In Search of a Better ~~MEMS~~ Landau Switch

How nanostructured dielectrics soften landing, increase travel Range, and reduce Energy dissipation

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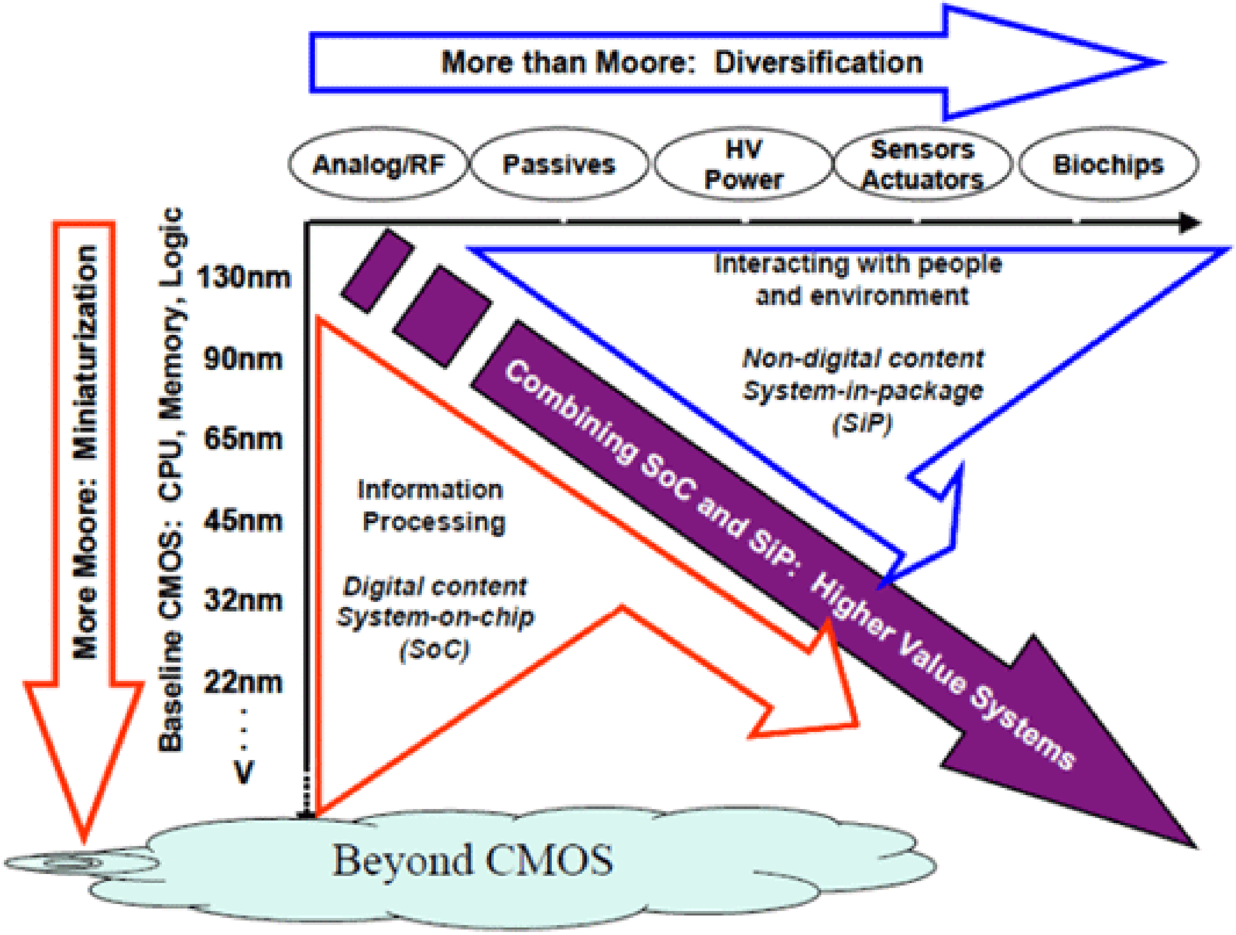
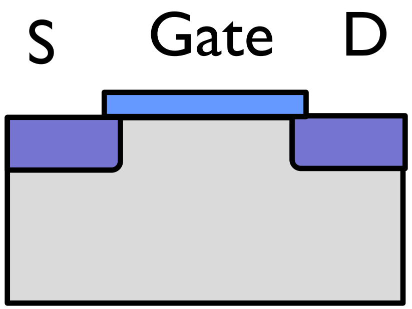
Focus Center M S D Materials Structures Devices

Alam CEED Group

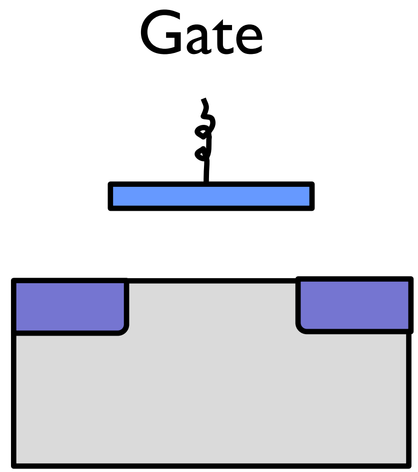
'More than Moore' Technologies



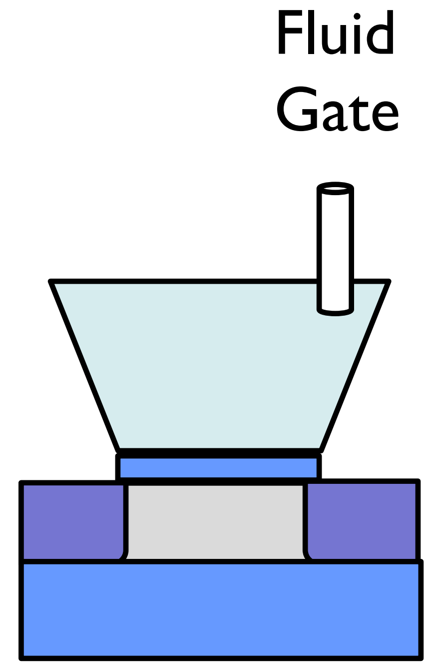
MOSFET, MEMS, and ISFET



A classical MOSFET switch



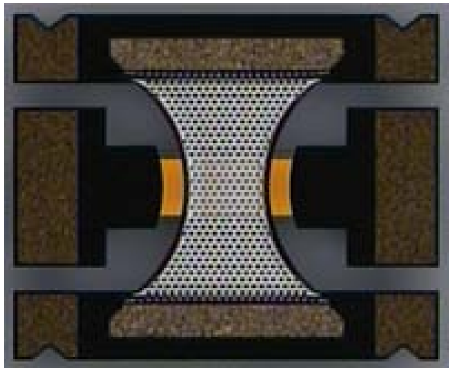
Beats thermo-dynamic limit of 60 mV/dec



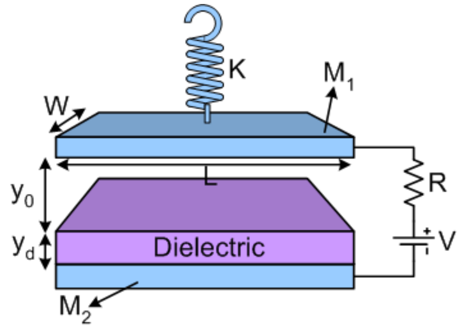
Beats Nernst limit of 60 mV/pH

Applications of MEMS Switches

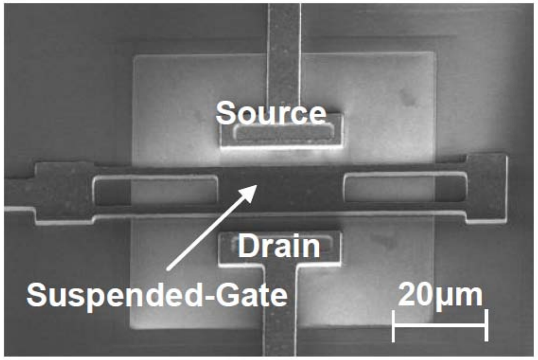
1. Communication



RF-MEMS Switch

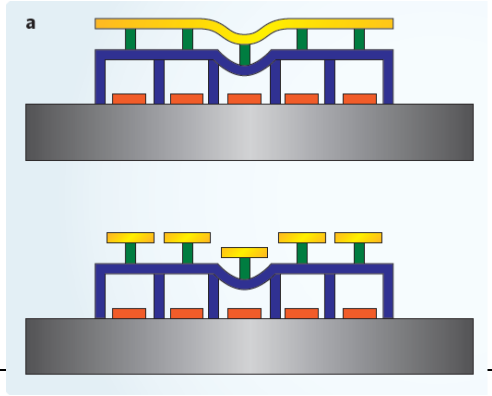


2. Computation



NEMFET

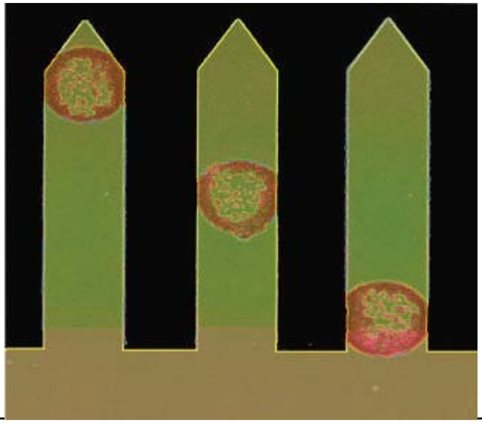
3. Optics



Deformable
Mirrors

Mirasol Display

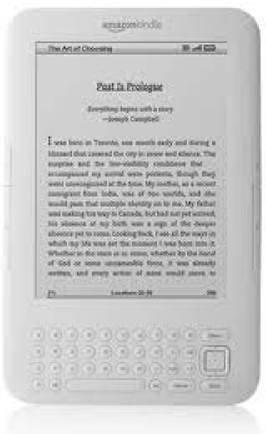
4. Biosensor



Resonator / Mass Sensor

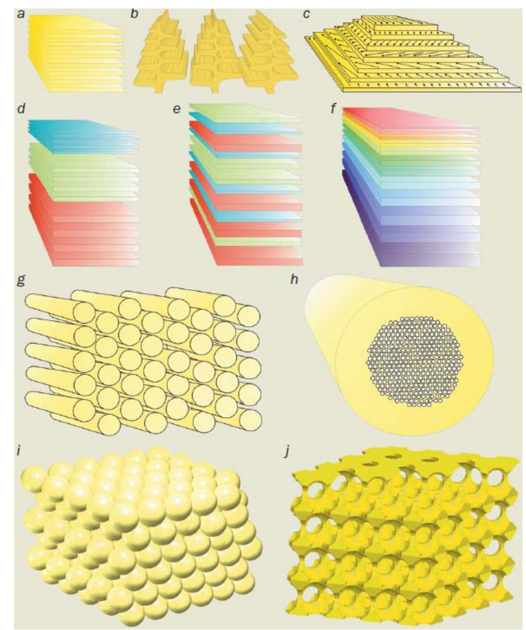
Active and Passive Displays

Kindle



IPAD

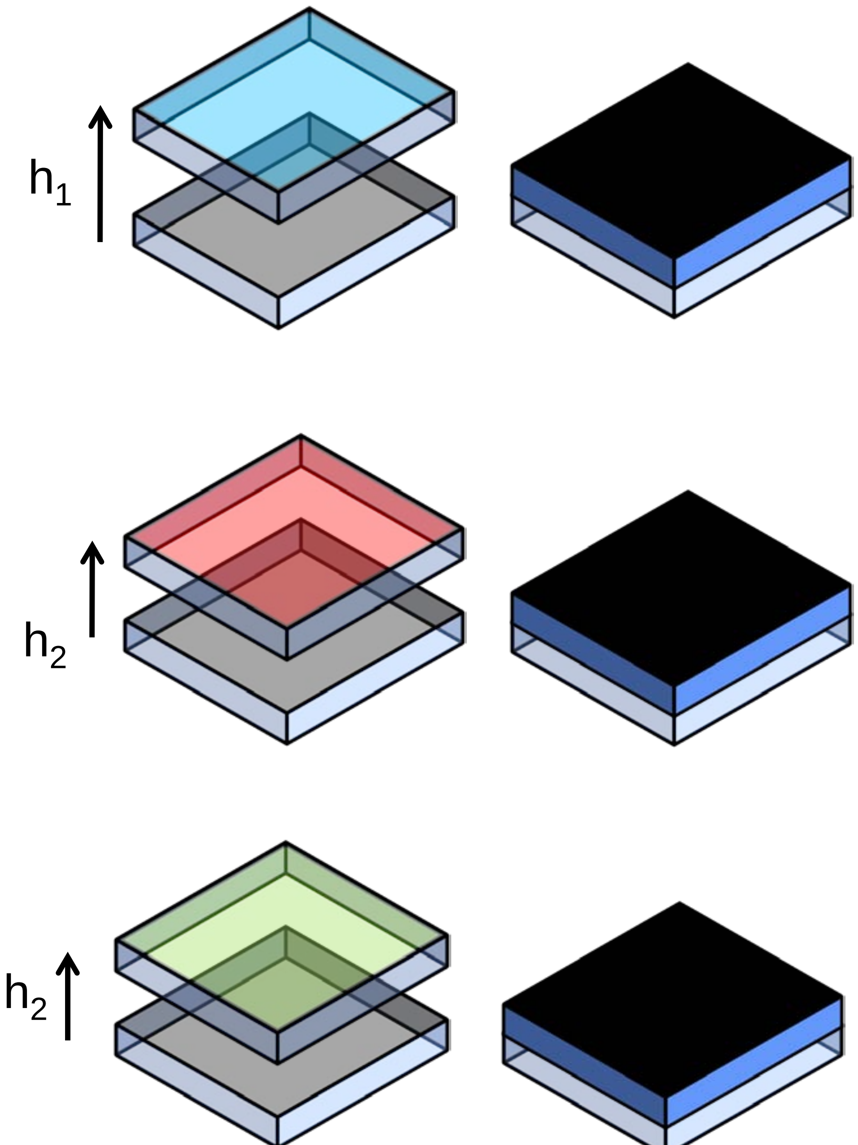
Newton/Hooke

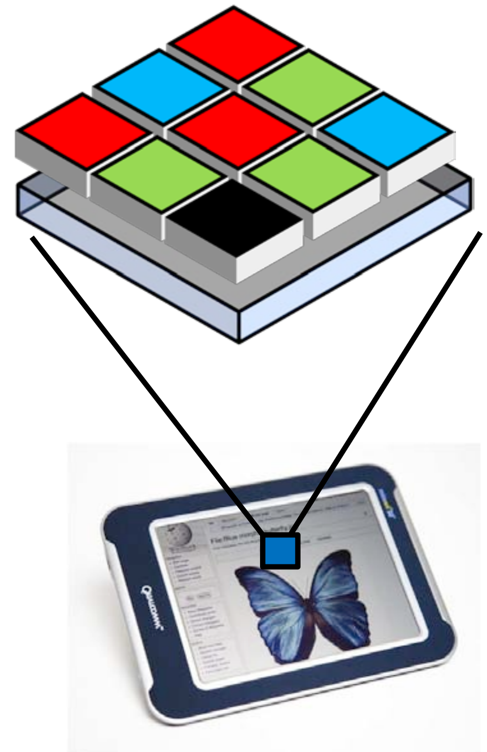


?

P.Vukusik, PW, 2004

MEMS and Mirasol Display

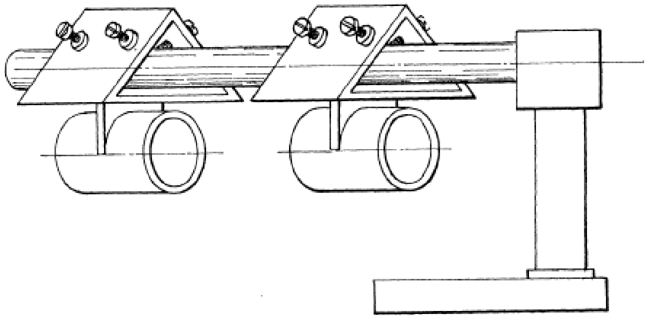




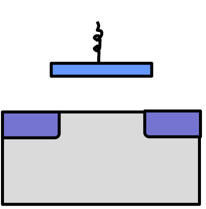
Physics of switch closing
Tunability of the physical spacing
MEMS as a Landau switch

Outline

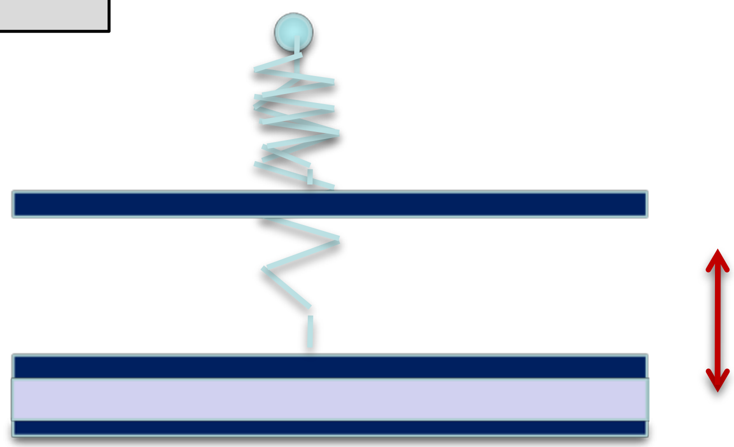
- Introduction to More than Moore Technology
- Elementary Physics of MEMS
- Theory of Soft Landing
- Physics of Travel Range
- Hysteresis-Free Switching
- Conclusions



Taylor, PRS, 1968



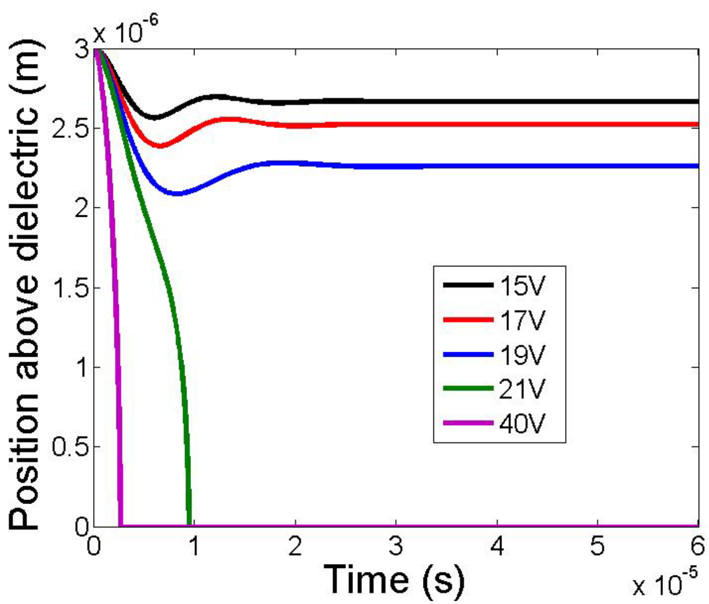
Mechanical model for cantilever movement



Net force — Spring force — damping

$$m\frac{d^2y}{dt^2} = F_{elec(down)} - k(y_0 - y) - b\frac{dy}{dt}$$

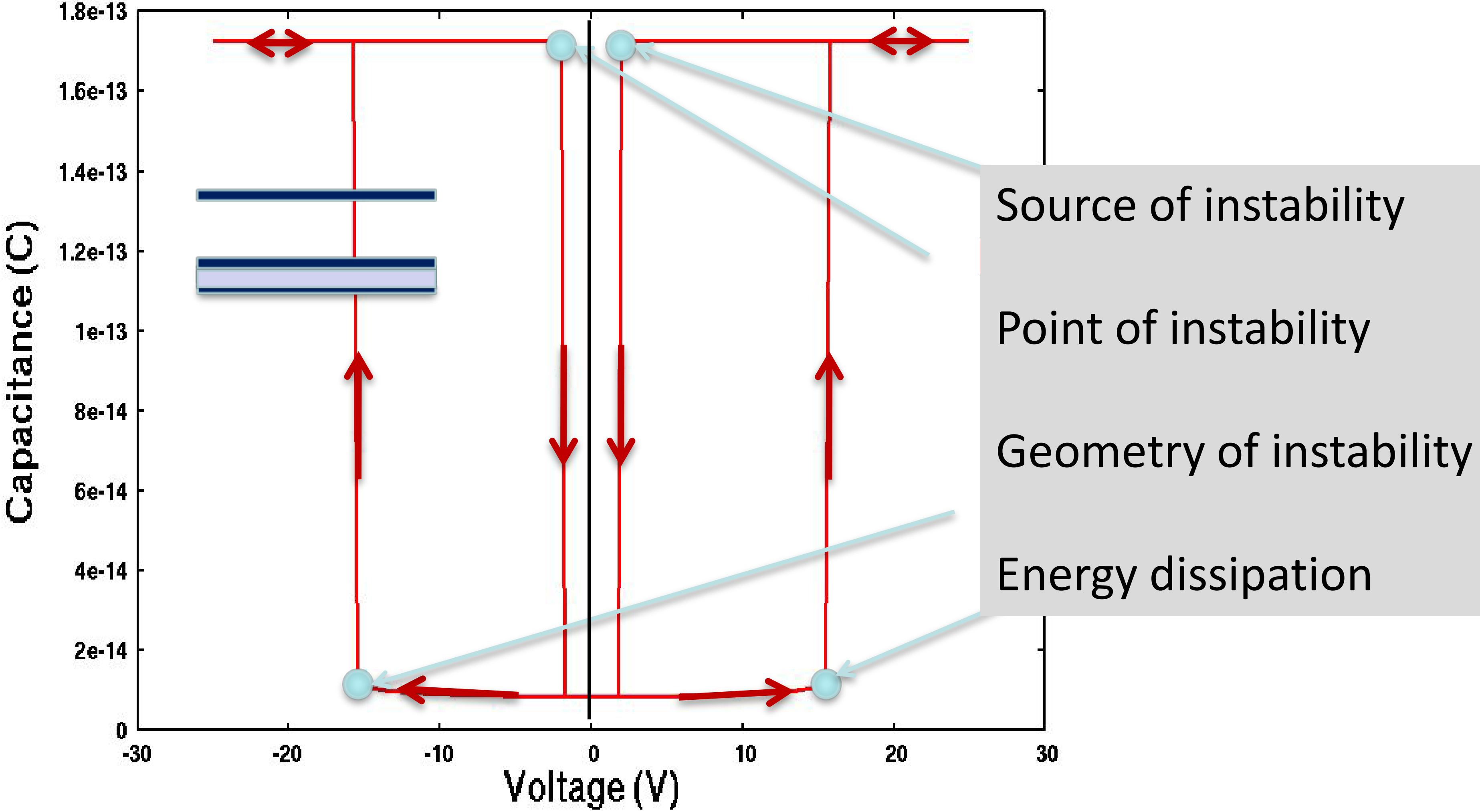
$$F_{elec(down)} = \frac{\varepsilon_0 \varepsilon_r^2 A V^2}{2\left(y_d + \varepsilon_r y\right)^2}$$



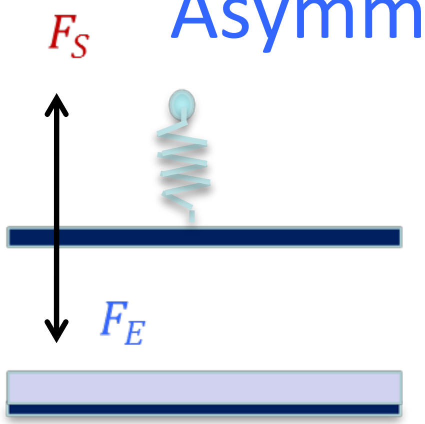
MATLAB simulation

Why does it snap?

Many Puzzles of MEMS C-V



Asymmetry in Pull-in and Pull-out Voltages



$$E = \frac{1}{2} C V_A^{2}$$

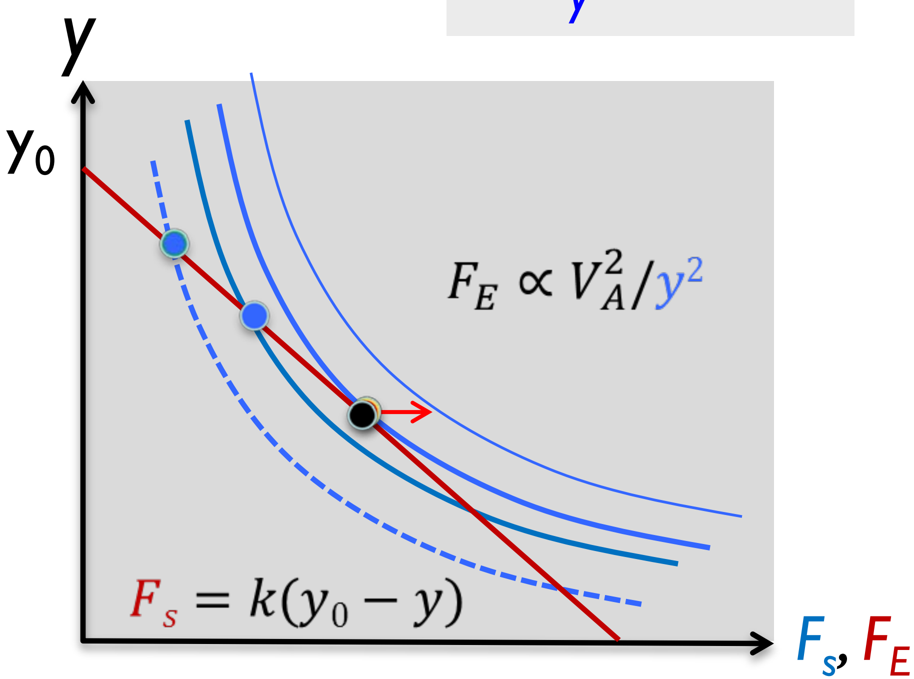
$$F_E = \frac{dE}{dy} =$$

$$C = \frac{\varepsilon_0 A}{y}$$

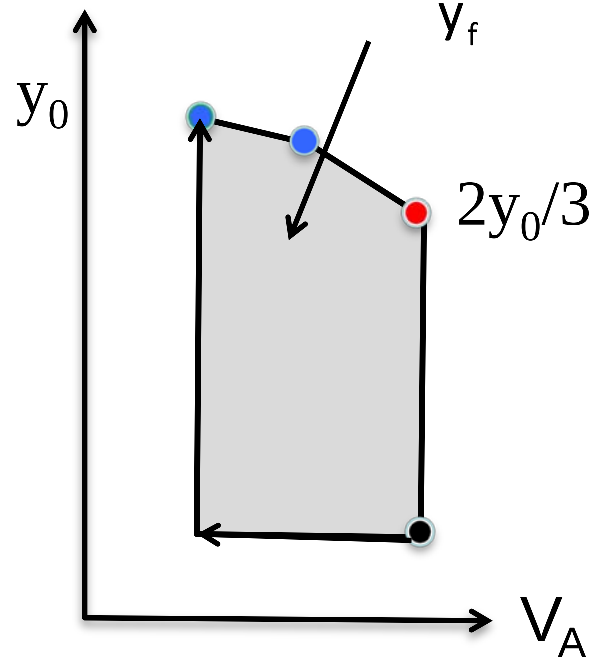
$$F_E = F_S$$

$$dF_E/dy = dF_S/dy$$

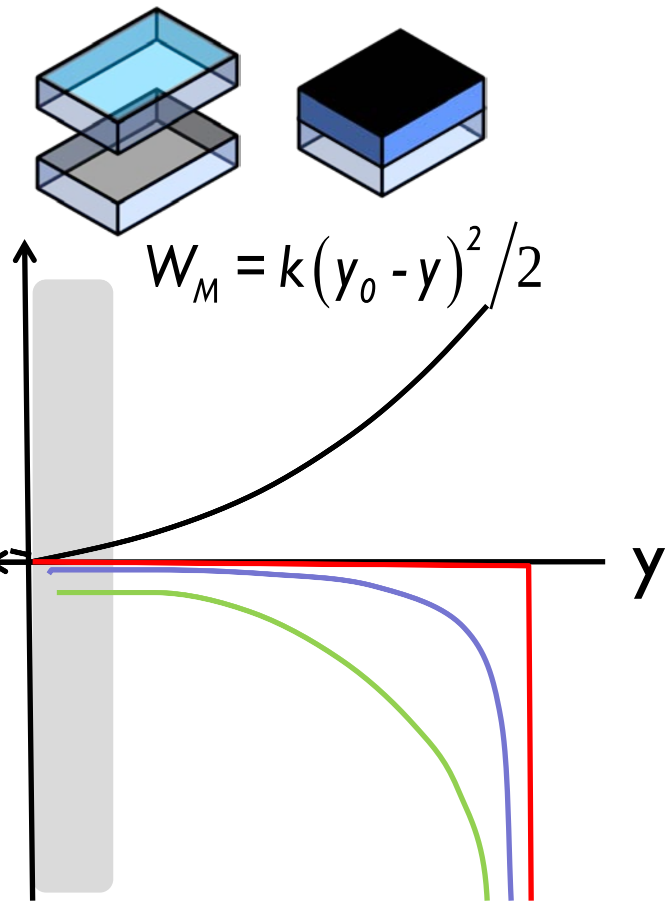
$$y_s = 2/3 y_0$$



$$E_{diss} = \frac{\frac{1}{2}\varepsilon V_{pi}^2 A}{y_f} - \frac{k y_f^2}{2}$$

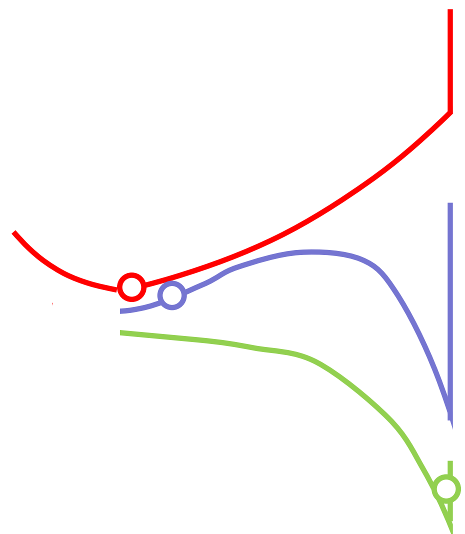


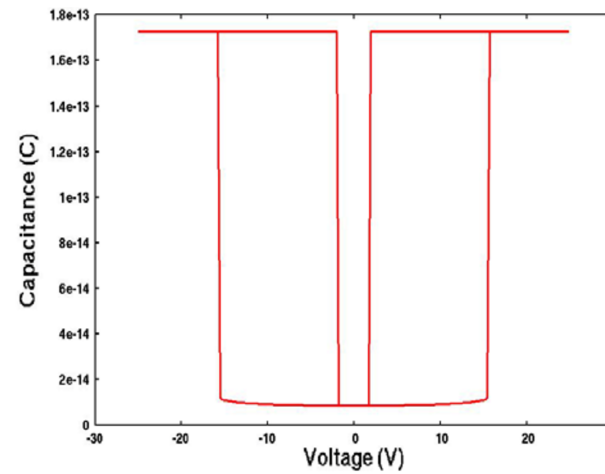
Energy Landscape of MEMS Transition



$$W_M = k(y_0 - y)^2/2$$

$$W_T = W_M + W_E$$

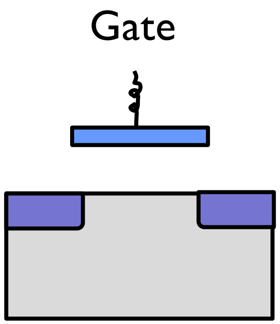


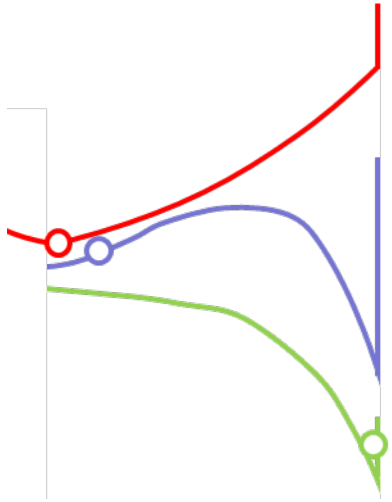


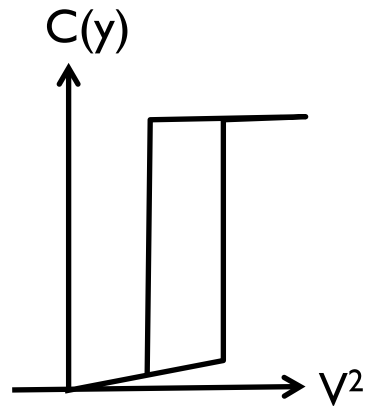
$$W_E = (1/2)(\varepsilon_0/y)V^2$$

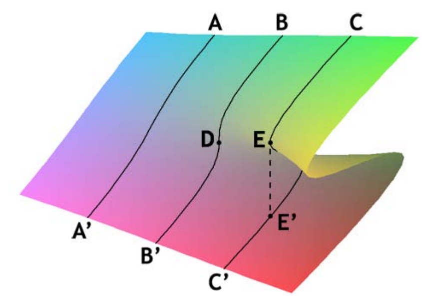
Order parameter y, …in other system M or P are order parameter
Sub kT transition is fundamentally related to absence of states in the gap

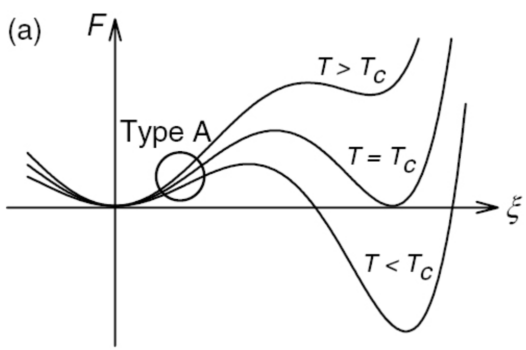
MEMS, 1st order Phase Transition, Cusp Catastrophe

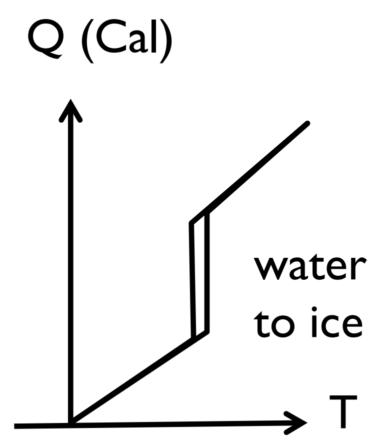




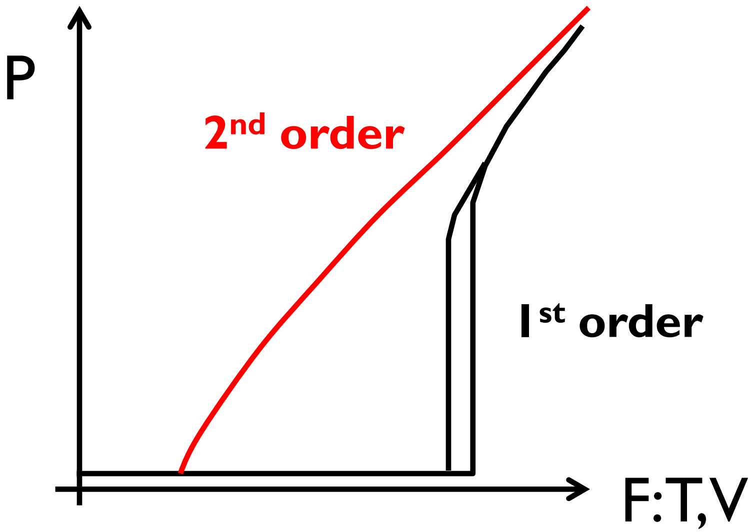


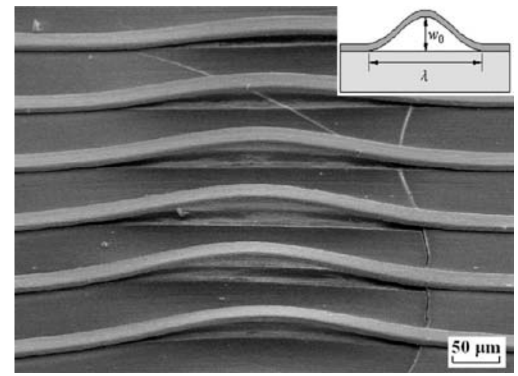




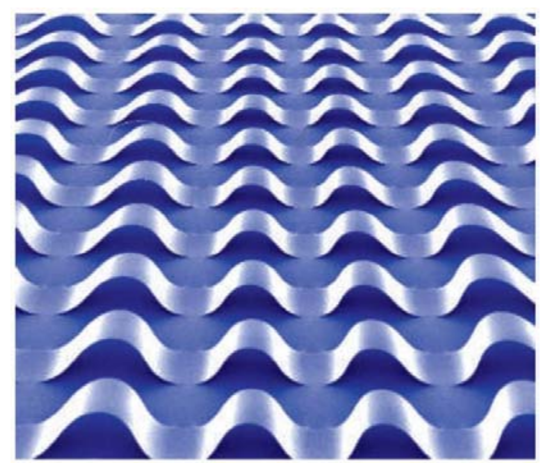


Is there a 2st order Phase Transition in MEMS? Physics of Bows and Arrows

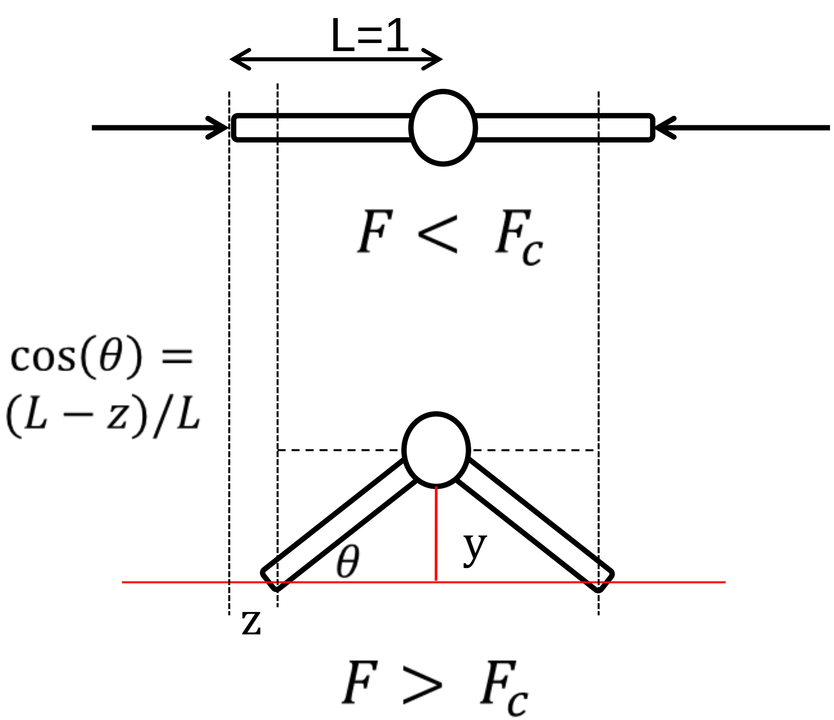




Q. Wang, J. Colloid and Itf. Sci. v. 458(2), 491, 2011



Euler Buckling, 2st order Phase Transition, Fold Catastrophe



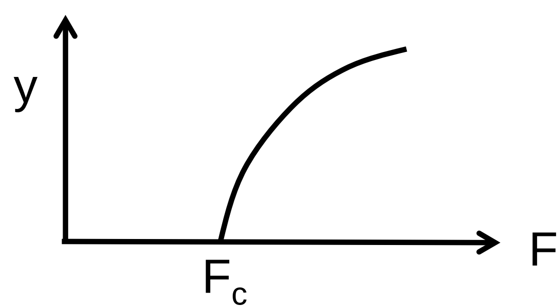
$$W_T = W_\theta + W_M$$

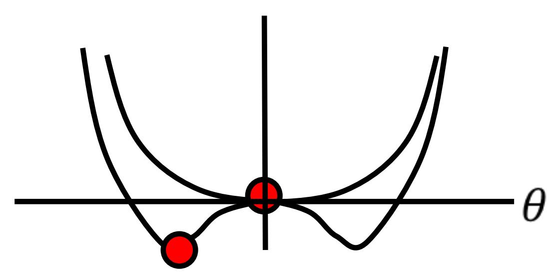
$$W_\theta = (\mu/2)(2\theta)^2$$

$$W_M = 2 \times F \times z \approx \beta\left(\frac{\theta^2}{2!} - \frac{\theta^4}{4!}\right)$$

$$W_T = (2\mu - F \times L)\theta^2 + (F \times L/12)\theta^4$$

$$F_c = 2\mu/L$$





Symmetry breaking, power-law expansion of the order parameter …

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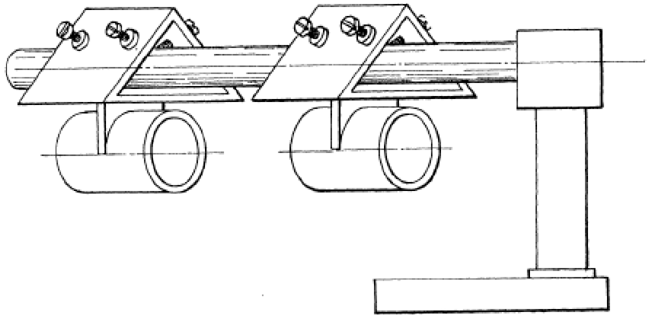
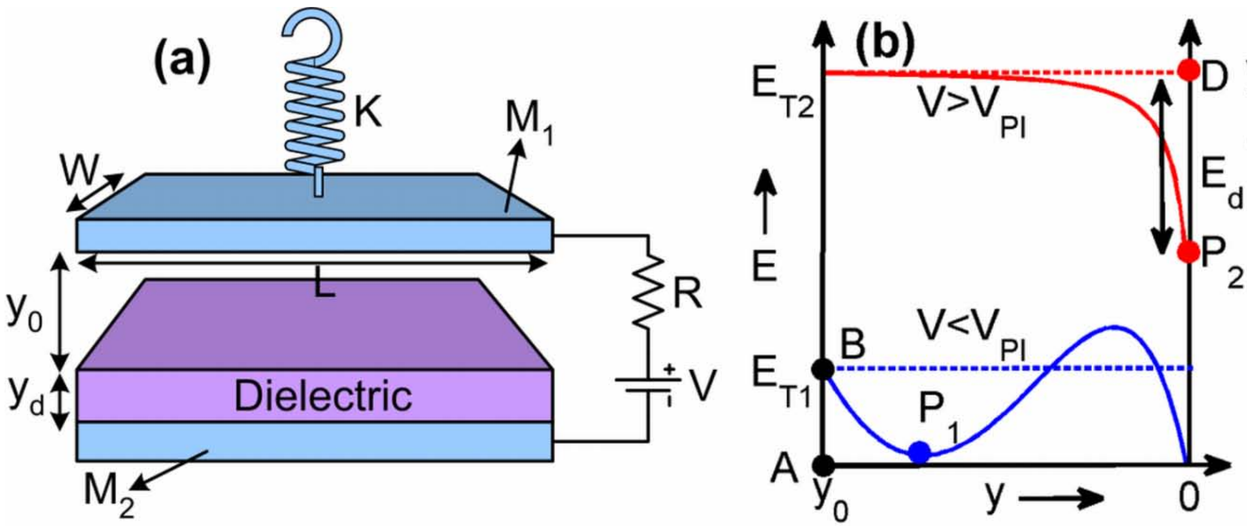


Reliability: The problem of Hard Landing

$$m\frac{d\upsilon}{dt} = k(y_0 - y) - F_{elec} - b\upsilon$$

A. Jain et.al., APL, 98, 234104 (2011)

$$F_{elec} = \frac{1}{2}\frac{d}{dy}\left(CV^2\right)$$



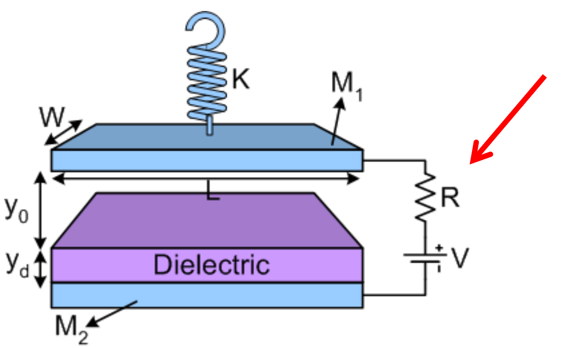
The hard landing damages the surface and can lead to stiction …

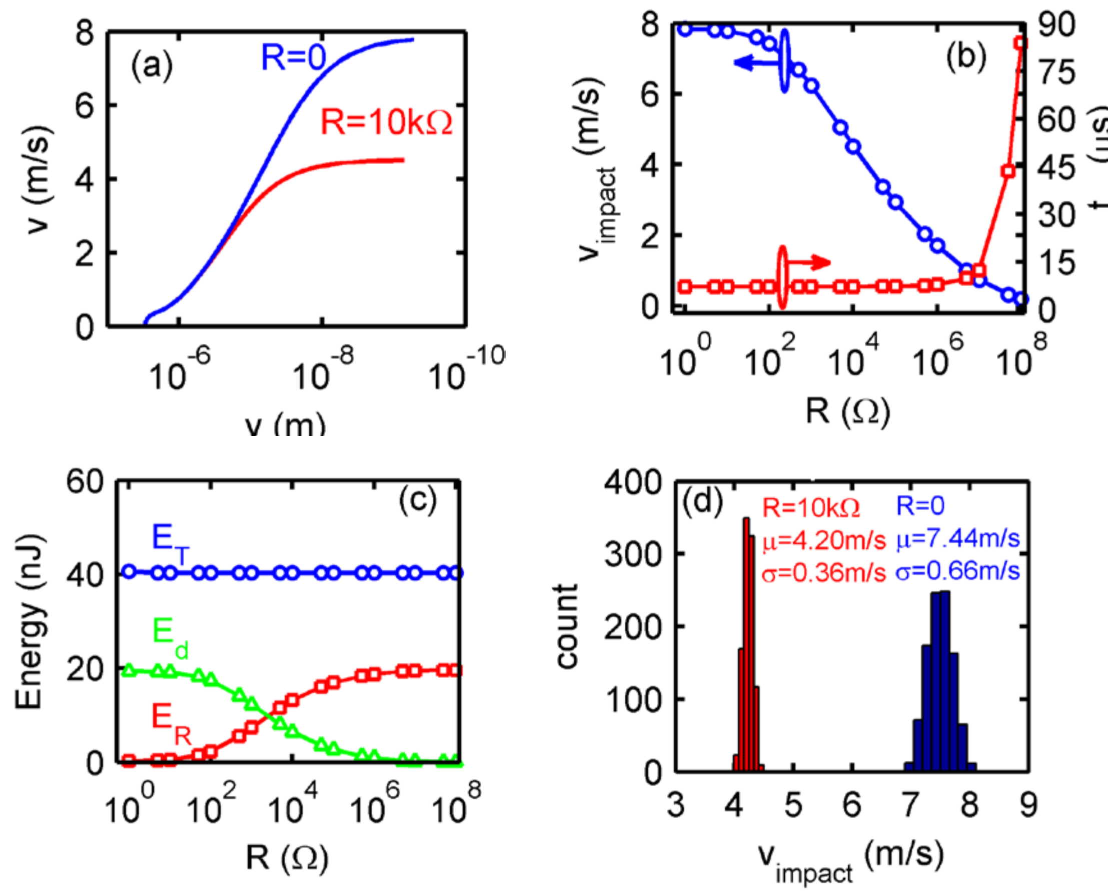
Soft Landing by Resistive Braking

$$m\frac{d\upsilon}{dt} = k(y_0 - y) - F_{elec} - b\upsilon$$

$$I = \frac{d(CV_c)}{dt}; \quad V = I \times R + V_c$$

$$F_{elec} = \frac{1}{2}\frac{d}{dy}\left(CV_c^2\right) = \frac{1}{2}V_c^2\frac{dC}{dy} + \frac{1}{2}C\frac{dV_c^2}{dy}$$

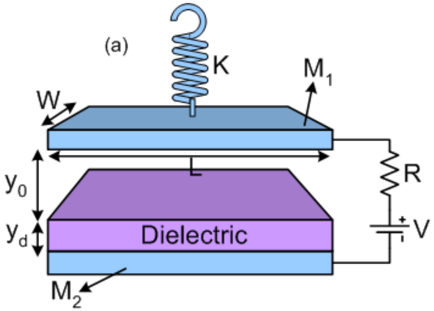




Reduction in impact velocity and reduced variability

A. Jain et.al. Patent 61/483225

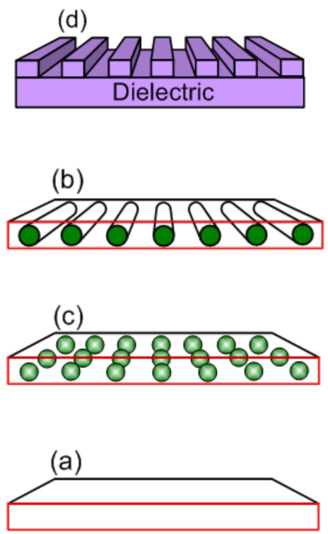
Operation: Geometry and Capacitance

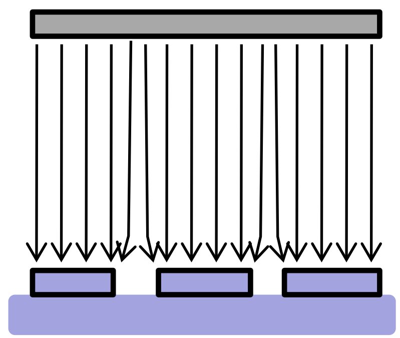


$$F_{elec} = \frac{1}{2}\frac{d}{dy}\left(CV^2\right) = \frac{1}{2}V_c^2\frac{dC}{dy}$$

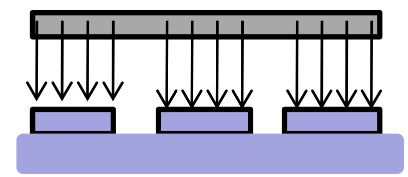
$$C_{up} = Ay^{-1}$$

$$C_{down} = A(y) \times y^{\alpha} \gg C_{up}$$



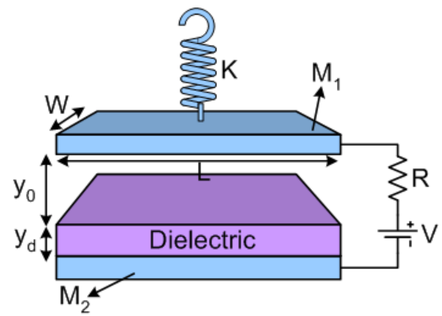


Before Pull-in



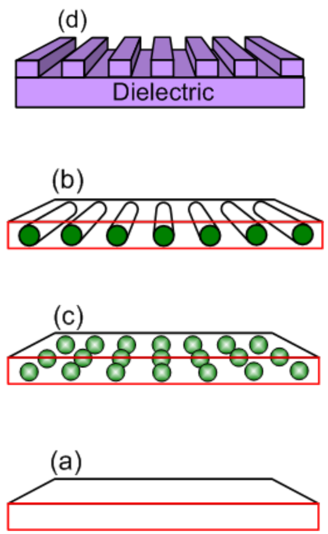
Close to contact

Soft Landing by Capacitive Braking



$$F_{elec} = \frac{l}{2}\frac{d}{dy}\left(CV^2\right)$$

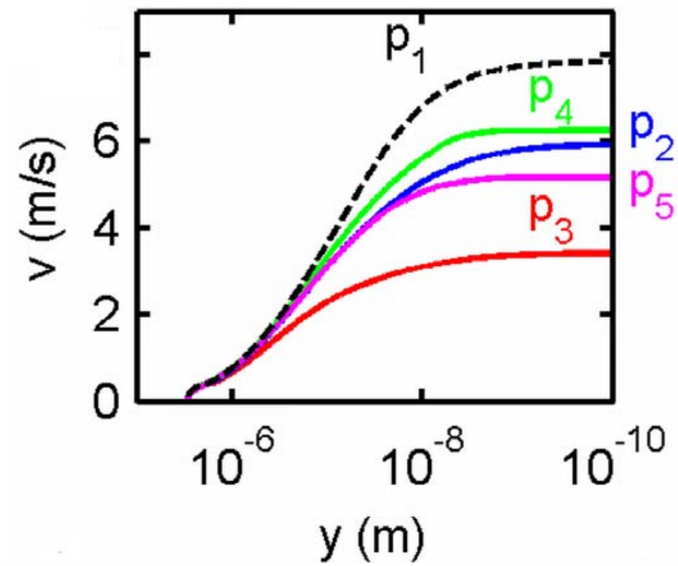
$$= \frac{l}{2}V_c^2\frac{dC}{dy}$$

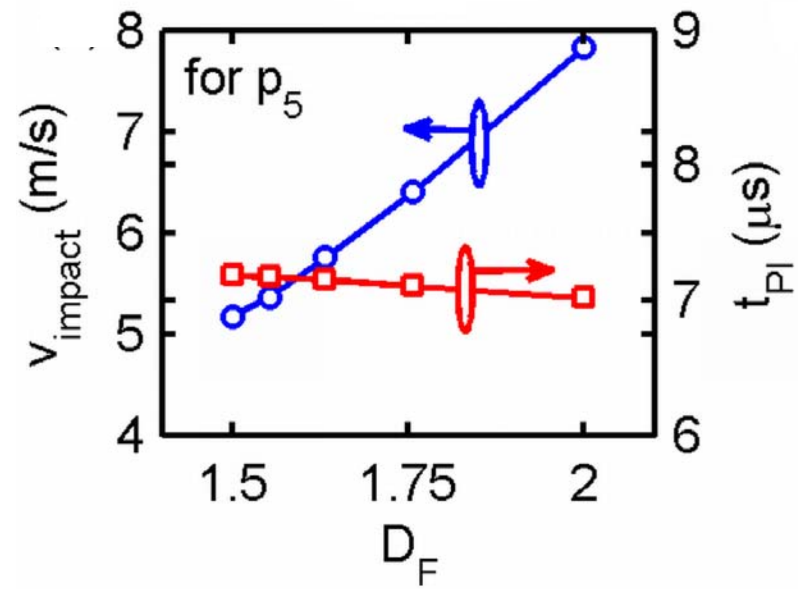


$C = Ay^{-1}$ (< PI)

$C = A(y) \times y^{\alpha}$

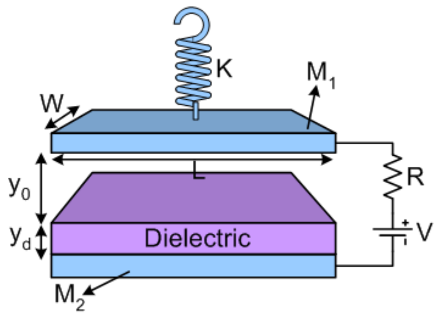
(near contact)

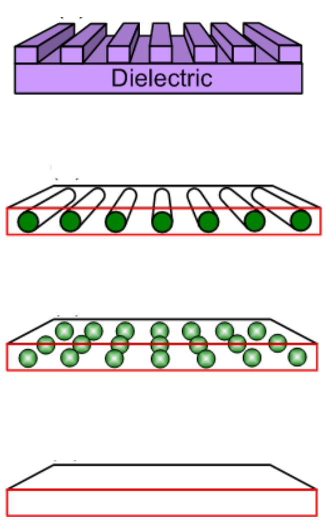


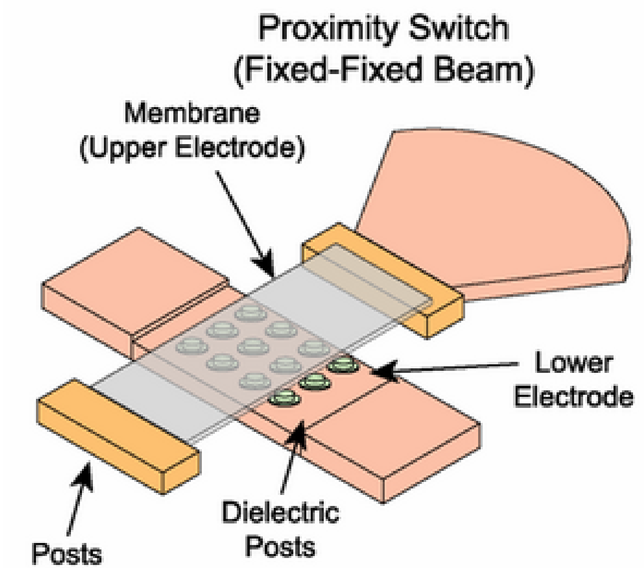


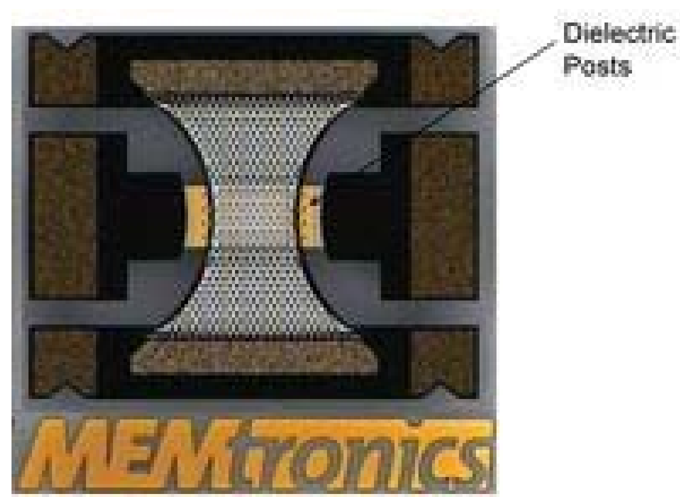
A. Jain et.al., APL, 98, 234104 (2011)

Patterning is Widely used …









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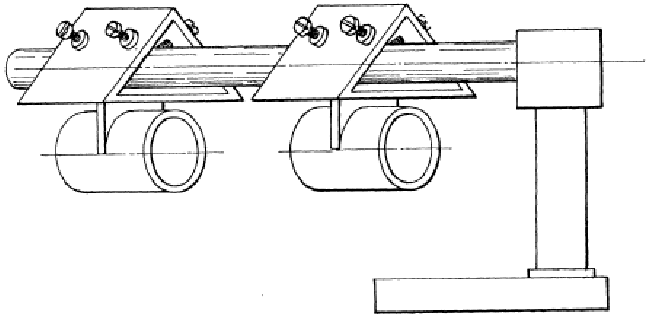
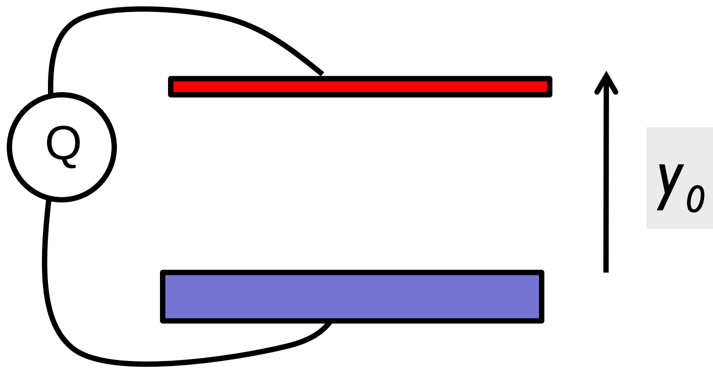
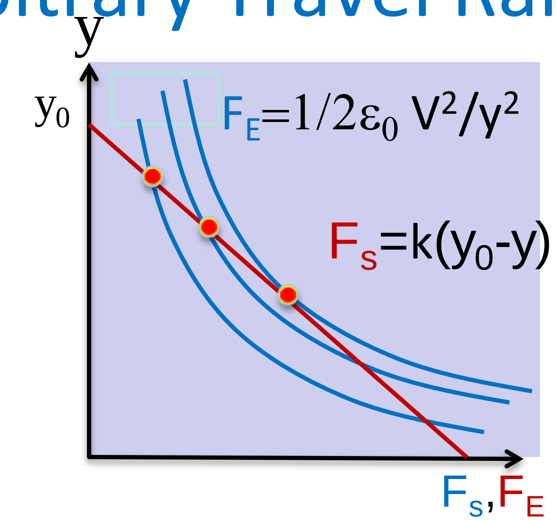


Charge Controlled Arbitrary Travel Range



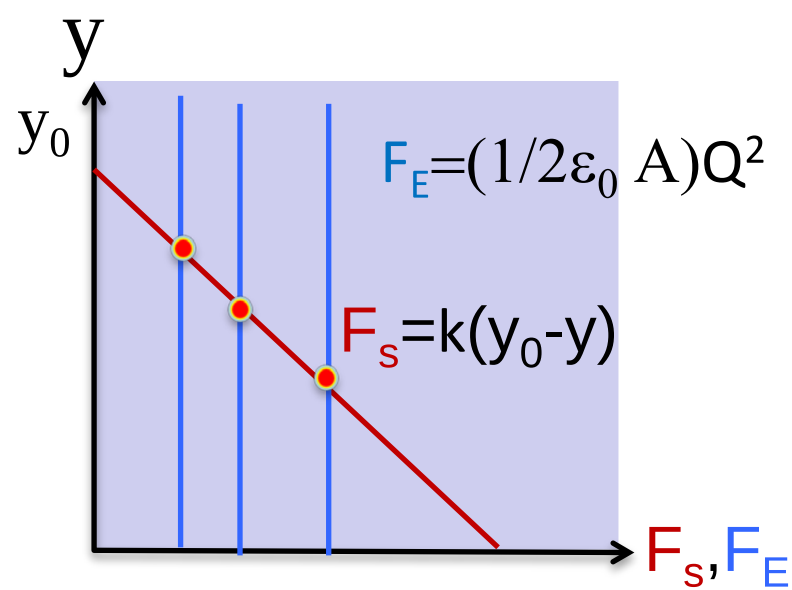


$$E = \frac{1}{2} C V_A^2 = \frac{1}{2}\frac{Q^2}{C}$$

(The term $\frac{1}{2} C V_A^2$ is crossed out.)

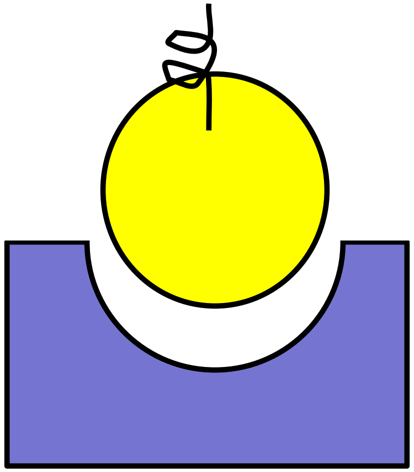
$$C = \frac{\varepsilon_0 A}{y}$$

$$F_y = \frac{dE}{dy} = \frac{1}{\varepsilon_0 2A} Q^2 = \text{const.}$$



… depositing precise amount of charge could be difficult?!

Manipulating stability point: Sculpting the Electrode



$F_E = F_M$

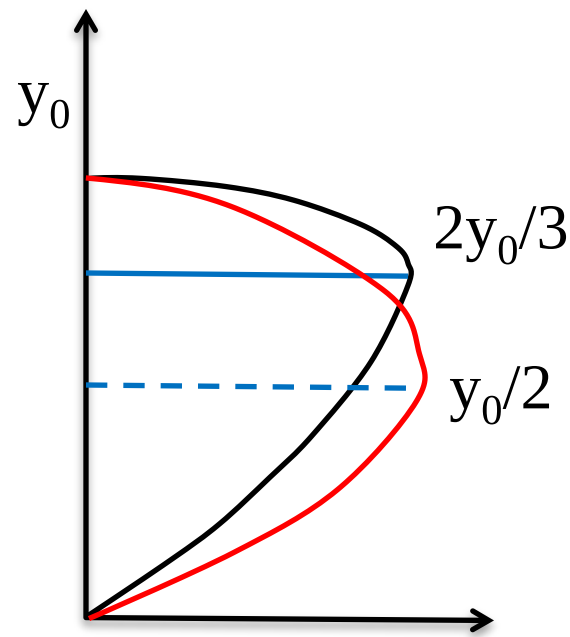
$dF_E/dy = dF_M/dy$

$y \sim y_0/2$

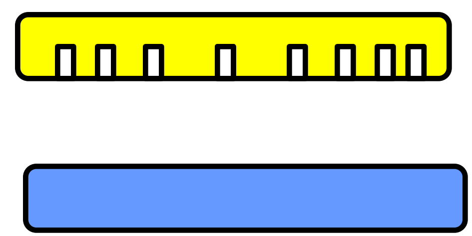
$$E = \frac{1}{2} C V^2$$

$$F_y = \frac{dE}{dy} = \frac{1}{2} V^2 \frac{dC}{dy}$$

$$C = \frac{2\pi\varepsilon_0}{\ln\left(a + y/a\right)}$$

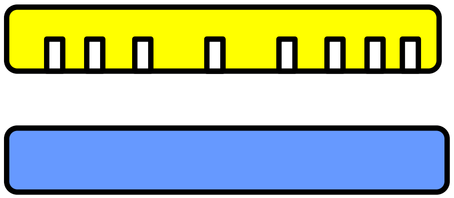


Shaping the 2D e-field …



Geometry allows tailoring of the critical gap !

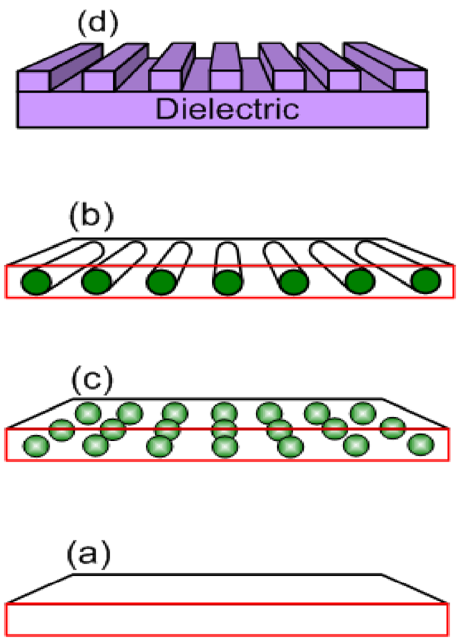
Manipulating stability point: Fractal Sculpting of the Electrode



$$C(y) = \alpha y^{-n} = \alpha y^{-(D_F - 1)}$$

$$k(y_0 - y) = F_{elec} = \frac{1}{2} V^2 \alpha y^{-(n+1)}$$

$$y_c = \frac{1+n}{2+n} = \frac{D_F}{D_F + 1}$$

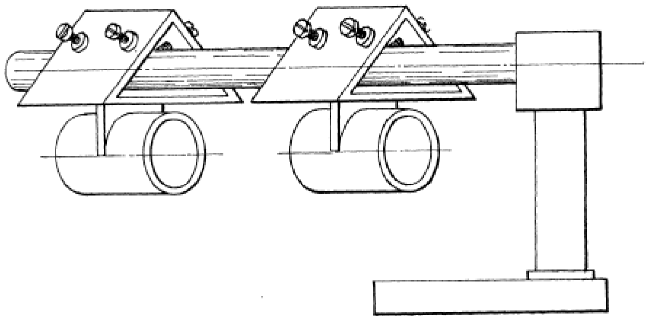


y_c=2/3 for planar electrode

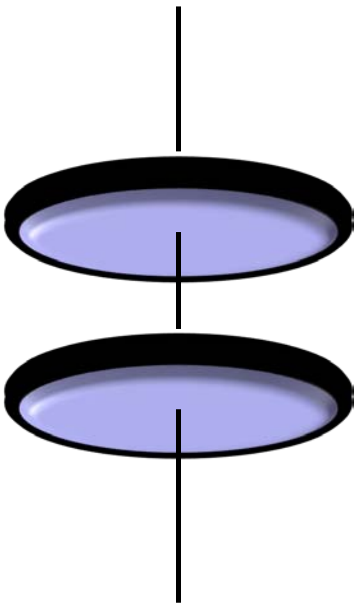
y_c=1/2 for cylindrical electrode

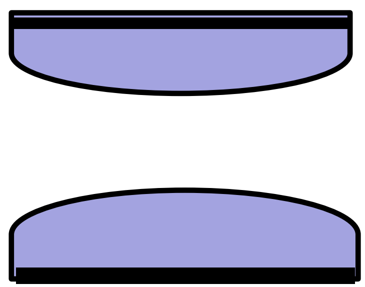
y_c=0! for spherical electrode

Taylor, soup bubble and cloud formation

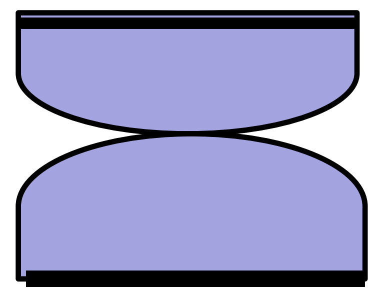


… when he was 82 years old!





Below pull-in

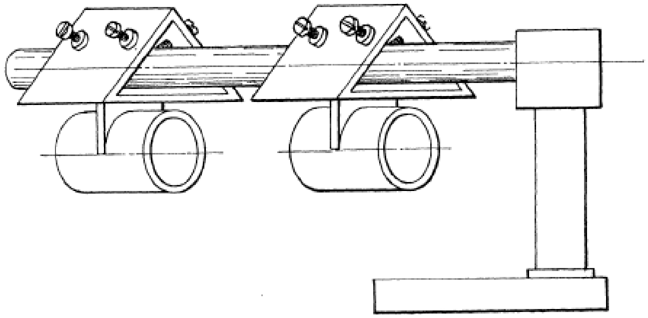


Above pull-in

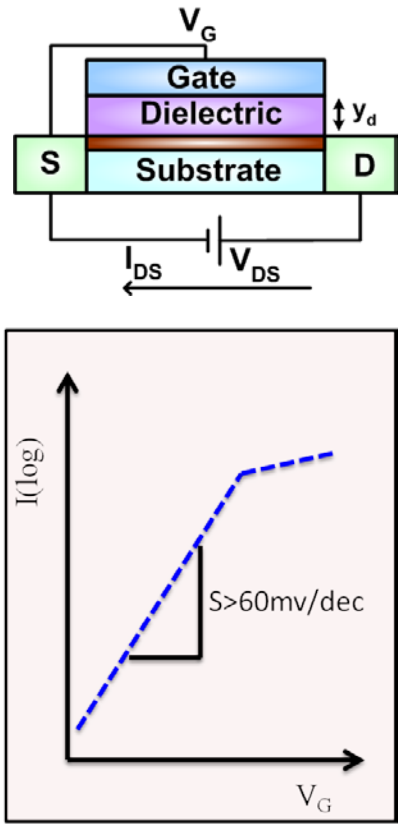
Travel range > 0.5 !

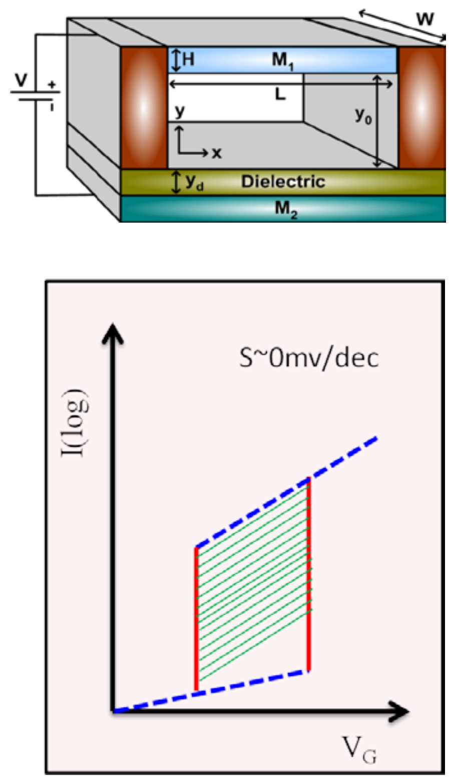
Outline

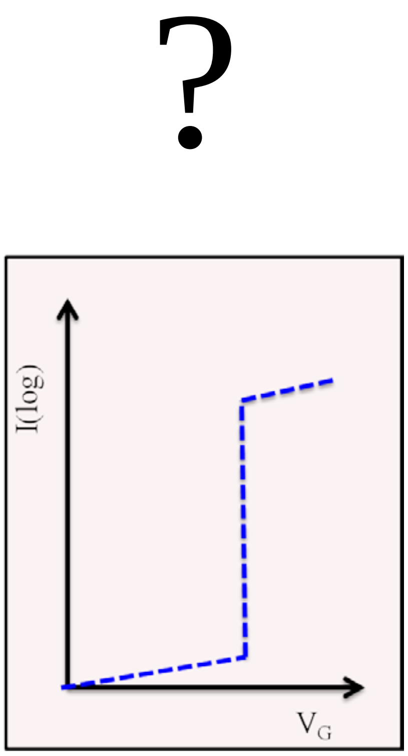
- Introduction to More than Moore Technology
- Elementary Physics of MEMs
- Theory of Soft Landing
- Physics of Travel Range
- Hysteresis-Free Switching
- Conclusions



Hysteresis and Power Dissipation

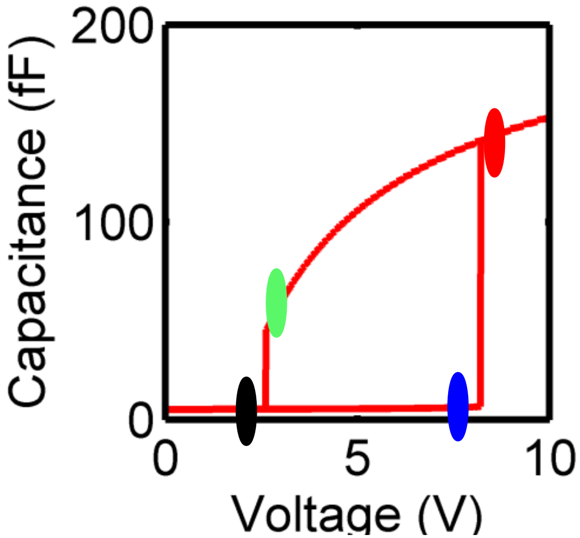


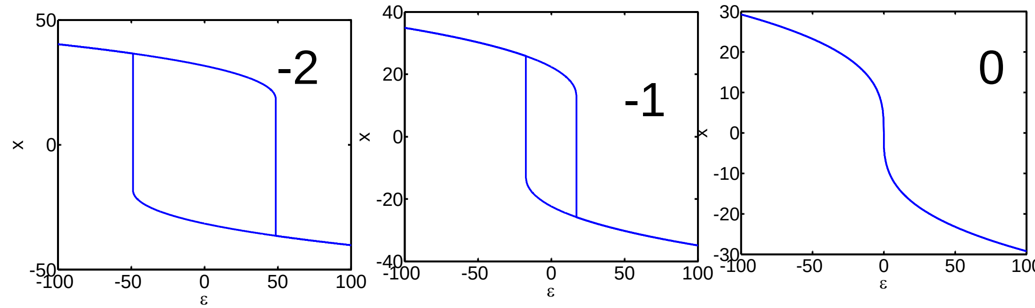


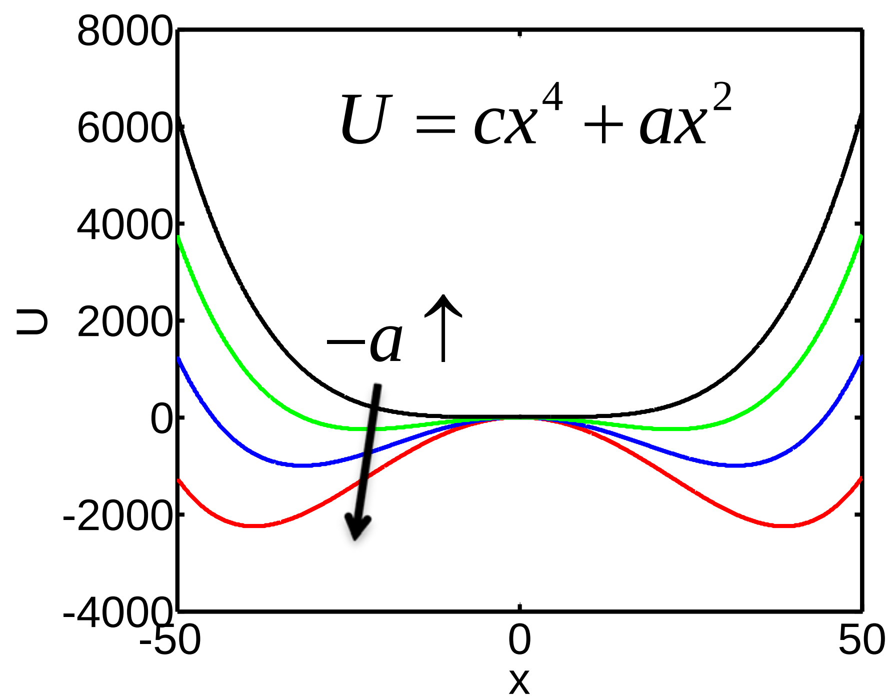


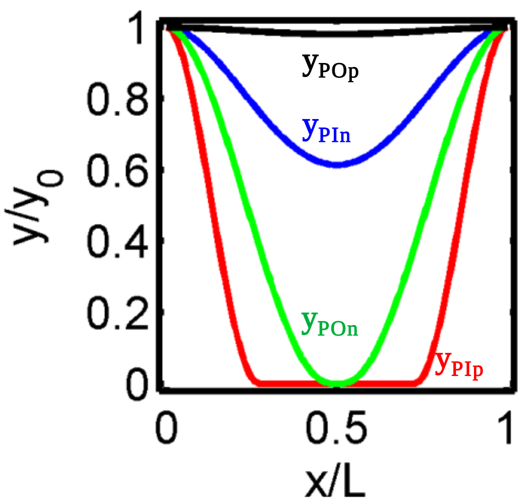
Is hysteresis free MEMS operation possible?

Origin of Hysteresis Loss

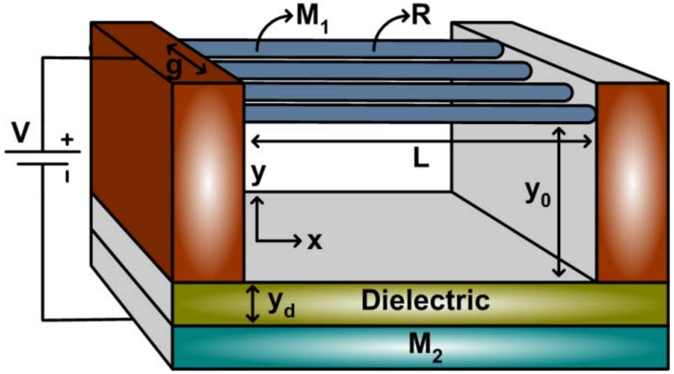


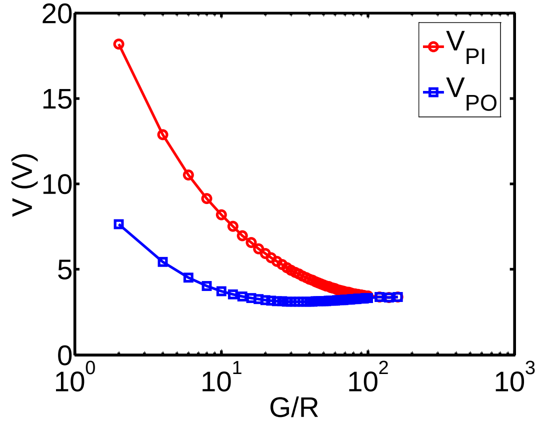




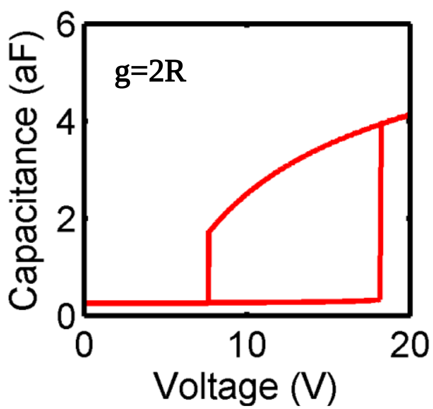


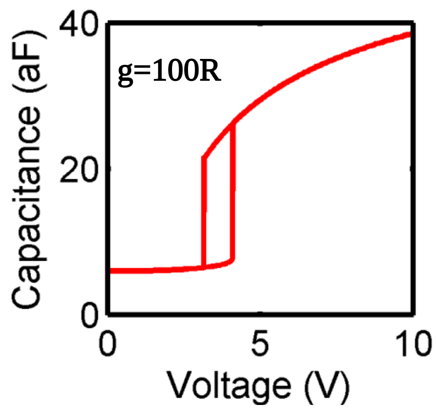
Landau theory suggests optimum landscape ..

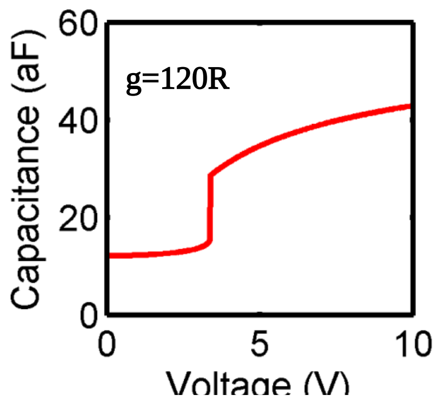


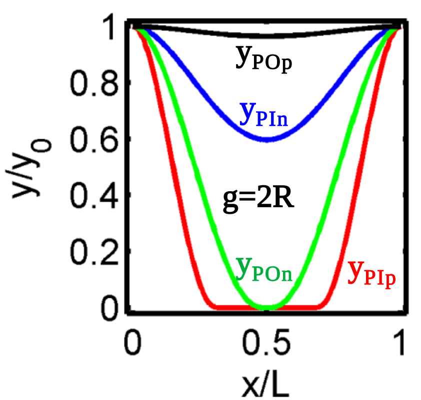


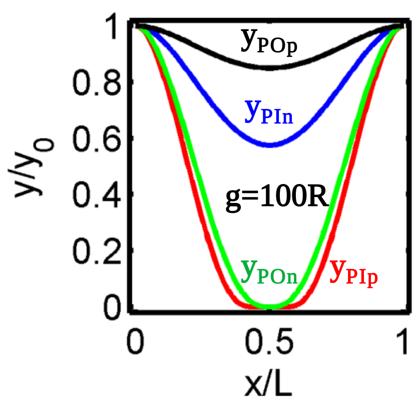
There is always a hysteresis-free geometry with minimum dissipation

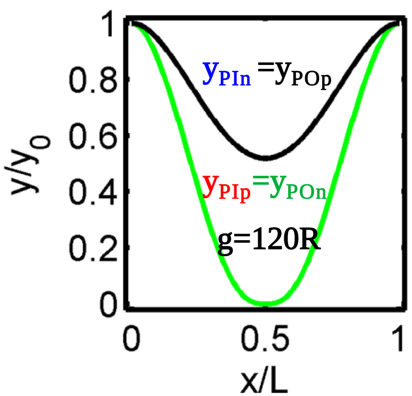




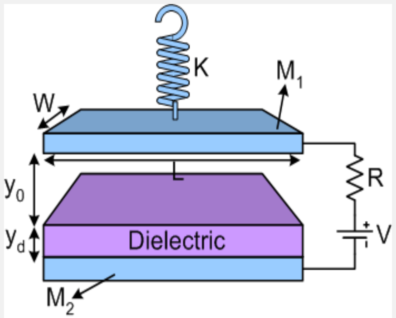


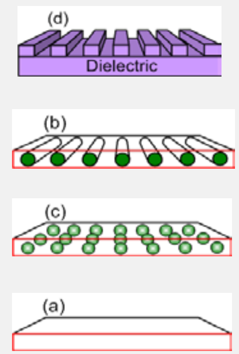


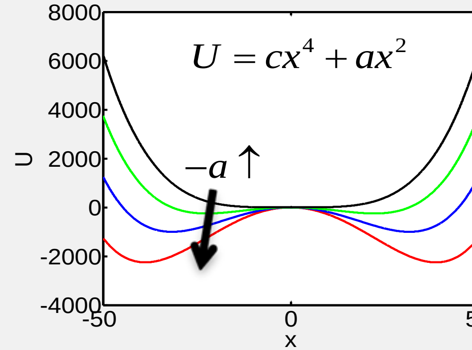


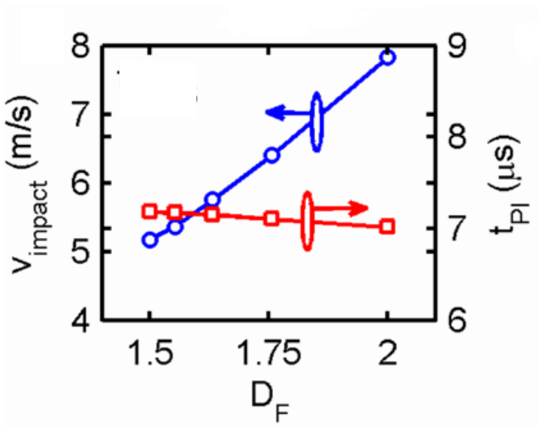


Conclusions: MEMS & Nanostructured Electrodes





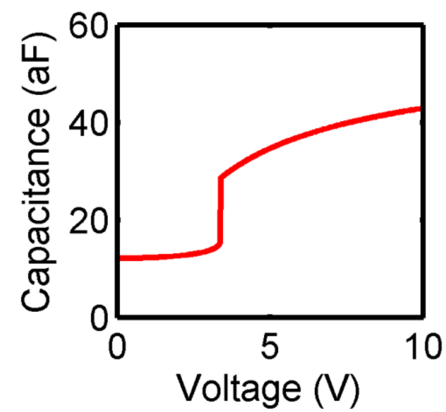




Impact velocity

$$y_c = \frac{D_F}{D_F + 1}$$

Travel Range

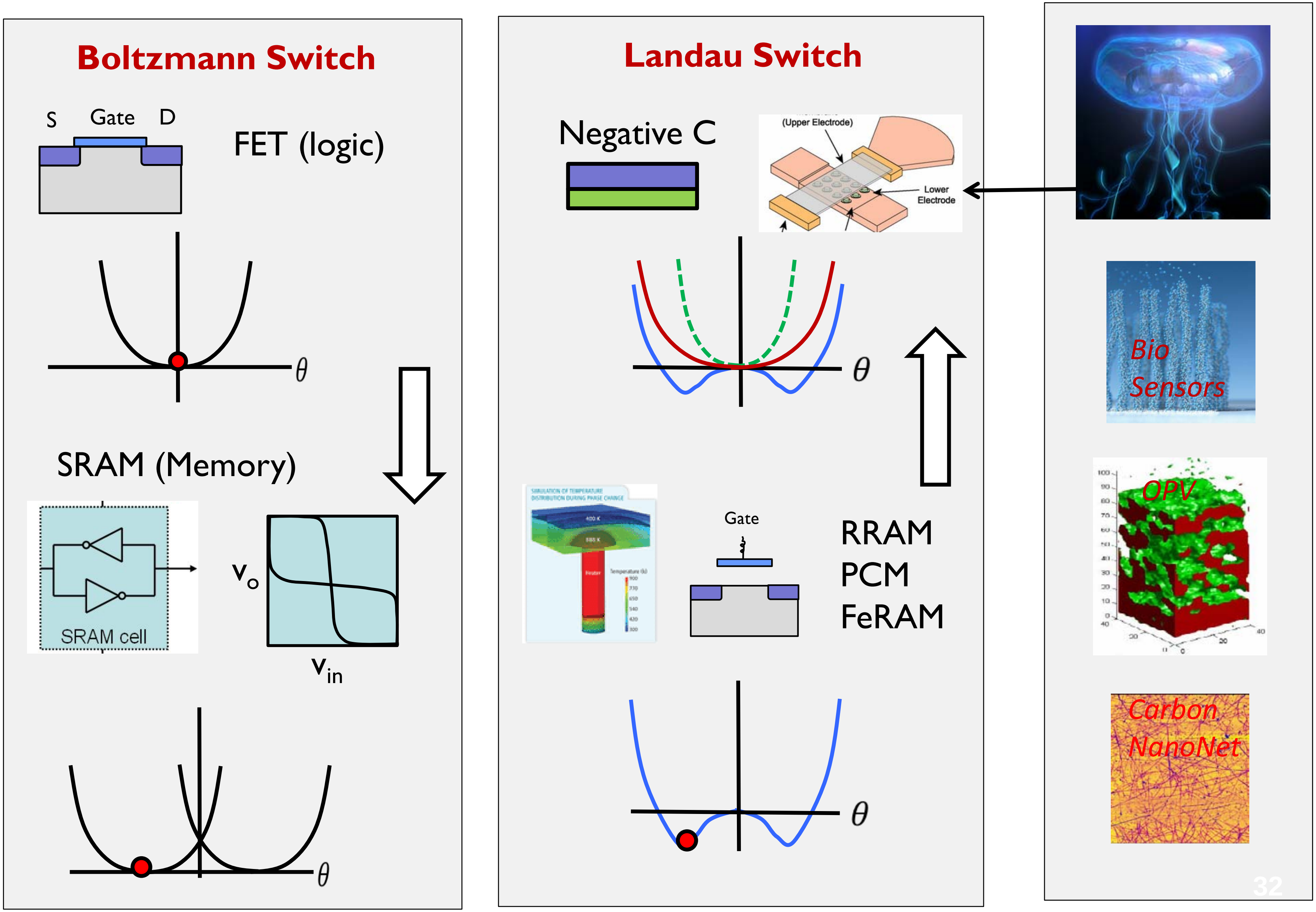


Hysteresis free

Geometrization of Electronic Devices:

www.ncn.purdue.edu/workshops/2009summerschool

Conclusions: Future of CMOS+ Technology



References

- H. Torun, APL, 91, 253113, 2007. Spring constant tuning of active atomic force microscope.
  G. Taylor, The coalescence of closely space drops" Proc. Roy. Soc. A, 306, 423, 1968. As a model for spherical electrodes in the MEMs configuration.

  http://www.memtronics.com/page.aspx?page_id=15 (Goldsmith dimpled structure)
  http://www.memtronics.com/files /Understanding%20and%20Improving%20Longevity%20in%20RF%20MEMS%20SPIE%206884-1.pdf
  http://www.google.com/patents?hl=en&lr=&vid=USPATAPP11092462&id=BEeZAAAAEBAJ&oi=fnd&dq=muldavin+switch+dimpled&printsec=abstract#v=onepage&q&f=false
  (corrugated top electrode).