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Si-Capped Annealing of HfO_2-based Dielectrics for Suppressing Interface Layer Growth and Oxygen Out-Diffusion

Masashi Takahashi[1], Hideki Satake[1,*], Masaru Kadoshima[1,**], Arito Ogawa[1], Kunihiko Iwamoto[1], Hiroyuki Ota[2], Toshihide Nabatame[1] and Akira Toriumi[2, 3]

[1]MIRAI-ASET, AIST Tsukuba West 7, 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan
Phone: +81-29-849-1553 Fax: +81-29-849-1529 E-mail: takahashi.masashi@mirai.aist.go.jp
[2]MIRAI-ASRC, AIST Tsukuba West 7, 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan
[3]Department of Materials Engineering, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-8656, Japan

1. Introduction

High-k gate stacks with sub-nm EOT are required for further scaling of CMOS devices. The interface layer (IL) control is a key step for achieving a high mobility and a low gate leakage current as well as a thin EOT. In fact, it is well known that the carrier mobility is very sensitive to the IL thickness and quality [1-3]. Conventionally, post deposition annealing (PDA) is employed just after high-k dielectric deposition for curing both dielectric films and the interface. But there is challenge of the EOT increase due to the IL growth caused by the residual oxygen in an annealing ambient (Fig. 1(a)), while there is challenge of the dielectric film degradation due to the out-diffusion of oxygen from high-k films and/or IL in case of a minimized oxygen concentration in the annealing ambient [3].

In this paper, we propose a post Si-deposition annealing (PSA) at high temperatures with a Si capping layer on the high-k film (Fig. 1(b)) to block both in- and out-diffusion of oxygen. The point of making this process successful is to grow high-k films with a small amount of impurity such as carbon and sufficient oxygen bonds in the matrix before the PSA.

2. Device Fabrication

Figure 2 shows the process flow used in this work. HfAlON ([Al]=7-19 at. %) films formation involves the LL-D&A process [4] on HF-last Si surfaces and the following oxygen annealing process at 850 °C [5], to ensure a negligible amount of impurity and sufficient oxygen bonds. An additional annealing after the HfAlON formation and after the Si deposition were performed in the PDA Process (Fig. 2(a)) and PSA process (Fig. 2(b)), respectively. After these processes, FUSI NiSi gate electrodes were formed at 400 °C [6]. We also fabricated a control sample without PDA or PSA for comparison.

3. Results and Discussion

(A) HfAlON Film Properties

The cross-sectional TEM images of both control sample and 1050 °C PSA sample are compared in Fig. 3. Note that the IL thickness does not increase after the PSA. Figure 4 shows film densities dependences on the PSA temperature. Film densities of both high-k and IL were determined by X-ray reflectivity (XRR). It is clearly seen that the HfAlON film and IL are densified with the increase of PSA temperature. The in-depth profiles of O, N, Al, Hf and C atoms for control and 1050 °C PSA samples were measured by SIMS (Fig. 5). It is seen that O atoms diffuse to the IL/Si interface, while N atoms diffuse to the surface after the PSA process (Fig. 5(a)). This implies that a part of N atoms in the IL region were replaced by O atoms. Al atoms also diffuse to the interface, while no change of Hf and C atoms are observed (Figs. 5(b), (c)). Furthermore, it is noted that the total amount of each element is kept unchanged after the PSA. These structural properties changes affect the electrical characteristics of MISFETs as discussed below.

(B) Electrical Characteristics of MISFETs

We calculated EOT from Cg-Vg characteristics as a function of annealing temperature (Fig. 6). A significant increase of EOT in the case of PDA is observed, while in the case of PSA, EOT slightly changes with PSA temperature. Figure 7 shows the gate leakage current (Jg) dependence on EOT with a parameter of PSA temperature. As PSA temperature increases, the Jg decreases due both to a slight increase of EOT and/or to high-k film density improvement. Figure 8 shows the dependence of effective electron mobility at 0.8MV/cm on EOT measured at different PSA temperatures. We found the PSA temperature significantly affects the electron mobility in spite of a very slight change of EOT. This fact suggests that a significant improvement of the interface quality accompanies with the structural and compositional changes in the high-k/IL region. In fact, we confirmed that D_{it} decreases after PSA by the charge-pumping measurement. These improvements mainly come from the densification of HfAlON and IL, and oxygen replacement of nitrogen at the interface after PSA, while Al diffusion to the IL does not affect the interface properties very much. As a result, we achieved Jg of 8×10^{-2} A/cm^2 and the mobility of 200 cm^2/Vs with 1.0 nm EOT HfAlON MISFETs with 1050 °C PSA. On the other hand, both Jg distribution (Fig. 9) and mobility (14 % reduction compared with 1050 °C) were degraded by the higher PSA temperature above 1100 °C.

4. Conclusions

We have demonstrated the 1nm-EOT HfAlON gate stack with FUSI NiSi electrode. The high temperature annealing of high-k films with the Si capping layer is very effective for achieving the low gate leakage current as well as the high mobility at no expense of additional IL growth. This method provides a way of enabling the high performance HfO_2-based gate stack with sub-nm EOT.

Acknowledgement

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Present affiliation : * Toshiba, ** Selete

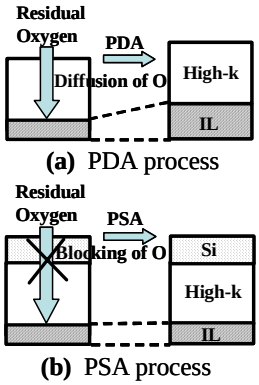

Fig.1 Concept of PSA process. During PDA, residual oxygen diffuses to cause IL growth (a), while during PSA, oxygen is blocked by Si capping layer, resulting in no IL growth (b).

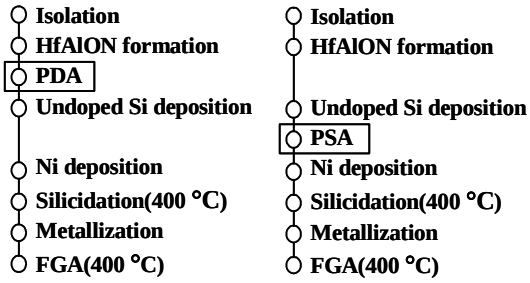

Fig.2 Fabrication process of HfAlON MISCAP with fully silicided NiSi gate. PDA is annealing just after HfAlON formation (a) and PSA is annealing just after undoped Si deposition for FUSI (b).

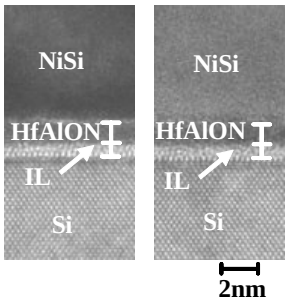

Fig.3 Cross-sectional TEM images of (a) control and (b) 1050 °C PSA samples. IL thickness does not increase after the PSA process.

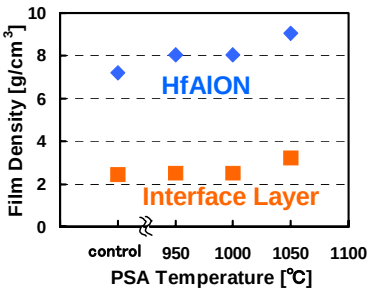

Fig.4 Film density vs. PSA temperature by XRR analysis. The density of both layers increases with increasing PSA temperature.

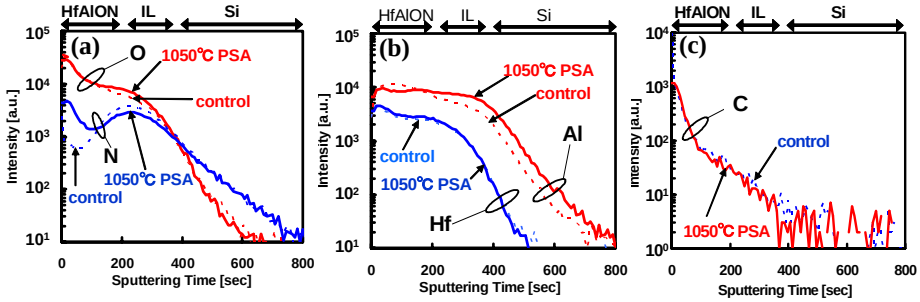

Fig.5 SIMS depth profiles of (a) O, N, (b) Al, Hf and (c) C for control sample and 1050 °C PSA sample. N atoms diffuse to the surface, while O and Al atoms diffuse to Si interface by PSA treatment. Hf and C atoms remain unchanged.

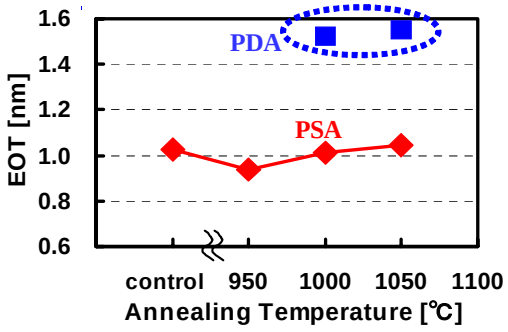

Fig.6 EOT vs. annealing temperature. EOT of PDA samples is about 0.5 nm thicker than PSA samples, while EOT of PSA slightly changes.

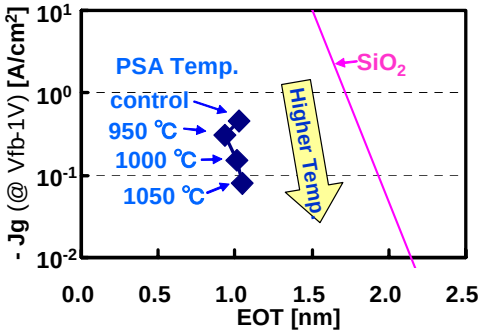

Fig.7 Jg vs. EOT. Jg reduction is observed with suppressing EOT increment, as PSA temperature increases.

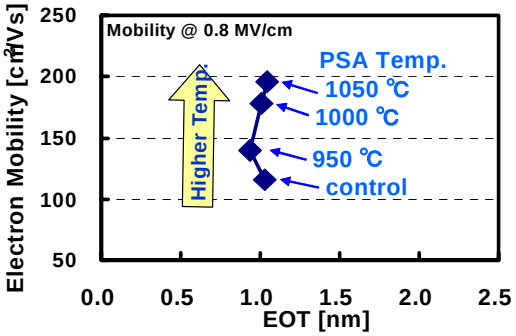

Fig.8 Mobility vs. EOT. Mobility enhancement is realized with suppressing EOT increase, as PSA temperature increases.

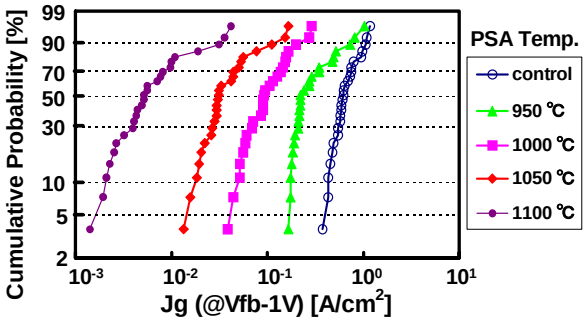

Fig.9 Distribution of Jg. Distribution after 1100 °C PSA is degraded compared with PSA below 1100 °C.