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ENHANCED LOW-RATE RADIATION-INDUCED CHARGE TRAPPING AT THE EMITTER-BASE/OXIDE INTERFACE OF BIPOLAR DEVICES

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The critical gate-SiO_2 to Si interface of advanced MOS devices is passivated by a thin (< 12 nm) high-quality oxide. The electric fields that influence radiation induced charge trapping and annealing in these gate oxides are greater than 1 MV/cm and are vertical with respect to the interface. In contrast, the most critical interface for many advanced bipolar or BiCMOS devices is that between the surface of the emitter-base junction and the overlying base oxide that passivates it. These base oxides often are 500-1000 nm thick, and are usually of low quality due to damage caused by base implantation and high-temperature emitter drive-in annealing [1-3]. Moreover, the electric field in these insulators during device operation is primarily due to the emitter-base fringing field (typically << 0.1 MV/cm).

The performance, reliability, and radiation hardness of modern bipolar/BiCMOS devices and IC's is limited by changes in surface recombination velocity and surface potential due to oxide-trap charge in the base oxide and near-midgap interface traps at the emitter-base/oxide interface [3-5]. While the defects that control the charge trapping in these bipolar base oxides are familiar from MOS transistor and capacitor studies, defect growth and annealing rates can be qualitatively different in bipolar IC applications than in traditional MOS IC applications [1,3]. One surprising effect in many bipolar devices that is not observed in MOS devices is an *enhanced* buildup of net positive oxide-trap charge, ΔN_{ot}, with decreasing radiation dose rate, in contrast to the decrease in radiation-induced charge with decreasing dose rate observed in MOS gate (and parasitic field) oxides [1-5]. This increase is often accompanied by a dramatic increase in interface-trap density, ΔN_{it}, at lower dose rates that cannot be predicted from higher-rate irradiation and annealing. This is a significant problem for predicting the response of linear bipolar devices and ICs in the space environment, and the origin of these effects is a topic of great controversy [1-3].

To obtain insight into these charge trapping processes, we have performed thermally-stimulated-current (TSC) and capacitance-voltage (C-V) measurements as functions of bias, dose rate, and temperature during irradiation on bipolar base oxides built in a development version of Analog Devices' RF25 process [6]. Its base oxide is grown by a 600 nm wet thermal process. During processing, it sees base ionimplantation and high-temperature annealing steps, making it quite susceptible to radiation-induced charge [1]. 1-MHz C-V measurements were performed using the method of Winokur et al. [7]. The midgap voltage shift is proportional to the net oxide-trap charge density, and the C-V stretchout is proportional to interface-trap density in these devices [7]. Switched-bias irradiation, high-temperature annealing, and C-V hysteresis tests confirm that interface traps cause most of the stretchout in these devices, and not border traps or charge lateral nonuniformities [8-10]. TSC measurements were also performed on the RF25 capacitors [11,12]. For the biases used here, combined TSC and C-V measurements allow separation of trapped hole and electron contributions to the net oxide-trap charge density [11,12] for the RF25 capacitors.

Figure 1 shows flatband voltage shifts (ΔV_{fb}) and components due to midgap voltage shifts and the flatband-to-midgap stretchout (ΔV_{mg} and ΔV_{so}) from C-V measurements on RF25 base oxides as functions of radiation dose rate. The ΔV_{mg} and ΔV_{so} curves show that both the net-oxide and interface-trap charge increase dramatically with decreasing dose rate. Figure 2 shows TSC results for RF25 base oxides irradiated at 320 and 0.83 rad(SiO_2)/s. At large negative bias, TSC measures the total radiation-induced trapped positive charge emitted and transported across the oxide [11,12]. Despite the very different *net* oxide-trap charge densities for the two dose rates in Fig. 1, the TSC is nearly identical in the two cases in Fig. 2! Hence, the large decrease in net oxide-trap charge at high rates in Fig. 1 is not due to a large decrease in total trapped positive charge density. Instead, it is caused by a difference in trapped electron densities at high and low rates.

Integrating the TSC in Fig. 2, we find ~ 2.5 x 10^{12} cm^{-2} holes trapped after either 320 or 0.83 rad(SiO_2)/s irradiation. The net oxide-trap charge density is ~ 1.7 x 10^{11} cm^{-2} for the high rate case, and ~ 4.6 x 10^{11} cm^{-2} in the low-rate case (Fig. 1). This implies ~ 93 % of the positive charge is compensated by trapped electrons at high dose rates, and ~ 82 % is compensated at low rates.

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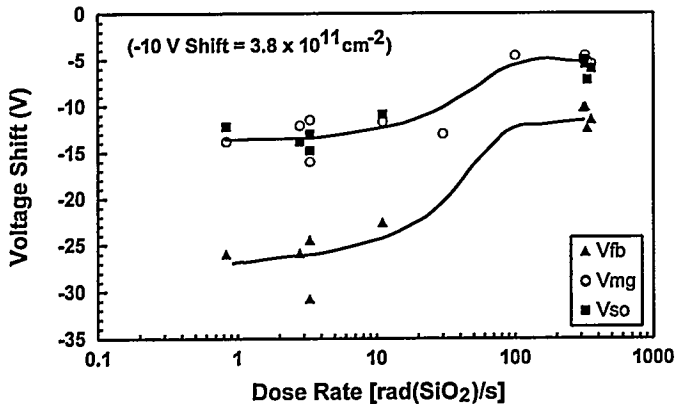

Figure 1. ΔV_{fb}, ΔV_{mg}, and ΔV_{so} vs. dose rate for RF25 base oxides on p substrates. Devices were irradiated at room temperature with 10-keV x rays at 0 V to 200 krad(SiO_2). A conversion from voltage shift to trap density is provided for estimates of net oxide-trap and interface-trap charge density from ΔV_{mg} and ΔV_{so}, respectively.

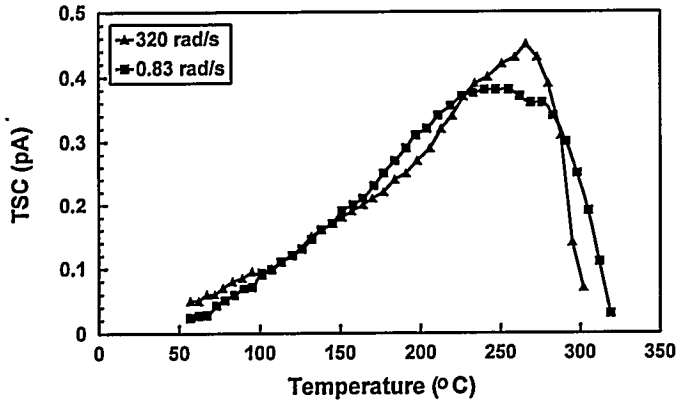

Figure 2. TSC corrected for background leakage for RF25 base oxides irradiated to 200 krad(SiO_2) with 10-keV x rays at 0 V at 25°C. The TSC ramp rate was ~ 7°C/min and the TSC bias was -60 V [11].

Thus, most trapped positive charge is compensated by electron trapping in each case. But the relatively *small* difference in trapped electron density leads to a *large* difference in ΔN_{ot}.

Similar trends for ΔN_{ot} and ΔN_{it} were observed with increasing temperature during 10-keV x-ray irradiation (22 to 125°C) as with decreasing dose rate, as we will show at the SISC. That is, an *increase* in ΔN_{ot} is observed for increasing irradiation temperature for these bipolar base oxides, in contrast to the *decrease* in net oxide charge with increasing irradiation temperature due to thermal annealing that is typically observed in MOS devices [13]. A significant increase in ΔN_{it} with increasing irradiation temperature is also observed.

At the SISC, we will present a physical model for these results, which emphasizes the importance of metastable hole trapping at E_δ' centers [1,14,15], compensating electron trapping [8-12,14,16], and retarded proton drift [10] in the bulk of these soft oxides irradiated at low electric fields combine to account for the surprising results of Figs. 1 and 2. We will also discuss the potential implications of these results not only for radiation induced charge trapping in bipolar devices, but for bulk and SOI MOS devices as well.

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