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Charge-trapping properties of gate oxide grown on nitrogen-implanted silicon substrate

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Charge-trapping properties of ultrathin gate oxide grown on a nitrogen-implanted silicon substrate were investigated using high-field Fowler–Nordheim injection. By applying an empirical model and monitoring threshold voltage shift due to current stress, it was found that both hole trapping and electron trapping are suppressed in the nitrogen-implanted oxide. Smaller trap-generation rate compared to pure SiO_2 film was also noticed. Our results indicate that nitrogen implantation into silicon substrate before gate oxide growth is an alternate way to incorporate nitrogen into the Si/SiO_2 interface. © *1999 American Institute of Physics.* [S0003-6951(99)04941-4]

Reduction of gate leakage current and prevention of boron penetration from substrate are two major challenges faced by scaling of complementary metal-oxide-semiconductor (CMOS) circuits. It is, therefore, required to have ultrathin gate oxides with improved reliability. Recently, nitrogen was incorporated in gate oxides by growing oxides on nitrogen-implanted silicon substrate.[1] Besides, there is a high degree of interest in using high-dose nitrogen implant to change the oxidation rate for multiple-oxide-thickness technology. Gate oxides grown on substrates with N_2^+ doses of $5\times10^{13}/cm^2$–$5\times10^{14}/cm^2$ have shown superior electrical characteristics with improved immunity to plasma charging damage[2] while effectively preventing boron penetration.[3] Though nitrogen incorporation is well studied using other means of nitridation, dielectric integrity such as charge-trapping characteristics of oxides grown on implanted substrates is not clearly understood. In this letter, we would like to report a charge-trapping phenomenon in thin gate oxides when the oxide is grown on a nitrogen-implanted silicon substrate using high-field stress. A light N_2^+ implant dose of $\sim 2\times10^{13}/cm^2$ was used to implant the silicon substrate before the gate oxide was grown. At this dose level, a 3% variation (within measurement limit) of gate oxide growth rate was noticed. This makes it easier to compare with the control oxide (thermal oxide) grown on silicon substrate with no nitrogen implant, that followed the same processing cycle as that of the nitrogen-implanted oxide. High-field electron injection (based on the effect of Fowler–Nordheim (FN) tunneling) into gate oxide has been a technique extensively used for characterization of technology related reliability of metal-oxide-semiconductor (MOS) transistors. This high-field injection was employed to evaluate the charge-trapping characteristics of both the oxide types.

The investigation was carried out on fully processed transistors up to metal-1 using a 0.25 μm CMOS technology. N^+ was implanted into the (100) Si substrates at 25 keV through a 200 A sacrificial oxide. After the sacrificial oxide was etched the gate oxide was grown in dry O_2 at 800 °C. Approximately 3–4 at. % of nitrogen was incorporated into the oxide. The oxide thickness for 25 min oxidation was 52 Å for both the splits of (a) without N^+ ion implant (control oxide) and (b) with $2\times10^{13}/cm^2$ N^+ ion implant. The gate oxide thickness was measured by multi-angle ellipsometry ($\lambda = 632.8$ nm). The transistors had a physical gate length of 0.35 μm. Only *n*-channel transistors were evaluated. The wafers were annealed in forming gas (400 °C, 30 min) before measurement started. Initial transistor parameters such as threshold voltage (V_t) and transconductance (g_m) before stress were very uniform across the wafer. To determine the charge-trapping behavior of the gate oxides, electrons were injected in the Fowler–Nordheim region from the gate electrode at a constant current density (J_{ox}) of 400 mA/cm^2 for 4.5 s. V_t shift and g_m degradation were obtained from the before and after current stress measurements. Poststress transistor measurements were carried out at fixed delay in an automated setup.

To evaluate the charge buildup during FN injection the voltage necessary to sustain constant-current high-field injection is monitored. Figure 1 shows gate voltage shifts ΔV_g during a constant-current FN stress for nitrogen-implanted oxide and control oxide. In both the oxides ΔV_g decreases initially and then increases almost linearly with increasing injected charge, $Q_{inj}(J_{ox}.t)$. During FN injection, hole trapping is responsible for positive charge buildup, whereas negative charge buildup is due to electron trapping of empty electron traps existing in the oxide prior to injection and traps generated during high-field stress.[4] The initial decrease in Fig. 1 indicates that hole trapping occurs in the beginning.

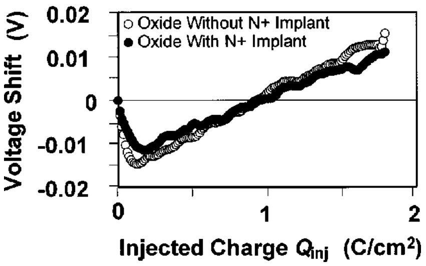

FIG. 1. The gate voltage shifts ΔV_g during a constant-current FN stress for nitrogen-implanted and control oxide as a function of injected charge, Q_{inj}.

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TABLE I. The fitting parameters C_1, σ_1, C_2, σ_2 and C_3 for control oxide and nitrogen-implanted oxide.

Oxide type	C_1(V)	σ_1(cm^2)	C_2(V)	σ_2(cm^2)	C_3(V cm^2)
Control oxide	0.001 156	1.6×10^{-18}	0.0152	3.83×10^{-18}	0.0163
N+ implanted oxide	0.000 865	1.4×10^{-18}	0.0115	3.63×10^{-18}	0.0121

Electron trapping then dominates (after hole trapping saturated) causing ΔV_g to increase. The initial slope of dV_g/dQ_{inj} corresponds to the preexisting electron traps. Clearly ΔV_g of the nitrogen-implanted oxide shows smaller positive shifts during hole trapping and smaller slopes during electron trapping compared to control oxide. This behavior is closely related to smaller charge trap density in the nitrogen-implanted oxide.

To get a quantitative estimate of charge-trapping properties an empirical expression[5,6] of ΔV_g as a function of injected charge Q_{inj} was used

$$\Delta V_g(Q_{\text{inj}})=C_1[1-\exp(-\alpha_1 Q_{\text{inj}}) - C_2[1-\exp(-\alpha_2 Q_{\text{inj}})+C_3(Q_{\text{inj}}/q), \quad (1)$$

where C_1, C_2 and C_3 are the fitting parameters, q is electronic charge and $\alpha_1=\sigma_1/q$ and $\alpha_2=\sigma_2/q$ with σ_1 and σ_2 the capture cross sections of electron and hole traps, respectively. The first term on the right hand side in Eq. (1) represents the filling of preexisting electron traps, the second term corresponds to the effect of hole trapping[6] and the third term represents new electron trap generation during FN injection. C_3 is the corresponding trap generation rate and is constant, as shown in Fig. 1. To further explain the charge-trapping process, these parameters are fitted to the experimental data and the fitting parameters are listed in Table I. The calculated capture cross sections of electron and hole traps are higher in control oxide compared to the nitrogen-implanted oxide. The values of C_1 and C_2 are weakly dependent on oxide quality, whereas C_3, the electron trap generation rate, is smaller in nitrogen-implanted oxide with respect to control oxide. During FN injection electrons with kinetic energy above 3 eV produce new trap sites by breaking weak SiH and SiOH bonds. Smaller trap generation rate is due to the presence of nitrogen that reduces the number of weak SiH and SiOH bonds in nitrogen-implanted oxide.[5] In addition, it is widely believed that during oxide growth after nitrogen implantation more nitrogen piles up at the Si/SiO$_2$ interface forming a nitrogen rich layer at the substrate interface compared to gate interface. During high-field injection electrons are first injected from the cathode into the conduction band of SiO$_2$ owing to F–N tunneling. The injected electrons gain kinetic energy from the oxide field, then create or release a ''positive species'' (holes or hydrogen-related species) near the anode which returns to the cathode while creating oxide traps. Therefore, during gate injection, as in our case, the released positive species face a barrier due to the presence of nitrogen at the substrate interface thereby decreasing overall oxide trap creation.[7,8] This further explains the reduction in trap generation rate in nitrogen-implanted oxide (Table I).

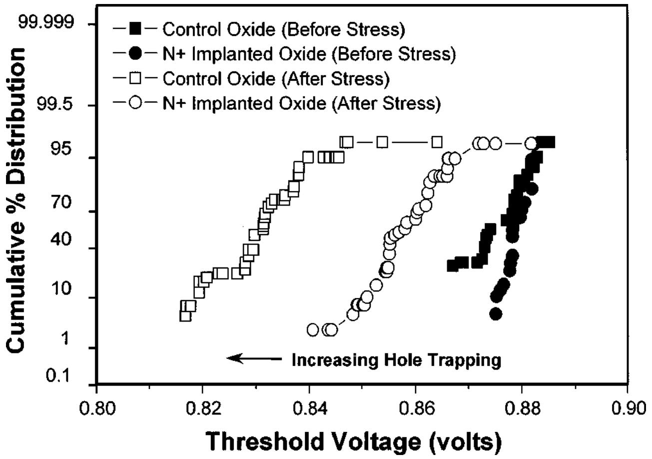

FIG. 2. Cumulative plot of threshold voltage in n-MOS devices with control and nitrogen-implanted oxides before and after FN stress. The shift in threshold voltage shows that the nitrogen-implanted oxide suffers from less hole trapping compared to control oxide.

Figure 2 gives the cumulative percentage distribution of devices before and after FN stress as a function of threshold voltage for both the control and nitrogen-implanted oxides. Before stress, both the oxides show a tight distribution without much difference. After the devices were subjected to negative FN injection (electron injection from the gate), it was observed from the distribution that the devices with control oxide suffer from larger Vt shift (Fig. 2) compared to devices with oxides grown on a nitrogen-implanted substrate. It can be clearly seen that Vt shift for both types of devices is negative after stress indicating larger positive effective charge in the oxide due to hole trapping.[4] However, devices with control oxide show a larger positive charge buildup (larger negative Vt shift) compared to nitrogen-implanted oxide. With a smaller Vt shift and a smaller slope during electron trapping (Fig. 1) devices with nitrogen-implanted oxide have lower than expected density of trapped holes similar to most of the nitrogen incorporated gate oxides.[9]

Figure 3 shows the average $\Delta g_m/g_m$ value of 41 devices with the control oxide and nitrogen-implanted oxide. As expected, $\Delta g_m/g_m$ for nitrogen-implanted oxide is lower than control oxide after the same stress. Since $\Delta g_m/g_m$ is quite sensitive to interface state density it is clear that nitrogen-implanted oxide has a superior Si/SiO$_2$ interface. The detrap-

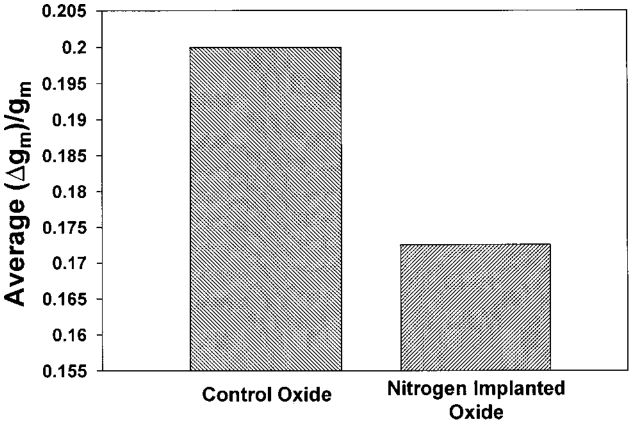

FIG. 3. The average $\Delta g_m/g_m$ values of devices with control and nitrogen-implanted oxide. Δg_m is the difference of g_m measurements taken on 41 devices, in each case before and after the FN stress.

ping kinetic study[10] suggests that the observed $\Delta g_m/g_m$ change could be due to electron traps near the interface. Besides, it is believed that the presence of nitrogen at the interface seems to reduce the acceptor-like interface states produced by weak Si–O bonds.[11] The reduction in g_m degradation is another evidence that generation of interface states in nitrogen-implanted oxide is suppressed.

Though nitrogen implantation has improved the charge-trapping characteristics of the oxide compared to the control oxide, the improvement is much smaller compared to nitridation due to N_2O annealing, as reported by Kukuda and Namura.[5] They noticed the charge-trapping characteristics of nitrided oxides are several times better than those of thermal oxide. In this work, it is believed that the reduced improvement in N^+ implanted oxide is affected by ion implantation. Nitrogen implantation, therefore, may not be suitable for critical oxides like gate oxide but can be used to control the oxidation rate for multiple-oxide-thickness technology.

In summary, we have investigated the charge-trapping properties of gate oxide grown on nitrogen-implanted silicon substrate using high-field electron injection. It was found that both hole trapping and electron trapping are suppressed in the nitrogen-implanted oxide. Reduction in trap generation rate was also noticed. Our result indicates that nitrogen implantation into silicon substrate before gate oxide growth is an alternate way to incorporate nitrogen into the Si/SiO_2 interface.

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