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Quantitative Analysis of Surface Potential Fluctuation at MOS interfaces Using Conductance Method

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Introduction Recent progress in advanced gate stack structures including high k/metal gate technologies keeps demanding more accurate characterization and deeper understanding of MOS interface properties. In order to characterize MOS interfaces, surface potential fluctuation at MOS interfaces is an important physical quantity. The surface potential fluctuation is attributable to randomly-distributed point charges near/at MOS interfaces (Fig. 1(a)) [1], which can be regarded as one of sources causing statistical variation of MOSFET performance [2]. The amount of the surface potential fluctuation(σ_s), which can be extracted from the conductance method shown in Fig. 1(b) and (c), can be related to the total density of charged center set or near MOS interfaces [1, 3], independent of the charge polarity, negative or positive, which can directly determine Coulomb scattering mobility of MOS inversion carriers. In spite of this importance of the surface potential fluctuation, the physical properties and origins have not been fully investigated yet.

In this paper, we experimentally study σ_s in SiO_2/Si MOS interfaces from the view point of MOS interface charges, which are intentionally controlled by Fowler-Nordheim (FN) stress and de-trapping fixed charges.

Experiments The devices used in this study were N^+ poly-silicon gate SiO_2/Si MOS capacitors having different doping concentration with oxide thickness of 25 and 8.6nm. The values of σ_s and interface trap density (D_{it}) were evaluated through the conductance method shown in in Fig. 1 (b) and (c). The fixed charge density, N_{fix}, was evaluated from the mid-gap voltage shift in the C-V_g curves [4].

The interface charges were intentionally introduced by FN injection. It was found, here, that the FN injection with negative gate bias mainly generates positive fixed charges, while that with positive gate bias generate both positive fixed charges and interface states, meaning that the different estimation of the total density of “charged centers” is needed between the two stress conditions.

In the negative bias stress, as shown in Fig. 2, generated positive fixed charges de-trap as a recovery process after the stress. This de-trapping phenomenon was utilized to intentionally change N_{fix} and evaluate the impact on σ_s. Thus, the change in σ_s was monitored during this recovery process, as shown in the measurement step of Fig. 3. In the positive-bias stress generating both positive fixed charges and interface trapped charges, on the other hand, the stress time was varied to evaluate the relationship between σ_s and the interface charges.

Result and Discussion In the negative gate bias stress, a large amount of positive charges is generated (Fig. 4 (a)). On the other hand, as shown in Fig. 4 (b), the amount of D_{it} is much smaller than N_{fix}, suggesting that the total charge density at MOS interfaces is dominated by N_{fix}. This interpretation is also confirmed by the fact of Fig. 4 (b) that σ_s is independent of the surface potential, which changes the charging condition of interface states. On the other hand, σ_s significantly changes with changing N_{fix}. Fig. 5 shows the decrease in the broadening of the conductance curves corresponding to σ_s after recovery of positive charges. The relationship between σ_s and N_{fix} is shown in Fig. 6. N_{fix} decreases rapidly in the early stage and finally saturates. It is found that N_{fix} and σ_s exhibit the similar recovery time dependence. Fig. 7 shows the experimental relationship between σ_s and N_{fix}. It is found that σ_s is proportional to $N_{fix}^{0.5}$, which is in good agreement with analytical model proposed by Brews [1, 3]. It is also found in Fig. 7 (a) and (b) that the power of σ_s against N_{fix}, 0.5, is universal for different substrate impurity concentration, n or p-type substrates, and different oxide thickness. Also, it is observed that in Fig. 8 σ_s slightly decrease with an increase in the impurity concentration due to screening effect from the impurity. This is the first experimental evidence that σ_s is proportional to $N_{fix}^{0.5}$ in a wide range the of MOS device parameters.

In the positive gate bias stress, both positive fixed charges and interface states are observed to be generated. Here, it is necessary to evaluate the areal density of charged centers due to interface states. By assuming that interface states in the lower half of the band gap are of donor type (Fig. 9), the charge density, int D_{it}, was estimated by integrating D_{it} over the surface potential from the midgap to a given potential. Fig. 10 shows N_{fix}, int D_{it} (E_{SF} - E_i= -0.15eV) and the total density of charged centers, N_{tot}, which is the sum of N_{fix} and Int D_{it}, as a function of the FN injection time. While N_{fix} is almost constant, int D_{it} and N_{tot} increase with increasing the injection time. This fact indicates that the contribution of interface states on N_{tot} is quite important for the positive gate bias stress. The contribution of interface states is also confirmed by the surface potential dependence of σ_s shown in Fig. 11. The increase in with moving the surface potential to the valence band edge is attributable to the increase in the amount of positive charges in the surface states. Fig. 12 shows the relationship between $\sigma_s$and N_{tot} for MOS capacitors with T_{ox} of 8.6nm is shown in Fig. 11.The log-log plot of σ_s and N_{tot} has the slope of 0.5, which is the same as the results with the negative bias stress. It is also found that the values of σ_s under the positive gate bias are on the same line as those under the negative gate bias, dominated only by N_{fix}. This finding demonstrates that σ_s can be represented universally by has the total amount of interface charges.

Conclusion The relationship between σ_s and MOS interface charge density, N_{tot}, was experimentally and systematically studied, for the first time. As a result, it was found that σ_s is universally described as a function proportional to $N_{tot}^{0.5}$.

This finding indicates that σ_s obtained from the conductance method can be a useful tool for quantitative analysis of MOS interfaces.

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References[1] E. H. Nicollian and J. R. Brews, MOS Physics and Technology (Wiley, New York, 1982) [2] A.T.Putra et al., Proc. SISPAD (2008) 25 [3] J. Brews., J. Appl. Phys., **43**, 5 (1972)[4] A. El-Hdiy et al, J. Appl. Phys. **32**, 13 (1999)

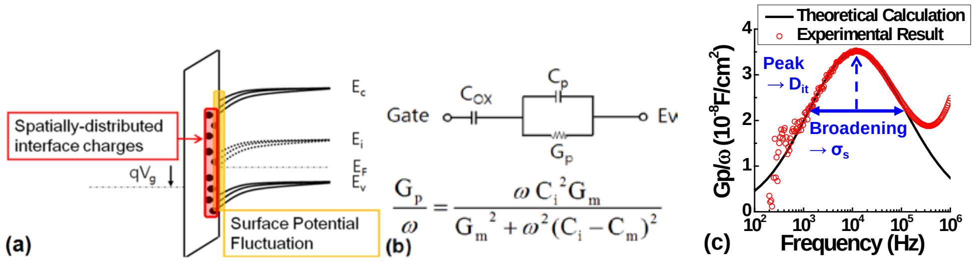

Fig. 1 (a) Schematic of Conductance method, (b) Equivalent Circuit for MOS device, (c) Conductance Curve its equation for conductance (Gp/ω)

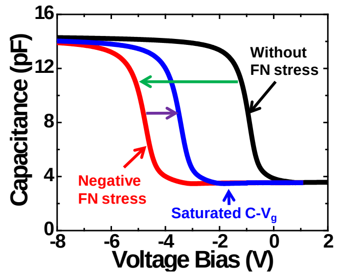

Fig. 2 After negative FN injection, C-Vg shift

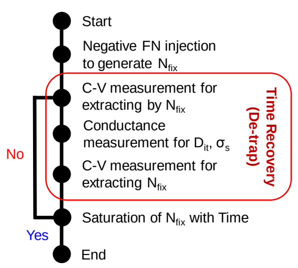

Fig. 3 Negative FN injection experimental process of MOS device

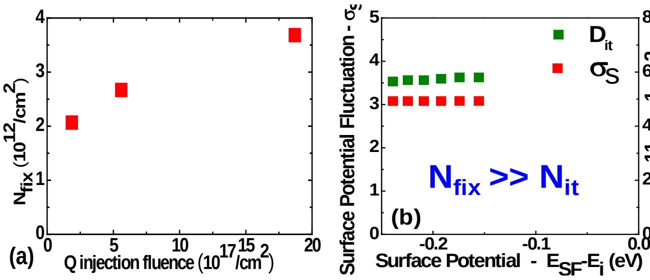

Fig. 4 (a) N_{fix} generation depending on negative FN injection (b) σ_s, D_{it} depending on ψ_s to confirm dominant N_{fix} ($N_A = 2.05 \times 10^{16}$cm^{-3}, T_{ox} = 25nm)

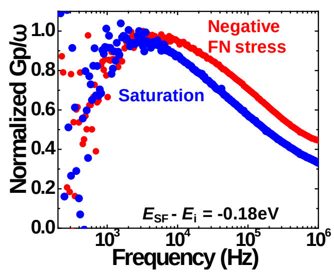

Fig. 5 Normalized Curves of Gp/ω – f directly after negative FN injection

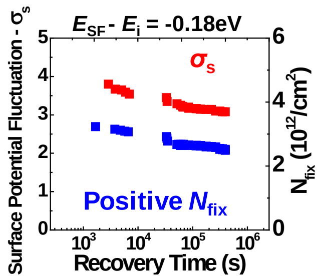

Fig. 6 Time dependence of N_{fix} and σ_s (N_A = 2.05 × 10^{16}cm^{-3}, T_{ox} = 25nm)

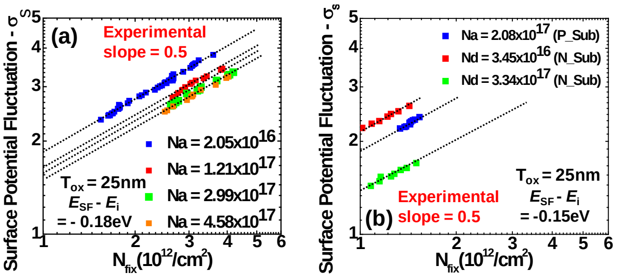

Fig. 7 σ_s depending on N_{fix}
(a) $N_A = 2.05 \times 10^{16} \sim 4.58 \times 10^{17}$(cm^{-3}), T_{ox} = 25nm
(b) $N_A = 2.08 \times 10^{17}$, $N_D = 3.45 \times 10^{16}$, 3.35×10^{17}(cm^{-3}), T_{ox} = 8.6nm

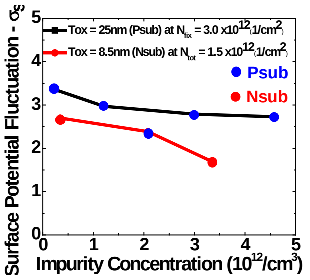

Fig. 8 Effect of impurity concentration on Surface Potential fluctuation (σ_s)

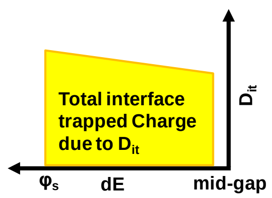

Fig. 9 Integration schematic for int D_{it}

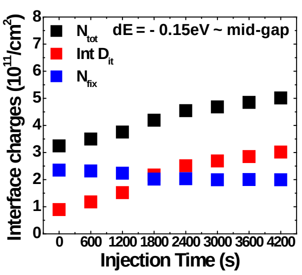

Fig. 10 Change in Total Interface charge ($N_{tot} = N_{fix}$ + Int D_{it}) with increasing positive FN injection time

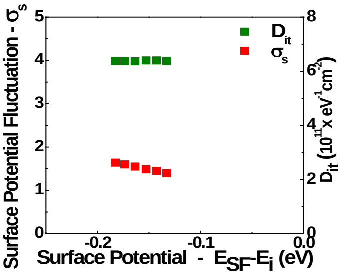

Fig. 11 σ_s, D_{it} depending on ψ_s ($N_A = 2.08 \times 10^{17}$cm^{-3}, T_{ox} = 8.6nm)

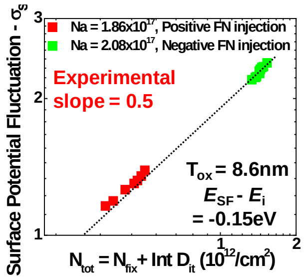

Fig. 12 Green dots – N_{fix} dominant with negative FN injection Red dots –Both Dit and N_{fix} exist with positive FN injection (σ_s is extracted at 0.15eV)