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REVISED MODEL OF THERMALLY STIMULATED CURRENT IN MOS CAPACITORS*

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35-wd Abstract

It is shown analytically and experimentally that thermally stimulated current (TSC) measurements at negative bias incompletely describe oxide-trap charge in SIMOX and bipolar base oxides irradiated at 0 V. Positive-bias TSC is also required.

I. Introduction

Thermally stimulated current (TSC) measurements have been used to estimate oxide-trap charge densities and energies in irradiated MOS capacitors in a large number of studies [1-21]. In a typical experiment, a MOS capacitor is irradiated under positive bias, leading to the buildup of net trapped positive charge near the Si/SiO_2 interface. TSC measurements under negative bias are usually presumed to provide accurate estimates of trapped-hole densities and energy distributions if performed at large enough electric fields [7,10,11]. Under these experimental conditions, combined TSC and capacitance-voltage (C-V) measurements have been used to infer the densities of compensating trapped electrons near the Si/SiO_2 interface [8,10-12]. Recently the TSC method has also been applied to assist the understanding of charge trapping in SIMOX [17,19] and bipolar base oxides [14,21]. For the latter device types, especially when irradiated at 0 V bias, there is the potential for greatly enhanced hole and electron trapping in the bulk of the oxide, as compared with conventional thermal oxides [14,17-21]. Conventional TSC experiments and analysis methods [1-11] do not consider the effects of this additional charge that can contribute to the TSC in these increasingly important cases.

In this paper, standard TSC analysis methods are extended to include the contributions of positive and negative charge with arbitrary distributions through the oxide. Combined TSC and C-V measurements performed on identically prepared capacitors are presumed to be made at both negative and positive TSC bias. Distinctions are made between the contributions of electrons trapped in the bulk of the oxide, which can contribute to the measured TSC, and electrons trapped in border traps, which cannot contribute to the TSC [7,11,12,20]. In each case, expressions for the resulting trapped positive and negative charge densities can be derived. The analysis is illustrated for radiation-hardened thermal oxides irradiated under several bias conditions, and for SIMOX and bipolar base oxides irradiated at 0 V. Implications are discussed for models of radiation-induced trapped oxide charge.

II. Theory

A. Trapped Positive Charge.

Figure 1 shows model postirradiation charge distributions for MOS capacitors, neglecting the contributions of electrons in bulk oxide traps or border traps. In each case, the total trapped positive charge density is Q_h. However, in (a) the charge is presumed to be trapped infinitesimally close to the Si/SiO_2 interface, so the accompanying negative image charge $-Q_h$ is located almost entirely at the Si/SiO_2 interface. In (b) the centroid of the trapped charge is in the bulk of the oxide, at a distance y from the gate, so the image charge splits between the gate and the Si electrodes. The image charge in the Si is $-(y/t_{ox})Q_h$, while the image charge on the gate is $-(t_{ox}-y)(Q_h/t_{ox})$. With the usual assumption of midgap interface-trap charge neutrality [12,22,23], the C-V charge $Q_{CV} \equiv -C_{ox}\Delta V_{mg} = Q_h$ in case (a), and $(y/t_{ox})Q_h$ in (b), where C_{ox} is the oxide capacitance per unit area and ΔV_{mg} is the midgap voltage shift.

The TSC in a typical experiment is cause by the redistribution of the image charge in response to trapped charge emission and transport across the oxide as a device is heated under bias [1,7]. Thus, for large negative TSC bias in Fig. 1, the magnitude of the total charge per unit area Q_- sensed in case (a) is the total charge Q_h, and in case (b) it is the charge that moves from the Si to the gate, $(y/t_{ox})Q_h$. For large positive bias, on the other hand, the TSC charge $Q_+ \approx 0$ in case (a), since there is no redistribution of image charge when the trapped positive charge travels the infinitesimal distance into the Si [7,10]. In case (b) $|Q_+| = (t_{ox}-y)(Q_h/t_{ox})$, which is the image charge that moves from the gate to the Si through the sensing ammeter. Adding the total charge collected during TSC measurements under large positive and

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negative bias, the total charge collected in the two cases Q_T is $|Q_+|+|Q_-| = Q_h$. Thus, TSC measurements at *both* positive and negative bias are generally required to determine the total trapped positive charge densities of irradiated MOS capacitors, even without considering the possible contributions of trapped electrons. This differs from common experimental practice, where negative bias TSC has been used almost exclusively [1-21]. The impact of this point is discussed below.

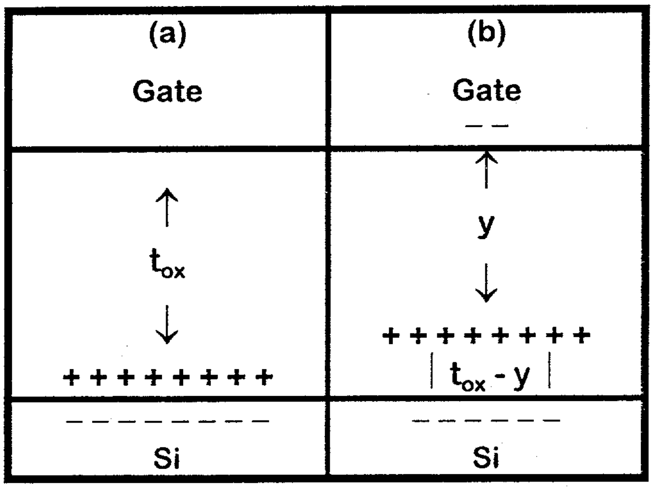

Figure 1. Illustration of trapped positive charge Q_h in MOS capacitors (a) near the Si/SiO$_2$ interface, and (b) in the bulk of the oxide.

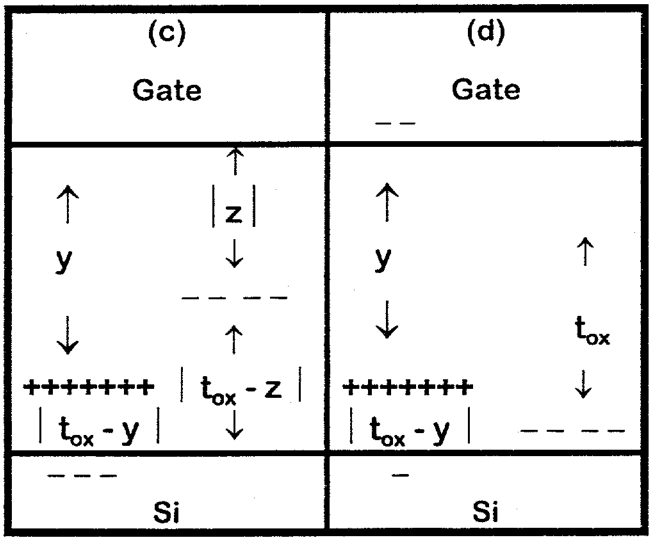

Figure 2. Illustration of trapped positive Q_h and negative Q_e charge in MOS capacitors (c) with the negative charge trapped predominantly in the bulk of the oxide and able to contribute to the TSC, and (d) with the dominant source of negative charge being electrons in border traps, which are unable to contribute to the TSC.

B. Trapped Positive and Negative Charge.

Figure 2 illustrates examples in which both positive and negative charge (e.g., holes and electrons) are trapped in a MOS capacitor. There are two important cases here for irradiated MOS devices. Case (c) illustrates the possibility that both types of charge are distributed throughout the bulk of the oxide, each with a different charge centroid, and each contributing to the TSC. Case (d) illustrates a contrary example where the only significant source of negative charge is electrons in border traps. It has been demonstrated that electrons in border traps do not contribute to TSC under positive or negative bias because they do not transport across the oxide during the TSC measurements in either case [7,12,16,21]. In principle, both types of negative charge may be present in an irradiated MOS capacitor, and the dominant type must be determined by experiment.

By analogy with the discussion in Fig. 1, it is straightforward to list the expressions for the C-V and TSC charge in cases (c) and (d) in Fig. 2. Taking y to be the distance from the gate to the centroid of the trapped positive charge distribution in (c) and (d), z to be the distance from the gate to the trapped negative charge centroid in (c), and noting that positive and negative charge transport to opposite interfaces during TSC measurements, we find for the two cases that:[*]

i. Case (c): Negative Charge in Bulk of Oxide.

$$Q_{CV} = (y/t_{ox})Q_h - (z/t_{ox})Q_e \tag{1}$$

$$|Q_-| = (y/t_{ox})Q_h + (1-z/t_{ox})Q_e = Q_e + Q_{CV} \tag{2}$$

$$|Q_+| = (1-y/t_{ox})Q_h + (z/t_{ox})Q_e = Q_h - Q_{CV} \tag{3}$$

So:

$$Q_e = |Q_-| - Q_{CV} \tag{4}$$

$$Q_h = |Q_+| + Q_{CV} \tag{5}$$

ii. Case (d): Negative Charge in Border Traps.

$$Q_{CV} = (y/t_{ox})Q_h - Q_e \tag{6}$$

$$|Q_-| = (y/t_{ox})Q_h = Q_e + Q_{CV} \tag{7}$$

$$|Q_+| = (1-y/t_{ox})Q_h = Q_h - |Q_-|. \tag{8}$$

So:

$$Q_e = |Q_-| - Q_{CV} \tag{9}$$

$$Q_h = |Q_+| + |Q_-| \tag{10}$$

$$y = (1 + |Q_+|/|Q_-|)^{-1}\, t_{ox} \tag{11}$$

The complementary nature of the TSC and C-V measurements permit analytical solutions for Q_h and Q_e

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[*] Note that Eqs. (2)-(3) differ significantly from expressions in Ref. [1] for TSC due to bias-temperature instabilities.

in each case, despite the fact that there are four unknowns (y, z, Q_h, Q_e) and only three equations in case (c). What is lost in Eqs. (4) and (5) is a unique analytical solution for the positive and negative trapped charge centroids, though one can use Eqs. (1)-(3) to determine physical limits on the values of y and z, as will be shown in the full paper. Equations (6)-(8) yield analytical solutions for Q_h and Q_e as well as the centroid of the trapped positive charge in case (d). Note that equations (4) and (9) are identical! Thus, whether electrons contribute to the TSC or not, a combination of C-V and negative-bias TSC measurements gives an unambiguous estimate of the trapped *electron* density in the SiO_2. This reaffirms the method by which C-V and TSC measurements were used in previous work to estimate the densities of electrons in irradiated MOS capacitors [8-12,20]. However, the value of Q_h *cannot* be determined unambiguously through separate or combined TSC and/or C-V measurements, as illustrated below. The derivation and implications of Eqs. (1)-(11) will be discussed in more detail in the full paper.

Table I. Summary of TSC and C-V experiments on three types of devices. The first row for each part type represents positive-bias TSC (Q_{+}, taken to be negatively valued), and the second row represents negative-bias TSC (Q_{-}, taken to be positively valued). Only one set of TSC/C-V analysis is obtained from Eqs. (1)-(11) for each ± TSC bias pair; average values of Q_{CV} are used in this analysis. Part 1 is a 45-nm thermal oxide (C_{ox} = 754 pF) irradiated at 5.6 krad(SiO_2)/s to (A) 5 Mrad(SiO_2) at 5 V, (B) 2 Mrad(SiO_2) at –5 V, and (C) 2 Mrad(SiO_2) at 0 V; TSC was measured at ± 10 V for A-C. Part 2 is a 580-nm bipolar base oxide (C_{ox} = 7.2 pF) irradiated (A) at 2.0 rad(SiO_2)/s and (B) at 320 rad(SiO_2)/s to 200 krad(SiO_2) at 0 V; TSC was measured at ± 60 V. Part 3 is a 370-nm SIMOX oxide (C_{ox} = 98 pF) irradiated at 333 rad(SiO_2)/s to 50 krad(SiO_2) at (A) 0 V and (B) –5 V; TSC was measured at ± 40 V. Irradiations were performed with 10-keV x rays at 25°C. "Best" estimates of the true Q_h are shown in bold text for each part type. The value of y is based on Eq. (11) of the text for case (d).

Pt. No.	ΔV_{mg} (V)	$Q_\pm$ *TSC* (pC)	*Ave.* Q_{CV} (pC)	Q_e (pC)	Q_h (pC) (c)	Q_h (pC) (d)	y (nm) (d)
1A	-4.69	–243	*	*	*	*	*
	–5.17	6543	3700	2843	3943	**6786**	43.4
1B	–0.54	–134	*	*	*	*	*
	–0.15	784	264	520	399	**918**	38.4
1C	–2.02	–343	*	*	*	*	*
	–1.83	3226	1446	1780	1789	**3569**	40.7
2A	–16.6	–148	*	*	*	*	*
	–12.2	454	103	351	251	**557**	437
2B	–4.2	–103	*	*	*	*	*
	–4.5	492	31.5	460.5	134.5	**595**	480
3A	–3.3	–490	*	*	*	*	*
	–2.3	562	274	288	**764**	1052	198
3B	–3.7	–1529	*	*	*	*	*
	–2.3	661	293	368	**1822**	2190	112

III. Results

Results are shown in Table I from three different types of oxides, including a radiation-hardened 45-nm thermal oxide [11], an Analog Devices' RF25 bipolar base oxide [21], and a standard Ibis SIMOX oxide [21]. TSC and C-V measurements were performed using the method of Ref. [10]. Illustrative positive and negative bias TSC data are shown for the 45-nm thermal (1B) and SIMOX (3A) oxides irradiated at 0 V in Figs. 3 and 4, respectively. TSC data for other part types and biases in Table I will be shown in the full paper.

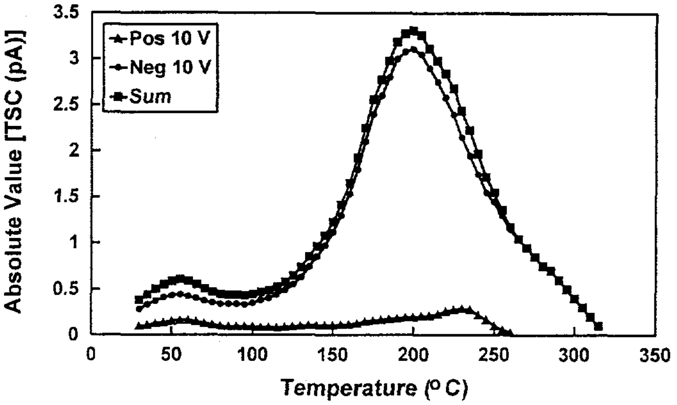

Figure 3. TSC at ± 10 V for 45-nm thermal oxides (1B, Table I). Devices were irradiated to 2 Mrad(SiO_2) at 5.6 krad(SiO_2)/s and 0 V.

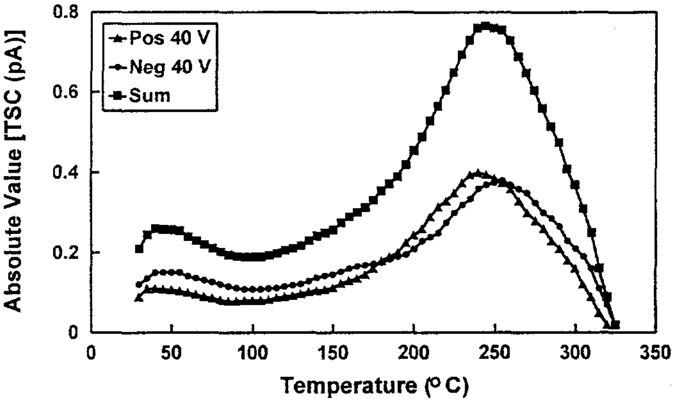

Figure 4. TSC at ± 40 V for 370-nm SIMOX oxides (3A, Table I). Devices were irradiated to 50 krad(SiO_2) at 320 rad(SiO_2)/s and 0 V.

In Fig. 3 the TSC at negative bias greatly exceeds that at positive bias for the 45-nm thermal oxide. It will be shown in the full paper that the results of Fig. 3 and the data in Table I are consistent with radiation-induced trapped positive charge being located very near the Si/SiO_2 interface, and the majority of trapped electrons being located in border traps, consistent with the interpretation of previous results on similar radiation-hardened devices [7,8,10-12,14]. Thus, the appropriate estimate of trapped-hole charge is that for case (d) in

Table I for this device type (1A-C) because electrons in border traps do not contribute to the TSC [7,20]. For the SIMOX devices of Fig. 4, in contrast, the positive and negative bias TSC magnitudes are quite similar. The results of Fig. 4 and Table I for the SIMOX devices are consistent with positive charge trapping throughout the bulk of the oxide [24], as discussed further in the full paper. Moreover, most trapped electrons in these devices also lie within the bulk of the oxide, as opposed to border traps [24], and therefore can contribute to the TSC. Thus, the appropriate value of Q_h for these devices is case (c) of Table I. Estimates that incorrectly use Q_- as a measure of trapped-hole charge would lead to 25-60 % errors in this case. Results for bipolar base oxides at high and low dose rates are consistent with a combination of bulk and near-interfacial hole trapping [14,21], as illustrated by the values of y in Table I, as will be discussed in the full paper.

IV. Summary and Conclusions

A revised model has been developed for TSC in MOS capacitors that distinguishes between the contributions of electrons trapped in the bulk of the oxide from those in border traps. An unambiguous estimate of the density of trapped electrons in the oxide can be obtained from C-V measurements and TSC at negative bias, regardless of the location of the trapped electrons. However, knowledge of the location of trapped electrons is required to estimate the trapped hole density. The interpretation of past TSC experiments on radiation hardened oxides is not significantly affected by this point, but TSC experiments on SIMOX and bipolar base oxides require more detailed analysis to avoid potential errors in estimates of trapped hole densities in the oxide, especially for technologically relevant 0 V irradiations.

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