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Low-Temperature Silicon Oxide Offset Spacer Using Plasma Enhanced Atomic Layer Deposition for High-k/Metal Gate Transistor

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1. Introduction

High-k/metal gate technology is the first candidate for 32 nm technology node and beyond [1-3]. Gate-stack structure using metal gate electrode and high-k dielectric is shown in Fig. 1. Offset spacer (OSS) is deposited on sidewall of the high-k/metal gate stack. In order to decrease in fringe capacitance, the OSS film with lower dielectric constant is required. Silicon oxide (SiO) is more suitable for the OSS film than silicon nitride (SiN), because the SiO film exhibits lower dielectric constant than the SiN film. There are two main requirements for the SiO deposition of the OSS film in the high-k/metal gate technology. One is the suppression of side-edge oxidation of high-k/metal gate stack due to high-deposition temperature of the SiO deposition such as low-pressure chemical vapor deposition (LPCVD). The other is the precise control of film thickness. Therefore, low-temperature deposited SiO (LT-SiO) film is one of the solutions for the OSS of the high-k/metal gate technology. Plasma enhanced chemical vapor deposition (PECVD) and plasma enhanced atomic layer deposition (PEALD) are suitable for low-temperature film growth [4-6]. In particular, using PEALD technique is able to deposit the film with high controllability of film thickness at low-deposition temperature [4-5].

In this study, we discuss film characteristics of the LT-SiO films with PECVD and PEALD techniques at the temperature of 200 ℃ and the effect of LT-SiO OSS on drain current (I_{on}) of the high-k/metal gate transistor.

2. Experimental Procedure

SiO films deposited with PECVD (CVD-SiO) and PEALD (ALD-SiO) were prepared using the same plasma chamber at the temperature of 200 ℃. The CVD-SiO and ALD-SiO films were deposited with SiH_4-N_2O-He gas mixtures, and the flow rates of each gas were equal between CVD-SiO and ALD-SiO depositions. Other deposition conditions such as gas pressure, width of electrode gap, and power of radio frequency (RF) of 13.56 MHz were set to the same value between CVD-SiO and ALD-SiO depositions. In the PEALD, the SiO film was deposited by alternating SiH_4 gas and N_2O-He plasma exposures. The film characteristics of CVD-SiO and ALD-SiO films were compared to a SiO film grown by thermal oxidation at 950 ℃ (Thermal SiO). Film thickness, dielectric constant, film density, compositions, amount of water in the film, elastic modulus, and bonding structures were measured with ellipsometry, mercury probe method, X-ray reflectivity (XRR), X-ray photoelectron spectroscopy (XPS), thermal desorption spectroscopy (TDS), nanoindentation method, and Fourier transform infrared spectroscopy (FT-IR), respectively. In the TDS measurement, integrated intensity of m/z = 18 at the temperature range from 100 ℃ to 1000 ℃ was defined as the amount of water in the films. Wet etch rate of the films was evaluated with a diluted HF solution (HF : H_2O = 1 : 50). Step coverage of ALD-SiO film was measured with transmission electron microscope (TEM) at a pattern with line/space of 28/220 nm. The effects of ALD-SiO film for the OSS in the high-k/metal gate technology on I_{on} of n-type metal oxide semiconductor field effect transistor (nMOSFET) were demonstrated, compared to a thermal-CVD SiO film deposited at the temperature of 650 ℃ for the OSS.

3. Results and Discussion

Figure 2 shows dependence of film thickness on cycle number of the ALD-SiO deposition. The film thickness increased linearly with increasing the cycle number. The growth rate obtained from gradient of approximated line was 0.13 nm/cycle. This result indicates that the PEALD technique has excellent controllability of film thickness.

Figure 3 shows FT-IR spectra at the frequency range from 500 cm^{-1} to 4000 cm^{-1} of three SiO films in the thickness of 500 nm. Two peaks around 820 cm^{-1} and 1080 cm^{-1} in each spectrum correspond to a Si-O bending vibration and a Si-O stretching vibration, respectively. Figure 4 shows FT-IR spectra at the frequency range from 900 cm^{-1} to 1400 cm^{-1} in the Si-O stretching vibration in three SiO films. The peak wavenumbers of the Si-O stretching vibration of ALD-SiO and Thermal SiO films were almost same value as shown in Table I. This result indicates that ALD-SiO film is composed of Si-O bond network like stoichiometric SiO_2 film. On the other hand, the peak wavenumber of Si-O stretching vibration of CVD-SiO film was lower than those of ALD-SiO and Thermal SiO films. According to the central force model, the wavenumber of the Si-O stretching vibration is expressed as a function of Si-O-Si bond angle [7]. The lower wavenumber of the Si-O stretching vibration in the CVD-SiO film is attributed to decrease in the Si-O-Si bond angle due to sub-oxide such as three-fold ring [8]. It is speculated that the sub-oxide strains Si-O bond network, leading to degradation of film properties [7, 8].

Structural properties of the films such as wet etch rate, film density, and elastic modulus are listed in Table I. ALD-SiO film exhibits lower wet etch rate, higher film density and higher elastic modulus than CVD-SiO film. These results are consistent with the result of FT-IR analysis. From these results, Si-O network dominated by stoichiometric Si-O bonds in ALD-SiO film leads to higher film density and higher elastic modulus, resulting in lower wet etch rate of the film. Therefore, ALD-SiO film exhibits high film quality in extremely low-deposition temperature at 200 ℃ and is suitable for the OSS film in the high-k/metal gate technology.

The dielectric constants of ALD-SiO and CVD-SiO films were higher than that of Thermal SiO film as shown in Table I. It can be considered that the increase in the dielectric constant is caused by the increase in film density, the incorporation of nitrogen into the film due to the gas mixture including N_2O gas, or increase in polarization due to the increase in the amount of water in the film. The film densities of ALD-SiO and CVD-SiO films were little lower than that of Thermal SiO. Nitrogen was not detected in ALD-SiO and CVD-SiO films and the composition ratio of O/Si in three SiO films was 2.0. The amounts of water in ALD-SiO and CVD-SiO films were higher than that in Thermal SiO film. In particular, CVD-SiO film contains the largest amount of water in three films. There were strong relationship between the dielectric constant and the amount of water in the films. From these results, the increase in the dielectric constants is caused by the increase in polarization in the film due to the increase in the amount of water in the film.

Figure 5 shows cross-section TEM image as deposited ALD-SiO film. Thicknesses on the top of poly-Si gate and on the side of metal gate are 5.0 nm and 4.0 nm. We speculate that the reasons why step coverage is not 100% are caused by the low-deposition temperature and by the shape of negative slope at the metal gate [9].

Figure 6 shows comparison of I_{on}-I_{off} characteristics of nMOSFET between OSS films of ALD-SiO and the thermal-CVD SiO. I_{on} of nMOSFET with ALD-SiO film is 40% higher than that with the thermal-CVD SiO film at I_{off} = 2 nA/μm and V_{dd} = 1.1 V. We believe that the low-deposition temperature of the ALD-SiO deposition suppresses side-edge oxidation of metal gate electrode and high-k dielectric during the deposition, leading to improvement in the I_{on}-I_{off} performance [10].

4. Conclusion

We have demonstrated that high-quality SiO film for OSS of high-k/metal gate stack is successfully deposited at extremely low temperature of 200 ℃ by PEALD technique using SiH_4-N_2O-He gas mixture. Using this SiO film for the OSS, I_{on} of nMOSFET has drastically increased by 40% compared to a conventional SiO film for OSS.

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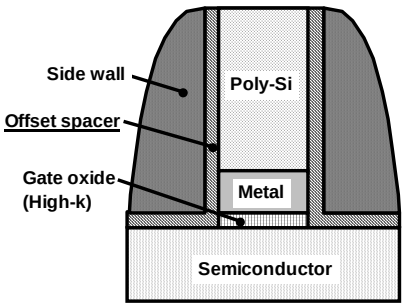

Fig. 1 Schematic cross section of gate stack using metal gate electrode and high-k dielectric.

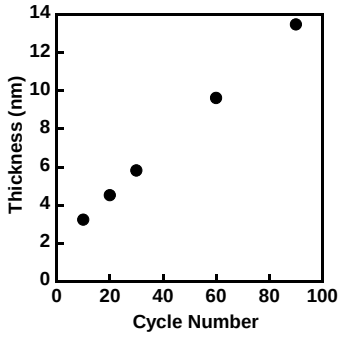

Fig. 2 Dependence of film thickness on cycle number of the ALD-SiO deposition.

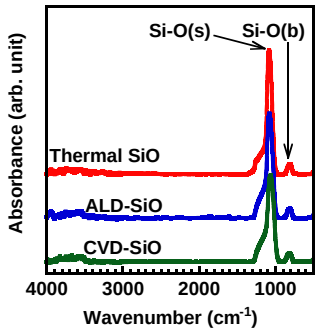

Fig. 3 FT-IR spectra of three SiO films. Si-O(s): Si-O stretching vibration. Si-O(b): Si-O bending vibration.

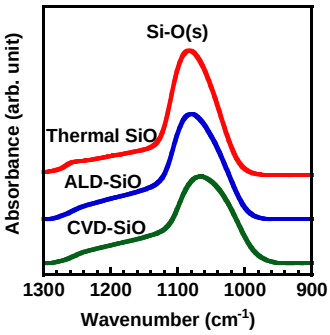

Fig. 4 FT-IR spectra of the Si-O stretching vibration for three SiO films.

Table I Comparison of film characteristics among ALD-SiO, CVD-SiO and Thermal SiO films.

	ALD-SiO	CVD-SiO	Thermal SiO
Wavenumber of Si-O bond peak(cm^{-1})	1082	1067	1081
50:1 HF Wet Etch Rate (arb. unit)	2.0	5.8	1.0
Density of film (g/cc)	2.26	2.23	2.28
Elastic modulus (GPa)	87.6	82.9	92.6
Dielectric constant	4.34	4.48	3.90
Composition ratio of O/Si	2.0	2.0	2.0
The amount of water (arb. unit)	9.7×10^{21}	1.4×10^{22}	3.7×10^{21}

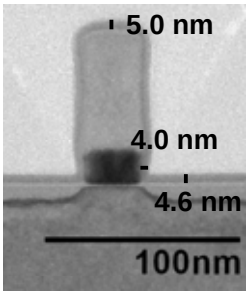

Fig. 5 Step coverage of the ALD-SiO film evaluated with TEM.

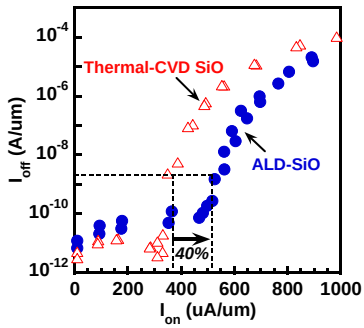

Fig. 6 Comparison of I_{on}-I_{off} characteristics of nMOSFET between the OSS films of ALD-SiO and the thermal-CVD SiO.