Comprehensive Modeling of Threshold Voltage Variability Induced by Plasma Damage in Advanced MOSFETs

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1. Introduction
With the scaling of advanced MOSFETs, the variation of device parameters such as “$V_{th}$-variability” has been recently focused [1]. This issue is primarily discussed from the viewpoint of the gate line-edge roughness (LER) [2] or the fluctuation of impurity doping. Plasma processing is widely used in manufacturing process and plasma-induced damage (PID) has been studied extensively. In general, PID is classified as charging damage, physical damage and radiation damage [3]. The charging damage induces the gate dielectric reliability degradation [3], while the physical damage, Si recess structure, leading to device performance degradation are comprehensively considered for realizing high performance devices. In this article, the effects of the charging and physical damage on the device performance degradation are comprehensively modeled in terms of the plasma-induced $V_{th}$-variability.

2. Model for plasma-induced threshold voltage shift
Basic mechanisms of PID are illustrated in Fig. 1. Both charging and physical damage are focused in the below.

\[ \Delta V_{th} \approx g(T) \cdot t_a \cdot I_{stress}^{\alpha} \Rightarrow I_p^{\alpha} (\sim r^\alpha), \]

where $g(T)$ and $t_a$ are the temperature-acceleration factor and stress time, respectively. $n$ and $\alpha$ are the respective power-law components. From Fig. 1 and eq. (1), one can obtain for the charging-induced $\Delta V_{th}$-variability,

\[ \frac{\partial (\Delta V_{th})/\Delta V_{th}}{I_{dc} / I_p} \approx \alpha \frac{\partial (T)}{T}. \]

Thus, the $\Delta V_{th}$-variability depends on variations of the plasma and device parameters as suggested in Fig. 1.

Threshold Voltage Shift Variation by Physical Damage
Si recess structure is associated with the physical damage and has become a key issue [4]. The recess depth ($d_R$) depends on the energy of ion from plasma and the surface reaction layer thickness [5]. As shown later (Fig. 4), we can write its dependence on plasma parameters as,

\[ d_R \approx A \cdot (V_p - V_{dc})^\beta = A \cdot E_i^\beta, \]

where $A$ is a constant and $\beta$ is the power-law component dependent on process conditions. The dependence of $\Delta V_{th}$ on $d_R$ was found to be expressed by [7]

\[ \Delta V_{th} \approx - B \cdot d_R / L_g, \]

where $B$ is defined by device structural parameters [7] and $L_g$ is the gate length. Thus, one can obtain

\[ \frac{\partial (\Delta V_{th})/\Delta V_{th}}{d_R / L_g} \approx \beta \frac{\partial (E_i)}{E_i}. \]

Note that the range of $\Delta V_{th}$ variation ($\delta (\Delta V_{th})/\Delta V_{th} \Delta V_{th}$) should also be considered for evaluating the $V_{th}$-variability.

3. Experimental
The damage was produced in an inductively coupled plasma (ICP) reactor with an Ar gas for 30 s. RF bias at 13.56 MHz was applied with various powers ranging from 0 to 150 W. Plasma diagnostics determined the average self dc bias ($V_{th}$) and the plasma potential ($V_p$). The present configuration results in an average impacting ion energy $E_i$ ($= q(V_p - V_{th})$) ranging from 11 to 190 eV. N-MOSFETs with 7-nm-thick SiO2 and high-k gate stack (HfAlO/SiO2) were used for the charging damage study. Drain current-voltage ($I_d-V_g$) characteristic were obtained for various devices (different antenna ratios). N-type Si wafers were used for the physical damage study and the $I_d-V_g$ characteristics were simulated by TCAD with various $d_R$ being introduced, by assuming an offset spacer etch.
4. Results and Discussion

Figure 2 shows typical examples of $I_d-V_g$ characteristics. $V_{th}$ is clearly shifted. By using constant current stress (CCS) and comparing the $V_{th}$ of damaged devices (See Fig. 2), we predicted $I_p$ as $1 \times 10^{-9}$ (A). This value is consistent with that determined from plasma diagnostics ($3 \times 10^{-9}$ (A)). As seen in Fig. 3, the $\Delta V_{th}$ increases with an increase in effective antenna ratio $r$. The power-law component $\alpha$ of $r$ in eq. (1) was estimated to be 0.30 for the charging damage. This is consistent with the value by CCS (0.34), verifying the model by eq. (1). Therefore, we can speculate that the variations of $I_{cco}, I_p$, and $n_p$ impact on the $\Delta V_{th}$-variability by a factor of 0.30 via $I_p$ (See Fig. 1). Moreover, one should consider two critical scenarios: (1) Although high-k devices determine similar $\alpha$ (0.37), they naturally exhibit larger charge trapping [3] ($\sim \Delta V_{th}$). This unique feature may enhance the $V_{th}$ variation range. (2) Even if the variations of $I_{cco}, I_p$, and $n_p$ are suppressed, that of $r$ is difficult to be done. Consideration of the effect of antenna ratio range (a few orders) on the $\Delta V_{th}$ variation is indispensable.

Fig. 2 $I_d-V_g$ characteristics of plasma-exposed and constant current-stressed (CCS) samples. (W/L=30/30μm) The time dependences of $V_{th}$ under CCS are shown in the inset.

Fig. 3 $\Delta V_{th}$ as a function of antenna ratio for plasma-exposed MOSFETs with SiO2 and high-k gate dielectrics. $\Delta V_{th}$ electrically damaged by CCS is also shown for various currents (open square).

Figure 4 shows the $d_R$ as a function of $(V_p-V_{dc})$. The $d_R$ was calculated from the thicknesses of damaged layers obtained by spectroscopic ellipsometry with optimized optical structure and from surface sputtering mechanism predicted by molecular dynamics simulations [5]. The $\beta$ in eq. (3), i.e., "the impact factor" $\beta$ in eq. (5), was determined experimentally to be 0.33. The $\Delta V_{th}$ calculated from TCAD for various $d_R$ is illustrated in Fig. 5. As seen in Fig. 5, although the impact factor $\beta$ is close to those by charging damage (0.3), one should note that the $I_p$ shrinkage enhances the $V_{th}$ variation range in scaled devices.

Fig. 4 Calculated recess depth as a function of $(V_p-V_{dc})$.

Fig. 5 Recess structure-induced $\Delta V_{th}$ as a function of $(V_p-V_{dc})$, estimated by TCAD for various gate length ($L_g$).

5. Conclusion

The impacts of plasma-induced damage on the $V_{th}$-variability were modeled and experimentally clarified in terms of plasma parameters. We found the similar effects on $V_{th}$-variability for both charging and physical damage. In addition to the above effects, one should consider that high-k dielectrics, antenna design rule and device shrinkage enhance the $V_{th}$ variation range in advanced MOSFETs.

Acknowledgements

This work was supported in part by MIRAI, STARC and Grant-in-Aid for Scientific Research (B) 20360329 from JSPS.

References