OBSERVATION OF H^+ MOTION DURING INTERFACE TRAP FORMATION

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ABSTRACT

Changes in MOSFET threshold voltage V_{th} and number of interface traps N_{it} have been measured in the same sample as a function of time following pulsed irradiation. When the gate bias during irradiation V_{gI} is positive, the initial $|\Delta V_{th}|$ is large due to trapping of radiation-induced holes at the Si-SiO_2 interface, and the post-irradiation time dependence of ΔV_{th} is dominated by hole de-trapping as expected. On the other hand, when V_{gI} is negative, interfacial hole trapping is minimized. In this case, an unusual peak in the ΔV_{th} vs. time curve provides striking new evidence of the involvement of H^+ ions in the N_{it} formation process.

I. INTRODUCTION

Despite many years of research, the mechanism(s) whereby interface traps N_{it} are created by ionizing radiation in MOS devices remains controversial. In all models, the process begins by the production of electron-hole pairs in the oxide by ionizing radiation. In many models, called here "trapped hole" models, the holes then drift to the Si-SiO_2 interface. Some holes are trapped near the interface and are subsequently converted to interface traps N_{it} [1-5]. The important features in common to all "trapped hole" models are that the holes are trapped near the interface, and that subsequent conversion to N_{it} is the rate-limiting step in the N_{it} formation process. Hole transport through the oxide cannot itself be rate-limiting since it is much faster than the (relatively slow) N_{it} formation [6].

In an alternative model based upon hydrogen chemistry [7-9], radiation-induced holes react in the oxide to produce hydrogen ions. The H^+ then drifts through the oxide to the Si-SiO_2 interface. Once at the interface, the H^+ reacts with Si-H trap precursors and electrons from the substrate to produce silicon dangling bonds (the interface traps) and neutral H_2 [9]. In this model, the rate-limiting step is H^+ drift through the oxide. Considerable, if circumstantial, evidence exists that hydrogen is somehow involved in the trap formation process [10-14].

There is considerable experimental evidence in support of both models, and unfortunately much of this data appears contradictory. These issues have been reviewed elsewhere [15-16].

In this work, we investigate in detail the time dependence of changes in the oxide trapped charge Q_{ot} during interface trap formation. Our goal was to develop new data to differentiate between the H^+ and trapped hole models. Since both models involve motion and/or annihilation of charged species (holes or H^+) in the oxide, changes in Q_{ot} should affect the MOSFET threshold voltage V_{th} *on the same time scale as the N_{it} build-up.* However, to our knowledge, no such correlation has ever been explicitly reported. In some cases, the time dependencies of N_{it} and V_{th} were reported, but no correlation was established [14,17]. Instead, most reported time-dependent changes in V_{th} appear to be dominated by hole de-trapping. Since the change in V_{th} due to N_{it} formation is a relatively small effect, the large background of hole de-trapping makes it difficult to resolve.

In this work, we report the first observation of time-dependent changes in V_{th} which are unambiguously linked with N_{it} formation. We will show that this behavior is readily explained by the hydrogen model. In order to observe the effect, we have employed two techniques to minimize the problem discussed above. First, MOS devices with high hydrogen concentration were used to increase the number of interface traps formed. Second, the samples were irradiated with negative gate bias in order to minimize hole trapping at the Si-SiO_2 interface and subsequent de-trapping.

II. EXPERIMENTAL DETAILS

The samples are p-channel MOSFETs with polysilicon gates from several different process lots fabricated at NRL. P-channel devices are used to minimize post-irradiation field oxide edge leakage. PMOS1/3 samples have a 42 nm thick oxide grown in O_2 at 900°C. For PMOS5/12 samples, the wet gate oxide was grown 100 nm thick at 900°C and etched back to 48 nm in buffered HF (this procedure was performed for a different experiment). This sample was then annealed in 33% H_2 in N_2 at 900°C for 1 hr. PMOS6 samples have 35 nm oxides grown in oxygen at 900°C. One wafer (PMOS6/4B) was annealed in pure H_2 at 900°C for 1/2 hr after oxidation. This procedure [18,14] dramatically increases the number of radiation-induced interface traps with relatively small effect on

Q_{ot}. Initial trap densities D_{it} were about 1 x 10^{10} traps/cm^2-eV (±40%) in all samples.

The samples were irradiated to 20-40 krad(SiO_2) with 25-40 MeV electrons at the NRL LINAC using a short 1.5 μs radiation pulse. Results presented here are normalized to 20 krad dose to facilitate sample-to-sample comparisons (at these low doses, changes in N_{it} and Q_{ot} are linear with dose in these samples). Experimental gate biases V_g were adjusted for the different oxide thicknesses to achieve oxide fields of ±2 MV/cm. D_{it} was measured as a function of time following the radiation pulse using charge pumping with a 1 MHz triangular waveform [19,8] on 100/10 μm (width/length) MOSFETs . Resulting D_{it} values are an average over approximately the central 0.6 eV of the silicon band-gap. The samples were kept in a flowing nitrogen ambient to eliminate the effects of post-irradiation hydrogen exposure [13], which otherwise caused uncontrollable time-dependent increases in N_{it}.

Threshold voltage shifts ΔV_{th} were measured from the change in MOSFET source current I_S with V_{drain}= -100 mV. V_g was set such that I_S was in the sub-threshold region at 1-10 x 10^{-8} A (the smallest possible value of I_S, consistent with obtaining an accurate, noise-free measurement in the short time allowed, was used). Our use of the term "V_{th}" is somewhat arbitrary here, since V_{th} determined in this way is typically 100-200 mV smaller than the usual value of V_{th} obtained by extrapolation of the linear MOSFET I_S-V_g characteristic. Both I_S and I_{cp} were determined *in the same MOSFET* during separate 20 ms intervals every 250 ms; for the rest of the time, a constant "dc" bias was applied to the gate. (Application of the measurement signals for short 20 ms intervals does not materially affect the N_{it} build-up [19]). The sample temperature was stabilized within ±1°C to prevent temperature dependent variations in V_{th}.

In this measurement of ΔV_{th}, which was chosen for its simplicity, speed, and compatibility with measurement of I_{cp}, the measured quantity is actually I_S vs. time. To obtain ΔV_{th}, we use the fact that I_S depends exponentially on V_g in the subthreshold region and calculate the (time-dependent) gate voltage required to maintain a constant I_S, assuming that the subthreshold slope S does not change after irradiation. Of course, this assumption is not generally correct. Large increases in N_{it} cause a decrease in S. (Surface mobility μ_p, which also affects I_S, did not change significantly at these relatively low doses.) To minimize changes in S, the total dose was kept small and S was determined pre- and post-rad to insure that these changes did not significantly affect the ΔV_{th} calculations. In the worst case, we estimate that this effect causes about 10% error in ΔV_{th}. (These errors are relatively small for the case of switched bias, where, due to the minimal hole trapping, the change in I_S is only a factor of 2-3). In order to determine Q_{ot}, the mid-gap shift ΔV_{mg} is required rather than ΔV_{th}, since ΔV_{th} includes a contribution from charge in the interface traps [20,21]. ΔV_{mg} was calculated from ΔV_{th} by extrapolating to the calculated mid-gap value of I_S using the subthreshold slope. In this calculation, the interface trap charge is taken into account using the time-varying value of D_{it} measured *independently* using charge pumping. Rather than using the above technique to determine V_{mg}, it would have been preferable to measure the entire MOSFET I_S-V_g characteristic, but this was not possible in these experiments due to equipment constraints and the very limited time available for the measurements.

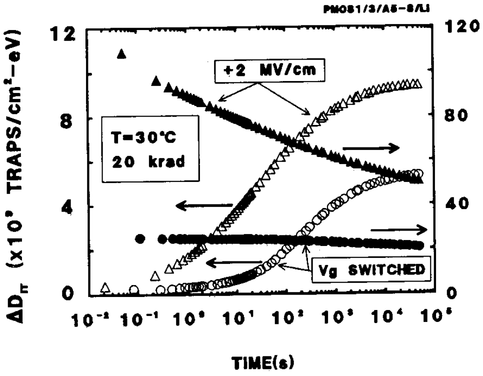


Fig. 1 ΔD_{it} and ΔV_{th} for two non-annealed MOSFETs with constant Eox (+2 MV/cm), or switched E_{ox} (-2MV/cm at t≤10 ms, +2 MV/cm at t>10 ms).

III. EXPERIMENTAL RESULTS and DISCUSSION

A. Non-hydrogen annealed samples

Typical experimental results for normal samples *not* annealed in hydrogen are shown in Fig. 1. These 42 nm oxide MOSFETs were irradiated with two different gate bias conditions V_g: Bias case (a): constant positive V_g = +8.4 V (+2 MV/cm, triangle symbols), and case (b): V_g= -8.4V for times ≤10 ms, switched to +8.4V after 10 ms (circle symbols). (All ΔD_{it} data here for the all-positive V_g cases are shown after subtraction of the small constant "early" component to show just the slow build-up [19].) The D_{it} build-up in both bias cases is quite slow, occurring between 10^{-2} to 10^4 s, with saturation at long times, in agreement with previous results [7,19]. Note that a very large number of interface traps are formed in the switched bias case, showing that transport of radiation-induced holes through the Si-SiO_2 interface is not required to obtain significant interface trap formation. (The reduction in the magnitude of ΔD_{it} in the switched case is addressed below.)

Threshold voltage shifts for these two gate bias cases are also shown in Fig. 1. First, for all-positive V_g, significant V_{th} annealing takes place, approximately as $\Delta V_{th} \propto$ log(time). Qualitatively similar behavior has been widely observed previously [22,23], which has been ascribed to de-trapping of radiation-induced holes trapped close to the Si-SiO_2 interface [22-25]. The deviation from straight line log(time) behavior at long times suggests that the trap density decreases with distance from the Si-SiO_2 interface. This is reasonable since the hole traps are believed to be concentrated at the interface [24]. Second, for the switched bias case, the ln(time) ΔV_{th} annealing behavior has almost completely disappeared. When the gate bias is negative during irradiation, the radiation-induced holes drift away from the Si-SiO_2 interface and exit the oxide at the gate. (The hole transport time, estimated at ≤ 1 μs for this oxide thickness at 295 K [26], is much shorter than the 10 ms switch times.) Consequently, ΔV_{th} is much smaller (the small remaining shift is probably due to hole trapping in the bulk oxide) and does not show significant annealing. This result clearly demonstrates that the V_{th} annealing observed in the all-positive bias case is indeed due to hole de-trapping.

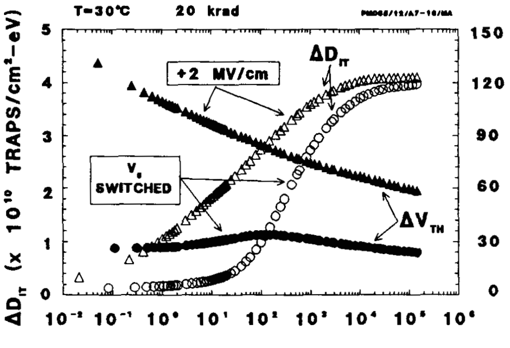


Fig. 2A ΔD_{it} and ΔV_{th} for two *hydrogen-annealed* MOSFETs with E_{ox} constant (+2 MV/cm) or switched (-/+2 MV/cm).

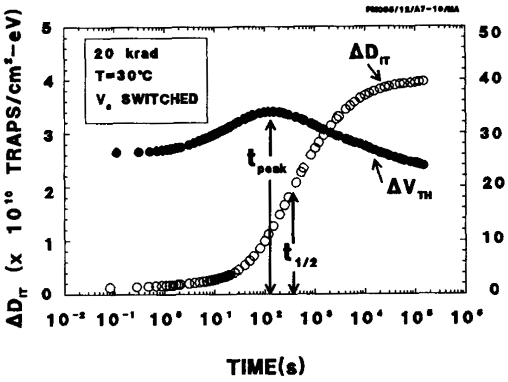


Fig. 2B ΔV_{th} (on magnified scale) and ΔD_{it} for switched bias sample from Fig. 2A showing definitions of t_{peak} and $t_{1/2}$.

B. Hydrogen annealed samples

The data in Fig. 1 do not, however, show any obvious correlation between the time dependencies of ΔV_{th} and ΔD_{it}, which is the goal of this work (see section C below). In order to improve the chances of observing such a correlation, some MOSFETs have been hydrogen annealed as discussed above. The time dependencies of changes in V_{th} and D_{it} after a short radiation pulse are shown for a typical annealed MOSFET in Fig. 2A. At 20 krad, the saturated ΔD_{it} is 4-7 times larger than the non-annealed MOSFET in Fig. 1, depending on bias during irradiation. The magnitudes of ΔV_{th} in Figs. 1 and 2A are comparable, but a small peak occurs in ΔV_{th} at time t_{peak} for the switched bias in Fig. 2A (ΔV_{th} from Fig. 2A is shown on a magnified scale in Fig. 2B to show the shape of the data more clearly). Although small in magnitude, this peak has been reproducibly observed on about 10 different hydrogen-annealed samples from two different process lots. This peak has not been observed previously. The peak is definitely not an artifact of the data analysis because the source current I_S undergoes a clear minimum at the same time (i.e., at t_{peak}). Note that t_{peak} and the interface trap formation time (characterized by $t_{1/2}$, the time required for formation of 1/2 the saturated ΔD_{it}) are similar. This suggests that the peak may be caused by the same process as the D_{it} formation.

To investigate whether the ΔV_{th} peak is caused by the same process as the D_{it} formation, the dependencies of the peak on temperature, applied gate bias, and magnitude of ΔD_{it} have been determined. As shown in Fig. 3, the time scales for both the D_{it} build-up and the ΔV_{th} peak are strongly temperature activated, with a similar activation energy of about 0.8 eV, in good agreement with previous measurements of the D_{it} build-up [7,19]. Next, the dependencies of t_{peak} and $t_{1/2}$ on the magnitude of the gate bias during the D_{it} build-

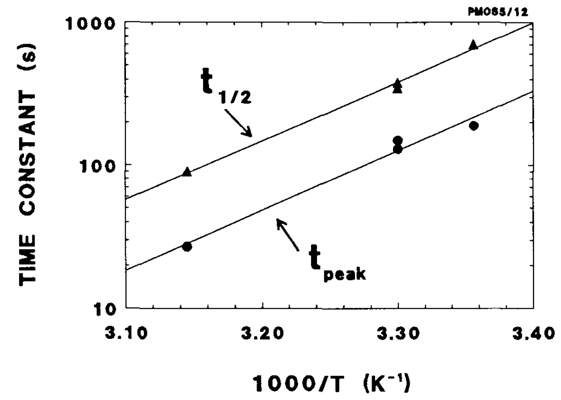


Fig. 3 Dependence of $t_{1/2}$ and t_{peak} on temperature. Both have about the same activation energy (≈0.8 eV). t_{peak} is consistently smaller.

up are shown in Fig. 4. (All samples were biased at -9.6V for the first 10 ms after irradiation, then switched to the variable positive bias.) Both t_{peak} and $t_{1/2}$ decrease rapidly as the bias increases, in good agreement with previous results where $t_{1/2}$ decreased as $E_{ox}^{-1.6}$ [8]. The field-dependent decrease is caused by faster motion of the hydrogen ions at higher oxide fields [7,19]. In both Figures 3 and 4, t_{peak} is consistently about a factor of 3 smaller than $t_{1/2}$. Finally, the magnitudes of the ΔV_{th} peak and the saturated ΔD_{it} have been compared using PMOS6 MOSFETs with the same oxide thickness and bias conditions (Fig. 5). Differences in the magnitude of saturated ΔD_{it} arise from either different total doses or different radiation sensitivities (two data points were obtained on non-hydrogen annealed samples--see below). The solid line is the best fit of a linear relationship to the data.

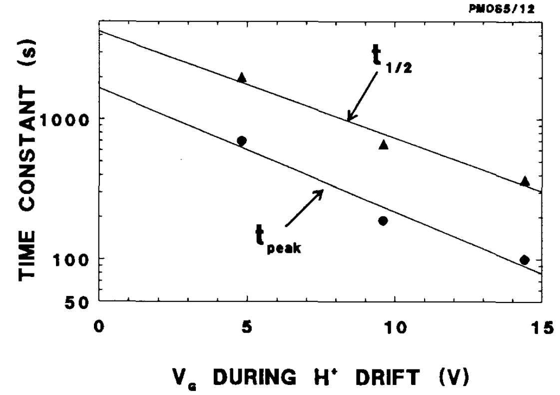


Fig. 4 Dependence of t_{peak} and $t_{1/2}$ on oxide field after switch to +2 MV/cm (switched bias). Changes in t_{peak} track changes in $t_{1/2}$.

The result is that the magnitude of the ΔV_{th} peak is linearly related to the magnitude of ΔD_{it}. Thus, the clear correlation between the ΔV_{th} peak and ΔD_{it} from Figures 3-5 strongly suggests that the ΔV_{th} peak arises from the same mechanism as the D_{it} build-up. Our explanation of the cause of the peak is given below.

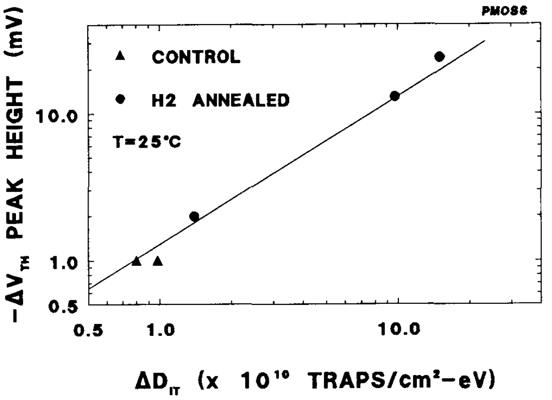


Fig.5 Magnitude of the ΔV_{th} peak height as a function of the saturated increase in ΔD_{it}. Solid line is a best fit of a straight line to the data.

C. ΔV_{th} peak in non-hydrogen annealed MOSFETs

One concern in the work presented thus far is that the ΔV_{th} peak may be a phenomenon associated only with hydrogen annealed oxides, and therefore is representative only of "abnormal" behavior. There is clear evidence that this is not the case. First, the annealed MOSFETs appear normal before irradiation [18]--that is, the hydrogen annealing does not affect the pre-irradiation electrical characteristics. Also, we have found that the normalized time, oxide field, and temperature dependencies of the D_{it} build-up are very similar in both types of oxides. Additional evidence comes from the ΔV_{th} data of the non-annealed MOSFETs. As shown in Fig. 6, which is the switched bias data from Fig. 1 on a magnified scale, close examination of the data strongly suggests the existence of a small ΔV_{th} peak even in a non-annealed sample [superimposed on weak ln(time) annealing behavior represented by the dashed line]. Note that the magnitude of this peak, and the time at which the peak occurs (t_{peak} ≈70 s, which is about a factor of 3 smaller than $t_{1/2}$ =200s) are consistent with the hydrogen-annealed results (see Fig. 5 to compare the magnitude data). Similar results are obtained on other non-annealed samples. These results make us confident that our model below, although derived from data on hydrogen annealed samples, is in fact applicable to "normal" samples. This is not unreasonable since "normal" MOS samples, although not intentionally hydrogen annealed, are typically exposed to hydrogen at high temperatures during fabrication [12].

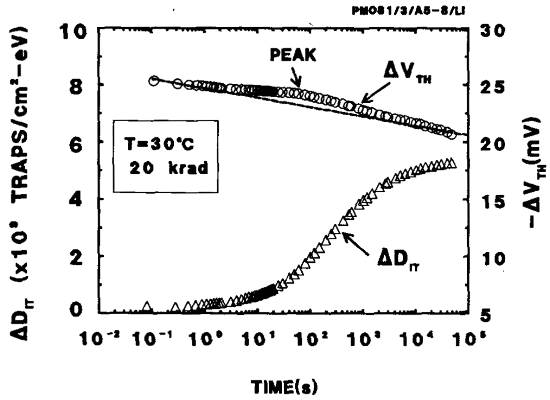
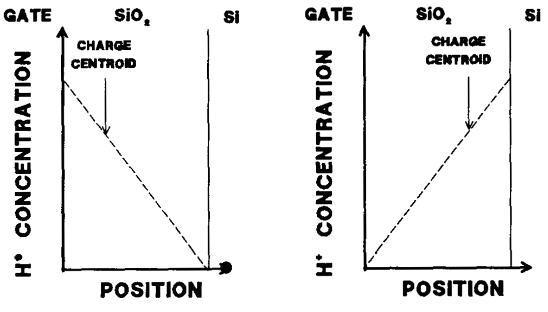


Fig. 6 ΔV_{th} vs. time for a *non-hydrogen annealed MOSFET* (data from Fig. 1 on magnified scale). Note small but apparent peak in ΔV_{th}.



A. $V_g<0$ B. $V_g>0$

Fig. 7 Idealized model of initial H^+ distributions immediately after irradiation [8]. Triangular distributions depend only on the sign of the gate bias during irradiation (see text).

IV. MODEL FOR THE ΔV_{th} PEAK

The question now arises *why* a peak is observed in ΔV_{th}. To this end, we employ a model based on H^+ transport developed previously [8-9]. In this model, the H^+ distributions immediately post-irradiation are triangular functions of position which depend only on the sign of the gate bias during irradiation V_{gI} [8,27] (see Fig. 7). These distributions result from the simple assumption of a uniform hydrogen distribution in the oxide *before* irradiation as described in detail in ref. [8]. For negative V_{gI}, the maximum H^+ concentration occurs near the gate [Fig. 7(A)], while for positive V_{gI}, the maximum H^+ is at the Si-SiO_2 interface [Fig. 7(B)]. With these initial distributions, the *normalized* D_{it} build-up takes longer for negative V_{gI} because the average H^+ ion must travel farther to reach the Si-SiO_2 interface.

Using the H^+ model together with these initial triangular H^+ distributions, a qualitative understanding of why a peak is observed in ΔV_{th} is quickly obtained. When V_{gI} is negative, the centroid of initial H^+ is close to the gate where their contribution to ΔV_{th} is relatively small. As time increases after V_g is switched positive, the H^+ drifts towards the Si-SiO_2 interface and the (absolute) magnitude of V_{th} increases. However, as the H^+ ions reach the interface, they are neutralized by electrons from the substrate (creating H^0, which in turn react to produce N_{it}), and no longer contribute to V_{th}. Therefore the magnitude of ΔV_{th} increases at short times and then decreases at long times, producing a peak. Note that the neutralization of the H^+ by substrate electrons is not an *ad hoc* hypothesis introduced here just to explain this peak, but rather is a fundamental part of the model required by the chemistry of the N_{it} formation process [9].

This H^+ model has been employed to obtain a *quantitative* prediction of ΔV_{mg} caused by the H^+ motion. An initial triangular H^+ distribution with the maximum at the gate (since V_{gI} is negative) is assumed as in Fig. 7A [8,28]. The H^+ drift is described by dispersive transport [7,28] which requires two fitting parameters: the D_{it} formation time constant $t_{1/2}$, and α, a parameter which describes the degree of "dispersiveness" (i.e., characterized by a wide variety of time constants) of the transport process ($0 \leq \alpha \leq 1$, where $\alpha=1$ is normal non-dispersive transport). These parameters are determined by fitting to the ΔD_{it} build-up *using just the switched bias data.* Results for a hydrogen annealed sample are shown in Fig. 8. Values of the fitting parameters determined from this data are $\alpha=0.38$ and $t_{1/2}=300$ s. These values are then used to predict ΔV_{mg} (for the switched bias case) and ΔD_{it} (for the all-positive bias case) as a function of time. As discussed above, V_{mg} is used rather than V_{th} because V_{mg} is generally assumed to have no contribution from charge in the interface traps [20,21]. The calculations take into account motion of the H^+ ions towards the gate during the short time of initial negative bias. This was found to be negligible for the short 1 ms switch time for the sample in Fig. 8. For previous samples where a 10 ms switch time was used (as in Figures 1, 2, and 6), the initial H^+ motion was found to be small but perhaps not negligible, which is the reason that a sample with the shorter 1 ms switch time was used for comparison to theory. The α value of 0.38 is reasonably close to previous values of 0.32 obtained by the same fitting procedure [8] and 0.3 obtained by McLean fitting to data obtained at an oxide field of +2 MV/cm [29]. In addition, the model gives a very accurate prediction of the normalized ΔD_{it} build-up for the all-positive bias case (Fig. 8), which was a main point of previous work [8].

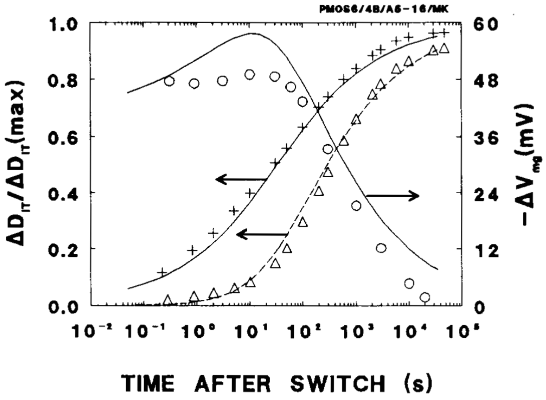


Fig. 8 Comparison of H^+ model (lines) with experimental data (symbols) from two hydrogen-annealed MOSFETs. Gate bias is +2 MV/cm (+ symbol) or switched (○,▵ symbols).

A comparison of predicted and experimental ΔV_{mg} is shown in Fig. 8. (The experimental ΔV_{th} has been corrected to mid-gap shift ΔV_{mg} as discussed above to account for the amount of charge in the interface traps, assuming neutrality at mid-gap.) The model predicts that a small peak exists in ΔV_{mg}. This peak occurs at about 12 s, as compared to the experimental peak at 10-30 s. Also, the model predicts that the time of the peak is significantly smaller than $t_{1/2}$. This is an important qualitative corroboration of the model, since t_{peak} is reproducibly smaller than $t_{1/2}$ for all MOSFETs measured (see Figs. 2-5). [For the sample in Fig. 8, t_{peak} (before correcting ΔV_{th} to mid-gap) occurs at 100s, as compared to $t_{1/2}$ = 280 s. The times at which the peaks occur in V_{mg} and V_{th} are not the same because correcting to mid-gap shift changes the shape of the V_{th} curve. Before correction, the V_{th} data for the sample in Fig. 8 is very similar to Fig. 2B, and it does not rapidly approach zero shift at long times.] Agreement between model and experiment for ΔV_{mg} at long times is also very good. Overall, agreement between the model and ΔV_{mg} data is impressive considering that only the switched bias ΔD_{it} data is used to obtain the two fitting parameters $t_{1/2}$ and α.

One aspect of the model which is not known is the (average) number of H^+ ions required to produce one interface trap. The model prediction in Fig. 8 was generated using a ratio of H^+ ions/ΔN_{it} of 0.7, obtained by a best fit to the experimental data, assuming that the total number of traps/cm^2 created equals the average ΔD_{it} times 1.1 eV (the silicon band-gap). (Note that this ratio affects the *magnitude* of the model's prediction but not the normalized time dependence.) This value of 0.7 is somewhat surprising in that the process of converting the H^+ ions to interface traps appears very efficient--that is, few ions are lost to other processes. For example, some H^+ ions could react in the oxide before reaching the Si-SiO$_2$ interface without creating an interface trap. Indeed, at first glance it appears difficult to explain how the H^+/N_{it} ratio could be less than 1.0, since this means that more than one trap is created by each H^+ ion. This difficulty is resolved by the amphoteric trap model [21], wherein two electrically active traps (one above mid-gap, one below) exist for each physical defect. Thus, the smallest possible H^+/N_{it} ratio should be 0.5. Using the "best fit" value here of 0.7, about 70% of the moving hydrogen appears to be ultimately involved in N_{it} production in these samples, which could of course be different in different oxides.

In Fig. 7, different *distributions* of H^+ ions are obtained depending on the sign of the gate bias during irradiation (V_{gI}), but the *total number* of H^+ ions is independent of the sign of V_{gI}. This leads to the prediction that the saturated magnitude of ΔD_{it} will not depend on the sign of V_{gI}, although the time dependence of ΔD_{it} will. This prediction is indeed in good agreement with experimental results on hydrogen annealed samples here (see Fig. 2) and on hydrogen annealed samples from Sandia National Laboratories in previous work (Fig. 5 in [8]). The triangular distributions shown in Fig. 7 result from the assumption that the *initial* hydrogen in the oxide is uniformly distributed. However, some evidence suggests that these triangular distributions are idealized approximations, especially for the non-hydrogen annealed samples. For example, the magnitudes of the saturated ΔD_{it} increases for the two bias conditions is not the same for non-annealed samples, as shown here in Fig. 1, and in Fig. 4 in [8]. These results suggest an excess hydrogen concentration near the Si-SiO$_2$ interface in non-annealed samples. In Fig. 1, 43% of the H^+ are in excess of the expected amount for the triangular distribution. This is also probably a contributing factor to the different α values of 0.38 in this work for a hydrogen-annealed sample vs. 0.32 found previously [8] for a non-annealed sample. We are currently investigating what effect a non-uniform distribution of initial hydrogen, perhaps with excess hydrogen at both oxide interfaces, would have on the D_{it} build-up and ΔV_{th} peak (to be published elsewhere).

A final issue in regard to Fig. 8 is the correction of the experimental threshold shift to mid-gap shift to remove the effect of charge in interface traps. This correction relies heavily on the assumption that the traps are neutral at mid-gap. Although there is considerable evidence that this is at least approximately correct [20,21], never-the-less the magnitude of the correction is large and has a major effect on the curve shape. In Fig. 8, the ΔV_{mg} peak occurs at 100 s with a magnitude of about 10 mV (the data is very similar to Fig. 2, although the absolute shift is somewhat larger). These values are changed substantially by the correction to ΔV_{mg}. Small errors in this correction--if, for example, the interface traps are neutral at a slight distance from mid-gap, can result in a large error in the calculated effect of the H^+ alone. Unfortunately, at present we see no way of improving the accuracy of this correction, or even testing its validity.

V. COMMENTS ON "TRAPPED HOLE" MODELS

A interesting question is whether the data presented above provides any new support or refutation of the trapped hole models. First, the simplest versions of this model such as that due to Hu and Johnson [2] cannot explain the existence of a ΔV_{th} peak, since simple hole annealing can only result in a reduction in the magnitude of ΔV_{th}. However, Wang *et al.* have proposed a considerably more complex version of the trapped hole model wherein there are two distinct types of trapped holes: "near-interfacial trapped holes", located 2-7 nm from the Si-SiO$_2$ interface, and "interfacial trapped holes", located within 1.8 nm of the interface [3]. In this model, the holes are first trapped at the relatively deeper "near-interfacial" traps, and over time may convert to "interfacial" trapped holes, which then capture an electron during conversion to interface traps. Using this model, 1.4×10^{10} holes/cm^2 would be trapped at 7 nm using the data in Fig. 2B (assuming trapping at 7 nm maximizes the predicted peak height). This is about 13% of all radiation-induced holes created in the first 7 nm of the oxide. Assuming that the transfer occurs from 7 to 1.8 nm, this model predicts a possible maximum 3 mV peak during transfer of the trapped holes, which is somewhat smaller than observed. In addition, the calculated 1.4×10^{10} trapped holes is too small to account for the total ΔN_{it} of 4.4×10^{10} traps/cm^2 ($=\Delta D_{it} \times 1.1$ eV) in Fig 2B. This model does successfully predict that a ΔV_{th} peak will occur, and that t_{peak} will be less than $t_{1/2}$. Unfortunately, the model is not sufficiently detailed to provide a numerical prediction of time dependence. A further objection is that this line of reasoning also appears to predict a much larger peak for the all-positive bias case (since there is much more hole trapping)--which is clearly not observed.

We also note that even qualitative examination of the ΔV_{th} data in Figs. 1 and 2 appears to give little support to the hole trapping models. First, for the all-positive-bias case, assuming that all hole trapping is at the Si-SiO$_2$ interface, the ratio of created interface traps to de-trapped holes is 0.41 for the non-annealed MOSFET in Fig. 1, and 1.4 for the annealed sample in Fig. 2 (positive bias data), as compared with a ratio of 1.0 as predicted by Hu and Johnson [2]. Why does the ratio vary, if not due to the hydrogen anneal? Second, there is clearly a major experimental dependence of ΔV_{th} on bias during irradiation, whereas the total number of interface traps formed differs by less than a factor of two (un-annealed sample), or are nearly identical (annealed sample), which is difficult to explain using the trapped hole models. Third, the *shape* of ΔV_{th} vs. time does not appear to reflect any variations in the time-dependence of D_{it} vs. time. In particular, at long times ΔD_{it} saturates, but ΔV_{th} does not saturate in either Figs. 1 or 2(A), although a reduction in slope is apparent. Finally, we note that Kenkare and Lyon [30], who are proponents of the trapped hole model, have recently investigated switched bias experiments. They concluded that these results can only be explained by an ion drift model, although they suggest that the ions are created at the oxide interfaces rather than uniformly in the bulk.

VI. SUMMARY AND CONCLUSIONS

In summary, we report the first observation of a peak in the time dependence of the threshold shift following pulsed irradiation. The time at which the peak occurs is approximately the same as for the N_{it} build-up. The dependence of this peak time is found to be identical to changes in the N_{it} build-up as temperature and gate oxide bias are varied. Also, the magnitude of the peak increases linearly with the magnitude of ΔN_{it}. These data firmly establish that the ΔV_{th} peak is caused by the same mechanism as the N_{it} build-up.

Two unusual experimental techniques have been used to observe the ΔV_{th} peak. First, to obtain sufficient sensitivity, these experiments were performed primarily on hydrogen annealed samples, but the behavior of non-annealed samples is qualitatively similar. Second, switched gate bias has been used to minimize hole de-trapping at the Si-SiO$_2$ interface, which otherwise dominates the ΔV_{th} results.

The hydrogen model, using initial triangular H^+ distributions and dispersive H^+ transport, *quantitative-*

ly predicts the time dependence of the ΔV_{th} peak. The model has no *ad hoc* assumptions or new fitting parameters, but rather is derived directly from previous concepts and parameter values. This result must be taken as very strong evidence supporting McLean's H^+ model. To date, this is the *only* model which is capable of quantitative predictions of the time dependence of the N_{it} build-up. Lastly, we have not been able to form a simple, reasonable explanation for the threshold voltage peak based on the alternative model of interfacial hole trapping.

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