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Properties of Al_2O_3/Nb_2O_5 and Ta_2O_5 /Nb_2O_5 Stacked and Mixed Films for Gigabit DRAM Capacitor

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1. Introduction

The requirements for Gigabit DRAM are the leakage current less than 0.1 fA/cell and the capacitor dielectric film physical thickness of approximately 8 nm. Therefore, equivalent oxide thickness (EOT) must be less than 0.7 nm and the leakage current density must be less than 10^{-8} A/cm^2 at 1 V. In order to satisfy the requirements, both wide band gap and high dielectric constant materials must be investigated. In this study, the stacked films shown in Fig. 1, having Al_2O_3 and Nb_2O_5, Ta_2O_5 and Nb_2O_5 whose thicknesses are less than 10 nm have been investigated as candidates for wider bandgap and higher dielectric constant materials.

2. Experimental

After RCA cleaning, Si (100) substrate was cleaned in 0.5 % HF solution. 50 nm thick SiO_2 was grown by wet oxidation at 1000℃. A 140 nm thick Pt bottom electrode was deposited on SiO_2 using DC magnetron sputtering at the sputtering power and gas pressure of 50 W and 1 Pa, respectively. Al_2O_3 and Nb_2O_5 thin films were deposited by RF magnetron sputtering with the sputtering power of 50 W and gas pressure of 2.5 Pa (Ar / O_2 = 35 / 35 sccm) at 450℃. Ta_2O_5/Nb_2O_5 mixed and stacked films were deposited by RF magnetron sputtering with the power of 50 W and gas pressure of 0.5 Pa (Ar / O_2 = 10 / 10 sccm) at 300℃. A Pt top electrode was deposited on Nb_2O_5/Al_2O_3 thin films with a screen mask having ϕ1.6 mm. Sample structure is shown in Fig. 1(a). The films were annealed in a furnace at 600℃ in O_2 ambient for 5 min.

3. Results and Discussion

Figure 2 shows loss energy spectra of Nb_2O_5, Ta_2O_5 and Al_2O_3 films. The bandgap was determined by the difference between core level peak of the O1s and the threshold of the energy loss spectra [1]. The band gaps of Nb_2O_5, Ta_2O_5 and Al_2O_3 were determined as 4.25 eV, 4.70 eV and 6.80 eV, respectively. Figure 5 shows valence band spectra of Pt, Nb_2O_5, Ta_2O_5 and Al_2O_3. The valence band offset from Fermi level of Pt was calculated by differentiating threshold energies of photoelectron intensities between Nb_2O_5 and Pt, Ta_2O_5 and Pt, and Al_2O_3 and Pt, respectively. The valence band offset of Nb_2O_5, Ta_2O_5 and Al_2O_3 were 2.60 eV, 2.90 eV and 3.10 eV, respectively. The conduction band offset was calculated from the difference between the band gap and the valence band offset. The conduction band offset of Nb_2O_5, Ta_2O_5 and Al_2O_3 were calculated as 1.65 eV, 1.80 eV and 3.70 eV, respectively. Figure 4 shows the leakage current density of Nb_2O_5, Ta_2O_5 and Al_2O_3. The Ta_2O_5 and the Al_2O_3 films which have wider band gap suppressed leakage current than Nb_2O_5 film. Figure 5 shows the influence of the thickness on the dielectric constant and the EOT. All films were crystallized, and oriented Nb_2O_5 (001) and (002). The dielectric constant decreased as the Nb_2O_5 thickness decreased below 20 nm. The EOT was approximated as a straight-line and intercepted at about 0.4 nm of EOT. Therefore, Nb_2O_5 film has an interface layer whose dielectric constant was lower than the crystalline layer. Then, the EOT of Nb_2O_5 film was calculated by the following equation.

$$EOT = \frac{3.9 \times d}{k_C} - \frac{3.9 \times d_A}{k_C} + \frac{3.9 \times d_A}{k_A} \qquad (1)$$

Where, d is the thickness of Nb_2O_5 film, k_C is the dielectric constant of crystalline layer, k_A is the dielectric constant of interface layer, d_A is thickness of the interface layer. By using the slope of the fitted line, the dielectric constant of the crystalline Nb_2O_5 layer was found to be 158. Figure 6 shows XRD spectra of Nb_2O_5/Pt and $Nb_2O_5/Sr_5Nb_9O_{25}$/Pt films. $Nb_2O_5/Sr_5Nb_9O_{25}$/Pt film did not show Nb_2O_5 diffraction peak. This is because the mismatch of the lattice constants between Nb_2O_5 and $Sr_5Nb_9O_{25}$ occurred and the resulting dielectric constant became as low as 51. d_A was calculated by use of equation (1) and k_A =51 as well as y-intercept of the fitted line in Fig.7. The calculated value of d_A was 4.9 nm. Figure 7 shows Nb_2O_5 thickness versus the XRD intensity peak of Nb_2O_5(001) annealed at 600°C and 800°C. The thickness of the interface layer can be obtained by the intercept of x-axis. The thicknesses of NbO interface layers annealed at 600°C and 800°C were 4.60 nm and 4.52 nm, respectively. The thicknesses of the interface layers are in good agreement with the electrical properties, and they showed no dependence on anneal temperatures. Figures 8 and 9 show the influences of Al_2O_3 and Ta_2O_5 thicknesses on the dielectric constant and the EOT, respectively. The dielectric constant stayed constant as approximately 8.5 and 23, respectively. The fitted lines of EOT did not have the intercept, so that Al_2O_3 and Ta_2O_5 films were found to be homogeneous. In order to achieve thinner EOT and lower leakage current, mixed and stacked films are investigated. At first, Al_2O_3/Nb_2O_5 stacked films were investigated. The structure of stacked film was $Pt/Al_2O_3/Nb_2O_5/Pt/SiO_2$ as shown in Fig.1(b). Figures 10 and 11 show the EOT and the leakage current density at 1V, respectively. Nb_2O_5 thicknesses were fixed at 6 nm and 10 nm, while Al_2O_3 thickness was varied. The EOT decreased and the leakage current density at 1V increased with decreasing the Al_2O_3 thickness. The minimum EOT of 1.30 nm was obtained with suppressing leakage current at 6×10^{-8} A/cm^2 at 1V. Figures 12 and 13 show the loss energy spectra of O1s and the leakage current at 1V for TaNbO mixed films. The band gap of TaNbO mixed film increased with increasing Ta content so that the leakage current decreased. The EOT and the leakage current density at 1V for TaNbO mixed films and Ta_2O_5/Nb_2O_5 stacked films were investigated as shown in Figs.14 and 15. Film structures are shown in Figs.1(c), (d) and (e). The minimum EOT of 0.66 nm was obtained with suppressing leakage current at 2.6×10^{-8} A/cm^2 at 1V by using $Nb_2O_5/Ta_2O_5/Nb_2O_5$ stacked structure whose Ta content was 25 %.

4. Conclusion

By using $Nb_2O_5/Ta_2O_5/Nb_2O_5$ stacked structure whose Ta content was 25 %, minimum EOT of 0.66 nm was obtained with suppressing leakage current at 2.6×10^{-8} A/cm^2 at 1V. For Al_2O_3/Nb_2O_5 stacked films, the EOT could not be reduced less than 1 nm when the Al_2O_3 thickness was 2 nm, This is attributed to the fact that Nb_2O_5 has an interface layer between Nb_2O_5 and Pt, whose thickness and dielectric constant were 4.6-4.9 nm and 51, respectively.

Reference

[1] S. Miyazaki, J. Vac. Sci. Technol. B **19**, 2212 (2001)

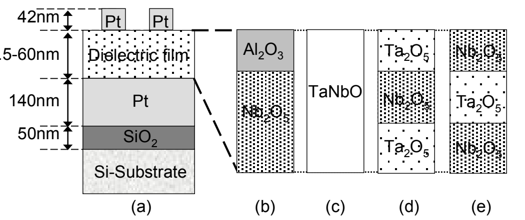

Fig.1. Cross-sectional structures of MIM capacitors (a). (b) Al_2O_3/Nb_2O_5. (c) $Ta_xNb_yO_z$. (d) $Ta_2O_5/Nb_2O_5/Ta_2O_5$. (e) $Nb_2O_5/Ta_2O_5/Nb_2O_5$.

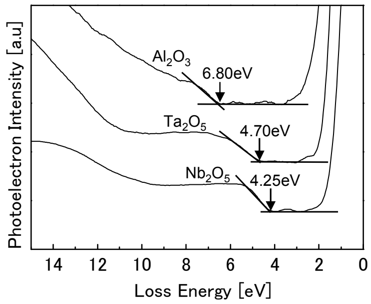

Fig.2. Loss energy spectra of O1s of Nb_2O_5, Ta_2O_5 and Al_2O_3.

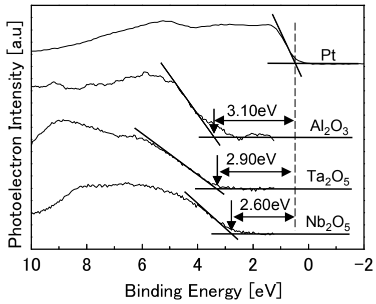

Fig.3. Valence band spectra of Nb_2O_5, Ta_2O_5 and Al_2O_3.

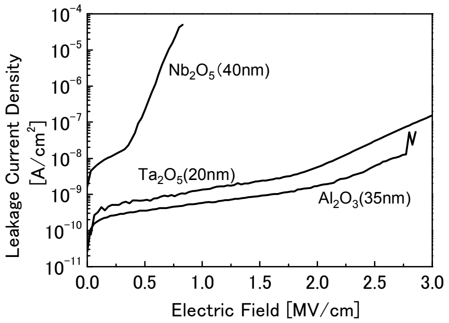

Fig.4. Leakage current density of Nb_2O_5 , Ta_2O_5 and Al_2O_3 versus electric field.

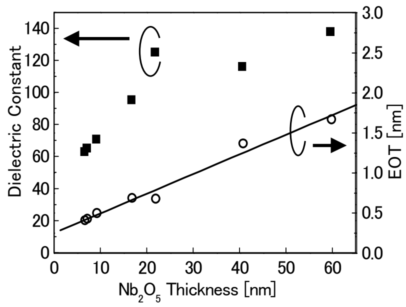

Fig.5. Dielectric constant and EOT versus Nb_2O_5 thickness.

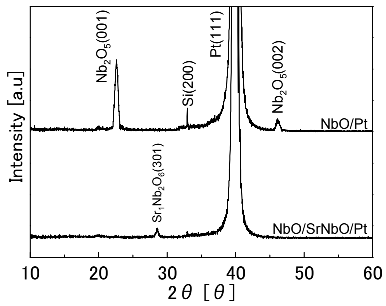

Fig.6. X-ray diffraction spectra of Nb_2O_5/Pt and $Nb_2O_5/Sr_5Nb_9O_{25}$/Pt structures.

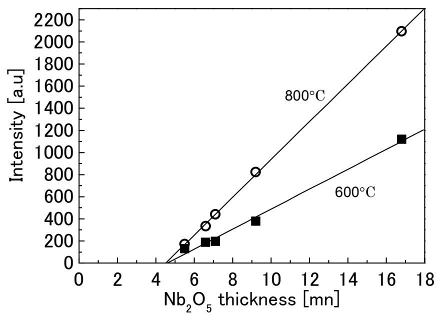

Fig.7. Intensity of x-ray diffraction spectra of Nb_2O_5 (001) versus Nb_2O_5 thickness.

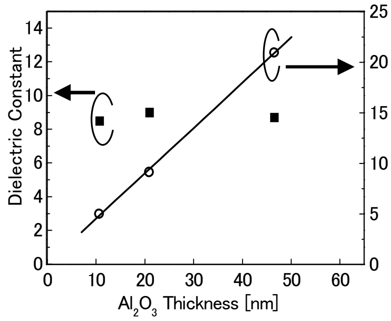

Fig.8. Dielectric constant and EOT versus Al_2O_3 thickness.

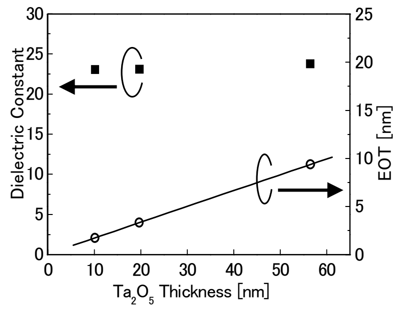

Fig.9. Dielectric constant and EOT versus Ta_2O_5 thickness.

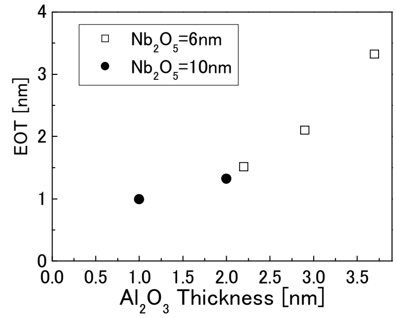

Fig.10. EOT versus Al_2O_3 thickness for Al_2O_3/Nb_2O_5 stacked films.

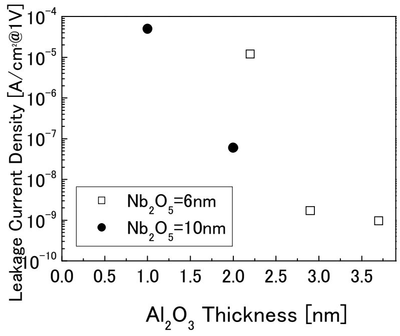

Fig.11. Leakage current density at 1V versus Al_2O_3 thickness for Al_2O_3/Nb_2O_5 stacked films.

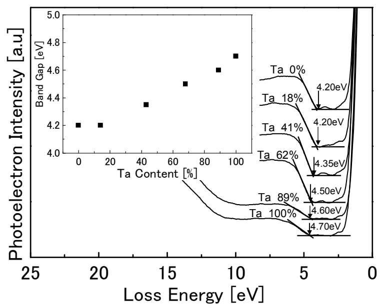

Fig.12. Loss energy spectra for $Ta_xNb_yO_z$ mixed film.

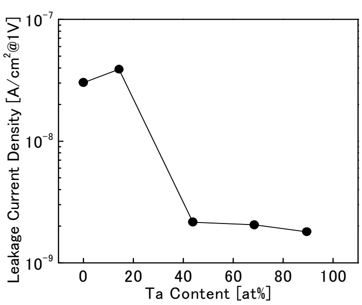

Fig.13. Leakage current density at 1V versus Ta content for $Ta_xNb_yO_z$ mixed film.

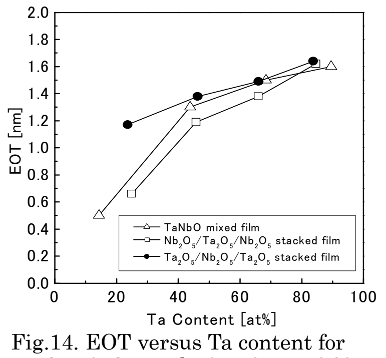

Fig.14. EOT versus Ta content for Ta_2O_5/Nb_2O_5 stacked and mixed films.

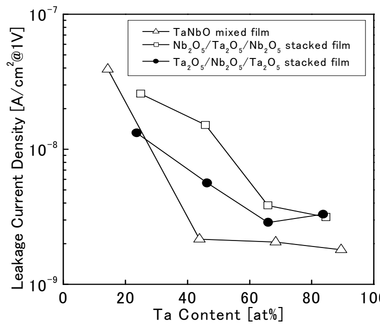

Fig.15. Leakage current density versus Ta content for Ta_2O_5/Nb_2O_5 stacked and mixed films.