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Surface Molecular Coating for Adhesion Minimization in NEM Switches

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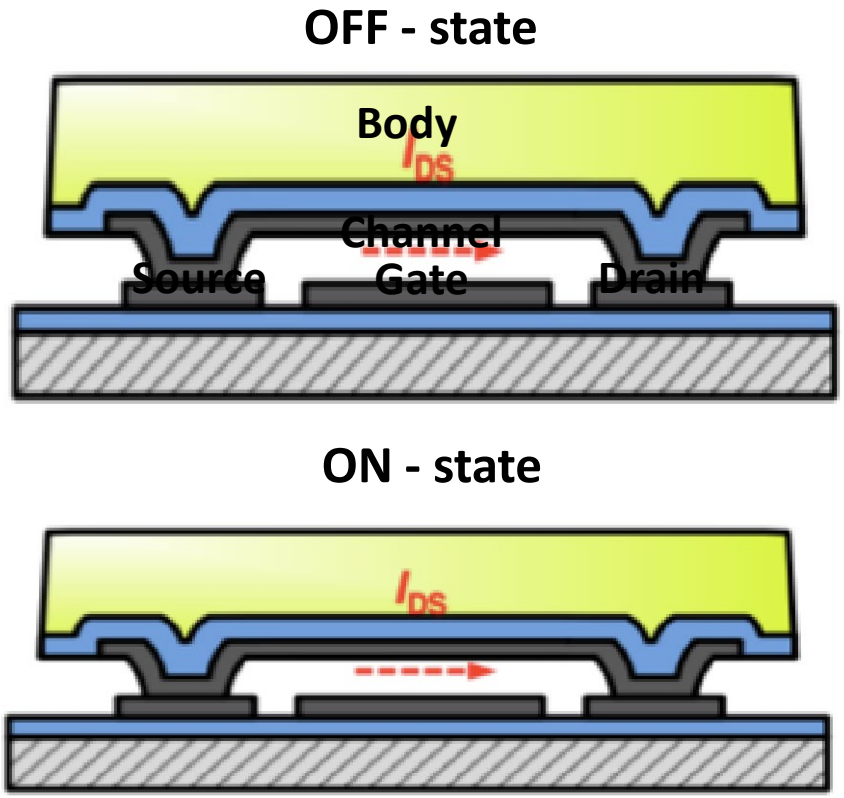
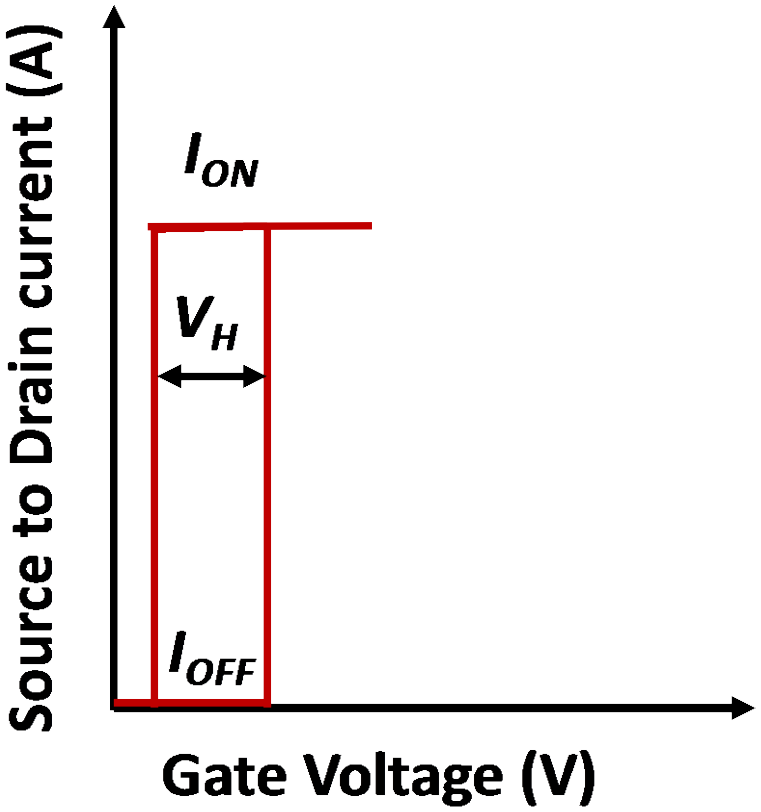
Working principle of a NEM switch



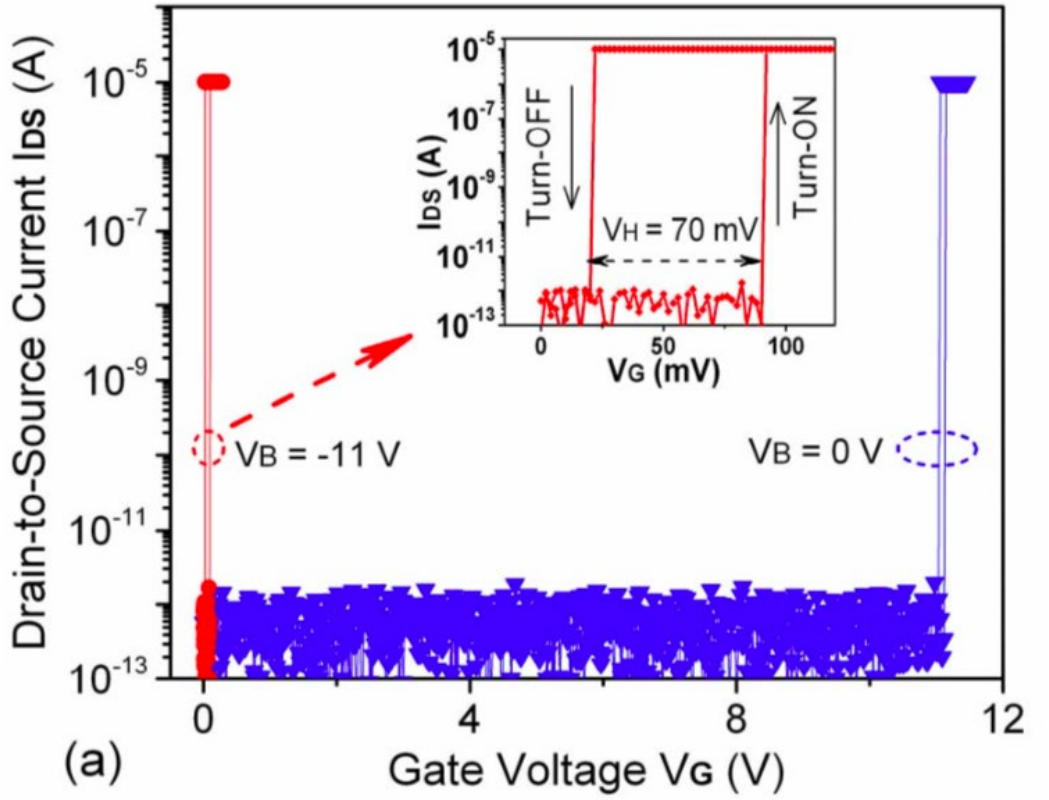
Yenhao Chen (thesis), 2017.



Zero OFF – state current , high ON state conductance and abrupt switching

Hysteresis in *I-V* characteristics of a NEM relay

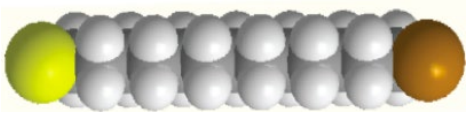
C. Qian et all., IEEE Trans. on electron Dev. 64 (2017).



Contact adhesion ↑ ⇒ **Hysteresis** ↑ ⇒ **Operating Voltage** ↑

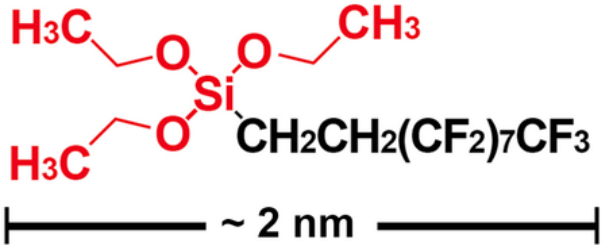
Reducing adhesion, without deteriorating conduction by use of an anti-stiction coating

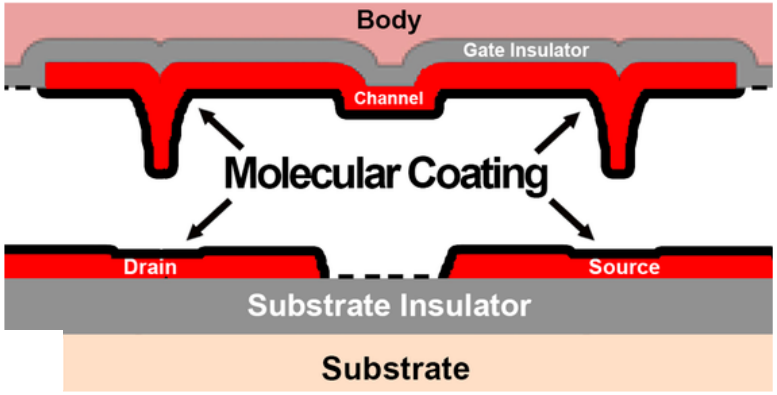
Using self-assembled molecules to reduce stiction (Prior work)

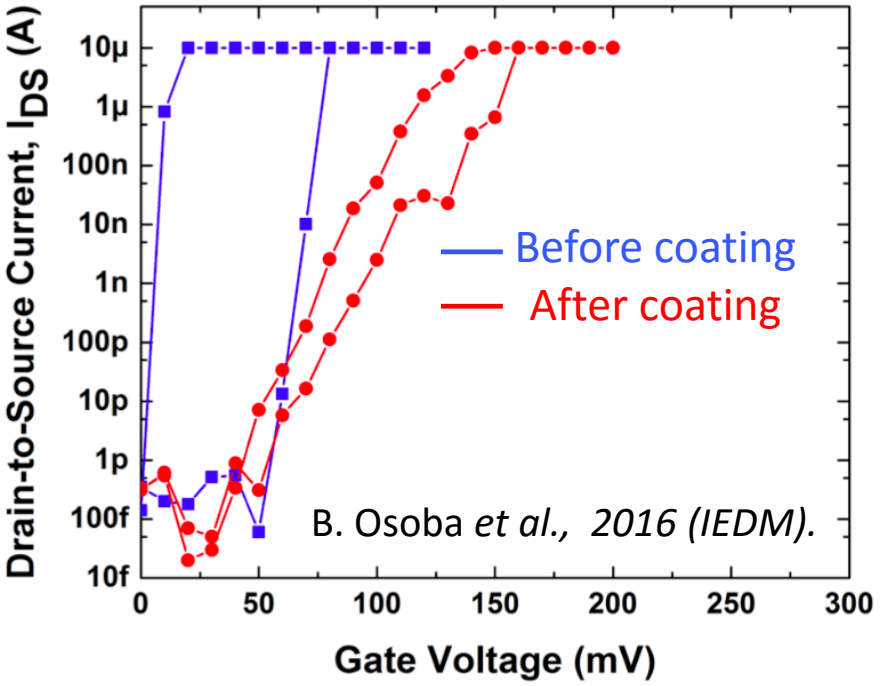


Schematic of a self assembled molecules

perfluorodecyltriethoxysilane (PFDTES)

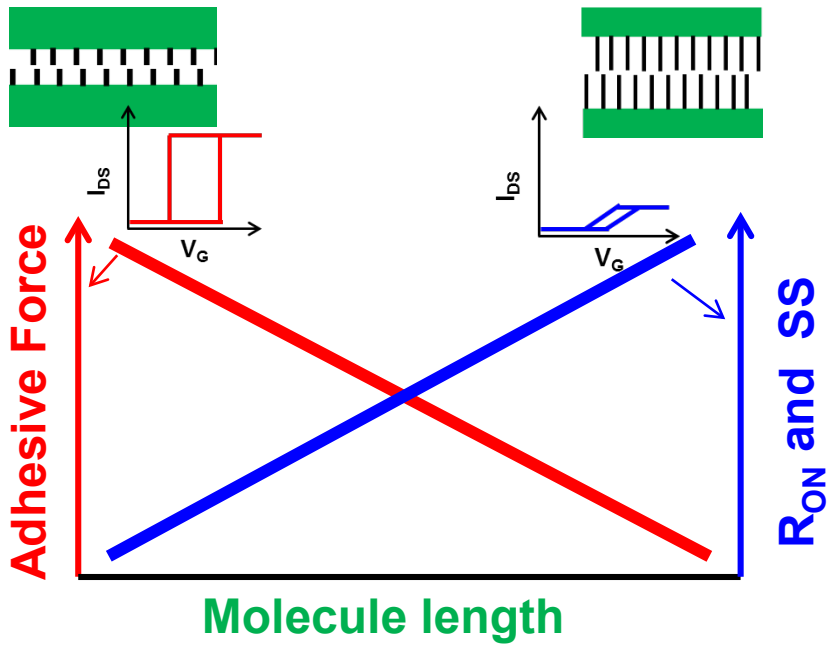




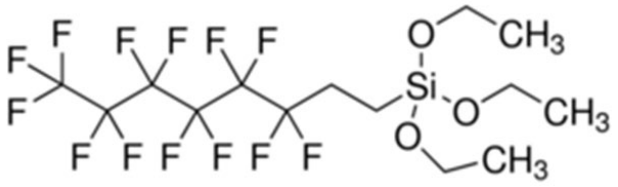


- **PFDTES Deposition in gas phase after the release step in a desiccator**
- **Use of PFDTES : Reduces hysteresis, but it deteriorates subthreshold swing**

Summarizing prior work

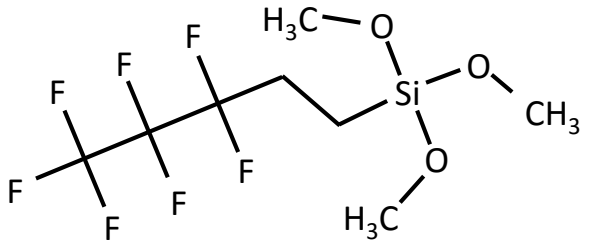


PFOTES Length ~ 1.3 nm



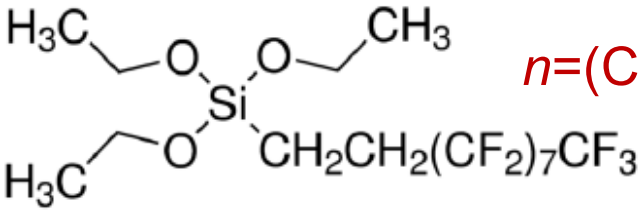
n=5

PFPTES Length ~ 0.8 nm



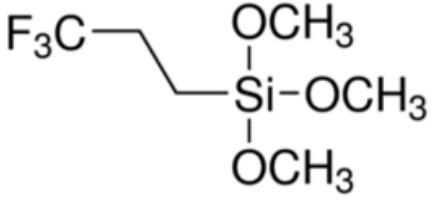
n=2

PFDTES Length ~ 1.5 nm



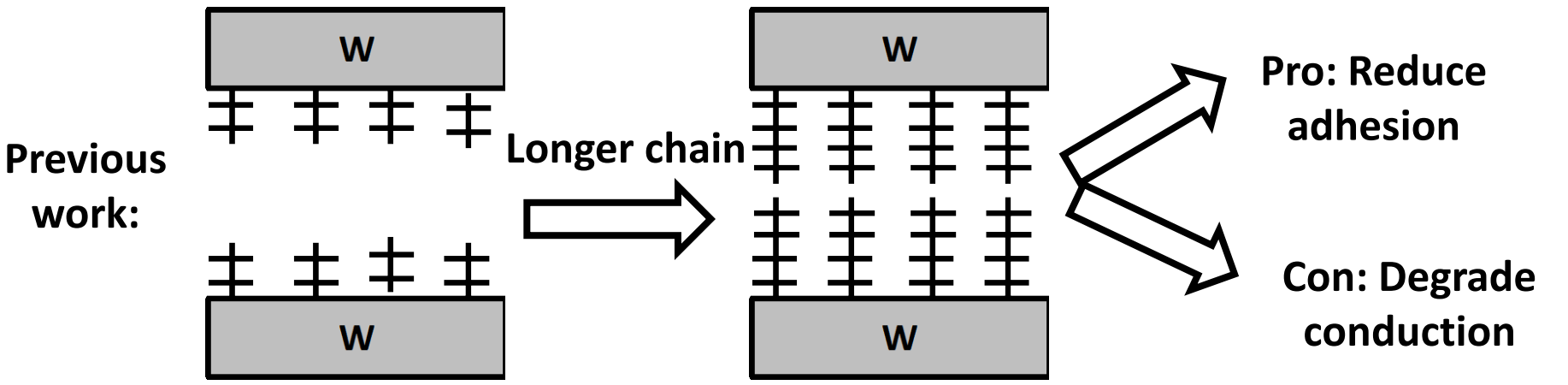
n=(CF_2)=7

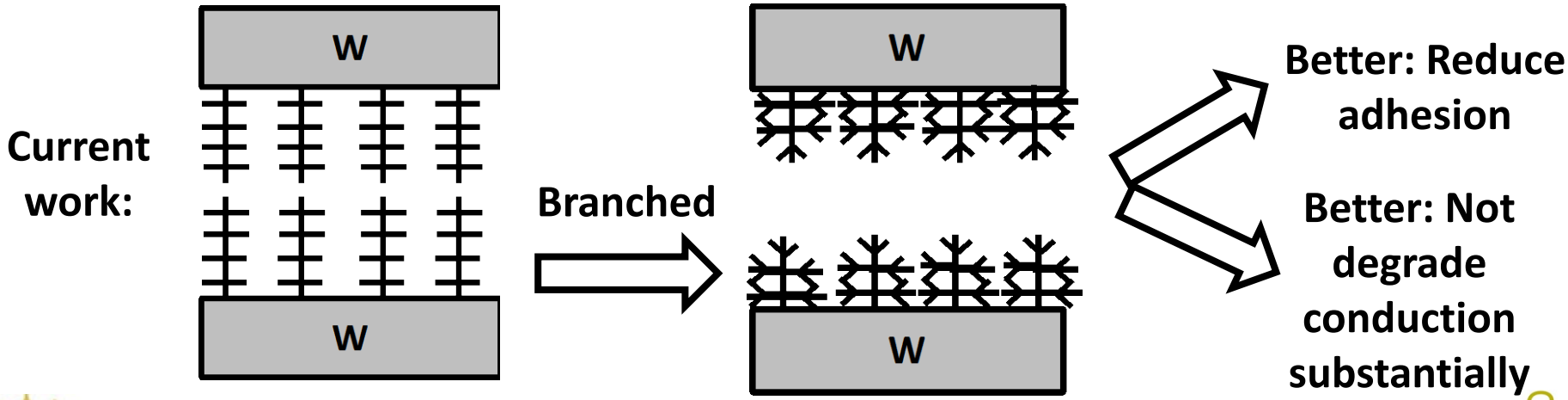
PFTTES Length ~ 0.5 nm



n=0

Motivation for the current work

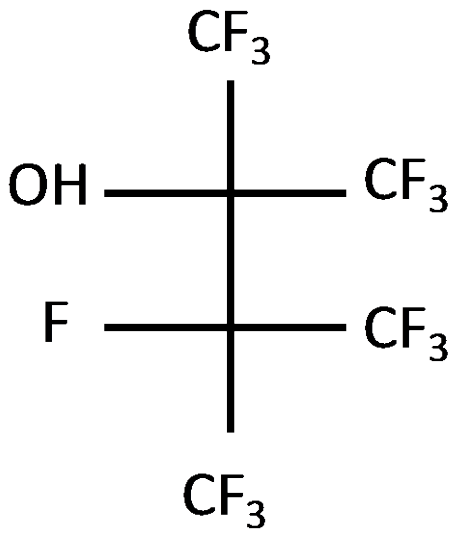




Self assemble molecule used in this work

Perfluoro(2,3-dimethylbutan-2-ol)

Perfluro has ~24 F atoms/nm vs. ~10 F atoms/nm in PFOTES

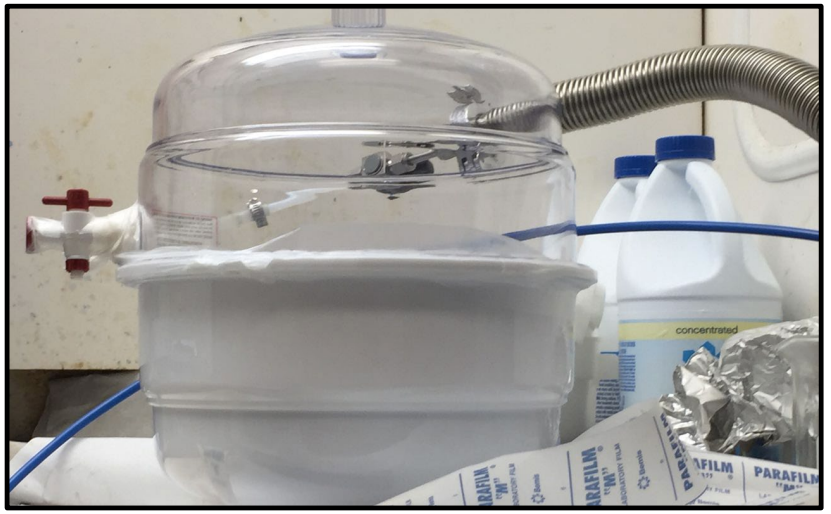


Material characterization:

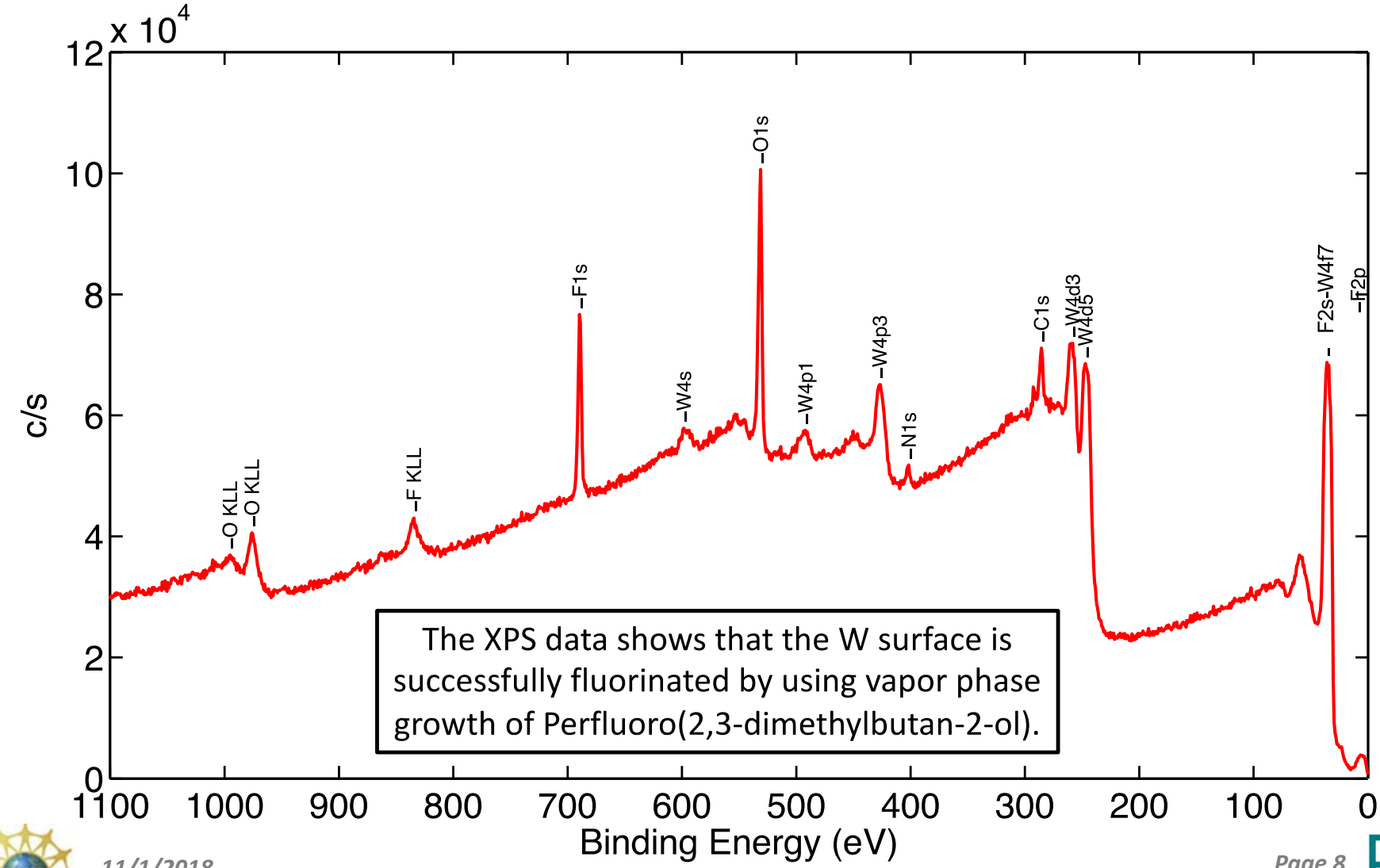
- XPS
- Adhesive force measurement by AFM

Growth Procedure:

- Vapor-phase growth in desiccator
- Pressure: Low vacuum (1 Torr)
- Room temperature
- Time: 14 hours
- Precursor: 250 mg of SAM

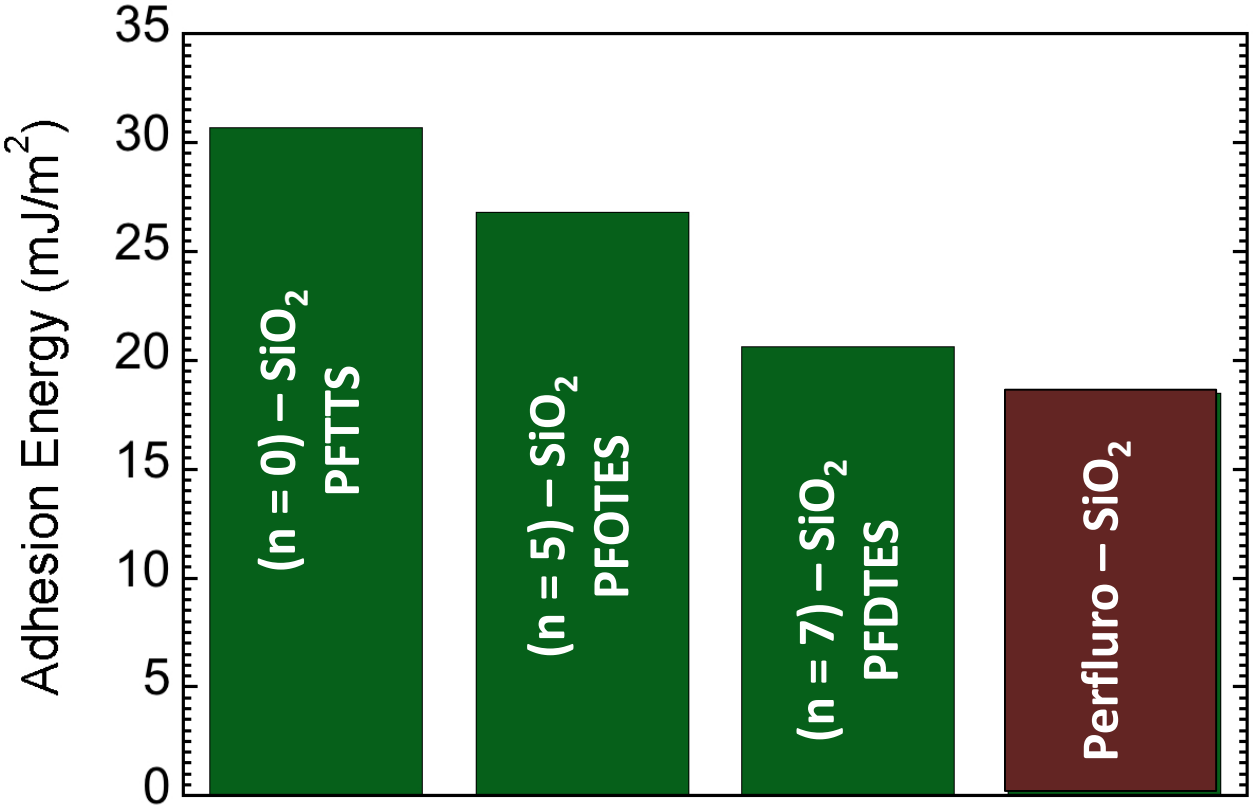


XPS result after vapor phase growth of SAM on W



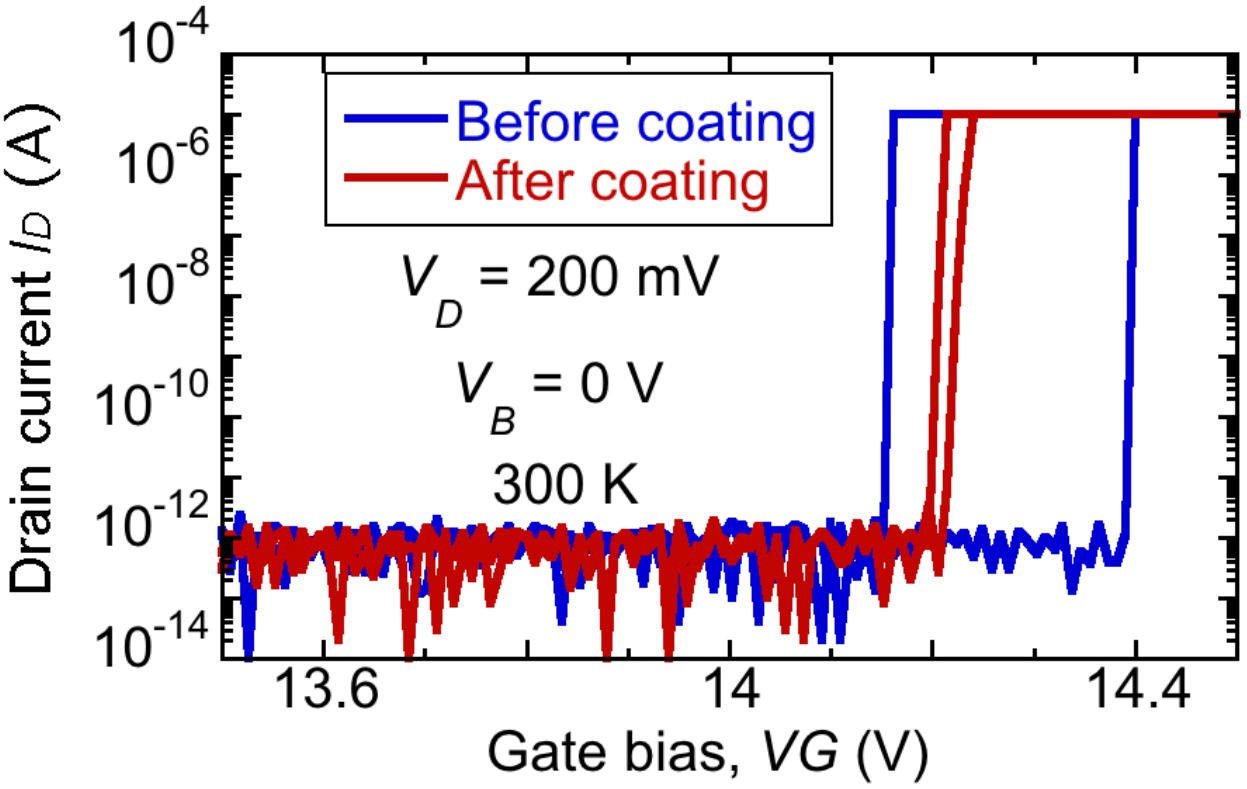
The XPS data shows that the W surface is successfully fluorinated by using vapor phase growth of Perfluoro(2,3-dimethylbutan-2-ol).

Comparison of adhesion energy with the previous coating



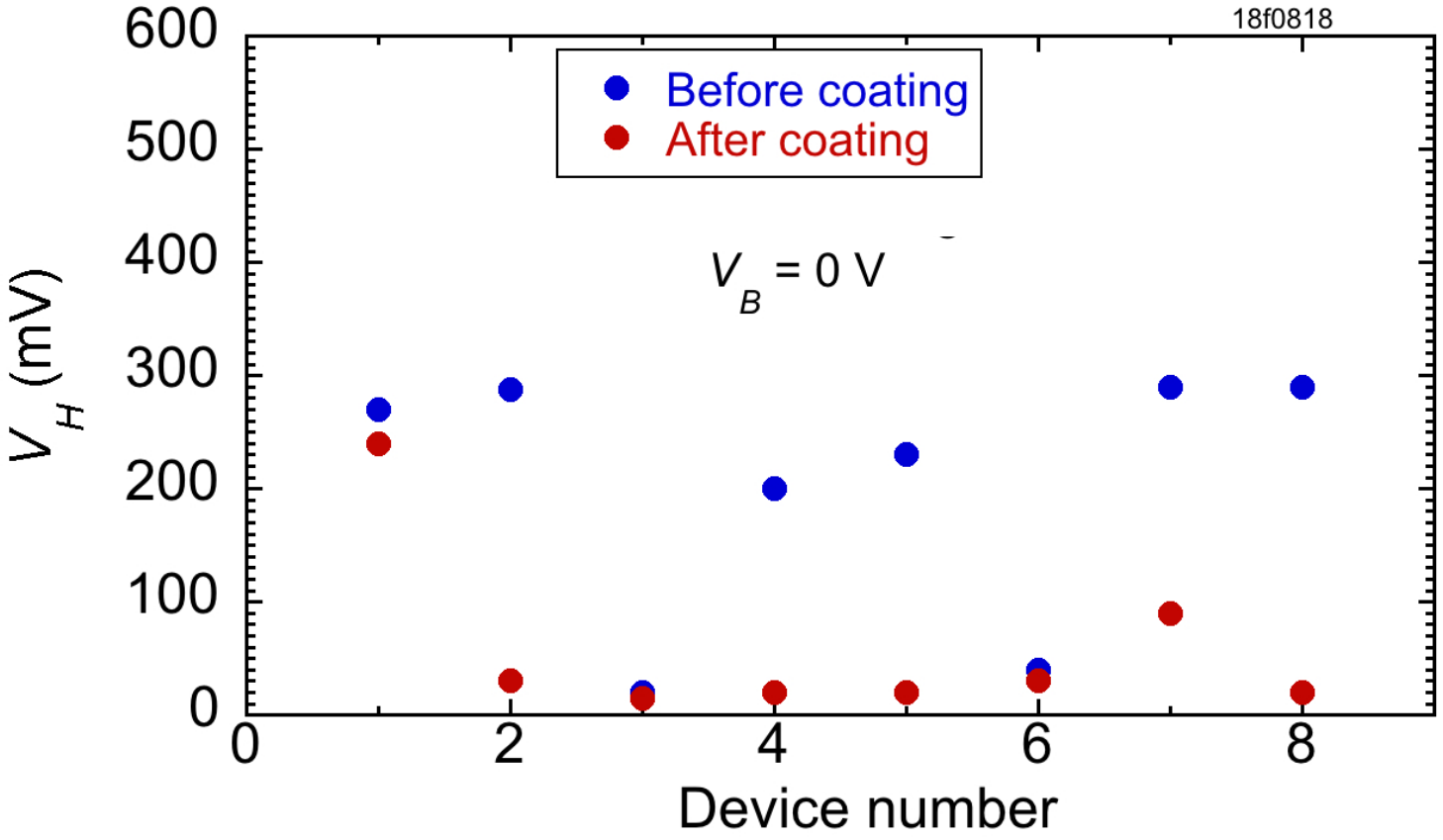
- **Adhesion energy between Perfluro– SiO_2 is slightly smaller than the adhesion energy between PFDTES-SiO_2 and PFOTES-SiO_2.**

Transfer characteristics without body bias



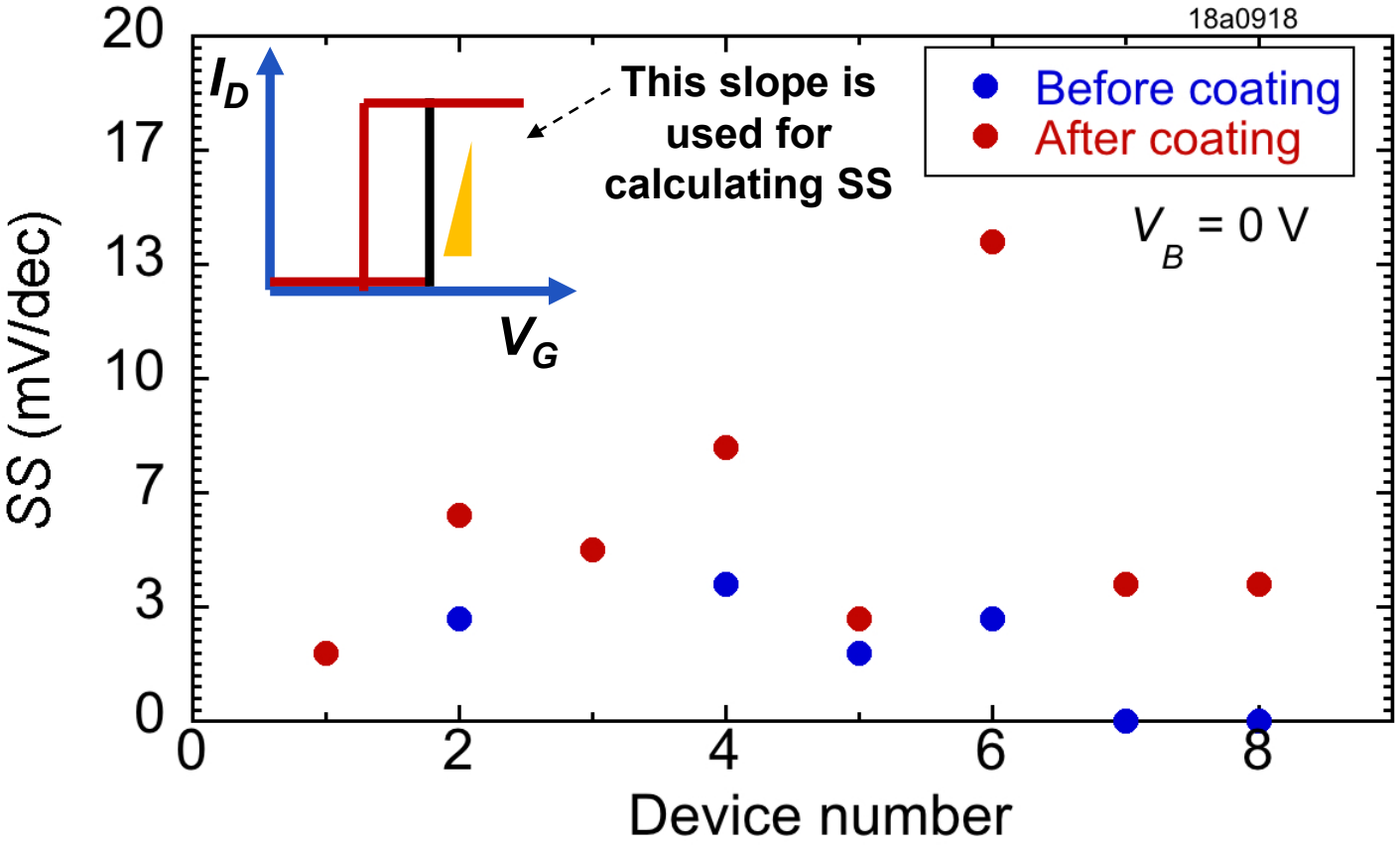
- **Reduction in hysteresis with no substantial change in switching slope (SS).**

Perfluro coating effect on hysteresis voltage



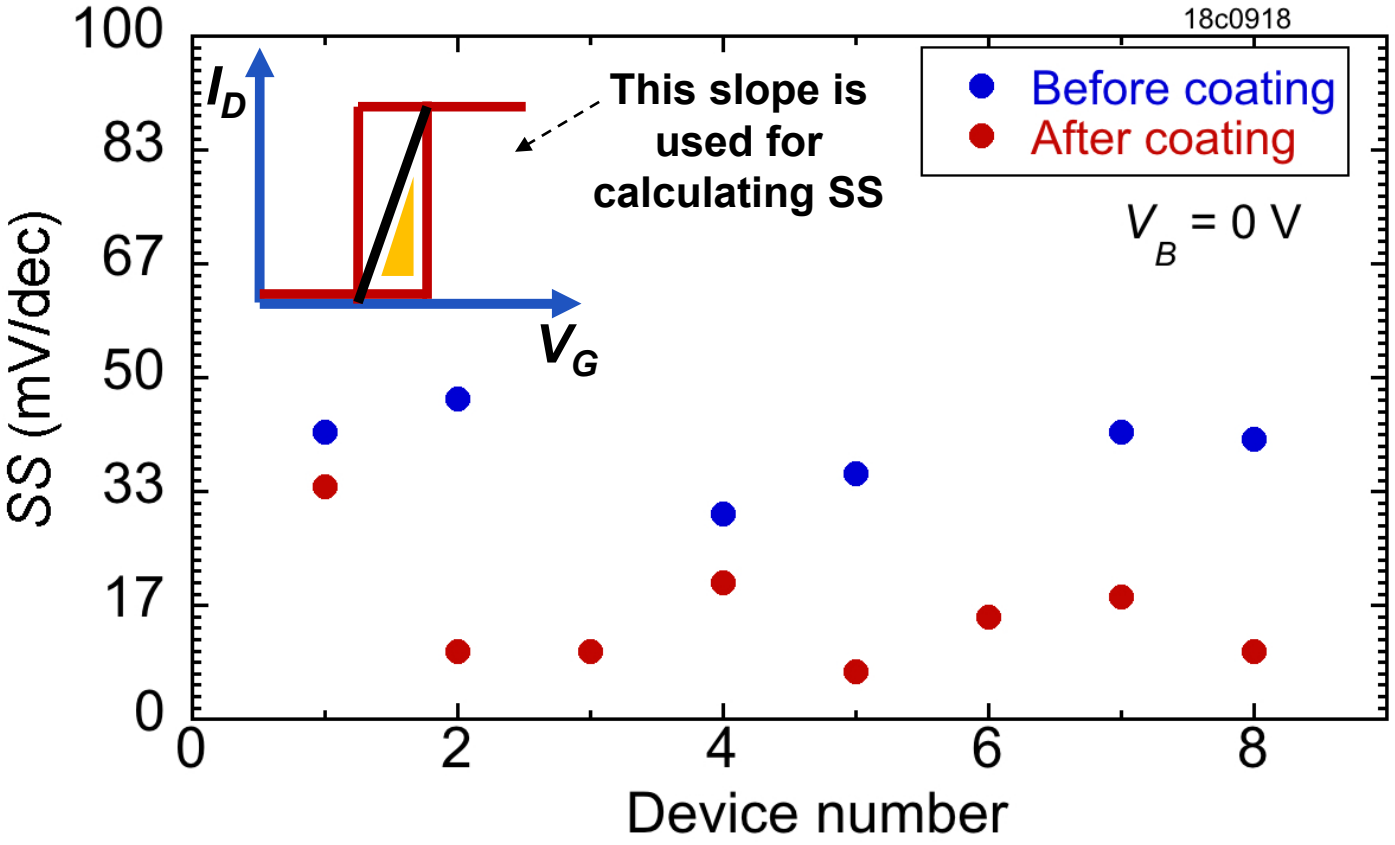
- **Hysteresis reduced after perfluro coating.**
  - **Average of V_H before coating 204 mV.**
    - **Average of V_H after coating 58 mV.**

Perfluoro coating effect on switching slope



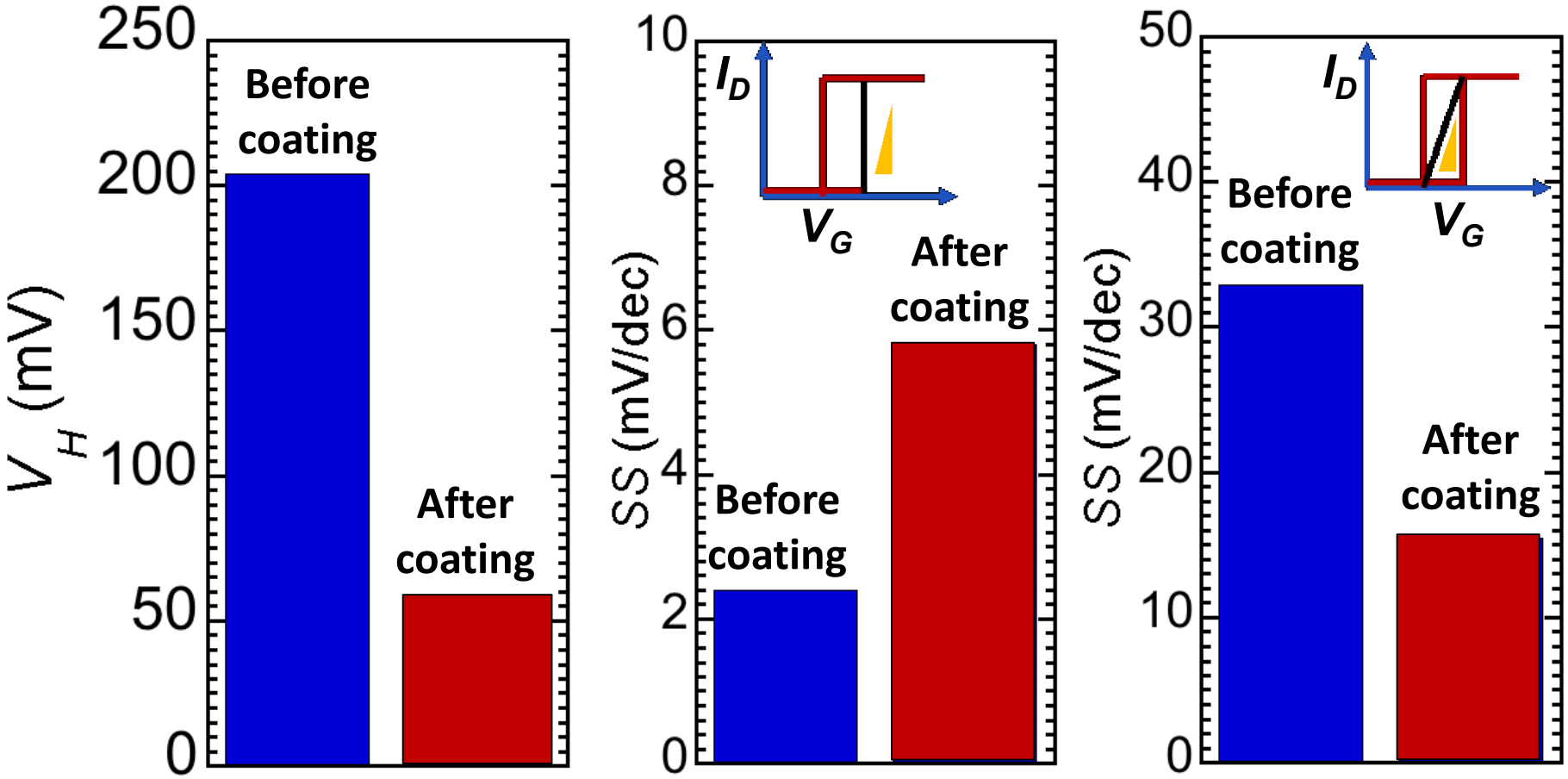
- **Switching slope increased after perfluoro coating.**
  - **Average of SS before coating 2.4 mV/dec**
  - **Average of SS after coating 5.8 mV/dec**

Perfluoro coating effect on switching slope



- **Switching slope decreased after perfluoro coating.**
  - **Average of SS before coating 32.9 mV/dec**
  - **Average of SS after coating 15.5 mV/dec**

Summary - Perfluoro coating effect on hysteresis voltage and switching slope

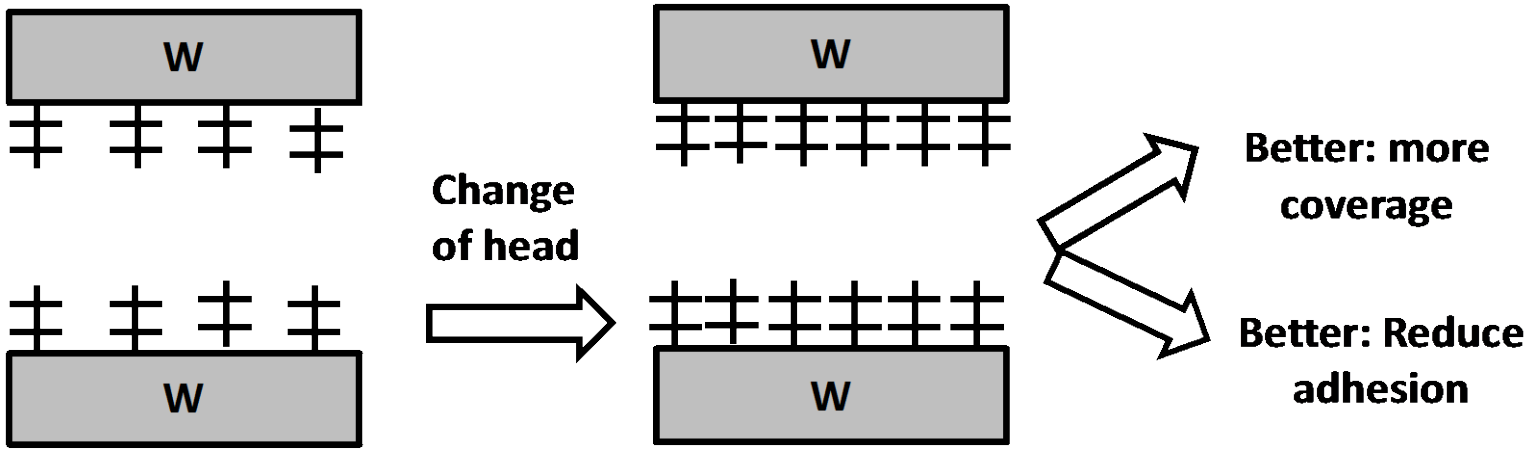


Using Perfluoro coating:

- **V_H is reduced by ~62%.**
- **Average SS is reduced by 52%.**

Future work

- Exploring different kind of molecules with branched fluorinated back bone or with different head groups as anti-stiction coating.



- Material and electrical characterization of such molecules will be done.

Appendix

NEM Relay Equations

Non-Pull in Mode

$$V_{ON} = \sqrt{\frac{2k_{eff}\, g_{CONT}(g_{ACT} - g_{CONT})^2}{\varepsilon\ A_{ACT}}}$$

$$V_{RL} = \sqrt{\frac{2(k_{eff}\, g_{CONT} - F_{adh})(g_{ACT} - g_{CONT})^2}{\varepsilon\ A_{ACT}}}$$

$$V_H = V_{ON} - V_{RL} \approx \frac{F_{adh}\ (g_{ACT} - g_{CONT})}{\sqrt{2\varepsilon\ A_{ACT} k_{eff}\, g_{CONT}}}$$

Forces in a NEM relay

Adhesive force:

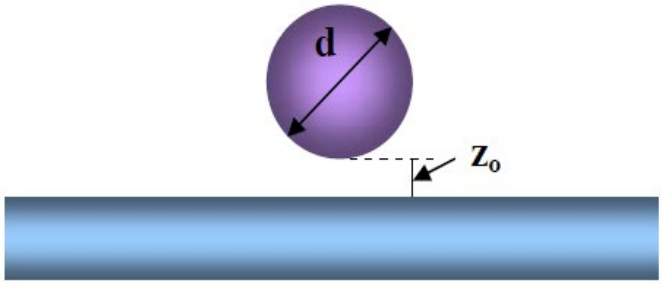
$$F_{ad} = \frac{AS}{g^3}$$

A is Hamaker constant

$$A = \pi^2 \times C \times \rho_1 \times \rho_2$$

Density

Particle-Particle interaction coefficient



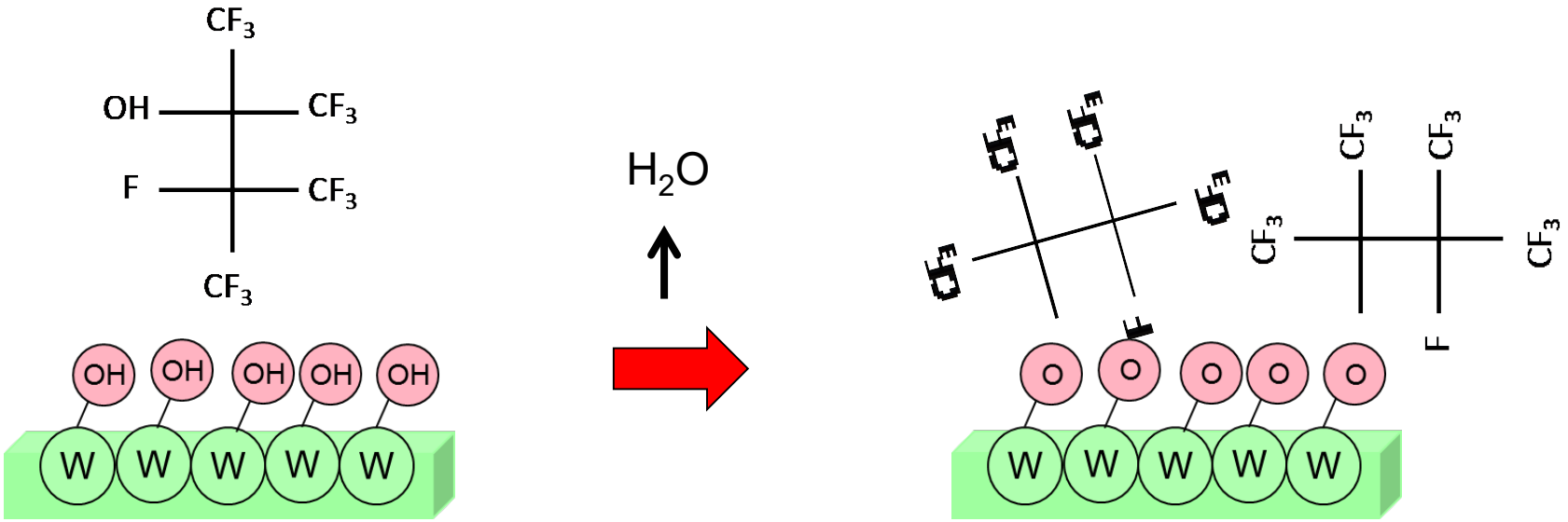
Electrostatic force:

$$F_{es} = Q\mathbb{E} = S\varepsilon V^2/g^2$$

Spring force:

$$F_s = -kx$$

Self-assembled Molecular (SAM) Coating



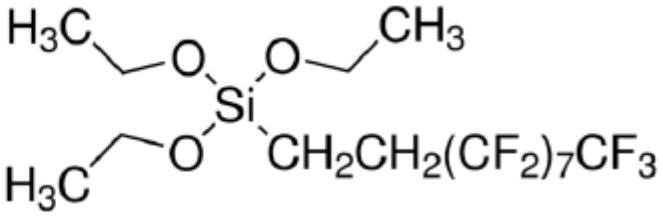
Self-assembled Molecular (SAM) Coating

Silane functional groups for molecular self-assembly.

1H,1H,2H,2H-perflurodecyltriethoxysilane

PFDTES

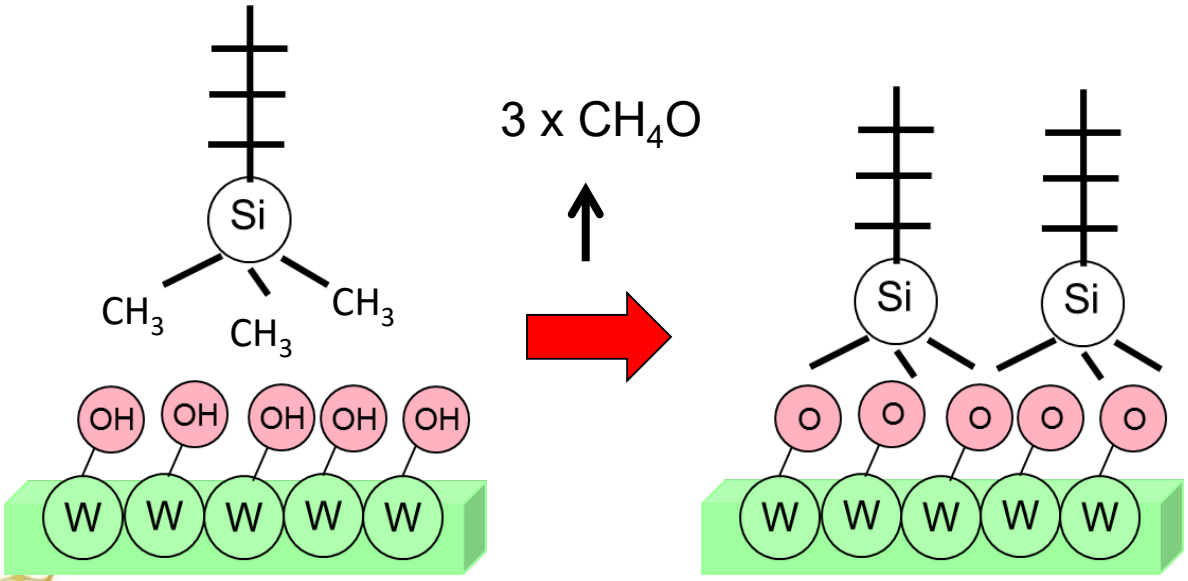
Length ~ 1.5 nm

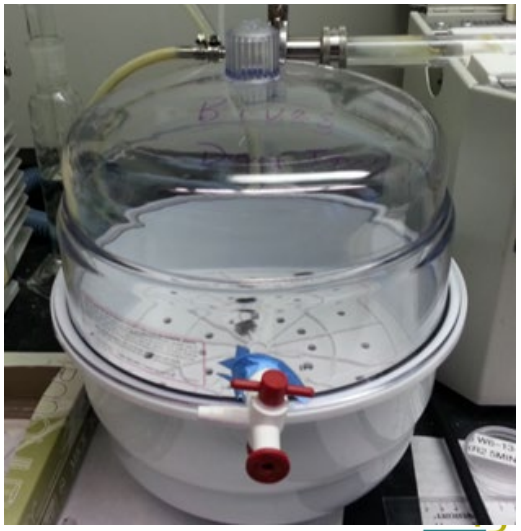


(CF_2)= n = 7

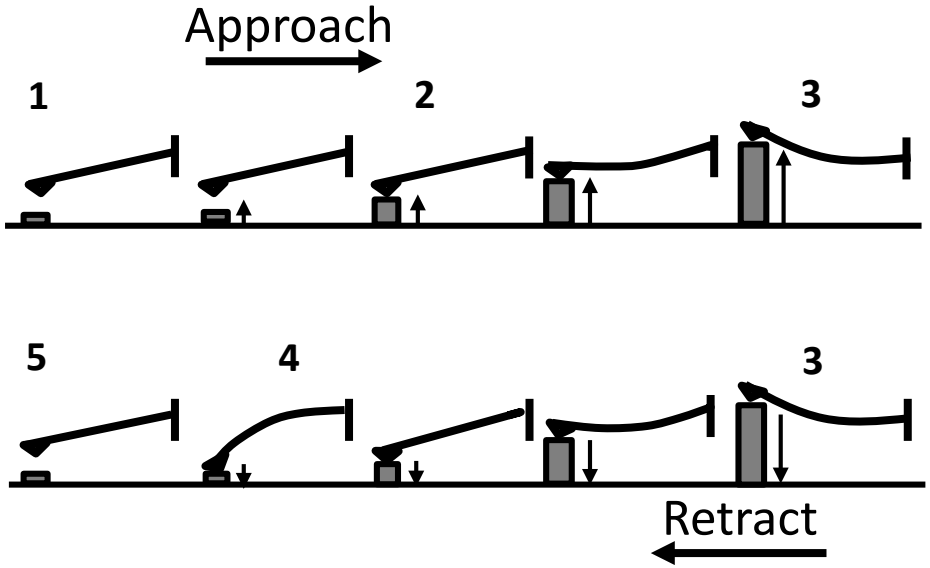
Chemistry of Relay Coating

Vapor-phase SAM growth in a low vacuum environment.





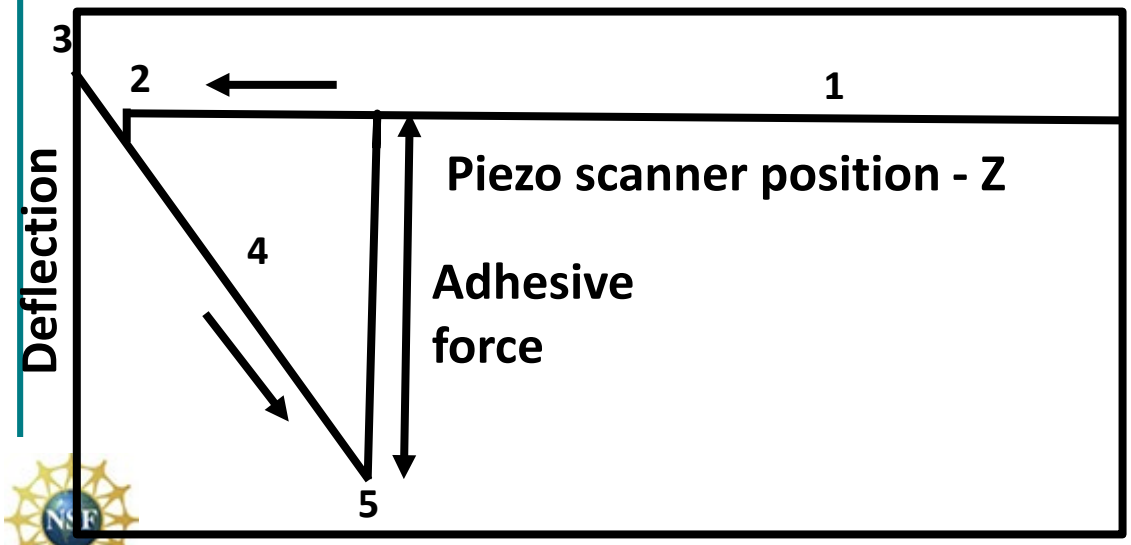
Adhesive force measurement with AFM



- After adhesive force is extracted from AFM measurement, adhesion energy can be calculated using the following formula (the roughness of the surface is ignored):

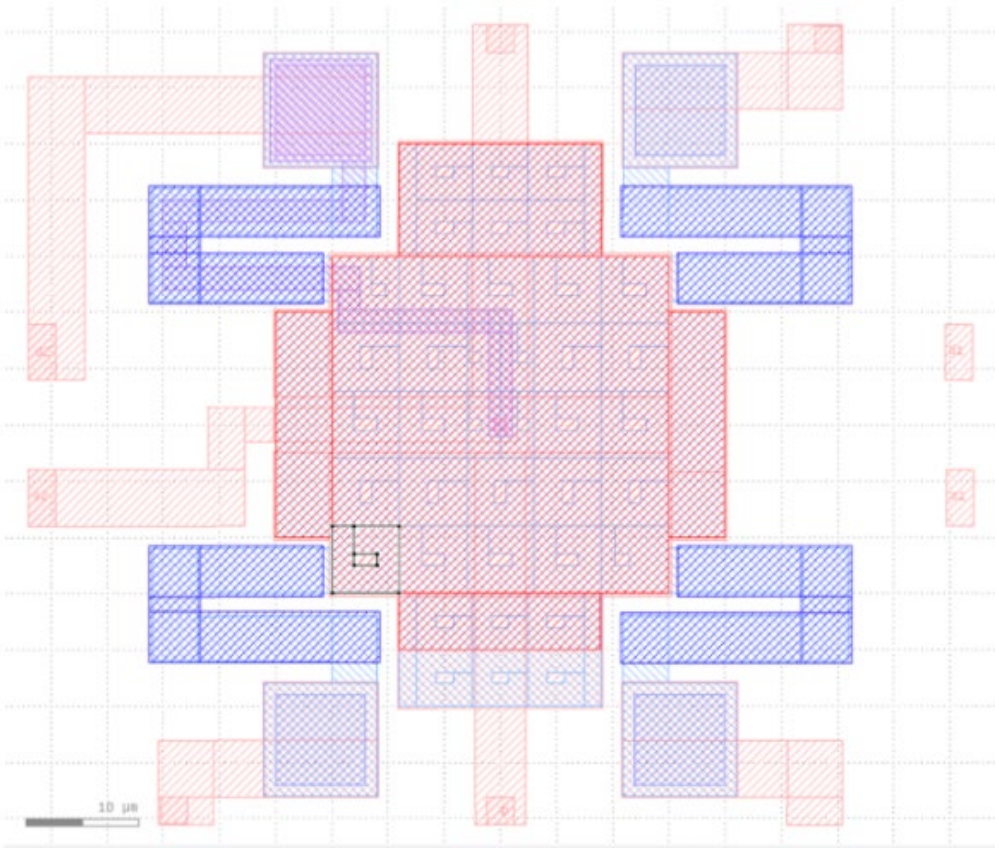
$$W_{Ad.} = \frac{F_{Ad.}}{2\pi R_{tip}}$$

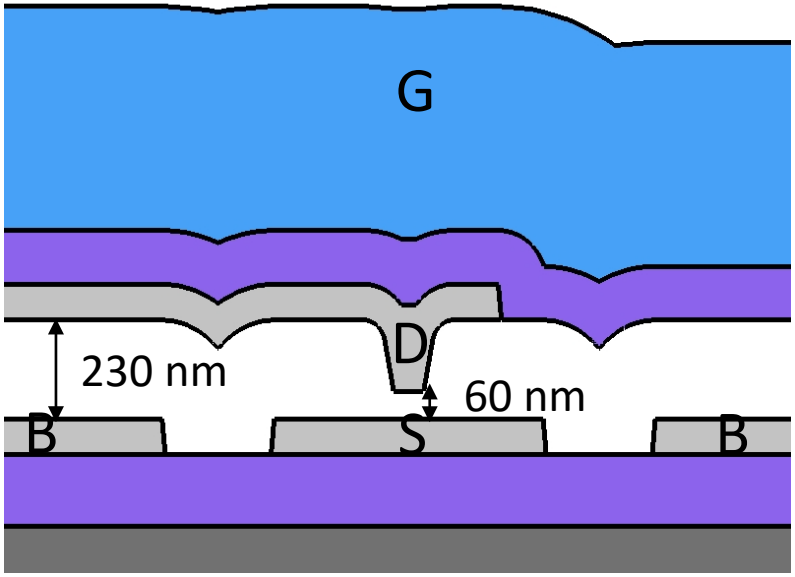
R_{tip} is the tip radius



- For this measurement micro spherical tip should be used instead of a conventional sharp tip, to have more contact area with the surface.

Device structure

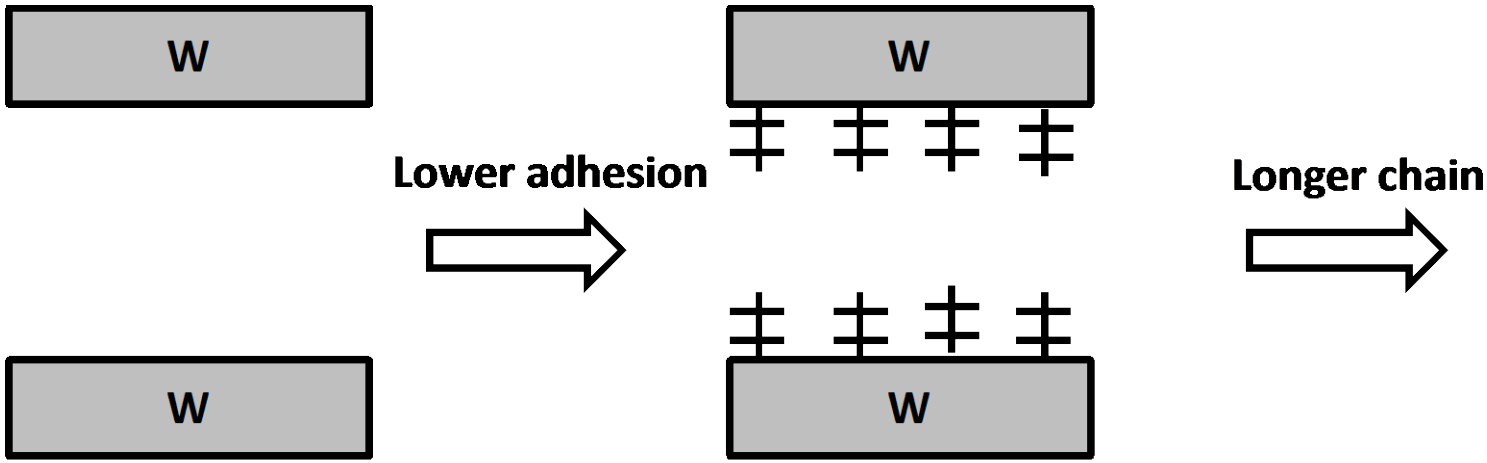


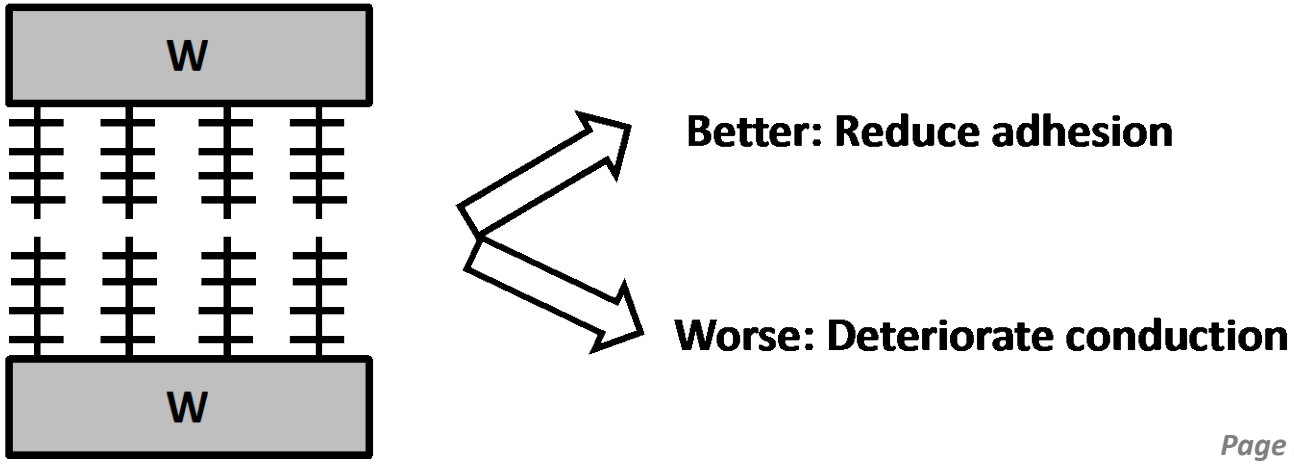


Contact dimple area: 1 x 1 um^2

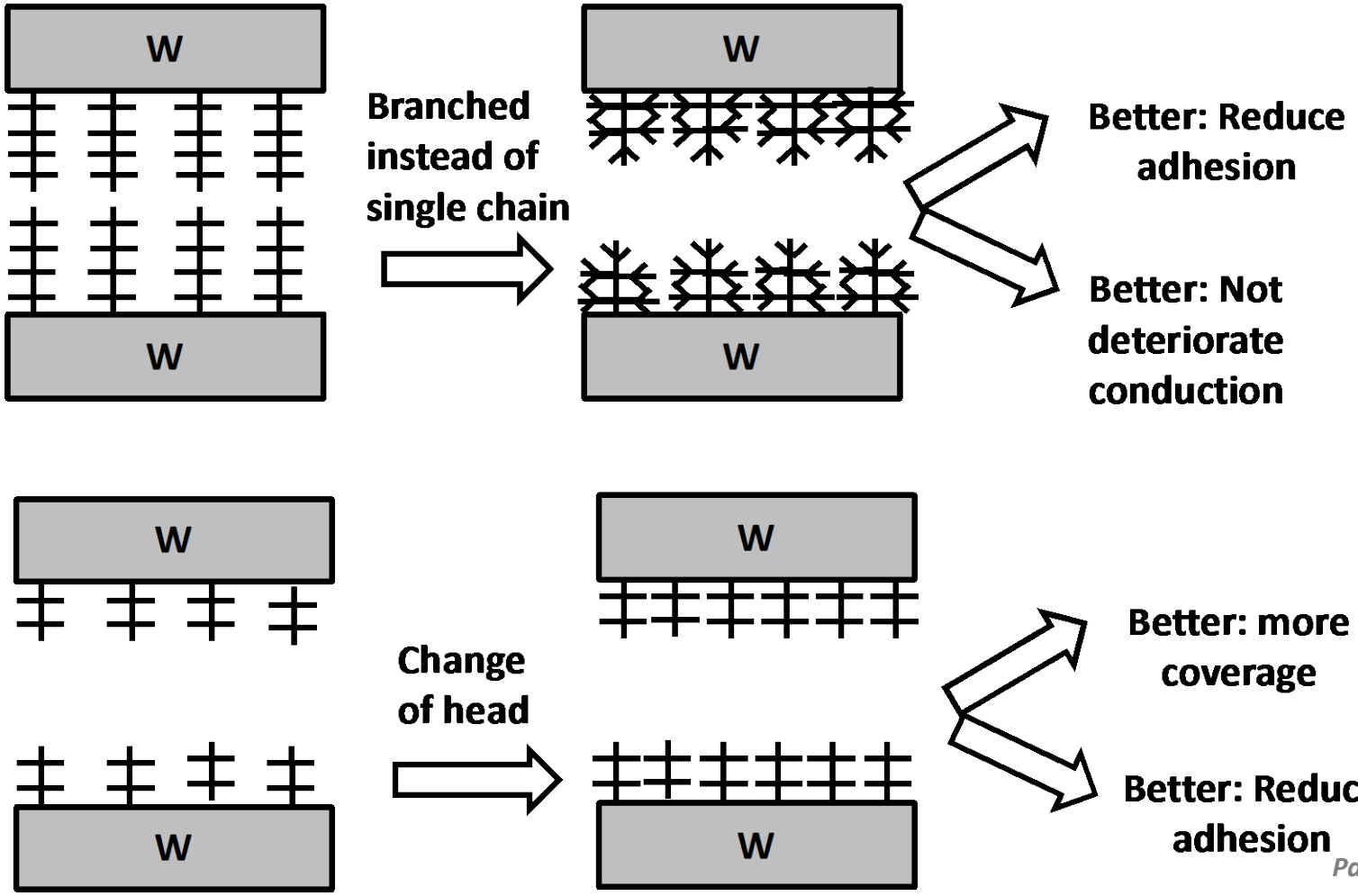
Total area: 773.25 um^2

Using SAMs as anti-stiction coating (Prior work)



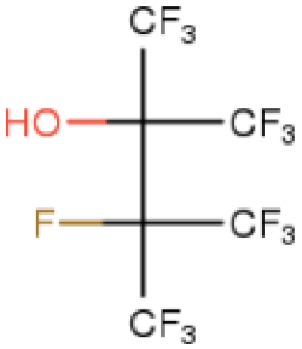


Using SAMs as anti-stiction coating (Current work)

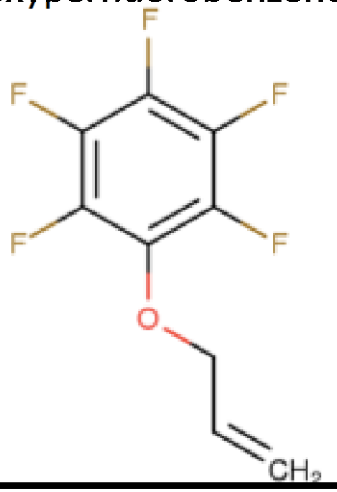


Self-assembled molecules as anti-stiction coating

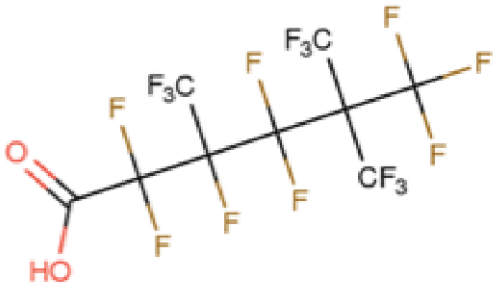
Perfluoro(2,3-dimethylbutan-2-ol)



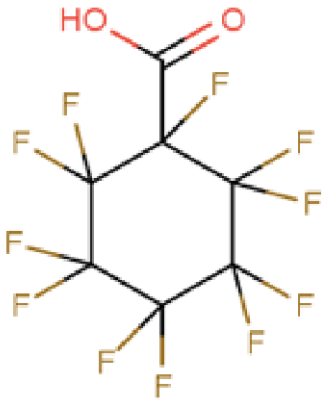
Allyloxyperfluorobenzene



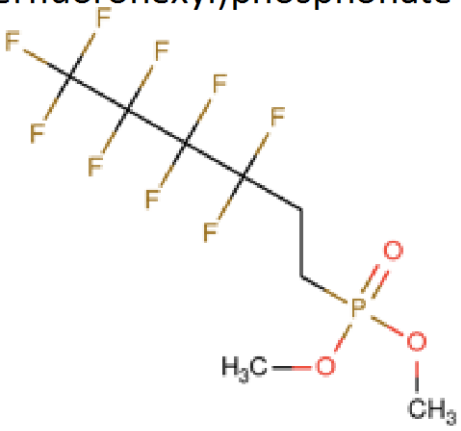
Perfluoro-3,5,5-trimethylhexanoic acid



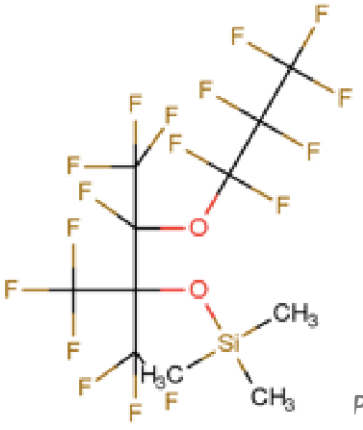
Perfluorocyclohexylcarboxylic acid



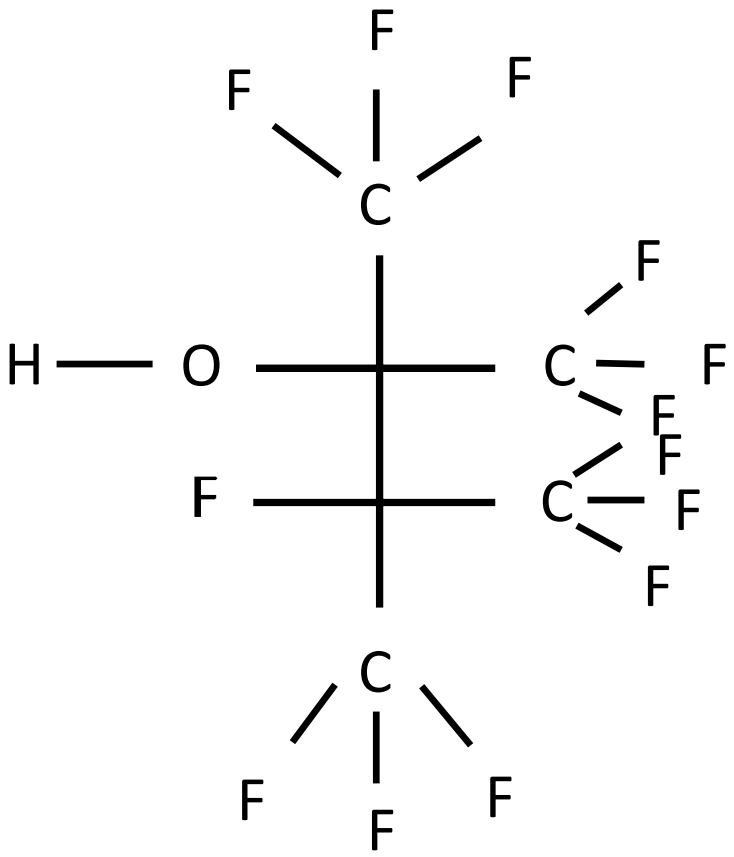
Dimethyl (1H,1H,2H,2H-perfluorohexyl)phosphonate



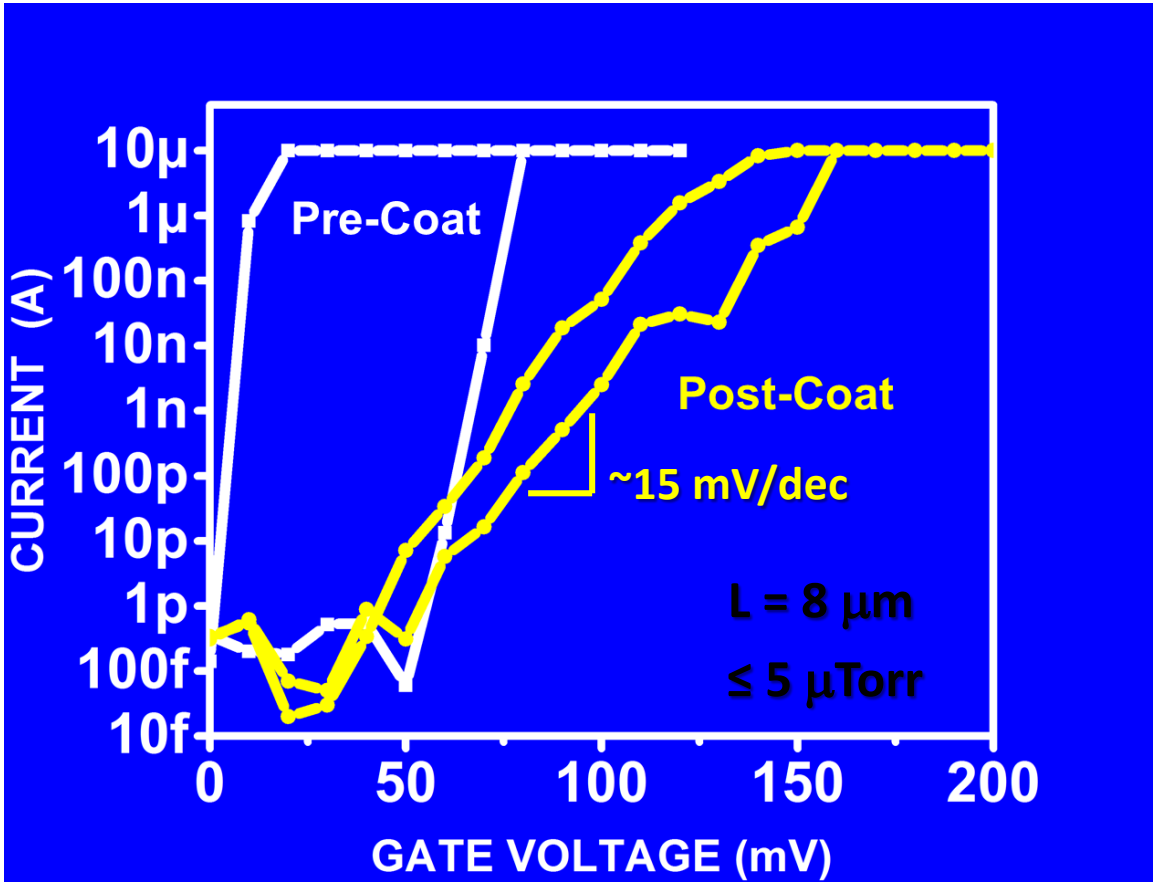
Trimethyl(perfluoro-1,1,2-trimethyl-3-oxahexyloxy)silane



Perfluoro(2,3-dimethylbutan-2-ol)

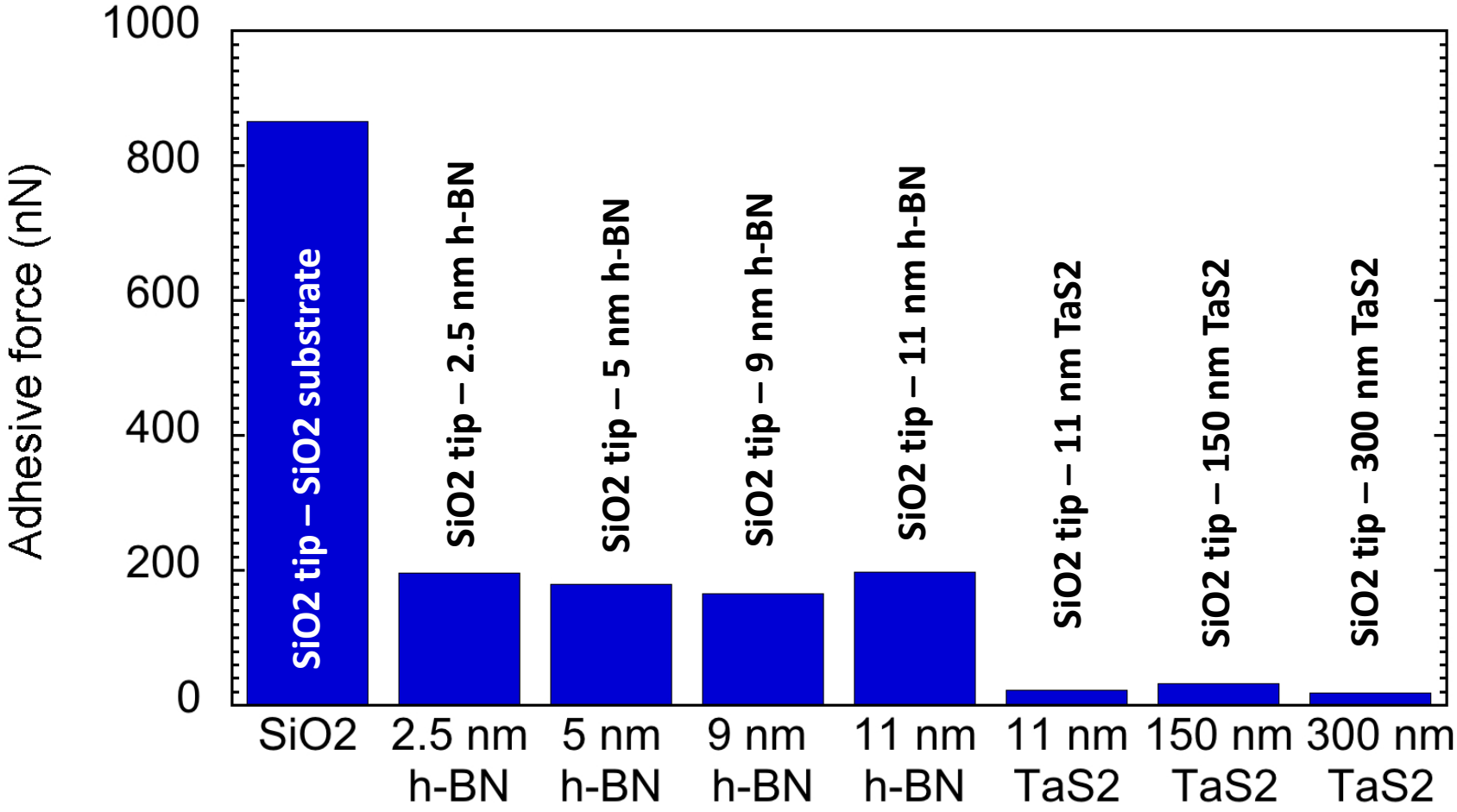


Measured I-V Characteristics



- Coating enables lower V_{DD} but at a tradeoff of lower I_{ON}/I_{OFF} ratio (higher effective R_{ON})

Comparison of adhesive force between SiO2 AFM tip and different bulk 2D materials



- **Adhesive force between AFM tip and TaS2 is less than the adhesive force between AFM tip and h-BN.**