# Role of Electron Traps in the Radiation Hardness of Thermally Nitrided Silicon Dioxide

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*Abstract*—**In this paper, we have studied a number of samples of thermally nitrided $SiO_2$ having varying concentrations of electron traps in an attempt to correlate the radiation-induced oxide charge to the number of electron traps. We have also studied the detrapping characteristics of irradiated devices, and performed etch-back experiments to locate the centroid of the trapped charge. The results show that electron trapping does play a role in the improved radiation hardness of nitrided $SiO_2$, but is not the sole cause of it.**

## I. Introduction

The thermal nitridation of silicon dioxide in an ambient containing ammonia produces an insulator which has many advantages, one of which is improved resistance to ionizing radiation [1]. Because of this, there has been interest in using nitrided oxide (NO) as a gate insulator. However, NO also has some problems, mainly a larger oxide fixed charge and a larger electron trap density $N_{et}$.

NO shows less radiation damage than $SiO_2$ in the presence of ionizing radiation like $\gamma$-rays and electron beams. There is less radiation-induced buildup of positive oxide charge, and almost no buildup of interface states. Though these phenomena have been widely observed, there is no clear explanation for them. With reference to the oxide charge, Pancholy and Erdmann [2] suggest that the improvement stems from structural changes in the oxide during nitridation resulting in fewer hole traps to capture radiation-generated holes, whereas Sunderesan *et al.* [3] have invoked the presence of the large number of electron traps, which capture radiation-generated electrons, and compensate the trapped holes. Dunn *et al.* [4], [5] have argued that electron trapping by native traps is unlikely to take place because of small capture cross sections. However, with the large number of electron types present in NO, some trapping cannot be ruled out. Simulation results [6] do indicate electron trapping, especially at low fields.

This paper seeks to determine the extent to which electron traps present in the oxide affect its radiation hardness. We have fabricated a large number of MOS capacitors with NO using varying conditions of nitridation, resulting in different $N_{et}$. We measured $N_{et}$, density and centroid of radiation-induced positive charge, and detrapping behavior in these devices.

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## II. Experiments

MOS capacitors were fabricated on 0.1–0.2-$\Omega \cdot$ cm p-type $\langle 100 \rangle$ Si wafers. Oxides of thicknesses 400 and 1500 Å were grown at 1000°C, followed by a 30-min $N_2$ anneal. Nitridation was done at 1000, 1050, and 1100°C for 30, 60, and 120 min using 25%, 40%, 60%, and 100% mixtures of $NH_3$ (99.99% pure) in $N_2$, followed by a 30-min $N_2$ anneal. This gave a total of 36 different conditions of nitridation. Aluminum was deposited in an e-beam evaporation system, and defined into 1-$mm^2$ gates using photolithography. Finally, the wafers were annealed in $H_2$ at 450°C for 30 min.

The MOS capacitors with both NO and $SiO_2$ were characterized by taking high-frequency *CV* (HFCV) plots via a computer. Electron trap densities $N_{et}$ were measured by performing constant-current avalanche injection [7] for 30 min and measuring the flat-band voltage shifts $\Delta V_{FB}$ from the HFCV plots. Samples were irradiated unbiased using a $Co^{60}$ $\gamma$-ray source, and $\Delta V_{FB}$ measured from HFCV plots. This measures the trapped oxide charge since interface trap generation in NO is negligible. Field and thermal detrapping of the radiation-induced charge was done. Again, $\Delta V_{FB}$ was measured to monitor the amount of detrapping. All the above experiments were done on 400-Å devices. The centroid of the radiation-induced trapped charge was determined on 1500-Å devices by etching the oxide and making repeated $\Delta V_{FB}$ measurements using a mercury probe.

## III. Results and Discussion

The electron trap density in NO is considerably larger than in $SiO_2$. $V_{FB}$ shifts for $SiO_2$ were of the order of 0.5 V, whereas those for NO were between 6 and 15 V depending on the nitridation conditions [8]. $N_{et}$ was computed assuming that the traps lie within 100 Å of the interface [8].

Capacitors with various types of NO were exposed to radiation up to a total dose of 400 krd (Si), and the radiation-induced $\Delta V_{FB}$ measured within 24 h of irradiation. A plot of $\Delta V_{FB}$ versus $N_{et}$ is shown in Fig. 1 for 400-Å devices. Although all NO samples show smaller $\Delta V_{FB}$ than $SiO_2$, there is no clear trend of decreasing $\Delta V_{FB}$ with increasing $N_{et}$, which would have been expected if electron traps were the *only* factor affecting the radiation hardness of the NO.

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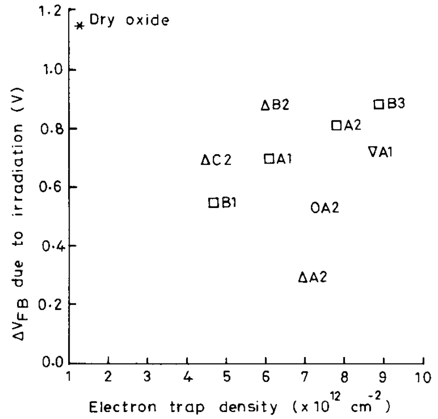


Fig. 1. Plot of radiation-induced flat-band voltage shift $\Delta V_{FB}$ versus electron trap density $N_{et}$ for 400-Å oxides nitrided under different conditions: (○) 25% $NH_3$, (△) 40% $NH_3$, (□) 60% $NH_3$, (▽) 100% $NH_3$; (*A*) 1000°C, (*B*) 1050°C, (*C*) 1100°C; (1) 30 min, (2) 60 min, (3) 120 min.

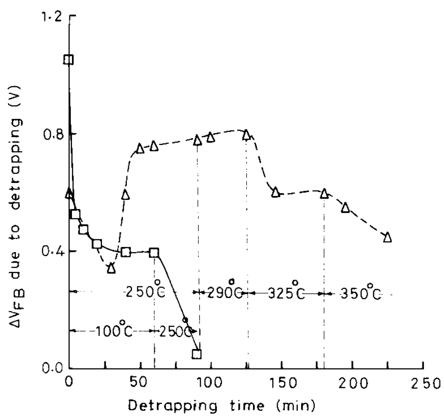


Fig. 2. $\Delta V_{FB}$ due to thermal detrapping versus detrapping time for 400-Å $SiO_2$ (solid line) and NO (dashed line).

However, Fig. 1 does not rule out that electron traps do play some role.

This was explored further by doing thermal detrapping at temperatures of 100–350°C. Fig. 2 shows $\Delta V_{FB}$ versus time for both $SiO_2$ and NO. The decrease of $\Delta V_{FB}$ for $SiO_2$ is monotonic, consistent with the hypothesis that the trapped holes start detrapping at the elevated temperatures. However, for NO, $\Delta V_{FB}$ decreases, increases, and then decreases again, going at times beyond the initial value. Similar curves were obtained for other NO oxides also. This nonmonotonic behavior strongly suggests that the NO contains both trapped electrons as well as holes, which are simultaneously emptying out. Depending on the energetic location of the (distributed) traps, the detrapping of either holes or electrons may dominate, resulting in a decrease or increase of $\Delta V_{FB}$. It should be noted that the residual $\Delta V_{FB}$ after long detrapping times is quite different in the two cases, again indicating that although electron traps are playing a role, they are not the *sole* determining factor.

Further evidence for electron trapping during irradiation of NO comes from the results of field detrapping. Field detrapping at room temperature with $\pm 15$ V (corresponding to about $\pm 3.5$ MV/cm) applied to the gate shows $V_{FB}$ shifts of less than 50 mV for $SiO_2$. In the case of NO, the shift is still about 50 mV for $+15$ V, but about 200 mV (with the *CV* curve moving towards the *left*) for $-15$ V. It has been shown [9] that the electron traps in the NO lie close to the $Si/SiO_2$ interface, and can be detrapped by tunnelling to the silicon. Applying $-15$ V to the gate causes some of the electron traps to empty out, resulting in an increase of $\Delta V_{FB}$ by 200 mV.

Finally, we did etch-back measurements to find the centroid of the radiation-induced trapped charge. This experiment [10], [11] consists of etching away the oxide and doing repeated $V_{FB}$ measurements. If $\delta V_{FB}$ is the difference between the $V_{FB}$ measured after and before irradiation and etching, then it can easily be shown that

$$\delta V_{FB} = -\frac{Q_{ot}}{\epsilon_{ox}}(d_{ox} - \overline{X}) + \frac{Q_f}{\epsilon_{ox}}(d_{ox0} - d_{ox})$$

where $Q_{ot}$ is the total (electron plus hole) oxide trapped charge, $\overline{X}$ is its centroid, $Q_f$ is the oxide fixed charge, $d_{ox}$ is the oxide thickness after etching, and $d_{ox0}$ is the initial thickness before etching. If the etching does not penetrate into the charge distribution (so that $Q_{ot}$ is not affected), a plot of $\delta V_{FB}$ versus $d_{ox}$ is a straight line, and both $Q_{ot}$ and $\overline{X}$ can be found, since $Q_f$ is known.

Etch-back experiments were done for both $SiO_2$ as well as NO, with $d_{ox0}$ of 1300–1600 Å. The samples were irradiated to a total dose of 1.1 and 2.7 Mrd (Si) for $SiO_2$ and NO, respectively. The $d_{ox}$ was measured after each etch by ellipsometry as well as capacitance. Fig. 3 shows that $\delta V_{FB}$ versus $d_{ox}$ for $SiO_2$ and NO are good straight lines, indicating that the etching did not penetrate into the charge distribution. The values of $Q_{ot}$ and $\overline{X}$ for $SiO_2$ and NO are, respectively, $5.4 \times 10^{11}$ and $2.4 \times 10^{11}$ q/cm$^2$, and 210 and 710 Å. The last result is surprising at first sight since the etching went down to 400 Å without the data deviating from a straight line. This can only be explained if we assume that there exist *both* trapped holes and electrons at centroids $\overline{X}_h$ and $\overline{X}_e$. The net centroid is at $\overline{X} = (Q_{ot,h}\overline{X}_h + Q_{ot,e}\overline{X}_e)/Q_{ot}$, where $Q_{ot} = Q_{ot,h} + Q_{ot,e}$. Since $Q_{ot,h}$ and $Q_{ot,e}$ are of opposite signs, it is quite possible for $\overline{X}$ to be larger than both $\overline{X}_h$ and $\overline{X}_e$. For example, if $\overline{X}_h = 200$ Å and $\overline{X}_e = 100$ Å (typical values), and $Q_{ot,h} = 0.8\ Q_{ot,e}$, then $\overline{X} = 600$ Å. Similar results (with $\overline{X}$ between 400 and 700 Å, and straight lines down to about 300 Å) were obtained with oxides nitrided under different conditions. These etch-back results clearly indicate the presence of electron trapping in the nitrided oxides. Furthermore, the values of $Q_{ot}$ and $\overline{X}$ obtained suggest that while the electron traps are not the only cause of hardening in NO, they do play a significant role. Although the etch-back measurements were performed with thicker oxides, the basic results of the role of electron trapping would hold for 400-Å (or even thinner) oxides as well.

Our experiments on the correlation between radiation hardness and electron trap density, however, do show that elec-

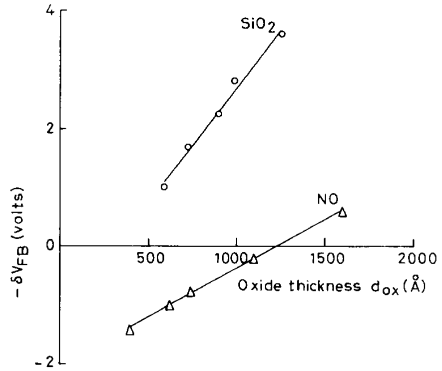


Fig. 3. Plot of $-\delta V_{FB}$ versus $d_{ox}$ for the etch-back experiment for $SiO_2$ (○) and for 60% $NH_3$ 1050°C 60-min nitrided oxide (△). The $SiO_2$ was irradiated to a total dose of 1.1 Mrd (Si), and the NO to 2.7 Mrd (Si).

tron trapping is not the *sole* cause of improved radiation hardness, and some other mechanism, possibly a decrease in the number of hole traps, also plays a role. As shown by Severi *et al.* [12], hole traps in NO reduce with strong nitridation such as used by us. It has recently been reported [4] that reoxidized nitrided oxides (RNO) show improved radiation resistance without a concomitant increase in $N_{et}$. The reason for this is probably due to the reduction or redistribution [5] of hole traps.

In conclusion, our experiments show that in nitrided oxides, *both* electron trapping and some other mechanism (perhaps a reduction in hole traps) contribute to hardness.

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