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Novel Integration Scheme of Replacement Metal Gate Module using Pre-Metal Dielectrics with High Gap-Fill Capability and Chemical Reaction Based H_2O_2 Cure

T. Yamaguchi, M. Inoue, A. Yoshitomi, T. Hayashi, M. Kadoshima,
S. Kato, S. Muranaka, T. Maruyama, T. Yamashita, and M. Matsuura

Device Technology Div., Renesas Electronics Corp., 751 Horiguchi, Hitachinaka, Ibaraki 312-8504
Email: tadashi.yamaguchi.pz@renesas.com

Abstract

Novel integration scheme of replacement metal gate (RMG) module using pre-metal dielectrics (PMDs) with high gap-fill capability and low-temperature chemical reaction based H_2O_2 cure for highly reliable embedded memory is demonstrated. High wettability of precursors achieves void-free PMD gap-fill, and oxidation-reduction reaction of H_2O_2 enhances dehydration condensation reaction at low temperature in SiO_2 films as PMDs. As a result, PMD films can be effectively densified. This densification improves the endurance of PMD films to wet chemical etching and suppresses the PMD recess defect during RMG process. Furthermore, embedded metal-oxide nitride oxide silicon (MONOS) integrated with high-k/metal gate (HK/MG) CMOS using H_2O_2 cure technique results in no degradation of the MONOS reliability.

Introduction

Low power operation and high reliability of microcontroller units (MCUs) are continuously required in advanced automotive systems. According to these demands, scaling of MCUs has been aggressively promoted, and reliability and scalability of future MCUs has been demonstrated [1,2]. However, to completely satisfy further requirements for low power operation, embedded memory integration with high-k/metal gate (HK/MG) logic CMOS is needed. In the HK/MG integration, void-free pre-metal dielectric (PMD) gap-fill and the replacement metal gate (RMG) are critical processes since PMD voids cause contact piping defects and the PMD recess defect during RMG process leads to the device yield loss. To suppress the PMD voids and PMD recess defects, novel integration scheme of RMG module without the penalty of the device reliability is strongly required.

In this paper, we demonstrate that high gap-fill capability of PMDs and low temperature H_2O_2 cure ensure highly reliable MONOS Flash with HK/MG integration.

Experimental

Silicon dioxides (SiO_2) were formed using O_3-TEOS based SACVD systems as PMD films. TEOS, O_3 and other gases were varied to control the incubation time. The incubation time was calculated by the relationship between the film thickness and the deposition time.

Vaporized H_2O_2 was supplied to wafers in the quartz reactor after the deposition of the PMD film. The temperature was varied in the range from 150 to 400°C. Cured SiO_2 films were characterized by wet etching rate ratio (WERR), FTIR and C-V measurement using blanket wafers. Characteristics of split-gate (SG) MONOS with HK/MG integration using H_2O_2 cure were also evaluated.

Result and Discussion

The relationship between the incubation time and Si-O-H/Si-O-Si ratio measured by FTIR for each PMD film with various deposition parameters was summarized in Fig. 1. Si-O-H/Si-O-Si ratio increases with decreasing the incubation time. Fig. 2 shows contact piping defects in FinFET MONOS using PMD films with the long and short incubation time. The PMD film with the short incubation time drastically reduces contact piping defects. It is considered that precursors including much hydroxyl (O-H) and moisture are hydrophilic, and as a result, gap-fill capability can be improved. However, dielectric constant of PMD films increases with decreasing the incubation time, as shown in Fig. 3. In addition, poor WERR of the PMD film with high gap-fill capability causes PMD recess defect, as shown in Fig. 4.

To improve poor WERR, H_2O_2 cure was carried out. Fig. 5 shows WERR of SiO_2 films cured in H_2O_2 and O_2 ambience as a function of cure temperature. WERR decreases with increasing cure temperature, and the cure effect in H_2O_2 ambience is obviously larger than that in O_2 ambience. These results indicate that the H_2O_2 cure effect might be caused by not only thermal energy but also chemical reaction. To understand the cure mechanism, Fig. 6 shows FTIR spectra of SiO_2 films. The Si-O-H stretching peak decreases, and the Si-O-Si stretching peak increases after H_2O_2 cure at 400°C. These results indicate that H_2O_2 cure causes dehydration condensation reaction in SiO_2 films, as expressed by $2Si\text{-}O\text{-}H \rightarrow Si\text{-}O\text{-}Si + H_2O \uparrow$ [3]. The increase of Si-O-Si networks causes the film shrink with tensile stress, as shown in Fig. 7. Moreover, the decrease of dielectric constant due to dehydration in the SiO_2 film by H_2O_2 cure has an advantage in the parasitic capacitance between gate and contact, as shown in Fig. 8.

Fig. 9 shows RMG process flow in which H_2O_2 cure is implemented to suppress PMD recess defects caused by CMP and dummy-gate removal. Fig. 10 shows the decrease of the CMP rate in PMD films with H_2O_2 cure. Fig. 11 shows cross-sectional TEM images after the removal of dummy-gates. Despite excessive wet chemical etching in this evaluation, the increase of endurance to wet chemical etching by H_2O_2 cure suppresses the amount of PMD recess. Figs. 12 and 13 show program and erase (P/E) and retention characteristics of SG-MONOS Flash integrated by HK/MG flow with H_2O_2 cure, respectively. It has been reported that hydrogen atom penetration into the bottom oxide of ONO stacks degrades the reliability of MONOS memory [4]. However, H_2O_2 cure causes no degradation of P/E and retention characteristics after 250K cycles. There is no side effect for the MONOS reliability by H_2O_2 cure. It is concluded that chemical reaction based H_2O_2 cure ensures high reliability of MONOS Flash with HK/MG integration.

Conclusion

Novel integration scheme of RMG module using PMD with high gap-fill capability and H_2O_2 cure was demonstrated for the first time. The RMG module using PMD films cured by H_2O_2 ensured high reliability of MONOS Flash with the HK/MG integration due to the improvement of PMD film qualities. This technology is a promising candidate for highly reliable embedded memory.

References

[1] S. Tsuda et al., IEDM, 280, (2016). [2] S. Tsuda et al., IEDM, 469, (2017). [3] N. Hirashita et al., Jpn. J. Appl. Phys. **32**, 1787, (1993). [4] Z. Liu et al., IRPS, 705, (2008).

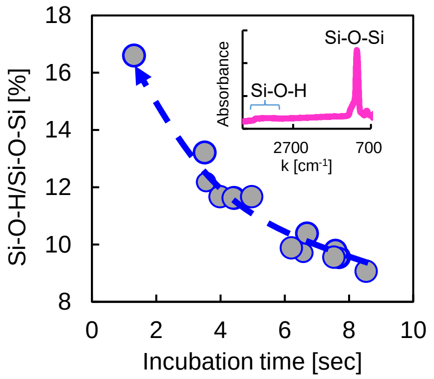

Fig. 1. Si-O-H/Si-O-Si ratio calculated from FTIR spectra as a function of incubation time of PMD films.

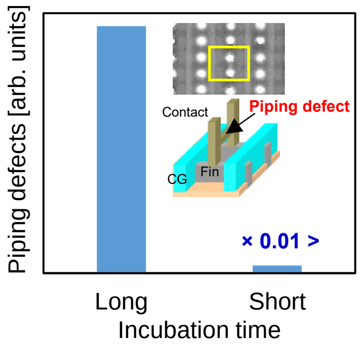

Fig. 2. Contact piping defects in FinFET SG-MONOS array using PMD film with long and short incubation time.

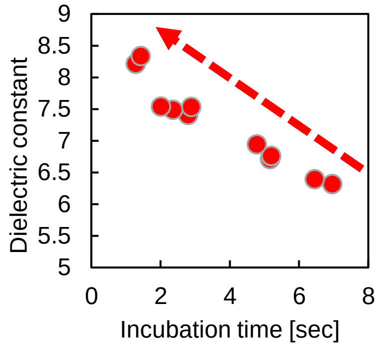

Fig. 3. Dielectric constant of PMD films

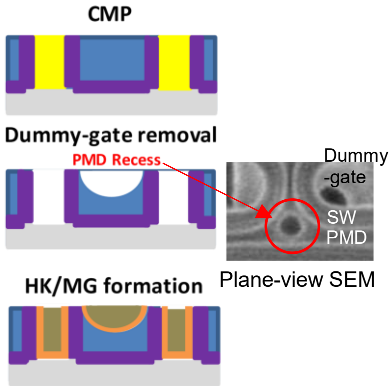

Fig. 4. Schematic illustrations of PMD recess defects caused by RMG process.

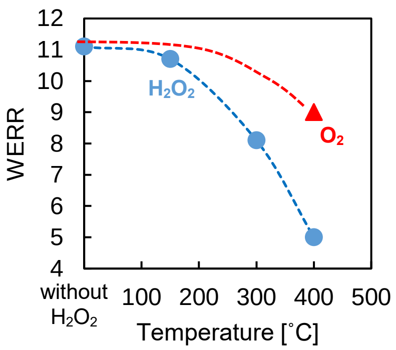

Fig. 5. Wet etching rate ratio of PMD films cured in H_2O_2 and O_2 ambience as a function of cure temperature.

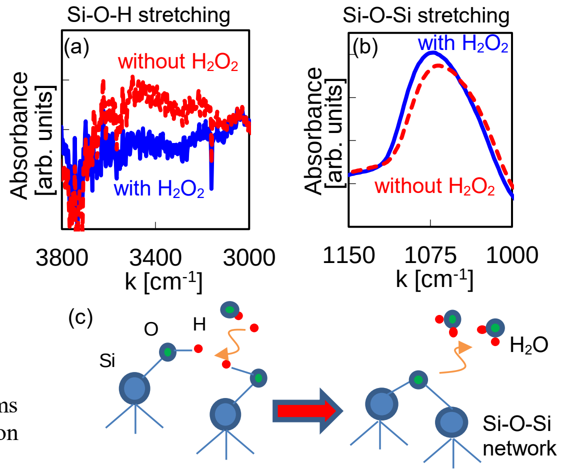

Fig. 6. FTIR spectra of PMD films with and without H_2O_2 cure at (a) Si-O-H, (b) Si-O-Si stretching and (c) schematics of dehydration condensation reaction in SiO_2 films by H_2O_2 cure.

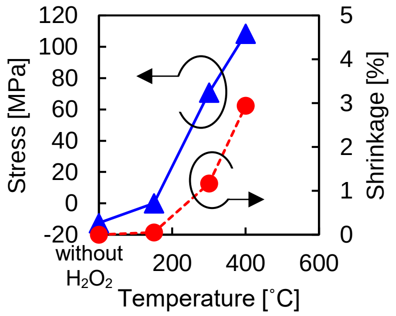

Fig. 7. Stress and shrinkage of PMD films cured in H_2O_2 ambience as a function of cure temperature.

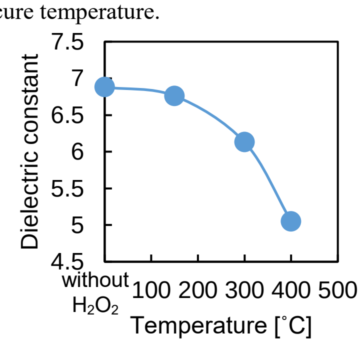

Fig. 8. Dielectric constant of PMD cured by H_2O_2 as a function of cure temperature.

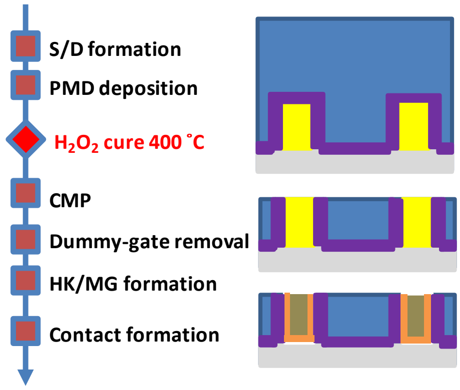

Fig. 9. Process flow of RMG module with H_2O_2 cure.

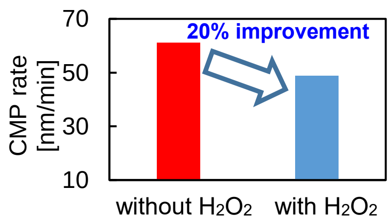

Fig. 10. CMP rate with and without H_2O_2 cure.

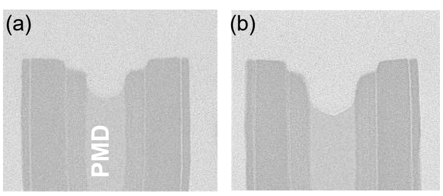

Fig. 11. Cross-sectional TEM images of PMD recess after dummy-gate removal (a) with and (b) without H_2O_2 cure at 400°C.

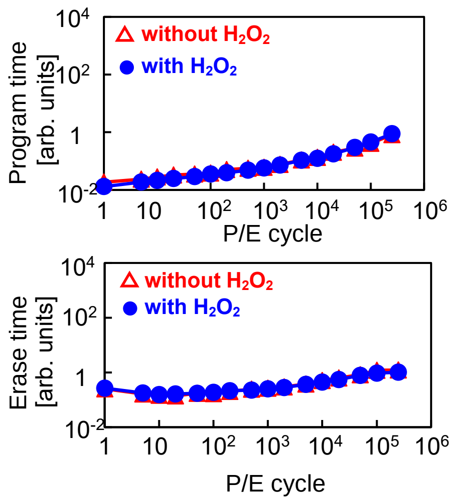

Fig. 12. P/E endurance of SG-MONOS Flash integrated by HK/MG flow with and without H_2O_2 cure.

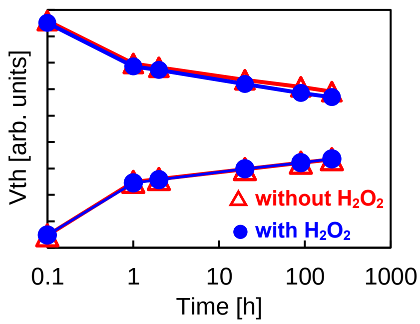

Fig. 13. Retention characteristics of SG-MONOS after 250K cycles at 150°C.