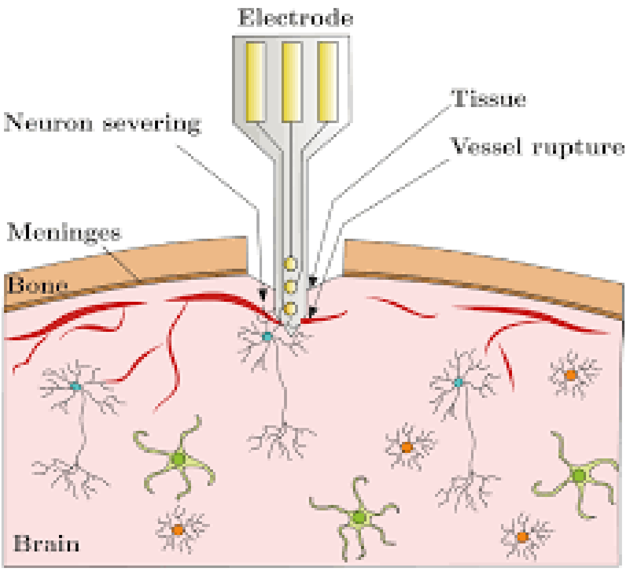
# Mechanical considerations for designing neural implants

Applications in Neural Microsystems
Lecture 10

# Source of interactions between device and tissue

- Surgical procedure: insertion (penetration)
- Repositioning of the device inside the tissue
- Oscillatory motions (Micromotions)



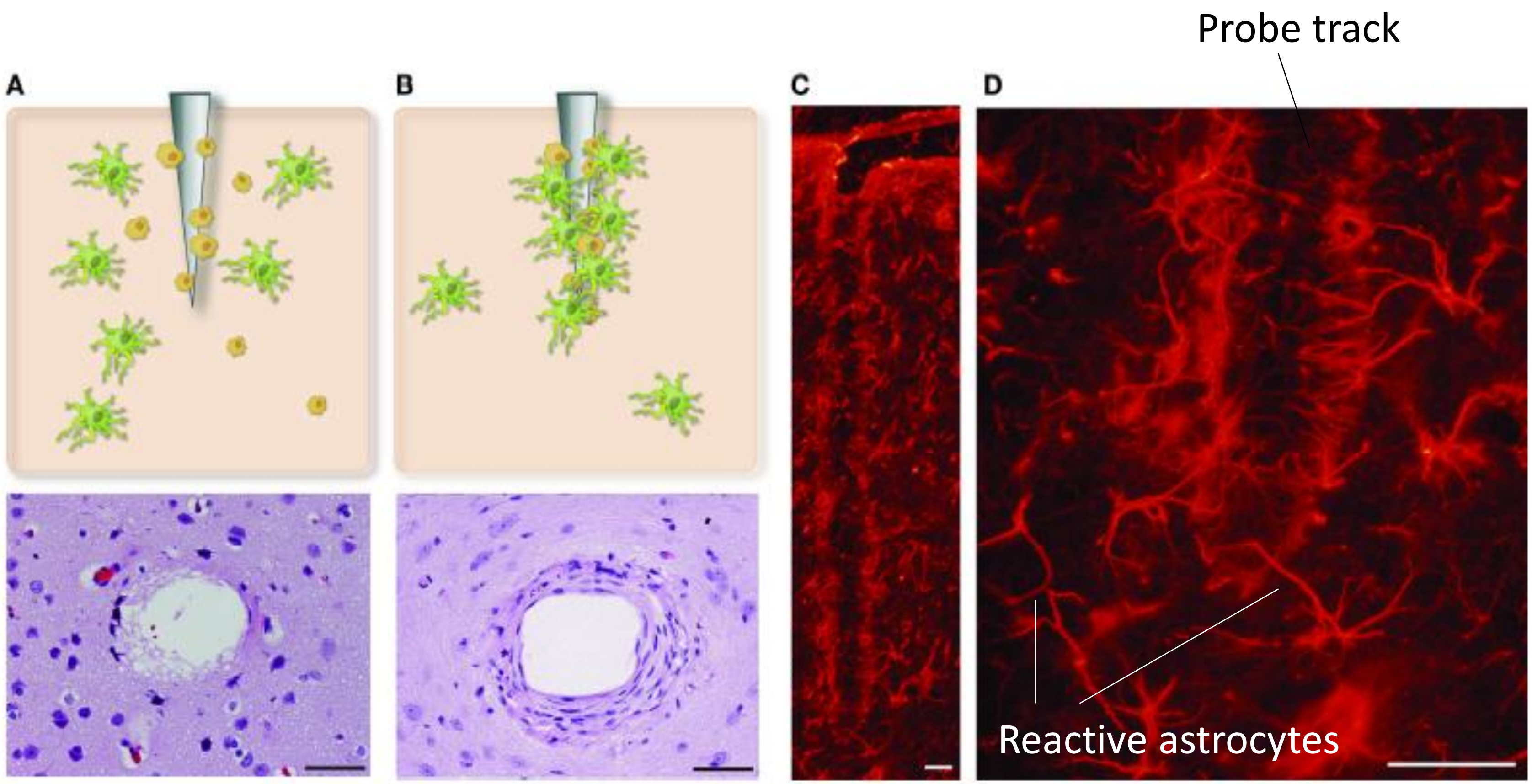
Trauma of insertion

## Significance

- Induces neuronal loss
- Contributes to structural failures of the device

# Results of tissue trauma

Implanted device elicit foreign body response (encapsulation)




*Marin, 2010*

# Device perspectives

# Device properties influencing mechanical response

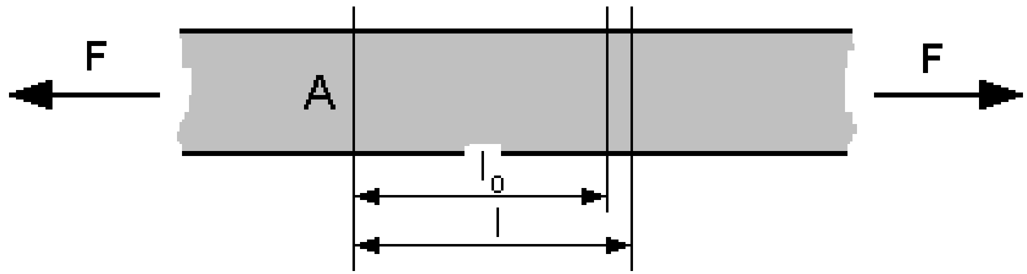
- Sensor geometry (structural design)
- Chemical and physical nature of boundary interfaces
- Bulk properties (Flexibility, softness, density)
- Packaging, interconnections

Other important variables:

- Implantation methods (device sterilization, insertion speed)
- Variability in biological properties of the target tissue

# Mechanical loads during tissue-device interaction

# Definitions in solid mechanics




Stress

(compressive, tensile)

$$\sigma = \frac{F}{A}$$ [N/m²]

Strain

$$\varepsilon = \frac{l - l_0}{l_0}$$ [ - ]

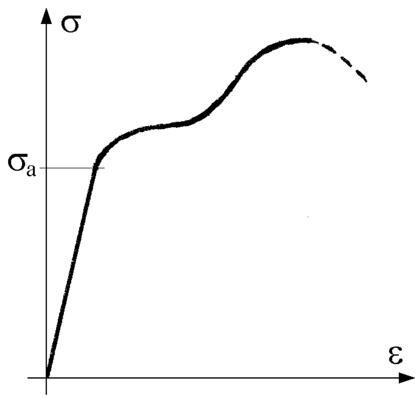
# Definitions in solid mechanics

$\sigma$ vs $\varepsilon$?

Linerar approximation:

**Hooke's law**

$$\boxed{\sigma = E \cdot \varepsilon}$$




***E*** constant parameter

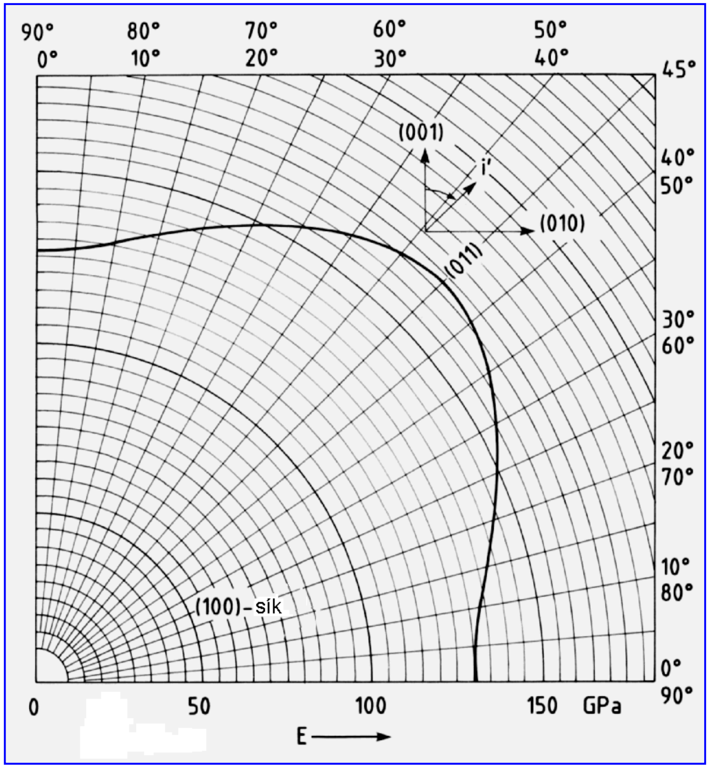
Elastic modulus

**Young's modulus** [N/m$^2$]

Silicon as mechanical carrier of neural probes is particularly sensitive to the direction of load

In crystalline structures:

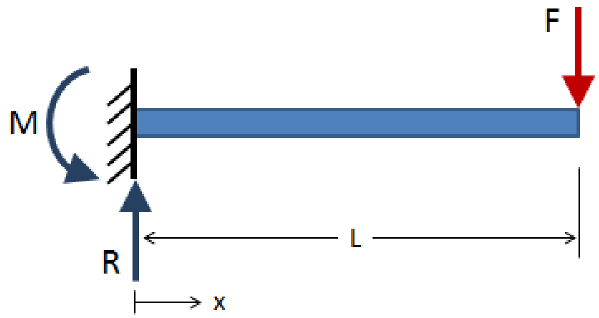
***E*** is anisotropic




**Silicon**

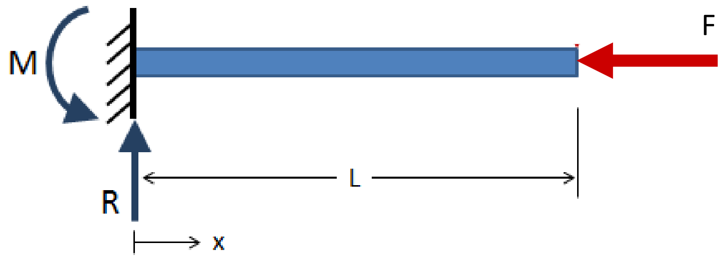
# Mechanical loads during insertion

Bending




Tangential forces during insertion
Lateral forces after insertion

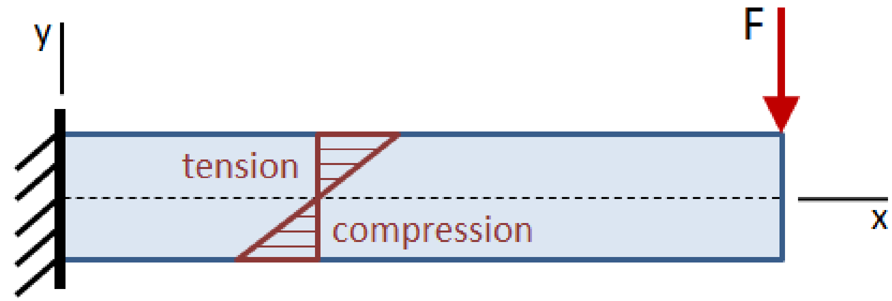
Buckling




Normal forces during penetration

Fracture - thin film or substrate

# Bending

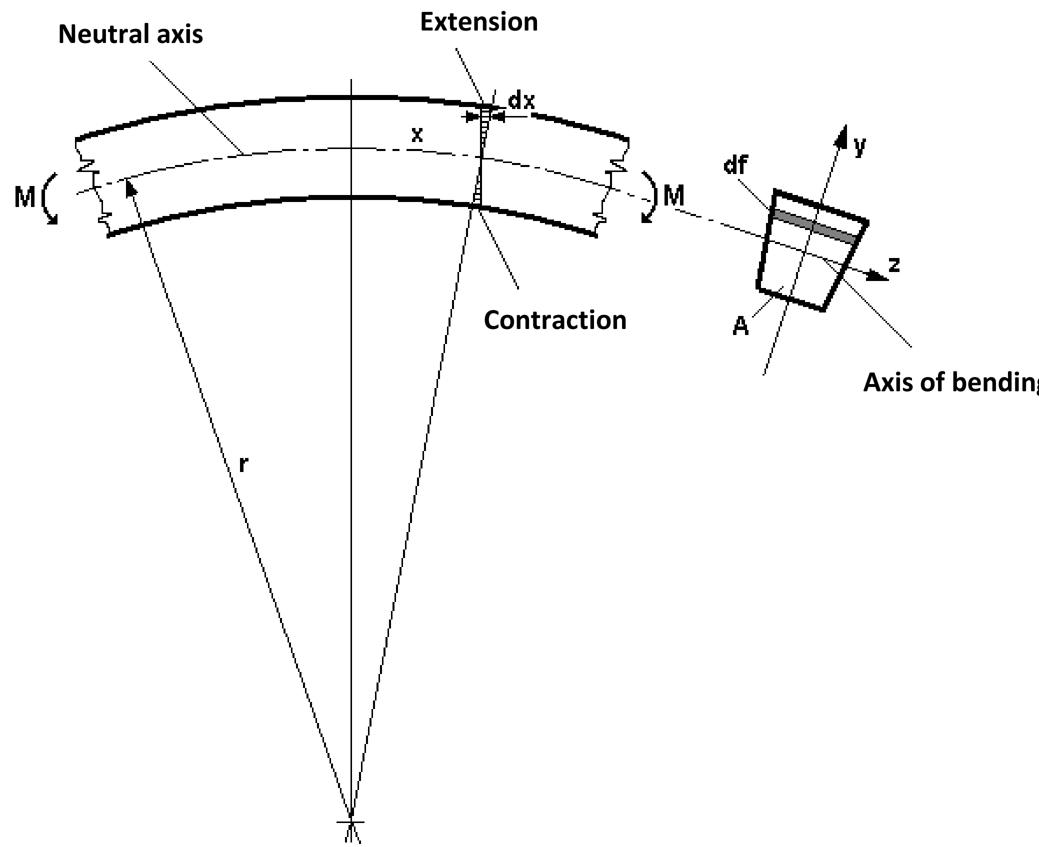



$$\frac{x}{r} = \frac{dx}{y} \quad \rightarrow \quad \varepsilon = \frac{dx}{x} = \frac{y}{r} \;,$$

$$\sigma = E\varepsilon = \frac{E}{r}\,y$$

$$F = \int_A \sigma \, df = \frac{E}{r}\int_A y \, df = 0 \;,$$

$$\boxed{\int_A y \, df = 0 \;.}$$




Neutral axis goes through the center of mass. Neutral axis is less prone to the change in bending/buckling force.

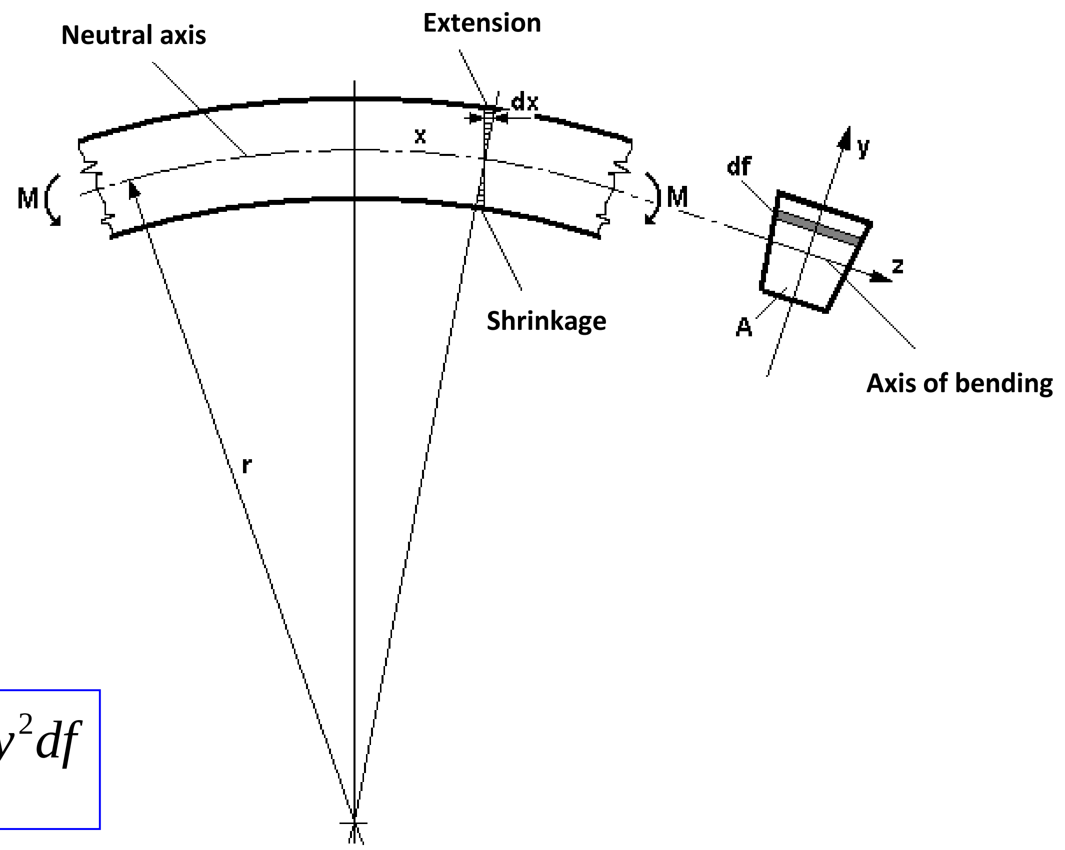
# Bending

How to calculate bending radius?

$$\sigma = E\varepsilon = \frac{E}{r} y$$

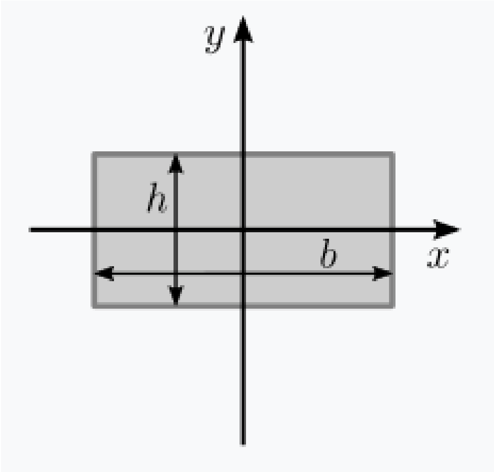
$$M = \int_A y\,\sigma\, df = \frac{E}{r}\int_A y^2\, df \quad ,$$

$$\boxed{\frac{1}{r} = \frac{M}{E\,I}}$$ where $$\boxed{I = \int_A y^2 df}$$



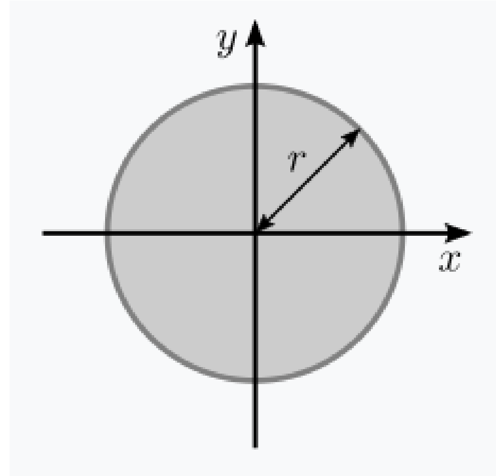

$\boldsymbol{I}$ - second moment of area → depends on cross-section only!

# Second moment of inertia for various canteveler cross-sections in MEMS




$$I_x = \frac{bh^3}{12}$$

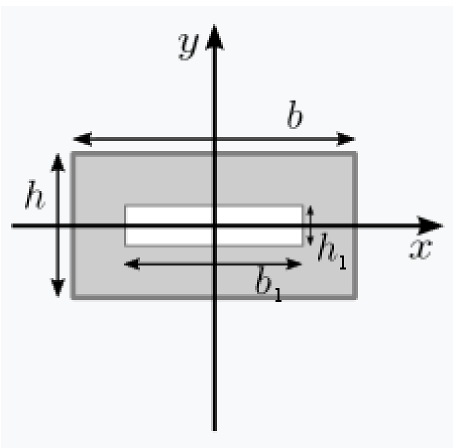
$$I_y = \frac{b^3 h}{12} \text{ [4]}$$




$$I_x = \frac{\pi}{4} r^4$$

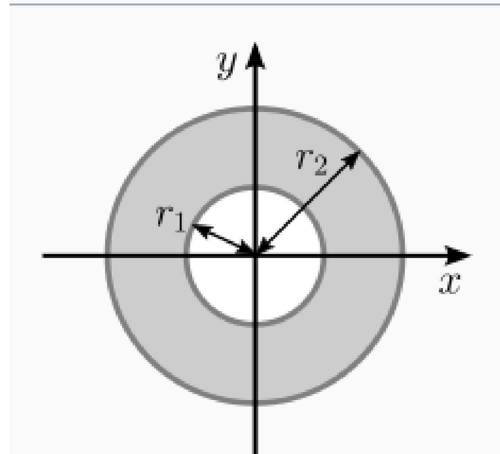
$$I_y = \frac{\pi}{4} r^4$$

$$I_z = \frac{\pi}{2} r^4 \text{ [1]}$$




$$I_x = \frac{bh^3 - b_1 {h_1}^3}{12}$$

$$I_y = \frac{b^3 h - {b_1}^3 h_1}{12}$$




$$I_x = \frac{\pi}{4} \left({r_2}^4 - {r_1}^4\right)$$

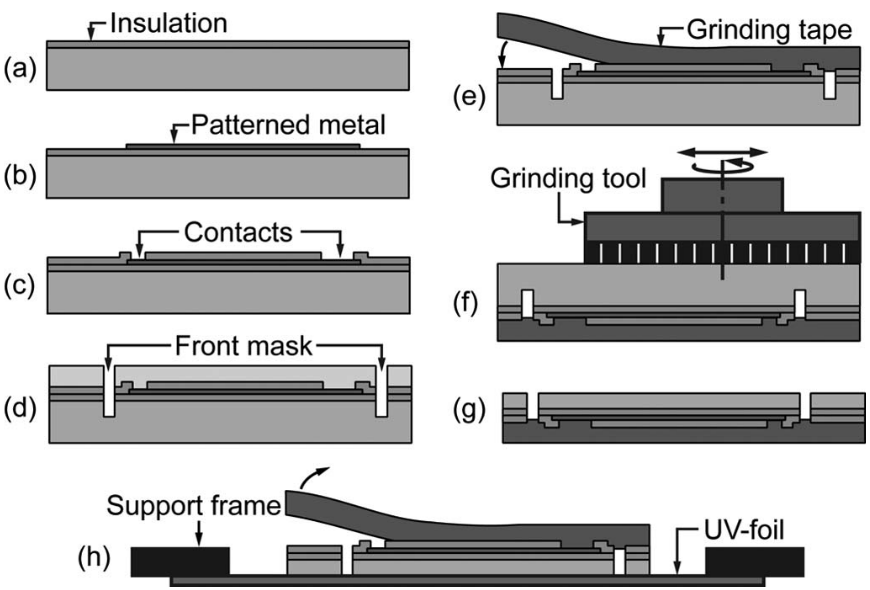
$$I_y = \frac{\pi}{4} \left({r_2}^4 - {r_1}^4\right)$$

$$I_z = \frac{\pi}{2} \left({r_2}^4 - {r_1}^4\right)$$

Functional components integrated in the substrate of neural probes (e.g. microfluidics, waveguides etc) alters $\boldsymbol{I}$.

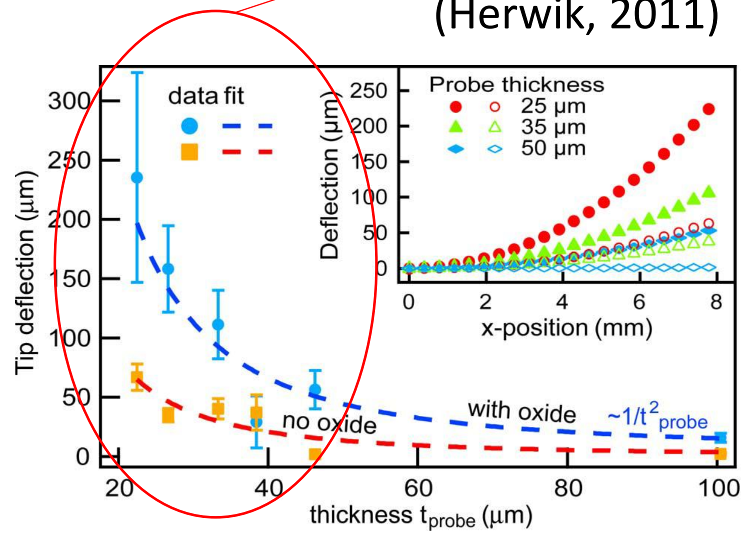
# Thin probes are prone to deflection without external forces

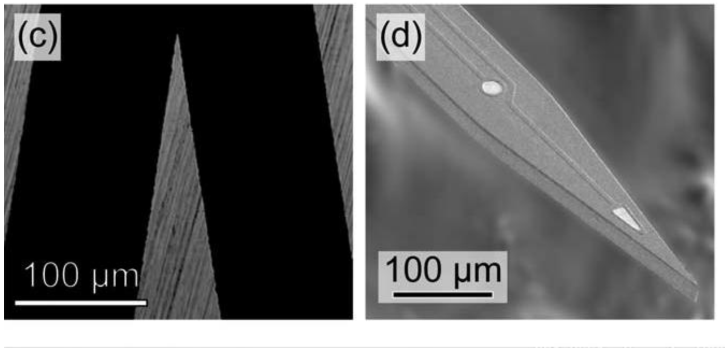
Technology to thinning: etching-before grinding



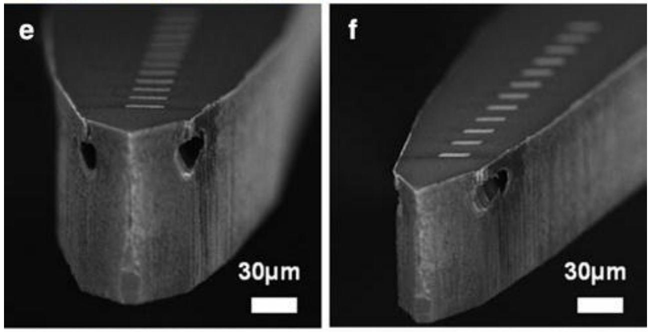

Residual stress!

(Herwik, 2011)

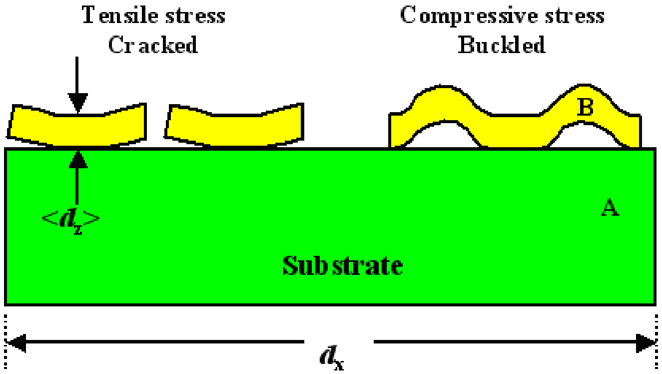



Fekete, 2015



# Reason for inherent deflection: Residual stress




Reason: high-temperature processes/annealing

- mismatch in CTE (coefficient of thermal expansion)

Example: $SiO_2$ is deposited on a 4" Si wafer at *700 °C* ($\alpha_{Si}=3*10^{-6}\ 1/K$, $\alpha_{SiO2}=0.6*10^{-6}\ 1/K$)

$\Delta L = \alpha * L0 * \Delta T$ $\Delta L_{Si} < \Delta L_{SiO2}$ Compressive stress is built up!

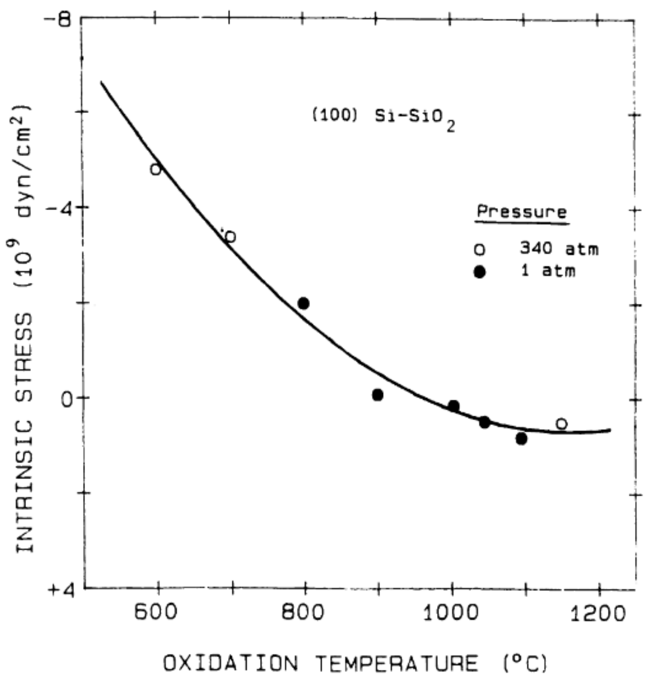
Thermal strain: $\varepsilon_{therm} = \Delta T * \Delta\alpha \sim 0.2mm$

Stress management is an essential part of technology design!

# Residual stress depends on deposition parameters

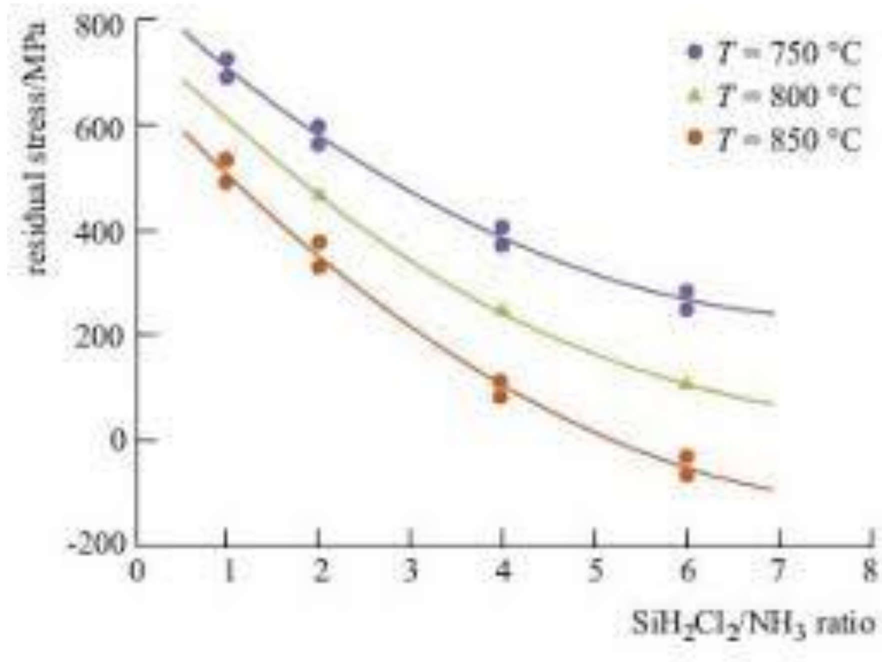
**Examples**

Silicon dioxide




*Lang, 1992*

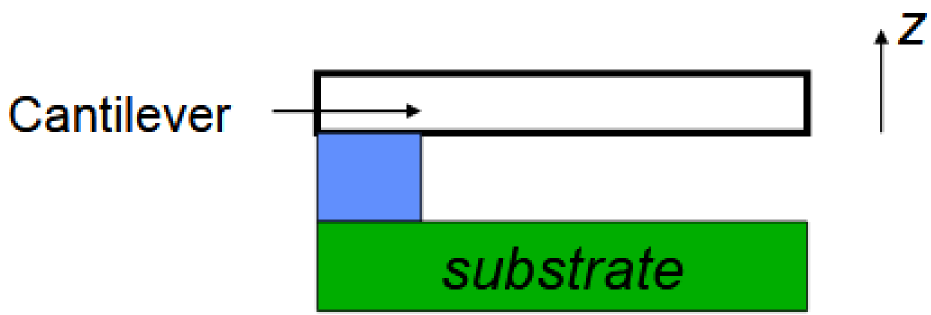
Silicon-nitride



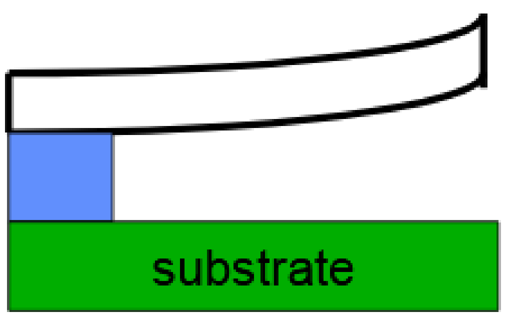

*Open.edu*

What parameters determines instrinsic stress?
Process temperature, precursor (gas) ratio, annealing profile, initial CTE of materials

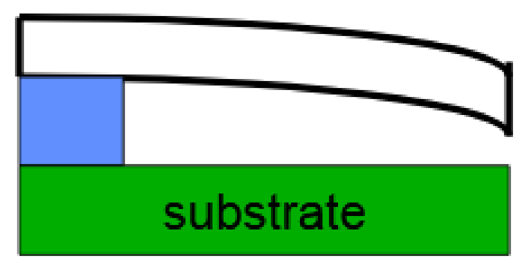
# Effects of intrinsic stress on cantilever deflection




(1) No stress gradient along z-direction

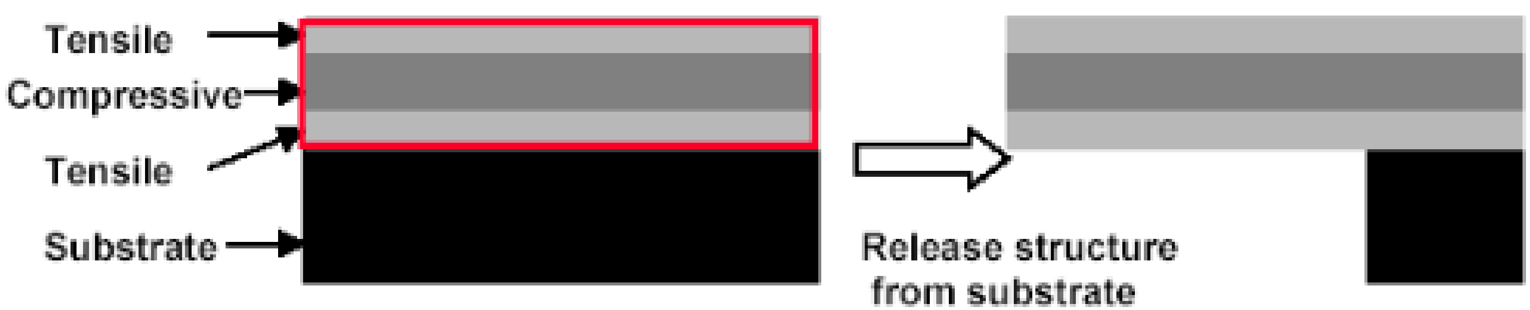



(2) Higher tensile stress near top surface of cantilever before release from substarte

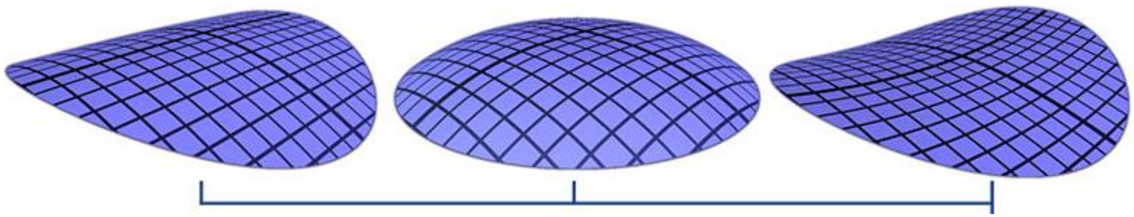



(3) Higher compressive stress near top surface of cantilever before release from substrate

# How to compensate thin film stress?

# How to measure residual stress?



Radius of Curvature of warpage

$$r = \frac{E_s \times t_s^2}{(1-\nu)_s \times 6 \times \sigma_f \times t_f}$$

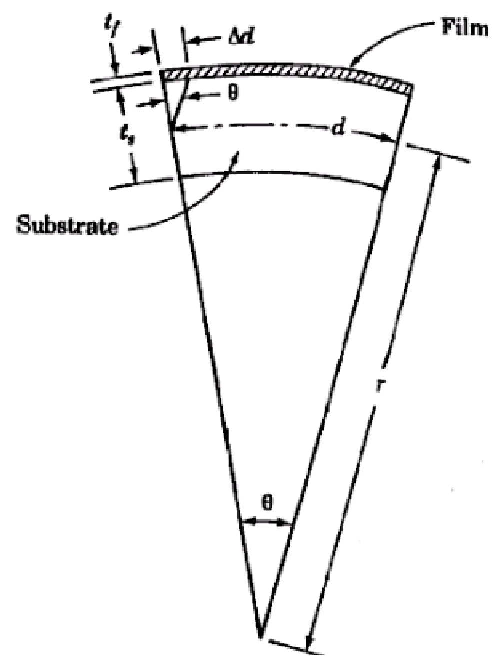
**"Stoney Equation"**

$t_s$ = substrate thickness

$t_f$ = film thickness

E = Young's modulus of substrate

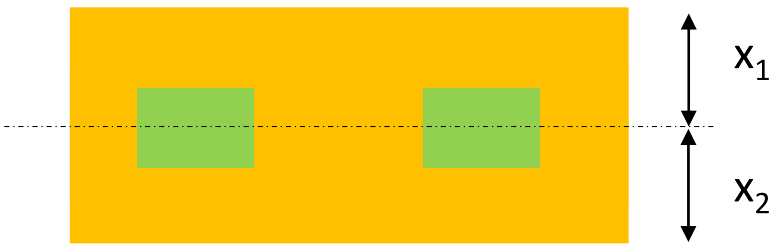
n = Poisson's ratio of substrate



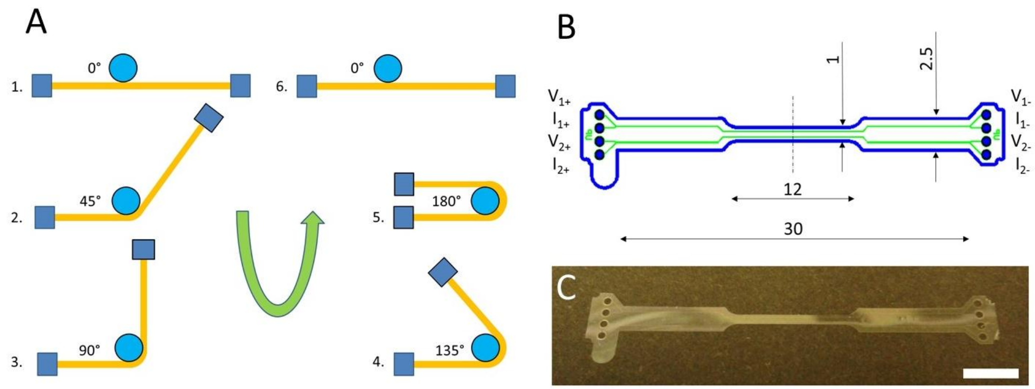

Residual stress typical of a deposition step can be derived from wafer (substrate) curvature

# Optimal location of thin film elements to reduce failure due to bending stress

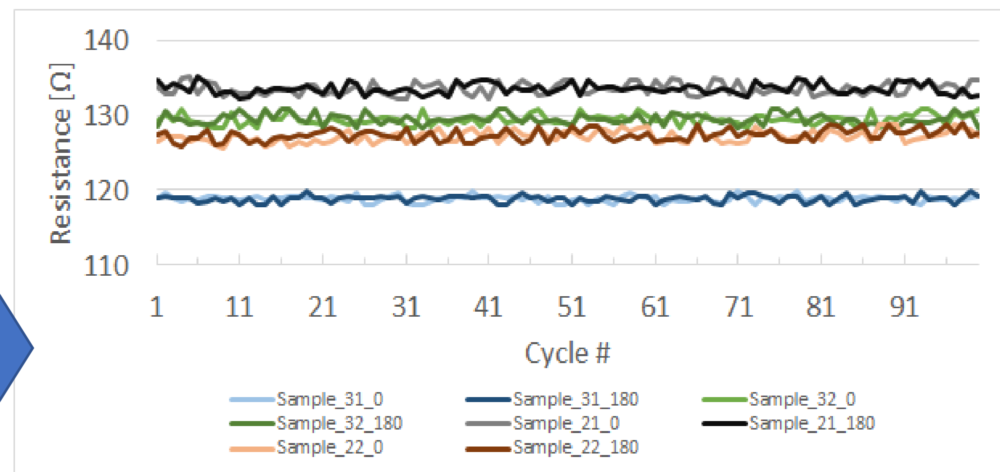
Recommended composition for flexible probes:




Polymer Metal $X_1 = X_2$




Result: no change in electrical behaviour of flexible implants with brittle conductive layers (Pt, ITO etc)



# Buckling

Unlike bending, its a failure mode! (structural damage is induced if occurs)

$$P_{CR} = \frac{\pi^2 EI}{L^2}$$

Euler's Equation

$P_{CR}$ = critical or maximum axial load on the column just before it begins to buckle.

E = modulus of elasticity for the material

I = least moment of inertia of the column's cross-section

L = unsupported length of the column, whose ends are pinned

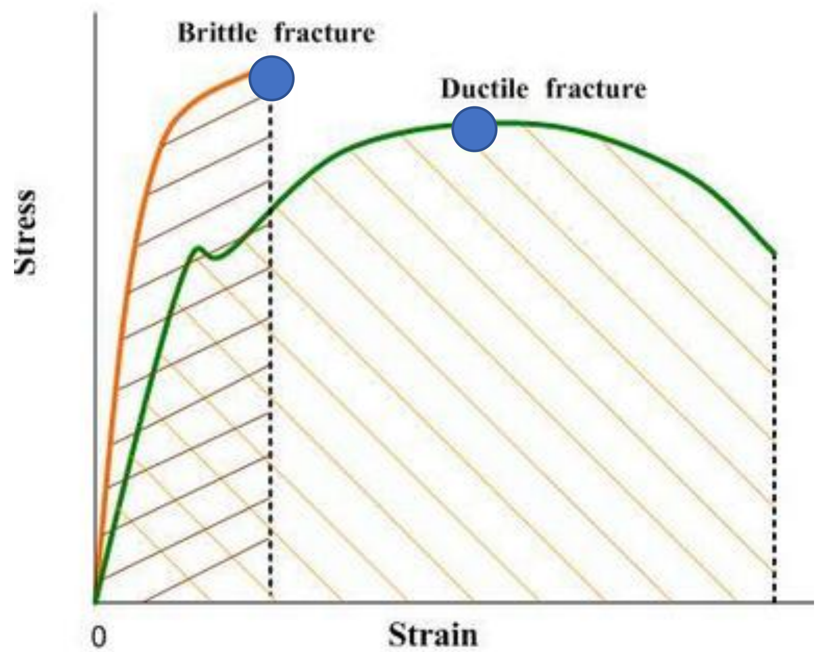
# Fracture

- External axial forces above the critical buckling force may lead to fracture.
- The overall stress during buckling leads to fracture when approaching the ultimate tensile strength

Ultimate tensile strength: maximum stress that a material can withstand while being stretched or pulled before breaking. ( ● )

Silicon is hard, but brittle.
(7000 MPa).

Thin films have usually lower tensile strength. (Signal quality may predict device failure)



# Application perspective

# Device insertion (biomechanics)

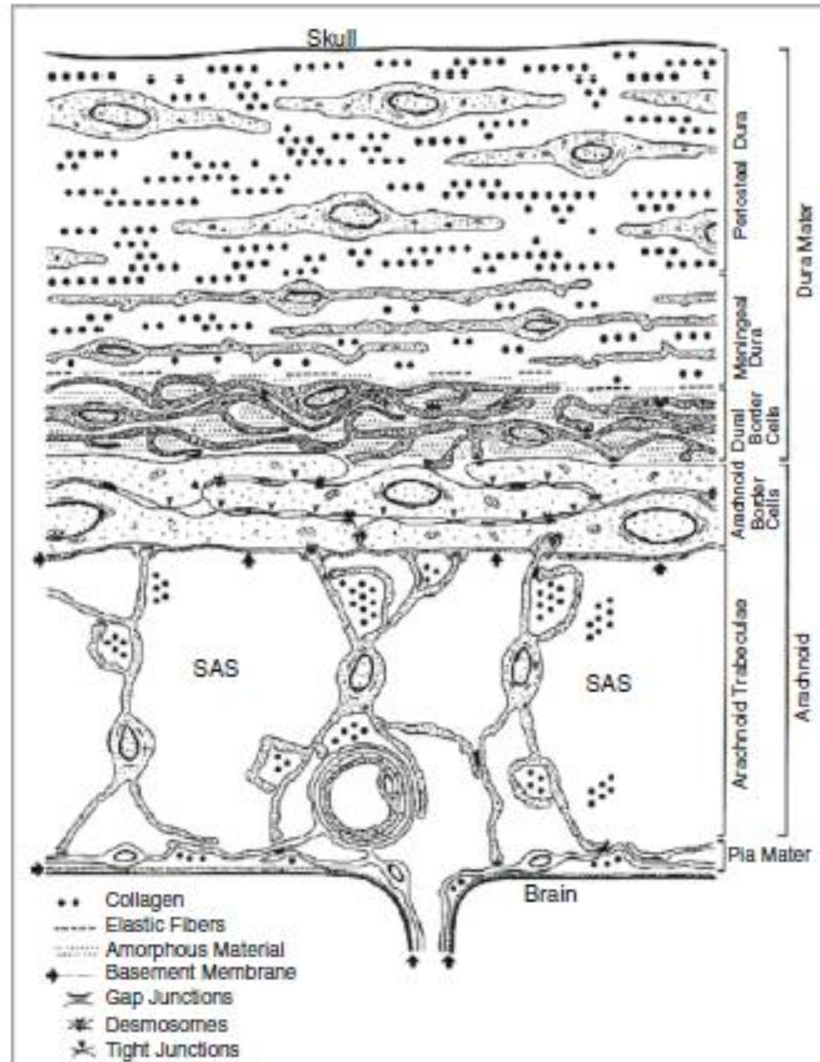
Trade-off between two fundamental aims:

- To avoid device failure
- To avoid tissue damage

Major biological barriers:

- Meninges (dura and pia mater)
- Gray and white matter

Rupture of this barrier iniate foreign body response (detailed in upcoming lecture)

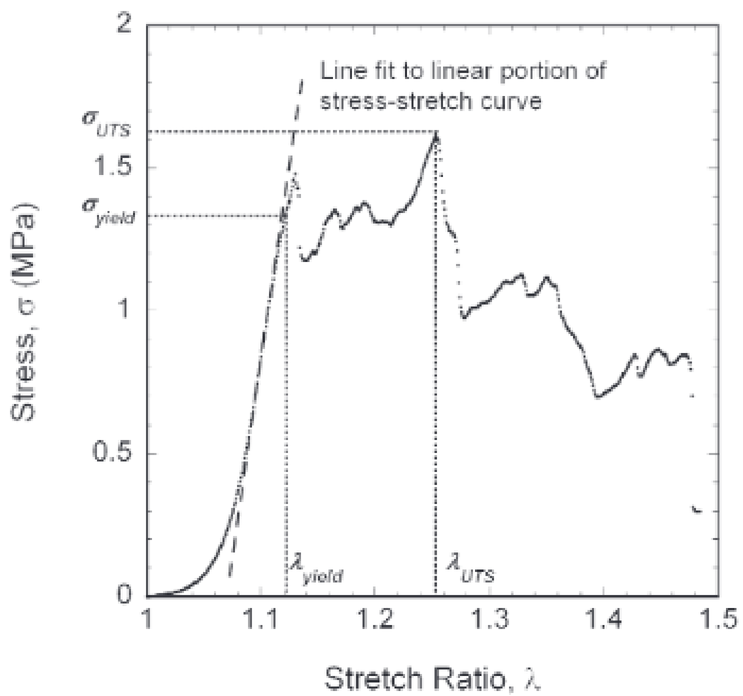



*Haines, 1991*

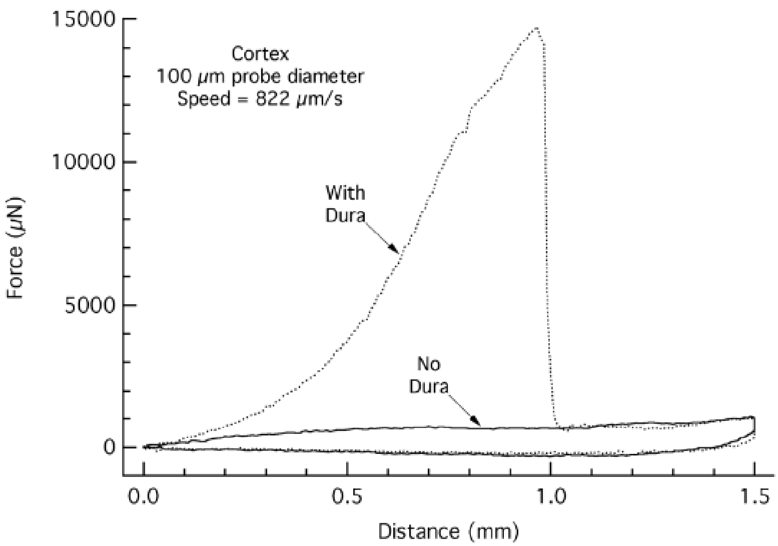
# Mechanical properties of meninges and tissue

Physical description by a hyperelastic model: strain-strain curve is non-linear

| Biological tissues | Mechanical properties | |
|---|---|---|
| | Young modulus (MPa) | Tensile strength (MPa) |
| Cranial dura | 60 | 2.91 |
| Spinal dura | 100 | 2.49 |
| Retina | 0.02 | - |
| Brain tissue | 0.01 | - |
| Bone | 5,000-21,000 | 150 |



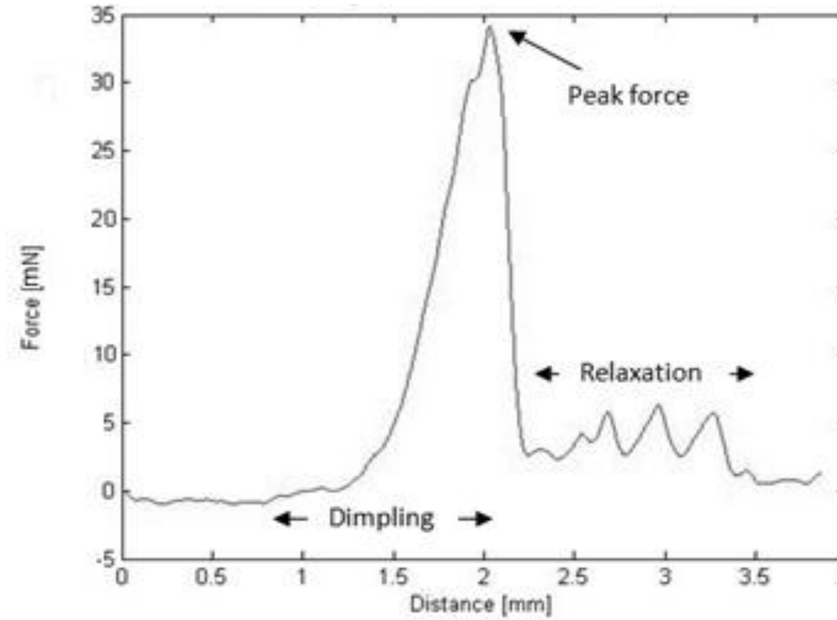

*Maikos, 2008*




*Sharp, 2009*

# Penetration loads

- Significance: device should withstand penetration forces
- Possible loads: bending and buckling
- $F_{penetration} > F_{crit}$ leads to fracture!

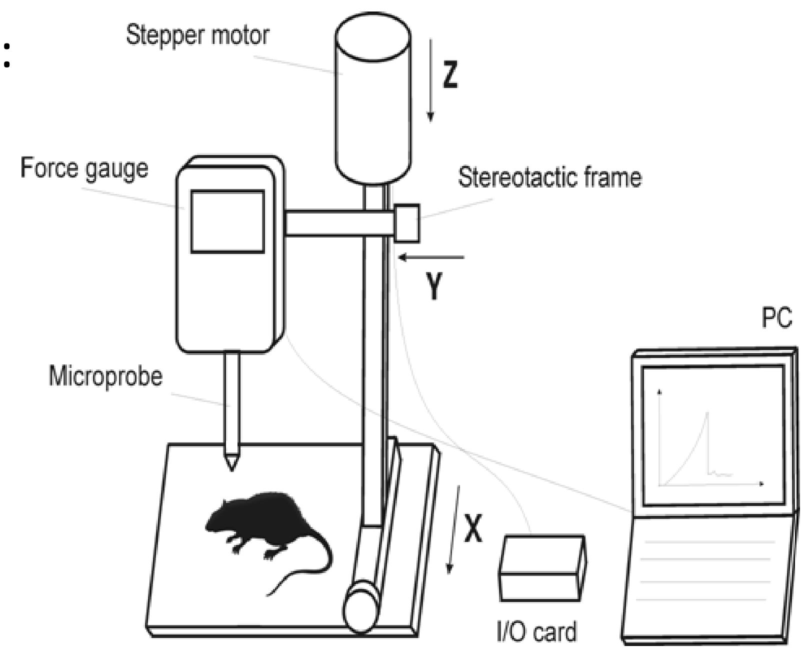



Characteristic parts of force-distance curves:

- Penetration force (insertion)
- Dimpling (insertion)
- Rest force (tissue relaxation)
- Retraction force (explantation)

How to measure?

Neural probes mounted on a force gauge

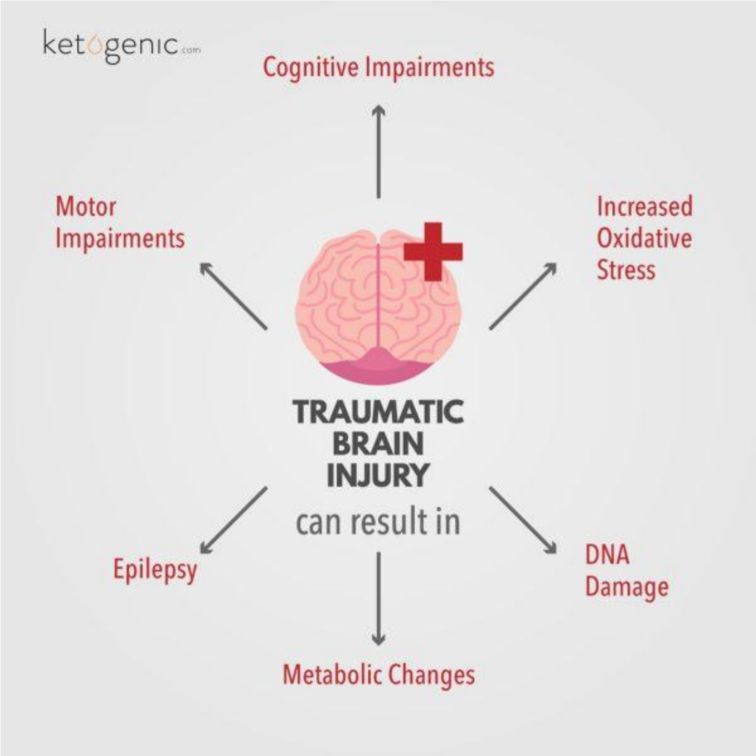


# Significance of dimpling

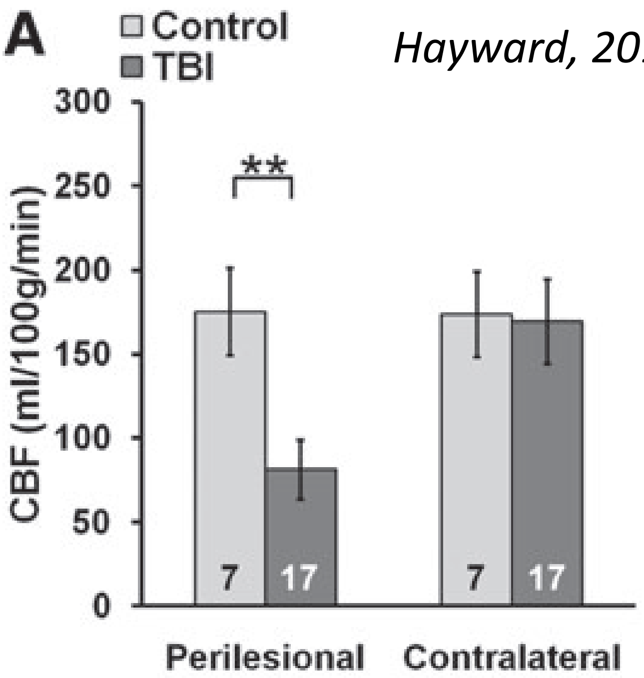
**Dimpling:** Indentation of superficial tissue layer before tissue rupture

Identification on force-distance curve: at maximum load

**Reason to minimize:** may lead to TBI (traumatic brain injury)




*TBI may lead to secondary degeneration*

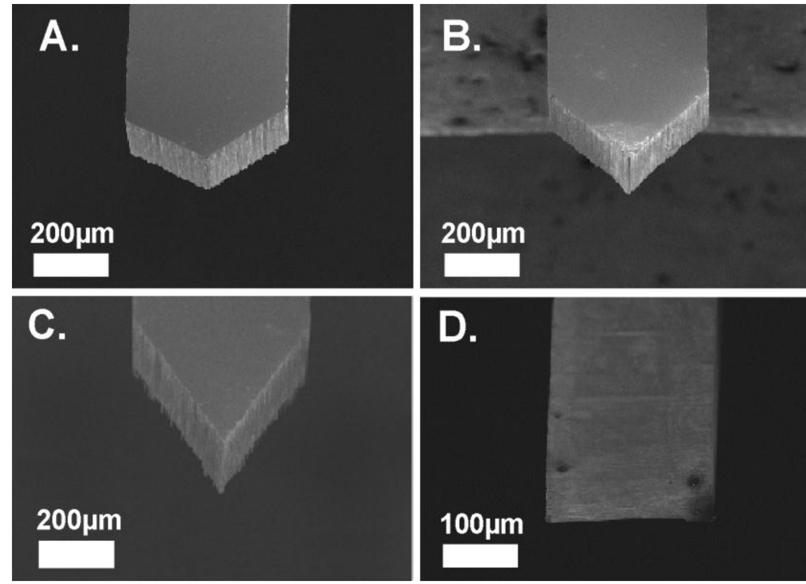



*Hayward, 2010*

*TBI may lead to block in cerebral blood flow*

# Sensor geometry (structural design)

# Probe geometry




**Significance:**

All forces are coupled to interfacial area, which in general should be reduced.

**Relevant design parameters:**

Length: depends on implantation target

Width: depends on integrated functionalities

Thickness: depends subtrate thickness, post-processing technologies

Tip: depends on both layout and technology

Symmetry: depends on technology (wet or dry chemical etching)

# Investigation of interfacial parameters during penetration

| Objectives | Shaft length (mm) | Shaft width x thickness (µm *x* µm) | Tip angle (°) | Insertions per data points | Insertion speed (mm/min) |
|---|---|---|---|---|---|
| Force vs. Speed;<br>Dimpling vs. Speed | 30 | 200x200 | 30 | 8 | 1.2, 3, 5.2, 7.5, 10.5 |
| Force vs. Cross-sections<br>Dimpling vs. Cross-section | 30 | 200x200, 200x400, 400x200, 400x400 | 30 | 10 | 3 |
| Force vs. Tip angle<br>Dimpling vs. Tip angle | 7 | 400x100 | 30, 60, 90 | 4 | 3 |
| Force vs. Sharpening | 7 | 500x00 | 45 | 5 | 3 |
| Force vs. Age;<br>Dimpling vs. Age | 30 | 200x200, 400x400 | 30 | 4 | 3 |

*Fekete, 2015*

# Effect of geometry on insertion

| Shank thickness x width (µm *x* µm) | Penetration force (mN) | Dimpling (mm) |
|---|---|---|
| 200 x 200 | 58 ± 8 | 1.06 ± 0.2 |
| 200 x 400 | 70 ± 10 | 1.19 ± 0.21 |
| 400 x 200 | 98 ± 11 | 1.56 ± 0.12 |
| 400 x 400 | 93 ± 12 | 1.70 ± 0.26 |

Trends are in agreement with literature on retracted dura: Davis, 2004; Jensen, 2006; Sharp, 2009; Andrei, 2012;

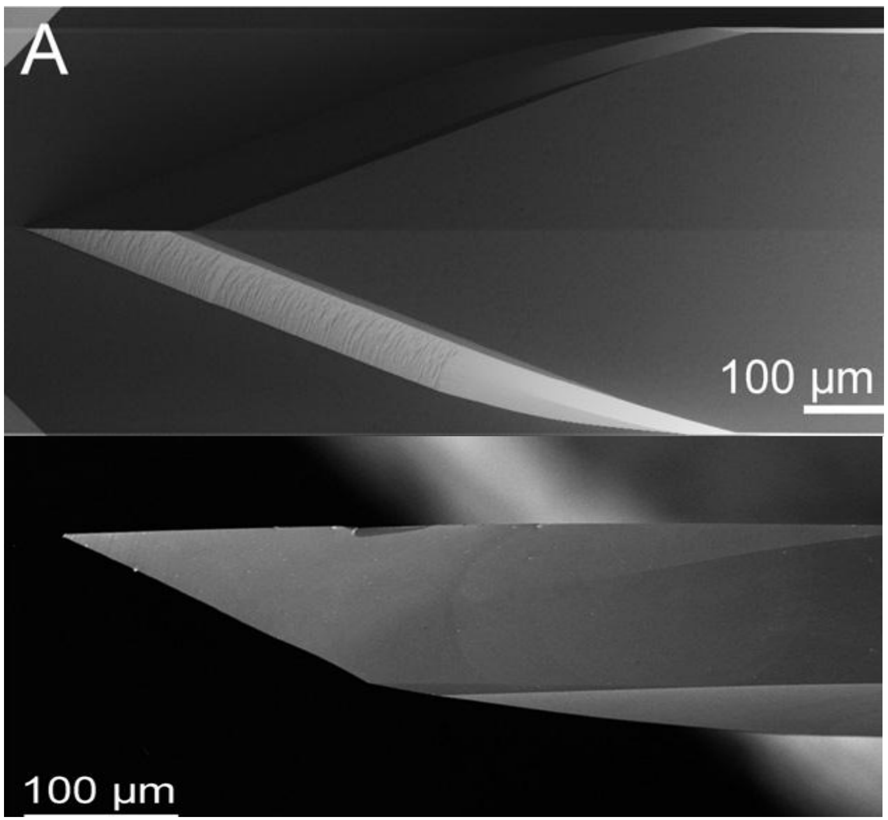
| Tip angle (°) | Penetration force (mN) | Dimpling (mm) |
|---|---|---|
| 30 | 27 ± 3 | 0.78 ± 0.08 |
| 60 | 72 ± 22 | 0.93 ± 0.11 |
| 90 | 112 ± 28 | 1.03 ± 0.08 |

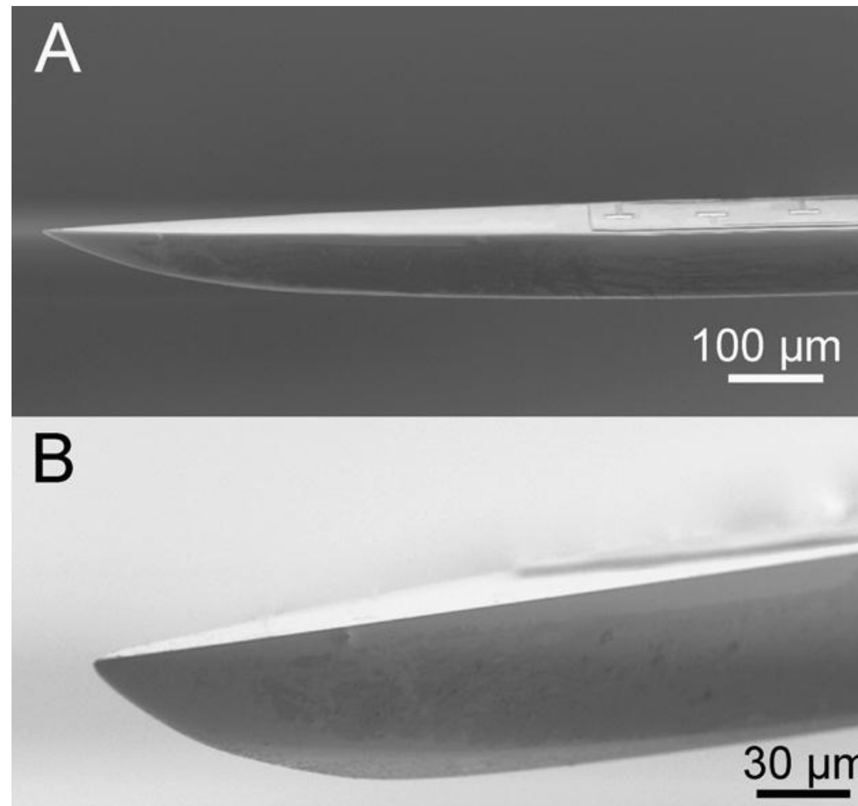
First experimental data in the case of intact dura mater

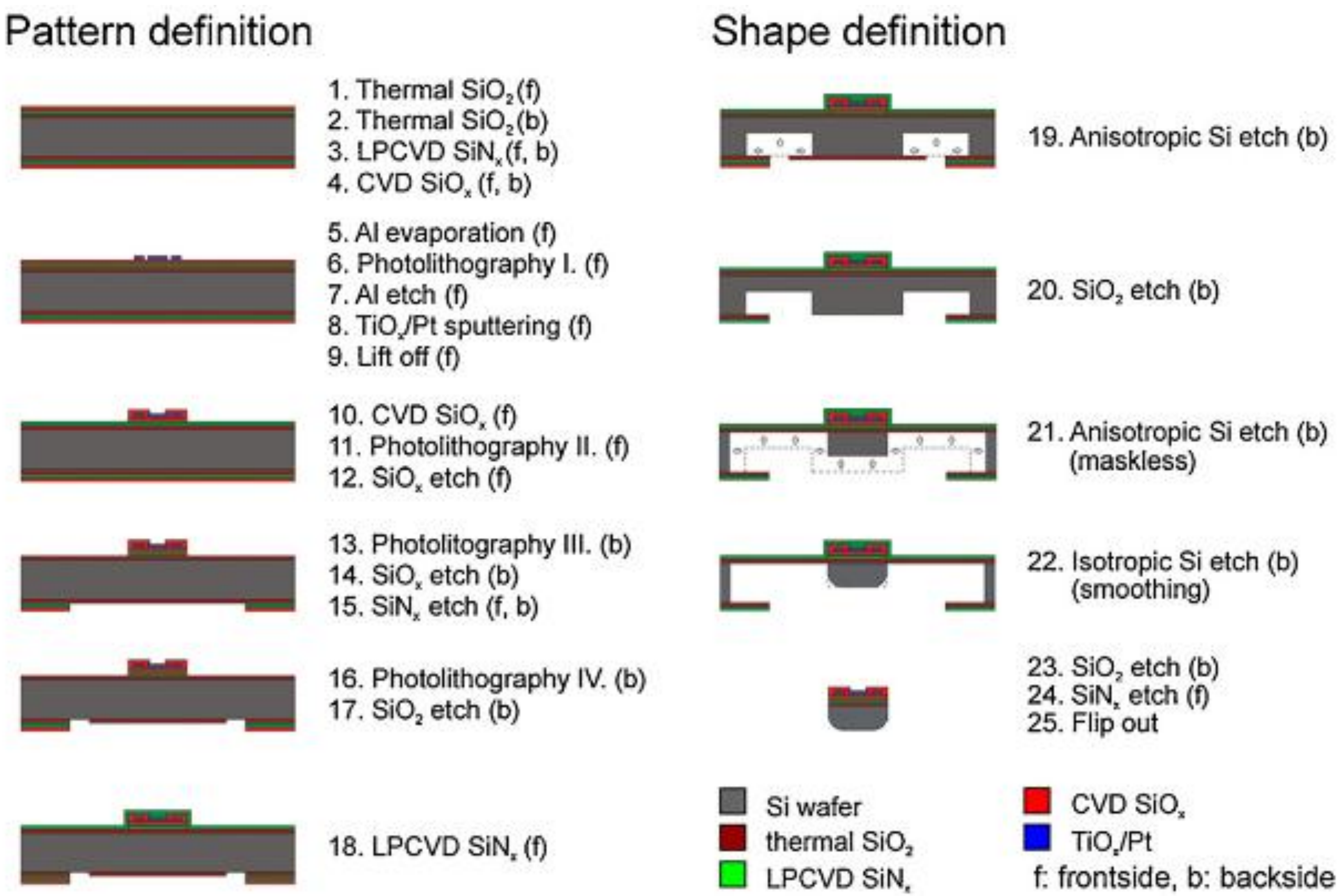
*Fekete, 2015*

# Improved technologies

Sharpening of the probe tip with multiple-step wet chemical etching (Grand, 2010)

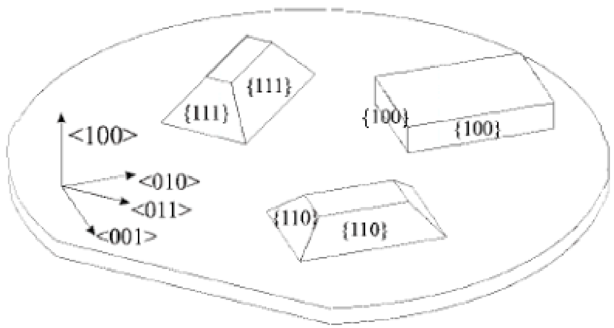


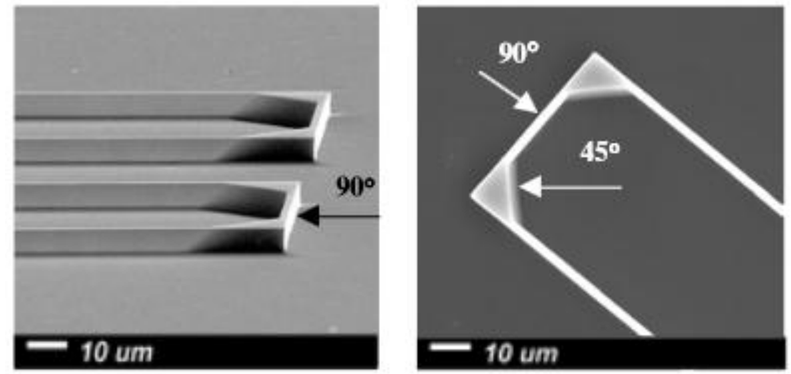




Pattern definition
1. Thermal SiO2 (f)
2. Thermal SiO2 (b)
3. LPCVD SiNx (f, b)
4. CVD SiOx (f, b)
5. Al evaporation (f)
6. Photolithography I. (f)
7. Al etch (f)
8. TiOx/Pt sputtering (f)
9. Lift off (f)
10. CVD SiOx (f)
11. Photolithography II. (f)
12. SiOx etch (f)
13. Photolitography III. (b)
14. SiOx etch (b)
15. SiNx etch (f, b)
16. Photolithography IV. (b)
17. SiO2 etch (b)
18. LPCVD SiNx (f)
Shape definition
19. Anisotropic Si etch (b)
20. SiO2 etch (b)
21. Anisotropic Si etch (b) (maskless)
22. Isotropic Si etch (b) (smoothing)
23. SiO2 etch (b)
24. SiNx etch (f)
25. Flip out
Si wafer
thermal SiO2
LPCVD SiNx
CVD SiOx
TiOx/Pt
f: frontside, b: backside

*Grand, 2010*

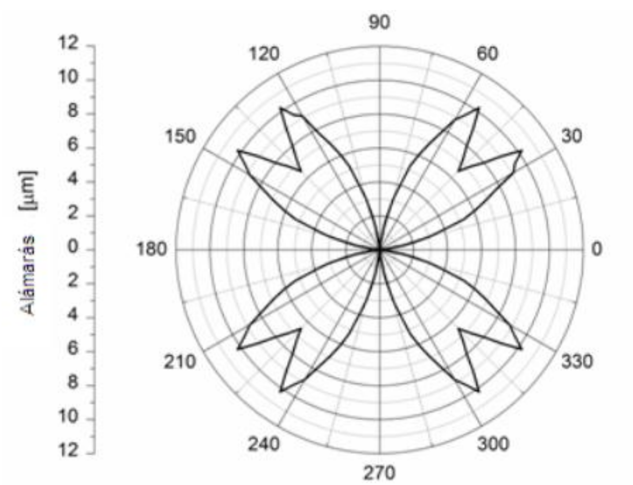
# Etching anisotropy in crystalline materials

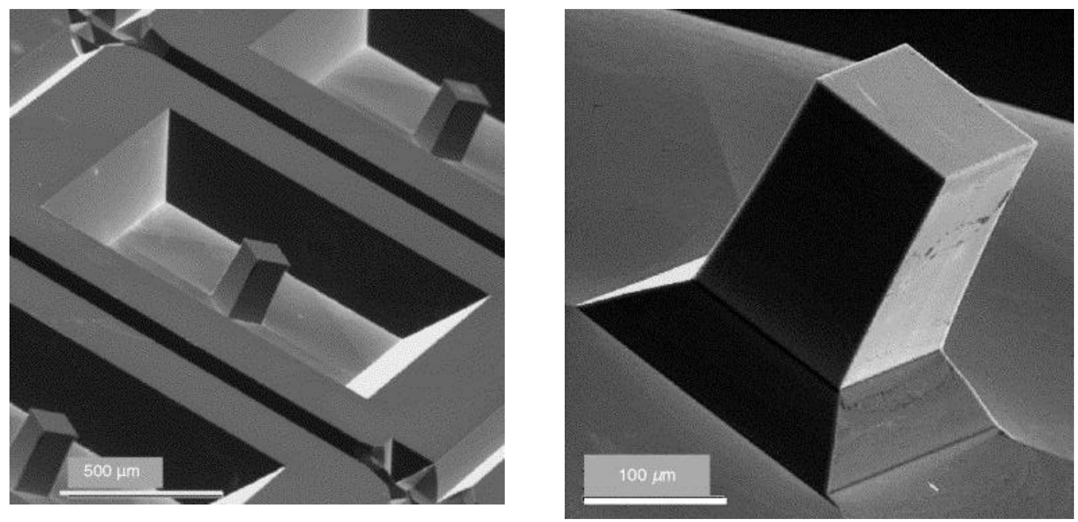



Orientation of patterns determines the etch rate!

*Vazsonyi, 2003*



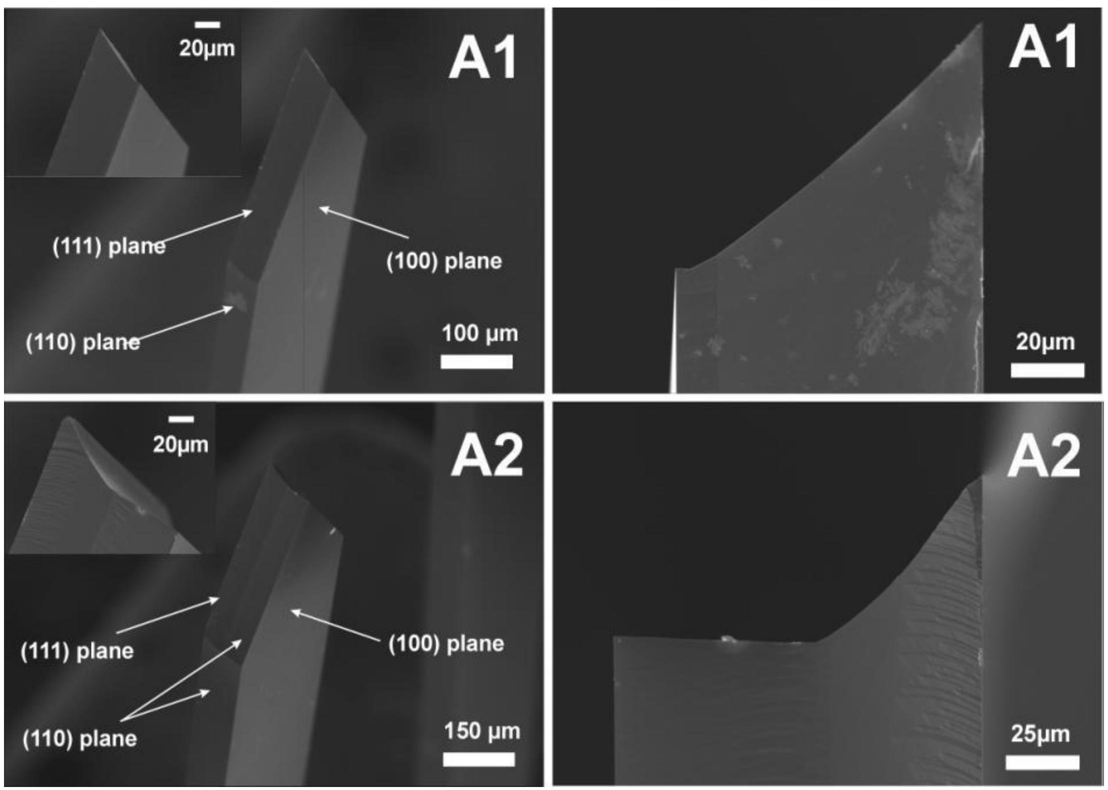




Underetching for Si with KOH

*Vázsonyi, 2005*

# Performance of sharpened probes

Surface quality after deep reactive ion etching (DRIE) improved by subsequent wet etching in a mixture of NaOH:NaOCl




Fekete, 2015

| Samples | Penetration force (mN) |
|---|---|
| A0 | 49 ±13 |
| A1 | 20 ± 6 |
| A2 | 11 ± 3 |
| $A_{ref}$ | 5 ± 1.5 |

A0: DRIE probe with intact dura

$A_{ref}$: DRIE probe with retracted dura

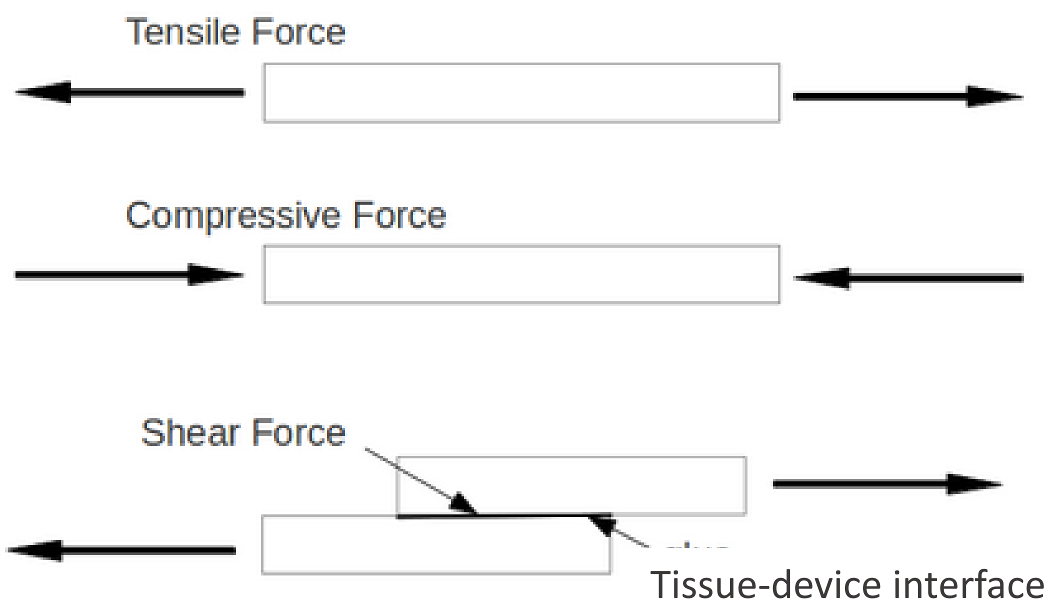
Insertion forces can be subtantially lowered even with dura mater on top.

# Chemical and physical nature of boundary interfaces

# Interfacial load (shear stress)

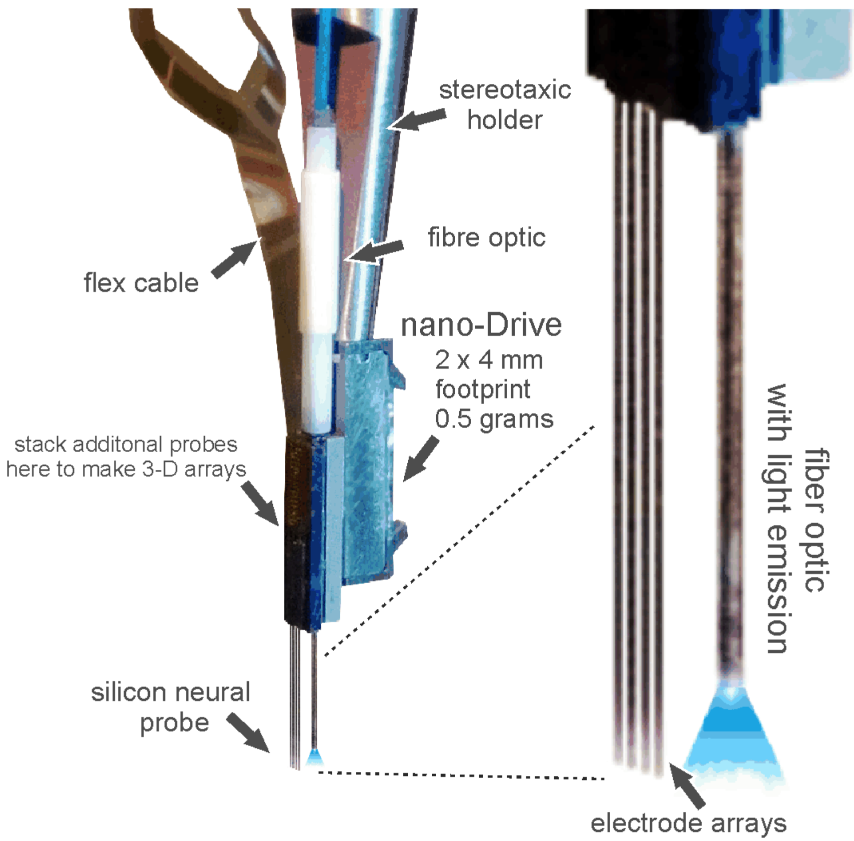
Depends on the characteristic roughness of device surfaces.

Induced by insertion, repositioning and micromotions in tissue.



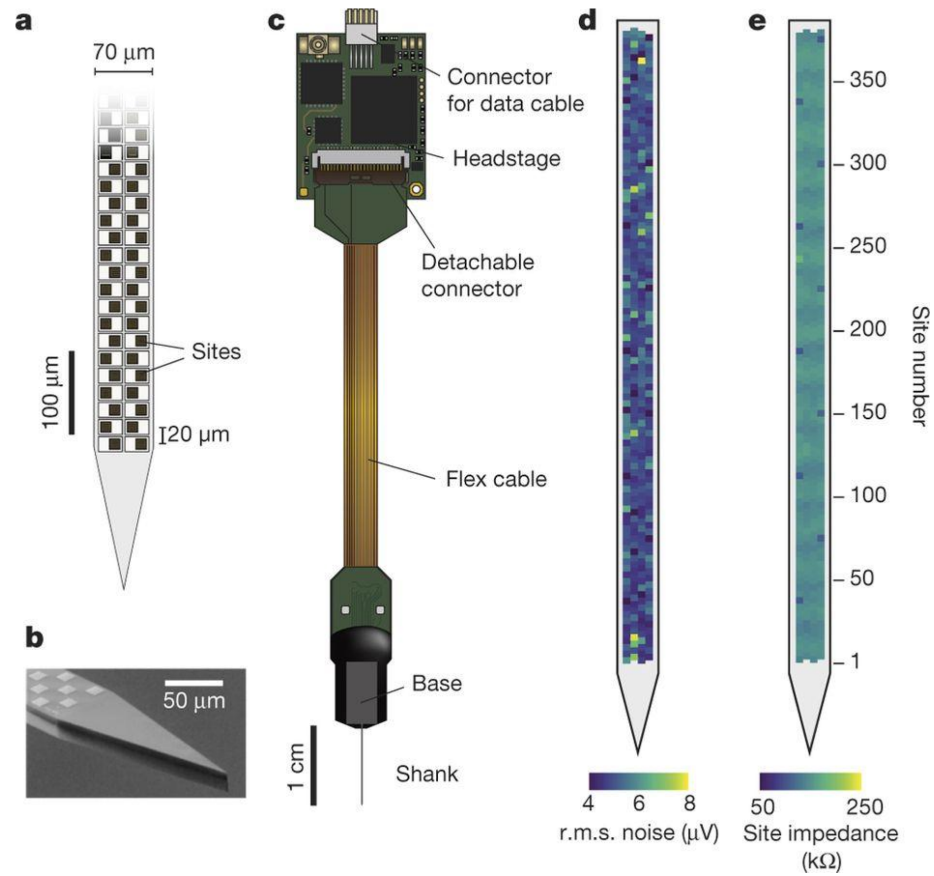
# Concepts for repositioning  recording depth

## Mechanical (for passive probes)




*Cambridge Neurotech*

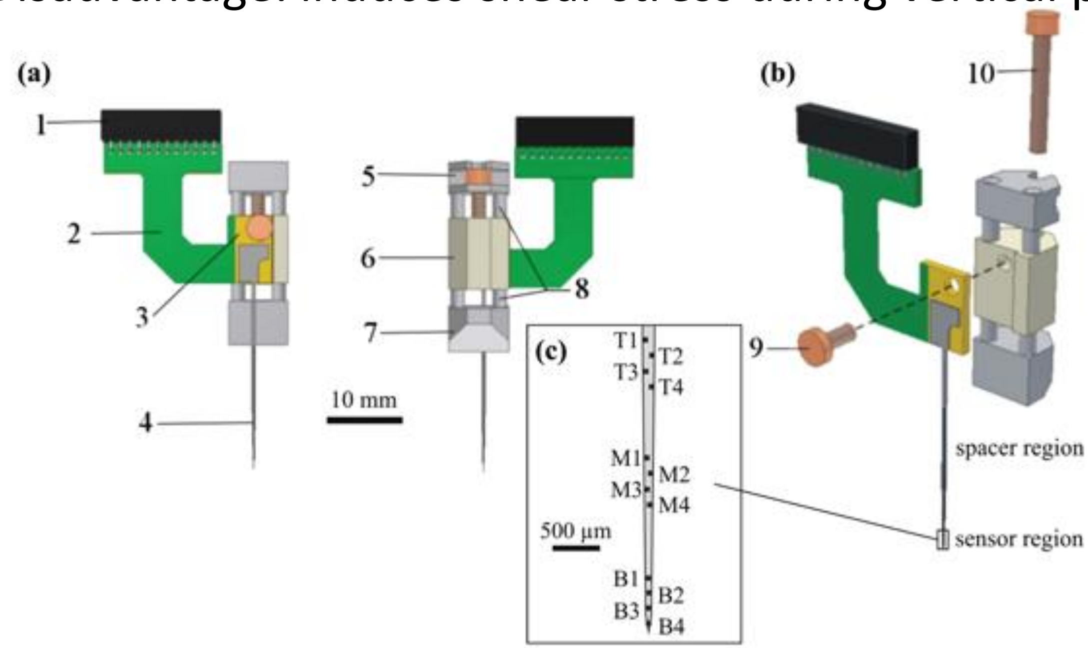
## Electrical (for active probes)

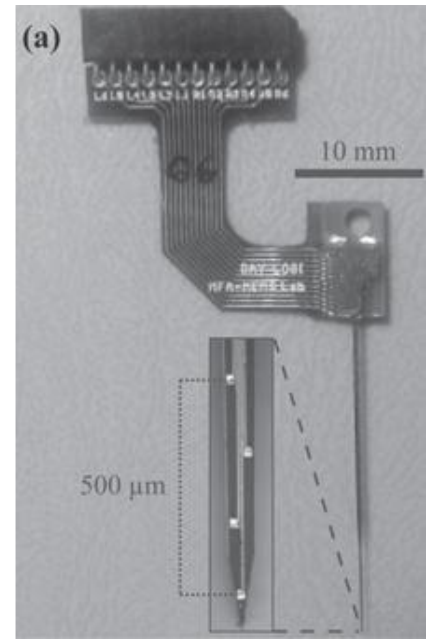


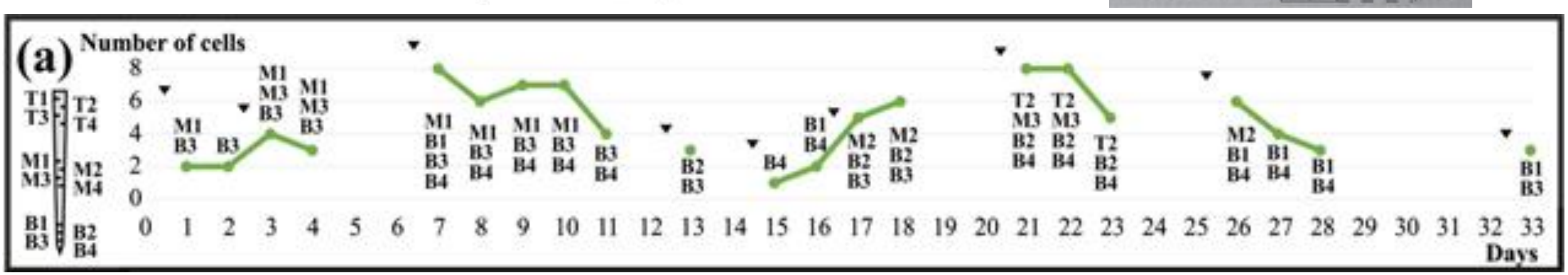

*Jun, 2017*

# Microdrives

Advantage: single units can be recorded at higher yield in spite of the ongoing glial encapsulation
Disadvantage: induces shear stress during vertical positioning along the probe track



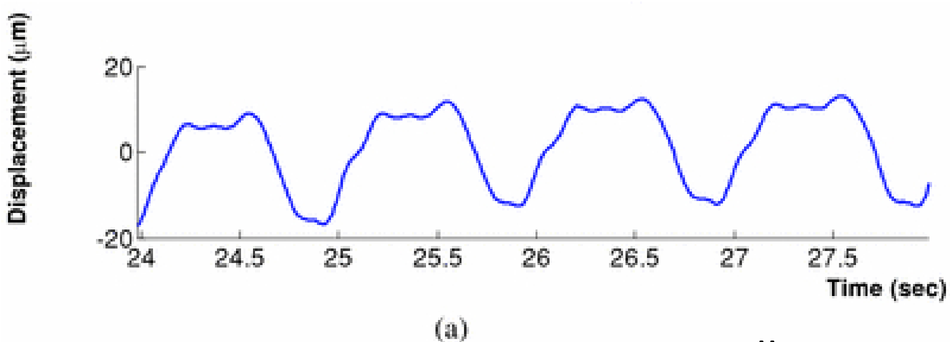



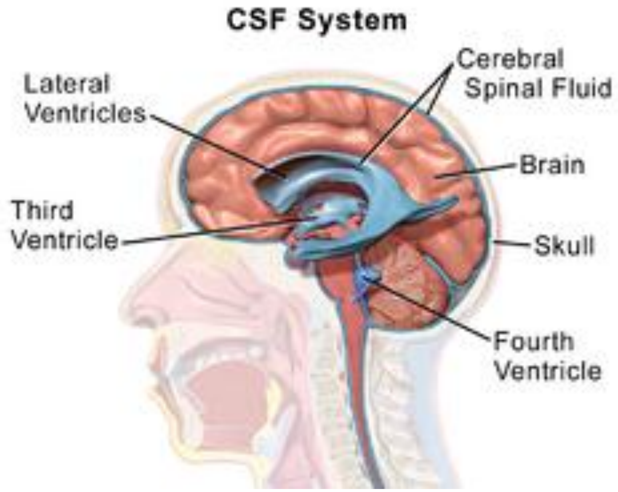

*Márton, 2016*

# Micromotions

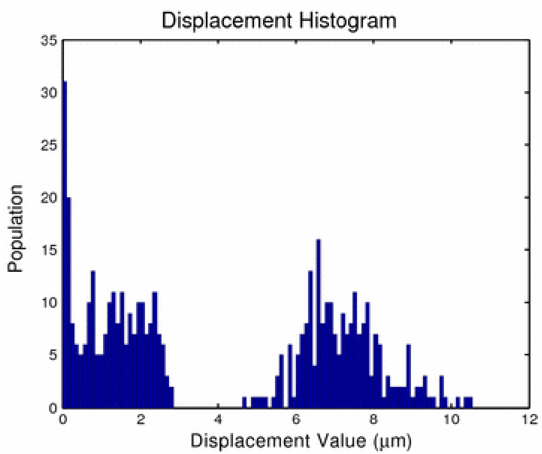
Displacements caused brain movement modulated by physiological activity



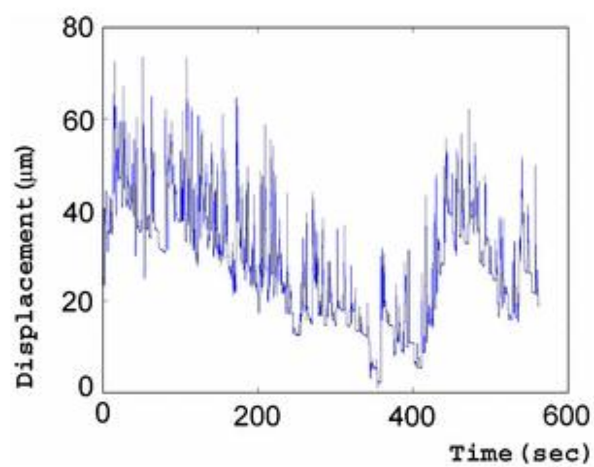

Gilletti, 2006




*Effects of vasculature and pulmonary activity*



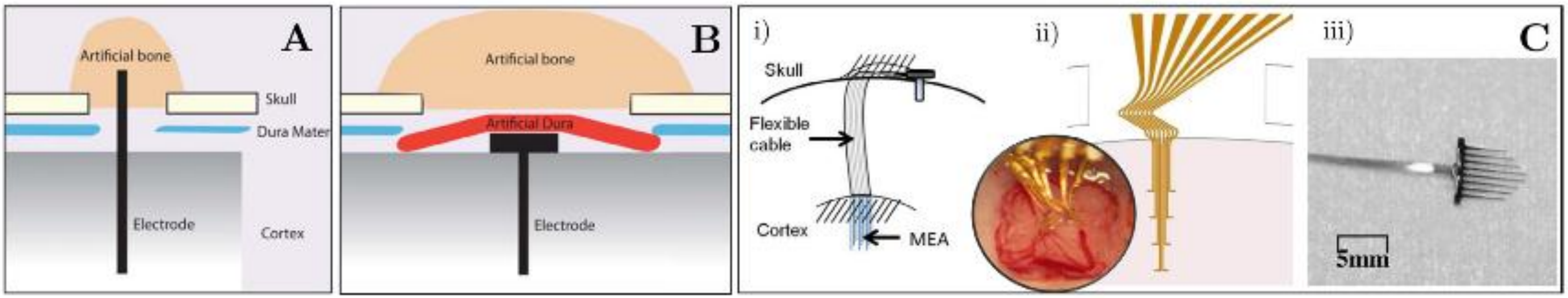

*Cortical surface drift*



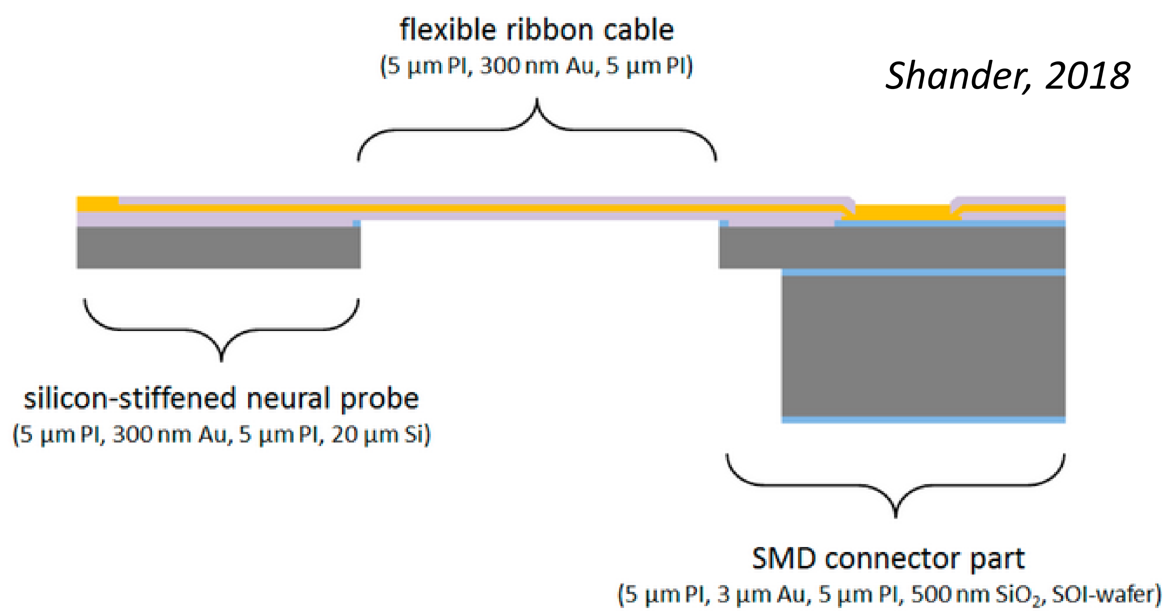
# Packaging, interconnections

How to mitigate mechanical coupling between microdevice and connectors?

*Lecomte, 2017*



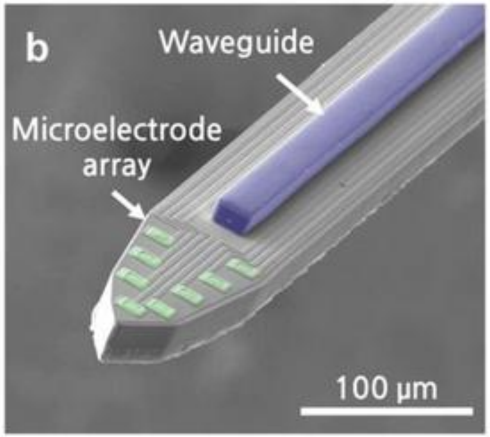

*Shander, 2018*




**Concept:**
Formation a hybrid stiff-flexible device configuration

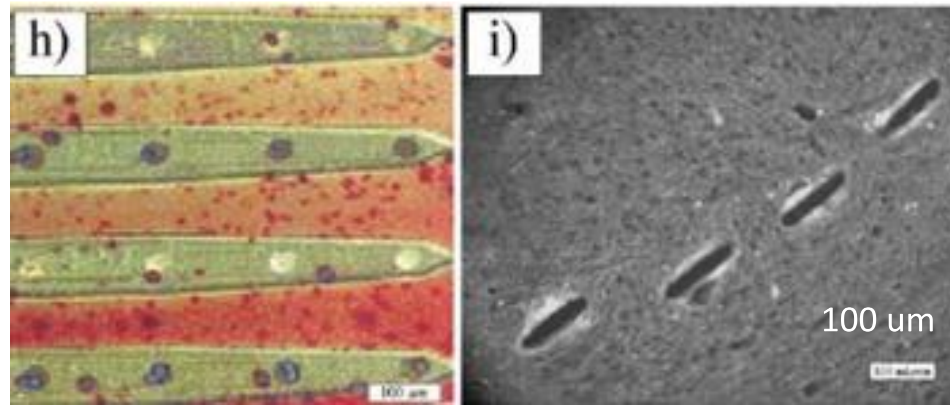
# Reason for lateral displacement during insertion

## Integrated MEMS components



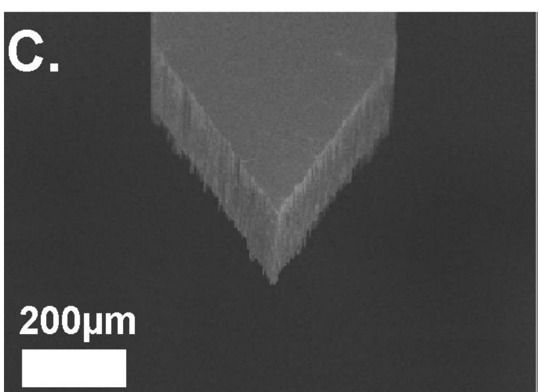

*Son, 2015*

## 3D config. or assembly methods




*Cui, 2003*

## Tip symmetry




*Fekete, 2013*

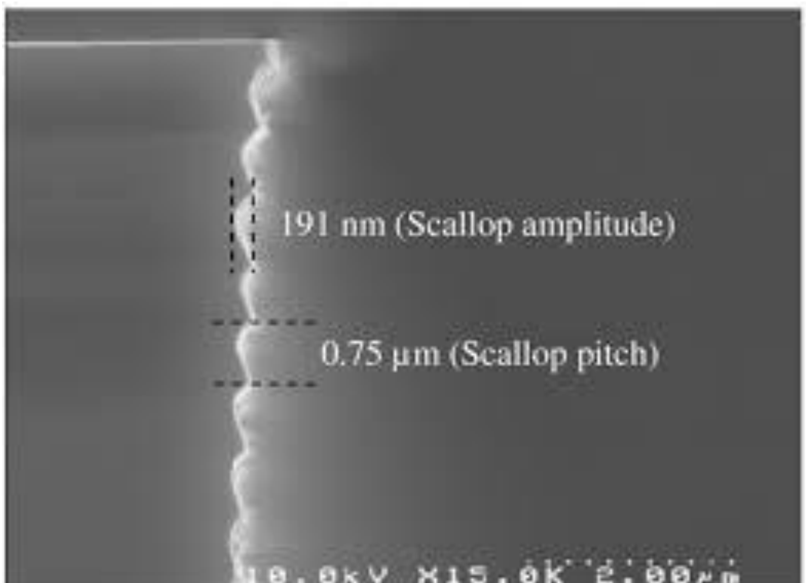

*Grand, 2010*

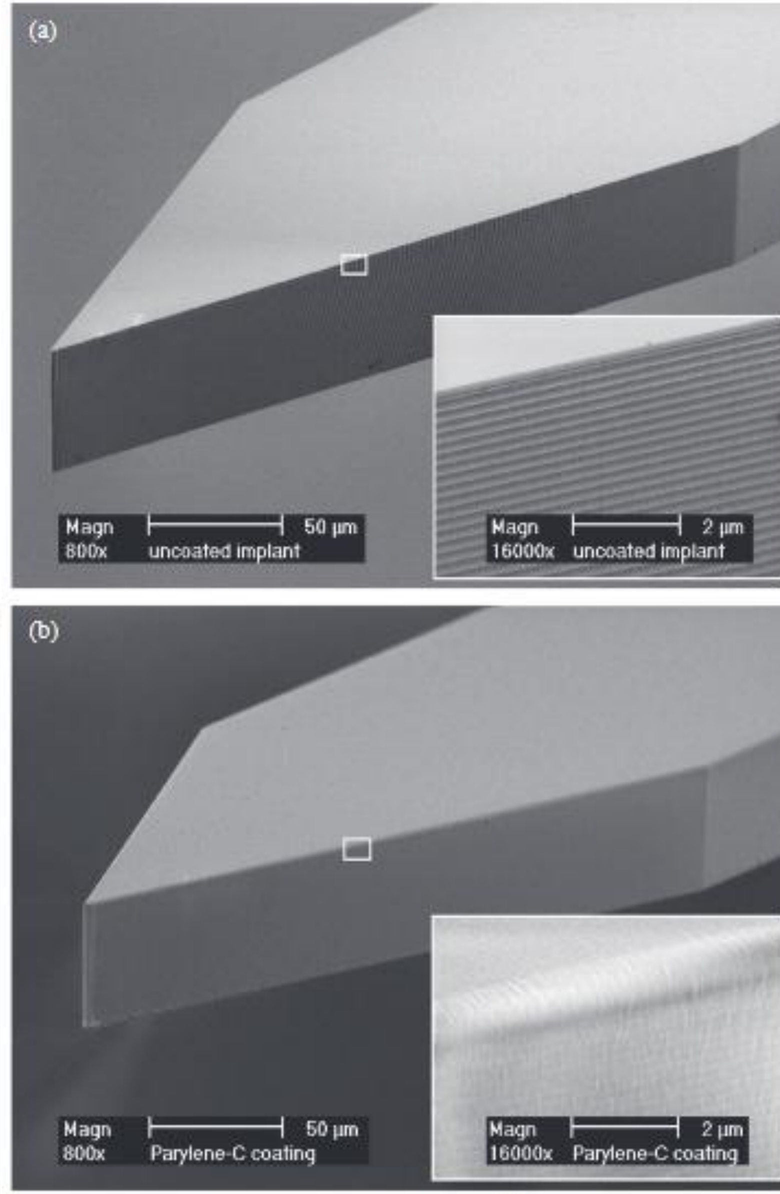
# Interface stress

Reason: rough device surfaces (typically on sidewalls)

Approaches to mitigate:

- Parylene C coating (Andrei, 2012)
- Hydrogel coating (Spencer, 2017)
- PVA coating (Sridharan, 2015)

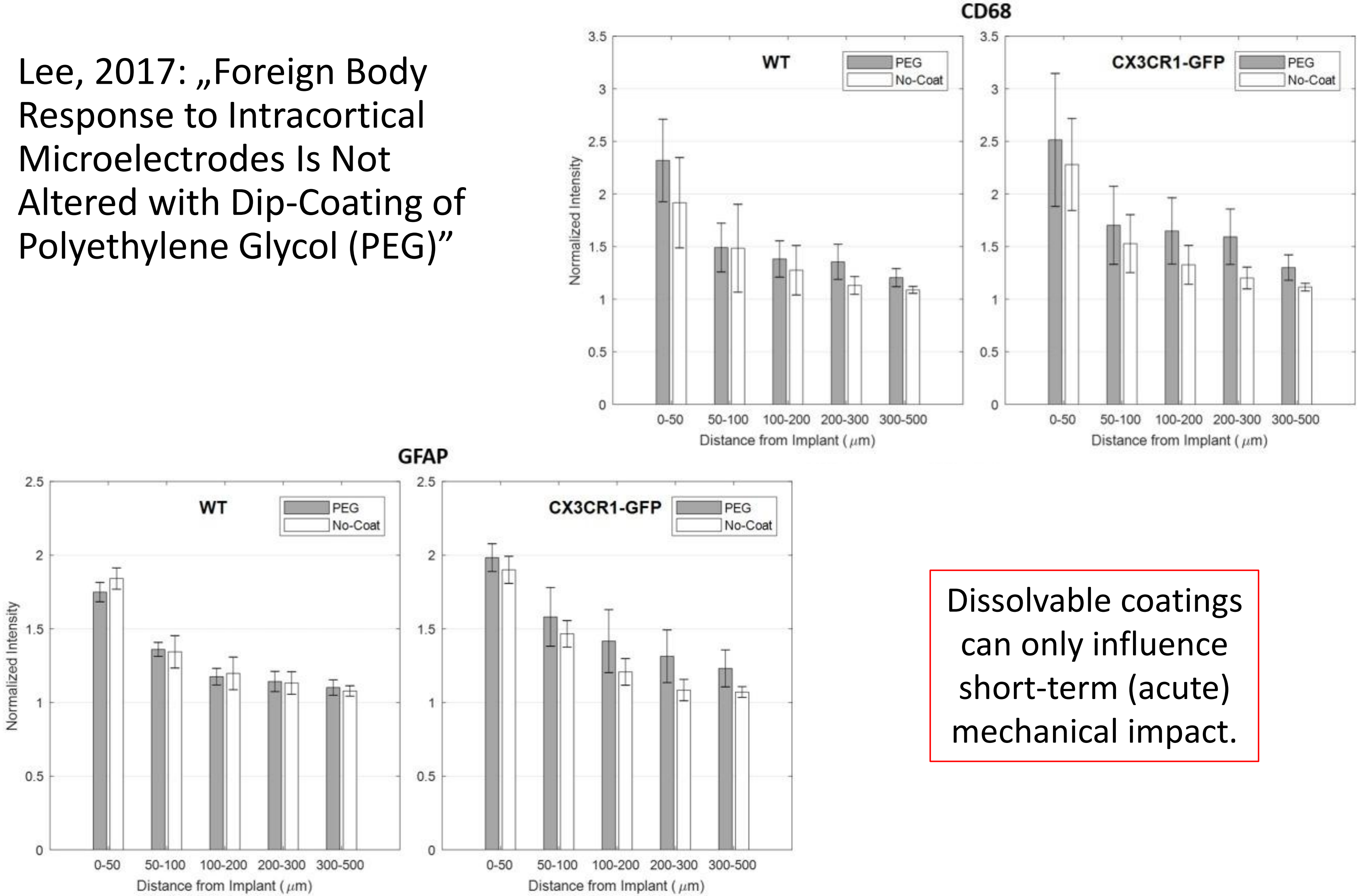



Andrei, 2012

# Dissolvable coatings vs interfacial stress

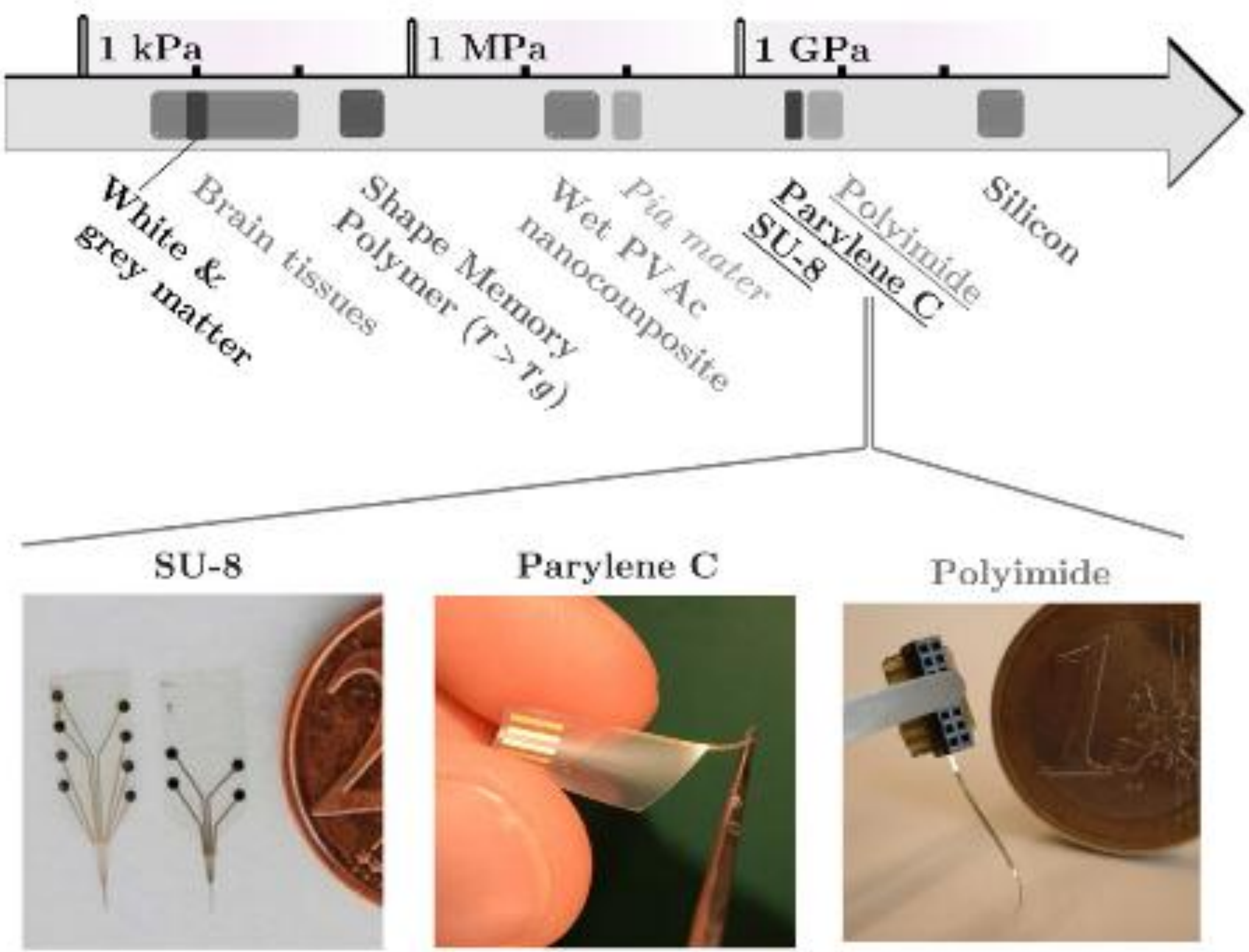
Lee, 2017: „Foreign Body Response to Intracortical Microelectrodes Is Not Altered with Dip-Coating of Polyethylene Glycol (PEG)"




Dissolvable coatings can only influence short-term (acute) mechanical impact.

# Bulk properties of the sensor

# Softness



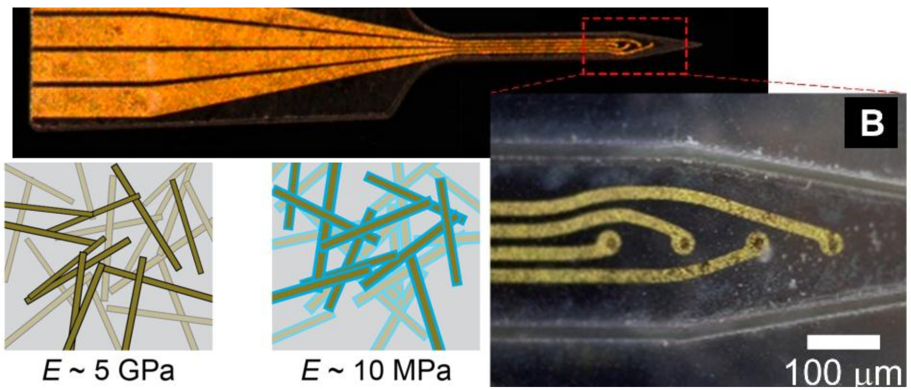

*Lecomte, 2017*

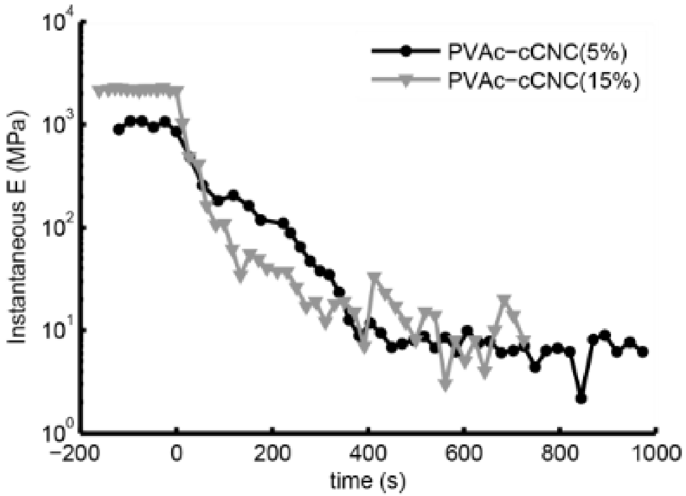
Device substrates are usually much stiffer than tissue.

# Responsive neural interfaces

Device that alters their mechanical properties at physiological conditions (pH, temperature, liquid) may mitigate micromotion induced damage

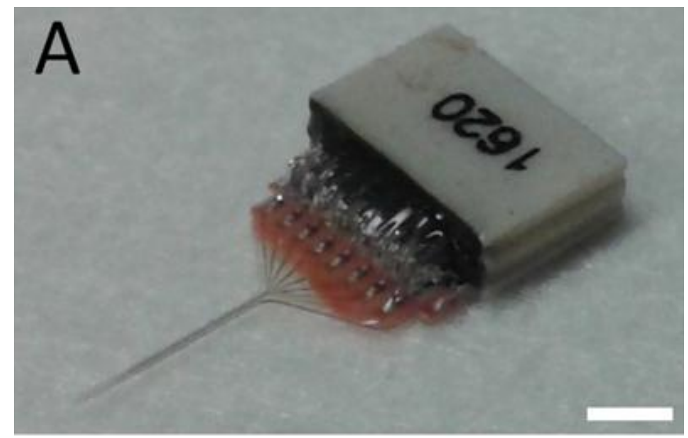
*Cellulose nanocomposites*

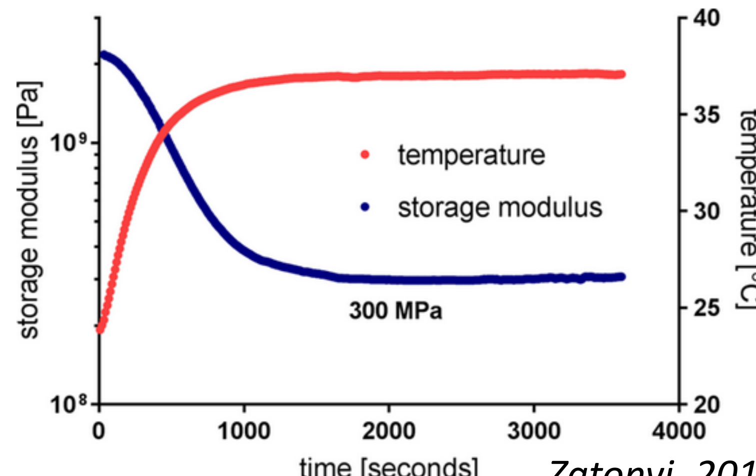



*Dunning, 2018*

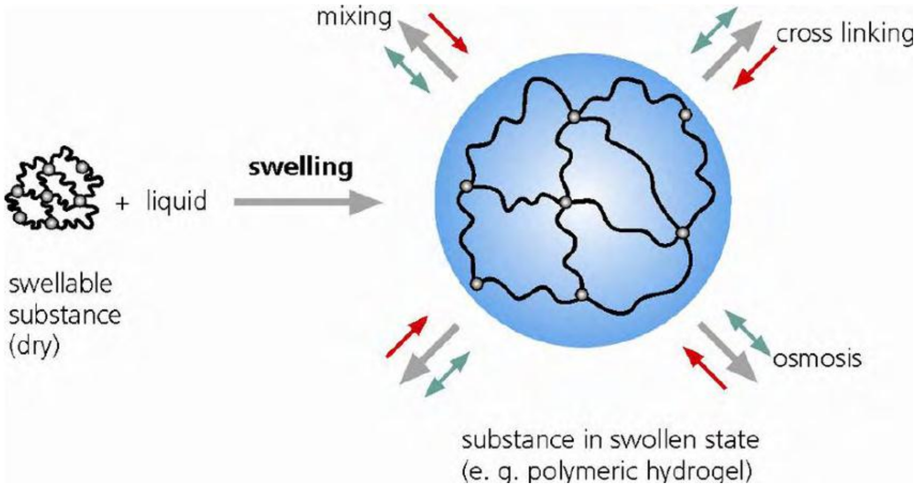
*Shape memory polymers*




*Zatonyi, 2019*

# Swelling



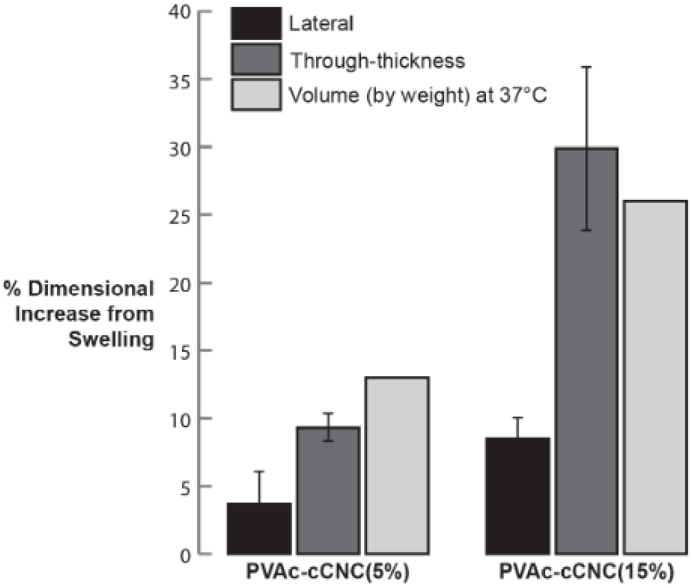

Phenomenon: increase in device volume if exposed to liquids (water)

To be considered for implants made of polymers, hydrogels, composite fibers!

**Advantage:** reduces density mismatch between device and tissue

**Disadvantage:** increase strain in swollen states

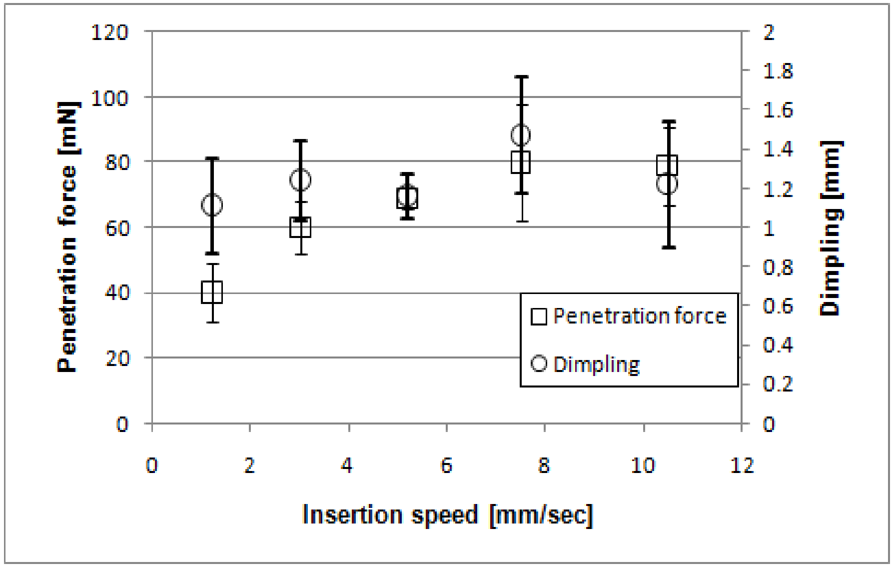
- may induce injuries in blood capillaries
- may lead to thin film cracks



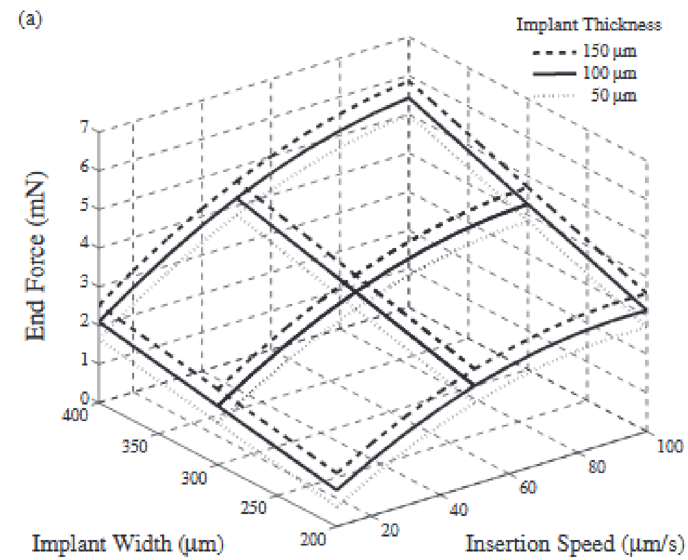

*Dunning, 2014*

# Surgical conditions

# Ways to mitigate insertion forces?




*Fekete, 2015*

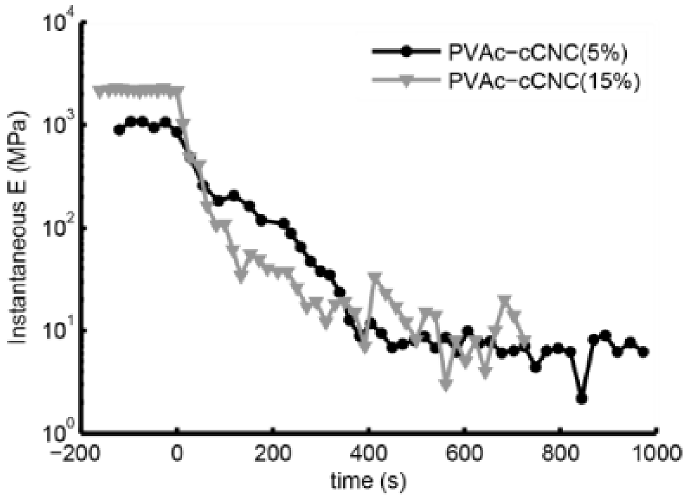



*Andrei, 2012*

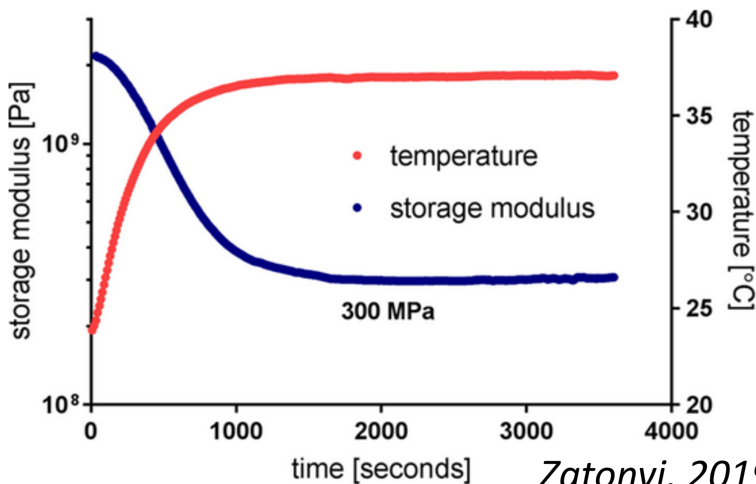
- Low speeds results in low insertion forces, but have no effect on dimpling. Dimpling is influenced by interfacial area only.
- Increase in penetration force between cases of retracted and intact dura: one order of magnitude (!)

# Implantation time window

- Undefinite for stiff implants
- To be carefully considered for responsive materials (e.g. shape memory polymers, cellulose nanocomposite)
- Shortest for chemoresponsive materials, longer for thermoresponsive materials >> induces elevated penetration forces due to large insertion speed



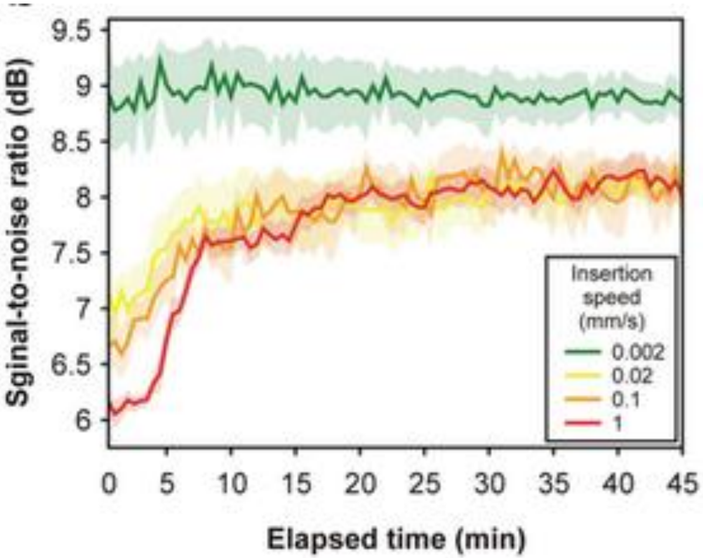

*Dunning, 2018*

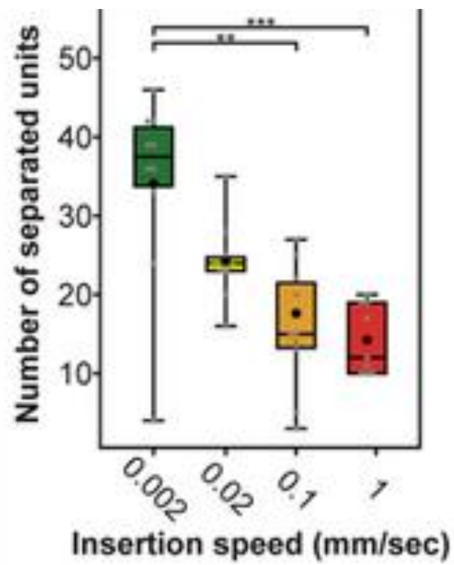


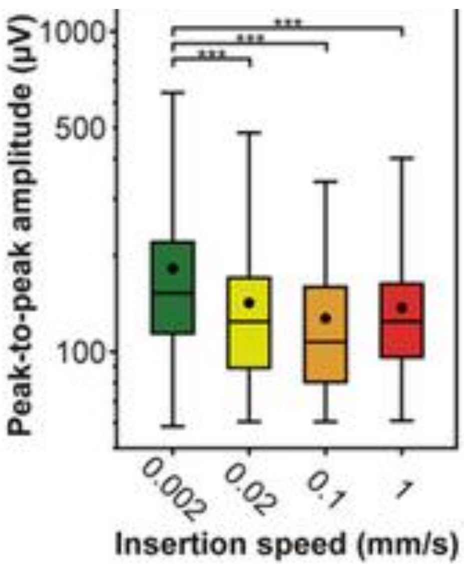

*Zatonyi, 2019*

# Effects on neural recording

Fiáth, 2019



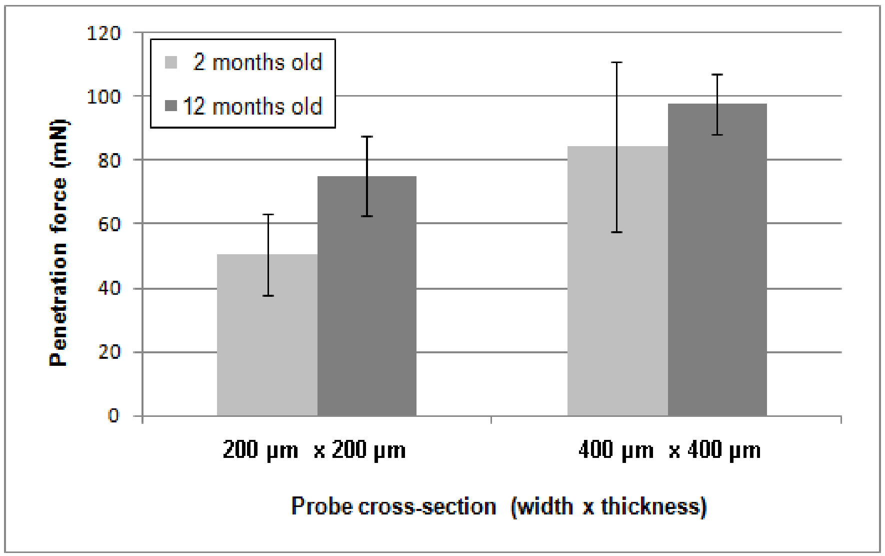

Higher signal-to-noise ratio

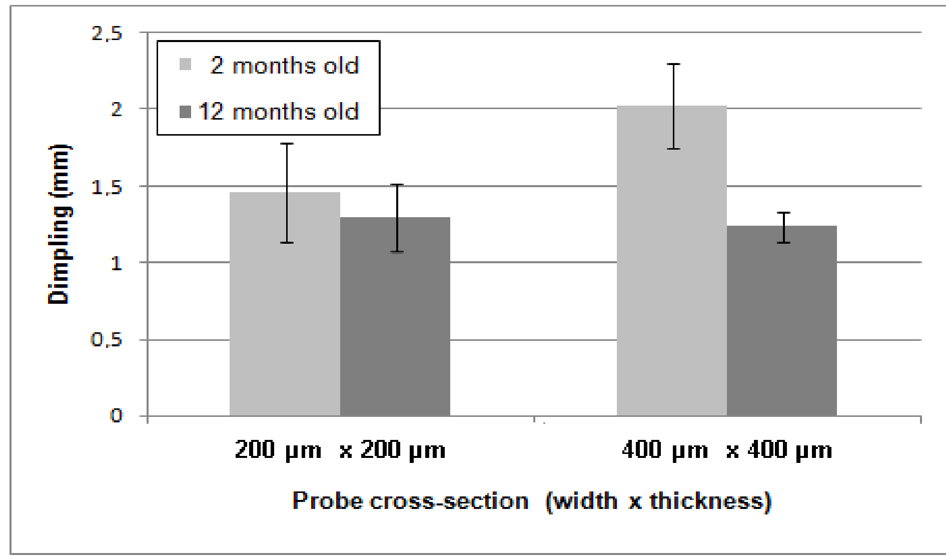
More clustered units

No effect on spike amplitude

Low insertion speed provides high yield in neural recordings

# Effect of tissue conditions




*Fekete, 2015*

Explanation: dura is getting thicker and less flexible by age

Similar results: Van Noort, 1981 (human dura)

# Questions

1. List relevant device properties that have influence on device-tissue interactions.
2. List the main sources of mechanical interactions between device and tissue.
3. How does an integrated bulk component change response of needle-like implants to bending and buckling loads?
4. What is residual stress in MEMS devices and why it is important?
5. What is the relationship between buckling and fracture? What is the critical buckling force of a needle?
6. What is tissue dimpling during device penetration, and why it is important to be reduced?
7. What is the effect of device geometry on insertion forces and dimpling measured during implantation ?
8. What is tethered and untethered probe configuration?
9. Describe micromotions inside the brain. What kind of forces are induced around the implants due to micromotions?
10. What is the relationship between insertion speed and penetration forces?
11. Describe the relevance of responsive neural implants regarding their mechanical properties.