

# Fully-Depleted SOI-MOSFET Model for Circuit Simulation and its Application to $1/f$ Noise Analysis

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## 1 Abstract

We have developed a fully-depleted SOI-MOSFET model HiSIM-SOI for circuit simulation by solving the potential distribution along all three important SOI-surfaces self-consistently. Besides comparison to measured  $I$ - $V$  data, the model is verified with  $1/f$  noise analysis, sensitive to the carrier concentration and distribution along the channel. The carrier concentration increase, due to confinement of the silicon layer, results in enhanced  $1/f$  noise in comparison with the bulk-MOSFET. Our results show that further reduction of the silicon-layer thickness for achieving higher driving capability will cause unavoidable enhancement of the noise.

## 2 Introduction

MOSFET is the most widely applied device, and possible future variations such as double-gate MOSFET as well as FinFET have been intensively investigated [1]. Their models for circuit applications are now under development with different approaches [2]. Our objective is to develop a circuit simulation model for the fully-depleted SOI-MOSFET as the first step for describing phenomena caused by the channel confinement between two oxide layers. Advantage of pursuing the fully-depleted SOI-MOSFET is that the modeling accuracy is easily verified by measured characteristics of production-level SOI-MOSFET technologies.

Existing SOI-MOSFET models are suffering convergence problems in circuit simulation. The main reason is a violation of the charge conservation. The SOI-MOSFET has three important Si-SiO<sub>2</sub> surfaces as can be seen in Fig. 1. Charges are induced at all surfaces. Thus surface-potential-based modeling is the only solution for the SOI-MOSFET to secure the charge conservation in a consistent way. We have developed the SOI-MOSFET model HiSIM-SOI based on this charge conservation guideline. Our investigation here focuses on carrier density changes in the SOI channel in comparison to the bulk-MOSFET. For this purpose the  $1/f$  characteristics are studied, since the  $1/f$  noise is sensitive to the carrier concentration as well as its density distribution in the channel [3].

## 3 Method and Results

To include all device features of the SOI-MOSFET accurately, HiSIM-SOI determines not only the surface-potential at the channel surface, but also at the back side, as well as at the bulk back-gate self-consistently as schematically depicted in Fig. 1 [4]. The total iterative potential calculation requires only about twice as much calculation time as for the bulk-MOSFET case, solving just at the channel-surface. Fig. 2 demonstrates the accuracy of the three calculated

surface potentials in comparison to the results with the 2D-device simulator MEDICI. Fig. 3 compares HiSIM-SOI simulation results of the channel-inversion charge with MEDICI for two silicon-layer thicknesses  $T_{\text{SOI}}$ . The bulk-MOSFET result is also depicted for comparison. Enhancement of the carrier concentration is obvious. The model reproduces measured  $I$ - $V$  characteristics within numerical accuracy as shown in Fig. 4, and is verified to show stable convergence in circuit simulation.

Fig. 5 compares simulation result of the  $1/f$  noise with measurements. For the HiSIM-SOI simulation two model parameters are fitted:  $NFTRP$  determining the magnitude of the  $1/f$  noise; and  $NFALP$  determining the contribution of the mobility fluctuation due to carrier trap/detrap. The fitted  $NFTRP$  value is the nearly the same as that of the bulk-MOSFET, and  $NFALP$  is very small in comparison with  $NFTRP$  but about 10 times larger than for the bulk-MOSFET. Good agreement of the measured and simulated noise-voltage characteristics is the proof of accurate calculation of the carrier concentration and its distribution along the channel. Deviation of three measurement points (open triangles) from simulation results is attributed to impact ionization, which is not yet included in HiSIM-SOI.

Comparison with the bulk-MOSFET is shown in Fig. 6. Increased noise density is obvious and explained by the higher carrier concentration in the channel, as evident from Fig 3. Fig. 7 shows the expected noise increase for reduced  $T_{\text{SOI}}$ , which will cause serious problems in circuit applications.

## 4 Discussion and Conclusion

Reduction of  $T_{\text{SOI}}$  enhances the driving capability of the SOI-MOSFET. However, we have found the necessity of considering a trade-off between the driving capability and the  $1/f$  noise. The enhanced noise due to the increased carrier concentration, caused by the inversion-layer confinement, will also cause serious problems in future devices such as the double-gate MOSFET and the FinFET.

## 5 Reference

- [1]T. -J. King, Ext. Abs. SSDM, p.280, 2003.
- [2]M. Chan et al., Proc. MSM, p.280, 2003;  
T. Nakagawa et al., ibid, p.330, 2003.
- [3]S. Matsumoto, Master Thesis, Hiroshima University, March 2003.
- [4]D. Kitamaru et al., Jpn. J. Appl. Phys., in press, April 2004.

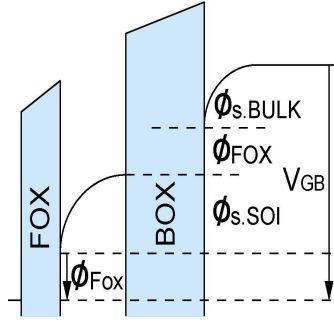


Fig. 1. Schematics of the fully-depleted SOI-MOSFET. The three surface potentials are solved iteratively with the Poisson equation.

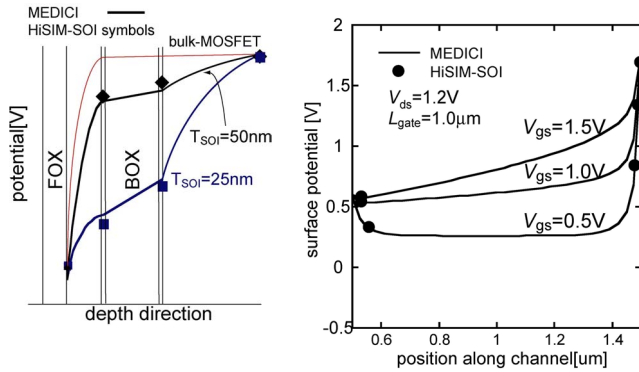


Fig. 2. Comparison of HiSIM-SOI calculated surface potentials with the results of the 2D-device simulator MEDICI.

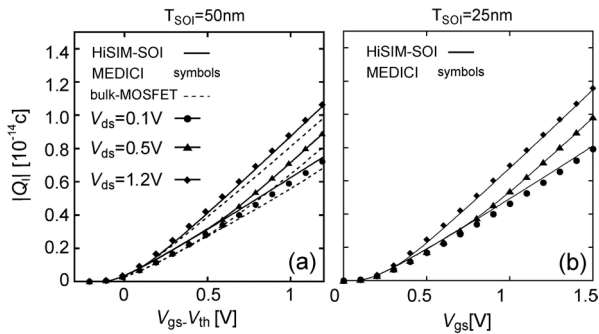


Fig. 3. Comparison of calculated inversion charge  $Q_i$  with MEDICI results, for a silicon-layer thickness of (a) 50nm and (b) 25nm. The bulk-MOSFET result is plotted in addition in (a).

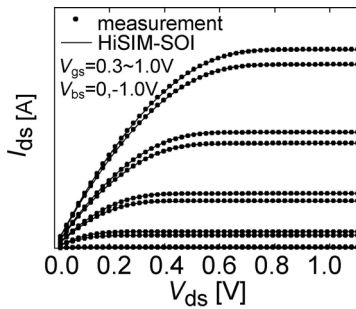


Fig. 4. Calculated drain current  $I_{ds}$  as a function of drain voltage  $V_{ds}$ . Symbols are measurements.

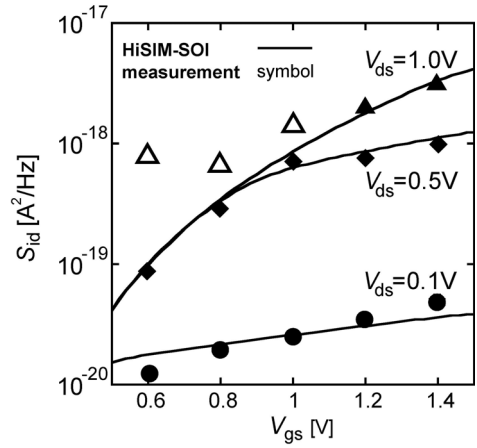


Fig. 5. Calculated  $1/f$  noise density as a function of gate voltage  $V_{gs}$ . Symbols are measurements. Deviation of the three open triangles from the HiSIM-SOI result is attributed to impact ionization, which is not yet included in HiSIM-SOI.

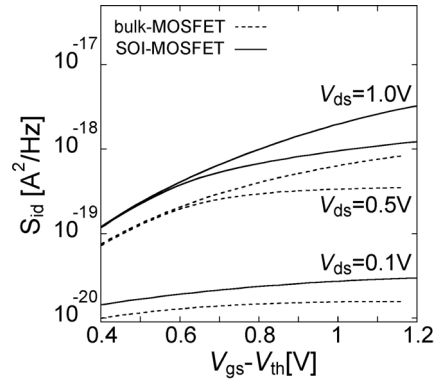


Fig. 6. Comparison of calculated  $1/f$  noise for the fully-depleted SOI-MOSFET with that of the bulk-MOSFET.

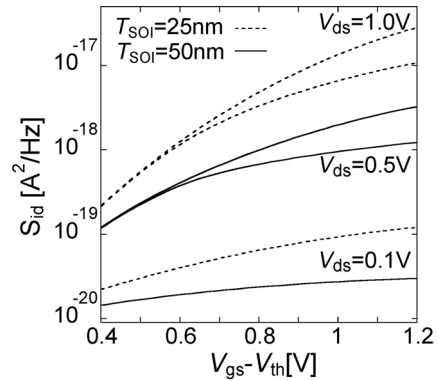


Fig. 7. Comparison of calculated  $1/f$  noise for the different SOI-layer thicknesses.

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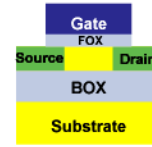
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COE WorkShop December 6, 2004

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## Objectives

FD SOI-MOSFET



Surface-Potential-Based Circuit Simulation Model for FD SOI-MOSFET

↓  
**HiSIM-SOI**

- Reduced Capacitance
- Low Leak Current

Reliable circuit simulation model for SOI is missing.

Develop HiSIM-SOI based on HiSIM framework

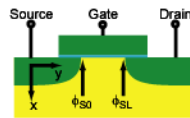
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## HiSIM: Hiroshima-University STARC IGFET Model

HiSIM for bulk-MOSFET

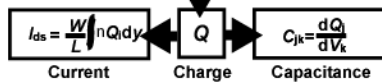
Charge-Sheet Approximation  
Gradual-Channel Approximation

$\phi_s$ : Solution of the 1D Poisson Equation solved iteratively



Dependent on Device Parameters (e.g.  $C_{ox}$ ,  $N_{sub}$ )

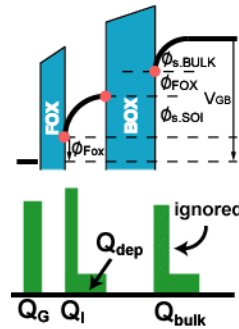
Surface Potential



Calculation of  $\phi_{SO}$  and  $\phi_{SL}$  is the key to formulate a model.

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## Surface Potential Calculation



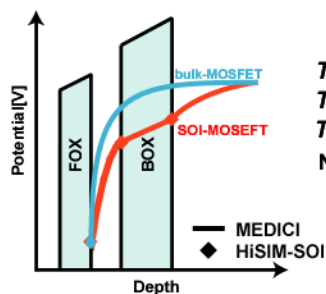
$$E_s \epsilon_{si} = Q_{dep} + Q_I + Q_{bulk}$$

$E_s$ : vertical electric field at the FOX surface

HiSIM-SOI calculates potentials at three interfaces.

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## Surface Potential Calculation

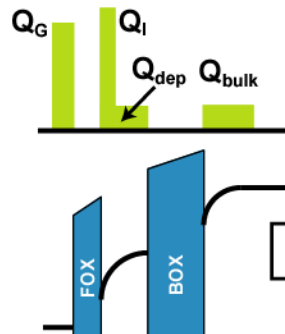


$T_{SOI} = 50\text{nm}$   
 $T_{BOX} = 115\text{nm}$   
 $T_{FOX} = 3.5\text{nm}$   
 $N_{sub} = 3 \times 10^{17}$

Calculated potentials are in good agreement with MEDICI results.

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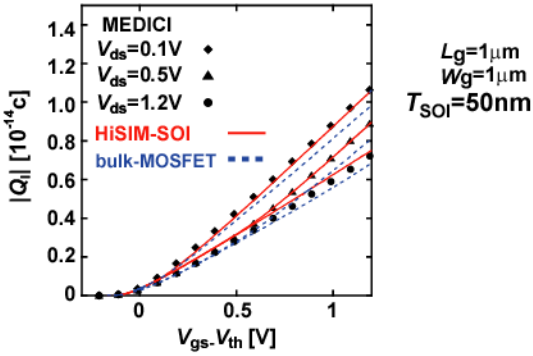
## Model Consistency



All variables are calculated from the surface potentials.

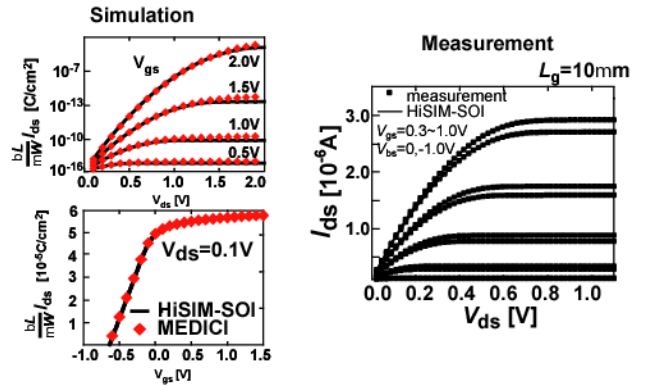
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## Accuracy of Calculated Charge



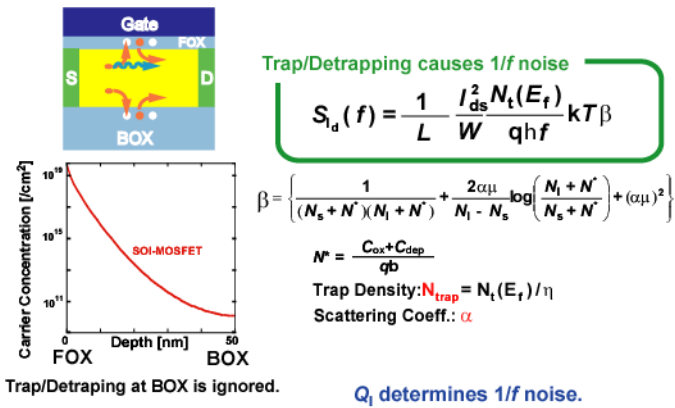
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## Current-Voltage Characteristics



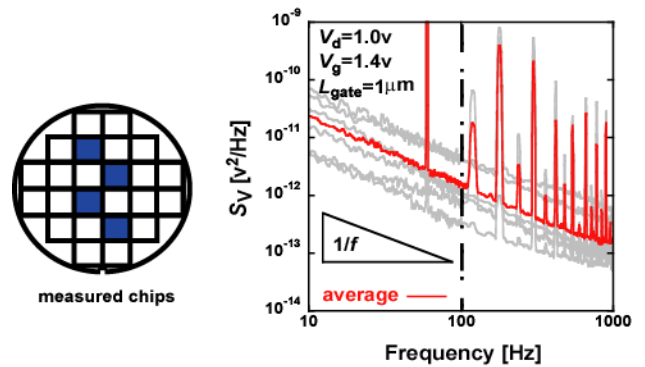
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## 1/f Noise Model



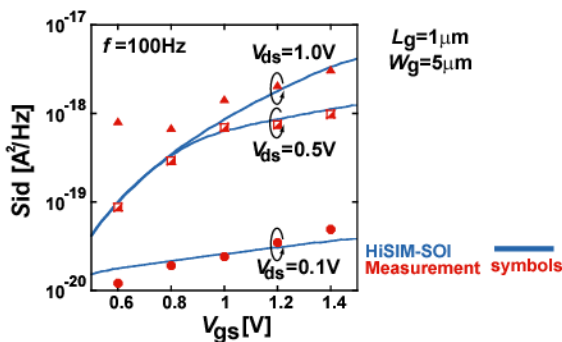
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## Measured Results



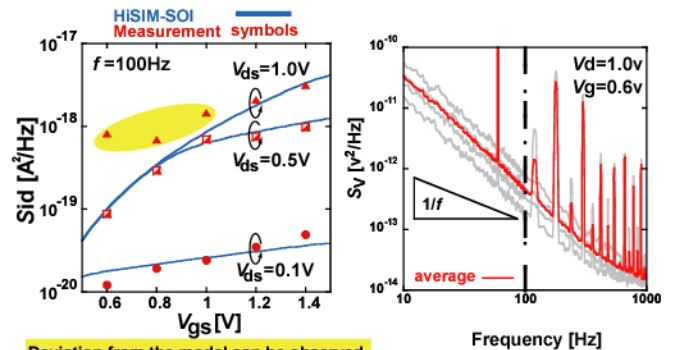
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## Comparison with Model Calculation



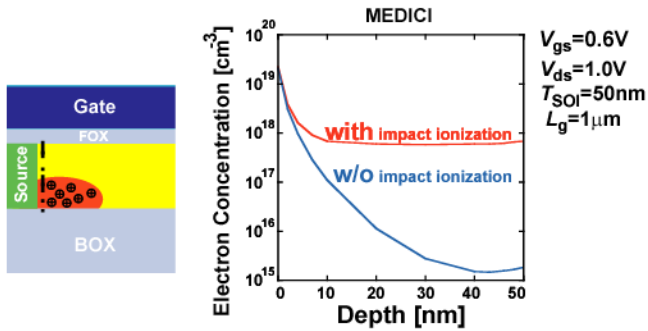
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## Deviation from the model



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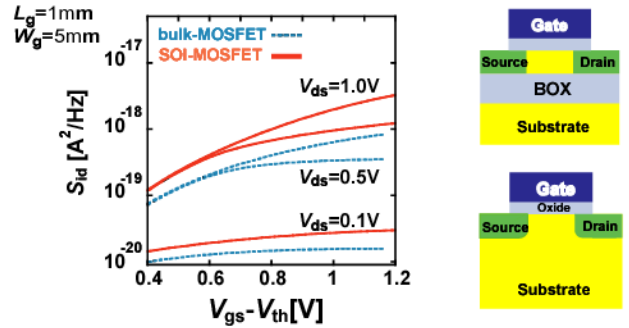
### Increase of Electron Concentration



Due to the increased hole concentration, electron concentration is also enhanced.

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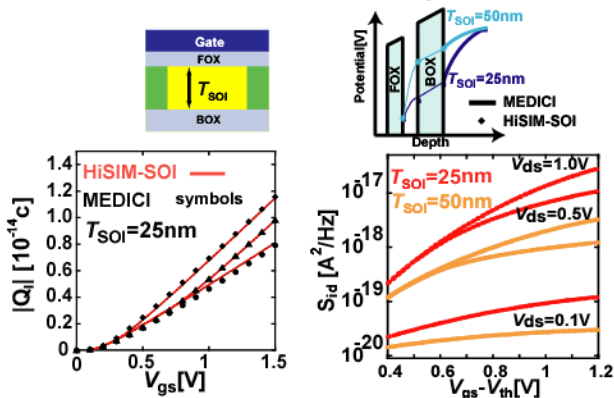
### Comparison with Bulk-MOSFET



SOI-MOSFET has larger 1/f noise than bulk-MOSFET.

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### Effect of Thinner SOI-Body Thickness



Decrease of Body thickness enhances 1/f noise.

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### Summary

- We have developed HiSIM-SOI for Fully-Depleted SOI-MOSFET.
- Simulation time is about twice as much as HiSIM for bulk-MOSFET.
- HiSIM-SOI accurately reproduces measured drain current, as well as correctly predicts 1/f noise characteristics when impact-ionization can be neglected.
- 1/f noise in SOI-MOSFET is greater than in the bulk-MOSFET due to enhanced carrier concentration
- For the similar reason, decreasing the SOI body thickness increases 1/f noise.

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