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MOSFETs with nm-Thick Gate SiO_2 Grown at Low Temperatures Utilizing Activated Oxygen

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1. Introduction

In order to realize precise control of oxidation and interface formation for ultra-thin SiO_2 gate insulators, a low-temperature process is strongly required in advanced ULSI processes for the next generation. Several methods of plasma oxidation and/or CVD have been proposed, but very few was reported for the application to Si MOSFETs. In this study, we propose a novel technique of direct oxidation of Si surfaces at low temperatures (< 500 ℃) using activated oxygen. Atomic level SiO_2 formation could be realized, and the feasibility for nm-thick gate insulators of MOSFETs was demonstrated for the first time. Electronic properties of formed SiO_2 were investigated in detail using current/voltage and capacitance/voltage characteristics. Observed tunneling current showed device-quality properties with excellent Si/SiO_2 interface characteristics as in thermal oxides prepared at high temperatures. Performance of fabricated MOSFETs is discussed related to oxidation processes and interface properties.

2. Experiments and Discussions

Atomic level oxidation could be realized using activated oxygen at as low as 300 - 500 ℃ [1]. Activated oxygen species were generated in Ar based ECR plasma with typical conditions of 100 W and 10^{-3} Torr. Substrates were n-Si(001) epi-wafers, and a conventional RCA cleaning process was used before oxidation. Oxidation rates are shown in Fig.1 as a function of substrate temperature. Oxidation by activated oxygen (□,●) dominated in a range of 300~500℃, and so, the oxidation rate has no temperature dependence with much higher oxidation rates compared to thermal oxidation (▲). The oxidation rate could be varied in the range of 0.05 ~ 0.25 nm/min reproducibly by changing the dilution rate of oxygen by Ar, which gave an appropriate controllability in ultra-thin SiO_2 formation. Optical emission spectroscopy revealed that the number of activated oxygen species increased with the dilution rate of oxygen by Ar.

In Fig.2, typical current/voltage characteristics are shown for films grown using a two-step oxidation process (oxidation using a high Ar dilution (□ in Fig.1) for 20 ~ 30 min followed by a low Ar dilution (● in Fig. 1) for 10 min together with thermally-grown SiO_2 at high temperatures. A high resistivity of 10^{15}~10^{16}

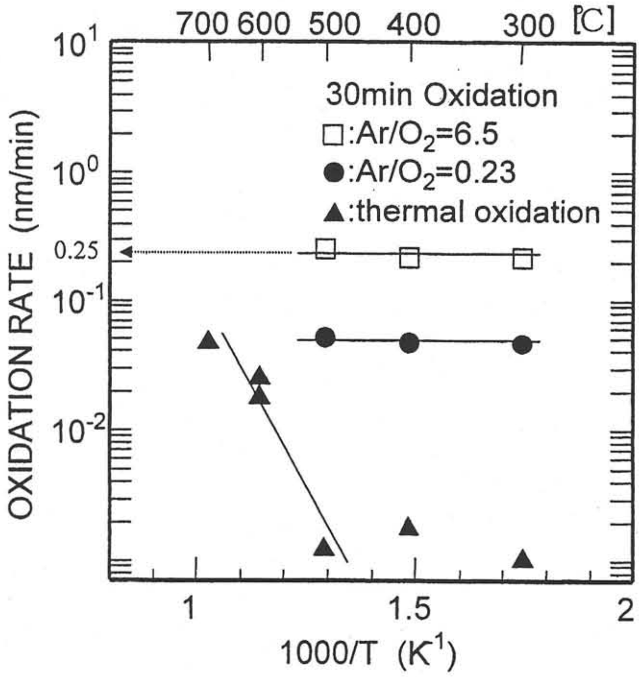

Fig.1 Oxidation rate as a function of substrate temperature.

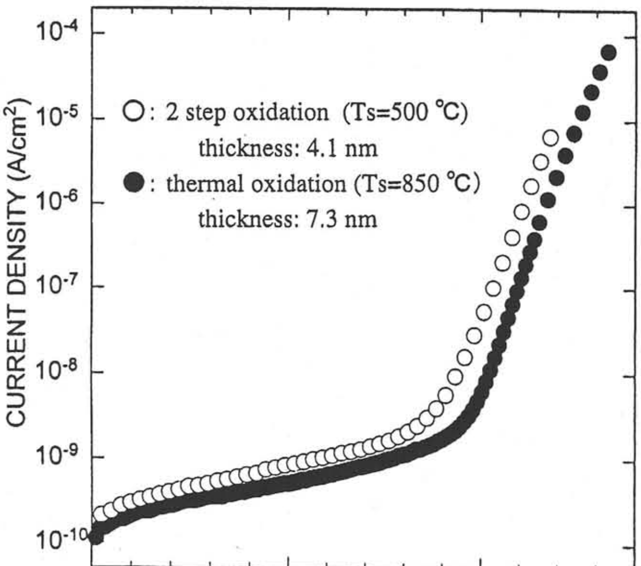

Fig.2 Current/voltage characteristics for ultra-thin SiO_2 films grown by activated-oxygen and thermal oxidation.

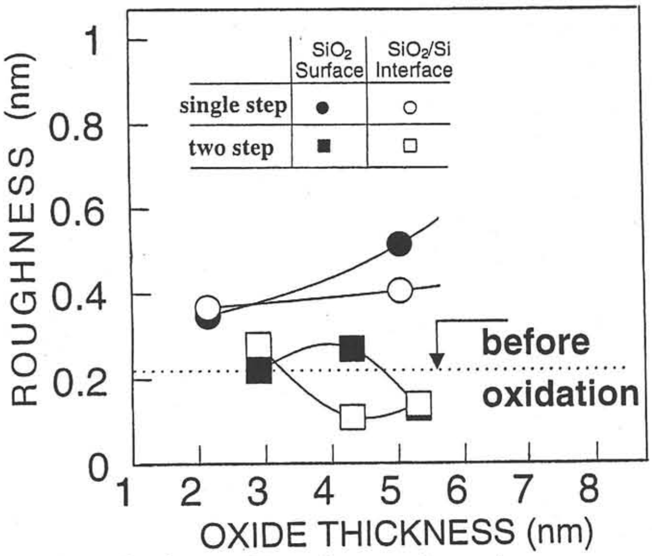

Fig.3 Surface and interface roughness (root mean square) processed with various sequences.

Ωcm was achieved at a low electric field strength. The steep increase in a range higher than 10 MV/cm was caused by a Fowler-Nordheim tunneling current. A F-N tunneling plot [2] gave a barrier height (Si/SiO_2) of 3.25 eV and an electron effective mass of 0.4, which showed that the interface formed by activated oxygen at low temperatures had almost the same property as SiO_2 by a thermal process at high temperatures [3]. Capacitance/voltage characteristics showed no hysteresis, and the estimated interface state density was as low as $3\times10^{11}\,cm^{-2}eV^{-1}$.

Surface roughness after oxidation and interface roughness were examined by AFM. The interface roughness was observed after etching off SiO_2 by buffered HF. As shown in Fig.3, the roughness increased monotonously with increasing film thickness by a single oxidation process at high Ar dilution (●:for surface, ○ :for interface). On the contrary, the roughness showed almost the same value as before oxidation (dotted line in the figure) by the two-step oxidation process (■:for surface, □:for interface). It should be noted that the film thickness was fixed by the oxidation process at the high Ar dilution, and the following process at the low Ar dilution was considered to be annealing by activated oxygen, since the total film thickness showed little increment during the second process. A minimum roughness value of 0.15 nm agreed with a mono-layer step of Si (001) surface, which shows that atomically flat interface could be realized by activated oxygen oxidation and annealing.

MOSFETs with a channel length/width of 30/250 μm were fabricated using ultra-thin gate SiO_2 on p-Si(001). Obtained effective electron mobilities were shown in Fig.4 for single- and two-step oxidation. A maximum channel mobility of 294 cm^2/Vs was obtained for two-step oxidation, which reflects the excellent interface properties as discussed above. To authors' knowledge,

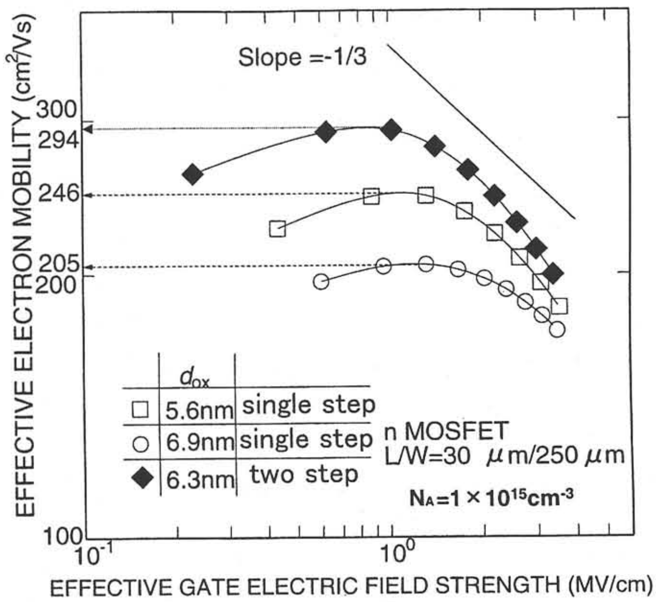

Fig.4 Effective electron mobility as a function of effective gate electric field strength.

the achieved mobility is one of the high values reported up to now for low-temperature processed gate insulators [4], but is about 40% of thermal SiO_2. Further improvement of interface properties is required by , *e.g.* , hydrogen annealing and/or ozone treatment.

3. Conclusions

Nanometer-thick SiO_2 was grown at low temperatures using activated oxygen, and the feasibility for gate insulators of Si MOSFETs was demonstrated for the first time. Atomic level oxidation could be achieved with an atomically flat Si/SiO_2 interface. Tunneling transport through ultra-thin SiO_2 showed high-quality electronic properties as a thermal process at high temperatures. The achieved electron mobility was one of the high values reported up to now.

Acknowledgements

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