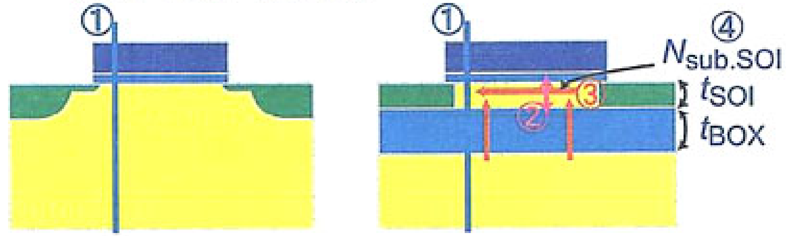
Requirements in Developing HiSIM-SOI

① Derivation of surface potential
Physical structure is complex.

② Derivation of charge–potential relationship
Conventional relationship cannot be applied.

③ Derivation of channel current
Current-density equation must be integrated.

④ Establishment of parameter extraction method
Parameters unique to SOI-MOSFET (t_{SOI}, t_{BOX}, $N_{sub.SOI}$) are added.

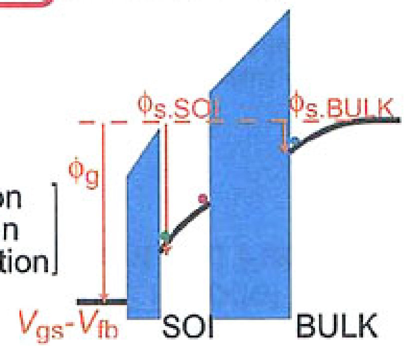


① Derivation of surface potential (1)

$\phi_g = f(\phi_{s.BULK}, \phi_{s.SOI}) \rightarrow V_{gs}-V_{fb}$ ← solve using iteration

SOI-MOSFET :
ϕ_g is very difficult to solve

[SOI-layer surface, SOI-layer back, BULK surface] X [Inversion, Depletion, Accumulation]

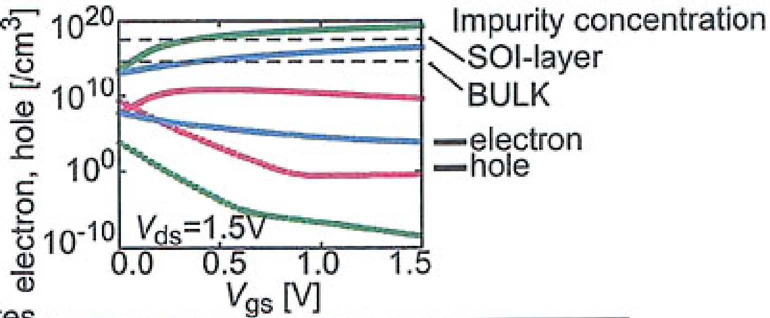


Too much time is needed for iteration.
Iteration does not converge.

① Derivation of surface potential (2)

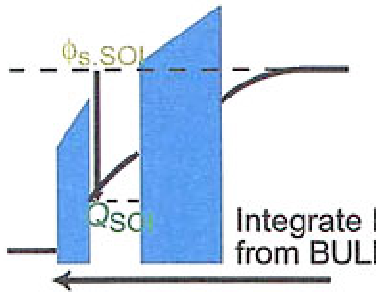
Demands from circuit simulation
$0 < V_x < V_{DD}$ → Accuracy
$V_x < 0$, $V_{DD} < V_x$ → Stability

→ Simplify state of each position



States
SOI-layer surface : Depletion Inversion
SOI-layer back : Depletion
BULK surface : Depletion Accumulation

②Derivation of charge–potential relationship (1)



Integrate Poisson equation from BULK to Gate.

SOI-layer

$\phi_{s.SOI}$ is a function of Q_{SOI}.

Q_{SOI} is a function of $\phi_{s.SOI}$.

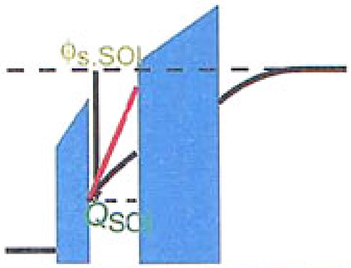
Q_{SOI} cannot be derived analytically.

②Derivation of charge–potential relationship (2)

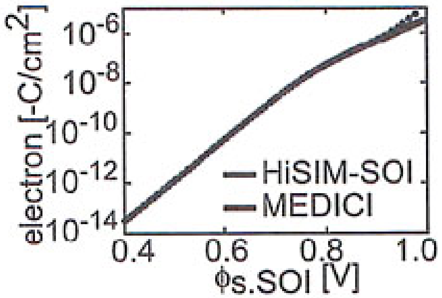
Q_{SOI} : Depletion + Inversion

Constant

Triangle-potential approximation



1. Calculate $\phi_{s.SOI}$ from depletion charge.
2. Calculate inversion charge from $\phi_{s.SOI}$.



③Derivation of channel current (1)

Current-density equation : $j_n = q\mu_n n\boldsymbol{E} + qD_n\nabla n$

Poisson equation : $\nabla^2\phi = -\frac{\rho}{\varepsilon}$

Simplification

SOI-layer surface : Depletion Inversion

SOI-layer back : Depletion

BULK surface : Depletion

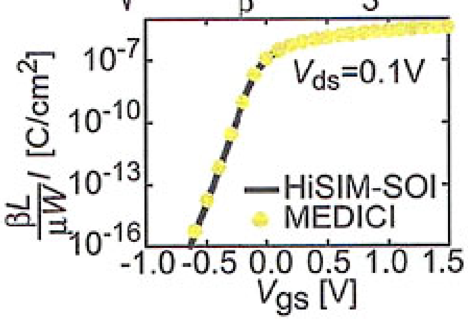
Charge-sheet approximation

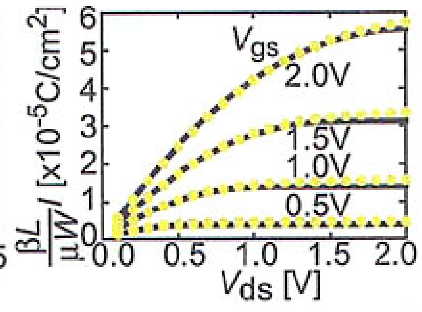
Gradual-channel approximation

Integration

③Derivation of channel current (2)

$$\frac{\beta L}{\mu W} I = \beta((V_{gs}-V_{fb})C_{FOX}+Q_{dep.SOI})(\phi_{sL.SOI}-\phi_{s0.SOI}) - \frac{\beta C_{FOX}}{2}(\phi_{sL.SOI}{}^2-\phi_{s0.SOI}{}^2)+Q_{nL}-Q_{n0} - \frac{\beta}{2C_{BOX}//C_{SOI}}(Q_{sL.BULK}{}^2-Q_{s0.BULK}{}^2) - \sqrt{\frac{2q\varepsilon_{si}N_{sub.BULK}}{\beta}}\frac{2}{3}[(\beta\phi_{sL.BULK}-1)^{3/2}-(\beta\phi_{s0.BULK}-1)^{3/2}]$$



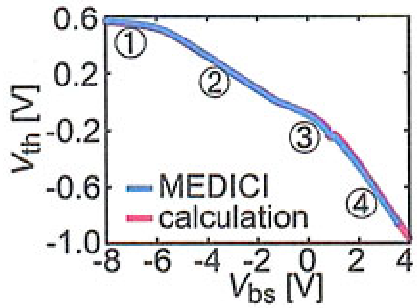


④Establishment of parameter extraction method (1)

Unique to SOI-MOSFET
t_{SOI} , t_{BOX} , $N_{sub.SOI}$

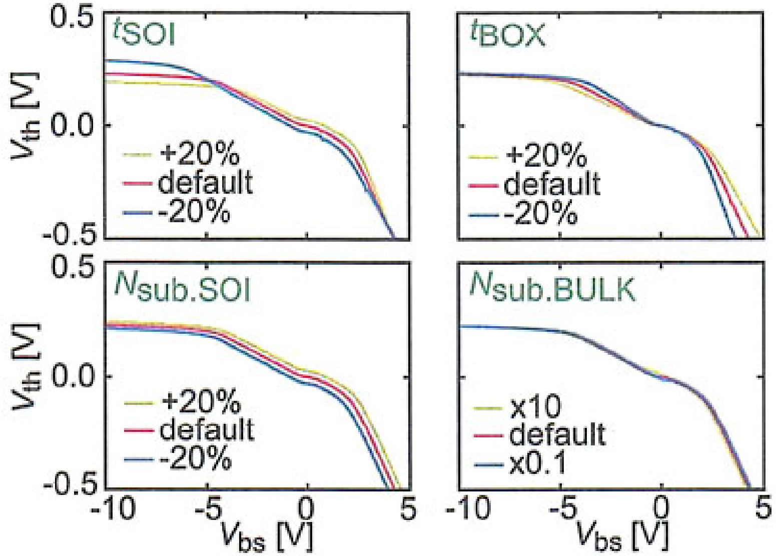
Accurately calculate V_{th}.

Fit to measurements.



	SOI-layer Back	BULK surface	Parameters
①	Accumulation	Inversion	t_{SOI} $N_{sub.SOI}$
②	Depletion	Inversion	t_{SOI} t_{BOX}
③	Depletion	Depletion	t_{SOI} t_{BOX} $N_{sub.BULK}$
④	Inversion	Accumulation	t_{SOI} t_{BOX}

④Establishment of parameter extraction method (2)



Conclusion

- We have developed HiSIM-SOI, a surface-potential-based model of a FD SOI-MOSFET for circuit simulation. HiSIM-SOI is the first existing surface-potential-based model in the world.
- HiSIM-SOI is verified to calculate DC current accurately and realizes stable circuit simulation.