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Improving Characteristics of Tantalum Oxide Thin Film Devices with Copper Electrodes

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1. Introduction

High performance capacitors are heavily in demand passive components, owing to their essential role in realizing RF and microwave systems, and greater capacitor densities result in reduced chip sizes. [1,2] Metal-insulator-metal (MIM) capacitors, and particularly Ta_2O_5 MIM devices that are formed above back-end-of-line Cu, can be integrated. However, the formation of Cu oxidizes occurred mainly during the initial stage of Ta_2O_5 reactive sputtering, and hillock or particle formation was observed after annealing oxygen ambient. [3,4] Considerable efforts have been made to identify an appropriate diffusion barrier layer for Cu-based electrode. Among these diffusion barrier materials, tantalum (Ta) was chosen for Cu-based electrode. Unfortunately, the grain boundaries of the sputtered Ta layer generally provide paths for oxygen atom diffusion when the Ta_2O_5 dielectrics require high temperature and ambient oxygen. Protection against oxidation is essential when growing Ta_2O_5 dielectric film on Cu-base electrode. This study introduced a structure by using an ultra thin Al layer added between the Ta_2O_5 dielectric and Ta diffusion barrier. The mechanism of improvement in the leakage characteristics of Ta_2O_5 film capacitors is investigated via various electrical and physical characteristics.

2. Experiment

Thermally grown SiO_2 film was formed on p-type Si (100) substrate for the isolation. The Cu (300 nm)/Ta (50 nm), Ta (50 nm)/Cu (300 nm)/Ta (50 nm), and Al (20 nm)/Ta (30 nm)/Cu (300 nm)/Ta (50 nm) electrode multilayers were deposited sequentially. High-ε Ta_2O_5 film, thickness 40 nm, was deposited on the Cu-based electrodes by magnetron sputtering from the Ta metal target. Following deposition, Ta_2O_5 film was treated using thermal annealing at 500 and 600°C, respectively, for 30 min in oxygen ambient. For the top electrode, reactively sputtered 50 nm Ta and 150 nm Cu films were deposited after post-annealing of Ta_2O_5 film.

3. Results and Discussion

Figure 1(a) illustrates the SIMS depth profiles of the O concentration in the Ta_2O_5/Ta/Cu sample after annealing at 500 and 600°C in oxygen ambient. The diffusion appeared to occur for most of the oxygen atoms after annealing and increased with the annealing temperature. The oxygen atoms in the Ta film are considered to react to the Ta layer, and diffuse along the grain boundaries Ta crystal. Figure 1(b) displays the O concentration confirmed reaction of the Ta_2O_5/Al/Ta/Cu sample after annealing at 500 to 600°C. Almost no indication exists that oxygen atoms diffuse into the Ta and Cu layer. The high-resolution TEM image in Fig. 2(a) clearly shows the interfacial oxidation thickness lies between 4-5 nm growths in the Ta_2O_5/Ta/Cu structure. However, no oxygen defection or reaction is observed between the Ta and Cu layers in the Ta_2O_5/Al/Ta/Cu samples. Significant improvement in thermal stability was obtained compared with the samples without thin Al film, apparently due to the barrier effectiveness of Al/Ta layers. Figure 3 shows the TEM micrograph of the Cu/Ta/Ta_2O_5/Al/Ta/Cu device after thermal annealing at 600°C, and indicates that the ultra thin film between Ta_2O_5 and Al has an amorphous structure.

Figure 4 clarifies the leakage current densities on the different bottom electrodes as a function of electrical field up to 6 MV/cm after annealing at 600°C for 30 min in oxygen ambient. The lowest leakage current densities are measured for the Al/Ta/Cu bottom electrode, resulting in a value of 1 nA/cm^2 at 1 MV/cm, below the 15-10^5 nA/cm^2 for Cu bottom electrode and the 1.2-1.5 nA/cm^2 for Ta/Cu bottom electrode, respectively. The breakdown voltage for Al/Ta/Cu bottom electrode of approximately 5.2 MV/cm increases to that for the Cu and Ta/Cu bottom electrodes of around 1.4 and 3.7 MV/cm (at 10^{-6} A/cm^2). In this study, almost no asymmetry was observed in the I-V characteristics of Ta_2O_5 MIM capacitors with Al/Ta/Cu as bottom electrodes, and Ta/Cu as top electrodes. This behavior clearly indicates that Poole-Frenkel emission is the dominant conduction mechanism in the high electric field region, as shown in Fig. 5(a). Furthermore, e values deduced from the slopes of the linear region of the Schottky emission graph are inconsistent with the dielectric constant values measurements illustrated in Fig. 5(b). The measurement results demonstrate that the current of the Ta_2O_5 films in this investigation is bulk limited in high electric field regions (>1MV/cm), can be accurately described based on the Poole-Frenkel emissions. Figure 6 illustrates the breakdown characteristics of Ta_2O_5 capacitors at the current density of 10^{-6} A/cm^2. Obviously, the MIM structures with Cu/Ta/Ta_2O_5/Al/Ta/Cu capacitor exhibits better breakdown behavior than other capacitors. Figure 7 interprets the Ta_2O_5 MIM capacitor with Al/Ta/Cu bottom electrodes has a longer lifetime than the others. The extrapolated long-term lifetime indicates can survive for ten years at a stress field of 1.2 MV/cm.

4. Conclusion

Integrated an ultra thin Al film provides an efficient enhancing the quality of Ta_2O_5 MIM devices with Cu-based electrodes. This investigation found that MIM devices with

Cu-based electrodes demonstrated a major improvement against oxygen diffusion ability after inserting Al film. This improvement resulted from the Al self-protection to oxidation and the formation of a dense Al_2O_3 film on the Cu-based bottom electrode after thermal annealing in oxygen ambient. The Cu oxide disappeared by the novel integration of the Al_2O_3, resulting in decreased leakage current and increased breakdown voltage (5.2 MV/cm at 10^{-6} A/cm^2) in the Ta_2O_5 MIM capacitor with Cu-based electrodes. Therefore, the ultra thin Al film integrated Ta_2O_5 MIM capacitors with Cu-based electrodes are highly desirable for applications to RF and microelectronic devices.

Reference

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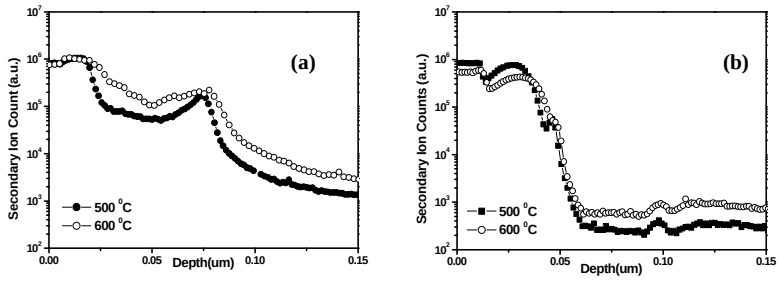

Fig.1: SIMS depth profiles of oxygen concentration in (a) Ta_2O_5/Ta/Cu and (b) Ta_2O_5/Al/Ta/Cu samples after furnace annealing at 500 and 600^{0}C for 30 min in oxygen ambient.

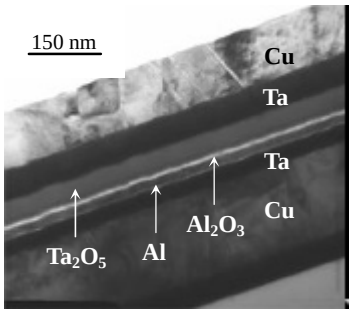

Fig.3: TEM image of Cu/Ta/Ta_2O_5/Al/Ta/Cu MIM capacitor. The annealing was conducted at 600°C for 30 min in oxygen ambient after Ta_2O_5 film was deposited.

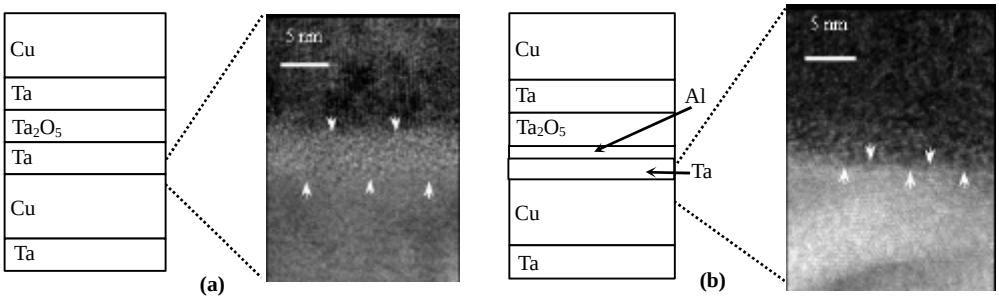

Fig.2: High-resolution TEM image of the interlayer between Ta and Cu layer in (a) Ta_2O_5/Ta/Cu and (b) Ta_2O_5/Al/Ta/Cu samples after furnace annealing in oxygen ambient.

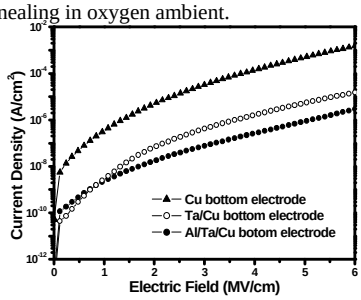

Fig.4: Current density-voltage characteristics of the Ta_2O_5 MIM capacitors with various bottom electrodes after annealing at 600°C in oxygen ambient for 30 min.

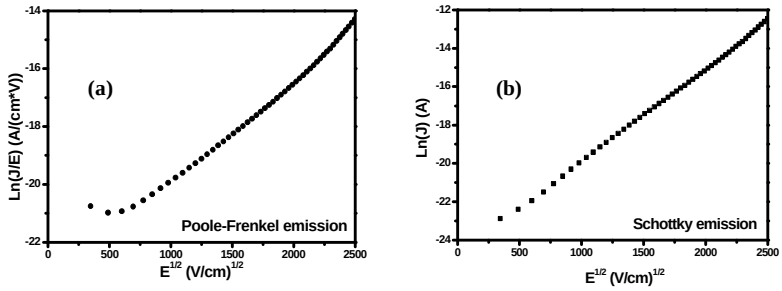

Fig.5: (a) The ln(J/E) is plotted as a function of $E^{1/2}$ for the Ta_2O_5 MIM capacitor at high electric field (>1 MV/cm), and (b) The ln(J) is plotted as a function of $E^{1/2}$ for the Ta_2O_5 MIM capacitor at low electric field (<1 MV/cm).

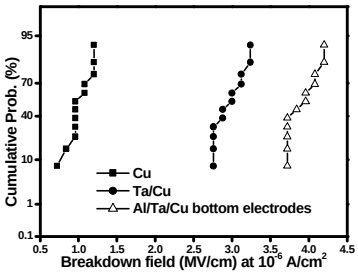

Fig.6: Breakdown characteristics of Ta_2O_5 MIM capacitors at the current density of 10^{-6} A/cm^2.

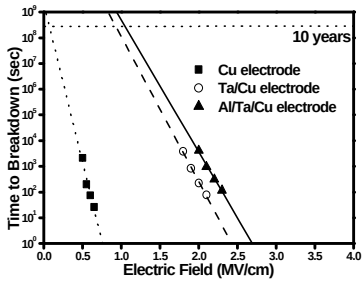

Fig.7: TDDB lifetime as a function of electric field for Ta_2O_5 films deposited on various bottom electrodes.