Improvement of Charge Trapping Characteristics of N_2O-Annealed and Reoxidized N_2O-Annealed Thin Oxides

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Abstract—**It is found that increasing N_2O annealing temperature and time monotonically reduces electron trapping in the resulting oxides. The improvement increases with oxide thickness. Reoxidation does not enhance but reduces the improvement. The behavior is different from and simpler to understand than that after NH_3 annealing, apparently due to the absence of deleterious hydrogen. Hole trapping and interface trap generation are also suppressed by N_2O annealing, though an optimum anneal condition may exist. Charge to breakdown exhibits modest improvement consistent with reduced electron trapping.**

THE use of N_2O as an oxidant or a post-oxidation annealing ambient has attracted much attention recently [1]–[3]. Comparing direct oxidation of silicon in N_2O with annealing pregrown oxides in N_2O, we conclude that the latter is more promising because oxide growth in pure N_2O is self-limited to less than 50 Å under normal processing conditions (e.g., 950°C, 40 min). To increase the oxide thickness, high oxidation temperature and extended oxidation time are required. However, high-temperature processing steps are not preferable for future technologies. When N_2O is used as a post-oxidation annealing ambient, a wide range of final oxide thicknesses is achievable [4]. Although it has been reported that N_2O-annealed gate oxides can improve the electrical stability of MOSFET's [1], [3], reliability issues for the gate dielectric such as charge trapping, interface stability, charge to breakdown Q_{bd}, as well as their process dependencies, have not been reported. In this work, electron and hole trapping and their process dependencies are evaluated. The effects of reoxidation on the N_2O-annealed oxide are also examined.

MOS capacitors were fabricated with p-type, 15–25-$\Omega \cdot$ cm ⟨100⟩ silicon substrate in a standard four-mask polysilicon-gate process. For the gate dielectric, initial oxides were grown to 50–100 Å in dry O_2. Next, N_2O annealing was done at 900 or 950°C for 10 to 80 min in pure N_2O. Reoxidation was done in O_2 to selected samples. Determined by auger electron spectroscopy, about 0.6–1 atomic% of nitrogen (depending on the annealing time and temperature) is incorporated at the oxide/substrate interface. The final effective oxide thicknesses (using $\epsilon_{ox} = 3.9$) were determined by *CV* measurement and ranged from 75 to 123 Å. Unless otherwise specified, the gate area of the test structures is 10 μm × 10 μm.

Fig. 1 depicts the quasi-static *CV* data before and after Fowler–Nordheim (FN) stress for control, N_2O-annealed, and reoxidized N_2O-annealed oxides. Before stressing, all samples had nearly identical normalized *CV* characteristics. Interface trap generation induced by FN injection is much smaller in the N_2O-annealed devices compared with the control oxide, as indicated by the much smaller *CV* distortion. Fig. 1 also shows that the flat-band and mid-band voltage shifts after stressing are less in N_2O-annealed oxides. This suggests that the net charge trapping is lower in N_2O-annealed oxides. However, reoxidation does not further improve, as in the case of NH_3 annealing [5], [6], but degrades the interface hardness of the N_2O-annealed oxide.

In order to study the bulk charge trapping characteristics, V_g shifts during 50-mA/cm^2 constant current stress are monitored instead of V_{fb} shifts so that the effects of the interface trap charges are minimized [7]. The results are shown in Fig. 2 for both polarities of gate voltage. Fig. 2 shows that both the amplitude of the V_g shifts and the rate of V_g change are reduced by N_2O anneal. This suggests that the electron trap generation and trapping are reduced by N_2O anneal. Again the reoxidation step tends to increase electron trapping. Low-density (0.01 mA/cm^2) constant current injection is done to study the hole trapping rate of these oxides [7]. The data are shown in Fig. 3. It appears that N_2O anneal actually modifies the hole trapping rate modestly when electrons are injected from the substrate ($+V_g$ injection). When electrons are injected from the gate ($-V_g$ injection), hole trapping is

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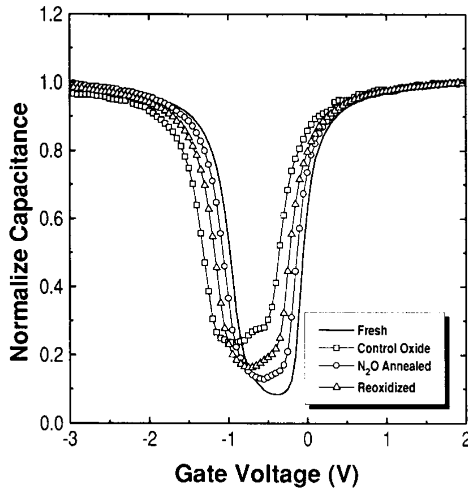

Fig. 1. Normalized quasi-static CV curves before and after 0.1-C/cm^2 $-V_g$ constant current injection ($J = 0.1$ mA/cm^2) for control, N_2O-annealed (950°C, 20 min), and reoxidized (950°C, 20-min N_2O; 900°C, 20-min O_2) oxides. The gate area is 80 μm × 80 μm. Since the fresh CV curves for these oxides are comparable, only one set of fresh data is plotted. A comparable thickness of about 10 nm is achieved by varying the initial oxide thickness.

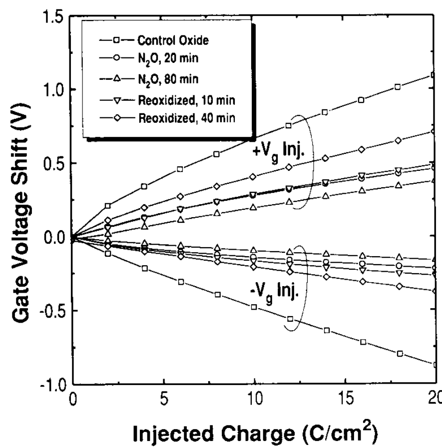

Fig. 2. Gate voltage shifts during 50-mA/cm^2 constant current injection for control ($T_{ox} = 97$ Å), N_2O-annealed (950°C, $T_{ox} = 91$ Å), and reoxidized N_2O-annealed (950°C, 20-min N_2O; 900°C, 10- or 40-min O_2, $T_{ox} = 96$–104 Å) oxides. Electrons are injected either from the gate ($-V_g$ injection) or from the substrate ($+V_g$ injection).

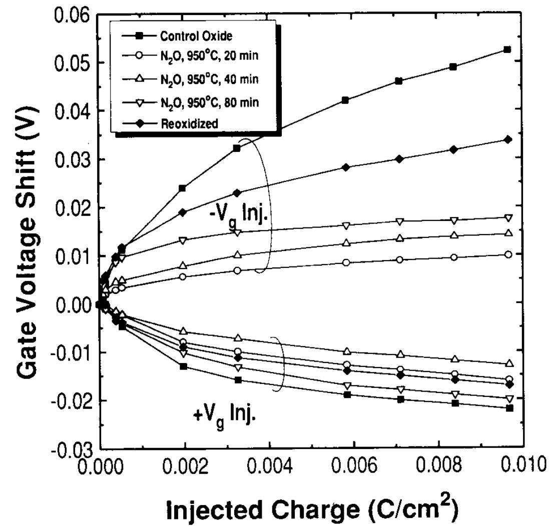

Fig. 3. Gate voltage shifts during 10-μA/cm^2 constant current injection for control, N_2O-annealed, and reoxidized N_2O-annealed (950°C, 20-min N_2O; 900°C, 20-min O_2) oxides with similar thicknesses as those used in Fig. 2.

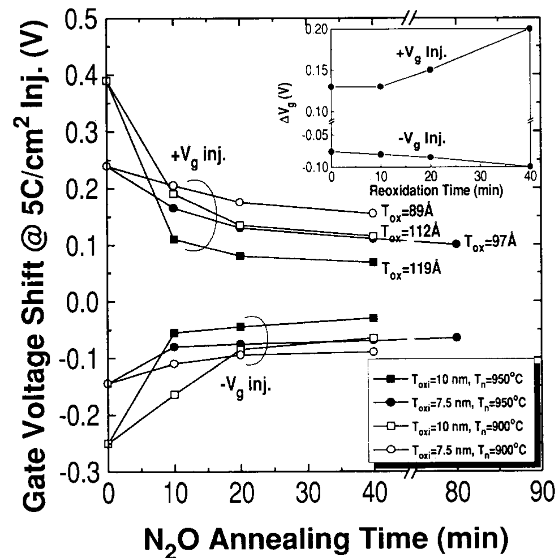

Fig. 4. Process dependence of the gate voltage shifts at 5 C/cm^2 ($J = 20$ mA/cm^2) injection. The initial (before annealed) oxide thickness T_{oxi} and the final (after annealed) oxide thickness T_{ox} are labeled in the figure. The effects of reoxidation on gate voltage shifts for 20-min, 950°C N_2O-annealed oxide are also plotted in the inset. The temperature for reoxidation is 900°C.

greatly suppressed. We speculate that this polarity-dependent hole trapping suppression is due to the presence/absence of nitrogen pileup at the oxide–substrate interface/oxide surface [1], [2]. It is worth noting that hole trapping increases when the anneal time is extended. This arises because the thickness continues increase after saturated nitrogen incorporation [4]. As expected, reoxidation also leads to increased hole trapping.

The process dependence of electron trapping is illustrated in Fig. 4. N_2O anneal significantly reduces V_g shift, and hence, electron trapping. Moreover, the effects of N_2O anneal are more significant in thicker oxides than in thinner ones. Annealing at higher temperature and longer time produces greater benefits in the ranges studied here. Results for reoxidized N_2O-annealed devices are also shown in the same figure. No further reduction in electron trapping is achieved by the reoxidation step. Instead, it seems that the reoxidation step tends to convert the

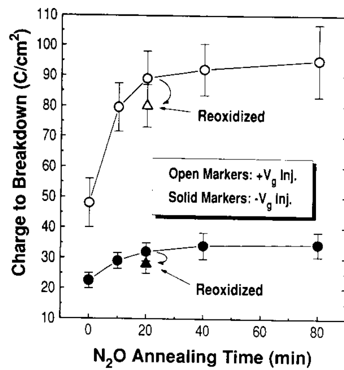

Fig. 5. Charge to breakdown Q_{bd} versus N_2O annealing time under 20-mA/cm^2 constant current injection. The N_2O annealing temperature is 950°C and reoxidation is performed at 900°C for 20 min. The oxide thickness is about 10 nm. Note the increase in error limits when extending annealing time.

N_2O-annealed oxide back to thermal oxide. It has been reported that reoxidation helps remove the hydrogen incorporated in the oxide during the NH_3 anneal step [5], [6]. In the N_2O anneal, there is no hydrogen involved [1]; it is therefore consistent that the reoxidation does not help to improve the quality of N_2O-annealed oxides. This observation supports the hypothesized role of hydrogen in charge trapping. Fig. 4 also shows that the N_2O annealing step does not change the polarity dependence of electron trapping, as has been observed in NH_3 nitridation [6], [8]. Some oxide thicknesses of these devices are labeled in this figure. For a specific final oxide thickness, the choice of the N_2O annealing condition tends to be high temperature and short time. This result is in agreement with the conclusions of a study of interface hardness against hot-electron injection [4].

Fig. 5 shows the Q_{bd} data for different types of oxides with comparable final oxide thicknesses. Q_{bd} is improved by N_2O annealing. This is basically consistent with the charge trapping data since it is known that Q_{bd} can be improved by reducing charge trapping [9]. Comparing the values of Q_{bd} for different polarities, one can also find that the polarity dependence is not obviously enhanced by N_2O annealing and insuring reoxidation. For instance, the ratio of Q_{bd} under $+V_g$ injection to Q_{bd} under $-V_g$ injection is 2.3 for control oxide and 2.7 for N_2O-annealed oxide (950°C, 80 min), while for NH_3-nitrided oxides, the reported difference between these ratios is 3 times larger [6], [8]. Consistent with the charge trapping results, reoxidation does not further increase Q_{bd}.

In summary, the charge trapping characteristics were compared for thermal oxide, N_2O-annealed thermal oxide, and reoxidized N_2O-annealed thermal oxide. The suppression of electron and hole trapping after N_2O anneal can be significant. The reduction in electron trapping rate monotonically increases with increasing annealing time and temperature in the range studied and is greater for thicker oxides. Reoxidation does not reduce charge trapping further.

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