

A HIGH QUALITY STACKED THERMAL/LPCVD GATE OXIDE FOR ULSI

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ABSTRACT

A high quality LPCVD SiO₂ film with interface quality, trapping behavior, and intrinsic dielectric integrity comparable to dry thermal oxide is demonstrated. By stacking thermal and high quality LPCVD SiO₂ films, gate oxides with very different defect densities are demonstrated. The tradeoffs between the quality of each SiO₂ layer and the ability of one layer to compensate for defects in the other layer are presented. The lowest defect density (much lower than a conventional dry thermal oxide film) is observed in a stacked gate oxide consisting of a 95Å thermal oxide followed by a 25Å LPCVD oxide deposition and a short reoxidation. Thicker LPCVD oxide layers increase the defect density of the stacked dielectric compared to this optimal case. These results demonstrate that an optimized thermal/LPCVD oxide stacked dielectric is a promising candidate as the gate oxide of ULSI MOS devices.

INTRODUCTION

The need for highly reliable thin gate oxide films for ULSI MOS devices has generated interest in LPCVD silicon dioxide films¹⁻⁵. Stacked dielectrics consisting of equal thermal and LPCVD oxide thicknesses have been demonstrated to have lower defect densities than conventional thermal oxide films. The lower defect density has been attributed to a mismatch of micropores at the thermal oxide/LPCVD oxide interface³⁻⁴. These micropores are 10Å to 25Å in diameter and can significantly influence the integrity of the gate dielectric⁶⁻⁸. However, little has been reported on the effects of the deposition sequence and structure of the film on the electrical properties. This paper demonstrates the impact of the stacked dielectric deposition and growth sequence and the ratio of thermal to LPCVD oxide thickness on gate dielectric integrity. Based on these results, possible mechanisms responsible for the improvement in defect density are discussed.

INTRINSIC CHARACTERISTICS

LPCVD SiO₂ films are deposited at 450°C using silane and oxygen. The deposition rate is controlled by the silane flow rate and is reproducible for rates as low as 5Å per minute. A short anneal in N₂ ambient at high temperature (800 to 900°C) is required to obtain a high intrinsic quality densified LPCVD film. Following the gate oxide deposition and anneal, in-situ doped n⁺ polysilicon is deposited and annealed at 900°C. Figure 1 demonstrates typical C-V and I-V characteristics of a densified LPCVD SiO₂ film deposited directly on silicon. The densified films have very low interface state density and exhibit Fowler-Nordheim tunneling characteristics comparable to thermal SiO₂ films. However, the electron trapping rate is enhanced significantly which may be a result of incomplete oxidation of the LPCVD oxide film during the deposition. It is possible to suppress the trapping rate with a short reoxidation (dry O₂) at high temperature as shown in Figure 1c. Reoxidized LPCVD oxide films also exhibit intrinsic time-dependent dielectric breakdown characteristics very similar to thermal oxides⁹.

Stacked thermal/LPCVD oxide films are prepared using two different sequences: In the two-step sequence, LPCVD oxide is deposited directly on (100) n-type and p-type silicon followed by densification and reoxidation. In the three-step sequence, a thermal oxide film is grown first followed by LPCVD oxide deposition, and densification and reoxidation. For each sequence, the thickness of the thermal and LPCVD oxide is varied to study the effect on the dielectric integrity. The resulting stacked dielectrics have thicknesses between 130Å and 150Å and exhibit comparable intrinsic behavior to dry thermal oxide as shown in Figure 2. However, the stacked dielectric growth sequence and the thickness of each component film dramatically affect the breakdown strength of the stacked films as presented below.

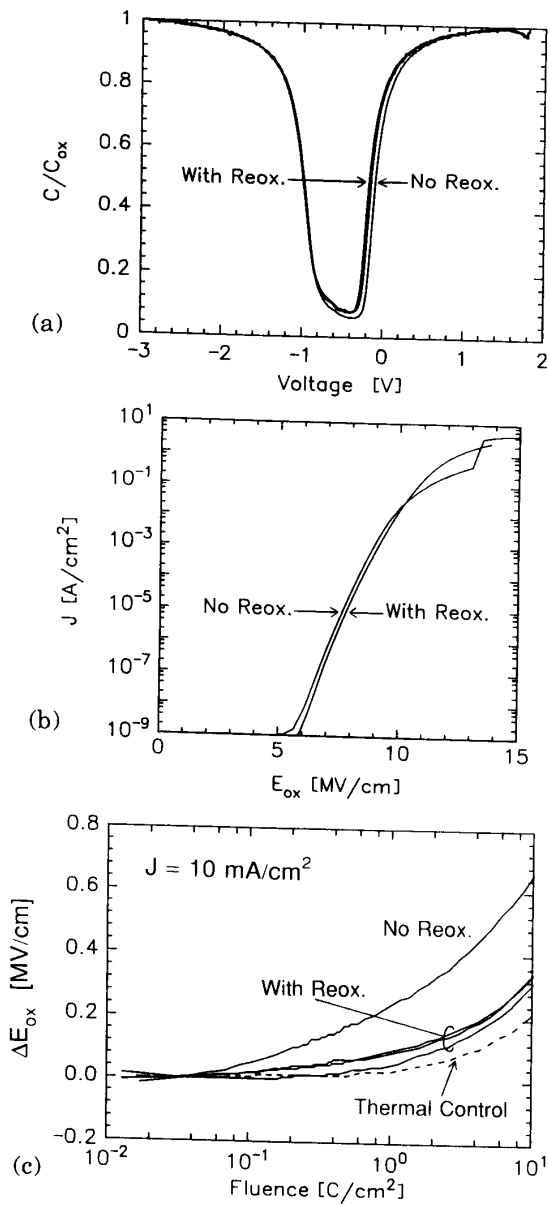


Figure 1. A densified 115Å LPCVD SiO₂ film exhibits (a) interface quality and (b) tunneling characteristics comparable to a thermal oxide film. (c) The enhanced electron trapping rate is suppressed by reoxidizing the LPCVD film at 825°C. The reoxidation process has virtually no effect on the C-V and I-V characteristics shown in (a) and (b). The difference in the C-V characteristics between LPCVD SiO₂ films with and without reoxidation is due to the change in thickness of the film after reoxidation.

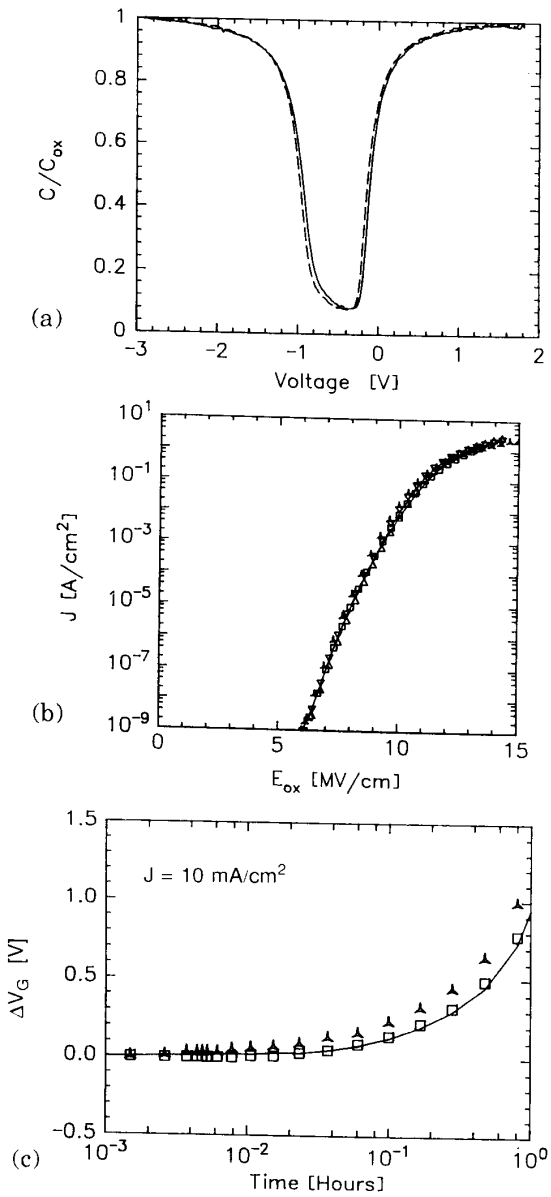


Figure 2. Comparison of the (a) MOS C-V, (b) I-V, and (c) high-field trapping characteristics of typical 140Å two-step and three-step stacked thermal/LPCVD dielectrics with conventional 140Å dry thermal oxide (solid lines) demonstrates the high intrinsic quality of the stacked dielectrics.

DEFECT-INDUCED BREAKDOWN

Even though all of the oxide films have comparable intrinsic characteristics, the defect density of the films is strongly dependent on the oxidation sequence. Note that an LPCVD oxide film alone does not improve the gate oxide reliability. In fact, a densified LPCVD oxide film deposited directly on silicon has extremely high defect density which is likely due to a large pinhole density (see Figure 3). A short reoxidation (6 minutes at 825°C) reduces the defect density but the resultant film is still poor compared to a thermal oxide film. Longer reoxidation times effectively reduce the number of severe defects (occurring at very low breakdown fields) but do not improve the concentration of less severe defects significantly as demonstrated in Figure 4.

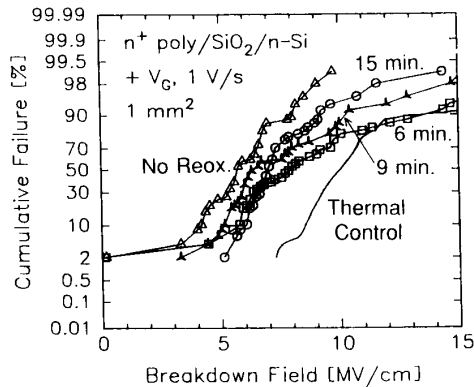


Figure 3. The effect of reoxidation of LPCVD SiO₂ films on defect-induced breakdown. For this experiment, a 115Å LPCVD film was deposited directly on silicon, densified (N₂ ambient), and reoxidized (dry O₂) at 825°C for the specified times. A nitrogen anneal followed the reoxidation.

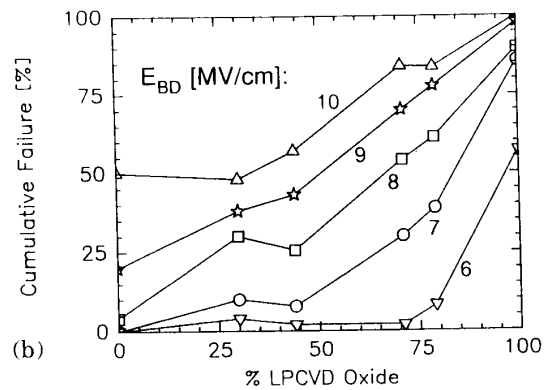
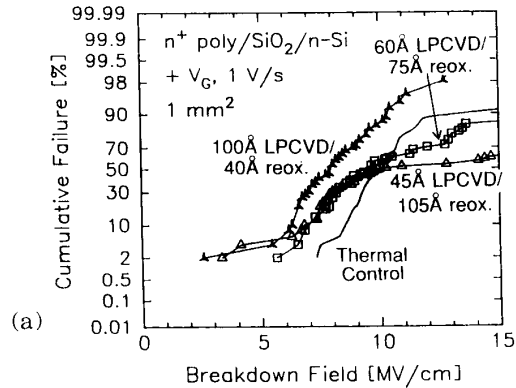
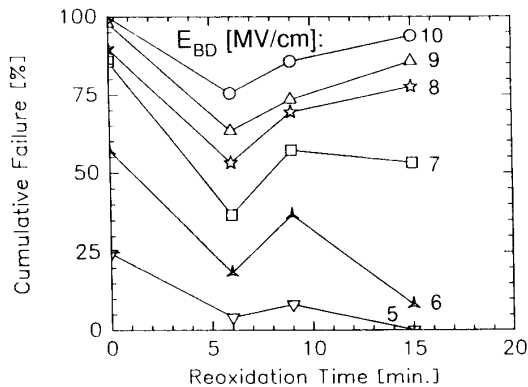
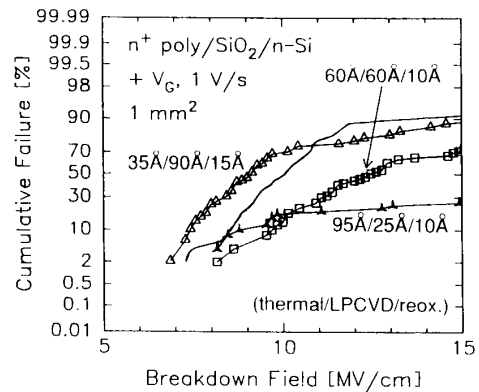


Figure 5. (a) Thermal reoxidation is not effective in reducing the defect density of LPCVD SiO₂ films as shown here because the thermal oxide does not compensate for defects in the LPCVD film. (b) At low breakdown fields (E_{BD} < 10 MV/cm), the defect density increases monotonically as the thickness of the LPCVD oxide layer relative to the thermal oxide layer increases. This implies that the LPCVD oxide film has a higher defect density than an otherwise equivalent thermal oxide film.

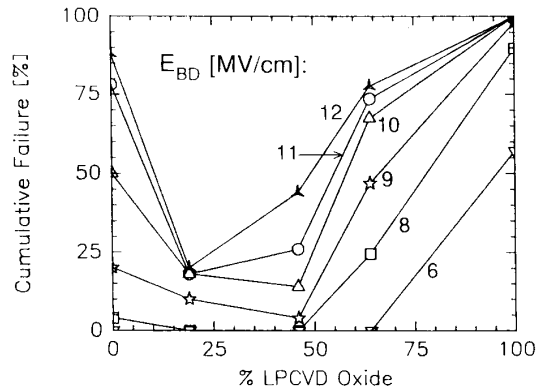
Figure 4. Replot of data in Figure 3 to show the change in the defect population as a function of reoxidation time. The solid lines represent contours of constant breakdown field, E_{BD}. Longer reoxidation times reduce severe defects in the LPCVD film (low-field failures) but are not effective in reducing less severe defects (E_{BD} = 8–10 MV/cm).

The defect density of stacked thermal/LPCVD films prepared using a two-step sequence (LPCVD oxide deposition followed by densification and reoxidation) changes considerably as the relative thermal to LPCVD oxide layer thickness changes. In order to interpret the results, it is necessary to consider the effects of defects in each layer on the overall reliability of the stacked oxide. As shown above, it is evident that the LPCVD oxide layer has a higher defect density than an otherwise equivalent thermal oxide film. Therefore, a short thermal oxidation of a thick LPCVD oxide layer is ineffective for reducing defect-induced failures because the thermal oxidation process does not compensate for pinholes or pores in the LPCVD film (the thermal oxide growth rate is not in the parabolic regime). As the LPCVD oxide layer thickness is reduced and the thermal oxide layer increased, severe defects near or at the silicon/thermal oxide interface (such as metal precipitates) still limit the breakdown strength of the stacked structure (see Figure 5).

In order to reduce defect-induced failures significantly, one layer has to compensate for defects in the other layer. This appears to be the case for the three-step stacked films (thermal oxidation followed by LPCVD oxide deposition and reoxidation): A stacked film consisting primarily of thermal oxide (such as the 95Å thermal/25Å LPCVD/10Å reoxidized film shown in Figure 6), has very low defect density. Since the reduction in defect density is so dramatic in this case, the primary source of early failures in the thermal oxide film appears to be the micropore structure⁶⁻⁷ and the decrease in defect density is attributed to the filling of micropores by the LPCVD oxide film. However, a thin (e.g. 25Å) LPCVD oxide layer is not effective in compensating for severe defects such as pinholes or metallic precipitates as apparent from the significant number of early failures in Figure 6. As the thickness of the LPCVD oxide layer relative to the thermal oxide layer increases, the tradeoffs between the quality of each oxide layer and the effectiveness of the LPCVD oxide layer in compensating for the micropore structure of the thermal oxide become apparent. For example, depositing a thick (90Å) LPCVD oxide film on a thin (35Å) thermal oxide layer results in a very poor stacked structure because both layers have high defect densities. A stacked structure consisting of equally thick LPCVD and thermal oxide layers (such as the 60Å thermal/60Å LPCVD/10Å reoxidized film in Figure 6) is considerably better but not the optimal since the LPCVD oxide layer is very effective in compensating for the thermal oxide micropore structure but also adds its own defects to the stacked structure.



(a)



(b)

Figure 6. (a) By introducing a thermal oxidation step prior to the LPCVD oxide deposition, the defect density can be improved appreciably. In this case, the improvement is attributed to the filling of the micropore structure in the thermal oxide layer during the LPCVD oxide deposition. Note that a 25Å LPCVD oxide layer is sufficient to dramatically reduce the defect density of the stacked structure. Thicker LPCVD oxide layers are not as effective as this optimal case because of the high defect density of the LPCVD film as shown by the turnaround in failure probability in (b).

SUMMARY AND CONCLUSIONS

A high quality LPCVD oxide film with interface quality, tunneling current, trapping behavior, and intrinsic time-dependent dielectric breakdown characteristics comparable to dry thermal oxide is demonstrated. Stacked dielectric films consisting of thermal and LPCVD oxide layers are prepared to study defect-induced breakdown properties. In general, the defect density increases monotonically for both two-step (LPCVD oxide deposition/ reoxidation) and three-step films (thermal oxidation/ LPCVD oxide deposition/ reoxidation) as the thickness of the LPCVD oxide layer increases suggesting that the LPCVD oxide film has a higher defect density than the thermal oxide film. However, the lowest defect density (much lower than a conventional dry thermal oxide film) is observed in a three-step dielectric consisting of a 95Å thermal oxide followed by a 25Å LPCVD oxide deposition and a short reoxidation. This result is consistent with the concept that the principal defects responsible for low breakdown strength in high quality thin thermal oxides are micropores. Furthermore, a thin (25Å) LPCVD oxide layer is sufficient to cover these micropores. Thicker LPCVD oxide layers increase the defect density of the stacked dielectric compared to the optimal case shown here. These results demonstrate that an optimized thermal/LPCVD oxide stacked dielectric is a promising candidate as the gate oxide of ULSI MOS devices.

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