Interface Trap Generation Induced by Charge Pumping Current Under Dynamic Oxide Field Stresses

Shiyang Zhu, *Member, IEEE*, Anri Nakajima, Takuo Ohashi, and Hideharu Miyake

***Abstract*—Stress-induced interface trap generation $(\Delta N_{\rm it})$ in the mid-channel region of standard n-channel MOSFETs with ultrathin plasma-nitrided $\mathrm{SiO_2}$ films (2.34 and 3.48 nm) were systematically studied under static and dynamic (both bipolar and unipolar) oxide field stresses over a wide frequency range from 1 to 10^7 Hz using a direct-current current–voltage measurement. At the bipolar stresses, $\Delta N_{\rm it}$ increases with the stress frequency significantly when the frequency is larger than $\sim 10^4$ Hz while it saturates or decreases at the frequency larger than $\sim 10^7$ Hz. The frequency dependence of the $\Delta N_{\rm it}$ enhancement can be attributed to a charge pumping current during the dynamic stress. Nitrogen incorporation increases not only $\Delta N_{\rm it}$, but also the frequency dependence.**

***Index Terms*—Charge pumping, interface traps, MOSFET, reliability.**

I. INTRODUCTION

INTERFACE trap and bulk charge generations under both static and dynamic oxide field stresses in MOSFETs constitute a major device reliability concern and have attracted much research interest [1]–[5]. It has been reported that the oxide lifetime is significantly improved under bipolar pulsed bias [2], [3] or under dynamic negative bias temperature instability stress [6] as compared with the static counterparts due to the partial recovery of interface traps $(\Delta N_{\rm it})$ during the "off" state of the stress. However, $\Delta N_{\rm it}$ is found to be enhanced, not suppressed, under the dynamic oxide field stress [1], [2], while the reported behaviors about the frequency dependence of $\Delta N_{\rm it}$ were inconsistent in literature. For example, Chen *et al.* [1] observed that $\Delta N_{\rm it}$ is essentially independent of frequency for frequency less than 3×10^5 Hz and then increases linearly with frequency, but Rosenbaum *et al.* [2] found that $\Delta N_{\rm it}$ under bipolar stress increases first and then decreases with frequency with a maximum around 2×10^4 Hz. Hence, systematical studies are necessary to resolve the controversial issues and to understand mechanisms of the interface trap generation. This is the motivation of this letter.

II. DEVICES AND MEASUREMENT

The devices studied in this experiment were poly-Si gate lightly doped drain n-channel MOSFETs fabricated by a standard process with a base gate $\mathrm{SiO_2}$ thickness of 2.34 or 3.48 nm. Plasma nitridation was performed to introduce nitrogen into the gate $\mathrm{SiO_2}$ with different nominal concentrations of 0% (pure $\mathrm{SiO_2}$), 9%, 11%, and 12%, respectively. Devices were stressed by applying a square voltage waveform with the rise and fall time less than 8 ns and the duty factor of 50% to the gate electrode while the substrate, drain and source were grounded. The waveform keeps its normal square form up to 10 MHz as monitored by an oscilloscope. A substrate current $(I_{\rm bulk})$ was measured during stress. The interface trap density $(N_{\rm it})$ was measured by a direct-current current–voltage (DCIV) method [7], [8] before and after stress. In measurement, the drain and source were connected together and biased at -0.3 V, while the substrate was grounded. The DCIV current $(I_{\rm DCIV})$ was measured at the substrate by sweeping the gate voltage (V_g) from -1 to 0.6 V. An $I_{\rm DCIV}$ peak at $V_g = -0.2 \sim -0.4$ V is observed when the recombination current via the interface traps along the mid-channel region (MCR) reaches a maximum. The height of the $I_{\rm DCIV}$ peak above the baseline is directly proportional to $N_{\rm it}$ approximately, thus $N_{\rm it}$ can be calculated [7]. The stress-induced $N_{\rm it}$ at MCR is obtained by $\Delta N_{\rm it} = N_{\rm it}(\text{stressed}) - N_{\rm it}(\text{fresh})$. In our experiments, $\Delta N_{\rm it}$ (fresh) is 1.2–2.8 $\times$ 10^9 $\mathrm{cm^{-2}}$ for all tested devices, demonstrating the well controlled interface states in mature production technologies. Threshold voltage and transconductance were also measured before and after stress. A close correlation between the threshold voltage shift $(\Delta V_{\rm th})$, the degradation of the transconductance $(\Delta G_m/G_{m0})$ and $\Delta N_{\rm it}$ at MCR has been observed (not shown here).

III. RESULTS AND DISCUSSION

Fig. 1 show the frequency dependence of $\Delta N_{\rm it}$ under bipolar and unipolar (positive and negative) stresses for nMOSFETs with 2.34-nm pure $\mathrm{SiO_2}$ gate dielectric. Other devices which have different base $\mathrm{SiO_2}$ thickness and nitrogen contents display quite similar frequency dependence but with different magnitudes. First, for a frequency less than about 10^4 Hz, $\Delta N_{\rm it}$ is almost independent of frequency. At the same amplitude of the stress voltage (V_a), $\Delta N_{\rm it}$ of bipolar stress equals approximately to the sum of that of positive and negative unipolar stresses, indicating that $\Delta N_{\rm it}$ of bipolar stress is a simple accumulation of $\Delta N_{\rm it}$ generated at each one half cycle for unipolar stresses [2].

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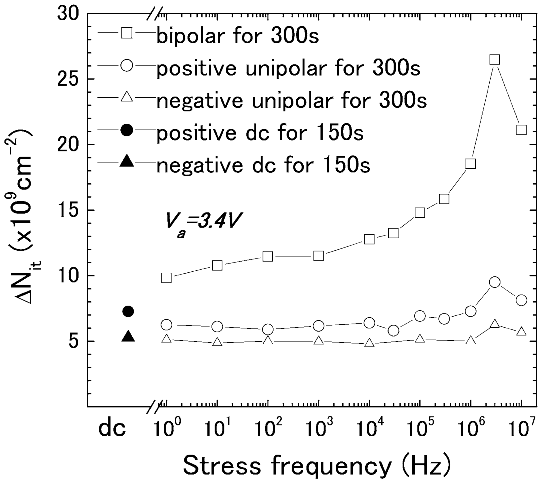

Fig. 1. Frequency dependence of interface trap generation under bipolar and unipolar (positive and negative) stresses for n-channel MOSFETs with 2.34-nm pure SiO_2 gate dielectric and $W/L = 10/10\,\mu$m. The data of dc stresses are also given for comparison. All other samples show similar frequency dependence. Different MOS devices were tested for each data point. Note that the absolute value of N_{it} may suffer a systematical error due to uncertainty of the electron and hole capture coefficients used to calculate N_{it} from the measured I_{DCIV} peak.

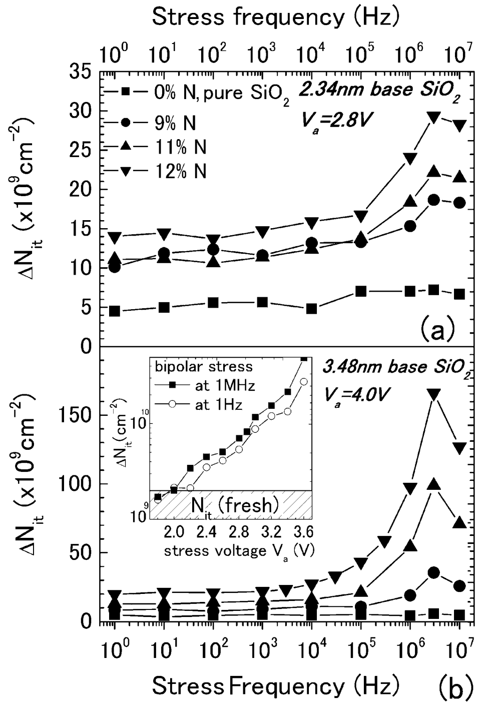

Fig. 2. Frequency dependence of interface trap generation under bipolar stresses for two series samples with different base SiO_2 thickness of (a) 2.34 nm ($W/L = 10\ \mu$m/10 μm, $V_a = 2.8$ V) and (b) 3.48 nm ($W/L = 10\ \mu$m/1 μm, $V_a = 4.0$ V) with different nitrogen concentrations of 0%, 9%, 11%, and 12%, respectively. The stress time remains 300 s. EOTs for series (a) samples are 2.34, 2.03, 2.04, and 1.94 nm and for series (b) samples are 3.48, 3.14, 3.04, and 2.94 nm, respectively. Inset shows the stress-induced interface trap density as a function of the voltage amplitude of the bipolar stress at two typical frequencies.

Moreover, ΔN_{it} after 300 s unipolar stress of 50% duty factor is close to that of 150 s dc stress for both polarities. These findings strongly suggest that there is no ac effect at low frequencies. The apparently larger ΔN_{it} of the positive (both unipolar and dc) stress than that of negative polarity can be attributed to the fact that the oxide voltage (V_{ox}) is larger in the positive case than that in the negative case at the same V_{a} due to the flat-band voltage and the surface potential variation. Second for frequencies between 10^4 and 10^6 Hz, ΔN_{it} of the bipolar stress shows strong frequency dependence while the frequency dependence of unipolar stresses is very weak. Similar frequency dependence was also observed by Chen *et al.* [1]. Third, at the megahertz frequency region, the ΔN_{it} enhancement saturates or reduces at even higher frequency.

Fig. 2 compares the frequency dependence of ΔN_{it} under bipolar stresses for samples with different nitrogen concentrations. Nitrogen incorporation increases not only ΔN_{it} at the low-frequency region, but also its frequency dependence at the high-frequency region. Higher nitrogen concentration results in larger ΔN_{it} and stronger frequency dependence. It can be partly attributed to the fact that the dielectric film with the same base SiO_2 thickness but higher nitrogen concentration has a smaller equivalent oxide thickness (EOT) and a larger gate leakage current due to the barrier height lowering. The similar EOT of the 2.34-nm samples with 9% and 11% nitrogen results in the similar ΔN_{it} at the low-frequency region. Another possible reason is the trapping of H^+ by nitrogen in the silicon oxynitride film [9]. Both ΔN_{it} and its frequency enhancement decreases as V_{a} decreases, e.g., for the 2.34-nm pure SiO_2 devices, with V_a reducing from 3.4 V [Fig. 1(□)] to 2.8 V [Fig. 2(a)(■)], ΔN_{it} at low frequency decreases from ~12 to ~5×10^9 cm^{-2}, and the ΔN_{it} enhancement at high frequency almost disappears. Other samples show similar V_{a} dependent behavior (not shown). This finding is in contrary to the observation of Chen *et al.* [1], possibly due to the different gate oxide thickness and the different stress voltage in their experiments.

The observed frequency dependent behaviors can be understood by a reaction-diffusion model [10] taking a charge pumping current during dynamic stress into account. According to the reaction-diffusion model, the interface trap generation includes two procedures 1) the dissociation of hydrogen-terminated trivalent Si bonds (Si–H) by energetic species (electrons, holes, released hydrogen ions or atoms, etc.); and 2) diffusion of the released hydrogen from the interface to avoid initial recovery. In dc or low-frequency dynamic stress, the energetic species are mainly contributed by the tunneling current as it has reported that interface trap generation starts to occur at the voltage at which tunneling through the oxide starts to build up [1]. In the dynamic cases, besides the tunneling current, we propose that the charge pumping (CP) current, which is arisen from recombination of trapped electrons at/near interface with holes from the substrate upon the Si surface potential reversal from inversion to accumulation, can also contribute energy to break the Si–H bonds. Fig. 3 shows I_{bulk} measured during stress as a function of the stress frequency. I_{bulk} is composed of the averaged dc tunneling currents of both polarities and the CP current ($I_{\mathrm{CP}} \propto f \cdot \Delta F(f)$, where f is the stress frequency and $\Delta F(f)$ is the filling fraction [11]). Because of the variation of I_{bulk} during stress, I_{bulk} in Fig. 3 are the averaged values measured at the first 10 s. We can see that I_{bulk} in Fig. 3 shows quite similar frequency dependent behaviors as ΔN_{it} in Fig. 1

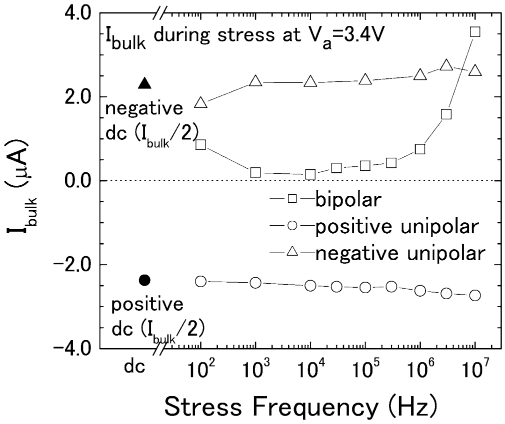

Fig. 3. Bulk current measured during stress as a function of frequency of the sample of Fig. 1. For comparison, the values of dc stresses were divided by two taking the 50% duty factor into account. I_{bulk} was averaged from the I_{bulk} values measured at the first 10 s stress.

except at the MHz region, i.e., I_{bulk} of unipolar stress for both polarities is almost frequency-independent. Taking the 50% duty factor of the dynamic stress into account, the I_{bulk} value is close to that of dc stress. For bipolar stresses at low frequencies, I_{bulk} is also independent of frequency and the value is close to the sum of those of positive and negative unipolar stresses, indicating the negligible I_{CP} component at the low frequency region. As the frequency increasing, I_{bulk} of bipolar stress increases with frequency significantly due to the domination of I_{CP}, associated with the enhancement of ΔN_{it} at the similar frequency region. The ΔN_{it} vs. V_{a} curves at 1 and 10^6 Hz bipolar stresses shown in the inset of Fig. 2(b) confirms this assumption. At small V_a (2.2 V), no ΔN_{it} enhancement occurs at 1 Hz stress due to the negligible tunneling current, while it occurs at 1 MHz stress due to the I_{CP} contribution. This model also explains the very weak frequency dependence of ΔN_{it} in the unipolar stresses as observed in [1], [2] and this letter, because I_{CP} of unipolar stress is small at the whole frequency range.

The absence of I_{bulk} saturation in Fig. 3 at the megahertz region as ΔN_{it} in Figs. 1 and 2 may be explained as follows. It is well known that the oxide traps distributed within X^{CP} (the maximum distance from the Si interface within which the trap states can communicate with free charges at Si interface by tunneling) can also contribute I_{CP} [11], [12], namely, $I_{\mathrm{CP}} = I_{\mathrm{CP-FS}}(\text{contributed by interface states}) + I_{\mathrm{CP-SS}}$ (contributed by near-interface states). We speculate that $I_{\mathrm{CP-SS}}$ may create interface traps more effectively because the released H atoms can diffuse away more easily than those at the interface. The filling fraction of $I_{\mathrm{CP-SS}}(\Delta F_{\mathrm{SS}})$ depends on the distance from the interface and begins to reduce at much lower frequency ($\sim 10^6$ Hz [11]) than ΔF_{FS} (the filling fraction of $I_{\mathrm{CP-FS}}$). At the stress frequency larger than $\sim 10^6$ Hz, ΔF_{SS} begins to reduce while ΔF_{FS} is still maintains a value close to 1, hence $I_{\mathrm{CP-FS}}$ increases continuously while $I_{\mathrm{CP-SS}}$ begins to reduce with stress frequency larger than $\sim 10^6$ Hz, resulting in the monotonous increase of the measured I_{bulk} and the saturation or reduce of ΔN_{it} at the megahertz region.

IV. CONCLUSION

The frequency dependence of ΔN_{it} under dynamic oxide field stress can be divided into three regions: no ac effect at low frequency, increasing of ΔN_{it} with frequency at frequencies larger than $\sim 10^4$ Hz and saturation of ΔN_{it} at the megahertz region. An assumption is proposed to explain the observed behaviors that ΔN_{it} may be generated by $I_{\mathrm{CP-SS}}$ effectively. Nitrogen incorporation increases both the interface trap generation and its frequency dependence.

REFERENCES

[1] T. P. Chen, S. Li, S. Fung, and K. F. Lo, “Interface trap generation by FN injection under dynamic oxide field stress,” *IEEE Trans. Electron Devices*, vol. 45, no. 9, pp. 1920–1926, Sep. 1998.

[2] E. Rosenbaum, Z. Liu, and C. Hu, “Silicon dioxide breakdown lifetime enhancement under bipolar bias conditions,” *IEEE Trans. Electron Devices*, vol. 40, no. 12, pp. 2287–2295, Dec. 1993.

[3] B. Wang, J. S. Suehle, E. M. Vogel, and J. B. Bernstein, “Time-dependent breakdown of ultrathin SiO_2 gate dielectrics under pulsed biased stress,” *IEEE Electron Device Lett.*, vol. 22, no. 5, pp. 224–226, May 2001.

[4] J. S. Suehle and P. Chaparala, “Low electric field breakdown of thin SiO_2 films under static and dynamic stress,” *IEEE Trans. Electron Devices*, vol. 44, no. 5, pp. 801–808, May 1997.

[5] R. Rodriguez, M. Nafria, J. Sune, and X. Aymerich, “Trapped charge distributions in thin (10 nm) SiO_2 films subjected to static and dynamic stresses,” *IEEE Trans. Electron Devices*, vol. 45, no. 4, pp. 881–888, Apr. 1998.

[6] G. Chen, M. F. Li, C. H. Ang, J. Z. Zheng, and D. L. Kwong, “Dynamic NBTI of p-MOS transistors and its impact on MOSFET scaling,” *IEEE Electron Device Lett.*, vol. 23, no. 12, pp. 734–736, Dec. 2002.

[7] J. Cai and C. T. Sah, “Monitoring interface traps by DCIV method,” *IEEE Electron Device Lett.*, vol. 20, no. 1, pp. 60–63, Jan. 1999.

[8] B. B. Jie, W. K. Chim, M. F. Li, and K. F. Lo, “Analysis of the DCIV peaks in electrically stressed pMOSFETs,” *IEEE Trans. Electron Devices*, vol. 48, no. 5, pp. 913–920, May 2001.

[9] C. H. Ang, C. M. Lek, S. S. Tan, B. J. Cho, T. Chen, W. Lin, and J. Z. Zhen, “Negative bias temperature instability on plasma-nitrided silicon dioxide film,” *Jpn. J. Appl. Phys.*, pt. 2, vol. 41, no. 3B, pp. L314–L316, 2002.

[10] S. Mahapatra, P. B. Kumar, and M. A. Alam, “A new observation of enhanced bias temperature instability in thin gate oxide p-MOSFETs,” in *IEDM Tech. Dig.*, 2003, pp. 337–340.

[11] C. E. Weintraub, E. Vogel, J. R. Hauser, N. Yang, V. Misra, J. J. Wortman, J. Ganem, and P. Masson, “Study of low-frequency charge pumping on thin stacked dielectrics,” *IEEE Trans. Electron Devices*, vol. 48, no. 12, pp. 2754–2762, Dec. 2001.

[12] R. E. Paulsen and M. H. White, “Theory and application of charge pumping for the characterization of Si-SiO_2 interface and near-interface oxide traps,” *IEEE Trans. Electron Devices*, vol. 41, no. 7, pp. 1213–1216, Jul. 1994.