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Scanning probe microscopy imaging before and after atomic layer oxide deposition on a compound semiconductor surface

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Most of the highest performance n-channel enhancement mode InGaAs MOSFETs have been fabricated using trimethylaluminum (TMA) and water atomic layer deposition (ALD) for the Al_2O_3 gate oxide consistent with TMA being an unusually favorable precursor on InGaAs. Half cycle room temperature ALD of trimethylaluminum (TMA) and dimethylaluminium ethoxide (DEAE) have been performed on InAs(001) and InGaAs(001) surfaces to compare two precursors for the same oxide, one of which is oxygen-free and one which contains oxygen. Scanning tunneling spectroscopy and microscopy (STS and STM) and Kelvin probe force microscopy (KPFM) studies determined that the Fermi levels of the clean InAs and InGaAs (4×2) surfaces are pinned 0.3eV above the valance band while DFT studies show that the surfaces are pinned by homodimers in the trough. STM and STS show that TMA forms an ordered monolayer of absorbates (Fig 1) which unpins the Fermi level (Fig 2) suggesting that an ordered monolayer layer might be a requirement for unpinning. Conversely, STS shows that DEAE also unpins InGaAs(001)-(4x2), but STM shows this precursor forms a nearly amorphous monolayer layer. The influence of the larger ligands on the DEAE might account for more degeneracy in bonding configurations making absorbates less ordered while retaining monolayer instead of multilayer coverage. The results are consistent with a multitude of bonding configurations being able to unpin the Fermi level as long as the pining sites are removed and the presence of oxygen in the precursor not being an impediment to passivation as long as there is still attractive interaction between the absorbates which promote monolayer formation.

While planar STM and KPFM are ideal to study nucleation of ALD reactions, different tools are needed to probe the buried oxide-semiconductor interface once the full gate oxide has been deposited. In cross-sectional KPFM, (X-KPFM), a fully functional MOSFET or MOSCAP is cleaved in UHV, and the potential inside the working device is measured in two-dimensions (Fig 3); UHV cleaving is critical to preserve an oxide-free surface so the unperturbed potentials can be measured. Cross-sectional KPFM can determine the effect of surface passivation of the gate oxide in operational devices, influence of the fixed charge in the gate oxide with semiconductor channel material, structural features and their effects on the potential distribution, and even work function offsets of the gate and semiconductor. The cleave edge of the sample drastically affects the stability of the cantilever. In order to increase the stability, the devices were embedded in a >300nm insulator; therefore, the device of interest in not located directly on the edge face. Using this capping technique, high spatial resolution in a UHV cleaved MOSCAP with KPFM (Fig 4) shows the amount of band bending in the semiconductor channel caused by the fixed charge in the oxide. High resolution KPFM has also been demonstrated for a range of external gate biases, illustrating the flexibility of KPFM for investigating MOS devices.

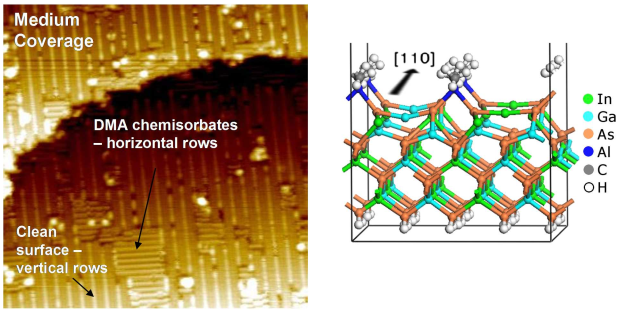

FIG. 1: (left): STM image (-2.00 V, 100 pA) of InAs(001)-(4×2) exposed to TMA with 200°C anneal showing the formation of ordered domains of reaction sites (dimethyl aluminum, DMA). Similar results observed on $In_{0.53}Ga_{0.47}As(001)$-(4x2) (right) DFT ball-and-stick diagram of the ½ ML DMA adsorption which induces the β3'(4 × 2) to ι(2 × 2) reconstruction allowing formation of Al bridge bonding to two As atoms.

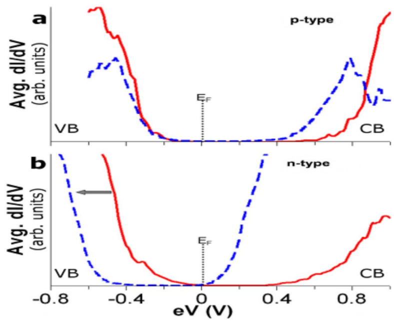

FIG. 2: STS of clean (red lines) vs. ML TMA dosed and 200°C annealed (blue lines) InGaAs(001)-(4×2). a) For p-type, the E_F is unchanged with respect to the VBM. b) The clean n-type surface shows p-type behavior, consistent with a pinned Fermi level. After full ML coverage of TMA-induced surface reaction, the E_F shifts towards the CBM consistent with passivation of the surface via TMA reaction.

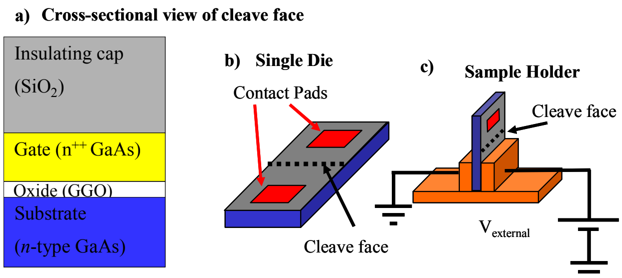

Figure 3: (a) Cross-sectional view of MOSCAP gate stack. (b) Top down view of a single sample Die. Triangle indicates location of nick on surface prior to entering UHV. (c) Schematic of the sample holder and external contacts.

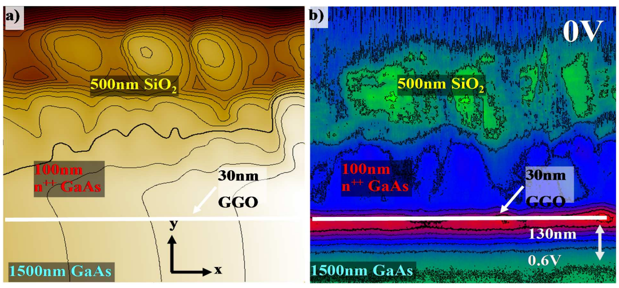

Figure 4: KPFM of UHV Cleaved MOSCAP: (a) 1000 nm ×1000 nm topology image of UHV cleaved GaAs MOSCAP, corresponding to the 0 V gate bias CPD image. Contour lines 10 nm increments. (b) 1000×1000nm high resolution CPD image at 0 V gate bias. Contour lines 100 mV increments.

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