Electron Trapping During Irradiation in Reoxidized Nitrided Oxide *

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Abstract

Isochronal detrapping experiments have been performed following irradiation under different gate biases in reoxidized nitrided oxide (RNO) MOS capacitors. These show electron trapping by the nitridation-induced electron traps at low oxide fields during irradiation. A difference in the detrapping behavior of trapped holes and electrons is observed, with trapped holes being detrapped at relatively lower temperatures compared to trapped electrons. Electron trapping shows a strong dependence on the magnitude of the applied gate bias during irradiation but is independent of its polarity. Conventional oxide devices, as expected, do not show any electron trapping during irradiation by the native electron traps. Finally, a comparison of the isochronal detrapping behavior following irradiation and following avalanche injection of electrons has been made to estimate the extent of electron trapping. The results show that electron trapping by the nitridationinduced electron traps does not play the dominant role in improving radiation performance of RNO, though its contribution cannot be completely neglected for low oxide field irradiations.

I. INTRODUCTION

In the search for an alternative insulator to silicon dioxide for VLSI applications, Reoxidized Nitrided Oxide (RNO) shows-great promise. Higher dielectric strength, improved barrier against diffusion of impurities and contaminants, and improved resistance under electrical stress and radiation are the reasons why RNO has received much attention in the last several years [1-15]. It is well-known that nitridation introduces a large number of electron traps in the insulator [6,8,9,12,16-19] and reoxidation reduces these traps [8,9,12,19]. The reduction of these traps following reoxidation, however, depends upon the degree of initial nitridation. A trade-off is normally required between radiation hardness and the number of these electron traps. The exact role of these nitridation-induced electron traps in improving radiation hardness is not clear.

To explain the improved radiation performance of Nitrided Oxide (NO), Sundaresan et al. [20] suggested that the effect of radiation-induced trapped holes is partially compensated by trapped electrons because of the presence of the large number of electron traps in NO. Pancholy et al. [21], however, speculated that nitridation brings about structural changes resulting in fewer hole traps which are responsible for the improved radiation performance of NO. Dunn et al. [4,12] argued that electron trapping during irradiation by these native electron traps is unlikely because of the small capture cross-sections of these traps.

Field and thermal detrapping and etch-back experiments following irradiaiton by Ramesh et al. [22] clearly demonstrated that electron trapping does play a significant role though it is not the sole cause of improved radiation performance of NO. Simulation results by Vasudevan and Vasi [23] indicate electron trapping at low oxide fields which reduces at large fields. Simulation results by Krantz et al. [24] also indicate electron trapping during irradiaiton.

In this paper, we report an investigation of electron trapping during irradiation by the nitridation-induced electron traps (hereafter refered to as native traps) in RNO. Isochronal detrapping experiments following irradiation were performed to find out the extent and characteristics of electron trapping during irradiation. A comparison of the results of isochronal detrapping experiments following irradiation and following avalanche injection of electrons was made to estimate the role of electron trapping in improving radiation performance.

II. EXPERIMENTAL

The MOS capacitors used for this study were fabricated on 0.8-1.2 and 0.1-0.3 Ω -cm p-type boron doped (100) silicon wafers. The low resistivity wafers were used for avalanche injection experiments. For the RNO devices, initial oxidation was done at 1000°C in pure oxygen followed by nitridation in ammonia for 20 min followed by reoxidation for 75 min in pure oxygen followed by post-reoxidation annealing for 25 min [7]. The thickness of the oxide after initial oxidation was 33 nm, and the final thickness of RNO was 36 nm. Oxidation for control (dry) oxide devices was done at 1000°C in pure oxygen followed by post-oxidation annealing in nitrogen for 25 min at the same temperature. The reason for the post-oxidation anneal, despite the fact that it is known to degrade radiation hardness [25], is to

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Table 1: Electron trap parameters in RNO and control devices.

	Effective trap density (cm^{-2})	Capture cross-section (cm ⁻²)
Control	3.3×10^{11}	3.5×10^{-18}
RNO	4.2×10^{12}	4.7×10^{-18}

put the control samples through an anneal like the RNO samples. The thickness of the oxide was 36 nm, same as the final RNO thickness. Aluminum was deposited by e-beam evaporation through a metal-mask defining the gate electrodes of area 0.785 mm². Finally, all the devices received a forming gas anneal at 450°C for 30 min.

The devices were characterized by the high-frequency capacitance-voltage (HFCV) technique. Electron injection was performed using the constant-current avalanche injection technique at a current density of $25 \ \mu A/cm^2$. Irradiation was performed using a ⁶⁰Co gamma-ray source with a dose rate of 300 krad (Si)/hour.

III. ELECTRON TRAPS IN RNO

It has been widely accepted that nitridation introduces a large number of electron traps in the insulator. The capture cross-section of these traps has also been reported to be larger compared to traps in conventional oxides [17,19]. On the contrary, reoxidation has been found to reduce, though not eliminate, these traps. These native electron traps in RNO are highly process sensitive and their number and capture cross-section are dependent on the degree of nitridation and reoxidation [19].

Figure 1 shows the plot of midgap voltage shift (ΔV_{mg}) as a function of injected fluence for our RNO as well as conventional dry oxide (control) devices. It is evident from Fig.1 that the number of electron traps is significantly higher in RNO devices compared to the control devices. The values of effective trap density and capture crosssection were calculated using the data of Fig.1 and the values are shown in Table 1. The presence of a relatively large number of electron traps in RNO is not surprising because a "hard insulator" requires relatively heavy nitridation and for such a heavily nitrided oxide, reoxidation cannot remove the nitridation-introduced electron traps fully [8].

IV. ELECTRON TRAPPING UPON IRRADIATION

To find out the extent of electron trapping during irradiation by these nitridation-induced native electron traps, we performed isochronal detrapping experiments following irradiation. In the isochronal detrapping experiment [26,27], the devices are subjected to progressively higher



Figure 1: Midgap voltage shift as a function of injected electron fluence for RNO and conventional dry oxide devices.

temperatures from room temperature to 300°C in steps of 25°C. At each temperature, the devices are kept unbiased (floating) for 10 min, followed by HFCV measurements at room temperature. The unannealed fraction, N, which is a measure of annealing of the radiation-induced trapped charges, is defined as

$$N = \frac{\Delta V_{mg}(T)}{\Delta V_{mgo}},$$

where ΔV_{mgo} is the midgap voltage shift following irradiation and $\Delta V_{mg}(T)$ is the midgap voltage shift following detrapping at temperature T, both measured with respect to the pre-irradiated value of midgap voltage. The value of N is 1 immediately after irradiation and approaches zero as annealing proceeds.

Figure 2 shows the plot of unannealed fraction as a function of temperature for RNO as well as control devices. The devices were irradiated to a total dose of 1 Mrad(Si) with gate floating. We see that for the control devices, the unannealed fraction decreases monotonically as the temperature increases and approaches zero at high temperatures. On the other hand, for the RNO devices, the unannealed fraction decreases with increasing temperature, crosses zero (point A) and becomes negative. As the temperature is further increased, N continues to decrease, passes through a valley (point B) and finally tends to come back to zero (point C). The following conclusions can be drawn from Fig.2. (i) The change of sign of unannealed fraction (super-recovery of the radiationinduced trapped charges) for the RNO devices indicates that electron trapping does occur during irradiation. (ii) The unannealed fraction reaches point A when the unannealed trapped holes are fully compensated by the trapped electrons, reaches point B when almost all the trapped holes get detrapped but some unannealed trapped electrons remain and finally tends to come back to zero when these trapped electrons also get detrapped at higher temperatures. It is possible that the final reduction of ΔV_{mg} to zero is due to complete neutralization of trapped holes and trapped electrons, although the data of section V does seem to indicate that electrons detrap almost completely by about 300°C. The absense of the super-recovery for the control oxide devices indicates little or no electron trapping during irradiation by the native electron traps, or at least that these electrons all detrap at low temperatures, which is unlikely considering the reported detrapping characteristics for dry oxides [28]. (iii) There is a difference in the detrapping behavior of the radiation-induced trapped holes and electrons in RNO. The trapped holes are almost completely detrapped at about 275°C when significant trapped electrons still remain. Since the amount of electron trapping is small compared to hole trapping, as explained later, and since the fraction of the trapped electrons which get detrapped at lower temperatures (upto about 200°C) is also small, the overall detrapping behavior in the lower temperature range is essentially determined by the detrapping behavior of the trapped holes. At the higher temperatures (after about 275°C), when the trapped holes are almost completely detrapped, the overall detrapping behavior is determined by the detrapping behavior of the trapped electrons. The overall detrapping behavior is determined by both detrapping behavior of holes and electrons for a small range of temperature around the temperature when unannealed fraction crosses zero (point A).

To find out the dependence of electron trapping on the gate bias during irradiation, the isochronal detrapping experiment was repeated following biased irradiation. This was done for RNO devices only since little or no electron trapping is observed for the control devices under the floating bias condition, when the probability of electron trapping is maximum. Figure 3 shows the results of isochronal detrapping experiments performed again with gate floating following irradiation to a total dose of 1 Mrad(Si) with $\pm 3V$ gate bias for RNO devices. We see from Fig.3 that there is a slight difference in the detrapping behavior in the lower temperature range indicating that the detrapping behavior of the trapped holes is dependent on the polarity of the gate bias. In the higher temperature range, however, there is no difference in the detrapping behavior and a super-recovery, similar to that of the RNO devices in Fig.2, is observed. For either polarity of gate bias during irradiation, the unannealed fraction decreases as temperature increases, crosses zero and becomes negative, then passes through a valley, and finally tends to come back to zero at higher temperatures. This confirms that electron trapping does occur in RNO during irradiation. The coincidence of the detrapping behavior at higher temperatures in Fig. 3 indicates that the fraction of electron trapping is independent of the field direction during irradiation.



Figure 2: Results of the isochronal detrapping experiments following irradiation under floating gate for RNO and conventional dry oxide devices. The values of ΔV_{mg} were -0.78 and -1.66 V for RNO and dry oxide devices respectively.



Figure 3: Results of the isochronal detrapping experiments following irradiation under $\pm 3V$ gate bias for RNO devices. The values of ΔV_{mg} were -1.11 and -1.41 V for +3V and -3V gate bias respectively.

The results of the isochronal detrapping experiments performed again with gate floating following irradiation to a total dose of 1 Mrad(Si) with $\pm 5V$ gate bias are shown in Fig.4. The difference in the detrapping behavior in the lower temperature range in Fig.4 is consistent with the results in Fig.3, which confirms that the hole detrapping behavior is dependent on the polarity of the gate bias during irradiation. Under different polarity of gate bias, there could be a difference in the physical location of the trapped holes. The activation energy for these differently located traps can be different. Alternatively, a local variation in the band bending within the insulator can give rise to a difference in the effective activation energy of these differently located trapped holes. No super-recovery of the radiation-induced trapped charges is observed in Fig.4 for either polarity of the applied gate bias indicating little or no electron trapping during irradiation. There are probably two separate reasons for this. Firstly, as shown by simulation results [23], at low bias during irradiation there is a significant potential minimum created by the trapped holes which encourages electron trapping in that vicinity. At higher biases, this potential minimum is erased by the large applied field. This fact also explains why there is a non-negligible amount of electron trapping occurring in these oxides at low or floating bias despite the low capture cross-section (~ $5 \times 10^{-18} \text{cm}^2$) of the electron traps. Secondly, as shown by Ning [29], the capture cross-section for electron trapping in oxides decreases rapidly with increasing electric fields, and the same may be true in RNO as well. The results of Fig.4 again confirm that electron trapping is independent of the polarity of bias applied during irradiation.

To compare the relative amount of electron trapping for different biasing conditions, the detrapping behaviors for floating, +3V and +5V gate biases are replotted in Fig.5. It is seen in Fig.5 that there is no difference in the detrapping behavior in the lower temperature range. However, a difference is seen in the higher temperature range which is due to the different extent of electron trapping for different magnitudes of the applied bias. The amount of electron trapping is maximum when the devices are irradiated floating and decreases with increasing gate bias. The slight difference between +5 V gate bias and other biasing conditions in the medium temperature range can be explained if electron trapping is taken into consideration. The following conclusions can be drawn from the coincidence of the detrapping characteristics in the lower temperature range. (i) Hole detrapping behavior does not depend upon the magnitude of the applied gate bias during irradiation but does depent on the polarity. (ii) The ΔV_{mg} values corresponding to a dose of 1 Mrad (Si) are -0.78, -1.11 and -2.0 V respectively for floating, +3V and +5V gate biases. This means that although there is a large difference in the amount of hole trapping for these biasing conditions the hole detrapping behavior is independent of the amount of hole trapping. (iii) Although there is a difference in the amount of electron trapping for these biasing



Figure 4: Results of the isochronal detrapping experiments following irradiation under $\pm 5V$ gate bias for RNO devices. The values of ΔV_{mg} were -2.0 and -2.63 V for +5V and -5V gate bias respectively.

conditions during irradiation, this does not influence the hole detrapping behavior. As we have pointed out earlier, this is because firstly the amount of electron trapping is small compared to hole trapping, and secondly the fraction of trapped electrons which get detrapped in this temperature range is also small.

The detrapping behavior following irradiation with -3V and -5V gate biases are plotted in Fig.6. In this figure we again see that the detrapping behavior following irradiation under negative gate bias is almost identical in the lower temperature range, as in the case for positive gate biases (Fig. 5). The difference in the detrapping behavior at higher temperatures in Fig.6 confirms our earlier observation that the amount of electron trapping is strongly dependent on the magnitude of the applied gate bias during irradiation, with the amount being maximum for floating gate and decreasing with increasing gate bias. Coincidence of the detrapping behavior following irradiation under negative gate biases in the lower temperature range again confirms that the detrapping behavior of the trapped holes is independent of i) the magnitude (but not polarity) of applied gate bias, ii) the amount of hole trapping, and iii) the amount of electron trapping.

V. ROLE OF ELECTRON TRAPPING

To find out the role of electron trapping in improving radiation performance of RNO, the following experiment was designed. The isochronal detrapping experiment, as described in the previous section, was repeated following avalanche injection (A1) of electrons in a separate set of



Figure 5: Results of the isochronal detrapping experiments following irradiation under floating gate, +3V and +5V gate bias for RNO devices. The values of ΔV_{mg} were -0.78, -1.11 and -2.0 V for floating gate, +3V and +5V gate bias respectively.



Figure 6: Results of the isochronal detrapping experiments following irradiation under -3V and -5V gate bias for RNO devices. The values of ΔV_{mg} were -1.41 and -2.63 for -3V and -5V gate bias respectively.

RNO devices. During irradiation, hole as well as electron trapping can occur as we have seen in the previous section. whereas only electron traps are filled during AL Since there is a difference in the detrapping behavior of hole and electron traps, a comparison of the detrapping characteristics following AI and irradiation gives an estimate of the electron trapping upon irradiation. The fluence corresponding to 1 Mrad(Si) dose is ~ 1.6×10^{13} cm⁻² whereas the devices were subjected to a fluence of ~ 1.7×10^{18} cm⁻² during AI. Therefore, the question of validity of such comparison may arise because of the difference in the fluence the devices were subjected to before detrapping, since the amount of trapped electrons would be different in these cases. However, in the previous section we have seen in the case of holes that the detrapping behavior does not depend upon the initial amount of trapped charge. One important point to note here is that for the same fluence, the amount of electron trapping during irradiation and during AI would be different. The probability of electron trapping would be more during irradiation compared to during AI where the voltage drop across the oxide is about 14 V (corresponding to an oxide field of 3.9 MV/cm). The following assumptions are made in order to estimate the amount of electron trapping : i) holes and electrons detrap independently of one another, ii) the detrapping behavior of the electron traps is independent of the trap filling process i.e., whether the traps are filled by AI or irradiation, and iii) the detrapping behavior is independent of the initial amount of trapped charge.

Figure 7 shows a comparison of isochronal detrapping with floating gate following AI (data set I) and following irradiation under the floating gate condition (data set II). We now wish to estimate the extent of electron trapping. The percentage of electron trapping, considering hole trapping as 100%, is estimated as follows. The value of unannealed fraction is 0.34 at 275°C for data set I. This implies that 34% of the trapped electrons remain unannealed after detrapping at 275°C. Similarly, the value of unannealed fraction is 0.1 at 275°C for data set II. Assuming that all the trapped holes get detrapped at this temperature, we can say that this 0.1 is 34% of the total electron traps which were filled during irradiation. Hence, the fraction of the electron trapping is $0.1/0.34 \sim 0.29$ of the net charge trapping. The percentage of electron trapping, considering hole trapping as 100% is, therefore, $0.29/1.29 \times 100 \sim 23\%$. Following a similar procedure, estimates were made for the other biasing conditions as well and we found the percentages as ~ 13% for ± 3 V and 0% for ± 5 V.

...The accuracy of these figures largely depends upon the assumption that all the trapped holes get detrapped at 275°C. In the isochronal detrapping data following irradiation with ± 5 V gate bias (Fig.4), when no electron trapping is observed, we see that about ~3% of the trapped holes remain unannealed at 275°C. If we take this into consideration, the percentage of electron trapping becomes 28%, 18% and 0% for floating, ± 3 V and ± 5 V gate bias respectively. We would like to mention here that these fig-



Figure 7: A comparison of the isochronal detrapping experiments following irradiation under floating gate and following avalanche injection of electrons. The values of ΔV_{mg} were -0.78 and +7.95 V respectively soon after irradiation and avalanche injection.

Table 2: Electron trapping upon irradiation at different gate biases.

Gate bias	% of electron
(V)	trapping
Floating	25
+ 3	15
- 3	15
+ 5	0
- 5	0

ures, though not very accurate, are reasonable enough and give a good estimate of the extent of electron trapping. The figures for different biasing conditions are therefore rounded-off and tabulated in Table 2.

The results of the biased irradiation experiments are shown in Fig. 8. In this figure, ΔV_{mg} for a 1 Mrad(Si) dose is plotted against biasing conditions. The solid curves represent the results of biased irradiation as experimentally observed for RNO as well as control oxide devices. The dotted curve represents the result of biased irradiation for RNO devices if there would not have been any electron trapping during irradiation. In this case, the corresponding ΔV_{mg} values were estimated using the data points in the solid curve and the data in Table 2. It is evident from Fig.8 that electron trapping does not play the dominant role in improving radiation performance of RNO. However, its contribution cannot be completely neglected.



Figure 8: Midgap voltage shift as a function of gate bias during irradiation for 1 Mrad(Si) dose. Solid curves represent experimental ΔV_{mg} whereas dotted curve represents estimated ΔV_{mg} if there would not have been any electron trapping.

As seen in Fig.8, RNO performs better than control oxide for positive gate bias. However, the control devices show less ΔV_{mg} than RNO devices when negative gate bias is applied during irradiation because the hole traps in conventional dry oxides are located near the Si – SiO₂ interface, whereas, on the other hand, the dominant hole traps in RNO are located near the gate-SiO₂ interface [12,30].

The radiation performance of any insulator is determined by i) hole trapping, ii) radiation-induced charge neutralization (RICN) [31,32], iii) electron trapping by holetrap-induced electron traps [33], and iv) electron trapping by the native (as-grown) electron traps. Radiation-induced charge neutralization reduces the net hole trapping. This is important for switched-bias operation and has been found to be significant for conventional oxides [31,32]. Similarly, hole-trap-induced electron trapping has also found to be significant in case of conventional oxides [33]. Electron trapping by the native electron traps is, however, negligible in the case of conventional dry oxides. In this paper, we have addressed the issue of electron trapping by the as-grown electron traps in RNO and found that this cannot be completely neglected, especially at low fields during irradiation, since there exists a large number of nitridationinduced electron traps in RNO. In order to get a complete picture of what happens upon irradiation in RNO, hole trap induced electron traps as well as RICN has to be studied.

VI. SUMMARY AND CONCLUSIONS

The extent of electron trapping upon irradiation by the nitridation-induced electron traps in reoxidized nitrided oxide was studied by performing isochronal detrapping experiments following irradiation. A super-recovery of the radiation-induced trapped charges was observed which indicates the presence of electron trapping. The superrecovery is a result of a difference in the detrapping behavior of the radiation-induced trapped holes and electrons. The trapped holes get detrapped at relatively lower temperatures compared to the trapped electrons. The results of the detrapping experiments following irradiation under different gate biases show that the electron trapping is maximum when the devices are irradiated floating and decreases rapidly as the magnitude of the bias increases. The electron trapping, however, was found to be insensitive to the polarity of the gate bias. No electron trapping was observed in conventional dry oxides upon irradiation.

On the other hand, the detrapping behavior of the trapped holes in RNO was found to depend upon the polarity of the applied bias during irradiation but is insensitive to its magnitude. The detrapping behavior of the trapped holes was also found to be insensitive to the amount of the hole trapping as well as the extent of electron trapping.

A comparison of the detrapping behavior following irradiation and following avalanche injection of electrons was made to estimate the extent of electron trapping. We found that electron trapping by the nitridation-induced electron traps in RNO does not play a dominant role in improving its radiation performance. However, its contribution cannot be completely neglected for low oxide field irradiations.

VII. REFERENCES

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