Integration Issues of HfO$_2$-Al$_2$O$_3$ Laminate for Gate and Capacitor Dielectric

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1. Introduction

The aggressive scaling of CMOS and memory devices is quickly driving the need for high-κ dielectric and the intensive studies on high-κ narrow down to HfO$_2$ based materials among the many candidates [1]. Although the industry has seen the promising results from HfO$_2$ based high-κ such as HfAlO(N) and HfSiO(N) for gate dielectric and HfAlO for capacitor dielectric, high-κ gate dielectric introduction is thought to be premature for CMOS devices up to now and application of high-κ capacitor dielectric for memory devices is also faced with urgent problems to full in the year of mass-production. In this paper, some key issues of high-κ gate and capacitor dielectric in terms of device integration will be described.

2. Integration Issues of High-κ Gate Dielectrics

Experimental

Al$_2$O$_3$ or HfAlO(HfO$_2$-Al$_2$O$_3$ laminate) film was deposited by ALD(Atomic Layer Deposition) on Si substrate. HfAlON denotes nitrogen incorporated HfAlO by in-situ 3-step post-deposition annealing including thermal nitridation [2]. HfCl$_4$, TMA[Al(CH$_3$)$_3$], and H$_2$O were used as ALD reactants. After poly-Si gate deposition, standard CMOS integration process was applied.

Process Induced Flatband Voltage Shift

HfAlO combines the characteristic features of both constituents, i.e., positive fixed charges of HfO$_2$ and negative fixed charges of Al$_2$O$_3$ [3,4]. Consequently, there is little difference in Vth (flatband voltage) of HfAlON compared to SiO$_2$ as shown in Fig.1(a). However, the Vth increased by 200~250mV after full logic process (Fig.1(b)). The cause of this Vth shift after device integration is not clear up to now.

Gate Depletion

The possibility of phosphorus diffusion from poly-Si gate into the Al$_2$O$_3$ was already reported [3]. The phosphorous diffusion could be dubbed a sort of sucking. In case of HfO$_2$, the phosphorous sucking is thought to be more severe than Al$_2$O$_3$. As a result, the gate depletion of MOS capacitor with HfAlON is larger than with SiO$_2$ (Fig.1(b)). The degree of phosphorous sucking depends on combinations of high-κ materials and may generate the reliability problem, especially for nMOSFET.

Undercut formation during wet cleaning

Fig.2 shows TEM view of gate edge with Al$_2$O$_3$ after wet cleaning in CMOS integration. The careful selection of wet chemicals is required to minimize the undercut formation which brings about the abnormal Vth increase at short channel MOSFET (Fig.3).

Threshold Voltage Shift from Poly-Si Reoxidation

Fig. 4 shows Vth roll-off characteristics with various poly-Si reoxidation process conditions. As reported [5], excess oxygen severely reduces the capacitance in the high-κ (HfAlO). Currently, we can simply prevent this high Vth problem by skipping poly-Si reoxidation. However, from the poly-Si reoxidation results, the special regard should be paid to the fact that the oxidant during the following integration process after gate patterning plays an important role for transistor performance.

Boron Penetration

Fig.5 shows the drop of channel breakdown voltage of pMOSFET due to the boron penetration under a certain physical thickness of HfAlO. The boron penetration was suppressed through the thermal nitridation and relatively good current performance with low leakage currents was obtained (Fig.6).

3 Integration Issues of High-κ Capacitor Dielectrics

Poor Step Coverage and Low Throughput of ALD HfO$_2$

As HfO$_2$-Al$_2$O$_3$ laminate film is applied to capacitor application, there are two major drawbacks using solid source (HfCl$_4$) which is being generally used for gate dielectric application. First, HfO$_2$ using HfCl$_4$ shows poor step coverage (~42%) on high aspect ratio (40:1) as shown in Fig.7. Secondly, the saturation time (1.6sec) of the self-limiting reaction for HfCl$_4$ is longer than that of liquid precursor(0.8sec), TEMAH(Tetrakis-Ethyl-Methyl-Amido-Hafnium) as shown in Fig.8.

Insufficient Evaluation for Liquid Precursors

Fig.9 shows that the leakage current of MIS capacitor using TEMAH is comparable to that of HfCl$_4$. Even if TEMAH is expected to be a promising candidate for HfO$_2$ deposition by ALD, quite a few items to be checked still remain in terms of the precursor-decomposition behavior. In addition, other hafnium liquid precursors should be evaluated using the various oxidizing reactants such as H$_2$O, ozone, and radical oxygen.

3. Conclusions

Several integration issues of high-κ dielectric (HfO$_2$-Al$_2$O$_3$) were reviewed. The process technologies for high-κ gate and capacitor dielectric can help mutually for the development of reliable precursors and mass-productive equipment.
References

Fig. 1. C-V curves of nMOSCAP (a) before and (b) after full logic process

Fig. 2. Cross-sectional TEM view of gate edge with Al₂O₃

Fig. 3. Vth roll-off characteristics of Al₂O₃ compared to that of SiO₂

Fig. 4. Vth roll-off characteristics of HfAlON with various poly-Si reoxidation conditions such as (a) skip, (b) N₂O, (c) low partial pressure O₂, and (d) high partial pressure O₂ ambient

Fig. 5. Channel BV at 10nA with various HfAlON thickness

Fig. 6. Ion - Ioff characteristics of (a) nFET and (b) pFET with HfAlON

Fig. 7. TEM views of HfO₂-Al₂O₃ laminate using solid source (HfCl₄) on (a) top and (b) bottom of cylinder-type MIS capacitor

Fig. 8. Deposition rate of HfO₂ as a function of Hf source dose

Fig. 9. Comparison of leakage current of MIS capacitor with HfO₂-Al₂O₃ laminate using solid Hf source and liquid precursor at the same EOT(22Å)