Recovery of ferroelectric property after endurance test by positive reset voltage application for CeO_x-capped ferroelectric HfO_2 films

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Abstract

The influence of CeO_x capping on HfO_2 films on the ferroelectric property is investigated. An improved switching endurance was found with the capping, but a fatigue effect appeared. A better breakdown only in the negative voltage application indicates the movement of oxygen ions in the capped layer to the underlying HfO_2 layer. A slight recovery with a better endurance property was obtained by applying a negative voltage among the switching pulses.

1. Introduction

Ferroelectric HfO_2 films have attracted considerable attention owing to their scalability below 10 nm thickness [1]. Reliability issues, however, including switching endurance, wake-up, or fatigue effects, remain. The ferroelectric property in HfO_2 films is influenced by oxidation time during atomic layer deposition (ALD) processes; thus, the control of the oxygen vacancy (V_O) concentration in HfO_2 films is essential [2,3]. Recently, an improvement in the endurance by CeO_x capping on Y-doped HfO_2 (Y:HfO_2) films was reported [4]. The capping function is reported to supply or absorb O atoms to the underlying HfO_2 layer to control the V_O concentration in the HfO_2 layer [5]. However, a detailed analysis of the reliability is not clarified yet. In this study, we show that oxygen ion (O^{2-}) movement in the capped layer may be the origin for better endurance and the appearance of the fatigue effect.

2. Device structure

Metal-insulator-metal (MIM) capacitors were fabricated on an n^+Si substrate with bottom and top W electrodes. 7.5-nm-thick Y:HfO_2 films were all deposited by ALD using tetrakis-dimethylamino hafnium (TDMAH), tris-isopropyl-cyclopentadienyl yttrium ($(^iPrCp)_3Y$), and precursors. The doping concentration in the Y:HfO_2 layer is designed to be 5 mol%. The capped CeO_x layer with a thickness of either 0.6, 1, or 2 nm was deposited by tris-ethyl-cyclopentadienyl cerium $(EtCp)_3Ce$ precursor. The MIM capacitors were annealed at 500ºC for 1 min or 100 min in a forming gas (3%H_2+97%N_2) atmosphere.

3. Ferroelectric property and endurance with CeO_x-capping

The MIM capacitor, annealed for 1 min, showed better ferroelectric hysteresis loops when the capping thickness is more than 0.6 nm (fig. 1). Annealing for a long period (100 min) further increases the ferroelectricity, but the capping still has the advantage (fig. 2).

Switching cycle test at V_{pp}=4V revealed a wake-up effect for non-capped capacitor and showed breakdown before 10^8 cycles. The capped capacitor, on the other hand, showed a reduced wake-up effect but with a fatigue effect once the switching cycle exceeds 10^6 times. The breakdown occurred before 10^{10} cycles, a significant improvement to the non-capped capacitor (fig.3). The DC current is measured regularly among the cycling test and is shown in fig. 4. Note that 0.5 V includes the switching current component and 1.5 V is the leakage component. A gradual current decrease at 0.5 V for capped capacitor indicates the reduction of P_r along with the cycle test. We can confirm that the suppressed leakage current contributes to the prolonged endurance. The effect is more pronounced for lower switching voltage (V_{PP}=3.6V).

The breakdown measurements of the MIM capacitors are shown in fig. 5. While no difference was found in the positive voltage application, a larger breakdown voltage was obtained in the negative direction with the capping. As the oxygen ion conductivity of CeO_x is known to be large [6], one can suspect that O^{2-} ions drift to the underlying HfO_2 layer to compensate for the created V_O filament in the layer (fig. 6 (a)). Besides the compensation of the V_O in the HfO_2 layer, the O^{2-} ions may pin the ferroelectric domain wall and might be the reason for the fatigue effect (fig. 6 (b)).

4. Recovery of ferroelectricity with negative voltage

A reset voltage (V_{reset}) was applied to the capped capacitor after switching of 10^8 times. We observed a recovery in the ferroelectric property when a V_{reset} of 2 V was used (fig. 7). By applying a V_{reset} for every 10^6 cycles, the fatigue effect was found to be suppressed (fig. 8). The impact of the positve V_{reset} is hypothesized to the extraction of O^{2-} as well as electrons trapped at CeO_x/HfO_2 interface.

5. Conclusion

The effect of CeO_x capping on Y:HfO_2 layer on the ferroelectric properties is investigated. Improvement in ferroelectricity with better endurance was obtained. The effect is presumably due to the oxygen ion movement in the CeO_x to compensate for the V_O in the HfO_2 layer. The fatigue effect can be considered to be the O^{2-} and electrons to pin the domain. Applying a positive reset voltage among the cycling test recovers the ferroelectricity, unpin the domains.

Acknowledgment

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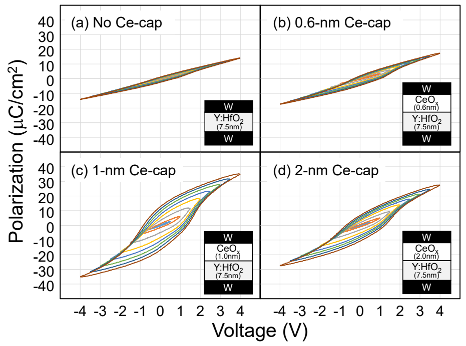

Fig. 1 Hysteresis loops with different CeOx-capping layer thicknesses.

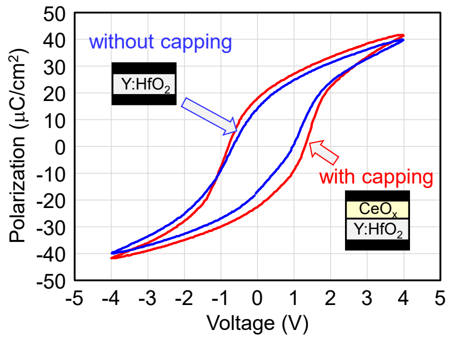

Fig. 2 Hysteresis loops with capacitors annealed at 500°C for 100 min.

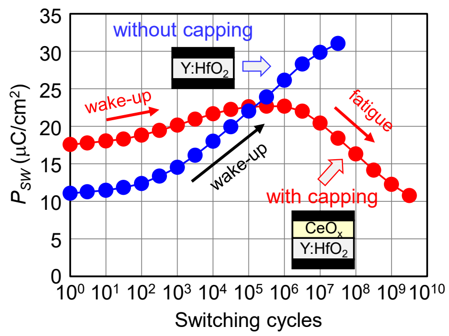

Fig. 3 Switching endurance under V_{PP}=2 V at 500 kHz.

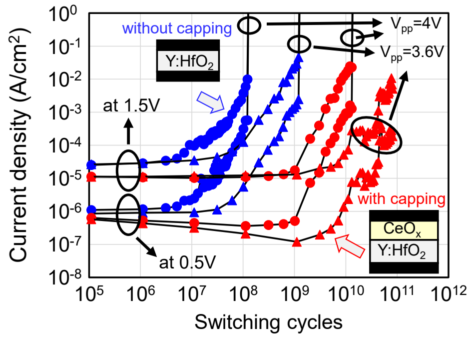

Fig. 4 Current (J) measured during switching cycles. Note that J at 0.5 V includes the switching current component and J at 1.5 V is the leakage current.

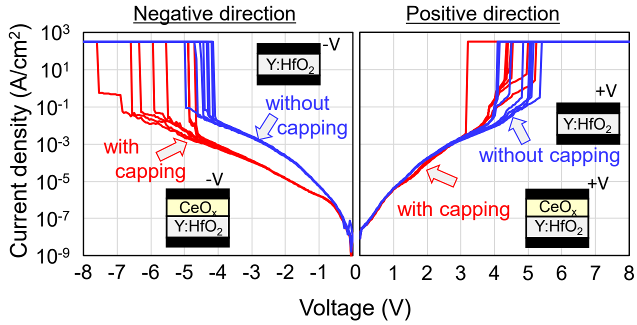

Fig. 5 Breakdown measurement of the capacitors for both negative and positive directions.

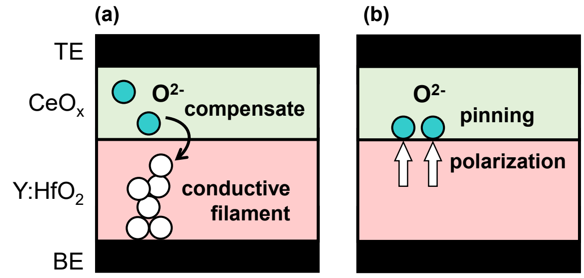

Fig. 6 (a) O^{2-} ions in the capping layer compensate the V_O in the HfO_2 layer to prevent from breakdown. (b) O^{2-} ions can pin the ferroelectric domain to decrease the ferroelectricity.

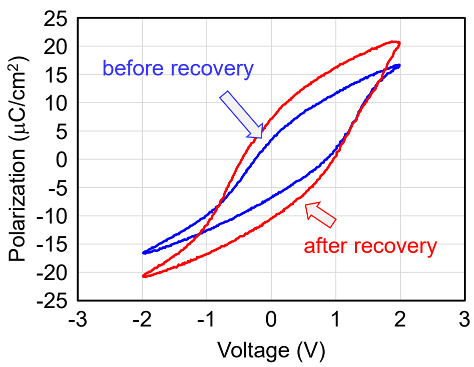

Fig. 7 Recovery of the ferroelectricity with positive V_{reset} application. (V_{reset}=2V for 1 s)

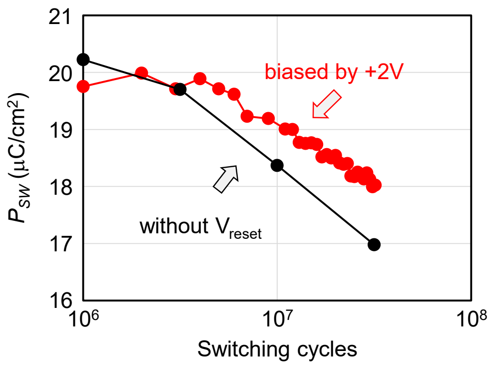

Fig. 8 Relaxed fatigue effect with positive V_{reset} for every 10^6 cycles.