Interface States at high-κ/InGaAs interface: H_2O vs. O_3 based ALD Dielectric

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1. Introduction

Interface states at the high-κ/III-V interface are considered to be one of the major showstoppers for the implementation of III-V channel MOSFETs in VLSI technology. Due to the large interfacial state density, D_{it}, comparable with density of states of free carriers the standard, high-low freq., Terman, and conductance methods become unreliable. Recently, [1,2] proposed obtaining the parameters of the equivalent admittance circuit (including substrate capacitance, D_{it}, trap time constant, channel resistance and gate leakage) by fitting the experimental frequency dispersion of the capacitance and conductance curves in a self consistent manner.

In this study, we identify the D_{it} distribution and the traps characteristic time constant vs. the trap energy by *combining the above mentioned method [1,2] with the low-high frequency [3] and Terman techniques [4].* We apply the technique to study the defects in the water (H_20) based ALD Al_2O_3/ $In_{0.53}Ga_{0.47}As$ and in the ozone (O_3) based ALD Al_2O_3/$In_{0.53}Ga_{0.47}As$ stacks. H_2O-based ALD allows reduction in the formation of the native oxide at the high-κ/IIIV interface, while O_3-based oxide is known to contain less OH groups within the high-κ resulting in less bulk trapping of carriers. Comparing the extracted trap capture cross-section dependences vs. temperature and trap energy, we conclude that: (i) water-based ALD allows reducing the number of electrically active traps (ii) the traps in the water-based ALD high-κ film respond (recharge) by more than an order of magnitude slower that those in O_3-based high-κ film.

2. Device Fabrication

N and P doped $In_{0.53}Ga_{0.47}As$ was epitaxially grown on a InP substrate. After the ammonia based surface clean the Al_2O_3 films were deposited on $In_{0.53}Ga_{0.47}As$ using either a H_2O-based or O_3-based atomic layer deposition (ALD) followed by post anneal. The TaN/TiN metal was deposited and patterned as top electrode. The AuGe alloy was deposited to form a backside ohmic contact.

3. Results

D_{it} extraction: The admittance characteristics of the fabricated capacitors were measured for 200K to 425K temperature range. Fig. 1 and 2 show the measured capacitance at RT for the H_2O and O_3-based ALD high-κ. Fig. 3 shows the calculated ideal C-V dependency for the 8nm Al_2O_3 high-κ/ $In_{0.53}Ga_{0.47}As$ stack [5] taking into account the conduction band non-parabolicity and carrier distribution in Γ, L and X valleys. We have used low temperature and high temperature C-V data sets in order to accurately evaluate the effects of interface and border traps. At 425 K the traps are fast enough ($2\pi f\ \tau >> 1$, see Fig. 5(b)) for the 1kHz C-V to be considered as a true low frequency C-V. In this case the trap response is quasi-static and the trap capacitance, $C_{it}=qD_{it}$. The high temperature low frequency C-V and the "stretch-out" of the low temperature high frequency C-V characteristic (a "true" high frequency C-V) were theoretically reproduced. Fig. 4 shows the result of this iterative fitting exercise for both H_2O-based and O_3-based ALD high-κ. The C-V with non-parabolic (NP) correction including all valleys was used for this exercise. The simulated C-V with C_{it} represents the quasi-static case and C-V without C_{it} represents the high frequency case (includes the stretch-out in gate bias due to D_{it}). The evaluated D_{it} from p and n type samples are in good agreement (Fig. 5(a)). The trap density for the O_3-based ALD is ~1.5 times higher than that of H_2O-based ALD sample.

Interfacial layer analysis: An XPS study on these samples shows the presence of the As-O bonds in the O_3-based ALD sample. The use of O_3 as oxidant for the ALD growth of Al_2O_3 on $In_{0.53}Ga_{0.47}As$ has resulted in excessive interfacial oxidation consistent with [6]. Due to the presence of a native oxide at the oxide-substrate interface the measured oxide capacitance for the O_3-based ALD is ~ 10% lower than that of the H_2O-based sample.

Trapping kinetics: The characteristic traps capture times (for the mid gap traps) obtained from the conductance peaks (Fig. 5(b)) shows an order of magnitude faster response time for the O_3-based ALD high-κ. The extracted capture cross-section of the mid gap traps in both samples were found to be weakly depend on temperature (Fig. 5(b)) and for the O_3-based sample to be ~1 orders of magnitude larger than that for the H_2O-based sample. It is opposite to the expected trend if the electrons were to tunnel through the native oxide in the O_3-based sample before they can get trapped by the high-κ defects, leading to a decrease in the capture cross-section. This observation indicates that the traps may have a significantly different atomic structure, and chemical bonds. It is worth noting that the energy dependence of the capture time is rather weak in both samples (Fig. 6(a) and 6(b)). Fig. 7 shows the comparison of the mid-gap D_{it} compared with other works reported in literature.

4. Conclusion

By combining the capacitance and conductance analysis techniques, we obtained the D_{it} distribution throughout the band gap of $In_{0.53}Ga_{0.47}As$ capacitors with H_2O-based and O_3-based ALD oxides. The choice of appropriate temperature to obtain the quasi-static C-V and the DC voltage sweep rate is an essential for the correct extraction of D_{it}. Simultaneously we obtained the trap kinetics characteristics. We claim that: (i) the H_2O-based ALD deposition results in a fewer traps in the lower portion of $In_{0.53}Ga_{0.47}As$ band gap, (ii) is

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related to the formation of the thicker native oxide in the O_3-based samples; (iii) the mid gap traps in the H_2O-based samples are significantly slower than those in the O_3-based samples, which indicate their different nature.

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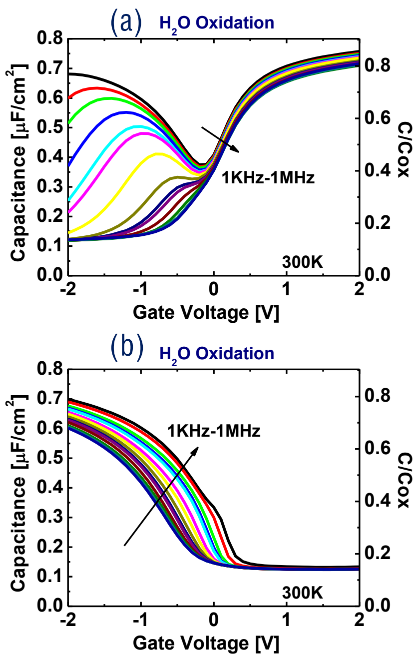

Fig.1: C-V characteristics as a function of frequency of (a) ntype and (b) ptype $In_{0.53}Ga_{0.47}As$ Moscap with H_2O based ALD Al_2O_3.

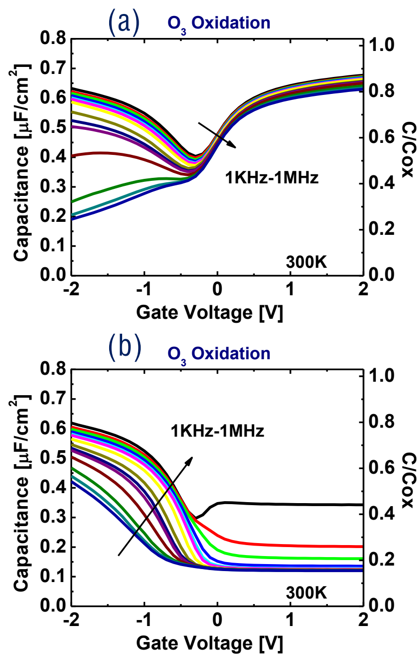

Fig.2: C-V characteristics as a function of frequency of (a) ntype and (b) ptype $In_{0.53}Ga_{0.47}As$ Moscap with O_3 based ALD Al_2O_3.

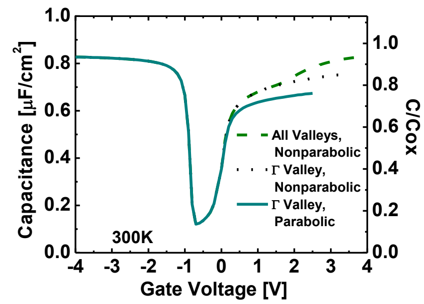

Fig.3: Simulated capacitance showing the effect of non parabolic approximation and satellite valley for $In_{0.53}Ga_{0.47}As$ with 8nm Al_2O_3 high-κ (εr~8) as a function of gate bias.

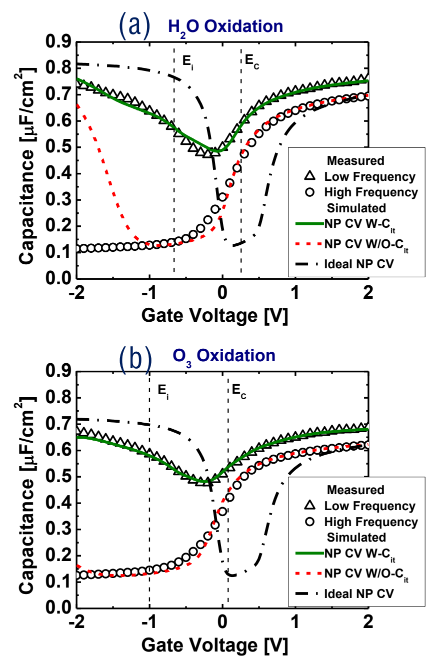

Fig.4: Measured true Low and High frequency fitted with calculated C-V with D_{it} for ntype $In_{0.53}Ga_{0.47}As$ Moscap with (a) H_2O and (b) O_3 based ALD Al_2O_3.

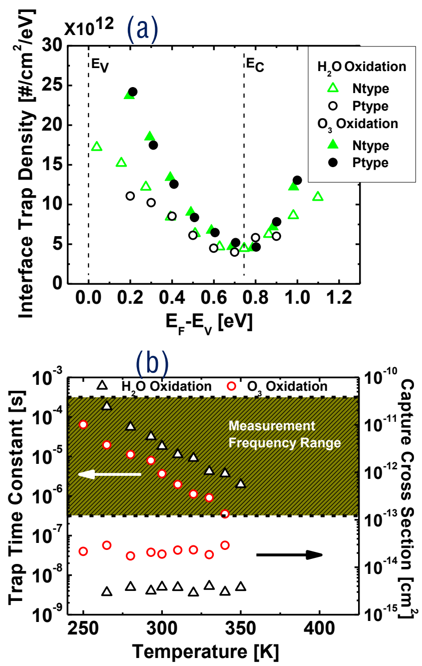

Fig.5: Extracted (a) interface trap density and (b) interface trap time constant and capture cross section at E_F~Eg/2 for the water and ozone based ALD Al_2O_3.

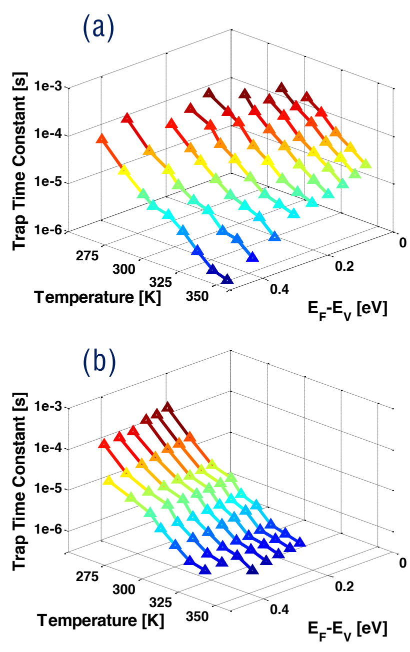

Fig.6: Trap time constant as a function of energy and temperature for (a) H_2O and (b) O_3 based ALD Al_2O_3.

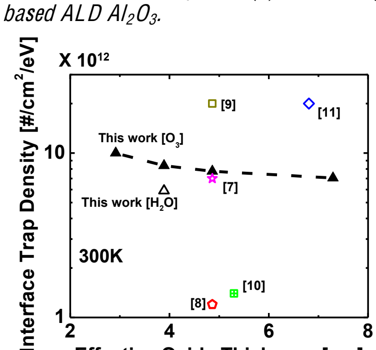

Fig.7: Midgap D_{it} evaluated by conductance method at room temperature compared with other work reported in literature.