Improvement of S-factor method for evaluation of MOS interface state density

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Abstract In this paper, the accuracy of the S-factor method for evaluating density of interface states (Dd) at MOS interfaces is examined by simulation. Based on the analysis, we propose an improved S-factor method including the accurate depletion layer capacitance (Cd, dep) determined by gate-substrate capacitance (Cgs) and gate-channel capacitance (Cgd), and a new term in the analytical formulation of S factor. The accuracy of this method is also quantitatively studied.

Introduction Accurate interface state density (Dd) evaluation of MOSFETs is still quite important, because the superior MOS gate stacks and reliability keep being a challenging issue for the advanced gates stacks and channels. Among a variety of the techniques, the S-factor method is taken as one of the simple and easy methods for evaluating Dd of MOSFETs [1]. Since the sub-threshold slope of IV curves of MOSFETs changes with the amount of Dd, Dd in the weak inversion region can be extracted from the sub-threshold slope values, which is called the S-factor method [1-3]. However, to our best knowledge, the accuracy of Cd extracted by the present S-factor method has not been examined yet.

In this paper, accuracy of the conventional S factor method is examined by using device simulation. Here, we provide two modifications to the S-factor method for higher accuracy of extracted Dd and obtaining Dd as a function of the surface potential (ϕs). One is more accurate determination of ϕs by using Cd extracted from Cgs and the other is to use more rigorous expression of the S factor by adding a new term. The correctness of Dd extracted by the modified method is quantitatively evaluated. Finally, experimental results of the energy distribution of Dd obtained by applying the present method to Si MOSFETs are shown.

Experiment Conventional Si nMOSFET with gate area 100 μm x 100 μm is used for device simulation as well as experiments. Figure 1 shows the simulation. I-V, Cg-ϕs and Cgd-ϕs curves with and without Dd are simulated for nMOSFETs with different gate oxide thickness (Tox) and substrate impurity concentration (Nd).

Results and discussion In the S factor method, as shown in Fig. 1, the slopes of logJD-VT curves in sub-threshold region, the S factor equation, is employed. In order to obtain the energy distribution of Dd, Cd, Cdshould be determined as a function of Vg and ϕs. Based on the equivalent circuit of the gate capacitance shown in Fig. 2, Cd can be determined as a function of Vg by the equation of Fig. 2 using Cgs and Cgd, curves, which can be experimentally measured, shown in Fig. 1. Fig. 3 shows the comparison between constant and extracted Vg-dependent Cd. The difference in Cd can lead to some error in Dd extraction. Fig. 4 shows the Dd values extracted from Vg-dependent Cd and constant Cd for simulations with constant Dd of 5x10¹¹ cm⁻²e⁻¹. It is found that more accurate Dd is obtained for the present Vg-dependent Cd model. In order to check the accuracy of extracted Cd values, the present Vg-dependent Cd with different Tox are also compared with the direct expression of Cd defined by dQ/dϕs, as shown in Fig. 5. Good agreement means the high accuracy of the present Cd extraction. In spite of the accurate Cd values, however, it is found that there are still remaining errors in Dd extraction. The energy distributions of Dd are obtained from the S factors by the conventional equation with the correction of Cinv, shown in Fig. 2, for MOSFETs without any Dd. Fig. 6 and 7 show the results with different Tox and Nd, respectively. It is observed that Dd of meaningful orders, which is in a range of 10⁹ to 10¹⁰ cm⁻²e⁻¹, is inappropriately detected from interface-state-free MOSFETs, especially for thinner Tox and lighter Nd. This fact suggests that the accuracy of any factors related to the diffusion current model is not sufficient.

The conventional analytical equation of the diffusion current in sub-threshold regions, which is a basis of the S factor method, is given in the inset of Fig. 8 [5]. In order to verify the accuracy of this expression, the S factors extracted from I-V curves are compared between the simulated and the analytical calculations, as shown in Fig. 8. The good agreement guarantees the accuracy of the present analytical equation for diffusion current. It is found, on the other hand, that, when differentiating this equation with respect to ϕs, a term proportional to S/ϕs should be added to the conventional expression of Dd. The relationship between Dd and S including the new term is given by

\[
D_d = \frac{1}{q} \frac{\partial S}{\partial \phi_s} = \frac{1}{q} \left( S_{\text{inv}} - 1 \right) \frac{C_d}{q} - \frac{C_d}{q} - \frac{C_{\text{inv}}}{q}
\]

Fig. 9 and 10 show the energy distributions of Dd extracted by the new expression for MOSFETs without any Dd with different Tox and Nd, respectively. Here, the vertical axis is taken as the absolute values of Dd, because the error component of Dd can be either positive or negative. It is found that the drift current component, which is found that the drift current component, which is not included in the equation, the remaining error component of Dd becomes lower by about one order of magnitude than that in Fig. 6 and 7. The minimum Dd is around 2x10⁹ cm⁻²e⁻¹, which can be the resolution limit of the present S-factor method. Also, the error component increases with increasing ϕs toward the conduction band edge, attributable to the increase in the drift current component with an increase in ϕs. Fig. 11 shows the energy distributions of Dd extracted from the improved S factor method for MOSFETs with 1x10¹¹ and 5x10¹¹ cm⁻²e⁻¹. The good agreement between extracted and assumed Dd values demonstrates the validity of the improved S factor method. Here, the energy range where the accurate extraction is realized seems to be from Emin to 2kT to Emin/3kT and becomes wider for higher Dd. Fig. 12 shows the experimental energy distributions of Dd evaluated by the present method for Si nMOSFETs before and after FN stress to generate interface states. It is confirmed that Dd is successfully extracted down to lower half of 10¹⁰ cm⁻²e⁻¹ order as the minimum level.

Conclusion We have improve the S factor method in terms of the accuracy of Dd of MOSFETs by including Vg-dependent Cd based on Cgs and Cgd, and the correction term for the analytical equation of the S factor, allowing us to obtain the energy distribution of Dd. It has been found that the accuracy of lower half of 10¹⁰ cm⁻²e⁻¹ order can be obtained for Dd.

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References

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**Fig. 1** $C_{gb}, C_{ox}$, and $I_{d}-V_{g}$ curves in order to determine $C_{gb}$ and sub-threshold slope.

**Fig. 2** Equivalent circuit of MOS structure.

**Fig. 3** $C_d$ from different extraction method.

**Fig. 4** $D_d$ energy distribution determined by constant $C_d$ and $V_g$-dependent $C_{gb}$.

**Fig. 5** Comparison between simulation and analytical calculation result of $C_d$.

**Fig. 6** $D_d$ extracted from S-factor method with different $T_{ox}$ for the interface-state-free devices.

**Fig. 7** $D_d$ extracted from S-factor method with different $N_A$ for the interface-state-free devices.

**Fig. 8** Comparison between simulation and analytical calculation result of S.S.

**Fig. 9** $D_d$ extracted from S-factor method with different $T_{ox}$ for the interface-state-free devices.

**Fig. 10** $D_d$ extracted from S-factor method with different $N_A$ for the interface-state-free devices.

**Fig. 11** Energy distribution of $D_d$ for nMOSFET with given $D_d$ values. Dotted line is the calculation result; Solid line is the $D_d$ values used in the simulation.

**Fig. 12** Experimental result of $D_d$ extracted by the improve S-factor method.