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PMOSFET Vth Modulation Technique using Fluorine Treatment through ALD-TiN Suitable for CMOS Devices

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Abstract

We propose that fluorine treatment (F treatment) through ALD-TiN is an excellent technique for modulating Vth. Low Vth with no mobility degradation is achieved with F treatment through ALD-TiN/HfO_2 fabricated by the gate last process. Vth shift value is almost the same for each gate length. The barrier height shift attributable to F treatment corresponds closely to the Vth shift. It is found that F treatment through ALD-TiN modulates an effective work function. No Vth shift of nMOSFET, namely the ALD-TiN/$HfSi_x$/HfO_2 stack structure, is observed with F treatment. It is confirmed that F treatment is a suitable technique for CMOS devices due to confinement of Vth shift to pMOSFETs.

Introduction

We have reported that $HfSi_x$/HfO_2 using the gate last process realizes extremely high performance for nMOSFETs. Low Vth is obtained in $HfSi_x$/HfO_2 due to the work function near the conduction band edge [1-3]. We have also reported that ALD-TiN/HfO_2 realizes excellent device performance for pMOSFETs [4-5]. Therefore, ALD-TiN is considered to be an attractive material. However, an effective work function of ALD-TiN shows a quarter gap from the valence band edge [4], and a higher work function is preferable for obtaining lower Vth. It has been reported, especially for p-metal/high-k stacks, that Vfb shifts as a result of post process anneal conditions [6], and also that applying O_2 annealing directly to the metal/high-k can realize a higher work function [7]. However, the influences of these processes on device characteristics have been rarely discussed. F implantation in the channel has been reported as an effective method for modulating Vth [8], but effects of fluorine on work-function-control metal have not been reported. In this study, we fabricated ALD-TiN/HfO_2 with F and O treatments through ALD-TiN, then evaluated the results for influences of Vth modulation and device characteristics.

Experiments

The pMOSFETs were fabricated by the gate last process as shown in Fig. 1. After dummy gate removal, HfO_2 was deposited by the ALD method followed by post deposition anneal (PDA). TiN gate electrodes were deposited using the ALD method, and then several gas treatments were performed through the ALD-TiN in order to control work functions. F and O treatments (with low and high O_2 concentrations) and N_2 annealing were performed at 400^{o}C and a low O_2 concentration treatment at 450^{o}C was also performed. CVD-W/TiN was deposited to fill the gate electrode. The CMP process was used for gate formation. The interlayer dielectric was formed followed by metallization, and forming gas annealing was performed at 400^{o}C.

Results and Discussion

Id-Vg characteristics of ALD-TiN/HfO_2 with F and O treatment results are compared with the control (without treatment) as shown in Fig. 2. A lower Vth is achieved with both F and O treatments. A larger shift is obtained with F treatment. Fig. 3 shows the Vth shifts from the control with several kinds of gas treatments. The same Vth as the control is obtained with N_2 annealing which indicates a Vth shift cannot be brought about only for the thermal budget. Stronger oxidation causes a larger Vth shift, and almost the same Vth shift as is obtained using F treatment is achieved using a higher temperature O treatment. Fig. 4 shows hole mobility of ALD-TiN/HfO_2 with F treatment, O treatments at 400^{o}C and 450^{o}C with low O_2, and the control. Tinv of these samples is 1.65 nm. Hole mobility of F treatment is identical to the control while mobility degradation is observed with O treatment. In addition, further degradation is observed using the 450^{o}C O treatment, which realizes a larger Vth shift. Fig. 5 shows the interface state density of ALD-TiN/HfO_2 with F and O treatments and the control evaluated by the charge pumping measurement. Interface state density resulting from F treatment is the same as the control, whereas it increases with O treatment despite lower O_2 concentration and lower temperature. We can conclude that F treatment through ALD-TiN is an excellent technique for realizing lower Vth without mobility degradation.

In order to investigate the Vth shift mechanism resulting from F treatment, ALD-TiN/HfO_2 stacks with and without F treatment were analyzed using backside SIMS and XPS. Backside SIMS depth profiles are compared with and without F treatment in Fig. 6. A larger F concentration is observed with F treatment, and F exists from the ALD-TiN to the HfO_2/ interfacial layer (IFL). Fig. 7 (a) and (b) show backside XPS spectra of F1s and Hf4f with and without F treatment. An F-Hf or Ti bond is clearly observed only in the F treatment sample. The Hf4f spectrum shape of the F treatment sample is different from that of the control. This indicates that the high binding energy ratio is further increased as a result of the F-Hf bond. The barrier heights at the ALD-TiN/HfO_2 interface with and without F treatment are analyzed by measuring Jg versus Vg curves for Vg > 0V as discussed in [9-10]. The peaks in Fig. 8 show the barrier heights at the ALD-TiN/HfO_2 interface with a 160mV higher value obtained using F treatment. The barrier height shift of F treatment corresponds closely to the Vth shift in Fig. 3, proving F treatment through ALD-TiN modulates an effective work function.

Fig. 9 shows a cross-sectional TEM image of the ALD-TiN/HfO_2 gate stack of a 40nm gate length pMOSFET. Fig. 10 shows Jg-Tinv characteristics of ALD-TiN/HfO_2 with and without F treatment. The Tinv of ALD-TiN/HfO_2 is 52% thinner than that of P+poly-Si/SiO_2 at the same Jg. The same Jg characteristic is obtained with and without F treatment. Vth roll-off characteristics of ALD-TiN/HfO_2 are shown in Fig. 11. Low Vth is achieved by F treatment and the Vth shift value is almost the same for each gate length. In order to evaluate F treatment effects of nMOSFET, dual metal gate structures are fabricated. The same process flow [3, 5] is used and ALD-TiN/$HfSi_x$/HfO_2 (the inserted structure in Fig. 12) is formed for nMOSFET. Fig. 12 shows Vth roll-off characteristics of ALD-TiN/$HfSi_x$/HfO_2 nMOSFETs. No nMOSFET Vth shift is observed with F treatment. We consider that the $HfSi_x$ layer under the ALD-TiN remarkably suppresses F effects. The confinement of Vth shift to pMOSFETs confirms that F treatment is a suitable technique for CMOS devices.

Conclusions

In order to achieve low Vth, F and O treatments through ALD-TiN are performed and device characteristics are evaluated. O treatment modulates Vth while mobility degradation is observed because of interface state density increase. F treatment also modulates Vth and realizes no mobility degradation. Vth shift value is almost the same for each gate length. F treatment through ALD-TiN modulates an effective work function. It is also confirmed that F treatment is a suitable technique for CMOS devices due to confinement of Vth shift to pMOSFETs.

Acknowledgements

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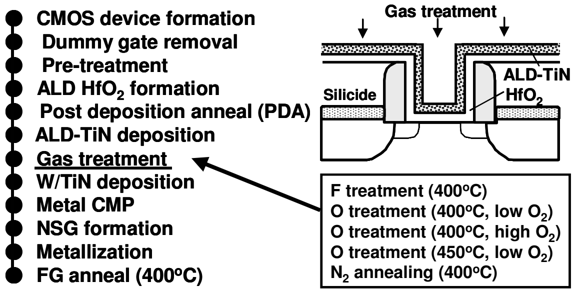

Fig. 1 Gate last process flow of ALD-TiN/HfO_2 gate stacks. Several kinds of gas treatments were performed through ALD-TiN film.

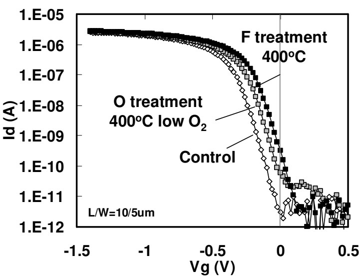

Fig. 2 Id-Vg characteristics of ALD-TiN/HfO_2 with F and O (400°C low O_2) treatments and control (without treatment) at Vd = -50mV.

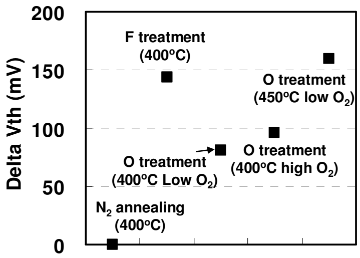

Fig. 3 Vth shift form the control with several kinds of gas treatments. Larger Vth shift is obtained with F and 450°C O treatments.

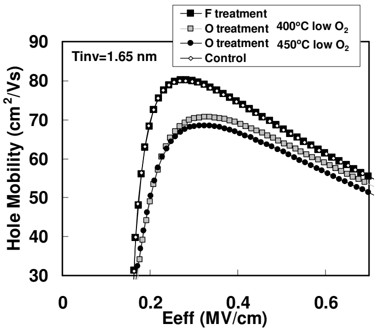

Fig. 4 Hole mobility of ALD-TiN/HfO_2 gate stacks with F treatment, with 400°C and 450°C with low O_2 treatments, and with control.

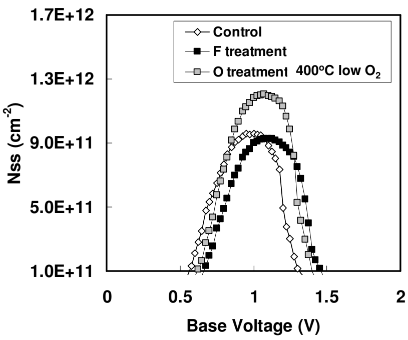

Fig. 5 Interface state density of ALD-TiN/HfO_2 gate stacks with F treatment, O treatment at 400°C low O_2 and control evaluated by charge pumping measurement.

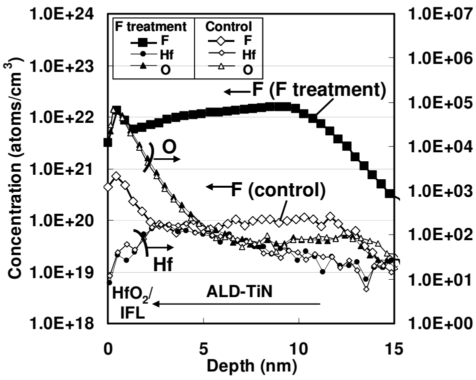

Fig. 6 Backside SIMS depth profiles were compared with and without F treatment.

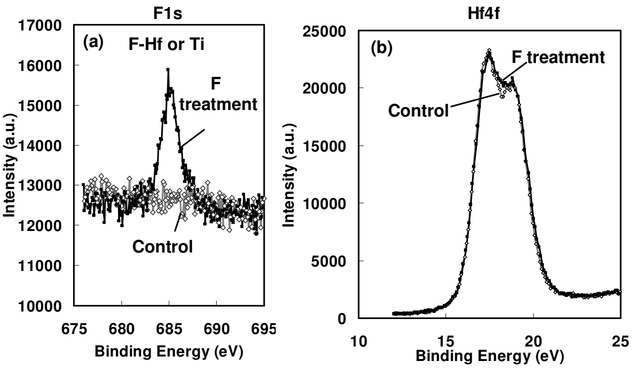

Fig. 7 Backside XPS (a) F1s and (b) Hf4f spectra of F treatment and control.

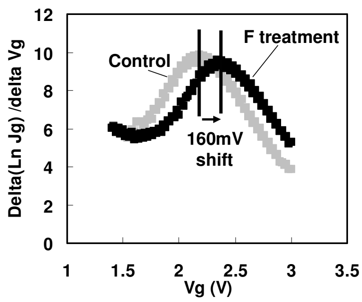

Fig. 8 Barrier heights at ALD-TiN/HfO_2 interface with and without F treatment.

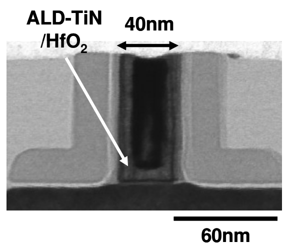

Fig. 9 Cross-sectional TEM image of ALD-TiN/HfO_2 gate stack of 40 nm gate length pMOSFET.

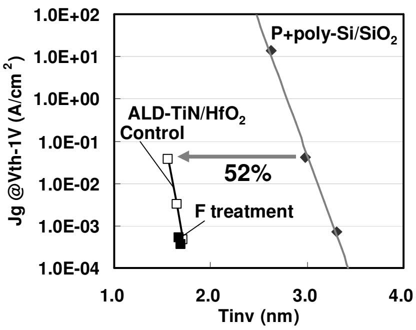

Fig. 10 Jg-Tinv of ALD-TiN/HfO_2 in pMOSFET. The same Jg-Tinv characteristic is obtained with and without F treatment. Tinv is reduced 52% from P+poly-Si/SiO_2 at the same Jg.

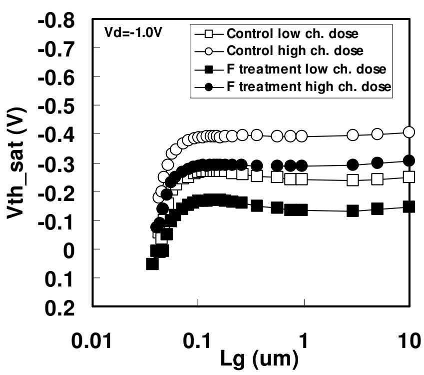

Fig. 11 Vth roll-off characteristics of ALD-TiN/HfO_2 gate stack with and without F treatment. Vth shift shows the same trend in each gate length.

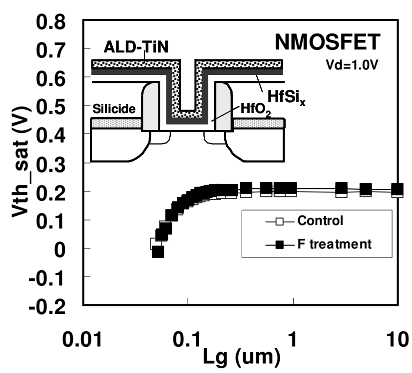

Fig 12 Vth roll-off characteristics of ALD-TiN/$HfSi_x$/HfO_2 nMOSFETs with and without F treatment. No nMOSFET Vth shift is observed with F treatment.