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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 cm^2/V-s, large I_{ON}/I_{OFF} ratio in I_D-V_G of ~10^4, 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. GeO_2 IL is easy to degrade into GeO_x while the temperature of process is higher than 400 °C [1], which may lower the band-gap of GeO_x IL to increase gate leakage current density (J_G) [2]. The thermal stability of GeO_2 can be improved by a nitrited 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 NH_3 plasma and MWA on Ge pMOSFETs are comprehensively studied.

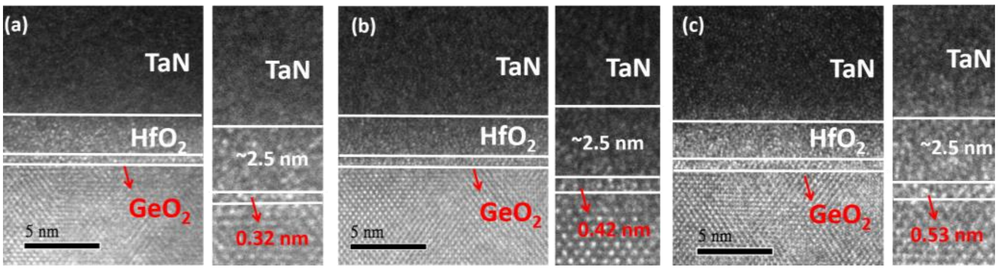
2. Results and Discussion

Various thicknesses of GeO_x 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 GeO_x IL, which were formed by H_2O plasma. GeO_x is shown as a sharp line on Ge substrate. Fig. 2 shows XPS analysis of samples with various GeO_x IL thicknesses. There is no difference in binding energy shifting of GeO_x against Ge substrate, indicating that the chemical components of GeO_x for all samples are almost identical. Fig. 3 shows XRD analysis of samples with various GeO_x IL thicknesses. High-k dielectrics are obtained according to the tetragonal phase (t) (111) and (220) formation of HfO_2. Fig. 4 shows (a) J_G-V_G and (b) C-V curves of samples with various GeO_x IL thicknesses. EOT of all samples are around 0.4 nm thanks to the t-HfO_2 formation. J_G can be reduced by increasing GeO_x IL thickness. Fig. 5 shows J_G@V_G=V_{FB}+1 V versus EOT of samples with various GeO_x IL thicknesses. The sample with GeO_x IL thickness of 0.53 nm can obtain a lower J_G and similar EOT value of ~0.4 nm. Fig. 6 shows cumulative probability versus J_G @ V_G= V_{FB} +1 V of samples with various GeO_x thickness. Sample with GeO_x = 0.53 nm shows the smallest variance of J_G among all. Considering both good interface quality and minimized EOT, a GeO_x 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 NH_3 plasma were studied. Fig. 7 shows XPS analysis of HfON in N 1s 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) J_G-V_G of samples with various N contents in HfON. Sample with N= 2.5 % shows a larger EOT and lower J_G. Fig. 9 shows J_G@V_G=V_{FB}+1 V versus EOT of samples with various N contents in HfON. Sample with N= 2.5 % shows the lowest J_G and largest EOT. Fig. 10 shows cumulative probability versus J_G @ V_G= V_{FB} +1 V of all samples. The variance of J_G 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 GeO_x in Ge 3d spectra [5] of samples (a) w/o NH_3 plasma, w/o MWA, (b) w/o NH_3 plasma, w/ MWA, (c) w/ NH_3 plasma, w/o MWA, and (d) w/ NH_3 plasma, w/ MWA. Sample with NH_3 plasma and MWA shows significant difference in Ge oxidation states, which can be attributed to the efficient MWA. Sample w/o NH_3 plasma, w/o MWA and w/o NH_3 plasma, w/ MWA show similar contents of Ge^{+1}, Ge^{+2}, Ge^{+3}, and Ge^{+4} in GeO_x IL. GeON signal corresponding to Ge^{+3} is increased by sample with NH_3 plasma, w/o MWA. Fig. 12 shows (a) C-V and (b) J_G-V_G of samples with various NH_3 plasma and MWA treatments. Sample with NH_3 plasma and MWA show the lowest J_G of ~2×10^{-5} A/cm^2, which can be attributed to the high oxidation states of Ge in GeON IL. Fig .13 shows J_G @V_G= V_{FB} +1V versus EOT of sample with NH_3 plasma, w/ MWA. Some benchmarks are also included for comparison. Sample with NH_3 plasma and MWA shows J_G of ~ 2×10^{-5} A/cm^2 at EOT of 0.57 nm, thanks to the GeON with good interface quality. Fig. 14 shows (a) I_D-V_G and (b) hole mobility- Ninv of samples with various plasma and MWA treatments. Sample with NH_3 plasma and MWA shows the lowest S.S of ~110 mV/dec, largest I_{ON}/I_{OFF} ratio of ~10^4 in I_D-V_G and the highest peak hole mobility of ~652 cm^2/V-s among all. Fig. 15 shows peak hole mobility versus EOT of sample w/ NH_3 plasma and w/ MWA. Some benchmarks are also included for comparison. Sample with NH_3 plasma and MWA shows peak hole mobility of ~652 cm^2/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.

4. Reference: [1] S. K. Wang et al., (2010) JAP 108(5): 054104. [2] S. H. Yi et al., EDL vol. 38, no. 5, pp. 544-547, May 2017. [3] C. M. Lin et al., IEDM, 2012, pp. 23.2.1-23.1.4. [4] Y. J. Lee et al., IEDM, 2014, pp. 32.7.1-32.7.4. [5] S. H. Yi et al., SNW, 2017, pp. 11-12.



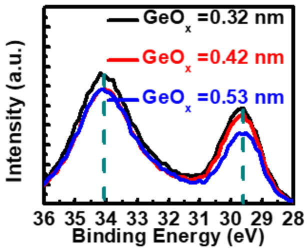


Fig. 1 TEM images of samples with various GeO_x IL thickness (a) ~0.32, (b) ~0.42 and (c) ~0.53 nm formed by H_2O plasma.

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

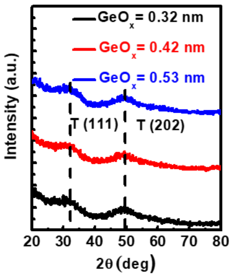


Fig. 3 XRD analysis of samples with various GeO_x thicknesses

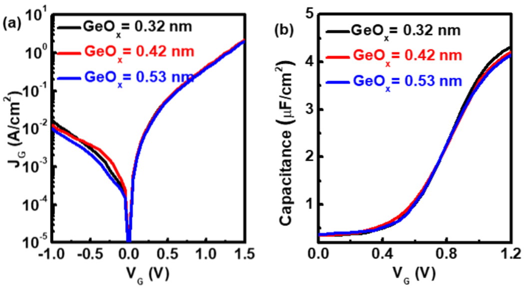


Fig. 4 (a) J_G-V_G and (b) C-V of sample with various GeO_x thicknesses.

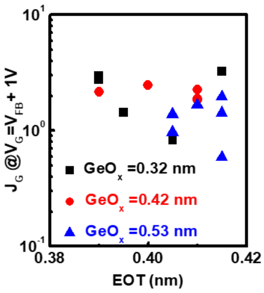


Fig. 5 J_G-EOT of samples with various GeO_x IL thicknesses.

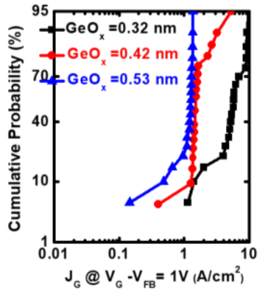


Fig. 6 Cumulative probability versus J_G @ V_G= V_{FB} +1 V of all samples.

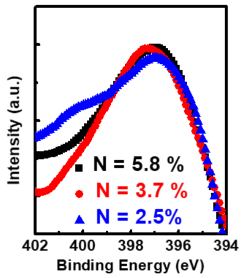


Fig. 7 XPS analysis of HfON in N 1s spectra.

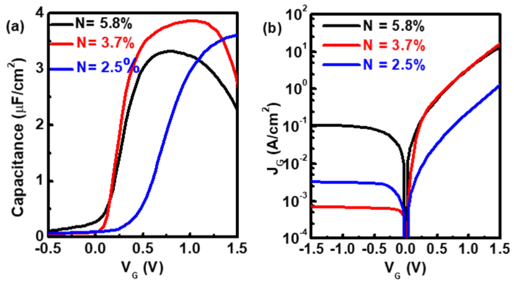


Fig. 8 (a) C-V and (b) J_G-V_G of samples with various N % in HfON.

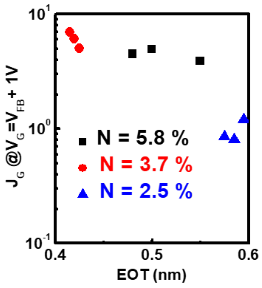


Fig. 9 J_G-EOT of samples with various N % in HfON.

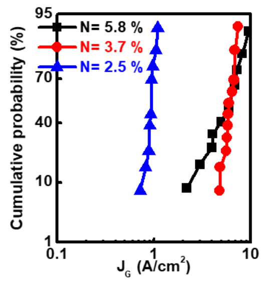


Fig. 10 Cumulative probability vs J_G @ V_G= V_{FB} +1 V of all samples

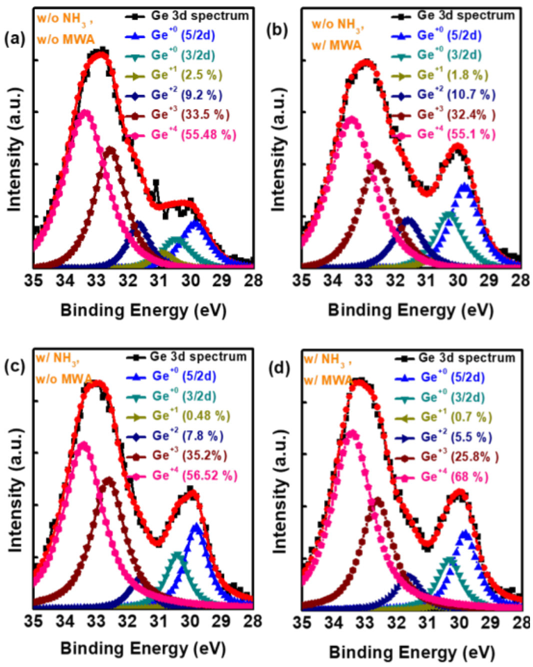


Fig. 11 XPS analysis of GeO_x IL in Ge 3d spectra for samples (a) w/o NH_3 plasma, w/o MWA, (b) w/o NH_3 plasma, w/ MWA, (c) w/ NH_3 plasma, w/o MWA, and (d) w/ NH_3 plasma, w/ MWA.

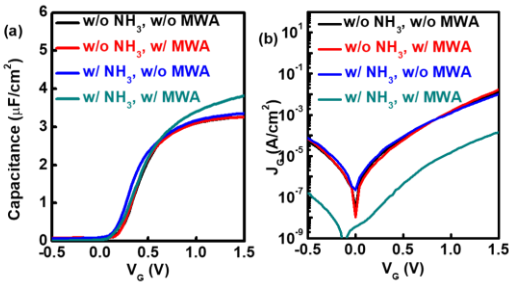


Fig. 12 (a) C-V and (b) J_G-V_G of samples with various plasma and MWA treatments

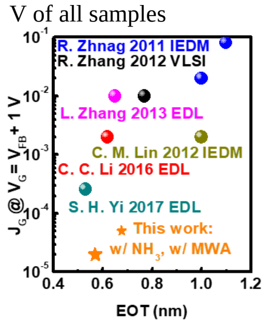


Fig. 13 J_G @V_G= V_{FB} +1V - EOT of sample with NH_3 plasma and w/ MWA.

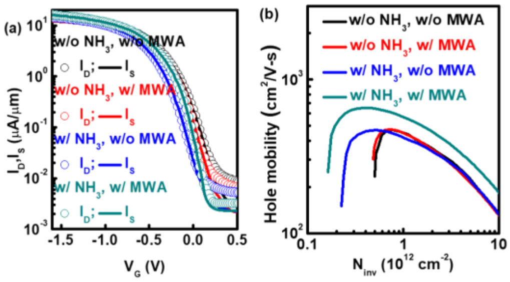


Fig. 14 (a) I_D-V_G and (b) hole mobility- Ninv of samples with various plasma and MWA treatments.

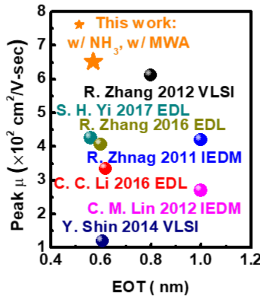


Fig. 15 Peak hole mobility- EOT of sample w/ NH_3 plasma and MWA.