Comparison of NTBI and Irradiation Induced Interface States

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***Abstract*—The generation of interface states created by depassivating dangling bonds at the interface between the gate dielectric and silicon substrate is important for both the growth of Negative Bias Temperature Instability threshold voltage shift in MOSFETs and the radiation sensitivity of the devices. In this paper we present results comparing the generation of interface states for both processes and their possible annealing at high temperatures.**

***Keywords*—NBTI, reliability, interface states**

I. Introduction

As microelectronic technology has continued to decrease the size of devices while simultaneously increasing the number in processors, the circuit reliability measured in mean service lifetime has decreased and is expected to continue to decrease [1]. Devices for space based applications continue to be susceptible to radiation effects, but the primary driver of decreased device lifetime is expected to become the microelectronic reliability of the devices. Furthermore, there has been much conjecture by the radiation effects community as to whether or not some synergistic effect may exist. In this case radiation effects, when coupled with such degradation mechanisms as those common in electronic reliability, may produce an enhanced combined effect. In any event, the combined device lifetime is definitely expected to drop below the minimum acceptable lifetime of 10 to 15 years for space and aviation applications. It is therefore necessary to improve our understanding of the basic failure mechanisms in order to develop high level modeling which, based on accelerated measurements, can accurately predict the device behavior over years of standard operation.

The work presented here focuses on Negative Bias Temperature Instability (NBTI), which is known to be one of the primary drivers of decreased device reliability in p-channel metal-oxide-semiconductor field effect transistors (PMOS) [2]. NBTI is comprised of multiple components [3, 4], some "permanent" and others recoverable. A better physical understanding of the "permanent" term (defined for these purposes as long lived on an experimental time scale (10000 s) is necessary to enable modeling of the effect of those components on circuit reliability. The permanent components [4-6] appear to partly consist of switching traps, referred to as field recoverable charge in which a trapped hole doesn't discharge but can be compensated under positive bias by a trapped electron. A second permanent component is generally linked to the de-passivation of Si-H bonds at the substrate/ gate insulator interface. Interface states arise from the dangling silicon bonds, though deep traps in the oxide may exist as well and behave as permanent trapped charge. In this report we will analyze the measured permanent component as a function of temperature and show that recovery of the interface states due to reverse reactions increases with increasing temperature. The NBTI data will be compared to similar results for the "prompt" interface state generation resulting from ionizing radiation [7, 8] with low accumulated total doses.

In both NBTI and radiation experiments, there is long lived trapped charge identified with interface states (IS). Usually, radiation induced IS are explained [8] by the breaking of Si-H bonds at the passivated interface via a complex sequence of reactions. In this sequence electron-hole pairs are generated in a radiation cascade leading to positively charged oxygen vacancies via a trapping interaction. This charged defect can then interact with molecular hydrogen releasing a proton. The proton then drifts/diffuses to the interface where it interacts with the passivated dangling bond, breaking the bond and resulting in a charged IS and some hydrogenic species. A similar process is assumed to be active in NBTI except that the source of the holes is different. In NBTI, the holes tunnel into the existing defect from the inversion layer in the silicon substrate to begin the process. The dominant mechanism ultimately giving rise to interface states has not been evidenced yet.

II. Experiment

Utilizing the experimental protocol we developed previously [4], measurements were made of the interface state contribution to the threshold voltage using a Keithley Instruments Inc. 4200-SCS Semiconductor Characterization System. To a good approximation [4], this experimental protocol enables extraction of the different components contributing to the NBTI induced threshold voltage shift including the isolation of the interface state component. The PMOS devices studied were 130 nm channel length by 5 μm channel width with 3.4 nm thick oxy-nitride gate insulators. They were heated to various temperatures and the interface component of NBTI was measured using an AC pulsed technique [4] for a stressing gate bias -3.25 V, a pulse repetition frequency of 10 kHz, and the duty cycle of 0.10. Full details of the measurement methodology and approximations can be found elsewhere [4, 6].

III. Analysis

In order to interpret the results presented in the next section, we will assume a simplified model for charged

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interface creation which basically allows the number of charged interface states, N^+, at any time to be expressed in terms of a first order rate equation,

$$\frac{dN^+}{dt} = \sigma_f(N^0 - N^+) - \sigma_r(N^+) \qquad (1)$$

where N^0 is the total density of passivated bonds, N^+ is the density of interface states, and σ_f is a forward reaction cross section, σ_r is an annihilation reaction which may consist of multiple terms. The annihilation reaction is not necessarily simply the reverse of the forward one chemically, and has yet to be fully identified [8], but it must involve re-passivation of the dangling bond. Again reiterating that this mathematical approach is an oversimplification of the physical reality which may involve a sequence of reactions/interactions the interface state density at any time, t, is

$$N^+(t) = \frac{\sigma_f}{\sigma_f+\sigma_r} N^0(1 - e^{-(\sigma_f+\sigma_r)t}) \qquad (2)$$

One sees immediately that inclusion of a recovery term, σ_r, results in a saturation of the time dependent growth curve which is lower than for the case where there is no recovery. If the recovery is much slower than the creation this can be approximated as

$$N^+(t) \approx N^0(1 - e^{-\sigma_f t}). \qquad (3)$$

IV. Results

The interface state component of the NBTI induced threshold voltage shift after 100 s of stress time for temperatures between 50 and 180°C is shown in Fig. 1 as a function of temperature. We note that the threshold voltage shift $\Delta V_{th}(IS) = qN^+t_{ox}/\varepsilon$. and that it increases with increasing temperature suggesting a thermally activated process : $\sigma_f = \sigma_{f0}\, e^{-E_f/kT}$. This means

$$\Delta V_{th}(IS) = V^0\left(1 - e^{-\left[\sigma_{f0}\, e^{-(E_f/kT)}\right]t}\right). \qquad (4)$$

where $V^0 = qN^0t_{ox}/\varepsilon$. By fitting the temperature dependence of the threshold voltage shift due to interface states after 100 s of stress for temperatures between 50 and 180°C using Eq. 4, we can extract an activation energy of 0.30 eV. (The fit is shown as the solid curve in Fig. 1.) This is in reasonable agreement with the energy for de-passivation of a silicon hydrogen bond by a proton of 0.2 eV predicted by calculation [9]. Based on the fitting, there seems to be no significant recovery of the interface states at these temperatures.

The charged interface state density in arbitrary units can then be plotted on a natural log scale as a function of the inverse temperature and compared to a corresponding experimental result for irradiation reported in [7, 8]. The two results are shown in Fig. 2. The slopes and, thus, the relative activation energies are close (0.28 eV for NBTI and 0.23 eV for radiation) bearing in mind the limited number of data points available in each case. This approach gives an activation energy similar to the result from Eq. 4, but both do not allow for a recovery reaction.

At higher temperatures, the dependence on temperature of the interface state component of NBTI changes. As can be seen in Fig. 3, there seems to be a decrease in the slope at the higher temperatures we were able to reach and an eventual turn

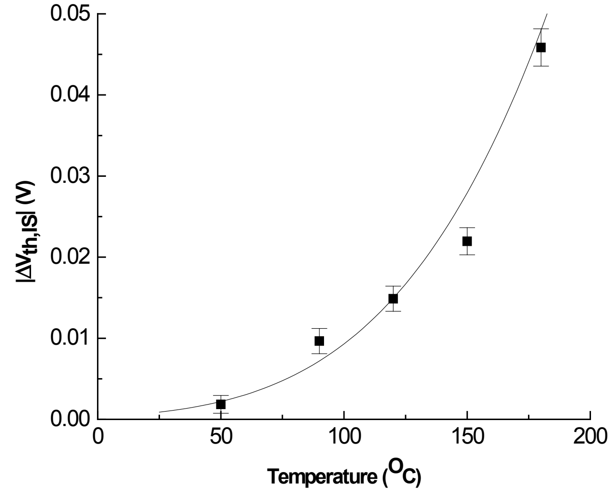

Fig. 1. The magnitude of the interface state component of the threshold voltage shift after 100 s of stress as a function of device temperature. The error bars are based on the scatter in the measurement. The solid line is a fit assuming the reverse reaction is negligible.

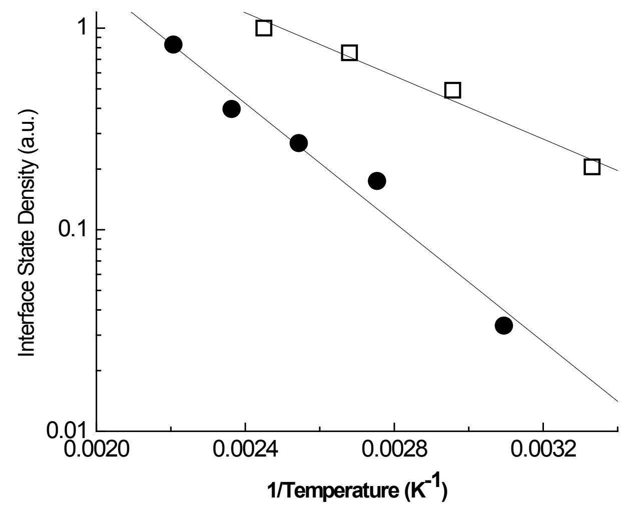

Fig. 2. The interface state density as a function of inverse absolute temperature for interface states created by NBTI (●) and irradiation(□) [7, 8].

around, whilst the fitting using Eq. 3 continues to grow. A similar behavior is observed in the experimental results for radiation induced interface states reported in reference [7, 8] and shown in Fig. 4 and including our data from Fig. 3. Bearing in mind the approximations used to generate Eq. 2 the observed decrease in the NBTI data decrease can be fitted using similar substitutions to those in Eq. 4. Assuming that the forward process cross section and activation energies are defined by the fit at low temperatures and the recovery has a distinct cross section and activation energy compared to the forward reaction : $\sigma_r = \sigma_{r0}\, e^{-E_r/kT}$. This fitting is shown as the dashed line in Fig. 3 and results in a crude estimate of the recovery activation energy of 1.2 eV. This is again in good agreement with the predicted re-passivation energy of 1.3 eV [9].

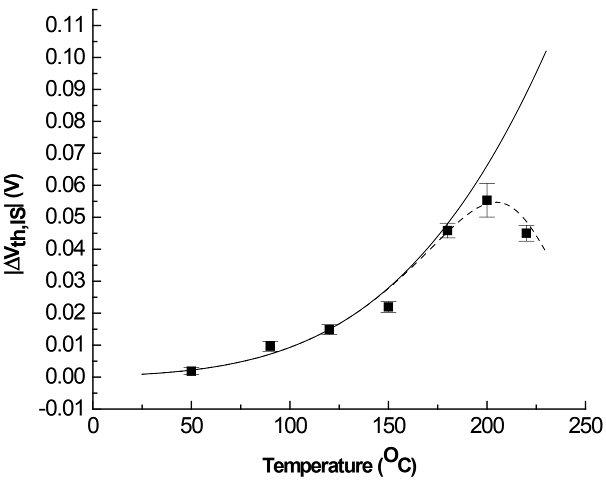

Fig. 3. The magnitude of the interface state component of the threshold voltage shift after 100 s of stress as a function of device temperature including higher temperatures. The error bars are based on the scatter in the measurement. The solid line is a fit assuming the reverse reaction is negligible, whilst the dashed curve is a fit assuming a reverse reaction whose effect is only measureable at high temperatures.

Due to the device failures at higher temperatures we were unable to measure the NBTI induced threshold voltage shift with reasonable confidence at temperatures in excess of 220 °C. Thus, it is difficult to clearly say for certain that the interface state term has reached a maximum at 200 °C but it is clear that a roll over has occurred indicating that indeed the reverse reaction has become active and in fact, dominant.

Based on the fitting it is possible to predict the time required at various temperatures for the reverse reaction to become significant. At 100 °C the reverse reaction will lower the threshold voltage shift caused by a gate-source bias stress voltage of $V_{gs} = -3.25$ V by less than 5% compared to the result ignoring the reverse reaction after 100000 s (~ 28 hours). In contrast, at 200 °C for the same V_{gs} value there is a 22 % difference after only 100 s.

The radiation induced interface state behavior reported in reference [7, 8] and plotted in Fig. 4 shows a peak in generation at ~ 130 °C whereas the NBTI induced interface states peak at ~ 200 °C. According to reference [8], the position of the peak depends upon the concentration of H2 in the dielectric as shown in Fig. 5. On this basis we assume the concentration in our devices is lower than for the irradiated devices shown in Fig. 4. There seems to be no doubt that radiation and NBTI induced interface state generation results from similar mechanisms requiring proton generation through hole trapping. The “reverse” reaction annihilation term whose onset occurs at higher temperature consistent with a higher activation energy also appears similar in the radiation and NBTI cases. These observations would suggest that if both radiation and NBTI were present simultaneously there would be a competition for the same available interface state pre-

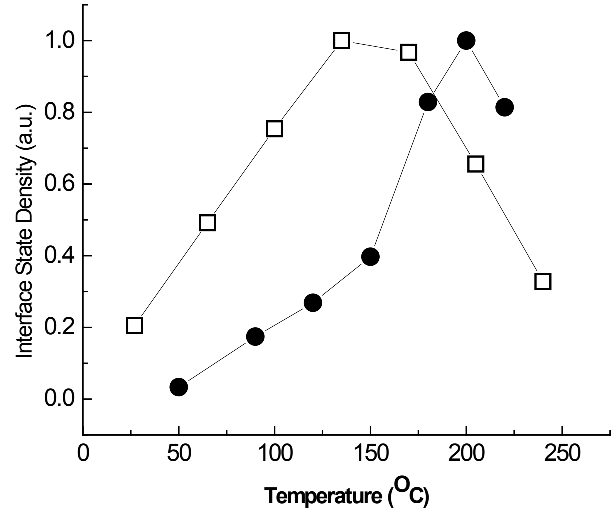

Fig. 4. The interface state density as a function of temperature showing apparent recovery for interface states created by NBTI (●) and irradiation (□) [7, 8].

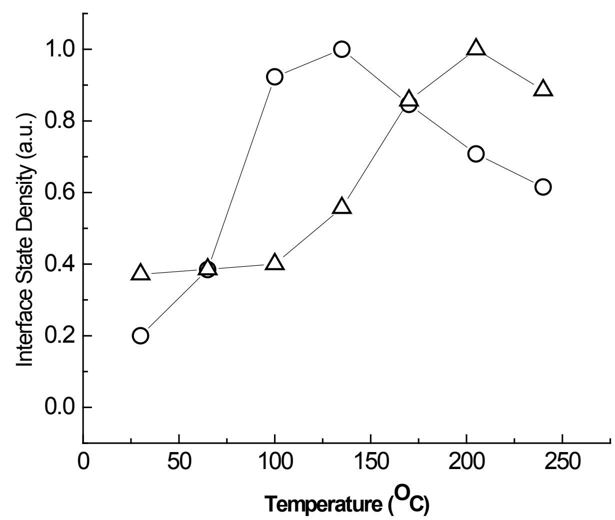

Fig. 5. The normalized interface state density as a function of temperature showing apparent recovery for interface states created by irradiation according to Hughart [5]. The simulated effect of changing the initial density of molecular hydrogen [5] is shown by comparing the results for densities of 5×10^{15} cm^{-3} (△) and 5×10^{17} cm^{-3} (○) resulting in peak temperatures of 200 °C and 125 °C, respectively.

cursors. Therefore the states would be generated faster but not in overall larger numbers. It is therefore hard to see a physical mechanism which would lead to true synergy.

One interesting contrast between radiation effects at low doses and NBTI is that the application of a negative gate bias decreases the generation of IS by radiation as compared to the positive bias case, but such a negative gate bias is required for NBTI. While a full understanding of the physical mechanism for IS is needed to comprehensively explain this contrast, the answer may be that NBTI is already partially depressed by the field. In the radiation case there are so many holes present in the oxide that the primary effect of a negative gate bias is on the mechanism which turns holes into charged interface states. In contrast the primary effect of increasing the negative gate bias in NBTI is to increase the number of holes present in the oxide, this additional field might slow the physical mechanism down, but the net effect is to increase IS generation.

V. CONCLUSIONS

The results reported here suggest the activation energy for interface state creation at low temperatures (< 180 °C) ~ 0.3 eV both for radiation and NBTI. Above 180 °C there is experimental evidence for the onset of a re-passivation of the interface states created by both by irradiation and by NBTI for high temperatures. The activation energy for re-passivation is approximately 1.2 eV, consistent with theory. Generation/annihilation mechanisms for radiation induced and NBTI induced interface states are clearly similar. The re-passivation reaction and its strong dependence on temperature suggest potential issues with accelerated testing at very high temperatures.

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