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The Dielectric Reliability of Very Thin SiO_2 Films by Rapid Thermal Processing

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Very thin SiO_2 films, 3-10 nm in thickness, by rapid thermal processing (RTP) have been formed on silicon, and their dielectric reliability has been investigated in comparison with furnace grown oxides. The SiO_2 films grown by RTP are superior to furnace oxides on both the dielectric breakdown and the Si-SiO_2 interface characteristics. On the RTP SiO_2 films, the quantum oscillation in MOS tunneling is clearly observed at 300 K. The Si-SiO_2 interface roughness is estimated to be 0.15 nm from the Fowler-Nordheim plot. These results indicate that the Si-SiO_2 structure is ordered within one atomic layer.

1. Introduction

In future submicron MOS LSI's, gate insulators less than 10 nm in thickness will be required owing to the device scalling down. However, it is known that the thin SiO_2 films formed by the conventional furnace oxidation at low temperature or in diluted oxygen, are poor in the interface characteristics [1]. To obtain good electrical reliability, rapid thermal processing (RTP) is applied to the thin oxide growth. Its advantages are as follows : very thin oxide films can be formed at high temperature above 1000 ^{o}C, and good uniformity of oxide films over large area is expected[2)-4)].

In this paper, we discuss the breakdown characteristics and uniformity of the thin SiO_2 by RTP in comparison with the conventional furnace grown oxides. Then, the Si-SiO_2 interface roughness formed during the RTP oxidation has been investigated from the tunneling characteristics.

2. Experimental

In this experiment, MOS capacitors composed of polysilicon gate-oxide-silicon were fabricated as follows : first, very thin (3-10 nm) SiO_2 films were formed by irradiation of light from halogen lamps in dry oxygen at 1000-1200 ^{o}C on p and n type (100) silicon wafers . And then n^+ polysilicon gates were formed on the oxide. Electrical properties of the MOS capacitors were characterized by high frequency (1 MHz) and quasi-static C-V , and ramp-voltage I-V measurements. The dielectric reliability of the SiO_2 has been investigated with the breakdown histogram and the data of time-dependent dielectric breakdown (TDDB) test.

3. Results

3.1 Breakdown characteristics of SiO_2 grown by various methods of oxidation

Figure 1 shows breakdown histograms for both RTP SiO_2 and furnace grown SiO_2 in diluted and wet atmospheres.

Breakdown frequencies for the furnace oxides are centered around 11 MV/cm, and small percentages of breakdown frequency are also found in the range of field less than 8 MV/cm. On the other hand, the RTP SiO_2 grown at 1050 ^{o}C had the muximum of breakdown frequency at higher field about 1 MV/cm than those of the above furnace oxides. Moreover, some RTP capacitors showed high fields breakdown above 15 MV/cm, and there was no breakdown in the range of field below 9 MV/cm in the histogram.

Figure 2 shows the cumulative failure of TDDB test for furnace grown and RTP SiO_2 films. A difference between RTP SiO_2 films grown at 1050 ^{o}C and at 1150 ^{o}C is clealy observed. The RTP SiO_2 grown at 1150 ^{o}C gave a longer life time failure mode in the intrinsic breakdown region.

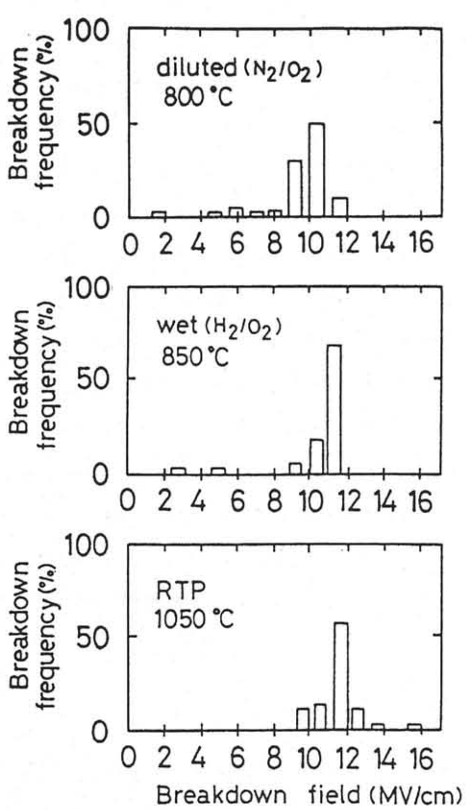

Fig.1 Breakdown histograms for MOS capacitors made with furnace grown and RTP SiO_2 films. The gate area is 10.2 mm^2.

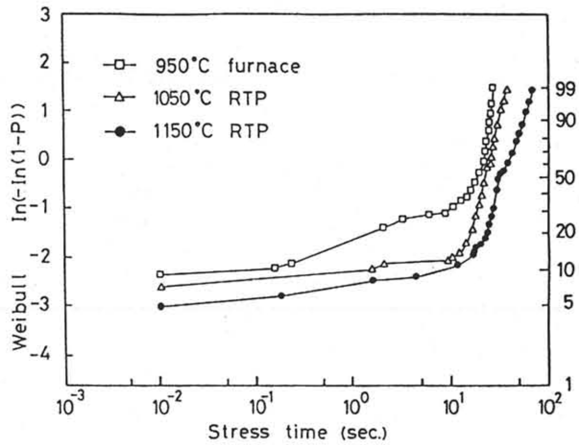

Fig.2 Cumulative % failure-stress time relation in TDDB for both RTP SiO_2 and furnace grown oxide films. The film thickness is 9.5 nm, and the current density is 0.5 A/cm^2

3.2 The $Si\text{-}SiO_2$ interface characteristics of thin RTP SiO_2 films

Figure 3 shows the interface trap density (D_{it}) versus surface potential characteristics of MOS capacitors obtained from quasi-static C-V measurements. It is found that D_{it} for RTP SiO_2 is much smaller than those of furnace grown oxides. On the RTP SiO_2 grown at 1200 ^{o}C, D_{it} at the midgap is about $8x10^{10}\ cm^{-2}eV^{-1}$.

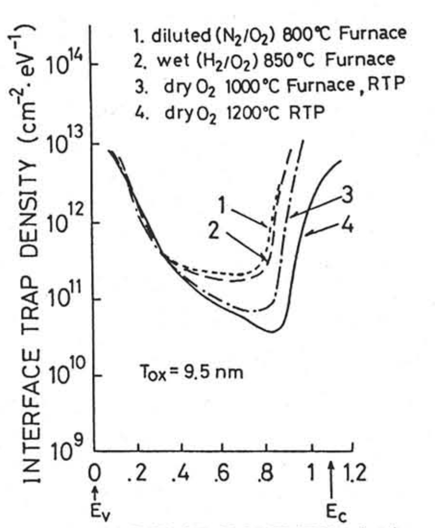

Fig.3 Interface trap densities of the MOS capacitors with the RTP SiO_2 and furnace grown SiO_2 . Oxidation conditions are shown in the figure.

The characteristics of tunneling current versus voltage was measured on MOS capacitors with very thin RTP SiO_2 films. The data were taken for capacitors having gate area of 0.02 mm^2 , at 300 K. As shown in Fig.4, oscillation in the region of the Fowler - Nordheim (F-N) current is observed for negative gate bias, but for positive bias.
The amplitude of oscillation is enhanced with decreasing SiO_2 thickness ($\leq$6 nm).

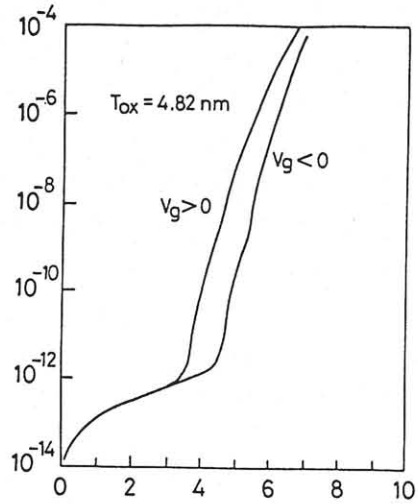

Fig.4 Characteristics of tunneling current versus bias voltage . The oxide thickness is 4.82 nm.

3.3 Characteristics of time-to- breakdown for the RTP SiO_2 films

The effect of oxide thickness on the constant current TDDB characteristics has been investigated in the oxide thickness range of 3 - 10 nm. Figure 5 shows the dependence of time-to- breakdown (t_{BD}) on injected current density (J_{OX}), where the oxide thickness is taken as a parameter. From Fig.5 , it is found that t_{BD} decreases with increasing J_{OX} for all samples. The t_{BD}- J_{OX} characteristics also shows a tendency that t_{BD} increases with decreasing the oxide thickness , in particular in the range of J_{OX} less than 1 A/cm^2.

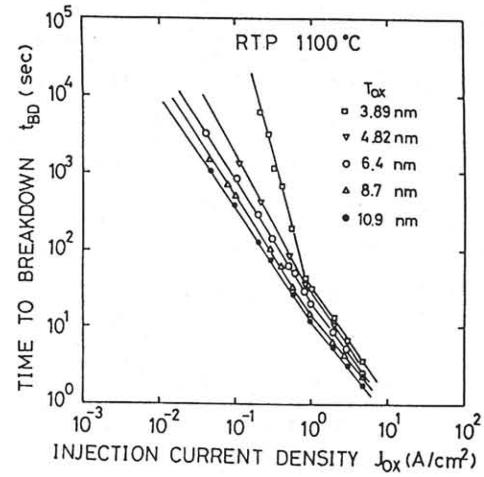

Fig.5 Time-to-breakdown versus injection current density. Oxide thickness is shown as a parameter.

4. Discussion

The MOS capacitor with the RTP SiO_2 film has a lower interface trap density in comparison with furnace grown oxides. It is considered that the RTP oxidation induces considerable reduction of Si dangling bond and/or unterminated oxygen at Si-SiO_2 interface. Under these conditions, the oscillation in MOS tunneling becomes clearly appreciable. In most oxides grown by furnace oxidation at the temperature below 900 °C, the oscillation has been very weak [9]. It is due to poor quality of Si-SiO_2 interface or defects in bulk SiO_2 . The oscillation in MOS tunneling occurs by the quantum interference between tunneled electron waves and reflected electron waves at Si-SiO_2 interface. Thus, if there is a transition region at interface, electron waves are scattered and the interference is strongly damped.

The Si-SiO_2 interface roughness is is estimated from the slope of the F-N plot [10]. Figure 6 shows the F-N plot for an oxide thickness of 4.82 nm, in which the asperity (a) at Si-SiO_2 interface is indicated as a parameter. In Fig.6, the value of a=0.15 nm is best fitted to the data obtained here. These results indicate that the Si-SiO_2 structure is ordered within one atomic layer. However, as I-V measurements are done repeatedly, the oscillation in MOS tunneling becomes weak, and the slope of F-N plot becomes to be small. These indicate that the transition region at the Si-SiO_2 interface is spread due to that the strained Si-O-Si bonds are broken by electron impact. As a result, the interface trap density also increases with increasing the electron injection into SiO_2 film.

The oxide breakdown due to F-N electron injection shows that the t_{BD} increases as oxide thickness is reduced. In SiO_2 above 10 nm in thickness, tunneled electrons are accelerated in the SiO_2 conduction band and bring to impact ionazation. The oxide breakdown under these conditions is caused by the electron trapping and hole generation[11].

For thinner SiO_2 films ($\leq$6 nm), some electrons go along to the oxide conduction band by F-N tunneling, but the other electrons are tunneled directly.

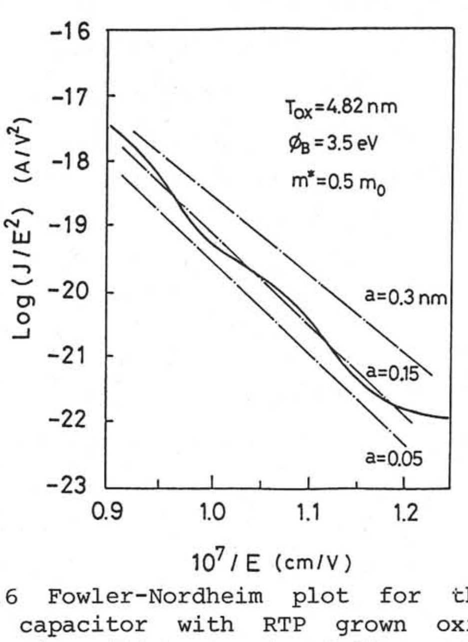

Fig.6 Fowler-Nordheim plot for the MOS capacitor with RTP grown oxide. The SiO_2 thickness is 4.82 nm. The asperity (a) is shown in figure.

Thus, the probability of electron trapping becomes to be small, then the time-to-breakdown becomes longer.

5. Conclusion

The electrical properties and the dielectric reliability of RTP SiO_2 film have been investigated as compared with furnace grown oxide film. The SiO_2 film grown by RTP is superior to furnace oxides, as evidenced by their excellent uniformity of breakdown field and a lower interface trap density. Furthermore, the oscillation in MOS tunneling is clearly observed on capacitors having thin RTP SiO_2 films ($\leq$6nm). From these results, it is concluded that the thin SiO_2 film grown by RTP has an excellent Si-SiO_2 interface uniformity and a longer lifetime on oxide break-down compared with furnace grown oxides.

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