Sub-50 mV Nano-electromechanical (NEM) Switch Devices

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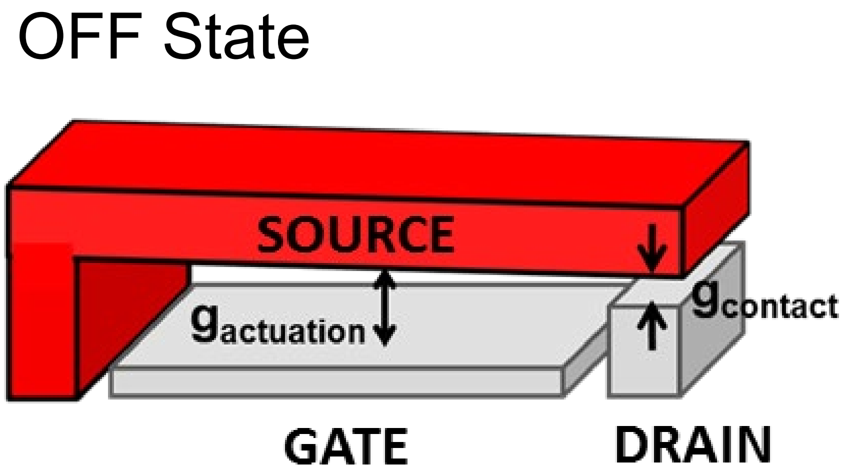
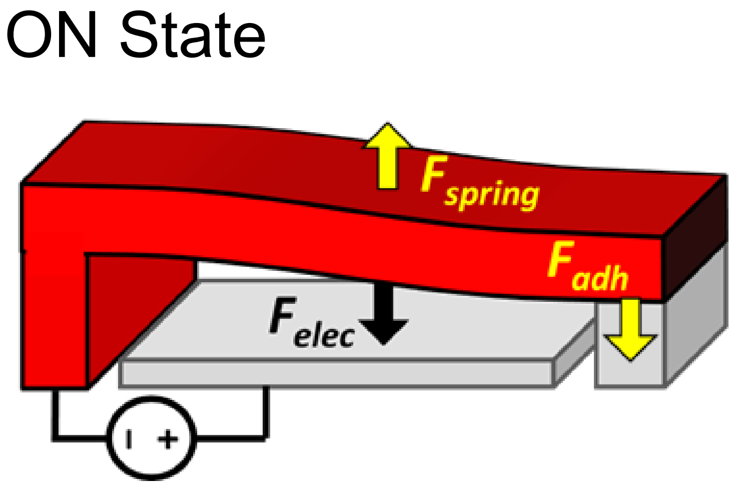
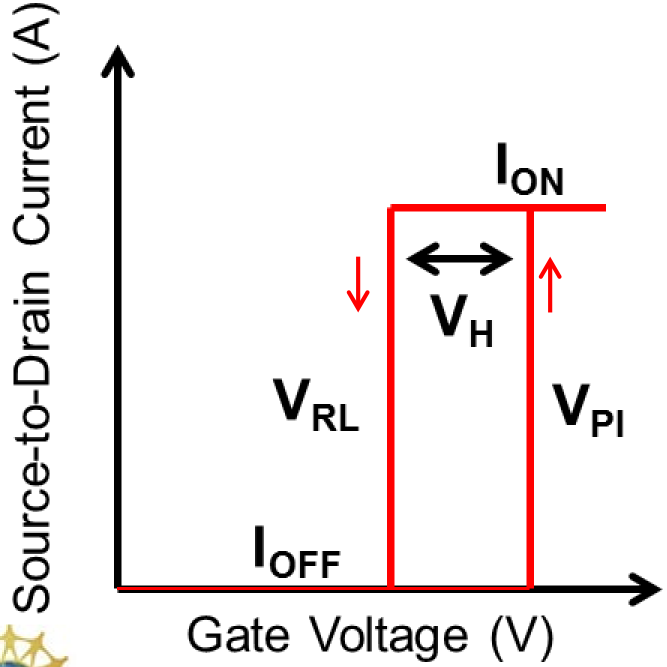
Nano-electromechanical (NEM) Relays

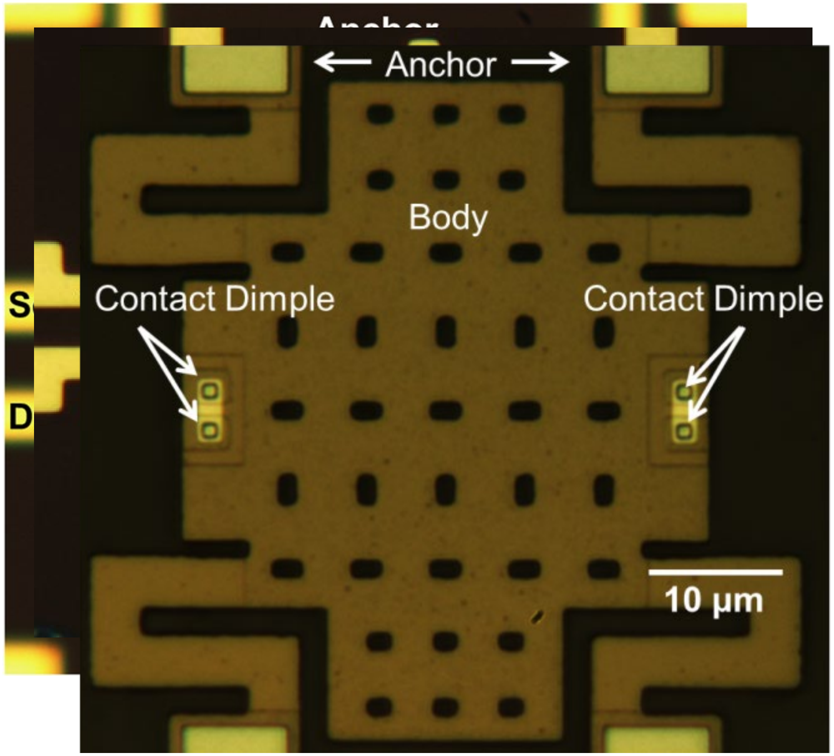




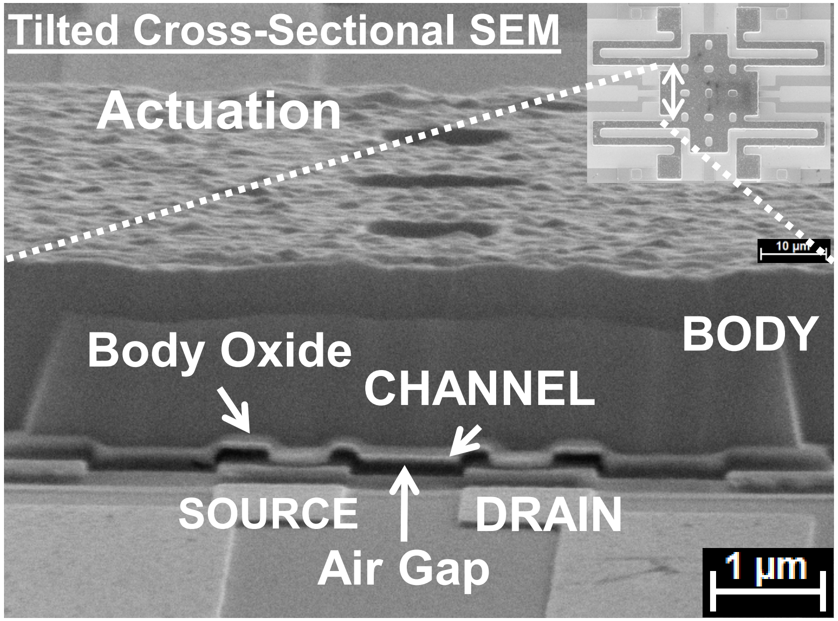


- ☐ **Abrupt Switching.**
- ☐ **High ON-state Conductance.**
- ☐ **Large ON/OFF Current Ratio.**
- ➢ **Low Operating Voltage and Switching Energy.**
- ➢ **Speed, Reliability, Endurance and Cost.**

Body-Biased Relay Structure & Operation

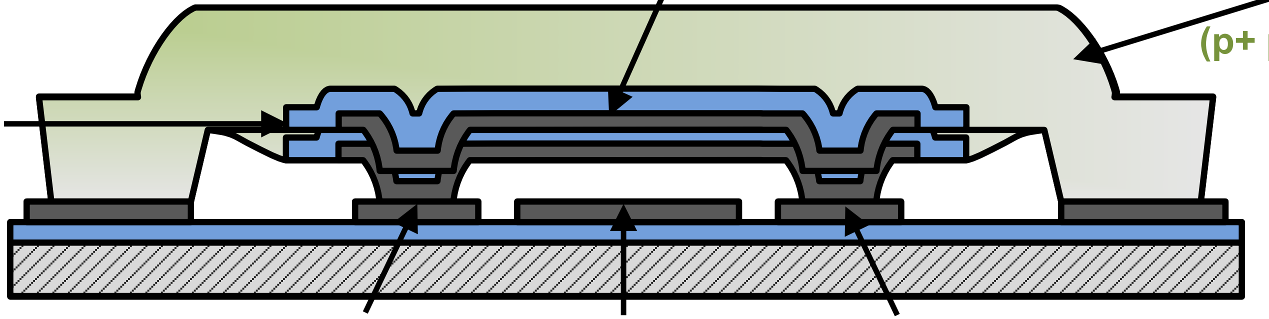


Plan-View SEM

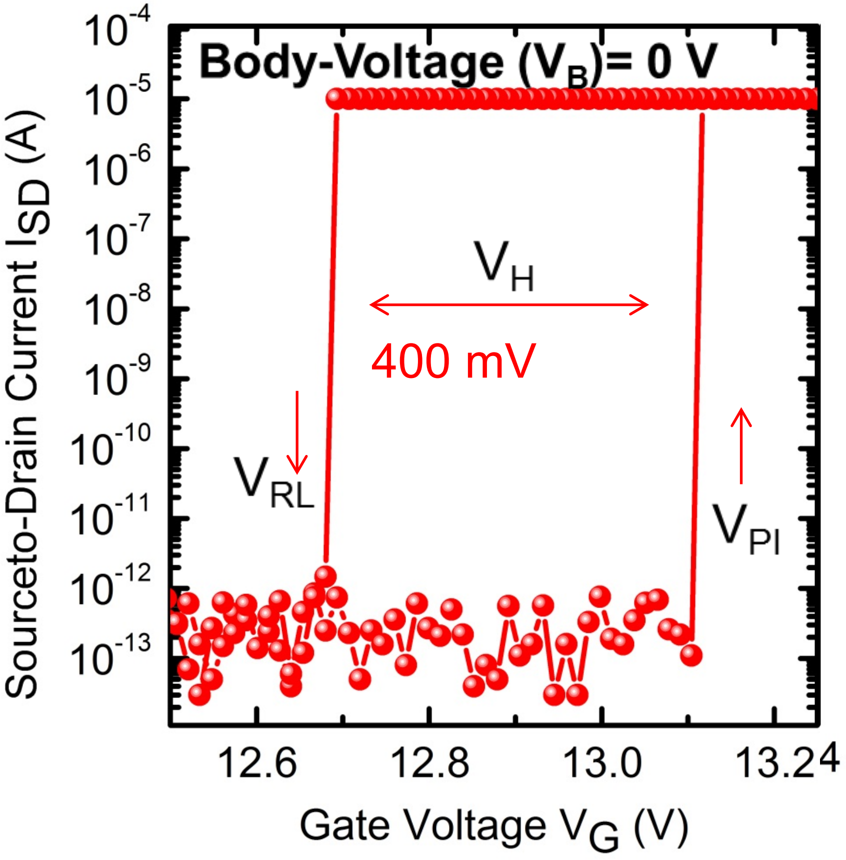


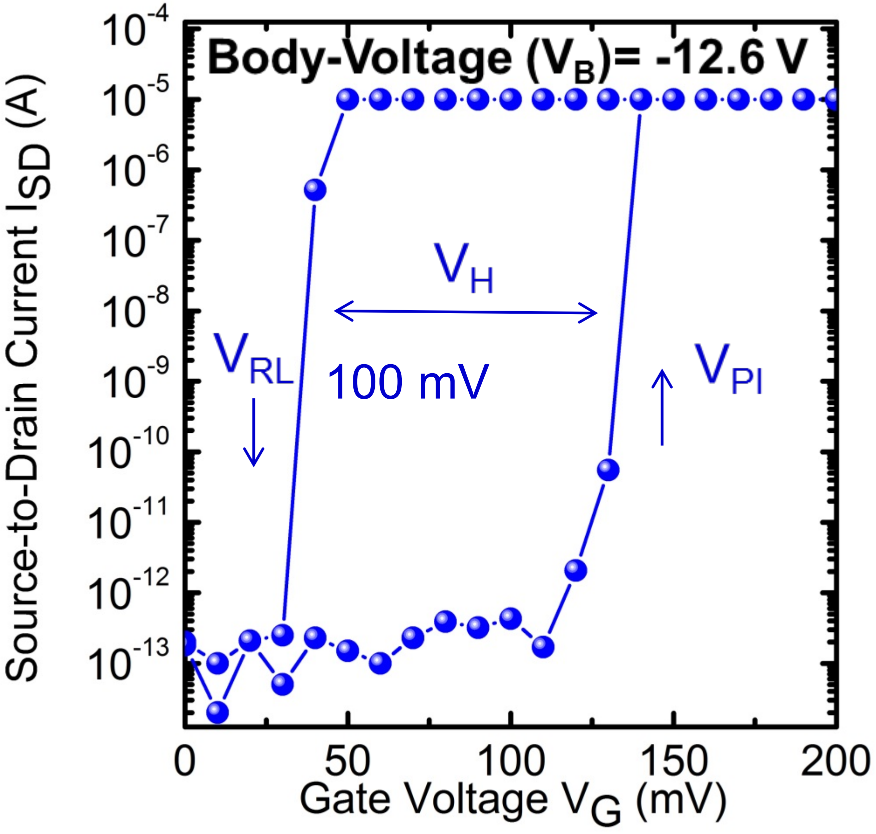
I-R. Chen et al. (UCB), Transducers 2013

Schematic Cross-section



Low-Voltage Operation via Body-Biasing

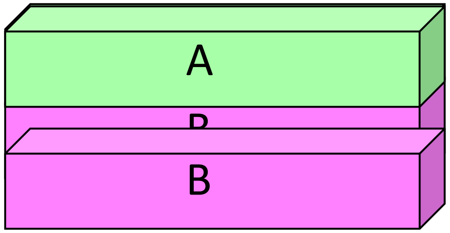




- ❑ Operating voltage (V_{DD}) can be lowered with body-biasing to be as low as the hysteresis voltage (V_H).
- ❑ V_H is limited by adhesive force ($F_{Ad.}$), decreasing with $|V_B|$

  e.g. $V_{H,\ VB\ =\ 0\ V} \approx$ (300-400) mV ; $V_{H,\ VB\ =\ -12.6\ V} \approx$ 100 mV

How to Further Reduce V_H (beyond 100 mV?)



Adhesion Energy

σ_A = *Surface Energy*

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

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.

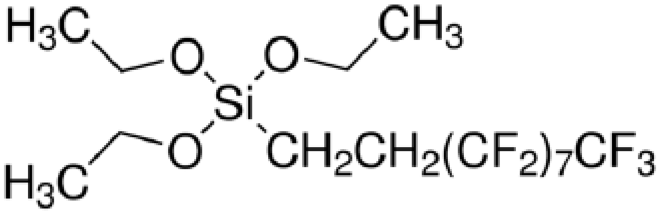
Self-assembled Molecular (SAM) Coating

Silane functional group for molecular self-assembly.

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

PFDTES

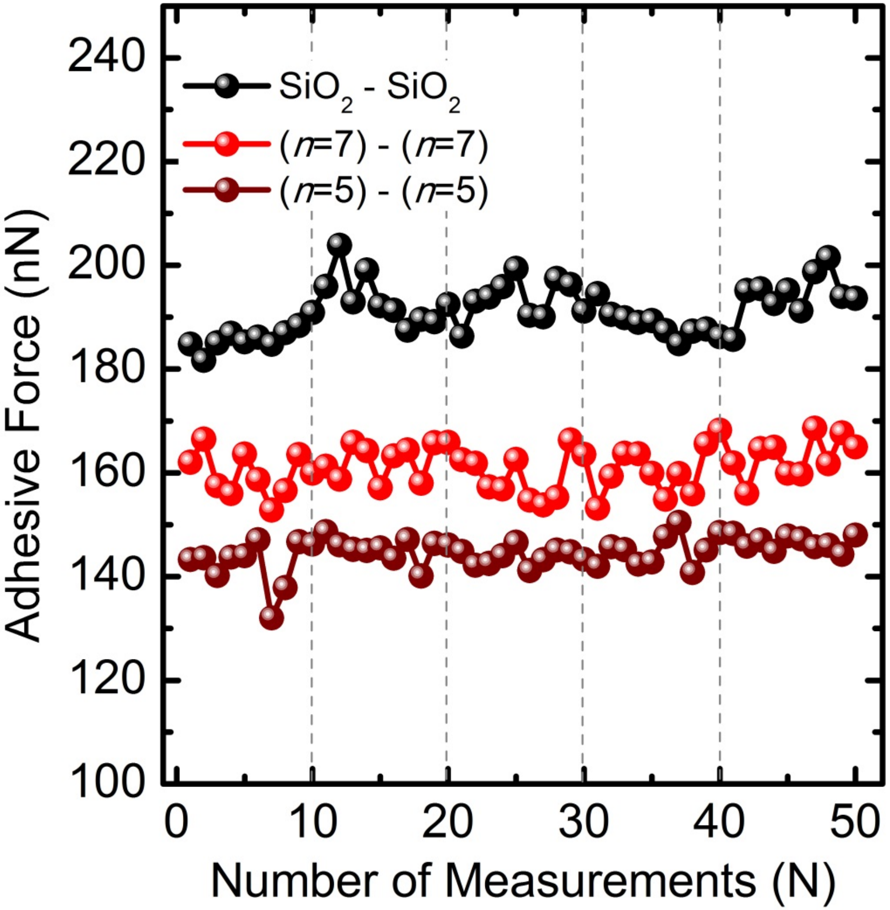
Length ~ 1.5 nm



n of (CF_2) = 7

Vapor phase growth of molecule on functional relay surfaces.

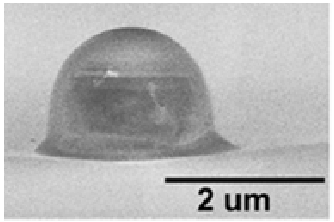
Adhesive Force Characterization by AFM

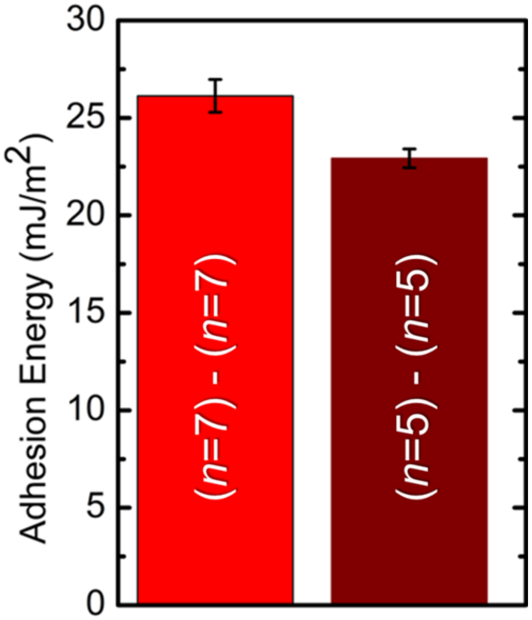


DMT Model for Adhesion Energy

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

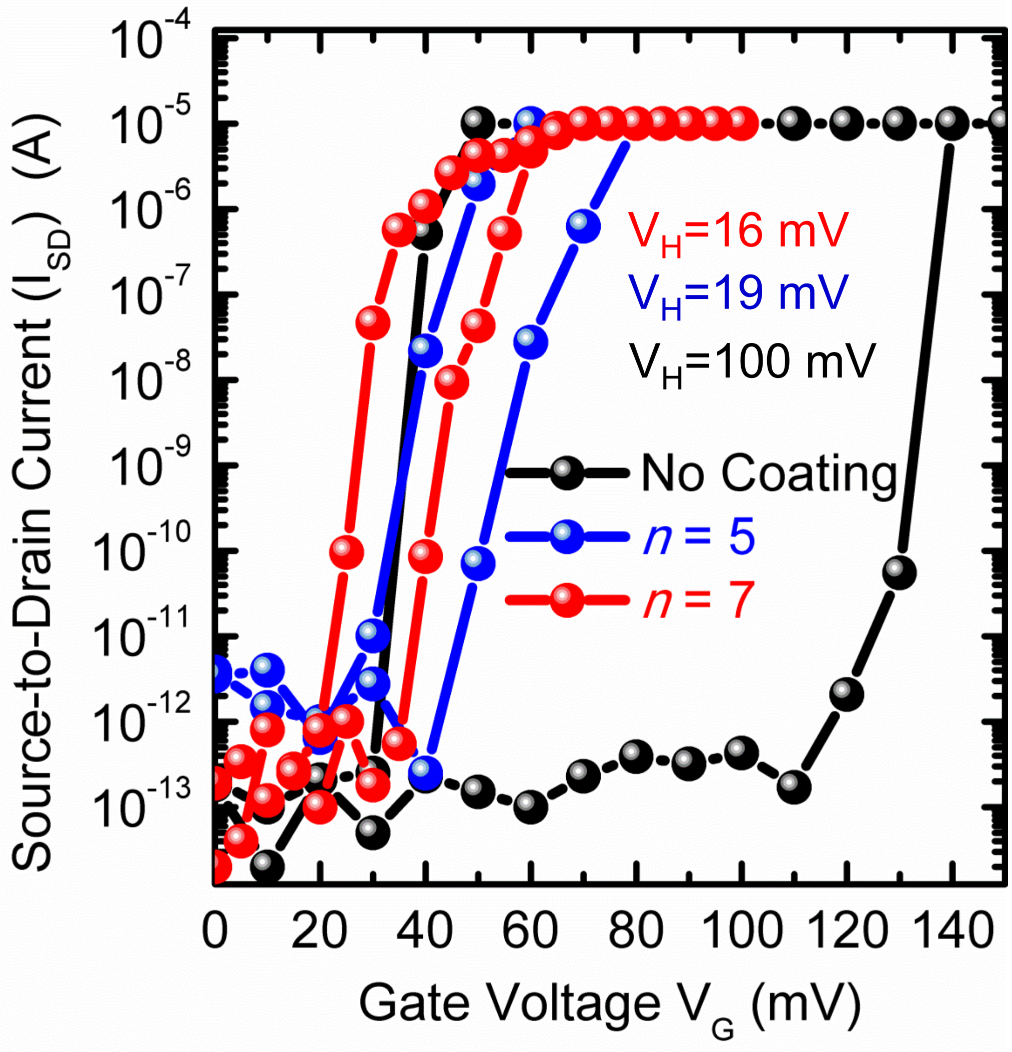
R_{tip} is tip radius





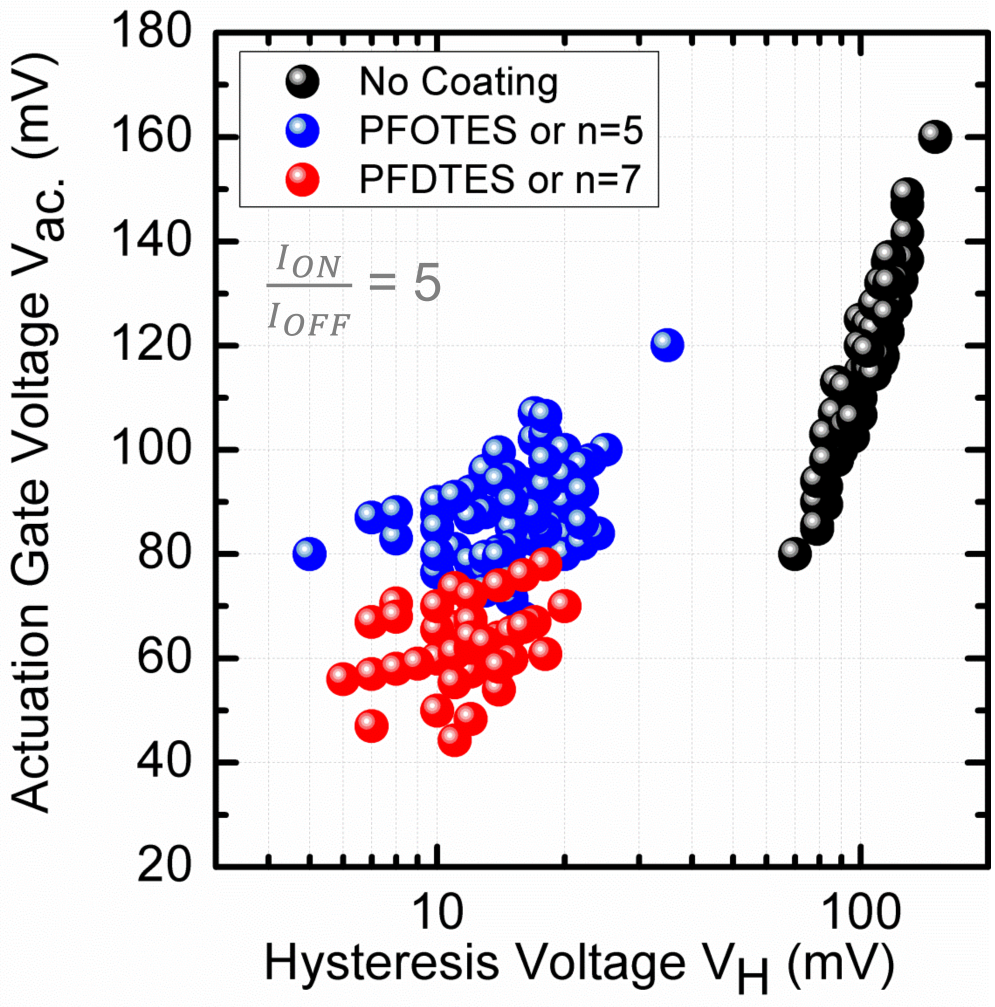
- ❑ Adhesion energy of the molecules are very small, ~ 25 mJ/m^2.
- ❑ Adhesive force values are stable (nearly constant) over 1000 operating cycles (not shown here).

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}. *(further reduction of gate actuation voltage by 20 mV is possible).*
- ❑ Actuation gate voltage may also be reduced by allowing a lower current on/off ratio.
- ❑ Molecules with n < 5 do not reduce hysteresis voltage, hence do not enable low voltage operation.

Effects of SAM Coating on NEM Performance

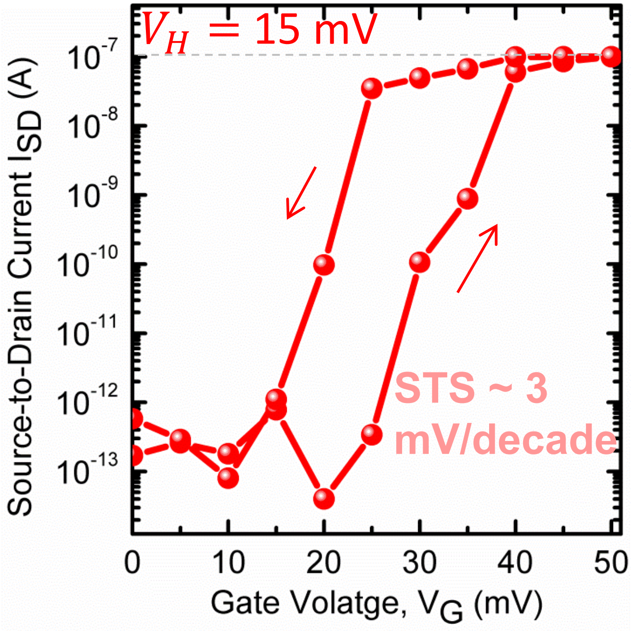


- ❑ Molecular coating reduces hysteresis voltage by ~10×.
- ❑ Actuation gate voltage reduced by ~2×.

- ❑ Full benefit of the hysteresis voltage reduction cannot be leveraged due to the increase in sub-threshold swing.

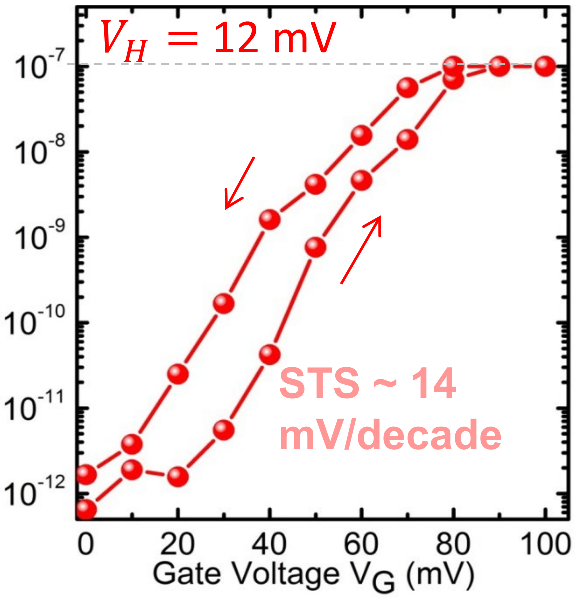
- ❑ Molecular coating also reduces random variations in V_{PI}, V_{RL} and V_B, beneficial for voltage scaling. (Poster: Benjamin Osoba)

Effect of SAM Coating on NEM Performance



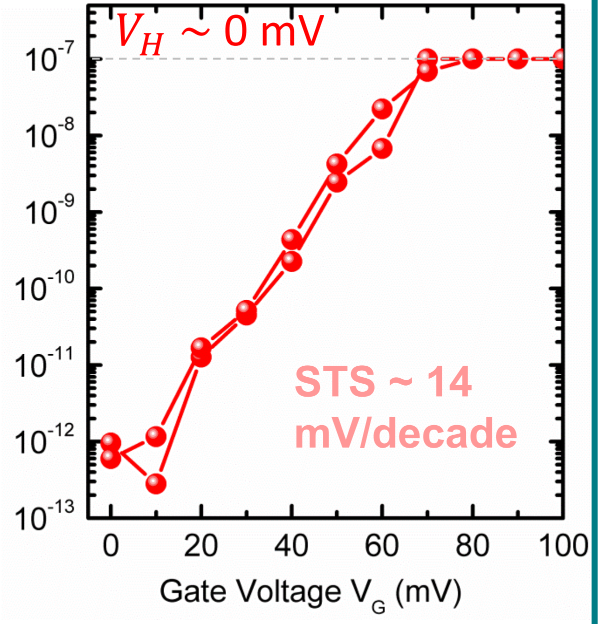
Case I: Low V_H and low STS.

Occurrence: Low (10%)



Case II: Low V_H and high STS.

Occurrence: High (80%)

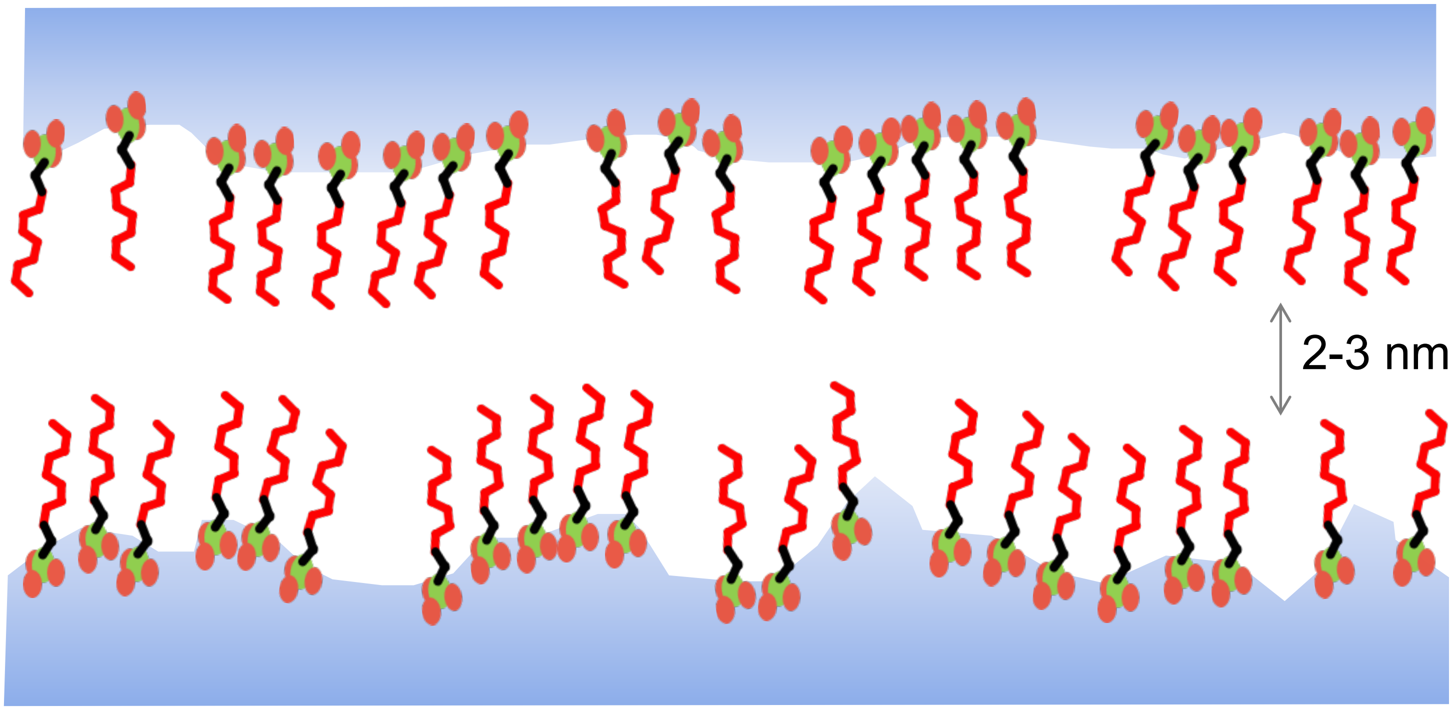


Case III: Very low V_H and high STS.

Occurrence: Low (10%)

Three Types of I-V Characteristics

How Current Flows? (Hypothesis)



Young's Modulus:
Molecule
~ **10s of MPa**.
Solid
~ **100s of GPa**.

Molecules are in general ~1000× less stiff than solids.

Case I: At $V_B \cong |V_{RL}|$, molecule-molecule gap ~2-3 nm.

Conduction Mechanism: Direct metal-metal electrical contact.

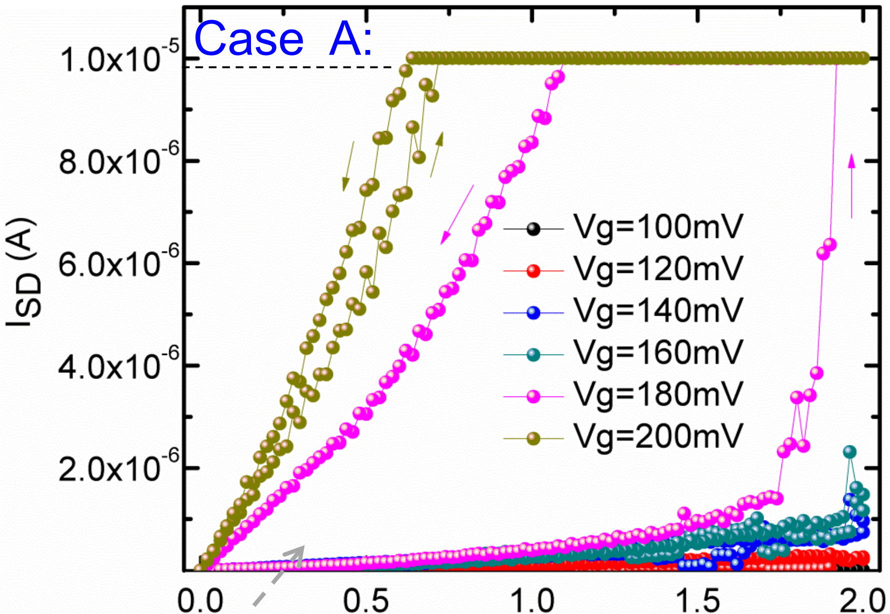
Case II: At $V_B \cong |V_{RL}|$, molecule-molecule gap ~2-3 nm. (Modeling Urmita Sikder)

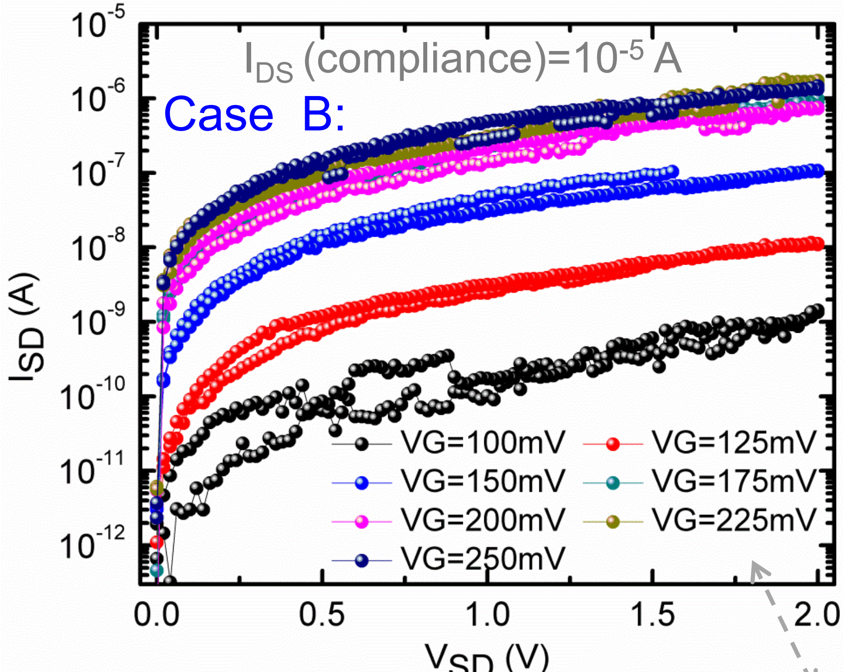
Conduction Mechanism: Tunneling along with thickness modulation.

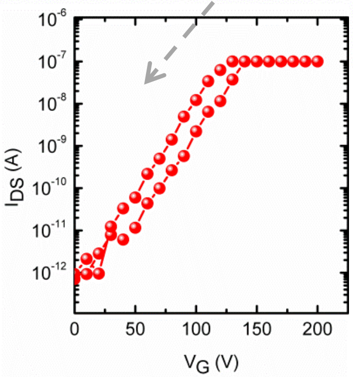
Case III: At $V_B \cong |V_{RL}|$, molecule-molecule gap ~0 nm.

Conduction Mechanism: Tunneling along with thickness modulation.

How Current Flows? (n=5 coated relay)

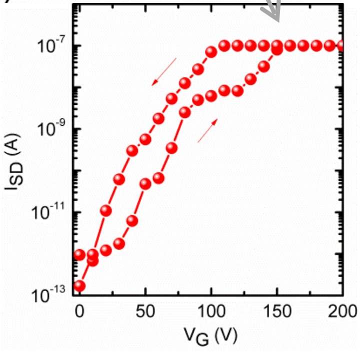






Case B: Uniform Molecular Coating

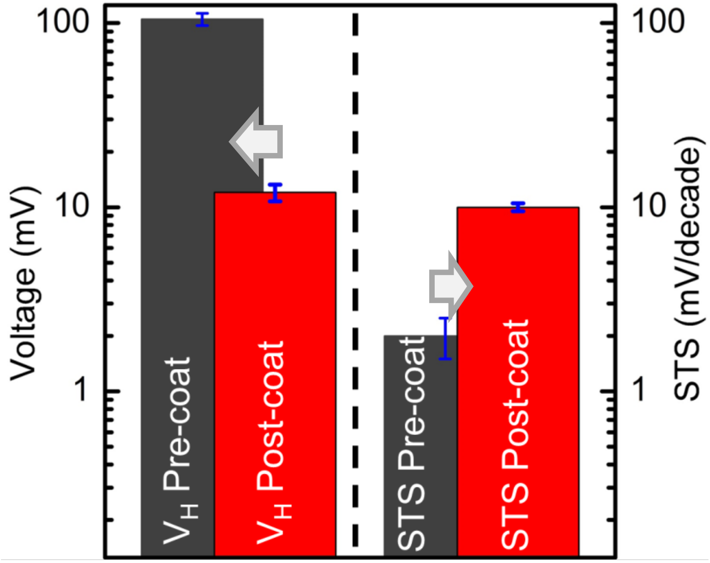
- ☐ Tunneling through the molecules, and thickness modulation.
- ☐ No Hysteresis in I_{DS} vs $V_{DS.}$
- ☐ High ON-state resistance ~2 MΩ @ 1V_{SD}

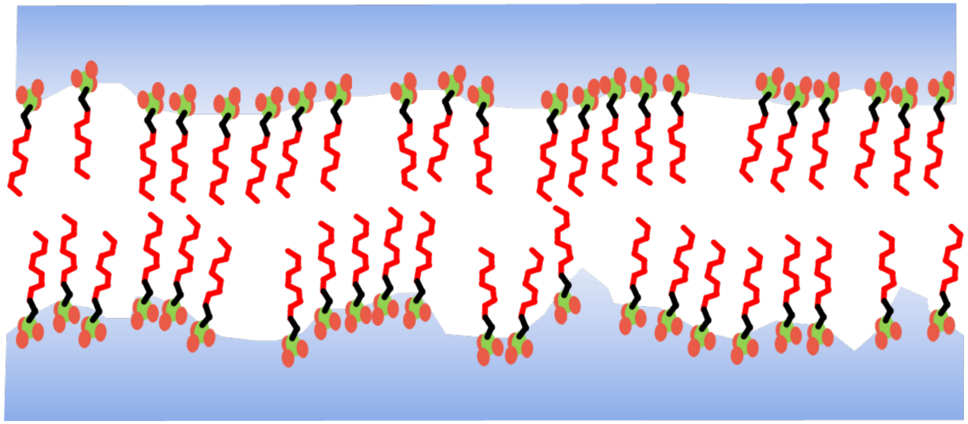


Case A: Non-uniform Molecular Coating

- ☐ Tunneling through the molecules, and subsequent metallic contact.
- ☐ Hysteresis in I_{DS} vs V_{DS} (Contact area increased with V_{SD})
- ☐ Low ON-state resistance.

Where are we and how to move forward?





Fundamental (theoretical and/or modeling) analysis on –

- ❑ Is there any fundamental physical limit on how small adhesion energy can be?
- ❑ What is the optimal structure of an molecule for it to be an anti-adhesion coating?
- ❑ Can an anti-adhesive coating molecule be also electrically conductive?

Ideal: Conductive Molecule that is also Anti-adhesive.

Conclusion

- **Sub-50 mV** Nano-electromechanical Relay Switch Devices Demonstrated.
- Conjugation of chemistry, physics, materials science and device research promises a new era in NEM switch technology.

Graduate Students/postdocs.

- Sergio Almeida Loya.
- Urmita Sikder.
- Alice Ye.
- Farnaz Niroui.
- Chung Qian.

Undergraduate Students

- Jane Edgington.
- Liam Dougherty.
- Jatin Patil.
- Laura Brandt.
- Don Rollings.
- Steven Chan.

Appendix

Vision for the Future

The Cloud
(Millions)

Mobiles
(Billions)

The Swarm
(Trillions)

Smart Grid

Traffic

Smart Building

Infrastructure

Emergence of Ambient Intelligence

Sense/monitor, communicate and react to environment

Ultra-low-Power and Robust Technology is Required!

The Voltage Matching Crisis at Nanoscale

Energy Cost Due to Noise in a Circuit

$$V_{noise}=\sqrt{4KTR\Delta f}$$

	V_{noise}
Transistor @ 2GHz	1 mV

Good Signal to Noise Ratio (SNR) =10

The Penal on

(1Volt/1mV

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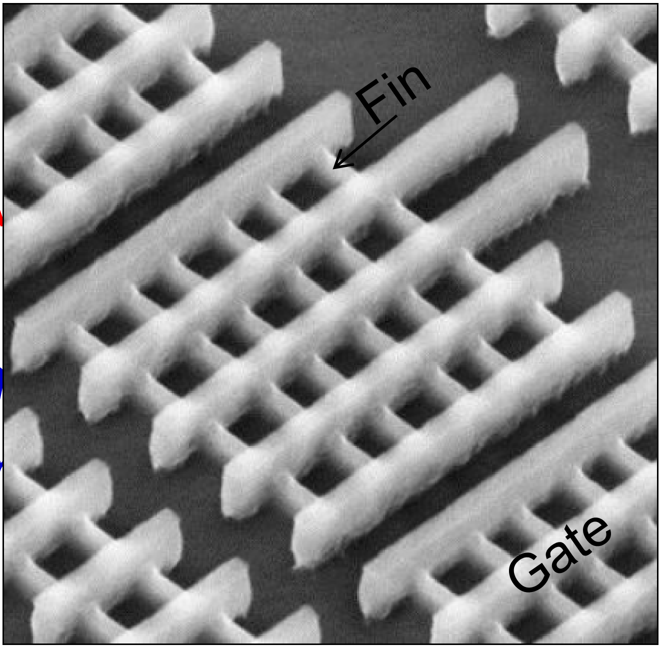
22 nm Intel Tri-Gate Transistor

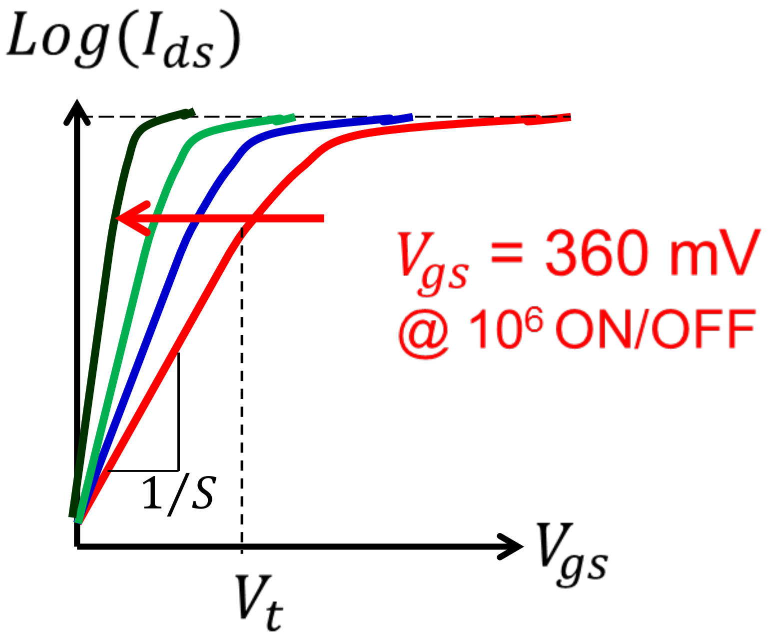


Technology Node	250 nm	180 nm	130 nm	90 nm	65 nm	45 nm	32 nm	22 nm	16 nm	14 nm
V_{dd} *(V)*	2.5	1.8	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.8
Year	2000	2001	2003	2004	2007	2008	2010	2012	2014	2016

V_{dd} scaling has slowed after 130 nm node (~2003)

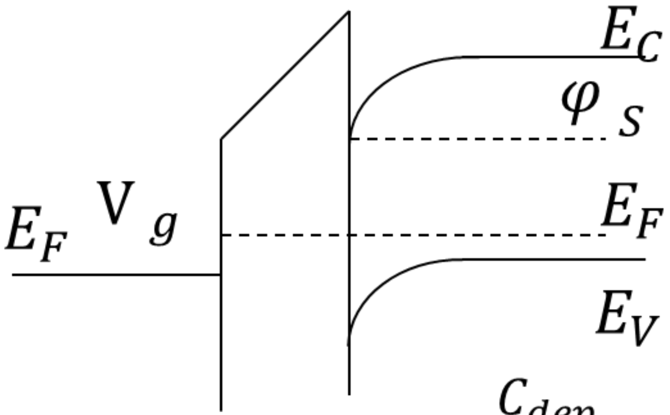
E. Yablonovitch EE 290B (UCB)

The Next Switch: Why CMOS is Reaching its Limit



V_{gs} = 360 mV

@ 10^6 ON/OFF



$$\eta = 1 + \frac{C_{dep}}{C_{ox}}$$

Limitations of CMOS Technology

- ☐ Boltzmann factor (60 mV per decade subthreshold swing limit.)
- ☐ Off-State leakage current.
- ☐ Device electrostatic properties degrades when channel length is shortened.
- ☐ In some specific applications (e.g. inside a nuclear reactor) Si-CMOS does not work.

$$I_{ds} \propto n_s \propto e^{qV_g/\eta KT}$$

$$S\left(\frac{mv}{decade}\right)=\eta\,.60\text{ mV}.\frac{T}{300K}$$

Power consumption ∝ $(\text{Voltage})^2$

Criteria for The New Switch

1. **Steepness (or sensitivity)**

   Switches only with a few-millivolts.

   60 mV/decade ⇨ 1 mV/decade.

2. **ON/OFF ratio**

   $10^6 : 1$

3. **Current Density or Conductance Density**

   (for miniaturization)

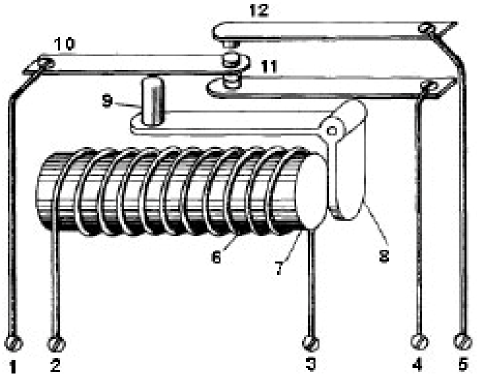
   Spec at 1 Volt: 1 mAmp/micron

A Brief History of Relays

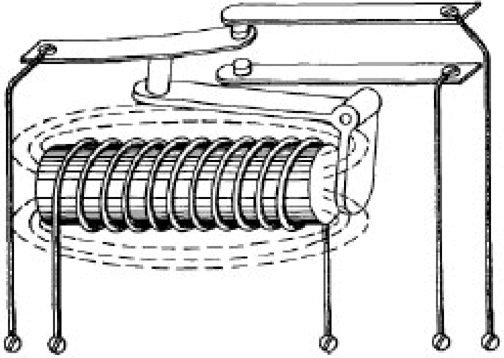
Joseph Henry (1835)

The First Relay

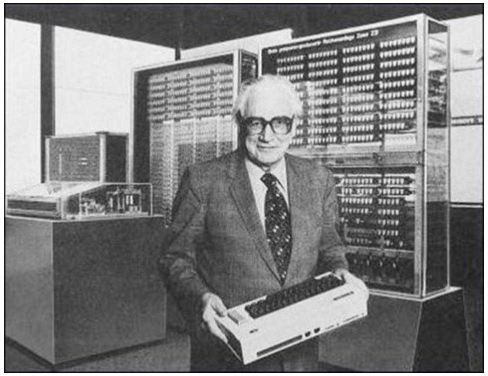
OFF State



ON State



Electromagnetic relays used in telephone switching.



Konrad Zuse with Z3

1941: The First electrically powered digital computer!

- ❑ 2000 relays used in Z3 having a binary 22-bit floating point and ~6 hertz speed.
- ❑ Computers based on vacuum tube and transistor took over at and around the WW-II.

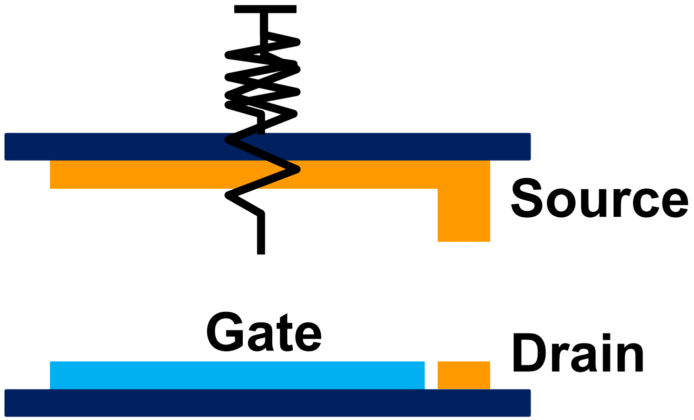
The Rest is History!

CMOS Transistor Dominated Last 70 Years

21st Century Relay Design for Digital Logic

3-terminal design

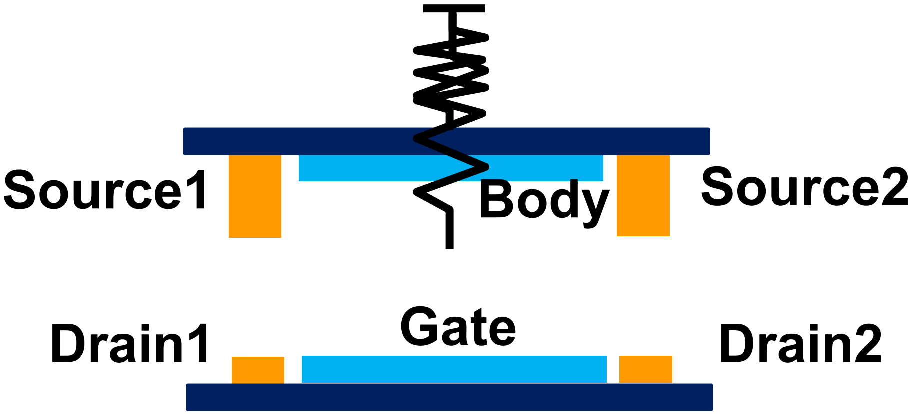
Source as reference



- ☐ Switching is dependent on source voltage.
- ☐ Current modulation is dependent on source voltage.

4 or 6-terminal design

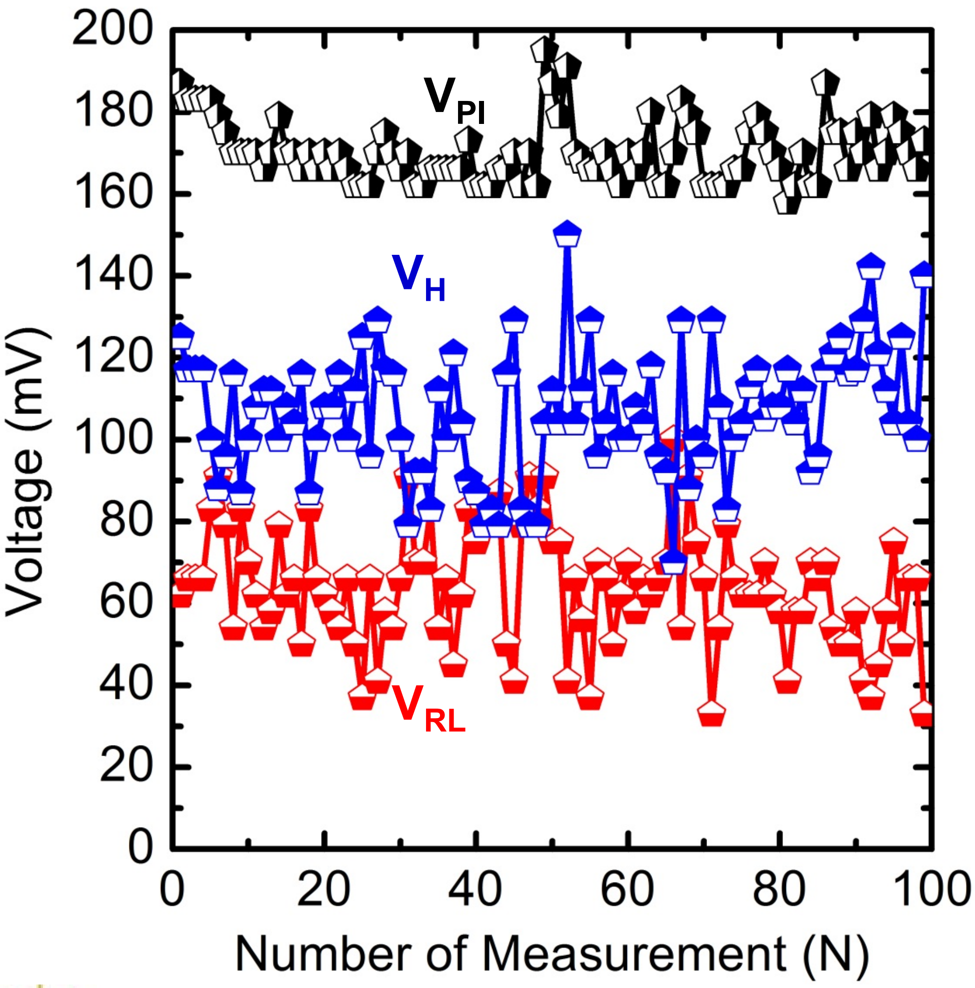
Body as reference

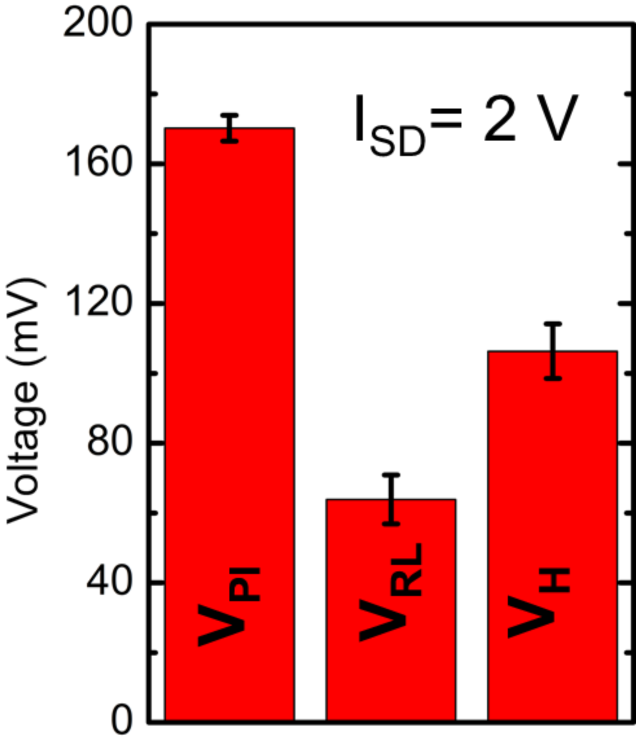


- ☐ Switching is independent of source voltage.
- ☐ Can act as “pull-up” (*p*-relay) or “pull-down” (*n*-relay) switch.

Variability in V_{PI}, V_{RL} and V_H

Body-biased Relay Operation





- ☐ Within a single device the variation of electrical properties are small.
- ☐ Variations are significant across multiple devices.

IEDM (2017) Submitted

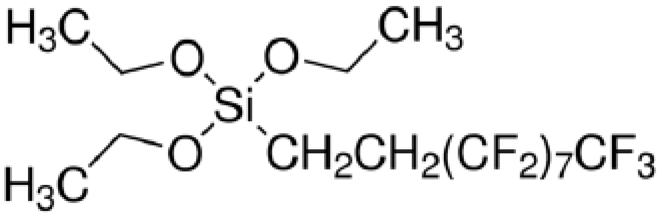
Self-assembled Molecular (SAM) Coating

<u>Silane</u> functional groups for molecular self-assembly.

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

PFDTES

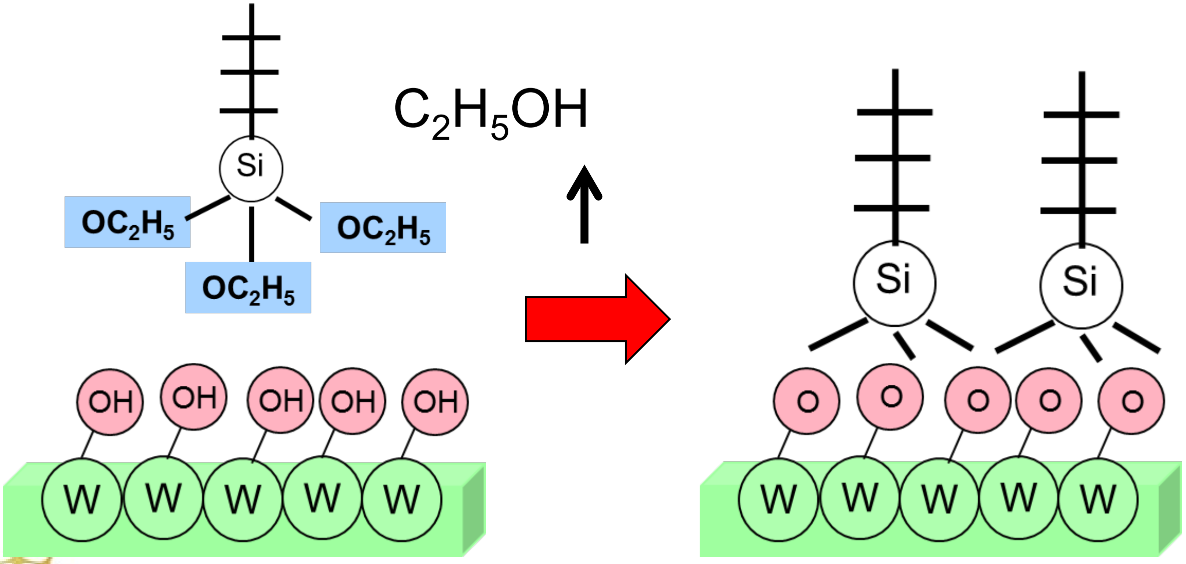
Length ~ 1.5 nm

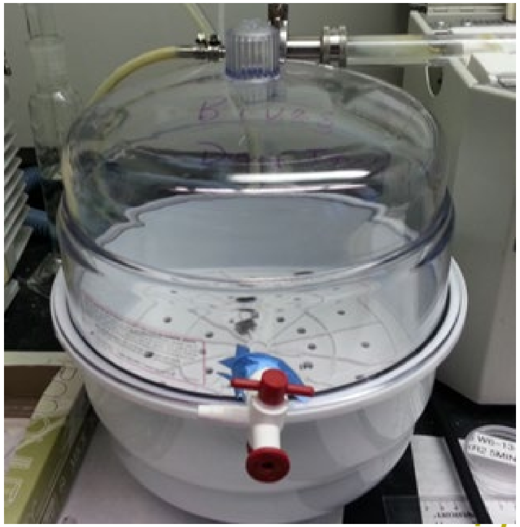


$(CF_2) = n = 7$

<u>Chemistry of Relay Coating</u>

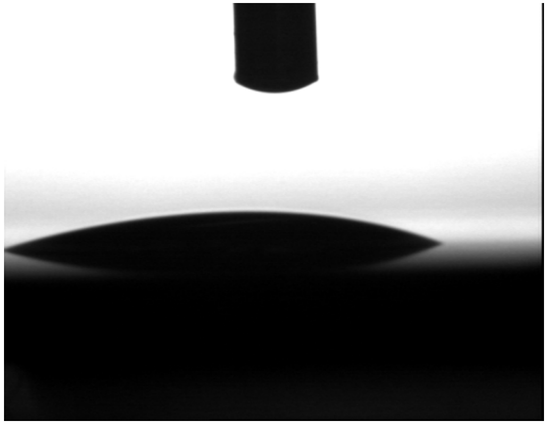
Vapor-phase SAM growth in a low vacuum environment.





Characterization of SAM (Contact Angle)

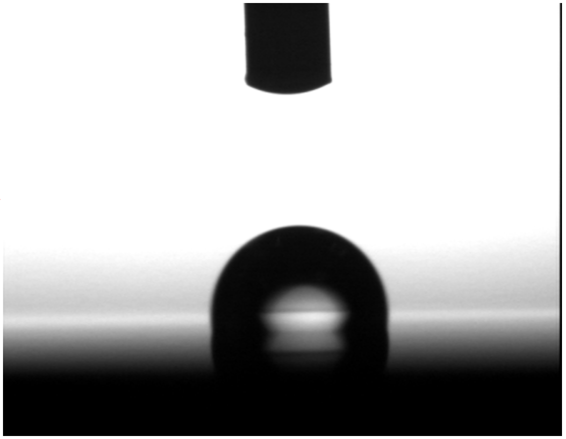
Bare Si Surface



Contact Angle ~30°

Measured at 3 points

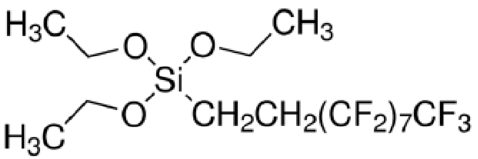
PFDTES coating on Si



Contact Angle ~97°

Measured at 3 points

Changes in the contact angle between water and sample surface suggest self-assembled molecule growth.

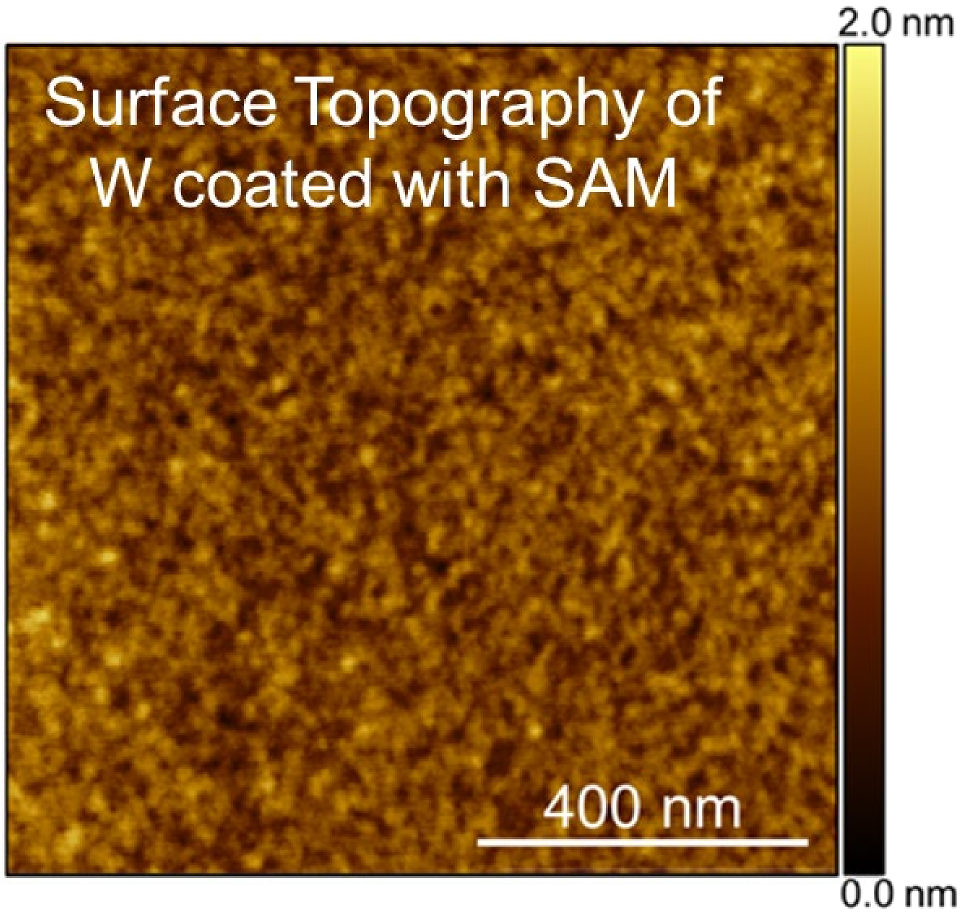


(CF_2)= n = 7

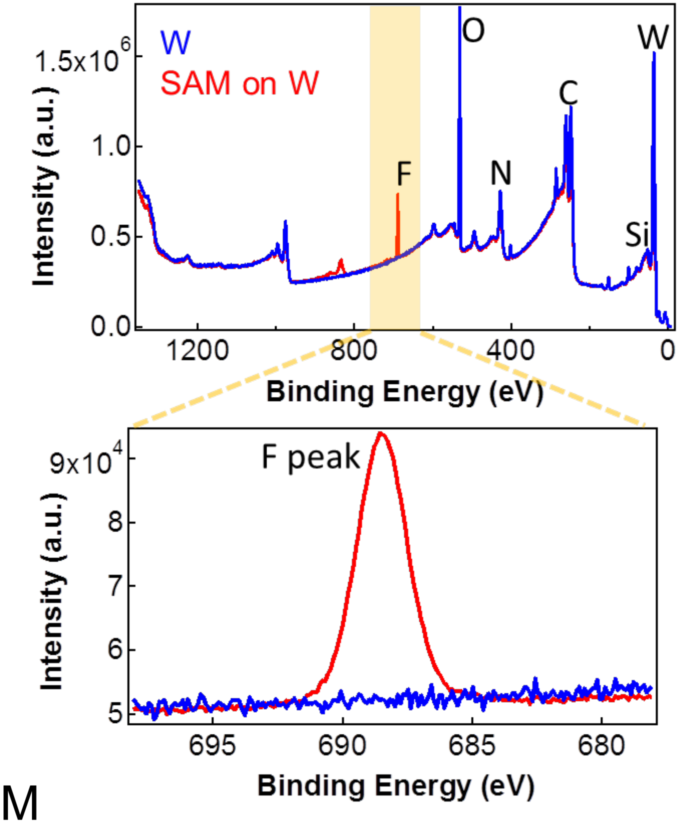
n	t (nm)	α (°)
Bulk		109
7	1.5	97±2
5	1.3	92±3
0	0.5	85±2
None	0.0	30±3

- SAM layers are grown on bare-Si (and bare-W) substrates for the contact angle measurements.
- SAM growth were achieved for all the “*n*”.

Characterization of SAM (XPS and EDX)

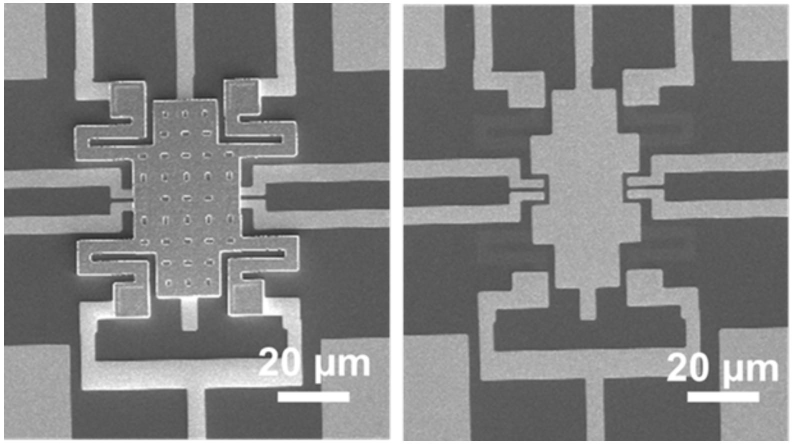


X-ray Photoelectron Spectroscopy (XPS)

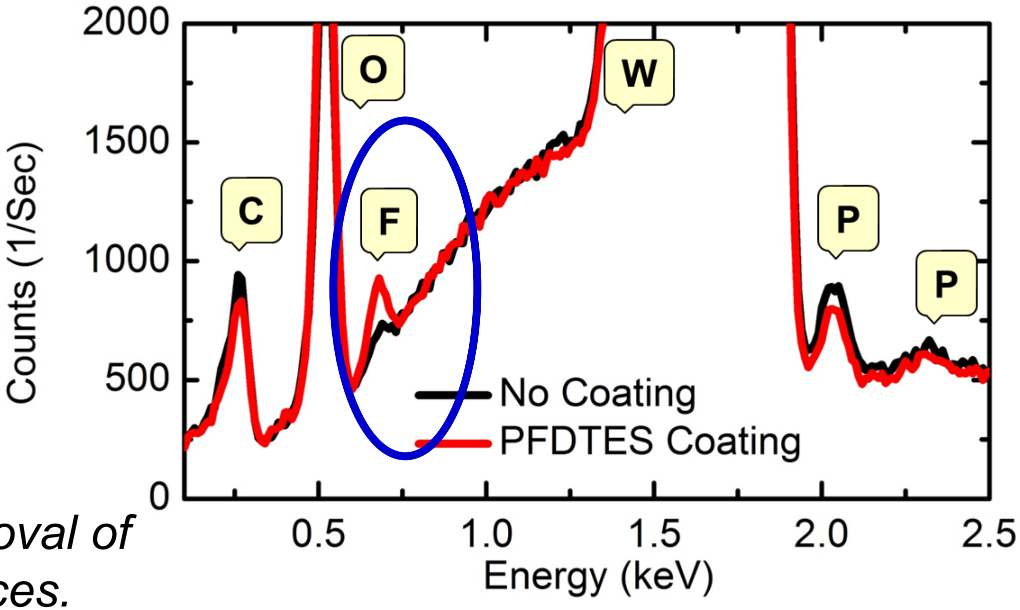


XPS confirms self-assembly of fluorinated SAM on bare W surfaces.

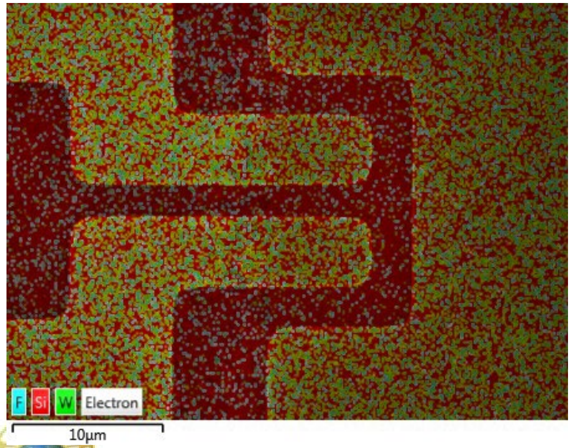
Characterization of SAM (XPS and EDX)



Self-assembly of molecules and removal of the "Body" to access switching surfaces.

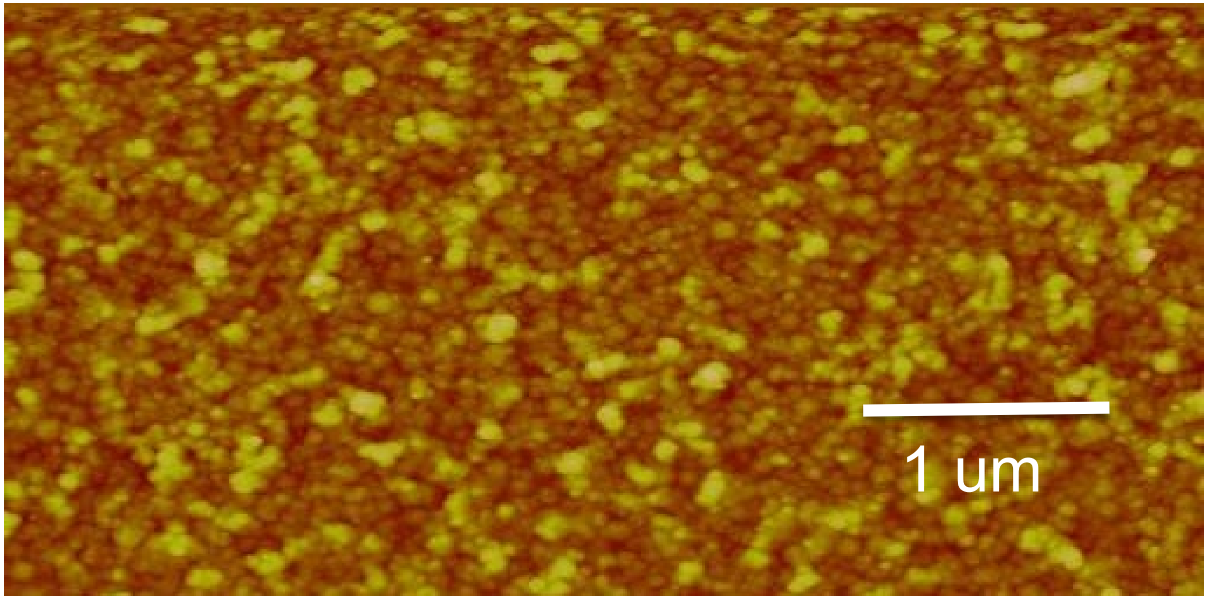


Energy Dispersive X-ray Spectroscopy



Fluorine signal suggest presence of molecule.

Surface Roughness on W Electrodes



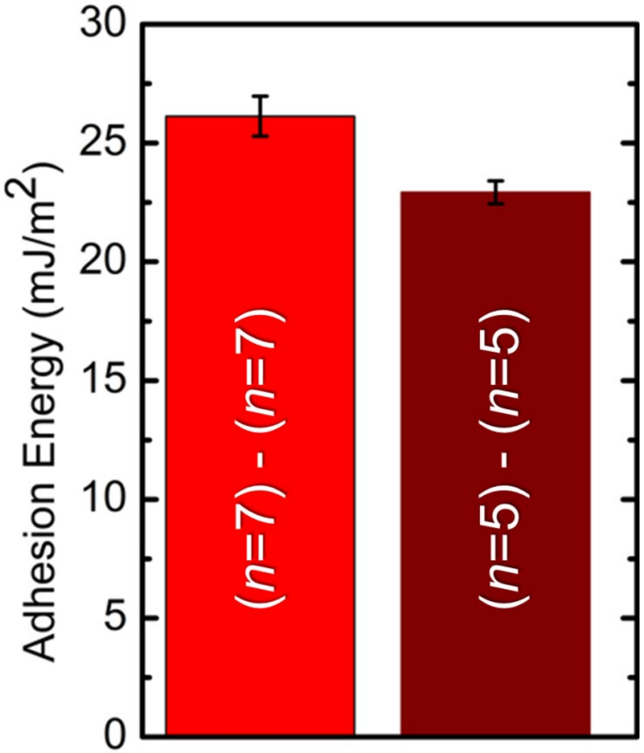
Atomic Force Microscopy measurement of Relay W contact Surfaces before and after coating.

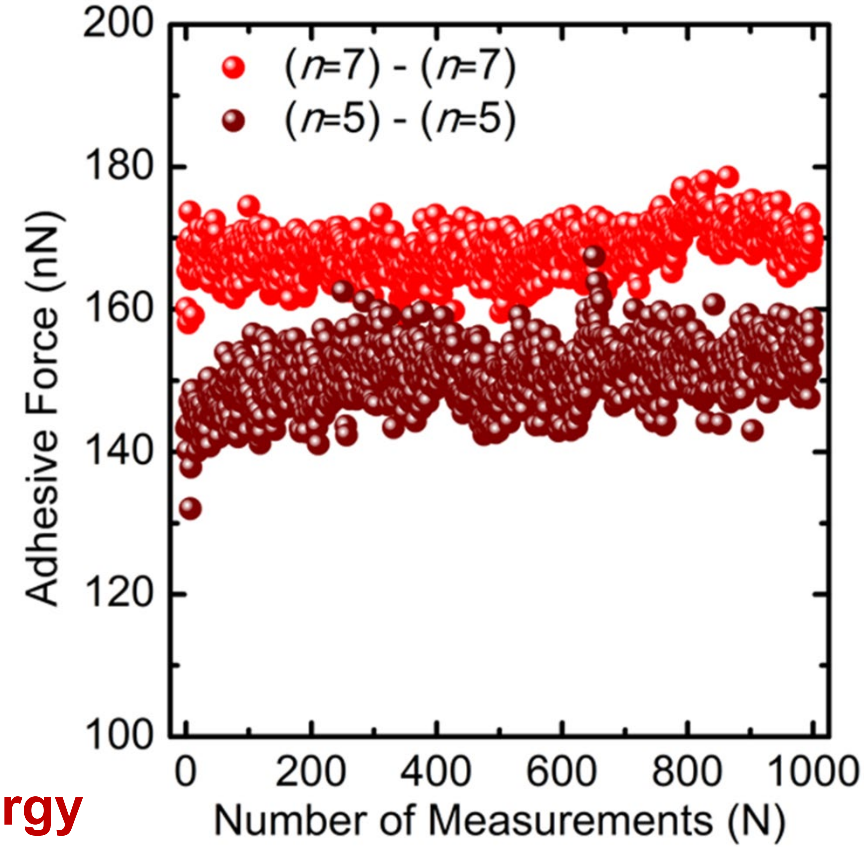
- Roughness before *and* after coating = **7.6 nm.**
- Asperity Density
  - Before coating: **17 +/- 4** asperities / μm^2
  - After coating: **18 +/- 3** asperities / μm^2
- Average Asperity Separation

  Before coating **108 +/- 63 nm spacing,**

  After coating **102 +/- 50 nm spacing**

Adhesion Energy and Cycling Test





DMT Model for Adhesion Energy

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

R_{tip} is tip radius

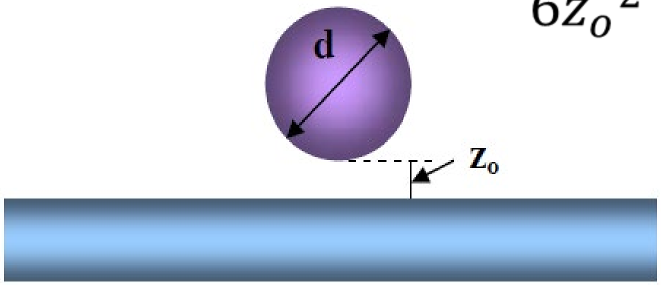
- ☐ Adhesion energy of the molecules are very small, in ~ 25 mJ/m^2 range.
- ☐ Adhesive force values are stable (nearly constant) over 1000 operating cycles.

Hamaker Constant

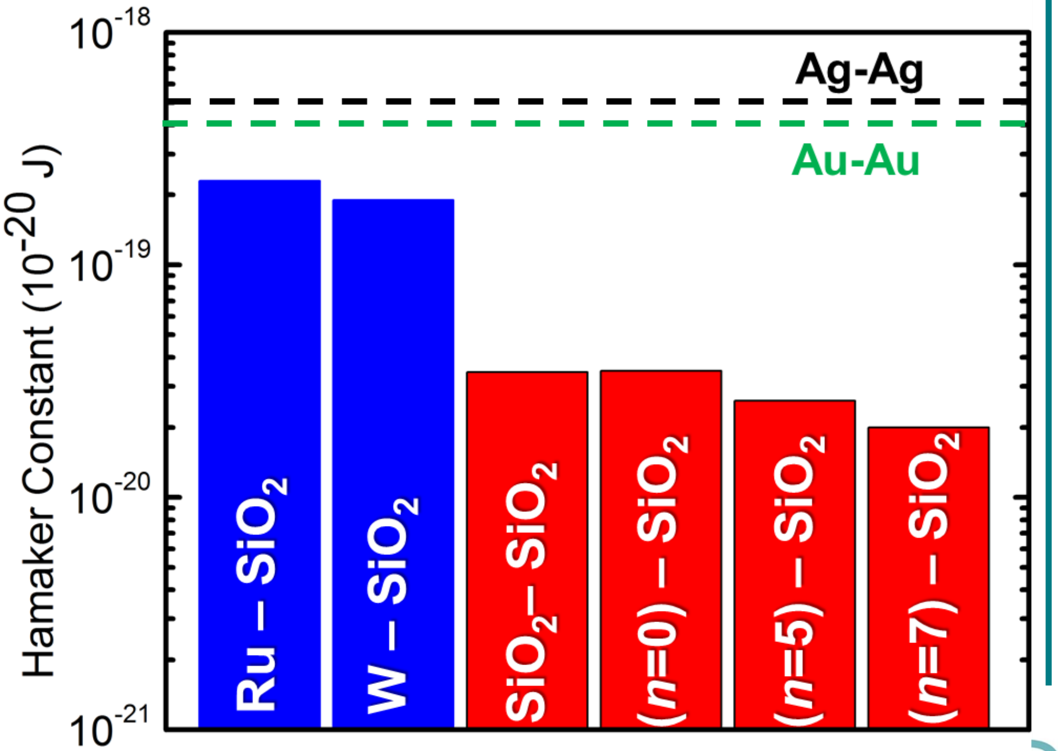
The London-van der Waals force:

- ❑ Attractive, short range force and decays rapidly to zero away from a surface.
- ❑ The origin lies in the instantaneous dipole generated by the fluctuation of electron cloud surrounding the nucleus of electrically neutral atoms.

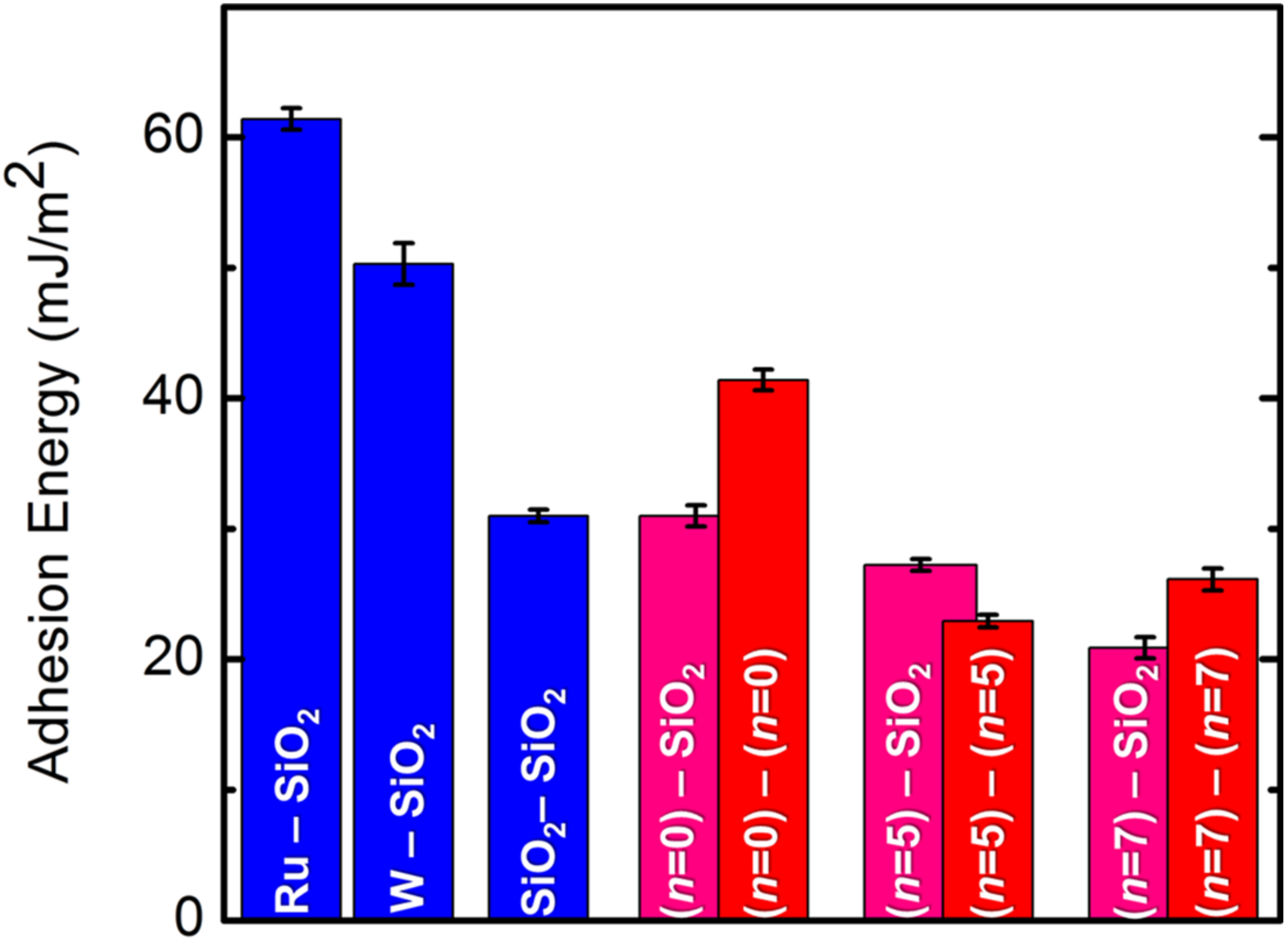
$$F = \frac{A_H R}{6 z_o^2}$$



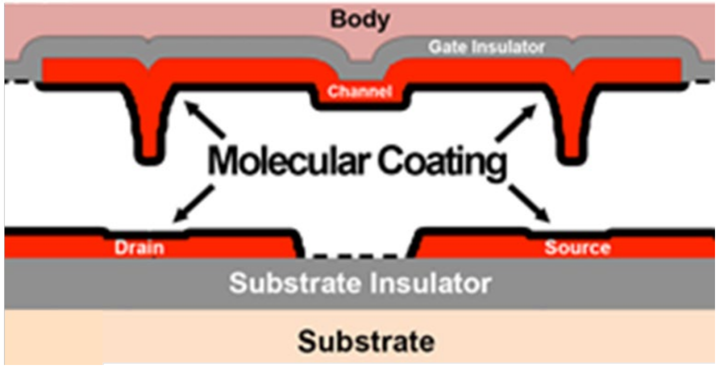
$$A_H = Hamaker\ Constant$$

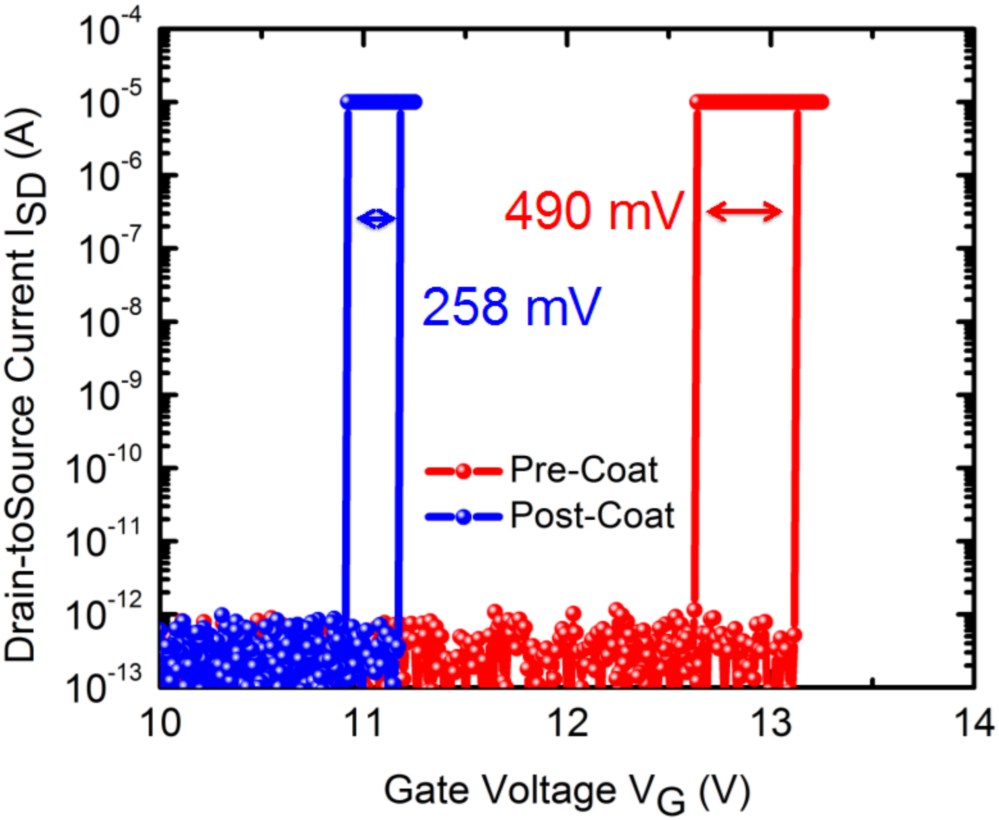


Summary of Adhesion Energy Densities



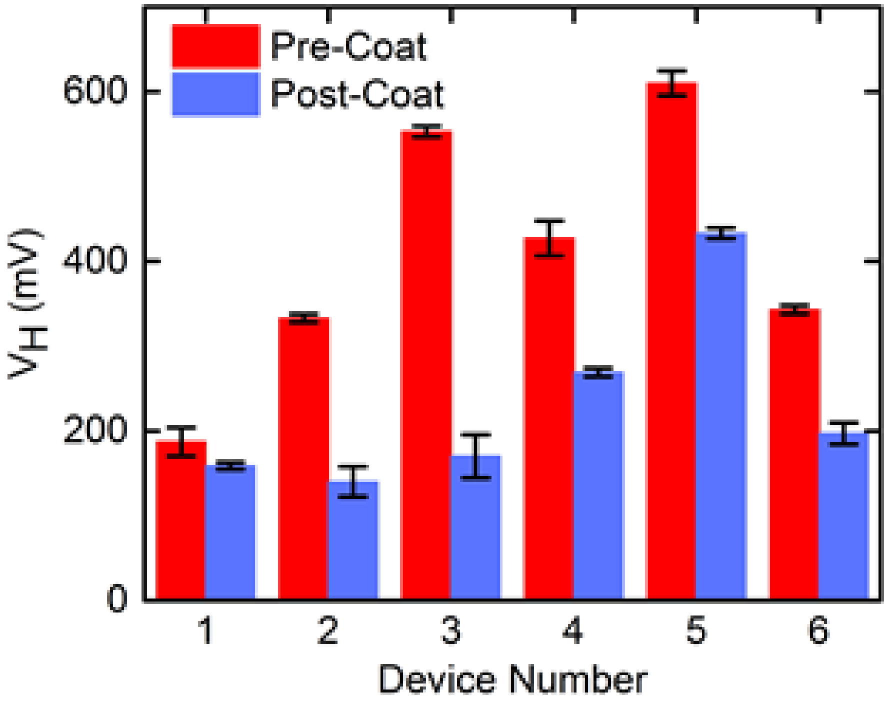
Effect of SAM Coating on Relay Operation

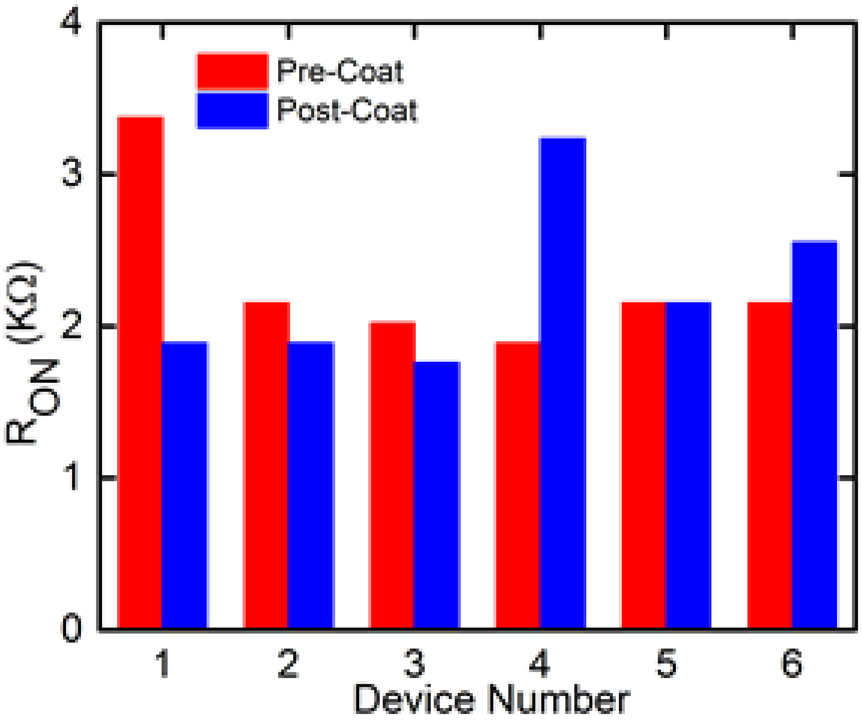




- V_H decreases, V_{PI} shifts (change in effective actuation gap and electrostatic interaction).
- Sub-threshold swing (SS) increases slightly.

SAM Coating Effect on V_H and R_{ON}

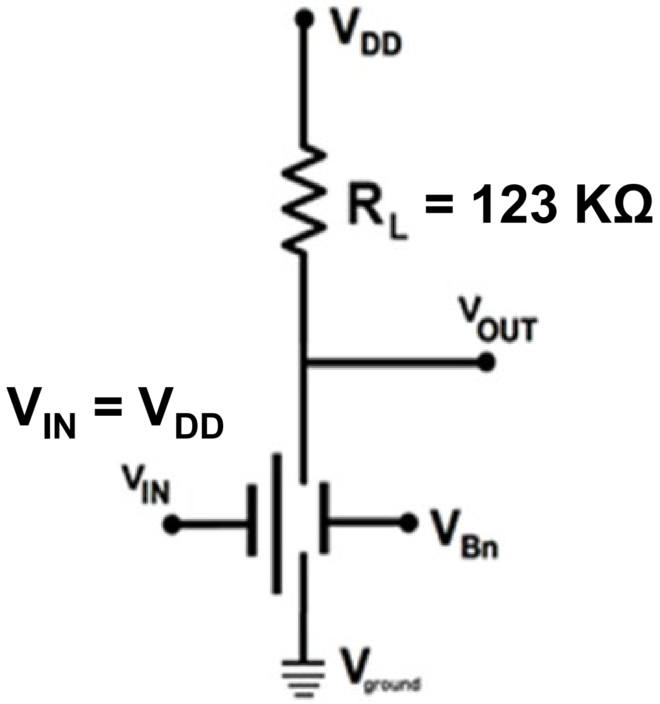




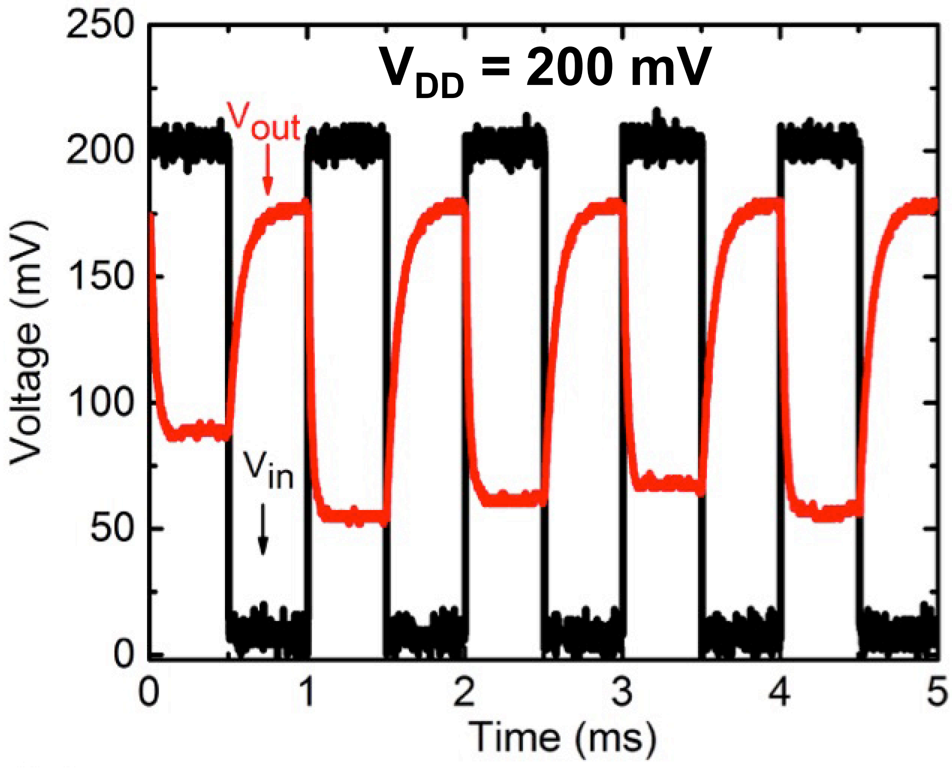
- ☐ V_H is reduced (by ~41%) with SAM coating.
- ☐ ON-state resistance (R_{ON}) is not greatly affected.

Relay-Based Inverter Circuit

Pull-down or "n"-relay



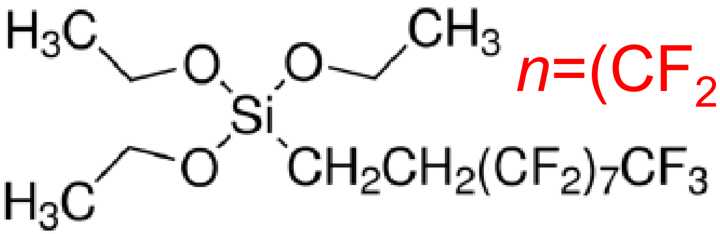
Measured voltage waveforms



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

Engineering SAM Chain Length

PFDTES



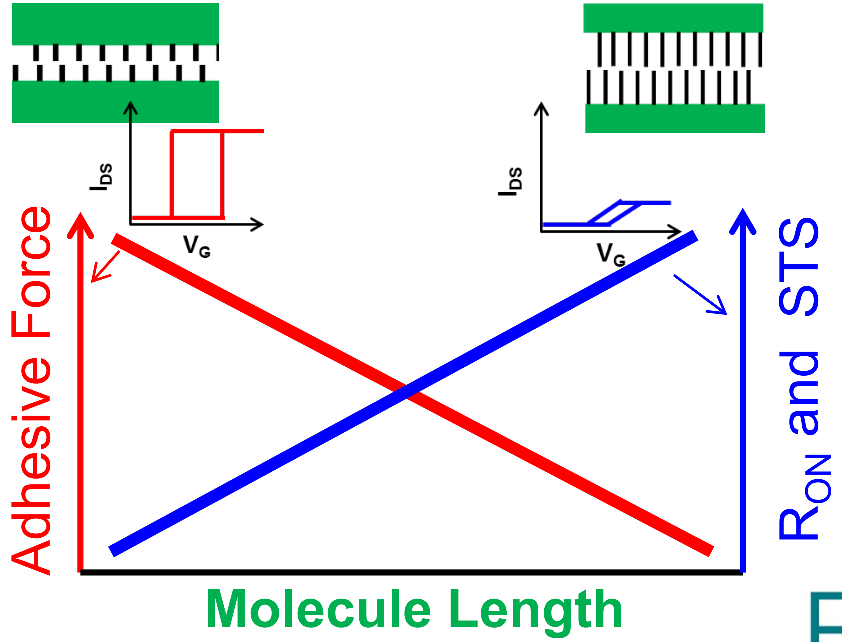
$n=(CF_2)=7$

Length ~ 1.5 nm

- Adhesive Force and Hysteresis Voltage Reduces
- Sub-threshold Swing Increase (that ultimately is its limiting factor)

Can the adhesive force/ hysteresis voltages be reduced while retaining abrupt switching?

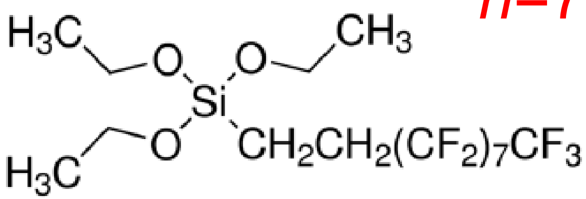
Critical thickness (volume) for lowering adhesive force vs. critical thickness for low R_{ON}, sub-threshold swing.



Engineering SAM Chain Length

PFDTES

n=7



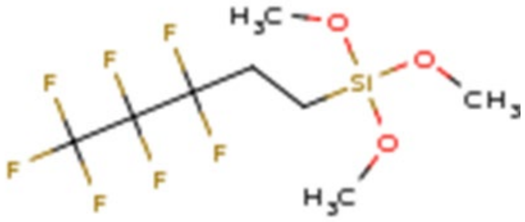
Length ~ 1.5 nm

- Adhesive force and Hysteresis voltage reduces
- Sub-threshold Swing increase (that ultimately is its limiting factor)

n = 6 - 1

PFPTES

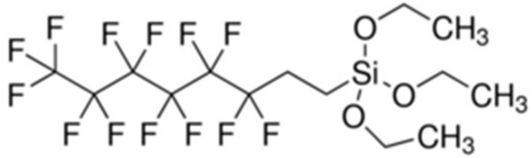
n =2



Length ~ 0.8 nm

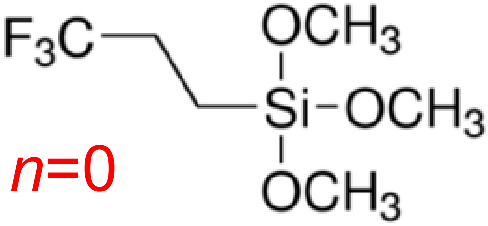
PFOTES

n =5



Length ~ 1.3 nm

PFTTES

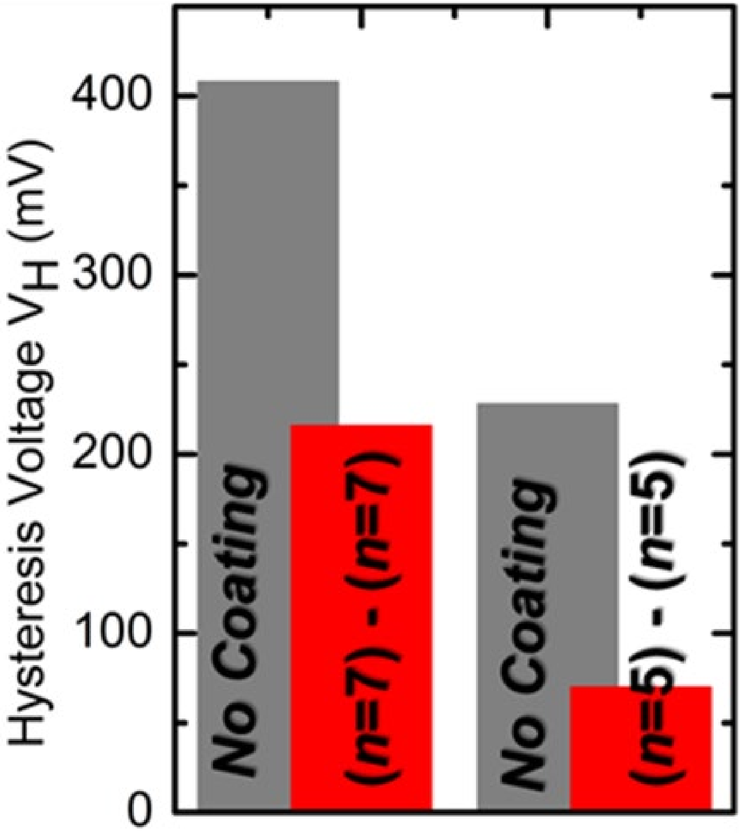


n=0

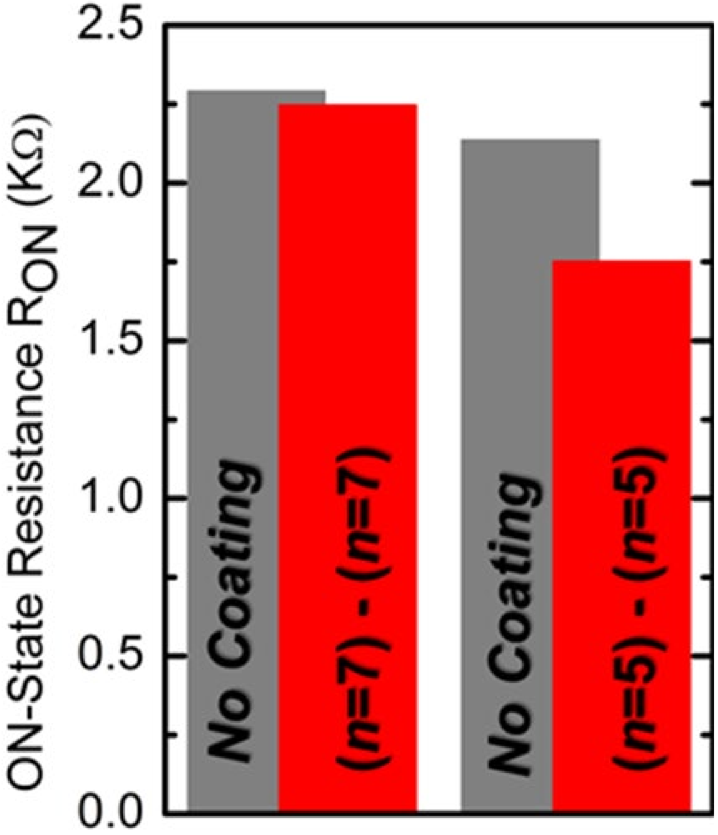
Length ~ 0.5 nm

- Adhesive force and hysteresis voltage does not reduce.
- Sub-threshold Swing decreases w.r.t PFDTES.

Affect of SAM Coating on Electrical Properties

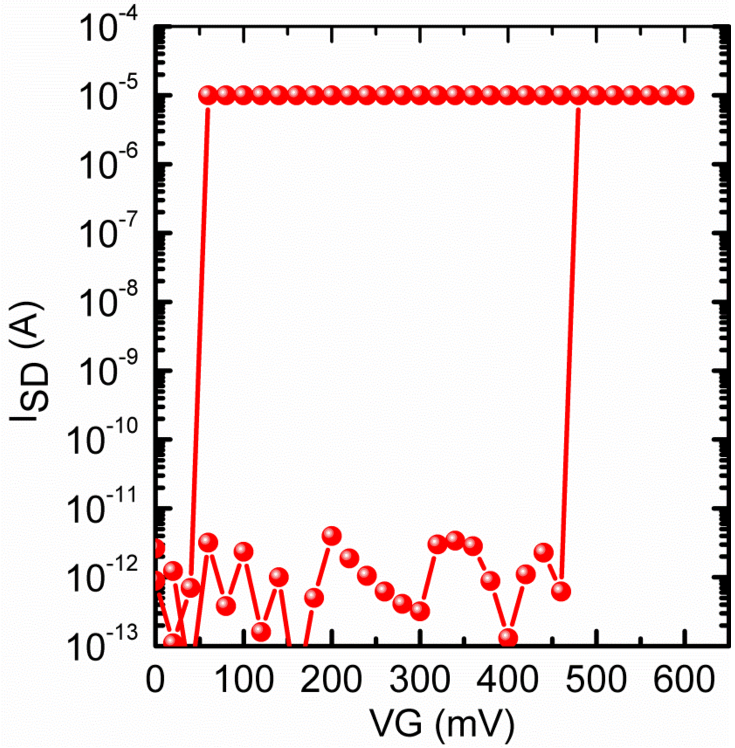


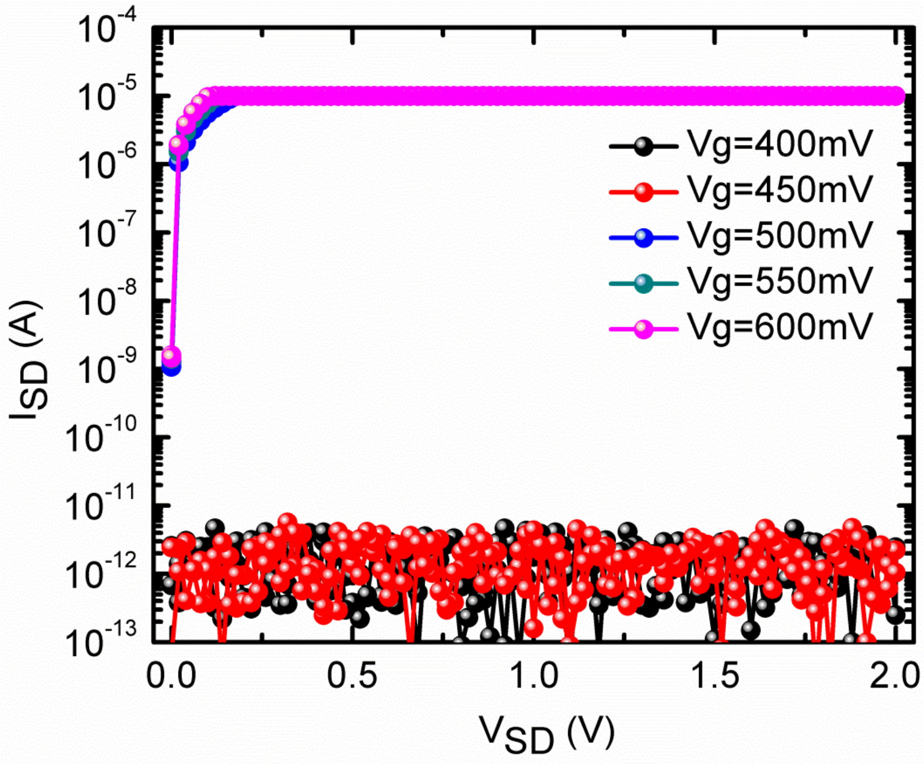
- ☐ On an-average the hysteresis voltage decreases by ~41% for PFDTES and by ~60% for the PFOTES Coating at V_B=0 V.



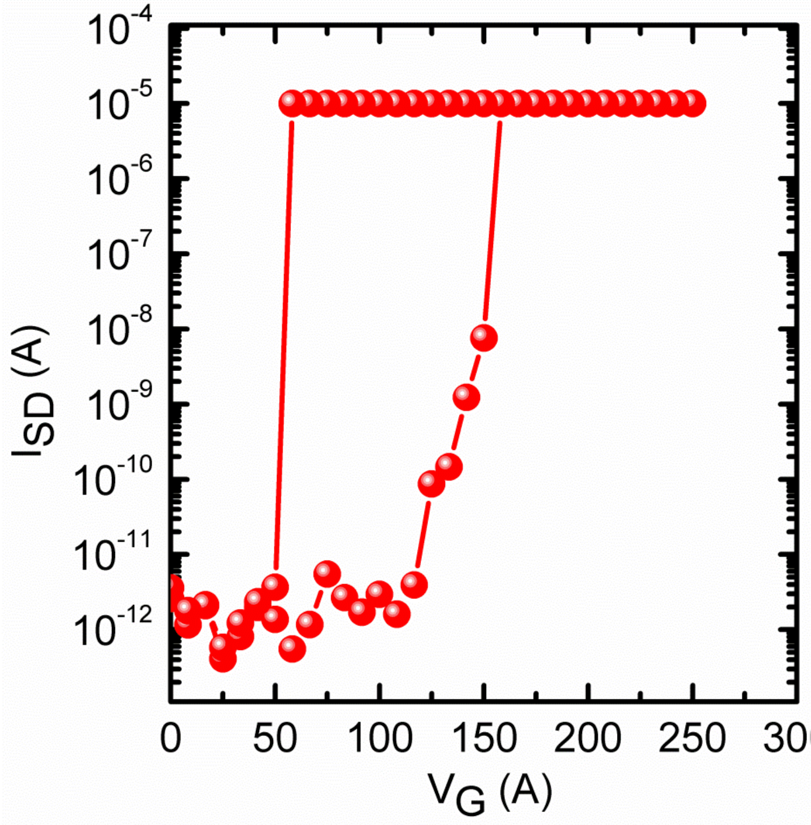
- ☐ On an-average the ON-state resistance remain unchanged before and after SAM coating at V_B=0 V.

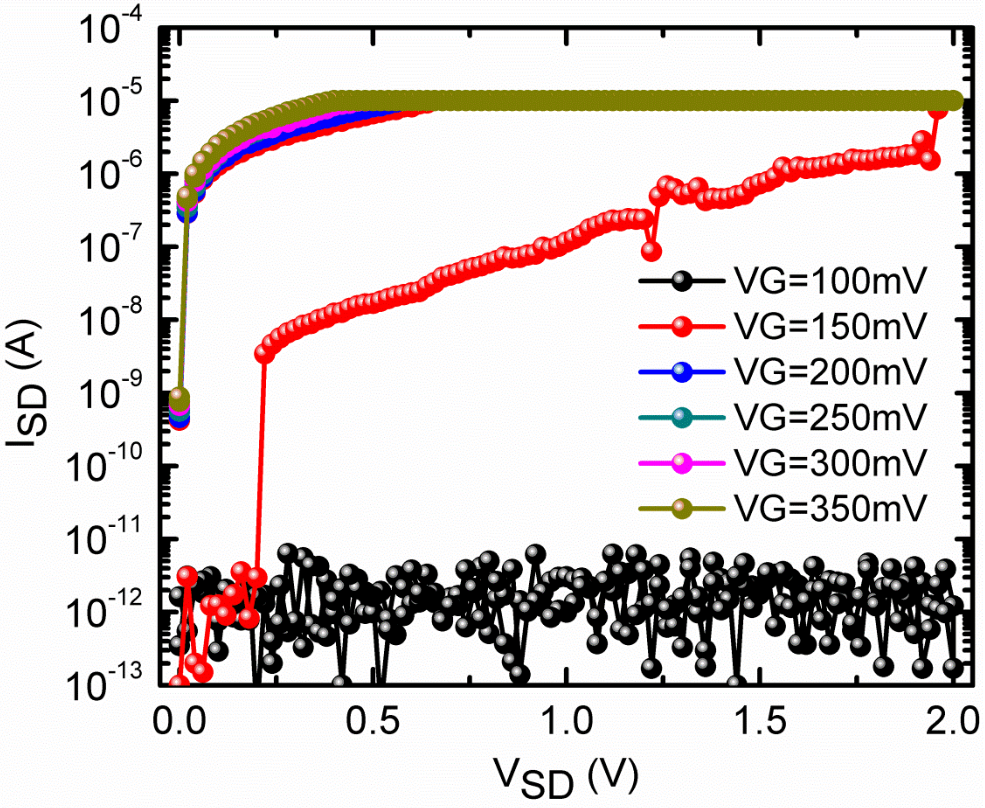
How Does Current Flow?





How Does Current Flow? No Coating

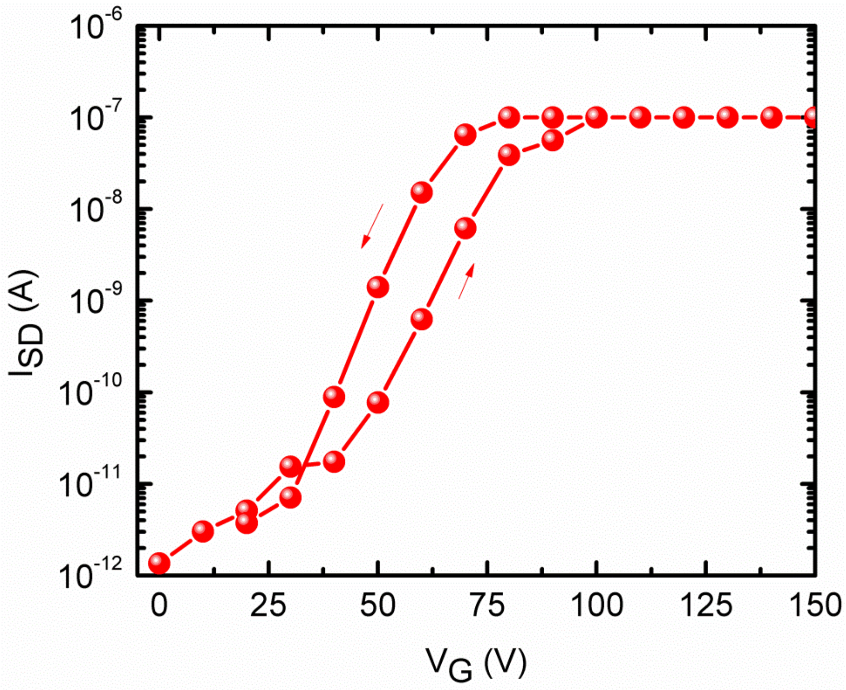


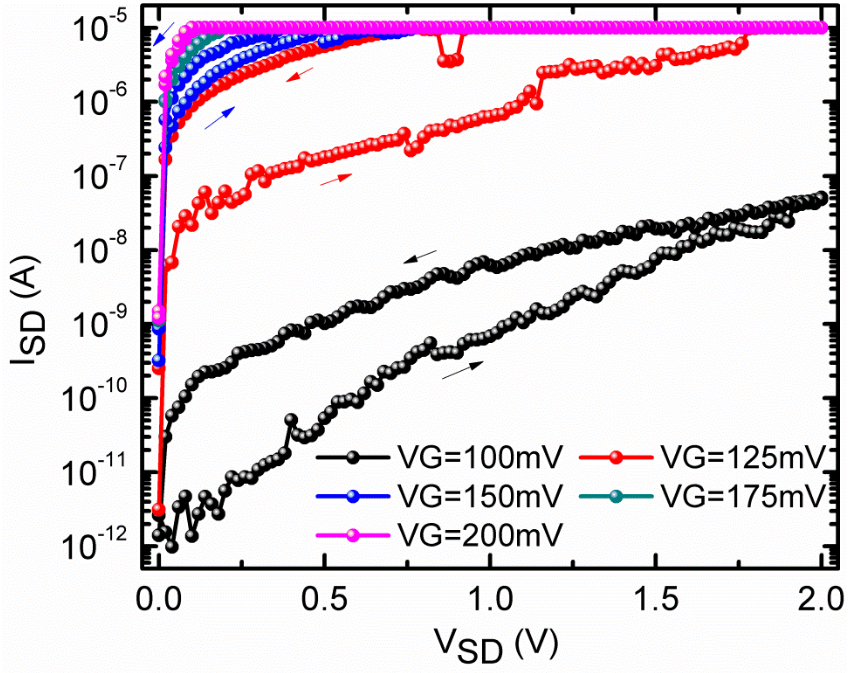


V_G (mV)	R_{ON} (K-Ω)
150 (R)	66
200	58
250	46
300	45
350	40

How Does Current Flow?

Relay Coated with n=5 molecule

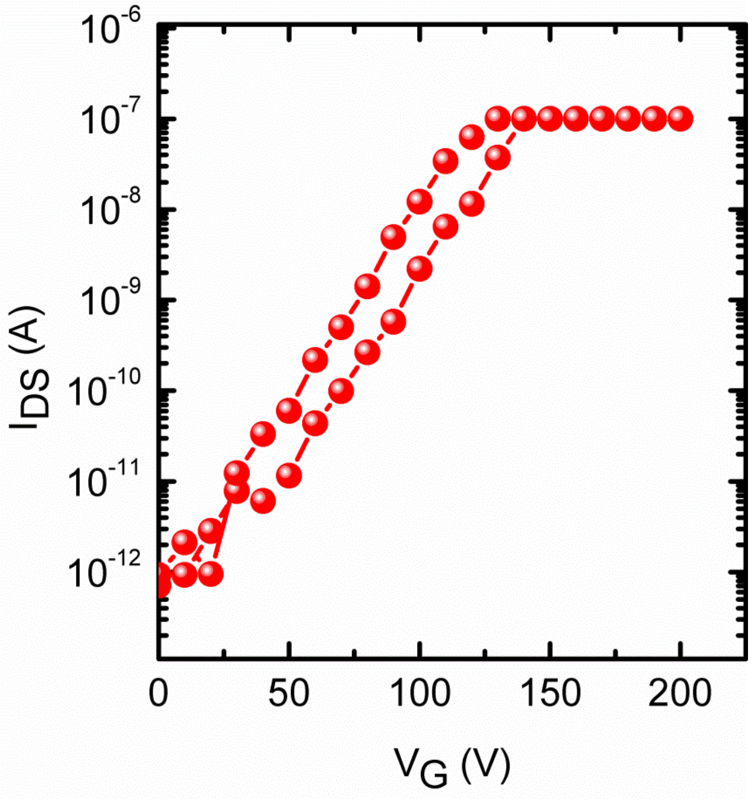


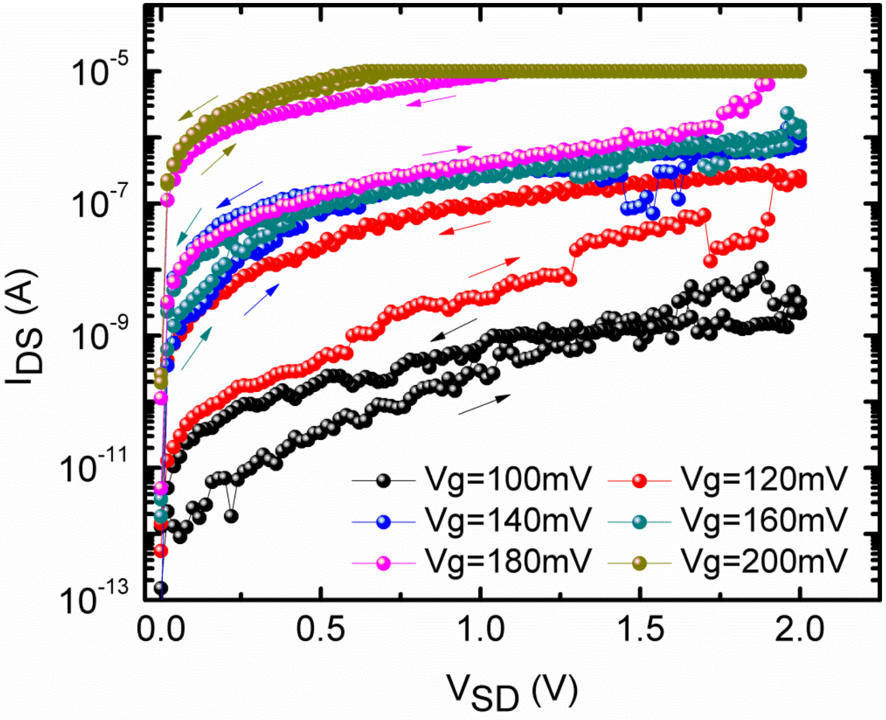


V_G (mV)	R_{ON} (K-Ω)
125 (R)	76
150	51
175	20
200	12

How Does Current Flow? *(one more example)*

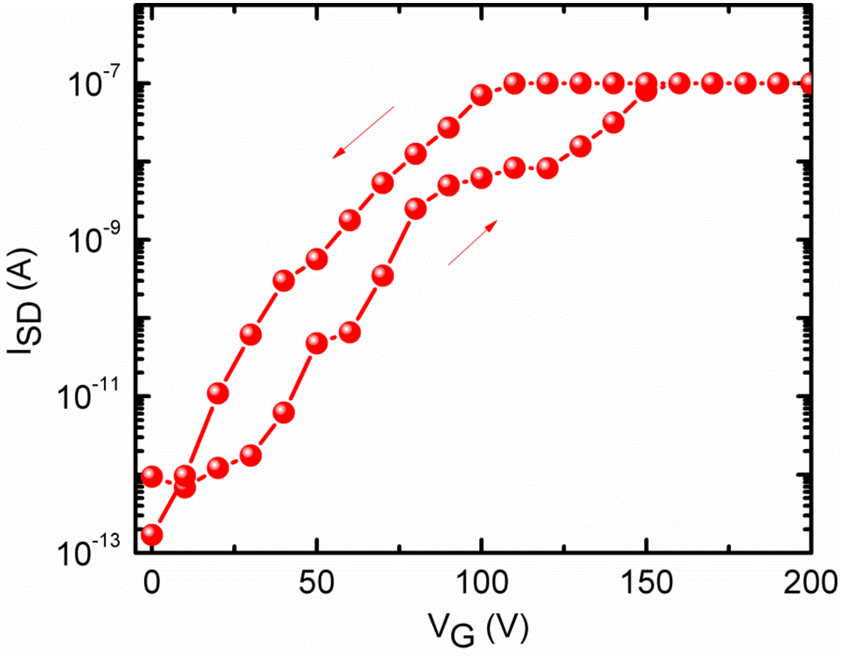
Relay Coated with n=5 molecule

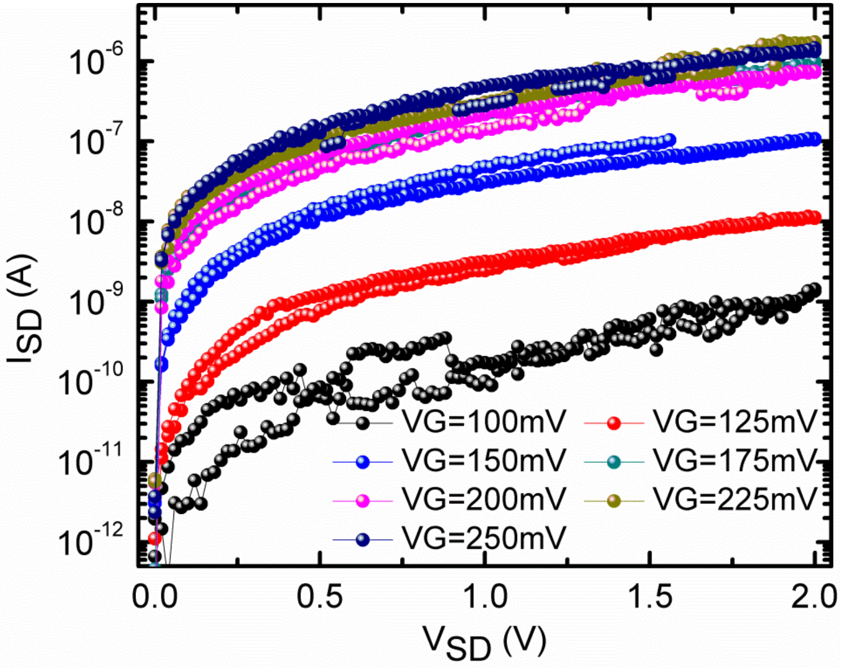




V_G (mV)	R_{ON} (K-Ω) @ V_{SD}=1V
100 (R)	10^6
120 (R)	10^4
140 (R)	384
160 (R)	384
180 (R)	119
200 (R)	70 @ V_{SD}=0.66V

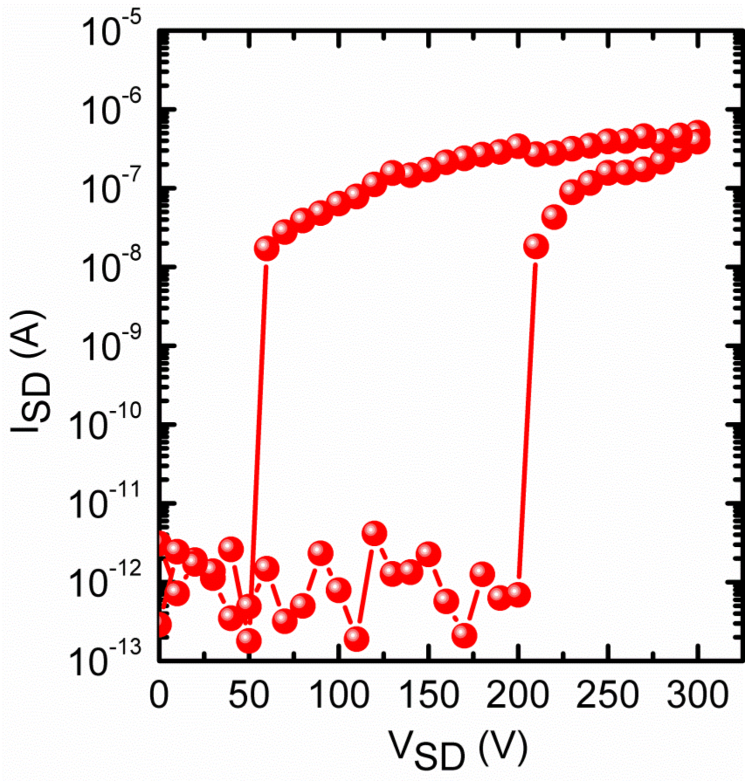
How Does Current Flow? *(one more example)*

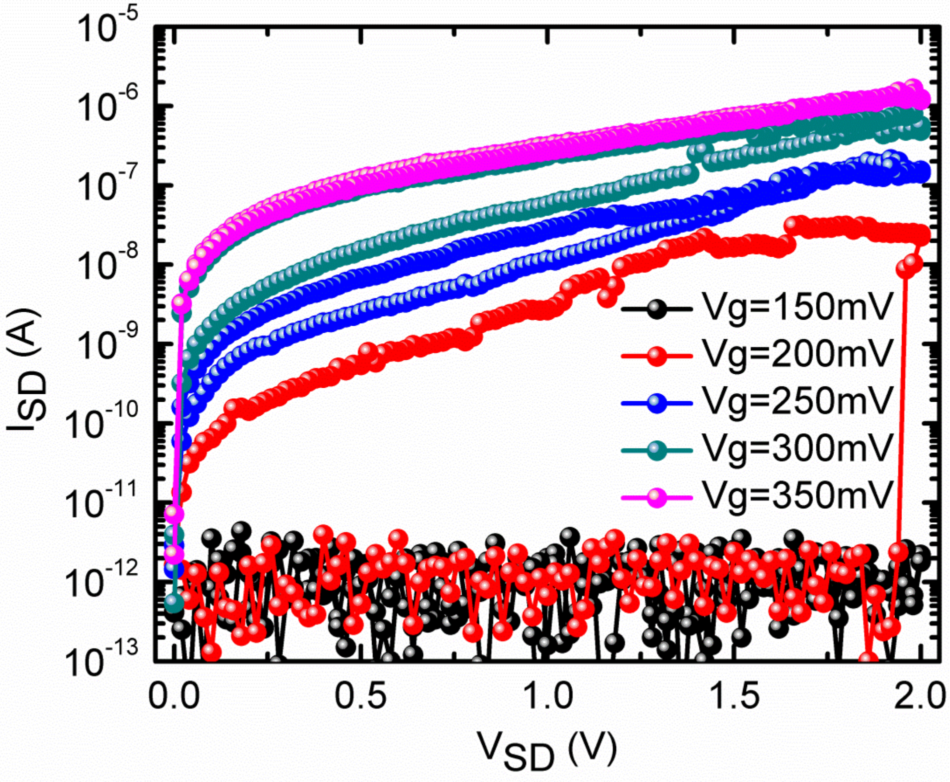




V_G (mV)	R_{ON} (K-Ω) @ V_{SD}=1V
100 (R)	6x10^{9}
125 (R)	3x10^{8}
150 (R)	2x10^{7}
175 (R)	4x10^{6}
200 (R)	3.5x10^{6}
225 (R)	3x10^{6}
250 ®	2x106

How Does Current Flow? *(Oxidized and uncoated!)*

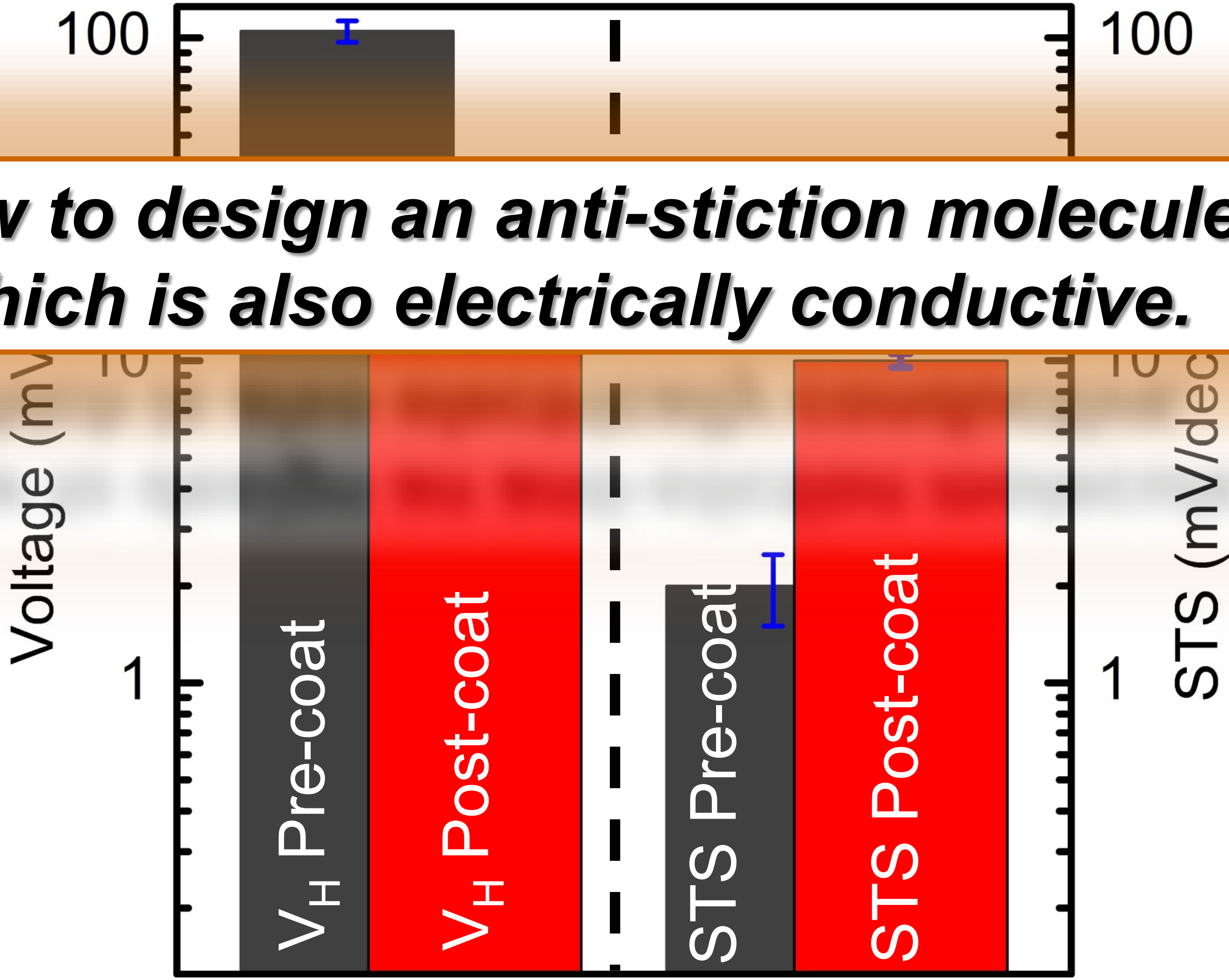




- Allowed to oxidize deliberately.
- Current doesn't reach compliance of 10^{-5}A.

- Tunneling through the Oxides?

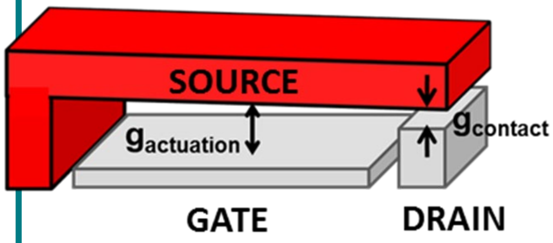
Future Challenges



How to design an anti-stiction molecule which is also electrically conductive.

Comparison With Other Sub-thermionic Switches

Mechanical Relay



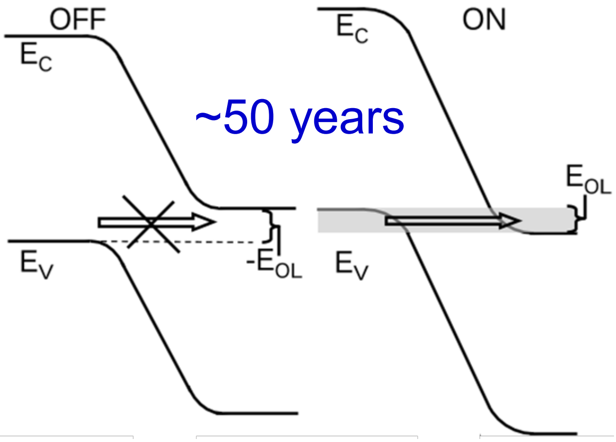
~200 years

☐ Use mechanical contact make/break to achieve device operation.

Gate Actuation Voltage ~ 50 mV

Challenges: Speed, reliability, large-size and others.

Tunneling Transistor



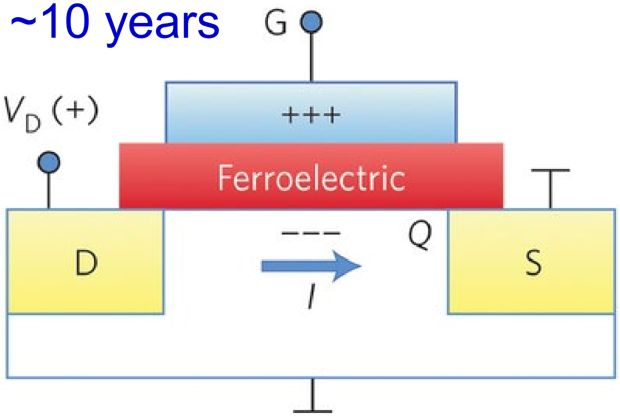
~50 years

☐ Use tunneling at homo/hetero-interfaces to reduce the STS.

Gate Actuation Voltage ~ 250 mV

Challenges: Interface and trap states, band edge sharpness and etc.

Negative Capacitance



~10 years

☐ Use a ferroelectric material as gate to achieve negative capacitance, and, hence reduce sub-threshold swing..

Currently Developed

Challenges: Proof of concept, and beyond.

Conclusion

- **Sub-50 mV** Nano-electromechanical Relay Switch Devices Demonstrated for the First-time.
- A conjugation of chemistry, physics, materials science and device research promises a new era in electronic devices.

Center for Energy Efficient Electronics and Sciences @ UC Berkeley

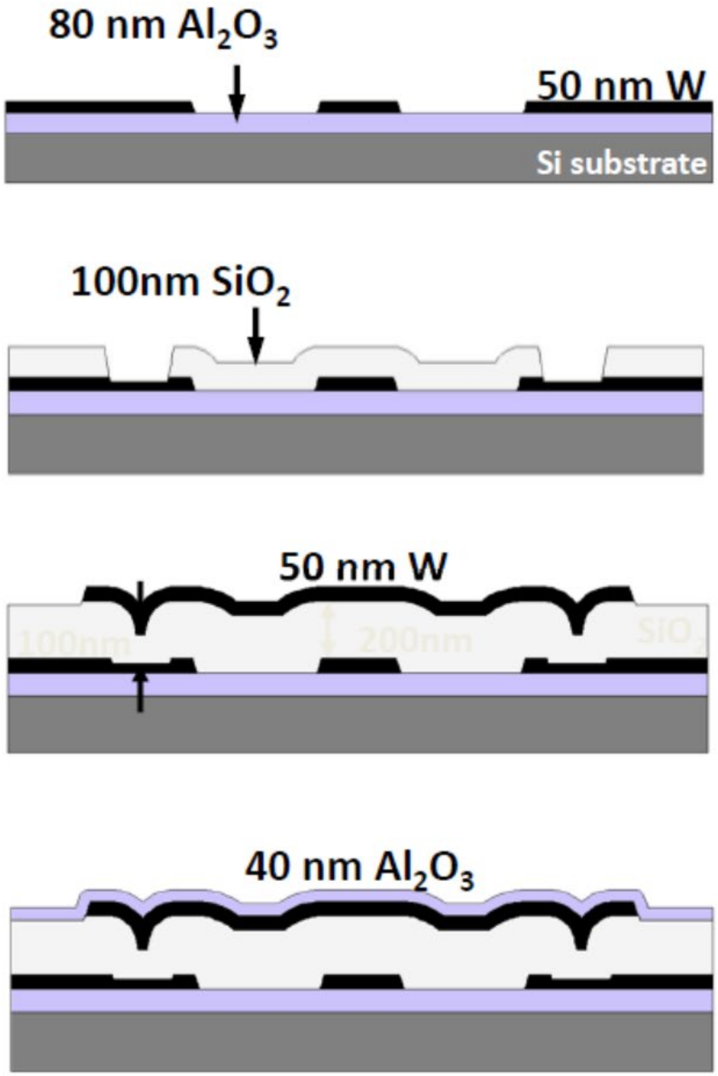
Researchers:

1. Benjamin Osoba.
2. Jane Edgington.
3. Liam Dougherty.
4. Laura Brandt.
5. Jatin Patil.
6. Don Rollings
7. *Farnaz Niroui*
8. *Chung Qian*

THANK YOU

THANK YOU

Relay Fabrication Process



Deposit Al_2O_3 substrate insulator
- ALD at 300°C

Deposit & pattern W electrodes
- DC magnetron sputtering

Deposit 1st sacrificial LTO
- LPCVD at 400°C

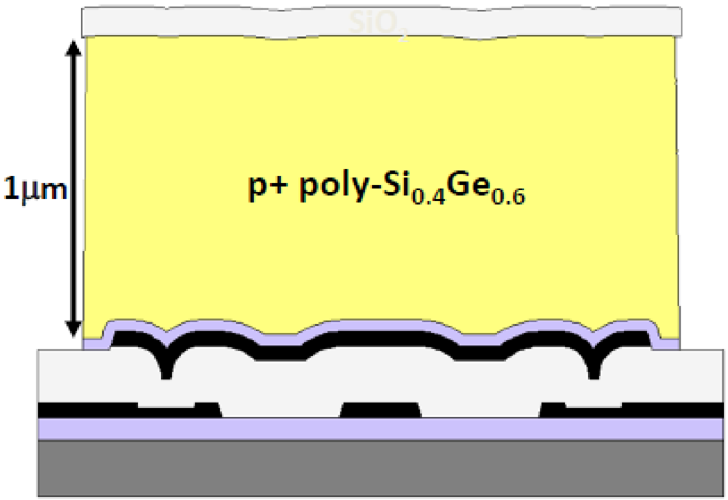
Define contact regions

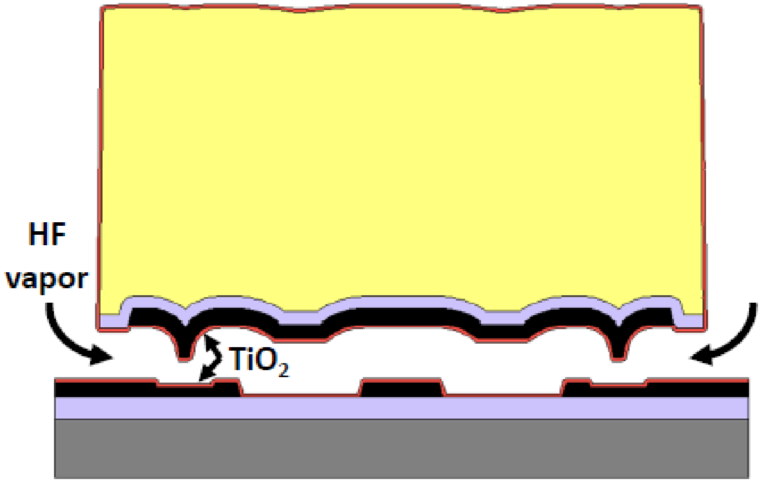
Deposit 2nd sacrificial LTO
- $t_{dimple} = t_{gap} / 2$

Deposit & pattern W channel

Deposit Al_2O_3 gate oxide

Relay Fabrication Process (Cont'd)





⋮

Deposit p+ poly-Si$_{0.4}$Ge$_{0.6}$ gate

- LPCVD at 410°C

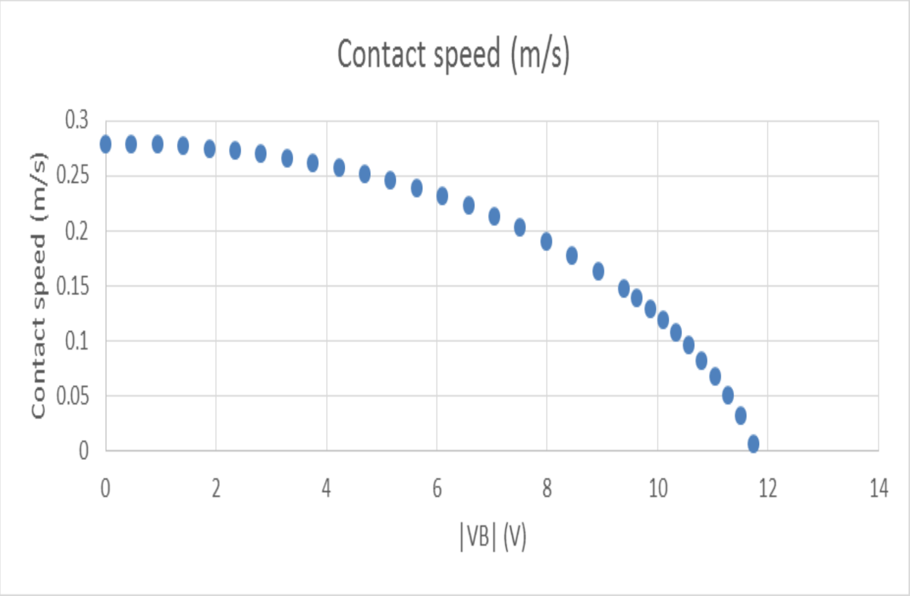
Pattern gate & gate oxide layers using LTO as a hard mask

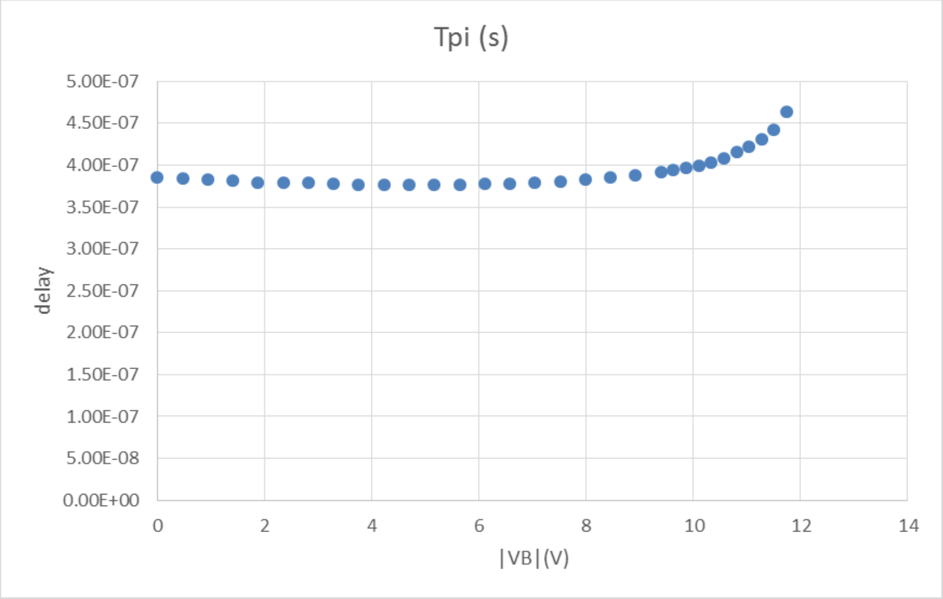
Release in HF vapor

Coat with ultra-thin (~0.3nm) TiO$_2$

- ALD at 300°C

Effects of Body Bias





NEM Relay Equations

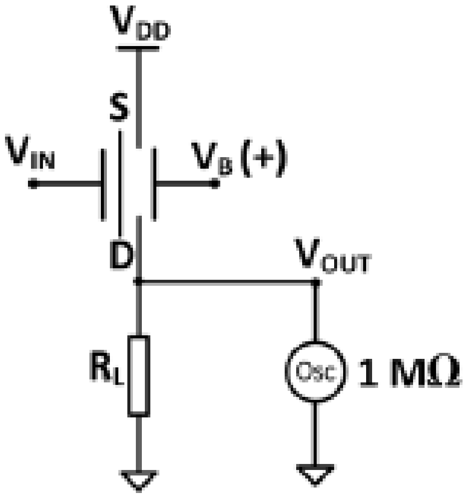
Non-Pull in Mode

$$V_{\mathrm{ON}} = \sqrt{\frac{2k_{\mathrm{eff}}\, g_{\mathrm{CONT}} (g_{\mathrm{ACT}} - g_{\mathrm{CONT}})^2}{\varepsilon_0 A_{\mathrm{ACT}}}}$$

$$V_{\mathrm{RL}} = \sqrt{\frac{2(k_{\mathrm{eff}}\, g_{\mathrm{CONT}} - F_{\mathrm{adh}})(g_{\mathrm{ACT}} - g_{\mathrm{CONT}})^2}{\varepsilon_0 A_{\mathrm{ACT}}}}$$

$$V_H = V_{\mathrm{ON}} - V_{\mathrm{RL}} \approx \frac{F_{\mathrm{adh}}\,(g_{\mathrm{ACT}} - g_{\mathrm{CONT}})}{\sqrt{2\varepsilon_0 A_{\mathrm{ACT}} k_{\mathrm{eff}}\, g_{\mathrm{CONT}}}}$$

Inverter

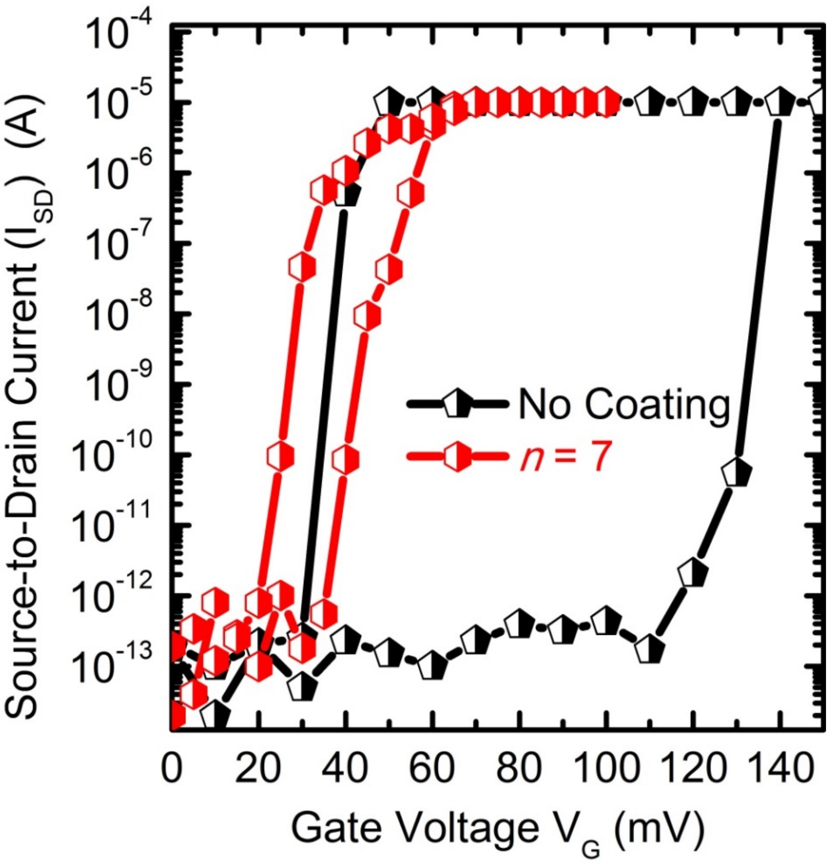


$$V_{\mathrm{OUT}} = \frac{R_{\mathrm{ON}} R_{\mathrm{osc}}}{R_{\mathrm{ON}} R_{\mathrm{osc}} + R_L (R_{\mathrm{ON}} + R_{\mathrm{osc}})} V_{\mathrm{DD}}.$$

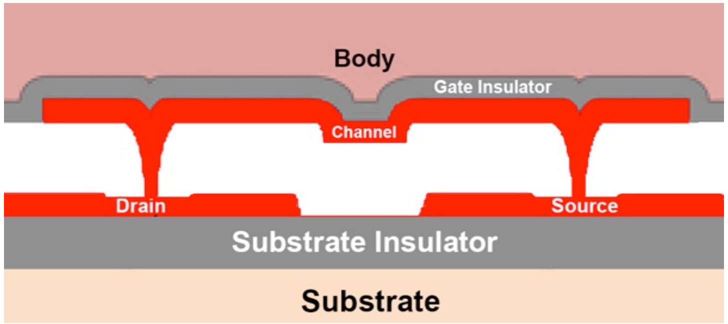
Relay Motion Eq.

$$m_{\mathrm{eff}}\, \ddot{g} + b\dot{g} - k_{\mathrm{eff}}(g_{\mathrm{ACT}} - g) = \frac{-\varepsilon_0 A_{\mathrm{ACT}} (V_G - V_B)^2}{2\left(g + \frac{d}{\varepsilon_r}\right)^2}$$

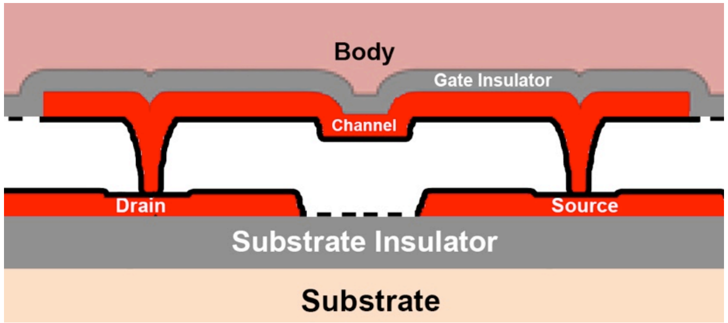
Impact of SAM Coating on Subthreshold Swing



ON-State: Before Coating

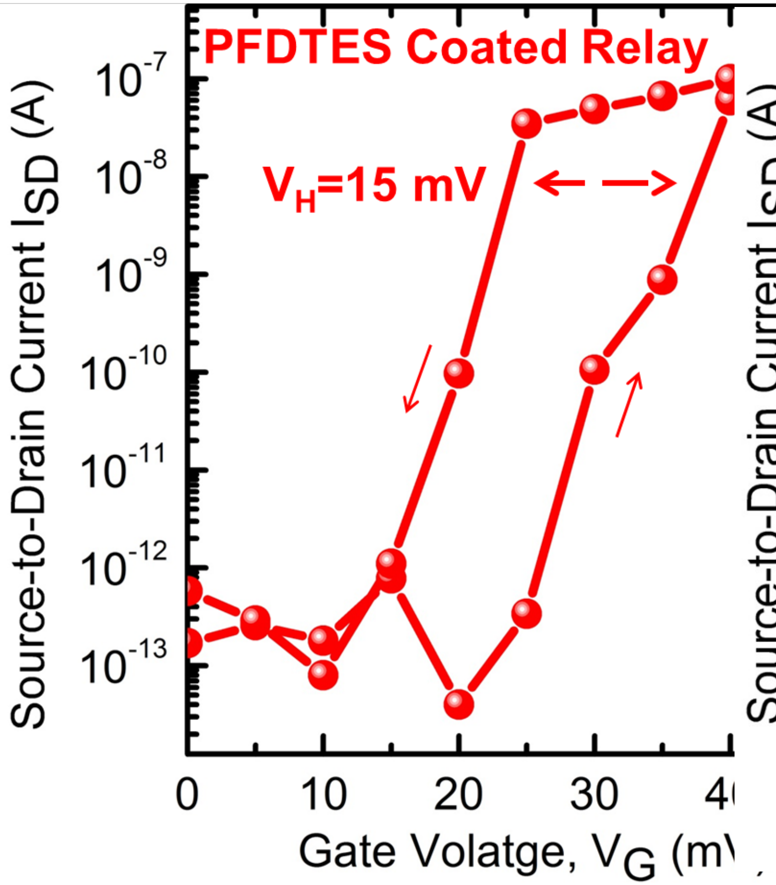


ON-State: After Coating

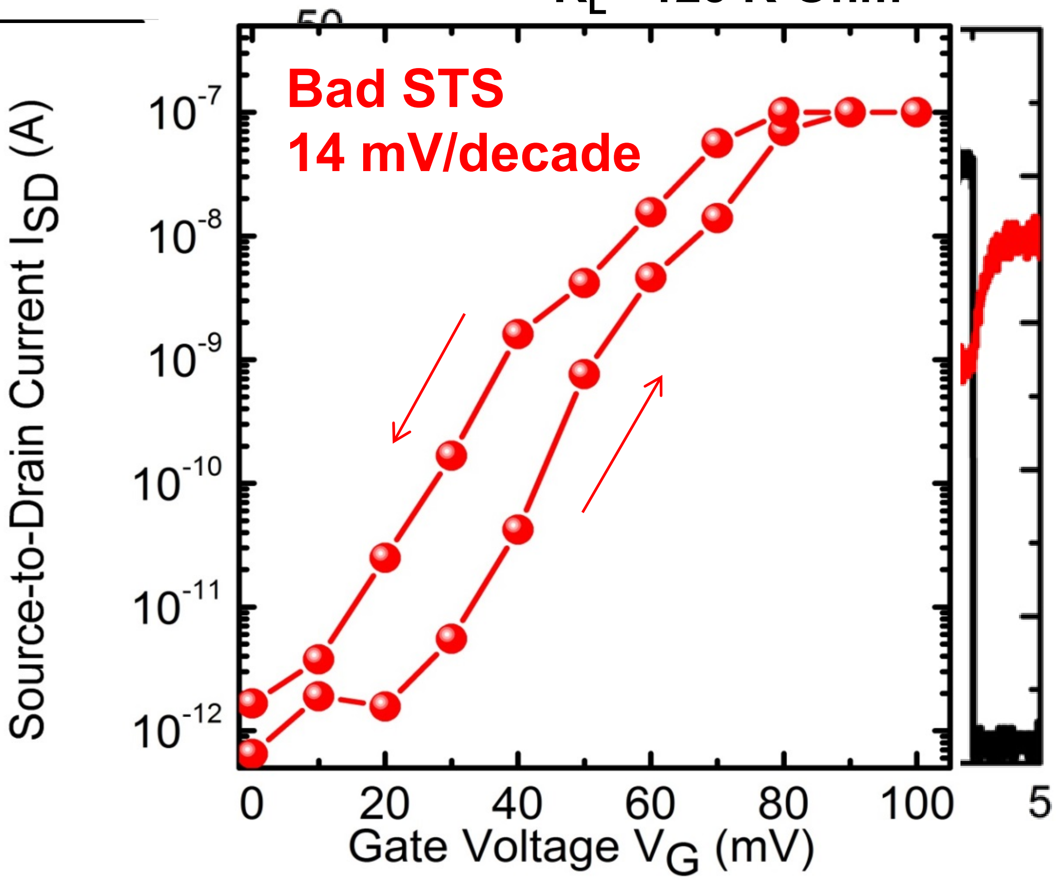


- ☐ Thickness of PFDTES at the contact is ~3 nm; since the molecule is insulating, it impedes current flow and increases sub-threshold swing.

PFDTES Coating



R_L= 123 K-Ohm



- ❑ Sub-threshold swing increases to unacceptable values, which prevents advances made due to hysteresis voltage reduction.