Stiction failure in microswitches due to elasto-plastic adhesive contacts

L. WU, J.-C. GOLINVAL ,

L. NOELS

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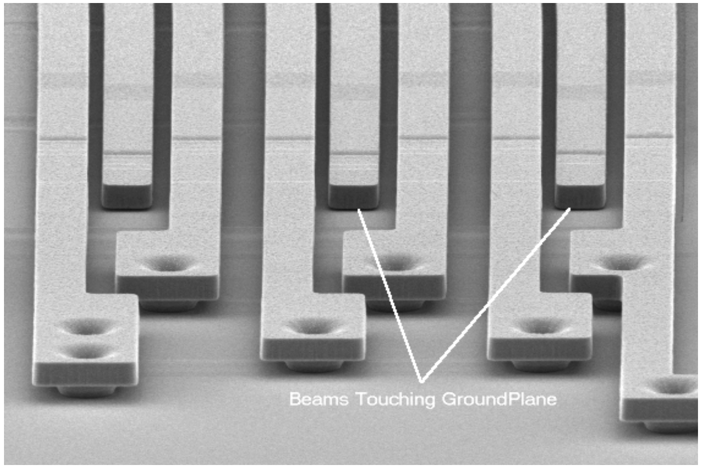
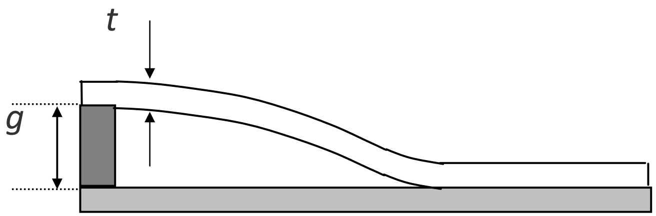
Introduction

- **Stiction in MEMS**



Stiction failure in a MEMS sensor

(Jeremy A.Walraven Sandia National Laboratories. Albuquerque, NM USA)



Reason:

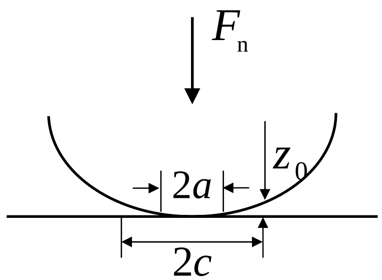
Relatively high surface area: volume ratio (1,000:1 to 10,000:1 m^{-1})

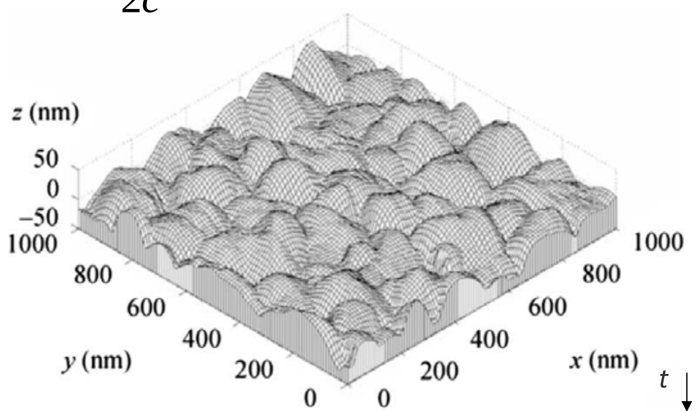
Adhesive forces:

Electrostatic force, Van der Waals force, Capillary force, Hydrogen bridging…

Introduction

- **Multiscale approach developed**

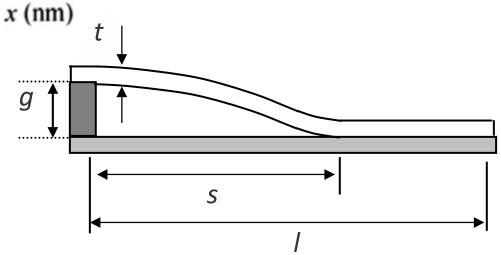




Single asperity adhesive-micro contact

Adhesive elastic contact model between rough surfaces

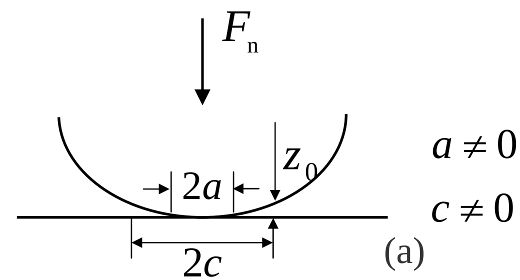
Integration with FEM



Single asperity adhesive-micro contact

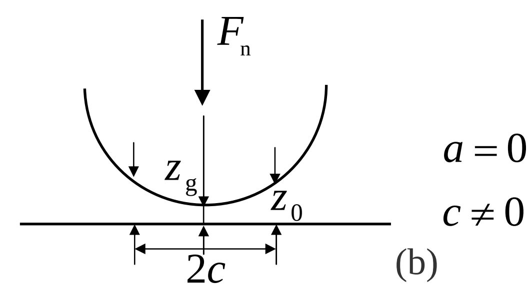
- **Adhesive-elastic contact (Hertz) theories**
  - **Johnson, Kendall, and Roberts (JKR)**
    - Short ranged surface forces
    - Act only inside the contact area

      $\Rightarrow$ Soft, compliant materials with high surface energy



  - **Derjaguin, Muller and Toporov (DMT)**
    - Long-ranged adhesive forces
    - Outside of the contact area

      $\Rightarrow$ Harder, less compliant materials with low surface energy and small asperity tip radius

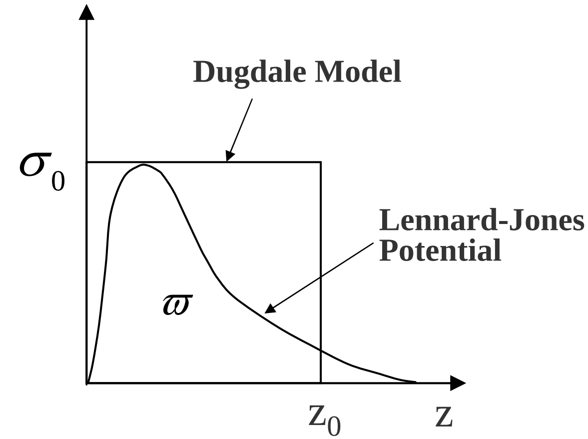


  - **Maugis transition solution**
    - Intermediate cases between JKR and DMT

      $\Rightarrow$ For all elastic materials

Single asperity adhesive-micro contact

- **Maugis transition solution**
  - **Based on a Dugdale assumption for interaction potential**
    - Constant traction σ_0 within a critical value of separation z_0
    - Zero traction for gap larger than z_0
  - **Maugis transition parameter λ**
    - Representation of the surface properties
      - R: asperity radius
      - K: equivalent elastic constant
      - $\varpi = \sigma_0 \, z_0$: adhesive work



$$\varpi = \sigma_0 \cdot z_0$$

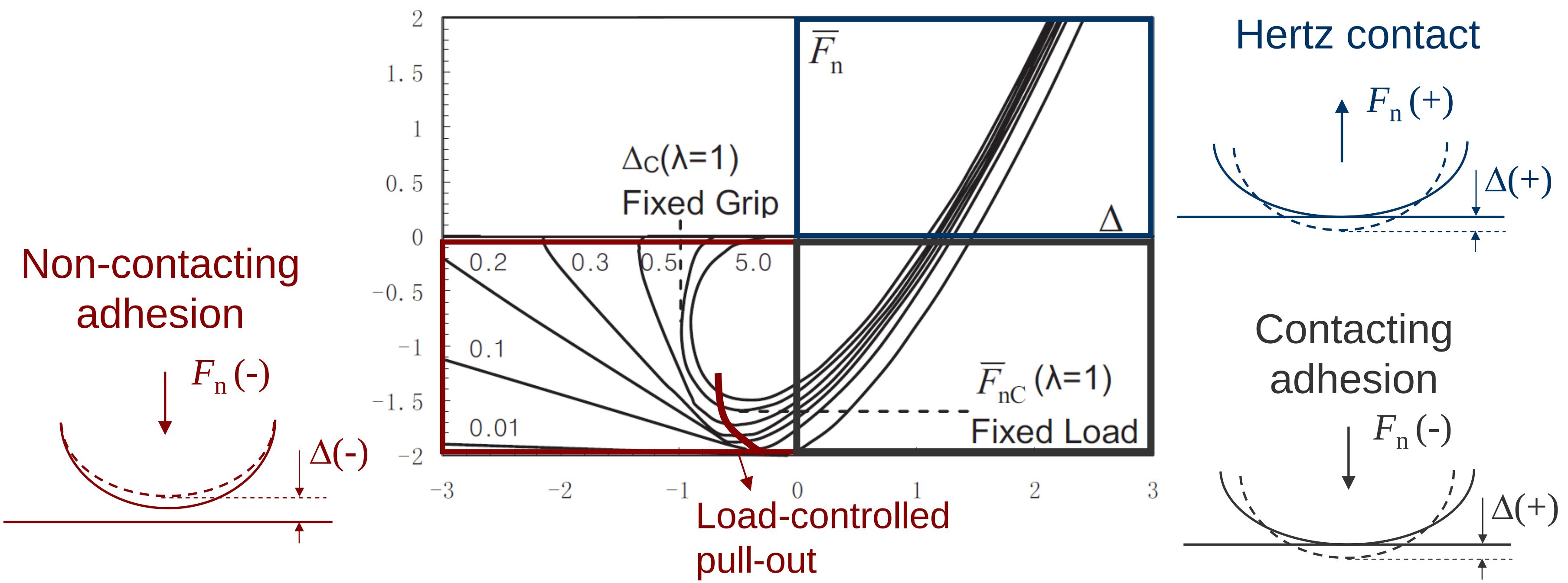
$$\lambda = \frac{2\varpi^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}} \quad \Rightarrow \quad \begin{array}{l} \varpi\uparrow, R\uparrow, K\downarrow \;\Rightarrow\; \lambda\uparrow \\ \varpi\downarrow, R\downarrow, K\uparrow \;\Rightarrow\; \lambda\downarrow \end{array}$$

JKR model (short ranged)

DMT model (long ranged)

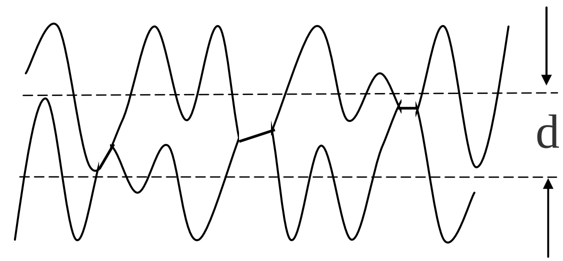
Single asperity adhesive-micro contact

- **Maugis transition solution (2)**
  - **Adhesive-micro (elastic) contact force during unloading**
    - In term of Maugis transition parameter $\lambda = \dfrac{2\varpi^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}}$



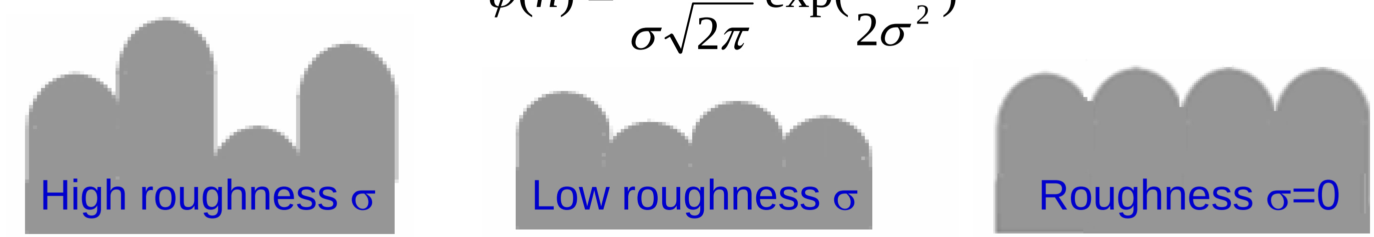
Adhesive contact between rough surfaces

- **Rough surfaces**
  - **Reduced number of interacting asperities**
  - **In terms of interference *d***



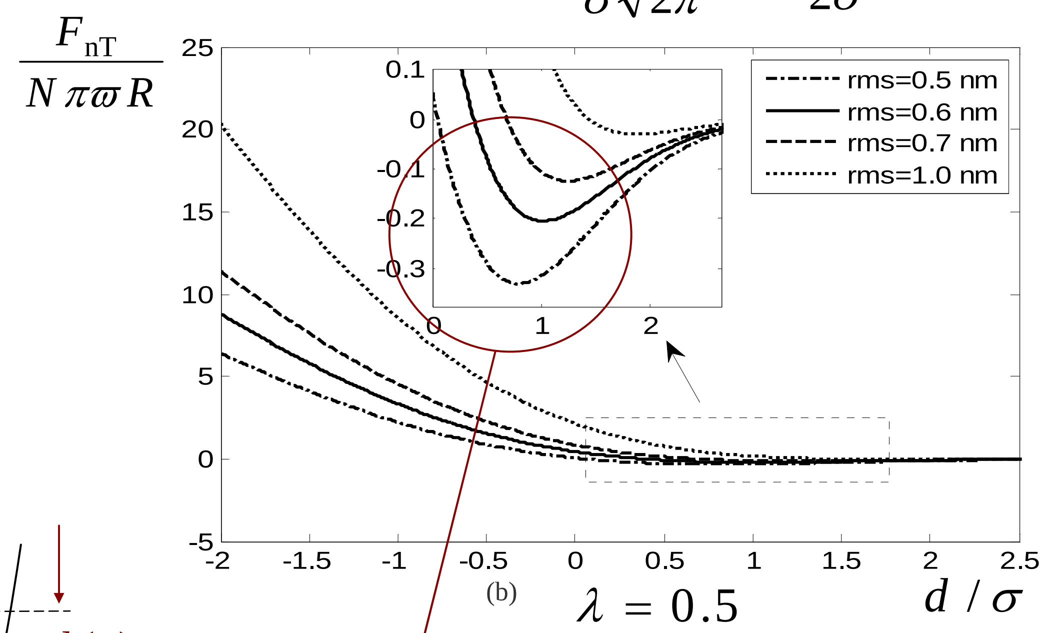
- **Rough surfaces model**
  - **Constant asperity tip radius**
  - **Statistical distribution in height *h***

$$\varphi(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-h^2}{2\sigma^2}\right)$$

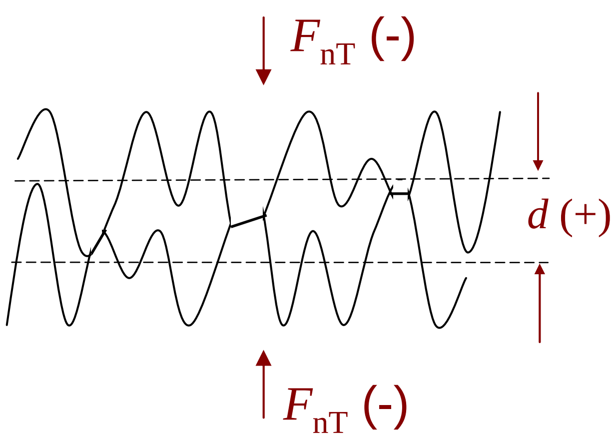


Adhesive contact between rough surfaces

- **Micro adhesive contact forces of rough surfaces**
  - **Integrate Maugis solution using** $\varphi(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp(\frac{-h^2}{2\sigma^2})$



Responsible for stiction

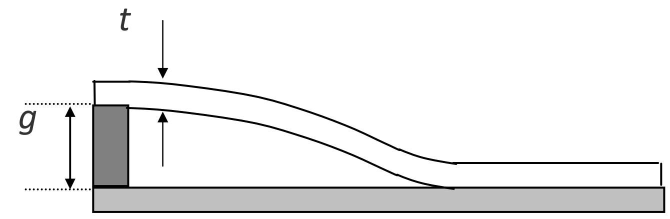


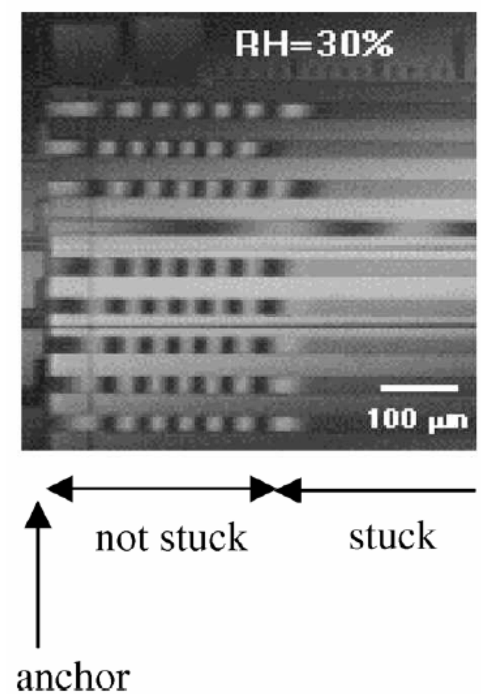
Multiscale Model

- **Design example: cantilevers**
  - **Finite element model**
    - Timoshenko Beams
    - Interacting with pad
  - **Use adhesive micro-contact law at interface**
    - Polysilicon-Polysilicon interactions
    - Surfaces properties from
      - AFM
      - Surface energy measured

In vacuum	$\varpi = 2.54$ J/m^2
In air	$\varpi = 0.167$ J/m^2

    - Contact remains elastic
  - **Validation vs literature experiments***

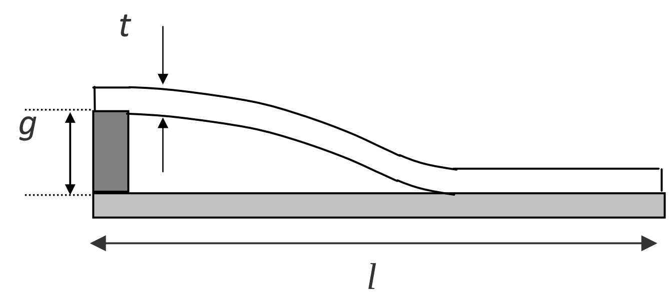


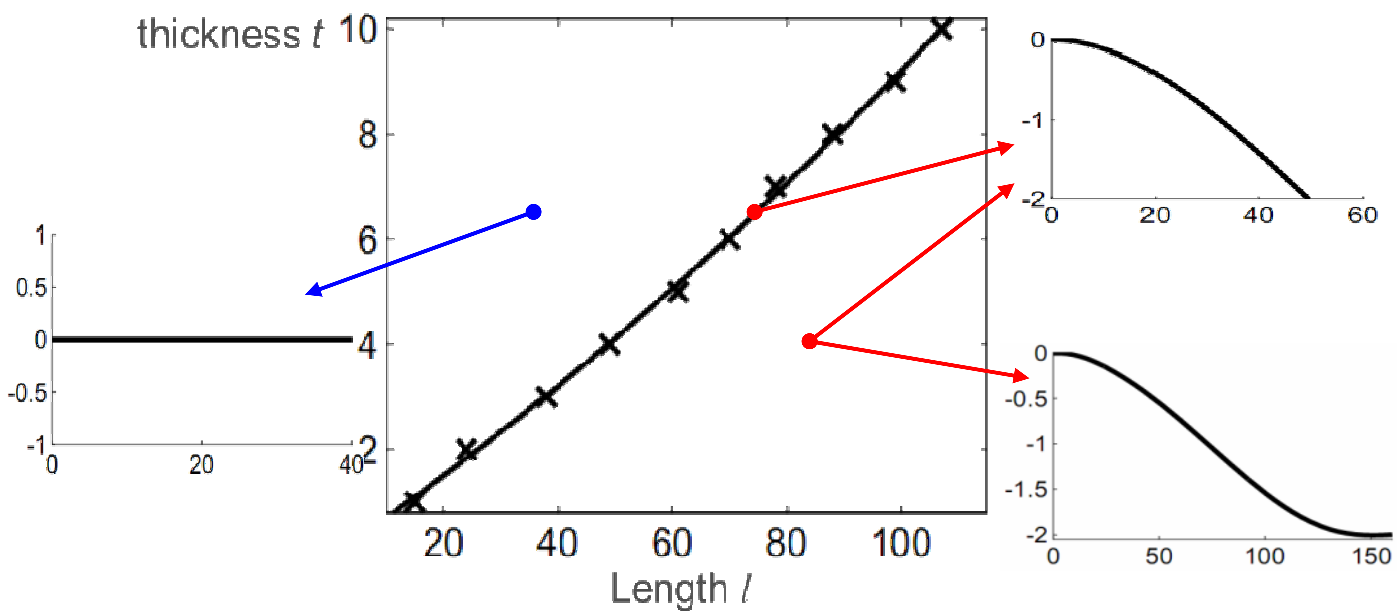


* W. M. van Spengen,, R. Puers and I. De Wolf, "On the physics of stiction and its impact on the reliability of microstructures," *J. Adhesion Sci. Technol.*, vol. 17, no. 4, pp. 563–582, 2003 (Analytical)
* M.P. de Boer, "Capillary adhesion between elastically hard rough surfaces," *Experim. Mech.*, vol. 47, pp. 171–183, 2007 (Experiment)

Multiscale Model

- **Design example: cantilevers (2)**
  - **Initial gap g = 2.0 μm**
  - **Admissible thickness *t* (μm) & length *l* (μm) ???**





Validation

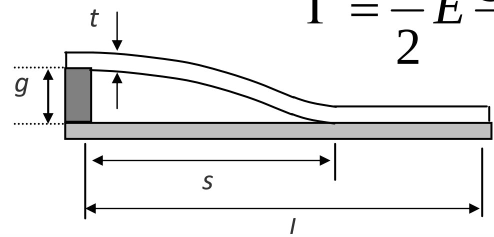
- **Literature*:**
  - **Measures of apparent adhesion energy Γ**
  - **Simplified models of Γ**
- **Numerical methods**
  - **Extract Γ from s**
  - **Environmental effect**

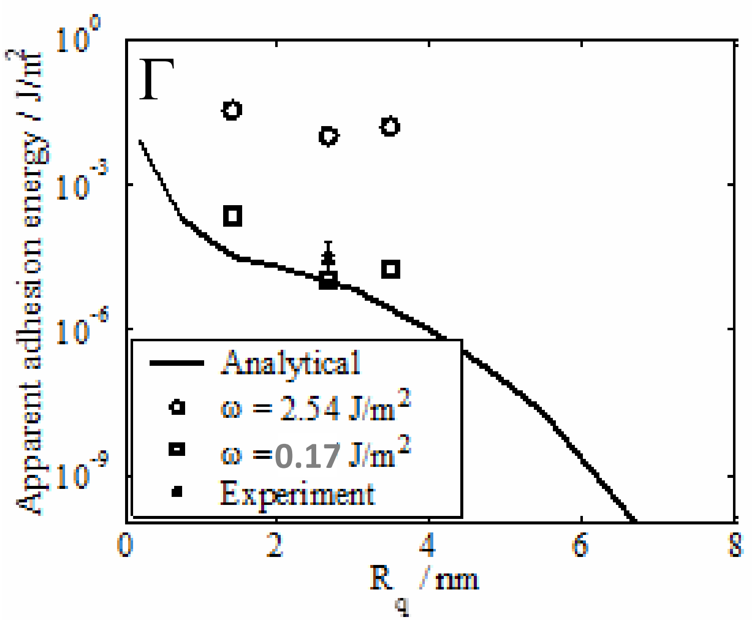
In vacuum	ϖ =2.54 J/m^2
In air	ϖ =0.167 J/m^2

- **Different samples**
  - **Surface roughness**

Sample	A	B	C
R_q (nm)	1.4	2.67	3.47

$$\Gamma = \frac{3}{2} E \frac{g^2 t^3}{s^4}$$





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Elasto-plastic adhesive contact

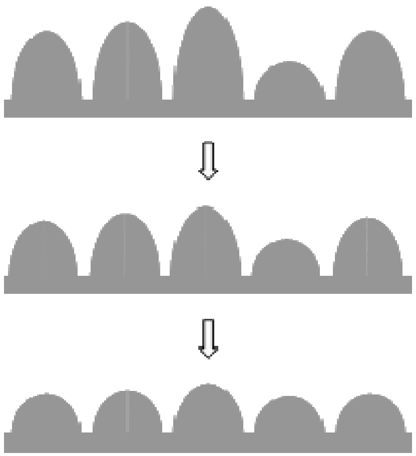
- Elasto-Plastic materials
  - Plastic deformations of asperities
- Repeated contact

Tip radii R of a part of asperities $\uparrow$

Surface roughness R_q $\downarrow$

Adhesive forces $\uparrow$

Stiction can appear after some cycles



- Elasto-plastic adhesive contact model is needed !

Elasto-plastic adhesive contact

- **Basic idea**
  - **Adhesive contact model of the elastic-plastically deformed of asperity**

Numerical results for an elasto–plastic loaded sphere in contact without adhesive forces

Maugis' adhesive contact theory is performed on the equivalent elastic deformed asperity

  - **Asperity-based rough surface model**

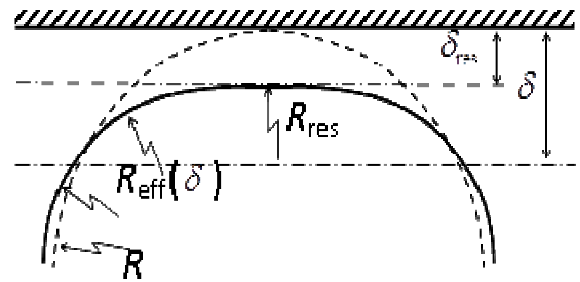
Elasto-plastic adhesive contact

- **Plastic deformations of a loaded single asperity**
  - **Curve fitting of FE simulations***
    - Effect of maximum inteference δ_{max} reached during loading
    - Material parameters: yield S_Y, yield interference δ_{CP}
  - **Residual interference**

$$\delta_{res} = \delta_{\max}\left(1-\left(\frac{\delta_{\mathrm{CP}}}{\delta_{\max}}\right)^{0.28}\right)\left(1-\left(\frac{\delta_{\mathrm{CP}}}{\delta_{\max}}\right)^{0.69}\right)$$

  - **Residual tip radius**

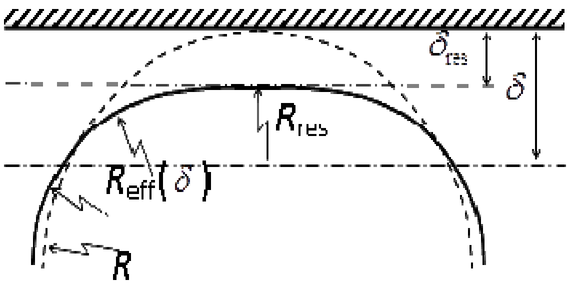
$$R_{\mathrm{res}} = R\left(1+1.275\left(\frac{S_y}{E}\right)^{0.216}\left(\frac{\delta_{\max}}{\delta_{\mathrm{CP}}}-1\right)\right)$$



* Etsion I., Kligerman Y., Kadin Y., Unloading of an elastic–plastic loaded spherical contact, International Journal of Solids and Structures 42 (2005) 3716–3729

Elasto-plastic adhesive contact

- **Adhesive unloading of a single deformed asperity**
  - **Define an equivalent elastic asperity**
    - Interference $\delta_{\mathrm{eff}} = \delta - \delta_{\mathrm{res}}$
    - Asperity tip radius $R_{\mathrm{eff}} = R_{\mathrm{eff}}(R, \delta, \delta_{\max})$



  - **Apply Maugis**
    - Extract adhesive-micro contact force

$$F_{\mathrm{n}} = F_{\mathrm{n}}(\delta - \delta_{\mathrm{res}}, R_{\mathrm{eff}})$$

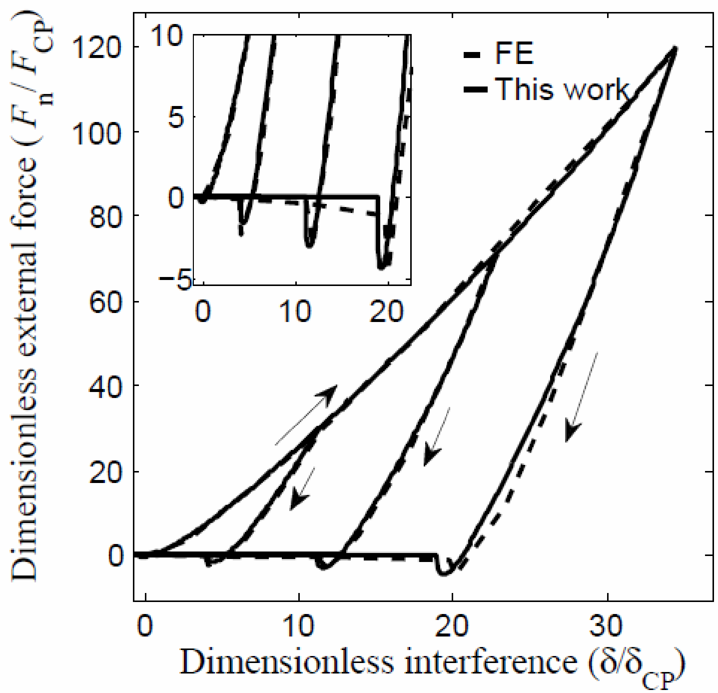
* Etsion I., Kligerman Y., Kadin Y., Unloading of an elastic–plastic loaded spherical contact, International Journal of Solids and Structures 42 (2005) 3716–3729

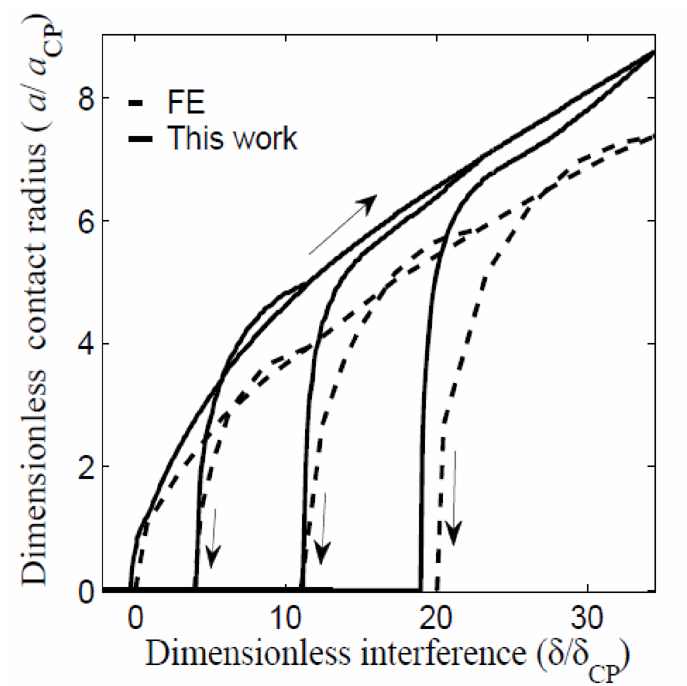
Elasto-plastic adhesive contact

- Adhesive loading/unloading of a single asperity
  - Material: Ru

R	E	ν	S_Y	z_0	ϖ
4 nm	410 GPa	0.3	3.42 GPa	0.169 nm	1 J/m^2

  - Model vs FE*





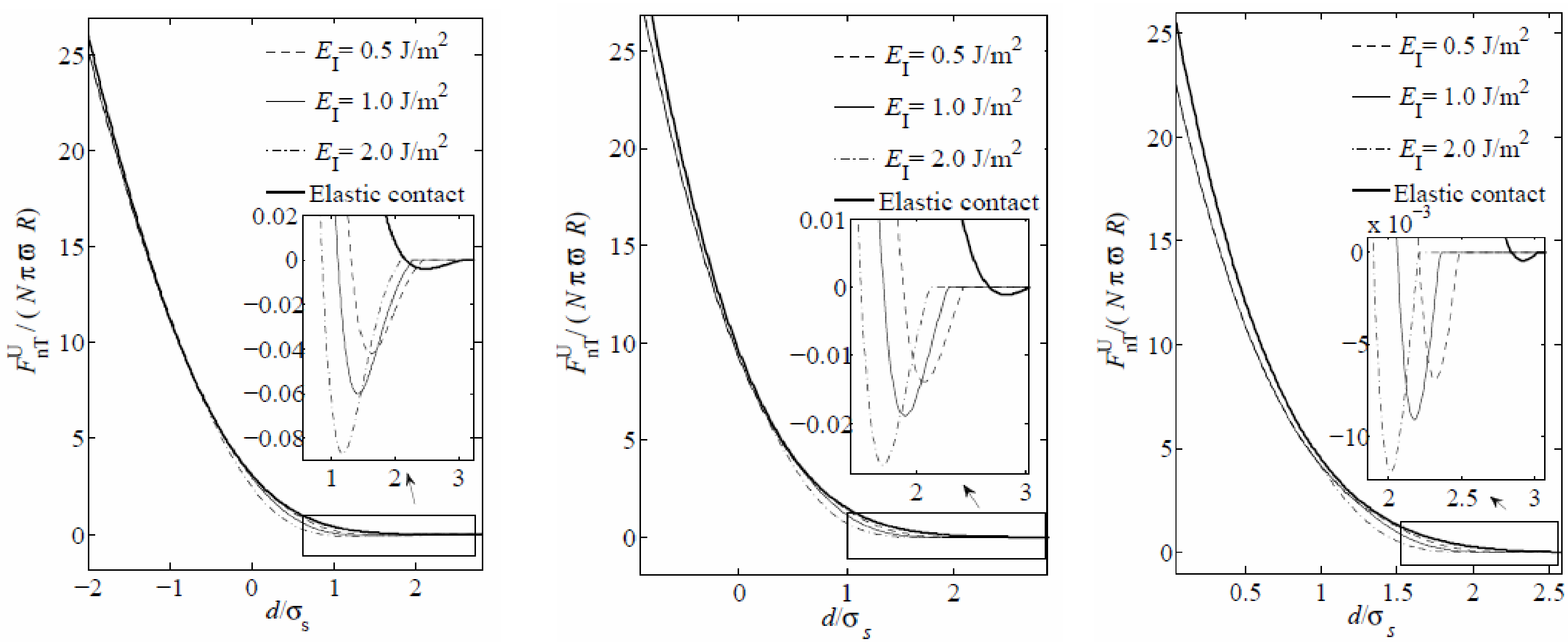
* 28Y. Du, L. Chen, N. McGruer, G. Adams, and I. Etsion, Finite element model of loading and unloading of an asperity contact with adhesion and plasticity," Journal of Colloid and Interface Science 312, 522 - 528 (August 2007)

Elasto-plastic adhesive contact

- **Adhesive unloading of rough surfaces**
  - **Different Ru samples**

Sample	A	B	C
R_q (nm)	2.03	3.99	7.81

  - **Effect of impact energy at pull-in on plastic deformations**

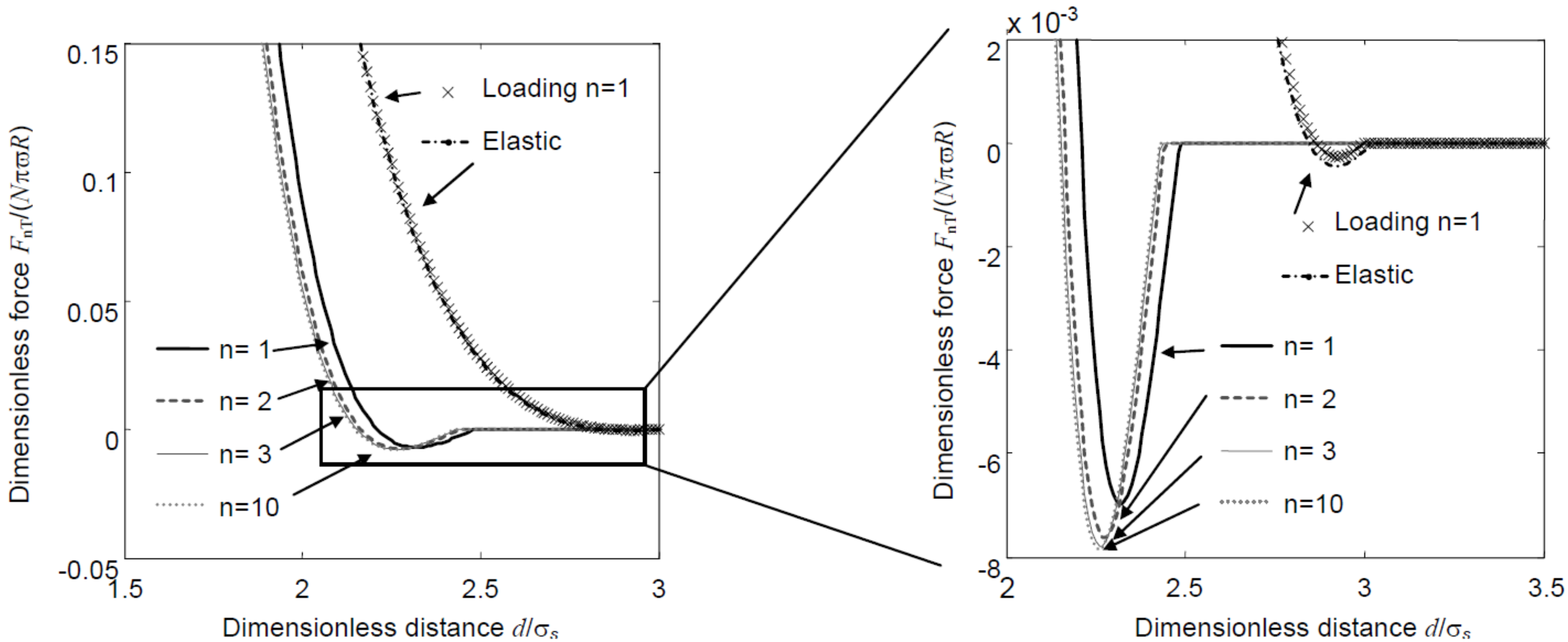


(a)Sample A (b)Sample B (c)Sample C

Elasto-plastic adhesive contact

- **Time life of MEMS**
  - **Repeated loading/unloading ⇨ changes in surfaces profile**
  - **Asperity profile can be updated by tracking history $\delta_{max}(h)$**
  - **Ru sample**

Sample	Rq (nm)	E_I (J/m^2)
C	7.81	0.5



Conclusions

- The adhesion between the contact surfaces has large influence on the design of MEMS switches, and need to be considered carefully
- The adhesive work and the surface roughness are the main factors of adhesive force
- The analytical adhesive contact results can be combined with FEM to predict the stiction of more complicated structures
- Effect of plasticity can be accounted for
- The other kinds of adhesive forces, such as capillary force, electrostatic force from dielectric charging, are not considered

Thank you!