Diamond:H/Transition Metal Oxides Transfer-Doping: Efficiency and Transistor Performance

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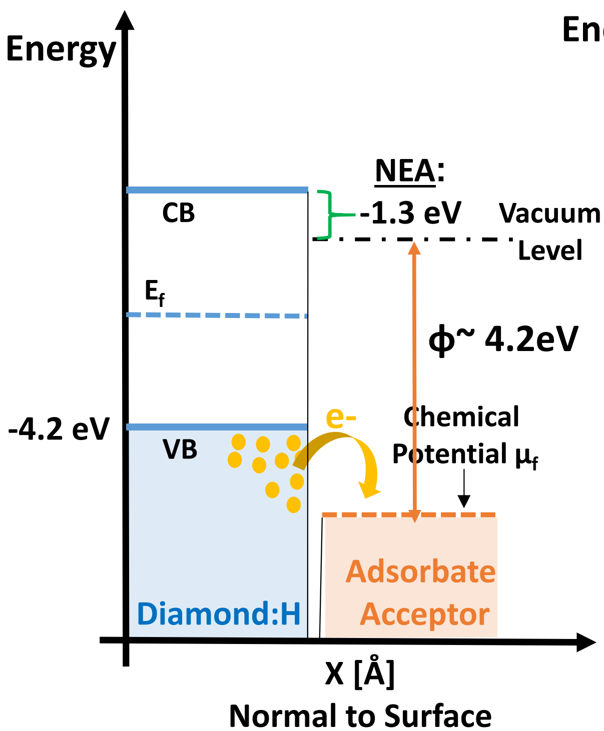
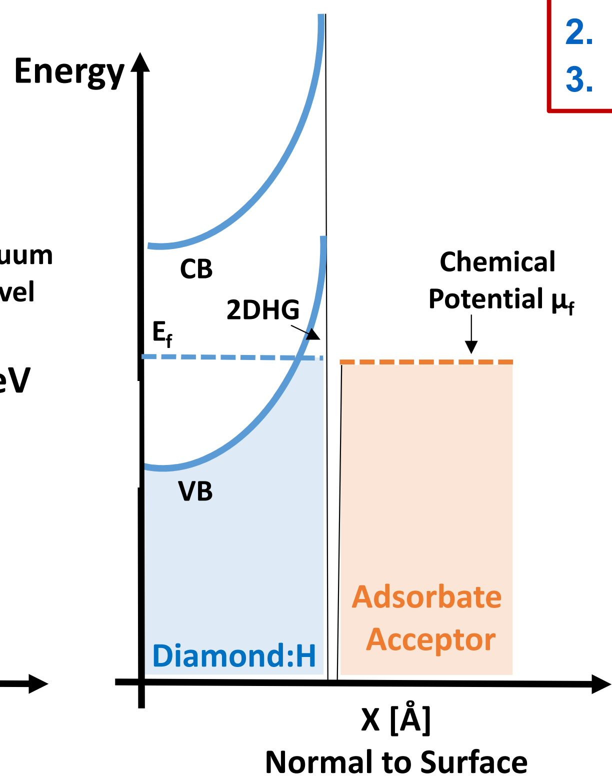
Diamond Surface Transfer Doping with **Adsorbates Molecules**

Before
Electron Transfer

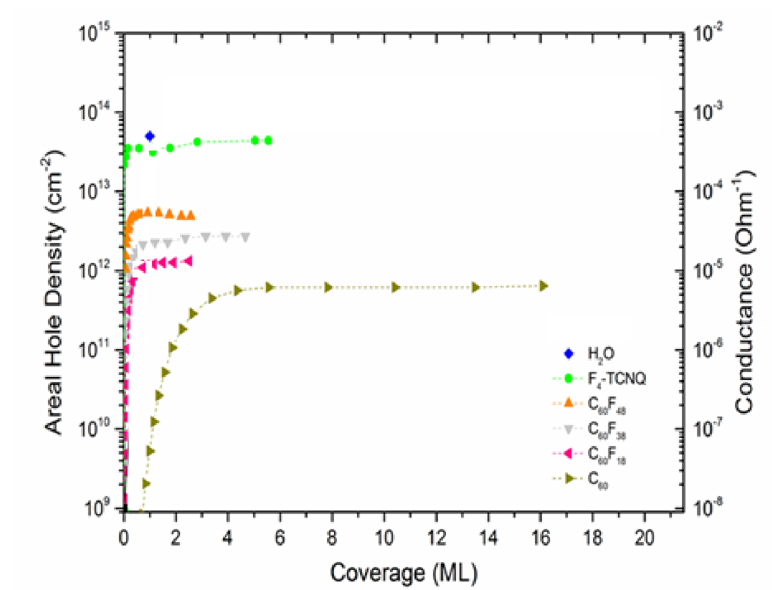


After
Equilibrium State



Drawbacks:

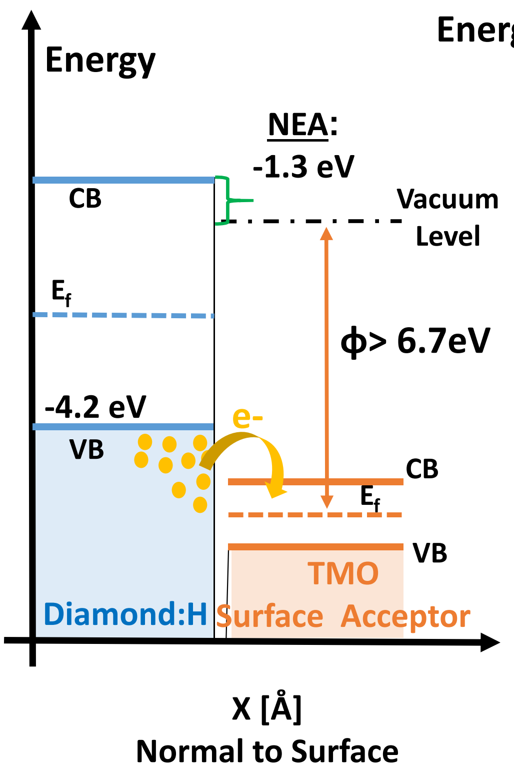
1. **Volatile and Sensitive to Atmospheric Fluctuations.**
2. **No Temperature Stability.**
3. **Low Work Function→ Limited conductivity**



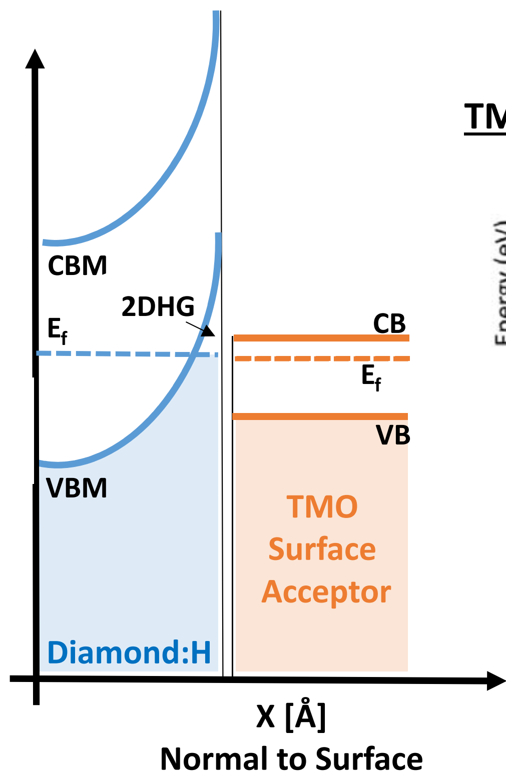
Strobel et.al Nature,430, (2004) ; W. Chen, Prog. Surf. Sci (2009)

Diamond Surface Transfer Doping with **T**ransition **M**etal **O**xides

Before
Electron Transfer



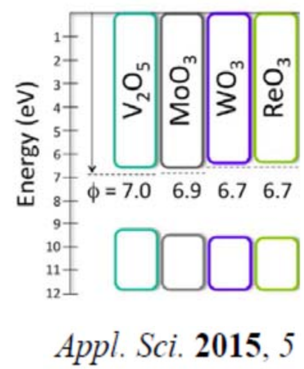
After
Equilibrium State

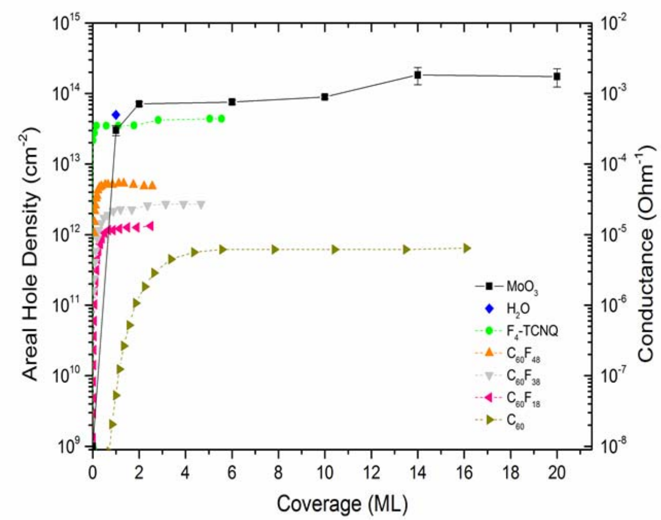


Advantages:

1. **Temperature Stability (up to 350-450°C).**
2. **Higher Work function → Higher conductivity.**

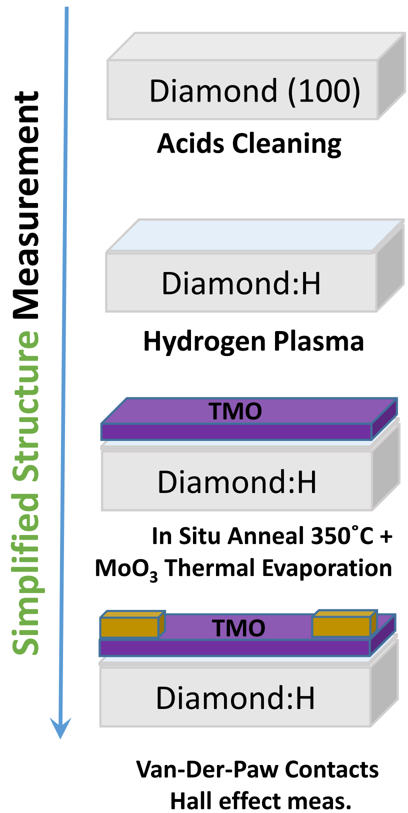
TMOs Surface Acceptors:

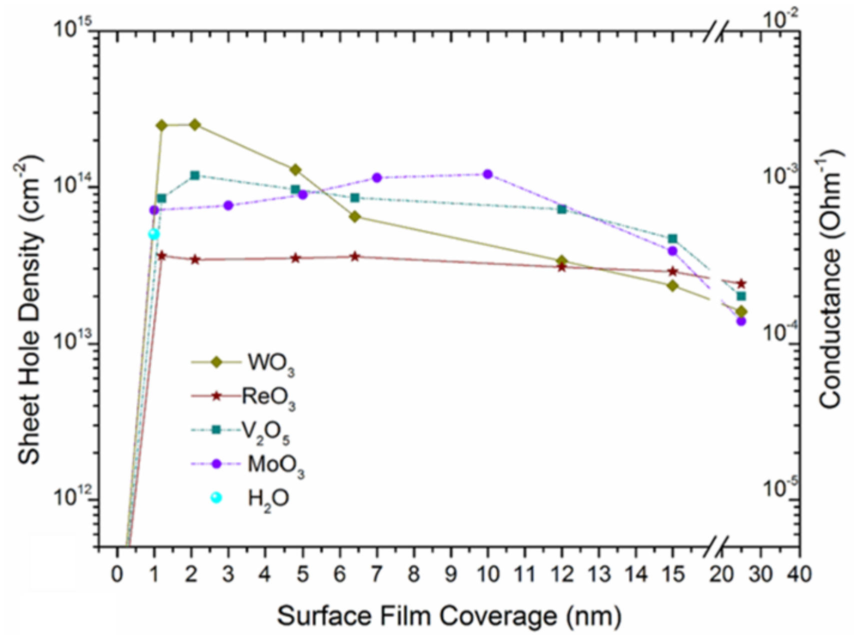




Tordjman et. al. *Advanced Materials Interfaces* , 201300155, (2014).

Diamond:H/TMO Transfer Doping





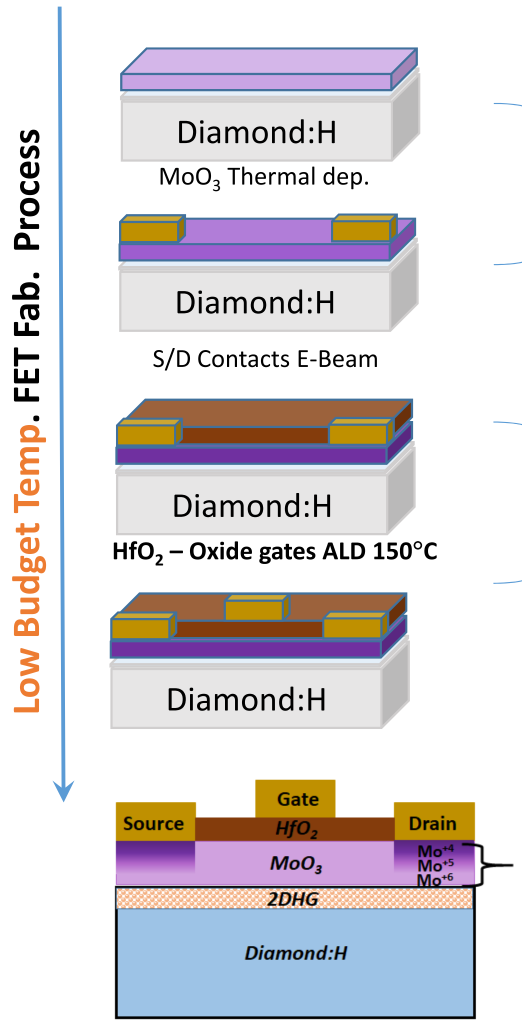
TMO	ReO_3	MoO_3	WO_3	V_2O_5
Lattice constant[A]	3.742	3.96x13.85x3.69	7.30x7.54x3.84	11.51x3.55x4.37
Crystallization Phase		Hexagonal	Tetragonal (>740C)	
	Cubic, cP4	Orthorhombic	Orthorhombic (330-740C)	Orthorhombic
		Monoclinic	Monoclinic (17-330C)	
			Triclinic (-50-17C)	
Density [g/cm^3]	6.92	4.69	7.16	3.357
Work Function [eV]	6.7	6.9	6.7	7

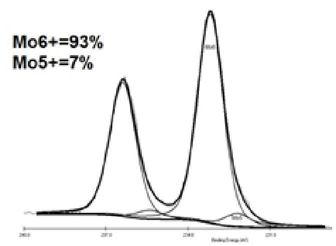
<u>TMOs come into Various:</u>

1. **Crystallization Structures.**
2. **Oxidation phases. (i.e. MoO_{3-x}, V_2O_{5-x} , WO_{3-x} etc..)**
3. **Coverage Uniformity.**

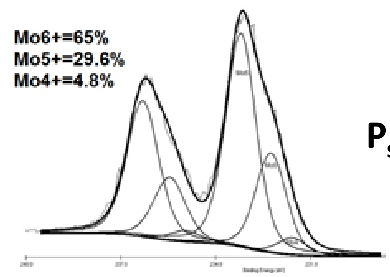
Tordjman et.al. Appl. Phys. Lett.111, 111601 (2017)

MoO_3 **Thermal Evaporation** Integrity to FET Fabrication Process

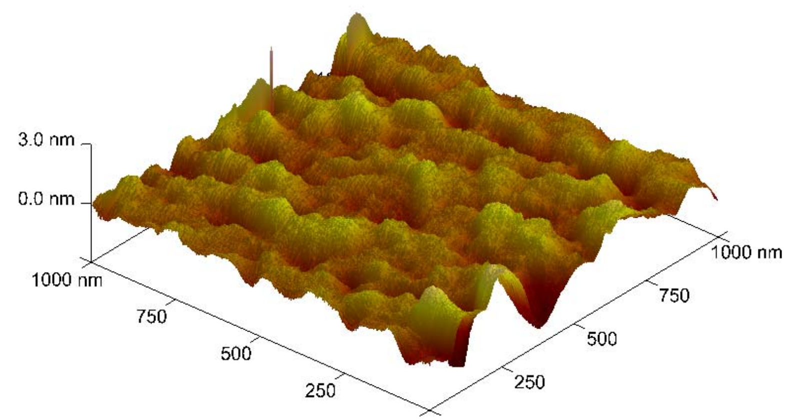




P_s=1x10^{14}cm^{-2}

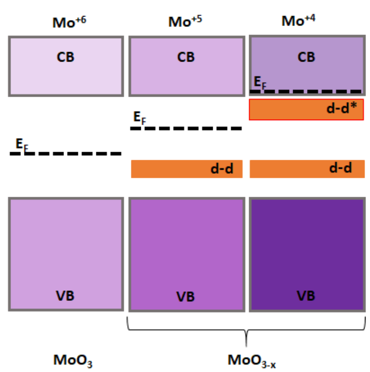


P_s=4x10^{12}cm^{-2}



Ra=0.86nm

ϕ : 6.7eV → 5eV

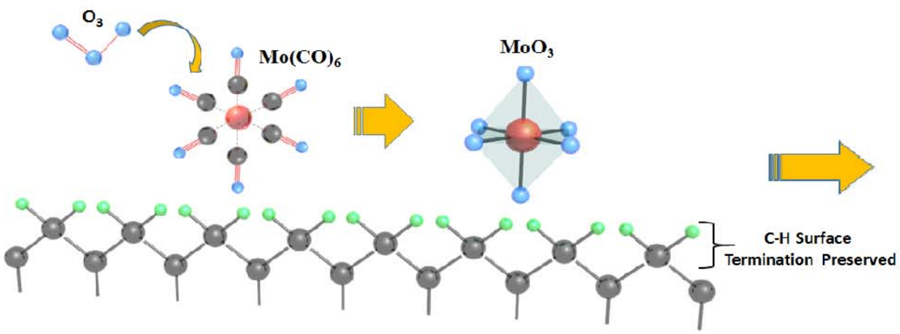


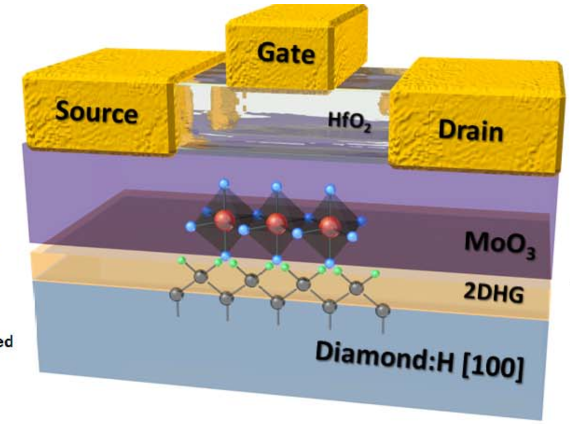
Challenges:

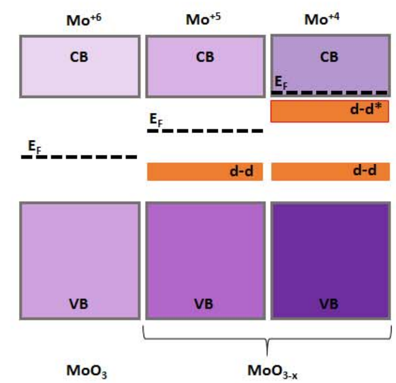
1. **Nonhomogeneous Morphology.**
2. **Stoichiometry Changed by Fab. Process.**
3. **Carrier Loss due to band-energy Misalignment.**

Vardi et.al. EDL .35,12 (2014)

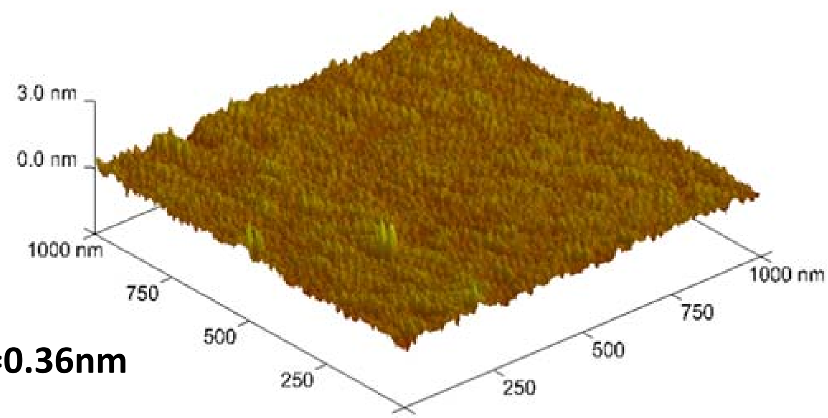
ALD MoO_3 Surface Acceptor







ALD 170℃: *$Mo(CO)_6$ / O_3 → MoO_3*

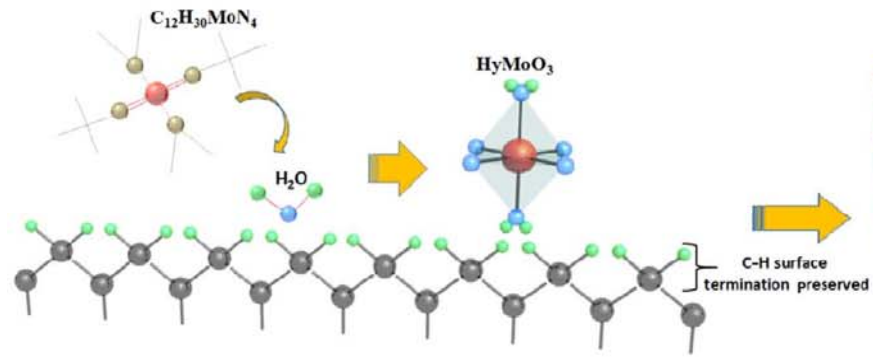


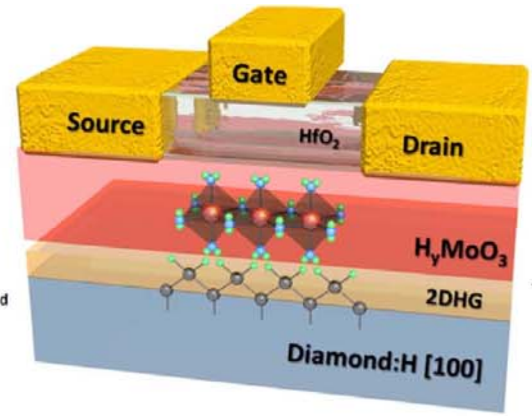
Ra=0.36nm

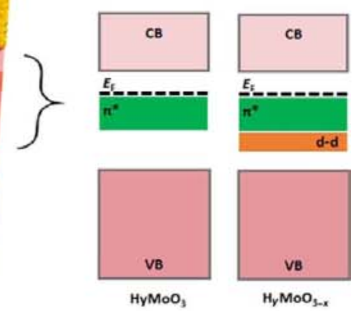
- ✓ **Roughness Quality improved.**
1. **Electronic Gap- States- reducing WF .**
2. **Band Energy Misalignment.**

Yin & Tordjman et. al. *Science Advances*, 4:eaau0480,(2018).

ALD H_yMoO_3 Surface Acceptor

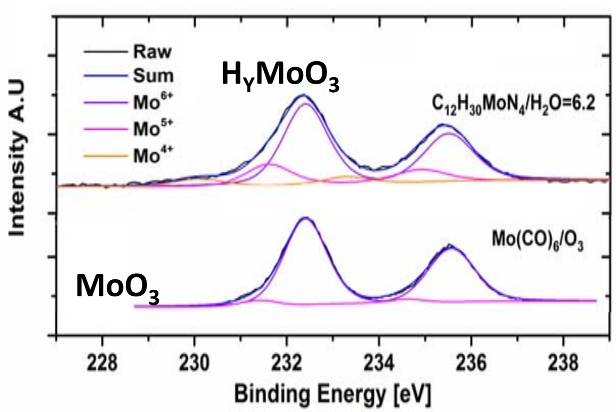




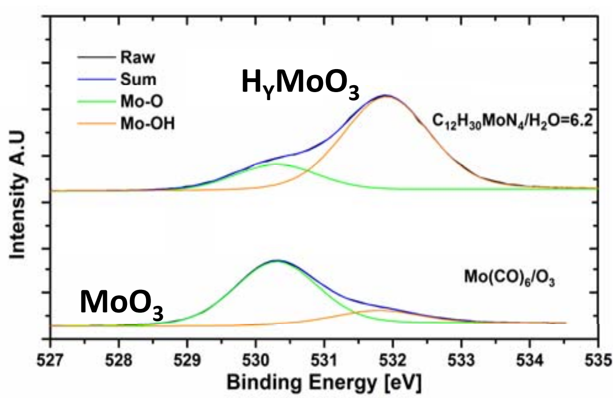


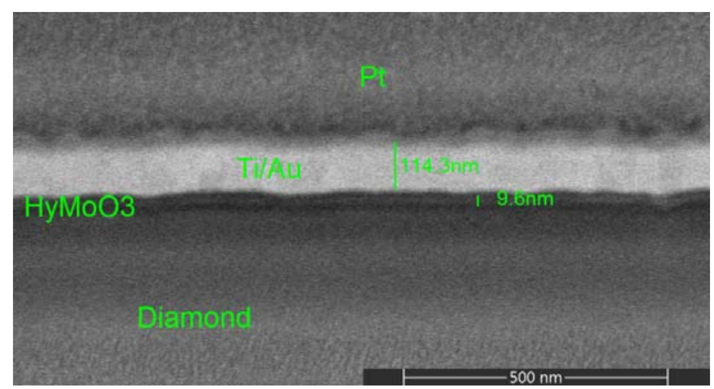
ALD 350℃: $C_{12}H_{20}MoN_4$ / H_2O → H_yMoO_3

Mo3d XPS



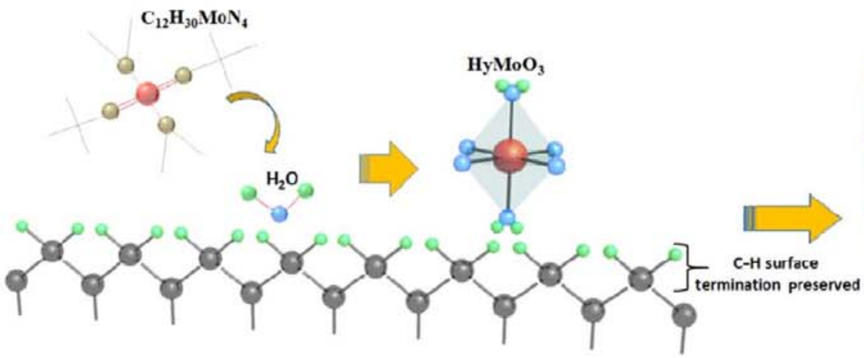
O1s XPS

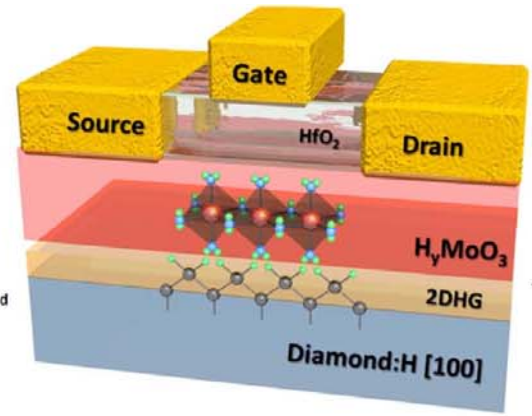


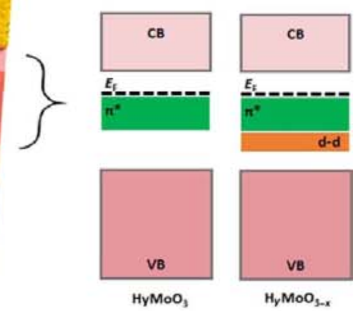


Yin & Tordjman et. al. *Science Advances*, 4:eaau0480,(2018).

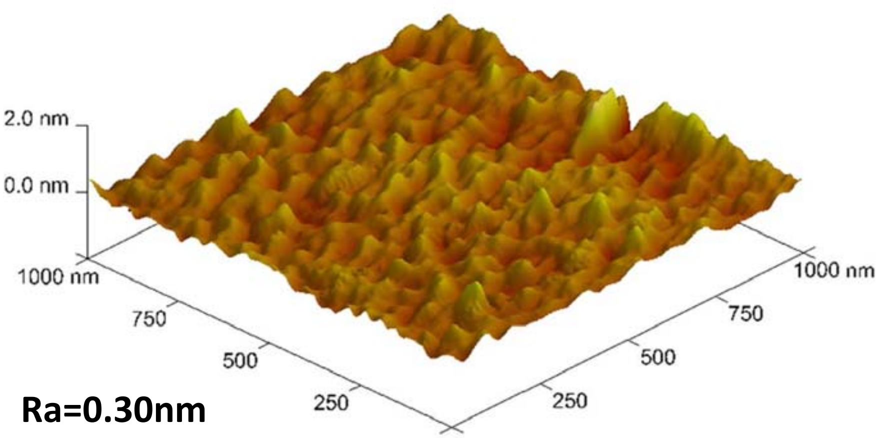
ALD H_yMoO_3 Surface Acceptor







ALD 350℃: *$C_{12}H_{20}MoN_4$ / H_2O → H_yMoO_3*



Ra=0.30nm

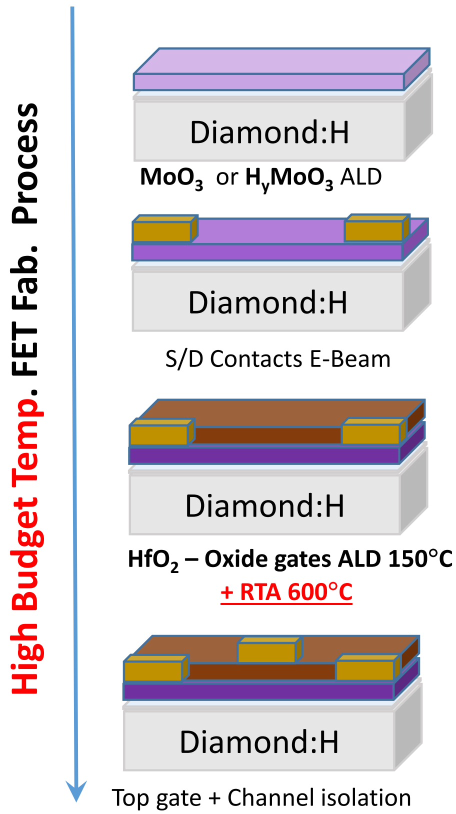
Hydrogen Incorporation Contributes:

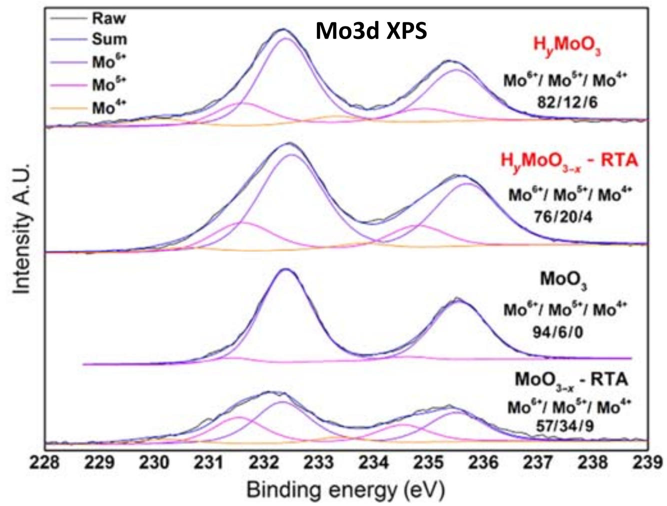
1. **Strengthen Covalent bonds.**
   → No O Reduction.
   → No Work Function Degradation.
2. **Improved Surface Roughness Quality.**

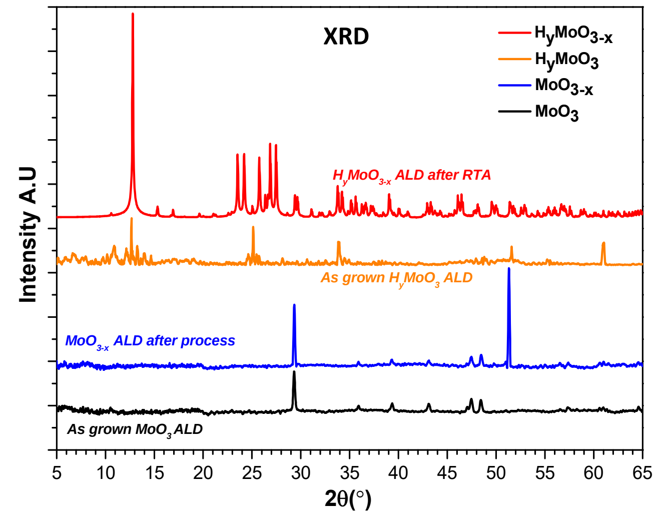
- **What about Energy- Band Alignment?**

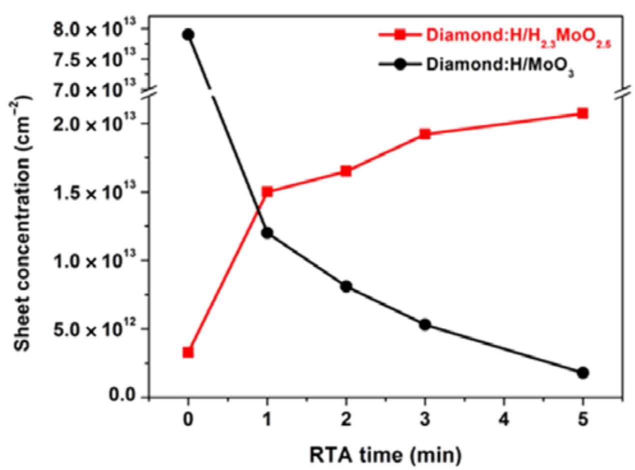
Yin & Tordjman et. al. *Science Advances*, 4:eaau0480,(2018).

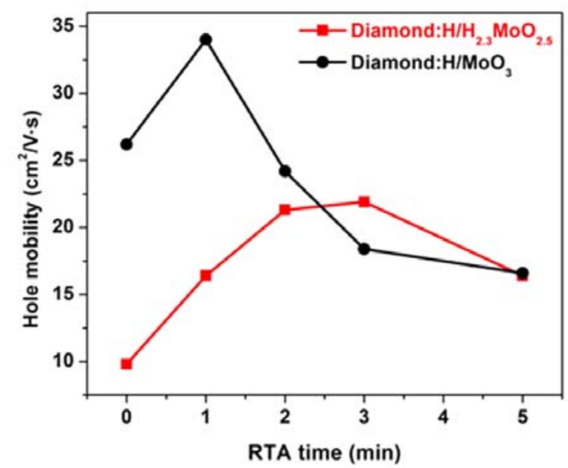
Diamond:H/MoO_3 Vs. H_yMoO_3 Properties







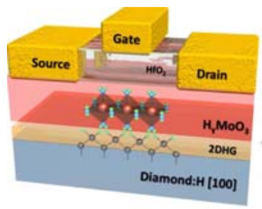




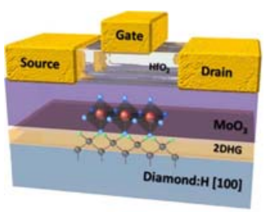
Yin & Tordjman et. al. *Science Advances*, 4:eaau0480,(2018).

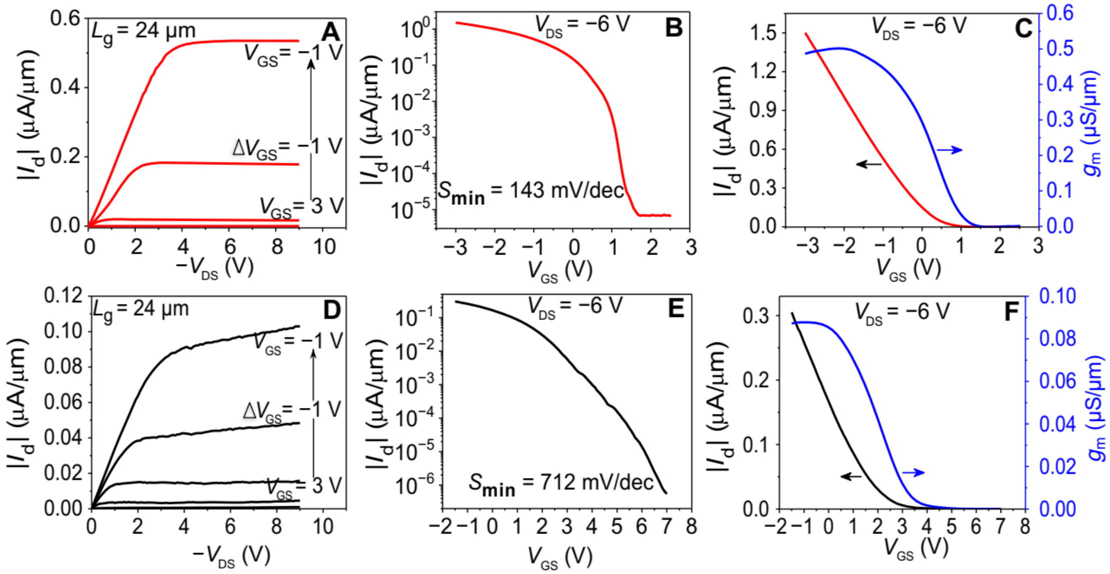
Diamond:H/MoO_3 Vs. H_yMoO_3 FETs

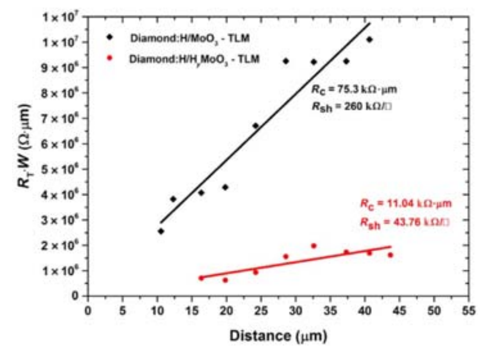
H_yMoO_3



MoO_3



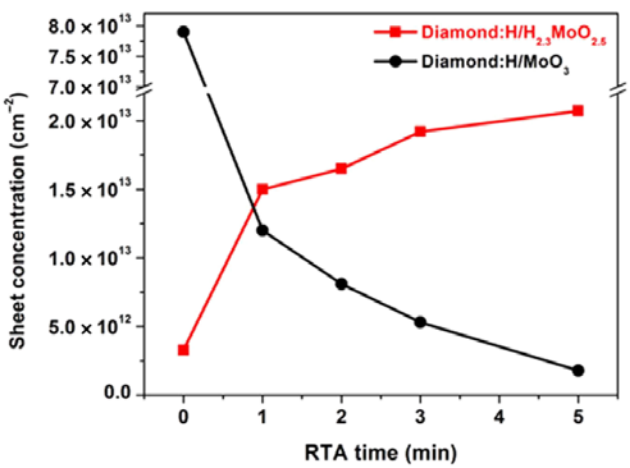


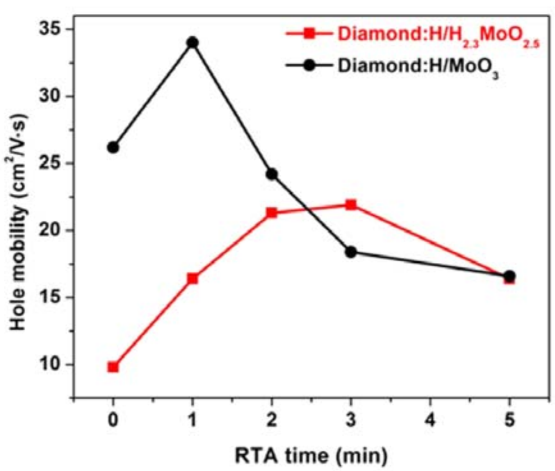


Configuration	FET							Hall		
Measured parameters	Completed device - Post-process fabrication							Pre-processed structure		
	Hole mobility ($cm^2/V{\cdot}s$)	Hole concentration (cm^{-2})	Sheet resistance (kΩ/sq)	Contact resistance (kΩ·µm)	Maximum drain-current ON/OFF ratio	Maximum transconductance (µS/µm)	Minimum subthreshold swing (mV/dec)	Hole mobility ($cm^2/V{\cdot}s$)	Hole concentration (cm^{-2})	Sheet resistance (kΩ/sq)
Diamond:H/MoO_3	1.7	3.2×10^{12}	260	75	2.7×10^4	0.09	712	26.2	7.9×10^{13}	3.02
Diamond:H/H_yMoO_{3-x}	20.2	5.1×10^{12}	43	11	2.1×10^5	0.5	143	22.4	1.9×10^{13}	15

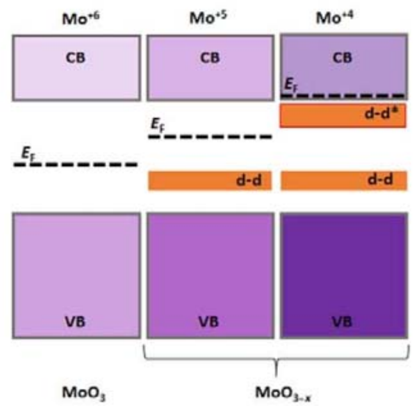
Yin & Tordjman et. al. *Science Advances*, 4:eaau0480,(2018).

MoO_3 Vs. H_yMoO_3 Band-Energy Alignment

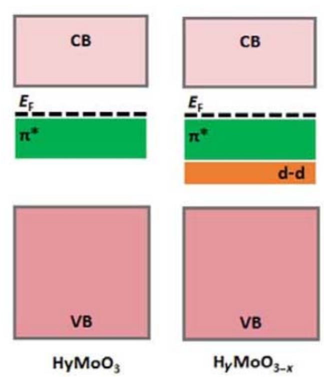


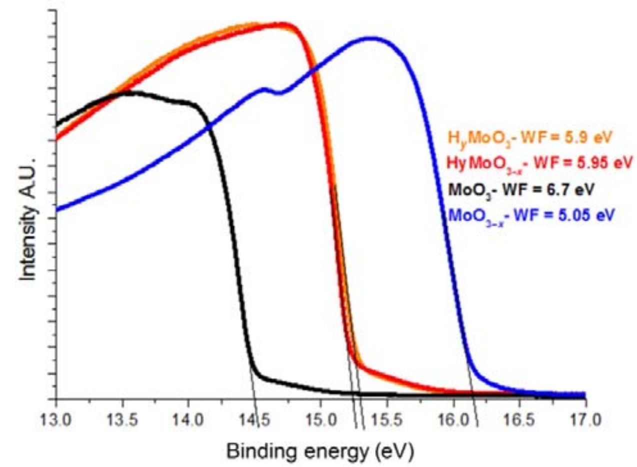


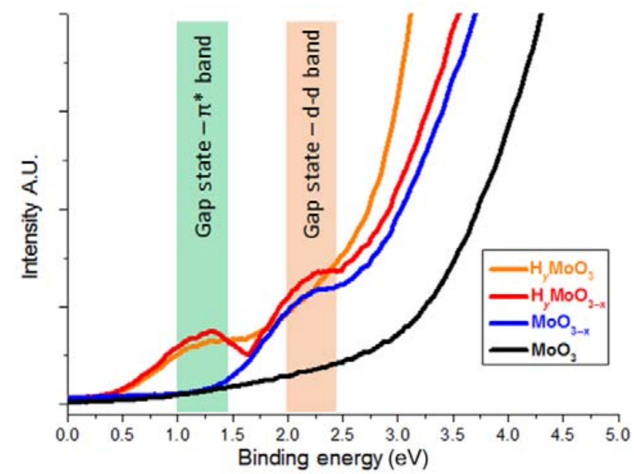
MoO_3 **ϕ : 6.7eV → 5eV**



H_yMoO_3 **ϕ : 6eV → 5.9eV**







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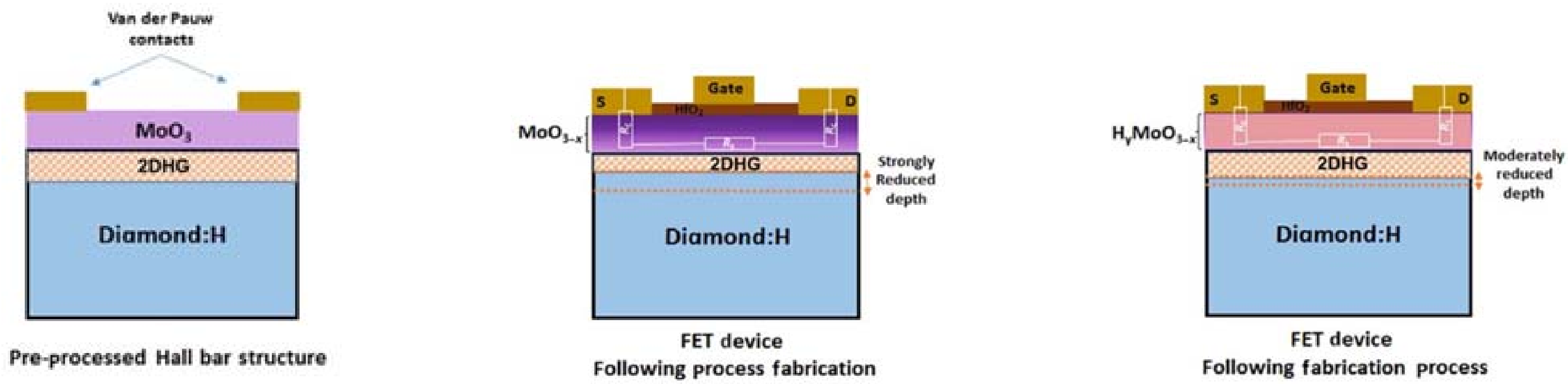
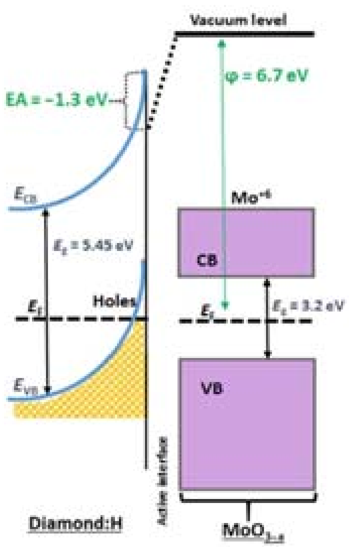
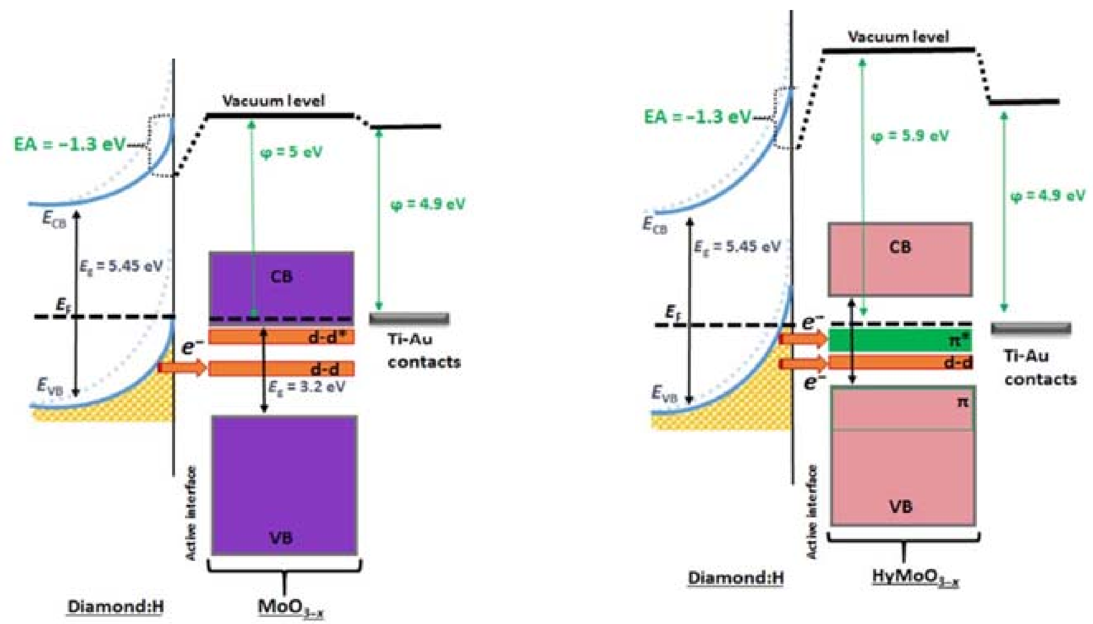
MoO_3 Vs. H_yMoO_3 Band-Energy Alignment







Yin & Tordjman et. al. *Science Advances*, 4:eaau0480,(2018).

Conclusions

- A Novel Advantageous Surface Acceptor: **H_yTMO**
- General Strategy for **Integrating and Modulating Electronic States** in H_yTMO.
- **Diamond:H/H_yMoO_3** Surface Acceptor shows:

1. **Improved Morphology Smoothness**.
2. **Immunity to Harsh Processing FET Fab.**
3. **Improved Cross-Transport via band-energy alignment.**

Thank YoU

Technion Israel Institute of Technology

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