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Interface Stabilizing and EOT Scaling of Al_2O_3 /Ge Gate Stack with Ozone Post-Oxidation without Additional Interface Layer Formation

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1. Introduction

Ge is being widely considered as a promising alternative to Si as a new channel material of metal-oxide-semiconductor field effect transistors (MOSFETs) beyond the traditional device scaling because of not only the higher carriers mobility than Si but also the compatibility with the conventional Si integration technologies [1~3]. However, it has been well reported that the interface properties of high *k*/Ge MOS devices are very difficult to be controlled and stabilized [4]. One possible solution is to introduce a thin GeO_2 layer between the high *k* layer and Ge substrate. However, during the high *k* layer growth process (like atomic layer deposition (ALD)), the GeO_2 film could be damaged inevitably and the final MOS interface might be degraded. On the other hand, the EOT scaling is another important issue for Ge MOS. With the conventional thermal oxidation method, it's a very tough work to obtain a thin high quality GeO_2 layer, resulting in a thin EOT.

Recently, a novel plasma post oxidation (PPO) method has been proposed by Zhang, et al. [5, 6]. With this PPO method, the EOT could be controlled by tuning the original high *k* layer thickness and the plasma power. The key point of the PPO method is to pre-grow a thin barrier high *k* layer before the plasma oxidation, which could make the plasma oxygen ions have a limited penetration thickness into Ge substrate. Therefore, it might be not necessarily required to use a plasma oxidation method, which needs complex equipment such as electron cyclotron resonance (ECR) plasma generator, to achieve this task.

In this study, we propose a new ozone-post-oxidation (OPO) method for Al_2O_3/Ge MOS devices. The electrical properties of the devices are systemically investigated. The experimental results show that, with this OPO method, the Ge MOS interface could be effectively stabilized and there is also no additional GeO_2 interface layer formed after the OPO treatment.

2. Experimental and Results Discussion

Al_2O_3/Ge gate stack formation

The ozone (O_3) oxidation process was done under the air pressure and at room temperature with a home-made ozone generation equipment (Fig. 1). The power of the UV lamp is 20W. The fabrication process of Al_2O_3/Ge MOS capacitors is schematically shown in Fig. 2. n-Ge wafers with (100) orientation and a resistivity of 0.21Ω cm～0.26 Ω cm were used. After the Ge substrate was cleaned with deionized water, acetone and cyclic HF-water etching, a thin Al_2O_3 layer was grown on it with ALD, followed by an ozone post oxidation (OPO) with different time.

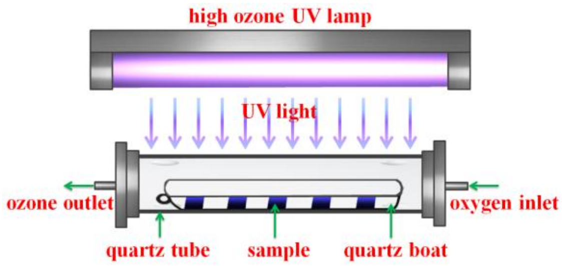

Fig. 1 Ozone post oxidation equipment.

N_2 ambient annealing was performed after the OPO treatment for all samples at 400ºC for 30min in an annealing furnace. In order to investigate the electrical properties of Al_2O_3/Ge gate stacks, Pt gate electrodes and Au back contacts were fabricated by magnetron sputtering.

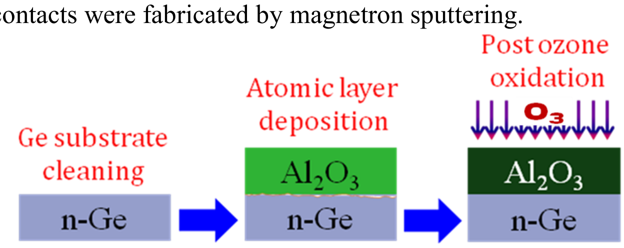

Fig. 2 Process flow of fabricating Pt/Al_2O_3/Ge gate stack with OPO treatment.

The interfacial stoichiometry between Al_2O_3 and Ge substrate was examined by X-ray photoelectron spectroscopy (XPS) measurements (Fig. 3). Almost no Ge^{4+} peak signal could be observed in the XPS spectrum of the sample with 4 min OPO (Fig. 3 (a)), indicating that the GeO_2 interface layer is very thin or its amount is under the XPS's detect limit. Meanwhile, it could be easily found that the O1s peak is enhanced obviously after 4 min OPO (Fig. 3 (b)), which might be due to the increase in the oxygen content in the Al_2O_3 layer.

To further understand the impact of the OPO treatment on properties of Al_2O_3/Ge gate stack, the spectroscopic ellipsometer (SE) measurements were performed. Two stack structures were used to fit SE results, Al_2O_3/Ge and Al_2O_3/GeO_2/Ge (Table I). From the fitting results, we could know two things. One is that the Al_2O_3 thickness was decreased due to the OPO treatment. It means that OPO could enhance the Al_2O_3 film density and then improve the film quality. The other thing is that in $Al_2O_3/GeO_2/Ge$ structure fitting, there is no GeO_2 increase observed after the long time OPO. This is consistent with the XPS results (Fig. 3). However, high resolution transmission electron microscope (TEM) analysis is strongly needed to clarify the real interface structure.

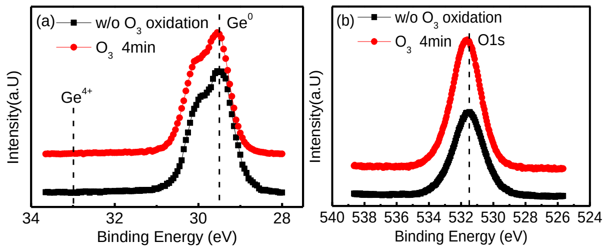

Fig. 3 (a) Ge and (b) O1s XPS spectra of Al_2O_3/Ge structure before and after OPO treatment.

Table I Fitting results of Spectroscopic Ellipsometer measurements

O_3 oxidation time (min)		0	2	3	4	5
Structure 1 (Al_2O_3/Ge)	Al_2O_3 (nm)	4.8	4.74	4.6166	4.3528	4.3186
	R^2	0.997197	0.997865	0.997207	0.997596	0.997388
Structure 2 (Al_2O_3/GeO_2/Ge)	Al_2O_3 (nm)	3.5317	3.8204	3.4026	3.3684	3.118
	GeO_2 (nm)	1.4525	1.0555	1.39	1.1272	1.375
	R^2	0.998316	0.998456	0.998252	0.998303	0.99845

The C-V characteristics and the frequency dispersion properties of Al_2O_3/Ge MOS capacitors with different time OPO and without OPO are shown in Fig. 4 and Fig. 5, respectively. It could be found that the C-V characteristic of Al_2O_3/Ge MOS could be improved significantly with OPO process, which is also dependent on the OPO time (Fig. 4). Furthermore, the frequency dispersion of the sample treated with OPO is very small, suggesting a very good Ge MOS interface and low parasitic resistance (Fig. 5).

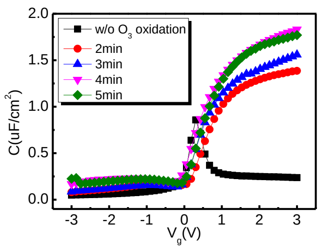

Fig. 4 C-V characteristics (1MHz) of Al_2O_3/Ge MOS with and without OPO treatment.

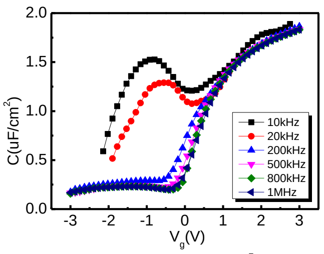

Fig. 5 Frequency dispersion (10 kHz~1MHz) of Al_2O_3/Ge stack with OPO treatment.

Fig. 6 (a) shows the J_g-V_g characteristics of the Pt/Al_2O_3/Ge MOS capacitors with an OPO treatment for different time (2, 3, 4, and 5 min) and without an OPO treatment. Obviously, OPO treated devices show much lower gate leakage current than the device without OPO. Furthermore, the gate leakage decreases with the increase in the OPO time (Fig. 6 (b)). This could be attributable to the increase in the density of Al_2O_3 layer with the increase in the OPO time.

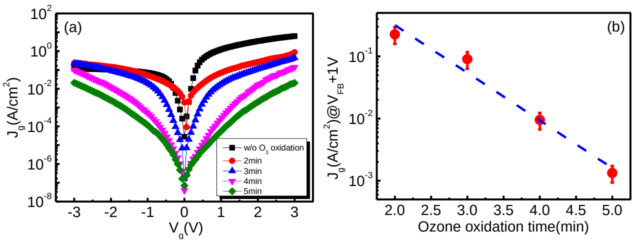

Fig. 6 gate leakage currents of Al_2O_3/Ge MOS capacitors with different time OPO.

Next, we discuss the EOT scaling of Ge MOS devices with the OPO technology. Fig. 7 shows the relationship between the EOT and the OPO time of Al_2O_3/Ge MOS capacitor. It could be found that the value of EOT decreases with the increase in the OPO time. The main reason for this phenomenon might be as follows. The thickness of Al_2O_3 layer became thinner after the OPO treatment, as discussed earlier. Consequently, the permittivity of Al_2O_3 film was enhanced, resulting in a smaller EOT. We think that after a careful process optimization, sub-1nm EOT is achievable with this OPO technology for Ge MOS devices. Also, the gate current decreases with the increase in the OPO time (Fig. 8). This could partly be due to the decrease in the oxygen deficiency or other defects in Al_2O_3 film after the OPO treatment.

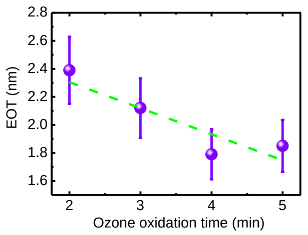

Fig. 7 OPO time dependence of the EOT value.

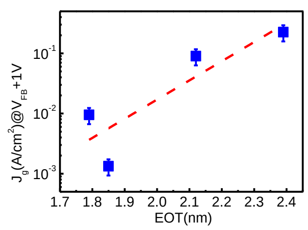

Fig. 8 EOT versus leakage current density (J_g) of MOS capacitors with different OPO time.

3. Conclusions

One novel ozone-post-oxidation (OPO) method has been proposed for preparing superior Al_2O_3/Ge gate stack with low EOTs. Both EOT and the gate leakage current were reduced significantly with this OPO process, while there was no significant GeO_2 interface layer formation.

Acknowledgements

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