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Ge and O Valence States in GeO_x Interfacial Layer on Hole Mobility of Low EOT Ge pMOSFET

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Abstract

Very high hole mobility in Ge pMOSFET with low EOT is achieved by reducing metastable germanium oxide of Ge^{+1} and Ge^{+3} in GeO_x layer, which are oxygen vacancies to act as scattering centers resulting in mobility degradation. Correlation between hole mobility and metastable germanium oxide or oxygen vacancy in GeO_x interfacial layer of Ge pMOSFET with different gate stacks are studied in depth.

1. Introduction

Interfacial layer (IL) is one of the key factors for achieving high mobility Ge pMOSFETs. Yttrium-based gate dielectric with GeO_x IL [1] and post-deposited- oxidation (PPO) technique with $AlGeO_x$ IL [2] were proposed to obtain high mobility Ge MOSFETs. Although the behaviors of carrier mobility in Ge MOSFET were widely reported [3], [4], [5], effects of valence state of germanium and oxygen in GeO_x interfacial layer (IL) on mobility are not clear yet. In this work, Ge pMOSFETs with different gate stacks were analyzed by X-ray photoelectron spectroscopy (XPS) to investigate the correlation between hole mobility and valence state of germanium and oxygen.

2. Experimental:

Ge pMOSFETs were fabricated by gate first process in this work. After HF clean, a germanium oxide IL was grown by H_2O plasma, and then HfO_2 gate dielectrics was deposited, the gate stack for samples were in-situ deposited in the ALD chamber to ensure dielectric quality. Next, a TiN metal gate of 100 nm was sputtered and patterned. After that, B ion implantation was applied at 15 keV and 5×10^{15} cm^{-2} to form source and drain. A PMA process at 450 °C for 30 s was performed to activate junction. A Ni metal of 50 nm was deposited to serve as electrode. A sintering at 350 °C was carried out for 30 min. The cross-sectional view, detailed process flow, and experimental conditions of Ge pMOSFETs are shown in Fig. 1. Illustration of gate stacks for samples in this work is shown in Fig. 2. HfO_2 and ZrO_2 were generally used as high-k gate dielectric [6]. Al_2O_3 and metal-caps were proposed to serve as buffer layer for Ge MOSFET [7]. The gate stacks of sample S1, S2, S3 and S4 are HfO_2/GeO_x, $HfO_2/Al_2O_3/GeO_x$, $ZrO_2/Al_2O_3/GeO_x$ and ZrO_2/ZrO-cap/GeO_x, respectively. The channel width/channel length (W/L) of Ge pMOSFET tested in this work is 400 μm/10 μm. X-ray photoelectron spectroscopy (XPS) was applied to analyze valence state of germanium and oxygen in the GeO_x interfacial layer.

3. Results and discussion:

Fig. 3 shows X-ray photoelectron spectroscopy (XPS) of GeO_x IL with percentages of Ge^{+1}, Ge^{+2}, Ge^{+3} and Ge^{+4} for sample (a) S1, (b) S2, (c) S3 and (d) S4, respectively. The contents of Ge^{+1} and Ge^{+3} in GeO_x IL for sample S1, S2, S3 and S4 are 45.23 %, 45.31 %, 30.24 % and 18.56 %, respectively. It is noted that the nature germanium oxides are Ge^{+2} (GeO) or Ge^{+4} (GeO_2); while Ge^{+1} and Ge^{+3} are metastable state with oxygen vacancy. Fig. 4 shows XPS O 1s spectra of GeO_x IL in percentage of germanium oxide and oxygen vacancy. The contents of oxygen vacancy of sample S1, S2, S3 and S4 are 53.56 %, 46.52 %, 42.54 % and 39 %, respectively. The trend of Ge^{+1} and Ge^{+3} in Fig. 3 exactly matches with that of Fig. 4. Fig. 5 shows hole mobility versus inversion charge density (N_{inv}) of samples with different gate stacks, evaluated by split C-V method. Peak hole mobility of sample S1, S2, S3 and S4 are 410, 504, 650 and 802 cm^2/V-s, respectively. The difference in hole mobility could be attributed to the contents of Ge^{+1}, Ge^{+3} and oxygen vacancy. The oxygen vacancy in GeO_x IL plays crucial roles on hole mobility of Ge pMOSFET. Fig. 6 shows drain current versus gate voltage (I_D-V_G) of samples with different gate stacks. A low sub-threshold swing (S.S.) value of 119 mV/dec and high Ion/Ioff ratio of $\sim10^4$ are obtained for sample S4. The difference in I_{on}/I_{off} ratio may be attributed to that in its gate leakage density. Fig. 7 shows peak hole mobility versus EOT of sample S4 with some benchmarks for comparison. Thanks to a low content of Ge^{+1}, Ge^{+3} and oxygen vacancy, sample S4 exhibits very high peak hole mobility at an EOT value of ~0.6 nm.

4. Conclusions:

The hole mobility of Ge pMOSFET is strongly correlated to metastable germanium oxide and oxygen vacancy in GeO_x IL. Low content of Ge^{+1}, Ge^{+3} and oxygen vacancy in GeO_x interfacial layer is required to achieve high hole mobility in Ge pMOSFET.

References:

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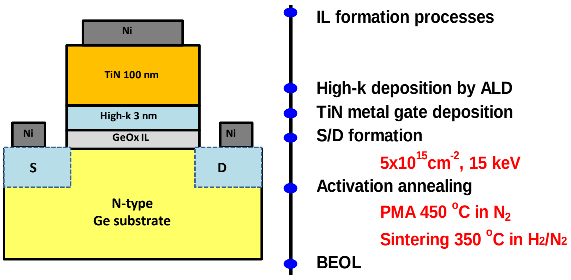

Fig. 1 Cross-sectional view of Ge pMOSFET and process flow in this work.

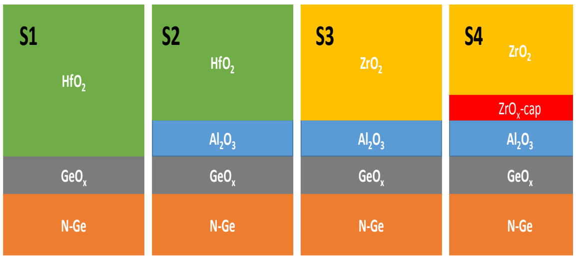

Fig. 2 Illustration of gate stack for samples in this work

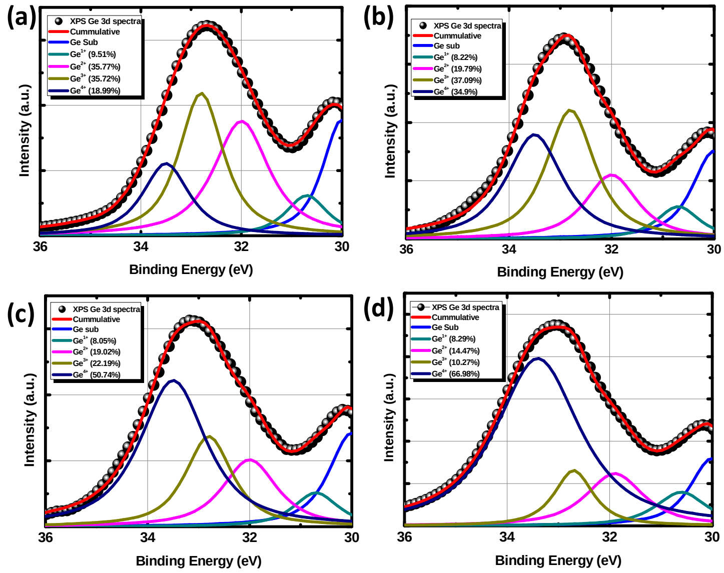

Fig. 3 XPS analysis of Ge oxidation state with percentage of Ge^{+1}, Ge^{+2}, Ge^{+3} and Ge^{+4} in GeO_x IL for samples (a) S1, (b) S2, (c) S3, and (d) S4.

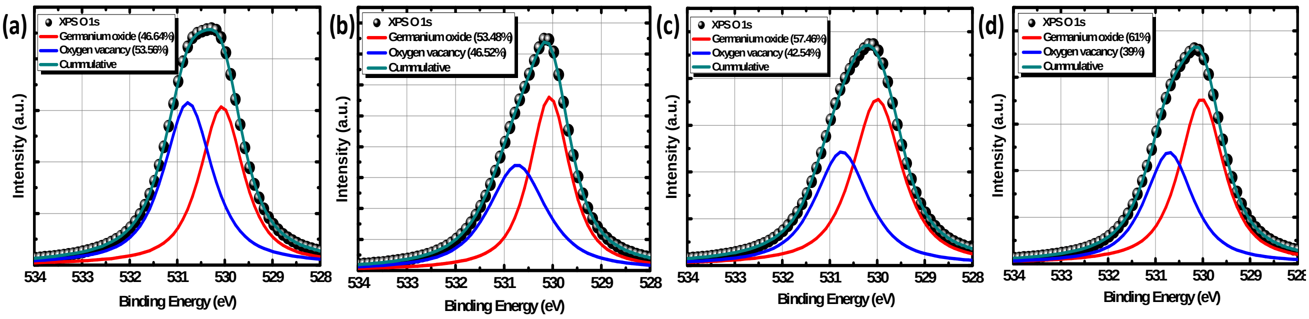

Fig. 4 XPS analysis of oxygen valence state with percentage of germanium oxide and oxygen vacancy in GeO_x for samples (a) S1, (b) S2 (c) S3 and (d) S4. The contents of oxygen vacancy of sample S1, S2, S3 and S4 are 53.56 %, 46.52 %, 42.54 % and 39 %, respectively. The contents of Ge^{+1} and Ge^{+3} are obviously suppressed for sample S4 with ZrO_2/Zr-cap/GeO_x gate stack, which shows the lowest contents of Ge^{+1} and Ge^{+3} among all samples.

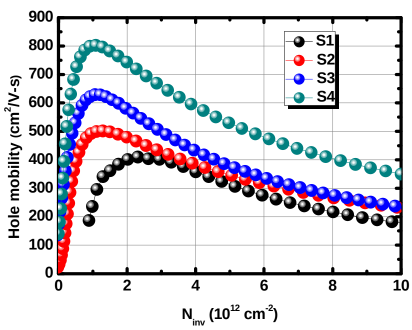

Fig. 5 Hole mobility versus N_{inv} of samples with different gate stacks in this work. The mobility strongly correlates with contents of Ge^{+1}, Ge^{+3} and oxygen vacancy.

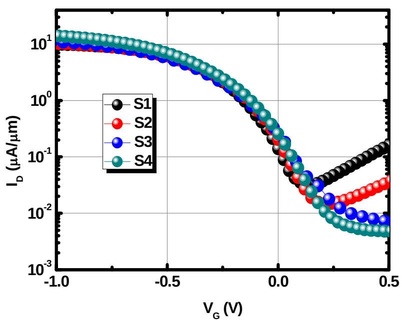

Fig. 6 Drain current I_D versus gate voltage V_G of samples with different gate stacks in this work.

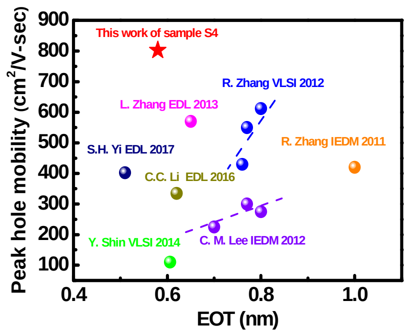

Fig. 7 Peak hole mobility–EOT of sample S4 in this work with some benchmarks.