Record-high Electron Mobility in Sub-nm EOT Ge n-MOSFETs with Y-doped GeO$_2$ Interfacial Layer

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[Introduction] We have examined the effect of metal cation (Y, Sc, Al, Hf) doping into GeO$_2$ on improvements of thermal stability and water solubility as well as interface properties [1-3], and trivalent metal cation (Y and Sc) seemed to be the most effective way to overcome the intrinsic disadvantages of pure GeO$_2$ interfacial layer (IL). The objective of this work is to verify our IL engineering for sub-nm EOT Ge MOSFETs. The EOT scaling of high-$k$ gate stacks on Ge with Y-doped GeO$_2$ (YGO) IL is first provided, and the record-high electron mobility in 0.7 nm EOT Ge n-MOSFETs is demonstrated for a wide range of $N_s$.

[Experiment] To achieve sub-nm EOT gate stacks with superior interface properties, YGO formation on Ge was optimized. 1 nm-thick YGO was deposited on Ge by co-sputtering of Y$_2$O$_3$ and GeO$_2$ targets. The thickness and chemical states of YGO were estimated by Ge 3$d$ core level spectra of XPS measurements, and the atomic concentration of Y was estimated by Y/Ge atomic composition ratio in YGO. Then, HfO$_2$ was deposited on 1 nm-thick 10% YGO IL to examine the EOT scaling with YGO IL. PDA was carried out at 500°C for 30 sec in N$_2$/O$_2$ (0.1%) ambient. Finally, Ge n-MOSFETs were fabricated on atomically flat Ge (111) surface [4] to verify our IL engineering concept.

[Results and Discussion] Fig. 1 shows bidirectional $C$-$V$ curves of Au/HfO$_2$/YGO/Ge stacks measured at 1 MHz. A very small hysteresis (~20 mV) and no $V_{FB}$ shift indicate the excellent interface properties similar to YGO/Ge stacks. Note that HfO$_2$/YGO/Ge stack is thermally stable up to 550°C without interface degradation. 0.47 nm-thick EOT on Ge was achieved with 1 nm-thick HfO$_2$/YGO(1 nm)/Ge stack, which is one of the lowest EOT on Ge gate stacks. Excellent gate leakage current and superior interface properties of HfO$_2$/YGO/Ge stack are originated from strong barrier properties of YGO against oxygen. This is clear evidence that our thermodynamic-based guideline for YGO IL on Ge is valid for gate stack formation. The high-$N_s$ electron mobility benchmark in the sub-nm region of Ge n-MOSFETs is shown in Fig. 2, which indicates that the present results are far above the results reported so far. Both the highest peak mobility (828 cm$^2$/Vs) and high-$N_s$ mobility (437 cm$^2$/Vs) in Ge n-MOSFETs with 0.7 nm EOT were demonstrated, which is two times higher than the scaled Si n-MOSFETs. Note that the enhancement of high-$N_s$ electron mobility in HfO$_2$/YGO/Ge stack was observed by maintaining atomically flat YGO/Ge interface similar to GeO$_2$/Ge one [5]. This can be achieved by superior bulk and interface properties of YGO IL, and further EOT scaling is possible without a cost of mobility degradation thanks to thermodynamically robust YGO IL.


Fig. 1 Bidirectional $C$-$V$ characteristics of HfO$_2$/YGO/Ge stacks. It shows good $C$-$V$ curves similar to YGO/Ge stack, and 0.47 nm-thick EOT on Ge was achieved with 1 nm-thick HfO$_2$/YGO(1 nm)/Ge stack.

Fig. 2 High-$N_s$ electron mobility as a function of EOT at $N_s$ = $1 \times 10^{13}$ cm$^{-2}$. The highest high-$N_s$ mobility of 437 cm$^2$/Vs in Ge n-MOSFETs with 0.7 nm EOT is demonstrated. This can be achieved by superior interface properties of YGO IL.