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Electrical Characteristics and TDDB Reliability of $ZrO_2/Al_2O_3/ZrO_2$ Stack High-κ Gate Dielectric

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1. Introduction

As devices dimension continuing scaling, the gate oxide film is also shrunk below 1.6 nm, and it will increase the gate leakage current, and degrades in the device performance and power consumption issues. Thus, high κ dielectric materials such as HfO_2, Ta_2O_5 and ZrO_2 have been intensively investigated to replace the conventional silicon dioxide [1-5]. Among these high κ materials, the dielectric constant of ZrO_2 material can be controlled by different crystal phase [5,6]. The tetragonal phase of ZrO_2 film possesses higher dielectric constant (κ~47) than that of cubic phase ZrO_2 (κ~37) and monoclinic phases ZrO_2 (κ~29) [5]. To reduce the leakage current and to get the higher κ value, the amorphous Al_2O_3 thin film is inserted into the ZrO_2 film to achieve the superior dielectric. $ZrO_2/Al_2O_3/ZrO_2$ (ZAZ) structure has been used to improve the characteristics of MIM capacitance [6]. Little study investigates the characteristics of ZAZ gate stack dielectric and the reliability. In this work, we investigate the electrical characteristics and TDDB reliability of ZAZ gate dielectric. Additionally, the post deposition nitrogen annealing (PDA) and post metal deposition nitrogen annealing (PMA) are also investigated. The optimal annealing temperature is also investigated in this work.

2. Experimental

Metal-insulator-semiconductor (MIS) structure was used to evaluate the characteristics of ZAZ dielectric. The starting materials were p-type, (100)-oriented silicon wafers. After a standard RCA cleaning, tegragonal-ZrO_2 (4.5nm), amorphous-Al_2O_3 (0.6nm), tegragonal-ZrO_2 (4.5nm) layers were subsequently deposited by the atomic layer deposition (ALD). After that, samples were separated to two groups. One group samples were introduced to the PDA treatment (from 400 to 700°C). A 50nm-thick TaN film was deposited as the top metal gate electrode. The other groups were introduced to the PMA treatment (from 400 to 900°C). Finally, a 200 nm-thick Al was evaporated at the backside as another electrode, the schematic of MIS structure and process steps was shown in Fig. 1.

3. Results and Discussion

Fig. 2 and 3 show the gate leakage currents of TaN/ZAZ/p-sub samples of TaN/ZAZ films following PDA treatment at 400, 500, 600, and 700°C, and the ZAZ films following PDA treatment at 400, 700, and 900°C in accumulation mode. The leakage currents are obviously reduced at 400°C PMA and 700°C PDA treatments. This is attributed to the fact that thermal annealing reduced the number of defects/traps in the high-κ film. Presumably, the thermal annealing changed the microstructure of ZAZ film, leading to the large leakage current at higher PDA and PMA treatment. The cumulative distribution of voltage ramp dielectric breakdown (V_{RDB}) is shown in Fig. 4. For PMA treatment, the distribution of V_{RDB} at 600°C treatment is starting toward negative bias direction. In the other hand, the 900°C PDA treatment, the distribution reveals the smallest value of V_{RDB}. The cross-section TEM image of as-deposited TaN/ZAZ/p-sub sample is shown in the Fig. 5. Obvious crystalline phase of ZrO_2 and amorphous Al_2O_3 were observed. The interfacial layer is around 1.5 nm in the interface of ZrO_2/p-sub. From the XRD analysis as shown in Fig. 6, we presume the PMA treatment above 600°C, the top TaN metal is enhanced to form the crystalline phase of Ta_2N(101), and/or the TaN is intermixed with under ZrO_2 film, leading to the degradation the intensity of ZrO_2(111) phase. This also degrades the κ value (see Fig. 10). For PDA treatment, although the tetragonal-ZrO_2(111) phase is increased by the temperature of PDA treatment, another crystalline phases of ZrO_2(220) and ZrO_2(311) also appears in the film, the net contribution of tetragonal-ZrO_2(111) phase will degrade by others crystalline phases appearance. Fig. 7 and 8 show the reliability of time dependent dielectric breakdown (TDDB) of ZAZ structure with PMA and PDA treatment, respectively. The time to breakdown (T_{BD}) is increased with PMA treatment, except for the 700°C PMA treatment. Some progressive breakdowns are observed in the as-deposited and 400°C PMA treatments. At 700°C PMA treatment, more defects/traps in the ZAZ structure, resulted in the soft breakdown happen and inferior reliability [3]. For PDA treatment, more clearly hard breakdowns are observed at the 400°C and 700°C PDA treatments. But PDA treatment at 900°C, ZrO_2 film reveals more crystalline phases, leading to more defects/traps in the grain boundaries, and resulted in the inferior reliability. Fig. 9 shows the Weibull distribution of TDDB reliability, the PMA 500°C and PDA 700°C show the longest T_{BD}s. Fig. 10 shows the capacitance versus voltage (CV) curve of ZAZ dielectric with PMA and PDA treatments. The largest capacitance value is found at PMA 500°C treatment. Additionally, the PDA treatment will degrade the capacitance. Presumably, more non-tetragonal ZrO_2 crystalline phases are appeared and degraded the dielectric constant. The effective dielectric constant (κ_{eff}) is calculated by the capacitance at -4V and the thickness of ZAZ stack structure (including IL layer). Thus, the highest κ_{eff} is 38 for the ZAZ structure following 500°C PMA treatment.

4.Conclusion

This work investigates electrical characteristics and TDDB reliability of $ZrO_2/Al_2O_3/ZrO_2$ (ZAZ) stack high-κ gate dielectric. The PMA and PDA treatments are beneficial to improvement the TDDB reliability. In addition, the capacitance of ZAZ dielectric with PMA treatment shows the higher value of capacitance than that of PDA treatment. The PDA treatment will lead to more non-tetragonal crystalline phases in the ZrO_2 film, and degrade the value of capacitance (κ value). Thus, the PMA treatment is better than the PDA treatment. The optimal temperature of PMA treatment is at 500°C, and the effective dielectric constant is 38.

Acknowledgments

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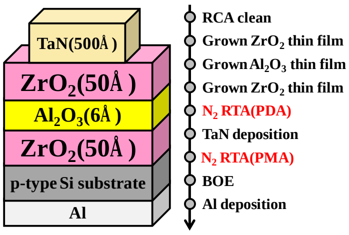


Fig. 1 The structure of metal insulator semiconductor (MIS) sample, and sample preparation process steps.

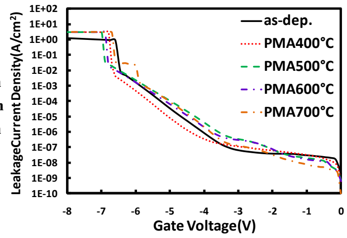


Fig. 2 Gate leakage current of ZAZ dielectric under accumulation gate voltage for various temperatures of N_2 PMA treatment.

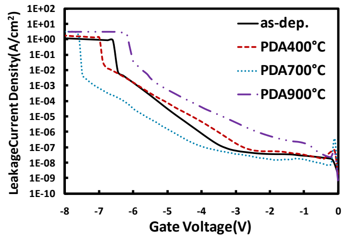


Fig. 3 Gate leakage current of ZAZ dielectric under accumulation gate voltage for various temperatures of N_2 PDA treatment.

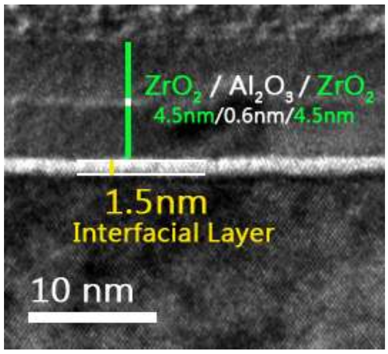


Fig. 5 TEM microscopy of as-deposited $ZrO_2/Al_2O_3/ZrO_2$/p-sub sample.

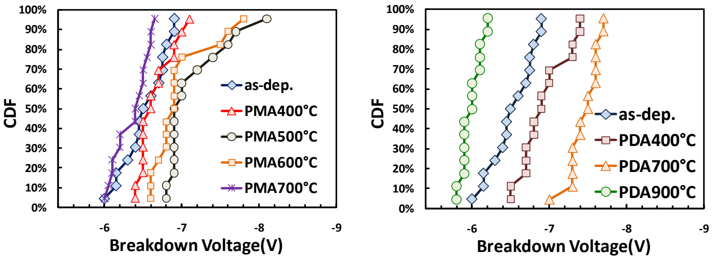
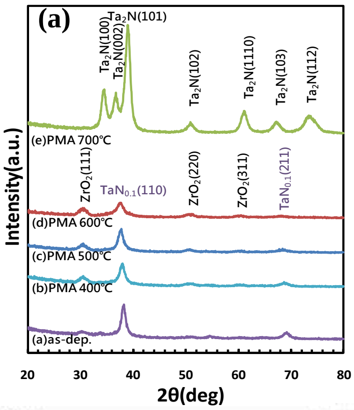


Fig. 4 CDF of breakdown voltage (V_{RDB}) of TaN/$ZrO_2/Al_2O_3/ZrO_2$/p-sub samples with various temperatures of PMA and PDA treatments.



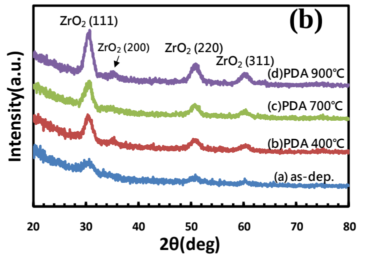
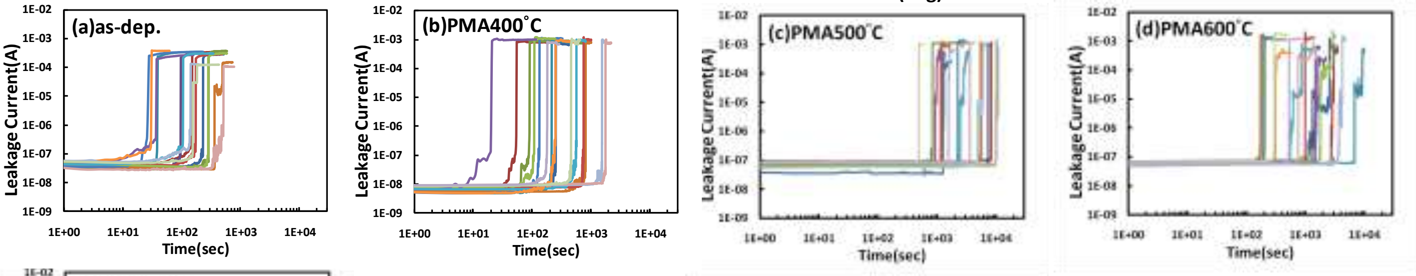


Fig. 6 X-ray diffraction patterns of ZAZ samples with (a) PMA and (b) PDA treatments at various temperatures.



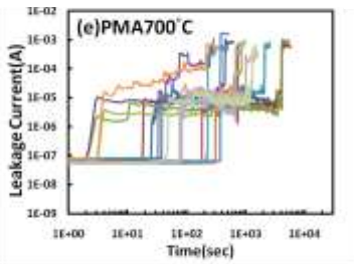


Fig. 7 Gate leakage currents versus time (I-t) plots of TaN/$ZrO_2/Al_2O_3/ZrO_2$/p-sub samples under constant voltage stress (CVS) in accumulation mode at Vg= -5.3V for (a) as-deposited (b) 400℃ (c) 500℃ (d) 600℃ (e) 700℃ PMA treatments.

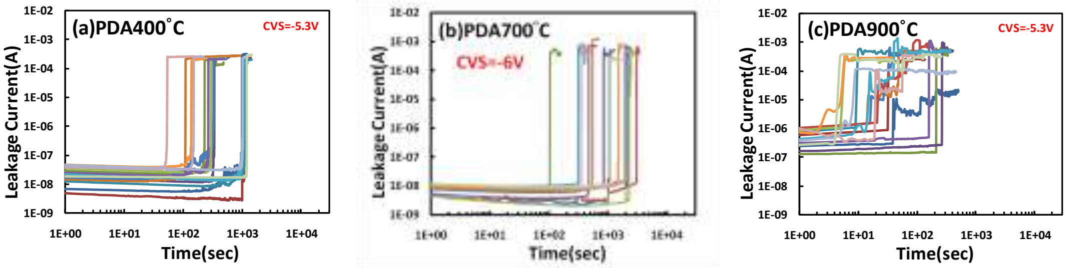


Fig. 8 Gate leakage currents versus time (I-t) plots of TaN/$ZrO_2/Al_2O_3/ZrO_2$/p-sub samples under constant voltage stress (CVS) in accumulation mode for (a) 400℃ (b) 700℃ (c) 900℃ PDA treatments.

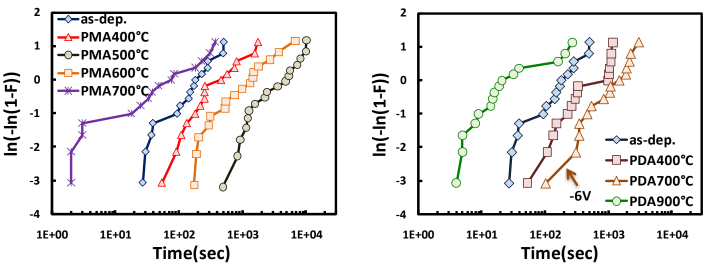


Fig. 9 Weibull distribution of time-to-breakdown (T_{BD}) for TaN/$ZrO_2/Al_2O_3/ZrO_2$/p-sub samples under constant voltage stress (CVS) in accumulation mode.

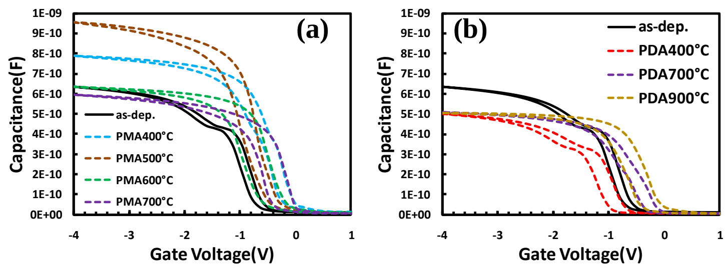


Fig. 10 Capacitance-voltage (CV) curves of TaN/$ZrO_2/Al_2O_3/ZrO_2$/p-sub samples with various temperatures of (a) PMA (b) PDA treatments.