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Student Paper

0.76 nm Inversion Equivalent Oxide Thickness and Enhanced Mobility in MOSFETs with Chlorine Plasma Interface Engineering

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

Introduction: The dielectric constant (k value) of HfO_2 with amorphous or monoclinic structure is not enough to obtain an effective oxide thickness (EOT) value below 0.8 nm for MOS devices. To further increase the k value of Hf-based dielectric, 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 even worse [1]. 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 [2]. Various halogen treatments were also applied on high-k gate dielectrics to improve electrical performance. A suitable amount of fluorine at the interface of HfO_2/SiO_2 can passivate oxygen vacancies and interface traps [3]. Chlorine plasma treatment at the HfO_2/Si interface can enhance the formation of tetragonal HfO_2 (t-HfO_2) [4]. In this work, effects of halogen plasma treatments on interface engineering in MOSFETs were investigated. The electrical characteristics of MOSFETs with the Cl_2 and CF_4 plasma treated ILs were compared.

Experiment: A chemical oxide IL was formed on p-type Si wafer by H_2O_2 solution at 75 °C, and then performed by Cl_2 and CF_4 halogen plasma treatment. A 3 nm thick HfON was deposited by an atomic layer deposition (ALD). Then, a post deposition annealing (PDA) was performed at 650 °C in N_2 ambient. 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. After pattern definition and S/D implantation, activation was carried out at 800 °C. A 500 nm thick Al film was then deposited and etched as a metal contact. Finally, a sintering was conducted in a N_2/H_2 ambient at 450 °C for 30 min.

Results and Discussion: Fig. 1 shows the 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 (ie, 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. Fig. 2 shows the X-ray diffraction (XRD) spectra of samples with different halogen plasma treatments after a PDA at 650 °C. The peak angles for samples with Cl_2 and CF_4 plasma treatments are close to the peak angle of t-HfO_2. 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 halogen plasma treatment on IL. The schematic mechanism is illustrated in Fig. 3. Cl would react with Si to form SiClx sub-products, which can diffuse into high-k dielectrics and enhance the formation of t-HfO_2 after a PDA of 650 °C [4]. Fig. 4 shows the drain current (Id) versus gate voltage (Vg) of MOSFETs with different halogen plasma treatments. The extracted transconductance (Gm) and the subthreshold swing (S.S.) are shown in Fig. 5. The maximum Gm and S.S. of the MOSFET with Cl_2 plasma treatment are about 340 uA/V and 63 mV/dec, respectively, which is close to the control sample. The scaling trend of leakage current (Jg) versus inversion equivalent oxide thickness (Tinv) is shown in Fig. 6. The EOT can be further scaled to 0.76 nm by the Cl_2 plasma treatment, which is below the dashed trend line of the control sample. Although more t-HfO_2 can also be obtained by the CF_4 plasma treatment, the IL regrowth is induced by the following thermal activation. Fig.7 shows the Id versus drain voltage (Vd) of MOSFETs with different halogen treatments. The MOSFET with Cl_2 plasma treatment still shows comparable Id, which is about 2.5 uA/um and 3.8 uA/um in linear and saturation regions, respectively. Electron mobility curves of MOSFETs with different halogen plasma treatments are shown in Fig. 8. At low inversion carrier concentration, the maximum value of mobility in MOSFET with Cl_2 plasma treatment is enhanced to 147 cm^2/V-sec. The scaling trend of mobility versus Tinv is shown in Fig. 9. It indicates that the mobility in MOSFET with the Cl_2 treated IL is still high with scaled EOT. However, the MOSFET with the CF_4 plasma treated IL is around the general scaling trend of mobility-Tinv.

In conclusion, the formation of a higher-k t-HfO_2 can be enhanced by halogen plasma treatments on IL, which could achieve ~0.76 nm Tinv in MOSFET. Furthermore, the leakage current is reduced and mobility is increased by the Cl_2 plasma treatment. Hence, Cl_2 plasma is a promising treatment for interface engineering of MOSFETs.

References

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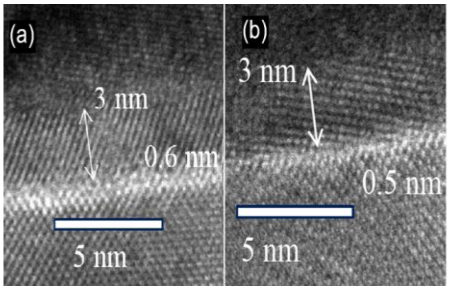

Fig. 1 TEM image of nMOSFETs (a) with and (b) without the Cl_2 treated IL

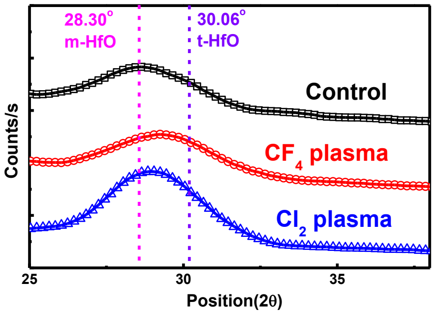

Fig. 2 XRD spectra of samples with different halogen plasma treatments

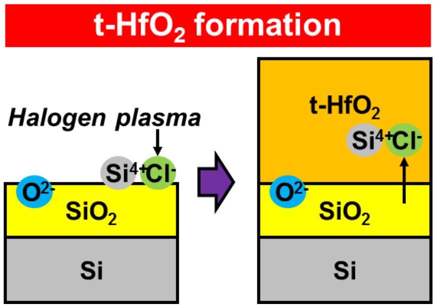

Fig. 3 Schematic mechanism of t-HfO_2 formation by Cl_2 plasma treatment

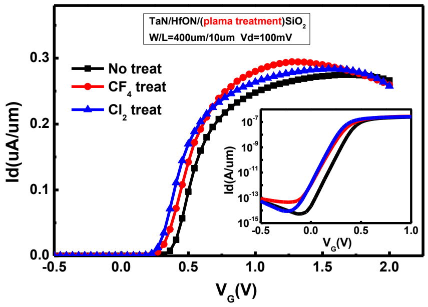

Fig. 4 Id-Vg curves of nMOSFETs with different halogen plasma treatments

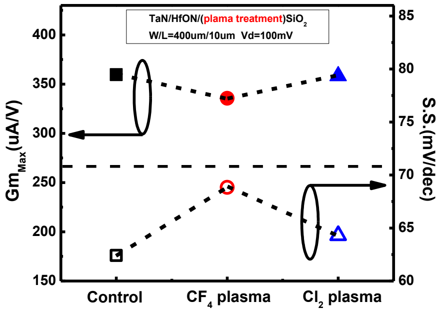

Fig. 5 Gm maximum and S.S. of nMOSFETs with different halogen treatments

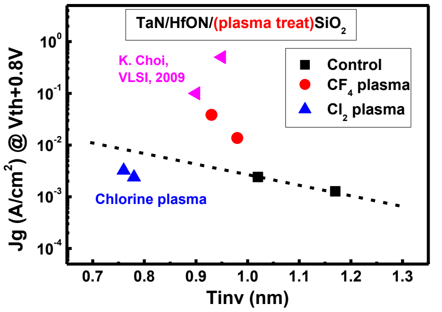

Fig. 6 Jg versus Tinv for nMOSFETs with different plasma treatments

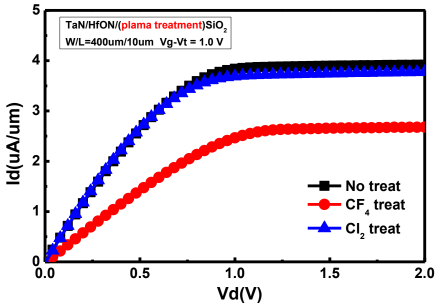

Fig. 7 Id-Vd curves of nMOSFETs with different halogen plasma treatments

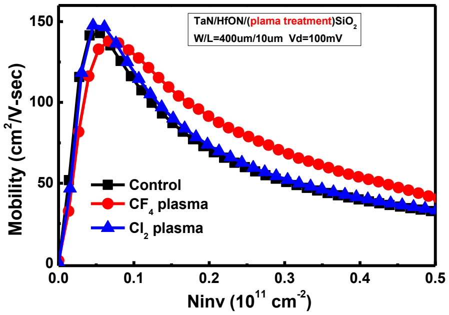

Fig. 8 Mobility for nMOSFETs with different halogen plasma treatments

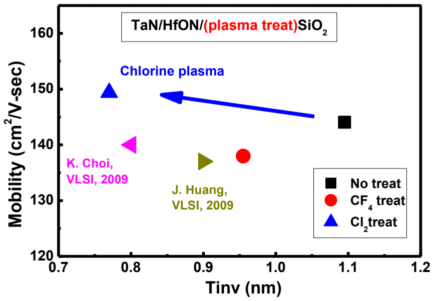

Fig. 9 Mobility versus Tinv for nMOSFETs with different halogen plasma treatments