1.2 nm-EOT Al₂O₃/Ge Gate Stack with GeOₓ-free Interface


¹ Department of Materials Engineering, The University of Tokyo, ² JST-CREST
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
Phone and Fax: +81-3-5841-7161, E-mail: tabata@adam.t.u-tokyo.ac.jp

1. Introduction

Ge is one of the promising semiconductor materials for the post Si-CMOS. In fact, very high electron mobility (peak μₓₓ=1.920 cm²/Vs) was accomplished in n-MOSFET with Y₂O₃ gate stack [1]. It is almost 2.5x larger than the Si-universal mobility. The EOT scaling is, however, still challenging, because the above MOSFET actually has a relatively thick GeO₂ interface layer (IL) due to employing high pressure oxygen annealing (HPOA). On the other hand, relatively low processing temperatures have been used in device fabrication to suppress GeO desorption, but high temperature process (~600°C) will be desirable when device stability and reliability are considered. Above requirements suggest us to use Al₂O₃ for gate dielectric film on Ge, because among various high-k oxides, Al₂O₃ has high resistances against oxygen diffusion and thermal reaction [2]. Furthermore, when the scalability is concerned, the direct Al₂O₃ on Ge might be desired than GeOₓ-IL insertion [3].

So, this paper discusses Al₂O₃ potentiality in Ge gate stack with GeOₓ-free interface even after relatively high temperature process (600°C), and then demonstrate thin EOT Al₂O₃/Ge MIS capacitor (MISCAP) characteristics with GeOₓ-free interface.

2. Experimental

Al₂O₃ film was deposited on p-type Ge (100) wafer by rf-sputtering in Ar. Al₂O₃ film thickness was determined by the X-ray reflectivity measurement. After the deposition, the post deposition annealing (PDA) was performed at 600°C for 30 sec in 1-atm O₂, and at 600°C and 550°C for 30 sec in 10-atm O₂ (at room temperature), as shown in Fig. 1. Then, Au and Al were evaporated as the gate electrode and the back ohmic contact, respectively.

3. Results and Discussion

The oxygen blocking capability of thin Al₂O₃ film is discussed. Fig. 2 (a) and (b) show the Ge3d core level spectra in XPS. Almost no GeOₓ growth was detected at the interface of as-sputtered Al₂O₃ on Ge. This means that Ge was not oxidized in the sputtering process, while it was grown in O₂-PDA at 600°C through ultra-thin Al₂O₃. We have noted, however, that the peak intensity of Ge²⁺ dramatically decreased with the increase of Al₂O₃ thickness. This indicates that only 2~3 nm-Al₂O₃ is thick enough to suppress the oxidation of Ge even at 600°C.

In Ge MIS gate stacks, GeO desorption should degrade the Ge interface quality and increase the Dₓₓ [4]. Fig. 3 shows the TDS (thermal desorption spectroscopy) results of GeO desorption for (i) Al₂O₃/Ge, (ii) Al₂O₃/GeOₓ/Ge, and (iii) GeOₓ/Ge stacks, respectively. From the comparison between (i) and (ii), it is revealed that there is no GeO desorption without GeOₓ-IL at the interface.

Furthermore, from comparison between (ii) and (iii), we can understand that Al₂O₃ works as a diffusion barrier than thick GeOₓ layer, because almost no GeO desorption was observed even at 600°C in the case of (ii).

The oxygen blocking effect of thin Al₂O₃ film was also observed in HPOA. Fig. 4 shows the Ge3d core level spectra of 3-nm-thick-Al₂O₃/Ge with HPOA at 600°C and 550°C. As-deposited sample is also shown. It is noted that GeOₓ-IL growth is entirely suppressed at 600°C even in HPOA. We reported that a relatively thick GeOₓ-IL growth was observed in the cases of rare-oxides though C-V characteristics were surprisingly good [5]. It is in striking contrast to the present results. This fact is a great advantage of Al₂O₃ gate stack for suppressing the interface degradation due to GeO desorption and for reducing the CET in terms of the scalability.

Next, electrical properties are discussed. The question is whether GeOₓ-free interface is really improved by HPOA or not. C-V characteristics of 3-nm-thick-Al₂O₃/Ge MISCAPs with N₂-PDA (1-atm), O₂-PDA (1-atm), and HPOA (10-atm) at 600°C, are shown in Fig. 5, respectively. The oxygen rich PDA clearly improves the interface in spite of GeOₓ-IL formation. Fig. 6 (a) shows bi-directional C-V characteristics of 3-nm-thick-Al₂O₃/Ge MISCAP in HPOA at 600°C as a parameter of measurement frequency. A small frequency dispersion at depletion region indicates that the interface was considerably improved by HPOA. Although the interface has not been clarified yet, the results are significantly different from those in HfO₂ gate stacks [6]. We infer that the interface might be stabilized due to the different valency between Ge and Al, which was also discussed in Y₂O₃/Ge gate stack [7], as well as the possible interface Al-Ge bonds might be recovered to Al-O-Ge one.

The accumulation capacitance is 2.1 μF/cm² (EOT~1.2 nm). Since the relative dielectric constant, k, of the present Al₂O₃ was ~7.5, and Al₂O₃ has a large band offset against Ge thanks to no d-electron, quite a low gate leakage is expected. Fig. 6 (b) shows I-V characteristic with a low leakage current density (4.0×10⁻⁶ A/cm²) at V GS=V FB+1 (V).

4. Conclusions

We have studied Al₂O₃ gate stack on Ge together with HPOA. Al₂O₃ shows the high resistance against O₂ diffusion, and no interfacial GeOₓ layer was formed even in HPOA. However, it was found that HPOA improved the interface very much. Further optimization is obviously needed, but we think that Al₂O₃ gate stack will provide a potential for Ge device expansion.

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References

Fig. 1. Schematic views of sample preparation. Intentional IL was not formed before Al2O3 deposition. HPOA was performed in a closed furnace with 10-atm O2 at room temperature in this experiment.

Fig. 2. The Ge3d core level spectrums of (a) as-sputtered and (b) 1-atm O2-PDA at 600°C samples of thin Al2O3/Ge stacks. Only a very small amount of GeO2 layers are detected for samples with Al2O3 thicker than 2.5 nm.

Fig. 3. TDS spectrums of GeO (m/Z=90) desorption from Al2O3/Ge, Al2O3/GeO2/Ge, and GeO2/Ge stacks. The heating rate of the measurement was 20°C/min. Note that a significant difference of the desorption temperature between w/ and w/o Al2O3 cap on GeO2/Ge. The Q-Mass current intensity difference comes from the sample size difference.

Fig. 4. The Ge3d core level spectrums of as-sputtered and HPOA samples of 3-nm-thick-Al2O3/Ge stacks. HPOA was applied at 600°C in 10-atm O2 (at room temperature).

Fig. 5. The 1MHz C-V characteristics of 3-nm-thick-Al2O3/p-Ge MISCAPs with N2-PDA (1-atm), O2-PDA (1-atm), and HPOA (10-atm) at 600°C.

Fig. 6. (a) The frequency dispersion of C-V characteristics of 3-nm-thick-Al2O3/p-Ge MISCAP with 10-atm HPOA. EOT~1.2 nm was obtained from the accumulation capacitance. The k-value of Al2O3 was ~7.5. (b) I-V characteristics of 3-nm-thick-Al2O3/p-Ge MISCAP with 10-atm HPOA.