Failure mechanisms and reliability issues of RF-MEMS switches

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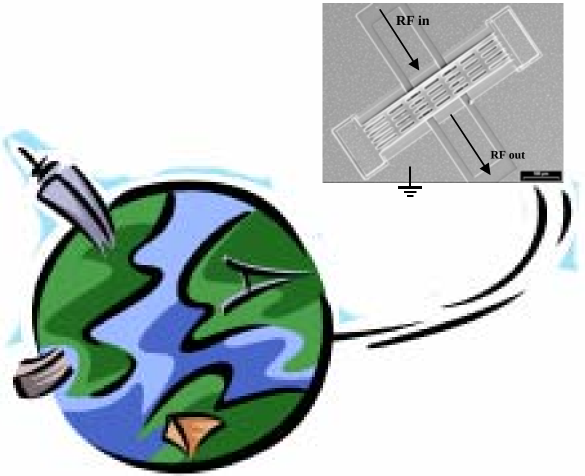


SEEDS FOR
TOMORROW'S
WORLD

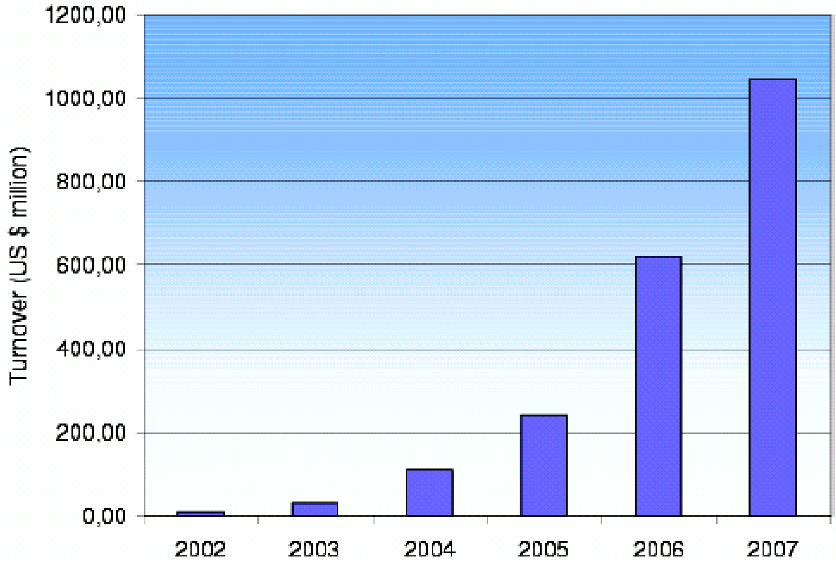
Outline

- Introduction
- FMEA of RF-MEMS switches
- Charging induced stiction
- Packaging effect on switch lifetime
- Conclusions

RF MEMS

Radio Frequency MEMS switches offer:

- **Low weight**
- **Low volume**
- **Lower insertion loss**
- **High isolation**
- **Large frequency range**
- **Extremely high linearity**
- **Low power consumption**
- **Integration possibilities**

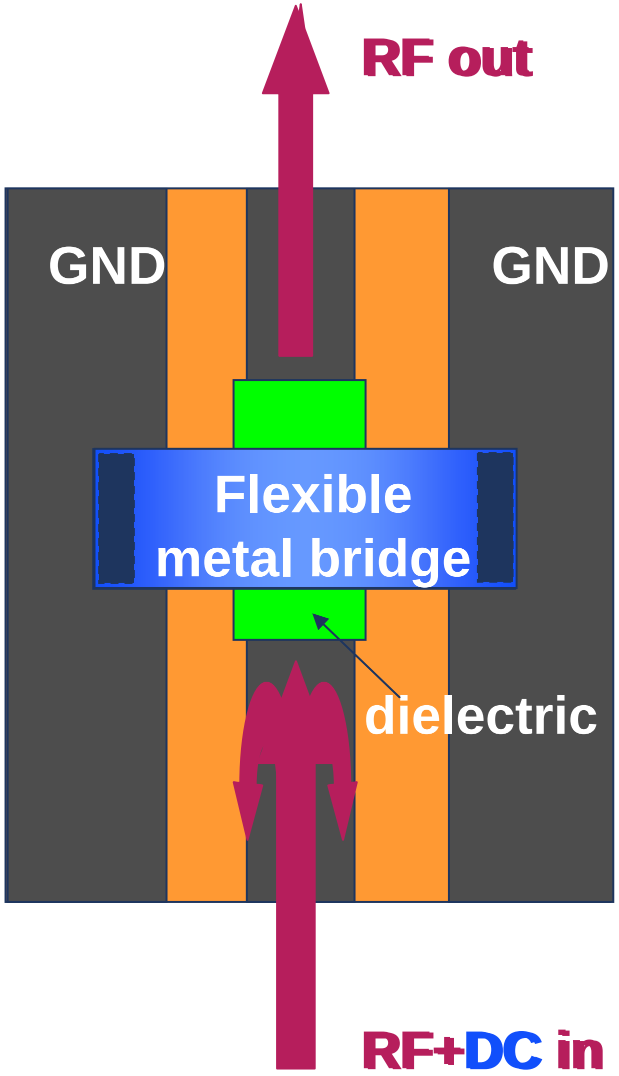


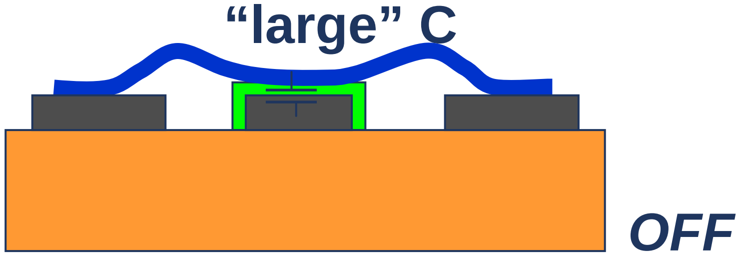
Uses in space:

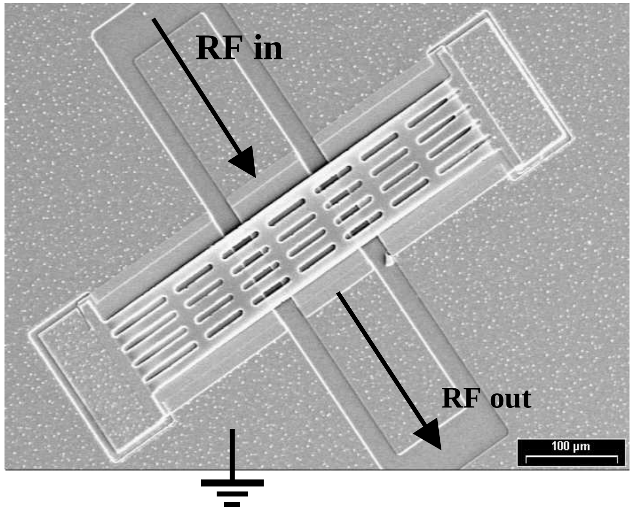
Wireless personal communication, satellite communication, phased array for beam steering, smart antennas ...

BUT: reliability is a problem

RF-MEMS capacitive switch







Radio frequency MEMS

ESA - ENDORFINS: synopsis

Title

Enabling deployment of RF MEMS technology in space telecommunication.

Objective

Perform an in-depth assessment of the reliability and related failure modes of RF-MEMS, in view of their deployment in space and improve this reliability (for switches) through processing optimization.

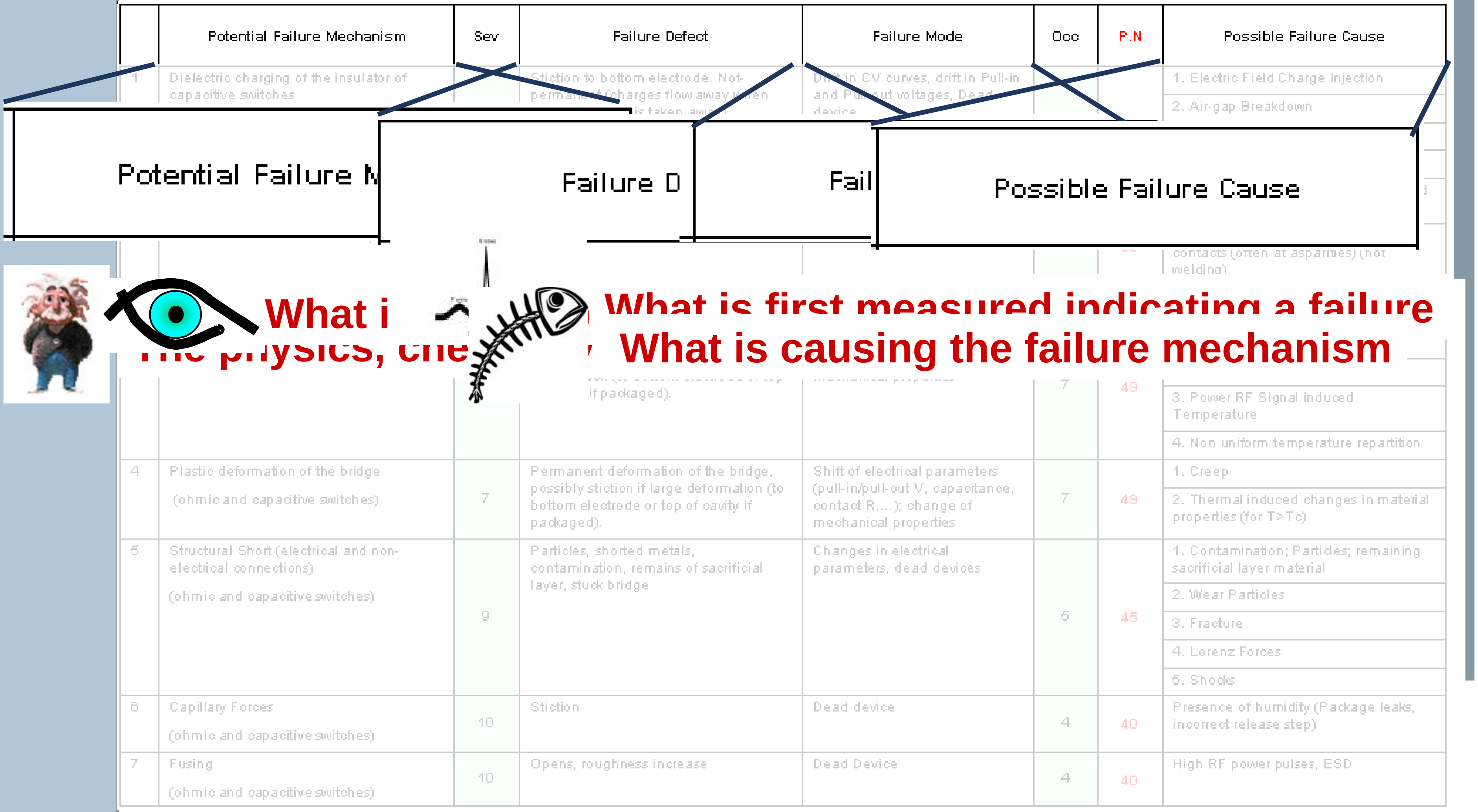
Starting date

Aug 15, 2005

Duration

24 months

FMEA: Failure Mode Effect Analysis



	Potential Failure Mechanism	Sev	Failure Defect	Failure Mode	Occ	P.N	Possible Failure Cause
1	Dielectric charging of the insulator of capacitive switches		Stiction to bottom electrode. Not-permanent (charges flow away when is taken away)	Drift in CV curves, drift in Pull-in and Pull-out voltages, Dead device			1. Electric Field Charge Injection 2. Air-gap Breakdown
							contacts (often at asperities) (not welding)
			if packaged).		7	49	3. Power RF Signal induced Temperature 4. Non uniform temperature repartition
4	Plastic deformation of the bridge (ohmic and capacitive switches)	7	Permanent deformation of the bridge, possibly stiction if large deformation (to bottom electrode or top of cavity if packaged).	Shift of electrical parameters (pull-in/pull-out V, capacitance, contact R,...); change of mechanical properties	7	49	1. Creep 2. Thermal induced changes in material properties (for T>Tc)
5	Structural Short (electrical and non-electrical connections) (ohmic and capacitive switches)	9	Particles, shorted metals, contamination, remains of sacrificial layer, stuck bridge	Changes in electrical parameters, dead devices	5	45	1. Contamination; Particles; remaining sacrificial layer material 2. Wear Particles 3. Fracture 4. Lorenz Forces 5. Shocks
6	Capillary Forces (ohmic and capacitive switches)	10	Stiction	Dead device	4	40	Presence of humidity (Package leaks, incorrect release step)
7	Fusing (ohmic and capacitive switches)	10	Opens, roughness increase	Dead Device	4	40	High RF power pulses, ESD

Potential Failure M

Failure D

Fail

Possible Failure Cause

What i

The physics, che

What is first measured indicating a failure

What is causing the failure mechanism

FMEA: Failure Mode Effect Analysis

	Potential Failure Mechanism	Sev	Failure Defect	Failure Mode	Occ	P.N	Possible Failure Cause
1	Dielectric charging of the insulator of capacitive switches	8	Stiction to bottom electrode. Not-permanent (charges flow away when charging cause is taken away).	Drift in CV curves, drift in Pull-in and Pull-out voltages, Dead device	10	80	1. Electric Field [illegible] 2. A[illegible] breakdown [illegible] electron emission 4. [illegible]iation
2	Micro welding (ohmic switches and capacitive switches with contact metal on dielectric)	9	Stiction	[illegible]	[illegible]	[illegible]3	[illegible] so[illegible] metals coming into contact (cold [illegible]lding) 2. [illegible]igh current through metal-metal contacts (often at asparities) (hot welding) 3. ESD
3	T-induced elastic deformation of the bridge (ohmic and capacitive switches)	7	Non-perma[illegible] bridge (is r[illegible] rem[illegible]ed);[illegible] deform[illegible] of cavity if [illegible]	[illegible]	[illegible]	49	1. Different Thermal Expansion Coefficients (CTE) 2. Environment Temperature 3. Power RF Signal induced Temperature 4. Non uniform temperature repartition
4	[illegible]lastic deformation of the bridge (ohmic and capacitive switches)	[illegible]	P[illegible]anent [illegible] po[illegible]y sti[illegible] bot[illegible] ele[illegible] packa[illegible]).	[illegible]	[illegible]	49	1. Creep 2. Thermal induced changes in material properties (for T>Tc)
5	Structural Short (electrica[illegible]d no[illegible] electrical connection) ([illegible]mic and [illegible] switches)	9	Pa[illegible]icles[illegible] contamina[illegible] layer [illegible]	[illegible]	[illegible]	45	1. Contamination; Particles; remaining sacrificial layer material 2. Wear Particles 3. Fracture 4. Lorenz Forces 5. Shocks
6	Ca[illegible]llary [illegible]rce ([illegible]hmic and capacitive switches)	10	Stiction	[illegible]	[illegible]	40	Presence of humidity (Package leaks, incorrect release step)
7	[illegible]using ([illegible]hmic and capacitive switches)	10	Opens, rou[illegible]	[illegible]	[illegible]	40	High RF power pulses, ESD

Dielectric charging of the i[illegible]sula[illegible] of capacitive swi[illegible]ches

M[illegible]o welding

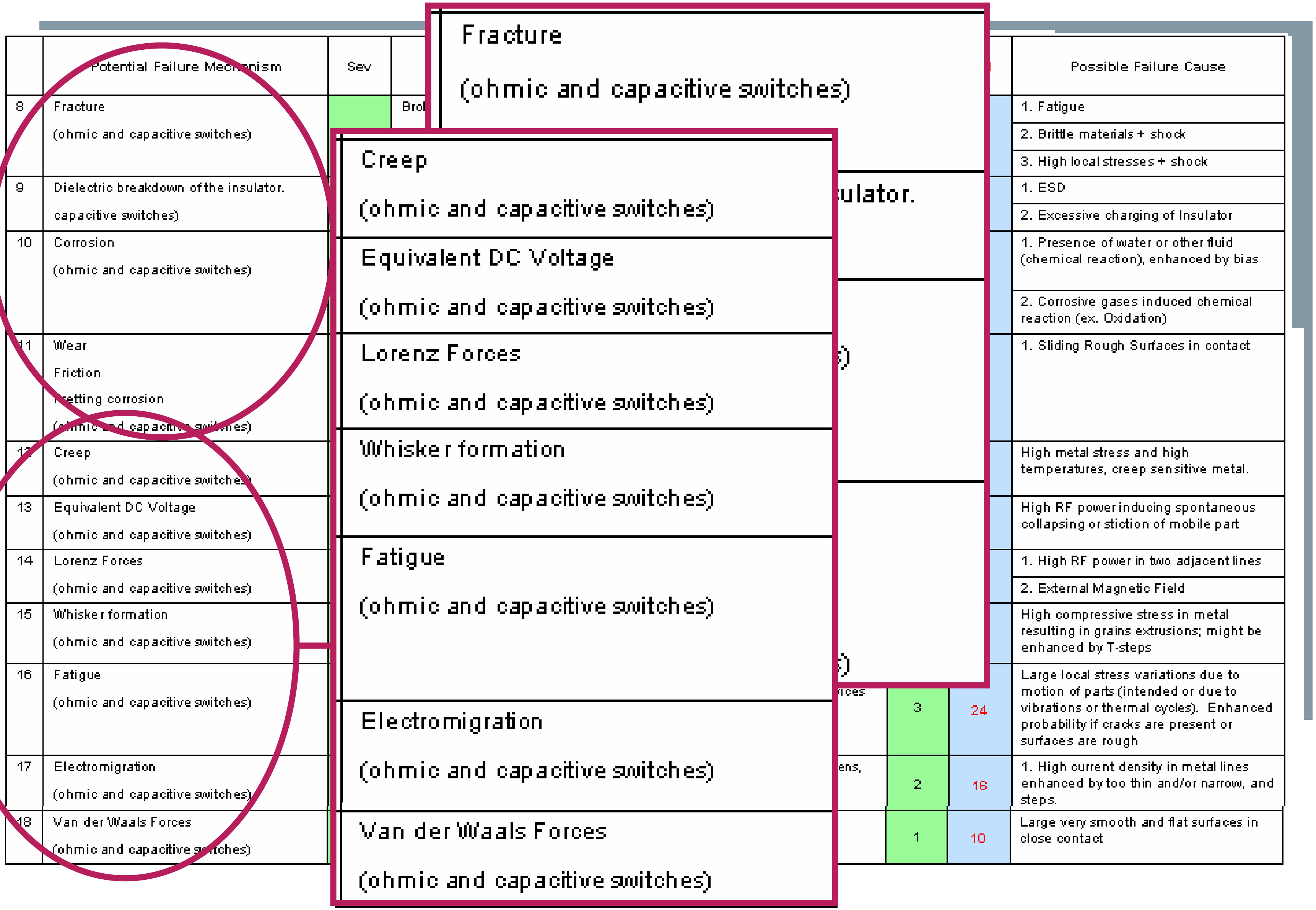
(ohmic switches and capacitive switches with contact metal on dielectric)

T-indu[illegible]tion of the bridge

(ohmic and capacitive switches)

18 different failure mechanisms were identified

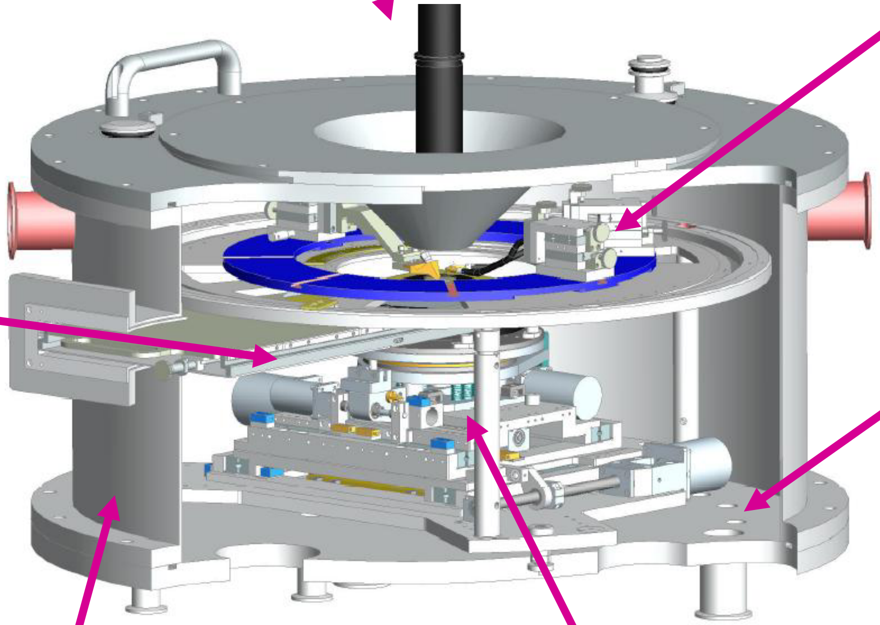
FMEA: Failure Mode Effect Analysis



	Potential Failure Mechanism	Sev				Possible Failure Cause
8	Fracture (ohmic and capacitive switches)		Brol			1. Fatigue 2. Brittle materials + shock 3. High local stresses + shock
9	Dielectric breakdown of the insulator. capacitive switches)					1. ESD 2. Excessive charging of Insulator
10	Corrosion (ohmic and capacitive switches)					1. Presence of water or other fluid (chemical reaction), enhanced by bias 2. Corrosive gases induced chemical reaction (ex. Oxidation)
11	Wear Friction Fretting corrosion (ohmic and capacitive switches)					1. Sliding Rough Surfaces in contact
12	Creep (ohmic and capacitive switches)					High metal stress and high temperatures, creep sensitive metal.
13	Equivalent DC Voltage (ohmic and capacitive switches)					High RF power inducing spontaneous collapsing or stiction of mobile part
14	Lorenz Forces (ohmic and capacitive switches)					1. High RF power in two adjacent lines 2. External Magnetic Field
15	Whisker formation (ohmic and capacitive switches)					High compressive stress in metal resulting in grains extrusions; might be enhanced by T-steps
16	Fatigue (ohmic and capacitive switches)		ices	3	24	Large local stress variations due to motion of parts (intended or due to vibrations or thermal cycles). Enhanced probability if cracks are present or surfaces are rough
17	Electromigration (ohmic and capacitive switches)		ens,	2	16	1. High current density in metal lines enhanced by too thin and/or narrow, and steps.
18	Van der Waals Forces (ohmic and capacitive switches)			1	10	Large very smooth and flat surfaces in close contact

Fracture
(ohmic and capacitive switches)
ulator.
Creep
(ohmic and capacitive switches)
Equivalent DC Voltage
(ohmic and capacitive switches)
Lorenz Forces
(ohmic and capacitive switches)
Whisker formation
(ohmic and capacitive switches)
Fatigue
(ohmic and capacitive switches)
Electromigration
(ohmic and capacitive switches)
Van der Waals Forces
(ohmic and capacitive switches)

Lifetime tests in dedicated chamber



XYZ-microscope stage
12x zoom

Vacuum resistant
RF and DC probes

Thermo-chuck
-10 to +150 °C

Gases inlet

Wafer load slot
Up to 200 mm
wafers

Pressure control
(down to 10^{-6} mbar)

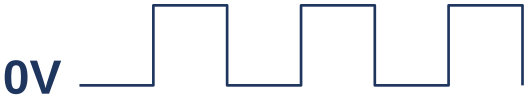
X-Y-Z- Θ Chuck stage
(150, 150,15 mm, ± 7°
travel range)

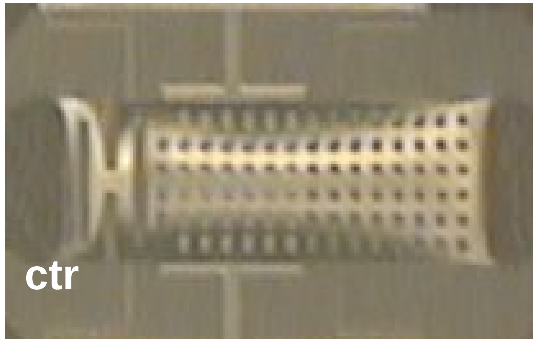
Charging induced stiction

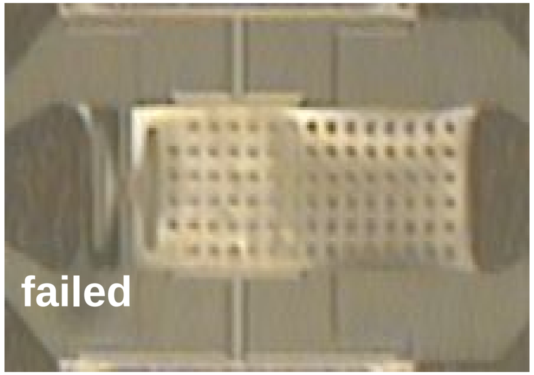
Lifetime test @ 100 Hz

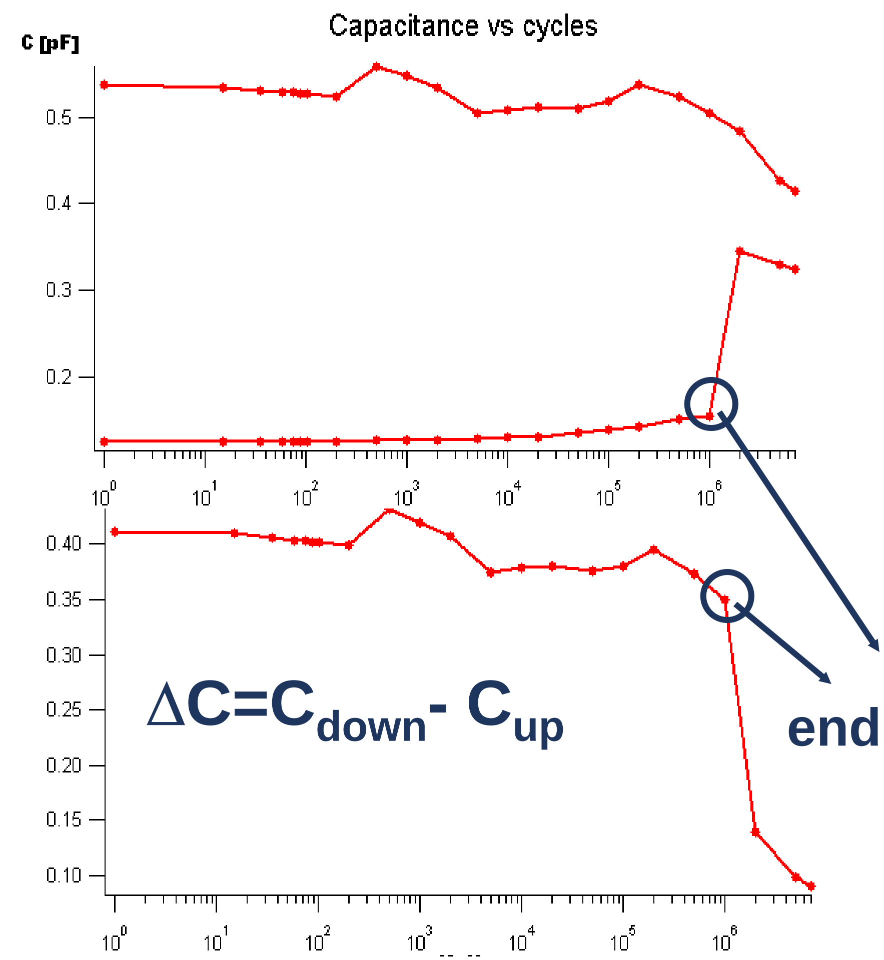
V_{act} = 25 V, unipolar actuation

N_2 environment







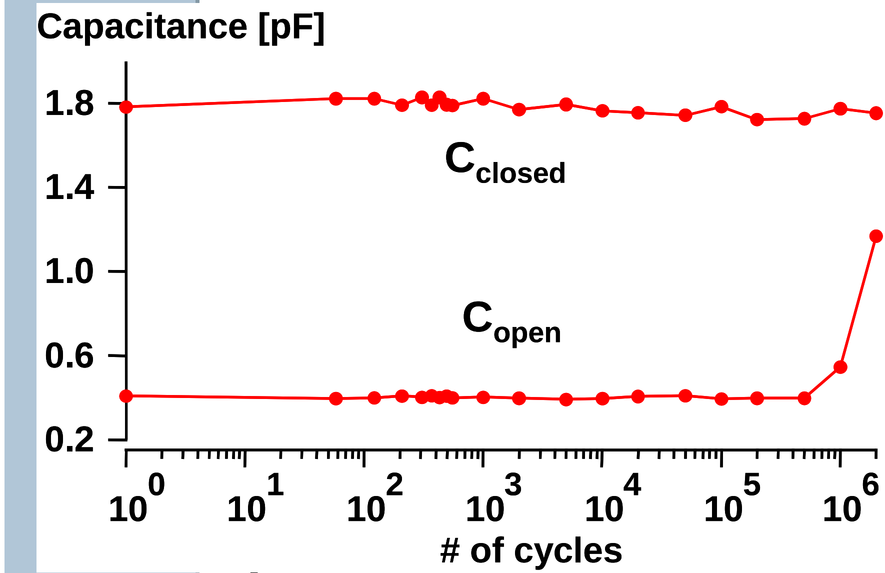


$\Delta C = C_{down} - C_{up}$

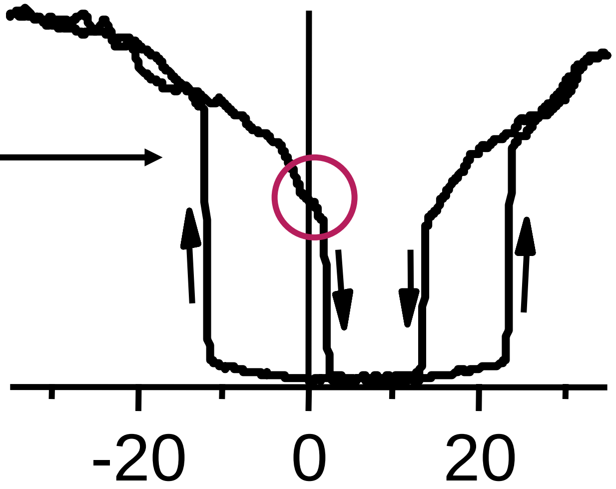
end of life (EOL)

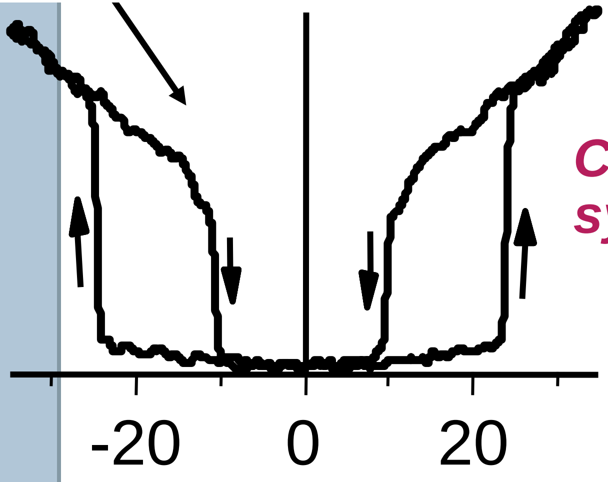
Failure due to charging induced stiction

Fast C-V



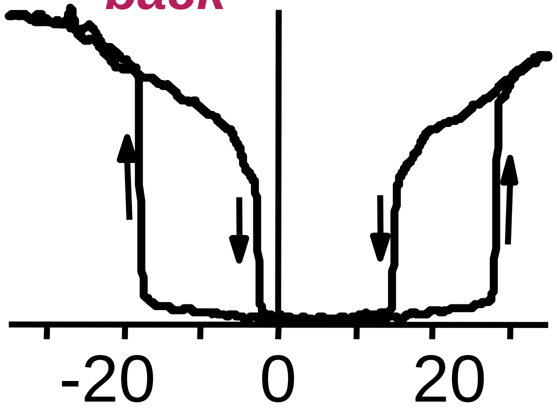
Failed: curve shifts to right.





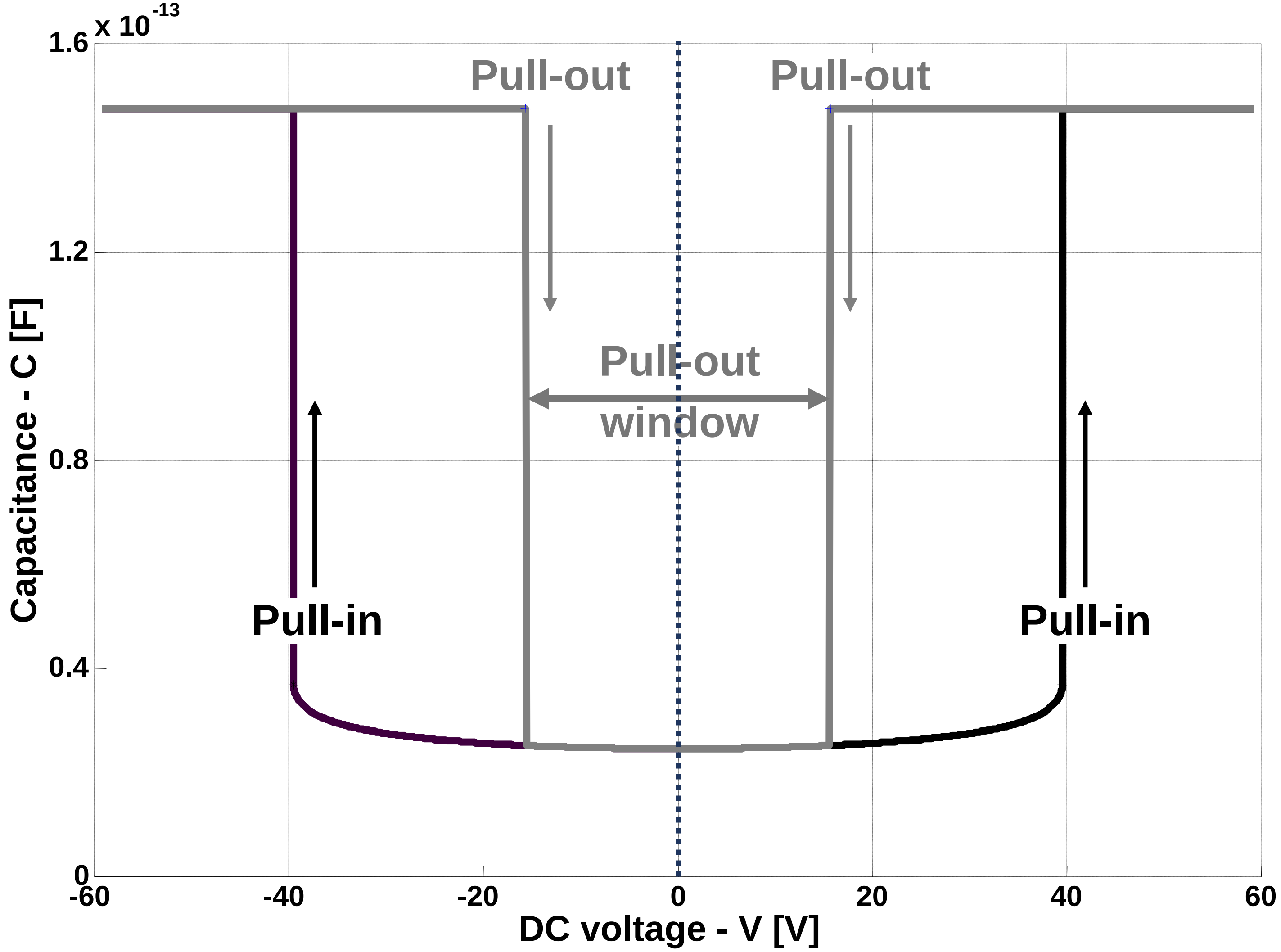
Control:
symmetric curve

19 hours later:
curve shifted partly back



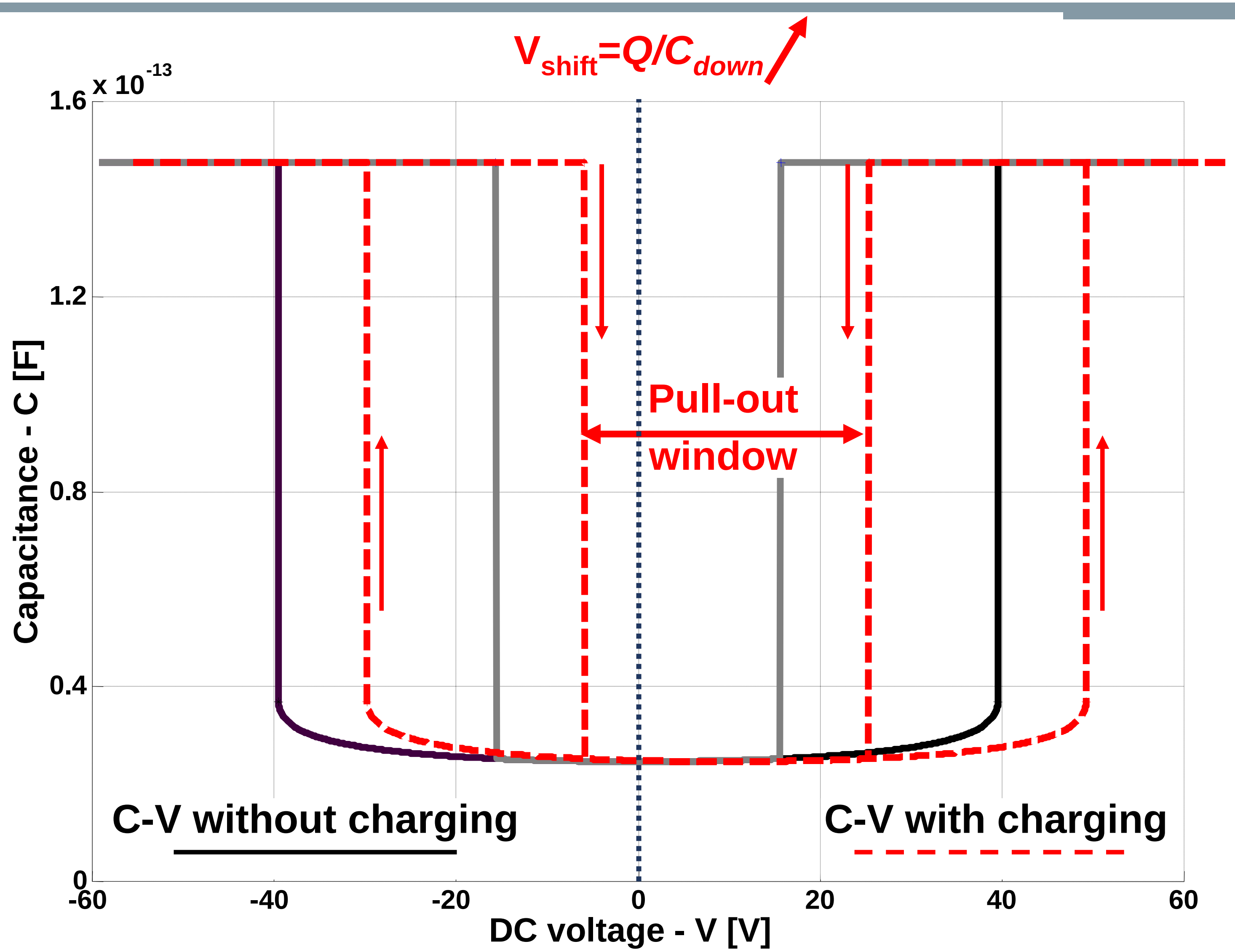
van Spengen et al, IRPS 2005, P. Czarnecki et al., MEMSWAVE 2005

C/V characteristic shift without surface charge



X. Rottenberg et al, 34th EuMW conf., 2004

C/V characteristic shift due to a positive surface charge



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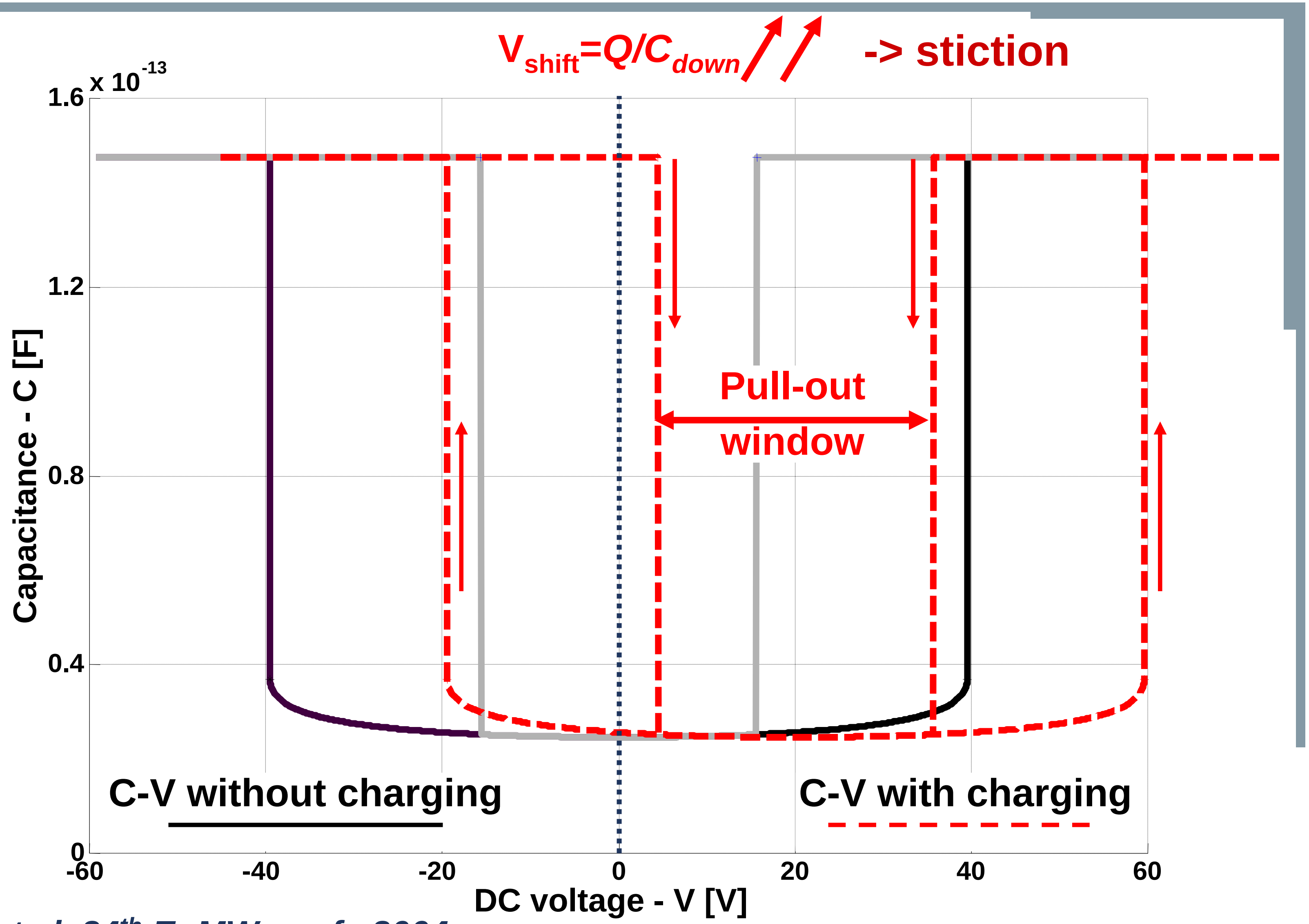
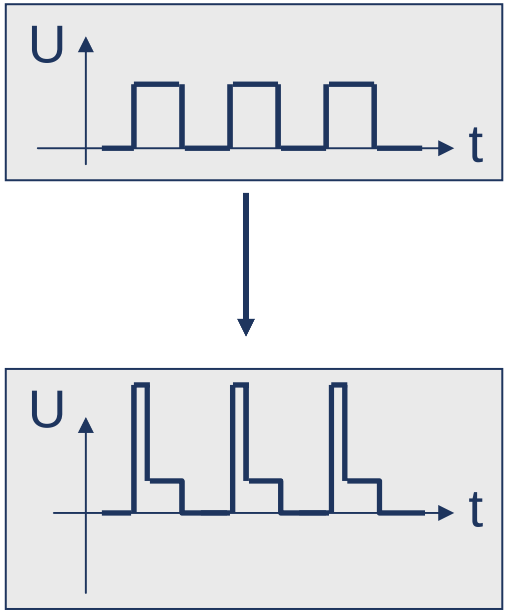
C/V characteristic shift due to a positive surface charge



X. Rottenberg et al, 34th EuMW conf., 2004,

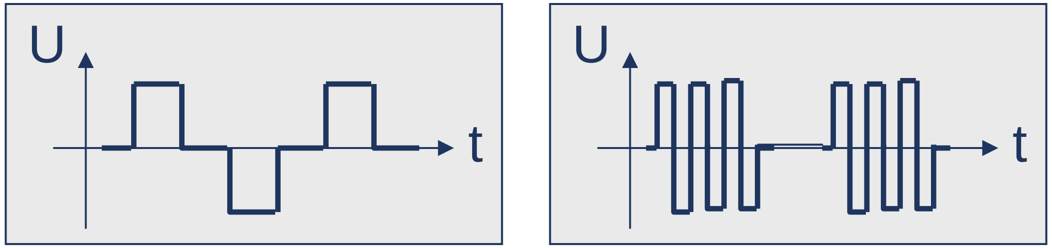
van Spengen et al., J. of Micromech. Microeng. 14, 2004

Solution: Alternative actuation



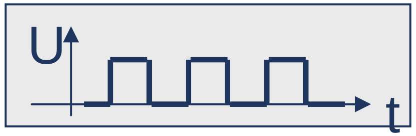
Reduced V across dielectric

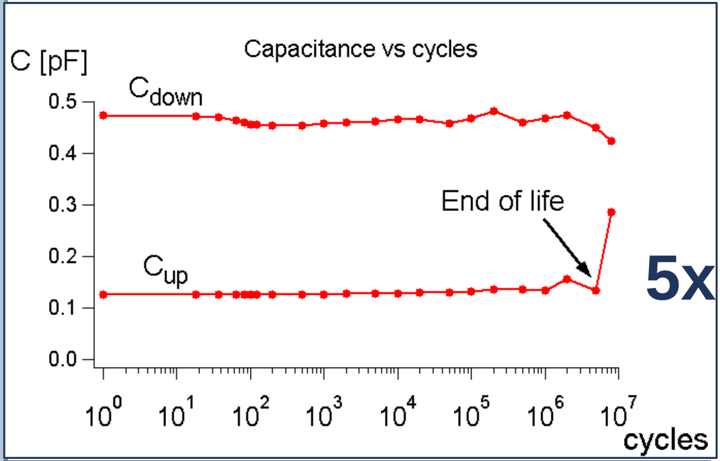
Bipolar



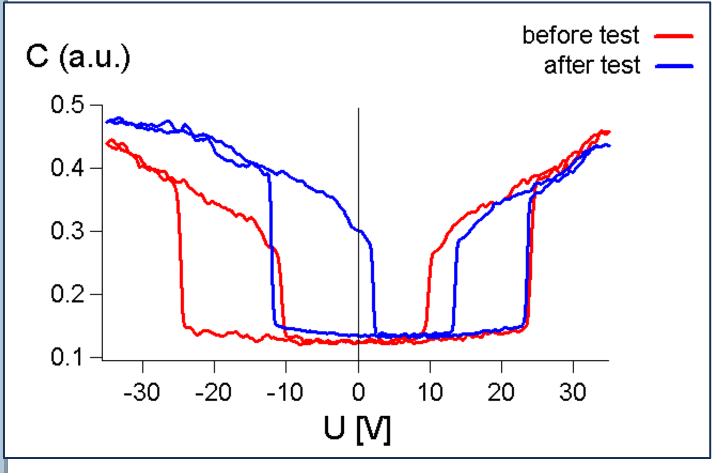
Unipolar vs bipolar

Unipolar actuation
35V, 100Hz

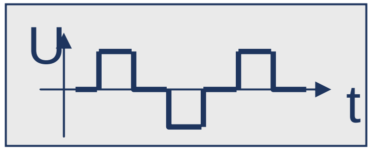


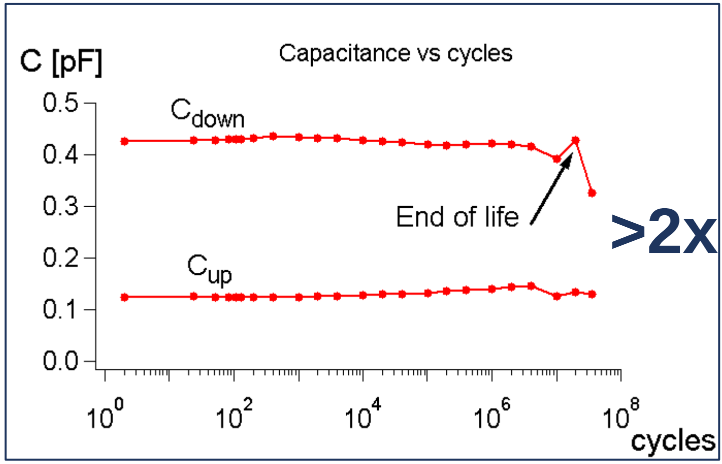


5×10^6

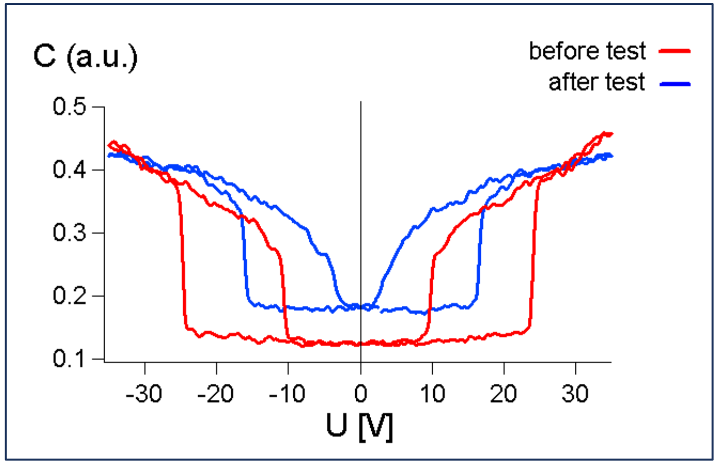


Bipolar actuation
35V, 100Hz





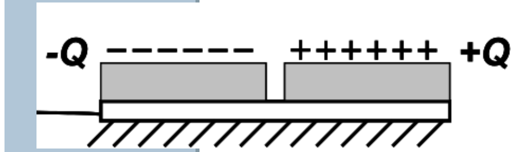
$>2 \times 10^7$

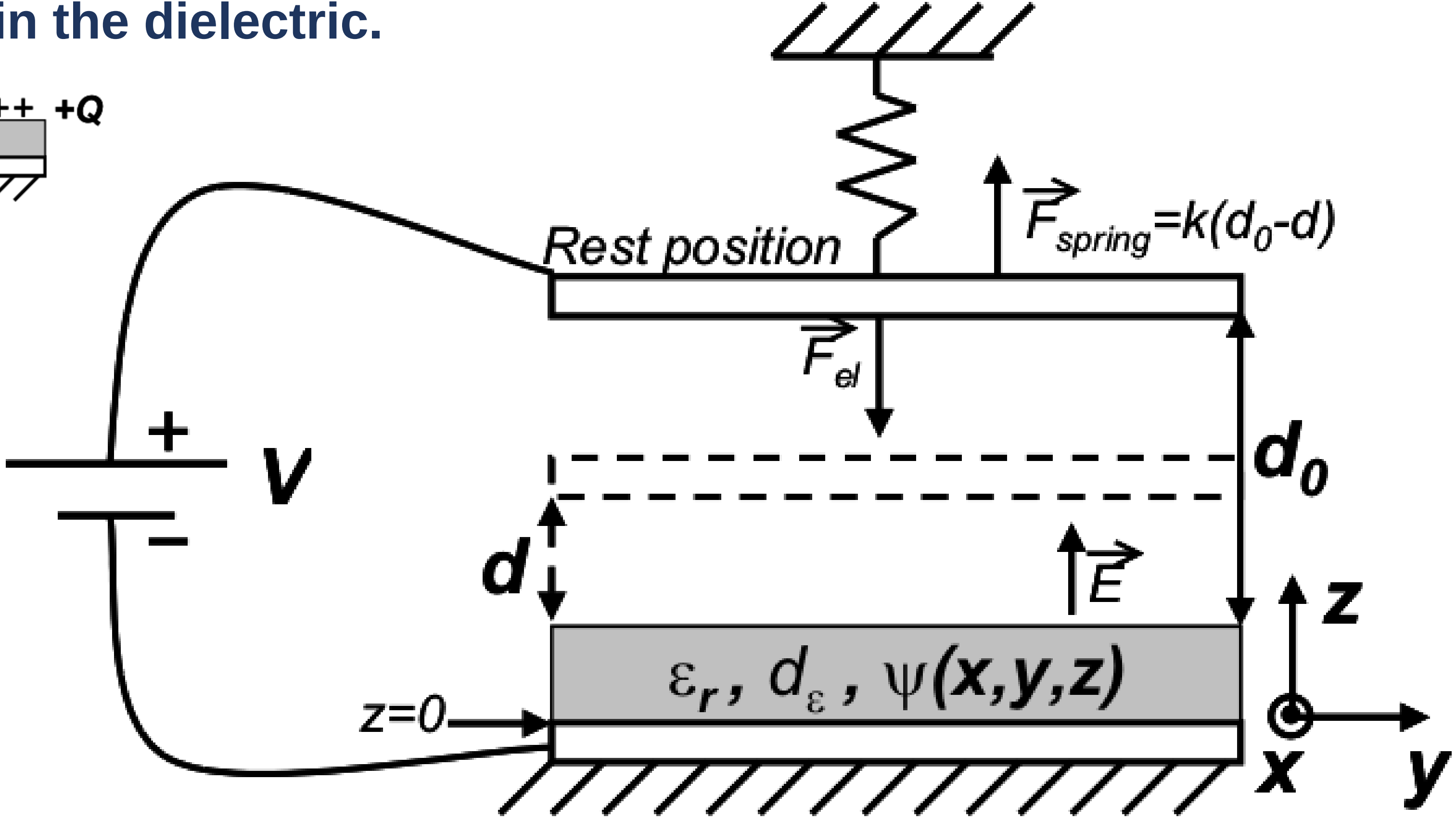


3D problem description

X. Rottenberg et al, 34th EuMW conf., 2004

The total charge (Q) can be zero, but there might be a charge distribution in the dielectric.





Assume a volume charge density $\Psi(x,y,z)$ in the dielectric.

-> **Equivalent charge distribution $\Psi_{eq}(x,y)$ (2D+ problem)**

2D+ problem description

$$F_{el}(d) = \frac{C_1(d)\ C_2^2}{2d\left(C_1(d)+C_2\right)^2}\left\{\underline{\left(V - Q_{eq}/C_2\right)}^{\,2} + \underline{\frac{Area^2}{C_2^2}\sigma^2(\psi_{eq})}\right\}$$

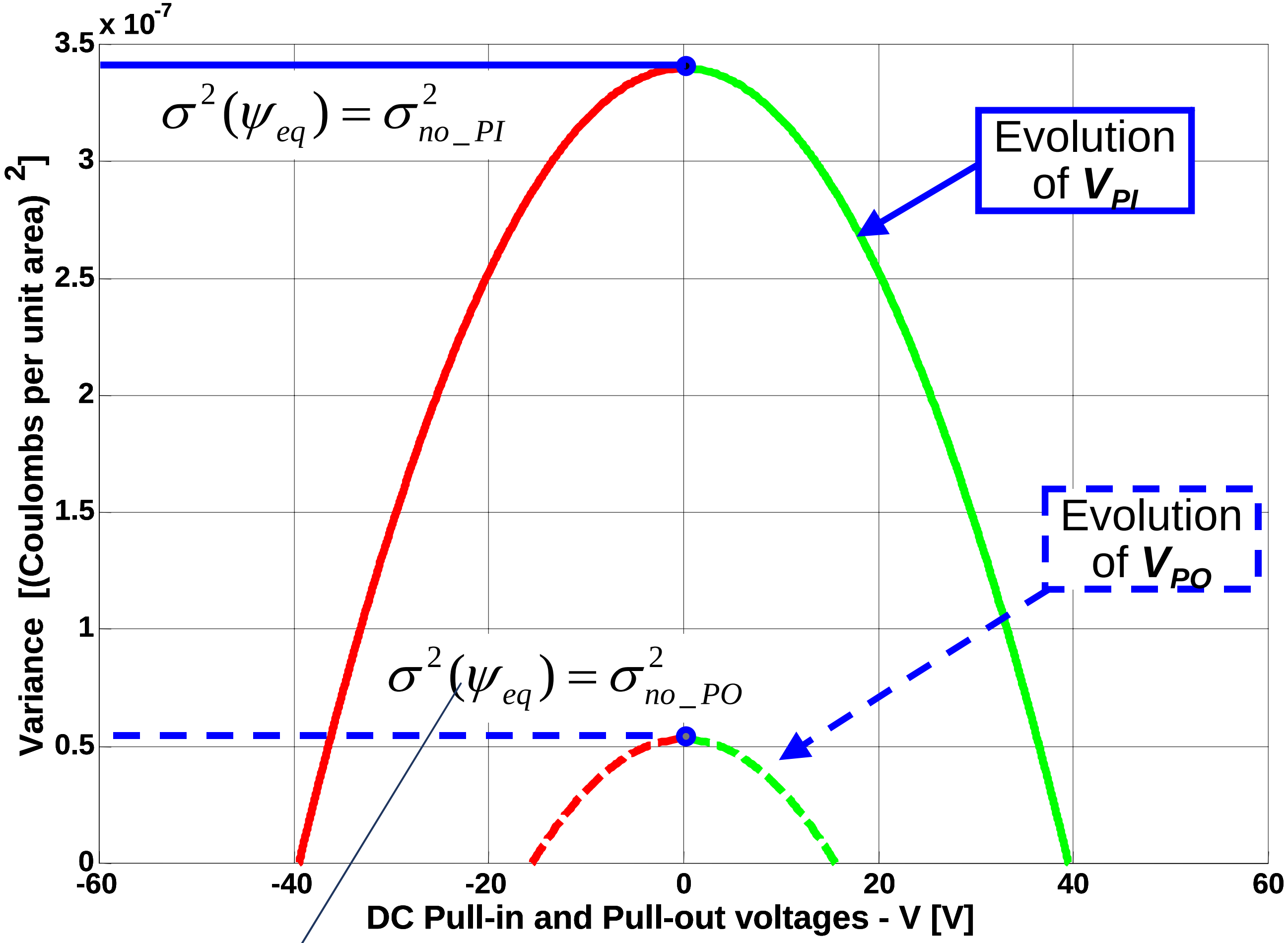
Q_{eq} = total equivalent charge = *Area* x mean of $\psi_{eq}(x,y)$

$\sigma^2(\psi_{eq})$ = variance of the equivalent charge distribution $\psi_{eq}(x,y)$

$\underline{Q_{eq}}$ realizes a voltage offset (x-shift in the F_{el} vs. V curve)

$\underline{\sigma^2(\psi_{eq})}$ realizes a force offset (y-shift in the F_{el} vs. V curve)

Evolution of Pull-in and Pull-out



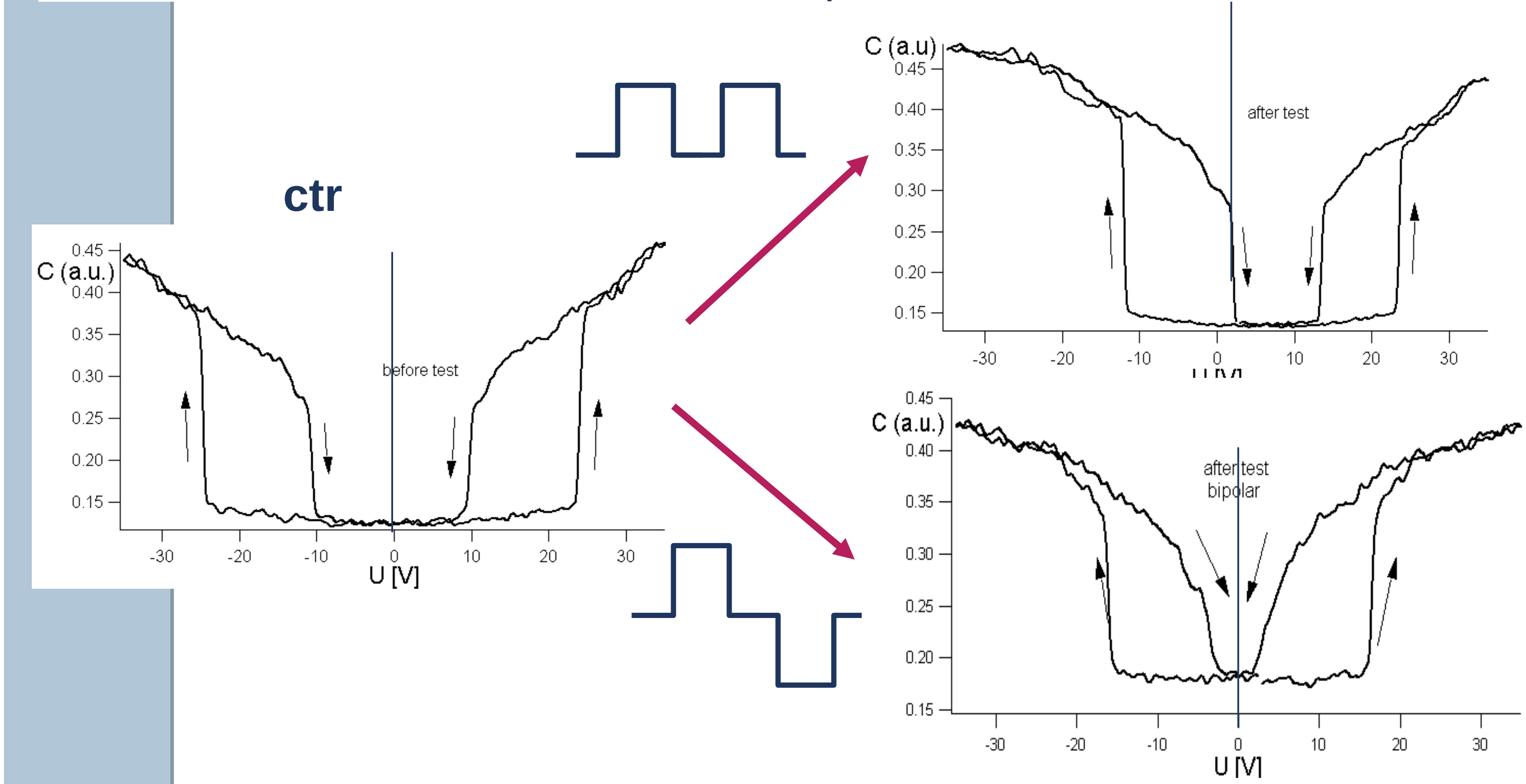
$$\sigma^2(\psi_{eq}) \geq \frac{2kd_0\varepsilon_0}{Area} = \frac{2k\varepsilon_0^2}{C_1(d = d_0)} = \sigma^2_{no\_PO}$$

Increasing k, d_0 and decreasing the Area decrease the sensitivity to the equivalent charge distribution

Charging induced stiction

Theory - Experiment

Unipolar actuation: $Q \neq 0$ -> shift of the C-V curves
Bipolar actuation: $Q = 0$ but $\sigma^2(\Psi_{eq}) \neq 0$ -> narrowing of Vpo and Vpi

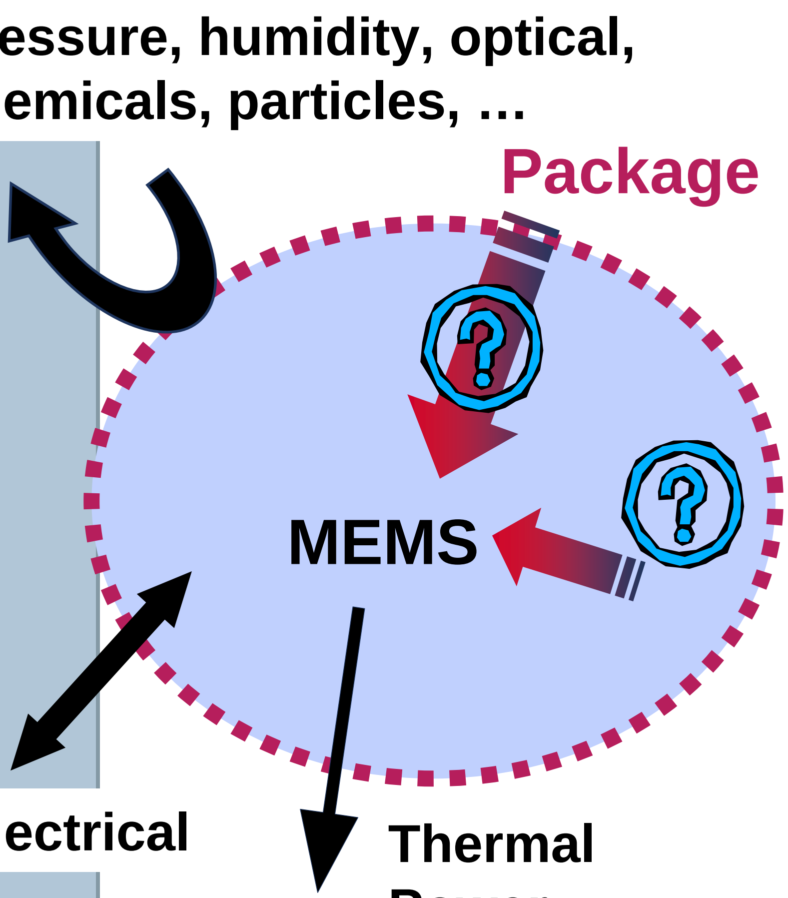


ctr

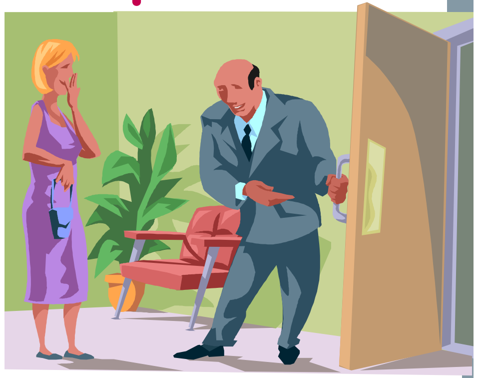
failed

X. Rottenberg et al, 34th EuMW conf., 2004, P. Czarnecki et al., submitted for MEMSWAVE 2005

MEMS package



Function: "Gate keeper"



- keep bad things out (particles, humidity, gasses,…)

-keep good things in (pressure, getters, …)

-throw excess things out (heath,…)

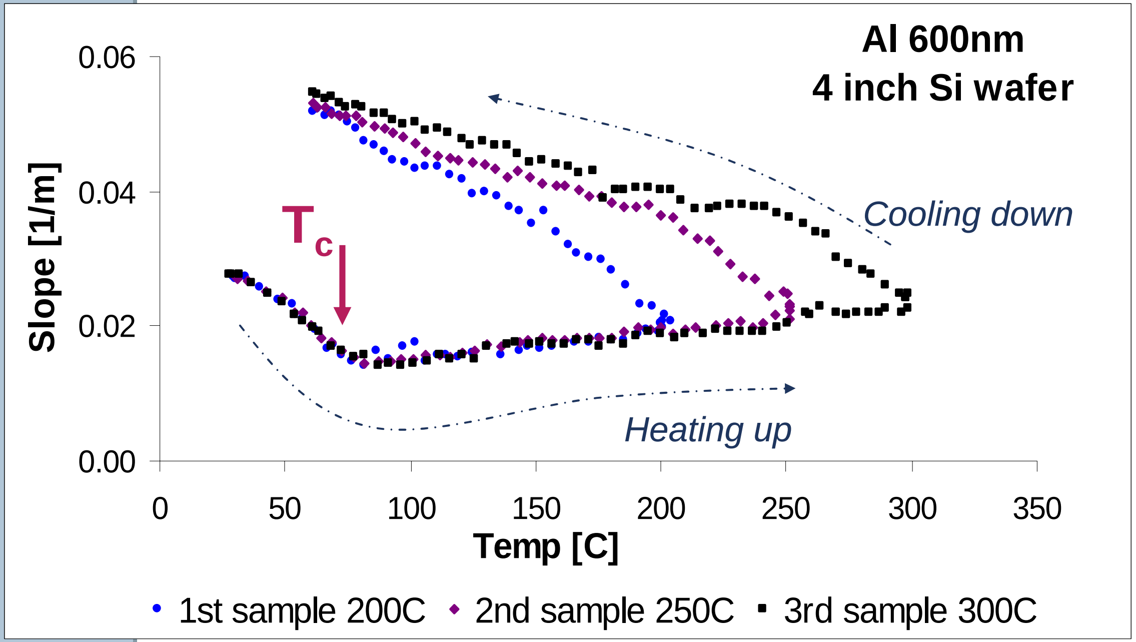
- allow easy in-out to VIPS (electrical, to-sense stuff,…)

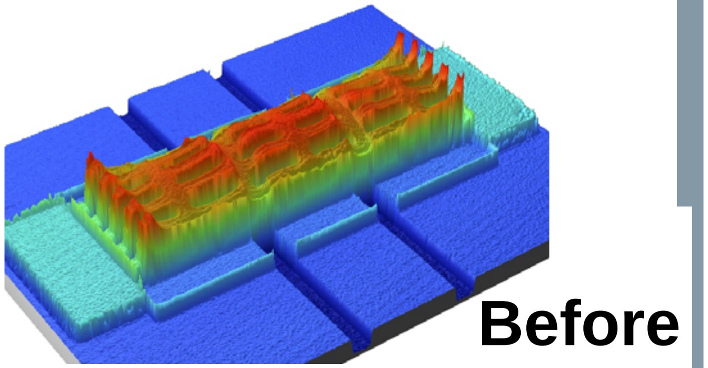
- give mechanical support

- be reliable

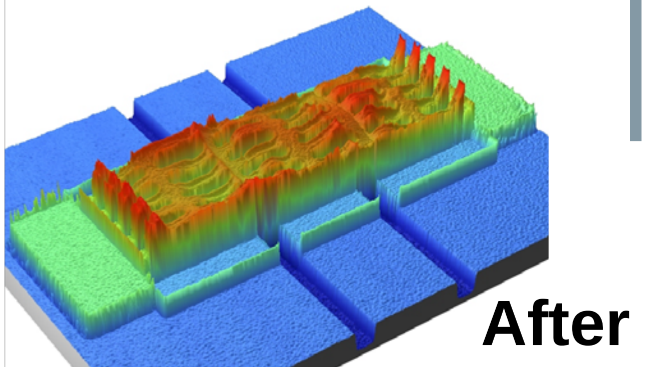
Deformation: T-effects

Some metals (ex. Al-alloys) change ‘stress’ when heated above T = T_c:





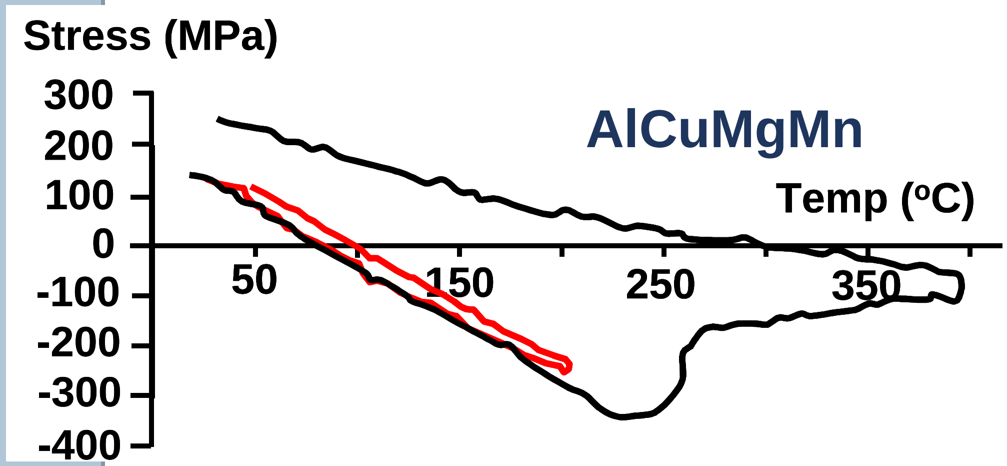
250 °C during
10 minutes

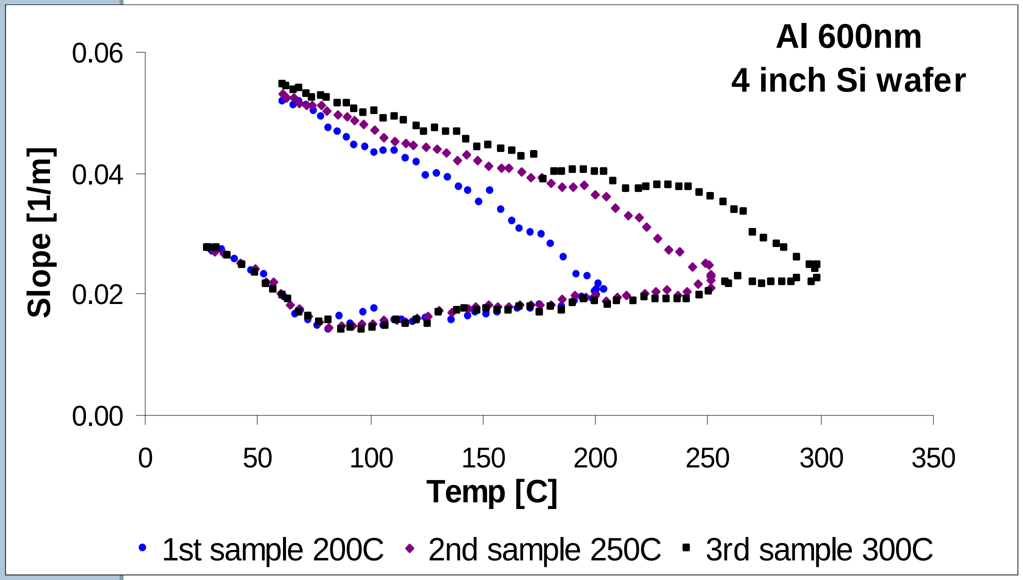


Temperature:
- during functioning
- during packaging

Deformation: T-effects

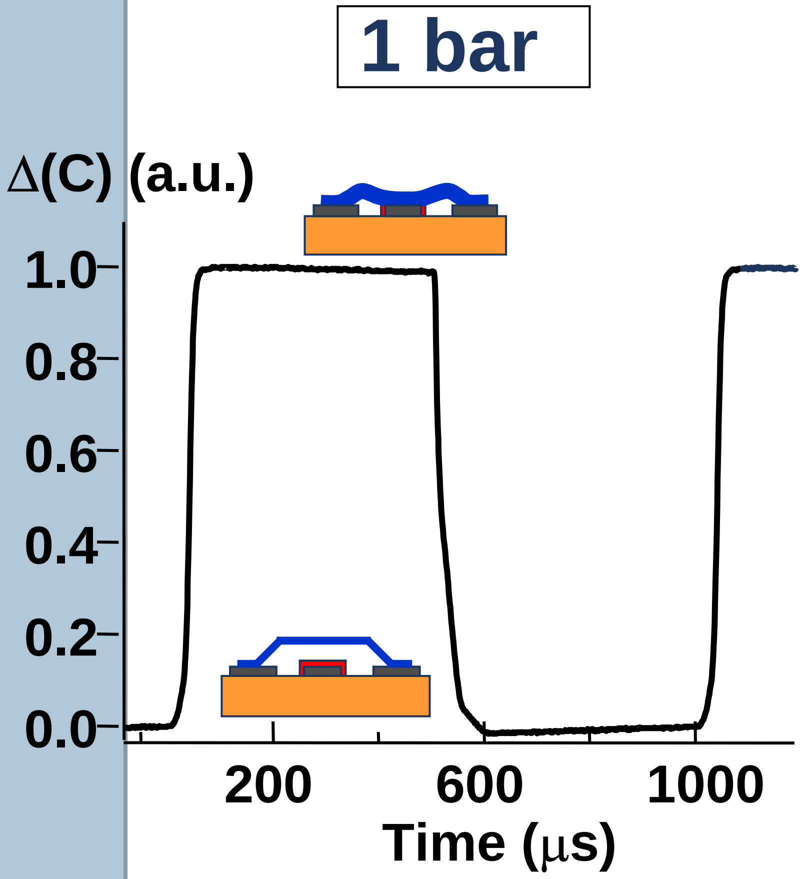
T_c is alloy dependent: T_c AlCuMgMn > T_c Al

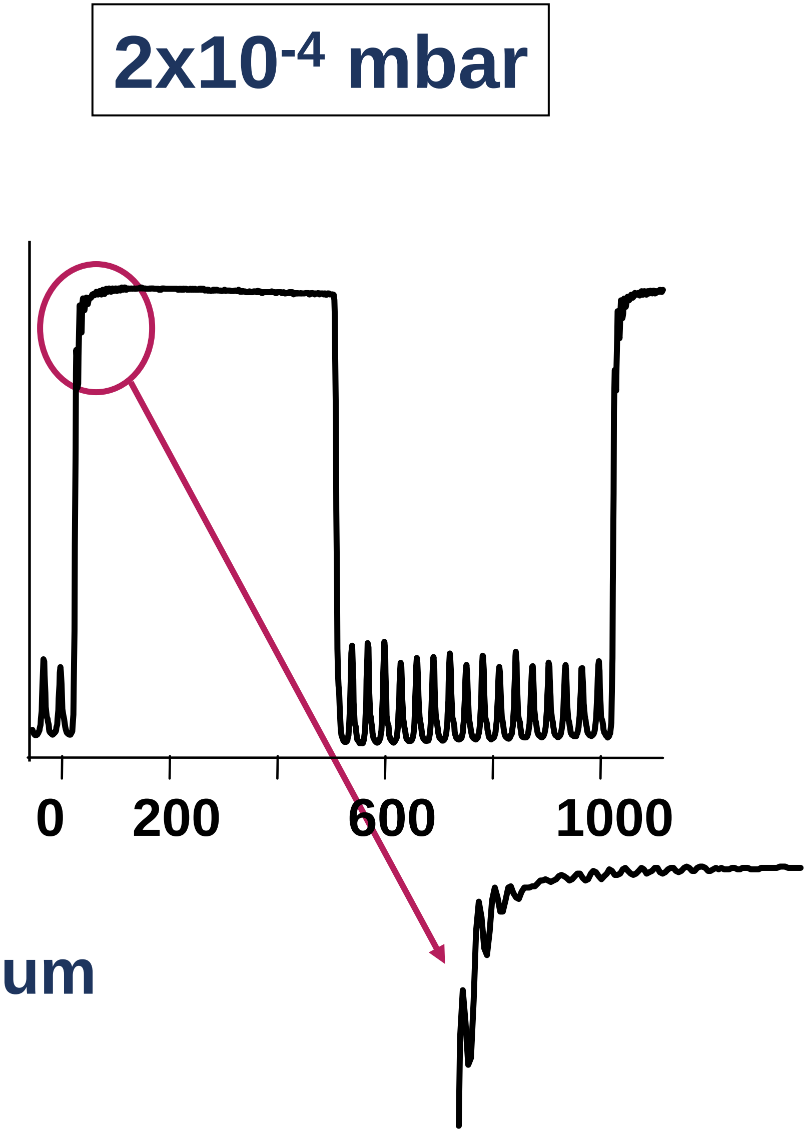




- Use metal with high Tc
- Or do a pre-anneal (but different stress)
- Optimize design to minimize the impact of stress changes on the shape of the bridge.

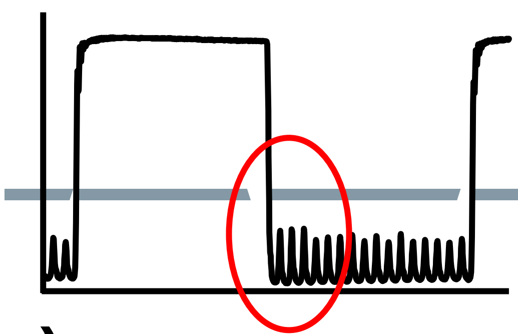
Pressure in cavity

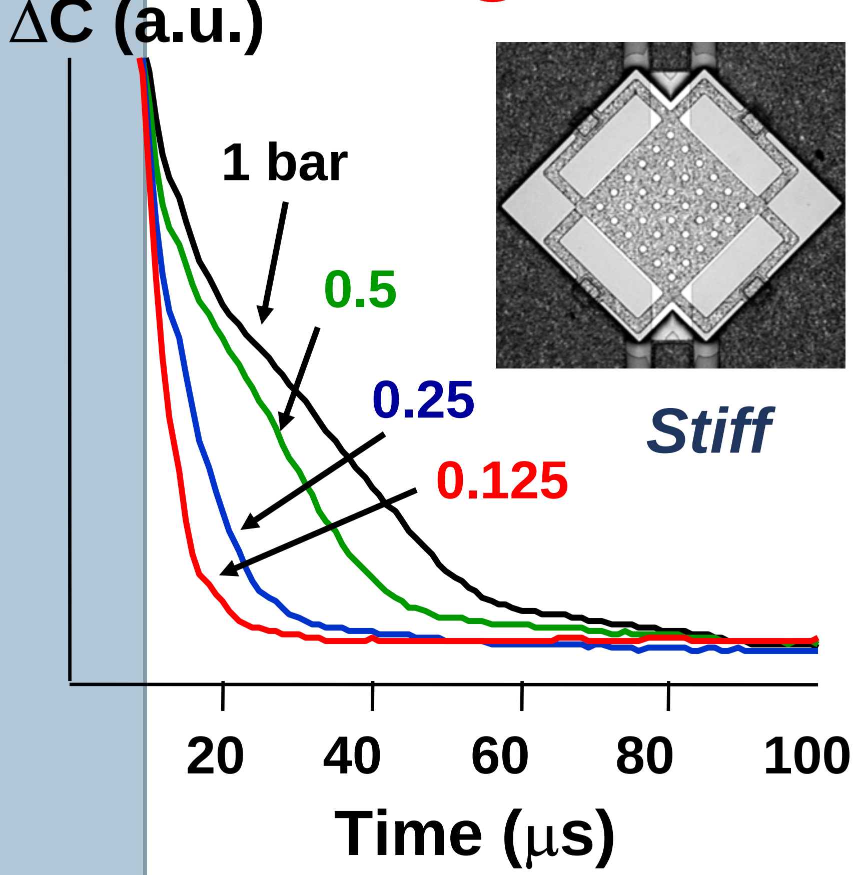


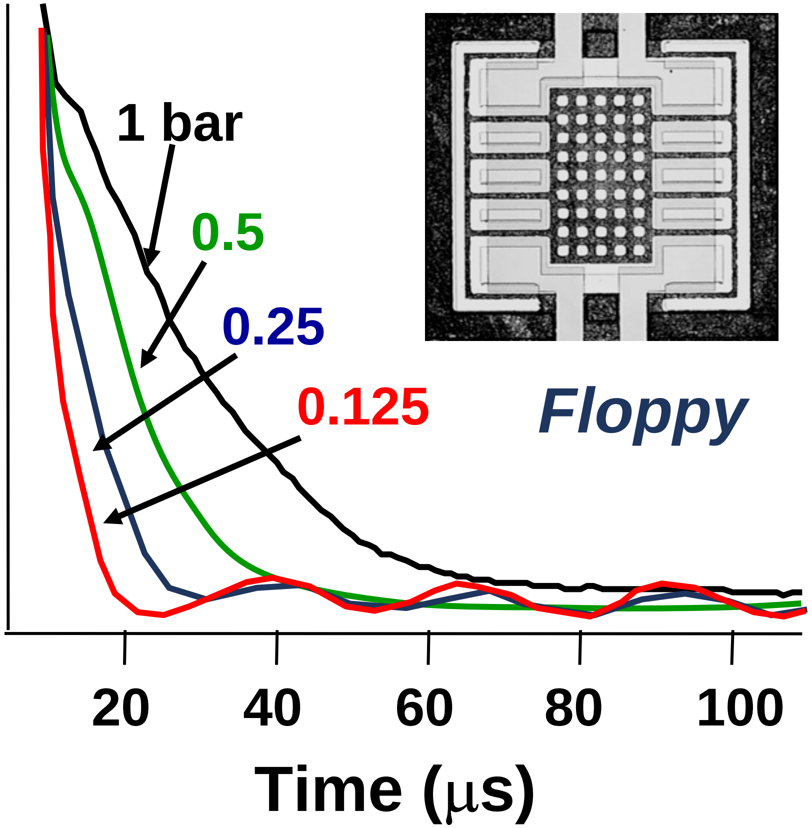


- faster switching in vacuum
- vibrations

Pressure in cavity

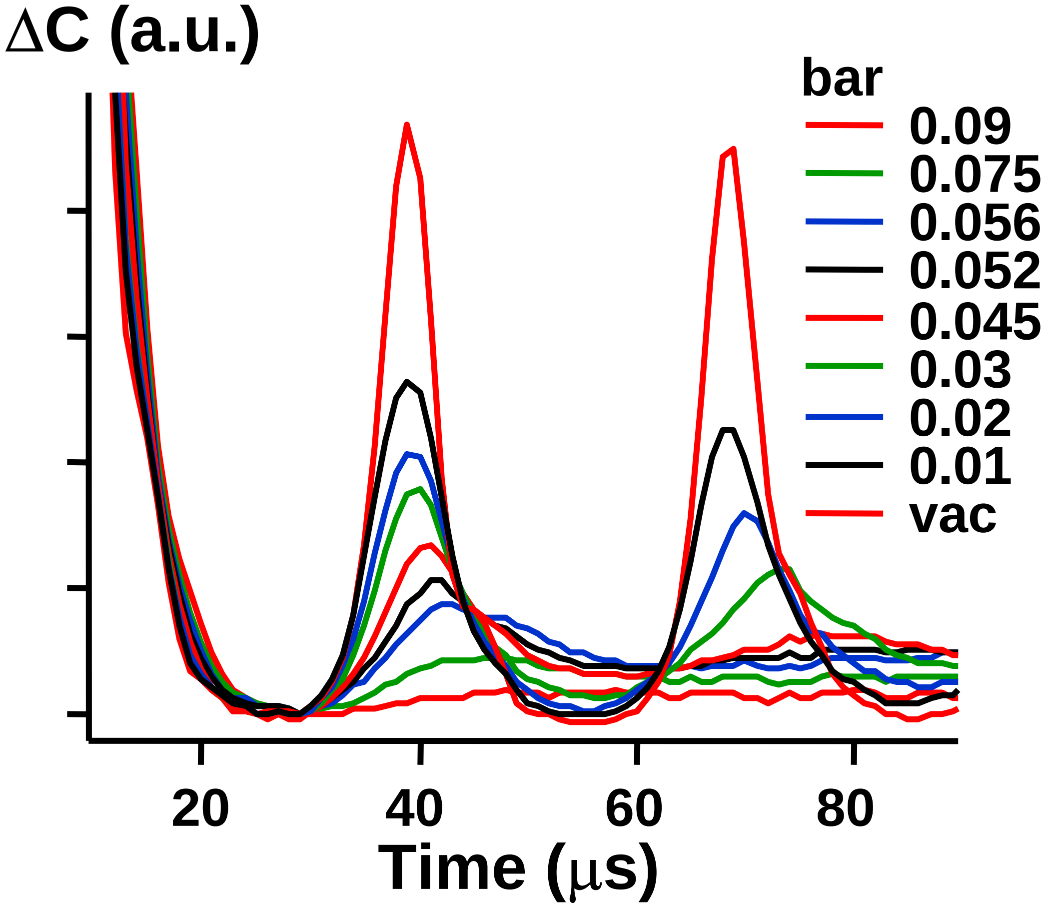


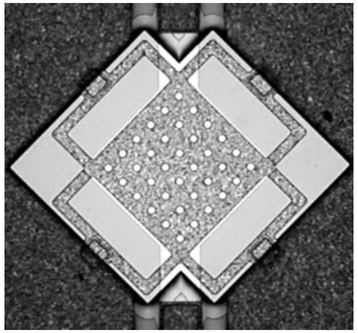




The ‘floppy’ switch shows overshoot already at 0.125 bar.

Pressure in cavity



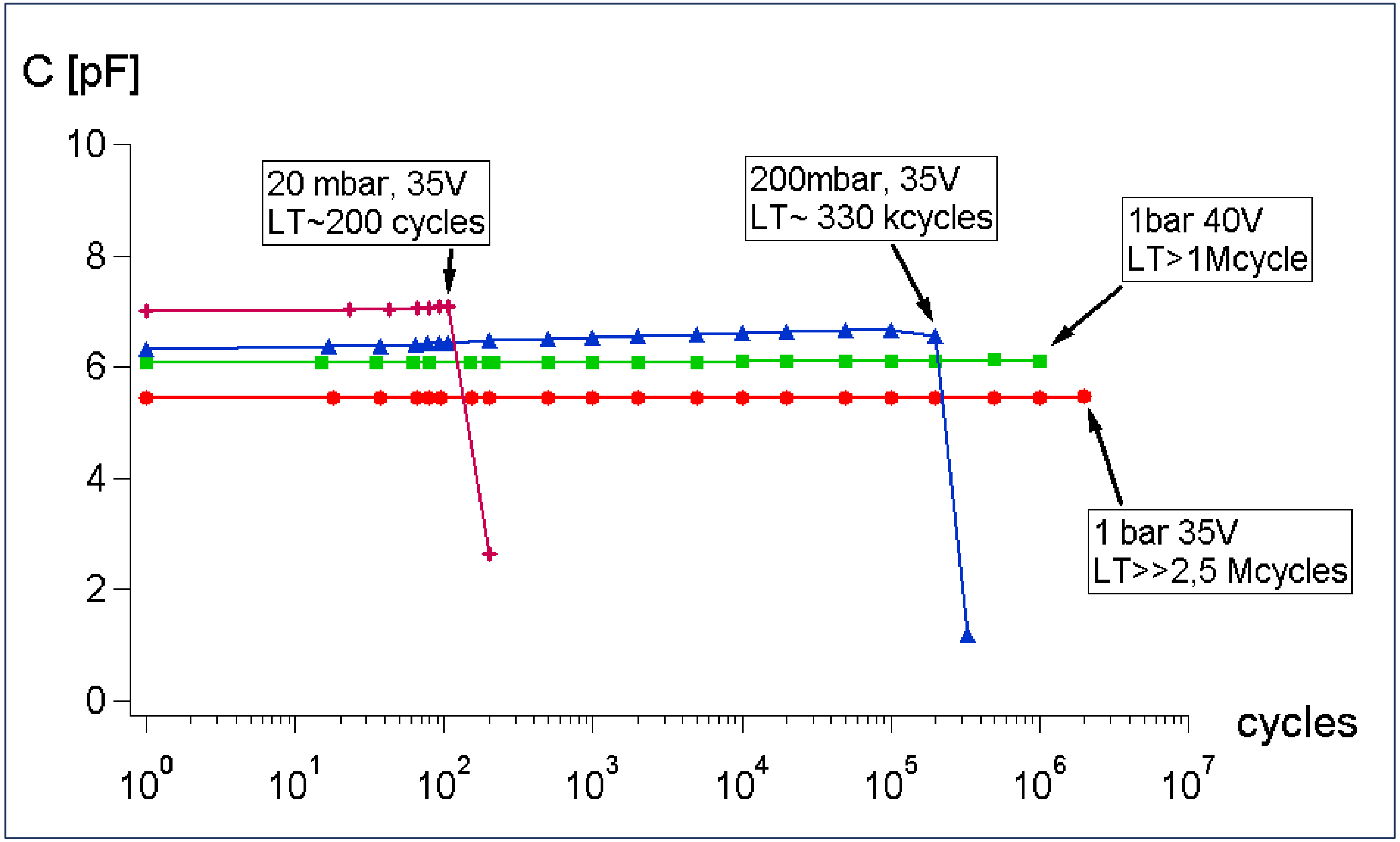


Stiff

The 'STIFF' switch shows overshoot at ~ 0.075 bar: clear dependence of the 'overshoot point' on the design

Pressure in cavity

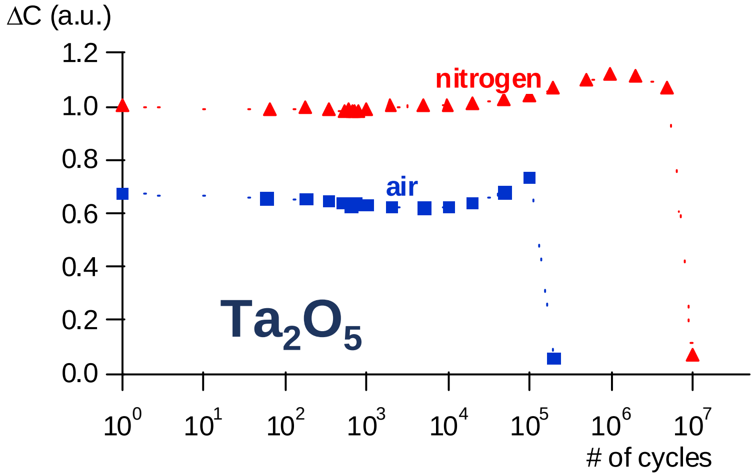
Lower lifetime at lower pressure (larger C_{down}, better charging).

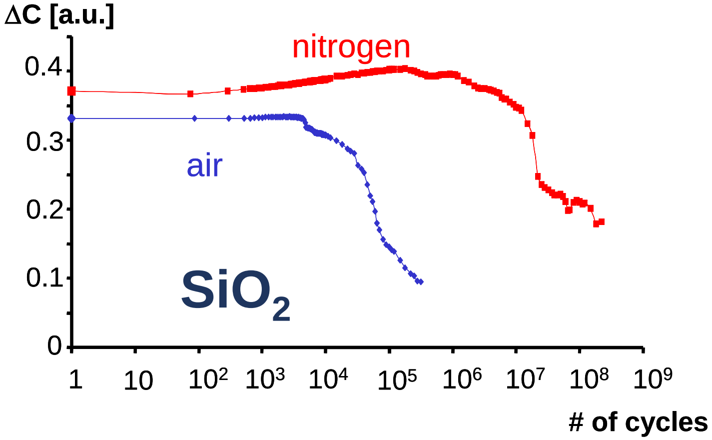


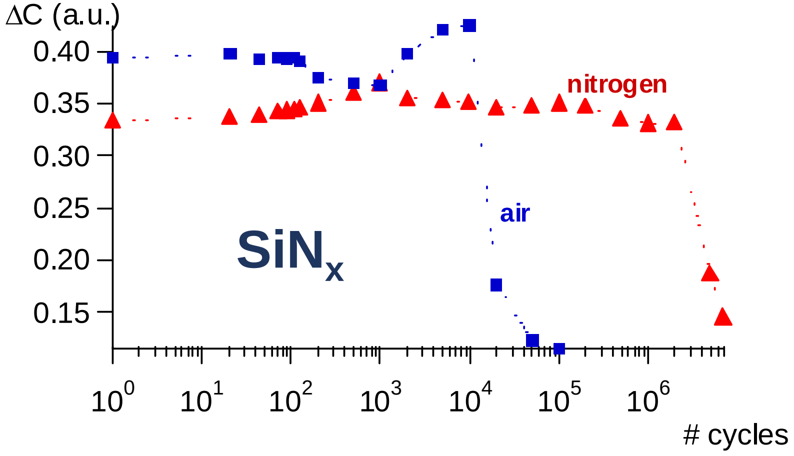
Details and more results will be presented at MEMS2006 by P. Czarnecki et al., IMEC

Gasses in cavity: N_2 vs air

Different technologies, different designs, different dielectrics, different electrical test conditions (V_{act}, freq.)







Nitrogen vs air:

longer lifetime + larger C_{down}

-> packaging in N_2 gives a better reliability

(different damping, dielectric constant, gap breakdown V, humidity,…)

Conclusions

- FMEA: main failure mechanism in capacitive RF-MEMS = charging of the dielectric leading to stiction of the bridge
- Possible solutions:
  - **Design for low Vpi, but high Vpo**
  - **Design for flat bridge (uniform charging + low charge distribution)**
  - **Make the insulator area as small as possible (lower sensitivity of Vpo)**
  - **Use bipolar actuation waveform**
  - **Package the switch in a nitrogen environment**
  - **Be careful with vacuum (bouncing + lower lifetime possible)**

- FMEA: main packaging induced failure is deformation of the bridge
- Possible solutions:
  - **Use metal with high Tc**
  - **Try to reduce the packaging T**

What else can be done?

- alternative ways of bipolar actuation
- better dielectric (less charging sensitive)
- worse dielectric (such that the charges disappear faster)

Acknowledgments

IMEC: MEMS, packaging, reliability and RF team

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