# Effects of interfacial layer between high-k gate dielectric and InGaAs surface on its inversion layer electron mobility

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## **1. Introduction**

Formation of high quality high-k/InGaAs MOS interface with thin EOT is crucial for realization of high-performance and low-power InGaAs channel MOSFETs. Although it has been shown that an  $Al_2O_3$  gate insulator grown by an atomic layer deposition (ALD) showed relatively small interface state density ( $D_{it}$ ) among various high-k MOS [1], thinner EOT with lower leakage required higher-k materials such as HfO<sub>2</sub>. Recently, HfO<sub>2</sub>/interfacial- $Al_2O_3$  stacked gate insulator structures were reported to be promising for this purpose [2-4]. However, an impact of  $Al_2O_3$  thickness on the inversion layer electron mobility, which is a critical issue due to possible trade-off between EOT and the quality of MOS interface, has not been well investigated yet. On the other hand, understanding of the effects of deposition temperature in ALD on the mobility has not been thoroughly studied in spite of its technological and scientific importance.

In this study, we have investigated the effect of ALD temperature on the MOS interfacial quality of InGaAs MOSFETs with  $Al_2O_3$  and HfO<sub>2</sub> gate dielectrics and found that lower deposition temperature leaded to thicker interfacial oxides and higher inversion layer electron mobility. We have also investigated the effect of the interfacial  $Al_2O_3$ thickness on the mobility in MOSFETs with HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> stacked high-k layers. It was found that higher electron mobility was obtained for the thicker ones.

#### 2. Experimental

300nm-thick p(n)-In<sub>0.53</sub>Ga<sub>0.47</sub>As layers doped with Zn(Si) of the concentration of  $2x10^{16}$  cm<sup>-3</sup> were grown on (001) p(n)-InP substrates by MOCVD. ALD processes were performed at temperatures between  $150^{9}$ C and  $275^{9}$ C for HfO<sub>2</sub> or Al<sub>2</sub>O<sub>3</sub> single layers. HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> stacked gate insulators with the interfacial-Al<sub>2</sub>O<sub>3</sub> layers of the thicknesses from 1 cycle to 10 cycles were formed at 200<sup>o</sup>C on the substrates. Fig. 1 shows the fabrication procedure of InGaAs n-MOSFETs on the p-InGaAs substrate. A self-aligned Ni-alloy metal source/drain structure was employed [5]. The inversion layer electron mobility was estimated by split-CV measurements for the MOSFETs. MOS Capacitors on the n-InGaAs substrates were also fabricated with the same stacks as the MOSFETs. XPS was performed to investigate oxide states at the MOS interfaces with thin (<1nm) Al<sub>2</sub>O<sub>3</sub> and HfO<sub>2</sub> after a post-deposition annealing (PDA) at 350<sup>o</sup>C in N<sub>2</sub> atmosphere to assess the thermal effect in the BEOL process for the MOSFETs.

#### 3. Results

Fig. 2 shows a deposition temperature dependence of the inversion layer electron mobility for the MOSFETs having the Al<sub>2</sub>O<sub>3</sub> and HfO<sub>2</sub> gate insulators. A notation of H150 or A200 means HfO2 75cycles deposited at 150°C or Al<sub>2</sub>O<sub>3</sub> 75 cycles deposited at 200°C, respectively. It shows that the inversion layer electron mobility of the MOSFET with Al<sub>2</sub>O<sub>3</sub> gate dielectric was higher than the (001) Si universal mobility while that with HfO2 layer was less than the universal mobility. It is also found that a lower deposition temperature resulted in higher electron mobility in the both cases. Fig. 3 shows minimum sub-threshold swing (S) and interface-state density (D<sub>it</sub>) estimated by the S factor with respect to the ALD deposition temperature. Lower D<sub>it</sub> values were observed for a deposition temperature of 150<sup>0</sup>C than for higher temperatures. These facts suggest that the degradation of the inversion layer electron mobility was related to the amount of the interfacial states density. Then we investigated chemical states of the interface between the high-k layer and the InGaAs channel by XPS. Fig. 4 shows As2p3 spectra of the HfO2/InGaAs interface and the

Al<sub>2</sub>O<sub>3</sub>/InGaAs interface as a parameter of the deposition temperature. It is confirmed that thicker As oxide grew during the PDA for lower deposition temperature, especially in the case of  $HfO_2$  (Ga oxide was also grown especially in  $HfO_2$ , not shown here). This fact indicates that the thicker As or Ga oxide is related to lower  $D_{it}$  and higher mobility although these oxides have been thought as the origin of  $D_{it}$  so far [1].

Then we investigated the impact of the thickness of the Al<sub>2</sub>O<sub>3</sub> interfacial layer on the electron mobility in the MOSFETs with HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> stacked gate insulator. The high-k dielectrics were deposited at  $200^{\circ}$ C. Fig. 5 shows the mobility of HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> MOSFETs with various Al2O3 thicknesses. H75/A5 means HfO2 75cycles/Al<sub>2</sub>O<sub>3</sub> 5cycles in this figure. It indicates that only Al<sub>2</sub>O<sub>3</sub> of 10cycles exhibited higher mobility than that for the HfO<sub>2</sub> single layer, but it was still lower than that for  $Al_2O_3$  single layer. The  $Al_2O_3$  thickness dependence of the mobility at  $N_s=2x10^{12}$  cm<sup>-2</sup> and  $9x10^{12}$  $cm^{-2}$  in the Fig. 5 is summarized in Fig. 6. It shows that the thin Al<sub>2</sub>O<sub>3</sub> layer below 10 cycles leaded to the degradation of the mobility while Al<sub>2</sub>O<sub>3</sub> of 10 cycles resulted in about 2 times as high mobility as that of 0 cycle (=HfO<sub>2</sub>) at N<sub>s</sub>= $2x10^{12}$  cm<sup>-2</sup>. S factor and D<sub>it</sub> around the mid-gap for each Al<sub>2</sub>O<sub>3</sub> thickness are plotted in Fig. 7, which shows that these values were positively correlated with the mobility. Fig. 8 shows frequency dispersions of MOSCAPs around accumulation region and flat-band voltage as a function of Al<sub>2</sub>O<sub>3</sub> thickness. These two dispersions showed a similar dependence on the Al<sub>2</sub>O<sub>3</sub> thickness. The former dispersion has been reported to correspond to D<sub>it</sub> and the latter has been thought to correlate with border traps in high-k [2] or interface states in conduction band which were pointed out to result from As-As anti-bonding states [6]. These traps or interface states would be one of the origins of the mobility degradation. Fig. 9 shows the correlation between the electron mobility and the mid-gap  $D_{it}.\ It$ was found that strong negative correlation existed between these parameters.

For examining the origin of the mobility degradation, the temperature dependence of the mobility in A75 and H75/A10 were evaluated at temperatures between  $-25^{\circ}$ C and  $150^{\circ}$ C. It was found from Fig. 10 that the mobility of A75 and H75/A10 below  $50^{\circ}$ C was very weakly dependent on the temperature, whose power index was -0.52 and -0.27 respectively. In this temperature region, the surface roughness scattering is found to be the dominant mobility-limiting mechanism, judging from the low power index of the temperature [7]. This result suggests that the correlation between the mobility and D<sub>it</sub> would reflect the correlation between the surface roughness and the interface states. On the other hand, the mobility of H75/A10 above  $50^{\circ}$ C seems to be dominated by the phonon scattering. This difference between HfO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> would result from the stronger remote phonon in HfO<sub>2</sub> than that in Al<sub>2</sub>O<sub>3</sub> [8].

## 3. Conclusions

We investigated the impact of ALD temperature and the  $Al_2O_3$ interfacial layer thickness on the inversion layer electron mobility in the HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>/In<sub>0.53</sub>Ga<sub>0.47</sub>As n-MOSFET. It was found that lower ALD temperature resulted in thicker interfacial oxides, higher electron mobility and lower Dit in the range of  $150^{\circ}C - 275^{\circ}C$ . The mobility of the HfO<sub>2</sub>/InGaAs MOSFET was improved by inserting Al<sub>2</sub>O<sub>3</sub> of 10 cycles between the HfO<sub>2</sub> layer and the InGaAs channel while its mobility was still lower than that of Al<sub>2</sub>O<sub>3</sub>/InGaAs. On the other hand, thin Al<sub>2</sub>O<sub>3</sub> (<10cycles) caused the degradation of the mobility and interfacial characteristics such as D<sub>it</sub>. The surface roughness is

suggested to be mobility limiting mechanism from the temperature dependence. These results imply that the degradation of D<sub>it</sub> strongly correlate with the interface roughening.

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## References

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500

400

300

200

100 S

900

factor (mV/dec)

AI2O3 S facto

-HfO2 S factor

Al2O3 Dit

HfO2 Dit

150



Fig. 2 Deposition temperature dependence of the inversion layer electron mobility in Al2O3/InGaAs and HfO2/InGaAs.



200

Depositon temperature (°C)



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[8] B. Laikhtman et al., J. Appl. Phys. 103, 014501 (2008)

- $(NH_4)_2S$  (5min) $\rightarrow H_2O(1min) \rightarrow Dry$  (N2)
- High-k deposition [ALD with H<sub>2</sub>O for oxidant,
- precursor(TEMAH, TMA) first @200°C~275°C]
- TaN 30nm deposition
- Gate definition : i-line lithography and RIE
- SD formation : Ni deposition and anneal at 350℃ 1min in N2
- Ni removal by HCl

1x10<sup>15</sup>

1x10<sup>1</sup> 멅

1x10<sup>13</sup>

300<sup>12</sup>

GIII

Fig. 1 Fabrication procedure of InGaAs n-MISFETs.





500

400



Fig. 4 As2p3 XPS spectra of (a) Al<sub>2</sub>O<sub>3</sub>/InGaAs and (b) HfO<sub>2</sub>/InGaAs for each deposition temperature. These samples were NH<sub>4</sub>OH treated and annealed at  $350^0\bar{C}$  in  $N_2$  atmosphere after high-k dielectric deposition.



Fig. 8 Frequency dispersion of capacitances around accumulation and flatband as a function of ALD Al2O3 cycle number. The accumulation capacitance dispersion is defined as  $(C_{1kHz}-C_{100kHz})/C_{100kHz}$  and the capacitance dispersion around flat-band voltage is defined as  $(C_{1kHz}-C_{100kHz})/C_{100kHz}$  at flat-band volatag+0.3V.

250





1x10<sup>15</sup>

Dit (cm-2eV-1)

function of  $Al_2O_3$  thickness HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>/InGaAs.

Electron mobility Fig. 6 at  $Ns=2x10^{12}$  and  $Ns=9x10^{12}$  cm<sup>-2</sup> as a in





Fig. 9 Correlation between Dit and the inversion layer electron mobility in HfO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> 0~10cycles /InGaAs MOSFETs at Ns=2x10<sup>12</sup>cm<sup>-2</sup> and  $9x10^{12}cm^{-2}$ .



Fig. 10 Temperature dependence of the electron mobility of Al<sub>2</sub>O<sub>3</sub> 75cyle and 75cycle/Al<sub>2</sub>O<sub>3</sub> HfO<sub>2</sub> 10cycle at  $Ns=9x10^{12}cm^{-2}$ .