SPATIAL DEPENDENCE OF TRAPPED HOLES DETERMINED FROM TUNNELING ANALYSIS AND MEASURED ANNEALING

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Abstract

Accurate predictions of the post-irradiation response of microelectronic circuits is an important and difficult problem. We present a tunneling model for MOS structures showing how the post-irradiation annealing deviates from a simple ℓn(t) dependence for a nonuniform spatial trap distribution. This model is applied to our measurements of post-irradiation response to extract spatial trap distributions for several oxides. Results of this analysis have important implications for testing and hardness assurance--accurate prediction of the long-term response of hardened circuits requires a measure of the deviation from logarithmic annealing.

Introduction

The post-irradiation response of metal-oxide semiconductor (MOS) structures has been an active research area almost since such structures were shown to be sensitive to ionizing radiation. Derbenwick and Sander [1] showed that annealing during extended radiation exposures could give rise to an apparent dose-rate dependence. They also showed that linear systems theory could be used to predict the response in many cases of low-dose-rate irradiation where the recovery was linear with ℓn(t). Winokur later showed that although the method presented in ref. 1 worked very well for many soft oxides [2], it was not entirely satisfactory for predicting the long-term response of hardened oxides because the recovery of hard oxides was generally not linear with ℓn(t) [3]. In all these papers, the authors assumed that the recovery of an exposed sample was linear with ℓn(t) in order to predict the recovery of the sample, but they did not discuss the mechanism(s) contributing to the ℓn(t) dependence. However, it has been widely recognized that tunneling of electrons into the oxide to recombine with trapped holes is an important part of the response of MOS structures, and tunneling can give rise to a ℓn(t) dependence if the trap distribution is uniform in space. (See, for example, ref. 4-7.) However, if the trap distribution is nonuniform, the annealing curve will deviate from a strictly ℓn(t) dependence [8]. In the work presented here, we have started from the assumption that the response of a device can be predicted from an equation of the form

$$\Delta V_T(t) = \int_0^t F(\tau)R(t - \tau)\, d\tau \ , \qquad (1)$$

where $F(\tau)$ is the radiation source term, and $R(t - \tau)$ is the response function of the device. Our approach is to break R into an oxide trapped charge component and an interface state component, R_{ot} and R_{it}, respectively. We have studied the annealing of hole traps in order to determine the mechanisms which control R_{ot}. In previous work [1-3], R was assumed to have the form $-C + A\,\ell n(t)$. We have extended this work by proposing a more general form for R, one which allows nonlogarithmic behavior. In addition, we have extracted information about the spatial distribution of hole traps from the annealing response of several kinds of samples. We find that the wide variations in annealing behavior which have been observed can be explained in terms of different spatial distributions of traps. We describe the analysis and compare the theory with experimental results on a hard oxide, a soft oxide, and an intermediate oxide. We also discuss the effectiveness of the midgap separation technique in interpreting our results. Finally, we draw conclusions about the spatial distribution of traps in different samples and discuss these conclusions in light of other findings which have been reported.

Analysis

When an MOS structure is irradiated, electron-hole pairs are created in the SiO_2 gate-oxide layer. Those carriers escaping initial recombination move under the influence of any fields present (internal or applied) toward the electrodes. Under positive gate bias, the electrons are collected at the gate and the holes transport toward the Si substrate interface, where a fraction of them are trapped in deep trap sites in a region generally thought to extend on the order of 5 to 10 nm from the Si interface. These trapped holes then give rise to long-term negative threshold voltage shifts in MOS devices. The actual fraction of holes trapped in the long-term states is found to vary between a few percentage points (in hardened oxides) and 30 to even 50 percent (in soft oxides), depending upon processing conditions.

The holes trapped near the Si substrate are assumed to anneal by a tunneling/recombination process involving electrons from the Si valence band levels. We do not discuss the theory of this process here, but we simply use the notion of a time-dependent "tunneling front," which emerges as a natural consequence of the exponential decay of the tunneling probability with distance into the insulator. According to tunneling theory [9-11] (upon convolving the tunneling probability with the trap occupancy), at a given time t the tunneling transition rate is sharply peaked spatially (with a width of ~0.2 nm) for transitions to traps at a depth $X_m(t)$ from the Si/SiO_2 interface, which increases logarithmically with time, as

$$X_m(t) = (1/2\beta)\ell n(t/t_o) \ , \qquad (2)$$

where the tunneling parameter β is related to the barrier height facing the tunneling electrons, and t_o, which sets the time scale for the process, is related to the fundamental transition rate to the closest traps. Practically, then, the tunneling proceeds via a sharp spatial front, moving into the insulator region as ℓn(t), with traps closer than $X_m(t)$ annealed out at time t and those beyond $X_m(t)$ still occupied. We note from Eq. (2) that the "logarithmic velocity" of the tunneling front is $\Delta X_m = (2\beta)^{-1}\ell n\ 10 = 1.15\beta^{-1}$ per decade in time. For thermal SiO_2, ΔX_m lies in the range 0.2 to 0.4 nm/decade, depending upon temperature and applied bias (see below).

Because of the sharpness of the moving tunneling front, the amount of charge transferred, ΔQ(t), via tunneling at time t can be written with good approximation simply as

$$\Delta Q(t) = q \int_0^{X_m(t)} dx\ N(x) \ , \qquad (3)$$

where x is the distance from the $Si-SiO_2$ interface, q is the electronic charge, $X_m(t)$ is given by Eq. (2), and N(x) is the spatial distribution of initially occupied hole traps. Note that for an initially uniform trapped hole distribution, a logarithmic time dependence of ΔQ(t) follows immediately from Eqs. (2) and

(3) and results in a ℓn(t) dependence in the annealing of threshold voltage shifts. For a nonuniform trapped hole distribution, the strict ln(t) dependence is modified, but as long as the spatial variation of the trapped hole density is small (on the scale of a few angstroms), the logarithmic annealing rate holds qualitatively, with modifications to it taking place only over several decades in time. Since the amount of charge being removed at a given time is proportional to the density of trapped charge at a position, differences in the slope of the annealing curve at different times can be related to different trap densities at different locations.

Although in general N(x) is unknown and arbitrary, to proceed further analytically we assume a simple exponential form $N(x) = N_o e^{\lambda x}$, where N_o is the occupied trap density near the interface at t = 0. (Strictly speaking, in terms of analyzing experimental data, N_o is the trap density at some x_o corresponding to the position of the tunneling front at time t_o, which we take to be the beginning of the post-irradiation measurements.) Then, performing the integration in Eq. (3), we have

$$\Delta Q(t) = \frac{qN_o}{2\beta} f_\nu(t) , \qquad (4)$$

where

$$f_\nu(t) = \frac{1}{\nu}\left[\left(\frac{t}{t_o}\right)^\nu - 1\right] \qquad (5)$$

and $\nu = \lambda/2\beta$. We note that in the limit $\nu \to 0$, $f_\nu(t) \to \ell n(t/t_o)$.

With the charge response given by Eq. (4), and assuming oxide thickness L_{ox} large compared with the tunneling distances involved (valid as long as $L_{ox} >>$ 10 nm), the threshold voltage shift response, $\Delta V(t)$, normalized to unit radiation dose, is given simply by

$$\Delta V(t) = -C + A f_\nu(t) . \qquad (6)$$

Here -C is the shift (per unit dose) at time t_o relative to the pre-irradiation value, and $A = qN_o/2\beta\, C_{ox}$ is the initial annealing slope right after t_o, where C_{ox} is the oxide capacitance. In the analysis of the data discussed later, we use Eq. (6) to fit the data and then use the values of C, A, and ν determined by the fits to infer information about the trap distribution functions.

To illustrate the effect of spatial variations in the trap distributions on post-irradiation annealing, we show in Fig. 1 calculated annealing curves from ref. 10 based on Eq. (6) (i.e., exponential variation of trap density) for several values of λ (where λ is expressed in units of $(2\beta)^{-1}$). In Fig. 1 the voltage scale is arbitrary and time is measured in units of t_o, here taken to be the actual early microscopic tunneling time α^{-1} (on the order of 10^{-13} s) for tunneling transitions to the closest traps at the interface. Clearly, the annealing reflects directly the spatial variation of the hole distribution. This is simply a consequence of the nature of the tunneling/recombination process, namely, that there is a distinct tunneling "front" $x_m(t)$, which moves into the insulator as log time, with the states behind the front filled and those beyond it still empty. At a time t, the tunneling takes place predominantly to traps located within a few angstroms of $x_m(t)$, and hence reflects the density of traps in that region. More specifically, it is the slope of the annealing curve which is directly proportional to the density of traps. Hence, for a constant spatial density (λ = 0.0) the annealing curve is very nearly linear with log(t) for $t > t_o$. For nonzero values of λ, the initial annealing behavior is very

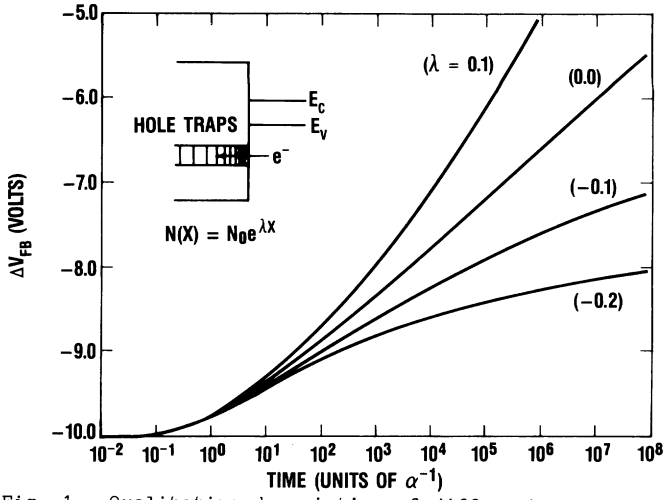

Fig. 1. Qualitative description of different annealing behavior expected for different trap distributions (different λ's).

similar to the constant density case, but with increasing time the slopes of the curves increase or decrease, reflecting either an increasing or decreasing trap density away from the interface. Therefore, if the tunneling/recombination mechanism is responsible for charge annealing, the spatial profile of the trapped hole distribution near the interface can be obtained by simple analysis of the experimental annealing curves.

In order to use the tunnel/anneal analysis to make quantitative estimates of the hole trap distribution (i.e., both the density N_o near the surface and the spatial profile parameter λ), we need to know the tunneling parameter β. In the absence of an applied bias, β is given within the simple quantum mechanical two-band, one-electron tunneling theory as

$$\beta = \left[\frac{2m_t^*}{\hbar^2} E_t\right]^{1/2} , \qquad (7)$$

where m_t^* is the tunneling effective mass and E_t is the hole-trap energy level with respect to the top of the SiO_2 valence band. E_t determines the potential barrier facing the electrons tunneling from the Si valence band into the sites of the trapped holes. (Alternatively, we may envision the trapped holes tunneling out of the oxide into the Si valence band. In the two-band model of tunneling, these are equivalent descriptions, but the tunneling barrier for the electronic transitions occurring in the lower half of the oxide bandgap must be determined relative to the top of the oxide valence band.) In a tunneling analysis of the discharge of trapped holes in SiO_2, Manzini and Modelli[11] determined $m_t^* = 0.42_o$, and $E_t = 3.1$ eV, from which the zero field value for β is found to be $\beta_o = 5.72\ nm^{-1}$.

The application of an applied bias modifies the tunneling potential barrier. Using a trapezoidal approximation and neglecting the image potential and space charge effects due to the trapped holes, one finds for tunneling transitions to traps located near $x \gtrsim x_o$ that

$$\beta(\varepsilon_{ox}) \simeq \beta_o(1 - q\varepsilon_{ox}x_o/E_t)^{1/2} , \qquad (8)$$

where ε_{ox} is the electric field in the oxide due to the applied bias. For hole traps in the region 3 to 4 nm from the Si/SiO_2 interface, which is the approximate range sampled by the annealing measurements in this study, Eq. (8) predicts a decrease in β of ~25 percent between zero field and an oxide field of 4 MV/cm. Since the annealing slopes are proportional to β^{-1}, there is thus a corresponding increase of ~33 percent in the predicted annealing slope.

Experimental Procedure

Three different sets of MOS field-effect transistor (MOSFET) samples were used in this study: two sets fabricated by Texas Instruments, Inc. (TI), and the other by Sandia National Laboratories (SNL). Both TI sets had 2-μm channel lengths and 27.5-nm oxides grown in dry O_2 at about 1000°C, but differed dramatically in their hardness. The "hard" TI samples experienced a half-volt negative shift in threshold voltage with a 1-Mrad dose, while the softer TI samples experienced the same shift at one-tenth this dose. Both TI sample sets had large channel widths (636 μm for the "hard" samples; 344 μm for the "soft" samples), which meant they had large midgap current values; thus, midgap voltage values for these samples could be measured directly without extrapolation of the subthreshold slope. The Sandia samples had 3-μm channel lengths, 8-μm channel widths (yielding a small midgap current which required extrapolation), and 97.0-nm oxides grown in dry O_2 at about 1100°C. Since this is not the standard radiation-hard Sandia process, these samples proved to be relatively soft, falling in between the two TI sets.

All the sample sets were irradiated with an ARACOR 10-keV x-ray source to a total dose that would produce a shift of ≈0.5 V with a 2-MV/cm field across the gate region. Both "soft" sets were irradiated for 2.5 minutes, but at different dose rates. The TI "soft" samples received a total dose of 90 krad (36 krad/min), while the Sandia samples received a total dose of 20 krad (8 krad/min). The TI "hard" samples required a 4-minute exposure (at about 250 krad/min), because of the ARACOR's dose rate limitations, to produce a 1-Mrad total dose. These dose values are uncorrected for dose enhancement effects. During irradiation, each transistor had its substrate grounded, source floating, 0.5 V on the drain, and a bias on the gate producing a 2-MV/cm field. Following the irradiation, the samples were placed on a stressing station with the same circuit configuration as above, but with varying annealing fields on the gate. Non-irradiated samples were also placed on the stressing station, with the same gate biases as the irradiated samples, to act as controls. Since the controls showed very little shift in any case, we are certain that the effects we observed are due to the radiation. Pre- and post-irradiation I-V data were taken with a Keithley 619 electrometer and a digital Keithley 230 power supply, which were part of a computer-controlled measuring system. The data generated were saved on magnetic disk. After irradiation, I-V curve measurements were taken approximately every half decade of time out to one million seconds. These data were also stored on disk.

Results

In Fig. 2 we present experimental data for a soft TI sample exposed and annealed at 2 MV/cm. Interface state buildup was essentially complete by the first post-irradiation measurement, and ΔV_{IT} was constant within experimental uncertainty over the post-irradiation measurements at about 150 mV. We have used the midgap voltage shift as a measure of hole trapping. (This assumption will be discussed later.) Since ΔV_{MG} recovers very slowly and ΔV_{IT} is small, these parts are unlikely to ever exhibit rebound or super-recovery. The relatively large ΔV_{MG} indicates that these samples are very soft--indeed we estimate the initial hole trapping fraction to range from 40 to 50 percent. (The hole trapping fraction has been determined as in ref. 12, where the recombination has been measured independently).

In Fig. 3 we present experimental results for soft TI samples annealed at different applied fields. Relatively little recovery occurs in these samples. At 10^6 s, only about 25 percent of the initial shift is removed at 1 or 2 MV/cm. The recovery shows some field dependence which is consistent with a tunneling model. The recovery is linear with $\ln(t)$ at all fields within experimental error. The fact that the recovery is linear indicates that the trap density is uniform in space in the region we are sampling; that is, $\lambda = 0$. Furthermore, since most of the holes are not removed, the distribution extends far into the bulk of the oxide. The fact that the slope of the annealing curve is field dependent is expected from a tunneling model, since the barrier height depends slightly on the applied field. The field dependence of the results in Fig. 3 is approximately that predicted by the theory.

In Fig. 4 we show experimental data for a hard TI sample exposed and annealed at +2 MV/cm. As in the soft parts, ΔV_{IT} saturates by the first post-irradiation measurement and remains constant thereafter at about 370 mV. This result, obtained at 1 Mrad, indicates that these devices would never fail by rebound at this dose. Indeed, since ΔV_{MG} does not seem to approach zero in the limit as $t \to \infty$, these devices would probably not fail by rebound at many megarads. These devices are extremely hard--we estimate the initial hole-trapping fraction at only about 3 percent. In addition, the hard samples recover faster--between 40 and 50 percent of the midgap shift has annealed out by 10^6 s. The curve is also clearly not linear on a $\ln(t)$ plot. We discuss this nonlogarithmic behavior in more detail later. From these data we obtain a characteristic length for the trap distribution $\lambda = -(0.9\ \text{nm})^{-1}$.

In Fig. 5 we present experimental results for hard TI samples annealed at different applied fields. The

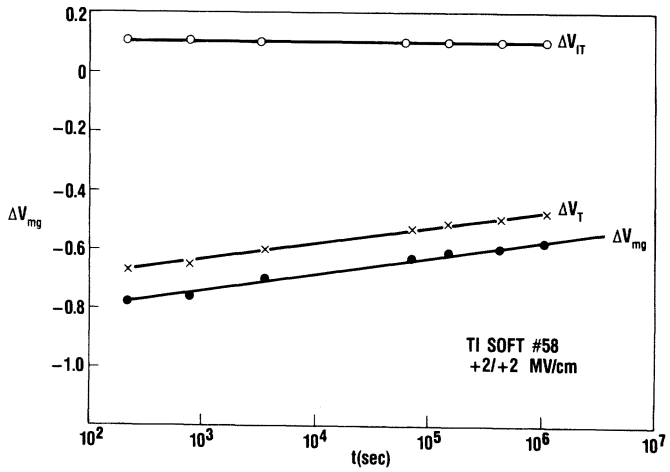

Fig. 2. ΔV_T, ΔV_{IT}, ΔV_{mg} for a soft TI sample irradiated at 2 MV/cm and annealed at 2 MV/cm.

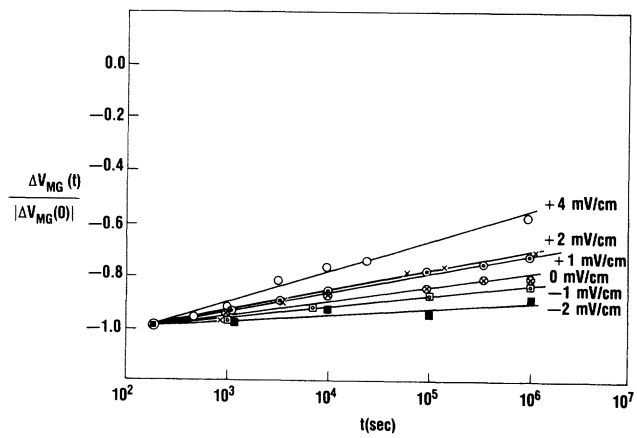

Fig. 3. Normalized ΔV_{mg} as a function of time for soft TI samples annealed at different fields.

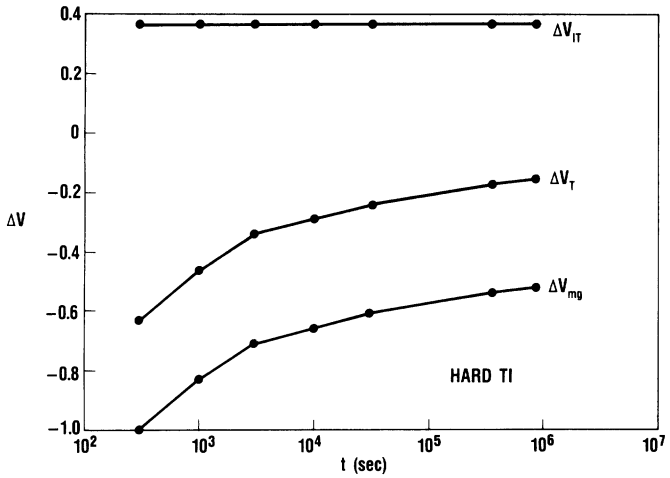

Fig. 4. ΔV_T, ΔV_{IT}, ΔV_{mg} data for a hard TI sample irradiated and annealed with an applied field +2 MV/cm.

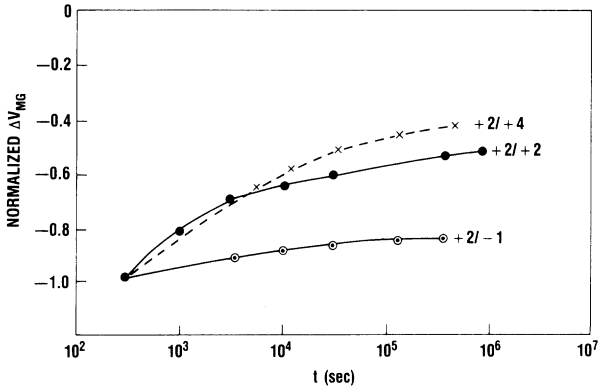

Fig. 5. Normalized ΔV_{mg} as a function of time for hard TI samples irradiated at +2 MV/cm and annealed at +4, +2, -1 MV/cm as indicated.

trend toward more recovery at higher fields is consistent with tunneling theory. However, we see more difference in the annealing between negative and positive bias than we expect. We plan further studies to understand this result.

In Fig. 6 we show experimental results for one of the specially softened Sandia samples. These samples are intermediate in hardness between the two TI samples with an initial hole-trapping fraction of about 14 percent. There is more uncertainty in the data points here because we could not read I_{MG} directly, but had to extrapolate from higher currents. However, ΔV_T seems to be slightly positive at 5×10^5 s, so these samples would probably rebound significantly at higher doses or later times. Given the scatter in the data, we are reluctant to conclude that ΔV_{IT} is increasing at late times, although it may be. The midgap curve seems to be deviating systematically from simple ℓn(t) behavior, but the uncertainty in this curve is certainly larger than for the other cases we have considered. From this data, we conclude $\lambda = -(1.1\ \text{nm})^{-1}$--slightly less deviation from logarithmic behavior than the hard TI samples, but more than the soft samples.

In Fig. 7 we show the experimental results at +2 MV/cm for each of the three types of samples replotted from Fig. 2, 4, and 6. In addition, each set of data is fitted with a curve obtained from Eq. (6), where the parameters C and A are obtained directly from the early time measurements. These parameters are the intercept and slope, respectively, shortly after the irradiation. The third parameter, ν (or λ), is a measure of the nonlogarithmic behavior of the response. The value of ν (or λ) is chosen to produce agreement

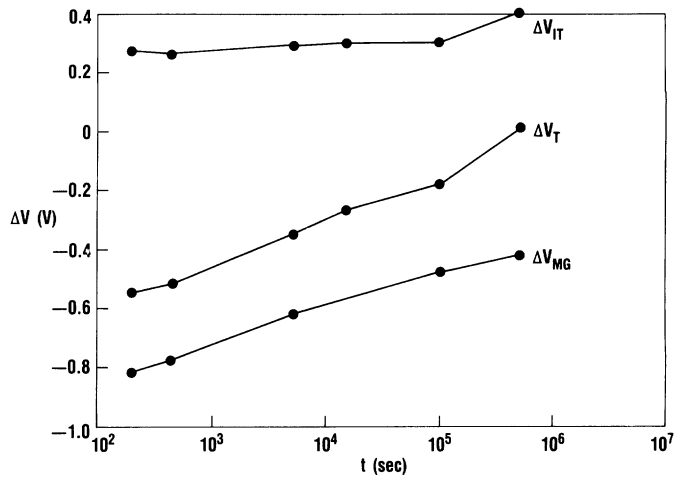

Fig. 6. ΔV_T, ΔV_{IT}, ΔV_{mg} for a Sandia sample irradiated and annealed at +2 MV/cm.

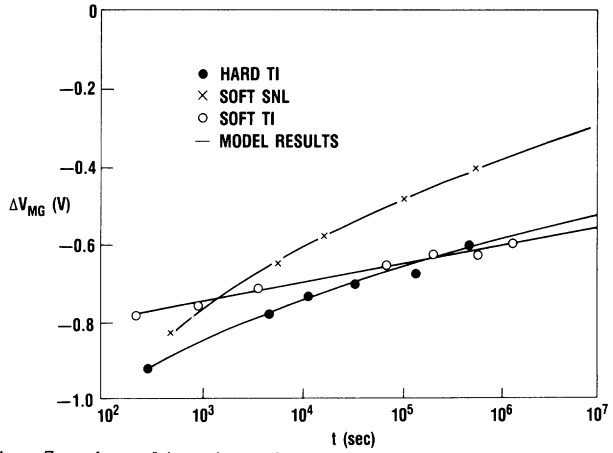

Fig. 7. Annealing data for three kinds of samples compared with model curves.

with the measurements at late time. For the hard TI samples $\lambda = -(0.9\ \text{nm})^{-1}$, for the Sandia samples $\lambda = -(1.1\ \text{nm})^{-1}$ and $\lambda = 0$ for the soft TI samples. The main point here is that the response of the soft samples follows a simple ℓn(t) dependence, but the hard samples deviate from simple ℓn(t) behavior.

In Fig. 8 we show the spatial distribution of traps for these three kinds of samples, which we obtain from the analysis shown in Fig. 7. (The vertical axis in Fig. 8 is trapping efficiency, trapped holes/cm^3 normalized to the same incident flux of holes.) The softer samples have more traps, but the density at the surface (actually the position of the tunneling front at the time of the first measurement) is not orders of magnitude higher. The real qualitative difference is that the trap density drops off rapidly in the hard oxides, but it does not drop off in the soft oxides. This picture agrees quite well with the results of XPS studies [13,14], in which the authors concluded that the hole traps are associated with a strained region near the Si/SiO_2 interface. They concluded that in hard oxides, the strained transition region was much narrower than in soft oxides.

Discussion

In discussing the post-irradiation hole trapping and detrapping of MOS structures, one must decide how to separate the hole-trapping component out of the observed threshold response. The midgap separation technique has been proposed [15-17] and used with good success in recent years. This technique rests on the assumption that interface states are uncharged at the midgap voltage, so the midgap voltage shift is due

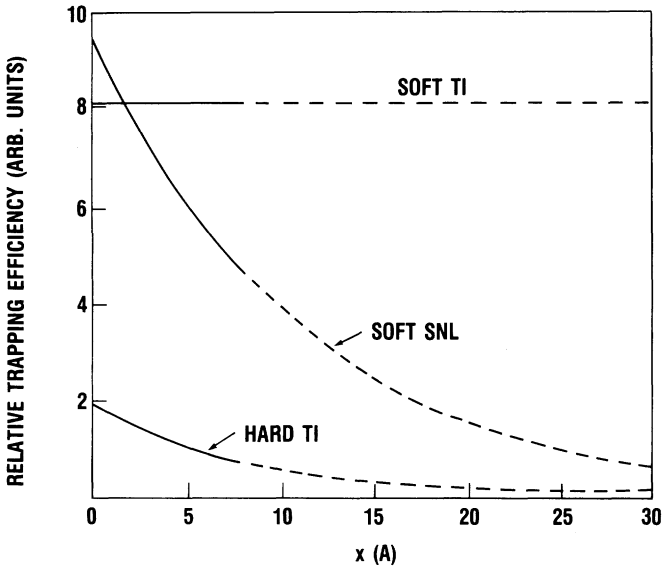

Fig. 8. Hole trapping efficiency as a function of position. Solid portions of curves obtained by fits to annealing data; dashed portions are extrapolations.

entirely to fixed charge in the oxide. ESR (electron spin resonance) experiments by Lenahan and Dressendorfer [18,19] identifying interface states with the P_b center have strongly supported the midgap assumption on (111) Si. However, other ESR experiments by Caplan et al [20] indicate that a second variety of interface state--a trivalent Si bonded to two Si and an oxygen with a second oxygen missing--is also present in (100) Si. Theoretical work by Edwards [21] indicates that this kind of interface state is neutral at an energy somewhat above midgap. Depending on the processing, one would expect different samples to have different numbers of these two kinds of interface states, so the point at which interface states exhibit net neutrality might vary somewhat from midgap. In the work we present here, we have used the midgap assumption, and we believe that we have introduced an error of no more than 3 percent into estimated hole trapping for the soft TI samples. For the hard TI samples, the error in the hole trapping is probably no more than 10 to 15 percent.

These error estimates were obtained by comparing the midgap shift with the shift two decades in current above midgap, and they are meant to be overestimates. It is unlikely that the point of net interface state neutrality is that high in the gap. In fact, the subthreshold curves are almost perfectly linear between threshold and midgap. For this reason, the revised measurement technique proposed by Dozier et al [22] (to account for donor state in the upper part of the gap) would result in a negligible correction. For our three sets of samples, we regard the errors associated with the midgap assumption as acceptable, and possibly negligible.

The main new idea in our analysis is a consequence of the tunneling front which is, in turn, a consequence of the exponential dependence of the tunneling rate. Since the mathematics of a tunneling model leads to the conclusion that tunneling at a particular time is sharply localized at a particular location for a narrow band of traps, it follows that differences in tunneling rates at different times can be used to extract information about the density of traps (actually, the density of target states) at different positions. Specifically, if we assume that the shift of the midgap voltage is due to the annealing of trapped holes by a tunneling process, then differences in the slope of the midgap recovery curve can be used to study differences in the distribution of hole traps. We see three main limitations to this approach. First, we assume that all final states of the tunneling process have approximately the same energy level. We will discuss evidence for and against this assumption. Second, the height of the barrier is a very important parameter in any tunneling calculation, and it depends on the applied field. In extracting spatial trap distributions from the midgap annealing curve, we have assumed a particular field, +2 MV/cm, in each case. Third, the tunneling front moves into the oxide at about 0.2 nm per decade [11], and we have sampled only three or four decades in time. Therefore, the exponential form which we assume is tested against real data only for a region about 1.0 nm in extent. We will discuss evidence which indicates that the exponential distribution does not hold at all points in the oxide. For these reasons, we do not claim great quantitive precision for our calculated hole trap distributions. However, we do believe our analysis indicates principles which can be used to study hole trap distributions. Further, we believe our results indicate qualitative differences among different kinds of oxides.

First, we will discuss the assumption that the hole traps are in a single, relatively narrow energy band. In making this assumption, we have followed the work of Manzini and Modelli [11] who avalanche-injected holes into the oxide and studied the annealing of the trapped holes at different applied fields. They concluded that the hole traps were in a narrow band about 3.1 eV above the valence band edge of SiO_2 (shown schematically in Fig. 1). This conclusion seems to be consistent with multiple ESR studies [18-20], in which the hole traps are identified as the E' center. The E' center is detected as a single, sharp, microwave resonance, and is described as a trivalent Si atom bonded to three oxygen atoms. Since these studies identify the hole traps as a single kind of site, it seems reasonable to assign them a single energy level, or, at most, a narrow band of energy levels. Also, photo depopulation studies by Harasi and Royce [23,24] indicate the traps are in a single level 2.9 eV ± 0.6 eV above the SiO_2 valence band edge. In this work, we have assumed a trap level centered at 3.1 eV above the SiO_2 valence band to detemine the tunneling parameter β and hence the tunneling velocity, 0.2 nm/decade. We also point out that the tunneling rate will be much more sensitive to the position of the trap than to its energy. The tunneling rate is proportional to $e^{-2\beta x}$ where x is the position and β is proportional to $E^{1/2}$. Thus x (to the first power) enters the argument of the exponential, but E enters only to the one-half power. For this reason, the annealing response of an oxide will be more sensitive to the spatial trap distribution than to the energy distribution unless the energy distribution is extremely wide.

The main evidence against the model of tunneling to a single kind of site seems to come from experimental results on the reversibility of the annealing process. In one test, we let an SNL sample anneal for 1000 hours under positive bias. Then we reversed the bias for another 1000 hours. About 30 percent of the midgap shift under positive bias was reversed when negative bias was applied for an equal time. In a similar test on a hard TI sample for a shorter time, about 50 percent of the shift was reversed. Since these results were obtained on single samples and at different fields, we are reluctant to draw firm conclusions. However, other researchers [5,25] have also reported evidence of reversed annealing. Taken together, all these results suggest that part of the observed midgap voltage recovery is due to removal of the holes and part is perhaps due to compensation of holes by injected electrons. Grunthaner et al [13,14], in analyzing XPS experiments, proposed that radiation breaks a strained bond near the interface, leading to a trivalent Si bonded to three oxygens (the E' center)

and a nonbridging oxygen. Relaxation of the strained bond causes the Si and nonbridging oxygen to move apart so that they are unlikely to reform the broken bond. However, the Si can trap a hole under the influence of radiation, and the oxygen can become an electron trap. Recombination can occur, then, under the influence of random thermal fluctuations in the lattice aided by the coulomb interaction of the trapped electron hole pair. Presumably, some sites will recombine, leading to trapped hole annihilation. Others may not combine, leaving a compensated hole where the electron can later tunnel back out. Grunthaner et al [13] assigned an energy level of 5.2 ± 0.5 eV below the SiO_2 conduction band to the negative oxygen. This level is only slightly higher than the trap level determined by Manzini and Modelli by a different technique. Although this discussion suggests how a single site and a single tunneling process could possibly lead to both hole removal and hole compensation, we plan further experiments to study this question more carefully.

We conclude then that tunneling studies [11], photo depopulation [23,24] studies, and XPS studies [13,14] have all led their authors to conclude that the hole traps lie in a relatively narrow energy band, and, further,they all estimate that the band falls in about the same place. Results of ESR studies also are consistent with a narrow band of trap states, although the energy level cannot be determined. The indications of reversibility in annealing are not inconsistent with this picture. We would have preferred to measure the energy level of the traps directly, rather than assuming values quoted in the literature. But the energy level that we assume has been reported by at least three different groups [11,13,14,23,24] using very different techniques.

The second main limitation of our analysis is that the annealing is obviously field dependent, which complicates the extraction of trap distributions from the data. In practice, the trap distribution is best determined from relatively low field annealing data because the barrier height is more predictable. We have actually used data taken at +2 MV/cm since this field corresponds to the normal operating voltage for the hard and soft TI samples. We typically see about 20-percent variation in λ from sample to sample for "identical" samples, and choosing a smaller positive field would lead to about the same variation.

The third main limitation of our analysis is that the exponential trap distribution we have assumed holds only over a limited range. If, for example, we take the limit of f_ν in Eq. (5) as $t \to \infty$ (for $\nu < 0$), we conclude that about 40 percent of the charge in the hard TI samples will not be removed. For the Sandia samples, this fraction is about 15 percent. These results indicate that the trap distributions do not go to zero as indicated by the dotted portions of the curves in Fig. 8. (The solid portion of each curve indicates where the exponential fit is based on actual data. The dashed portion is an extrapolation based on the exponential fit.) Grunthaner et al [13] also concluded that a portion of the trapped holes are located well away from the interface. This conclusion is consistent with our result--some of the holes will not be removed by tunneling on any reasonable time scale.

With these limitations in mind, we do not claim that our calculated hole trap distributions are exactly correct. But the qualitative differences we have observed in different oxides are real, and many other researchers have observed similar results in other oxides. That is, soft oxides recover slowly with a $\ell n(t)$ dependence. Harder oxides recover faster--a larger portion of the initial shift is removed within a few decades. But the recovery for hard oxides is sublinear on a $\ell n(t)$ plot. A variety of other results [2,3,26] support these general conclusions. We have presented an analysis which explains these observations in terms of a single mechanism--tunneling to different spatial distributions of trap states. This mechanism seems to be consistent with a number of other studies, especially the XPS studies by Grunthaner et al [13,14]. They concluded that in hard oxides the hole traps are in a strained transition layer on the order of 3 nm thick. In soft oxides, the strained layer is much thicker, so hole traps extend deeper into the oxide. The difference between hard and soft oxides, then, is simply that the transition to unstrained bulk oxide is accomplished more quickly in hard oxides. A tunneling experiment cannot measure bond strain, but our trap distributions fit very nicely with the picture of Grunthaner et al.

These results have important implications for testing and hardness assurance. The most complete testing scheme is probably that proposed by Winokur et al [2], who suggested that if devices were tested an hour after and again a day after irradiation, $\ell n(t)$ annealing could be used to predict the response at other times. This approach worked quite well for the soft oxides being tested at the time. However, Winokur also pointed out that $\ell n(t)$ annealing was not really adequate to describe the response of hard oxides [3]. To illustrate the practical difficulties one can get into, we plot data originally taken by Brucker et al [26], as replotted by Oldham [12], in Fig. 9. The dashed line is a $\ell n(t)$ annealing curve that passes through the actual data at an hour and at a day after irradiation. The solid line is the result of our analysis where we have determined $\lambda = -(0.44\ \text{nm})^{-1}$. The threshold is clearly curving--the points at early times and late times all lie below the dashed line, but the points in the middle lie above it. However, in the range of the actual data, the dashed line is never far from the data. The solid line from our analysis fits the data even better than the dashed line, and the key point is that the two curves predict radically different results at, say, one year (roughly 5×10^5 min). The difference in threshold would be about 0.3 V at a dose of 100 krad (where these data were taken). The dashed line predicts failure by rebound, whereas the solid line predicts the part will still function. (Of course, if the part were failing by going depletion mode, the solid curve would predict worse performance, not better.) We have chosen the data from ref. 26 to show in Fig. 9 because the data curve more than our measurements, but in Fig. 10 we perform this same exercise for our data for a hard TI sample. The difference between the dashed line and solid curve is smaller than in Fig. 9, but the basic idea is the same.

The sensitivity of the theoretical fit to the value of ν or λ is an important question here. If one

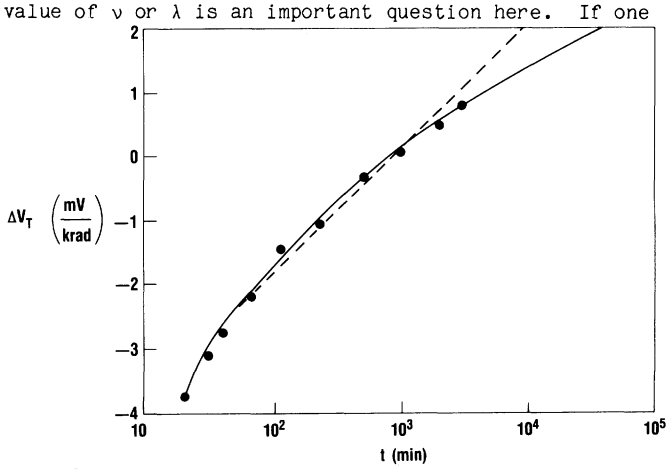

Fig. 9. Annealing data reported in ref. 26 compared with $\ell n(t)$ recovery (dashed line) and this work (solid line).

has a clean set of experimental data, small changes in ν or λ lead to noticeably poorer fits with experimental data. In Fig. 9, for example, changing λ by even ±10 percent will clearly cause the model to miss several of the data points. In Fig. 10, a 20-percent variation is necessary. Typically, we see more variation from sample to sample than the scatter about the theoretical fit for a given sample. Therefore, the uncertainties in the distribution for a given process are larger than suggested by these numbers. For this reason, we conclude that our calculated trap distributions offer general insights, but not necessarily great precision.

From our data and a large body of other literature, we can almost guarantee that hard parts will have a post-irradiation response which differs from $\ell n(t)$ by curving as in Fig. 9 or 10. We can absolutely guarantee that if one tries to fit a straight line to something which is not a straight line, one will introduce systematic errors. If one then extrapolates long enough along that straight line (possibly to the lifetime of a satellite), one can be absolutely certain of predicting an incorrect result. For these reasons, we believe that if one wants to make accurate predictions of the long-term response of hardened parts, it is essential to determine how much the response deviates from simple $\ell n(t)$. However, by performing the kind of analysis we have presented here, one could determine the deviation from simple $\ell n(t)$ annealing and the spatial distribution of traps which is characteristic of a given process. Then as long as the process does not change, that distribution can be used without additional measurements. A corollary to this last conclusion is that annealing behavior and trap distributions can be used to study the process. If the process changes, one would expect the trap distribution, and, therefore, annealing behavior, to change also. By determining trap distributions, one could study the effect of specific process changes.

Summary and Conclusions

We have performed experiments in which we monitored the post-irradiation response of MOSFET's with hard oxides, soft oxides (both by TI), and an intermediate oxide--specially softened by Sandia. We have observed certain qualitative differences in the behavior of these oxides which can be explained in terms of a tunneling model which assumes qualitatively different spatial distributions of hole traps in different kinds of oxides. This model can explain a variety of observations reported in the literature. For example, Johnston [27] reports that recovery times range over six orders of magnitude for different manufacturers. Six orders of magnitude in time corresponds to a difference in spatial extent of trap distributions of only about 1.2 nm in a tunneling model. We also show that this kind of analysis can be used to make improved predictions of the long-term response of hard parts. This finding has important hardness assurance and testing implications.

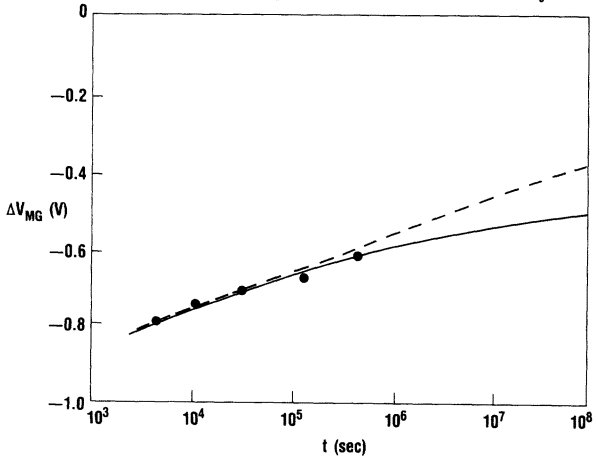

Fig. 10. Annealing data for hard TI samples compared with ln(t) recovery (dashed line) and this work (solid line).

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