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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 (D_{it}) at MOS interfaces is examined by simulation. Based on the analysis, we propose an improved S-factor method including the accurate depletion layer capacitance (C_d), determined by gate-substrate capacitance (C_{gb}) and gate-channel capacitance (C_{gc}), 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 (D_{it}) 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 D_{it} of MOSFETs [1]. Since the sub-threshold slope of I_d-V_g curves of MOSFETs changes with the amount of D_{it}, D_{it} 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 D_{it} evaluated 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 D_{it} and obtaining D_{it} as a function of the surface potential (φ_s). One is more accurate determination of φ_s by using C_d extracted from C_{gb} and C_{gc} and the other is to use more rigorous expression of the S factor by adding a new term. The correctness of D_{it} extracted by the modified method is quantitatively evaluated. Finally, experimental results of the energy distribution of D_{it} 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. A constant mobility model is employed in the simulation. I_S-, C_{gb}- and C_{gc}-V_g curves with and without D_{it} are simulated for nMOSFETs with different gate oxide thickness (T_{ox}) and substrate impurity concentration (N_A).

Results and discussion In the S factor method, as shown in Fig. 1, the slopes of $\log_{10}I_s$-V_g curves in sub-threshold region, the S factor are used for D_{it} extraction. The analysis of the S factor is divided into two parts. The first part contains the evaluation of φ_s under an equivalent capacitance model and the second part is related to the validity of the diffusion current model. As for the evaluation of φ_s, a constant C_d value at φ_s of $1.5\varphi_B$ is used, in the conventional S factor method [2, 3], under a series capacitance model of oxide capacitance (C_{ox}) and C_d for obtaining average D_{it}. In order to obtain the energy distribution of D_{it}, C_d must be determined as a function of V_g and φ_s. Based on the equivalent circuit of the gate capacitance shown in Fig. 2, C_d can be determined as a function of V_g [4] by the equation of Fig. 2 using C_{gb} and C_{gc} curves, which can be experimentally measured, shown in Fig. 1. Fig. 3 shows the comparison between constant and extracted V_g-dependent C_d. The difference in C_d can lead to some error in D_{it} extraction. Fig. 4 shows the D_{it} values extracted from V_g-dependent C_d and constant C_d for simulations with constant D_{it} of 5×10^{11} cm^{-2}eV^{-1}. It is found that more accurate D_{it} is obtained for the present V_g-dependent C_d model. In order to check the accuracy of extracted C_d values, the present V_g-dependent C_d with different T_{ox} are also compared with the direct expression of C_d, defined by $dQ_s/d\varphi_s$, as shown in Fig. 5. Good agreement means the high accuracy of the present C_d extraction. In spite of the accurate C_d values, however, it is found that there are still remaining errors in D_{it} extraction. The energy distributions of D_{it} are obtained from the S factors by the conventional equation with the correction of C_{inv}, shown in Fig. 2, for MOSFETs without any D_{it} Fig. 6 and 7 show the results with different T_{ox} and N_A, respectively. It is observed that D_{it} of meaningful orders, which is in a range of 10^{10} to 10^{11} cm^{-2}eV^{-1}, is inappropriately detected from interface-state-free MOSFETs, especially for thinner T_{ox} and lighter N_A. 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_S-V_g 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 φ_S, a term proportional to S/φ_S should be added to the conventional expression of D_{it}. The relationship between D_{it} and S including the new term is given by

$$D_{it} = \frac{1}{q}\left(\frac{qS}{kT\ln 10} - \frac{S}{2\varphi_s \ln 10} - 1\right)C_{ox} - \frac{C_d}{q} - \frac{C_{inv}}{q}$$

Fig. 9 and 10 show the energy distributions of D_{it} extracted by the new equation for MOSFETs without any D_{it} with different T_{ox} and N_A, respectively. Here, the vertical axis is taken as the absolute values of D_{it}, because the error component of D_{it} can be either positive or negative. It is found that, by taking the new term into account, the remaining error component of D_{it} becomes lower by around one order of the magnitude than that in Fig. 6 and 7. The minimum D_{it} is around 2×10^{10} cm^{-2}eV^{-1}, which can be the resolution limit of the present S-factor method. Also, the error component increases with increasing φ_s toward the conduction band edge, attributable to the increase in the drift current component with an increase in φ_s. Fig. 11 shows the energy distributions of D_{it} extracted from the improved S factor method for MOSFETs with 1×10^{11} and 5×10^{11} cm^{-2}eV^{-1}. The good agreement between extracted and assumed D_{it} values demonstrates the validity of the improved S factor method. Here, the energy range where the accurate extraction is realized seems to be from $E_{mid}+2kT$ to E_{inv}-$3kT$ and becomes wider for higher D_{it}. Fig. 12 shows the experimental energy distributions of D_{it} evaluated by the present method for Si nMOSFETs before and after FN stress to generate interface states. It is confirmed that D_{it} is successfully extracted down to lower half of 10^{10} cm^{-2}eV^{-1} order as the minimum level.

Conclusion We have improve the S factor method in terms of the accuracy of D_{it} of MOSFETs by including V_g-dependent C_d, based on C_{gb} and C_{gc}, and the correction term for the analytical equation of the S factor, allowing us to obtain the energy distribution of D_{it}. It has been found that the accuracy of lower half of 10^{10} cm^{-2}eV^{-1} order can be obtained for D_{it}

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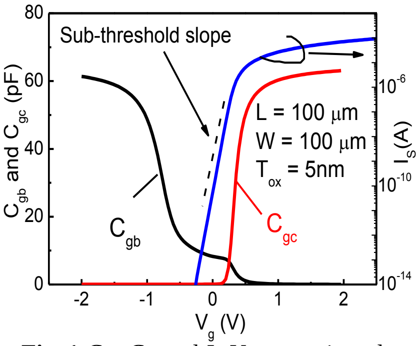

Fig. 1 C_{gb}, C_{gc} and I_S-V_g curves in order to determine C_d and sub-threshold slope

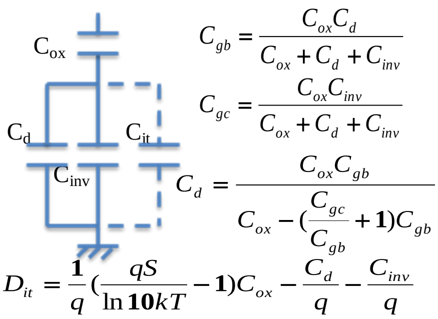

Fig. 2 Equivalent circuit of MOS structure.

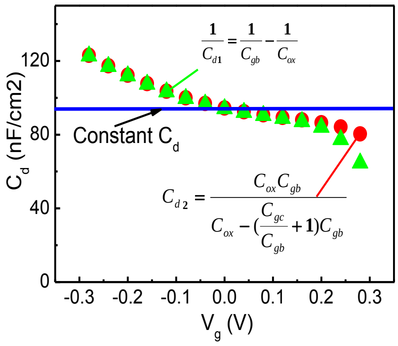

Fig. 3 C_d from different extraction method.

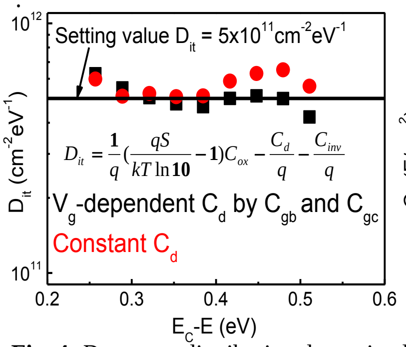

Fig. 4: D_{it} energy distribution determined by constant C_d and V_g-dependent C_d.

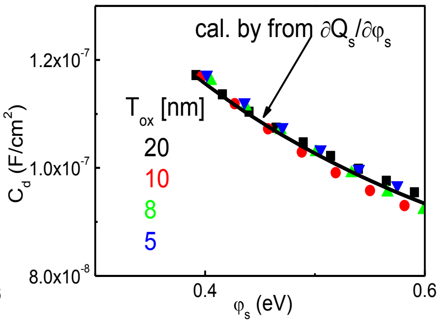

Fig. 5 Comparison between simulation and analytical calculation result of C_d.

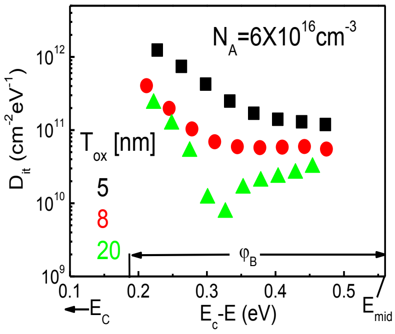

Fig. 6: D_{it} extracted from S-factor method with different T_{ox} for the interface-state-free devices.

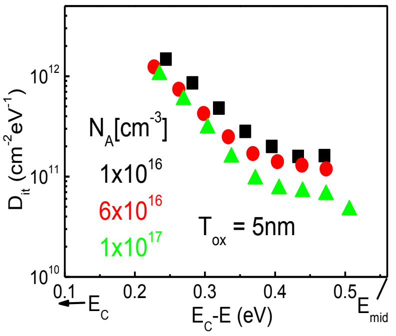

Fig. 7: D_{it} extracted from S-factor method with different N_A for the interface-state-free devices.

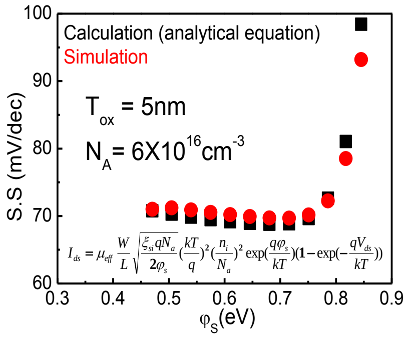

Fig. 8: Comparison between simulation and analytical calculation result of *S.S.*

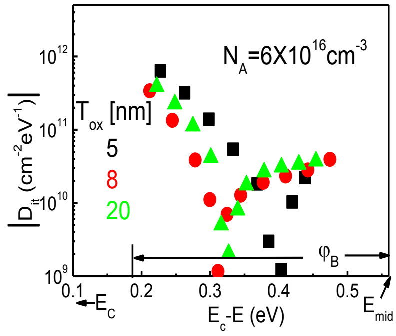

Fig. 9 D_{it} extracted from S-factor method with different T_{ox} for the interface-state-free devices.

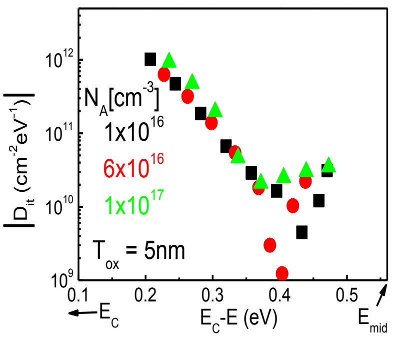

Fig. 10 D_{it} extracted from S-factor method with different N_A for the interface-state-free devices.

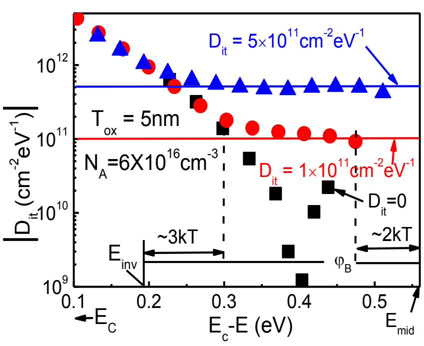

Fig. 11 Energy distribution of D_{it} for nMOSFET with given D_{it} values. Dotted line is the calculation result; Solid line is the D_{it} values used in the simulation.

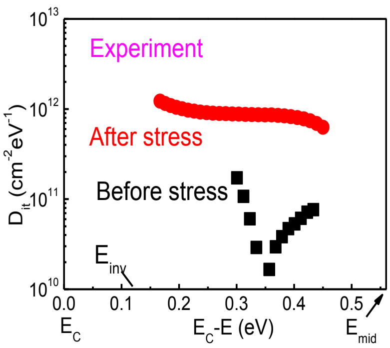

Fig. 12 Experimental result of D_{it} extracted by the improve S-factor method