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High Quality Ultrathin TaO_xN_y Gate Dielectric Prepared by Nitridation of Ta_2O_5

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1. Introduction

Considering the technology roadmap, an equivalent oxide thickness of less than 1.5nm will be necessary to meet the requirements for sub-100nm MOSFET devices [1]. No alternative high dielectric constant materials, which are capable of meeting the above requirements for sub-100nm MOSFET devices have been reported to date. Although Ta_2O_5 has been investigated in terms of MOS gate dielectric applications, it is difficult to obtain an equivalent oxide thickness of less than 2nm with acceptable leakage current [2,3]. It is known that nitrogen plasma annealing can significantly reduce leakage current and trap density [4]. In addition, it has been reported that the dielectric constant of Ta_2O_5, when deposited on a Ru layer was significantly improved by rapid thermal nitridation [5]. In this paper, we wish to report the TaO_xN_y thin film for gate dielectric applications in sub-100nm MOSFET devices.

2. Experiments

After cleaning a p-type silicon wafer using standard procedure, a 1nm-thick SiO_2 layer was grown by plasma oxidation in order to reduce the interface state density between Si and Ta_2O_5. 8-nm thick Ta_2O_5 and TaO_xN_y films were deposited by MOCVD. In addition, we have prepared TaO_xN_y films by rapid thermal nitridation of Ta_2O_5 films in NH_3. For comparison, nitridation in ND_3 ambient was also performed. For some samples, an additional wet reoxidation was performed. After a 200nm-thick aluminum deposition, MOS devices were defined by photolithography and etching.

3. Results and Discussion

Fig. 1 shows the accumulation capacitance versus leakage current at −1.5V for as-deposited Ta_2O_5 and TaO_xN_y. Compared with Ta_2O_5, TaO_xN_y exhibit better performance in terms of capacitance and leakage current. However, after rapid thermal oxidation, the capacitance of TaO_xN_y was almost the same as that of Ta_2O_5. Based on AES analysis as shown in Fig. 2, we found that a significant reduction of nitrogen concentration of TaO_xN_y after rapid thermal oxidation. Fig. 3 shows AFM roughness of Ta_2O_5 and TaO_xN_y. Compared with Ta_2O_5, the roughness of TaO_xN_y is degraded with increasing annealing temperature. Considering capacitance, AES nitrogen profile, and roughness, we believe that the as-deposited TaO_xN_y is unstable under post deposition annealing step.

To solve the problems of as-deposited TaO_xN_y, we have prepared TaO_xN_y films by rapid thermal nitridation of Ta_2O_5 films in NH_3. Fig. 4 shows an XRD spectra of as-deposited Ta_2O_5 films and processed via rapid thermal nitridation in NH_3 ambient. As-deposited and 700°C nitrided-Ta_2O_5 were amorphous, while crystalline peaks were observed at 800°C nitrided Ta_2O_5 film [6]. Fig. 5 (a) shows the C-V characteristics for as deposited Ta_2O_5, nitrided Ta_2O_5, oxidized Ta_2O_5, and reoxidized-nitrided Ta_2O_5. The accumulation capacitance of as deposited Ta_2O_5 is approximately 11pF, indicating an equivalent oxide thickness of 2.8nm. After nitridation of Ta_2O_5 in NH_3 at 700°C, the accumulation capacitance is approximately 19pF, which indicates an equivalent oxide thickness of 1.6nm. To minimize leakage current, a wet reoxidation of the Ta_2O_5 at 450°C for 10 minutes was performed as shown in Fig. 5(b). To obtain both a high accumulation capacitance and low leakage current, we performed nitridation, followed by a wet reoxidation. The findings show a significant improvement in the accumulation capacitance can be obtained without degradation of leakage current. To evaluate the effect of temperature on device characteristics, the nitridation and reoxidation at various temperatures were performed as shown in Fig. 6. As expected, the capacitance and leakage current increase with increasing nitridation temperature. In contrast, the capacitance and leakage current decreases with increasing reoxidationtemperature. It was found that the wet reoxidation of nitrided Ta_2O_5 at 450°C for 10min can reduce the leakage current over two order of magnitude with no detectable degradation in accumulation capacitance. Fig. 7 shows the nitrogen depth profile of the reoxidized-nitrided Ta_2O_5 which was confirmed by Auger Electron Spectroscopy (AES). As expected, nitrogen incorporation was detected in the case of the nitrided-Ta_2O_5.

Recently, we have reported that the charge-trapping of ND_3 nitrided-SiO_2 was significantly less than that of NH_3 annealed samples [7]. To improve charge trapping characteristics, we have investigated ND_3 nitrided-TaO_xN_y. As shown in Fig. 8, we found a significant reduction of charge trapping characteristics for ND_3 nitrided-TaO_xN_y. In addition, charge-to-breakdown characteristics of ND_3 nitrided-TaO_xN_y was significantly improved as shown in Fig. 9 .

4. Conclusion

TaO_xN_y have been investigated for use in gate dielectric applications of MOS devices. Nitridation of Ta_2O_5 in ammonia ambient increases the dielectric constant and light reoxidation in a wet ambient reduces the leakage current. By optimizing the nitridation and reoxidation process, we obtained an equivalent oxide thickness as thin as 1.6nm and a leakage current of less than 10mA/cm^2 at -1.5V. We also confirmed nitrogen incorporation in the amorphous tantalum oxynitride (TaO_xN_y) by AES. Compared with NH_3 nitridation, nitridation of Ta_2O_5 in ND_3 improves charge trapping and charge-to-breakdown. We conclude that TaO_xN_y thin film, formed by nitridation and wet reoxidation of Ta_2O_5 is a promising alternative for future MOS gate dielectric applications.

Acknowledgements
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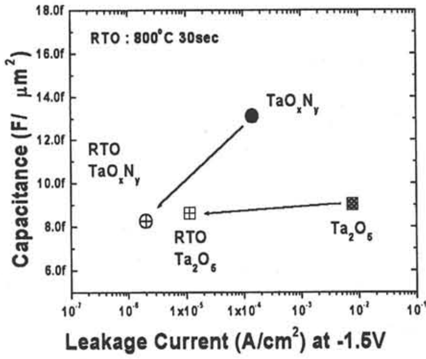

Fig. 1 Capacitance versus leakage current at −1.5V for Ta_2O_5 and TaO_xN_y by MOCVD.

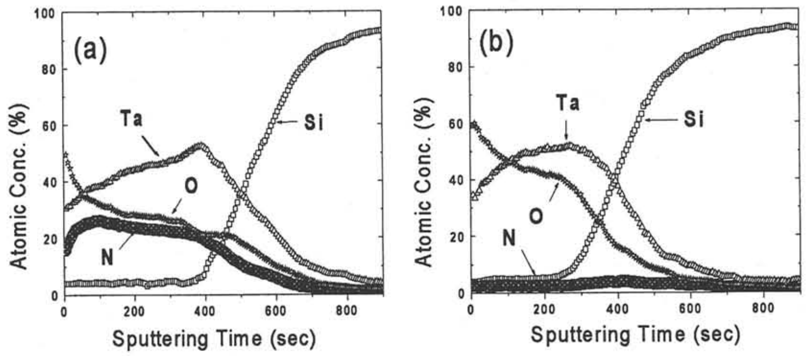

Fig. 2 AES depth profile of TaO_xN_y (a) As deposited (b) After RTO (800°C 30sec).

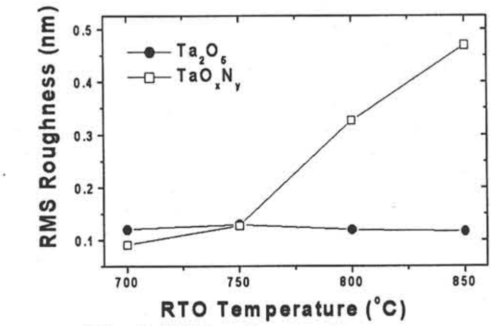

Fig. 3 AFM surface roughness versus RTO temperature.

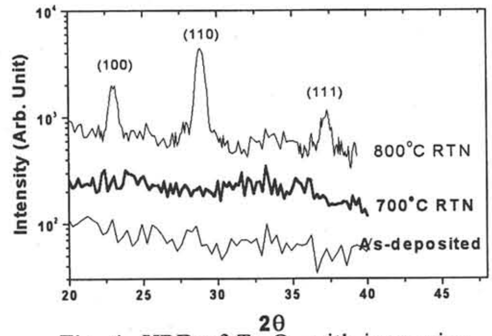

Fig. 4 XRD of Ta_2O_5 with increasing annealing temperature.

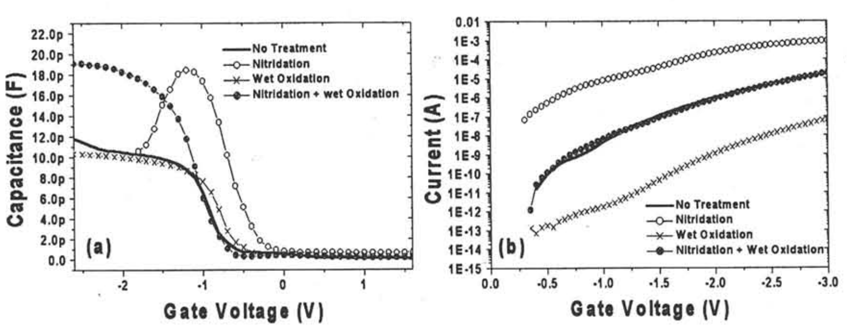

Fig. 5 (a) C-V characteristics for as deposited Ta_2O_5, nitrided-Ta_2O_5,oxidized Ta_2O_5, and reoxidized-nitrided Ta_2O_5. (b) I-V characteristics.

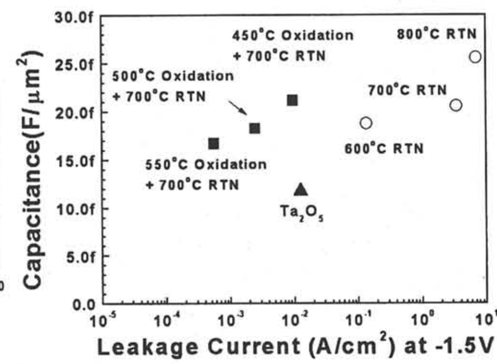

Fig. 6 Capacitance versus leakage current for various nitridation and reoxidation conditions.

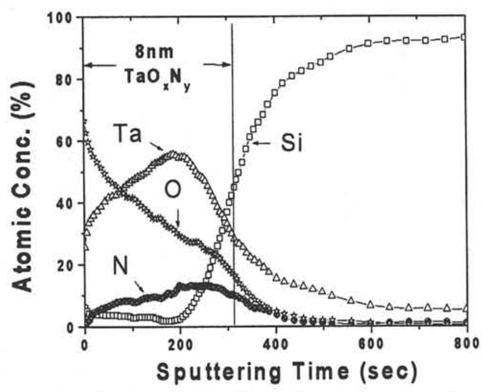

Fig. 7 Auger Electron Spectroscopy of 8nm-thick reoxidized-nitrided Ta_2O_5.

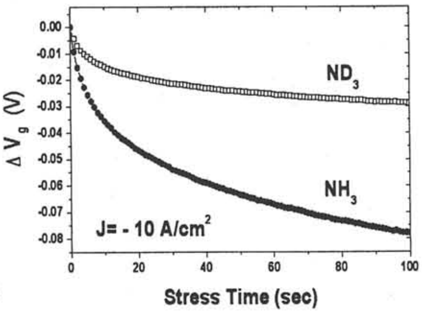

Fig. 8 Charge trapping characteristics of TaO_xN_y under constant current density of J_g=-10A/cm².

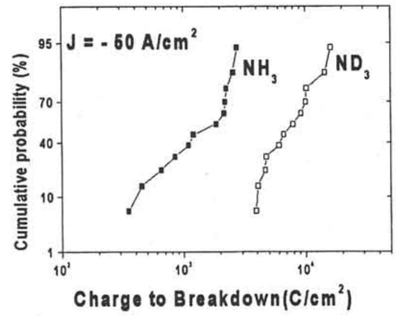

Fig. 9 Charge to breakdown characteristics under constant current stress.