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Low inversion equivalent oxide thickness and enhanced mobility in MOSFETs with chlorine plasma interface engineering

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ABSTRACT

High-k gated metal–oxide–semiconductor field-effect-transistors (MOSFETs) with Cl_2 and CF_4 plasma treatments are studied in this work. A higher-k HfON with more tetragonal phase is formed by the halogen plasma treatment on interfacial layer (IL). A low inversion equivalent oxide thickness in MOSFET is obtained with the Cl_2 plasma treated IL. In addition, high mobility and transconductance, and low subthreshold swing are obtained by the Cl_2 plasma treatment, which therefore is a promising interface engineering for advanced MOSFETs.

1. Introduction

High-k gate dielectrics have been implemented to replace SiO_2 or SiON for reducing leakage current with the same effective oxide thickness (EOT) [1,2]. To further achieve a low EOT, the dielectric constant (*k*-value) of HfO_2 with amorphous or monoclinic structure is not enough to obtain an EOT value below 0.8 nm for MOS devices. Therefore, an exotic higher-k dielectric such as HfTiO or HfBiO is formed by doping Ti or Bi atoms into HfO_2. However, their electrical characteristics such as the leakage current and reliability become worse [3]. The thermal stability and electrical characteristics for MOSFET with Ti/HfO_2 higher-k gate dielectric were also studied [4]. On the other hand, the bandgaps of HfO_2 with various crystal phases are similar, indicating that HfO_2 with the tetragonal and cubic phases are expected to increase *k* value without the degradation of leakage or mobility [5,6]. Various halogen treatments were also applied on high-k gate dielectrics to improve electrical performance [7–9]. A suitable amount of fluorine at the interface of HfO_2/SiO_2 can passivate oxygen vacancies and interface traps [10]. Chlorine plasma treatment at the HfO_2/Si interface can enhance the formation of tetragonal HfO_2 (t-HfO_2) [11]. However, effects of halogen plasma on carrier mobility and other characteristics of MOSFETs are not studied in details. In this work, effects of halogen plasma treatments on interface engineering in MOSFETs are investigated. The electrical characteristics of MOSFETs with the Cl_2 and CF_4 plasma treated interfacial layers (IL) are compared.

2. Experiment

MOSFETs are fabricated on (100)-oriented 6-inch P-type Si wafer with resistivity of 15–25 Ω cm. After a Radio Corporation of America clean, a chemical oxide IL is formed by H_2O_2 solution at 75 °C, and then Cl_2 and CF_4 plasma treatments are performed at a flow rate of 80 sccm and a bottom radio frequency power at 5 W. The control sample without halogen plasma treatment is also fabricated for clear comparison. A 3 nm thick HfON is deposited by an atomic layer deposition (ALD) with precursor and oxidizer of $Hf(NCH_3C_2H_5)_4$ (TEMAH) and H_2O, respectively. Then, a post deposition annealing (PDA) is performed at 650 °C in N_2 ambient. Subsequently, a 50 nm thick TaN film is deposited by a sputtering to serve as the metal gate, and a post metallization annealing (PMA) is carried out at 600 °C in N_2 ambient. After pattern definition and source/drain implantation, activation is carried out at 800 °C in N_2 gas for 30 s. A 500 nm thick Al film is then deposited and etched as a metal contact. Finally, a sintering is conducted in a N_2/H_2 ambient at 450 °C for 30 min.

The high-frequency capacitance–voltage (*C*–*V*) measurement is carried out at 100 kHz by using HP4284A. The inversion equivalent oxide thickness (T_{inv}) is extracted from the simulation program

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considering quantum effect [12]. The interface trap density (D_{it}) is estimated by the Hill–Coleman method [13,14] from the peak value of the conductance versus applied voltage (G–V) characteristics at a frequency of 100 kHz.

The threshold voltage (V_t), transconductance (G_m), drain current (I_d), subthreshold swing (S.S.), and mobility are extracted from the current–voltage (I–V) characteristics, which are measured by a HP4156 instrument.

3. Results and discussion

Fig. 1 shows cross-sectional transmission electron microscope (TEM) image of HfON/IL (a) with and (b) without Cl_2 plasma treatment. The IL thickness for the sample with Cl_2 plasma treatment is about 0.6 nm, and that without one (i.e., the control sample) is about 0.5 nm, which is close to the former. It indicates that the IL thickness is almost not changed by the Cl_2 plasma treatment although Cl may react with Si to form $SiCl_x$ sub-products.

Fig. 2 shows X-ray diffraction (XRD) spectra of samples with Cl_2 and CF_4 plasma treatments after a PDA at 650 °C. The peak angles for samples with these two treatments are close to that of t-HfO_2 (30.06°). It indicates that the crystallization phase is composed of both t-HfO_2 and m-HfO_2, and more t-HfO_2 can be formed by the halogen plasma treatment on IL. However, the peak angle of the control sample is located at 28.3°, which represents the monoclinic HfO_2 (m-HfO_2). The schematic mechanism of Cl_2 plasma treatment is illustrated in Fig. 3(a). Cl will react with Si to form $SiCl_x$ sub-products, which can diffuse into high-k dielectrics and enhance the formation of t-HfO_2 after a PDA of 650 °C [11]. On the other hand, the possible mechanism of CF_4 plasma treatment is illustrated in Fig. 3(b). Since IL would be slightly consumed with the CF_4 plasma treatment by desorbing COF_x and SiF_x simultaneously, the dangling bonds may be generated by the etching chemicals of CF_4 plasma [15–17].

Fig. 4 shows leakage current (J_g) versus gate voltage (V_g) of MOSFETs with Cl_2 and CF_4 plasma treatments. It is found that the sample with Cl_2 plasma treatment shows lower J_g than the control sample. Through the results of XRD data as discussed above, it is suggested that the diffusion of $SiCl_x$ sub-products may leave the oxygen radical, which can passivate the oxygen vacancies in IL. Hence, the low J_g of sample with Cl_2 plasma treatment can be attributed to its Cl_2-treated IL. However, the sample with CF_4 plasma treatment shows a higher J_g at a high V_g than the control

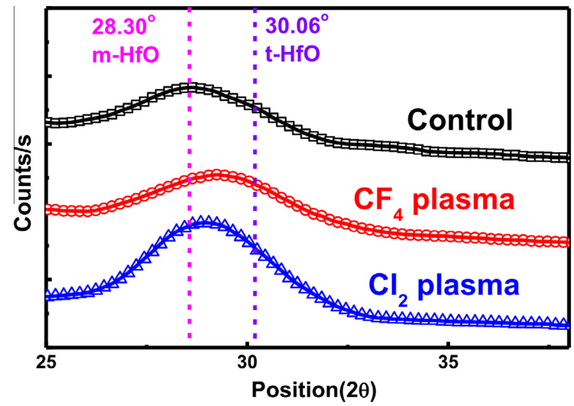

Fig. 2. XRD spectra of samples with Cl_2 and CF_4 plasma treatments.

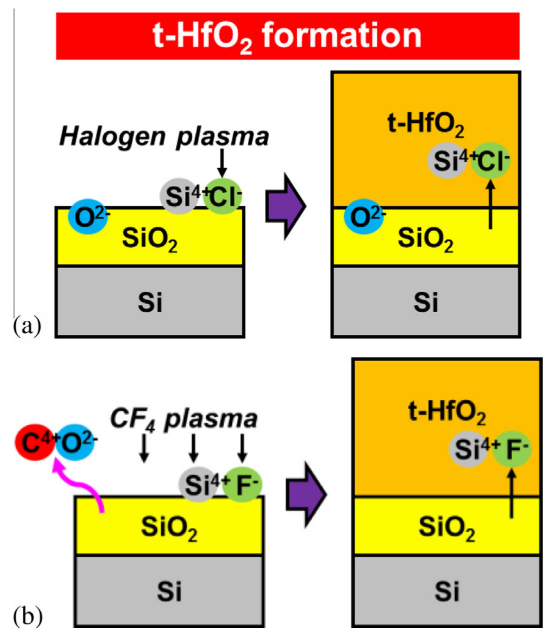

Fig. 3. Schematic mechanism of t-HfO_2 formation by (a) Cl_2 plasma treatment and (b) CF_4 plasma treatment.

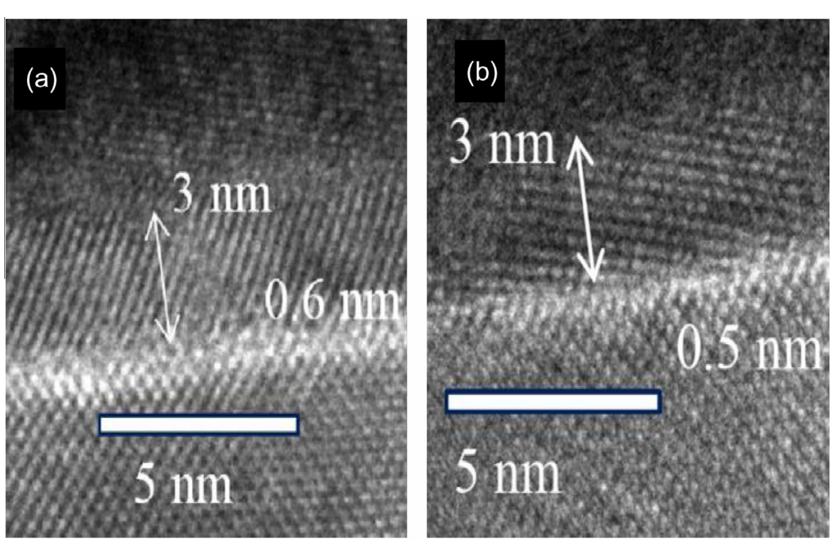

Fig. 1. TEM image of nMOSFETs (a) with and (b) without the Cl_2 treated IL.