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Electrical and Chemical Analysis of the in-situ H_2 Plasma Cleaned InGaSb-Al_2O_3 Interface

D.A.J. Millar[1], S. Supardan[2], U. Peralagu[1], M. Sousa[3], X. Li[1], V.R. Dhanak[2], Y.C. Fu[1], M. Steer[1], H. Schmid[3], I.Z. Mitrovic[2] and I.G. Thayne[1]

[1]School of Engineering, University of Glasgow, United Kingdom
[2]Department of Electrical Engineering & Electronics, University of Liverpool, United Kingdom
[3]IBM Zurich Research Laboratory, Switzerland

Antimony-based compound semiconductors are promising candidates to replace silicon as the channel material in future complementary metal oxide semiconductor (CMOS) technology nodes due to their excellent transport properties for both electrons and holes [1]. $In_xGa_{1-x}Sb$ ternary compounds offer the combined optimal performance for electrons and holes in the same material [2], from which CMOS devices with a common channel could be fabricated. Such a device has the potential to out perform Si CMOS while having greatly reduced fabrication complexity in comparison to hybrid technologies [3].
It has been recently shown that, qualitatively, surface treatments comprising a combination of ex-situ HCl treatment and in-situ H_2 plasma exposure prior to the atomic layer deposition (ALD) of Al_2O_3 gate dielectric yield significant improvements to the electrical properties of the $In_{0.3}Ga_{0.7}Sb$-Al_2O_3 interface [4,5]. In this work, the chemical composition of the $In_{0.3}Ga_{0.7}Sb$-Al_2O_3 interface is analysed by means of X-Ray photoelectron spectroscopy (XPS) and energy dispersive X-ray spectroscopy (EDX), with results presented for samples which were: untreated, cleaned ex-situ with HCl acid only, and cleaned with both ex-situ HCl acid and in-situ H_2 plasma exposure (HCl+H_2). Additionally, the experimental capacitance-voltage (CV) measurements reported in Ref. 5 for samples treated with the optimal plasma process have been modelled to enable quantitative analysis.
Details of the surface treatment and ALD parameters are summarised Fig.1 (a) with the corresponding XPS measurements shown in (b), where the spectra were fitted with Gaussian-Lorentzian line shapes for deconvolution subsequent to a Shirley-type background subtraction. For the native InGaSb surface, the XPS spectra shows the In $3d_{5/2}$, Ga $2p_{3/2}$, and Sb $3d_{3/2}$ peaks at binding energies (BE) of 444.1, 1116.8 and 537.13 eV respectively, in close agreement with literature values for InSb and GaSb [6-8]. A peak at 444.9 eV is observed corresponding to In_2O_3 which has been shown to exist at approximately +0.9 eV from the bulk [9]. The broad higher BE component at 1117.9 eV evident in the Ga $2p_{3/2}$ spectra corresponds the Ga-O bond. The oxide feature situated at +2.6 eV from the Sb $3d_{3/2}$ line appears to correspond predominantly to an Sb_2O_3 sub oxide phase: investigations into the oxide composition of the native GaSb surface have reported an Sb-O peak with a chemical shift from the bulk of +3.0 eV, which has been shown to comprise Sb_2O_3 and Sb_2O_4 components at +2.5 and +3.1eV respectively [10]. Cleaning the surface with HCl reduces all In, Ga and Sb sub oxides, with Ga-O remaining the most prominent. The Ga-O peak shifts by ~0.4 eV to a higher BE of 1118.3 eV, in agreement with reported values of Ga_2O_3 [7]. The In $3d_{5/2}$ and Sb $3d_{3/2}$ core level spectra for the HCl+H_2 plasma sample can be fitted well with single peaks corresponding to the bulk, indicating the complete removal of In and Sb sub oxides. The Ga $2p_{3/2}$ spectra shows Ga_2O_3 to have persisted, however the Ga-O:InGaSb ratio has been reduced from 8.18 in the HCl only sample to < 0.1.
Scanning transmission electron microscope (STEM) images of the dielectric interface for the HCl+H_2 plasma sample, shown in Fig 2(a), reveal the Al_2O_3 to be conformal and approximately 7.4 nm thick, with a 1.4 nm thick interfacial region visible at higher magnification. EDX (Fig. 2(b)) reveals the dielectric to be non-stoichiometric, with peaks of Al and O and at both interfaces to the gate metal and InGaSb. Intermixing between In,Ga and Sb with Al_2O_3 is found within the interfacial layer.
The previously reported CV data for the optimal plasma process [5] was modelled in the same manner as in Ref. [11] in order to extract the oxide capacitance (C_{ox}) and interface trap density (D_{it}) across the band gap. Low D_{it} was extracted with a minimum value of 1.73×10^{12} eV^{-1} cm^{-2} located ~110 meV below the conduction band edge. The extracted C_{ox} was 0.785 μF/cm^2 which corresponds to a relative permittivity for Al_2O_3 of 6.52. This low value is likely due to the varying composition of the oxide and intermixing between the semiconductor and dielectric.

These results elucidate the mechanism by which the electrical properties of the InGaSb-Al_2O_3 interface is improved by in-situ H_2 plasma exposure. The low D_{it} across the bandgap suggests Al_2O_3 to be a promising gate dielectric to InGaSb, with further investigation required to increase the equivalent oxide thickness.

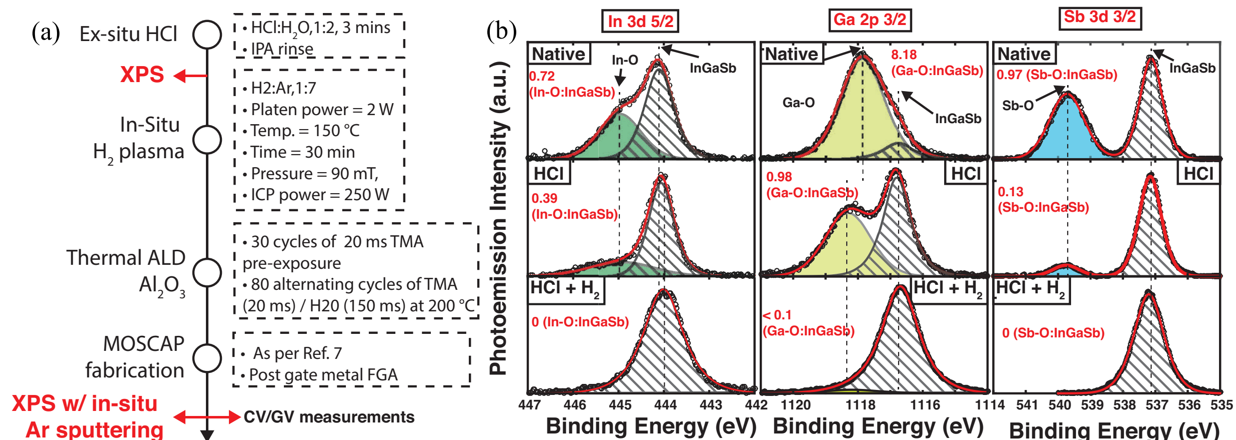

Fig. 1. (a) Processing parameters for samples analysed by XPS and EDX. (b) Deconvoluted XPS spectra of the In $3d_{5/2}$, Ga $2p_{3/2}$ and Sb $3d_{3/2}$ peaks for: a native air exposed $In_{0.3}Ga_{0.7}Sb$ surface, HCl cleaned and HCl+H_2 plasma cleaned InGaSb surfaces.

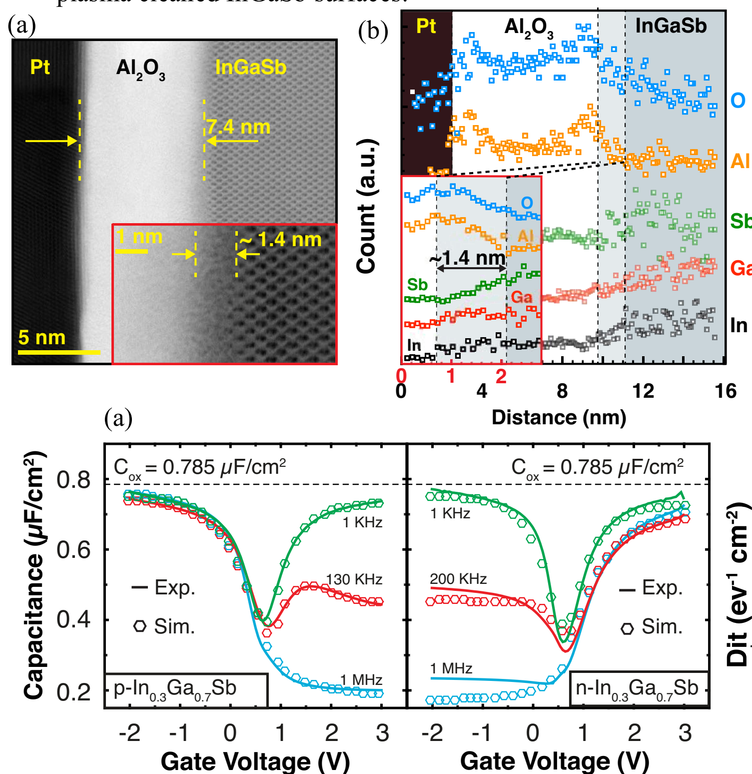

Fig. 2. (a) STEM image of the InGaSb-Al_2O_3 interface, treated with the process shown in Fig. 1(a). (b) Qualitative EDX linescan over the interface revealing the oxide to be non-stoichiometric. Inset: High magnification EDX measurements over the interfacial region, showing intermixing between In,Ga and Sb with the oxide.

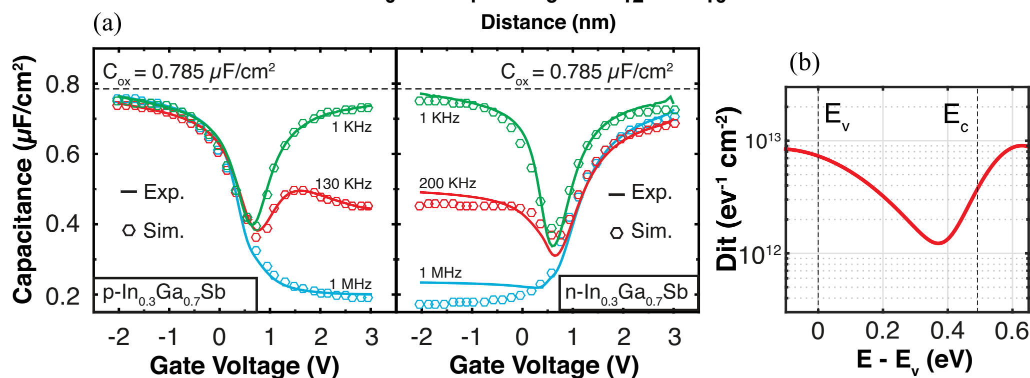

Fig. 3. (a) Comparison between the experimental room temperature CV measurements from Ref. 5 for samples treated with the optimal plasma process, and the corresponding simulation results. (b) The extracted D_{it} across the bandgap from simulation.

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