Impact of Fixed Charge at MOSFETs' SiO_2/Si Interface on V_{th} Variation

A.T. Putra[1], T. Tsunomura[2], A. Nishida[2], S. Kamohara[2], K. Takeuchi[2] and T. Hiramoto[1, 2]
[1]Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo, 153-8505, Japan,
[2]MIRAI-Selete, 16-1 Onogawa, Tsukuba, Ibaraki, 305-8569 Japan. E-mail: arifin@nano.iis.u-tokyo.ac.jp

***Abstract*— Randomness of discrete fixed charges at SiO_2/Si interface of NMOS, which is thought to be one of the possible origins of threshold voltage (V_{th}) variation, is investigated using 3D device simulation. Three cases of fixed charge types are assumed; (i) both negative and positive sheet charges exist with zero net charge (mix charges), (ii) only negative sheet charges exist, and (iii) only positive sheet charges exist. B_{VT} is used as a V_{th} variation indicator. It is found that, even if high concentration of fixed charge (10^{12} cm^{-2}) is assumed, the difference of V_{th} variation between measured NMOS and random dopant fluctuation model by 3D TCAD still can not be explained, which reveals that other fluctuated parameters exists.**

Keywords: 3D device simulation, fixed charge, MOSFETs, threshold voltage variation, V_{th}, fluctuation.

I. Introduction

Since the feature size of MOSFETs continuously shrinks, it is strongly required to reduce variation of characteristics. It has recently been reported that PMOS fluctuation can be almost fully accounted for by random dopant fluctuation (RDF) regardless of device generations and designs, whereas extra fluctuation mechanism(s) significantly contributes to NMOS [1, 2]. Therefore, mechanism of V_{th} variation is not fully understood yet. In other words, some origins (atomic roughness of gate oxide thickness, gate line edge roughness [3], etc) other than RDF should be considered. Fixed charges at SiO_2/Si interface is caused by ions incorporated in oxide during growth or deposition [4]. The presence of discrete fixed charges at SiO_2/Si interface affects the potential shape in the channel MOSFETs. Therefore, discrete fixed charge at SiO_2/Si interface may be one of the possible V_{th} variation causes.

In this work, we evaluated the impact of random discrete fixed oxide (sheet) charges by 3D device simulation for the first time. To determine whether it is the origin of V_{th} variation or not, B_{VT} [1] is used.

II. Standard Indicator of V_{th} Variation

V_{th} variation of measured NMOS is plotted using Pelgrom plot [5] and Takeuchi plot [6] which is shown in fig. 1. The slope of Pelgrom plot, which is A_{VT}, is a conventional index of V_{th} variation and has dependence on V_{th} and T_{inv} (electrical oxide thickness). In Takeuchi plot, σV_{th} is normalized considering V_{th} and T_{inv}, where the slope is defined as B_{VT}. It can be seen that B_{VT} of measured NMOS is approximate to a constant value 2.7. The formula of A_{VT} and B_{VT} are expressed in equation (1), where $V_0 = -V_{fb} - 2\phi_b \cong 0.1V$.

$$\sigma V_{th} = A_{VT}\frac{1}{\sqrt{LW}} = B_{VT}\frac{\sqrt{T_{inv}(V_{th}+V_0)}}{\sqrt{LW}}. \qquad (1)$$

Therefore, it is accepted that B_{VT} is independent on V_{th} and T_{inv} in measured MOSFETs, which is clearly observed in fig. 1. Consequently, V_{th} dependence of B_{VT} can be used as an indicator of V_{th} variation in simulation. Theoretically, if there is V_{th} dependence of B_{VT} induced by an expected fluctuated parameter, the parameter is not the main origin of V_{th} variation and vice versa.

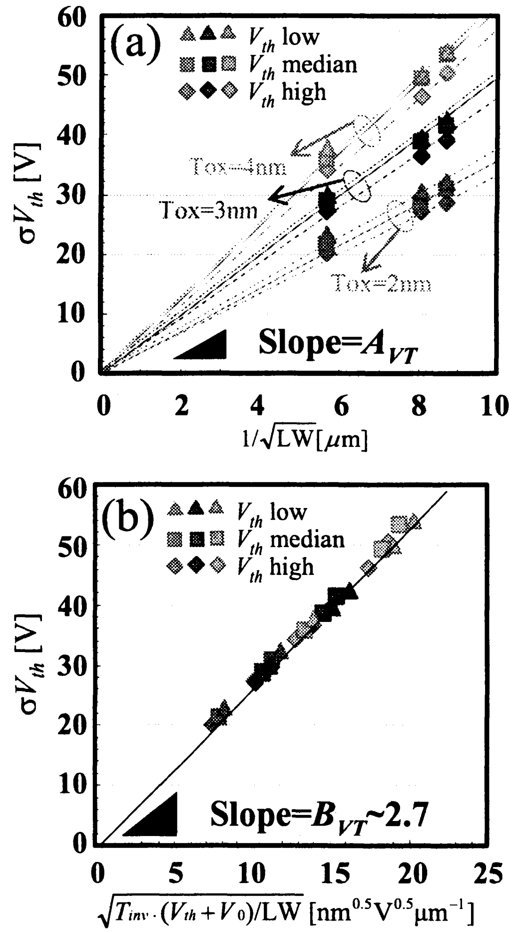

Fig.1. V_{th} variation of measured NMOS. (a) Pelgrom plot with slope A_{VT} and (b) Takeuchi plot with slope B_{VT}. It is shown that the slope A_{VT} depends on V_{th} and T_{inv} while B_{VT} does not.

III. Fluctuation In Fixed Charge

The presence of fixed charges existing at SiO_2/Si interface of MOSFET is depicted in fig. 2. In simulation, fixed charge is defined as a sheet charge at SiO_2 / Si interface. The local sheet charge density ρ_{int} of discrete fixed charges is expressed as

$$\rho_{\text{int}} = \frac{n_{\text{int}}}{S_l}, \tag{2}$$

where S_l is the area and n_{int} is the number of discrete sheet charges in S_l. The mean value of ρ_{int} within total channel area S_t is derived to be the total fixed charge density N_{int}:

$$\overline{\rho_{\text{int}}} = \frac{\sum n_{\text{int}}}{S_t} = N_{\text{int}}. \tag{3}$$

For small area S_l, n_{int} fluctuates statistically, then ρ_{int} fluctuates from place to place. The probability distribution function of n_{int} is assumed following Poisson distribution, which is known to be naturally random. This algorithm is then adopted into 3D device simulator.

The presence of oxide charges has major effect on the character devices. The charge in the interface interacts with the charge in the silicon near the surface and thus changes the silicon charge distribution and the surface potential. For random discrete sheet charges, we assume three cases: (i) both negative and positive sheet charges exist with zero net charge (mix charges), (ii) only negative sheet charges exist, and (iii) only positive sheet charges exist. Fig. 3 shows examples of the potential distribution in MOSFET channel in the three cases. The shapes of these potentials depend on the positions of the random fixed sheet charges at SiO_2/Si interface.

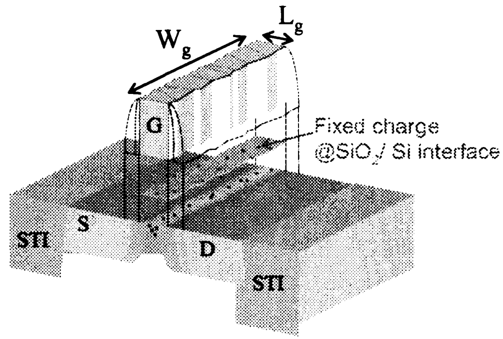

Fig.2. An illustrated NMOS structure with discrete fixed charge. In simulation, fixed charge is assumed to be a sheet charge located at the SiO_2 / Si interface.

IV. Simulation Result

The dependence of V_{th} and its variation on fixed sheet charge concentration are investigated. In this simulation, only discrete sheet charge is assumed as a random distribution and channel impurity concentration is assumed to be a continuous distribution (jellium). Fig.4 shows cumulative frequency of V_{th} deviation induced by each case of discrete fixed charge model with 200 samples. It is found that all cases of discrete fixed charges show normal distribution. Fig. 5 shows its standard deviation of V_{th} (σV_{th}). σV_{th} of positive charges and negative charges are the same and σV_{th} of mix charge is the largest which follows the square sum of rule indicating that positive and negative charge exist independently. The inset shows the average V_{th} ($\langle V_{th} \rangle$) due to discrete sheet charges. The $\langle V_{th} \rangle$ shift is almost the same as that of the jellium sheet charge model. This implies that when mix charges with zero net charges exist, σV_{th} become larger even though V_{th} is not shifted.

In order to estimate whether the discrete fixed charge is a main origin of V_{th} variation or not, T_{inv} and N_{sub} (substrate impurity density) dependences of B_{VT} are discussed. For comparison with the classical V_{th} indicator, T_{inv} and N_{sub} dependences of A_{VT} are discussed as well. Again, only random discrete sheet charge is assumed and channel impurity concentration is assumed to be jellium.

Simulated T_{inv} dependences of A_{VT} and B_{VT} are shown in fig. 6 and 7, respectively. It is clear that A_{VT} is a function of T_{inv} and it is normalized when B_{VT} is used. Simulated N_{sub} dependences of A_{VT} and B_{VT} are shown in Fig. 8 and 9, respectively. It is clear that A_{VT} does not depend on N_{sub}. When using B_{VT}, the normalization does not work out and consequently N_{sub} increases, B_{VT} decreases. From Figs. 6 to 9, it is found that positive, negative and mixed discrete fixed charges show the similar tendency in T_{inv} and N_{sub} dependences of B_{VT}.

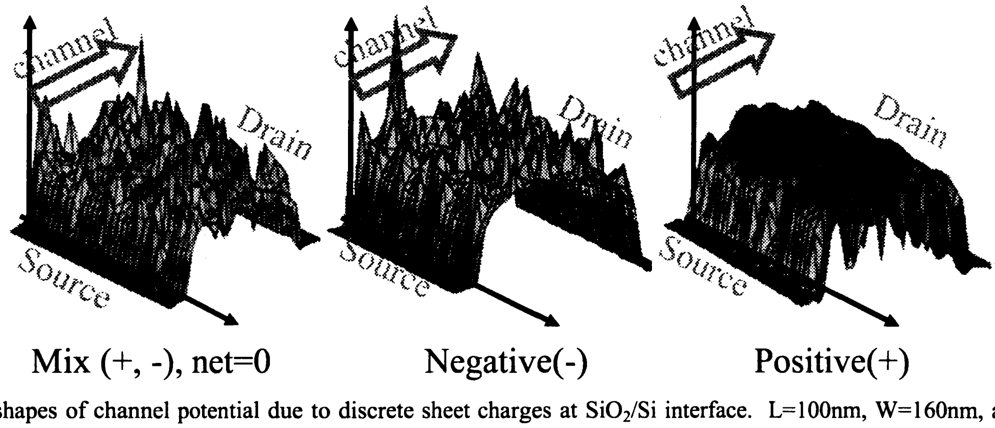

Fig.3. Random shapes of channel potential due to discrete sheet charges at SiO_2/Si interface. L=100nm, W=160nm, and fixed charges concentration at interface N_{int}=10^{12}cm^{-2}. "mix" has positive charge of 10^{12}cm^{-2} and negative charges of 10^{12}cm^{-2}.

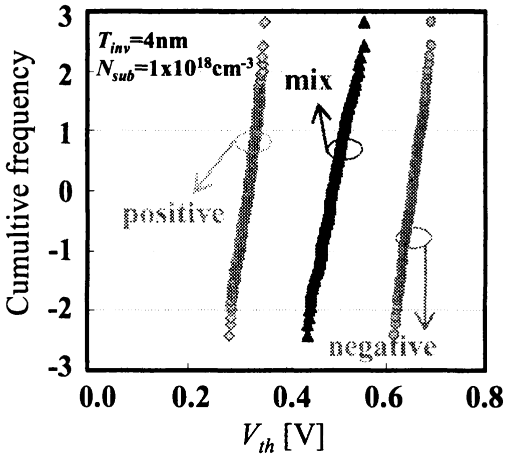

Fig.4. Cumulative frequency plot of *Vth* deviation induced by discrete sheet charge. All cases of fixed charges show normal distribution.

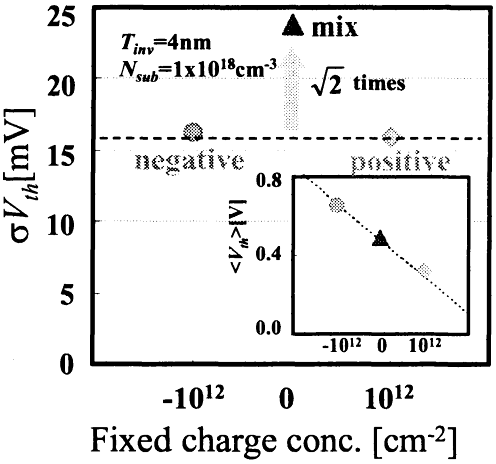

Fig.5. Standard deviation of V_{th} induced by discrete sheet charge on σV_{th}. Inset shows type of fixed charge dependence of V_{th}, where dot line corresponds to jellium model.

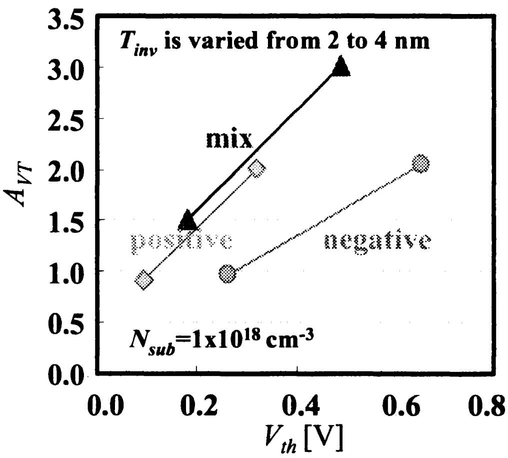

Fig.6. T_{inv} dependence of A_{VT}. All cases of fixed charges show A_{VT} is a function of T_{inv}. A_{VT} increases along with increased T_{inv}.

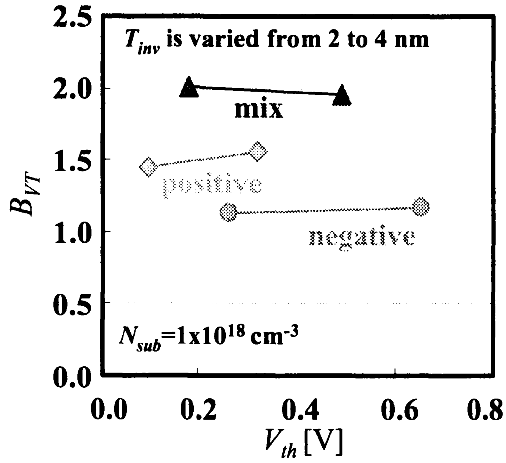

Fig.7. T_{inv} dependence of B_{VT}. All cases of fixed charges show V_{th} is well normalized using B_{VT}. This simulated V_{th} dependence of B_{VT} is similar to that of measured NMOS.

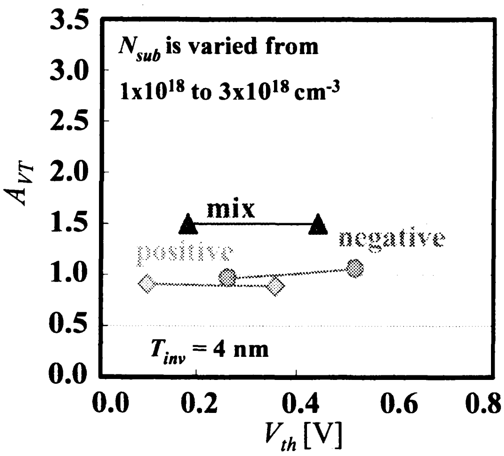

Fig.8. N_{sub} dependence of A_{VT}. All cases of fixed charges show A_{VT} is not a function of T_{inv}.

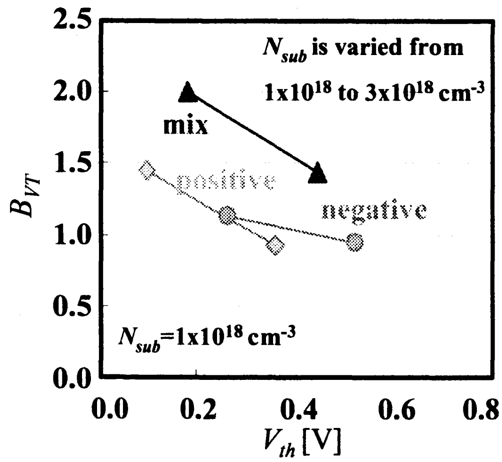

Fig.9. N_{sub} dependence of B_{VT}. All types of fixed charges show V_{th} is not normalized using B_{VT}. This simulated V_{th} dependence of B_{VT} is not similar to that of measured NMOS.

V. COMPARISON WITH MEASURED DATA

To evaluate further whether the discrete fixed charge is the main origin of V_{th} variation or not, we compare V_{th} variation of simulated fixed negative charge with that of measured NMOS shown in Fig. 10. The effects of discrete fixed charges and RDF (discrete channel dopants) are simulated independently. In measured NMOS, it is clear that B_{VT} is independent on N_{sub} and T_{inv}. In simulation assuming RDF, B_{VT} is also independent on N_{sub} and T_{inv}. On the other hand, in simulation assuming only discrete negative sheet charges, B_{VT} is independent on T_{inv} but dependent on N_{sub}, indicating that discrete sheet charges do not explain the measured large V_{th} variation in NMOS. In addition, even high concentration of fixed charge (10^{12} cm^{-2}) is assumed, the total simulated B_{VT} of RDF and fixed charge does not reach B_{VT} of measured NMOS. Therefore, the difference of V_{th} variation between measured NMOS and random dopant fluctuation model by 3D TCAD still could not be explained using fixed charge model.

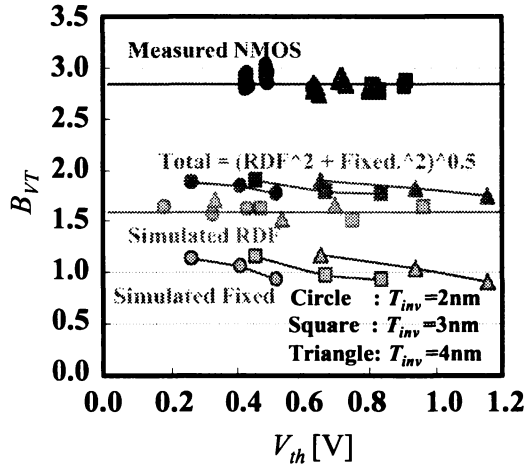

Fig.10. B_{VT} of measured data, simulation assuming negative sheet charges, and simulation assuming RDF. $N_{sub} = 1x10^{18}cm^{-3}$, $2x10^{18}cm^{-3}$, $3x10^{18}cm^{-3}$ are varied for the same T_{inv}.

VI. CONCLUSION

We have demonstrated the V_{th} variation induced by discrete sheet charges at SiO_2/Si by 3D simulation. It is found that discrete fixed (sheet) charge is not the main origin of V_{th} variation in NMOS due to two reasons. (i) Simulated B_{VT} induced by discrete fixed charge has dependences of N_{sub} but measured B_{VT} does not. (ii) Compared to B_{VT} of measured NMOS, the value of simulated B_{VT} induced by discrete fixed charge is small even high concentration of fixed charge (10^{12} cm^{-2}) is assumed. Our result indicates that other fluctuated parameters exist.

ACKNOWLEDGEMENT

This work was done in SELETE Inc. as part of MIRAI project commissioned by NEDO, Japan.

REFERENCES

[1] K. Takeuchi, T. Fukai, T. Tsunomura, A. T. Putra, A. Nishida, S. Kamohara, and T. Hiramoto, *IEEE International Electron Device Meeting (IEDM) Technical Digest*, pp.467-470, 2007.

[2] K. J. Kuhn, "Reducing Variation in Advanced Logic Technologies: Approaches to Process and Design for Manufacturability of Nanoscale CMOS," *IEEE International Electron Device Meeting (IEDM) Technical Digest*, pp. 471-474, 2007.

[3] G. Roy, A. R. Brown, F. Adamu-Lema, S. Roy, A. Asenov, "Simulation Study of Individual and Combined Sources of Intrinsic Parameter Fluctuations in Conventional Nano-MOSFETs," *IEEE Trans. Electron Devices*,,v 53, n 12, Dec. 2006, p.3063 - 3070.

[4] Y. Taur, T.H. Ning, "Fundamentals of Modern VLSI Devices", *Cambridge University Press*, 1998.

[5] M. J. M. Pelgrom, A. C. J. Duinmaijer, A. P. G. Welbers, "Matching properties of MOS transistors," *IEEE Solid-State Circuits*, vol. 24, Issue 5, pp.1433-1439, October 1989.

[6] T. Tsunomura, A. Nishida, F. Yano, A.T. Putra, K. Takeuchi, S. Inaba, S. Kamohara, K. Terada, T. Hiramoto, T. Mogami, "Analyses of 5σ V_{th} Fluctuation in 65nm-MOSFETs Using Takeuchi Plot," *IEEE Symposium on VLSI Technology*, 2008, p 156-157.