

# Passivation of InAs and GaSb with novel high $\kappa$ dielectrics

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## **Motivation:**

The research is conducted to understand the mechanism of surface Fermi level pinning/un-pinning in InAs and GaSb, and further effectively passivate them using the high  $\kappa$  dielectrics, well developed at National Tsing Hua University in Taiwan, to improve the device performance in mid-infrared InAs/GaSb superlattices.

## **Technical Milestones for 2010-2011:**

### **1. High $k$ dielectrics on InAs and GaSb**

***I*** · ***growth of high  $k$  dielectrics using molecular beam epitaxy (MBE) and atomic layer deposition (ALD)***

- i. materials including MBE-Ga<sub>2</sub>O<sub>3</sub> (Gd<sub>2</sub>O<sub>3</sub>) (amorphous) and Gd<sub>2</sub>O<sub>3</sub> (single crystals), and ALD-Al<sub>2</sub>O<sub>3</sub> and HfO<sub>2</sub>

***II*** · ***growth of InAs and GaSb epi-layers using molecular beam epitaxy (MBE)***

- i. un-doped epi-layers provided by Dr. Gail Brown's group in Air Force Research Laboratory (AFRL) for structural and interfacial chemical studies
- ii. doped epi-layers grown in Taiwan mainly for electrical characterizations

### **2. Characterizations on hetero-structures of high $k$ dielectrics on InAs and GaSb**

***I*** · ***structural studies using high-resolution x-ray reflectivity and x-ray diffraction, and high-resolution transmission electron microscopy (HR-TEM)***

- i. to determine crystallographic structure, epitaxial relationship, strain field, structural defects, to image the microstructures and interfaces of high  $\kappa$  gate stacks upon subsequent thermal treatments

***II*** · ***interfacial chemical studies using in-situ/ex-situ x-ray photoelectron spectroscopy (XPS), and high-resolution XPS using synchrotron radiation***

- i. to probe the chemistry (interfacial atomic bonding) in the hetero-structures, particular at the interfaces

# Report Documentation Page

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**III · electrical studies using capacitance-voltage (C-V) and current density-field (J-E) measurements**

**3. correlation between electrical measurements and structural studies leading to the understanding of surface Fermi level pinning/unpinning**

The research findings derived from *state-of-the-art* characterizations will be vital to build the scientific knowledge foundation for developing future semiconductor technology. Extra efforts need to be taken to minimize and to eliminate the contamination of the high  $\kappa$ 's during device processing.

**Experimental:**

The semiconductor epi-structures, shown in the following, were grown using molecular beam epitaxy (MBE), followed by the in-situ growth of  $Gd_2O_3$  3 ML thick in ultra high vacuum (UHV) with electron beam evaporation and then by atomic layer deposited (ALD)  $Al_2O_3$ . The semiconductor epi-layers were grown on semi-insulating GaAs. Sb-based III-V materials were found to give a good smooth growth on GaAs, laying down foundation for the growth of InAs.

<b>dielectric</b>	<b>ALD-<math>Al_2O_3</math></b>	<b>~14nm</b>
<b>dielectric</b>	<b><math>Gd_2O_3</math></b>	<b>~1nm</b>
<b>Channel (2)</b>	<b>InAs Be doping P-type <math>2e^{17} cm^3</math></b>	<b>~1.3 nm</b>
<b>Channel (1)</b>	<b>InAs Be doping P-type <math>2e^{17} cm^3</math></b>	<b>~5 nm</b>
<b>Bottom barrier</b>	<b>AlSb</b>	<b>12 nm</b>
<b>Mesa stop layer</b>	<b><math>Al_{0.75}Ga_{0.25}Sb</math></b>	<b>13 nm</b>
	<b>Te-doping</b>	
<b>Mesa stop layer</b>	<b><math>Al_{0.75}Ga_{0.25}Sb</math></b>	<b>1300 nm</b>
<b>Buffer layer</b>	<b>AlSb</b>	<b>200 nm</b>
<b>SI GaAs substrate</b>		

*1.3 %  
lattice  
mismatch*

*Fully relaxed  
with 8%  
lattice  
mismatch*

Note that the energy band gaps for InAs, AlSb, and  $\text{Al}_{0.75}\text{Ga}_{0.25}\text{Sb}$  are 0.35, 1.7, and 1.5 eV, respectively. AlSb layers were used for the purpose of buffer (on GaAs) and barrier to confine the carriers for better device performances. The AlGaSb layers were used for the mesa etching stop. There is a 1.3% lattice mismatch between InAs and AlSb. For a strained-layer growth, InAs with a total thickness of 6.3 nm was epitaxially grown on AlSb. InAs was doped with Be, intending to be p-doping. However, it was found out later that the InAs was still an n-type, as confirmed with our XPS and MOSFET device work.

## Results and Discussion

### (I) XPS studies

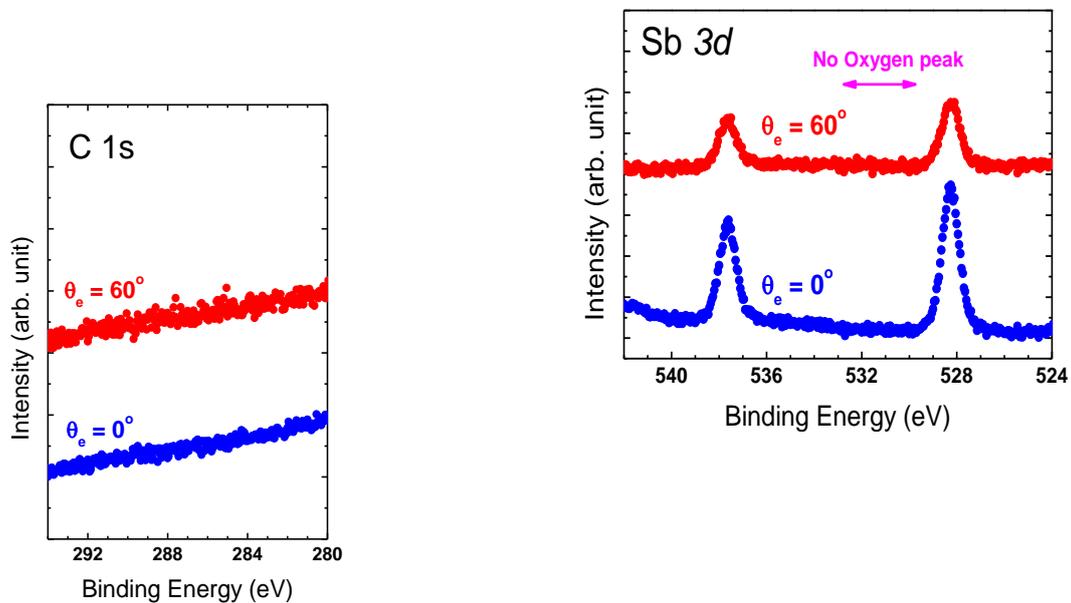


Fig. 1 C 1s and Sb 3d XPS spectra on freshly MBE grown InAs

No Carbon and Oxygen  
on the InAs surface

Channel	InAs Be doping P-type $2 \times 10^{17} \text{cm}^{-3}$	~1.3 nm
Channel	InAs Be doping P-type $2 \times 10^{17} \text{cm}^{-3}$	~5 nm
Bottom barrier	AlSb	12 nm
Mesa stop layer	$\text{Al}_{0.75}\text{Ga}_{0.25}\text{Sb}$	13 nm
	Te-doping	
Mesa stop layer	$\text{Al}_{0.75}\text{Ga}_{0.25}\text{Sb}$	1300 nm
Buffer layer	AlSb	200 nm
SI GaAs substrate		

Right after the MBE growth of InAs, the sample was in-situ moved to the XPS chamber for analysis. Using angle-resolved XPS (Fig. 1), no carbon and oxygen

were found on the freshly MBE grown InAs surface, as expected. Moreover, we have also observed intermixing between InAs and AlSb as shown in Fig. 2.

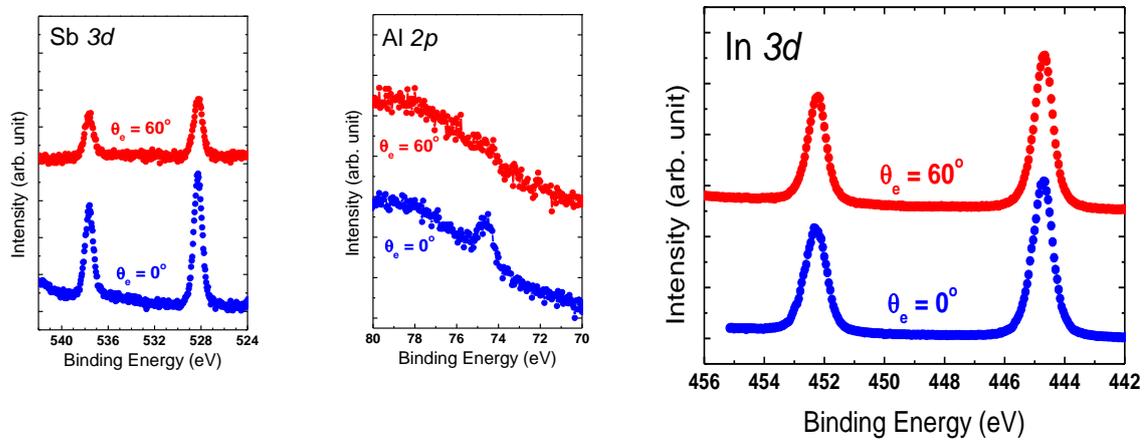
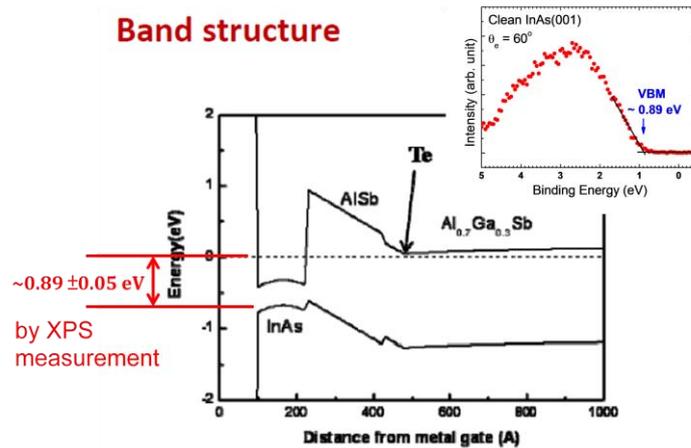


Fig. 2 Al 2p, In 3d, and Sb 3d XPS spectra on freshly MBE grown InAs

Channel	InAs Be doping P-type $2e^{17}cm^{-3}$	~1.3 nm	→ InAsSb intermixing layer
Channel	InAs Be doping P-type $2e^{17}cm^{-3}$	~5 nm	
Bottom barrier	AlSb	12 nm	
Mesa stop layer	$Al_{0.75}Ga_{0.25}Sb$	13 nm	
	Te-doping		
Mesa stop layer	$Al_{0.75}Ga_{0.25}Sb$	1300 nm	
Buffer layer	AlSb	200 nm	
SI GaAs substrate			



From NCU

Fig. 3 Band structure of InAs/AlSb/Te/Al<sub>0.7</sub>Ga<sub>0.3</sub>Sb with the inset showing the measured valence band maximum (VBM) of 0.89 eV.

From the results shown in Fig. 3, InAs is an n-type doping, despite the doping with Be.

After the 3 ML growth of Gd<sub>2</sub>O<sub>3</sub> on InAs, the sample was in-situ moved to the XPS for studying the interfacial chemistry.

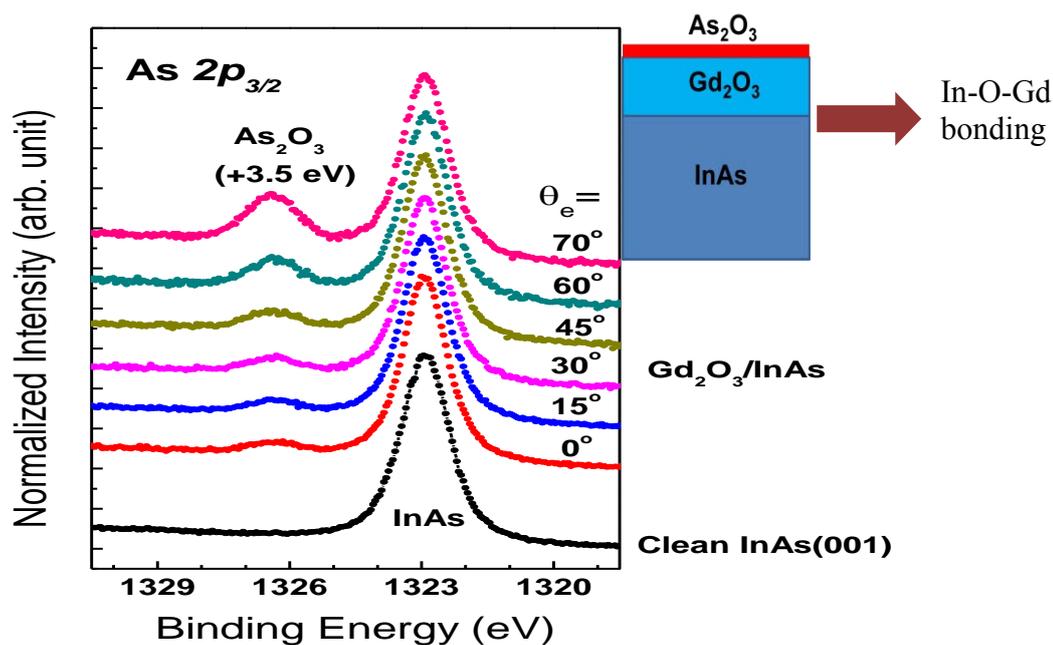


Fig. 4 As 2p spectra taken at different take-off angles.

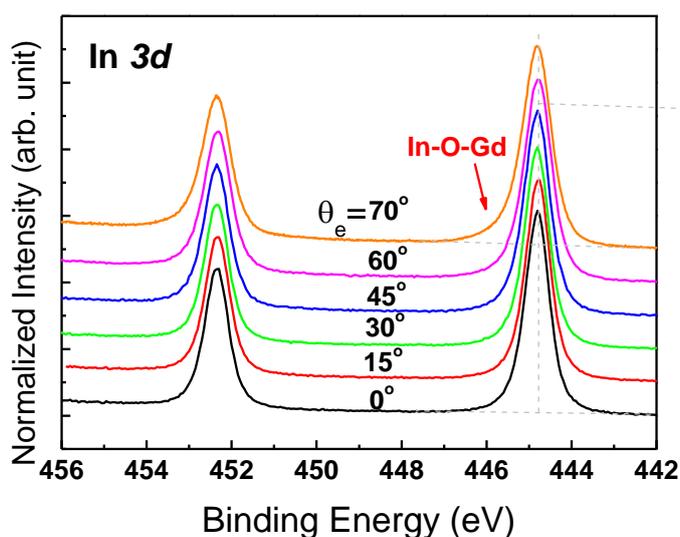


Fig. 5 In 3d spectra taken at different take-off angles.

From the results given in Figs. 4 and 5, deposition of 3 ML  $\text{Gd}_2\text{O}_3$  on InAs gave formation of In-O-Gd bonding, with As forming  $\text{As}_2\text{O}_3$ , which diffused to the top of  $\text{Gd}_2\text{O}_3$ .  $\text{As}_2\text{O}_3$  was then removed with the self-cleaning ALD- $\text{Al}_2\text{O}_3$  deposition, as evidenced from the As 3d spectrum as shown in Fig. 6.

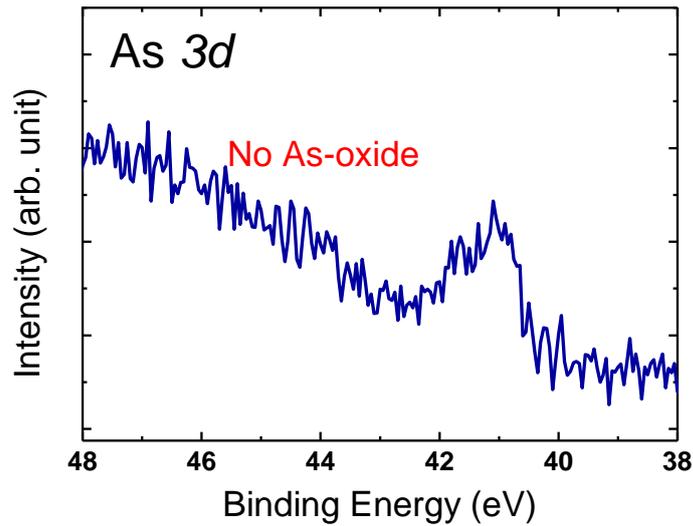
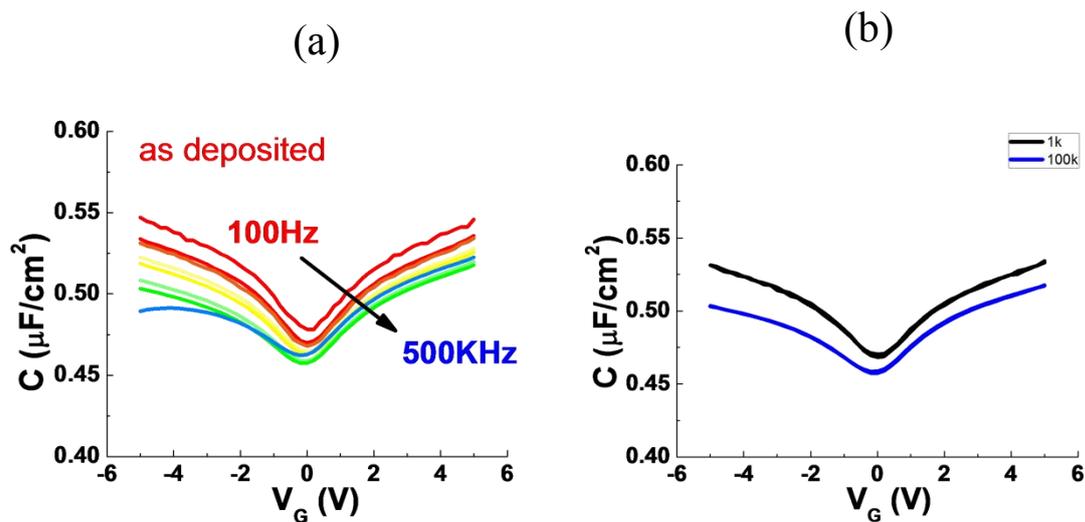


Fig. 6 As 3d spectrum on ALD- $\text{Al}_2\text{O}_3$  deposited on freshly MBE grown  $\text{Gd}_2\text{O}_3$ , which was grown InAs.

(II) Electrical properties of high  $\kappa$   $\text{Al}_2\text{O}_3/\text{Gd}_2\text{O}_3/\text{InAs}$  MOS and MOSFET



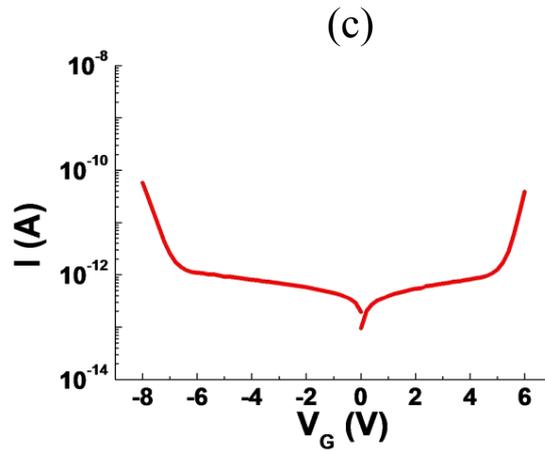


Fig 7 (a) Capacitance-voltage (C-V) characteristics, (b) C-V hysteresis at 1k Hz and 100k Hz, (c) gate leakage current for ALD- $\text{Al}_2\text{O}_3/\text{Gd}_2\text{O}_3/\text{p-InAs}$  MOSCAP with area= $7.85 \times 10^{-5} \text{ cm}^2$

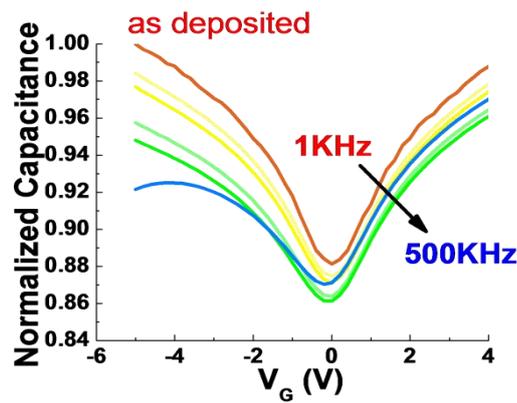
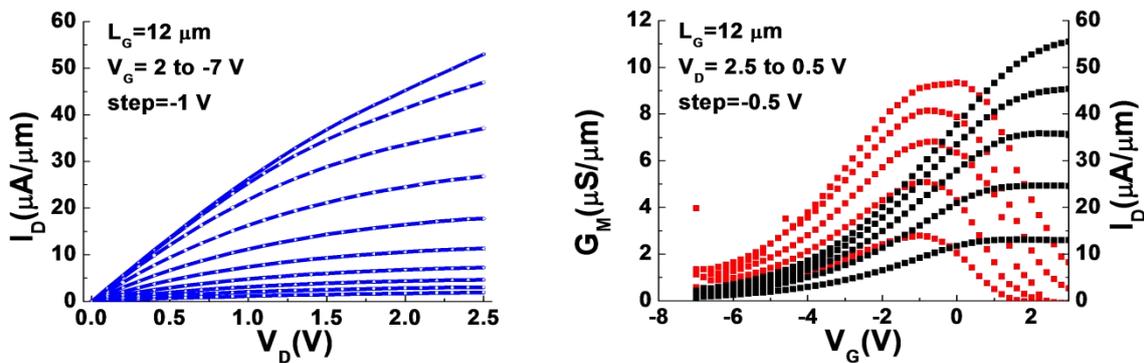


Fig. 8 Normalized Capacitance-voltage (C-V) characteristics for ALD- $\text{Al}_2\text{O}_3/\text{Gd}_2\text{O}_3/\text{p-InAs}$  MOSCAP with area= $7.85 \times 10^{-5} \text{ cm}^2$



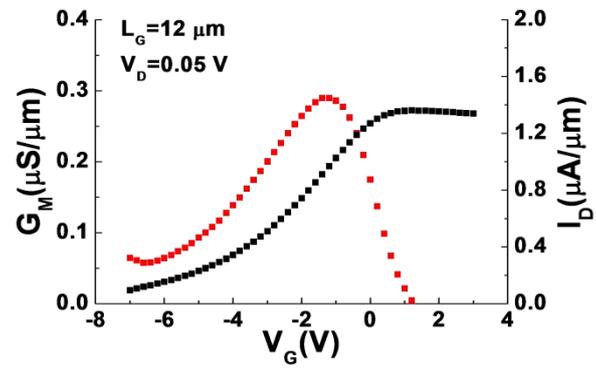


Fig. 9 (a) Output characteristics  $I_D$  vs  $V_D$  and (b) the transfer characteristics and transconductance  $G_M$  curve of a depletion-mode InAs MOSFET with  $12\mu\text{m}$  gate length.



