Self-assembled molecular coating to reduce adhesion in NEM switches

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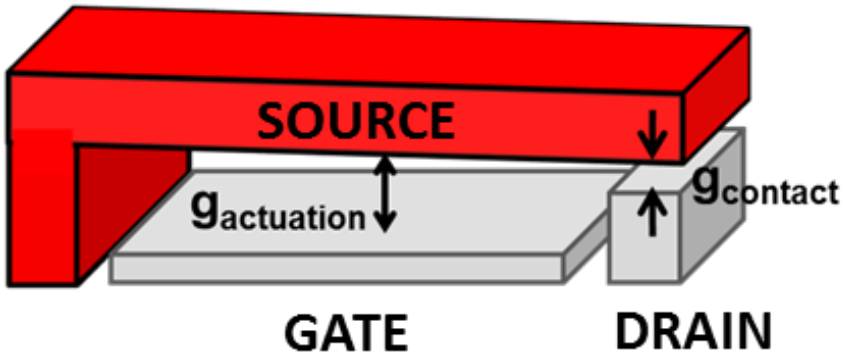
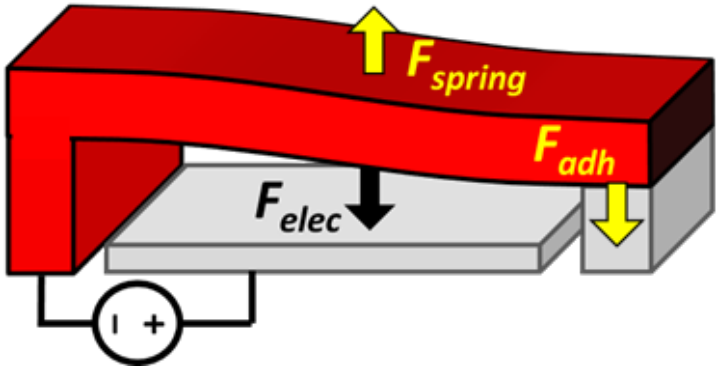
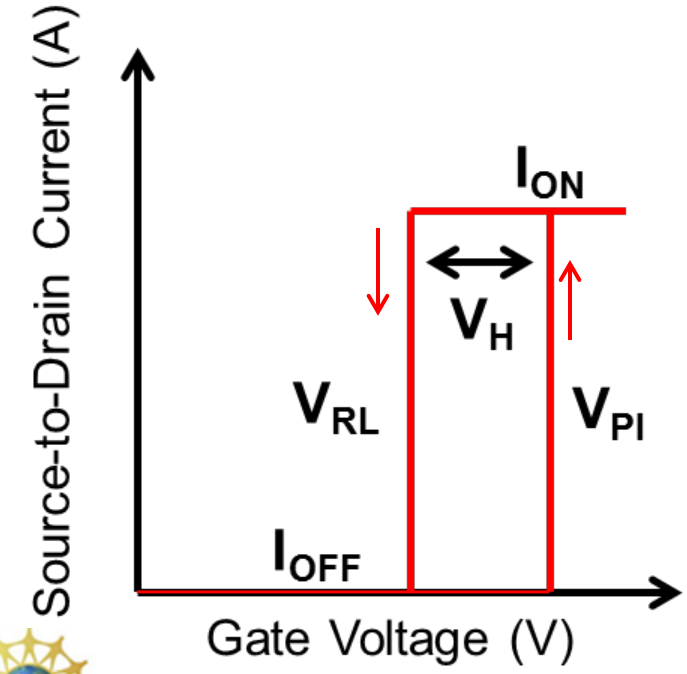
Nano-electromechanical (NEM) Relays

OFF State



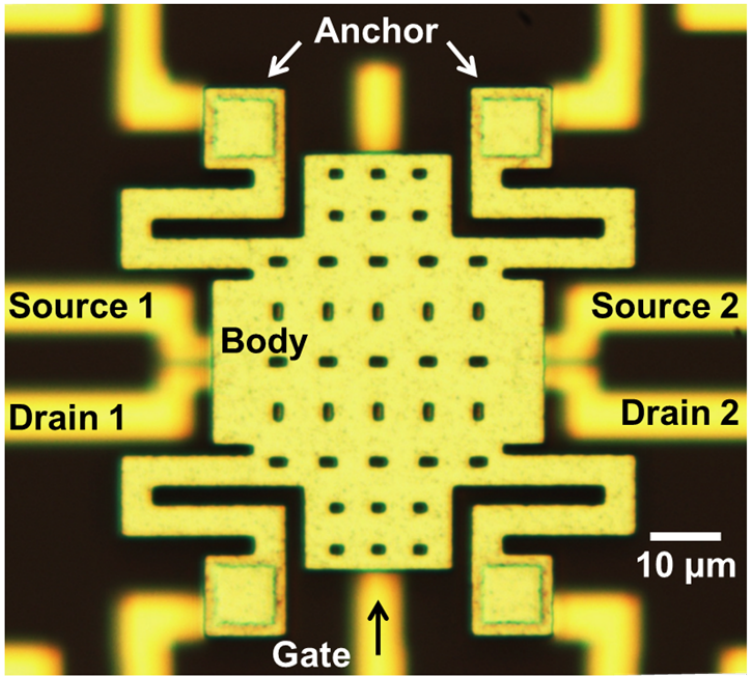
ON State

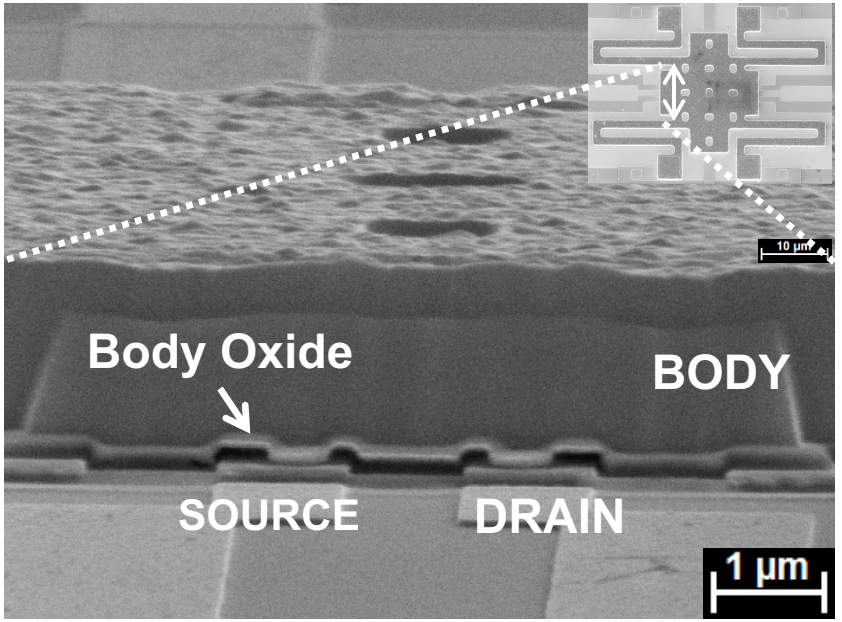




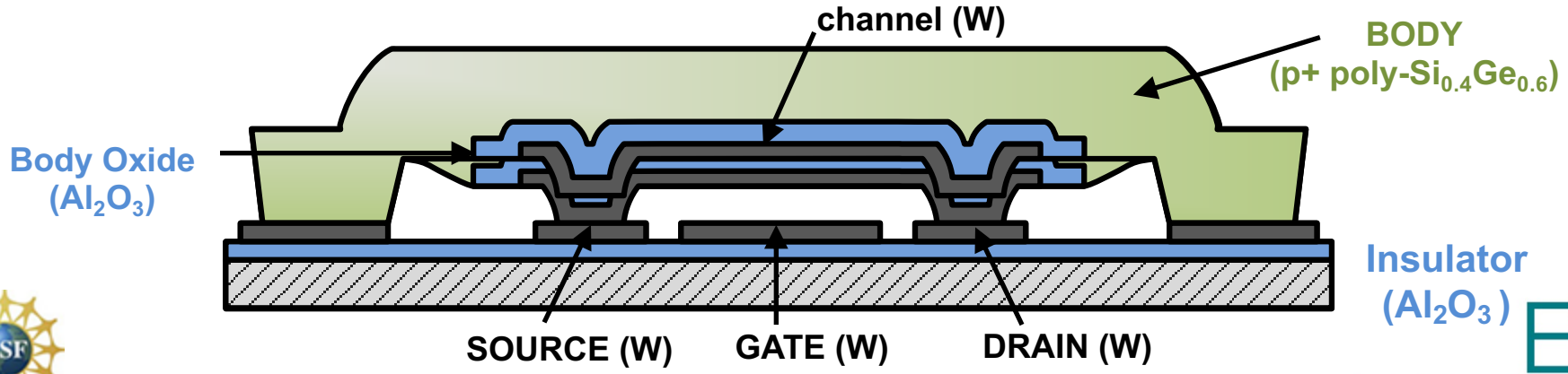
- Abrupt Switching.
- High ON-state Conductance.
- Large ON/OFF Current Ratio.
- Low Operating Voltage and Energy.
- Speed, Reliability, Endurance and Cost.

Body-Biased Relay Structure & Operation





I-R. Chen et al., Transducers (2013)



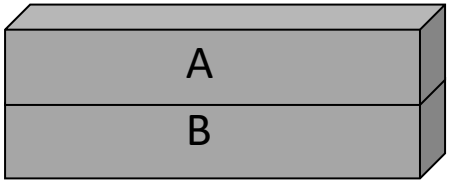
How to Reduce V_H (below 100 mV?)

Adhesion Energy

$$W_{Ad.} = \sigma_A + \sigma_B - \gamma_{AB}$$

σ_A= *Surface Energy*

γ_{AB}= *Interface Energy*



For A=B

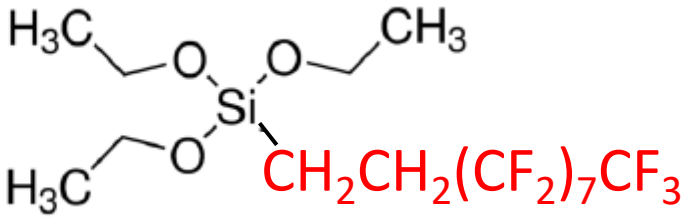
$$W_{Ad.} \sim 2\sigma_A$$

Goal: lower the surface energy, while keeping the electrodes as good electrical conductors.

Self-assembled Molecular (SAM) Coating

Perflurodecyltriethoxysilane (PFDTES):

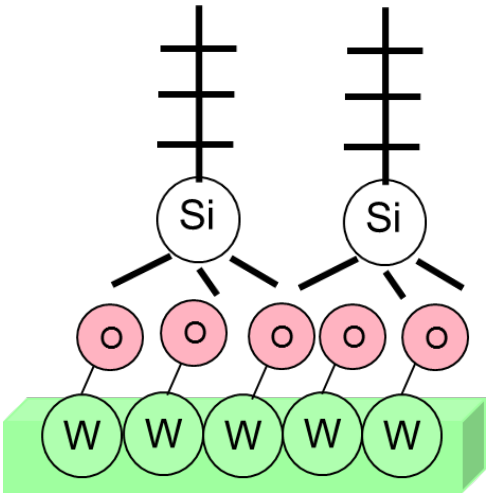
- CF_2 group for electronic repulsion
- CH_3 group for self-assembly

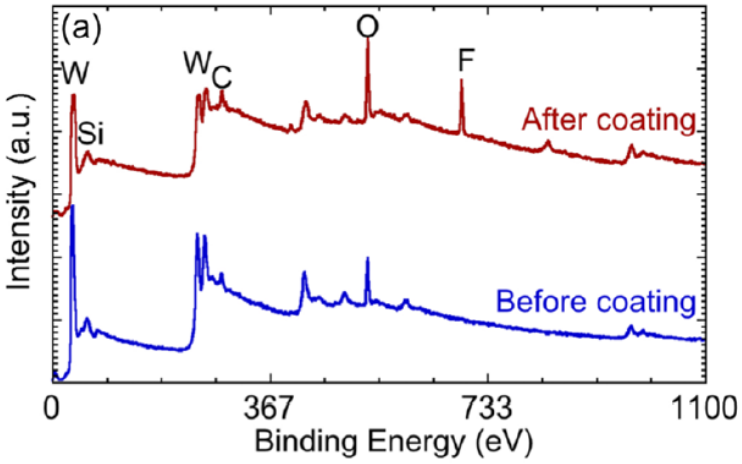


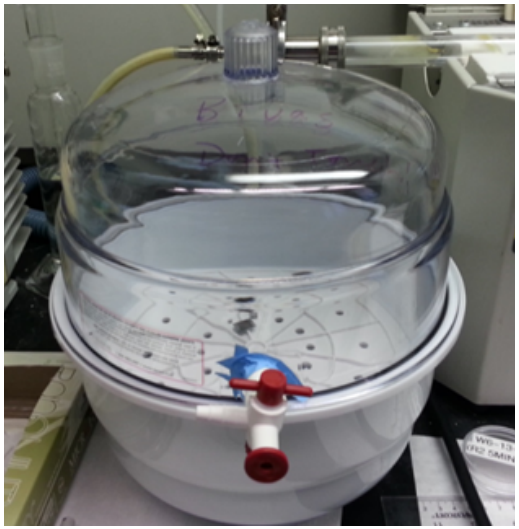
n of (CF_2) = 7

Self-assembled molecular (SAM) coating

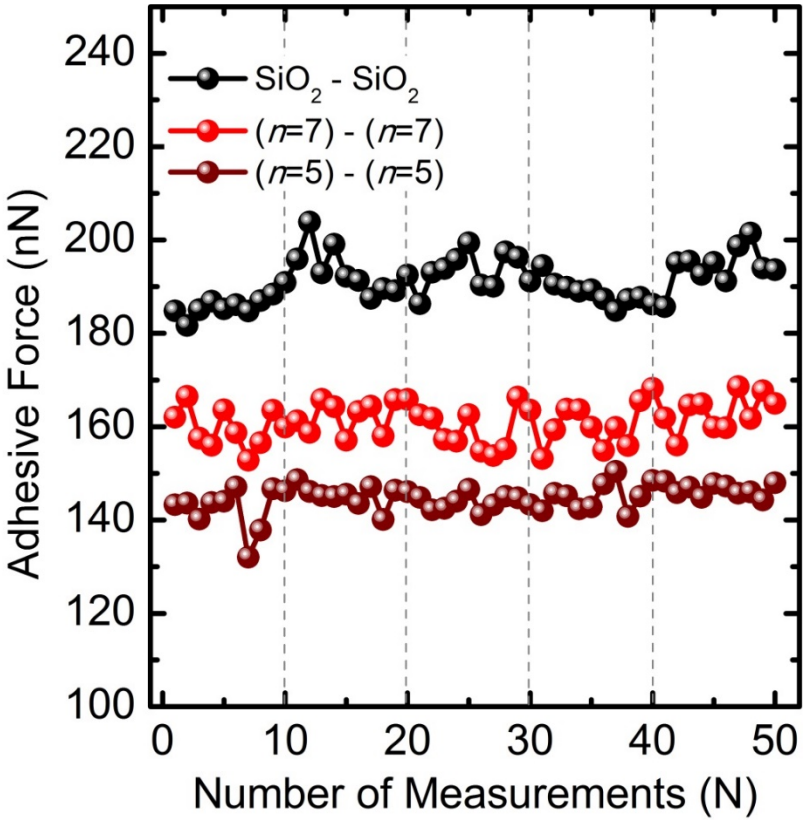
- Vapor-phase SAM growth at room temperature in low vacuum:
- A few drops of the molecules were placed in close proximity to the relay test chip inside a vacuum desiccator
- Pressure was reduced to vaporize the molecules.
- The chip was left in this environment for ~ 24 hours to ensure full molecular coverage of the device.

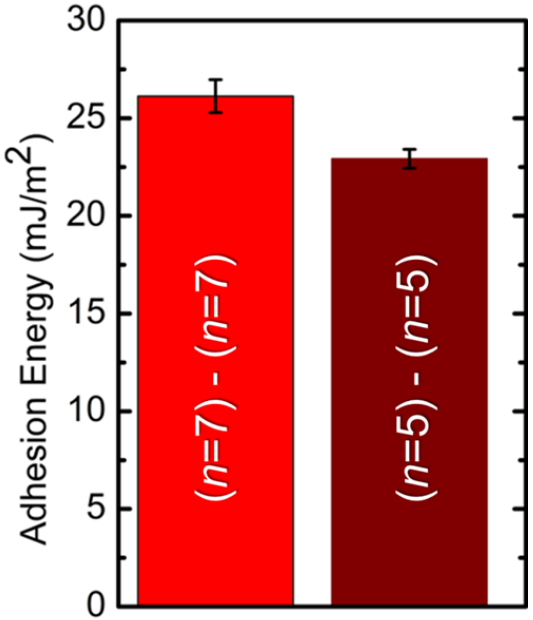




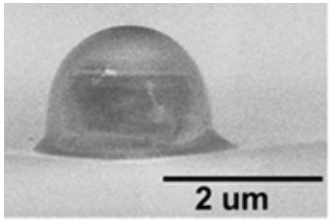


Adhesive Force Characterization by AFM





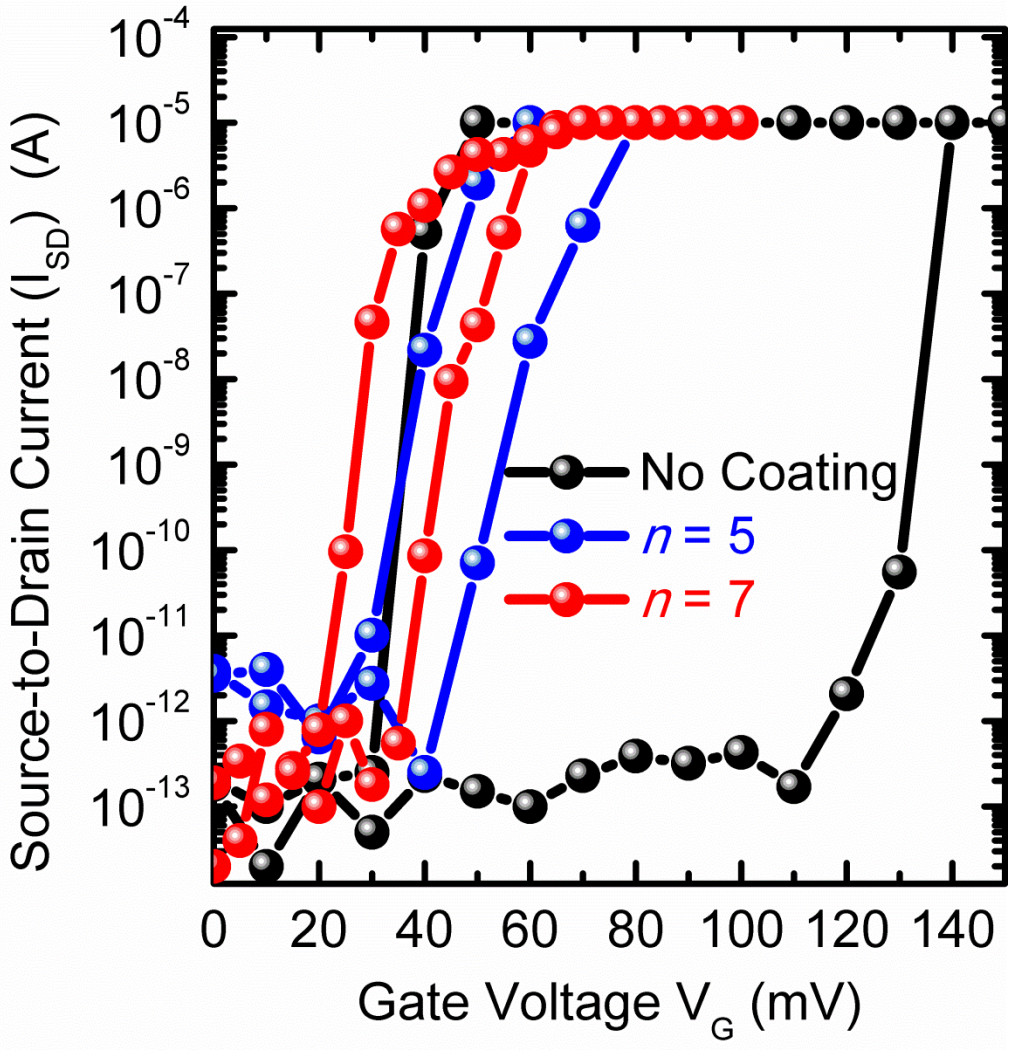
$$W_{Ad.} = \frac{F_{Ad.}}{2\pi R_{tip}}$$



Round AFM tip

- Adhesion energy from the molecules is reduced to ~ 25 mJ/m^2.
- Adhesive force values are stable over 1000 operating cycles.

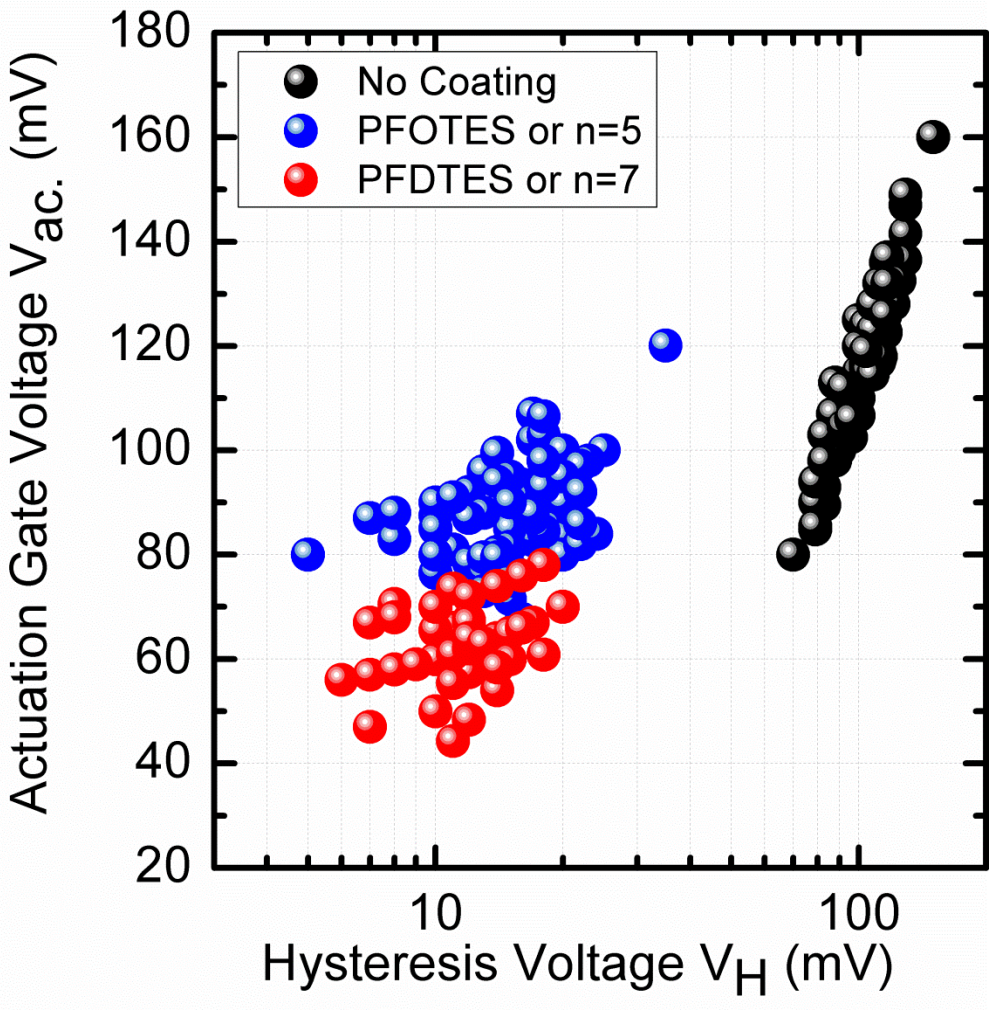
Effects of SAM Coating on NEM Performance



- Hysteresis voltage reduced from 100 mV (uncoated) to 16 mV (n=7) and 19 mV (n=5).
- Gate actuation voltage reduced to 60 mV and 80 mV, respectively, with 8 orders of magnitude I_{ON}/I_{OFF}.
- Molecules with n < 5 no longer reduce hysteresis voltage, hence do not enable low voltage operation.

Osoba, Saha, et al., IEDM (2016)

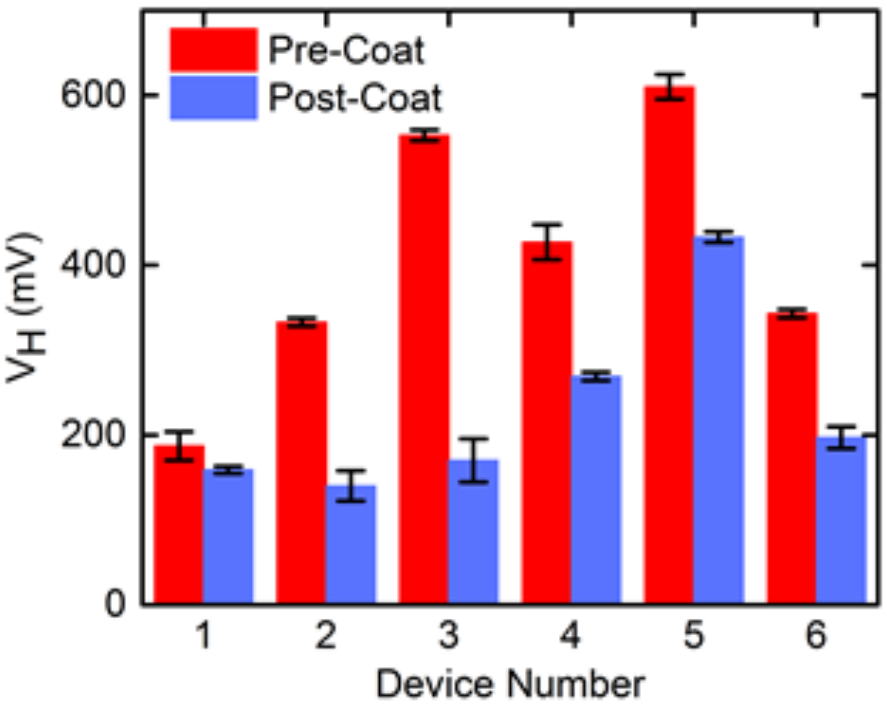
Effects of SAM Coating on NEM Performance

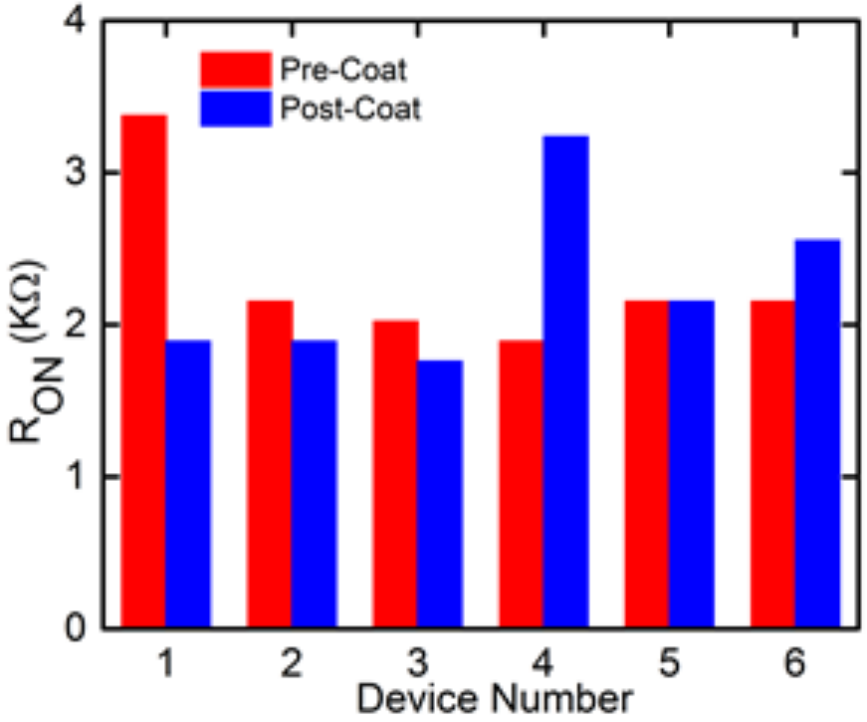


- Molecular coating reduces hysteresis voltage by ~10×.
- Actuation gate voltage reduced by ~2×.
- Molecular coating also reduces random variations in V_{PI}, V_{RL} and V_B, beneficial for voltage scaling.

Osoba, Saha et al, IEEE Trans. Electron Devices, 65, 1529 (2018).

SAM Coating Effect on V_H and R_{ON}

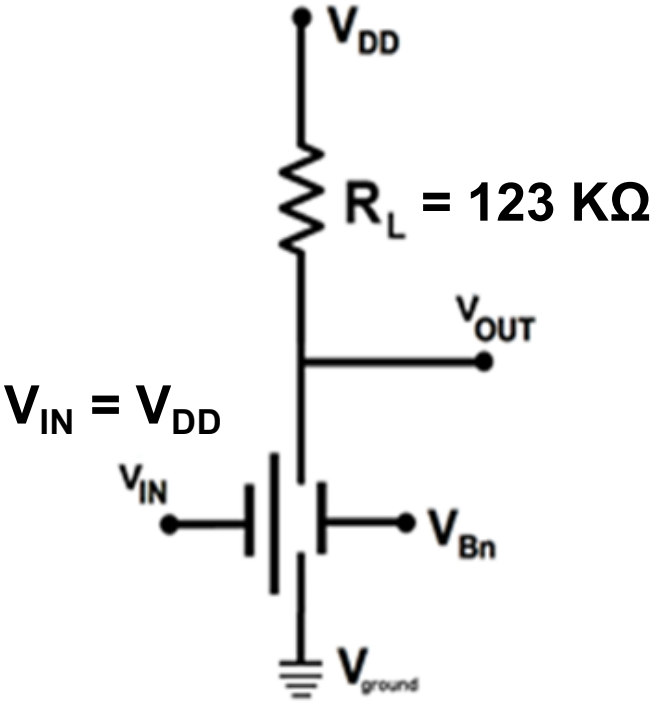




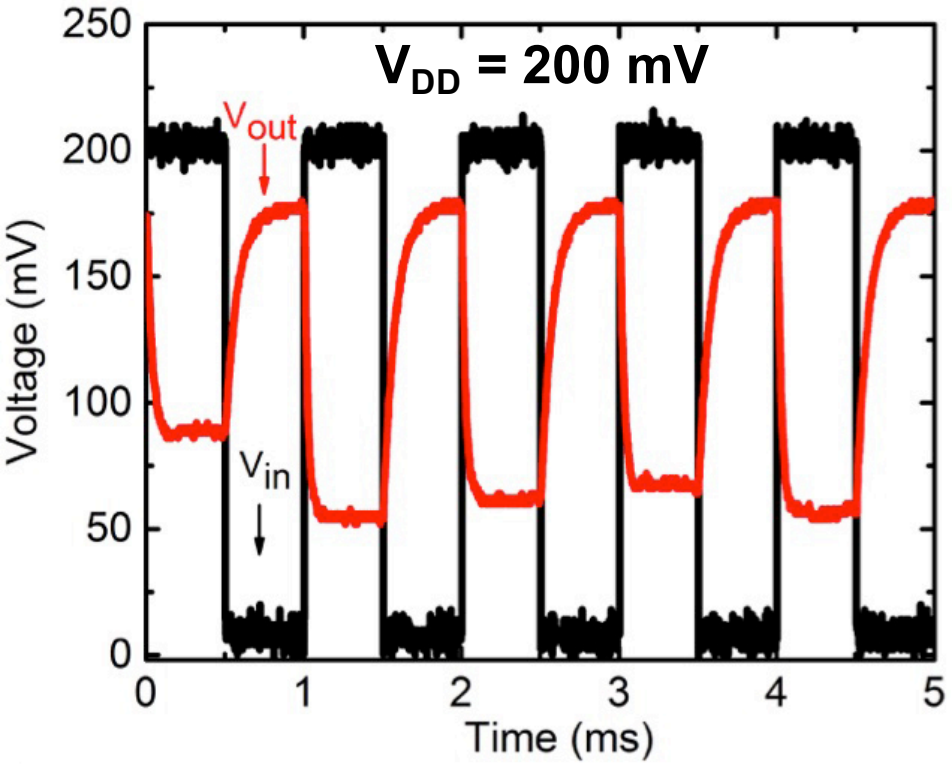
- V_H is reduced (by ~41%) with SAM coating.
- ON-state resistance (R_{ON}) is not greatly affected.

Relay-Based Inverter Circuit

Pull-down or "n"-relay



Measured voltage waveforms



- V_{OUT} does not reach V_{DD} due to 1 MΩ oscilloscope internal resistance.

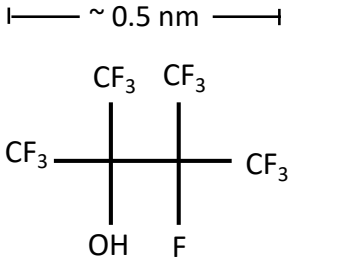
Osoba, Saha, et al., IEDM (2016)

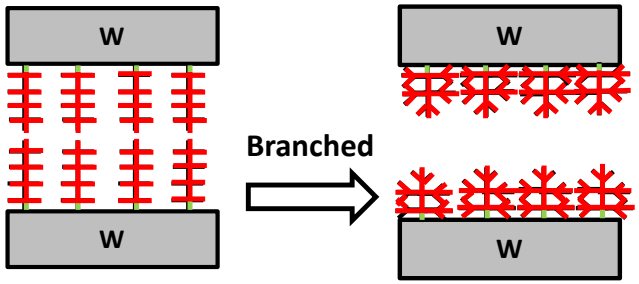
Further improvements

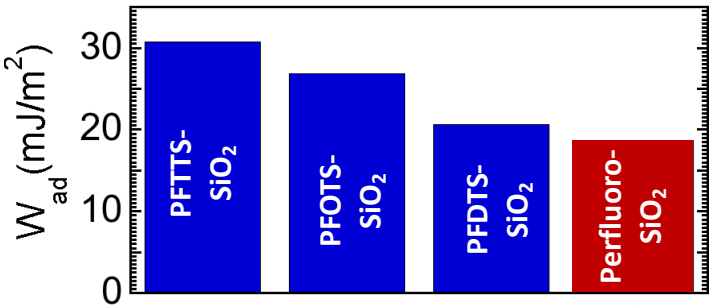
- Reducing adhesion → want more F atoms on chain
- Retaining ON current → want shorter chain
- → try branched molecules!

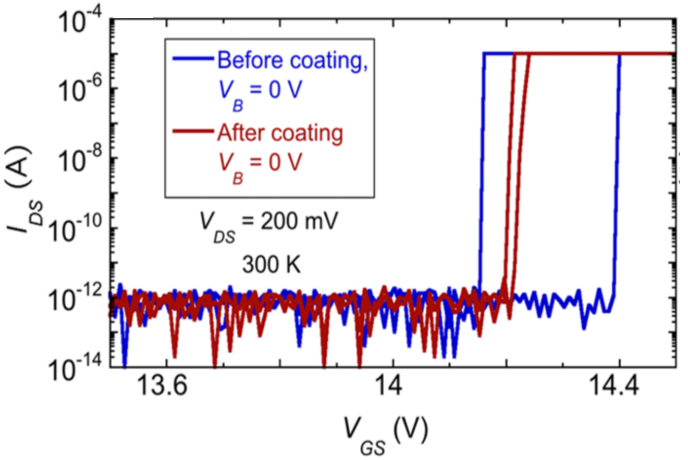
- Perfluro: 24 F atoms / nm, vs.
  PFOTES: 10 F atoms / nm

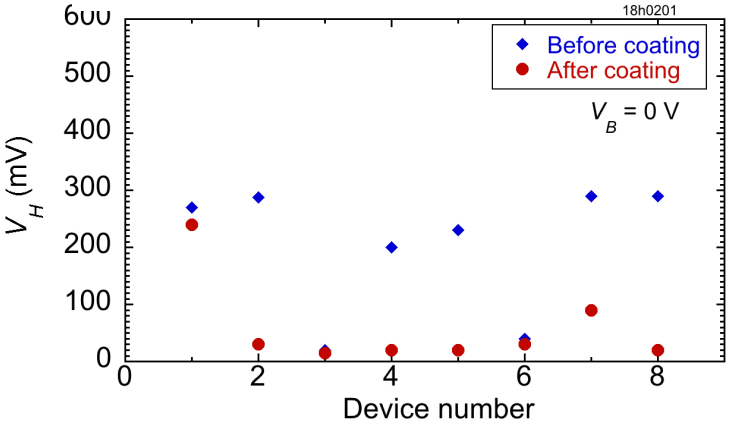
Perfluoro(2,3-dimethylbutan-2-ol)











S. Fathipour et al, AIP Advances, 9, 055329(2019)

Conclusions

- Sub-50 mV NEM relay switch demonstrated by adhesion reduction with self-assembled molecular coating.
- Branched molecules are the optimal.
- Successful conjugation of chemistry, physics, materials science and device research for NEM switch technology.

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