Predicting Radiation Response from Process Parameters: Verification of a Physically Based Predictive Model

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Abstract

We evaluate the hole trapping response of twenty-two oxides subjected to twenty-two different sets of processing parameters. The oxides were prepared in three different facilities, the Harris Semiconductor-Intersil Palm Bay facility, the former Naval Research and Development Laboratory (NRAD) 4" facility, and the new SPAWAR 6" fabrication facility in San Diego, California. In twenty of the twenty-two cases, oxide hole trapping is almost completely determined by the highest processing temperature and is in reasonable agreement with a recently proposed physically based predictive model. We have also evaluated Si/SiO_2 interface trap (D_{it}) generation in a subset of four very simply processed oxides utilized in the hole trapping study. The D_{it} results are also in reasonable agreement with the recently proposed model.

Our results indicate that it is possible to make reasonably accurate predictions of radiation response from processing parameters and that such predictions can be made with our current understanding of radiation damage phenomena. (It should be emphasized that the current level of understanding is not yet complete. This work does not demonstrate that precise predictions involving all imaginable process parameters are possible.)

I. Introduction

Radiation damage is a complex process involving trapping of holes in the oxide, the generation of interface states at the Si/SiO_2 boundary, the tunneling of electrons from the substrate into the oxide, and the subsequent annihilation of some of the trapped holes. It has been known for quite some time that radiation hardness is strongly dependent on device processing and device geometry.

A continuing goal of radiation effects work has been the development of models that can predict the complex radiation response of MOS devices and circuits based on the process parameters used to fabricate the devices. Implementation of these models into a TCAD framework could create a powerful tool that would make rapid design of rad hard parts possible with a minimum of build and test cycles, while at the same time minimizing performance and cost tradeoffs. Despite the great promise of TCAD tools, they are only as good as the underlying physical models upon which they are based. It is essential, therefore, to develop models that are based on a physical understanding of the effects of processing on radiation hardness.

A comprehensive physically based predictive model for both major aspects of MOS radiation damage, oxide hole trapping and Si/SiO_2 interface trap generation, has recently been proposed [1-4]. The model is based on the principles of the statistical mechanics of solids and a knowledge of defects involved, obtained through electron spin resonance (ESR) studies [5-20].

Earlier work showed that the model could predict hole trapping quite accurately for a narrow range of processing parameters[1,2] and that the model's D_{it} predictions are in at least semi-quantitative agreement with numerous observations in the literature[3,4].

In this paper we present results demonstrating that the D_{it} model can also provide fairly accurate predictions, albeit for somewhat idealized circumstances, and demonstrate with a broad range of samples the validity of most important assumption of the model, that oxide hole trapping is primarily determined by the highest processing temperature witnessed by the oxide. Furthermore, we demonstrate that a physically based predictive model can predict the hole trapping response in oxides subjected to complex technologically important processing steps in a leading commercial fabrication facility operated by Harris Semiconductor- Intersil, Palm Bay, Florida.

The model involves P_b centers ($Si_3 \equiv Si^\circ$) as the dominating interface state defects and E′ centers($O_3{\equiv}Si^\circ{+}Si{\equiv}O_3$) as the dominating hole trap sites.[1-5] These two defect centers and other defect centers have been discussed in a recent review[5]. The roles of these two defects in radiation damage were established many years ago in ESR studies at Sandia National Laboratories[7-12] The Sandia studies established that P_b centers are the dominating interface state centers and that E' centers are the dominating hole traps. Results supporting, extending, and confirming the Sandia findings have been generated by (among others) Miki et al.[13], Takahashi et al.[14], Triplett et al.[15], Lipkin et al.[16], Awazu et al.[17], Vranch et al.[18], Ohmameuda et al.[19], and Warren et al.[20].

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II. Experimental Details

Oxide Samples

Oxides for this study were prepared at Harris Semiconductor-Intersil, Palm Bay, Florida, the former Naval Research and Development Laboratory (NRAD) 4″ fabrication facility, and the new SPAWAR 6″ facility in San Diego, California.

The NRAD oxides were grown in dry oxygen at 825° C; after oxidation, polysilicon gates were deposited. After polysilicon deposition, the MOS structures were annealed for 30 minutes in N_2 at one of four temperatures: 875, 950, 1025, and 1100° C. The MOS structures were rapidly pulled from the furnace following the N_2 anneal, and the polysilicon gates were then removed.

The SPAWAR oxides were very simply processed. They were grown in a vertical furnace on 6″ substrates in dry oxygen at 850° C to a thickness of 45nm and then subjected to 30 minute anneals in N_2 at one of four temperatures: 850, 925, 1000, and 1075° C. No gate material was deposited on the SPAWAR oxide surfaces.

The role of realistic processing variations was investigated with Harris Semiconductor-Intersil oxides. Sample materials were obtained via normally available processing methods at the Palm Bay, FL, facility. Oxides were grown on lightly doped (100) Si substrates to a thickness of 110nm in steam at one temperature below 900°C and at a second temperature above 900°C. After oxidation, the samples were subjected to a variety of processing steps listed in Table I. After processing, the polysilicon gates were removed (As indicated in Table I, three of the fourteen Harris samples did not receive polygate deposition).

Oxide Hole Flooding

Holes were injected into the "bulk" and toward the Si/SiO_2 region of the oxides using vacuum ultraviolet (VUV) photons with $hc/\lambda = 10.2$ eV. Most of these photons are absorbed in approximately the top 10nm of the oxides, where they create electron-hole pairs. The holes are driven across the oxide to the Si/SiO_2 boundary by a potential created by corona ions deposited onto the surface of the oxide; the corona ion induced electric fields across the oxides are approximately 2 MV/cm. The electrons are extracted from the top of the oxide by the same corona ion bias. Fluences of 0.5, 1.0, and $2.0 \times 10^{13}/cm^2$ were utilized for each set of oxides. The VUV hole flooding process has been more fully described elsewhere [21].

Measurements

After flooding the oxides with holes, trapped hole densities were evaluated from high-frequency capacitance versus voltage (CV) mid-gap shifts, ΔV_{mg}. In the simply processed SPAWAR oxides, the high-frequency CV measurements were also utilized to evaluate the interface states generated between mid-gap and flat bands.

Each recorded data point was taken with a fresh sample (a single dose for each sample). CV measurements were made immediately after hole flooding. Each recorded data point is an average of approximately ten measurements

III. Results and Discussion

Hole Trapping

The physically based predictive model's hole trap expression is [1-4]:

$$\Delta V_{mg} = \frac{qAe^{-\Delta h / kT}}{C_{ox}} (1 - e^{-\sigma\eta}), \qquad (1)$$

where q is electronic charge, Δh = 1.5 eV, T is the highest processing temperature, k is the Boltzmann constant, σ is the hole trap cross section (3×10^{-14} cm^2 at these fields), η is the hole fluence, and C_{ox} is the oxide capacitance. As discussed elsewhere[1-4], the constant A includes the product of available trap sites and the exponential of the defects nonconfigurational entropy divided by the Boltzmann constant. The parameter A also includes the trapped hole charge centroid. The original study[1,2,4] obtained $A \approx 5 \times 10^{18}$ / cm^2 for 45nm oxides.

Figure 1 illustrates results of hole flooding on ΔV_{mg} for the (original) NRAD oxides. Figure 2 illustrates hole flooding for the very simply processed (bare) SPAWAR 6″ oxides. The results are in fairly good agreement with the model predictions, with $A=5x10^{18}/cm^2$.

Table II and figures 3 and 4 illustrate mid-gap voltage shifts for the 14 Harris-Intersil oxides. Figure 3 illustrates ΔV_{mg} results for the fourteen processing variations indicated in Table I. The "dots" illustrate the measurements. The solid lines indicate the theory results of equation (1) with the constant A slightly adjusted for the centroid ratio appropriate for 110nm oxides. Here we assume that the trapped hole centroid is 10nm from the Si/SiO_2 boundary in both the 45nm and 110nm oxides. (Thus in the 110nm oxides, $A = 5.8 \times 10^{18}$ /cm^2.) The dotted lines in figure 3 connect data points of the samples with the largest deviation from the average values at each temperature.

In figure 4 we plot the average mid-gap shifts of all of the lower temperature samples and all the higher temperature Harris-Intersil samples. These average values corresponded fairly closely to the predictions of the model.

The results of Table II and figures 3 and 4 demonstrate that, although various technologically relevant processing steps listed in Table I (such as RIE, polyetch, and anneals) clearly have some effect on oxide hole trapping, the highest process temperature generally dominates.

Table I. Summary of Process Parameters

Sample	Gate Temp	Poly Deposition	Phosphorous Deposition	RIE Poly	Implants	Contact	Anneal	Passivation Plasma
	(° C)	< 800° C	Temp	Etch	10^{12} / cm^2	Etch	< 500° C	Deposition/Etch
1	< 900	-	-	-	-	-	-	-
2	< 900	yes	> 900	-	-	-	-	-
3	< 900	yes	> 900	yes	-	-	-	-
4	< 900	yes	> 900	yes	-	-	-	-
5	< 900	yes	> 900	varied	yes	yes	yes	yes
6	< 900	yes	> 900	yes	yes	-	-	-
7	< 900	yes	> 900	yes	yes	yes	-	-
8	< 900	yes	> 900	yes	yes	yes	yes	-
9	< 900	yes	> 900	yes	yes	yes	yes	yes
10	> 900	-	-	-	-	-	-	-
11	< 900	-	-	-	-	-	-	-
12	< 900	yes	-	-	-	-	-	-
13	< 900	yes	> 900	-	-	-	-	-
14	< 900	yes	< 900	-	-	-	-	-

Conditions: Gate and Phosphorous deposition temperature settings are: high temp. (> 900 C) and low temp. (< 900 C); Poly deposition temperature < 800 C; Dry poly etch is reactive ion etch (RIE) mode; Implants are 10^{12} atoms / cm^2; Dry Contact etch utilized Hexode etcher; anneal is < 500 C; Passivation is plasma deposited and etched.

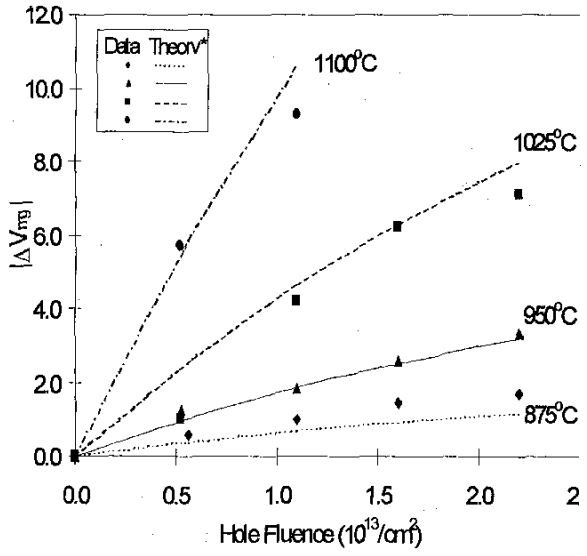

Figure 1. Summary of mid-gap voltage shifts versus hole fluence for four NRAD oxides. The oxides were subjected to anneals of 875° C (1148K), 950° C (1223K), 1025 ° C (1298K), and 1100° C (1373K). *The lines plot the physically based predictive model. The squares, circles, diamonds, and triangles represent the data. Note the fairly good agreement of the data and the model.

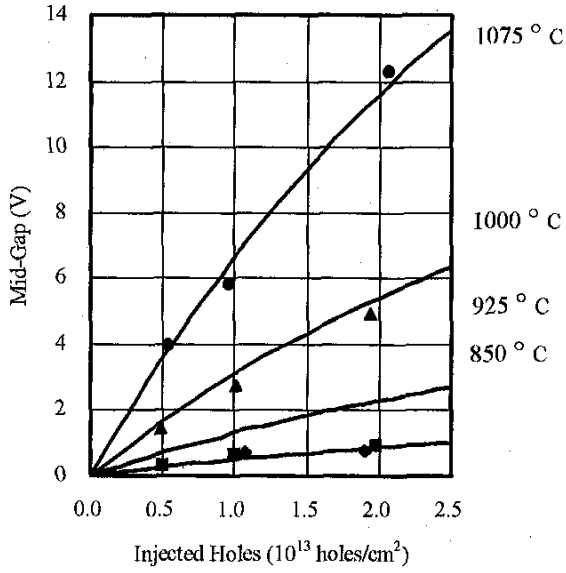

Figure 2. Summary of mid-gap voltage shifts versus hole fluence for four SPAWAR oxides subjected to anneals at 850° C, 925° C, 1000° C, 1075° C. Solid lines plot the physically based predictive model equation (1); the circles, triangles, squares, and diamonds represent data corresponding to the anneal temperatures. Note the fairly good agreement of data and the model.

Table II. Summary of Harris-Intersil Oxides Results			
Sample	ΔVmg at Hole Fluences (per square cm)		
	$5x10^{12}$ / cm^2	$1x10^{13}$ / cm^2	$2x10^{13}$ / cm^2
1	1.2	2.1	4.2
2	2.2	4.4	7.4
3	2.6	4.5	7.7
4	2.7	5.2	7.8
5	2.8	5.0	9.0
6	3.1	5.7	8.2
7	1.9	4.3	9.0
8	2.5	5.7	9.1
9	2.5	4.8	8.2
10	2.2	3.6	7.4
11	1.2	1.9	4.5
12	0.7	1.3	2.9
13	1.7	2.7	4.3
14	0.6	1.4	2.7

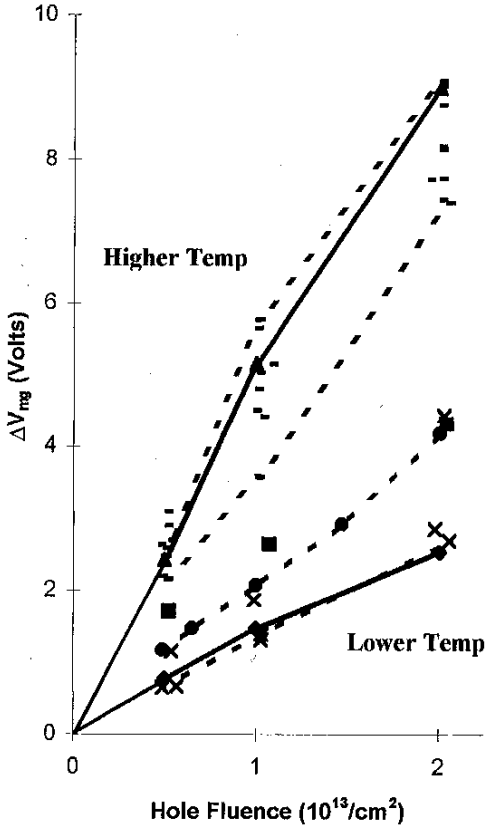

Figure 3. Summary of mid-gap voltage shifts versus hole fluence for 14 differently processed oxides. The solid line plots the physically based predictive model equation (1); the dashed lines connect data points for these samples which deviate the most from the average for each of the two temperatures. Note that with the exception of one oxide (sample 13), all data fits into two bands corresponding to the highest process temperature. Data of sample 13 are indicated with the solid square symbol.

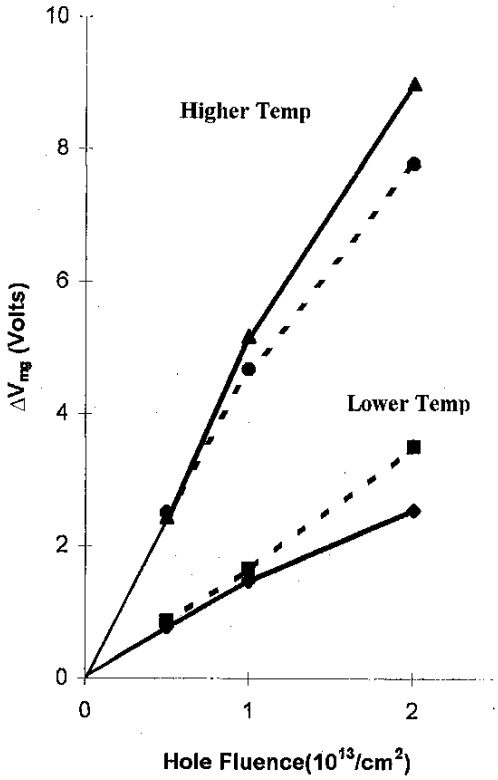

Figure 4. Plots of the average values of all the lower temperature oxide and higher temperature oxide responses. The solid lines are plots of equation (1) for the lower and higher temperatures. Note the fairly close correspondence between equation (1) and these average values.

The results further demonstrate that the hole trapping model provides reasonably accurate predictions of the hole trapping response for oxides subjected to complex processing encountered during device fabrication. (As discussed in reference 4, it should be emphasized that this is a first order model, which may not provide extremely precise results under all circumstances. One possible source of error is the ad hoc treatment of electron compensation.)

Interface Trap Generation

The interface trap (D_{it}) generation process is more complex than hole trapping[22-24]. This process is clearly initiated by holes liberating a hydrogenic species within the oxide[22-24] The hydrogenic species migrates to the Si/SiO_2 boundary creating interface state defects. Since we have not yet been able to calibrate this model for processing induced differences in the location and concentration of hydrogen, we have tested the D_{it} aspects of the model with the simply processed SPAWAR 6″ oxides.

The D_{it} model for the generation of P_b centers yields the following expression:

$$\Delta P_b \approx (\kappa/2)(P_bH)_i\{[1 + 4E'_i/[\kappa(P_bH)_i]]^{1/2} - 1\}, \quad (2)$$

where κ is a reaction constant of order 1 and $(P_bH)_i \cong 3 \times 10^{12}/cm^2$ and E'_i is the initial post irradiation E′ density. As discussed elsewhere[3,4], this expression should provide a slight overestimate of the P_b generation. It should be multiplied by an as of yet uncalibrated value of order one to adjust for hydrogen content. Also, as discussed previously [4], expression 2 represents a theoretical "final-equilibrium" value of the P_b concentration. Thus, in the proposed model, the P_b concentration would approach this value.

Figure 5 shows the results of the hole flooding on D_{it}. The data are indicated by the solid symbols; the solid lines indicate the model predictions. We calculated the initial post irradiation E′ density from expression (1). In that expression, we utilized the parameters mentioned above; these are exactly the same as those utilized in the original work[1,2,4]. In the D_{it} expression (2) we take the reaction constant to be 0.5 and make the very crude approximation that $D_{it} = [P_b]/1eV$. We use $1/2(\Delta P_b)$ as the model prediction. (Although the $D_{it} = [P_b]/1eV$ and the $1/2(\Delta P_b)$ choices are somewhat crude and arbitrary, they are consistent with the literature and the admittedly primitive present form of the model.)

As the figure shows, the correspondence between theory and data is fairly good for D_{it}. (The D_{it} numbers are the average of about 10 measurements per data point.)

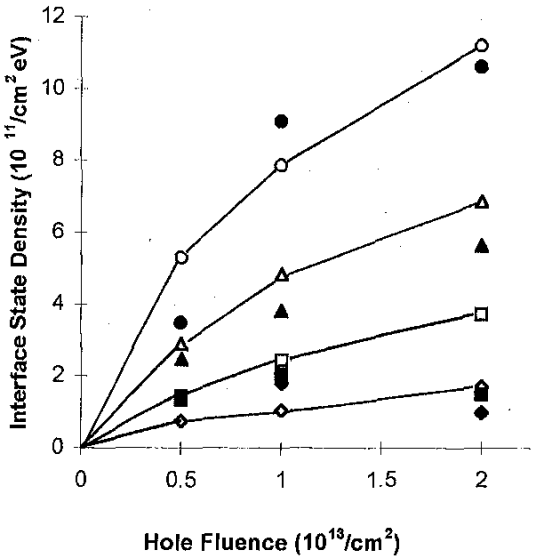

Figure 5. Flat-bands to mid-gap D_{it} plotted versus hole fluence. The solid lines represent the predictions of equation (2). Data are represented by the solid symbols: Diamonds (850° C), Square (925° C), Triangle (1000° C), and Circle (1075° C).

This study is the first to compare the model predictions to interface trap formation results. These results establish that the model predicts D_{it} to within a constant (which we know to about a factor of two) for a somewhat simplified type of irradiation in simply processed oxides.

Although the experimental study involved a somewhat simplified approximation of radiation damage, the fairly good agreement between model predictions and experiment strongly supports the contention that this model describes at least a fairly significant part (presumably the majority) of the radiation induced interface trap buildup process.

It is well established in the literature that the buildup of interface states occurs over a period of time after a brief irradiation[22-24]. The rate of buildup is rapid immediately after irradiation; The rate slows, typically logarithmically with the passage of time. The model[3,4] is in at least qualitative agreement with the observed time dependence. As discussed in earlier publications[3,4], the model involves interactions of radiolytic H_2 with E' center trapped holes and a subsequent reaction at P_b precursor sites. As radiolytic H_2 is dispersed the rate will slow. Our proposed D_{it} creation process itself creates a small additional amount of H_2 allowing the process to proceed quite slowly at longer times. In its current state of development, the model cannot precisely relate the data of figure 5 to a specific time on the logarithmic D_{it} buildup curve; however, since approximately the same amounts of time were involved in all measurements, we would expect that, to a rough approximation, our D_{it} values would all correspond to the same time value on that curve.

IV. Limitations of the Model and Data

The results presented in this paper support the physically based predictive model for radiation damage as expressed in equation (1) and (2). The results also support the contention that the model captures most of the physics of the radiation damage process. However, the results presented in this paper do not demonstrate that the model is complete in its description of the physics of radiation damage and do not demonstrate that the model can, in its present form, predict MOS radiation damage response under all circumstances. Although model limitations have been discussed to some extent in previous publications[1-4], several points bear mentioning.

P_b Centers and the Density of Interface States

The model is clearly limited in several respects with regard to interface state generation.

Although quite a few ESR studies indicate a dominating role for P_b centers[7-14, 17, 18, 25, 26] in the radiation damage process at the Si/SiO_2 interface, the model's treatment of a single type of P_b center as the sole source of interface states is only a (reasonable) approximation. This is so for several reasons.

Although one P_b variant, the P_{bo} center, clearly dominates radiation damage on the technologically relevant

(100) Si/SiO_2 interface[18,25,26] another variant, the P_{b1} center, plays a secondary role. The P_{b1} defect may typically account for ~ 20% of the interface states generated.[25] Spin dependent recombination (a very sensitive but less quantitative ESR technique) measurements suggest that, under certain circumstances the oxide silicon dangling bond defects, E` centers, can play a direct role in interface state density[26].

Perhaps the most important additions to the simple P_b picture are band tail states at the Si/SiO_2 boundary. Si/SiO_2 band tail states will inevitably be created by the sometimes charged P_b centers[27]. The band tail states will occupy ranges of space and energy which would also be occupied by P_b defect levels. Under such circumstances some rehybridization will inevitably occur[28,29]. Thus, viewing the Si/SiO_2 interface states as simply P_b levels is a reasonable but certainly not extremely precise approximation of reality.

One more point should be made with regard to the ESR evidence supporting the role of P_b centers as the dominating interface state defects. The evidence is compelling but not extremely precise. ESR measurements are accurate to about +/- 10% in relative number but only slightly better than a factor of two in absolute number. Thus, it is conceivable that, even though the P_b/D_{it} correspondence is clear, some other , as yet undiscovered defect could be responsible for a substantial minority of the radiation induced interface states. However, if such a large minority of additional sites were present, these other interface states would have essentially the same generation and annealing characteristics as P_b centers and would have to exhibit a rather broad distribution of states in the band gap at the Si/SiO_2 boundary[7-14, 18, 25].

One more general point should be made here: literally dozens of impurity related deep levels have been identified in silicon as well as intrinsic defect levels[30]. One could, at least in principle, create many more types of interface states at the Si/SiO_2 boundary, with the introduction of suitable impurities. It is also possible that other sorts of intrinsic near Si/SiO_2 interface state defects could be created, say by ion bombardment. It is virtually certain that one could create MOS systems in which defects other than P_b centers dominate Si/SiO_2 interface state density. However, the possible existence of such defect states have no obvious relevance to radiation damage in technologically meaningful circumstances.

Kinetics of Interface State Generation

When MOS devices are subjected to a brief burst of irradiation, for example in bombardment from a linear accelerator (LINAC), interface generation is initially rapid but slows approximately logarithmically with increasing time[22-24].

As discussed in a previous publication, the physically based model involves a reaction of radiolytic H_2 at E` center sites followed by a reaction at P_b precursor sites at the Si/SiO_2 boundary which could release H_2[3.4]. Such a process would at least qualitatively follow the time response observed in earlier LINAC studies. A rapid buildup would initially occur but as the initial radialytic H_2 dissipates, the rate would slow rapidly, continuing at an ever slower rate as the re-released H_2 concentration also dissipates. To zero order, the model predicts that the eventual P_b concentration would approach the value of expression (2). Our limited observations are consistent with this conclusion but neither the model in its present form nor the limited results of this work allow us to precisely predict the temporal dependence of interface state density buildup.

Thermodynamics and the Hole Trap Concentration

Although the hole trapping process is simpler than the interface state generation process, the hole trapping aspects of the model also involve simplifying assumptions. In its current form, the hole trapping model uses essentially the simplest possible expression for the hole trap density, n:

$$n = N_0 e^{\Delta s/k} e^{-\Delta h/kT}, \qquad (3)$$

where N_0 represents the density of available trap sites, Δs the non-configurational entropy per site, Δh the enthalpy of creation per site, k the Boltzmann constant, and T the highest process temperature maintained for a significant period [1,2,4].

Although this is a reasonable first order expression, it does not explicitly include all possibilities. In any real system , multiple defect reactions are possible , at least in principle. These reactions may involve ambients. To precisely calculate defect concentrations for all possible circumstances, one must simultaneously solve a number of defect reaction equations. Reactions involving ambients are particularly straightforward. Reasonable approaches for such calculations are very well established and are discussed in an excellent recent text[31].

We have yet to carry out the moderately extensive measurements required to incorporate these possible complications. Particularly important calibration studies would include the effects of oxygen and hydrogen partial pressures in high temperature anneals.

V. P_b and E` Center Controversies

The physically based model discussed in this paper involves P_b centers as dominating interface state defects and E` centers as dominating hole trap sites. As mentioned previously, the roles of these two defects were established many years ago in ESR studies at Sandia[7-12]. Results supporting and extending the original Sandia findings with regard to the basic roles of P_b and E′ centers have been generated by several dozen researchers associated with at least a dozen different institutions. (See references 13-20.) However, this work remains extremely controversial.

These controversies have been emphasized in very recent work involving the MOS Radiation Effects Group at the Naval Research Laboratory: an invited talk by R. Stahlbush at the 1999 Heart conference[32] and a very recent article in the Journal of Applied Physics by B. Mrstik et al.[33].

In his abstract and presentation (dealing with the "Non P_b Nature of Most Interface Traps") Stahlbush references work by Cartier, Stathis, and Buchanan[34], (Reference 34 of this paper.) Cartier et al.[34,35] have argued that, contrary to earlier studies, P_b centers account for only a small fraction of technologically meaningful D_{it}.

A reading of the Cartier et al.[34,35] work, as actually published by Cartier et al., immediately brings to mind quite a few possible reasons for the apparent discrepancy between their work and the results of others. These possible reasons have been discussed extensively in several publications[4,5].

However, what Stahlbush[32] presents as what Cartier et al. have published is quite significantly different from what Cartier et al. have actually published[34,35]. The quite significant differences between the Stahlbush presentation of the Cartier work and what was actually published by Cartier et al. obscure fairly obvious potential problems with the Cartier et al. studies. Two examples, both dealing with the introductory paragraphs and figure 1 of the "Non P_b Nature of Most Interface Traps" section of the Stahlbush abstract, serve as illustrations.

Figure 1 of the "Non P_b Nature of Most Interface Traps" section in the Stahlbush abstract shows a comparison of generated P_b center and interface state concentrations. The P_b curve is about a factor of twenty-five lower than the interface state concentration curve. His reference for this data is the 1993 Applied Physics Letter by Cartier et al. [34].

The Stahlbush figure 1 and the discussion (apparently) show that P_b centers are only about one twenty-fifth of the interface states. However, Stahlbush does not mention anywhere in his abstract that the P_b results were measured on 9.75nm oxides while the interface state densities were measured on 49.5nm oxides. Cartier et al.[27] make this difference in oxide thickness explicitly clear in the original figure caption (deleted from the Stahlbush abstract) as well as in the text of their publication, which is cited by Stahlbush as the source of the information.

Although results of various studies differ in detail[36-39], quite a few independent groups have established that radiation induced interface states increase quite strongly with increasing oxide thickness. Several careful early studies by Derbenwick and Gregory[36] and Viswanathan and Maserjian[37] indicate that interface state generation scales with oxide thickness squared. Several more recent studies indicate that an even stronger oxide thickness dependence would be observed in a comparison of the fairly thick (49.5nm) and fairly thin (9.75nm) oxides used in the study to which Stahlbush refers.

If one irradiated 9.75nm and 49.5nm oxides, one would expect to observe a large difference in the interface state densities of the two samples. Thus, even if the P_b and D_{it} densities were precisely equal in both samples, the 9.75nm/49.5nm comparison would inevitably indicate a very large discrepancy in irradiated samples. For example, assume the thickness squared dependence reported by both Derbenwick and Gregory[36] and Viswanathan and Maserjian[37]is correct: the ratio of interface state density would be about $(49.5/9.75)^2 \approx 25$. (More recent studies would indicate an even larger difference [38,39].) Thus, even if the P_b and D_{it} densities were precisely equal in both sets of samples, a square law dependence predicts a difference of a factor of about 25 in the P_b and D_{it} comparison reported in the Stahlbush abstract. (That is the difference reported in the Stahlbush abstract.) This is, arguably, not a particularly convincing argument for the "Non P_b Nature of Most Interface States."

By not mentioning the difference in oxide thickness, Stahlbush obscures a very obvious possible problem with the Cartier et al.[34,35] work. (If the hydrogen bombardment accurately simulates radiation damage, the 49.5nm/9.75nm comparison is meaningless. If the hydrogen bombardment does not accurately simulate radiation damage the 49.5nm/9.75nm comparison is also meaningless for radiation damage.)

A second problem with the Stahlbush figure 1 is its horizontal axis illustration of hydrogen fluence. In the original Cartier et al.[34] paper, the horizontal axis is not hydrogen fluence but hydrogen exposure time. However, in a follow up paper, in which the Cartier et al. figure 1 reappears[35] , Cartier and Stathis report that approximately 10^{21} hydrogen atoms / cm^2 are required to generate interface state densities of $\sim 10^{13}$ / $eVcm^2$ (See page 7 of our reference 35.) In the Stahlbush abstract figure, only about 10^{17} hydrogen atoms / cm^2 are required to generate $\sim 10^{13}$ / $eVcm^2$. Thus, the data in the Stahlbush abstract figure 1 differs by about four orders of magnitude from the data of Cartier et al.[35], the people he references for that data.

As has been pointed out in previous publications [4,5], the use of extremely high fluences of atomic hydrogen to simulate radiation damage and other technologically relevant MOS device stressing is a dubious choice. This is true for many reasons; consider just one of them. Briefly, a fluence of 10^{21} hydrogen atoms / cm^2 would involve at least 10^{21} hydrogen bond breaking events / cm^2. A 10nm oxide has only about 10^{17} total atoms / cm^2; thus, the energy required to break that many hydrogen bonds would be about four orders of magnitude more energy than would be required to vaporize the sample. This is, arguably, not a technologically relevant dose level. The reduction of the hydrogen fluences actually reported by Cartier and Stathis by four orders of magnitude in the Stahlbush abstract

considerably weakens what is, by far, the most obvious argument against the Cartier et al. work.

In assessing the role of P_b ESR centers, Stahlbush appropriately references one of the early Sandia papers with which he disagrees. (In that Sandia paper, reference 9 of this paper, the authors argued that "P_b defects account for a very large portion of radiation induced interface states.") However, none of the other papers referenced by Stahlbush in the "Non P_b Nature of Most Interface Traps" discussion involve any ESR measurements on irradiated MOS devices.

In assessing the validity of the original Sandia ESR radiation damage work, it would be useful to consider other independent studies which actually involve ESR and radiation damage in MOS systems. At least four groups independent of the original Sandia investigators have made ESR measurements on irradiated high quality MOS systems with initially low P_b concentrations. None of the four studies contradict the Sandia work. A particularly pertinent observation: Awazu et al.[17] reproduced the ESR/P_b generation measurements of the Sandia study to which Stahlbush specifically objects. (See figure 2a of reference 9 of this paper.) The Awazu et al. results are identical to those of the early Sandia study. (See Fig 2a and the discussion on p. 8523 which begins " Lenahan and Dressendorfer reported....." in reference 17 of this paper.)

In a recent publication, Mrstik et al.[33] reported measurements nearly identical to those reported earlier by Lenahan, Conley, and coworkers to verify the hole trap model. Although the measurements of the Lenahan / Conley study and in the Mrstik et al. study were quite similar, the results of the two studies are very different. (The Mrstik results are in similar conflict with the findings of this study.) The Lenahan / Conley model and the limited data of the original study as well as the much more extensive data of this study clearly indicate a very strong process temperature dependence of radiation damage[4,5]. In one set of samples, Mrstik et al. report very little difference in hole trapping for process temperatures between 975°C and 1200°C and a fairly modest difference between 925°C and 975°C. In another set of samples they report only small differences in flat band shifts (16 volts versus 24 volts) between 900°C and 1200°C process temperature. The findings of Mrstik et al. are in conflict with the observation and conclusions of quite a few independent groups with regard to the process temperature dependence of radiation hardness[10,37,40-43].

Mrstik et al.[33] also report that E′ centers and trapped holes are completely uncorrelated and further report that the E′ center densities were far too small to account for more than a fraction of the trapped holes in all of the samples studied. This result is also very different from the observations of Lenahan / Conley who reported roughly equal numbers of E′ centers and trapped holes. (The Mrstik et al. E` observations are also in conflict with observations and conclusions of quite a few independent groups, with regard to the lack of E′ - trapped hole correlation [8,10,11,13,14. 15,16,19,20].)

VI. Summary and Conclusions

We find that, in all but two of twenty-two oxides studied, the highest processing temperature is primarily responsible for the hole trapping response. Furthermore we find that the hole trapping can be predicted with reasonable accuracy using a recently developed physically based predictive model[2,3]. We find that other processing steps play significant but considerably smaller roles in hole trapping.

An earlier study involving four sets of oxide process parameters also showed reasonable agreement between the physically based predictive model and hole trapping. We think it is extremely unlikely that this widespread agreement between model and experiment is coincidental.

In measurements involving fewer (simply processed) samples we find that the physically based predictive model also predicts D_{it} generation, though only to within an as yet arbitrary factor of approximately two.

We conclude that moderately accurate predictions of the radiation response of most oxides may be obtained from a physically based predictive model as expressed in equations (1) and (2). In view of the reasonable agreement between theory and experiment, and the quite wide variety of experimental observations of others[4] explained by this model, we conclude that it is fundamentally correct. The model can predict hole trapping fairly accurately for a fairly wide variety of processing parameters. The predictive capabilities of the D_{it} model are less well established. Although this work strongly supports the conclusion that the D_{it} model explains a significant fraction (presumably most) of the Si/SiO_2 interface trap generation process, it should be emphasized that far more work is required to completely verify and calibrate the D_{it} model. It should also be emphasized that this work does not rule out other processes playing some role in D_{it} generation.

The results of this study strongly indicate that the statistical mechanics/ESR defect approach could be implemented into a TCAD framework for the rapid design of radiation hard parts. In fact, this process has been initiated; progress on such a framework has recently been reported[44].

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