Decrease in Trenched Surface Oxide Leakage Currents by Rounding Off Oxidation

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Abstract

It has been indicated in a one-dimensional model and experiment that, in a diluted oxygen ambient or at higher oxidation temperature, stress generated during Si oxidation can easily be reduced and convex corners of trenched Si surface is effectively rounded off. And, it has been theoretically and experimentally shown that oxide leakage current for an MOS capacitor with 10nm thick gate oxide on the convex corner can be sufficiently reduced by the rounding off oxidation with the thickness of about 100nm.

1. Introduction

Recently, three-dimensional structures, such as a trenched capacitor\(^1\) or a buried oxide isolation\(^2\), have been prevalently examined. These structures have right-angular convex and concave corners on which thermally grown SiO\(_2\) films indicate higher leakage current than on the plane surfaces. In order to solve this problem, the keen edge corners as trenched have to be rounded off before the gate oxidation.\(^1\) In order to round off these corners with high controllability and non-damage, the thermal oxidation technology was selected.

This report describes the electric field concentration and the oxidation at the convex corner in a one-dimensional model in Sections 2 and 3, respectively. In Section 5, we will report the dependence of the oxide leakage current for the MOS capacitors on the rounding off oxidation condition in the experiments.

2. Curvature and Field Concentration
   at Convex Corner

When MOS capacitor gate electrodes on the trenched Si surface are positively biased, the oxide field in the neighborhood of the cathode (Si substrate) at the convex corner, \(E_{\text{corner}}\), becomes more than the average electric field, \(E_{\text{ave}}\). From the calculation result shown in Fig.1, we know that the ratio, \(E_{\text{corner}}/E_{\text{ave}}\), depends on the ratio of the curvature radius of the interface to the oxide thickness, \(r/t_{\text{ox}}\). When the radius is more than 5 times as large as the gate oxide thickness, the ratio, \(r/t_{\text{ox}}\), can be suppressed to less than 1.1.

Fig.1. Oxide field concentration as a function of the ratio of curvature radius for Si/SiO\(_2\) interface to gate oxide thickness.

Fig.2. Geometrically relation between curvature radius and oxide thickness when the oxide is uniformly thermally grown on an initial right-angled corner.
When the oxide is uniformly thermally grown on the initial right-angled corner, as shown in Fig. 2, the ratio, \( r/t_{ox} \), is geometrically calculated to be about 0.5. Accordingly, if the gate oxide of 10 nm thick is grown on the as-etched right-angled convex Si corner, the radius, \( r \), becomes only about 5 nm. From the result shown in Fig. 1, the oxide field increase reaches more than 50%. We know that, in order to sufficiently suppress oxide leakage current for an MOS capacitor on the Si corner, an oxide of more than 10 times as thick as the gate oxide needs to be sacrificially grown prior to the gate oxidation (rounding off oxidation).

3. Corner Oxidation and Stress Relief

Oxide thinning at the convex and the concave corners has been considered to be due to the stress concentration in conversion from Si single crystals to the SiO2 films.\(^3\) If the stress is sufficiently relaxed, the oxidation rate near the vertex of the convex corner becomes higher than that of the planar surface and the curvature radius becomes larger. To make a precise estimation of the shape of Si/SiO2 interface by a two-dimensional oxidation of the corner, we need an explicit expression of the stress effect on the oxidation and two-dimensional simulation. However, a one-dimensional consideration of the oxidation and the stress relief helps in comprehending the qualitative trend of the rounding off oxidation. Figure 3 indicates a typical stress distribution in the oxide in calculation. Here, time interval, \( dt \), equals \( T_{ox}/n \), where \( T_{ox} \) is total oxidation time during which the oxide with thickness of \( t_{ox} \) is formed and \( n \) is an integer. \( X_i \) is the thickness of the oxide formed during the initial \( dt \), while \( X_i \) is the thickness of the partial oxide during the \( i \)-th \( dt \). Then, \( X_i \) is given by the following equations.

\[
\begin{align*}
X_1 &= f(1), \\
X_i &= f(i)-f(i-1), \quad (i>2) \\
f(i) &= A(\sqrt{i+td+t_1})/(AB^2)^{1/2}, \quad (3)
\end{align*}
\]

where \( B \) is the parabolic rate oxidation constant, \( B/A \) is the linear rate oxidation constant, \( t_1 \) represents a shift in the time coordinate to account for the presence of the initial oxide layer.\(^4\) On the other hand, a stress, \( S_0 \), in the partial oxide with the thickness of \( X_i \) is relaxed during the remaining oxidation time, \( (n-i)dt \), to be \( S_0 X_i \exp(-(n-i)dt/t_2) \).\(^5\) The value, \( t_2 \), is the relaxation time for the stress in the oxide, which steeply decreases with increasing temperature.\(^5\) In Figs. 4 and 5, total stresses normalized by \( S_0 \) are plotted as a function of oxide thickness.

Figure 4 shows the thickness dependence of the oxide stress at 950°C as a parameter of \( O_2 \) dilution by inert gas. From Fig. 4, we notice that the total normalized stresses increase with the oxide thickness and turn around. Figure 5 represents...
the thickness dependence of the total normalized stress as a parameter of oxidation temperature in dry $O_2$ ambient. Note that the peak value of the total stress decreases with decreasing the oxidation temperature; for example, the peak value for 900°C oxidation is reduced to 1/10 of that for 1000°C oxidation. This is explained as follows. While the activation energy value for oxidation constants in both reaction-controlled and diffusion-controlled regions are about 1eV and about 2eV$^6$, respectively, that for the stress relaxation time in the oxide is about 6eV. Accordingly, the relaxation rate tends to overcome the oxidation rate in the higher oxidation temperature.

4. Sample Preparation and Measurements

To evaluate the rounding off oxidation effects for the convex Si corner, poly-crystalline Si gate MOS capacitors were formed on n type (100) Si trenched by RIE or KOH etching. (There is no substantial difference between these two etching techniques for the purpose of this paper.) Total trench perimeter is about 50mm. The rounding off oxidations were sacrificially performed prior to the thin gate oxidation. The MOS capacitor area is $0.1\text{mm}^2$.

The poly-crystalline Si gate electrodes were biased positively for n type Si substrate. Then, the Si surface was in accumulation and an applied voltage appears across the oxide. The oxide thinning or the field concentration at the top convex corner of the trench edge can be evaluated by the oxide leakage currents.

5. Experimental Results and Discussion

5-1. Rounding Off Convex Corner and Oxide Leakage Currents

Figure 6 shows two cross-sectional scanning electron micro-scop ic photographs of the convex Si corner after the rounding off oxidation in dry $O_2$ at (a) 900°C and (b) 1100°C. Oxide thinning is seen to be more at 900°C than that at 1100°C. While at 900°C a "horn" of silicon is formed at the Si/SiO$_2$ interface of the convex corner, at 1100°C the interface is rounded off. Figure 7 illustrates the oxide leakage current vs. gate voltage (I-V) characteristics for three kinds of MOS capacitors formed on the plane surface, the trenched surface without the rounding off oxidation and with the rounding off oxidation.

![Cross sectional SEM photographs of convex corner after oxidation in dry $O_2$ at (a) 900°C and (b) 1100°C.](image)

![Oxide leakage current as a function of gate voltage characteristics for three kinds of MOS capacitors formed on the plane surface, the trenched surface without the rounding off oxidation and with the rounding off oxidation.](image)
considering the reduction in the oxide leakage currents for the trenched MOS capacitors.

5-2. Rounding Off Oxidation Condition and Oxide Leakage Currents

As described in Section 2, the curvature radius after the rounding off oxidation depends on the oxide thickness for the rounding off oxidation. Figure 8 indicates this oxide thickness dependence of the leakage current in 10%O₂/Ar ambient at 950°C. Here, gate oxide thickness is about 10nm and the oxide electric field is 7MV/cm. The leakage current of the gate oxide after the 100nm thick rounding oxidation is about 1/3000 as high as that of the gate oxide on an as-etched Si surface. The electric field concentration can be estimated from the deviation in the I-V characteristics and the curvature radius from the relation described above; \( r/\text{r} \text{ox} = 0.5 \). These results are plotted in Fig.1. We notice that the theoretical curve explains the experimental results.

Figure 9 indicates the oxidation rate dependence of the oxide leakage current for the trenched MOS capacitors. Here, the oxidation rate, which is controlled by the dilution of the oxidation species with inert gas, is obtained from the oxide thickness divided by the total oxidation time. Individual data points were obtained for cases where rounding off oxide and gate oxide thickness are 100nm and 10nm, respectively. These results are qualitatively consistent with that calculated based on the one-dimensional model in Fig.4.

6. Summary

It has been experimentally indicated that, by the thermal oxidation, the convex corner of the trenched Si surface can be rounded off and the oxide leakage current can be reduced. It was theoretically presumed and experimentally confirmed that the leakage current for 10nm thick gate oxide can be reduced to a reasonable level by rounding off oxidation of 100nm thick. It is presumed from the one-dimensional model that the more tenuous the oxygen species in the ambient is or the higher the oxidation temperature is, the more effective the rounding off oxidation for the convex corners is. This presumption is experimentally supported.

![Fig.8. Oxide thickness dependence of the leakage current in 10%O₂/Ar ambient at 950°C.](image)

![Fig.9. Oxidation rate dependence of oxide leakage current for the trenched MOS capacitors.](image)

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References