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The Effect of Radical Oxidation on DRAM Cell Transistor with S-RCAT

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1. Introduction

As the design rule of DRAM shrinks down below 100nm, the novel process technologies for DRAM integration have been proposed [1]. Sphere-Shaped–Recess-Channel-Array-Transistor (S-RCAT), which has been adapted from 80nm process technologies [2], is recently playing a major role in DRAM cell array transistors accompanying a remarkable improvement of data retention time, showing excellent product feasibility even down to 50nm node. However, as the gate oxide or equivalent oxide thickness decreases for high performance, the FN-stress in gate-oxide increases especially at the sharp profile of S-RCAT middle part. It induces threshold voltage (V_{th}) to degrade and sub-threshold swing to increase. To improve the degradation after FN-stress, Radical oxidation process has been introduced at S-RCAT and the effects of S-RCAT are evaluated. S-RCAT with radical oxidation process has more excellent electrical characteristics such as drain induced barrier lowering (DIBL), sub-threshold swing, body effect and Ion gain than wet oxidation.

2. Experiments and Results

A. Sample Preparation

DRAM using S-RCAT was integrated on p-type bulk Si (110) wafer and the process sequence is illustrated in Fig. 1. [2] Two different samples are grown in wet ambient and radical ambient each. After oxidation, decoupled-plasma-nitridation (DPN) was processed for the sake of preventing boron penetration at PMOS transistor in peripheral circuit. The n+ poly-silicon gates were doped. Figure 3 and 4 show transmission electron microscopy (TEM) images of gate oxide on the middle and bottom part of S-RCAT grown by wet oxidation and radical oxidation. In S-RCAT structure, Si surface orientation abruptly changes at both middle part and ball inside. While the gate oxide thicknesses of wet oxidation are various and the profile of middle part of S-RCAT is sharp, the gate oxide thicknesses of radical oxidation are uniform and the profile of middle part has been rounded. The thinnest thickness of radical oxidation is equal to that of wet oxidation at both the middle and bottom of S-RCAT. Uniform oxide thickness inside S-RCAT resulted from the property of radical oxidation which has low activation energy. [3]

B. Reliability of S-RCAT with Radical Oxide

For the sake of the evaluation of gate oxide reliability, the test patterns of S-RCAT were dc FN (Fowler-Nordheim) stressed. First we measured the threshold voltage and the sub-threshold swing of a test pattern. And then the test patterns were dc FN stressed for 30 seconds. After FN stress, we measured the threshold voltage and the sub-threshold swing of the stressed pattern. Figure 5 show the effect of gate oxide on the FN degradation of S-RCAT test pattern. As for wet oxidation in Fig. 5(a), while the sub-threshold swings are increased after FN stress, the threshold voltages of most test patterns are decreased by about 0.2V after FN stress with stress voltage of 6V. Increase of stress voltage to 6.4V results in further increasing sub-threshold swing and further decreasing threshold voltages up to below 0.6V. The decrease of threshold voltage after FN stress is very unusual phenomena and leads to the dynamic refresh fail after burn-in process. However, all the test patterns of radical oxidation show conventional FN degradation behavior. The increment of swing after FN-stress in radical oxidation has dramatically decreased than that in wet oxidation. The decrease of Vth in wet oxidation is due to de-trap of electrons at Si/Si_{O2} interface and V_{th} of radical oxidation has not decreased for the decrease of D_{it} and the decrease of captured electrons. In many searches, radical oxidation makes the gate oxide uniform regardless of crystal orientation and makes Si/SiO2 roughness and D_{it} decreased. [3,4] Fig.8 shows the electric field simulation during stress condition. The electric fields are crowded at the middle part of S-RCAT for sharp profile. In case of radical oxidation, the angle was increased and rounded, which help the electric field lowering at the gate oxide and FN-stress decreasing. Both rounded profile at the stress point and improvement of oxide quality such as interface trap in radical oxidation have improved the oxide reliability of S-RCAT.

C. Electrical Characteristics of S-RCAT with Radical Oxide

While the oxide thickness of radical oxidation at ball bottom is equal to that of wet oxidation, the oxide thickness of radical oxidation at ball side is thinner than wet oxidation. For that reason, the threshold voltage is lowered with same doping concentration as shown Fig.9. That the gate oxide decrease at side part of S-RCAT lead to the improvement of the operating current, I_{on} from 5uA/cell to 7uA/cell without increasing of the off current, Ioff as shown Fig.10 and 11. Increase of the operating current is suitable for low V_{DD} operation device. Fig. 12, 13 and 14 show that the sub-threshold swing, DIBL and body effect are decreased due to decrease of gate oxide at ball side. In radical oxidation, the gate oxide of S-RCAT has been scaled down naturally without scaling down the gate oxide of transistors in peripheral circuit and without reliability problems of S-RCAT. However, C_{WL} and gate induced drain leakage (GIDL) are increased due to decrease of gate oxide at neck part of S-RCAT as shown Fig. 15

3. Conclusion

It is demonstrated that the radical oxidation in S-RCAT structure improves the reliability and electrical characteristics, compared with conventional wet oxidation. These improvements can be explained by the effects of uniform oxide thickness inside the ball and rounded profile at weak point. On that count, radical oxidation is adequate for the gate oxide of transistor such as S-RCAT, which has been composed of various crystal orientations. Adapting the radical oxidation, we can get higher cell transistor I_{on} and lower cell transistor sub-threshold swing, DIBL, body effect in S-RCAT than those for wet oxidation technology.

Reference

[1] K.N.Kim et al., *IEEE Trans. SM.*, vol.15, pp.137-143, 2002
[2] Se Geun Park et al, *SSDM*, pp.624-625, 2005

[3] Yuji Saito et al, *VLSI Tech.* pp176-177, 2000
[4] Makoto Nagamine et al, *IEDM*, pp593-596, 1998

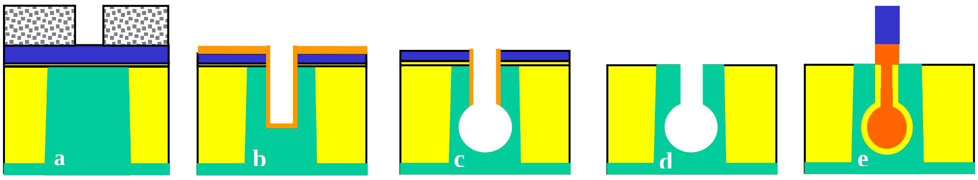

Fig. 1 Process sequences for S-RCAT structure. The core process is to make a spherical ball structure

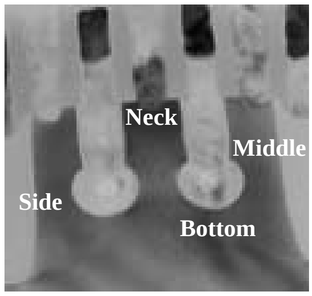

Fig. 2 S-RCAT TEM Profile.

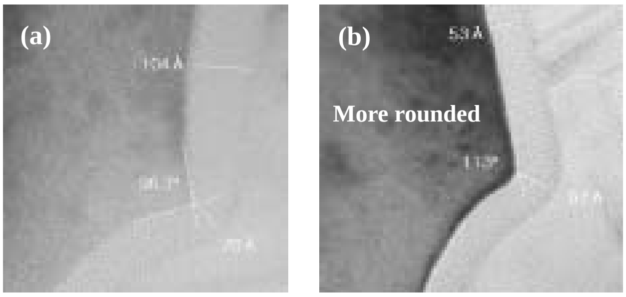

Fig. 3 TEM image of S-RCAT middle part
(a) Wet oxidation (b) Radical oxidation

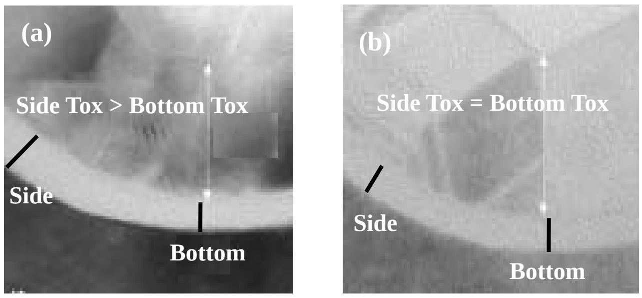

Fig. 4 TEM image of S-RCAT bottom part
(a) Wet oxidation (b) Radical oxidation

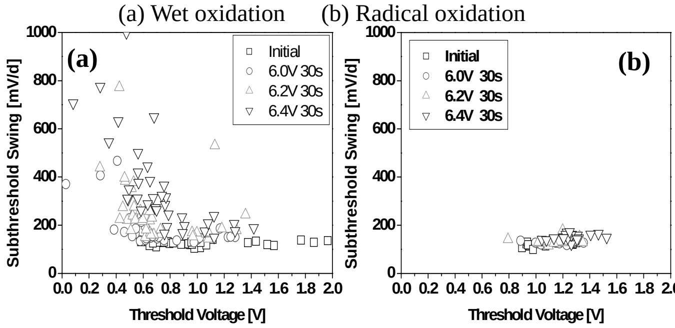

Fig. 5 Correlation plot between V_{th} and Swing after FN-stress
(a) Wet oxidation (b) Radical oxidation

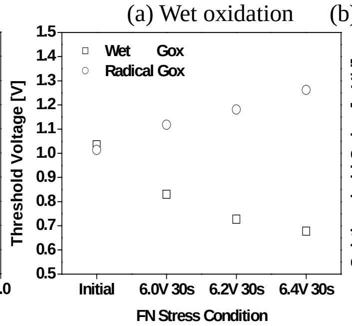

Fig. 6 degradation of V_{th} after FN-stress

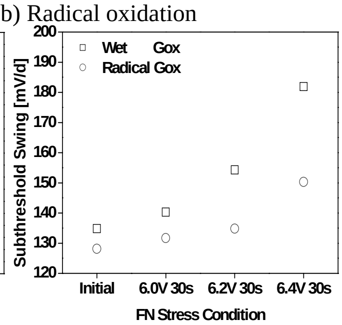

Fig. 7 increase of sub-threshold swing after FN-stress

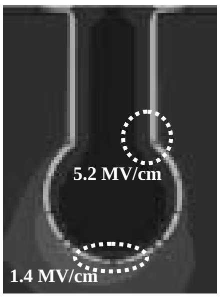

Fig.8 simulation of electric field in gate oxide of S-RCAT

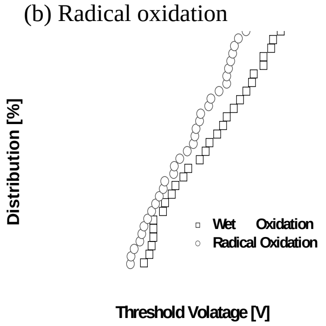

Fig. 9 Distribution of Vth

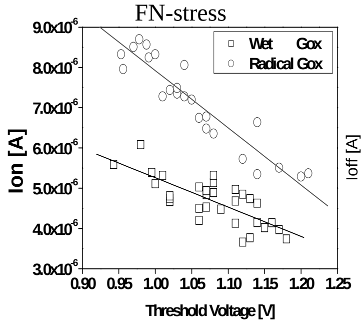

Fig. 10 Correlation plot between V_{th} and I_{on}.

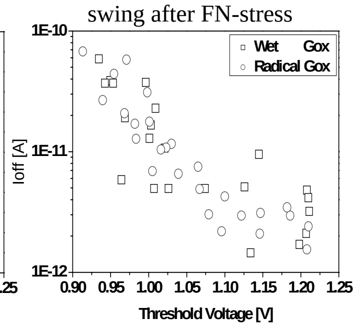

Fig. 11 Correlation plot between V_{th} and I_{off}.

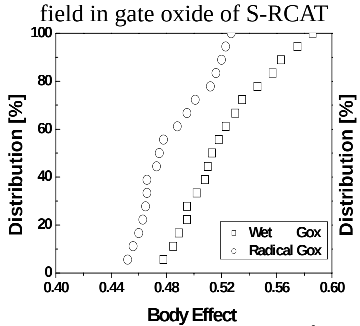

Fig. 12 Distribution curve of body effect

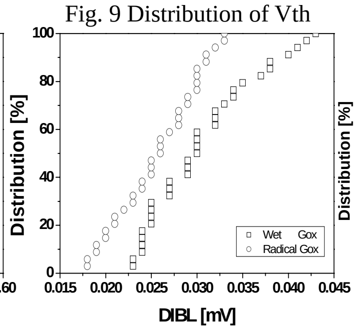

Fig. 13 Distribution curve of DIBL

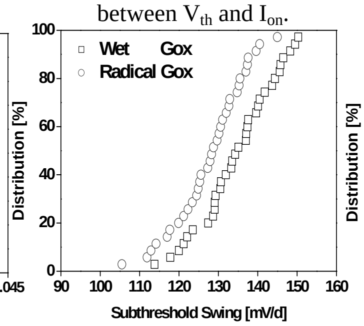

Fig. 14 Distribution curve of SW

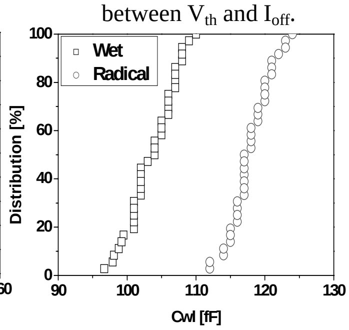

Fig. 15 Distribution curve of C_{WL}