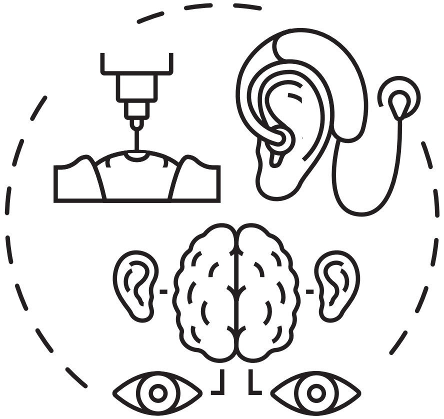
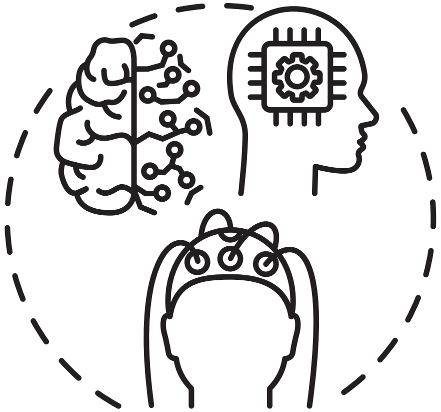




Neural Interfaces

NX-422

Flexible interfaces

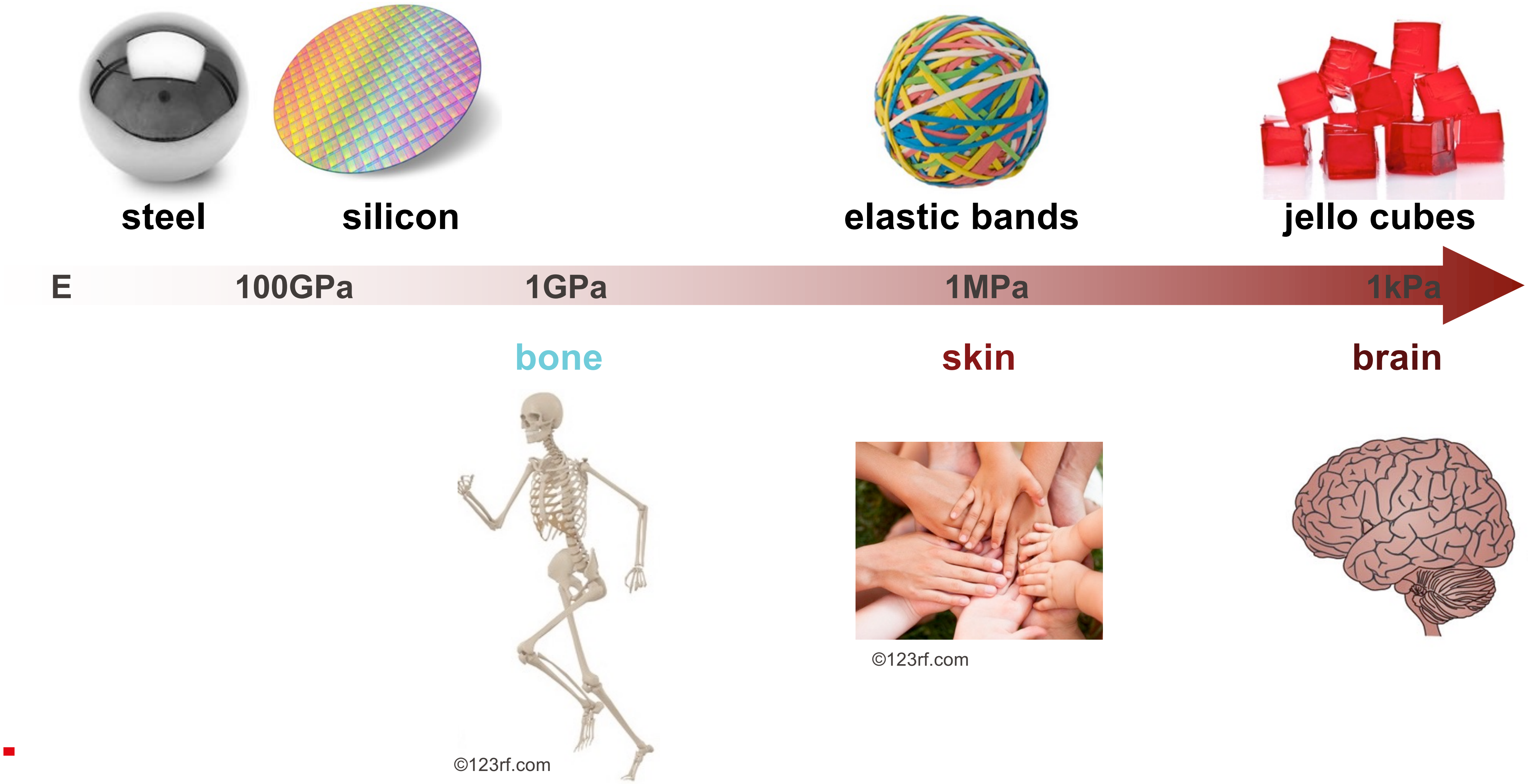
Stéphanie P. Lacour

Neuro-X Institute

Brain computer interfaces

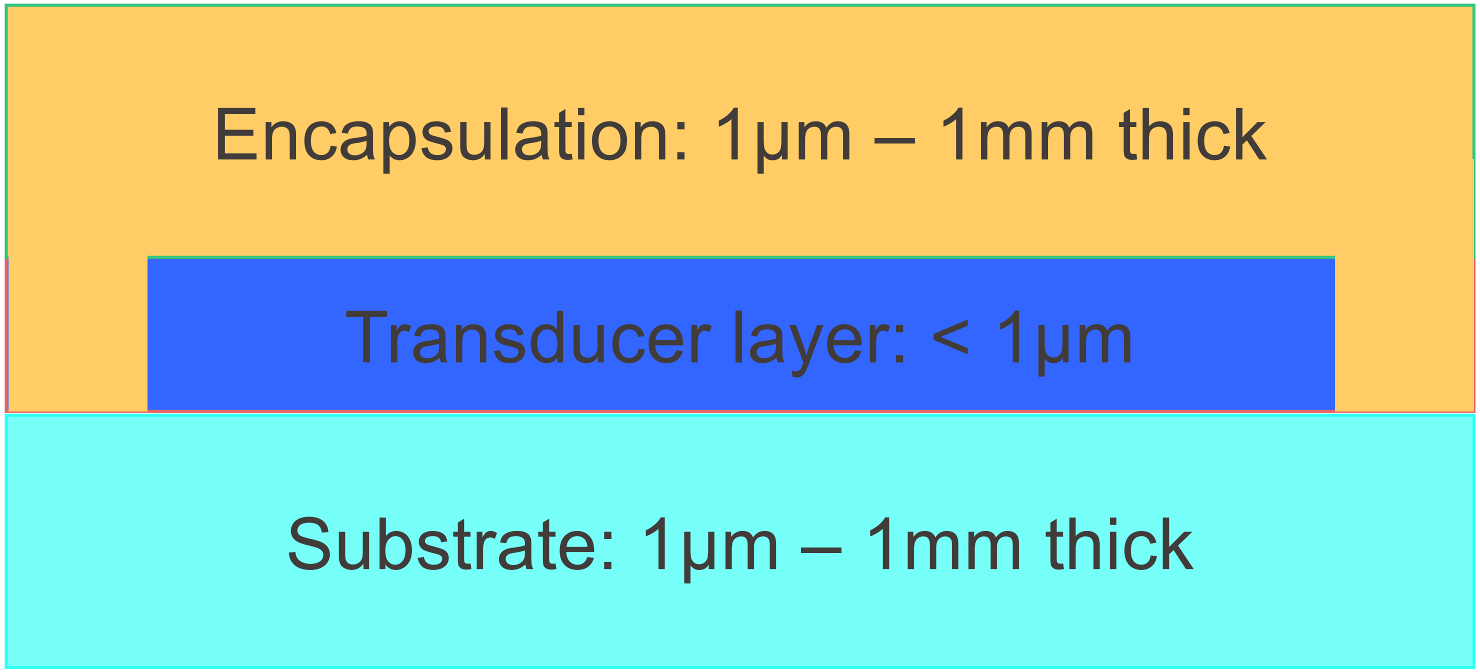
- Overview
- Silicon-based neurotechnology
- **Flexible implantable neurotechnologies**

Man-made vs biological materials



Lacour, Courtine, Guck | **Nature Reviews Materials** | 2016

Flexible implantable interfaces



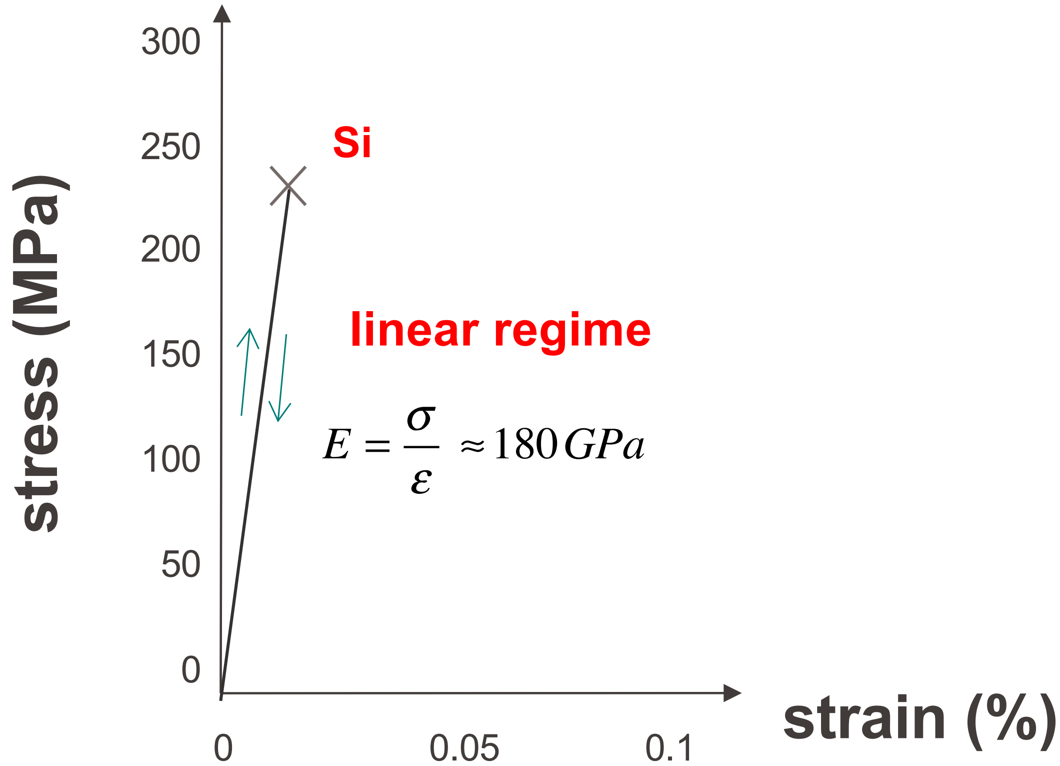
Desired properties for a flexible substrate

- **Physical**
  - Smoothness
  - Barrier properties / hermeticity
  - Dimensional stability
  - High robustness
  - Mechanical strength/flexibility
- **Thermal stability**
- **Optical transparency**
- **Dielectric properties**
- Biocompatibility / biodegradability

Thin = flexible

cellulose

http://www.paperonweb.com/



Critical strain

- The critical strain is the maximum applied strain before mechanical fracture

$$\varepsilon_{crit} = \pm \frac{h}{2\,R_{0,\min}}$$

material property
Brittle glass: <0.2%
Ductile metal: <20%

design parameter
10µm to 250µm

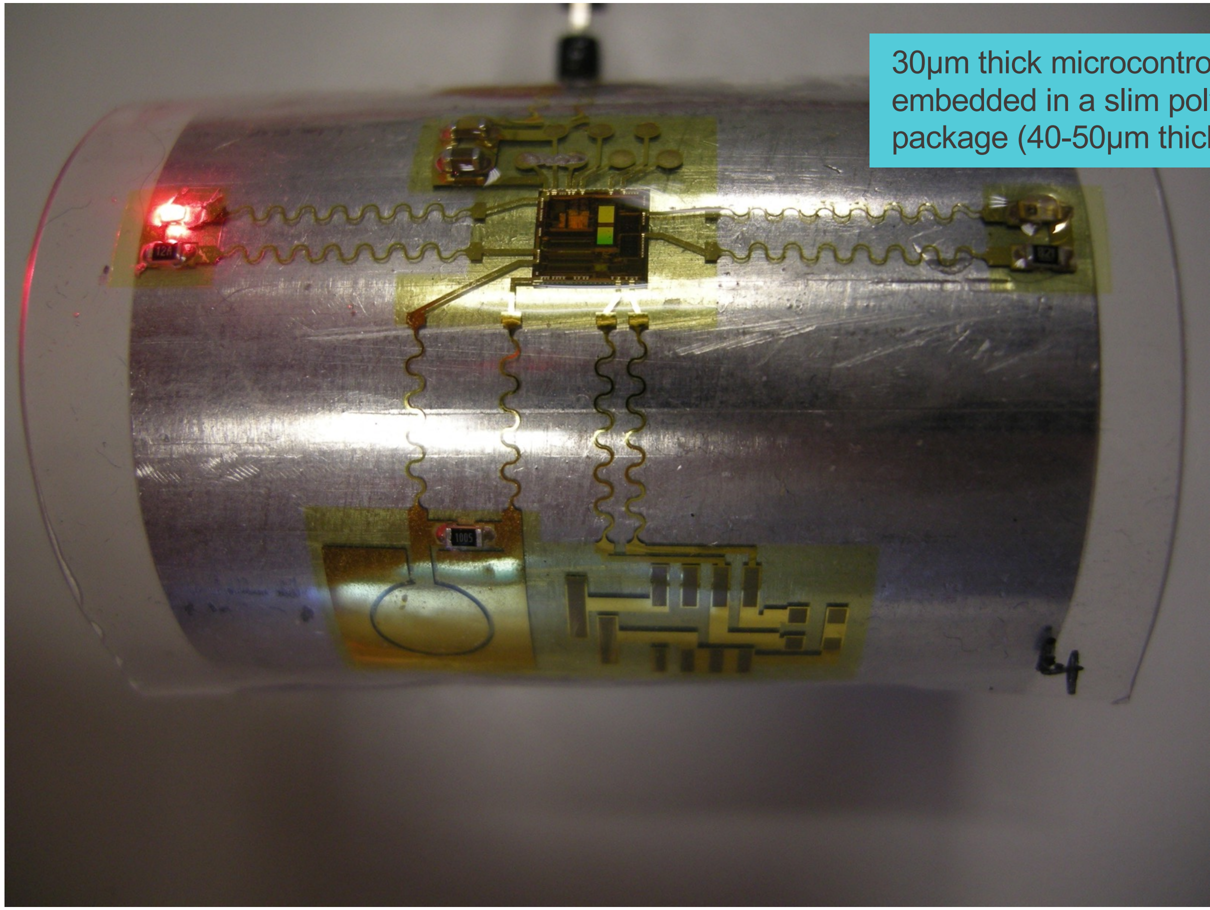
application driven
1mm to cm

Example: The critical strain is 0.5%; the application requires a 1cm min. bending radius. How thick should the substrate be?

a. 50µm   b. 100µm   c. 1mm

EPFL

Ultra-thin flexible chip

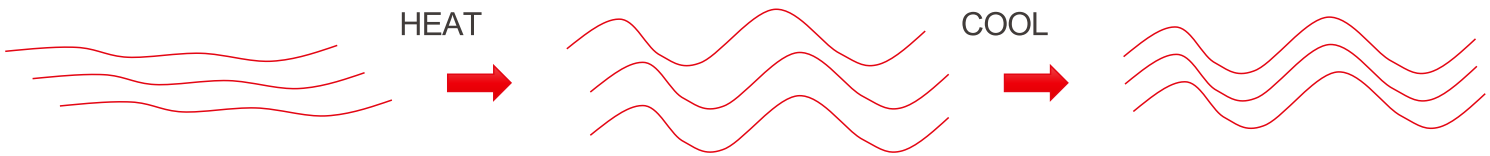


30µm thick microcontroller embedded in a slim polyimide package (40-50µm thick)

IMEC, 2012 ESTC Conference

Thermoplastics

- A polymer prepared with linear or ramified chains.
  - Chains are weakly linked (Van der Waals or hydrogen bonds)



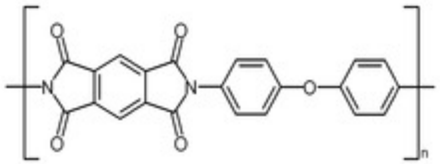
cold and hard polymer

hot and malleable polymer → new shape

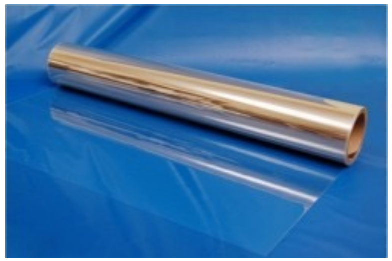
cold and hard polymer preserving the new shape

- A material, which softens and hardens reversibly on heating and cooling

Polyimide films



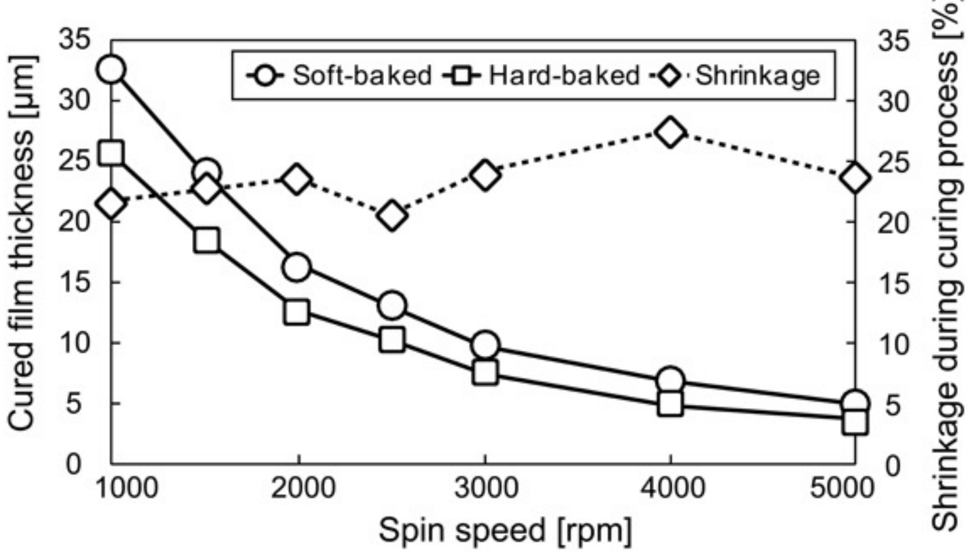
Kapton©

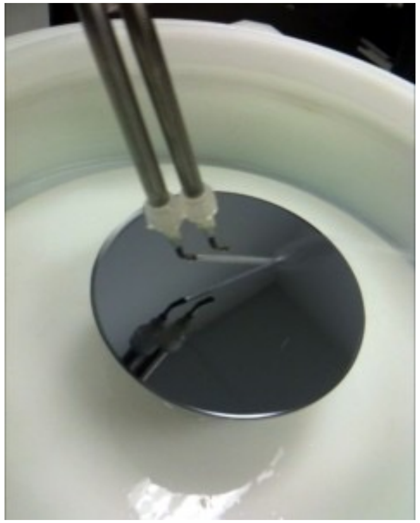


- **Imide-based polymer**
  - Imide: 2 acyl groups bonded to nitrogen
- **Thermoplastic**
  - Available as a foil
  - Spinable as an uncured resin
  - Can be photosensitive
- **Good thermal and mechanical stability**
  - Young’s modulus: ~2.5 GPa
  - CTE: 20 – 60 ppm/°C
- High resistance to solvents and weak acids

Forming a polyimide film

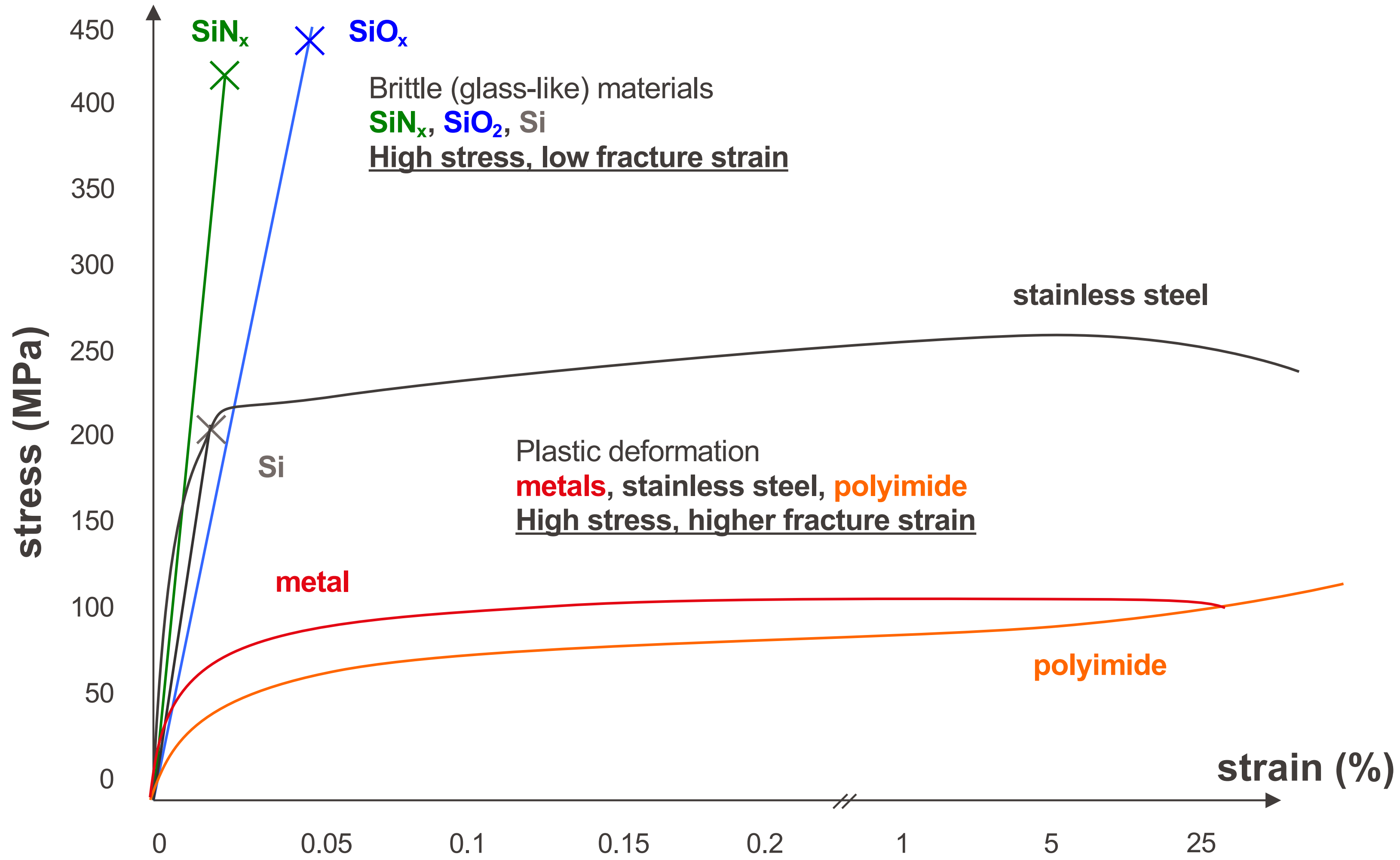
- 1. clean the rigid carrier e.g. a silicon or glass slide
- 2. spin-coat polyimide
  - Spin speed → thickness
  - Ramps → uniformity and edge beads
  - Soft bake





Kato et al, Front. Neuroeng. 2012 https://doi.org/10.3389/fneng.2012.00011

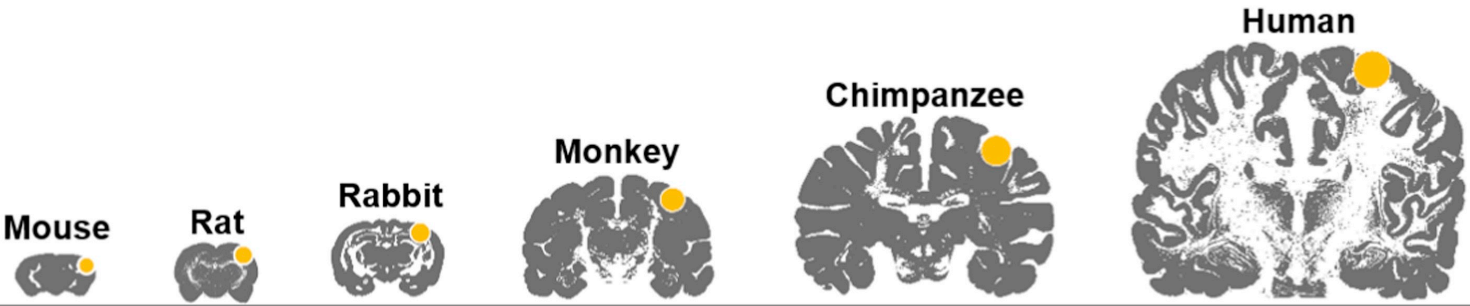
Typical stress(strain) responses



Brittle (glass-like) materials
SiN_x, SiO_2, Si
<u>High stress, low fracture strain</u>

Plastic deformation
metals, stainless steel, polyimide
<u>High stress, higher fracture strain</u>

Conformability and bending stiffness



Brain Radius of Curvature in mm	2.3	3.0	6.4	9.5	15.2	18.9

Elastic modulus and thickness control the compliance of the device.

Bending stiffness

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

elastic modulus (E)

thickness (h)

E_{PI} ~ 1-5GPa

M. Vomero et al, **Biomaterials 2020** 255 120178

Thin metal films

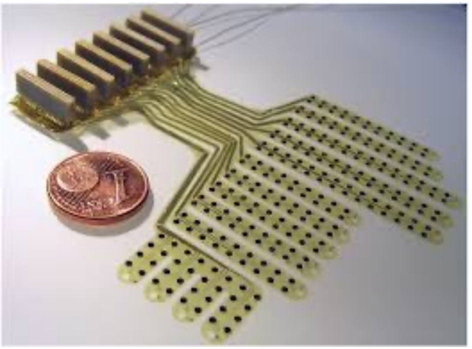
- Electrical conductors
  - **Physical properties**

Electrical conductivity/resistivity	σ/ρ	S/cm or Ω.cm
Thermal conductivity	k	W/m.℃
Thermal coefficient of resistance	TCR	ppm/℃
Coefficient of thermal expansion	CTE	ppm/℃
Young's modulus	E	MPa-GPa

  - **Process ability**
    - Deposition
    - Patterning

Interconnect resistance

Flexible ECoGs
T. Stieglitz's lab



$$R = \rho \frac{L}{t\,W} \quad [\Omega]$$

material	Resistivity [Ω/cm] for THIN film
Ag	~20µΩ.cm
Al	~3µΩ.cm
Pt	~10s µΩ.cm

Microfabrication of electrode array on polyimide substrate

Option 1

- Prepare the carrier substrate
- Deposit the metal film
- Pattern the metal film
- Deposit and pattern encapsulation film

Option 2

- Prepare the carrier substrate
- Pattern a masking film
- Deposit the metal film
- Remove the masking film
- Deposit and pattern encapsulation film

Process flow for a thin metal track

Option 1

1. Spin-coat the substrate polymer
   Material and thickness
2. Evaporate metal
   Material and thickness
3. Photolithogaphy
   Mask preparation, photoresist spin-coating & baking
   Curing, development
4. Metal etching
   Dry or wet process
5. Photoresist lift-off
   Wet process

Process flow for a thin metal track

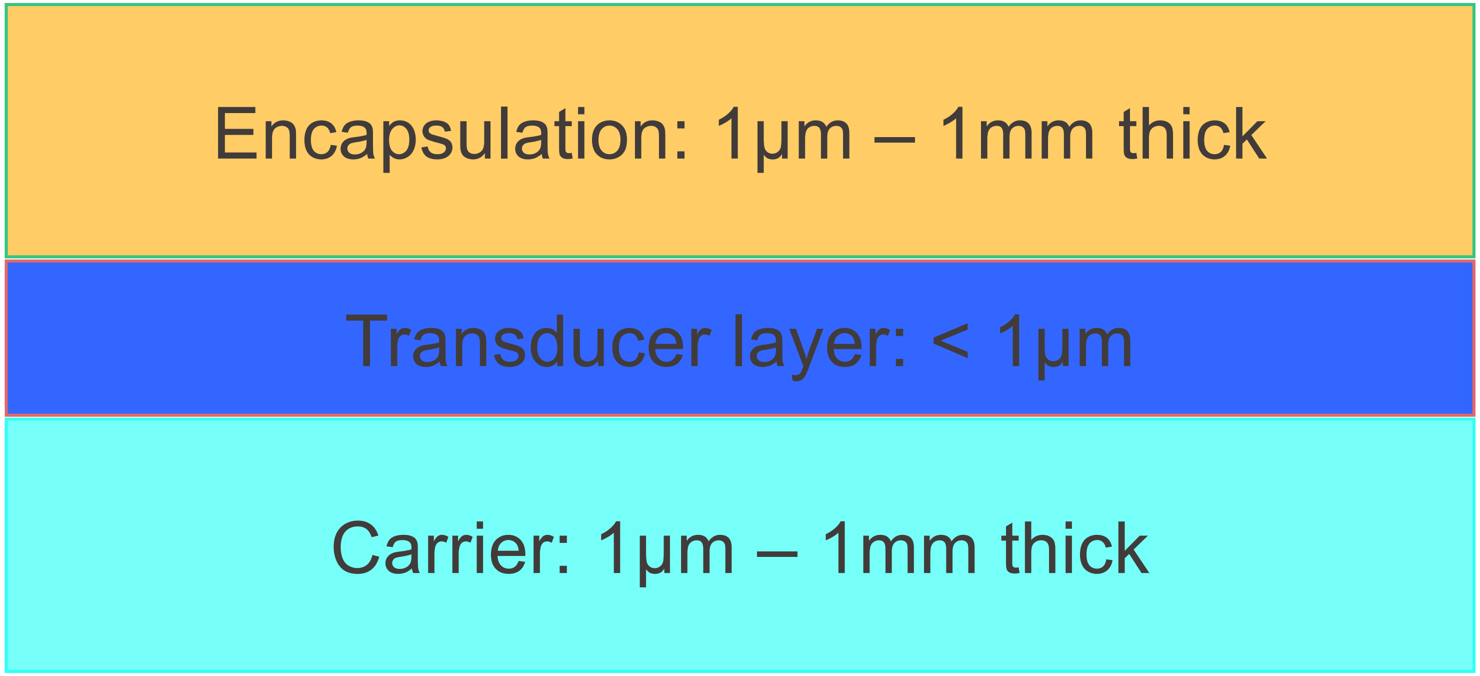
Option 1

6. spin-coat top encapsulation film
   material and thickness

7. pattern encapsulation film
   etching method and thickness

8. sample release

Encapsulation

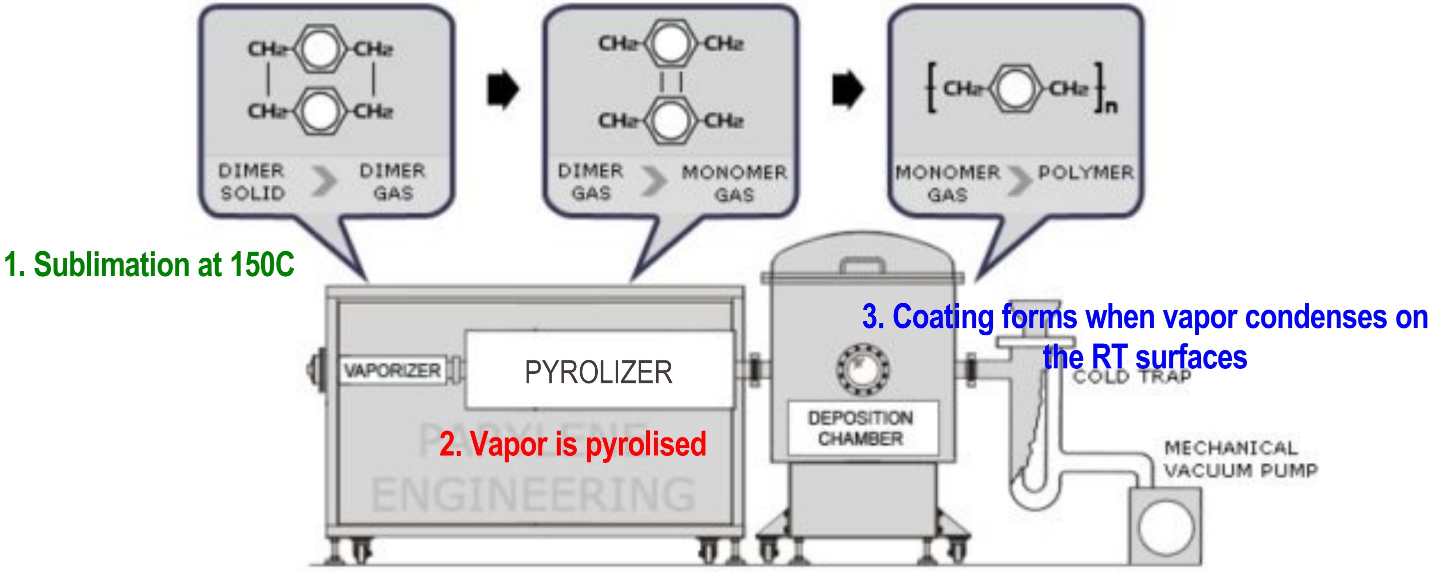


Encapsulation materials

- Polymers identical to the substrate
- Alternative polymers
- Inorganic thin films such as oxides, nitrides, etc.

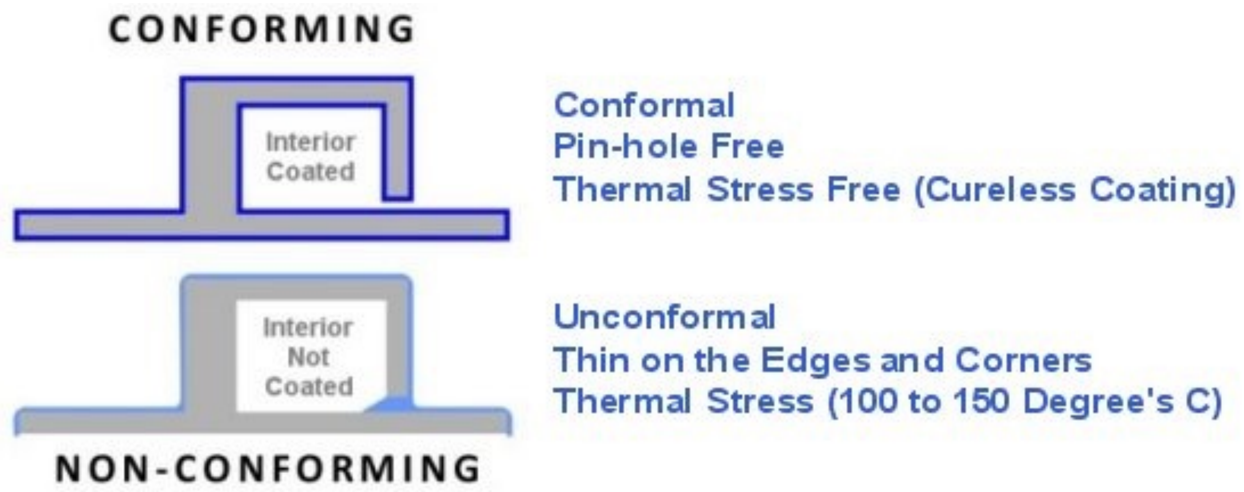
Vapor phase processed plastics

- **Parylenes: poly-para-xylylenes**
  - linear, highly-crystalline polymers produced as films or coatings
  - Vapor deposition polymerization
  - Insulating thermoplastic with high degree of chemical inertness



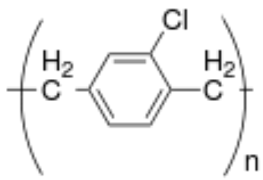
www.paryleneengineering.com

Parylene: conformal coating

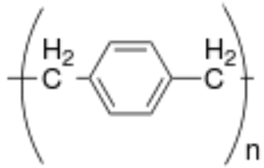


Types of parylenes

- Parylene C → standard compound



- **Parylene N → biomed. applications**



- Parylene D → higher temperature applications

- Parylene HT → high temperature and UV exposure stability

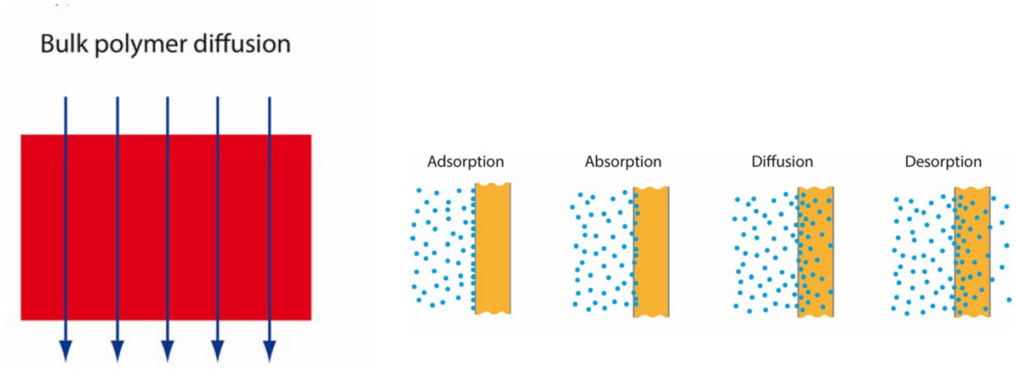
Parylene properties

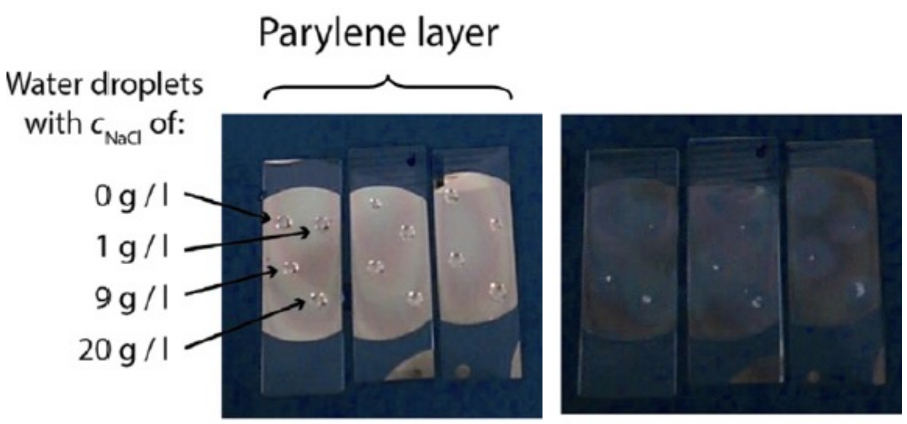
- **Mechanical properties**
  - Young's modulus: 0.5GPa – 2.75GPa
  - Low stress coating that does not form sites prone to crack initiation
- **Thermal stability**
  - CTE: **35 – 70** ppm/℃
- **Optical properties**
  - Transparent and colorless in the visible range
  - Autofluorescence – limited

Hermeticity

Surface and Coatings Technology (2014), 255, 124-129

Permeation process





t = 0 t = 8h

Test : Calcium mirror test

Water Vapor Transmission Rate (Par C)
WVTR ~ 10^{-2} g/m^2/day

WVTR
Thin Film Encapsulation

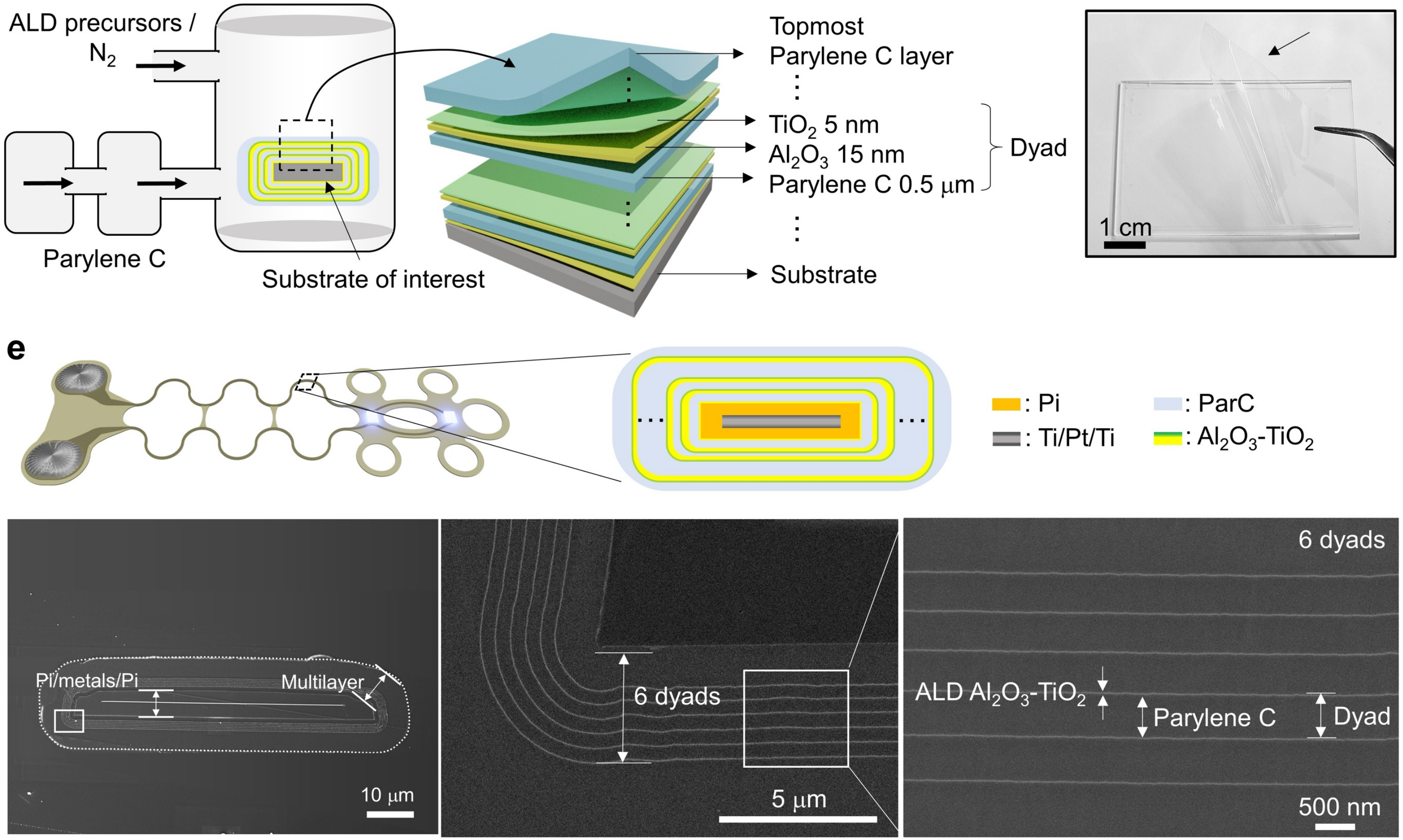
Organic Electronics Volume 50, November 2017, Pages 296-303

- Stable operation of flexible electronic devices
  - >10,000 h requires **$10^{-3} \leq$ WVTR $\leq 10^{-6}$ g m^{-2} d^{-1}**
  - Even more constraining for implantable devices

- Thermoplatics

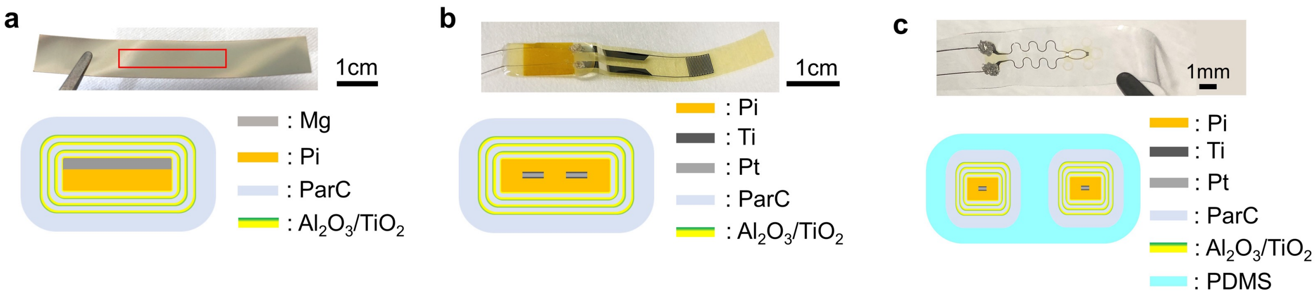
- Single-layered barrier films
  - e.g. SiO_x, SiN_x, SiC_x, SiO_xN_y, SiO_xC_y, Al_2O_3, AlO_xN_y, ZrO_2, TiO_2, MgO, ZnO, SnO_2
  - relatively high $10^{-1} \leq$ WVTR $\leq 10^{-3}$ g m^{-2} d^{-1}

Organic/inorganic multilayer encapsulation



K. Kim et al., Small, 2021, https://doi.org/10.1002/smll.202103039

Lifetime evaluation

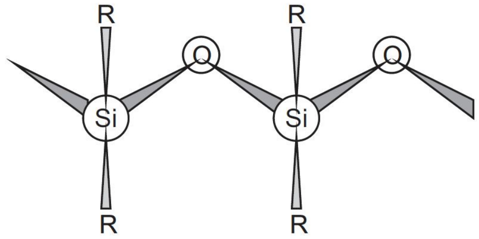


Mg test

IDE: Inter-digitated electrodes

OE: micro-LED

Silicones
encapsulation / packaging



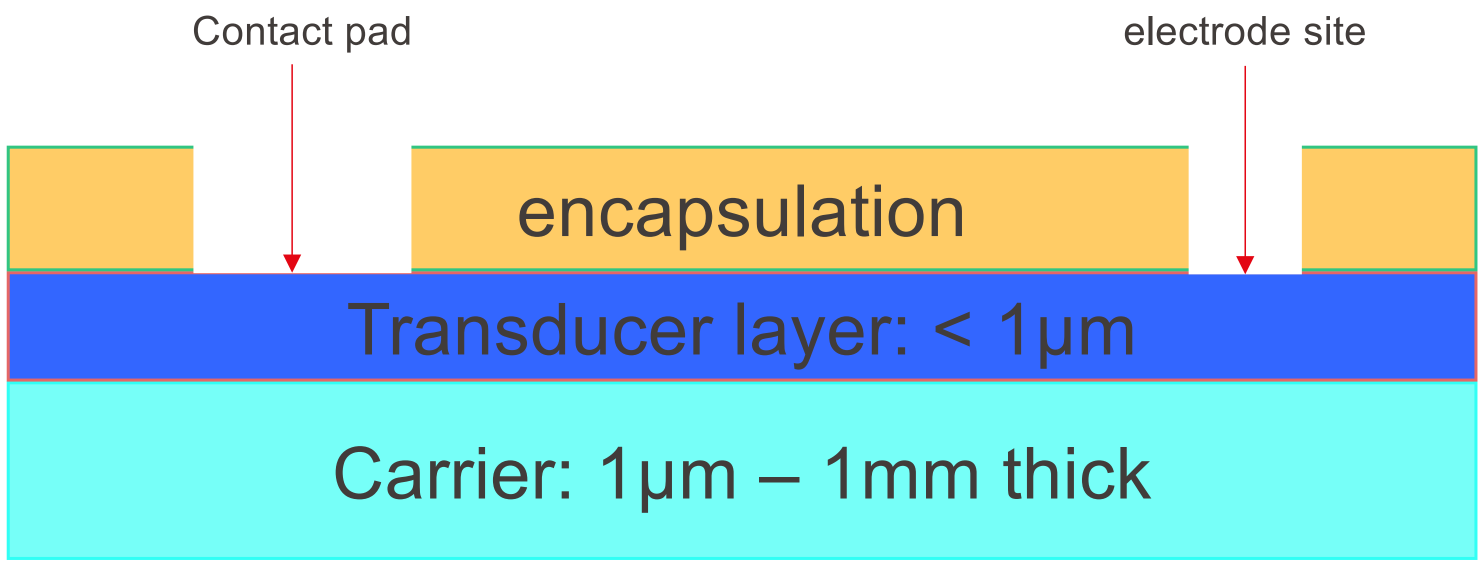
- Long-lasting material
- **Polymer** with simultaneous presence of organic groups attached to inorganic atoms

- Silicone elastomers (rubbers)
  - Molding, injection, spin-coating, printing
  - Cross-linked polymer

- Soft polymer : elastic modulus range: 10 kPa – 10 MPa

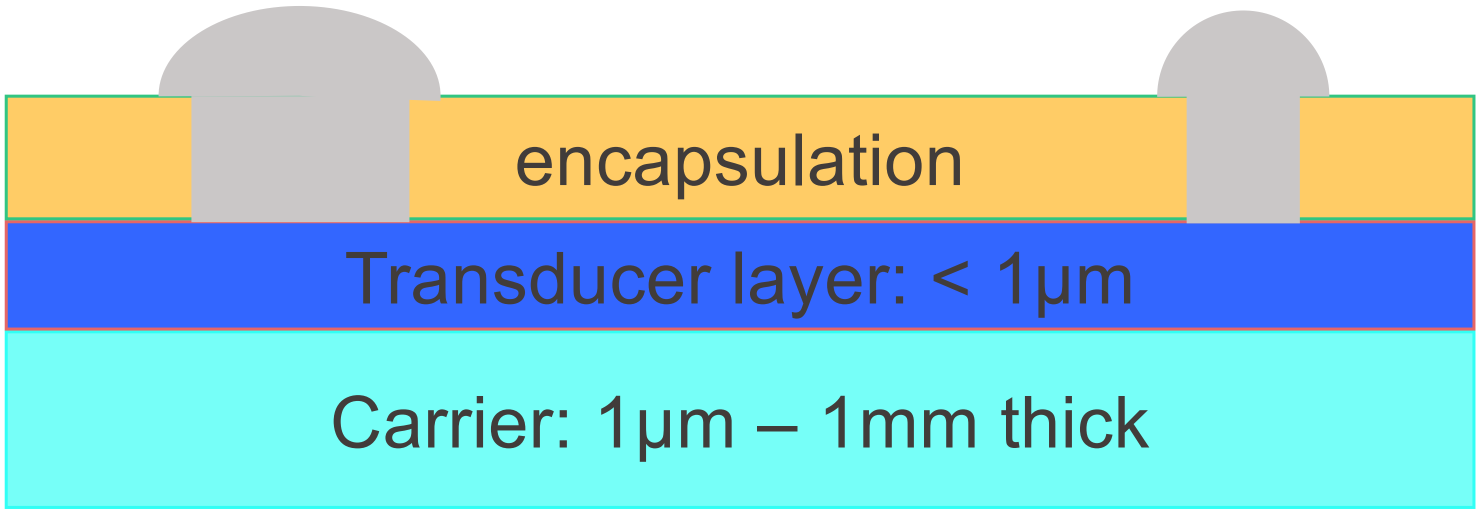
- Very good protection over corrosion of silicon and oxidizable materials
- Very good electrical insulators (esp. Fluoropolymers)

Encapsulation patterning



Conductive coating

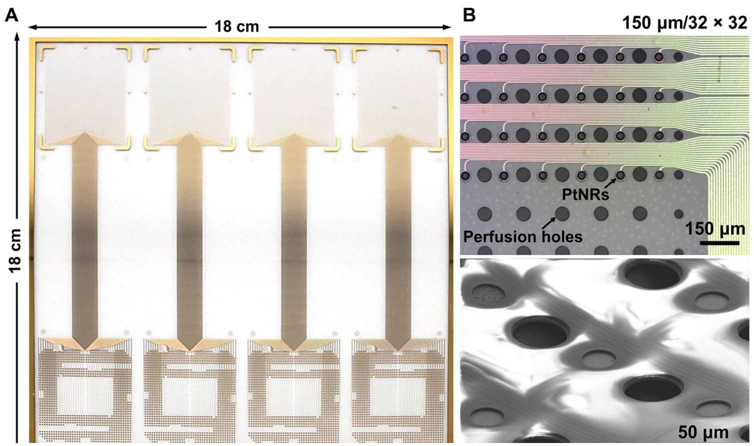
- Conductive paste
- Conductive composite
- Electrodeposited material: metal or organic conductors

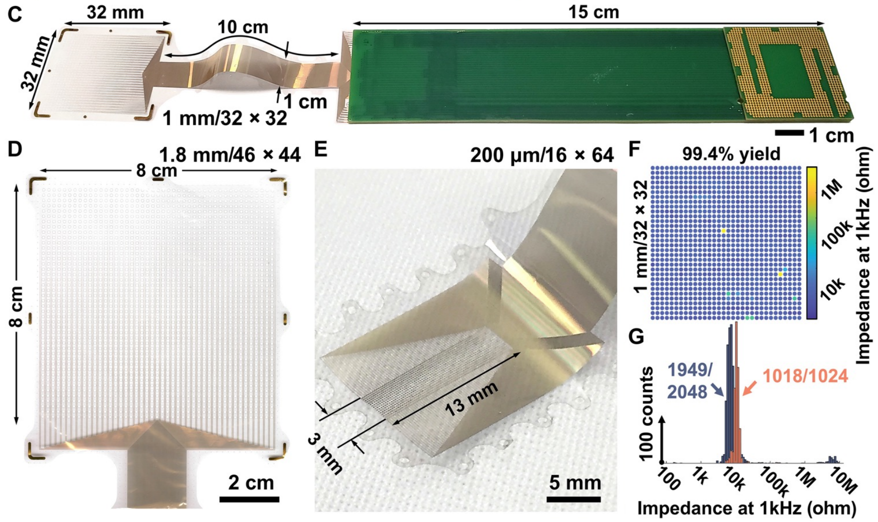


Thin film electrode arrays

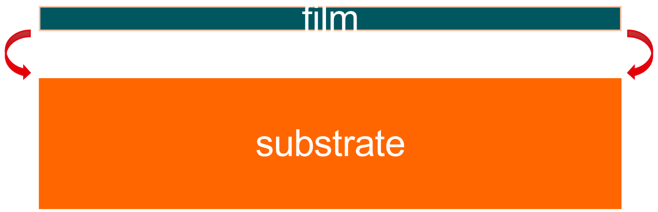
Science Translational Medicine
19 Jan 2022
Vol 14, Issue 628
DOI: 10.1126/scitranslmed.abj1441

- Multithousand-channel PtNRGrid ECoG arrays
  - 8 cm by 8 cm (2048 channels)
  - 30µm wide PtNR contacts recessed by ~2 µm below the surface of Par-C





Mechanical design of flexible thin-film devices



Young's modulus, thickness

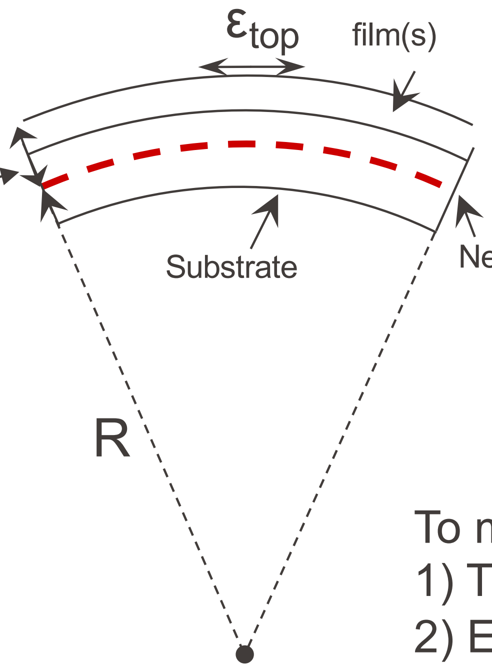
Film: E_f, d_f

Substrate: E_s, d_s

$E_f \cdot d_f << E_s \cdot d_s$	The substrate dominates; The film complies with it.	Ex. Film on glass
$E_f \cdot d_f \approx E_s \cdot d_s$	Equal strength of film and substrate	Ex. Film on plastic
$E_f \cdot d_f >> E_s \cdot d_s$	The film dominates, The substrate complies with it	Ex. Film on rubber

Bending a film-on-substrate stack

Stiff substrates $E_f \cdot d_f << E_s \cdot d_s$ *(often $d_f << d_s$)*



Distance from top to neutral plane $d = \frac{d_f + d_s}{2}$

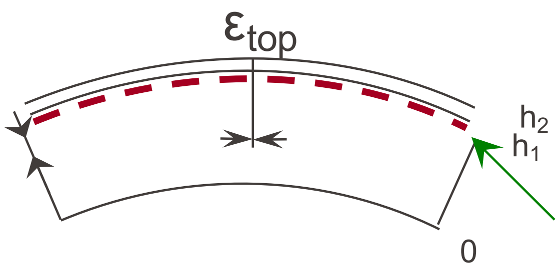
$$\varepsilon_{top} = \frac{d}{R} = \frac{d_s + d_f}{2R}$$

To minimize the strain use:
1) Thin substrate
2) Encapsulation
3) Compliant substrate

Bending a film-on-substrate stack

Compliant substrates $E_f \cdot d_f \approx E_s \cdot d_s$

Distance from top to neutral plane $d < \dfrac{d_f + d_s}{2}$



In pure bending mode, the neutral plane is located at the "weighted average" of the mid-points of each layer

mid-point of each layer $$h_{mi} = \frac{h_i + h_{i+1}}{2} = h_i - \frac{d_i}{2}$$

Z. Suo et al, 1999, Applied Physics Letters, 74 8, 1177-1179.

Strain at the top surface

- Case: Thin film *f* bonded to substrate *s*
  - d_i thickness
  - R bending radius

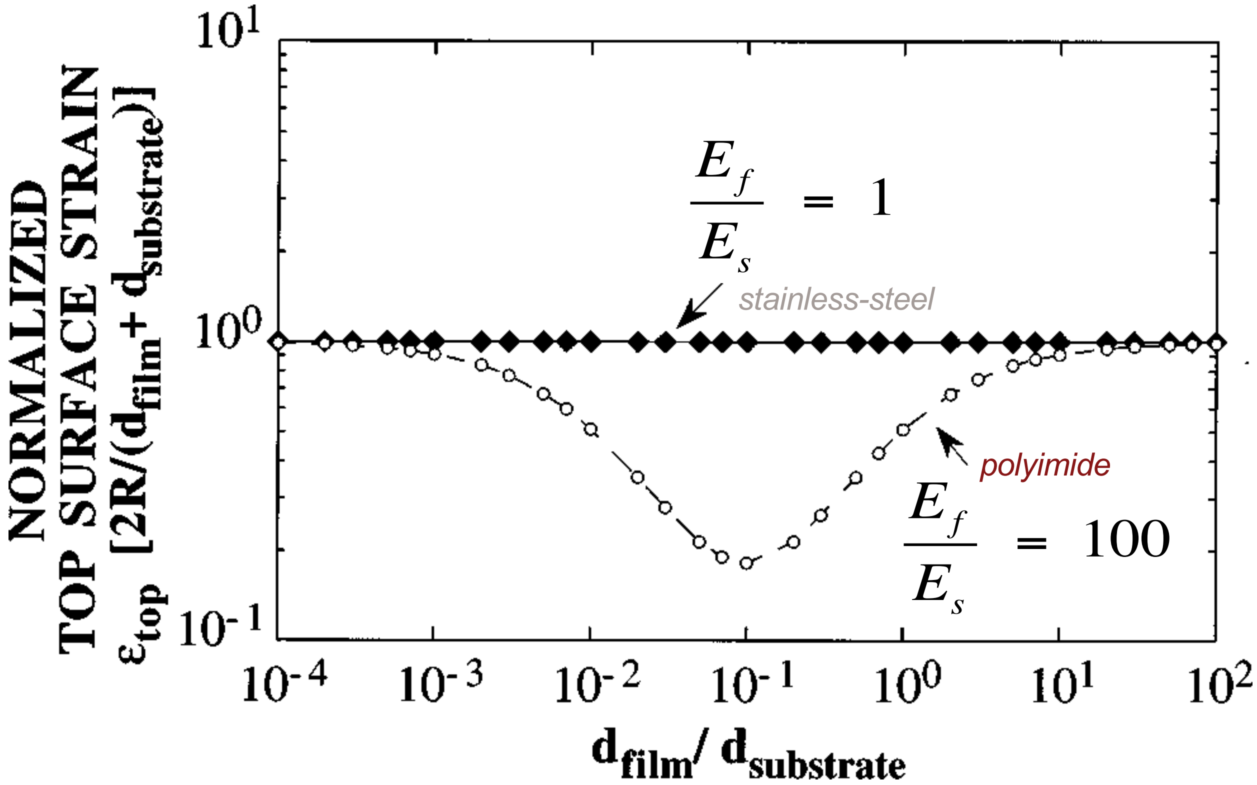
$$\varepsilon_{top} = \left(\frac{d_s + d_f}{2R} \right) \frac{1 + 2\eta + \chi\eta^2}{(1+\eta)(1+\chi\eta)}$$

with $\eta = d_f / d_s$
$\chi = E_f / E_s$

Z. Suo et al, 1999, Applied Physics Letters, 74 8, 1177-1179.

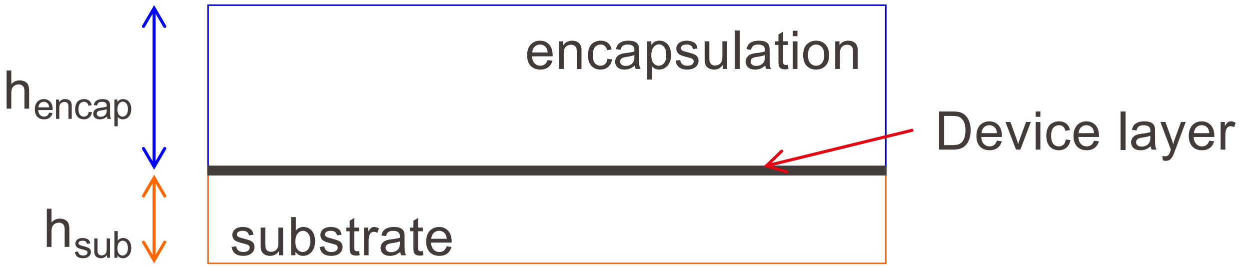
Film on compliant substrate

Strain in the film as a function of film/substrate thickness ratio



Z. Suo et al, 1999, Applied Physics Letters, 74 8, 1177-1179.

Placing devices in the neutral plane

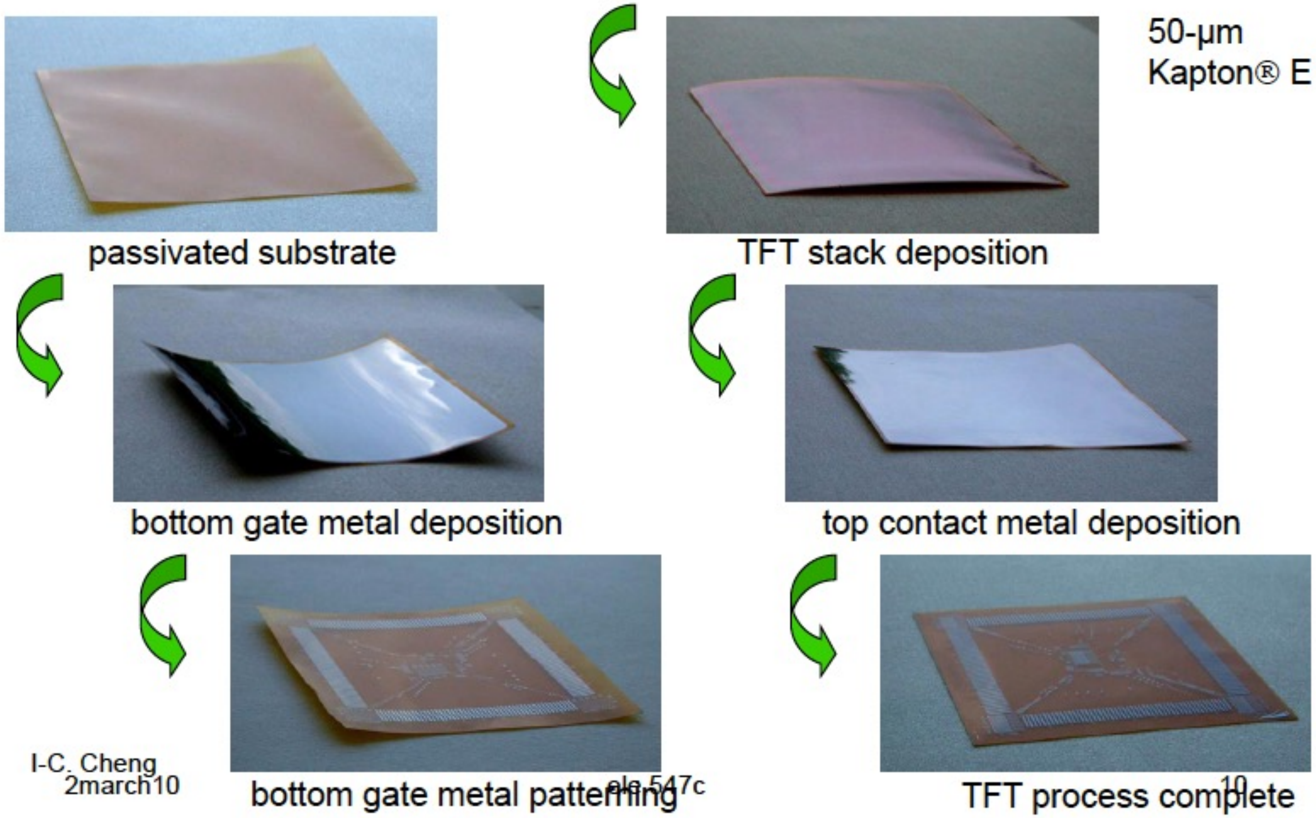


Design rule: place the device layer at the neutral surface

Brain computer interfaces

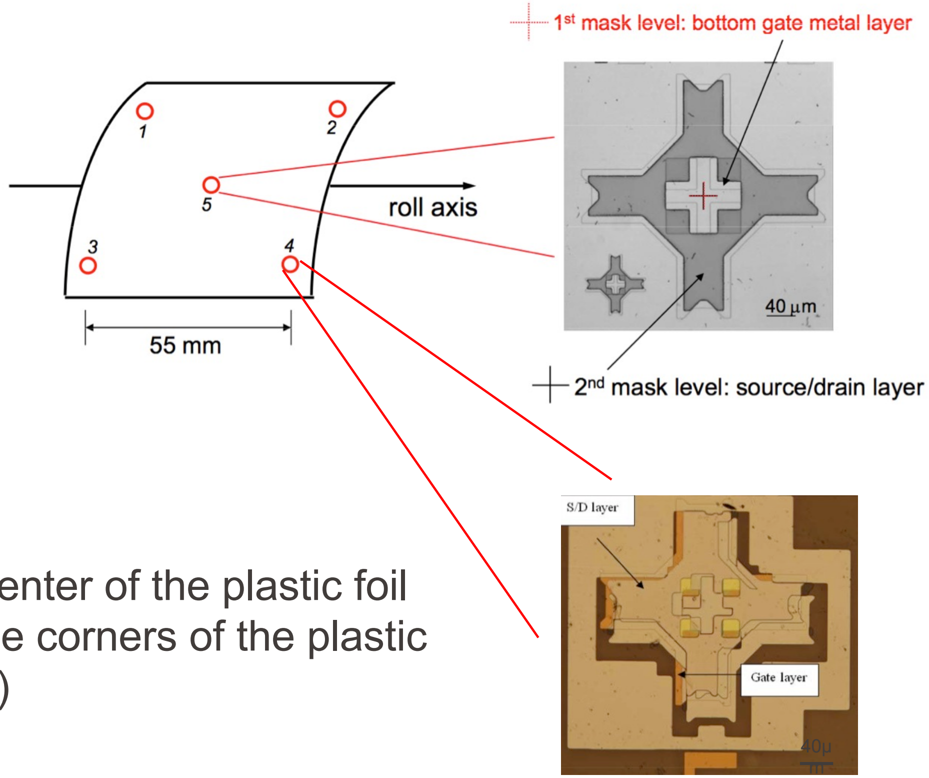
- Overview
- Silicon-based neurotechnology
- **Flexible implantable neurotechnologies**
  - **Challenges in microfabrication on flexible substrates**

Curvature during manufacturing



a-Si:H TFTs on Kapton foil
I-C Cheng, Princeton University

Misalignment



⇒ Aligned at the center of the plastic foil
⇒ Misaligned at the corners of the plastic foil (≈ 1000ppm)

S. Wagner et al, Flexible Flat Panel Displays, 2005 Chap. 14, 263

Summary

- Microfabrication
  - Borrowed from microelectronics processing
  - Thin-film processing

- Miniaturisation and reproducibility
  - High density electrode array
  - Active electrode array