

A FRAMEWORK FOR UNDERSTANDING RADIATION-INDUCED

INTERFACE STATES IN SiO₂ MOS STRUCTURES

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Abstract

An empirical model of radiation-induced interface states at the SiO₂/Si interface in SiO₂ MOS capacitors is developed. The formulation explicitly addresses the time-dependent two stage nature of the buildup process, and it gives the mathematical dependencies of the experimentally observed buildup on time, field, temperature, and dose. The model is applied to both wet and dry grown oxides. The implications of the empirical model for microscopic mechanisms involved in the buildup are discussed. In particular, it is argued that the experimental observations can best be understood in terms of a positive ion (probably H⁺) release in the SiO₂ bulk and the subsequent transport of the liberated ions to the SiO₂/Si interface (for positive gate bias). The induced interface states result from an interaction of the ions at the interface.

Introduction

Radiation-induced interface states at the SiO₂/Si interface in MOS structures continue to be an important technological problem, sometimes deleteriously affecting device performance after exposure to ionizing radiation. In other instances, however, these states are responsible for improving the radiation tolerance of MOS devices by reducing threshold shifts via negative charge compensation for trapped positive oxide charge. In addition, large variations in the magnitude of interface state buildup have been observed in oxides with different processing histories. Clearly, it is desirable to obtain some basic understanding of the generation process. In spite of considerable attention addressed to this problem, however, still little is known about the microscopic mechanisms of the buildup.

In recent years, a great deal of empirical information about the buildup of interface states has been obtained.¹⁻⁵ It has been found to be a complex time-dependent process involving two separate stages. The first stage, which occurs during the time (< 1s) required for radiation-generated holes to transport to the SiO₂/Si interface under positive bias, determines the final or saturation value of interface states and was found to be field dependent and temperature independent. This stage depends critically upon some interaction of the holes as they traverse the oxide film. The second stage, which begins after the holes have reached the SiO₂/Si interface and continues for thousands or even tens of thousands of seconds at room temperature, determines the time scale for the buildup and was found to be both field and temperature dependent. The buildup is observed⁴ only if positive bias is maintained on the gate during the entire buildup process. Switching to negative bias after the transport (first) stage is over but during the buildup stage inhibits further interface state growth, and if the bias is switched negative for some period of time and then back to a positive value, the saturated interface state density is reduced below the value obtained if positive bias is maintained throughout the process.

These observations were initially reported in radiation-hardened wet and soft-dry oxide capacitors. Recent results⁶ on hard dry oxides indicate that the same mechanisms are responsible for the interface state buildup in both wet and dry oxides, the major difference being only that the magnitude of the buildup is much smaller in the hardened dry as compared to the hardened wet oxide, the difference presumably reflecting different amounts of water incorporated in the oxide during processing. This result suggests that a water related specie or defect plays a principal role in the buildup process.

Therefore, evidence exists that two key factors involved in radiation-induced interface states are (1) an interaction of the radiation-generated holes in the oxide film, and (2) the role of a water related specie or defect. Two previous attempts have been made to combine these factors in a model of radiation-induced interface states. Sah⁷ in 1976 proposed that the holes under positive gate bias interacted in the interface region to break weak Si-OH bonds, freeing OH⁻ radicals to drift toward the gate, leaving behind dangling Si bonds, which resulted in interface states. However, the two-stage character of the buildup cannot be understood with this model, especially the long term generation process continuing long after the hole transport is complete. In 1978 Svensson,⁸ based on previous work of Revesz,⁹ postulated the essence of a possible two stage process, namely, that transporting holes broke Si-H bonds in the bulk of the oxide film leading to positively charged trivalent Si centers in the bulk and neutral interstitial hydrogen atoms which were free to diffuse away. Svensson then suggested that the atomic hydrogen which diffused to the interface reacted with Si-H bonds in the interface region to produce molecular hydrogen, H₂, and dangling Si bonds, which as in the Sah model, resulted in the creation of interface states. Although this model does involve a two stage process for the generation of interface states, it fails to explain the field and polarity dependencies of the second stage. In particular, it fails to explain how the field during the second stage affects the time scale for the buildup and how reversing the bias polarity inhibits further interface state generation.

In this paper, we first draw together the experimental results in an empirical model of the two-stage process which gives the mathematical dependencies of the interface state buildup on time, field, temperature and dose. Then with the empirical model as a guide, we discuss possible microscopic models of the buildup process. By combining the implications of the empirical model with some of the earlier ideas concerning interface state production, we develop a framework in which it is possible to understand the experimental observations in a consistent manner.

The Empirical Model

The two stage character of the buildup process can be succinctly expressed by the expression:

$$\Delta N_{SS}(t) = N_{SS}^{\infty}(E_1, D)f(t/\tau). \quad (1)$$

Here, the change in interface state density as a function of time, $\Delta N_{ss}(t)$, is written as a product of two expressions, the saturated values of N_{ss} at long time, N_{ss}^∞ , and a time dependent function, $f(t/\tau)$, which approaches unity at late time. The densities ΔN_{ss} and N_{ss}^∞ in eq. 1 represent integrated values of the interface state distributions over a selected energy interval in the Si bandgap. The saturation value N_{ss}^∞ is determined solely by the first-stage process, during the time that the holes transport through the oxide film, and is a function of dose D and of the field E_1 applied during the first stage, but is independent of temperature. The time dependence of the buildup is contained in the "second stage" function $f(t/\tau)$, where the time scale $\tau(T, E_2)$ depends on the temperature, T, and field, E_2 , applied during the long-term buildup stage, and not on the field or temperature during the first stage.

The explicit dose and field dependence of the "first stage" function N_{ss}^∞ is given by

$$N_{ss}^\infty(E_1, D) = AD^{2/3} \exp(\beta E_1^{1/2}). \quad (2)$$

The functional dependencies are the same in both wet and dry oxides,⁶ although the numerical constants vary between oxides. The rather unexpected 2/3 power law dependence on dose has been observed⁶ to apply to a number of different oxides (both wet and dry, hard and soft) over almost three orders of magnitude in dose with no apparent saturation with dose. The exponential dependence of N_{ss}^∞ on $E^{1/2}$ is evident from the semilog plot of N_{ss}^∞ vs $E^{1/2}$ shown in Fig. 1 for both hard wet and dry oxides for 5 Mrad(SiO₂) ⁶⁰Co irradiation. For the dry oxide the data were replotted from ref. 6; for the wet oxide the data from ref. 3 for a 0.8 Mrad (SiO₂) irradiation was utilized but scaled to a 5 Mrad (SiO₂) dose level. In both cases the data were adjusted to account for the field dependent yield of holes,¹⁰ i.e., adjusted to a constant number of radiation-generated holes. The numerical values of the constants A and β in eq. 2 are listed below.

	Wet	Dry
A (cm ⁻² Mrad ^{-2/3})	4.6 x 10 ¹⁰	2.0 x 10 ¹⁰
β (MV/cm) ^{-1/2}	1.32	0.89

Although for a fixed dose, N_{ss}^∞ is determined by the field during the first stage, $N_{ss}(t)$ does not achieve the saturation value until long times after the radiation pulse. At room temperature and for positive bias polarity the interface states begin to be manifested typically in the range from 0.1 to 1.0 s after the pulse and continue increasing in approximately logarithmic fashion until saturation occurs at thousands to tens of thousands of seconds. Hence, for positive bias the second stage time-dependent function can be expressed approximately as

$$f(t/\tau) = b \ln(1 + t/\tau) \quad (V_g > 0) \quad (3a)$$

for t less than the time t_s at which saturation occurs. The factor b is chosen so that $f(t/\tau) \rightarrow 1$ as $t \rightarrow t_s$, i.e., $b = 1/\ln(1 + t_s/\tau)$. For negative bias polarity,

$$f(t/\tau) = 0 \quad (V_g < 0). \quad (3b)$$

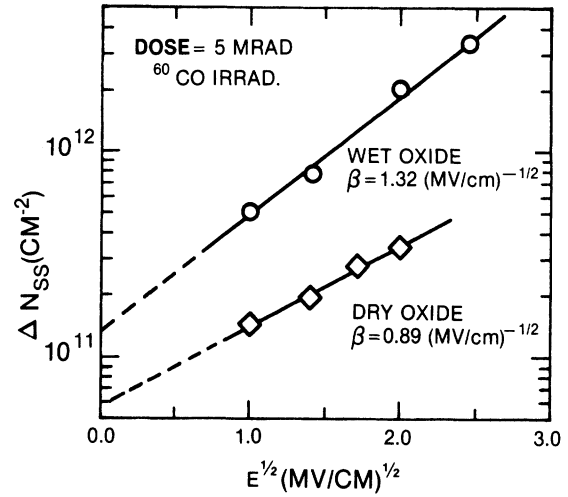


Fig. 1. Field dependence of final interface state density for radiation hardened wet and dry oxides.

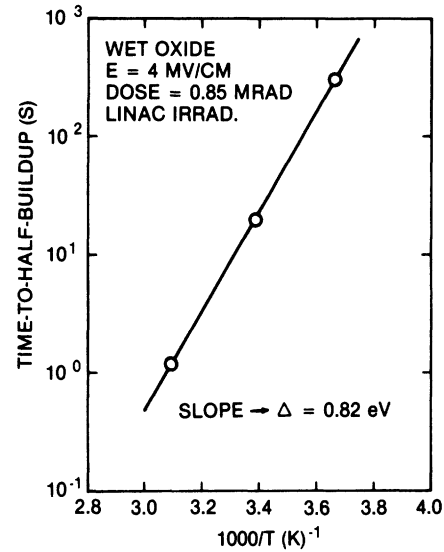


Fig. 2. Second-stage activation energy analysis for a hard wet oxide showing log of the time at which half the saturated interface state density is achieved vs reciprocal temperature.

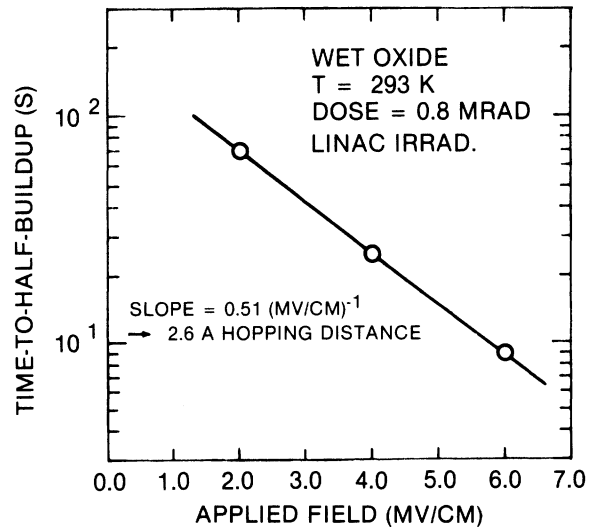


Fig. 3. Field effect on the buildup time showing log of the time at which half N_{ss}^∞ buildup occurs vs applied oxide field for the hard wet oxide.

The important quantity of interest associated with the second stage is the time scale τ for the buildup. τ has been found to be both temperature and field activated and can be described by the expression

$$\tau = \tau_0 \exp(\Delta/kT - \alpha E_2), \quad (4)$$

where Δ is an activation energy, k is the Boltzmann constant, and τ_0 and α are constants. We illustrate this behavior with an analysis of the time-dependent data as a function of temperature and field in a hardened wet oxide^{3,5}. As a convenient measure of the time scale for the buildup, we take the time $t_{1/2}$ at which half the final, or saturated, interface state density is reached. In fig. 2 we show an "Arrhenius plot" of $\log t_{1/2}$ vs reciprocal temperature for the temperature range 273 to 323 K at a constant applied field of 4 MV/cm. From the slope of the straight line fit to the data an activation energy of 0.82 eV is obtained. In fig. 3 $\log t_{1/2}$ is plotted against applied field between 2 and 6 MV/cm at room temperature. The exponential dependence of $t_{1/2}$ on field is evident, and a value $\alpha = 0.51$ (MV/cm)⁻¹ is obtained for the slope. Finally, using the room temperature value of $t_{1/2}$ along with the 0.82 eV activation energy determined from fig. 2, we obtain $\tau_0 = 2 \times 10^{-13}$ s for the pre-exponential factor of eq. 4 associated with the half buildup time.

A similar analysis of the buildup time in hardened dry oxides has not been performed due to the difficulties in producing observable change in N_{ss} with pulsed LINAC irradiation at sufficiently low dose to avoid problems associated with space charge and heating effects. Only with a different experimental approach is it possible to observe a time-dependent interface-state buildup in the hard dry oxides.⁶ But because such a time-dependent behavior is observed, which is qualitatively similar to that observed in wet oxides, and because the same dose and field dependencies of the saturated interface state density are observed in both hard wet and dry oxides, it is reasonable to assume the same mechanisms are involved in the buildup in both cases. Hence, one expects similar behavior for the time scale of the buildup in the dry oxide as expressed by eq. 4, but with perhaps different values for the constants.

Discussion: Implications for Microscopic Processes

It is clear from the empirical model of the interface state buildup that rather complex microscopic mechanisms must be involved in the process. We will now discuss the implications of the empirical model with regard to the first and second stages in turn, followed by a somewhat more speculative discussion of possible microscopic processes occurring at the interface.

A. First-Stage Process

Consider first the field dependence of the first stage, i.e., of the saturated interface state density (see Fig. 1 and eq. 2). The exponential dependence on the square root of the field is a classic signature of charge ejection over a field reduced coulomb-like (1/r potential) barrier, i.e., the Schottky effect. This would suggest as a possibility for the first stage process some interaction of the holes in which an ionic charge is released. The fact that the first stage is temperature independent indicates that thermal energy is insignificant in the process, i.e., essentially all the energy for bond breaking and ion release is derived from the transporting holes.

One envisions a process in which a hole makes a transition to a localized trap site adjacent to or involving a weakly bonded ion impurity, where the initial overall charge state of the impurity complex is neutral. In the light of what is known about hole transport in SiO₂,¹¹⁻¹⁴ a broad distribution of energies with an average in the range from 0.5 to 1.0 eV is expected to be deposited locally whenever a hole undergoes either a polaron hopping transition or a trapping event. (In a small fraction of transitions, such as for a long hop at high fields, the amount of energy transfer can be significantly higher than the average.) The ion is then liberated by the sudden localized energy excitation. If the released ion has positive charge (see below) then the interaction probably involves a charge transfer process in which the hole is annihilated by an electron initially involved in bonding the ion, and the positive charge is then carried by the ion. The defect site remains in a neutral charge state.

The question now arises as to where the first-stage (ion release) process occurs, i.e., whether at the SiO₂/Si interface or in the SiO₂ bulk (or at least extended into the bulk from the interface). Based on the observations that positive bias must be applied to the oxide in order for interface state buildup to occur,⁴ it was our feeling until recently that the first stage was associated with an interaction of the hole flux at the interface. However, recent further field switching experiments¹⁵ indicate that this is not the case. Table I shows the effect of gate bias polarity during the first and second stages on the N_{ss} buildup. The first three lines summarize the data base previously available.⁴ The recent experiments added the case where a negative gate bias was applied during the hole transport (first) stage, but then the polarity was switched positive at ~1s and maintained until ~10⁴s. The result (line 4 of Table I) was that N_{ss} buildup was observed in this case and indeed was comparable in magnitude to the case where bias was maintained positive throughout. Since, in the case of negative polarity during the hole transport phase, essentially all the holes are removed at the gate, these results strongly imply that the first stage interaction occurs in the bulk of the oxide film. Furthermore, the final number of interface states is directly related to the number of ions released during the first stage, and this number is determined by the magnitude (but not polarity) of the field applied during the hole transport.

Table I. Effect of Gate Bias Polarity on N_{ss} Buildup

1st Stage (0-1s)	Gate Polarity		N_{ss} Buildup
	2nd Stage (10 ⁰ - 10 ⁴ s)		
+	+		Yes
-	-		No
+	-		No
-	+		Yes

B. Second-Stage Process

With the first-stage process apparently being that of ion release in the bulk, the interpretation of the long term buildup stage becomes evident. It is simply that of a field-assisted ionic transport to the interface, with a subsequent interaction of the ions at the interface which produces the observed interface states. From Table I the important polarity condition for N_{SS} buildup is positive gate bias during the second, long-term buildup stage. This then argues for a positively charged ion specie, which would drift toward the Si interface under positive bias. It is reasonable to assume that the ion is H^+ , since hydrogen is expected to be relatively mobile in SiO_2 at room temperature and since the difference between N_{SS} buildup in hardened wet and dry oxides appears to be only one of magnitude. However, based on electrical measurements alone, other positive ions such as Na^+ cannot be ruled out completely. For the purpose of this discussion we will assume the ions to be H^+ .

In the light of the present discussion, let us consider the earlier field switching experiments,⁴ which demonstrated the inhibiting effect of a negative field across the oxide during the buildup stage. The field switching data for a wet oxide subjected to 0.6 Mrad (SiO_2) LINAC irradiation, consisting of a series of pulses completed within a time interval of 0.1 s, is shown in Fig. 4. Curve A shows the N_{SS} buildup for a positive field of 4 MV/cm applied throughout the experiment, for which the maximum interface state generation is observed. Curve E shows the result when the bias is maintained negative during and following the irradiation; no measurable N_{SS} buildup is observed. In curves B, C, and D a positive field of 4 MV/cm was applied during the irradiation and hole transport period. The bias polarity was then reversed at 0.8 s and maintained negative until 20, 200 and 2,000 s for B, C and D, respectively, at which times the bias was returned to positive polarity. The inhibiting effect of a negative field across the oxide during the buildup stage is evident, and the explanation is simply as follows. As long as the gate bias is positive during the buildup process (curve A), the positive ions drift toward the Si interface with subsequent appearance of N_{SS} ; but if the bias polarity is reversed (curves B, C, D) further N_{SS} production is inhibited as the remaining diffusing ions now drift back into the bulk. Furthermore, depending on the length of time the bias remains negative, a certain fraction of the ions will make it to the gate and be trapped or removed from the oxide there. Hence, when

the bias is switched positive again, N_{SS} approaches a lower final density, the reduction being greater the longer the time period of negative bias polarity. If the bias is kept negative for the time required for all the ions to transport through the film, then no further N_{SS} generation is observed. This is the case for curve D and it is evident that this time (~ 2000 s) is approximately the same as the time required for N_{SS} to achieve saturation with positive bias maintained throughout (curve A). This is certainly consistent with a bulk process (ion diffusion and drift) determining the time scale for the buildup.

If the time scale is indeed related to a field assisted thermally activated ionic transport process, then it should be possible to express eq. 4 as

$$\tau = \tau_0 \exp[(\Delta_0 - eaE/2)/kT], \quad (5)$$

where Δ_0 is the zero field activation energy for diffusion, a is an average hopping distance in the field direction, and a high field regime is assumed, i.e., $eaE/kT > 1$. Unfortunately, there is insufficient data at present to rigorously substantiate eq. (5), as the activation energy analysis was done for only one field value and the field dependence was determined at only room temperature. But if we assume the validity of eq. 5, we find from the measured slope of fig. 3 a hopping distance of $a = 2.6 \text{ \AA}$, and 0.87 eV for the zero field activation energy. An average hopping distance of 2.6 \AA is very reasonable. Indeed, this is precisely the average distance between nearest neighbor oxygen atoms in amorphous SiO_2 . One may well expect that H^+ ions would tend to temporarily bond to the lone pair, non-bonding p orbitals on the O atoms between hops and hence transport by hopping between nearby O atoms. This bonding may also explain the considerably higher activation energy ($\Delta_0 = 0.87 \text{ eV}$) observed here than that commonly quoted⁹ for diffusing neutral atomic hydrogen in SiO_2 ($\sim 0.3 \text{ eV}$). However, the higher activation energy found here lies within the range of activation energies (0.70 - 0.92 eV) observed¹⁶ in a detailed study of proton transport in a number of SiO_2 films. We may also note that the pre-exponential factor that was determined for eq. 4 ($\tau_0 = 2 \times 10^{-13} \text{ s}$) is reasonable for ionic transport; it is about a factor of 10 larger than the period associated with the optical phonon vibration in SiO_2 .

The approximate logarithmic buildup of N_{SS} with time follows simply from the dispersive nature of diffusive ionic transport, with the ions being re-released throughout the SiO_2 bulk. The buildup is generally observed to occur over about three decades in

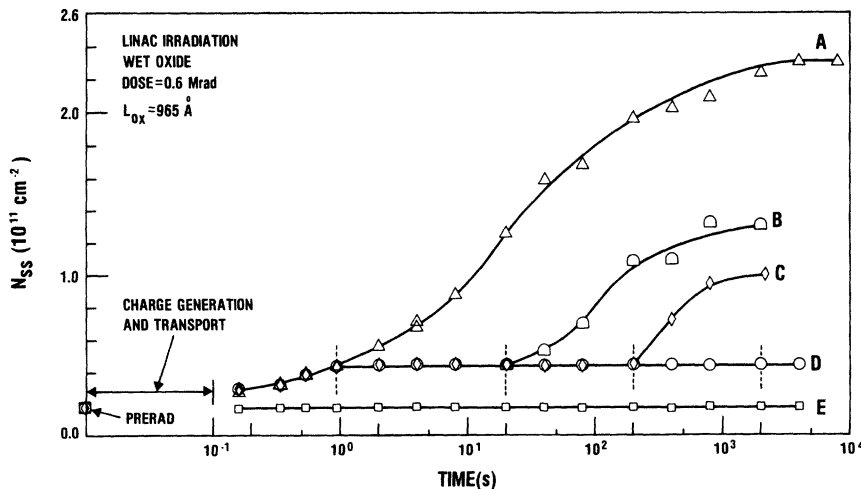


Fig. 4. Effect of reversing polarity of applied field across oxide at varying times for hardened wet-oxide capacitors, illustrating inhibiting effect of negative gate bias on N_{SS} buildup during second stage. The magnitude of the field was 4 MV/cm. Curve A: positive gate bias polarity throughout; Curve E: negative polarity throughout; Curves B, C, D: gate bias initially positive, but polarity reversed at 1 s and then switched back to positive at 20, 200, and 2000 s, respectively.

time. (See curve A of fig. 4). This spread in time is directly correlated with the number of hops required for an ion to transit the entire film (~400), which corresponds to the saturation time for the buildup, whereas the buildup begins at times comparable to a single hop time (for ions released in the immediate vicinity of the interface).

Because no tendency toward saturation with dose up to 20 Mrads (SiO_2) was discernible in either the hard wet or dry oxides, we are unable to estimate the initial concentration of hydrogen in our SiO_2 films. Lower bounds on the concentrations necessary to explain the experimental observations over the dose range studied are $\sim 1 \times 10^{19} \text{ cm}^{-3}$ and $2 \times 10^{18} \text{ cm}^{-3}$ in the wet and dry oxides, respectively. But these are lower bounds only; the actual concentrations may be significantly higher. (See ref. 9.)

We may summarize at this point with the statement that a great amount of the empirical information obtained from the electrical measurements of radiation-induced N_{ss} can be understood simply on the basis of a positive ion release in the bulk by hole transport and the subsequent field-induced drift of the ions to an interface. This, of course, agrees with the essence of the model proposed by Svensson⁸ with the modification that hydrogen ions instead of neutral atomic hydrogen are released and diffuse in the bulk.

C. Interactions at the Interface

When the ions reach the SiO_2/Si interface, they undergo a further interaction which results in the electrically observable interface states. It would appear that this reaction occurs immediately. The time scale for the second stage as well as the results of the bias switching experiments (Fig. 4) can be entirely understood on the basis of field-assisted ion diffusion, and there is no evidence of any significant time delay after the ions reach the interface before the appearance of N_{ss} . This is further indirect evidence that the positive ions involved are H^+ , as they are expected to be highly reactive, whereas the results of bias stress measurements on samples deliberately contaminated with alkali ions (Na^+ , K^+) indicate these ions can be moved freely back and forth across the oxide layer by reversing the bias polarity.

Based on purely electrical measurements one cannot say anything specific about the nature of the interaction at the interface. Assuming the ions are H^+ , it seems entirely reasonable that the H^+ interacts with Si-H bonds in the interface region to form molecular H_2 and leaves a dangling Si bond as suggested by Svensson⁸ and Revesz.⁹ It is also plausible that the H^+ combines with the OH^- in Si-OH bonds forming water and again a dangling Si bond. There is also XPS data¹⁷ which indicate the average oxidation state in the interface region is reduced after ionizing irradiation, the result perhaps of strained Si-O bonds being broken. If the H^+ ions are involved in breaking strained Si-O bonds, then the H^+ would probably actually be incorporated into the network structure at the interface by bonding to either the Si or O atoms.

One comment about the nature of the interface states may be made on the basis of the electrical measurements. That is, the radiation-induced interface state distributions (in energy across the Si bandgap) are almost always observed to be U-shaped, with a relatively flat minimum near midgap and rising sharply toward the conduction and valence band edges. Recent density of state calculations for the SiO_2/Si system¹⁸ indicate that a specific defect in the inter-

face region, e.g., a dangling Si bond, results in a peaked structure in the density of states distribution function, which sharply contrasts with the universally observed U-shaped distributions. The calculations show, however, that fluctuations in bond angles and lengths in the interface region can result in U-shape distributions via band tailing from both the Si conduction and valence bands. The most probable origin of such fluctuations is localized microscopic strain fields.

The presence of strain fields localized in the interface region of thermally grown oxides has been inferred from recent XPS studies.¹⁹ The generation of additional localized strain fields after irradiation is in principle compatible with any of the interactions mentioned above as well as other possible interactions. There is in general a certain amount of local reconstruction that occurs with the formation of any defect in SiO_2 , or even with changing the charge state of a defect due to the large lattice coupling with charge centers in SiO_2 (the polaron effect). As one example, there is well documented EPR evidence²⁰ of a local reconstruction associated with the formation of E' centers in vitreous SiO_2 . Another possibility is related to a class of defects, the so-called valence alternation pairs, which are under increasingly active discussion²¹⁻²³ in the theory of amorphous semiconductors, particularly the chalcogenide glasses, and have been discussed recently in connection with the nature of intrinsic defects in vitreous SiO_2 .²⁴⁻²⁶ They provide a possible link between dangling Si bonds, appearing perhaps via interactions with H^+ ions as discussed above, and large localized strain fields. Briefly, a dangling Si bond is thought to be unstable against bonding with a lone pair (nonbonding) p electron on a nearby O atom. This leads to a strained reconstructed region in which the Si atom is in the normal four-fold coordination configuration but bonded to a three-fold coordinated O atom which was previously doubly coordinated. The question of whether such defects can exist in SiO_2 is presently under active debate. The concept is in question precisely because of the large strain fields, namely, that the energy lost to the strain fields may more than offset the gain in electronic energy from the new bonding configuration.

D. Dose Dependence

Thus far the rather anomalous sublinear 2/3 power law dependence of the saturated interface state density on dose has not been addressed. Although the dose dependence enters in the first stage function, eq. 2, it seems to be somewhat separate from the issues discussed above. We note that the $D^{2/3}$ dependence appears to be universal in nature, independent of oxide processing. It was observed⁶ in a number of oxides grown at different laboratories and included both wet and dry, hard and soft oxides. It was observed over a dose range from 0.2 to 20 Mrad (SiO_2) with no evidence of saturation setting in with dose. The observations were made with ^{60}Co irradiation; hence, effects associated with high dose rates would appear to be ruled out. It is possible that a sub-linear dose dependence could result from a distribution of hydrogen bonding energies in the bulk, such that the weaker bonded H^+ would on the average be released first. Hence, as a function of time, the remaining H bonds would be on the average more difficult to break, and the number of ions released per unit dose would decrease with time. However, it would seem that the distribution of bonding energies would be highly sensitive to processing, and, furthermore, that the 2/3 exponent would be purely fortuitous.

It would appear that the universal-like $D^{2/3}$ dependence requires a more general, processing-independent explanation. One possible such explanation is that this dose dependence results from interactions between the electrons occupying the interface states. If one considers that the radiation-induced interface states constitute a surface energy band, then the total number of states is proportional to the total number of defects generated at the interface, and for low doses one expects a linear dependence of N_{SS} on dose. However, due to interactions between the electrons of the band, the states tend to be split apart in energy as the number of states increases. If an inverse distance interaction between the electrons occupying the surface band is assumed, and if the splitting is directly proportional to this interaction, then a sublinear dose dependence for N_{SS} follows in general. But more specifically, if the splitting of the states due to the electron interactions dominates the intrinsic (no interaction) bandwidth, then for regions of energy where the shape of the distribution remains relatively flat (i.e., around the midgap region), a $D^{2/3}$ dependence results. What this argument states in effect is that if two defect centers are created at the interface, each of which lead to an observable midgap interface state if infinitely separated, then due to the repulsive interaction between the interface state electrons the observed number of interface states for finite separation distance is less than two and decreases with decreasing separation distance.

The above discussion is speculative and somewhat over-simplified. The argument hinges to a certain extent on the fact that the observed N_{SS} is an integrated value over a fixed midgap energy range where the density of surface states is generally relatively flat. It also requires a strong interaction between the interface state electrons for the N_{SS} densities observed in the dose range (0.2-20 Mrad) used in the measurements. The density effect may be enhanced by lateral non-uniform (LNU) distributions of interface states, i.e., by clustering effects, and indeed there is experimental evidence²⁷ of a correlation between radiation-induced N_{SS} and LNU charge distributions. The question remains unresolved, however, and further work addressed to the dose dependence issue is clearly indicated.

IV. Summary

We have formulated an empirical model of the time-dependent, two-stage radiation-induced interface state buildup, which describes the dependencies of the buildup on time, field, temperature and dose. In particular, we have shown that the two stage character of the process can be expressed mathematically as the product of two functions, each corresponding to a single stage of the buildup. The first stage function is simply the long-term saturation value of N_{SS} and, for fixed dose, is determined by the magnitude of the applied oxide field during the first (hole transport) stage. The second-stage function describes the time dependence of the buildup, with the time scale related to the field (magnitude and polarity) and temperature during the long-term buildup stage.

We then used the implications of the empirical model to discuss microscopic processes involved in the buildup. Drawing also on some recent field-switching experiments, we attribute the first stage to positive ion release in the bulk of the oxide via interactions with the radiation-generated holes as they transport through the oxide. The ion release mechanism appears

to be ejection over field-reduced potential barriers due to energy transfer from the transporting holes. The final number of interface states (for positive bias) is determined simply by the total number of ions released during the first stage. We argue that the most likely candidate for the released positive ions is H^+ .

The time scale for the second, long-term buildup stage is simply understood by field-assisted ion diffusion through the oxide. Under positive gate polarity the ions drift toward the SiO_2/Si interface where a subsequent interaction results in the appearance of induced interface states. Under negative polarity the positive ions drift toward and are collected at the gate with no N_{SS} buildup observed. With the modification that ionic hydrogen replaces neutral atomic hydrogen, these conclusions concur with an earlier model suggested by Svensson.⁸

On the basis of electrical measurements alone we can say little specific about the interactions of H^+ at the interface. However, we suggest that the universally observed, U-shaped radiation-induced interface state distributions (in energy) may be related to localized strain fields at the interface, the strain fields being generated as the result of the H^+ interactions. We speculate that the rather anomalous $2/3$ power law dependence of N_{SS} on dose results from interactions of the electrons occupying the interface states.

As a final comment we note that the H^+ ion release/drift model for N_{SS} generation is also compatible with results on interface state generation under high field stressing of MOS capacitors recently reported by Hu and Johnson.²⁸ Upon positive bias stressing at 90 K with fields of 7.1-7.5 MV/cm, they found a buildup of positive charge in the oxide layer, but they observed no buildup of interface states. Upon warming the samples to room temperature, however, they observed a time-dependent buildup of N_{SS} , the number of which were correlated with the amount of positive charge initially present at 90 K after bias stressing. These results can be explained on the basis of H^+ ions being released in the bulk during the high field stressing, probably by holes generated as a result of impact ionization by the hot electrons moving under the high fields. But at 90 K the H^+ ions are essentially immobile and remain near their origin points (see fig. 2). However, when the samples are warmed to room temperature the H^+ become mobile, and those which reach the SiO_2/Si interface result in a time dependent N_{SS} buildup. This is completely analogous to the manner in which the time dependent buildup of radiation induced N_{SS} at room temperature was studied in the hard dry oxide⁶ after irradiation at liquid nitrogen temperature.

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