Leakage Current Reduction in Chemical-Vapor-Deposited Ta_2O_5 Films by Rapid Thermal Annealing in N_2O

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Abstract— **This study aims to improve the electrical characteristics and reliability of low-pressure chemical vapor deposited (LPCVD) Ta_2O_5 films by developing a new post-deposition *single-step* annealing technique. Experimental results indicate that excited oxygen atoms generated by N_2O decomposition can effectively repair the oxygen vacancies in the as-deposited CVD Ta_2O_5 film, thereby resulting in a remarkable reduction of the film's leakage current. Two other post-deposition annealing conditions are compared: rapid thermal O_2 annealing and furnace dry-O_2 annealing. The comparison reveals that RTN$_2$O annealing has the lowest leakage current, superior thermal stability of electrical characteristics and the best time-dependent dielectric breakdown (TDDB) reliability.**

I. INTRODUCTION

HIGHLY integrated DRAM's require an extremely thin dielectric film for three-dimensional (3-D) stacked or trenched capacitors [1]–[2]. To satisfy 256 Mb or 1 Gb DRAM requirements, considerably higher capacitance values are necessary to keep the cells structures simple and manufacturable. For this purpose, CVD Ta_2O_5 has been demonstrated to be a highly promising storage dielectric material for high-density DRAM applications [3]–[10] owing to its high dielectric constant and excellent step coverage [9]–[10]. The as-deposited CVD Ta_2O_5 capacitors exhibited an extensive leakage current [3]–[10]. Moreover, various post-deposition annealing techniques, e.g., plasma O_2 [4], UV-O_3 [5]–[6], furnace dry-O_2 (FO) [7]–[9], UV-O_3 and dry O_2 [5], and rapid thermal O_2 annealing (RTO) [11]–[12], have been proposed to reduce the leakage current and improve the quality of Ta_2O_5. During the thermal treatment in the oxygen-containing ambient, oxygen diffuses into the Ta_2O_5 films, leading to repair of oxygen vacancies, elimination of organic inclusions, and reduction of weak spots in the tantalum oxide films [5].

Our recent work presented preliminary results using a new fabrication technique for leakage current reduction of CVD Ta_2O_5 films [13]. The process involves a relatively simple and effective *single-step* thermal treatment of the as-deposited Ta_2O_5 films using rapid thermal annealing in N_2O (RTN$_2$O). In extending our previous work, this paper attempts to more thoroughly understand the effects of post-deposition RTN$_2$O on the electrical properties and reliability of CVD Ta_2O_5 deposited on NH_3-nitrided poly-Si substrates.

II. EXPERIMENTAL

Planar capacitors with phosphorus-doped poly-Si bottom electrodes, 16-nm CVD Ta_2O_5 dielectric materials, and TiN top electrodes were fabricated on 100 mm n-type (100) silicon substrates. Prior to Ta_2O_5 deposition, the polysilicon surface was treated by rapid thermal nitridation (RTN) in NH_3 at 900°C for 60 s. The $Ta(OC_2H_5)_5$ source was vaporized at 110°C and then introduced into the reaction chamber by argon carrier gas at the same time in which oxygen gas was introduced. The deposition temperature was 450°C and the total gas pressure was maintained at 80 Pa. After deposition, each CVD Ta_2O_5 film was subjected to one of the following annealing processes: a) RTO at 800°C for 60 s; b) FO at 800°C for 30 min; and c) RTN$_2$O at 800°C for 60 s. Finally, TiN and aluminum top electrode was formed by reactive sputtering and then patterned to form the capacitor's top plate.

III. RESULTS AND DISCUSSION

Fig. 1(a) and (b) present the typical results of the current-voltage characteristics of Ta_2O_5 films before and after annealing treatments with the gate positively and negatively biased, respectively. The effective oxide electric field E_{eff} was calculated from C-V characteristics and defined by $CV_g/\varepsilon_0\varepsilon_s A$, where C is the capacitance measured at 100 kHz, V_g is the applied voltage, ε_0 is the permittivity in vacuum, ε_s is the dielectric constant of SiO_2 (3.82), and A is the area of the capacitors. The capacitors with the as-deposited films have a large leakage current, possibly due to the inferior film structure. Small difference between the leakage current of positive and negative polarities suggests that the conduction mechanism may be primarily due to the bulk-limited conduction. The leakage current was reduced by the RTO annealing. FO annealing was more effective in reducing the leakage current than RTO annealing. RTN$_2$O annealing shows the lowest leakage current at the same operating voltage. The leakage current was significantly reduced to 10^{-8} A/cm^2 at $E_{\text{eff}} = 3$ MV/cm for a positively biased, RTN$_2$O annealed Ta_2O_5 films. On the other hand, leakage currents are 7×10^{-8} and 5×10^{-7} A/cm^2 for FO and RTO annealed samples. All annealed films show a polarity asymmetry of leakage current characteristics. The leakage current for a negative bias is smaller than a positive bias, the former having a value of

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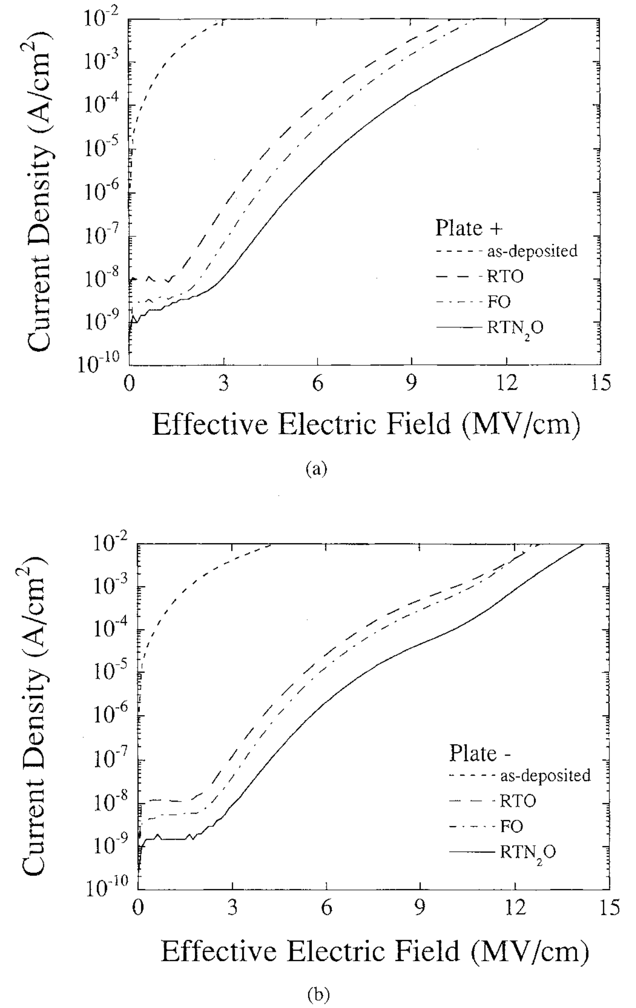

(a)

(b)

Fig. 1. Leakage current characteristics of 16-nm thick Ta_2O_5 capacitors before and after annealing processes at (a) positive and (b) negative gate bias.

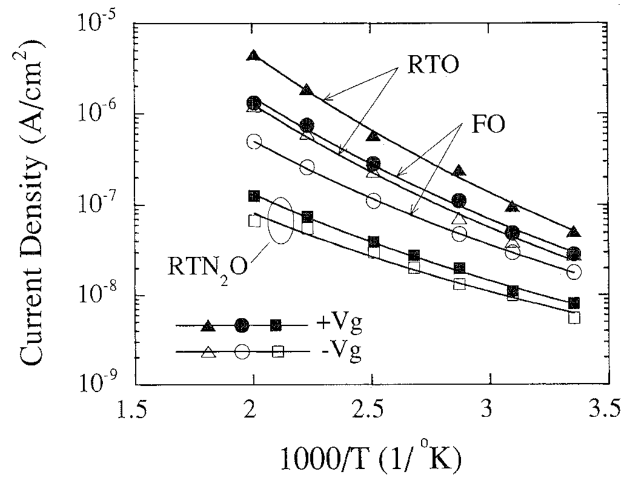

Fig. 2. Current density versus $1/T$ for capacitors with various annealing treatments.

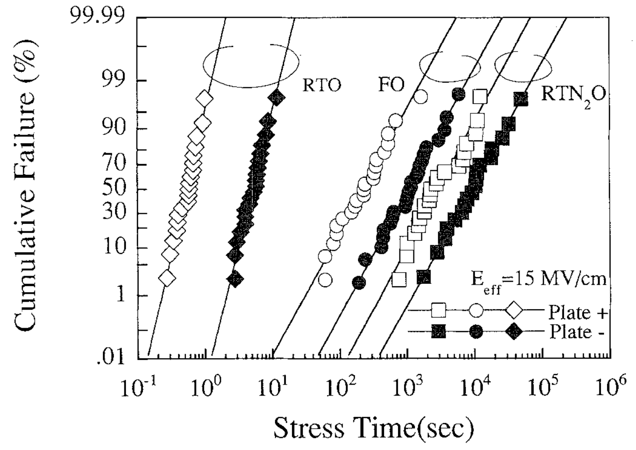

Fig. 3. TDDB stress time dependence of cumulative failure for Ta_2O_5 capacitors under both gate biasing polarities.

9×10^{-9}, 4×10^{-8}, and 10^{-7} A/cm^2 at 3 MV/cm for RTN$_2$O, FO, and RTO annealed samples, respectively. This can be explained by the difference in the work function of n^+ poly-Si and TiN electrodes and by the composite dielectric structure (e.g. Ta_2O_5 stacked with Si_3N_4 or SiO_2) [3], [8]. In comparing the leakage current, it must be noted that the effective oxide thickness for each capacitor before annealing is 3.4 nm. The effective oxide thicknesses are 3.7 nm, 3.8 nm, and 3.8 nm after RTO, FO, and RTN$_2$O annealing, respectively.

A plausible mechanism for leakage current reduction by RTN$_2$O annealing can be attributed to the reactive atomic oxygen species (O^+) generated by the dissociation of N_2O gas at elevated temperature ($N_2O \rightarrow N_2 + O^+$) during the rapid thermal process cycle [14]. These reactive oxygen species diffuse into Ta_2O_5 films and repair oxygen vacancies, thereby leading to a lower leakage current [5]. RTN$_2$O annealing is a *single-step* process capable of simultaneously providing the excited atomic oxygen species and high-temperature annealing. The excited oxygen atoms reduced the degree of imperfections caused by the deficiency of oxygen atoms adjacent to the tantalum atoms [15]. The remaining atomic oxygen recombines into molecular oxygen (O_2). High-temperature (800°C) O_2 annealing reduced the defect density due to weak spots and carbon contamination [5]. On the other hand, FO annealing and RTO annealing rely on the diffusion of molecular oxygen (which is less reactive than the atomic oxygen) in repairing the oxygen vacancies of Ta_2O_5 films. Notably, an FO annealing time of 30 min is not as effective as a 60 s of RTN$_2$O in reducing leakage current. Furthermore, RTO annealing is even less effective than FO annealing owing to the insufficient time to allow oxygen molecules to reduce defects.

A previous investigation indicated that NO-nitridation is a more efficient method for incorporating nitrogen in the Si/SiO_2 interface for gate dielectric formation than N_2O-nitridation [16]–[17]. In a separate work rapid thermal NO (RTNO) annealing was performed on as-deposited films [18]. Those results demonstrated that the RTNO annealing is less effective than RTN$_2$O annealing in reducing the leakage current. Therefore, incorporating nitrogen in the dielectric and piling up at the Ta_2O_5/poly-Si interface caused by the RTN$_2$O annealing apparently play only a minor role in leakage current reduction. The RTNO experiment also supports our earlier postulate that the atomic oxygen species generated by the N_2O dissociation is primarily responsible for the leakage current reduction.

Fig. 2 compares the temperature dependence of the leakage current characteristics for Ta_2O_5 capacitors under both gate biasing polarities at $|V_g| = 1$ V over the temperature range from 25°C to 225°C. The temperature stability of the low field leakage for RTN_2O annealed Ta_2O_5 film is superior to films annealed by either FO or RTO.

Fig. 3 shows the TDDB stress time dependence of cumulative failure for annealed Ta_2O_5 capacitors. The capacitor area is 1.44×10^{-4} cm^2. The stress conditions are positive or negative biases at a 15 MV/cm effective oxide field. The plotted points follow straight lines, and random failure modes are not observed, indicating that the CVD Ta_2O_5 capacitors are of high quality and good uniformity. The RTO sample always has the shortest breakdown time and the FO sample displays intermediate reliability characteristics. The TDDB stress time of 50% cumulative failure for RTN_2O capacitors is about 10, and 5000 times longer than that of FO and RTO capacitors. Also, TDDB under different electric fields was investigated. Capacitors with RTN_2O annealing show a longer lifetime than the others. The extrapolated long-term lifetime indicates that RTN_2O capacitors can survive 10 years at a stress field of 8 MV/cm. Therefore, we believe that capacitors with 800°C, 60 s RTN_2O have the best long-term reliability for actual DRAM applications.

IV. CONCLUSION

In conclusion, using RTN_2O post-deposition treatment of CVD Ta_2O_5 films results in capacitors with reduced leakage current, superior TDDB reliability, and excellent temperature stability of electrical characteristics as compared with rapid thermal O_2 annealing and furnace dry-O_2 annealing. This technique is a highly promising alternative for high-density DRAM technology.

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