

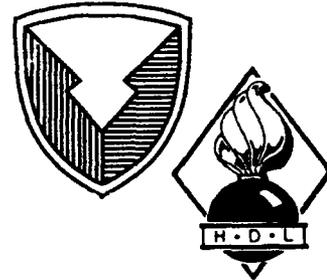
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# An Overview of Radiation-Induced Interface Traps in MOS Structures

by Timothy R. Oldham, F. Barry McLean, H. Edwin Boesch, Jr.,  
and James M. McGarrity

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<p>We focus on radiation-induced interface traps, describing first how they fit into the overall radiation response of metal-oxide semiconductor (MOS) structures. Detailed measurements of the time-, field-, and temperature-dependences of the buildup of radiation-induced interface traps indicate three processes by which the buildup occurs. The largest of these is the slow two-stage process described by McLean and coworkers, which is rate limited by the hopping transport of hydrogen ions. Two other faster processes also contribute small interface trap buildups in gate oxides. The processes seem to be controlled by hole transport to the Si/SiO<sub>2</sub> interface and by neutral hydrogen diffusion, respectively. We also discuss several models which fall into three classes, corresponding roughly to the three processes observed experimentally. Other topics discussed briefly are dose dependence, field oxide effects, chemical and processing dependences, and scaling effects.</p>					
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# 1. Introduction

It has been known for many years that metal-oxide semiconductor (MOS) devices are extremely sensitive to ionizing radiation [1] because electrically charged defects build up in the insulating oxide layers. These defects can cause changes in transistor switching characteristics and excessive leakage currents. The radiation response of MOS oxides involves several different processes, each with its own dependence on time, temperature, applied field, process history, and so on. Thus the overall radiation response of a MOS device is extremely complex. However, much research on this response has been performed by many workers over the years, and each process is understood to a reasonable degree. (For two recent reviews of a great deal of previous work, see ref 2 and 3, and their bibliographies.) The basic picture of the overall radiation response is illustrated schematically in figure 1, where four main processes are pointed out. (For each of the four processes in fig. 1, a corresponding threshold voltage shift is illustrated in fig. 2.)

First, the ionizing radiation interacts with the oxide to produce electron-hole pairs. On the average, one charge pair is produced for each 17 or 18 eV of energy absorbed [4,5]. Depending on the kind of radiation incident and on the applied field, some fraction of these charge pairs will undergo an initial recombination process. The electrons are much more mobile than the holes in  $\text{SiO}_2$ , and they are swept out of the oxide by the applied field in a time on the order of 1 ps [6]. The surviving holes remain near their point of origin. The fraction of holes which survive this initial recombination process can be as high as almost 100 percent for a  $^{60}\text{Co}$  irradiation with a 2-MV/cm applied field or less than 1 percent for, say, a high-energy cosmic ray ion with 0.1 MV/cm applied field [2,3,7,8]. The number of these surviving holes determines the initial response—for example, radiation-induced threshold voltage shift—after a short pulse of radiation.

\*References are listed at the end of the report.

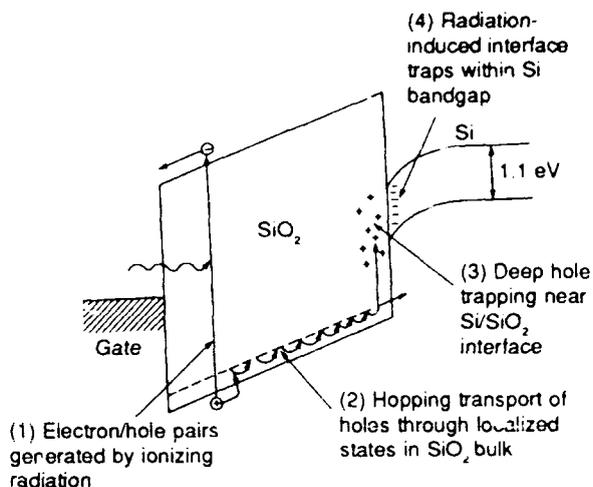


Figure 1. Schematic of basic radiation effects in MOS structures.

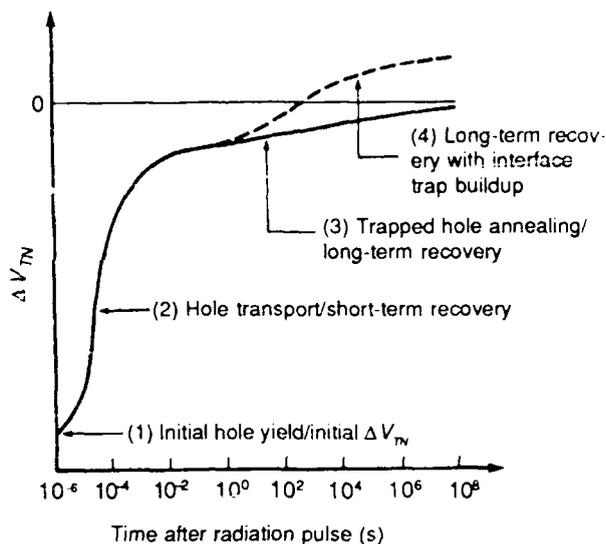


Figure 2. Time-dependent threshold voltage recovery of n-channel MOSFET. Labeled regions correspond to processes in figure 1.

The second process in figure 1 is the transport of the holes to the interface by a hopping transport mechanism which determines the short-term recovery of MOS devices. We discuss this process in more detail later. When the holes approach the interface, some fraction of them fall into deep traps. This fraction can be as little as 1 percent in specially processed radi-

tion hard oxides, or it can be 50 percent or more in unhardened commercial oxides. In figure 2, the threshold voltage recovery for a hardened oxide is shown; as the holes reach the interface, most of them escape. The few holes which are trapped produce a remnant threshold voltage shift which is only a small fraction of the initial shift. These trapped holes then undergo a long-term annealing process which has a roughly  $\ln(t)$  dependence (process No. 3 in fig. 1 and 2). This process extends from milliseconds to years, as we explain later.

The fourth process in figures 1 and 2 is the buildup of radiation-induced interface states, which is the focus of this paper. Since this process depends on the other three processes, it cannot really be treated by itself. Many years ago, radiation-induced interface states were actually considered a helpful thing. The worst-case test condition for radiation damage was usually an n-channel transistor irradiated with the gate voltage high, and the reason for failure was positive charge trapped in the oxide (negative  $\Delta V_T$ ). For this condition, the interface states are negatively charged so that they compensate the positive charge. If a device had enough of an interface state buildup, it might look *very hard*.

More recently, a large buildup of radiation-induced interface states was discovered to be an important problem leading to what was called rebound [9] or superrecovery failure [10]. Basically this problem arises when large numbers of both trapped holes *and* interface states are generated at the same time. The interface states are stable and do not anneal, but most of the trapped holes are eventually removed as a result of the  $\ln(t)$  annealing process we previously mentioned. This situation is illustrated in figure 3 [9], where the trapped hole and interface trap components of  $\Delta V_T$  were determined from the charge separation procedure proposed by Winokur et al [11]. Then one can eventually have a net excess of negatively charged interface states, or a positive  $\Delta V_T$  (this situation is also illustrated in fig. 2). If the positive threshold voltage shift is large enough, it can also cause device failure [9]. The rebound or super-

recovery problem is potentially important for space applications because space systems are typically irradiated at low dose rates for many years. The trapped holes have many years to anneal out, while the interface states have many years to build up.

Another interface-state-related problem of advanced very-large-scale integrated (VLSI) circuits is mobility degradation. It has been known since at least 1967 that a large interface state buildup could reduce channel mobility and, therefore, increase propagation delay times [12]. Although this effect was known, circuit clock speeds were such that it was not generally considered to be an important operational problem. Now, however, the clock speeds of some VLSI circuits are fast enough that mobility degradation from radiation-induced interface trap buildup is the subject of renewed interest [13].

In the remainder of this report, we focus on the radiation-induced interface traps in more detail. A large number of models for these interface traps have been proposed over the years, and they generally fall into three classes. Detailed experiments on the time, field, and temperature dependence of the interface state buildup reveal three separate paths by which interface states are generated. These three observed processes match up (roughly) with the three classes of models.

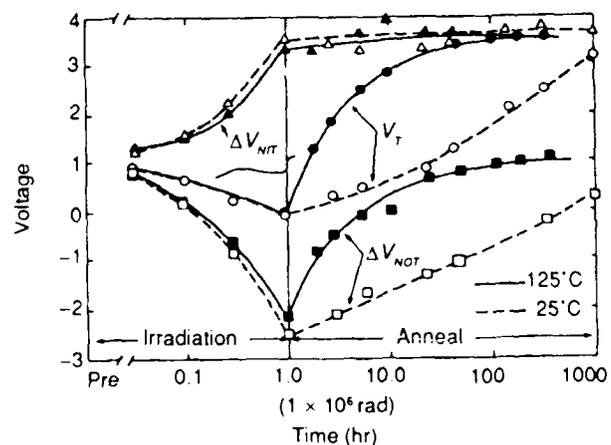


Figure 3.  $\Delta V_T$  to illustrate rebound or superrecovery problem (Schwank et al. [9]).

## 2. Experimental and Theoretical Background

We now review the work on radiation-induced interface traps and try to fit together the various reported results to construct a coherent framework to describe what is known. We also point out areas in which important questions remain unanswered. Specifically, we discuss several models which have been proposed, along with the relevant experimental results. These models fall into three classes. First, a two-stage model was presented by McLean [14], where radiation-generated holes free hydrogen ions in the  $\text{SiO}_2$  bulk as they transport through the oxide (first stage). Then, in the second stage, the liberated hydrogen ions undergo a dispersive hopping transport which controls the rate of interface state formation. This model was developed by McLean [14] to explain an extensive set of experimental results on Al gate devices obtained by Winokur, Boesch, and McGarrity over a period of several years [15-23]. Most of these results have been confirmed more recently by Saks and coworkers [24-26], and by further work by Boesch [27] using poly-Si gate devices.

The second broad class of models assigns a key role to the diffusion of neutral hydrogen at some point in the process of generating the interface states. An early model was proposed by Svensson [28], based on even earlier work by Revesz [29], for a two-stage model where  $\text{H}_2$  diffusion was critical in the second stage. However, this model does not predict the field and polarity dependences which have been observed [18-20]. A later diffusion model was proposed by Griscom [30] as an alternative to the McLean model for charged hydrogen transport. Griscom used some of the same experimental data [19-21] that McLean had used to develop his model. But Griscom originally argued that diffusion of neutral hydrogen could also explain the data if one assumed that the chemical reaction which occurred when the hydrogen reached the interface required an electron from the substrate. This electron would

be supplied only if positive bias were applied, accounting for the polarity dependence in the data. The Griscom model was extended by Brown [31], who showed that improving some of the initial assumptions also improved agreement with experiment.

The third class of models might be generally called trapped hole models. In these models, a hole is trapped near the Si/ $\text{SiO}_2$  interface and eventually converts into an interface state. For example, the so-called bond strain gradient (BSG) model [32-34] assumes that a radiation-induced hole is trapped in a narrow strained transition layer of oxide near the Si interface. The Si-O bonds are more strained closer to the interface. The trapping process breaks a strained Si-O-Si bond, leading to a trivalent Si which is not mobile and a mobile nonbridging oxygen. The nonbridging oxygen propagates to the interface, relieving more and more strain as it moves. When it reaches the interface, this oxygen undergoes an unspecified reaction, and an interface state results [33]. Other variations of this same basic idea have been proposed by Lai [35] and Wang et al. [36]. Lai [35] proposed that interface states are produced when an electron tunnels from the Si to annihilate the trapped hole. Wang et al. [36] propose a very similar model except that the trapped holes are divided into two classes, one near the interface which is converted into interface states and one farther from the interface which does not give rise to interface states.

Experimentally, a striking degree of consensus has emerged in the last few years. The original experimental work [15-23] leading to the McLean model [14] was performed using metal gate capacitors with a variety of different oxides. However, Winokur et al. [37] suggested that in poly-Si gate technologies, the mechanism for  $\Delta N_{it}$  generation might be different. Recently a similar series of experiments have been performed by Saks et al. [24-26] on poly-Si gate transistors. A major difference between these two groups of experiments is that the early work [15-23] used standard capacitance-voltage (C-V) techniques, whereas the later work

[24-27] used the more sensitive charge-pumping technique [38]. Both the charge-pumping experiments and the C-V measurements have led to the conclusion that the main effect is due to the relatively slow two-stage process first described by McLean [14]. However, the more sensitive charge-pumping technique has also allowed two other smaller processes to be resolved which also contribute part of the total radiation-induced interface state buildup. Following the first charge-pumping results presented by Saks [24], Boesch [27]—who also performed many of the early measurements—has also begun to use charge pumping to examine the early time interface-state generation. At this time, both groups are in agreement that three different processes contribute to the time-dependent buildup of radiation-induced interface states. Both groups are also in agreement on what those three processes are and on the relative magnitude of each process.

By far the largest effect is the relatively slow field-dependent two-stage process described by the McLean model [14]. Typically this process accounts for 90 percent or more of the total interface state buildup, depending somewhat on which samples one studies [15-27]. The second largest process is a relatively fast field-dependent process which correlates with the arrival of radiation-induced holes at the interface. This process accounts for most of the rest of the radiation-induced interface states [25,27]. (In VLSI oxides at room temperature, the hole transport process is typically complete in a time on the order of microseconds. If the trapping and defect conversion times are shorter than the transport time, this process might be reconciled with one or more of the hole-trapping models we have mentioned [32-36]). The third process, which leads to the smallest effect in gate oxides, seems to be a diffusion process of a neutral species because there is no field polarity dependence [26,27]. This process has also been reported by Boesch in thick field oxides [39,40]. This process is not always observed in the gate oxides, but it was reported by Saks [26] (only) at low temperature and by Boesch [27] at room

temperature (but not in all samples). Note that the three processes observed experimentally match up with the three classes of models, so that all the models may have to be invoked for a complete description of  $\Delta N_{IT}$ .

All the experiments we have mentioned so far are electrical measurements of the time, field, and temperature dependence of the interface state generation process. They can provide clues about the process by which one obtains a radiation-induced interface state, but electrical measurements by themselves do not reveal the microscopic nature of the defect. Although we have identified three paths to a radiation-induced interface state, it is possible, or even probable, that the final electrically active defect is the same in all three cases. The main technique for determining the structure of individual defects has been electron spin resonance (ESR).

Using ESR, Lenahan and others [41-45] have identified the  $P_{b0}$  center with the radiation-induced interface state on (111) Si. The  $P_b$  center was first observed by Nishi [46,47] and identified by Caplan et al. [48] as a trivalent Si bonded to three other Si atoms at the interface. The dangling fourth bond extends into the oxide, normal to the interface on a (111) surface. However, on the technologically important (100) surface, Poindexter et al. [49,50] have observed two  $P_b$  centers,  $P_{b0}$  and  $P_{b1}$ , which they identify as process-induced interface states. Poindexter et al. speculated that the  $P_{b1}$  center is a trivalent Si bonded to two Si atoms and one oxygen atom, with the dangling fourth bond extending into the oxide at a nonnormal angle [49]. However, they are not sure of this identification, so the exact structure of the  $P_{b1}$  center remains uncertain. Recently, Kim and Lenahan [51] have reported additional ESR studies of samples prepared on (100) surfaces. When they exposed the samples to ionizing radiation, they found that the radiation-induced interface state buildup consisted entirely of  $P_{b0}$  centers. They suggested that this result might be a general one because they observed no buildup of  $P_{b1}$  centers on any of three dissimilar oxides. We have no convincing explanation why the interface state

corresponding to the  $P_{b1}$  center does not increase with radiation, but the empirical evidence suggests that such is the case. We note that different annealing kinetics have been reported for  $P_{b0}$  and  $P_{b1}$  centers [52,53], but it is not clear that this observation is related to the radiation response of these centers.

The specific chemistry of interface state production and especially the processing chemistry by which one might control the buildup of radiation-induced interface states are subjects with an extensive literature—too extensive for us to cover in any detail in this report. However, we must briefly discuss these subjects, especially the role of hydrogen, because two of the groups of models we have mentioned require hydrogen to transport to the interface and to react there.

We next discuss the three groups of models and supporting experiments in more detail.

## 2.1 Two-Stage Model and Supporting Experiments

The full two-stage model was first developed by McLean [14] to explain results obtained by his coworkers over a period of several years [15-23]. In the first stage, holes transporting through the oxide interact with the oxide lattice to produce a positive ion (probably  $H^+$ ). A full description of the hole transport process is beyond the scope of this report. However, we will describe it briefly now because all the models and observed interface state generation processes depend to some degree on hole transport and because the hopping transport of hydrogen ions (in the second stage) is similar in many ways to the hole transport process.

The best overall description of the hole transport data seems to be provided by a stochastic hopping transport model. The continuous-time-random-walk (CTRW) formalism developed by Montroll, Weiss, and others [54-57] has been applied to hole transport in  $SiO_2$  by McLean, Hughes, and others [22,58-68]. (See also McLean and Oldham [2].) The specific intersite charge transfer mechanism seems to be

polaron-like hopping of the holes between localized, energetically shallow trap states having a random spatial distribution but separated by an average distance of  $\sim 1$  nm. The term polaron refers to the situation in which the charge carrier (hole) interacts with the lattice, inducing a significant distortion near the carrier. As the carrier moves through the oxide, it carries the lattice distortion with it. The hopping event itself seems to be a phonon-assisted tunneling transition between adjoining traps. The radiation response can be written generally as a function of a disorder parameter,  $\alpha$ , and a characteristic transit time,  $t_t$ . The parameter  $\alpha$  depends only on the degree of disorder in the material, and describes the shape of the response curve. The characteristic time,  $t_t$ , depends strongly on temperature, applied field, and oxide thickness. An important consequence of this model is that the farther a carrier goes, the more chance it has of finding itself in a hard hop situation, where the next hop is to a relatively faraway site. In a thick oxide, many carriers will eventually fall into very long-lived traps, and the average velocity of carriers will become very small. Thus, it is implicit in the model, and confirmed experimentally, that the transport is very dispersive, taking place over many decades in time. In a typical case for hardened oxides, the carrier transit time varies roughly as  $d_{ox}^4$  and the time for half the hole transport to be completed is about  $3 \times 10^{-4}$  s for a 100-nm oxide at room temperature with 1-MV/cm applied field.

Earlier, Revesz [29] and Svensson [28] had proposed that transporting holes broke Si-H bonds in the bulk of the oxide, leaving positively charged trivalent Si centers in the bulk and hydrogen atoms which were free to diffuse away. Svensson [28] also suggested that when this hydrogen reached the interface it could break an Si-H bond producing  $H_2$  and a dangling Si bond, agreeing in part with an earlier paper by Sah [69]. However, this diffusion model does not predict the field dependences in the interface state generation process which are actually observed, although it does predict

a two-stage process. Specifically, Winokur et al. [19] reported that the magnitude of the field (but *not* the polarity) in the first stage (hole transport) controlled the final late-time saturation value of the interface states. Positive field was necessary in the second stage for interface state formation, and the magnitude of the field during the second stage determined the rate at which interface states built up, but the saturation value of  $\Delta N_{it}$  was independent of oxide field magnitude during the second stage.

McLean [14] noted that the final saturation value of the interface state density at late time showed an exponential dependence on the square root of the applied field, which is a classic signature of the Schottky effect, charge ejection over a field-reduced coulomb-like ( $1/r$  potential) barrier (see fig. 4). This dependence suggests an interaction of the holes that releases an ionic charge. Since this first stage is temperature independent, all the energy for the ion release is obtained from the energy exchange between the transporting holes and the lattice via the polaron-hopping process. McLean concluded that "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." He argued that the ion was most likely  $H^+$ , and not, for example,  $Na^+$ . He also concluded from field switching experiments by Boesch and Winokur [19,23] that the interaction freeing the ions had to occur in the bulk oxide. If the bias was negative during the first stage, the holes would be removed at the gate, and the hole flux at the Si/SiO<sub>2</sub> interface would be much less than if the bias were positive. Whether the bias is positive or negative during the hole transport process, however, the interface state buildup is virtually identical if the same positive bias was applied during the second stage for  $t > 1$  s [14].

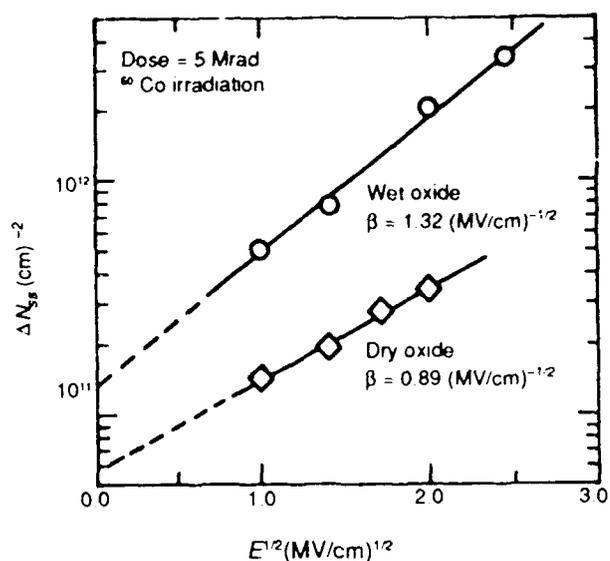


Figure 4. Saturation value of  $\Delta N_{it}$  with applied field during first stage of McLean two-stage model.

In the second stage, McLean [14] argued that the long-term interface state buildup could easily be explained as field-assisted ionic transport to the interface with a subsequent reaction at the interface. He noted that the temperature dependence of this second-stage process (see fig. 5) led to an activation energy  $\Delta = 0.82$  eV at zero applied field. Values of 0.7 to 0.92 eV had been reported for proton transport in SiO<sub>2</sub> [70], so this activation energy is consistent with hydrogen ion transport. (On the other hand, diffusion of neutral hydrogen has a much lower activation energy—0.3 eV is a value commonly quoted [29].) McLean also applied a hopping transport analysis and concluded that the average hopping distance is about 2.6 Å (see fig. 6). He points out that this is precisely the distance between nearest neighbor oxygen atoms in SiO<sub>2</sub>, and suggests that the  $H^+$  ions bond temporarily to the nonbonding lone pair-orbitals of the oxygen atoms. The ions then move by hopping from oxygen to oxygen through the oxide. The requirement for positive bias during the second (ionic transport) stage is then simply explained

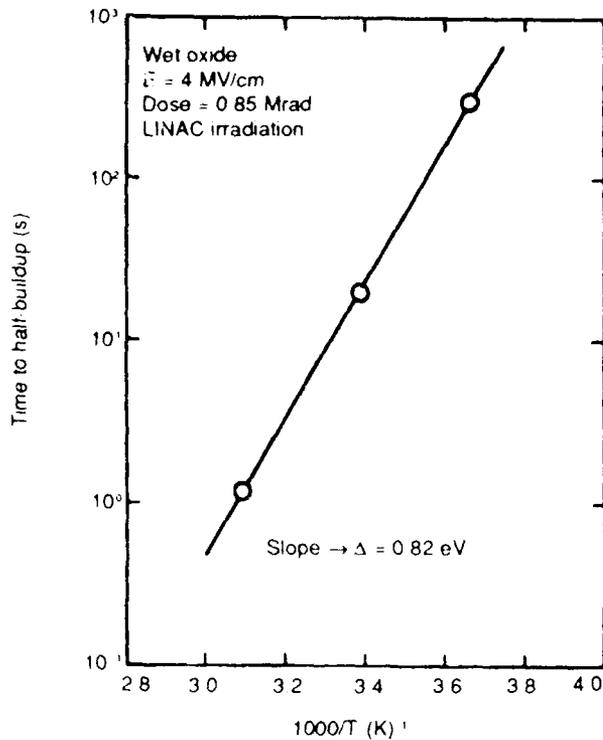


Figure 5. Temperature dependence and activation energy of second stage (hydrogen ion transport) of McLean model.

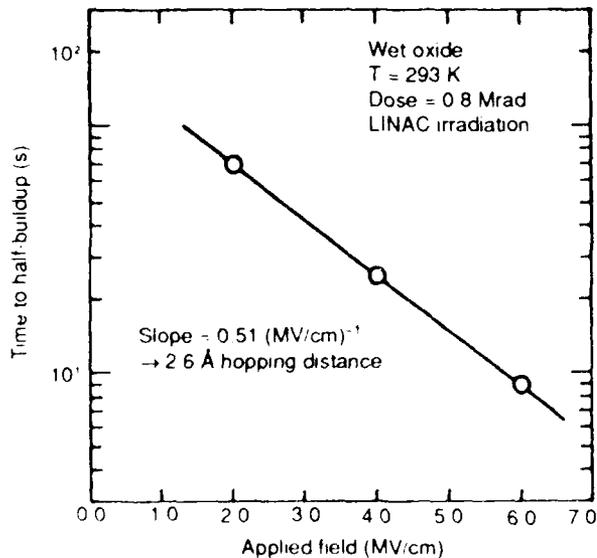


Figure 6. Field dependence of second-stage process (hydrogen ion transport) of McLean model.

because a positive field is necessary to move a positive ion to the interface.

In figure 7 [21] we show field switching data which illustrate how strongly a negative field applied during the second stage inhibits the interface state buildup. Samples with a field of  $\pm 4$  MV/cm applied receive a pulsed irradiation to a dose of 0.6 Mrad. In sample E, the field polarity is negative throughout the experiment, and no increase from the preradiation interface state value is observed. For sample A, the field is *positive* 4 MV/cm throughout, resulting in a late-time buildup from 1 to more than 1000 s after the radiation and hole transport. For samples B, C, and D, the field is positive for 1 s, which is much longer than the holes take to reach the interface. At 1 s, only a few interface states have formed, even though all the holes have reached the interface. Then the field is switched negative in all three samples. In none of the samples does the number of interface states increase while the field is negative. In samples B and C, the field is switched positive again after different amounts of time, and the interface state buildup resumes immediately, although approaching a lower saturation value for  $\Delta N_{IT}$  than in sample A.

Recently, two additional sets of experiments have been performed which have tended to confirm the model by McLean [14] and the experiments on which it was based [15-23]. First, Saks [24] measured the time scale for radiation-induced interface state buildup as a function of both oxide thickness and applied field. Saks concluded that the McLean hydrogen ion model fitted his results, in his words, "neatly and compactly." On the other hand, the Griscom diffusion model [30] failed to explain the oxide field dependence of either stage in the two-stage model.

A third set of field switching experiments performed by Boesch [27] led to basically the same conclusions. One remarkable result is shown in figure 8. In one case (open circles) a sample was exposed to a 4- $\mu$ s radiation pulse with a field of +2 MV/cm applied, and the same field was maintained after the pulse. The two-stage buildup of interface states seems to begin around 0.1 s, and by 1 s about  $10^{11}/\text{cm}^2\text{-eV}$

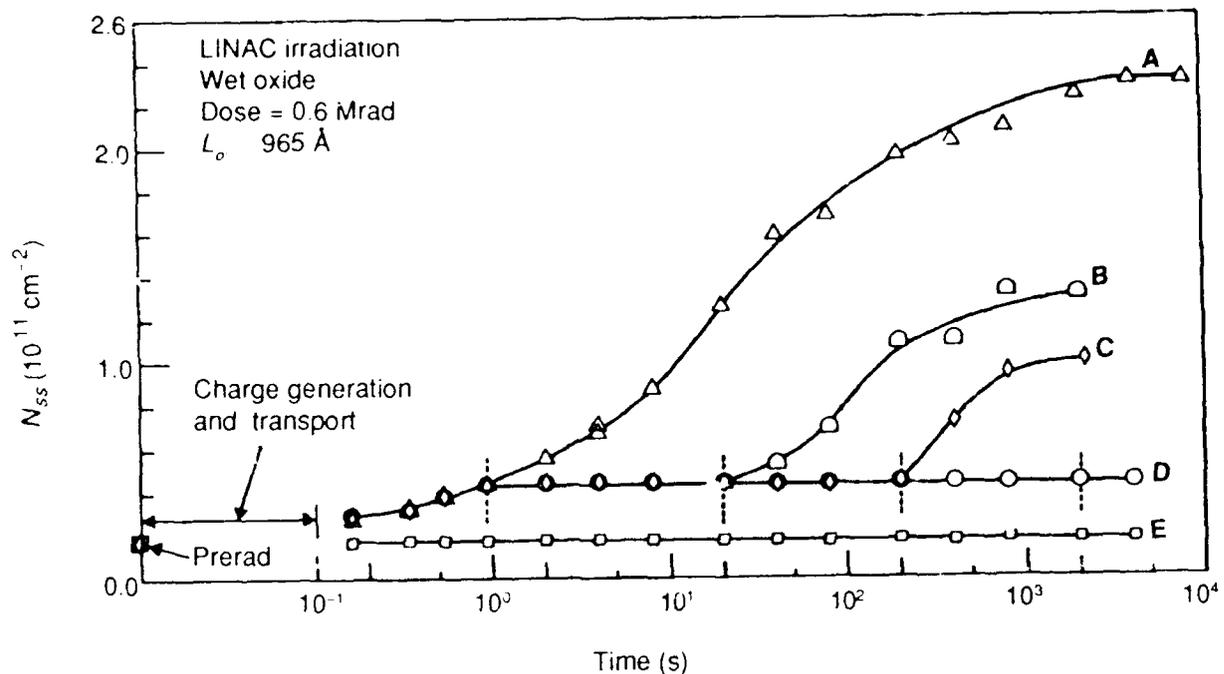


Figure 7. Field switching experiments showing importance of positive field during second stage of McLean model.

states have resulted. In a second case (solid triangles), Boesch irradiated another sample with a negative field applied, but  $10 \mu\text{s}$  after the pulse, he switched the bias to  $+2 \text{ MV/cm}$  (the same field as in the first case). A similar two-stage buildup of interface states is observed, but it is delayed by about two decades in time! The interface state buildup observed at  $1 \text{ s}$  in the first case is delayed until about  $100 \text{ s}$  by a change in the field during the first  $10^{-5} \text{ s}$ . (We note that Saks [25] performed a detailed set of similar experiments where he systematically varied the time at which the bias was switched over a wide range. He obtained comparable results.) This result can be explained by a dispersive charged particle hopping transport model, because the ions are initially pushed away from the interface. Then they have farther to go to reach the interface when the field is switched positive, and the transit time is a very strong superlinear function of thickness in a dispersive transport model, as we have already explained for the case of hole transport.

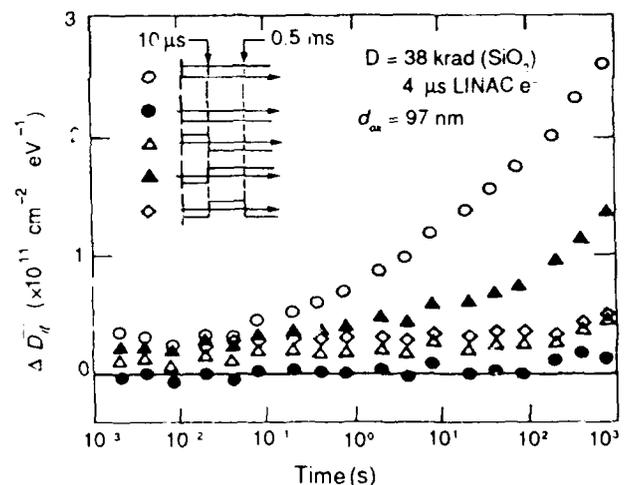


Figure 8. Time-dependent generation of interface states in field switching experiments on poly-Si gate MOSFET's determined by charge pumping.

On the other hand, there is no conceivable way to explain this result with a diffusion model. Recently, Brown et al. applied CTRW analysis to the  $\text{H}^+$  transport, with very good results [71].

## 2.2 Prompt Interface States and Models

All these experimental results taken together provide overwhelming evidence that the main process for radiation-induced interface state generation is the two-stage model proposed by McLean [14], where the hopping transport of hydrogen ions determines the time scale of the interface state buildup. However, it has become clear that at least two other processes also contribute to the total interface state buildup. Although Boesch had reported prompt interface states in field oxides [39,40], the paper which started serious discussion of these processes in gate oxides was presented by Schwank et al. in 1986 [72]. Schwank pointed out that up to that time, most of the experiments supporting the McLean model were obtained on metal-gate capacitors. In his experiments, he used poly-Si gate capacitors because they more nearly represent advanced MOS processes. He found that a significant part of the radiation-induced interface state buildup occurred too rapidly to be attributed to the slow two-stage hopping transport process. Schwank et al. speculated, "the rapid buildup component may result from hole transport and trapping at the silicon/silicon dioxide interface followed by injection of electrons from the silicon," which is similar to the Lai model [35]. Schwank was led to make the connection between hole trapping and prompt interface state buildup by results illustrated in figure 9. Both interface state buildup and hole trapping show the same qualitative field dependence, although the scales for the two processes are different.

Subsequently, Schwank et al. [73] performed additional studies varying the amount of hydrogen used in processing the samples. Schwank et al. then discussed several chemical processes which might account for the results in figure 9 and other results which he presented. Contrary to his earlier speculation [72], he concluded, "For none of the mechanisms described above is it necessary for an oxide trapped charge to be specifically converted di-

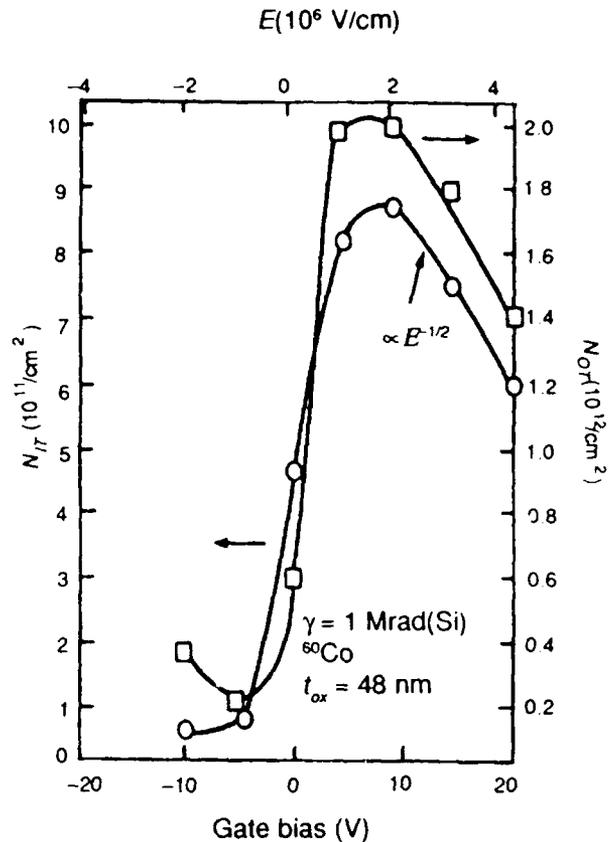


Figure 9. Field dependence of hole trapping and saturation value of  $\Delta N_T$  in Si-gate capacitors.

rectly into an interface trap," although this process could not be excluded completely. The results in figure 9 for the qualitative field dependence of the interface state buildup have been confirmed by Saks [25] and Boesch [26]. At this time it seems that this field dependence is the main experimental difference between the metal-gate samples described by McLean [14] and other more recent samples with more advanced gate deposition technologies. This work by Schwank et al. stimulated other studies by Saks et al. [24-26] and Boesch [27] on a variety of Si-gate samples.

These later studies by Saks et al. [24-26] and Boesch [27] have shown that the early-time interface state buildup discussed by Schwank et al. [72] is usually a small part of the total interface state buildup in gate oxides, and that

actually two processes are involved. In discussing these processes, we speak of prompt states, fast states, and so on. These labels are interchangeable, and we use them to refer to states which build up before the first measurement after, say, a linear accelerator (LINAC) pulse. If a radiation pulse of a few microseconds is delivered to a MOS structure, the photocurrents will persist for a time which generally precludes any measurement of  $\Delta N_{IT}$  before about 0.1 ms. These fast states are taken to be those already present at 1 ms at room temperature.

Boesch [27] concluded that the rate of prompt interface state generation is controlled primarily by the rate at which transporting holes reach the Si/SiO<sub>2</sub> interface. The reasons for this conclusion are illustrated in figure 10. The open circles show the change in interface state density as a function of time following a pulsed irradiation at room temperature for a sample with a field of +1 MV/cm maintained throughout. The data points (read from the vertical scale on the left) show an interface state density of  $2 \times 10^{10}/\text{cm}^2\text{-eV}$  at 20 ms, the time of the earliest measurement. The solid circles show the interface trap density for an identical experiment except that the temperature of the sample is lowered to 200 K. These points are to be read from the right-hand vertical scale which, we emphasize, is an order of magnitude different from the left-hand scale. The final interface trap density value at 800 s and 200 K is only approaching the level reached at 20 ms at room temperature. Thus the prompt buildup can be slowed down enough for study at 200 K. The results in figure 10 correlate very well with an independent calculation of the hole transport. For example, Boesch estimated that three-fourths of the transporting holes at 200 K will reach the interface by about 0.8 s. Almost three-fourths of the prompt interface traps are observed at this time. A number of experiments in which fields were switched from positive to negative (or vice versa) at different times are also described by Boesch [27], and the results

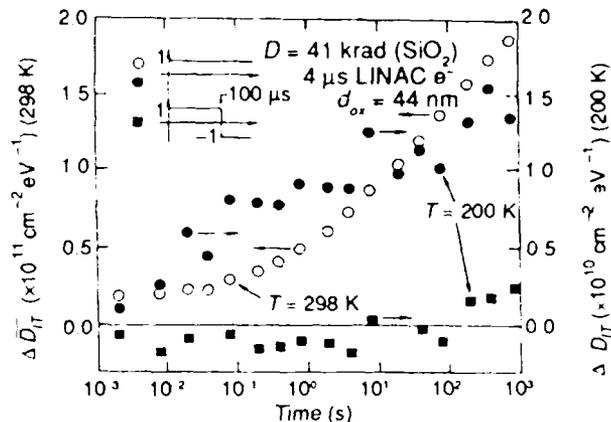


Figure 10. Low-temperature measurements of "fast"  $\Delta N_{IT}$  showing correlation with hole transport.

consistently supported the hole transport hypothesis. For a full discussion of these results, we refer the reader to the original paper.

We note that Saks et al. [25] also discussed this early time process, and he also concluded, "the early process appears rate-limited by hole transport to the interface." He reached this conclusion also from field switching experiments and calculations of hole transport times. Although both Saks [25] and Boesch [27] agree that this prompt buildup from the hole transport is typically around 10 percent of the total buildup, both have observed cases in which it is somewhat larger.

We have already cited several models based on the idea that a hole trapped near the interface somehow becomes an interface trap [32-36], and we have pointed out that these models might be reconciled with this prompt interface trap generation process. We note that the rate-limiting step is the hole transport process, which means that any trapping and defect transformation processes have to occur more rapidly than the transport itself. This constraint on the defect transformation rate is significant because the transport process is usually over in 1 ms or less at room temperature, and many experiments do not have this kind of time resolution. Of course the authors of these hole trap models [32-36] were not trying to explain a

small, second-order effect which occurred only at very early times and which has often been overlooked completely. Those authors were trying to explain the *entire* radiation-induced buildup of interface traps, or at least most of it. Our view is that these models may be applicable to the prompt second-order process, but they clearly fail to account for the largest component of the radiation-induced interface trap buildup. There are three reasons for this view.

First, in the field switching experiments cited by McLean, sets of measurements were performed in which the bias was either positive or negative during the hole transport. Obviously, the flux of holes at the Si/SiO<sub>2</sub> interface was much greater under positive bias than under negative bias, as was the number of holes trapped. But if the bias was switched positive immediately after the hole transport phase, essentially the same (large) interface buildup was observed in both cases. The interface trap buildup was the same, whether the hole trapping was large or small. Similarly, if the bias was switched negative after the hole transport, the interface trap buildup was the same, whether the hole trapping was large or small. Some of these results are shown in figure 11 [73], where curve A is maintained under constant +4 MV/cm. Curve B is from a sample irradiated at -4 MV/m, but the bias is switched positive at 0.8 s, long after the holes have been swept out of the oxide at the gate interface. Nevertheless, sample B and sample A have almost the same interface trap density by 2000 s. Similarly, if the bias was switched negative after the hole transport, the interface trap buildup was suppressed, whether the hole trapping was large or small (see fig. 7).

Second, Winokur et al. [17] showed that the hole transport and trapping process is separated by many decades in time from the interface trap formation process.

Third, the detrapping process (annealing) of trapped holes has been studied extensively, and it also has a time dependence different from that of the interface trap formation process [9,74-77]. A full discussion of the trapped

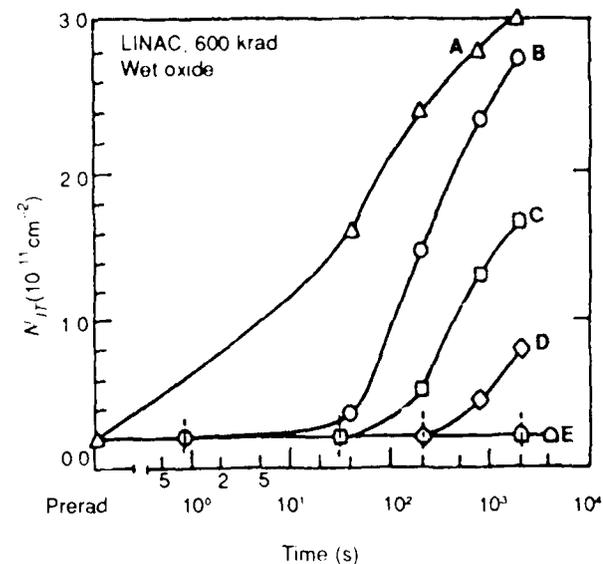


Figure 11. Comparison of hole transport times with interface trap formation.

hole annealing process is beyond the scope of this report, but many authors have attributed it to a tunneling process [9,77-83]. Experimentally, the annealing process in gate oxides is observed to be roughly logarithmic in time, with approximately the same number of trapped holes removed (or compensated) during each decade of time. Tunneling models predict exactly a  $\ln(t)$  dependence for this process if the hole traps all lie at the same energy level and if the trap density is uniform with depth into the oxide. If either of those assumptions is not strictly true, the annealing rate will deviate somewhat from a simple  $\ln(t)$  dependence. But *roughly*  $\ln(t)$  annealing behavior is normally observed. In our own annealing experiments, we have observed annealing of trapped holes from as little as 10<sup>4</sup> s to beyond 10<sup>7</sup> s in some cases, and have observed approximate  $\ln(t)$  for as long as we continue monitoring (see, for example, fig. 12). For some radiation soft oxides, only a few percent of the holes anneal per decade. For figure 12, the annealing rate is about 20 mV/decade (or about 5 percent of  $\Delta V_{OT}$ /decade) over 10 decades in time. A tunneling model predicts that this oxide would continue to show trapped hole annealing at the

same rate for another 10 decades before all the trapped holes are removed for a uniform spatial density of trapped holes. We point out that 10 more decades would be  $10^{17}$  s, which is approximately the present age of the earth! For the sample in figure 12, we did not do detailed measurements of interface trap formation rate. But in similar tests of other samples from the same wafer, the interface trap formation was complete before about 200 s, which is much less than the age of the earth. Thus the time history of the interface trap formation is quite different from the time history of the trapped hole annealing for the soft oxide in figure 12.

In figure 13, we compare the number of holes arriving at the interface per decade (curve A) with the number of trapped holes removed (or compensated) by annealing per decade (curve B) and with the number of interface traps produced per decade (curve C) for a hardened oxide. These curves were obtained from a series of exposures of radiation-hardened MOSFET's to 4- $\mu$ s LINAC pulses [27,84] and from the work by McLean [85] on the generic impulse response function. As we have noted, there is a small, second-order component of the radiation-induced interface trap buildup which correlates in time with curve A, but which is reduced by about two orders of magnitude. However, the peak of the main interface trap buildup occurs about eight decades in time after the peak of the hole flux at the interface. Similarly the annealing of trapped holes begins about three decades in time before the interface state formation begins. Furthermore, at the peak of curve C the number of interface traps formed exceeds the number of holes removed. Clearly a defect transformation model where one trapped hole becomes one interface state cannot account for many of the key features of the results in figure 13. (In fig. 13, the oxide is a radiation-hardened one which does not trap holes very efficiently.) The trapped hole annealing drops off after about  $10^3$  s because nearly all the trapped holes were annealed at that time. This time does agree roughly with the end of the interface trap formation.

This agreement does not hold in general, however. Recall that the trapped hole annealing continued at the same rate for many decades after the end of the interface trap formation process for the soft sample used in figure 12.

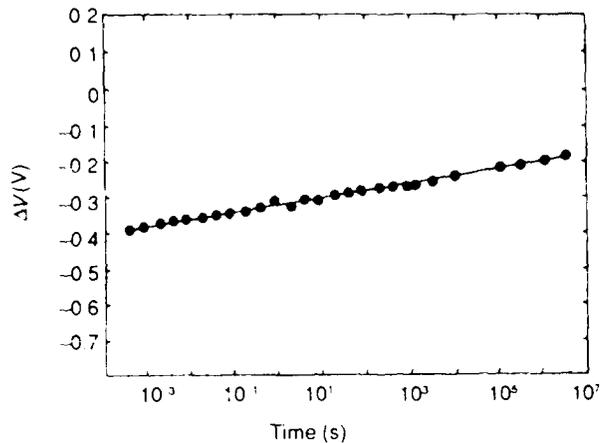


Figure 12. Trapped hole annealing (or compensation) of a soft oxide exposed to 100 krad( $\text{SiO}_2$ ) with +1.25-MV/cm applied field following 4- $\mu$ s LINAC exposure. Interface state formation was complete before 200 s.

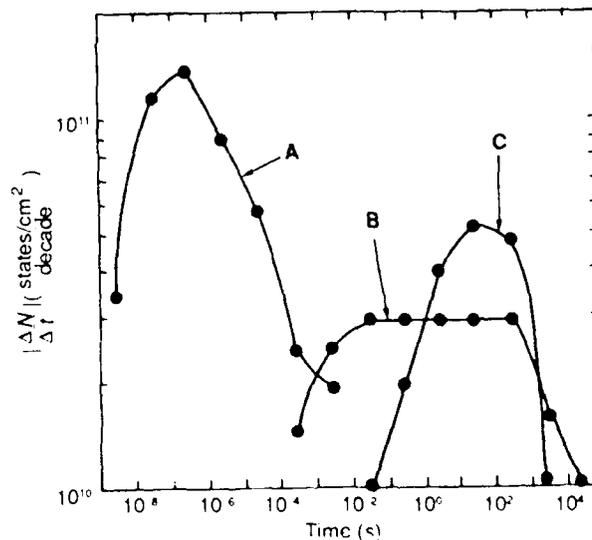


Figure 13. For hardened oxide exposed to a 4- $\mu$ s LINAC pulse: curve A—number of holes/cm<sup>2</sup> reaching interface per decade; curve B— number of trapped holes/cm<sup>2</sup> removed or compensated per decade; and curve C— number of interface traps/cm<sup>2</sup> formed per decade. Interface trap formation does not correlate with holes arriving at interface or with trapped hole annealing

The results we have discussed do not prove that a trapped hole can never be converted somehow to an interface trap, and as we have said, the small second-order process correlating with hole transport may actually fit very well with such models. But it is our view that trapped hole conversion models are—at best—seriously incomplete in that they fail to account for the main component of the radiation-induced interface trap buildup.

Nevertheless, these trapped hole conversion models still have proponents. Recently, for example, Wang et al. [36] concluded, "Our experiments clearly show that holes must be present in the oxide until the interface states form." They also cited McLean [14] and said, "We do not see any way to integrate our results with the experiments which appear to show interface state generation long after the holes have been swept out of the oxide." We see one possible way to reconcile the results we have presented here with some of the results of Wang et al. [36], but it raises the fundamental question of what an interface trap is. Our view is that interface traps are dangling bonds located at the Si/SiO<sub>2</sub> interface, having energy levels in or near the Si bandgap. This statement implies that interface traps are in equilibrium with the Si substrate, meaning that they exchange charge with the substrate freely in either direction in response to small voltage changes (e.g., a 15-mV ac probe voltage in a typical high-frequency CV measurement). For this reason, interface traps tend to appear in typical CV or IV measurements as slope changes rather than parallel translations of curves.

We recently presented the results of a new study on the nature of the hole trap [78]. We concluded that when a trapped hole is "removed" by capturing an electron, it is not necessarily always removed. Rather, it can be compensated by an electron trap nearby, so that the entire complex is neutralized. If, however, a large enough negative bias is applied, this compensating electron can tunnel back to the Si substrate, leaving a net positively charged defect again. In our view these states are hole

traps because they are typically located at least a few monolayers into the oxide, and we estimate their energy level to be well below the Si band gap. For this reason, these states appear in high-frequency CV and IV curves as parallel translations rather than slope changes. We recognize that we are dealing here in a gray area where different researchers might reasonably interpret results differently. We call these states hole traps because they do not act electrically as we expect interface traps to act. That is, they do not exchange charge with the substrate in the manner of "standard" interface traps. On the other hand, they might be taken for interface traps in some experiments because they do exchange charge with the substrate by a *different process*. Wang et al. [36] conclude that hole traps near the interface capture an electron, undergo an unspecified transformation process, and become interface traps—presumably meaning that they subsequently exchange charge with the substrate. Our results [78] suggest that hole traps near the interface can capture an electron by tunneling, which they can subsequently exchange with the substrate *without any defect transformation process*. So we offer as a hypothesis to be tested the view that no defect transformation is necessary to account for the results reported by Wang et al. [36]—hole traps which remain hole traps are sufficient if charge compensation is taking place.

### 2.3 Hydrogen Diffusion Process

The third and smallest component of the radiation-induced interface trap buildup in gate oxides is a fast process which is field (polarity) independent. Diffusion of neutral hydrogen is a natural candidate for the rate limiting step for this process. The most popular diffusion model is that of Griscom [30], who was, however, not trying to explain a small, second-order, fast process. He was trying to explain the main component of the radiation-induced interface trap buildup, so that he required an electron from the Si substrate (supplied by a positive applied bias) to complete the interface genera-

tion process. He also chose parameters so that the time scale for the generation process was on the order of  $10^3$  s. The states which are observed [26,27] experimentally and are attributable to a diffusion process have a different field dependence (none) and a time scale perhaps six decades faster than the original Griscom [30] model. For this reason, Griscom [86] has recently presented a major revision of his earlier work to bring his model into line with the new results. In this new work, he also agreed with McLean [14] that hopping transport of hydrogen ions controlled the time of formation of most of the radiation-induced interface trap buildup.

The results which led Griscom to this new model were obtained by Saks et al. [26], and we have already discussed many of them. In figure 14, we show additional results by Saks et al. [26] which clearly show the existence of a small field-independent component of the interface

trap buildup. Samples were irradiated at 77 K with either positive or negative bias. At 77 K, hole transport and many other processes are suppressed. When the samples are warmed up through a series of isochronal anneals, a small interface trap component—independent of bias polarity—occurs between about 120 and 150 K. This is the temperature at which diffusion of neutral hydrogen should be activated. Above 200 K, the familiar hydrogen ion transport process (released by moving holes) with its usual field dependence takes over. Saks did not report this diffusion-controlled process in his room temperature experiments, but Boesch [27] did—in some samples, but not others. Summarizing this third process then, it is often not observed at room temperature at all, but depending on how the experiment is done and which samples are used, up to 10 percent of the total buildup has been attributed to this process.

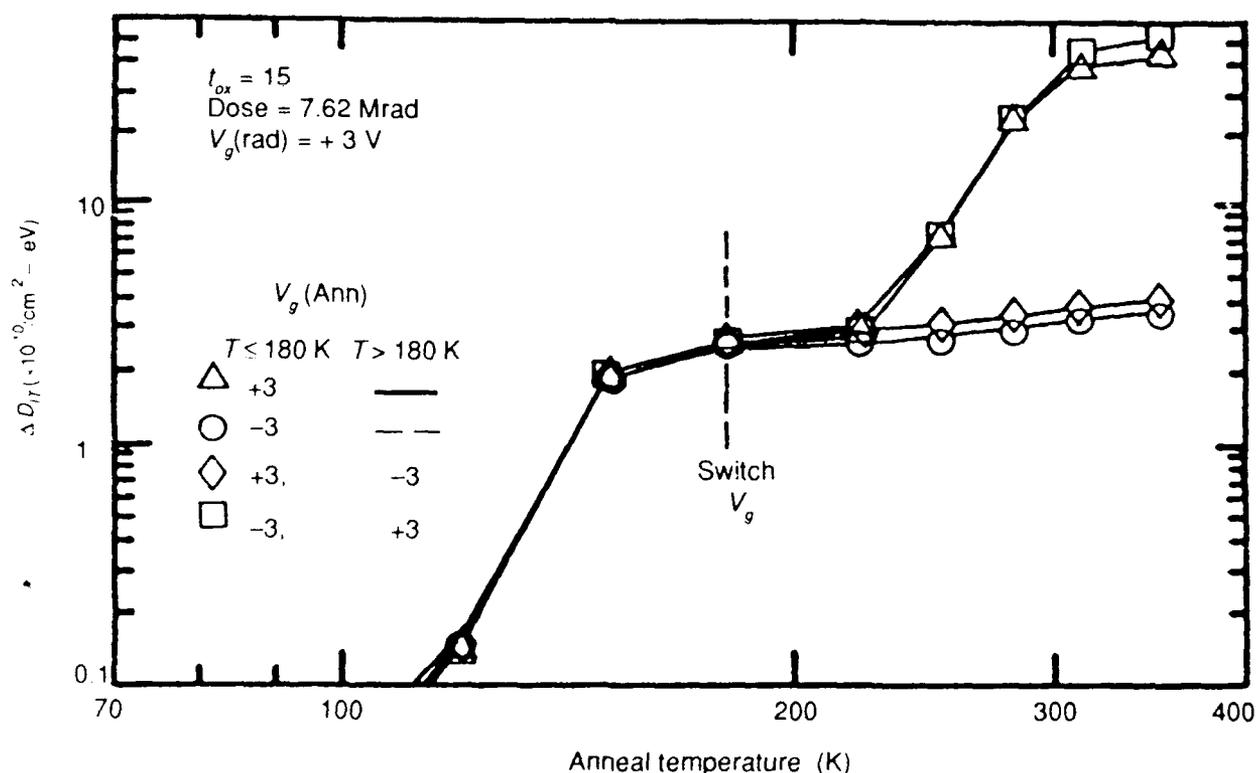


Figure 14 Isochronal annealing result showing a low-temperature process due to neutral hydrogen diffusion, and a much larger high-temperature process due to hydrogen ion transport.

### 3. Other Topics

#### 3.1 Dose Dependence

Based on work by Winokur et al. [19], McLean [14] reported that the final saturation value of the radiation-induced interface trap density varied as the dose to the two-thirds power, a result which he characterized as "anomalous." However, the result was consistent on several oxides over two to three orders of magnitude in dose, and it was later confirmed by Naruke et al. [87]. He speculated that this dependence might arise from shifts in the energy levels of the traps arising from quantum degeneracy effects. As the number of traps increased, the increasing overlap in their wave functions might shift the energy levels of the states. If the energy levels of the states shifted outside the part of the band gap sampled by the measurements, a sublinear dose dependence might be observed even though the basic interface trap generation was linear.

Subsequently, Boesch [39] reported a  $D^{0.89}$  dependence for interface traps in thick field oxides. Saks [24] reported a linear dose dependence, except at high doses where some saturation occurred. More recently, Fleetwood et al. [88] confirmed a linear dose dependence in some low-dose-rate, long-term irradiations which they performed.

Finally, Benedetto et al. [89] presented the result shown in figure 15. Several samples from the same wafer were irradiated under the same conditions, and the change in interface trap density is plotted as a function of dose. There is a large sample-to-sample variation at the lowest dose, 20 krad—about a factor of five difference in  $\Delta D_{it}$  between the highest and lowest samples. Then as the dose is increased the curves converge. We note that these samples are very small area transistors, and that the total number of states is small at low doses. As the dose is increased, the number of states increase and this statistical variation diminishes. Larger area samples did not show this kind of variation at

low dose. Depending on the sample, a dose dependence ranging from  $D^{1/2}$  to  $D^1$  could be observed. On other samples the response was linear with dose except that saturation was observed above about  $10^7$  rad( $\text{SiO}_2$ ). From these results Benedetto concluded that the dose dependence of the radiation-induced interface trap buildup was *basically* linear, except when saturation effects or sample-to-sample variation obscured the general trend. And this view seems to represent the consensus of workers in the field. Generally the response will be linear with dose but exceptions will occur, and these exceptions are too numerous to dismiss entirely, especially since they are not well explained.

Over the years, occasional reports have appeared, raising the possibility of true dose-rate effects in irradiated devices. One of the most prominent of these was by Winokur et al. [90], who reported a small increase in the buildup of radiation-induced interface traps in very low dose rate irradiations over results obtained at higher dose rates. However, a group including some of the same authors modified this conclusion the following year (1988), and attributed the earlier result to a subtle dosimetry problem at low dose rates. They concluded, "We have demonstrated that over 11 decades in exposure dose rate and nine decades in annealing time, there are no true dose-rate effects on CMOS device postirradiation response." At this writing, we are not aware of anyone who claims to have data showing a true dose-rate dependence to the radiation-induced interface trap buildup.

#### 3.2 Field Oxide Results

Up to this point we have primarily discussed results obtained on gate oxides, either in capacitors or transistors. However, some work has been done on thick field oxides as well [39,40,90]. Generally, interface traps in field oxides are helpful because they make parasitic leakage paths harder to turn on. The problem which is most likely to arise is the case

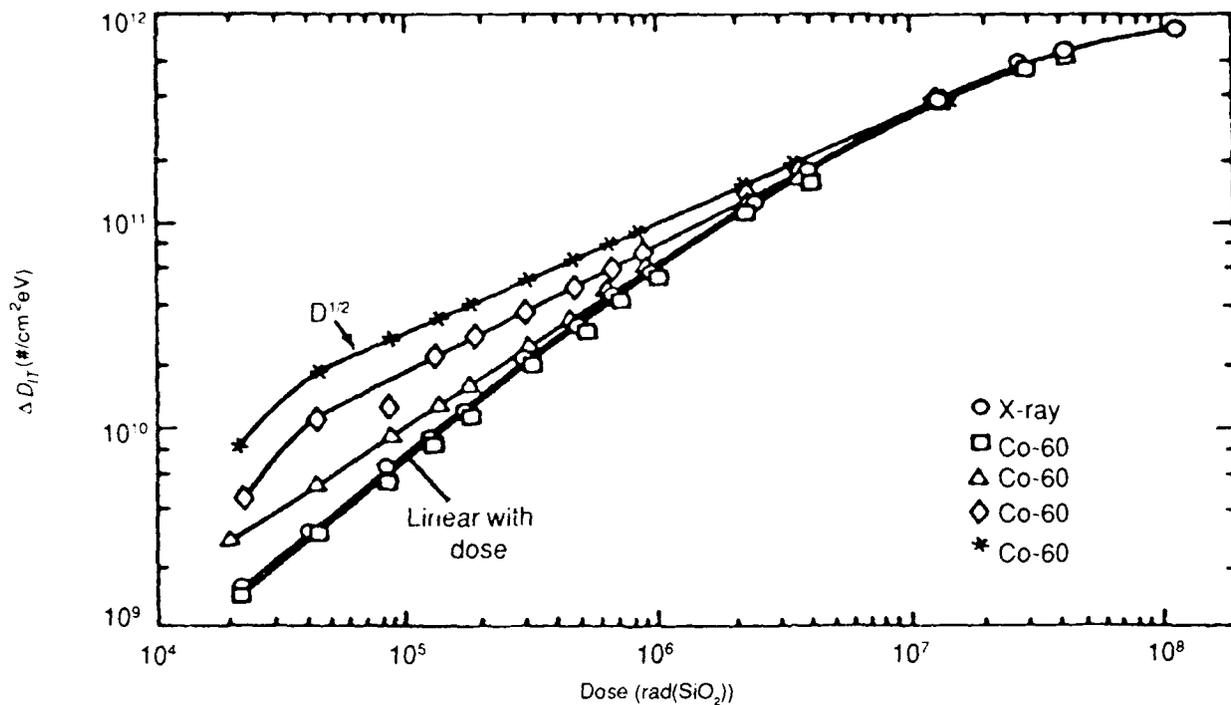


Figure 15. Variation of  $\Delta N_T$  with dose for samples from the same wafer.

in which a manufacturer is relying on a certain buildup of radiation-induced traps to keep a leakage path from turning on. If the buildup is not large enough, excessive leakage current can result.

Boesch [39,40] has studied the time, temperature, and field dependence of radiation-induced interface traps in field oxides, following in some ways the work he and others have done on gate oxides. Qualitatively the processes observed in gate oxides have all been observed in field oxides, but with one important difference: the processes which contribute to the early-time (fast) buildup are relatively much more important in field oxides than in gate oxides. The hopping transport of hydrogen ions requires  $10^{-2}$  to  $10^4$  s at fields on the order of 1 MV/cm in gate oxides of a few tens or 100 nm. But the transport time depends very strongly on field and oxide thickness. In a field oxide, the oxide is perhaps one order of magnitude thicker, so the hopping transport time is several orders of magnitude greater at a given field. But the field is also about an order of

magnitude reduced in a field oxide, which also increases the transport time by several orders of magnitude. For these reasons, the hydrogen ion hopping process is not observed on the time scale of many laboratory experiments (minutes to hours), where real circuit voltages are applied to field oxides. (We note that Boesch [40] has observed interface trap formation by this process in field oxides, but only at fields typical of gate oxides.) For this reason, the prompt processes we have discussed usually dominate the response of thick field oxides.

### 3.3 Specific Chemistry and Process Dependences

Revesz [29] concluded that "hydrogen is the most important impurity in Si/SiO<sub>2</sub> structures," and that achieving proper control of hydrogen is the most important task of MOS processing. Even earlier, Revesz [91] had suggested that Si-H bonds at the Si/SiO<sub>2</sub> interface were dissociated, leading to radiation-induced

interface states. Based on the results we have discussed here, we certainly agree on the central role of hydrogen. Two of the generation processes observed experimentally (and their models) depend on hydrogen freed in the bulk reaching the interface and reacting. For all three processes, the suggestion of Revesz that Si-H bonds at the interface are broken is almost certainly correct. Thus it is difficult to overstate the role of hydrogen in the buildup of radiation-induced interface states.

The need to break Si-H bonds at the interface suggests the reason why ionic hydrogen interactions produce most of the radiation-induced interface traps. Neutral atomic hydrogen is very reactive in SiO<sub>2</sub>, and can break an Si-H bond to form Si· + H<sub>2</sub>. However, Griscom [86] points out that neutral atomic hydrogen reacts very rapidly to form H<sub>2</sub>, and it is as H<sub>2</sub> that most of the neutral hydrogen reaches the interface. But, H<sub>2</sub> does not react with Si-H bonds. On the other hand, H<sup>+</sup> is apparently stable when it is bound to a nonbonding oxygen orbital, so most of the H<sup>+</sup> produced by radiation can eventually reach the interface if appropriate bias is applied.

We note that in the early experiments [15-23], a number of different oxides—hardened, unhardened, wet, and dry—were tested. The time, temperature, and field dependences were very consistent from one oxide to the next, indicating the same physical and chemical processes at work. However, the total number of interface traps produced by a given dose varied widely. Generally, the wet or steam-grown oxides had a much higher density of radiation-induced traps than the dry oxides. This result is consistent with hydrogen release in the bulk triggering the generation process, and again indicates that hydrogen plays a key role in radiation-induced instability due to interface traps. We note, however, that hydrogen is often intentionally introduced into MOS devices because it improves device stability in the absence of radiation. For example, Deal [92] (in 1974) and Balk [93] (recently) have discussed low-temperature hydrogen anneals as a method for reducing process-induced (pre-irradiation) in-

terface states. The conventional idea is that dangling Si bonds not passivated by the oxidation will be passivated by the hydrogen. But in the presence of radiation, these hydrogen bonds will be broken, leaving dangling bonds again. The point here is that hydrogen is neither a strictly favorable influence nor an unfavorable one. We note that hydrogen is present in almost all oxides in significant concentrations. Typically even dry oxides have  $\geq 10^{18}$  H/cm<sup>3</sup>. A certain amount contributes to device stability before irradiation. Too much leads to a serious radiation-induced instability—the buildup of interface traps. From a radiation hardening point of view, it is advisable to minimize the amount of hydrogen in the oxide.

### 3.4 Implications of Scaling

Several authors have reported that the buildup of radiation-induced interface traps is reduced in thinner oxides [81,87,94-96]. Indeed, Naruke et al. [87] have reported that  $\Delta N_{IT}$  is proportional to  $(d_{ox} - 13)^{2/3}$ , where  $d_{ox}$  is in nanometers. More recently Saks et al. [96] have reported  $\Delta D_{IT}$  values at midgap which vary as  $d_{ox}^n$  for  $d_{ox} \geq 12$  nm, where  $n$  varies from about 0.5 to 1.5 depending on how the oxide has been prepared. For  $d_{ox} < 12$  nm,  $\Delta D_{IT}$  decreases very rapidly for decreasing  $d_{ox}$ . These reports agree with some of our own observations [81] that very few interface traps are produced by large doses for very thin oxides, and the number generally increases with increasing oxide thickness.

These results suggest that scaling of devices to submicron (or beyond) design rules may eventually solve the problem of radiation-induced interface traps in gate oxides. Since it is well known that thinning the oxide also tends to reduce or eliminate the trapped hole instability [80,81,97,98], the general problem of radiation-induced gate-oxide threshold voltage shifts may eventually be eliminated by the natural development of more advanced microelectronic technology with thinner gate oxides. Then the special radiation problems in electronic devices will be found primarily in isolation structures.

## 4. Summary and Future Work (Unresolved Questions)

We have discussed a large number of experimental results and models which have been proposed to explain them. Generally three generation processes have been reported for radiation-induced interface traps. The largest of those is a slow two-stage buildup described by McLean [14], who proposed the hopping transport of hydrogen ions as the rate limiting step. The second largest generation process corresponds to the arrival of the radiation-generated holes at the interface. The third and smallest generation process depends on the diffusion of neutral hydrogen. Although a great deal of work has been done and many questions about radiation-induced interface traps have been answered, there are still several unresolved questions which should be the focus of future work.

An interesting experiment to try would be one detecting the  $H^+$  motion through the oxide. The number of charged hydrogens which have to move through the oxide to produce  $10^{11}$  or  $10^{12}$  interface traps could produce a detectable electrical signal. This signal has not been observed so far probably for two reasons. First, the  $H^+$  signal would be the difference of two competing effects. On the one hand, as the centroid of the  $H^+$  distribution approached the Si/SiO<sub>2</sub> interface, a *negative*  $\Delta V_{FB}$  or  $\Delta V_T$  would result. On the other hand,  $H^+$  reacts or is neutralized or somehow removed at the interface, rather than building up. Removal of  $H^+$  would produce a *positive*  $\Delta V_{FB}$  or  $\Delta V_T$ , and only the difference of these two processes would ever be observed electrically. Second, the remaining  $H^+$  electrical signal would have to be separated from the normal trapped hole neutralization process which occurs following irradiation. Typically, this trapped hole annealing is at least an order of magnitude greater than the likely  $H^+$  signal. For these reasons, direct measurements of  $H^+$  transport have proved elusive.

Generally, radiation-induced interface states are stable at room temperature, at least on the time scale of most experiments, but they have been observed to anneal out at elevated temperature [52,53]. Recently, however, three groups [99-104] have reported changes in the energy levels of radiation-induced interface traps following annealing. DaSilva et al. [99-101] have reported two peaks, one above midgap and a smaller one below midgap immediately following irradiation. During annealing, the large peak above midgap is reduced, but there is a corresponding growth in the smaller peak at lower energy. DaSilva [100] has proposed that a one-for-one defect conversion process is occurring, probably as a result of a structural relaxation [102]. The other groups have not confirmed these results; in fact, Stahlbush [103] has reported the opposite result. In addition, Barnes et al. [104] have reported that *both* peaks increase with time, but that the upper peak increases more than the lower one. We note that each of the three groups used different experimental techniques, samples with different process histories, and different test and annealing conditions. The only thing the three groups agree on completely is that the energy distribution does change with time. The physical basis of these transformations is at this point an unsettled issue which should be the focus of future work.

Another area for future work is identifying the nature of the  $P_{b1}$  center on the (100) surface. It may be that the  $P_{b1}$  center will never be an important contribution to the radiation response of MOS systems, as Kim and Lenahan [51] have suggested. But until the nature of the defect is determined, and it is understood whether it does or does not contribute to the radiation response, there should be some study of this defect.

Neither the role of hydrogen in the formation of radiation-induced interface traps at the microscopic level nor the connection with processing sequences is fully understood. Work on these questions will undoubtedly continue.

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