Space Charge Limited Degradation of Bipolar Oxides at Low Electric Fields

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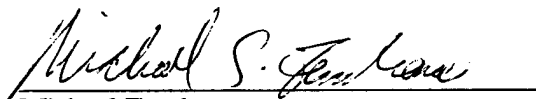
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P-type MOS capacitors fabricated in two bipolar processes were examined for ionizing radiation-induced threshold voltage shifts as a function of total dose, dose rate, temperature, and bias. Hydrogen passivation of acceptor impurities near the Si surface was observed through decreases in the Si capacitance. The reduction in net electrically active dopants shifts the threshold voltage negative with total dose. The relative contribution of dopant passivation to the radiation-induced threshold voltage shift is most significant for irradiations performed under zero bias above 100°C. For zero bias, dopant passivation and densities of radiation-induced interface traps and net positive oxide trapped charge all exhibit true dose rate and time dependent effects. A positive gate bias during irradiation eliminates the dose rate dependence. High dose rate irradiation at elevated temperatures enhances oxide degradation while simultaneously accelerating the annealing of damage. The enhancement in interface trap formation is greater than that of net positive oxide trapped charge and occurs over a greater range of temperatures. The temperature dependence of dopant passivation indicates that hydrogen transport through the oxides is accelerated with temperature. These results strongly suggest that metastably trapped charge in the oxide bulk reduces high dose rate degradation at room temperature by inhibiting the transport of holes and H^+ ions.

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Space Charge Limited Degradation of Bipolar Oxides at Low Electric Fields

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Abstract

P-type MOS capacitors fabricated in two bipolar processes were examined for ionizing radiation-induced threshold voltage shifts as a function of total dose, dose rate, temperature and bias. Hydrogen passivation of acceptor impurities near the Si surface was observed through decreases in the Si capacitance. The reduction in net electrically active dopants shifts the threshold voltage negative with total dose. The relative contribution of dopant passivation to the radiation-induced threshold voltage shift is most significant for irradiations performed under zero bias above 100°C. For zero bias, dopant passivation and densities of radiation-induced interface traps and net positive oxide trapped charge all exhibit true dose rate and time dependent effects. A positive gate bias during irradiation eliminates the dose rate dependence. High dose rate irradiation at elevated temperatures enhances oxide degradation while simultaneously accelerating the annealing of damage. The enhancement in interface trap formation is greater than that of net positive oxide trapped charge and occurs over a greater range of temperatures. The temperature dependence of dopant passivation indicates that hydrogen transport through the oxides is accelerated with temperature. These results strongly suggest that metastably trapped charge in the oxide bulk reduces high dose rate degradation at room temperature by inhibiting the transport of holes and H⁺ ions.

I. INTRODUCTION

For a given total dose, radiation-induced degradation of many types of bipolar transistors[1-15] and circuits[16-26] is more severe following low dose rate exposure than following high dose rate exposure. This behavior has been characterized by a combination of true dose rate and time dependent effects[1,10,17,23], where the former indicates the failure of high dose rate exposure and anneal to simulate the low dose rate response[1,3,10,17,19]. Since microelectronic devices in space are generally subjected to low dose rate irradiation, this complicates the hardness assurance testing of linear circuits and can lead to an overestimation of device lifetime in space.

Previous work examining the physical mechanisms responsible for this dose rate effect has focused primarily on oxide trapped charge above the emitter-base junctions of npn transistors[2,3,6,11,14,18,20,23,27-29] and/or device process flows[1,6,7,18,20,28]. Radiation-induced net positive oxide trapped charge degrades the current gain of npn transistors by increasing base recombination near the Si surface. Reduced base recombination following high dose rate irradiation has been attributed to the moderation of hole transport through the overlying oxide by space charge trapped metastably at O vacancy complexes[6,11,28,29]. Decreasing the dose rate or increasing the irradiation temperature leads to an increase in net positive oxide trapped charge near the Si-SiO₂ interface by reducing the amount of space charge in the oxide bulk.

In this work, hydrogen transport through p-type metal-oxide-silicon capacitors (MOS-Cs) simulating two types of bipolar base oxides is inferred from dopant passivation measurements. For 0 V irradiations, both the hydrogen passivation of substrate acceptors and the buildup of Si-SiO₂ interface traps are less pronounced at high dose rate than at low dose rate or elevated temperature. Consistent with established models for interface trap generation[30-46], it is argued that fewer interface traps are formed by high dose rate irradiation under zero bias, because fewer H⁺ ions can drift to the Si-SiO₂ interface and react with trap precursors. Similar to hole transport in these oxides, drift of the H⁺ ions is inhibited at high dose rates by space charge accumulated in the oxide bulk.

Furthermore, it is demonstrated that hydrogen passivation of the acceptor impurities results in a negative shift in the capacitor threshold voltage. The shift in threshold voltage is most dramatic between 125 and 150°C, where the synergism of accelerated H⁺ transport and hydrogen-acceptor complexing is greatest. A positive gate bias during irradiation reduces the amount of dopant passivation in the depletion region due to the absence of free carriers and H⁺ ion drift. When the passivation of dopants is accounted for, the in situ annealing of interface traps at elevated irradiation temperatures is found to be less severe than that of net positive oxide trapped charge. Implications of radiation-induced dopant neutralization for bipolar transistor gain degradation are discussed.

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II. EXPERIMENT

A. Sample Descriptions and Experimental Details

MOS-Cs from the RBCMOS and RF25 processes of Analog Devices, Inc. were studied in this work. The former is an experimental radiation-hardened bipolar complementary-metal-oxide-silicon technology developed for military applications, while the latter is a bipolar technology used for consumer amplifiers, mixers and switches that operate at radio and microwave frequencies[47]. The dielectric in either type of capacitor was fabricated similarly to the screen oxide overlying the emitter-base junctions of bipolar junction transistors from the same process. Both capacitor types employ wet thermal oxides grown on B-doped Si substrates. The oxides were subjected to similar ion implant and high-temperature anneal steps known to create O vacancies and vacancy complexes[48-57]. Capacitors from the RBCMOS process have an oxide thickness of 55 nm and a pre-irradiation surface doping of 8×10^{17} cm^{-3}. The oxide thickness and pre-irradiation surface doping of the RF25 capacitors are 570 nm and 2×10^{16} cm^{-3}, respectively.

The capacitors were irradiated with ^{60}Co γ-rays as a function of total dose, dose rate, temperature and bias. Lids on the device packages were removed to avoid dose enhancement due to photon scattering[58]. Pre- and post-irradiation high-frequency capacitance-voltage (C-V) measurements were performed at 1 MHz by sweeping the gate bias in both directions. The gate bias was ramped at 60 and 10 mV/s for the RBCMOS and RF25 capacitors, respectively, which was sufficiently slow to avoid deep depletion. To minimize dissociation of hydrogen-acceptor pairs by minority carriers[59-62], all of the irradiations and measurements were performed in the dark. For a given measurement, midgap voltage shifts computed from sweeps in both directions typically varied by 10%. However, the trends in the data were independent of the sweep direction. All raw C-V characteristics shown in this work were obtained by ramping the capacitors from accumulation to inversion, while the reported threshold voltage shifts represent averages from sweeps in both directions. Data points shown in all figures denote means of measurement results from replicate samples, while the error bars indicate minimum and maximum values obtained.

### B. Hydrogen Neutralization of Acceptors

Hydrogen transport through the bipolar oxides was inferred from measurements of dopant passivation and/or compensation in the underlying Si following irradiation. Hydrogen is known to neutralize many types of shallow acceptors (especially B) in Si[59-92]. Considerable evidence exists to suggest that the neutralization occurs primarily through two mechanisms. In the case of acceptor passivation[62,67,68,

70,72,75,78-80,82-90], atomic H^0 can deactivate B$^-$ through the reaction

$$B^- + H^0 + h^+ \rightarrow (BH)^0, \qquad (1)$$
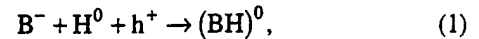
where h$^+$ represents a free hole. In the passivating state, the hydrogen atom occupies a bond-centered position along a <111> axis between a substitutional B site and a neighboring Si atom.

In the case of acceptor compensation[59,61,63,66,76, 82,87,88,92], electron-hole pair recombination occurs when H^0 donates an electron to the Si conduction band. The hydrogen and boron bond ionically according to

$$B^- + H^+ + e^- + h^+ \rightarrow (BH)^0, \qquad (2)$$
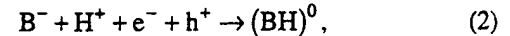
where e$^-$ represents the free electron. In (1), the presence of a hole is required, whereas, in (2), the Coulombic attraction of ions can occur in a region free of carriers. For either mechanism, the result is a reduction in the net concentration of electrically active impurities and a decrease in the semiconductor capacitance.

A representative set of C-V curves for an RBCMOS capacitor irradiated to several total doses is shown in Fig. 1, where the measured capacitances are normalized by the capacitance of the oxide. The irradiation was performed under zero gate bias at room temperature using a dose rate of 0.04 rad(Si)/s. Following irradiation, the C-V characteristics undergo a parallel shift due to net positive oxide trapped charge and stretchout due to interface traps. In addition, the capacitance measured in depletion and inversion decreases commensurately with dose. This reduction in capacitance is a direct indication of the neutralization of substrate acceptors by hydrogen[59-92]. Flatband, midgap and threshold capacitances, computed as a function of the net doping concentra-
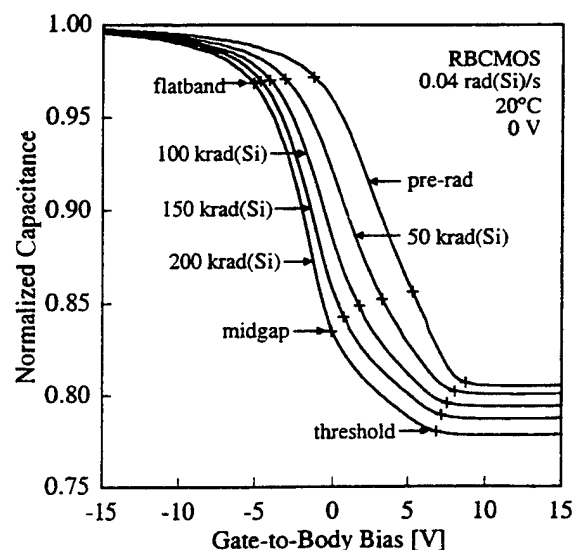

Fig. 1. Effect of total dose on the C-V characteristics of the RBCMOS MOS-C. The capacitance decrease in depletion and inversion is a direct indication of the neutralization of Si acceptors by hydrogen.

tion[93], are indicated in the figure for clarity. The amount of capacitance reduction increases with surface potential so as to exaggerate the slope of the C-V characteristics between flatband and threshold.

Assuming a uniform doping profile, the pre- and post-irradiation net doping concentrations were obtained by iteratively solving[94]

$$\frac{C_{ox}}{C_{min}} = 1 + C_{ox}\left[\frac{4kT}{\varepsilon_{Si}\varepsilon_0 \, q^2 N_B}\ln\left(\frac{N_B}{n_i}\right)\right]^{\frac{1}{2}}, \qquad (3)$$

where C_{ox} and C_{min} are the oxide and minimum capacitances per unit area, kT is the thermal energy, q is the electronic charge, $\varepsilon_{Si}\varepsilon_0$ is the permittivity of Si, n_i is the intrinsic carrier concentration of Si, and N_B represents the net concentration of electrically active dopants.

Fig. 2 shows the change in net doping concentration with total dose. Data for capacitors irradiated under a bias of +10 V are included for comparison. The positive gate bias ($E = 1.8$ MV/cm) is sufficient to strongly invert the Si surface. The changes in net doping concentration provide lower bounds on the amount of hydrogen transport, since not all of the hydrogen entering the Si passivates acceptors at room temperature[62,65,91]. For either bias, the net doping concentration decreases monotonically with total dose. However, for a given dose, dopant neutralization is less dramatic when the capacitor is positively biased. As discussed elsewhere[95], the potential gradient[59,76,82] and the absence of carriers[70,75] in the depletion region render the Si surface less conducive to dopant neutralization under positive bias. A 15 min post-irradiation anneal at 400°C restored the original doping profiles, indicating that the neutralization mechanisms are reversible[61,62,64,65,67,73,81,82,88]. Furthermore, a second radiation exposure demonstrated the reproducibility of the dopant neutralization[67,76].

C. Charge Separation of Radiation-Induced Threshold Voltage Shift

Densities of radiation-induced net positive oxide trapped charge and interface traps were determined from the high-frequency C-V characteristics. Because of the passivation of dopants by hydrogen (especially at elevated irradiation temperatures), it was necessary to take into account radiation-induced changes in the net doping concentration when performing charge separation of the threshold voltage shifts. The analysis used here[96] assumes a uniform doping profile, uniformly distributed oxide charge and charge neutrality of the interface traps at midgap. A more exact determination of the oxide defect densities would account for nonuniform doping profiles[97]. In the limit of no radiation-induced change in doping, this approach reduces to the familiar midgap charge separation technique[98] used widely in radiation studies of MOS devices.

Threshold voltage shifts due to radiation-induced net positive oxide trapped charge and interface traps, respectively, were estimated from

$$\Delta V_{ot} = \left(V_{mg} - V_{mg}^0\right)_{post} - \left(V_{mg} - V_{mg}^0\right)_{pre}, \qquad (4)$$

and

$$\Delta V_{it} = \left(V_{so} - V_{so}^0\right)_{post} - \left(V_{so} - V_{so}^0\right)_{pre}, \qquad (5)$$

where V_{mg} is the midgap voltage, V_{so} is defined as the stretchout between the threshold and midgap voltages, the subscripts pre and post refer to the measurement time relative to radiation exposure, and the superscript 0 denotes a theoretical value assuming the absence of oxide defects.

An additional component of threshold voltage shift due to dopant passivation was computed from

$$\Delta V_{dop} = \left(V_{th}^0\right)_{post} - \left(V_{th}^0\right)_{pre}, \qquad (6)$$

where V_{th} represents the threshold voltage.

Theoretical values for the midgap and threshold voltages, respectively, were evaluated at $V_{mg}^0 = V_G^0(\phi_s = \phi_f)$ and $V_{th}^0 = V_G^0(\phi_s = 2\phi_f)$, where[99][1]

$$V_G^0(\phi_s) = \phi_s + \frac{1}{C_{ox}}\left(2q\varepsilon_{Si}\varepsilon_0 N_B \, \phi_s\right)^{\frac{1}{2}} \qquad (7)$$

describes the ideal relationship between the gate voltage, V_G, and the surface potential, ϕ_s, and the Fermi potential is defined as

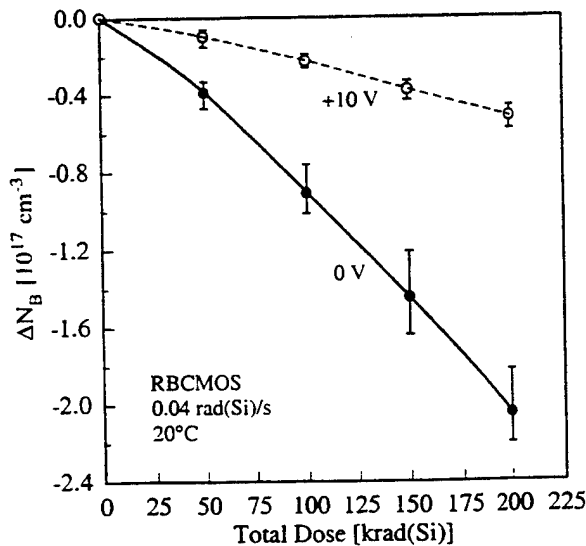$$\phi_f = \frac{kT}{q}\ln\left(\frac{N_B}{n_i}\right). \qquad (8)$$

Fig. 2. Effect of total dose on the net concentration of electrically active dopants in the RBCMOS MOS-C. Neutralization of dopants in the depletion region is less severe under positive bias due to the absence of free holes and the drift of H⁺ ions.

[1] The gate-to-body work function difference, ϕ_{gb}, is neglected in this analysis. Over the range of doses examined, radiation-induced changes in ϕ_{gb} are less than 1 mV for these capacitors.
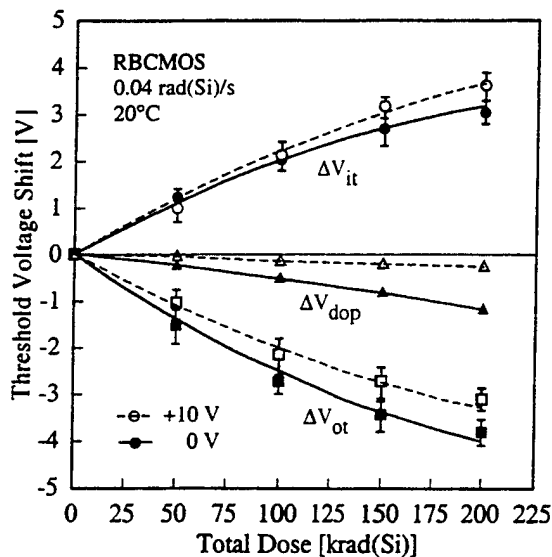
Fig. 3. Effect of total dose on the charge-separated threshold voltage shifts for the RBCMOS MOS-C. Hydrogen neutralization of the substrate acceptors shifts the threshold voltage negative.
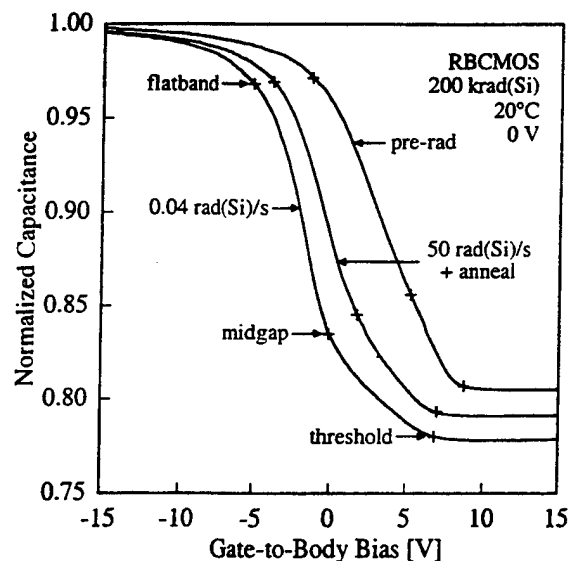

Fig. 4. Effect of dose rate on the C-V characteristics of the RBCMOS MOS-C. The smaller decrease in Si capacitance following high dose rate irradiation and anneal suggests that hydrogen transport through the oxide is inhibited at the high rate.

The major sources of error in determining ΔV_{dop} are the the uncertainty in C_{ox} and estimating the ratio C_{ox}/C_{min}. Additional sources of error related to ΔV_{ot} and ΔV_{it} include resolving the radiation-induced shifts in V_{mg} and V_{th}. Under the previously stated assumptions, it is estimated that ΔV_{mg} and ΔV_{so}, respectively, were resolved to within 0.05 and 0.1 V for a given sweep direction. Assuming an uncertainty of ±5 % in the gate oxide thickness, the resolution of ΔV_{dop} in this work is estimated to be 10 %, whereas the components ΔV_{ot} and ΔV_{it} are accurate to within 15 %.

Fig. 3 shows the separated components of threshold voltage shift as a function of total dose. Radiation-induced interface traps shift the threshold voltage positive, while net positive oxide trapped charge and dopant passivation shift the threshold voltage negative. Over the range of doses examined, ΔV_{ot} and ΔV_{it} are comparable in magnitude. Increased dopant passivation due to the lower E-field leads to a larger ΔV_{dop} for unbiased irradiation than for biased irradiation. The bias dependence of ΔV_{it} is consistent with well-known hydrogen[30-46] and/or trapped hole[33-35,37,100-108] models for radiation-induced interface trap formation, where a moderately positive E-field aids the transport of H⁺ ions and holes to the Si-SiO₂ interface. The trends in ΔV_{ot} at the low dose rate indicate more hole detrapping[37,38,109,110] and/or electron compensation of trapped holes[37,111-113] under positive bias. At room temperature, ΔV_{dop} is approximately 25% as large as ΔV_{ot} following unbiased irradiation.

D. Dose Rate Dependence of Oxide Degradation

The effect of dose rate on dopant passivation and the buildup of radiation-induced interface traps and net positive

oxide trapped charge was investigated. RBCMOS capacitors were irradiated to 200 krad(Si) at room temperature using dose rates of 50 and 0.04 rad(Si)/s. Following irradiation, the capacitors exposed at the high dose rate were allowed to anneal at room temperature. The gate bias for a given capacitor was maintained at either 0 or +10 V during the irradiation and the post-irradiation anneal.

In Fig. 4, normalized C-V curves are shown for capacitors irradiated under zero bias at the two dose rates examined. To allow fair assessment of the effect of dose rate, the C-V curve corresponding to the high dose rate irradiation was measured following a post-irradiation anneal equal in duration to that of the low dose rate irradiation. A pre-irradiation C-V curve is included for comparison. The radiation-induced decrease in minimum capacitance is less dramatic following high dose rate irradiation and anneal than it is following low dose rate irradiation. This implies that the amount of hydrogen transport into the Si substrate is reduced at the high dose rate. Furthermore, the additional decrease in capacitance at the low dose rate occurs over a wide range of gate biases, indicating that increased hydrogen neutralization of Si acceptors occurs within the entire depletion region.

Fig. 5 shows the change in net doping concentration as a function of irradiation and anneal time, where dose rate and gate bias are parameters. Under positive bias, essentially all of the dopant passivation at the high dose rate occurs during the post-irradiation anneal. The agreement in net doping changes at the two dose rates indicates a lack of dose rate sensitivity under positive bias. By contrast, the change in net doping concentration at zero bias exhibits both time and dose rate dependences. Under zero bias, approximately 50% more dopant neutralization occurs at the low dose rate than at
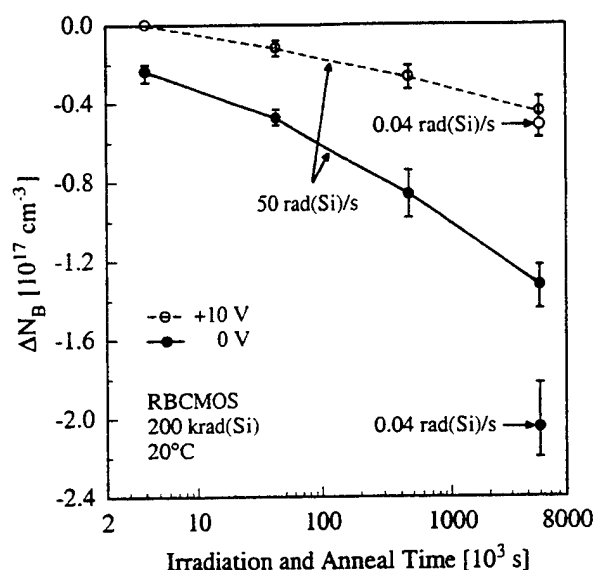
Fig. 5. Effect of dose rate on the net concentration of electrically active dopants in the RBCMOS MOS-C. Dopant neutralization is sensitive to dose rate under zero bias. A positive gate bias eliminates the dose rate dependence.

the high dose rate.

Densities of radiation-induced interface traps and net positive oxide trapped charge, respectively, are plotted as a function of irradiation and anneal time in Figs. 6(a) and 6(b), where the densities are related to the appropriate threshold voltage shifts through the proportionality constant C_{ox}/q[98]. Whereas some of the interface traps generated at the high dose rate are removed by the unbiased anneal, the biased anneal increases ΔN_{it} by a small amount due to dispersive hopping of H^+ ions to the Si-SiO$_2$ interface[30-46]. Under bias, the logarithmic decay of ΔN_{ot} with anneal time agrees with earlier work on MOS oxides[37,38,109-114], in which the annealing is attributed to trapped hole emission and the tunneling of substrate electrons. Within experimental uncertainty, no dose rate dependence of ΔN_{it} or ΔN_{ot} is evident under positive bias. This behavior is consistent with the radiation responses of MOS transistors from other processes[58,114]. By contrast, both ΔN_{it} and ΔN_{ot} exhibit a measurable sensitivity to dose rate under zero bias. The enhancement of ΔN_{it} or ΔN_{ot} due to dose rate is comparable to that of ΔN_B.

The trends in ΔN_{ot} support the premise that space charge accumulated in the oxide bulk inhibits the buildup of net positive oxide trapped charge at high dose rates[6,11,28, 29]. The correlation of ΔN_B and ΔN_{it} as a function of dose rate and bias further suggests that the space charge similarly affects the formation of interface traps by retarding the transport of H^+ ions. The unbiased irradiations are particularly relevant to degradation of the bipolar transistors simulated, since design of the transistors prohibits the external application of E-fields across the base oxide. The dose rate dependences of ΔN_{it} and ΔN_{ot} are qualitatively similar to that of
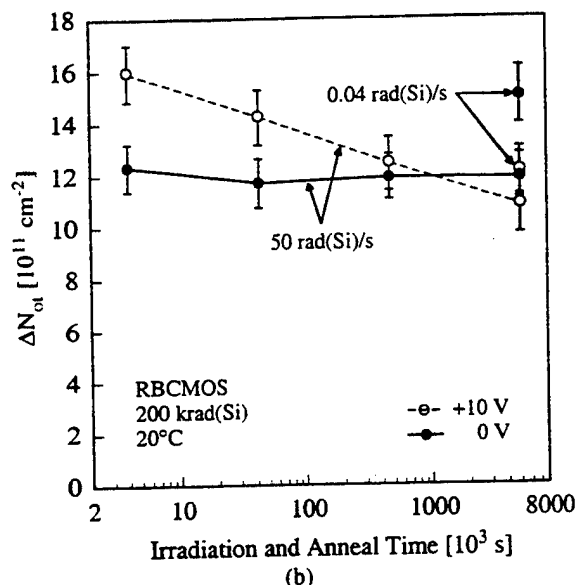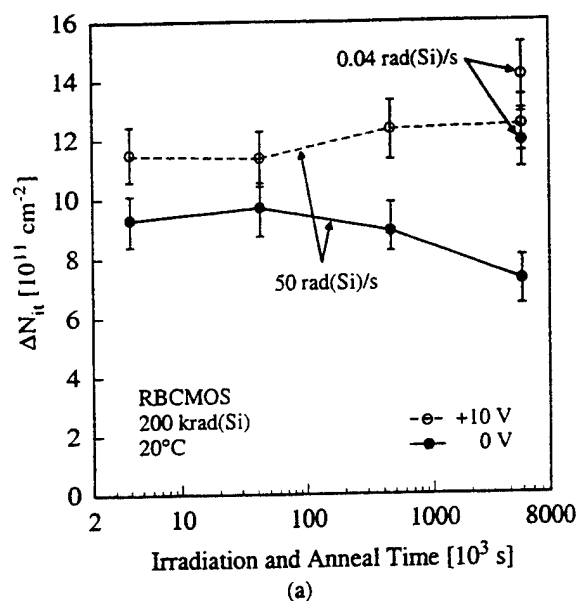

(a)

(b)

Fig. 6. Effect of dose rate on the densities of radiation-induced (a) interface traps and (b) net positive oxide trapped charge for the RBCMOS MOS-C. The buildup of oxide defects is sensitive to dose rate under zero bias. A positive gate bias eliminates the dose rate dependence.

excess base current reported previously for bipolar transistors from the same process[13]. Although room temperature, radiation-induced changes in the substrate doping of RF25 MOS-Cs were found to be smaller than those of the RBCMOS MOS-Cs, the dose rate response of these capacitors is otherwise consistent with the understanding of space charge limited degradation[9,28].

E. Irradiation Temperature Dependence of Oxide Degradation

The effect of irradiation temperature on high dose rate oxide degradation was examined for both the RBCMOS and RF25 capacitors. The capacitors were irradiated at seven
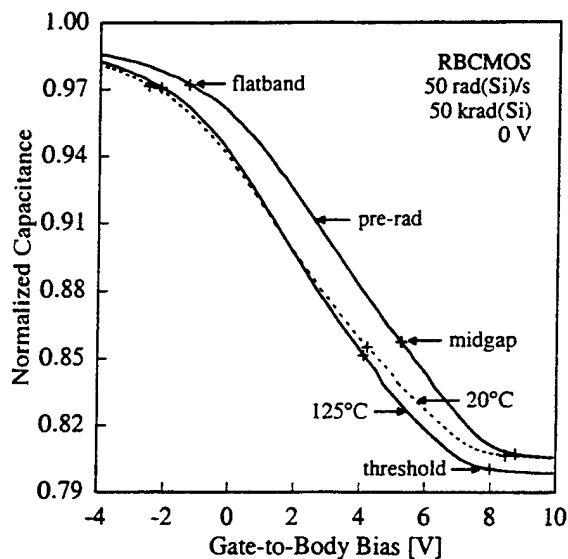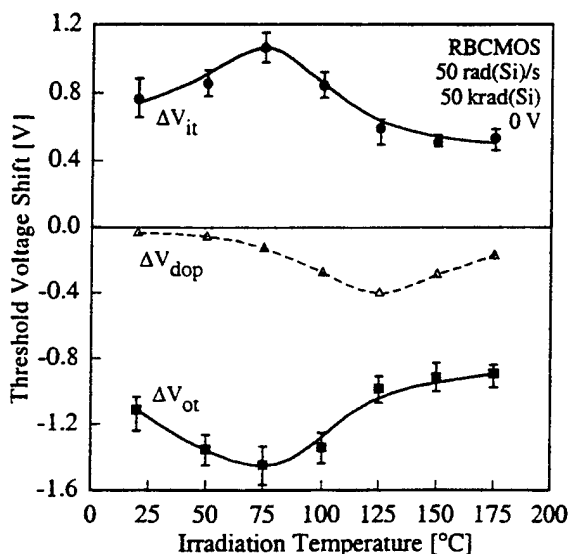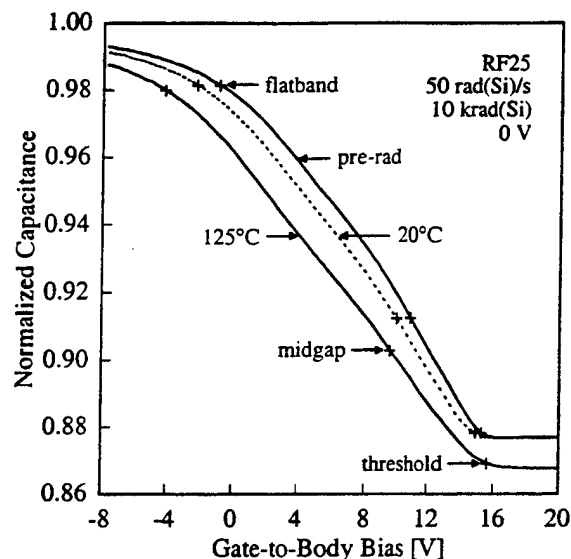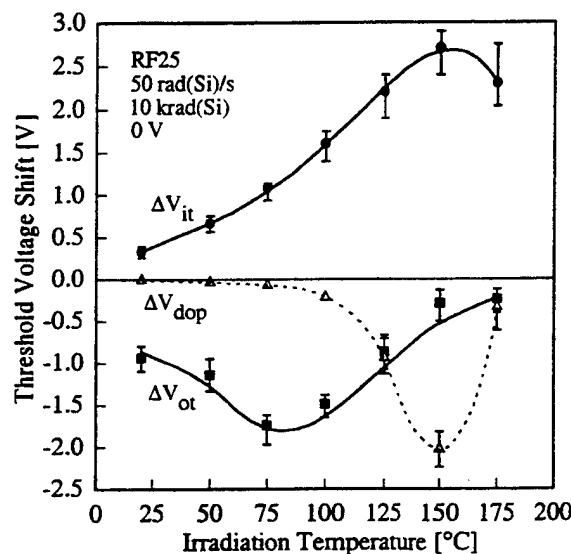
Fig. 7. Effect of irradiation temperature on (a) the C-V characteristics and (b) the charge-separated threshold voltage shifts of the RBCMOS MOS-C. Below 125°C, the Si capacitance decreases dramatically with temperature due to the accelerated transport of hydrogen and the thermal activation of B-H complexing.

Fig. 8. Effect of irradiation temperature on (a) the C-V characteristics and (b) the charge-separated threshold voltage shifts of the RF25 MOS-C. Near 150°C, the threshold voltage shift due to dopant neutralization is comparable in magnitude to those of interface traps and net positive oxide trapped charge.

temperatures between 20 and 175°C using a dose rate of 50 rad(Si)/s. All terminals were grounded during the irradiations. Post-irradiation C-V measurements were taken at 20±1°C immediately after allowing the samples to cool. A description of the heated test fixture and temperature metrology employed can be found elsewhere[12].

Fig. 7(a) shows representative C-V characteristics for RBCMOS capacitors irradiated to 50 krad(Si) at 20 and 125°C. Normalized C-V characteristics for an unirradiated capacitor are included for comparison. Below approximately 125°C, the reduction in Si capacitance due to radiation exposure is dramatically enhanced with temperature. The amount of capacitance reduction increases with surface potential between flatband and threshold. The additional decrease in ca-

pacitance results primarily from the sensitivity of B-H reactions to temperature. Because B-H complexes in Si are most stable near 100°C[91], increasing the irradiation temperature from 20 to 100°C significantly increases the likelihood that a given H atom will contribute to dopant neutralization. The fact that the Si capacitance continues to decrease through 125°C suggests that accelerated hydrogen transport through these oxides also contributes to the reduction in capacitance at elevated temperatures.

Fig. 7(b) shows the charge-separated components of threshold voltage shift for the RBCMOS capacitor as a function of irradiation temperature. Over a limited range, the magnitudes of ΔV_{it} and ΔV_{ot} increase with temperature. At sufficiently high temperatures, the enhancement in each of

these components is moderated by in situ annealing of the radiation damage such that a maximum value results. This response is qualitatively similar to the temperature dependence of radiation-induced excess base current observed in bipolar transistors from the same process[13]. Consistent with the trends in minimum capacitance, a peak in ΔV_{dop} occurs near 125°C.

Corresponding C-V characteristics and separated threshold voltage shifts for RF25 capacitors irradiated to 10 krad(Si) are shown in Figs. 8(a) and 8(b), respectively. The effect of temperature on radiation damage is considerably more dramatic for this process than for the RBCMOS process[10-13,24,28]. The thermal enhancement of ΔV_{it} is larger than that of ΔV_{ot} and occurs over a greater range of temperatures. The threshold voltage shifts are consistent with oxide trapped charge annealing at lower temperatures than interface traps[58,112,115-123] and support the previous assertion[13] that high dose rate irradiation at elevated temperature more effectively simulates the low dose rate response of bipolar devices whose degradation is dominated by interface traps. The peak in ΔV_{dop} well above 100°C is further evidence that the transport of hydrogen in SiO$_2$ is thermally activated. Within the range of 125 to 175°C, negative shifts in the threshold voltage are dominated by dopant passivation rather than by oxide trapped charge. The dependence of threshold voltage shift on irradiation temperature is complicated by the fact that the peaks in ΔV_{dop}, ΔV_{ot} and ΔV_{it} occur at different temperatures.

Preliminary irradiations of the RBCMOS capacitors to other doses indicate that both the amount of degradation enhancement and the temperature corresponding to maximum degradation decrease with dose for each of the components ΔV_{it} and ΔV_{ot}. Compared to those reported for related bipolar transistors irradiated at a higher dose rate[12,13], the lower optimum irradiation temperatures for these components reflect the increased annealing of radiation damage over longer exposure times. These trends in threshold voltage shift with temperature emphasize the relevance of dopant passivation in distinguishing radiation-induced oxide defects and suggest that hydrogen-acceptor interactions may play a critical role in the radiation-induced degradation and/or post-irradiation annealing of other MOS devices.

III. DISCUSSION

A. Physical Model For Bipolar Oxide Degradation

The strong dependence of hydrogen transport on dose rate and irradiation temperature in these oxides allows us to provide a more complete physical model for mechanisms contributing to dose rate dependent bipolar gain degradation. Fig. 9 provides a simplified illustration of this model for an
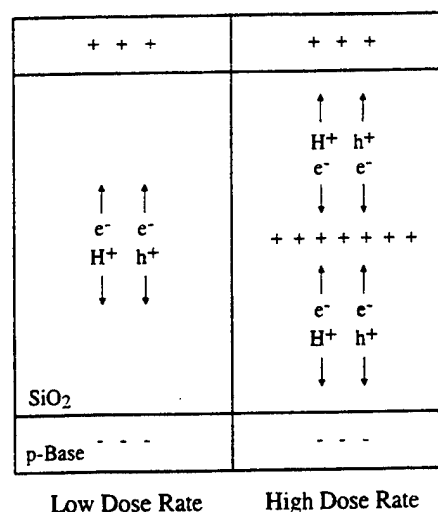

Low Dose Rate   High Dose Rate

Fig. 9. Simplified illustration of the space charge model for enhanced low dose rate oxide degradation at low-electric fields. Space charge in the oxide bulk reduces defect formation at high dose rates by inhibiting the transport of holes and H$^+$ ions to the Si-SiO$_2$ interface.

npn transistor, in which the focus is charge transport through the base oxide at low and high dose rates. Ionizing radiation degrades the gain of the transistor by introducing interface traps and net positive trapped charge into the oxide[1-8,11, 13,14,124-134]. The interface traps increase recombination along the base surface by providing additional energy levels through which the recombination can occur. Radiation-induced net positive oxide trapped charge increases the rate of recombination through a given trap by reducing the difference in carrier concentrations near the surface.

At low dose rates, degradation of the oxide essentially follows the usual models for irradiated MOS oxides[30-46] with the exception that charge transport is considerably slower. Assisted by material work function differences, radiation-induced holes transport slowly through metastable trapping centers to the Si-SiO$_2$ interface[6,11,28,29], where a fraction of them are captured by deep traps and contribute to changes in the Si surface potential. H$^+$ ions, coincidentally produced by the cracking of H$_2$ at other radiation-induced defects[40,42,43,45], transport by similar retarded interactions to the Si-SiO$_2$ interface[135,136], where they react with Si-H trap precursors and substrate electrons to form interface traps and H$_2$ molecules. The H$_2$ molecules and any residual H$^+$ ions subsequently diffuse into the Si, where they contribute to the neutralization of acceptors. The neutralization mechanisms are aided by the breakup of H$_2$ molecules[92], while the number of deactivated acceptors is moderated by radiation-induced minority carriers in the Si[59-62].

The O vacancy complexes and related defects[48-57, 137,138] that impede charge transport are often present in large numbers owing to oxide deposition techniques, high thermal budgets and base implants. At high dose rates, the

shallow trapping of holes[6,11,28,29] and H⁺ ions[135] at these defects significantly alters subsequent charge transport in the oxide. As the space charge accumulates, it eventually dominates localized E-fields and prevents a portion of newly created holes and H⁺ ions from ever reaching the Si-SiO₂ interface. Stated another way, once a critical amount of charge accumulates in the oxide bulk, holes and H⁺ ions created on the far side of the space charge centroid are pushed away from the device active region. As a consequence, the buildup of interface traps and net positive oxide traped charge are reduced along with the attendant dopant neutralization. In addition, the space charge can increase the number of compensating electrons in the oxide bulk, leading to further reductions in the Si surface potential[28].

At elevated irradiation temperatures, the buildup of space charge in the oxide bulk is reduced due to increased diffusion and faster emission of holes[28,29] and H⁺ ions[135,139] from the shallow traps. As with low dose rates, the reduction in space charge leads to larger oxide defect densities, since more holes and H⁺ ions are able to reach the Si-SiO₂ interface. An applied E-field would similarly reduce the buildup of space charge by affecting drift of the deleterious charge rather than diffusion[6,28,29]. Due to in situ annealing of the damage, the maximum densities of interface traps and net positive oxide trapped charge resulting from high-temperature irradiation are always smaller than those obtained at low dose rate and room temperature[7,12,13,15, 20,21,24]. By contrast, the amount of dopant deactivation near 125°C can exceed the room-temperature, low dose rate response due to more efficient B-H complexing. The relative effects of irradiation temperature on oxide defect annealing and dopant deactivation generally grow more severe with increasing total dose[12,13] or decreasing dose rate.

B. Implications of Radiation-Induced Dopant Neutralization for Bipolar Gain Degradation

The radiation response of these oxides raises the possibility that dopant passivation may be an important degradation mechanism previously not considered for bipolar devices. The potential for dopant passivation is heightened by the fact that E-fields in many bipolar base oxides are weak. The consequences of dopant passivation for gain degradation would depend on the device geometry and polarity considered. In a pnp device, acceptor passivation would exacerbate radiation-induced gain degradation by increasing the back-injection of electrons into the emitter and enhancing the emitter sensitivity to oxide trapped charge. As acceptors are neutralized, recombination in the emitter would increase due to spreading of the depletion region. These effects likely are more pronounced in lateral devices due to localized carrier injection near the Si surface. In an npn device, the deactivation of

base acceptors would similarly enhance gain degradation through depletion region spreading and increased series resistance in the base. Such enhancement, however, would be moderated by increased electron injection into the base. Because a decrease in base doping is accompanied by a reduction in the active base width, dopant passivation may also increase the device susceptibility to punch-through and base width modulation[140]. Lastly, due to its strong dose rate and temperature dependences, dopant passivation may be critical for microelectronics in space and impact hardness assurance techniques that prescribe high-temperature testing[6-8,10-15,18,20,21,24,25,28,29].

IV. SUMMARY AND CONCLUSIONS

This work provides new insight into the physical mechanisms contributing to enhanced low dose rate degradation of bipolar oxides. Hydrogen passivation of substrate acceptors was observed in irradiated p-type MOS capacitors from two bipolar processes. Using a novel technique, the radiation-induced threshold voltage shifts were separated into components due to interface traps, bulk oxide trapped charge and passivated acceptors. Dopant passivation shifts the threshold voltage negative with total dose and post-irradiation anneal time. The passivation is more dramatic under zero bias than under positive bias due to a smaller potential gradient and the presence of carriers in the Si.

When time-dependent effects are accounted for, the buildup of radiation damage under positive bias is independent of dose rate. Under zero bias, radiation-induced densities of interface traps, net positive oxide trapped charge and passivated acceptors are all smaller at high dose rate than at low dose rate. Elevating the temperature during high dose rate exposure enhances degradation while simultaneously accelerating the annealing of damage. These trends are consistent with a physical model in which metastably trapped space charge moderates charge transport in the oxide. At high dose rate, the space charge reduces the buildup of interface traps and net positive oxide trapped charge by inhibiting the transport of holes and H⁺ ions to the Si-SiO₂ interface. Elevating the irradiation temperature or applying a moderately positive bias reduces the accumulation of space charge by accelerating charge transport through the oxide.

Hydrogen passivation of acceptors may be an important degradation mechanism previously not considered for irradiated bipolar devices. Possible consequences of dopant passivation for the performance of bipolar transistors include a direct reduction in gain, increased device sensitivity to oxide trapped charge, punch-through and base width modulation. Future work in this area should include a critical examination of these issues and how they impact linear circuit and system performance in space.

ACKNOWLEDGMENTS

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