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Field Dependence of Interface Trap Buildup in Si-Gate MOS Devices*

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Abstract

Radiation-induced interface traps in Si-gate MOS devices follow an $E^{-1/2}$ electric field dependence for $E \geq +0.13$ MV/cm when electron-hole recombination effects are included. A hybrid model involving hole trapping and hydrogen transport is suggested.

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Summary

The electric field dependence of radiation-induced interface-trap formation is different for Al-gate capacitors and Si-gate capacitors and transistors. For Al-gate capacitors, the interface-trap formation steadily increases with increasing positive field [1]. On the other hand, for Si-gate capacitors and transistors, the field dependence of interface-trap buildup peaks near 1 to 2 MV/cm and decreases with an $E^{-1/2}$ dependence at higher fields [2,3]. The field dependence for interface-trap generation for Al-gate capacitors is consistent at all fields with the two-stage hydrogen model of McLean [4] and Winokur et al. [5], which depends on hydrogen release in the bulk of the oxide during hole *transport*. Above 1 to 2 MV/cm, the field dependence of interface-trap buildup for Si-gate devices is inconsistent with this model. Instead, the field dependence of interface-trap buildup in Si-gate devices is similar to what one observes for the effective hole capture cross section at the Si/SiO_2 interface [6], suggesting that hole *trapping* at the Si/SiO_2 interface may play a key role in interface-trap generation in Si-gate devices. However, recent work of Boesch [7] and Saks et al. [8] has shown convincingly that interface-trap generation cannot be due to hole transport and trapping at the Si/SiO_2 interface alone.

In this paper we investigate the radiation-induced oxide-trapped, ΔV_{ot}, and interface-trap, ΔV_{it}, charge buildup for Si-gate transistors over a wide range of dose rates and electric fields. Previous work [2,3] has shown that ΔV_{ot} and ΔV_{it} for Si-gate transistors follow an $E^{-1/2}$ depends only at fields higher than ~2 MV/cm. In this work we show the field dependence of ΔV_{ot} and ΔV_{it} follow an $E^{-1/2}$ dependence over a wide range of fields ($E_{ox} \geq$ +0.13 MV/cm) when electron-hole recombination effects are included. This field dependence provides further support for the idea that hole *trapping* is intimately involved in the interface-trap buildup process in Si-gate devices. A hybrid model involving hole trapping and hydrogen transport is introduced to explain the mechanism responsible for the interface-trap buildup in these samples.

Transistors used in this study were fabricated at the Allied-Signal Microelectronics Operation using Sandia National Laboratories' radiation-hardened 4/3 μm technology [9]. The gate oxides were grown at 1000°C in dry O_2 followed by a forming gas (10 % hydrogen, 90 % nitrogen) post-gate anneal. The gate oxide thickness was 45 nm. Irradiations were performed using a 10 keV ARACOR x-ray source at a dose rate of 1800 rad(SiO_2)/s, and at Boeing Physical Science Center's 10 MeV electron linear accelerator (LINAC). The LINAC supplied 20 krad pulses with a 10 μs pulse width at a 2 x 10^9 rad(SiO_2)/s dose rate per pulse with 7.5 Hz repetition rate. To determine the threshold voltage shifts due to oxide-trapped and interface-trap charge, the midgap [10] and dual-transistor [11] charge separation techniques were used.

Figure 1 is a plot of ΔV_{ot}, ΔV_{it}, and ΔV_{th} as a function of electric field for Si-gate n-channel transistors irradiated with 10 keV x rays to 1 Mrad(SiO_2). The irradiation bias was varied from -10 V to 20 V in 5 V steps. The maximum values of the magnitudes of ΔV_{ot}, ΔV_{it} and ΔV_{th} occur at an electric field of 1.24 MV/cm. At fields of 2.4 MV/cm and above, all three curves follow an $E^{-1/2}$ field dependence, consistent with previous results at comparable fields [3,13]. This $E^{-1/2}$ field dependence for ΔV_{ot} is consistent with the $E^{-1/2}$ dependence of the effective hole capture cross section [6]. However, at fields below 2.4 MV/cm, the field dependence for ΔV_{ot} deviates from an $E^{-1/2}$ form. This is because of electron-hole recombination. As the field decreases, the number of holes that escape electron-hole recombination decreases [14]. Figure 2 is a plot of the absolute value of ΔV_{ot} for the positive field data in Figure 1 adjusted for electron-hole recombination effects. To adjust the data, we used the empirical equation for electron-hole recombination for x-ray irradiation presented by Dozier et al. [14], i.e.,

$$f(E)_{x\text{-}ray} = ((1.35/E) + 1)^{-0.9} \qquad (1)$$

where f(E) is the fraction of holes which escape recombination at an electric field, E, in MV/cm across the oxide. Using equation 1 we divide the ΔV_{ot} field dependence by the field dependence of initial recombination. The adjusted oxide-trapped charge data follow an $E^{-1/2}$ field oxide dependence to within experimental uncertainty for all positive fields shown. Note that, the approximate 2 V difference between the adjusted data and the true $E^{-1/2}$ dependence at 0.13 MV/cm can be explained by only a 20% error in the empirical value determined for the electron-hole recombination. An exact $E^{-1/2}$ dependence is illustrated with the dashed line through the adjusted ΔV_{ot} data. Also shown in Figure 2 is the field dependence for interface-trap generation, where we have applied the same adjustment for electron-hole recombination as for ΔV_{ot}. Note that, at all fields shown (0.1 - 5 MV/cm) the adjusted field dependence for ΔV_{it} also follows an $E^{-1/2}$ field dependence to within experimental uncertainty.

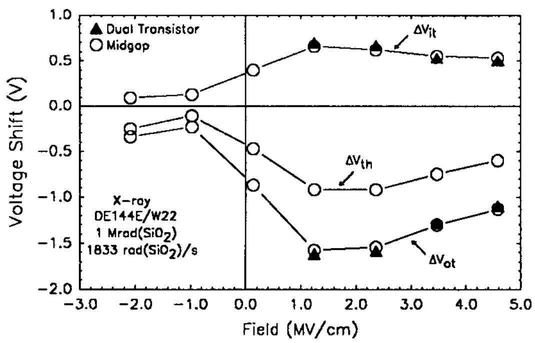

Figure 1: ΔV_{ot}, ΔV_{it}, and ΔV_{th} as a function of electric field for n-channel transistors irradiated to 1 Mrad(SiO_2) with x rays.

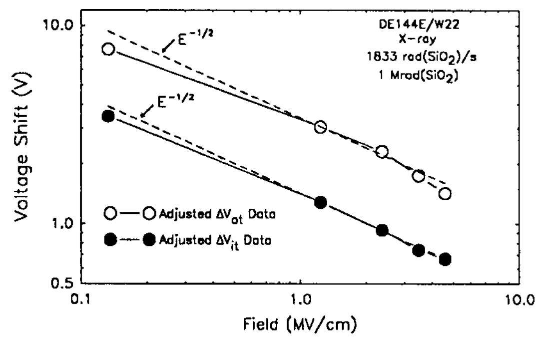

Figure 2: ΔV_{ot} and ΔV_{it} adjusted for charge yield as a function of electric field using the data of Figure 1. The dashed lines show a true $E^{-1/2}$ field dependence.

Similar field-dependences were observed at the higher dose rates for Si-gate devices. Figure 3 is a plot of ΔV_{ot}, ΔV_{it}, and ΔV_{th} versus electric field for n-channel transistors irradiated to 500 krad(SiO_2) using the Boeing LINAC. The bias was varied from -5 V to 20 V in 7 steps. The total time for the irradiation was 3.33 s. The first measurement point shown was taken at 4.33 seconds (~1 s after the last radiation pulse). Note the similarity of the field dependence for the high dose rate irradiations to that of the lower dose rate x-ray irradiations. The only major difference between the field dependence of the two irradiations is where the maximum shift in ΔV_{ot} and ΔV_{it} occur. Based on electron-hole recombination the maximum values for ΔV_{ot} and ΔV_{it} should occur at ~1.2 MV/cm and ~0.2 MV/cm for the x-ray and electron irradiation, respectively. Values of ΔV_{it} and ΔV_{ot} are shown for $E_{ox} \geq$ 0.7 MV/cm ($V_{gs} \geq 2.5$ V). For electric fields above 0.7 MV/cm, the magnitudes of ΔV_{ot}, ΔV_{it}, and ΔV_{th} decrease with increasing electric field. Similar to the x-ray irradiations, ΔV_{ot}, ΔV_{it}, and ΔV_{th} follow an $E^{-1/2}$ field dependence for fields above 2.4 MV/cm.

Figure 4 shows the data for positive fields in Figure 3 adjusted for electron-hole recombination. To determine the fraction of holes which escape electron-hole recombination at each electric field, we used the expression derived by Dozier et al. for Cobalt-60 irradiations, which is expected to be valid also for 10-MeV electron irradiations [14]. Also shown in Figure 4 are the absolute values for ΔV_{ot} and ΔV_{it} adjusted for electron-hole recombination, 300 s after irradiation. Note that, to within experimental uncertainty, ΔV_{ot} and ΔV_{it} for both the 4.33 s and 300 s data follow an accurate $E^{-1/2}$ field dependence from 0.7 to 5 MV/cm.

The data of Figs. 1-4 represent compelling evidence that the hydrogen model of McLean [4] and Winokur et al. [5], which depends on hydrogen release in the bulk of the oxide and is independent of hole trapping, does not explain the interface-trap buildup in *Si-gate* devices at any electric field. Moreover, at fields above ~0.1 MV/cm, both the oxide- and interface-trap buildup of these devices exhibits a field dependence that is strongly reminiscent of the decrease in effective hole capture cross section with increasing field after recombination effects are accounted for, suggesting that hole trapping is intimately involved in the interface-trap buildup process. However, this observation must be reconciled with recent evidence from time- and temperature-dependent studies of interface-trap buildup that shows that hydrogen must be involved in the rate-limiting step of interface-trap formation [7,8]. Previous hole trapping models (see for example ref. 12) do not involve hydrogen in the rate-limiting step of interface-trap buildup. The rate limiting step in these models is based on the hole transport and trapping at the SiO_2/Si interface where Si-H bonds are broken.

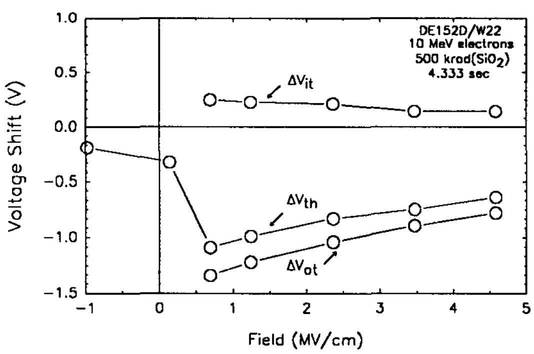

Figure 3: ΔV_{ot}, ΔV_{it}, and ΔV_{th} for n-channel transistors irradiated to 500 krad(SiO_2) with 10 MeV electrons versus electric field.

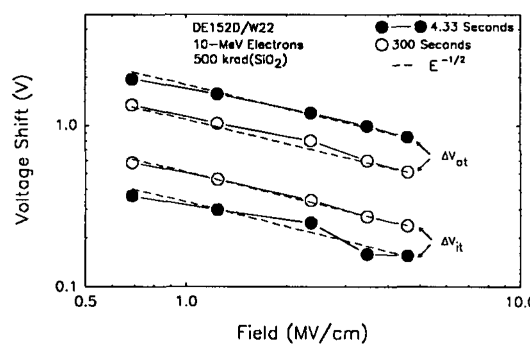

Figure 4: ΔV_{ot} and ΔV_{it} adjusted for charge yield as a function of electric field using the data of Figure 3. Also shown is data at 300 s. The dashed lines show a field dependence of $E^{-1/2}$.

We suggest that the data of Figs 1-4 and previous work on interface-trap buildup in Si-gate are consistent with a hybrid model that depends on hole trapping (and/or neutralization) processes to liberate the protons that subsequently drift to the interface and form interface traps. The number of interface traps in this model is determined by the number of protons released during hole capture (or neutralization) events. This is likely to occur within 10 nm of the interface [15]. Because the number of holes trapped scales with $E^{-1/2}$ (after recombination effects are accounted for), the $E^{-1/2}$ dependence of interface-trap buildup is naturally explained. Moreover, such a model is consistent with previous observations that, under positive bias, the protons that lead to the interface-trap buildup are predominantly released near the Si/SiO_2 interface [16,17], as well as work that relates interface-trap buildup to hole trapping or neutralization [16,18-20]. Further, depending on the way in which the hydrogen is incorporated into the oxide, e. g., its concentration, temperature, etc., either the proton drift or hydrogen release to the interface and subsequent interaction may be the rate limiting step in interface-trap formation.

In the full paper, we will discuss the hybrid hole-trapping/proton-drift model in more detail. We will show that the model is consistent with previous bias switching experiments performed on similar devices [3]. Finally, we will compare these results with similar experiments performed on metal gate transistors. We feel that the proposed model of interface-trap formation in Si-gate devices can reconcile many of the existing discrepancies in the interpretation of previous experiments, and should lead to increased insight into the roles of hole trapping and proton drift in the interface-trap buildup in Si-gate devices.

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