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Decrease in Trenched Surface Oxide Leakage Currents by Rounding Off Oxidation

Keitaro Imai and Kikuo Yamabe

VLSI Res. Center, Toshiba Corporation
1, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, 210, Japan
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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_{corner}, becomes more than the average electric field, E_{ave}. From the calculation result shown in Fig.1, we know that the ratio, E_{corner}/E_{ave}, depends on the ratio of the curvature radius of the interface to the oxide thickness, r/t_{ox}. When the radius is more than 5 times as large as the gate oxide thickness, the ratio, r/t_{ox}, can be suppressed to less than 1.1.

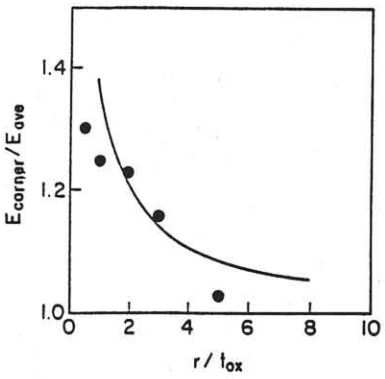


Fig.1. oxide field concentration as a function of the ratio of curvature radius for Si/SiO_2 interface to gate oxide thickness.

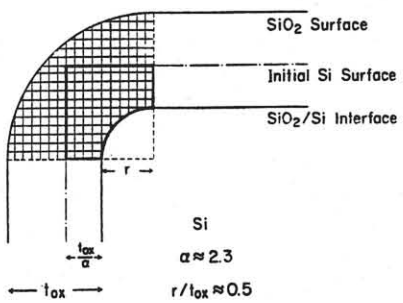


Fig.2. Geometrically relation between curvature radius and oxide thickness when the oxide is uniformly thermally grown on an initial right-angled corner.

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 10nm thick is grown on the as-etched right-angled convex Si corner, the radius, r, becomes only about 5nm. 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 SiO_2 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/SiO_2 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_1 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.

$$X_1 = f(1), \quad (1)$$

$$X_i = f(i)-f(i-1), \quad (i>2) \quad (2)$$

$$f(i) = A(\mathrm{sqrt}(1+(idt+t_1)/(A^2/4B))-1)/2, \quad (3)$$

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

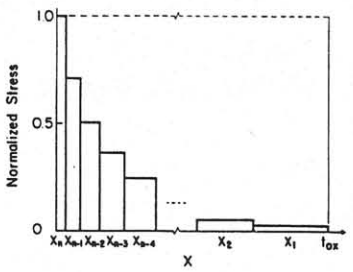


Fig.3. A typical stress distribution in the oxide in calculation.

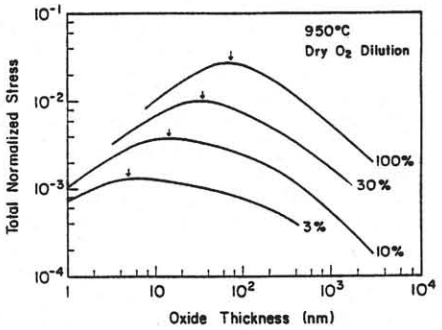


Fig.4. Thickness dependence of the oxide stress at 950°C as a parameter of O_2 dilution by inert gas.

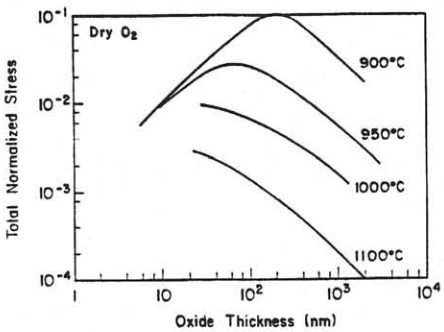


Fig.5. Thickness dependence of the oxide stress as a parameter of oxidation temperature in dry O_2 ambient.

layer.[4] On the other hand, a stress, S_o*X_i, in the partial oxide with the thickness of X_i is relaxed during the remaining oxidation time, $(n-i)*dt$, to be $S_o*X_i*\exp(-(n-i)dt/t_2)$.[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_o are plotted as a function of oxide thickness.

Figure 4 shows the thickness dependence of the oxide stress at 950C 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 900C oxidation is reduced to 1/10 of that for 1000C 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

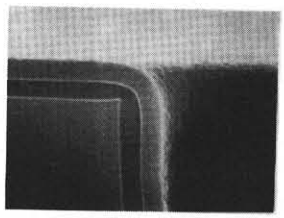
To evaluate the rounding off oxidation effects for the convex Si corner, poly-crystalline Si gate MOS capacitors were formed on n type (100) Si trenched by RIE or KOH etching. (There is no substantial difference between these two etching techniques for the purpose of this paper.) Total trench perimeter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

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.

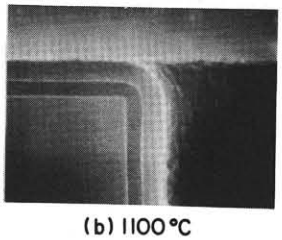
5. Experimental Results and Discussion

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

Figure 6 shows two cross-sectional scanning electron micro-scopic photographs of the convex Si corner after the rounding off oxidation in dry O_2 at (a) 900C and (b) 1100C. Oxide thinning is seen to be more at 900C than that at 1100C. While at 900C a "horn" of silicon is formed at the Si/SiO_2 interface of the convex corner, at 1100C the interface is rounded off. Figure 7 illustrates the oxide leakage current vs. gate voltage (I-V) characteristics for three kinds of MOS capacitors



(a) 900°C



(b) 1100°C

Fig.6. Cross sectional SEM photographs of convex corner after oxidation in dry O_2 at (a) 900°C and (b) 1100°C.

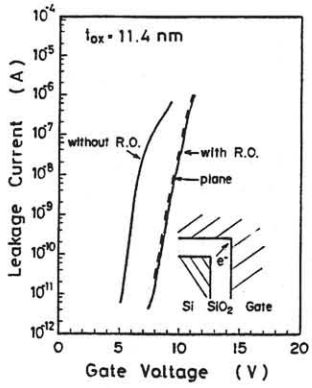


Fig.7. Oxide leakage current as a function of gate voltage charactreristics for three kinds of MOS capacitors formed on the plane surface, the trenched surface without the rounding off oxidation and with the rounding off oxidation.

formed on the plane surface, the trenched surface without the rounding oxidation and with the rounded oxidation. It can be seen that the leakage currents for the trenched MOS capacitors increase to 10^3 - 10^4 times as high as that for the plane or the rounded-off trenched MOS capacitors. Based on the dependence of the leakage current on the total trench periphery length, this increase in the leakage current can be considered to come from the keen convex corner of the trench edges. We also know that the high temperature oxidation is effective enough to reduce the oxide leakage current for the trenched MOS capacitors to that for the plane capacitors as presumed from the results in Fig.2. The discussions in Section 3 can be adopted in

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%O_2/Ar ambient at 950C. 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; $r/t_{ox}=0.5$. 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 thicknesses are 100nm and 10nm, respectively. These results are qualitatively consistent with that calculated based on the one-dimensional model in Fig.4.

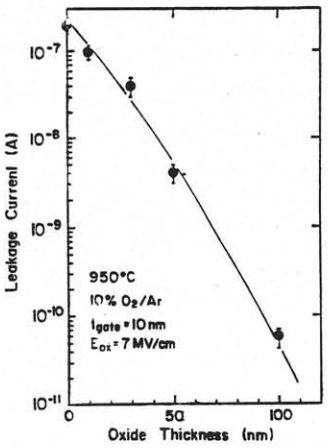


Fig.8. Oxide thickness dependence of the leakage current in 10%O_2/Ar anbient at 950°C.

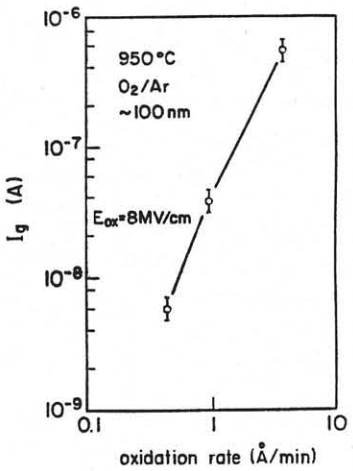


Fig.9. Oxidation rate dependence of oxide leakage current for the trenched MOS capacitors.

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 amobient 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.

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