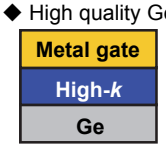
Study on HfO_2/GeO_2 interfacial reaction in Ge-MOS devices

Germanium (Ge) is expected to be an alternative material for high performance MOSFET due to its higher carrier mobility than silicon (Si). However, the deposition of HfO_2 film on Ge degrades the electrical properties of MOSFET. In this study, we investigated the HfO_2/GeO_2 interfacial reaction and thermal diffusion of the atoms to obtain the guideline for electrical improvement.

Motivation: Realization of high performance High-*k*/Ge based MOSFET

◆ High quality Ge-MOS stacks



✔ Ge channel: High carrier mobility
✔ High-*k* dielectric: Under 1nm-thick EOT
EOT: Equivalent Oxide Thickness

⇒ Realization of Metal/High-*k*/Ge stacks for high performance MOSFET

Comparison of Ge-MOS properties

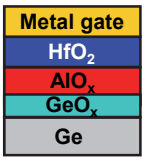
	Interface property	EOT
GeO_2/Ge stack	○ < 10^{11} $cm^{-2}eV^{-1}$ [1]	× (Low-*k*)
HfO_2/Ge stack	× Interface defects [2]	○ (High-*k*)

[1] H. Matsubara *et al.*, Appl. Phys. Lett. **93**, 032104 (2008).
[2] N. Wu *et al.*, Appl. Phys. Lett. **84**, 19, 3741 (2004).

✔ Need both good interface property and EOT scaling

Improvement techniques
⇒ Interfacial GeO_x layer: High-*k*/GeO_x/Ge stacks
⇒ AlO_x insertion into HfO_2/GeO_x interface [3, 4]

[3] R. Zhang *et al.*, VLSI Tech. Symp., 161 (2012).
[4] R. Asahara *et al.*, Appl. Phys. Lett. **106**, 233503 (2015).



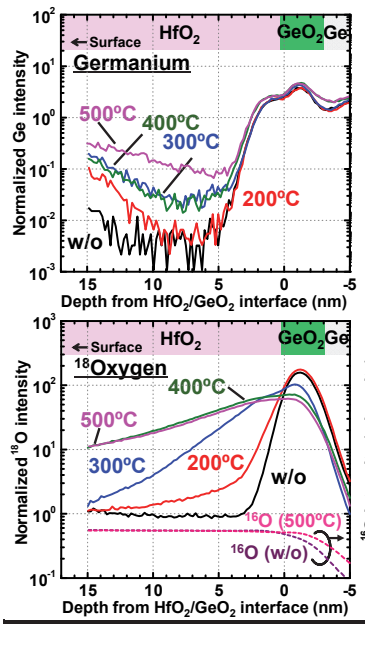
◆ **Purpose of this study: Control of HfO_2/GeO_x interfacial reaction**

✔ Evaluation of HfO_2/GeO_2 interfacial reaction and atomic diffusion
✔ Verification of effect of ultrathin AlO_x layer insertion

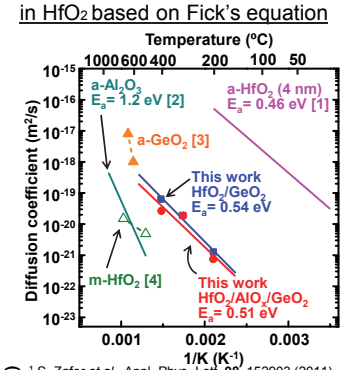
Evaluation of oxygen diffusion behavior by dynamic SIMS with isotope tracer (^{18}O)

◆ **we made the stacked structures using ordinary ^{16}O and heavy oxygen (^{18}O), to investigate the oxygen diffusion in HfO_2 film by SIMS.**

SIMS profiles of $Hf^{16}O_2/Ge^{18}O_2/Ge$



Diffusion coefficient of Oxygen in HfO_2 based on Fick's equation



[1] S. Zafer *et al.*, Appl. Phys. Lett. **98**, 152903 (2011).
[2] T. Nabatame *et al.*, Jpn. J. Appl. Phys. **42**, 7205 (2003).
[3] S. K. Wang *et al.*, Jpn. J. Appl. Phys. **50**, 04DA01 (2011).
[4] T. Nabatame *et al.*, SSDM, C-2-4 (2002).

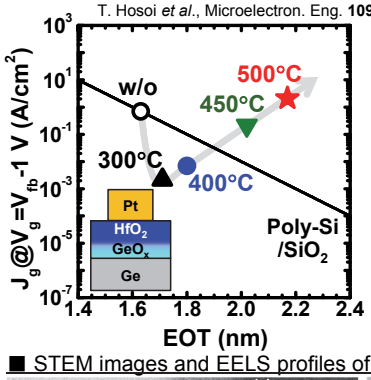
♦ Oxygen inter-diffused at HfO_2/GeO_2 interface.
♦ Low E_a of oxygen

⇒ Independent diffusion of Ge and oxygen
⇒ No relationship between oxygen diffusion and electrical properties

Evaluation of gate stacks by STEM-EELS (Study on HfO_2/GeO_x interfacial reaction)

◆ **Relationship between leakage current (J_g), EOT and annealing temperature after gate stack formation**

T. Hosoi *et al.*, Microelectron. Eng. **109**, 137 (2013).

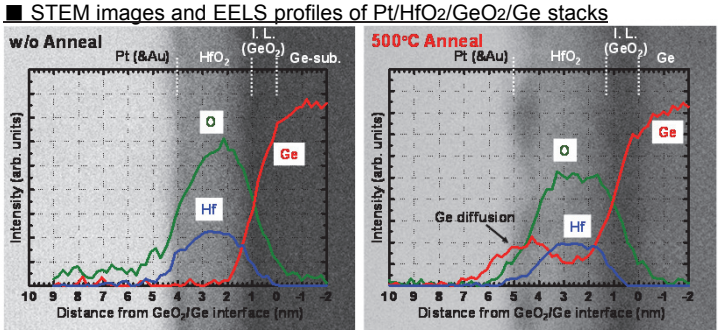


Increase in leakage current and EOT over 400°C annealing

⇓

Investigation of stacked structures and elemental distribution by STEM-EELS

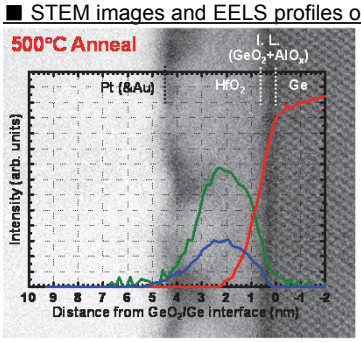
■ STEM images and EELS profiles of $Pt/HfO_2/GeO_2/Ge$ stacks



♦ Increase in GeO_x interlayer after annealing ⇒ Increase in EOT
♦ Ge diffusion into HfO_2 surface after annealing ⇒ Increase in J_g
⇒ Enhancement of HfO_2/GeO_x interfacial reaction by high temperature annealing (thermal instability)

◆ **Verification of effect of ultrathin AlO_x layer insertion**

■ STEM images and EELS profiles of $Pt/HfO_2/AlO_x/GeO_x/Ge$ stacks



♦ No change of GeO_x interlayer
⇒ Realization of sub-nm EOT
♦ No diffusion of Ge into HfO_2
⇒ Good interface properties
♦ Slight increase in roughness on HfO_2 film after 500°C annealing
⇒ Further improvement is needed

☆ Independent diffusion of Ge and oxygen in HfO_2
⇒ Ge diffusion is attributable to electrical degradation.
☆ Suppression of HfO_2/GeO_x interfacial reaction and atomic diffusion by ultrathin AlO_x layer insertion.
⇒ Control of interfacial reaction is key for improvement.

Guideline for high performance high-*k*/Ge MOSFET
✔ Understanding the characteristics of individual atoms
✔ Precise control of Interface properties