Student Paper

InGaAs n-MOS devices integrated using ALD-HfO_2/metal gate without surface cleaning and interfacial layer passivation

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The aggressive scaling of Si CMOS device has called for high κ dielectrics and metal gates. However, the phonon issue related to the high κ gate dielectrics has lead to degraded channel mobility. Extensive research activities are now being taken on channel materials, such as InGaAs, with mobility higher than that of Si. $In_{0.53}$ $Ga_{0.47}As$, lattice matched to InP, and $In_{0.15}Ga_{0.85}As$, strained growth on GaAs, have been used as a backbone for almost all the high-speed electronic devices in high electron mobility transistor (HEMT) with very high cutoff frequency. Oxide gates may improve device performance, e.g. in reducing gate leakage and increasing I_{on}/I_{off} ratio. Atomic layer deposited (ALD) high κ dielectric HfO_2 films on air-exposed $In_{0.53}Ga_{0.47}As$/InP and $In_{0.15}Ga_{0.85}As$ /GaAs were found to have an atomically sharp interface, free of arsenic oxides, which is believed to attribute to the Fermi level un-pinning. The energy band parameters were measured for $HfO_2/In_{0.53}Ga_{0.47}As$ and $HfO_2/In_{0.15}Ga_{0.85}As$, respectively.

Figure 1 (a)-(b) show the HR-TEM for air-exposed $In_{0.53}Ga_{0.47}As$ and ALD-HfO_2/ $In_{0.53}Ga_{0.47}As$, respectively. The detailed chemical state and distribution, including arsenic or arsenic oxides are studied using XPS, as shown in Fig. 2 (a)-(c). After the ALD-HfO_2 growth, As_2O_3 was removed from the oxide/InGaAs interface. No arsenic oxides (As_2O_3 or As_2O_5) were found to be on top of the as-grown ALD-HfO_2. The detection of Ga_2O_3, In_2O_3, and $In(OH)_3$ at the HfO_2-InGaAs interface was made possible with HR-XPS using synchrotron radiation or with AR (angle-resolved)-XPS. An abrupt transition from InGaAs to ALD-HfO_2 with a thin interfacial layer was observed using HR-TEM. The similar results were observed for air-exposed $In_{0.15}Ga_{0.85}As$ and ALD-HfO_2/ $In_{0.15}Ga_{0.85}As$, respectively. The removal of the arsenic oxides from HfO_2/InGaAs heterostructures during ALD process ensures the Fermi level unpinning, which was observed in the C-V measurements.

As illustrated in Fig. 3, C-V curves for $In_{0.53}Ga_{0.47}As$ show accumulation and inversion. The C-V at 1 kHz shows a similar behavior as the C-V of Si MOS diodes at 1 or 10Hz, namely the occurrence of inversion. In contrast, C-V curves show much larger frequency dispersion for $In_{0.15}Ga_{0.85}As$ sample (Fig. 4).

Low leakage current densities of ~10^{-7} to 10^{-9} A/cm^2 at electrical fields less than 4 MV/cm (Fig.5) were measured for the 7.8 nm HfO_2 on $In_{0.53}Ga_{0.47}As$/InP, annealed at 375°C for 60 min in forming gas. The current transport of the MOS device can be explained by the Fowler-Nordheim tunneling mechanism. Similar transport properties were measured on $In_{0.15}Ga_{0.85}As$ /GaAs. The conduction-band offset of ~ 1.8 and 1.48eV were determined for $HfO_2/In_{0.53}Ga_{0.47}As$ and HfO_2/ $In_{0.15}Ga_{0.85}As$, respectively. The valence band offset at the $HfO_2/In_{0.53}Ga_{0.47}As$ and HfO_2/ $In_{0.15}Ga_{0.85}As$ interface was determined using XPS to be ~2.9 eV and ~2.65 eV, respectively, as shown in Fig. 6. The energy band parameters determined from XPS and the transport measurement are listed in Fig. 7.

There is no surface cleaning and interfacial passivation layer prior to the ALD-HfO_2. However, the oxide/InGaAs interface is atomically sharp without the existence of arsenic oxides, strongly indicating self-cleaning of the ALD process. Excellent well-behaved J-E_G and C-V characteristics of ALD-HfO_2/ $In_{0.53}Ga_{0.47}As$/InP have been demonstrated in this work.

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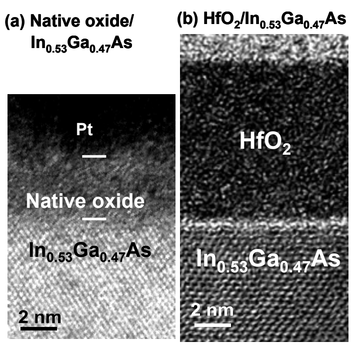

Fig. 1 Cross-sectional HRTEM images of the air-exposed $In_{0.53}Ga_{0.47}As$ sample (a) prior to (b) after deposition of HfO_2. Most of the native oxide (3.6nm) was annihilated after the ALD growth. The thickness of HfO_2 is about 7.8nm.

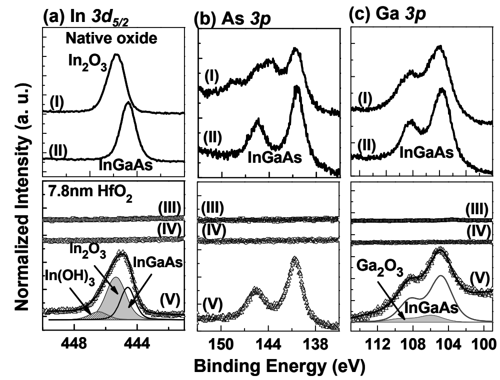

Fig. 2 (a) In $3d_{5/2}$, (b)As $3p$, (c) Ga $3p$, and core-level spectra of 7.8 nm thick HfO_2 film grown on $In_{0.53}Ga_{0.47}As$. (I) and (II) are designated for regions at the surface and in the bulk of air-exposed $In_{0.53}Ga_{0.47}As$.(III). (V), and (VI) are those at the surface, in the bulk of the ALD oxide, and at the oxide/$In_{0.53}Ga_{0.47}As$ Interface.

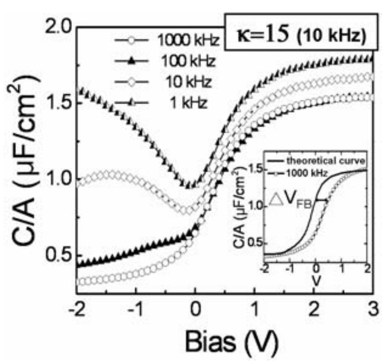

Fig. 3 C-V curves of TiN/ALD-HfO_2 (7.8 nm) /$In_{0.53}Ga_{0.47}As$ MOS diode under frequencies from 1kHz to 1 MHz, with inset showing the C-V curve measured at 1 MHz in comparison with the theoretical curve (D_{it}=0). The dielectric constant deduced from the 10 kHz CV curve is about 15.

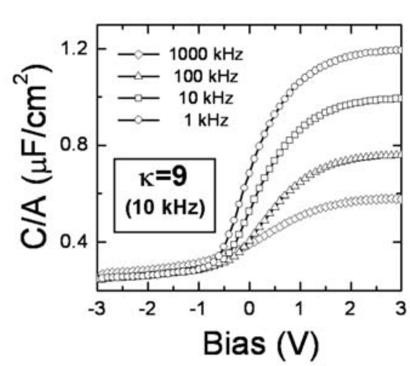

Fig. 4 C-V curves of a MOS diode consists of Au/Ti/ALD-HfO_2 (8.3 nm)/$In_{0.15}Ga_{0.85}As$. The dielectric constant deduced from the 10 kHz CV curve is about 9.

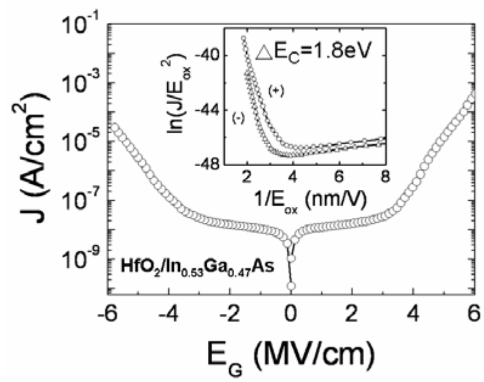

Fig. 5 Current density (J) as a function of gate electrical field (E_G) for the TiN/ALD-HfO_2/$In_{0.53}Ga_{0.47}As$ MOS diode of t_{ox}=7.8 nm, with the inset showing the electrical data in terms of $\ln(J/E_{ox}^2)$ versus $1/E_{ox}$. The linear region at high E_{ox} for both forward (+) and reverse (-) biase of inset is where the FN tunneling occurs.

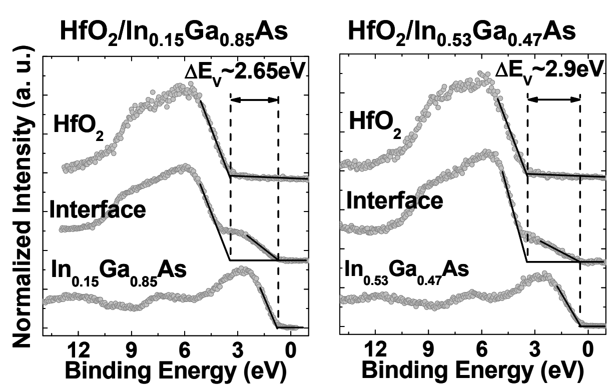

Fig. 6 The valence band offsets ΔE_V are defined as the energy difference between the valence band maximum (VBM) of the HfO_2 and InGaAs.

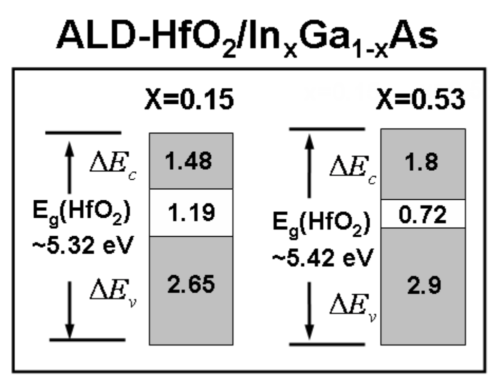

Fig. 7 Energy band parameters of ALD-HfO_2/ $In_xGa_{1-x}As$ (x = 0.15 and 0.53)