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Application of irradiation-then-nitridation to improve the radiation hardness in MOS gate dielectrics

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Abstract

In this paper, the irradiation-then-nitridation (ITN) method was suggested to prepare oxynitrides. After ^{60}Co 1 Mrad irradiation, oxides were nitrided in N_2O to become oxynitrides. They are more radiation hard than those nitrided in N_2O directly. The difference can be explained by assuming that ITN process introduces more nitrogen SiO_2/Si interfaces and hence improves radiation hardness.

1. Introduction

Recently, it has been suggested that oxynitrides are candidates in the next generation IC process used as the dielectric material. Because of the formation of strong Si–N bonds and stress compensation of better Si–N bonds at the SiO_2/Si interface, oxynitrides exhibit better performance and are more reliable than conventional oxides [1–5]. N_2O nitridation of thermal oxides is one of the methods used to incorporate nitrogen into the gate oxides. It is superior to RNO (nitridation of thermal oxide in pure NH_3 followed by pure O_2 reoxidation) since no hydrogen induced electron trapping problem occurs [1,6,7]. However, only a small amount of nitrogen atoms are incorporated into SiO_2 very slowly when the conventional N_2O nitridation method [8] is used. Therefore, long nitridation time is needed in the conventional N_2O nitridation process. In this work,

we report on the results of using an irradiation then N_2O nitration (ITN) method to prepare the N_2O nitrided oxides. It appears that more nitrogen atoms can be incorporated into oxides by ITN. We found that the ITN-treated oxides are more radiation hard than conventional N_2O nitrided oxides.

2. Experimental

MOS capacitors were fabricated on $8\text{--}12\ \Omega\cdot\text{cm}$ p-type Si(100) substrates. Control oxides (about 12 nm) were grown in a furnace at 980°C in dry O_2 for 18 min and then post oxidation annealed in N_2 at the same temperature for 10 min. Some of the samples were irradiated by ^{60}Co with a total dose of 1 Mrad. After this, N_2O nitridations were carried out for non-irradiated and irradiated samples in a rapid thermal annealing system at a pressure of about 0.5 atm. After nitridations, aluminum films were evaporated to form metal-oxide-semiconductor MOS structures. Finally, MOS capacitors were post metallization an-

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Fig. 1. Flow chart of irradiation-then-N₂O nitridation (ITN) process.

nealed (PMA) in N₂ at 400°C for 25 min. Fig. 1 shows the flow chart of the ITN process. The flat-band voltage V_{FB} and the interface trap density D_{itm} were calculated from the high–low frequency $C-V$ curves. The radiation hardnesses of the conventional and ITN treated N₂O nitridation samples were determined by measurements performed after ⁶⁰Co irradiation with a total dose of 1 Mrad.

3. Results and discussion

Figs. 2 and 3 show the temperature dependences of the flat-band voltage V_{FB} and midgap interface trap density D_{itm} , respectively, of the conventional and the ITN N₂O nitrided oxides. It is known that

Fig. 2. Flat-band voltage V_{FB} versus nitridation temperature T_N curves for the ITN and the conventional N₂O-nitrided samples.

Fig. 3. Midgap interface trap density D_{itm} versus nitridation temperature T_N curves for the ITN and the conventional N₂O-nitrided samples.

the interface trap density and oxide fixed charges are dependent on the amount of nitrogens incorporated into the oxide. From Figs. 2 and 3, it was found that the two control samples, i.e. samples without nitridations, have almost the same D_{itm} and V_{FB} . This means that after PMA, the irradiation induced ΔD_{itm} and ΔV_{FB} was recovered. However, after N₂O nitridations at various temperatures, the ITN N₂O nitrided oxides exhibit a large initial D_{itm} and more negative V_{FB} than the conventional N₂O nitrided oxides. This phenomenon may be due to the larger number of nitrogen atoms induced into the ITN oxides. Note that when radiation hardness is the goal there is a trade-off between good initial properties and high radiation resistance [9,10]. No one has as yet obtained a radiation hard sample with initial properties superior to those of a conventional sample. Noted also that the nitrogen incorporated into the gate oxide will introduce oxide traps into the bulk oxide and interface traps at the SiO₂/Si interface. This may explain why the initial conditions of the oxynitride are inferior to those of conventional thermal oxides. Since the Si–N bonds are stronger than Si–O bonds (the bond energy for Si–N and Si–O bonds are 4.6 and 4.5 eV respectively), the more nitrogen atoms incorporated into the gate oxide, the higher the radiation hardness of the device. From Figs. 2 and 3, it can be seen that the ITN process introduces more nitrogen atoms into the oxides than the pure N₂O process does. In addition, it was found that the higher the nitridation tempera-

Fig. 4. Radiation-induced midgap interface trap density shift ΔD_{itm} versus nitridation temperature T_N curves for the ITN and the conventional N_2O -nitrided samples after ^{60}Co 1 Mrad irradiation.

ture T_N , the larger the D_{itm} and the more negative the V_{FB} for the ITN samples. Higher temperature may introduce more nitrogen atoms into the oxide. However, for the conventional N_2O -nitrided samples, the D_{itm} decreases gradually with T_N . Probably because the more significant annealing effect occurs at higher T_N when the amount of nitrogen atoms is not high enough.

After ^{60}Co irradiation, all samples will be damaged and there will be an interface trap density shift ΔD_{itm} and flat-band voltage shift ΔV_{FB} . Fig. 4 shows

Fig. 5. Radiation-induced flat-band voltage shift ΔV_{FB} versus nitridation temperature T_N curves for the ITN and the conventional N_2O -nitrided samples after ^{60}Co 1 Mrad irradiation.

Fig. 6. The flat-band voltage V_{FB} and midgap interface trap density D_{itm} versus nitridation temperature T_N curves for the conventional N_2O -nitrided samples before and after ^{60}Co 1 Mrad irradiations.

the ΔD_{itm} versus T_N of the conventional and the ITN N_2O -nitrided oxides. Clearly, the ITN treated samples are more radiation hard than the conven-

Fig. 7. The flat-band voltage V_{FB} and midgap interface trap density D_{itm} versus nitridation temperature T_N curves for the ITN samples before and after ^{60}Co 1 Mrad irradiations.

tional samples. Fig. 5 shows ΔV_{FB} versus T_N of the conventional and the ITN N_2O -nitrided oxides. Once again, it is seen that the ITN samples exhibit more radiation hardness than the conventional samples.

Figs. 6 and 7 show D_{itm} and V_{FB} for the conventional and the ITN samples, respectively, before and after ^{60}Co irradiation with a total dose of 1 Mrad. Figs. 6 and 7 show that the high T_N will cause an increase of negative V_{FB} . Apart from the effect of oxide thickness, the incorporation of nitrogen is believed to increase as T_N is increased as stated above. In this work, it is suggested that the proper nitridation temperature is about 900–950°C. We offer the following explanation for the increased radiation hardness of ITN samples. In conventional thermal oxides, there is a thin strained layer near the SiO_2/Si interface. After irradiation, the stress in the strained layer is relaxed. At the same time, there are many unsatisfied Si bonds generated at the SiO_2/Si interface and in the strained layer. During nitridation, nitrogen atoms interact with these dangling Si bonds. This explains why more nitrogen atoms can be incorporated into the SiO_2/Si interface and into the oxides. Since Si–N bonds are stronger than Si–O bonds, more incorporation of nitrogen atoms into the oxide improves its radiation hardness.

4. Conclusion

ITN N_2O nitridation method was shown to improve the radiation hardness of oxides. This occurs because ITN N_2O nitridation increases the amount of

nitrogen incorporated in the oxides in comparison to the amount introduced by conventional N_2O nitridation.

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