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Improved electrical characteristics high-*k* gated MOS devices with in-situ remote plasma treatment in atomic layer deposition

Chen-Chien Li, Kuei-Shu Chang-Liao *, Chung-Hao Fu, Tsung-Lin Hsieh, Li-Ting Chen, Yu-Liang Liao, Chun-Chang Lu, Tien-Ko Wang

Department of Engineering and System Science, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC

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ABSTRACT

Metal oxide semiconductor (MOS) devices with in situ remote plasma treatment during high-*k* dielectric deposition are studied in this work. The EOT value and leakage current of the MOS device with in situ NH_3 plasma treated high-*k* dielectrics can be significantly reduced to 0.83 nm and 1.7×10^{-3} A/cm^2, respectively. The stress-induced flat-band voltage shifts and leakage current are obviously reduced as well. In-situ remote plasma treatment also provides a good approach of nitridation for high-*k* dielectrics. The oxygen vacancy can be passivated by nitrogen, which suppresses further oxygen diffusion and the formation of the oxygen vacancies. The in situ NH_3 plasma treatment is useful for high performance MOS devices with good reliability.

1. Introduction

High-*k* gate dielectrics such as HfO_2, ZrO_2, and Al_2O_3 have been proposed to reduce the gate leakage current in MOS devices with a low equivalent oxide thickness (EOT) value. Among these high-*k* materials, HfO_2 has a high dielectric constant, large band gap and is compatible with complementary metal oxide semiconductor (CMOS) processes. As EOT value below 0.8 nm, the dielectric constant (*k*) value of 18–20 for HfO_2 with amorphous or monoclinic structure is not enough for the MOS devices [1]. To further increase the *k* value of Hf-based dielectric without the degradation of leakage or reliability, the tetragonal and cubic phase HfO_2 are good candidates [2]. It was reported that the tetragonal phase of ALD-formed HfO_2 is obtained by post-deposition annealing in NH_3 or N_2 ambient, and nitrogen incorporation into the high-*k* gate dielectrics can also reduce crystallization and leakage current [3]. Besides, the density of interface traps (Dit) and bias-temperature-instability (BTI) reliability of high-*k* gate dielectrics are still issues. The electrical characteristics are affected by nitrogen incorporation, which is clearly regarded as the critical factor when nitrogen atoms diffuse to the Si interface and form Si–N bonds during the deposition of nitrided high-*k* dielectrics or nitridation processes [4]. In this work, a tetragonal phase HfO_2 dielectric in MOS devices was obtained by in situ NH_3 and N_2 plasma treatments during ALD processes. The electrical characteristics of high-*k* gated MOS devices with various in situ plasma treatments were also investigated. The EOT value and leakage current of MOS device can be significantly reduced with NH_3 plasma treated high-*k* dielectrics. The reliability is obviously improved as well.

2. Experiment

A chemical oxide interfacial layer (IL) was formed by H_2O_2 solution at 75 °C on (100)-oriented 6-inch p-type Si wafer with resistivity of 15–25 Ω-cm. A 3 nm thick HfO_2 was deposited by an atomic layer deposition (ALD), and the precursors are $Hf(NCH_3C_2H_5)_4$ (TEMAH) and H_2O. Simultaneously, in situ NH_3 or N_2 or H_2 remote plasma treatments were performed after every three deposition cycles in ALD. A brief cycling process of in situ remote plasma treatment is shown in Fig. 1. Then, a post deposition annealing (PDA) was performed at 650 °C in N_2 ambient for 30 s. Subsequently, a 50 nm thick TaN film was deposited by a sputtering to serve as the metal gate, and a post metallization annealing was carried out at 600 °C in N_2 ambient for 30 s. After a 300 nm Al deposition, the pattern was then defined by helicon-wave plasma etching. A 500 nm thick Al film was deposited on the backside of all samples. Finally, a sintering was conducted in a N_2/H_2 ambient at 400 °C for 30 min.

The electrical measurement was performed on MOS capacitors with a gate area of 100 × 100 μm^2 in this work. The HP4145B instrument was used to measure the current–voltage (*I–V*) characteristics, and the high-frequency capacitance–voltage (*C–V*) measurements were carried out at 100 kHz by using HP4284A. The equivalent oxide thickness (EOT) and flat-band voltage (Vfb) were extracted from the simulation program considering quantum effect

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* Corresponding author. Tel.: +886 3 5742674; fax: +886 3 5720724.
E-mail address: Lkschang@ess.nthu.edu.tw (K.-S. Chang-Liao).

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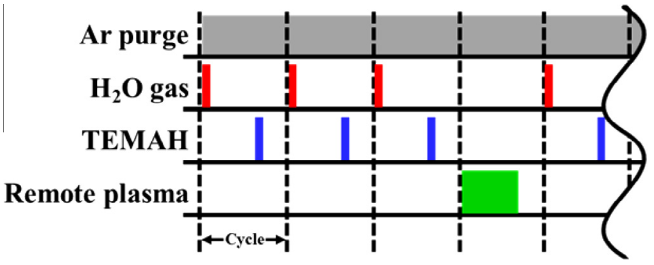

Fig. 1. Process of in situ remote plasma treatment in ALD.

[5]. Besides, stress-induced leakage current (SILC) and stress-induced Vfb shift were measured to investigate the reliability of MOS capacitors.

3. Results and discussion

Fig. 2 shows the X-ray diffraction (XRD) spectra at the diffraction angle (2θ) for (a) 20–40° and (b) 40–60° and a PDA at 650 °C of samples with different in situ plasma treatments. Since there is no obvious peak for the sample with H_2 plasma treatment, its data are not shown. As shown in Fig. 2(a), the angles of tetragonal and monoclinic HfO_2 are about 30.7 and 28.3°, respectively [6,7]. It is found that the diffraction angles for samples with in situ NH_3 and N_2 plasma treatments are close to that of tetragonal HfO_2 (t-HfO_2). It indicates that the crystallization phase of HfO_2 is composed of both t-HfO_2 and m-HfO_2, and more t-HfO_2 could be formed by in situ NH_3 and N_2 plasma treatments. For the sample with NH_3 plasma treatment, an obvious tetragonal peak can also be observed at about 54.33° as shown in Fig. 2(b) [6,8], suggesting more t-HfO_2 is obtained by NH_3 plasma than N_2 one.

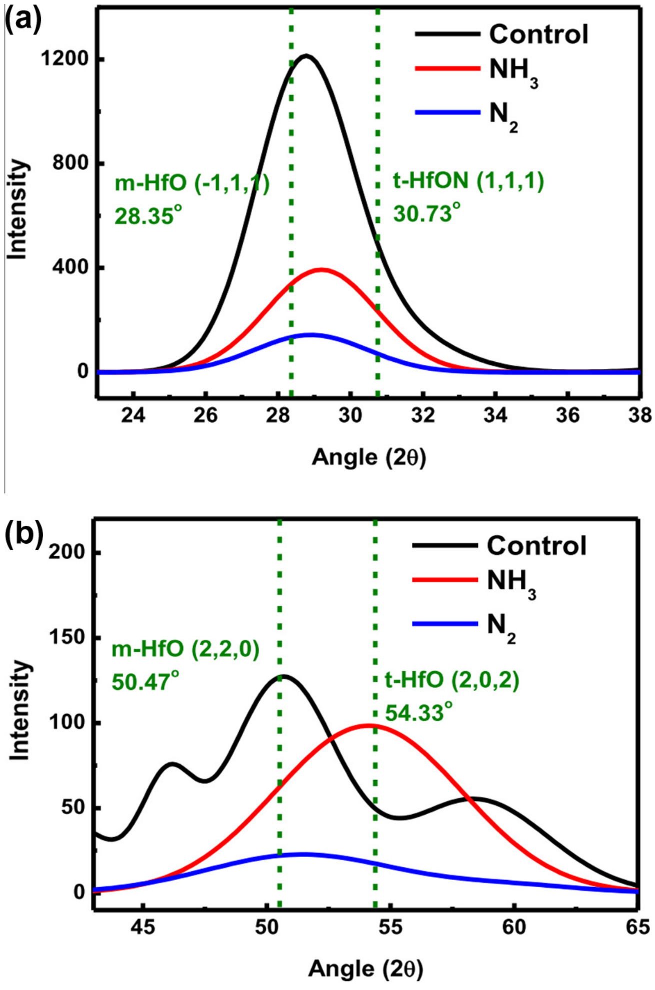

Fig. 2. XRD spectra of HfO_2 films with different plasma treatments at 2θ (a) for 20–40° (b) for 40–60°.

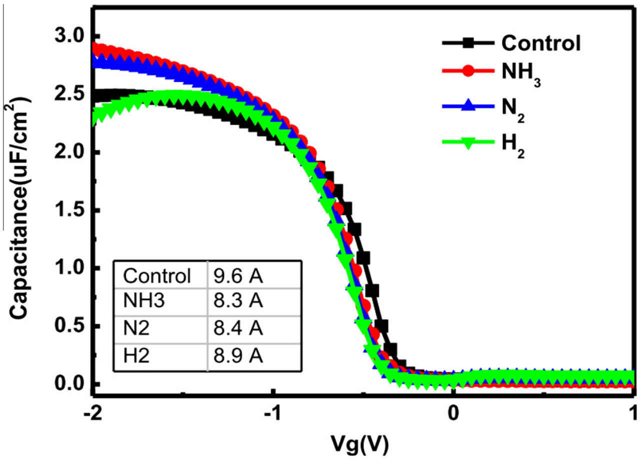

Fig. 3. *C–V* curves for MOS devices with different plasma treatments.

Fig. 3 shows the curves of capacitance versus applied voltage (*C–V*) for samples with different in situ plasma treatments. It is observed that the sample with in situ NH_3 plasma treatment shows a higher capacitance than the others. When the EOT data are correlated with XRD peaks in Fig. 2, the reduction on EOT can be attributed to the t-HfO_2 formation. More composition of t-HfO_2 in crystal HfO_2 can be obtained for the sample with in situ NH_3 plasma treatment in ALD. The *k* values of high-*k* dielectrics for samples with in situ NH_3 and N_2 plasma treatments estimated with IL having a fixed *k* value of 6 are about 29.4 and 28.5, respectively. However, the *k* value of the sample without any in situ plasma treatment is about 21.6. The *k* value of HfO_2 with more t-HfO_2 by in situ plasma treatment is indeed increased about 24%. The data of leakage current (Jg) versus EOT for the all samples are shown in Fig. 4. The EOT can be further scaled without increasing leakage current by in situ NH_3 plasma treatment, which is much below the dashed trend line of the sample without one.

Fig. 5 shows X-ray photoelectron spectroscopy (XPS) of (a) Si 2p and (b) N 1s for samples with different in situ plasma treatments.

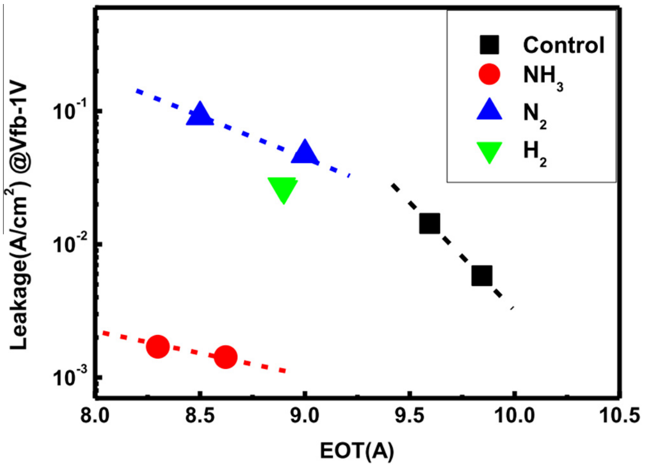

Fig. 4. Jg vs. EOT for MOS devices with different plasma treatments.