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Effects of Aluminum and Nitrogen Profile Control on Electrical Properties of HfAlON Gate Dielectric MOSFETs

Hiroyuki Ota[1], Arito Ogawa[2], Masaru Kadoshima[2], Kunihiko Iwamoto[2], Wataru Mizubayashi[1]
Kenji Okada[2], Toshihide Nabatame[2], Hideki Satake[2] and Akira Toriumi[1,3]
[1]MIRAI-ASRC, AIST Tsukuba, West-7, 16-1, Tsukuba, Ibaraki 305-8569, Japan
Phone/Fax: +81-298-61-3416 / +81-298-49-1529, Email: hi-ota@aist.go.jp
[2]MIRAI-ASET, AIST Tsukuba, Japan, [3]The University of Tokyo, Japan

1. Introduction

HfAlON has been expected as a candidate of the gate insulators for low power and low stand-by power CMOS. An incorporation of an Al_2O_3 layer into HfO_2 offers advantages of increasing the band-offset [1] and the higher crystallization temperature, while it gives rise to V_{TH} (V_{FB}) shift [2] and deteriorates the mobility [3]. In addition, an excess amount of nitrogen incorporation in order to further increase the crystallization temperature of HfAlON degrades the gate leakage current J_g[4]. This paper reports a significance of controlling aluminum and nitrogen profiles in HfAlON dielectric layers, based on the fact that appropriate aluminum and nitrogen profiles enable to achieve higher mobility and lower J_g with keeping EOT unchanged.

2. Experimental

Aluminum profiles in the HfAlON were changed by controlling the location of an ultrathin Al_2O_3 layer (0.5 nm) inserted in HfON as shown in **Fig. 1**, where [L], [M] and [U] stand for the Al_2O_3 insertion position. The HfON and ultrathin Al_2O_3 films were prepared by the LL-D&A process [5] and by a conventional atomic layer deposition, respectively. Hereafter, we denote HfAlON with a controlled aluminum profile as Al-profiled HfAlON. After stacking the tri-layers, high temperature oxygen annealing (HiTOA) [6] at 850°C was performed to remove excess nitrogen atoms and improve quality of high-k layers. MOSFETs with Al-profiled HfAlON were fabricated using conventional self-aligned source/drain formation processes.

3. Results and Discussion

Fig. 2(a) shows depth profiles of Al, N and Hf concentrations for the Al-profiled HfAlON, determined by high-resolution Rutherford backscattering spectrometry (HR-RBS). The profiles were measured after the HiTOA process. A clear dependence of aluminum profile on the Al_2O_3 insertion position can be observed. Moreover, we note that the nitrogen distributions are strongly affected by the aluminum distribution, especially, in the upper region of the Al-profiled HfAlON. The nitrogen distributions shown in **Fig. 2(a)** can be explained by assuming that the inserted Al_2O_3 layer blocks the out-diffusion of nitrogen during the HiTOA process as schematically shown in **Fig. 2(b)**, where the nitrogen out-diffusion occurs only in the region above Al-rich layer. We also found that the areal density of the nitrogen becomes smaller in order of sample [L], [M], and [U] (see **Table I**), as expected in **Fig. 2(b)**.

Figure 3 shows high-frequency capacitance-voltage (C-V) characteristics for MOS capacitors with the Al-profiled HfAlON together with a reference HfON dielectrics. We found that the equivalent oxide thickness (EOT) is about 2.1 nm, irrespective of the insertion position of the ultrathin Al_2O_3 layer, and that the influence of the Al_2O_3 insertion on EOT is negligibly small. However, the flat-band voltage V_{FB} for these gate dielectrics shifted systematically with the insertion position of Al_2O_3 from [U] to [L] toward positive direction because of the negatively trapped charge.

The effects of the aluminum and nitrogen profiles on the gate leakage current are shown in **Fig. 4**. Weibull plots of the gate leakage current J_g at V_{FB} - 1 V for Al-profiled HfAlON dielectrics are also shown in the inset. These clearly indicate that as the location of the Al_2O_3 layer gets closer to the interfacial SiO_2 layer, the gate leakage current is significantly reduced for the same EOT. In the previous study [7], we reported that excess nitrogen causes the increase of the gate leakage current. Thus, the difference of the gate leakage in **Fig. 4** is attributable to the difference of the nitrogen concentration and its volume in the Al-profiled HfAlON.

Figure 5 shows the effects of the aluminum and nitrogen profiles on the inversion layer mobility, which is significantly affected by the insertion position of the ultrathin Al_2O_3 layer. Namely, the electron mobility becomes larger as the insertion position of the Al_2O_3 layers gets closer to the interfacial SiO_2 layer. This fact suggests that the influence of the aluminum profiles in HfAlON layers on the mobility degradation is minor, because if the aluminum profile dominates the mobility, the best one should be achieved in sample [U]. But this is not the case. Moreover, there is no clear correlation between the interface trap density (**Fig. 6**) and the electron mobilities for the Al-profiled HfAlON MOSFETs (**Fig. 5**). Thus, we may conclude that the nitrogen density primarily affects the mobility degradation. A possible model for explaining the mobility change due to the Al_2O_3 insertion position is schematically illustrated in **Fig. 7**. In the case of the [U]-profile, a significant amount of N remains in HfAlON underneath the Al_2O_3 layer after HiTOA process, while in the case of the [L]-profile, the nitrogen-rich region spatially limited. Thus, it is inferred that the excess nitrogen acts as the scattering source such as the fixed charge or the enhancement of interface roughness and degrades the mobility.

4. Conclusion

We have demonstrated that the nitrogen profile in HfAlON can be controlled by the location of Al_2O_3 layer inserted in HfON. It was also shown that the gate leakage current and electron mobility were significantly affected by the nitrogen profile. These results indicate that the compositional profile engineering in HfAlON can lead to the optimum design of high-k dielectrics without deteriorating the electrical properties.

Acknowledgements

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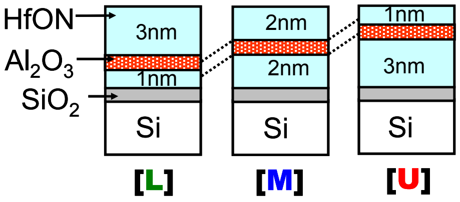
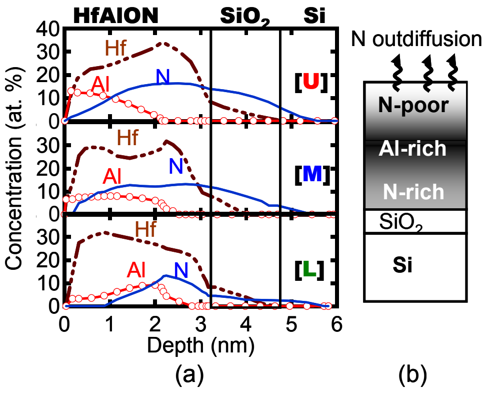


Fig. 1 Aluminum profile control by inserting an ultrathin Al_2O_3 layer (0.5nm). [L], [M], and [U] denote the Al_2O_3 insertion positions in HfON films. The thickness of the SiO_2 layers is 1.5 nm.



(a) (b)

Fig. 2 (a) The depth profiles of Hf, N and Al in the various Al-profiled HfAlON gate dielectrics determined by HR-RBS. The profiles were measured after the HiTOA process. A nitrogen rich region is located underneath the Al_2O_3 region. (b) A schematic illustration of Al-profiled HfAlON after HiTOA process. The black and gray regions in this figure indicate the Al-rich and the nitrogen-rich region, respectively. The white region in the upper side of this illustration depicts nitrogen-poor region due to

Table I The nitrogen density in the HfON and the Al-profiled HfAlON samples determined by HR-RBS.

Sample	Nitrogen density ($\times10^{15}$ cm^{-2})
[U]	4.9
[M]	4.1
[L]	3.1
HfON	2.3

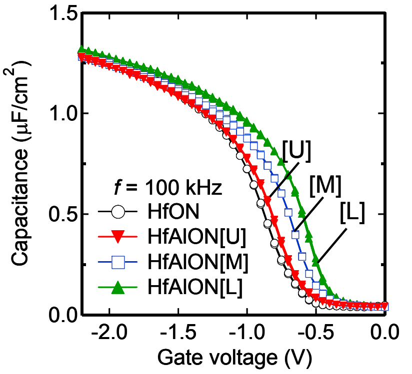


Fig. 3 High frequency *C-V* characteristics for the Al-profiled HfAlON and HfON dielectric *n*-MOS capacitors. EOTs extracted from the accumulated capacitances are 2.1nm, regardless of aluminum profiles.

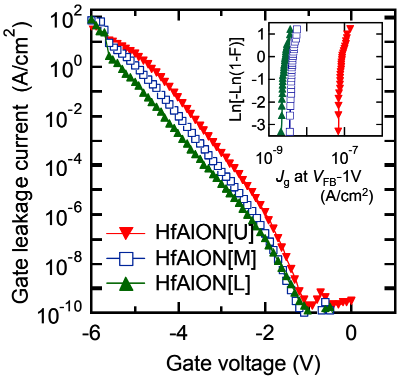


Fig. 4 Gate leakage currents as a function of the gate voltage for the Al-profiled HfAlON gate dielectrics. Inset shows Weibull plots of the gate leakage current J_g at V_{FB} -1V. The drastic Jg reduction by about 1.5 orders of magnitude was attained for the case [L].

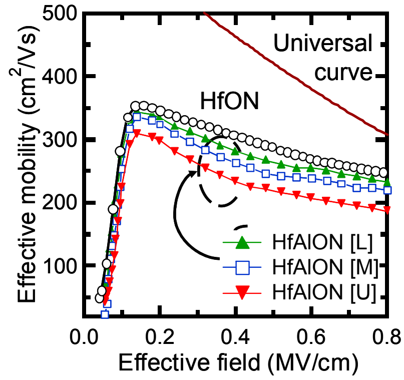


Fig. 5 The inversion mobilities of electron for HfON, Al-profiled HfAlON gate dielectrics MOSFETs as a function of the effective field.

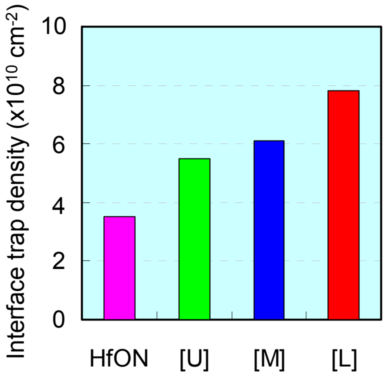


Fig. 6 The interface trap densities for the HfON and Al-profiled HfAlON gate dielectrics MOSFETs measured by the charge pumping method.

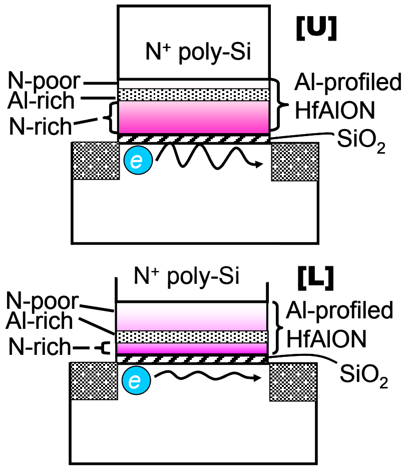


Fig. 7 A schematic illustration for the mobility difference due to the insertion position of Al_2O_3 ultrathin layer. The electron mobility seems to be affected by the nitrogen profile rather than Al-profiles. As the insertion position of Al_2O_3 get closer to the interfacial SiO_2 layer, nitrogen-rich region becomes spatially limited. Thus, the mobility in [L] case is improved since the scattering source such as the fixed charge and surface roughness due to nitrogen incorporation expected to become small.