HiSIM: Self-Consistent Surface-Potential MOS-Model Valid Down To Sub-100nm Technologies

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ABSTRACT

Surface-potential-based MOSFET modeling is shown to be the right direction. Model parameters reflect the physical device parameters of advanced technologies directly, and can therefore be even scalable with technology changes. These advantages are demonstrated with HiSIM, the first self-consistent surface-potential model for circuit simulation based on the drift-diffusion approximation and charge descriptions.

Keywords: MOSFET Model, Surface Potential, Charge-Based Modeling, Sub-100nm Technology

1 INTRODUCTION

MOSFET technology trends are toward further down scaling of device sizes [1]. This will make many new applications possible. Especially important are the commercial requirements of miniature and mobile equipment including operation at high frequencies (RF). However, MOSFET modeling is facing difficulties to achieve accurate description of such scaled down devices. The reason is that many complicated new phenomena are arising, which are difficult to be described analytically. In the coming SoC era, where different technology concepts will be merged on a chip, not only accuracy to reproduce single-device measurements but also robustness of model-parameter-meanings and their values are required. MOSFET models have to be available for all arising requirements. We demonstrate here that a charge-based model with the self-consistent surface-potential description offers the basis for successfully coping with the foreseeable challenges. HiSIM (Hiroshima-university STARC IGFET Model) is the first MOSFET model developed according to this concept [2].

2 BASIC CONCEPT OF HiSIM

HiSIM solves the Poisson equation and the current-density equation including both the drift and the diffusion contribution analytically. The fulfillment of the continuity equation is still restricted for the first release HiSIM1.0 to the quasistatic approximation. HiSIM adopts two additional approximations: the charge-sheet approximation and the gradual-channel approximation.

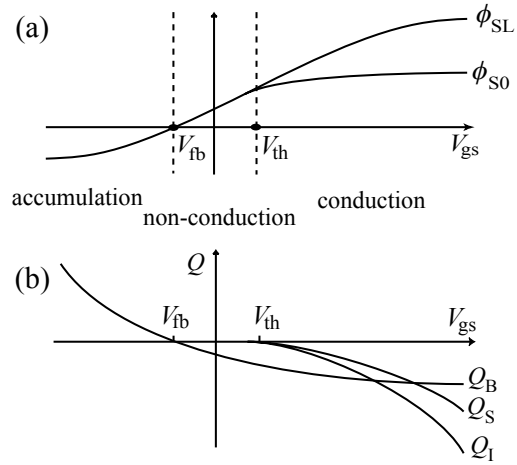

Figure 1: Schematics of calculated (a) surface potentials and (b) charges as a function of gate-source voltage (V_{gs}).

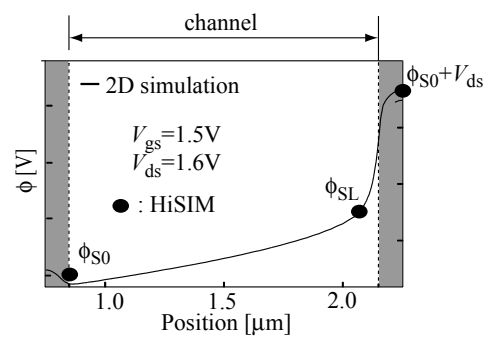

Figure 2: Simulated surface-potential distribution along the channel with the 2D simulator MEDICI under the saturation condition. Calculated surface potentials by HiSIM at the source side ϕ_{S0} and at the drain side ϕ_{SL} are also depicted. The ϕ_{SL} position varies consistent with the operating point of the MOSFET.

These approximations allow analytical formulations describing device performances as functions of the surface potentials at the source side ϕ_{S0} and at the drain side ϕ_{SL}. These potentials are calculated by solving the Poisson equation iteratively. It was shown that simulation time can, nevertheless, be reduced in comparison with a conventional model [3]. Fig. 1 shows schemat-

ics of the surface potentials and charges. Fig. 2 compares the surface potentials calculated by HiSIM with the surface potential distribution obtained by the 2D simulator MEDICI [4]. ϕ_{SL} is the value at the end of the gradual-channel approximation, namely the pinch-off point. HiSIM includes a self-consistent determination of the pinch-off-point position in the channel. This is achieved by solving the Gauss law in the pinch-off region with a potential increase in this region. The potential increase is dependent on the channel/drain junction condition, which determines the channel length modulation [5]. Thus HiSIM knows all potential values required to describe device performances. For reflecting the physical device structure, it's very important that surface potentials are functions of device parameters such as the oxide thickness and the substrate impurity concentration. Advanced MOSFET technologies undertake very elaborate channel engineering to extend the end of scaling down [6]. A main effort in the HiSIM development is given on direct reflection of the physical device parameters of such advanced technologies in the HiSIM model parameters.

In spite of the scaling down, long-channel transistor still reveals important technology features. Fig. 3 shows a HiSIM result for a 10nm MOSFET with an advanced pocket-implant technology. Without any smoothing parameters the correct result is easily obtained. This is exactly an essential advantage of the surface-potential-based modeling allowing to reproduce the complete channel-length (L_{gate}) dependence with the same parameter set.

3 MODEL DESCRIPTIONS

Table 1 summarizes the dependencies and effects included in HiSIM1.0. Here we shortly describe the outlines of some of the included features. Results are shown for n-MOSFETs. All together 71 model parameters are introduced to describe DC and AC MOSFET characteristics for any gate length (L_{gate}) and width (W_{gate}).

Table 1: Dependencies and effects implemented in HiSIM1.0.

V_{th} (L, W)
Gate-Poly Depletion
Quantum Mechanical Effect
Channel-Length Modulation
Temperature Dependences
I_{ds}
I_{bs}
I_{gate}
I_{GIDL}
1/f Noise
Capacitances
Source/Drain Symmetry
Diode

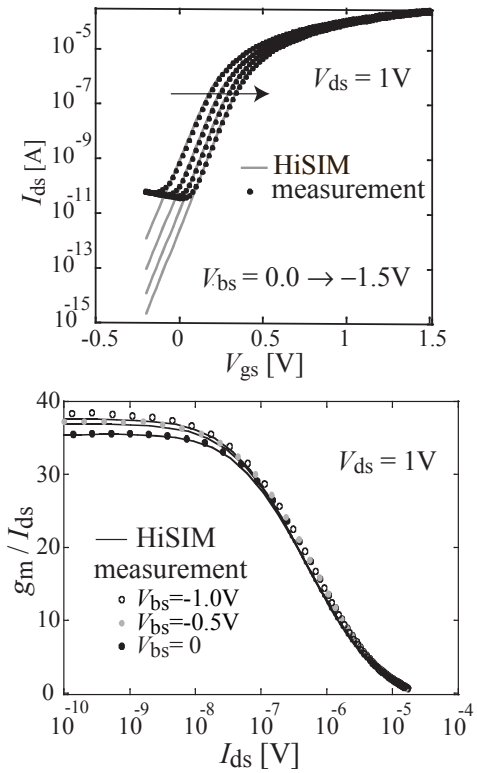

Figure 3: Calculated results by HiSIM in comparison to measurements for a n-MOSFET with the gate length (L_{gate}) of 10μm.

3.1 Pocket Implantation

Advanced MOSFET technologies suffer from strong short-channel effects. The pocket implantation technology has been developed to suppress these effects [6]. A strong dopant inhomogeneity along the channel is the origin of the suppression. HiSIM simplifies the impurity profile as shown in Fig. 4a [7]. With reduced L_{gate} the two pocket regions approach and overlap each other causing a strong increase of the threshold voltage (V_{th}) as a function of L_{gate} as shown in Fig. 4b. Further reduction of L_{gate} then causes dominant short-channel effects, which are described by taking into account the gradient of lateral electric field [3].

3.2 Mobility Universality

Fig. 5 shows extracted the low field mobility as included in HiSIM [8]. It is seen that the universality is preserved for any L_{gate} even though advanced MOSFET technologies induce unnegligible quantum effects and poly-depletion effects. The mobility universality is an important feature of HiSIM simplifying the parameter extraction and securing the reliability of model parameter values.

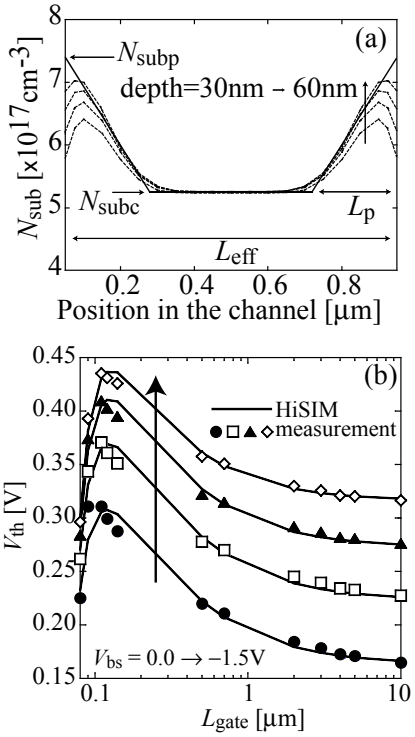

Figure 4: (a) 2D-pocket profile obtained by the 2D-process simulator TSUPREM to reproduce measured V_{th}-L_{gate} characteristics. The solid line is the simplified profile used by HiSIM. N_{subp}, N_{subc}, and L_p are model parameters. (b) Comparison of measured V_{th} with HiSIM results.

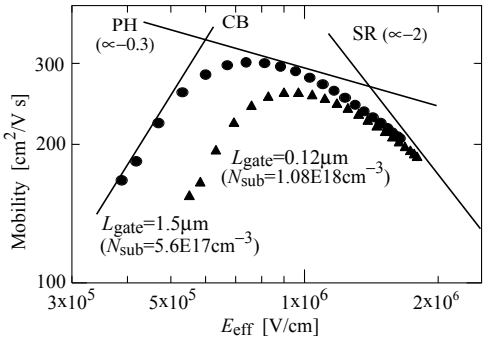

Figure 5: Extracted low field mobility by HiSIM as a function of effective electric field (E_{eff}).

3.3 Narrow Channel Effect

The necessity of small size devices, including the channel width, is increasing. In this case additional leakage currents caused by the shallow-trench isolation are no longer negligible. With the surface-potential-based modeling this can be included simply without singularities and with small additional calculation cost as demonstrated in Fig. 6. The number of model parameters introduced is only three.

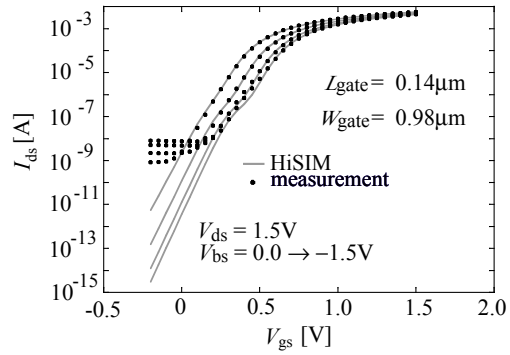

Figure 6: Comparison of calculated and measured drain current (I_{ds}) as a function of V_{gs} and V_{bs} for a narrow width device.

3.4 Scalability

Fig. 7 compares measured transconductances and channel conductances with calculated results by HiSIM. Model parameters are fitted only to measured I-V characteristics with L_{gate} of 10μm to 0.11μm. Good reproducibility is observed for any L_{gate}. The scalability of HiSIM to shorter L_{gate} is tested with L_{gate} = 80nm. The result is quite satisfactory. This is especially important for the SoC era, in which the technology optimization for each application is unavoidable. A prediction of the influence of an optimization step on the circuit is thus desired prior to fabrication.

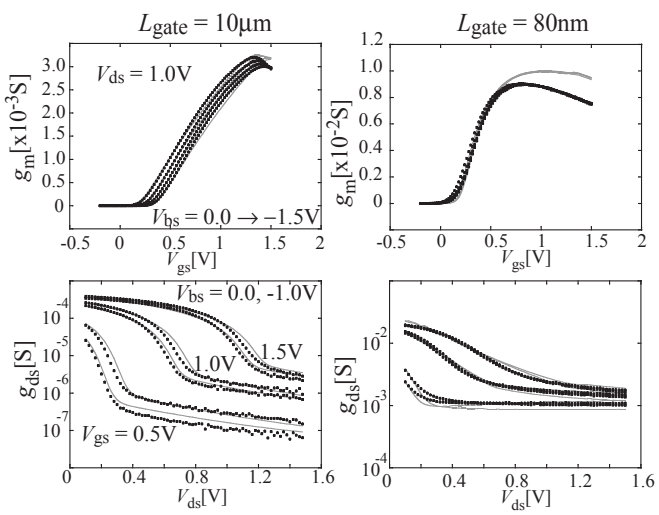

Figure 7: Comparison of calculated transconductance (g_m) and channel conductance (g_{ds}) by HiSIM with measurements for L_{gate} = 10μm. g_m and g_{ds} were not used for the parameter extraction. The same comparison is done for L_{gate} = 80nm, which is outside the L_{gate} range (10μm – 0.11μm) used for parameter extraction.

4 RF-APPLICATIONS AND SIMULATION TIMES

Fig. 8 shows simulation results of Y-parameters together with measurements [9]. If all capacitances and conductances are accurately simulated, as it is the case for HiSIM, the quasi-static approximation is not severe even up to cut-off frequency. The key for achieving this encouraging result with HiSIM is the charge-based modeling including a dynamic charge partitioning.

Another important issue for application is the simulation time. Fig. 9 demonstrates that the iteration steps can be reduced drastically by deriving good initial values.

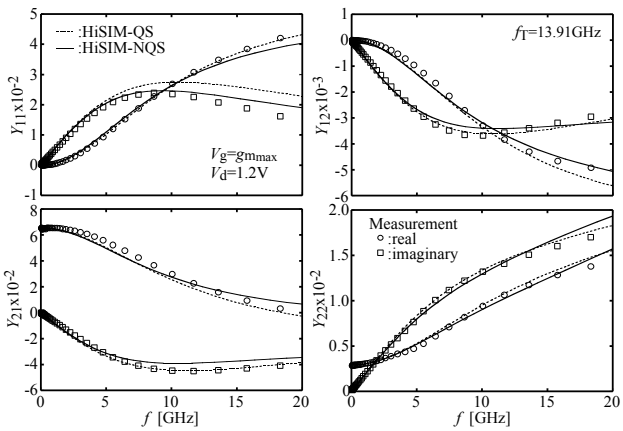

Figure 8: Comparison of calculated n-MOSFET Y-parameters with measurements for $L_{\mathrm{gate}} = 0.5\mu$m. Dotted lines are HiSIM results with the quasistatic approximation. Solid lines are also HiSIM results but with a simple inclusion of the non-quasistatic contribution.

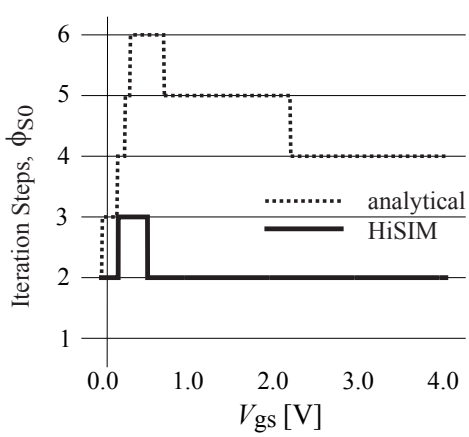

Figure 9: Number of iteration steps for solving the Poisson equation. "analytical" means to use an analytical solutions as initial values. HiSIM uses improved initial values to reduce iteration steps. V_{ds} is fixed 0.1V.

5 CONCLUSION

The MOSFET-modeling approach of HiSIM, based on a self-consistent surface potential and the drift-diffusion approximation, has been shown to be the right direction for future MOSFET models for circuit simulation. In particular, model parameters directly reflect the physical parameters of advance technologies, allowing a prediction of the results of technology changes. The biggest advantage of HiSIM is that the underlying model concept is very simple and physically consistent. Therefore, an expansion to more sophisticated future device generations will be easy.

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