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Low-Leakage and Highly-Reliable 1.5 nm SiON Gate-Dielectric Using Radical Oxynitridation for Sub-0.1 µm CMOS

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ABSTRACT

We have developed a low-leakage and highly-reliable 1.5 nm SiON gate-dielectric by using radical oxynitridation. In this development, we introduce a new method for determining ultra-thin SiON gate-dielectric thickness based on the threshold voltage dependence on the substrate bias in MOSFETs. It was found that radical oxidation followed by radical nitridation provides 1.5 nm thick SiON in which leakage current is two orders of magnitude less than that of 1.5 nm thick SiO_2 without degrading device performance. The 1.5 nm thick SiON was also found to be ten times more reliable than 1.5 nm thick SiO_2.

INTRODUCTION

A low-leakage and highly-reliable gate-dielectric is essential for high-performance sub-0.1 µm CMOSFETs [1]. Oxynitridation is one of the key techniques to achieve low-leakage gate-dielectrics [2]. The radial process can be also useful to improve SiO_2 quality [3]. We have investigated 1.5 nm SiON gate-dielectrics by using radical oxynitridation. In this investigation, we will introduce a new method of gate-dielectric thickness measurement, because it is important to measure electrical oxide equivalent thickness ($T_{OX\text{-}eq}$).

THICKNESS DETERMINATION

Large gate leakage current of the ultra-thin SiO_2 disturbs thickness measurement by using C-V characteristics (Fig. 1). A newly proposed thickness measurement method is based on the general relationship between the threshold voltage (V_{TH}) and the substrate bias voltage (V_B). In this method, the gate leakage current does not affect V_{TH} of a transistor (Fig. 2). Fig. 3 shows V_{TH} dependence on V_B, which is expressed as the following general equation:

$$V_{TH} = ((2\varepsilon_s\varepsilon_0 qN_{ch})^{1/2}/C_{OX})(V_B+2\phi_F)^{1/2} + V_{FB}+2\phi_F \qquad (1)$$

where N_{ch} is the channel concentration and C_{OX} is the gate-dielectric capacitance where the oxide electrical thickness ($T_{OX\text{-}ele}$) is a component part. In Fig. 3, the line slope consists of N_{ch} and $T_{OX\text{-}ele}$, and the y-intercept indicates V_{FB}. To determine $T_{OX\text{-}eq}$ of the ultra-thin SiO_2, we fabricated a 6 nm thick SiO_2 gate-dielectric NMOSFET using the same fabrication process as that used to make ultra-thin SiO_2 gate-dielectric NMOSFETs. First, we obtained C_{OX} by measuring the C-V curve of the 6 nm thick SiO_2, and obtained accurate N_{ch} by using (1) and the C_{OX}. Next, we calculated the ultra-thin SiO_2 thickness ($T_{OX\text{-}ele}$) by using (1) and N_{ch}. $T_{OX\text{-}ele}$ consists of an oxide thickness ($T_{OX\text{-}eq}$) and a parasitic thickness ($T_{OX\text{-}para}$), which is composed of poly-Si gate depletion and inversion layer quantization. $T_{OX\text{-}para}$ was extracted by using the C-V curve for 6 nm-thick (=$T_{OX\text{-}phy}$, physical thickness, = $T_{OX\text{-}eq}$) gate SiO_2 shown in Fig. 1. Finally, we obtained the electrical oxide equivalent thickness ($T_{OX\text{-}eq}$) of the ultra-thin SiO_2 by using $T_{OX\text{-}ele}$ and $T_{OX\text{-}para}$ ($T_{OX\text{-}eq} = T_{OX\text{-}ele} - T_{OX\text{-}para}$). Fig. 4 shows that obtained $T_{OX\text{-}eq}$ is almost the same as measured $T_{OX\text{-}phy}$ in SiO_2. Thus this film thickness determination method is a suitable means for obtaining $T_{OX\text{-}eq}$ of not only ultra-thin SiO_2, but also SiON with heavy nitrogen concentration and other types of gate-dielectric films having high ε and a stacked structure.

RADICAL OXYNITRIDATION

We used radical oxygen and nitrogen from an electron-cyclotron resonance (ECR) plasma to form an ultra-thin SiON film in an ultra-high vacuum (UHV) system where the base pressure was less than 1×10^{-9} Torr to produce a clean Si surface [4]. Four types of radical processes were tested as ways to form the films: radical oxidation (O*), radical nitridation after radical oxidation (O*→N*), radical oxidation and nitridation simultaneously (O*+N*) and radical oxidation after radical nitridation (N*→O*). Fig. 5 shows SIMS profiles of nitrogen in a gate oxide fabricated by the radical process [5]. Radical oxidation and nitridation enables us to control the nitrogen profile in an ultra-thin gate-oxynitride.

NITROGEN PROFILE ENGINEERING

Fig. 6 shows I_D, I_G-V_G characteristics of 1.5 nm thick gate-dielectric NMOSFETs using O* and O*→N*. The use of 7% nitrogen decreased gate leakage current by two orders of magnitude without decreasing the drain current. Fig. 7 shows the gate leakage current of SiON and SiO_2 formed by the radical processes and the conventional thermal process at the same bias. The leakage current of SiON is much lower than that of SiO_2. The SiON film formed by the O*→N* process with 7% nitrogen have lowest leakage current. Fig. 8 shows cross-sectional TEM photographs of the SiON whose gate leakage current is shown in Fig. 7. Table 1 compares the dielectric properties obtained with different radical processes. Nitrogen concentration in the SiON film formed by O*→N* is lower than that in the SiON film formed by N*→O*. However, the dielectric constant of the SiON film formed by O*→N* is larger than that of one formed by N*→O*. Fig. 9 and 10 show that the drivability of the NMOSFET formed by the O*→N* process with 7% nitrogen is comparable to that formed by O* at the supply voltage regime. Fig. 11 shows T_{BD} distribution under constant voltage stress. In Fig. 11(a), the 1.5 nm thick SiON formed by the O*→N* process was not broken within 10^3s, which is ten times more reliable than 1.5 nm thick SiO_2 formed by the O* process. Furthermore, as the figure (b) indicates, a 1.5 nm-thick (=$T_{OX\text{-}eq}$) SiON formed by the O*→N* process with 7% nitrogen is more reliable than a 2.3 nm-thick (=$T_{OX\text{-}phy}$) SiO_2 formed by thermal oxidation. Fig. 12 shows that the chemical shift of N 1s orbital for SiON films depends on the radical process. These results indicate that the nitrogen state depends on the nitrogen profile in SiON and may affect the dielectric property and electrical reliability.

CONCLUSIONS

By using radical oxynitridation, we have successfully achieved a low-leakage and highly-reliable 1.5 nm SiON with no degradation of device performance. This 1.5 nm thick SiON has two orders of magnitude less leakage current than 1.5 nm thick SiO_2 and shows ten times more reliable than 1.5 nm thick SiO_2. We have developed a new thickness determination method that is useful for measuring ultra-thin SiON thickness.

ACKNOWLEDGMENTS

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REFERENCES

[1] H. S. Momose et al., IEDM Tech. Dig., p. 819, 1999.
[2] H. Yang et al., IEDM Tech. Dig., p. 245, 1999.
[3] M. Nagamine et al., IEDM Tech. Dig., p. 593, 1998.
[4] K. Watanabe et al., MRS 1999 Spring Meeting Abstract, p. 268, 1999.
[5] K. Watanabe et al., MRS 1999 Fall Meeting Abstract, 1999.

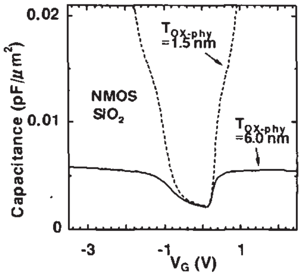

Fig. 1 C-V curves of thin and thick gate oxide dielectrics.

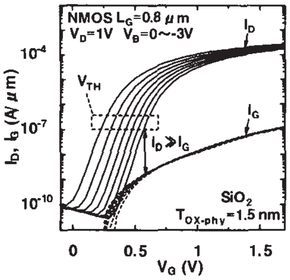

Fig. 2 I_D, I_G-V_G characteristics as a parameter of substrate bias for NMOSFET with thin oxide gate dielectric.

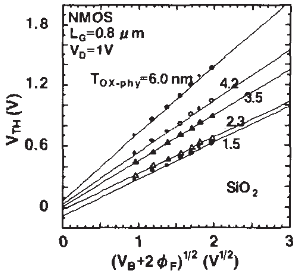

Fig. 3 V_{TH} as a function of substrate bias for NMOSFETs with thin and thick oxide gate dielectrics.

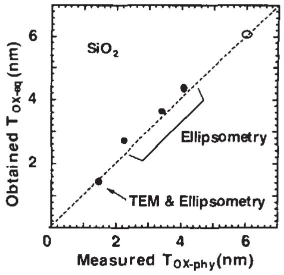

Fig. 4 T_{OX-eq} obtained by V_{TH} dependence on substrate bias and T_{OX-phy} measured by TEM and ellipsometry. $T_{OX-eq} = T_{OX-clc} - T_{OX-para}$.

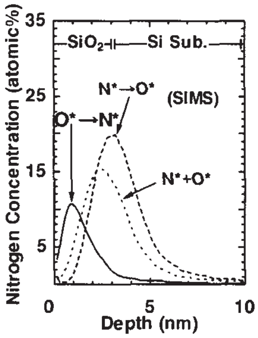

Fig. 5 SIMS profiles of nitrogen in SiON using radical processes (O*→N*, O*+N*, and N*→O*).

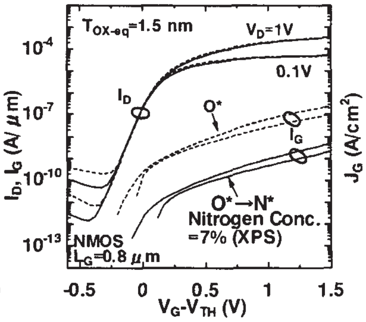

Fig. 6 I_D, I_G-V_G characteristics of NMOSFETs using radical processes (O* and O*→N*). XPS spectra intensity determines nitrogen concentration.

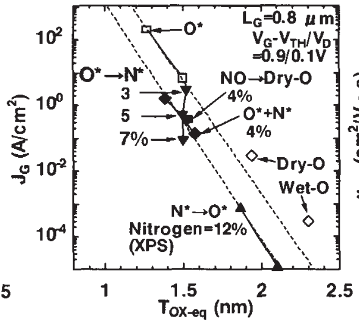

Fig. 7 Gate leakage current vs. T_{OX-eq} of SiON and SiO_2 using radical processes and using conventional thermal processes (Dry-O, Wet-O and NO→Dry-O).

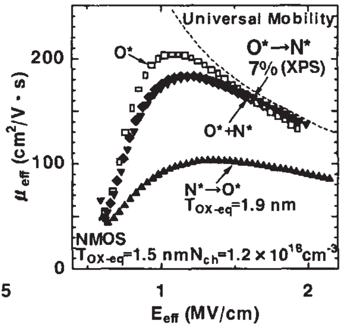

Fig. 9 Comparison of μ_{eff} for SiON and SiO_2 using radical processes.

Table 1 Comparison of dielectric properties.

Radical Process	Nitrogen in SiO_2 (XPS)	Physical/Electrical Thickness T_{OX-phy}/T_{OX-eq}	Dielectric Constant
O*→N*	7%	2.5/1.5 nm	6.5
N*→O*	12%	2.5/1.9 nm	5.1
O*	0%	1.5/1.5 nm	3.9

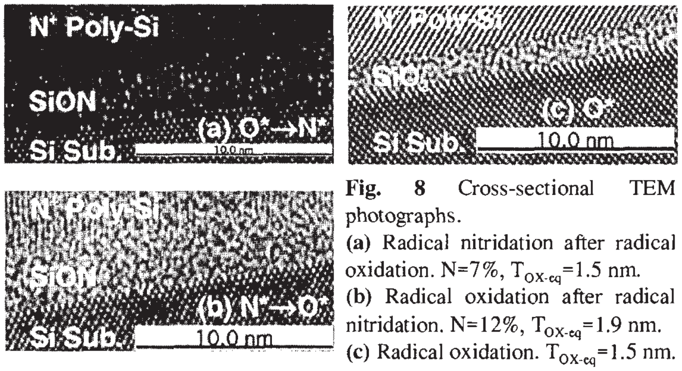

Fig. 8 Cross-sectional TEM photographs.
(a) Radical nitridation after radical oxidation. N=7%, T_{OX-eq}=1.5 nm.
(b) Radical oxidation after radical nitridation. N=12%, T_{OX-eq}=1.9 nm.
(c) Radical oxidation. T_{OX-eq}=1.5 nm.

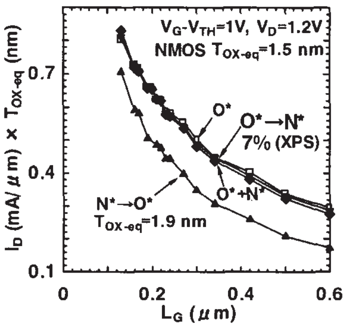

Fig. 10 Comparison of I_D for SiON and SiO_2 using radical processes.

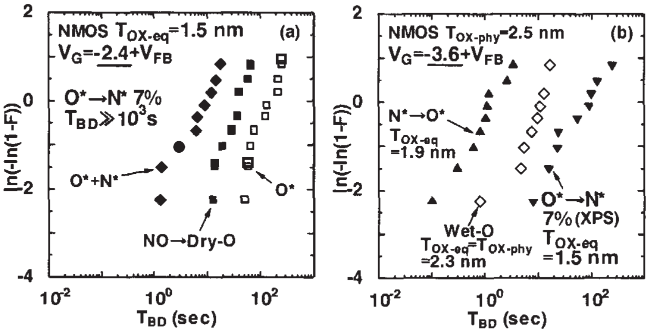

Fig. 11 T_{BD} distributions for SiON and SiO_2 using radical processes and conventional thermal oxidation. **(a)** Same T_{OX-eq}. SiON using O*→N* with 7% nitrogen was not broken within 10^3s at -2.4V+V_{FB}. **(b)** Same T_{OX-phy}.

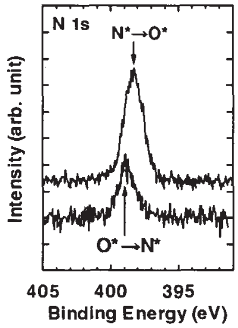

Fig. 12 XPS spectra of N 1s orbital for SiON using radical processes (N*→O* and O*→N*).