C–t Analysis of MOS Capacitors Under Constant Current Stress

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***Abstract*—The effect of high oxide field stress is studied using capacitance–time (C–t) measurements of MOS capacitors. The stress results in parallel shifts of the C–t curve along the time axis. The flatband voltage shift ΔV_{FB} obtained from the initial deep depletion capacitance $C(t=0^{+})$ follows the same trend as that from the high-frequency *C–V* characteristics. However, the discrepancy between the two flatband voltages becomes larger as the stress increases due to the effect of interface charges on C–t characteristics. The flatband voltage difference is converted to interface trap density, showing a steady increase of interface trap density with stress, similar to that from low-frequency *C–V* measurements.**

I. INTRODUCTION

THE DEGRADATION of thin tunnel oxides under Fowler–Nordheim (F–N) high field stress is of great importance to MOS devices, especially in applications such as EEPROM's where charge transfer through the oxide is the main mechanism for the device operation. Most of the previous studies on the oxide degradation of MOS capacitors (MOS-C's) have relied on high-frequency (HF) and quasi-static, low-frequency (LF) capacitance–voltage (*C–V*) measurements. They have indicated that significant damage is created in the SiO$_2$ layer due to the generation of traps inside the oxide and at the Si-SiO$_2$ interface, as well as electron and hole trapping [1]–[4]. However, there has never been an attempt to monitor this degradation with capacitance–time (C–t) measurements even though it may provide additional information. Theoretically, the C–t characteristic is affected by the flatband voltage shift ΔV_{FB} generated during high field stress. Furthermore, the surface generation velocity extracted by the Zerbst method [5] can also be used as a measure of interface trap density. The question is whether the same results of *C–V* measurements can be obtained with C–t measurements. In the present work, we investigate the C–t characteristics with MOS-C's under constant current stress.

II. C–t ANALYSIS

On of the most widely used interpretations of the C–t transient is the Zerbst method which extracts an effective generation lifetime τ_g' and an effective surface generation velocity's using the equation

$$-\frac{d}{dt}\left[\frac{C_{\mathrm{OX}}}{C(t)}\right]^2 = \frac{2n_i C_{\mathrm{OX}}}{N_A C_F \tau_g'}\left[\frac{C_F}{C(t)} - 1\right] + \frac{2n_i C_{\mathrm{OX}} s'}{K_S \epsilon_O N_A} \qquad (1)$$

for a p-substrate where C_{OX} is the oxide capacitance, $C(t)$ the measured capacitance, n_i the intrinsic carrier concentration, N_A the bulk doping concentration, C_F the final or equilibrium capacitance, K_S the silicon dielectric constant, and ϵ_{O} the permittivity of free space.

The second approach for utilizing the C–t measurements is based on the fact that the deep depletion capacitance $C(t)$ can be related to V_G through [6]

$$C(t) = \frac{C_{\mathrm{OX}}}{\sqrt{1 + \frac{2[V_G - V_{\mathrm{FB}} + Q_N(t)/C_{\mathrm{OX}}]}{V_O}}}. \qquad (2)$$

Here, $Q_N(t)$ is the inversion charge density and $V_O = qK_s\epsilon_O N_A/C_{\mathrm{OX}}^2$. Equation (2) states that V_{FB} can be determined from the measured $C(t)$ once $Q_N(t)$ is known. The treatment of $Q_N(t)$ requires the assumption that $Q_N(t=0^+)$, i.e., Q_N immediately after a depleting step voltage is applied, is small enough for the term $Q_N(t=0^+)/C_{\mathrm{OX}}$ to be ignored compared to both V_G and V_{FB} because no significant inversion charge is formed during the initial deep depletion state. Hence, ΔV_{FB} can be readily obtained by monitoring $C(t=0^+)$ of the C–t curve, where $\Delta V_{\mathrm{FB}} = V_{\mathrm{FB}}$ (after stress)–V_{FB} (before stress).

III. EXPERIMENTAL

MOS capacitors on n- and p-wells were fabricated on (100) n-type Si substrates with a 16–25 Ω-cm resistivity. A pocket p-well is formed by a 2.1×10^{13} cm^{-2}, 80-keV boron implant in the n-well with a 1.7×10^{13} cm^{-2}, 100-keV phosphorus implant. The gate oxides are approximately 100 Å thick determined by HF *C–V* measurements and ellipsometry. The capacitors are rectangular in shape with 6.4×10^{-4} cm^2 area.

MOS-C's were F–N stressed in accumulation mode at a constant gate current of 6.4 μA. After known time intervals, the stressing was interrupted and *C–V* and C–t characteristics were measured. This procedure was repeated until the devices broke down. The depletion mode stress was not used here to avoid using a light source which might affect subsequent C–t measurements.

IV. RESULTS AND DISCUSSIONS

Fig. 1(a) displays the C–t characteristics for a p-substrate MOS-C taken before and after stress. The effects of the stress on the C–t characteristics appear as parallel shifts of C–t curves

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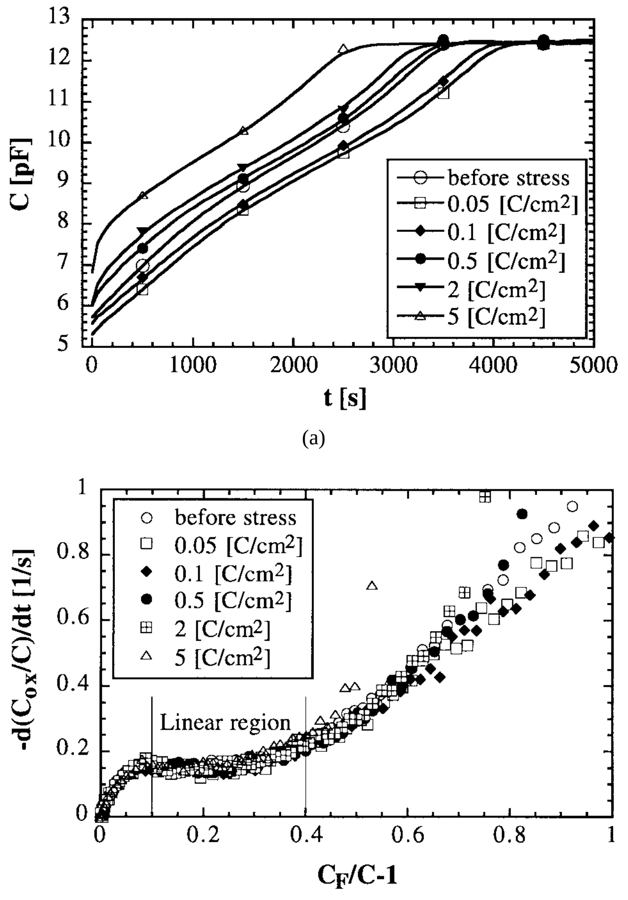
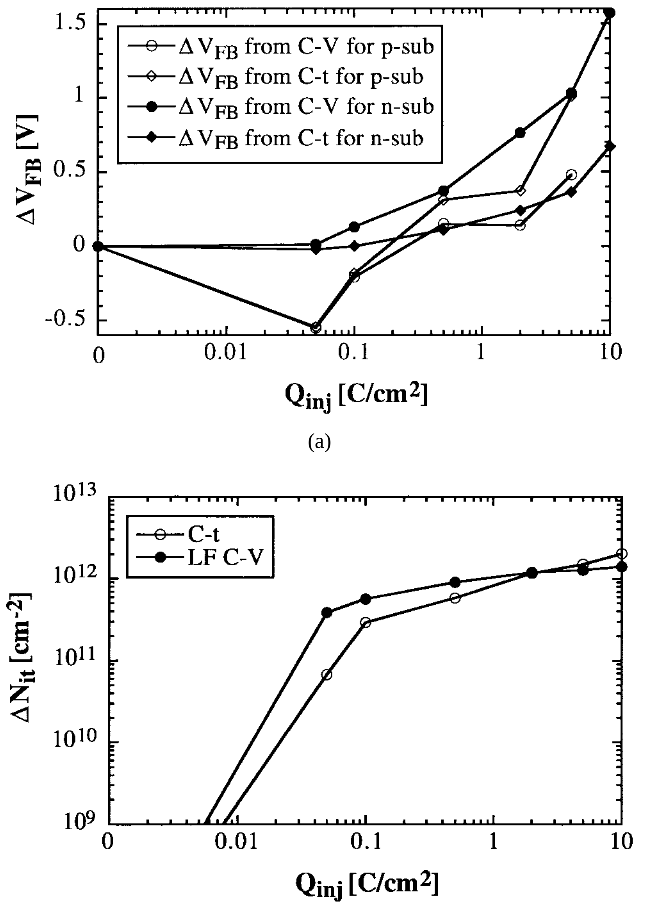


(a)

(b)

Fig. 1. (a) C–t characteristics for a p-substrate MOS-C before and after negative current stress (stress current density $J = 10$ mA/cm^2). (b) The corresponding Zerbst plots. The effective generation lifetime τ_g' and effective surface generation velocity s' are obtained from the slope and intercept in the linear region, respectively.



(a)

(b)

Fig. 2. (a) ΔV_{FB} obtained from HF C–V and C–t measurements for both n- and p-substrate MOS-C's. (b) Comparison of ΔN_{it} extracted from the difference of the two ΔV_{FB} values with that from LF C–V data for an n-substrate MOS-C. Here, the injected charge Q_{inj} was obtained by multiplying the stress current density (J) by the stress time (t), $Q_{\mathrm{inj}} = J \times t$.

along the time axis after each stress. Another observation is that $C(t = 0^+)$ is affected by the stress. The corresponding Zerbst plots are shown in Fig. 1(b). Each Zerbst plot provides essentially the same slope and intercept taken from the linear region, which indicates that the stress has negligible effect on both τ_g' and s'. We had expected s' to increase with stress since stress is usually thought to generate interface traps. However, s' is not the surface generation velocity alone as is frequently related to the interface traps but is the effective surface generation velocity [6] incorporating surface generation under the gate as well as quasi-neutral bulk generation components. Possible explanations could be either that quasi-neutral bulk generation components are dominant over surface generation under the gate or that most of the interface states are quickly filled with carriers reducing surface generation. For either case the change of the measured s' is not significant even after high stress.

ΔV_{FB} extracted using (2) shows the effects of the stress on C–t measurements more clearly because of the change of $C(t = 0^+)$ with stress. Fig. 2(a) compares the resulting $\Delta V_{\mathrm{FB,\,C-t}}$ due to the change of $C(t = 0^+)$ with $\Delta V_{\mathrm{FB,\,C-V}}$ from HF C–V data. Both ΔV_{FB} show very similar overall trends but the difference between the two increases with increasing stress. We attribute this discrepancy to the interface charge due to the stress. Interface charge stretches the HF C–V curve along the voltage axis, which implies additional change of $C(t = 0^+)$ due to the interface charge, and this eventually results in either over- or under-estimation of V_{FB} with the C–t analysis. In other words, ΔV_{FB} obtained from the C–t analysis includes the effect of interface charges as well as oxide bulk charges while that from HF C–V mainly reflects the effect of oxide bulk charges. Therefore, the difference of ΔV_{FB} between C–V and C–t measurements can be converted to an interface trap density $N_{\mathrm{it}} = C_{\mathrm{OX}}|\Delta V_{\mathrm{FB,\,C-t}} - \Delta V_{\mathrm{FB,\,C-V}}|/q$. As shown in Fig. 2(b), N_{it} increases monotonically with stress, which is quite close to the result from LF C–V measurements.

V. CONCLUSION

We used the C–t analysis to study the effect of high field stress on the oxide of MOS-C's. A parallel shift of the C–t characteristics along the time axis is observed after stress. However, τ_g' and s' values extracted using the Zerbst method did not show any dependence on stress. ΔV_{FB} derived from $C(t = 0^+)$ shows the same trend as that from HF C–V measurements. However, the discrepancy between the two flatband voltages becomes larger after each stress due to the effect of the interface charge on $C(t = 0^+)$. The difference between the two flatband voltages can be related to N_{it}, which is close to the result from LF C–V measurements. As a result, the C–t analysis coupled with HF C–V measurement can rapidly provide interface trap density since this requires the measurement of $C(t = 0^{+})$ only rather than time-consuming full C–t measurements and therefore can be an alternative method in place of LF C–V measurements.

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