Mechanical and Dielectric Reliability of an RF MEMS Capacitive Switch

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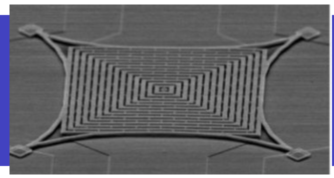
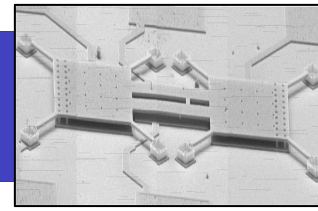
Outline

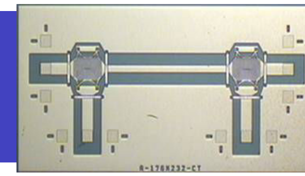
- **Introduction**
  - MEMS Activities at Tyndall
- **Reliability: Mechanical vs Dielectric**
  - Electrical method to isolate effects
  - Aluminium versus Titanium devices
- **Mechanical: Viscoelastic vs Creep**
  - Electrical method to isolate
  - Linear viscoelasticity
  - New alloy
- **Conclusions**

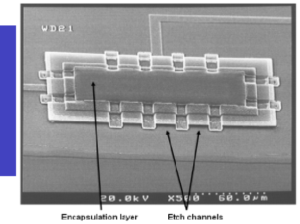
MEMS at Tyndall: Devices

RF Devices

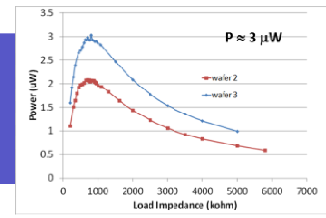


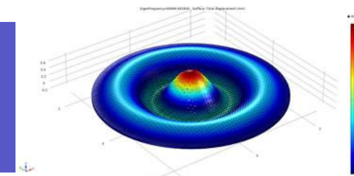




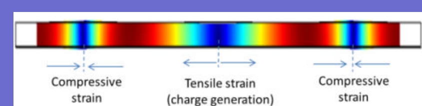


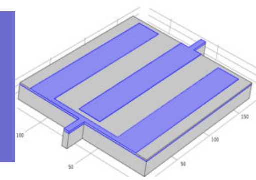
Mechanical Resonators

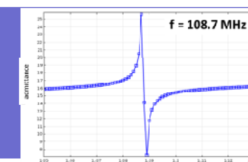




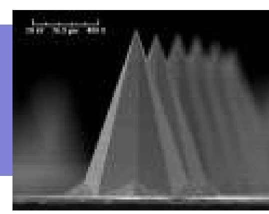
Acoustic Wave Resonators

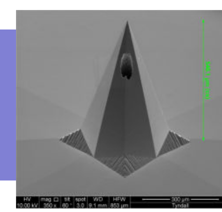


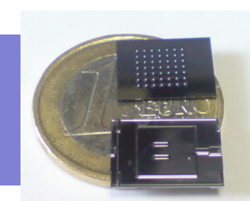




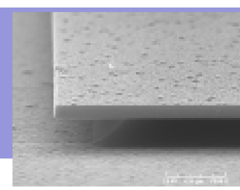
BioMEMS

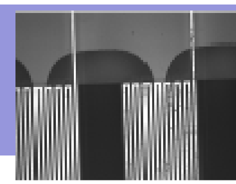


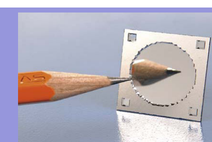


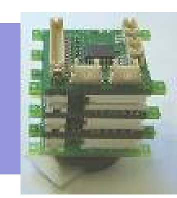


Sensors/Other



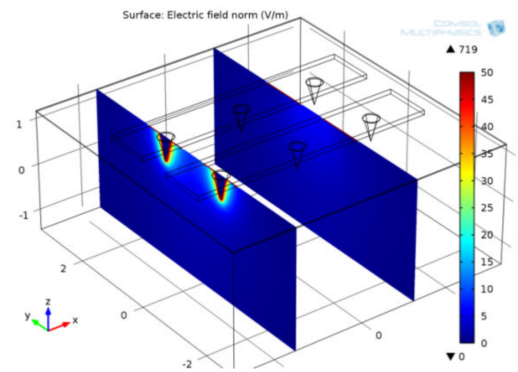


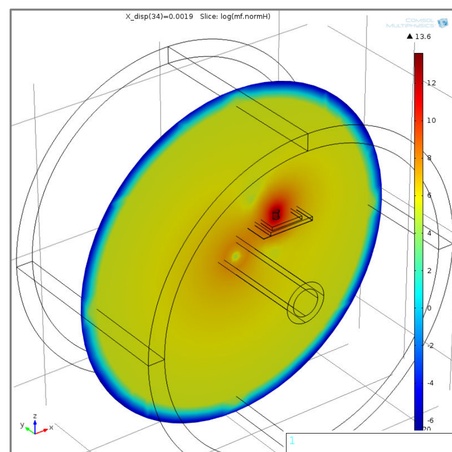


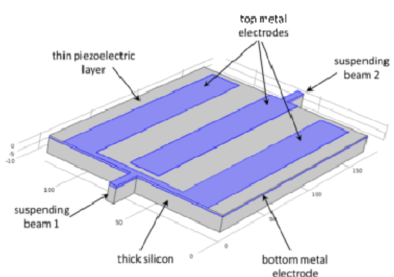


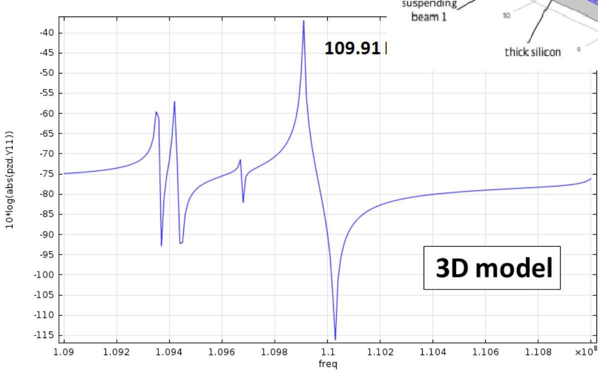
MEMS at Tyndall: Modelling

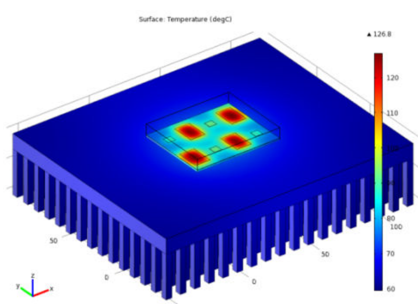
- **Levels** FEM, Circuit, System
- **Domains** Mechanical, Electrostatic, Magnetic, Thermal, Piezoelectric, Multiphysics
- **Model Types** Static, Modal, Harmonic, Transient
- **Tools** ANSYS, Comsol, Coventor, Matlab, Spice, HFSS
- **High Performance Computing**
- 1000-node cluster

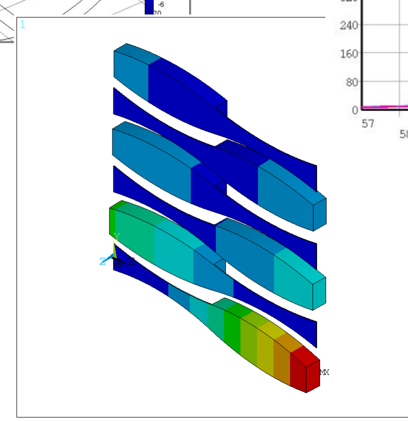


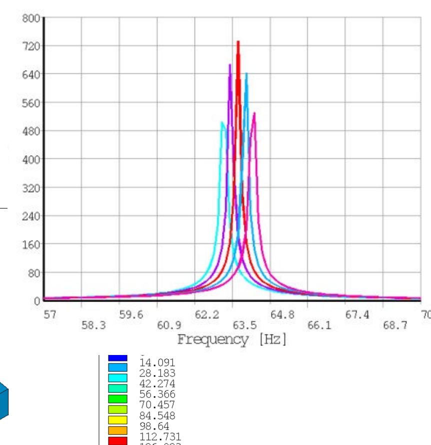






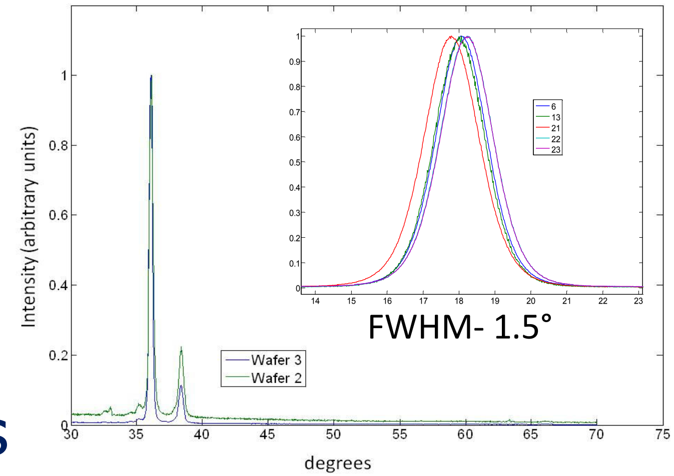


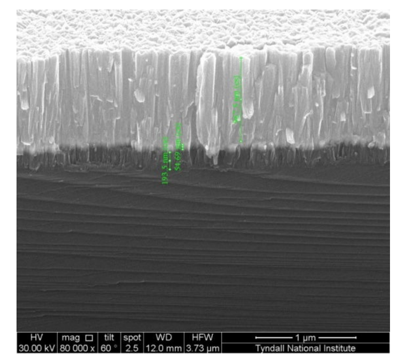




MEMS at Tyndall: Fabrication

- Fabrication Facility
  - CMOS
  - MEMS
    - Surface micromaching
    - Bulk micromaching
    - Piezoelectric/Magnetic Materials
  - III-V: Versatile prototyping solutions
  - Training Fab
- Packaging Lab

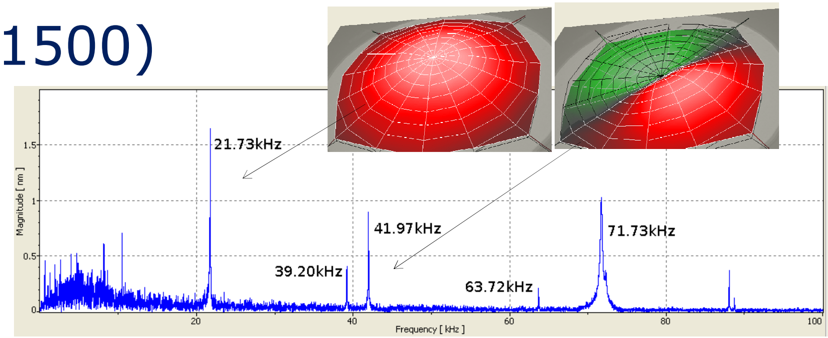


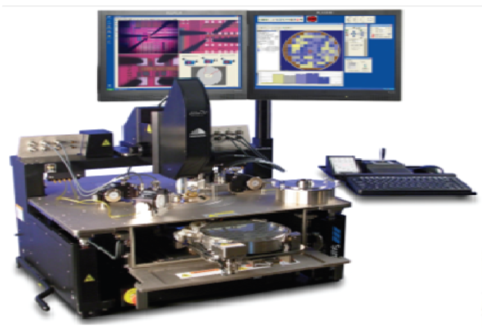


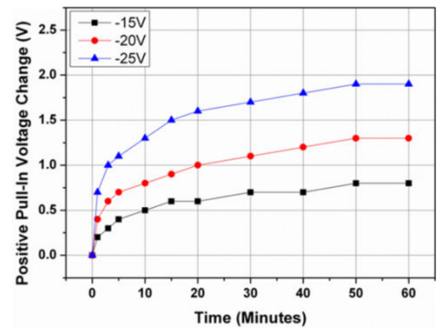
D31 = 2.97 pm/V
K^2 = 14%

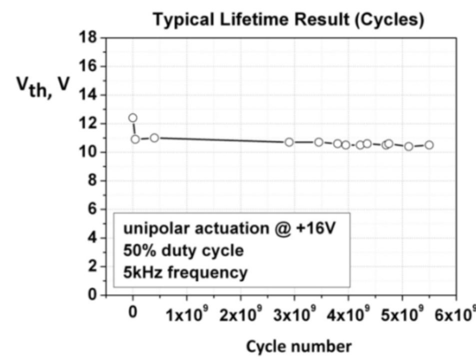
MEMS at Tyndall: Testing

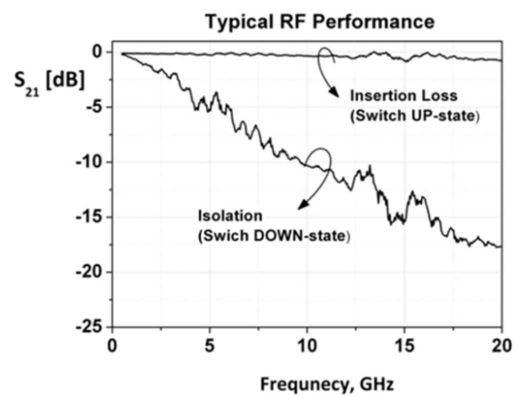
- Capacitance, current, etc. (e.g. Agilent B1500)
- RF tests (e.g. Agilent N5250A-PNA)
- Automatic probe stations (e.g. Cascade)
- Pressure, humidity, temperature
- FIB, SEM, AFM
- Polytec vibrometer (dynamic tests on MEMS)
- Zygo interferometer (static profiles on MEMS)

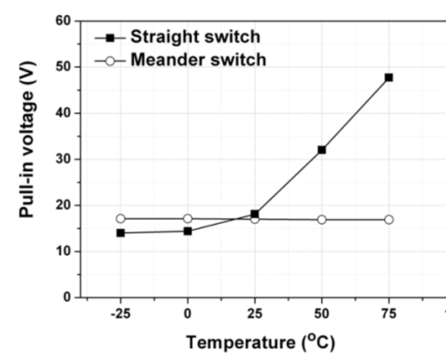




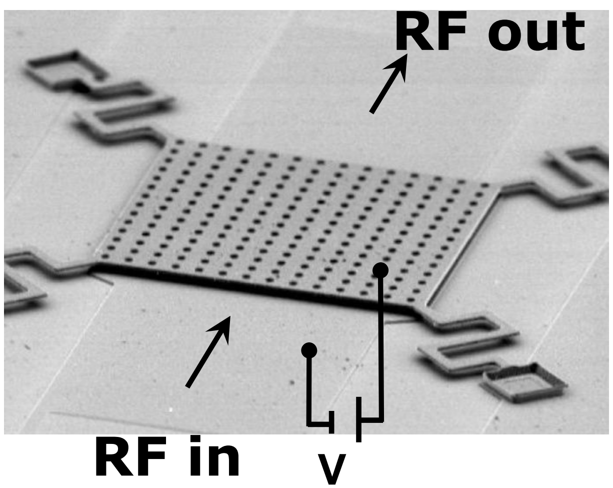


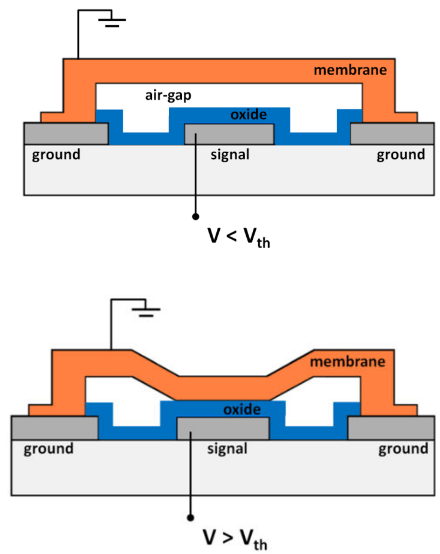


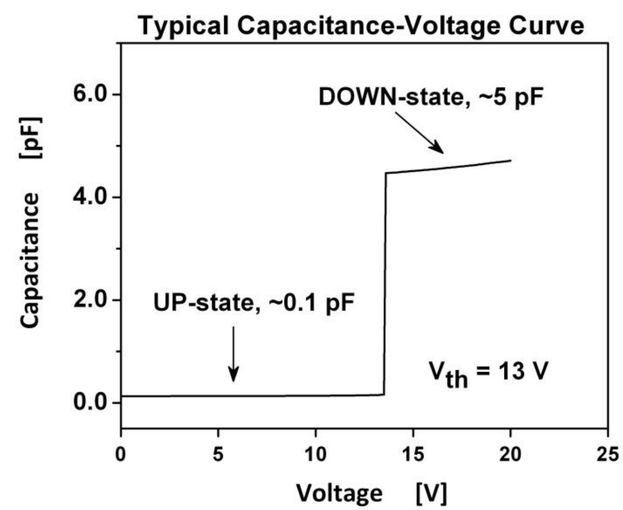




It started with a Switch…

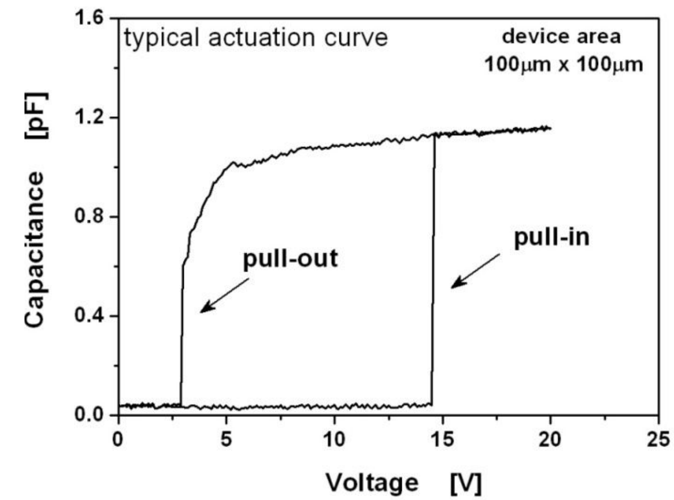


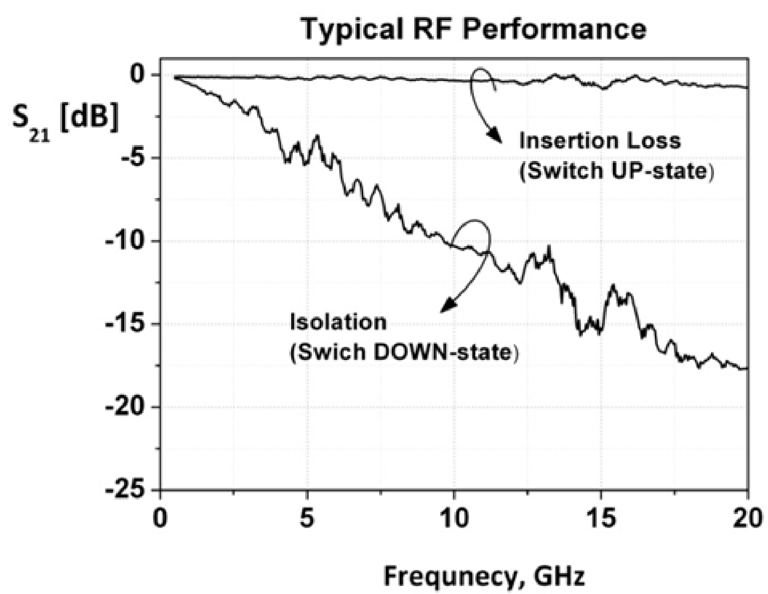


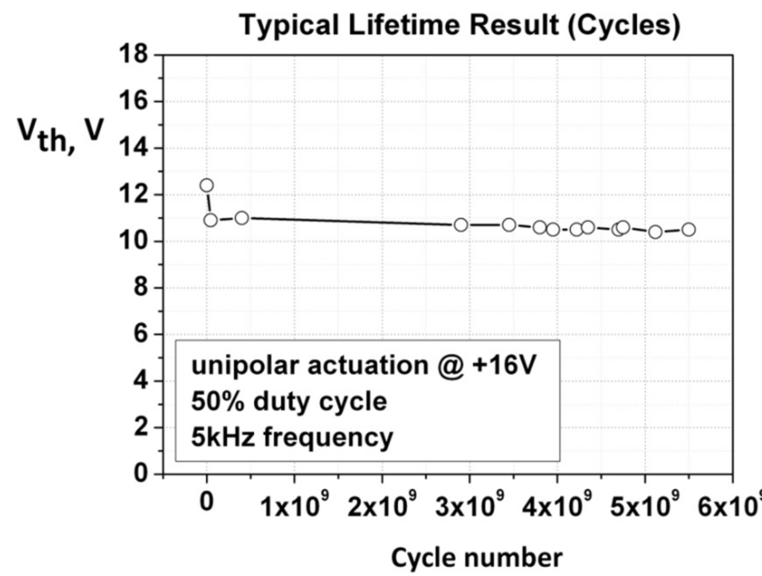


MEMS Reliability

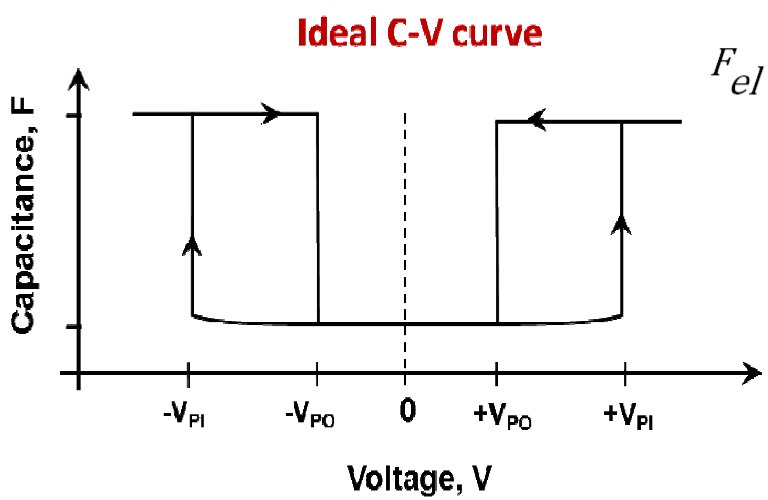
- Low temp process (< 350°C)
- Dielectric, CVD oxide, 100nm, ε_r=4.5
- Capacitance ratio, 5-30
- Switching speed, ≈ 100μs
- Low threshold voltage, V_{th} < 15 V
- Unipolar stress, >5x10^9 cycles



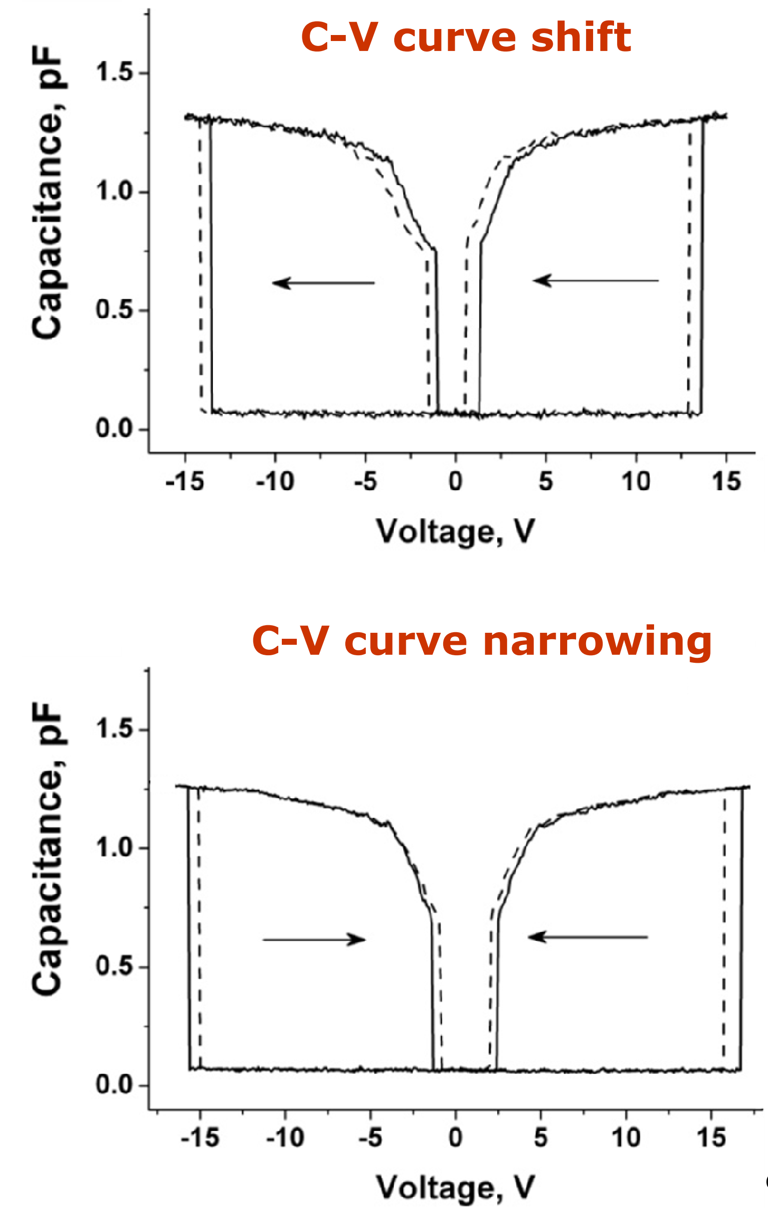




MEMS Reliability



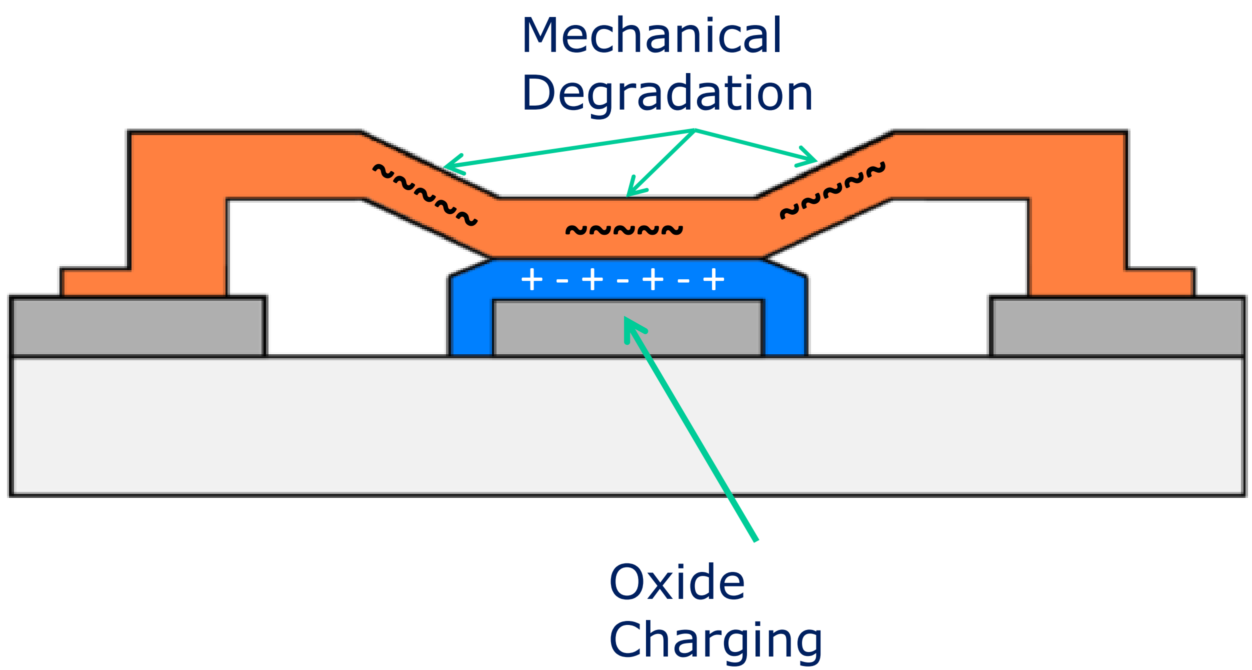
$F_{el} \propto V^2$



Oxide Charging and Mechanical Degradation of the switch metal can both result in changes in threshold voltages and lead to device failure.

Two Sources of Switch Degradation

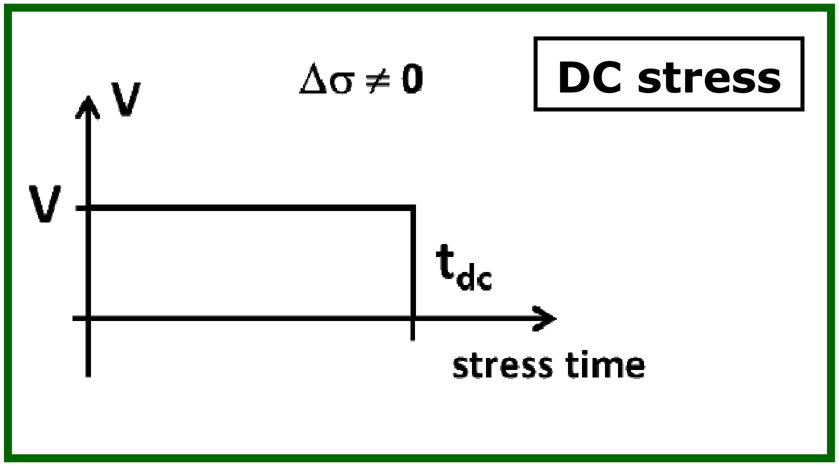
- Dielectric Charging
- Mechanical Degradation



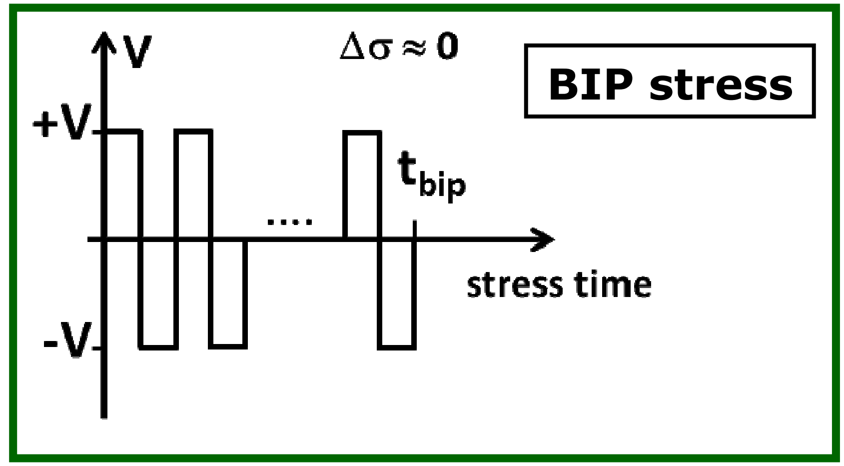
How can we isolate these two phenomena?

Isolation of degradation mechanisms

Accelerated stress tests



accelerated charging

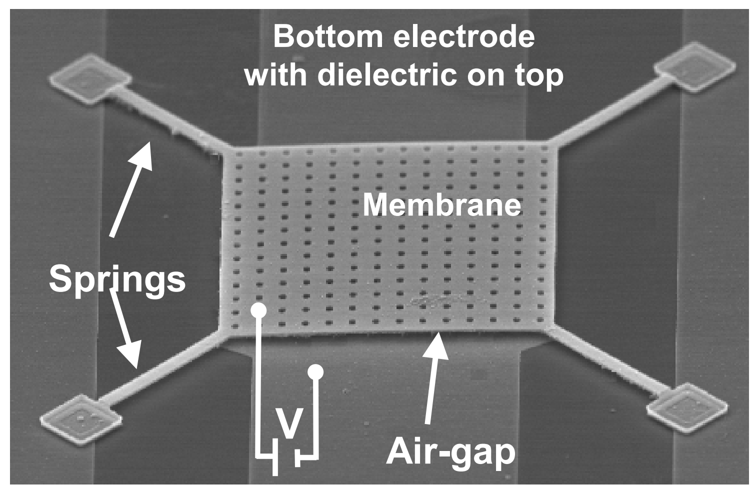


limited charging

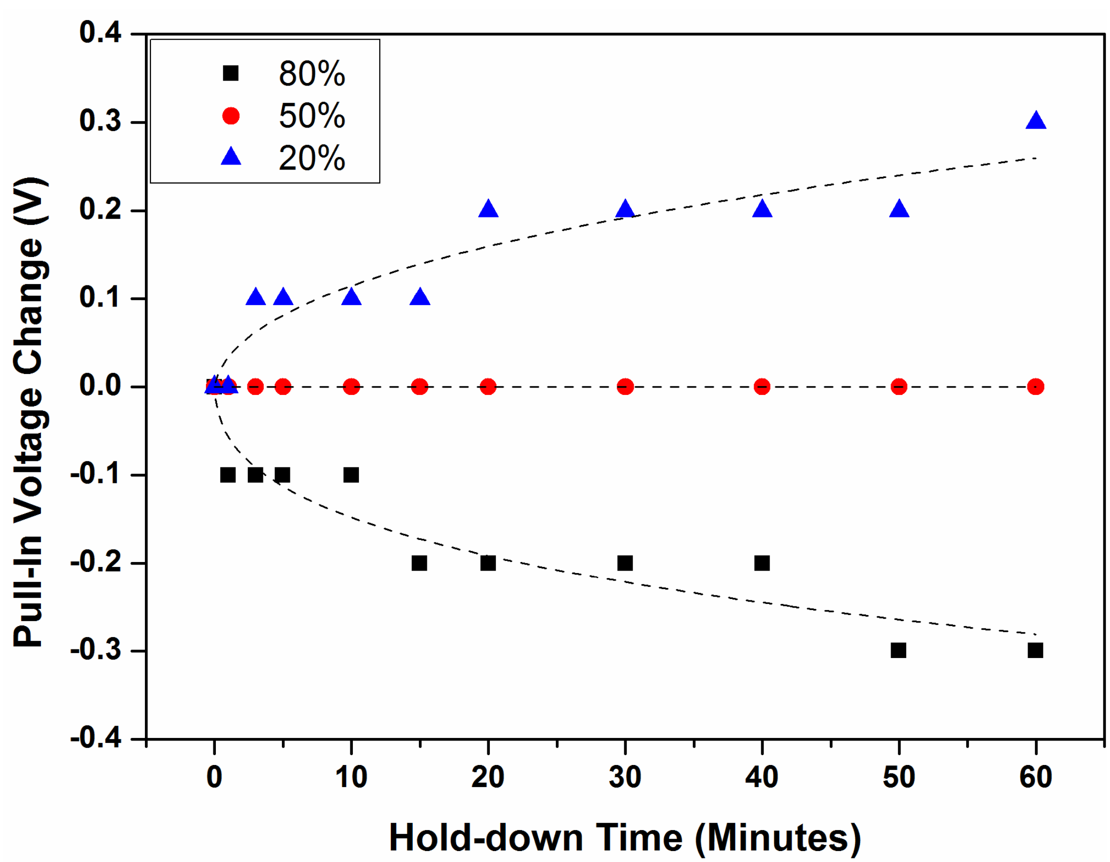
Switch remains in down-state during DC and BIP stress

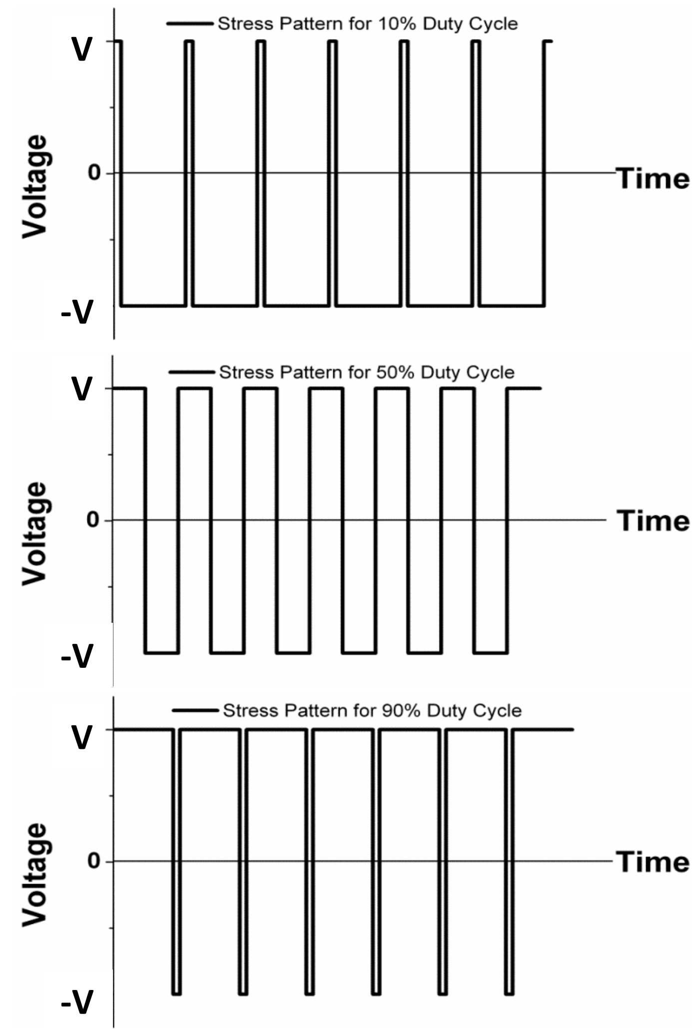
Test Structures

- ❑MEMS capacitive switches
- ❑Switch A: 0.5 μm thick titanium
- ❑Switch B: 1.0 μm thick aluminium

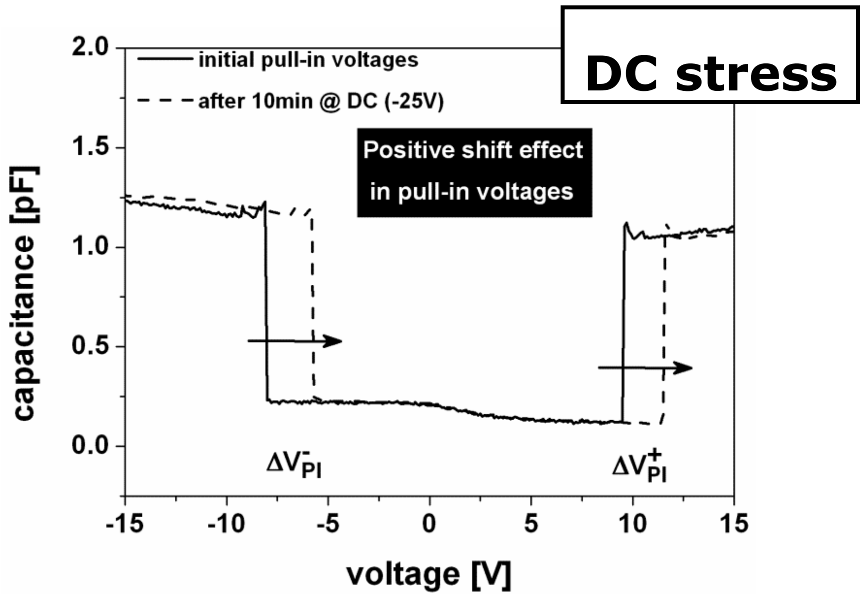


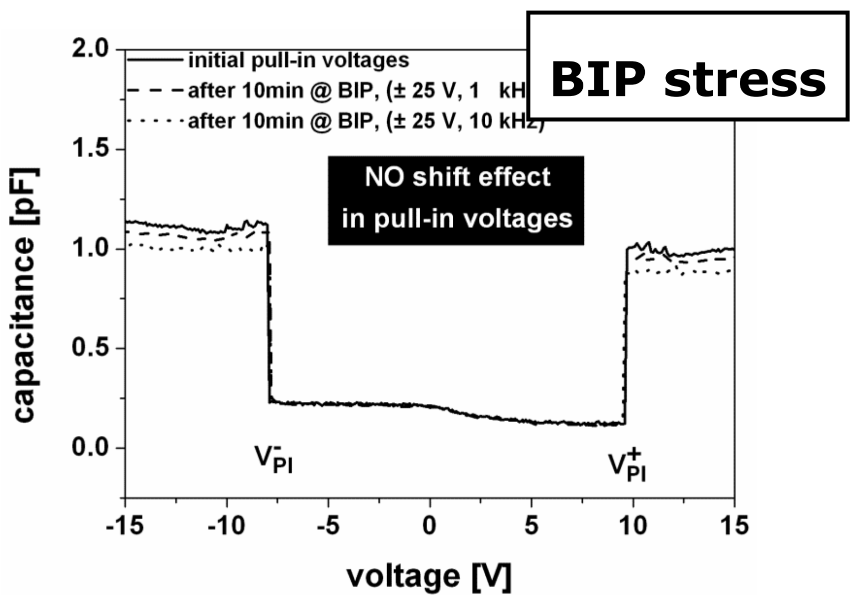
Symmetric Charging

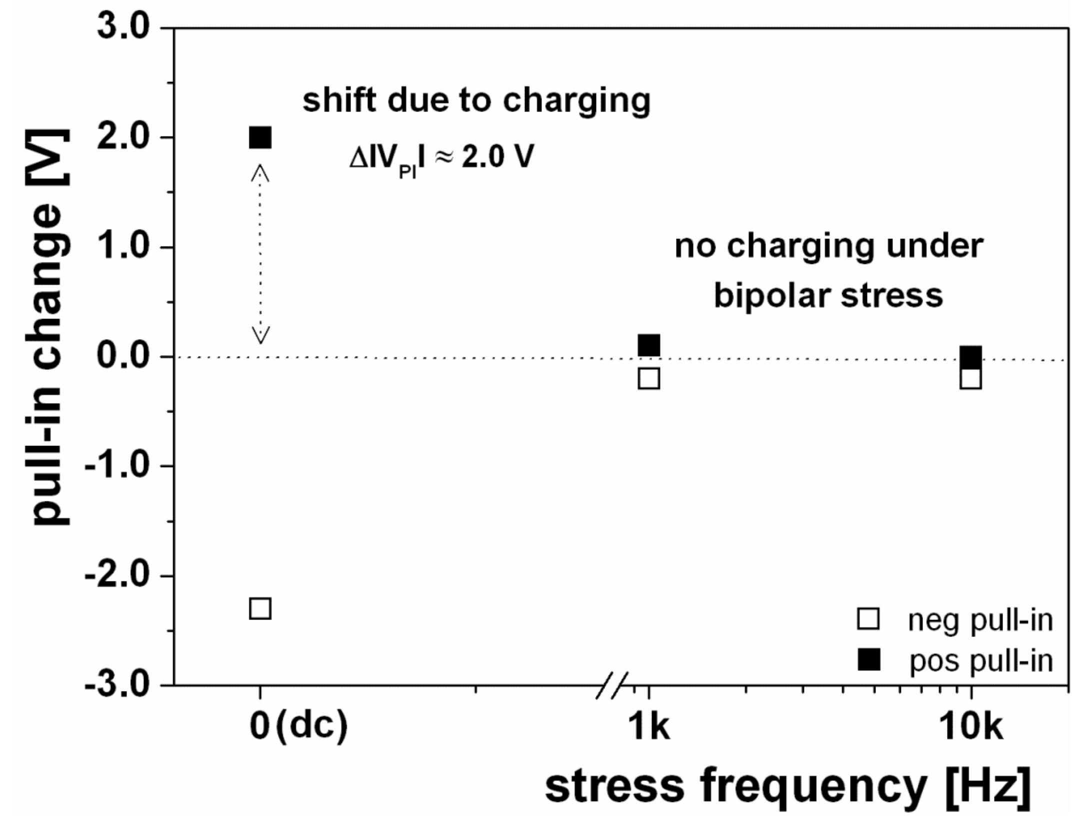




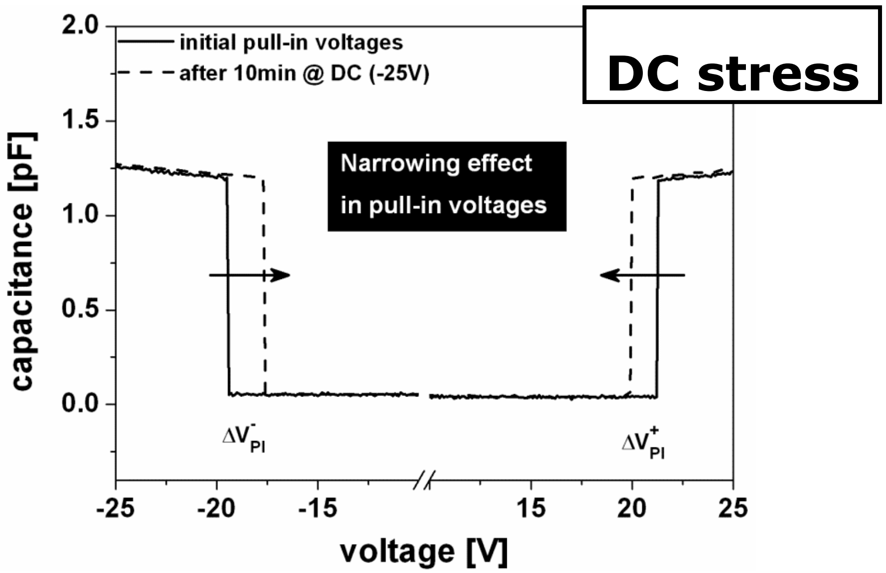
Isolation of degradation mechanisms: results – titanium switches

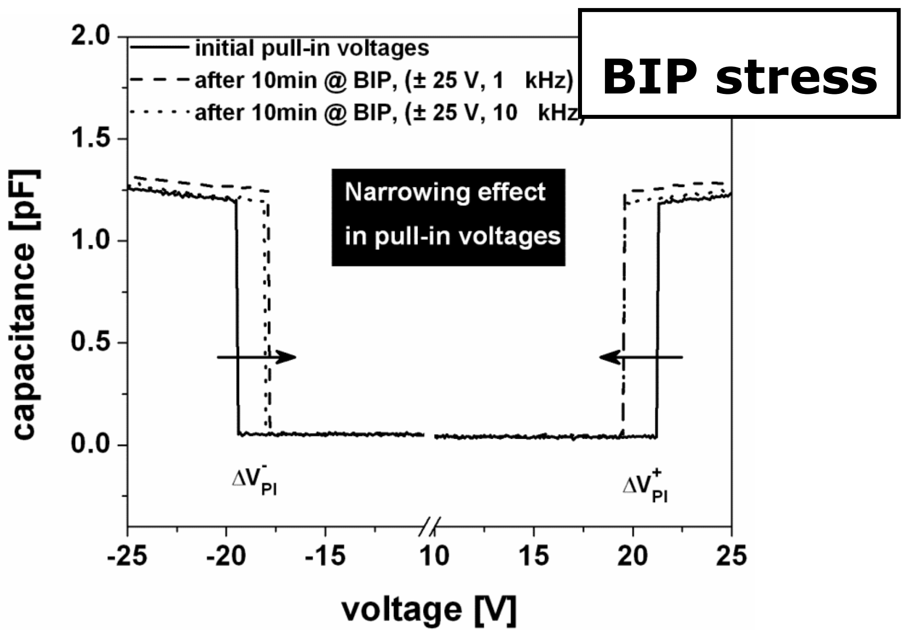


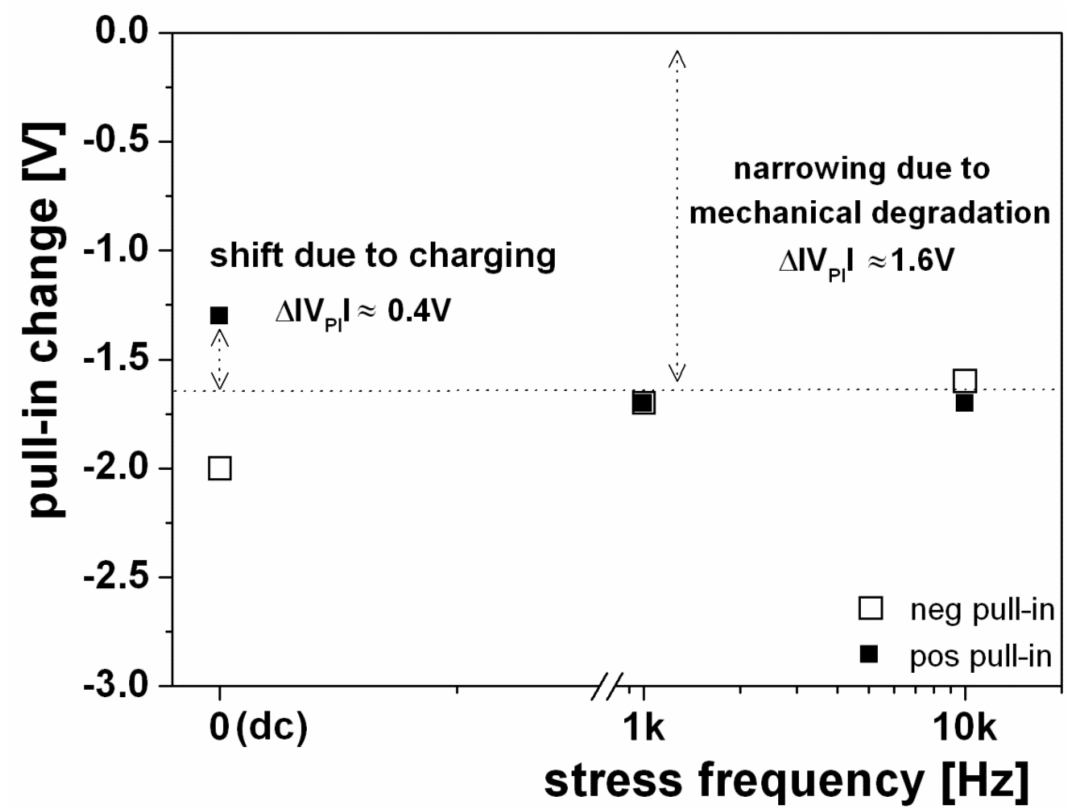




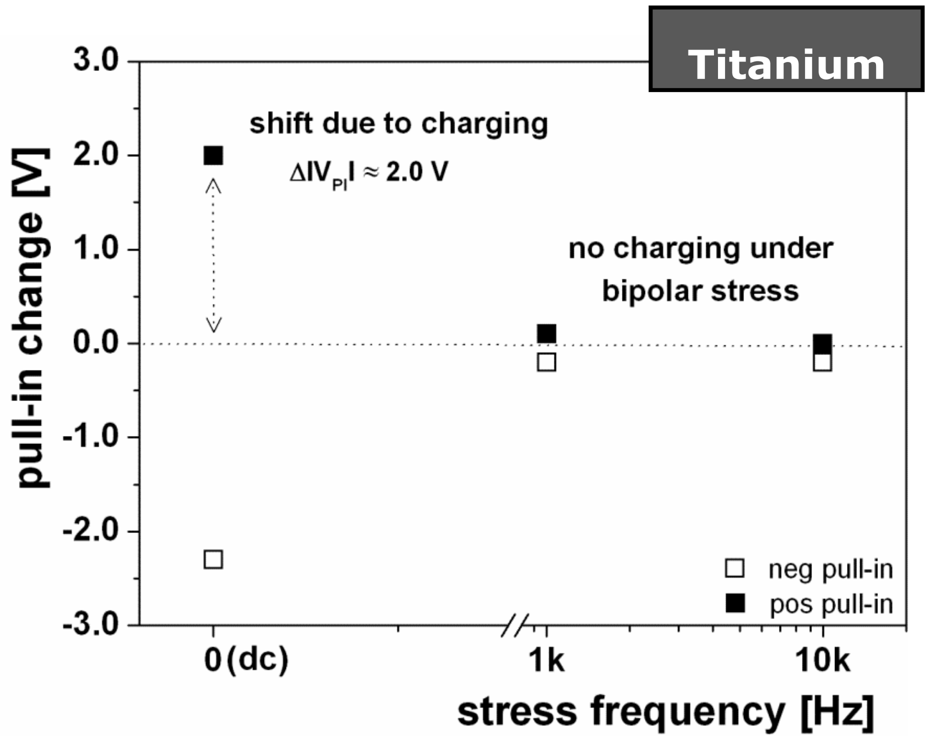
Isolation of degradation mechanisms: results – aluminium switches

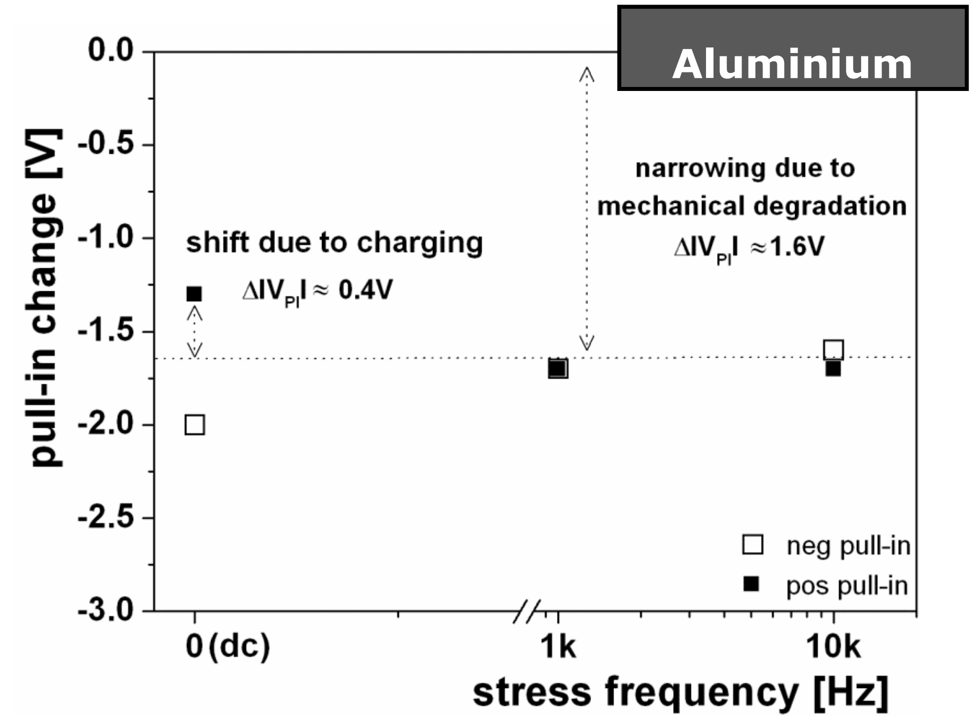






Isolation of degradation mechanisms: Titanium vs Aluminium





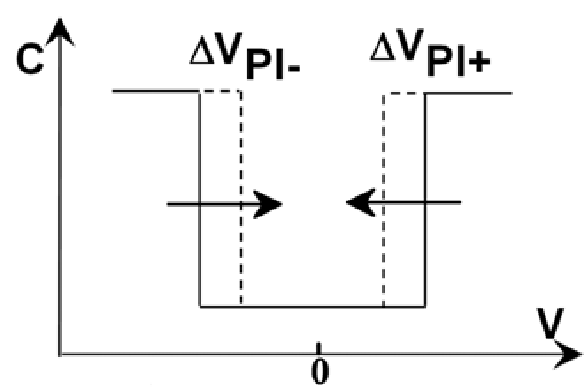
	DC stress @ -25V	BIP stress @ ±20V, 1kHz, 10kHz	Dominating mechanism
Titanium switches	shift	no change	charging
Aluminium switches	narrowing and shift	narrowing	mechanical degradation

Z. Olszewski, R. Houlihan, C. Ryan, C. O'Mahony, and R. Duane, "Experimental isolation of degradation mechanisms in capacitive microelectromechanical switches," *Applied Physics Letters,* vol. 100, pp. 233505-4, 2012.

Mechanical Degradation

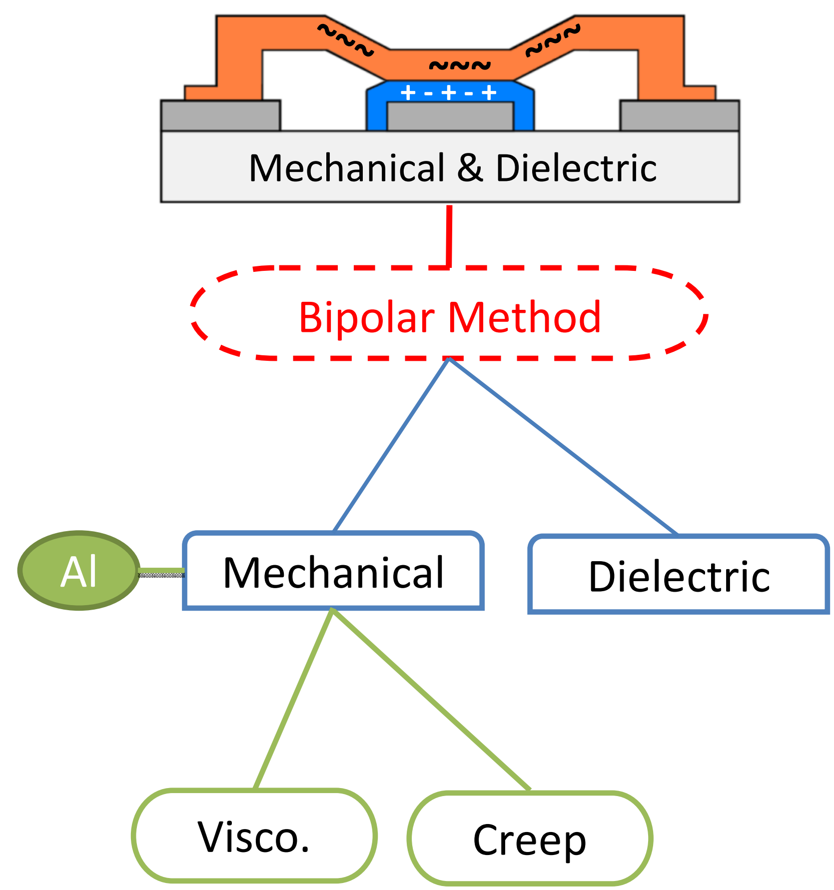
Effect: Change in pull-in voltage
- Spring constant, k
- Air gap, g

$$V_{PI} = \sqrt{\frac{8k}{27\varepsilon_0 A}\left(g + \frac{d}{\varepsilon_d}\right)^3}$$



$$\Delta V_{PI} \propto \sqrt{\Delta k \Delta g^3}$$

Two main forms
- Viscoelasticity
- Creep

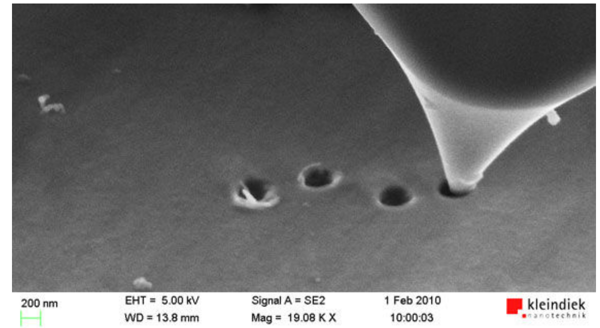


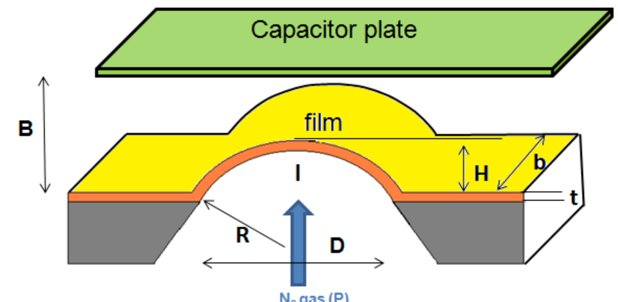
Mechanical Alternatives

- Nanoindentation
- Wafer Curvature
- Bulge Testing
- Microtensile
- Displacement Controlled Tests

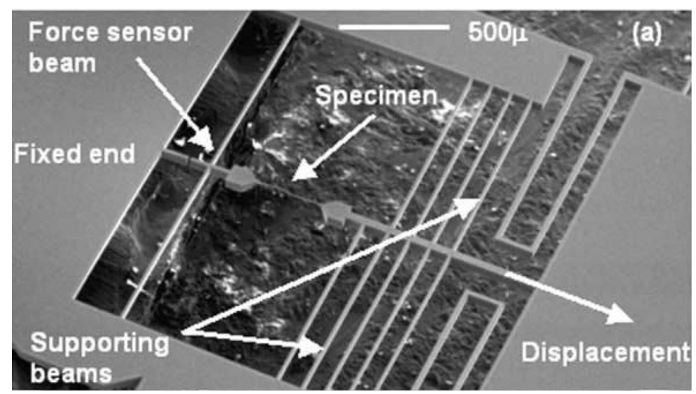
Problems

- Dedicated Equipment
- Dedicated Test Structures
- Destructive Testing
- Relevance to Actual Device





K. Mongkolsuttirat, *PhD Thesis,* Lehigh University, 2013



M. A. Haque et al., Experimental Mechanics **42** (1), 2002

Viscoelasticity

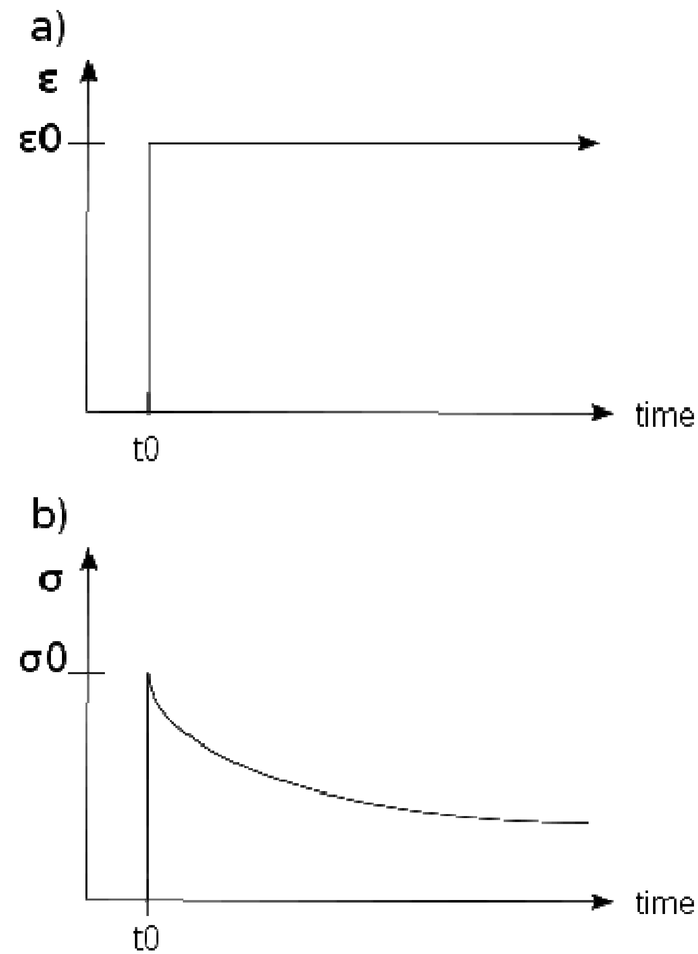
- Time dependent stress relaxation
- Fully recoverable (anelastic)
- Sliding of grain boundaries
- Time-varying Elastic Modulus

$$E(t) = \frac{\sigma(t)}{\varepsilon(t)}$$

- Effective spring constant

$$k_{eff}(t) = \frac{E(t)A}{L}$$

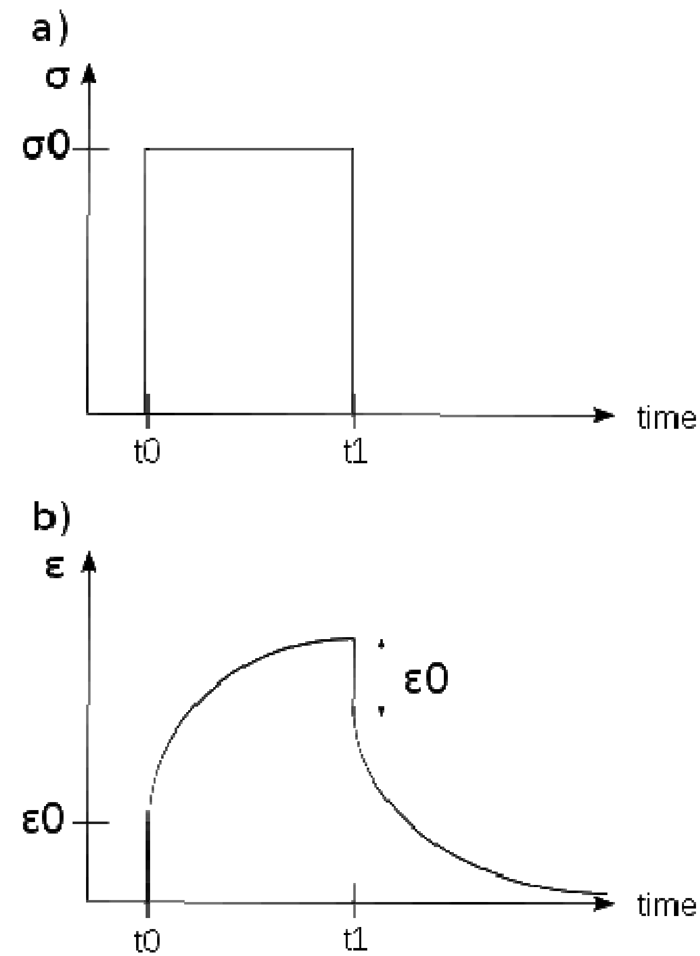
➢ Can be monitored through change in V_{pi}



Creep

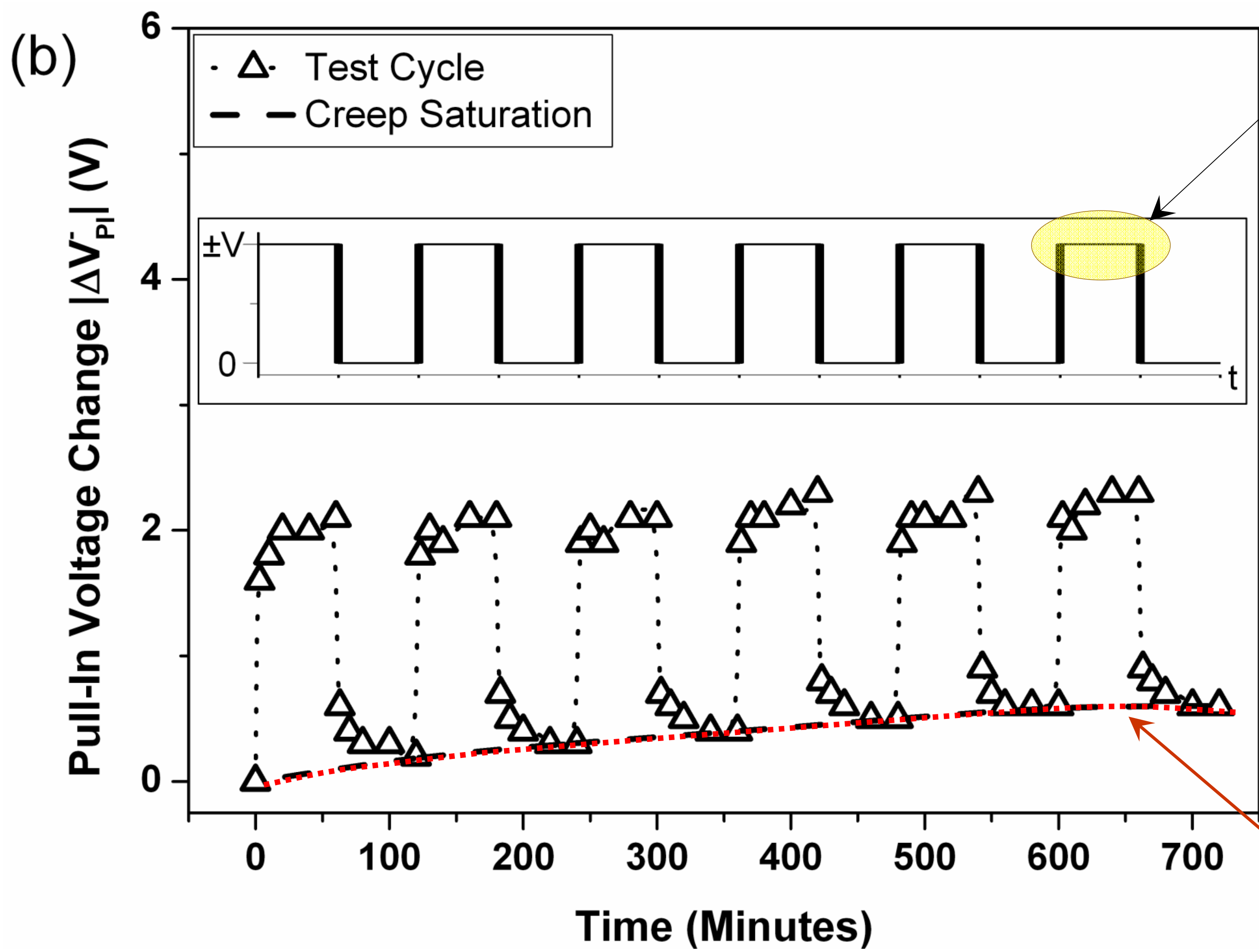
- Permanent change in device properties
- Movement of dislocations
- Increase in strain in response to an applied stress
- Also affects k_{eff}

➢ Can be monitored through change in V_{pi}



Total Mechanical Deformation	=	Creep	+	Viscoelasticity
		(permanent)		(recoverable)

Creep Saturation



Bipolar stress signal (21V)

Accumulated permanent change in ΔV over time due to Creep

C. Ryan, Z. Olszewski, R. Houlihan, C. Mahony, and R. Duane, "A simple electrical test method to isolate viscoelasticity and creep in capacitive microelectromechanical switches," *Applied Physics Letters,* vol. 104, p. 061908, 2014.

Isolation of Viscoelasticity

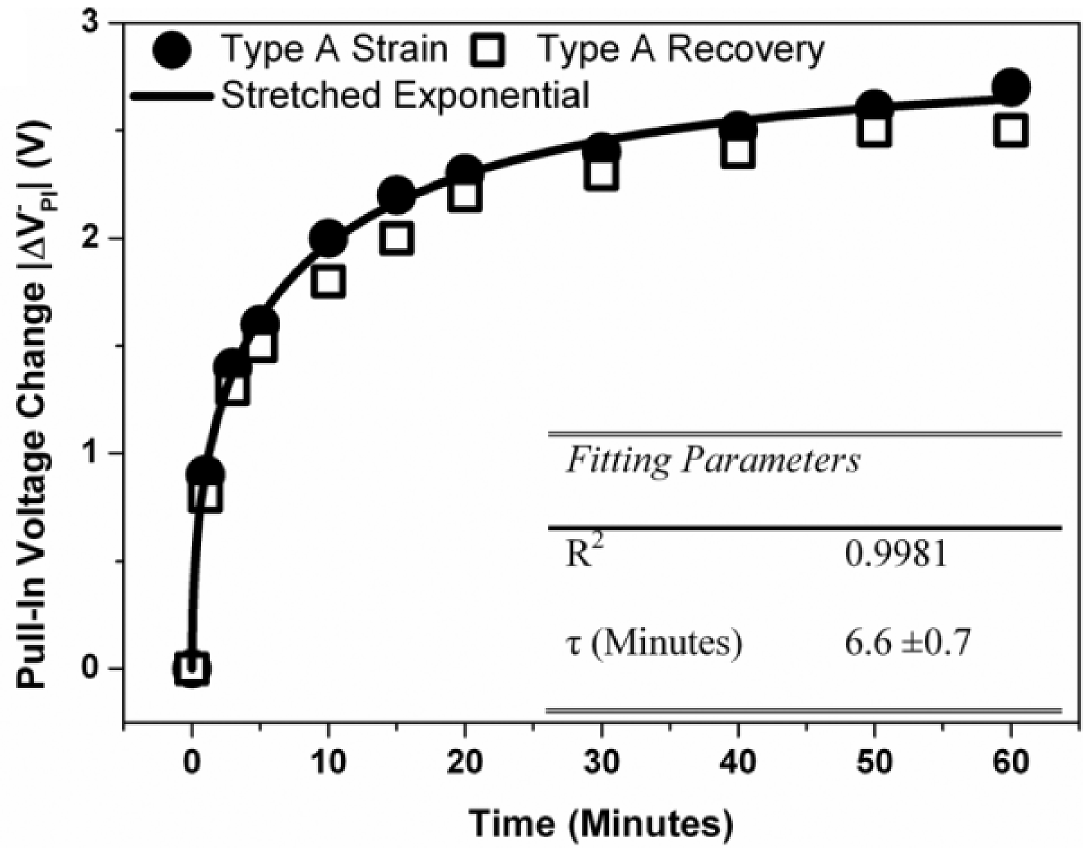
Continue strain & recovery cycling

Kelvin-Voigt Model

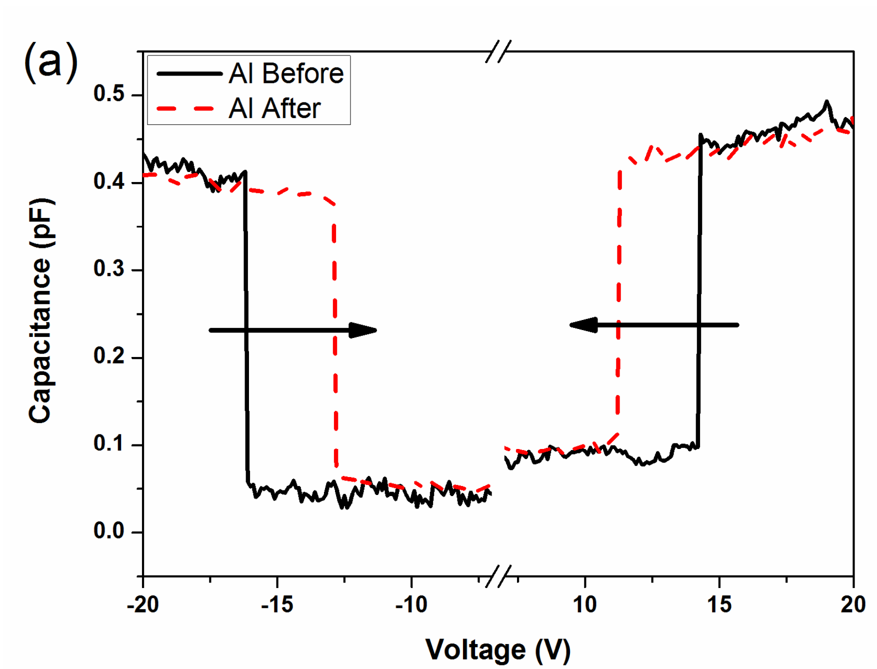
$$V_{PI}(t) = A\left(1-\exp\left(-\frac{t}{\tau}\right)^{\beta}\right)$$

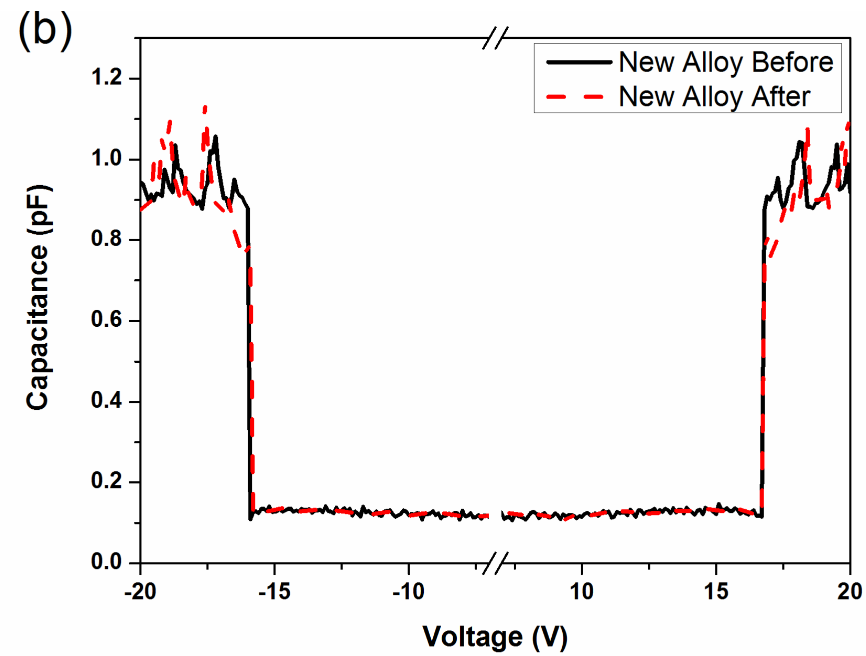
Same time dependence for strain & recovery

➔ Linear Viscoelasticity



Aluminium Alloy





- New metal alloy
- Mechanically robust

➢ Study of charging effects in isolation

Conclusions

- **Introduction to MEMS at Tyndall**
- **Simple electrical test for isolation of charging from mechanical degradation MEMS devices**
- **Simple electrical test for isolation of permanent deformation from recoverable deformation**
- **An aluminium alloy that is mechanically sound**
  - **Test vehicle for investigation of dielectric charging**
- **This work can contribute to establishing standardized reliability tests, charging models, accelerated tests**

Acknowledgments

- This work has been supported by
  - The Irish Research Council for Science, Engineering and Technology (IRCSET)
  - European Space Agency (ESA)
  - Science Foundation Ireland (SFI)