Silicon Dioxide Breakdown Lifetime Enhancement Under Bipolar Bias Conditions

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Abstract—Time to breakdown ($t_{BD}$) of silicon dioxide has a pronounced frequency dependence when measured under bipolar bias conditions. At high frequencies, bipolar $t_{BD}$ can be enhanced by two orders of magnitude over the $t_{BD}$ obtained using dc or unipolar pulse bias of the same frequency and electric field. The lifetime improvement is attributed to detrapping of holes. At high frequencies, the improvement is maximum because the trapped holes are concentrated at the interface where they can easily be removed upon field reversal. At low frequencies, the improvement is less because the trapped hole distribution extends further into the oxide. Two different mechanisms are proposed to explain the frequency dependent spreading of the trapped hole distribution away from the interface.

I. INTRODUCTION

OXIDE reliability studies are usually performed under dc bias conditions. These studies are performed on oxide fabricated in a particular technology to determine the dependence of time dependent dielectric breakdown (TDDB) on electric field and to measure the defect density [1]-[3]. However, inside a circuit, MOSFET gate and EEPROM tunnel oxides experience time-varying bias. Since it is desirable to use the results of dc reliability studies to predict circuit reliability [4], we must determine what, if any, effect waveform has on TDDB. This study extends previously published work: the low frequency (10 kHz and less) TDDB measurements reported in [5], [6], a study of the effect of rise time on EEPROM endurance [7], and a comparative study of TDDB under high frequency (up to 4 MHz) unipolar and bipolar dynamic stress at one electric field [8].

II. EXPERIMENT DESCRIPTION

N-MOSFET structures were biased with dc and square waveform voltages and time to breakdown ($t_{BD}$) was monitored. The MOSFET's were connected as capacitors, i.e., the source, drain and substrate were tied together. The devices were non-LDD, the gate oxide was grown in dry O2 to thicknesses of 8.5 and 11 nm, and polysilicon gate was used. The voltage waveforms were monitored by oscilloscope and the maximum signal frequency was limited to 4 MHz so that overshoot was minimal. Reasonably small device sizes (5 μm × 5 μm to 50 μm × 50 μm) were used so that we could examine intrinsic, rather than defect-related, TDDB. Three different square wave signals were used to study TDDB under time-varying ("ac") bias, these waveforms are shown in Fig. 1. The experiments are under computer control and oxide stressing is automatically stopped when the conductance suddenly increases due to breakdown. The amount of time which elapsed between the start of oxide stressing and breakdown is multiplied by duty cycle to arrive at the value of $t_{BD}$.

III. EXPERIMENTAL RESULTS

A. Unipolar Stress

Fig. 2 shows $t_{BD}$ for devices that were stressed with either a $+V_g$ unipolar waveform or a $-V_g$ unipolar waveform (refer to Fig. 1 for definitions) for signal frequencies ranging from dc up to 4 MHz. The stress voltages were selected such that the dc $t_{BD}$ was about the same in both polarities. $t_{BD}$ increases by about a factor of 2 between dc and 10 kHz. This finding is consistent with that reported in [5], [6] for stressing waveforms with 50% duty cycle. This increase in $t_{BD}$ has been attributed to 1) less net hole generation when short stress pulses are used [5], [7] and

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B. Bipolar Stress

Fig. 3 shows \( t_{BD} \) measured under bipolar bias conditions on devices with \( T_{ox} = 11 \) nm. Fig. 3 shows that bipolar \( t_{BD} \) is a much stronger function of frequency than is unipolar \( t_{BD} \). \( T_{BD} \) saturates at a field-dependent knee frequency; this maximum value of \( t_{BD} \) is over one order of magnitude larger than the dc and unipolar values. To verify that the data shown in Fig. 3 are not anomalous, we repeated the experiment on a set of devices with \( T_{ox} = 8.5 \) nm. As Fig. 4 shows, the results were qualitatively the same.

To further investigate the bipolar lifetime enhancement, devices were stressed with fixed \( V_{hi} \) and variable \( V_{lo} \). \( T_{ox} \) was 11 nm, stress frequency was 100 kHz, \( V_{hi} \) was 13.8 V, and \( V_{lo} \) was varied from sample to sample. Fig. 5 shows the results of this experiment. A dramatic increase in \( t_{BD} \) is seen when \( V_{lo} \) is decreased beyond \(-8\) V. Eventually, as the magnitude of \( V_{lo} \) approaches that of \( V_{hi} \), the value of \( t_{BD} \) starts to drop. The maximum measured value of \( t_{BD} \) was two and one-half orders of magnitude larger than that under unipolar stress conditions. In another experiment, \( V_{lo} \) was held constant and \( V_{hi} \) was varied; similar results were obtained.

Upon field reversal from \( V_{hi} \) to \( V_{lo} \), holes trapped near the gate or electrons trapped near the Si/SiO\(_2\) interface can tunnel to available states in the silicon (see Fig. 6). We have found that \( V_F = -3 \) V is sufficient to detract electrons which are near the Si/SiO\(_2\) interface (an illustration of this may be found in Fig. 7). In contrast, \( V_{lo} \) had to be decreased beyond \(-8\) V for a substantial increase in \( t_{BD} \). Changes in midgap voltage (\( \Delta V_{mid} \)), as determined from \( C-V \) measurements, are a good indicator of trapped oxide charge [9]. In Fig. 8, \( \Delta V_{mid} \) is plotted as a function of \( V_{lo} \) for devices with fixed \( V_{hi} \). The midgap voltage shifts were negative, indicating net positive charge.
Fig. 6. MOS band diagram under bipolar bias. From left to right, the materials are substrate, oxide, gate. "•" symbols represent holes, "••" symbols represent electrons. Two possible energy levels are shown for the interfacial hole traps.

Fig. 7. Quasi-static C-V curves before and after stressing with a 100 kHz $+V_o$ unipolar waveform ($V_{th} = 13.5$ V). Voltage during the C-V measurements was swept from $+V_o$ to $-V_o$. Electrons are detrapped when $V_o$ is negative and a second C-V measurement performed immediately after the first measurement shows significant shift toward negative voltages. $T_{ox} = 11$ nm.

Fig. 8. Midgap voltage shift (calculated from high frequency C-V) corresponding to the $t_{bd}$ data shown in Fig. 5. Stressing was interrupted after 2 s so that the C-V measurements could be made. Even though we observe a monotonic decrease in $\Delta V_{mid}$ with increasing $|V_o|$, $t_{bd}$ for the largest $|V_o|$ data point is not the maximum. At sufficiently high $|V_o|$, damage occurs during both $V_o$ and $V_{th}$ signal phases thus somewhat diminishing the benefits of the $V_{th}$ signal phase.

Fig. 9. Four devices ($T_{ox} = 11$ nm) were biased differently. Values of $V_{th}$ (~14.2 V) and $V_o$ (~13.5 V) were selected to give approximately equal $t_{bd}$ values at both polarities under dc bias conditions. Larger $|\Delta V_{mid}|$ is measured during $-V_o$ unipolar stressing than during $+V_o$ unipolar stressing because the centroid of trapped holes is located near the anode and $\Delta V_{mid}$ is most sensitive to charge located near the Si-SiO$_2$ interface (anode during $-V_o$ stress). The device with bipolar bias of 100 kHz has less hole trapping per unit time (smaller $|\Delta V_{mid}|$) than the one biased at 100 Hz and it also has longer $t_{bd}$. This data is not suitable for quantitative study of trapped hole density because electron trap generation and trapping are also taking place during the stressing.

trapping; the magnitude of $\Delta V_{mid}$ was reduced as the magnitude of $V_o$ was increased. The data shown in Figure 8 strongly suggest that the increase in $t_{bd}$ with decreasing $V_o$ (Fig. 5) is related to a reduction in the number of trapped holes. Likewise, the frequency dependencies of bipolar $t_{bd}$ (Figs. 3 and 4) can also be correlated with the amount of hole trapping (Fig. 9). Specifically, at high stress frequencies, hole trapping is reduced and $t_{bd}$ increased compared with low frequency stress results.

It is well known that temperature accelerates TDDDB measured with dc bias. Activation energy was measured for the samples with $T_{ox} = 11$ nm and its value (0.22 eV) was quite typical [10]. This activation energy was measured for both dc and unipolar stress. Fig. 10 shows the effects of ambient temperature on bipolar $t_{bd}$. Further discussion of Fig. 10 may be found in Section IV-B of this paper.

IV. DISCUSSION

A. Hole Trapping and TDDDB

Previous studies indicate that hole generation and trapping is a precursor to oxide breakdown [11]. Trapped holes may recombine with injected electrons to form (new) neutral electron traps [12]. It has been suggested that breakdown occurs when the neutral electron traps created during stressing reach a critical density [13], [14]. In light of this discussion, it is not surprising that we see a correlation between hole trapping and $t_{bd}$.

Fig. 6 shows the MOS band diagram including the location of holes generated during stressing and their direction of motion. It is widely agreed that holes are generated near the anode in thin oxide structures which are undergoing Fowler-Nordheim tunneling [15], [16]. The hole generation mechanism is uncertain; holes might be generated...
inside the oxide via impact ionization [17], [18] or inside the anode when an electron loses its energy [15]. The anode generation process involves the generation of hot holes and subsequent injection into the oxide. Some of the holes drift to the cathode under the influence of the electric field and this hole current can be measured [11], [19]. Holes are also trapped in the oxide; the fraction of generated holes that gets trapped is dependent on processing conditions and varies from 1% up. DiMaria et al. [20] found that the hole traps are located near the interface, but as the near-interface region was defined to be 5 nm, we may assume that hole traps are present throughout the bulk of our thin oxide samples. These hole traps are quite deep, as indicated in Fig. 6. Researchers have tried to pinpoint the energy level of the hole traps by monitoring flat-band voltage shifts following irradiation or avalanche injection of holes. The flat-band voltage recovers as trapped holes tunnel from the oxide into the silicon. It has consistently been found that the flat-band voltage recovery proceeds approximately logarithmically in time [21]; however, some researchers have found that the temperature and field dependencies are best modeled by assuming that the trap energy level is about 3 eV above the SiO$_2$ valence band [22] and others by assuming that they are located above the silicon conduction band [23]. These discrepancies probably arose from the use of overly simplistic models of the trapped charge spatial distribution and/or from the presence of multiple trap levels in the oxide.

Hole detrapping via tunneling is enhanced by the application of an electric field [21], [24]. Referring to Fig. 6, holes are trapped near the gate during the $V_{th}$ signal phase. During the $V_{io}$ signal phase, these holes may be detrapped and with increasing efficiency as the magnitude of $V_{io}$ is increased. This seems to explain the data shown in Figs. 5 and 8. However, the frequency dependencies of bipolar $t_{fd}$ (Fig. 3) and hole trapping (Fig. 9) are not as easily understood. The rest of this paper is devoted to analysis of those phenomena.

**B. Frequency Dependence of Bipolar $t_{fd}$**

Previously, it has been suggested that the free hole density reaches its steady-state value some finite time after oxide stressing commences [5], [7]. For the case of unipolar stress, the free hole density will certainly decrease when the stress signal is turned off ($V_{th} = 0$) and the hole density will have to build up when the stress signal is turned on. Therefore, in the half-cycle where during medium or high frequency unipolar stressing, $V_{th} \neq 0$, the average hole density will be less than the density during a comparable dc stressing [5]. This (presumably) is the source of the moderate improvement in $t_{fd}$ when unipolar, rather than dc stress, is used. However, this does not give us any clue as to why bipolar stress results in a stronger frequency dependence than does unipolar stress. We have to look at the time dependencies of hole detrapping to understand the bipolar stress $t_{fd}$ results.

Detrapping of holes located near an interface proceeds in time approximately as $m \log (t/t_0)$ [22]–24. $m$ is a constant, $t$ is time. $t_0$ is a parameter which decreases exponentially with increasing electric field [22] and should be in the millisecond or microsecond range for the electric fields used in this study. The logarithmic time dependence is characteristic of a tunneling process in which holes located progressively farther from the interface are detrapped as time proceeds [21]–[24]. The fraction of holes detrapped in a given time interval is independent of the trapped hole density but, instead, is a function of the distance away from the interface at which the holes are trapped. The detrapping 'front' moves away from the interface (into the oxide) at a rate of $m/t$. If the spatial distribution of trapped holes were independent of the duration of the $V_{th}$ signal phase, then detrapping during the $V_{io}$ signal phase would be increasingly efficient as the signal frequency were decreased and, thus, we would expect to see a reduction in hole trapping (and an improvement in $t_{fd}$) at low frequencies. This is opposite to the observed results (Figs. 3 and 9). Therefore, we conclude that as the signal frequency is lowered, the distribution of holes extends further into the oxide bulk from the anode interface. Furthermore, the rate at which the trapped hole distribution spreads into the oxide bulk (when $V_{th} = V_{io}$) must be faster than the rate at which the detrapping front moves (when $V_{th} = V_{th}$). As a result, when the signal frequency is lowered, an increasing portion of the trapped holes avoid detrapping and $t_{fd}$ decreases toward its value under unipolar stress conditions. In Section V, we examine two possible mechanisms by which the hole distribution may spread away from the interface.

The knee frequency seen in Figs. 3 and 10 is probably related to the hole generation time dependencies briefly discussed at the beginning of this section. Yamada et al. used the 'impact-ionization recombination' model to derive the density of generated holes ($p(t)$) as a function of time; they found that [7]

$$p(t) \propto 1 - e^{-at}$$

(1)
where \( a \) is a process dependent parameter, \( J \) is the tunneling current (\( J = AE_0e^{-\theta/E_0} \)) and \( t \) is the amount of time which has elapsed since the beginning of the pulse. A comparison of Figs. 3 and 10 shows that the knee frequency is a strong function of the oxide electric field \( (E_{ox}) \) while it is insensitive to temperature, at least in the range 25–150°C. This suggests that the knee frequency is related to the time it takes the hole density to reach steady-state. This time delay is a very strong function of the electric field [see (1)] but not of temperature.

V. SPATIAL DISTRIBUTION OF TRAPPED HOLES AT LOW SIGNAL FREQUENCIES

A. Hole Transport in SiO₂

One possible way for the trapped hole distribution to spread into the oxide bulk during the \( V_{th} \) signal phase is through actual movement of the trapped holes. It is known that trapped holes undergo a slow transport through SiO₂ and, at least in thick oxides, this is thought to be the primary mechanism for moving holes through a SiO₂ layer. Hole transport in SiO₂ is also dispersive. The term “dispersive transport” [25] refers to a process without a unique mobility at a particular electric field. In practical terms, this means that there is a very wide distribution of transit times for holes in oxide and that movement of holes across the oxide will take place over many decades of time. The distinctive characteristics of hole transport in SiO₂ have been observed primarily through radiation effects experiments.

Fig. 11, which looks very similar to Fig. 3, is a reproduction of a figure from the radiation effects study described in [26]. In this experiment, a group of PMOSFET’s (\( T_{ox} = 45 \) nm) were concurrently irradiated and biased with voltage waveforms that switched between 0 and \(-10 \) V. When \( V_g \) is equal to \(-10 \) V, only holes that are generated right near the Si/SiO₂ interface will be trapped there as the electric field will pull holes generated in the oxide bulk toward the gate. When \( V_g \) is at 0, holes generated in the bulk will drift toward the Si/SiO₂ interface because of a small, positive voltage drop across the oxide caused by the work function difference between the electrodes. Recall that all of the deep hole traps are said to be located near the interfaces and that only those holes which are trapped near the Si/SiO₂ interface will affect the threshold voltage. As Fig. 11 shows, larger threshold voltage shifts (\( \Delta V_{th} \)), indicating more hole trapping at the Si/SiO₂ interface, were found at low frequency bias than at high frequency bias. It was conjectured that this frequency dependence results from the characteristics of hole transport through SiO₂. Referring to Fig. 3, dispersive transport could certainly explain why the transition from the high frequency value of \( t_{th} \) (few holes move away from the interface) to the low frequency value of \( t_{th} \) (many holes move away from the interface) takes place over several decades of signal frequency. This simple picture ignores the possibility that the holes might move back toward the interface during the \( V_{th} \) signal phase. This simplification is acceptable since as time progresses from the instant at which a hole is generated, its effective mobility decreases (a characteristic of dispersive transport).

Despite the striking similarity between Figs. 3 and 11, some quantitative inconsistencies exist between this work and the radiation effects studies which have been performed on thick oxides. Figs. 3 and 11 indicate that both experiments are detecting phenomena with similar time constants. While this might at first appear to support the hypothesis that the bipolar \( t_{BD} \) frequency characteristics are related to hole transport, it actually introduces doubt about the veracity of this hypothesis. The electric field available to move holes away from the anode in Fig. 3 exceeds 10 MV/cm. The electric field which moves the radiation generated holes toward the Si-SiO₂ interface in Fig. 11 is less than 0.1 MV/cm. In fact, taking into consideration the superlinear dependence of hole transit time on distance, it has been predicted that, at room temperature, holes in 10 nm oxides should be transported across the oxide to the cathode in less than 1 μs [21], [24]. It is possible that most of the holes do have these short transit times but that it is the long-transit-time holes which are linked with oxide breakdown. Dispersive transport as seen in Fig. 11 is thought to occur either via thermal capture and emission from shallow hole traps that are distributed in energy level or via hopping (tunneling) between localized states with a distribution of separation distances [21].

These bulk hole traps are different from the traps shown in Fig. 6 in that they can be discharged comparatively quicker and at lower electric fields. It is not implausible that holes related to oxide breakdown exhibit a slower transport because they are located at deeper traps, such as those shown in Fig. 6. There is experimental evidence to support the hypothesis that a much slower transport takes place through the deep hole traps located near the interfaces [21] and (presumably throughout the thin oxides used in our study).

The data in Fig. 3 may be used to calculate the apparent...
speed at which the trapped holes move. At a particular frequency \( \nu \), we may use the ratio between unipolar \( f_{BD} \) and bipolar \( f_{B0} \) to estimate the fraction of holes that travel far enough from the interface to avoid detrapping in a time period \( 1/2\nu \). The starting point is the assumption that oxide wearout proceeds at the same rate as does hole trapping and, therefore, that time to breakdown can be correlated with the rate of hole trapping [27]. The oxide breaks down when a critical amount of damage \( (\Delta_{crit}) \) has been sustained [4], [28].

\[
\Delta_{crit} \equiv \kappa \cdot (\# \text{ holes trapped per cycle})
\]

\( \kappa \) is a process dependent proportionality factor, \( \nu \) is the signal frequency. When unipolar bias signal is used, the number of holes detrapped per cycle is negligible. It follows from (2) that

\[
\frac{\text{angular}}{\text{bipolar}} \left( \nu \right) = \frac{\# \text{ holes trapped per cycle} - \# \text{ holes detrapped per cycle}}{\# \text{ holes trapped per cycle}}.
\]

Since detrapping occurs through a tunneling process, the detrapping probability at a given electric field does not depend on the number of holes trapped but merely on their proximity to the interface. We define a quantity \( L \) as the maximum distance from the interface at which holes can be detrapped upon field reversal in a time period of \( 1/2\nu \). Recall, this distance increases with time as \( \log \left( t/t_i \right) \) [21]. The ratio in (3) reduces to

\[
\frac{\text{angular}}{\text{bipolar}} \left( \nu \right) \equiv \frac{\text{fraction of trapped holes located } x > L}{1}.
\]

The ratio in (4) is referring to the holes generated during the most recent positive pulse.

In Fig. 12 we plot the quantity \( 1/2\nu \) corresponding to \( \frac{\text{angular}}{\text{bipolar}} \left( \nu \right) \) equal to 0.2 for the data sets shown in Fig. 3. \( 1/2\nu \) should be loosely interpreted as representing the transit time of the holes in the 80th percentile for speed to move a distance \( L \). Studies of hole transport through SiO\(_2\) indicate that the velocity is a strong function of electric field, a property the data in Fig. 12 share. One study reported that, for samples which start with a uniform hole density, the time for 50% of the charge to be collected at the negatively biased electrode varies with electric field as \( e^{-3L/e} \) [29], where the electric field has units of MV/cm. A different study by the same authors showed that the electric field dependence was the same for 25% and 75% charge collection [30]. The field dependence of the data in Fig. 12 is close to that found in [29]; however, the transit time values are about \( 10^2\) times larger than extrapolation from radiation effect studies of dispersive hole transport in thick oxides would suggest [21], [24]. These observations are consistent with the hypothesis that we are observing transport through energetically deeper traps.

B. Hole Trapping Kinetics

Another mechanism might explain the spreading of the trapped hole distribution toward the oxide bulk during the \( V_0 \) signal phase at low frequencies. Holes are generated near the anode (Fig. 6). The anode has the largest density of free holes because a significant mechanism for their removal is recombination [16], [31]–[33] and, consequently, the trapped hole density is greatest near the anode. However, given enough time, the trapped hole dis-

\[
\text{# holes detrapped per cycle) \cdot \nu \cdot f_{BD}}
\]

tribution will spread out due to trapping kinetics. Trapping in energetically deep traps is modeled using a first order rate equation [34] as follows. The possibility that a trapped hole is annihilated by a captured electron is included.

\[
\frac{dp_i}{dt} = \sigma_h p \nu_n \left( P - p_i \right) - \frac{J_{0e}}{q} p_i
\]

\( P \) represents the density of hole traps, \( p \) is the free hole density, \( p_i \) is the trapped hole density, \( \sigma_h \) is the hole trapping cross section, \( \sigma_e \) is the cross section for electron trapping by a trapped hole, \( J \) is the tunneling current density and \( \nu_n \) is the hole thermal velocity. As long as the time interval of interest is sufficiently long so that the free hole density can be approximated as invariant with time [see (1)], (5) may be solved for the trapped hole density as follows.

\[
p_i = \left( \frac{P}{1 + \frac{J_{0e}}{q \sigma_h \nu_n}} \right) \left( 1 - \exp \left\{ -\left( \frac{p \sigma_h \nu_n + J_e}{q} \right) \right\} \right).
\]

Equation (5) shows that the trapped hole density will build up fastest in the region with the greatest free hole density (the interface); however, the trapped hole density eventually saturates, as shown in (6). These equations indicate that the trapped hole density will also build up in regions with a lower free hole density, but at a slower rate and to a smaller steady-state value. A plot of (6) may be found in Fig. 13. This equation was solved using reasonable values for all parameters. Since we expect \( p(x) \) to have its peak at the interface and be a decreasing function of \( x \), we made the arbitrary assumption that \( p(x) \) is a half-Gaussian.

According to the data shown in Fig. 3, as frequency is
increased, bipolar \( t_{\text{BD}} \) increases from 2–3\% times its value under unipolar bias conditions to 20–50\% times its unipolar value. These large improvements, when interpreted in the context of (4), imply that only the tail of the trapped hole distribution is being permanently trapped under bipolar bias conditions. Using the simulated \( p_L(t) \) found in Fig. 13, we do a "reasonableness" check on the assumption that the trapped hole distribution spreads into the oxide bulk (when \( V_g = V_{\text{bi}} \)) faster than the detrapping front moves (when \( V_g = V_{\text{bi}} \)). We define a distance \( L' \) such that 90\% of the trapped hole distribution lies within a distance \( L' \) of the interface (see Fig. 13). \( L' \) moves into the oxide at a rate of 3 nm/decade which is, indeed, faster than the 2 nm/decade typically cited as the rate of tunnel front movement [21].

For small shifts in the oxide electric field, the \( t_{\text{BD}} \) characteristics shift significantly along the frequency axis, as can be seen in Fig. 3. This observation is consistent with the hypothesis that hole trapping kinetics are the root cause of the bipolar \( t_{\text{BD}} \) frequency dependence. As shown in Fig. 13, the time scale for the spreading of the trapped hole distribution is proportional to the free hole density. Free hole density, in turn, is a strong function of electric field; specifically, it is said to have a dependence on electric field of \( e^{-H/E_{\text{ox}}} \) (\( H = 78 \text{ MV/cm} \)) [18]. Therefore, we would expect the \( t_{\text{BD}} \) characteristics shown in Figure 3 to shift along the frequency axis in response to changes in the electric field, as we believe \( t_{\text{BD}} \) is related to hole trapping.

VI. INTERFACE TRAP GENERATION

We previously reported that interface trap generation is enhanced under bipolar stress conditions [35]. This is not surprising in light of the evidence that interface traps can be generated by the recombination of trapped holes with electrons [36]. Fig. 14 contains a plot of interface trap generation during the \( t_{\text{BD}} \) experiment described by Fig. 5. A comparison of Fig. 14 and Fig. 5 shows that the enhanced interface trap generation does not track the \( t_{\text{BD}} \) improvement, but, rather, it appears when the tunneling current becomes appreciable in both polarities. The data presented in Fig. 14 might seem to suggest that the bipolar \( D_{\text{ox}} \) enhancement is nothing more than a reflection of the fact that current flows for one-half cycle under unipolar stress conditions and for the entire cycle under high field bipolar stress conditions. However, it was shown [35] that interface trap generation quickly saturates under unipolar stress conditions while it continues seemingly without end under bipolar stress conditions. Even though \( t_{\text{BD}} \) is large under bipolar stress conditions, the enhanced interface trap generation has negative implications for the long-term reliability of devices which experience bidirectional stress. EEPROM's, some Flash EPROM's, and oxide at the drain edge of a MOSFET fall into this class of structures.

Next, we examine the frequency dependence of this interface trap generation. Fig. 15 shows the increase in midgap interface trap density as a function of stress frequency and time. A maximum is seen at around 2 kHz. Comparison with Fig. 3 shows that this maximum occurs at about the same frequency we would expect \( n_{\text{free}} \) to occur in the bipolar \( t_{\text{BD}} \) characteristics at this electric field (11.6 MV/cm). Recall that in Section IV-B it was asserted that \( n_{\text{free}} \) occurs when the signal frequency is too high for the hole concentration to reach its steady-state value according to (1). The decrease in interface trap generation above \( n_{\text{free}} \) is simply due to there being fewer trapped holes in the oxide. As the frequency is decreased below \( n_{\text{free}} \), interface trap generation decreases, also. That is, for frequencies below \( n_{\text{free}} \), the fewer pulses per unit time, the less the interface trap generation. One possible explanation is that interface trap generation is most efficient right at the beginning of each \( V_g \) pulse when there is both a large concentration of trapped holes at the Si/SiO\(_2\) interface and electron injection from the substrate for recombinations to occur.
VII. CONCLUSIONS

The evidence that \( t_{PD} \) is enhanced under bipolar stress conditions due to detrapping of holes was presented. The improvement in \( t_{PD} \) is most marked at high bias frequencies. A self-consistent explanation for this frequency dependence is that holes are detrapped from the anode by tunneling under the reverse field and that the trapped hole distribution extends farther away from the interface at low frequencies. Holes located far from the interface are less likely to be detrapped upon field reversal. We have suggested two possible mechanisms for the spreading of the trapped hole distribution away from the interface. The first involves the movement of individual trapped holes under the influence of the electric field. This process, termed "dispersive transport," has been observed in radiation effect studies and can qualitatively explain the \( t_{PD} \) data presented in this paper. Quantitatively, however, the hole velocities implied by the data in this paper are orders of magnitude smaller than those observed previously in studies of hole transport in bulk oxide. This discrepancy may be due to a difference in hole trap energy between oxide bulk and interface. A second possible explanation is that the trapped hole distribution spreads out simply due to trapping kinetics. Qualitatively, the gradual rate at which the trapped hole distribution is predicted to spread out is consistent with our \( t_{PD} \) data. Although oxide lifetime is less of a worry under bipolar bias conditions than it is under unipolar or dc bias conditions, the enhanced interface trap generation found under bipolar bias conditions poses a potential reliability hazard for devices in which the oxide experiences bipolar stress.

REFERENCES


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