High Performance Ge pMOSFET with Nitrided Gate Dielectrics and Microwave Annealing

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Abstract
Ge pMOSFET with low EOT of ~0.57 nm, high peak hole mobility of ~652 cm²/V·s, large Ion/Ioff ratio in Id-Vg of ~10⁴, and low S.S. value of ~110 mV/dec are simultaneously achieved by suitable nitridation treatment and microwave annealing (MWA). The high oxidation states of Ge in GeON interfacial layer (IL) can be obtained by using a MWA with low thermal budget.

1. Introduction
Ge is regarded as a promising channel material because of its high carrier mobility. Gate stack engineering is always one of the key factors to achieve high performance Ge MOSFET. GeO2 IL is easy to degrade into GeO at the temperature of process is higher than 400 °C [1], which may lower the band-gap of GeO2 IL to increase gate leakage current density (JG) [2]. The thermal stability of GeO2 can be improved by a nitrided interfacial layer [3]. Good annealing effect with low thermal budget can be achieved by a microwave annealing (MWA) [4]. In this work, effects of nitrogen contents in GeON and HfON doped by in-situ NH3 plasma and MWA on Ge pMOSFETs are comprehensively studied.

2. Results and Discussion
Various thicknesses of GeO2 IL were investigated at first. Fig. 1 shows TEM images of Ge MOS capacitors with (a) 0.32, (b) 0.42, and (c) 0.53 nm thick GeO2 IL, which were formed by H2O plasma. GeO2 is shown as a sharp line on Ge substrate. Fig. 2 shows XPS analysis of samples with various GeO2 IL thicknesses. There is no difference in binding energy shifting of GeO2 against Ge substrate, indicating that the chemical components of GeO2 for all samples are almost identical. Fig. 3 shows XRD analysis of samples with various GeO2 IL thicknesses. High-k dielectrics are obtained according to the tetragonal phase (t) (111) and (220) formation of HfO2. Fig. 4 shows (a) JG-Vg and (b) C-V curves of samples with various GeO2 IL thicknesses. EOT of all samples are around 0.4 nm thanks to the t-HfO2 formation. JG can be reduced by increasing GeO2 IL thickness. Fig. 5 shows JG@Vg=VFB+1 V versus EOT of samples with various GeO2 IL thicknesses. The sample with GeO2 IL thickness of 0.53 nm can obtain a lower JG and similar EOT value of ~0.4 nm. Fig. 6 shows cumulative probability versus JG @ Vg=VFB+1 V of samples with various GeO2 thickness. Sample with GeO2 = 0.53 nm shows the smallest variance of JG among all. Considering both good interface quality and minimized EOT, a GeO2 IL of ~0.5 nm is applied in the following gate dielectric stacks. To enhance characteristics of gate dielectrics, HfON with various nitrogen contents formed by NH3 plasma were studied. Fig. 7 shows XPS analysis of HfON in N 1 s spectra. The existence of N in HfON can be confirmed by detecting the binding energy peak of N. Fig. 8 shows (a) C-V and (b) JG-Vg of samples with various N contents in HfON. Sample with N= 2.5 % shows a larger EOT and lower JG. Fig. 9 shows JG@Vg=VFB+1 V versus EOT of samples with various N contents in HfON. Sample with N= 2.5 % shows the lowest JG and largest EOT. Fig. 10 shows cumulative probability versus JG @ Vg=VFB+1 V of all samples. The variance of JG can be minimized by slightly doping N into HfON [3]. Therefore, HfON with N= 2.5 % is applied in the following gate stack. Fig. 11 shows XPS analysis of GeON in Ge 3d spectra [5] of samples (a) w/o NH3 plasma, w/o MWA, (b) w/o NH3 plasma, w/ MWA, (c) w/ NH3 plasma, w/ MWA, and (d) w/ NH3 plasma, w/ MWA. Sample with NH3 plasma and MWA shows significant difference in Ge oxidation states, which can be attributed to the efficient MWA. Sample w/o NH3 plasma, w/o MWA and w/o NH3 plasma, w/ MWA show similar contents of Ge⁺¹, Ge⁺², Ge⁺³, and Ge⁺⁴ in GeO2 IL. GeON signal corresponding to Ge⁺³ is increased by sample with NH3 plasma, w/o MWA. Fig. 12 shows (a) C-V and (b) JG-Vg of samples with various NH3 plasma and MWA treatments. Sample with NH3 plasma and MWA show the lowest JG of ~2×10⁻⁴ A/cm² at EOT of 0.57 nm, thanks to the GeON with good interface quality. Fig. 14 shows (a) J0-Vg and (b) hole mobility- Ninv of samples with various plasma and MWA treatments. Sample with NH3 plasma and MWA shows the lowest S.S of ~110 mV/dec, largest Ion/Ioff ratio of ~10⁴ in Id-Vg, and the highest peak hole mobility of ~652 cm²/V·s among all. Fig. 15 shows peak hole mobility versus EOT of sample w/ NH3 plasma and w/ MWA. Some benchmarks are also included for comparison. Sample with NH3 plasma and MWA shows J0 of ~2×10⁻⁴ A/cm² at EOT of 0.57 nm, thanks to the GeON with good interface quality. Fig. 14 shows (a) J0-Vg and (b) hole mobility- Ninv of samples with various plasma and MWA treatments. Sample with NH3 plasma and MWA shows the lowest S.S of ~110 mV/dec, largest Ion/Ioff ratio of ~10⁴ in Id-Vg, and the highest peak hole mobility of ~652 cm²/V·s among all. Fig. 15 shows peak hole mobility versus EOT of sample w/ NH3 plasma and w/ MWA. Some benchmarks are also included for comparison. Sample with NH3 plasma and MWA shows peak hole mobility of ~652 cm²/V·s at EOT of ~0.57 nm, which can be attributed to high quality GeON IL.

3. Conclusions
Nitridation of IL and high-k and MWA on gate stack of Ge pMOSFET are comprehensively studied in this work. High performance Ge pMOSFET can be achieved by HfON (N= 2.5 %)/GeON (0.5 nm) gate stack and MWA. A slight nitrogen contents in gate stack and MWA are promising for high-performance Ge pMOSFET.

Fig. 1 TEM images of samples with various GeOx IL thickness (a) ~0.32, (b) ~0.42 and (c) ~0.53 nm formed by H2O plasma.

Fig. 2 XPS of GeOx IL in Ge 3d spectra of all samples.

Fig. 3 XRD analysis of samples with various GeOx thicknesses.

Fig. 4 (a) JG-VG and (b) C-V of sample with various GeOx thicknesses.

Fig. 5 JG-EOT of samples with various GeOx IL thicknesses.

Fig. 6 Cumulative probability versus JG @ VG = VFB + 1 V of all samples.

Fig. 7 XPS analysis of HfON in N 1s spectra.

Fig. 8 (a) C-V and (b) JG-VG of samples with various N % in HfON.

Fig. 9 JG-EOT of samples with various N % in HfON.

Fig. 10 Cumulative probability vs JG @ VG = VFB +1 V of all samples.

Fig. 11 XPS analysis of GeOx IL in Ge 3d spectra for samples (a) w/o NH3 plasma, w/o MWA, (b) w/o NH3 plasma, w/ MWA, (c) w/ NH3 plasma, w/o MWA, and (d) w/ NH3 plasma, w/ MWA.

Fig. 12 (a) C-V and (b) JG-VG of samples with various plasma and MWA treatments.

Fig. 13 JG @ VG = VFB +1 V - EOT of sample with NH3 plasma and w/ MWA.

Fig. 14 (a) In-VG and (b) hole mobility - Ninv of samples with various plasma and MWA treatments.

Fig. 15 Peak hole mobility - EOT of sample w/ NH3 plasma and MWA.