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# Micro-311

Microfabrication of

Flexible and Stretchable Neuroelectronic interfaces

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# Microfabrication of Flexible and Stretchable Neuroelectronic interfaces

- Overview
- Silicon-based neurotechnology
- Flexible neurotechnology
- Stretchable neurotechnology

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# Why Flexible (or beyond → stretchable) Electronics?

- Mechanical / geometrical requirements from specific applications:
  → System must be able to withstand bending and deformation without failing
- Some applications driving the development of flexible electronics:

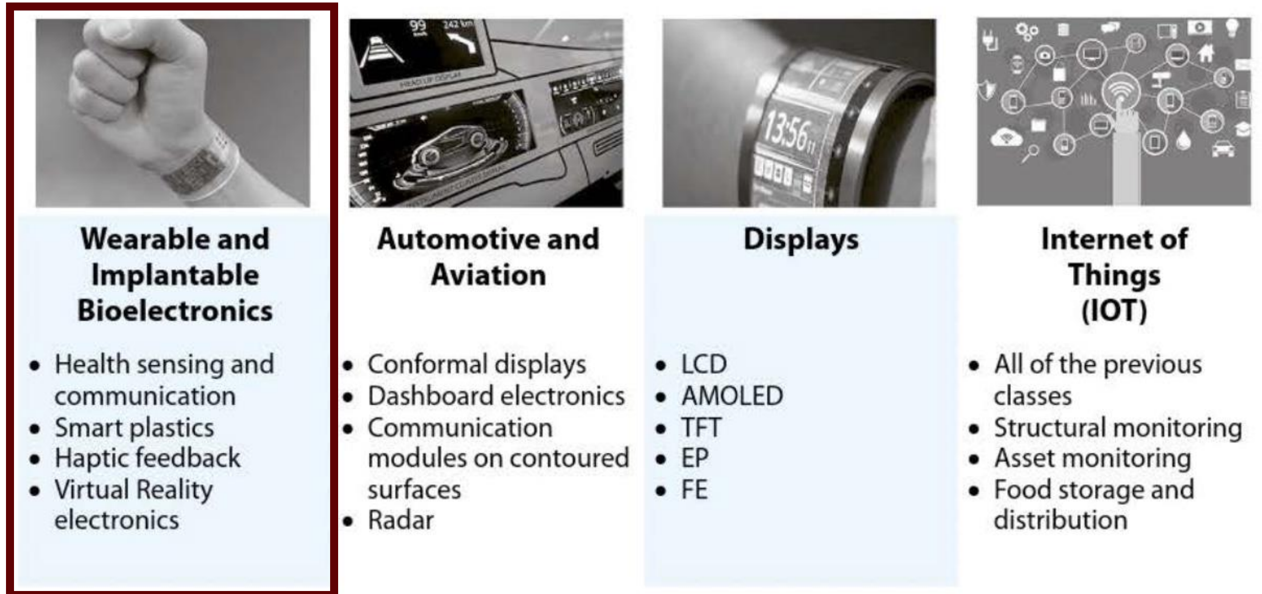


FIGURE 21.1 Applications of flexible electronic systems.

Tummala 2020

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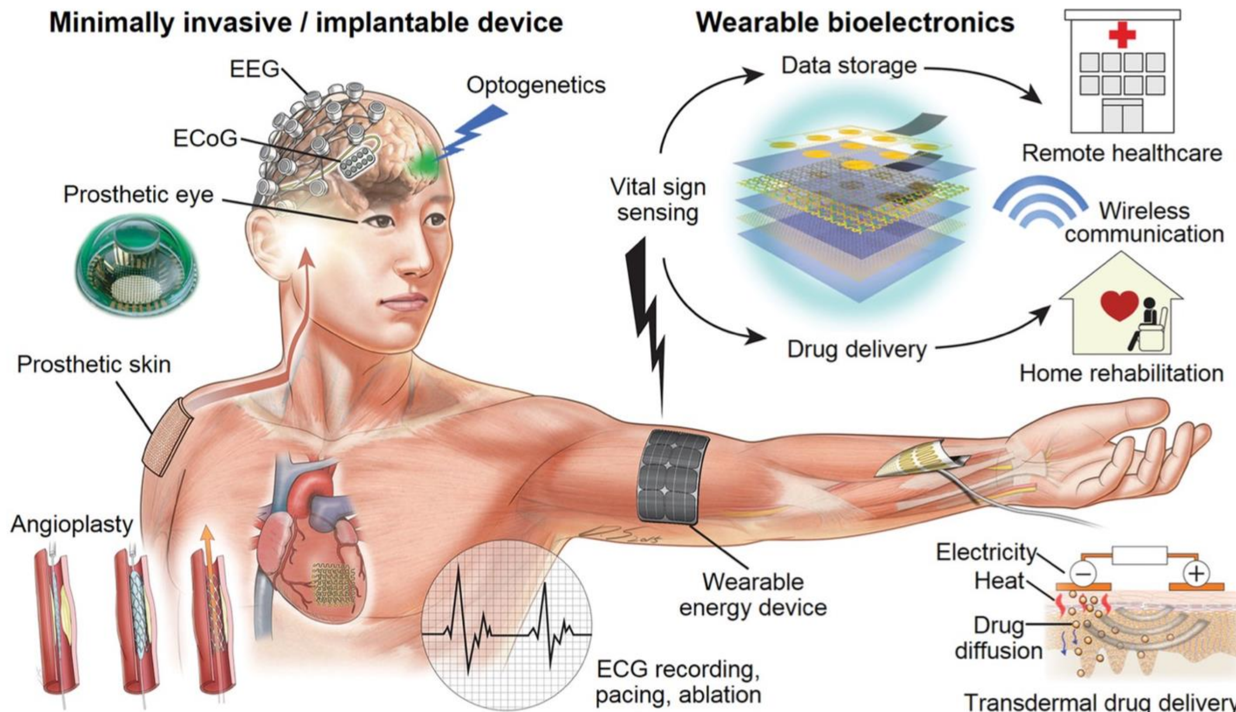
# *Wearables and Implantables*

- **Wearables**. Flexible electronic systems that can be worn by a consumer as an accessory or as a part of clothing. (In reality: can also be non electronic, can be applied to skin or other non-planar surface, can have a medical purpose.)

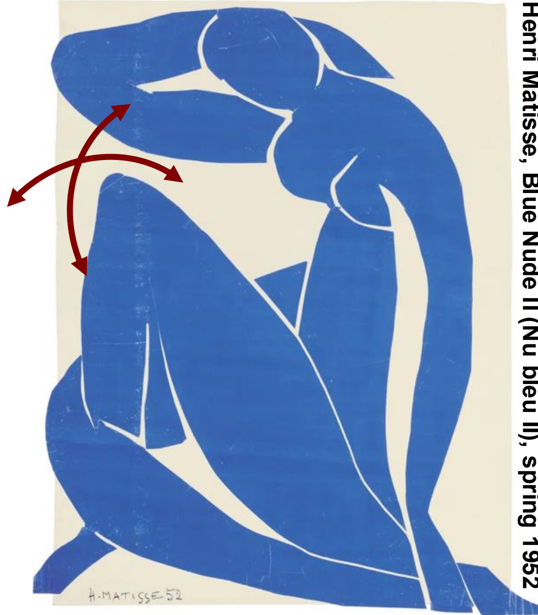
Choi *et al.*, 2016, Advanced Materials

- **Implantables**. A device that is deployed internally in the human (or animal) body.



# *A geometrical and mechanical challenge*

**Complex topologies**




Henri Matisse, Blue Nude II (Nu bleu II), spring 1952

**Mobile bodies**

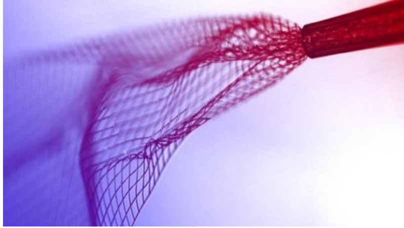
Henri Matisse, Two Dancers (Deux danseurs), 1937–38

→ Neurotechnology must **conform** curvilinear and mobile bodies

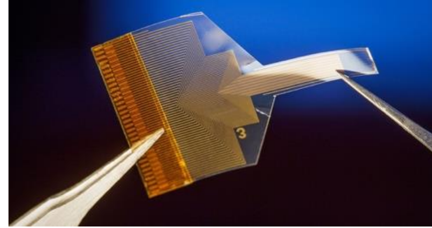
→ **Elasticity** is needed to follow the body movement and deformation

# Microfabricated Flexible Neural Interfaces

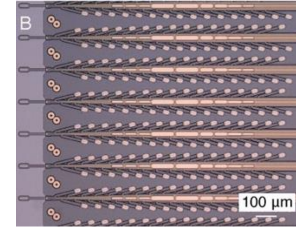


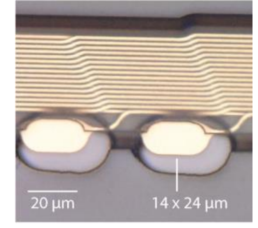


Nanomesh
Jia Liu - Harvard

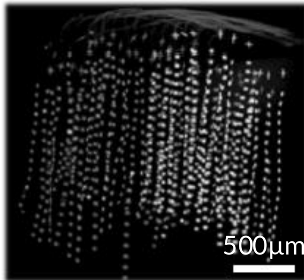


Transparent ECoG
D Kuzum- UCSD




Neuralink




NET 1’024 electrodes
L. Luan, Rice Univ.

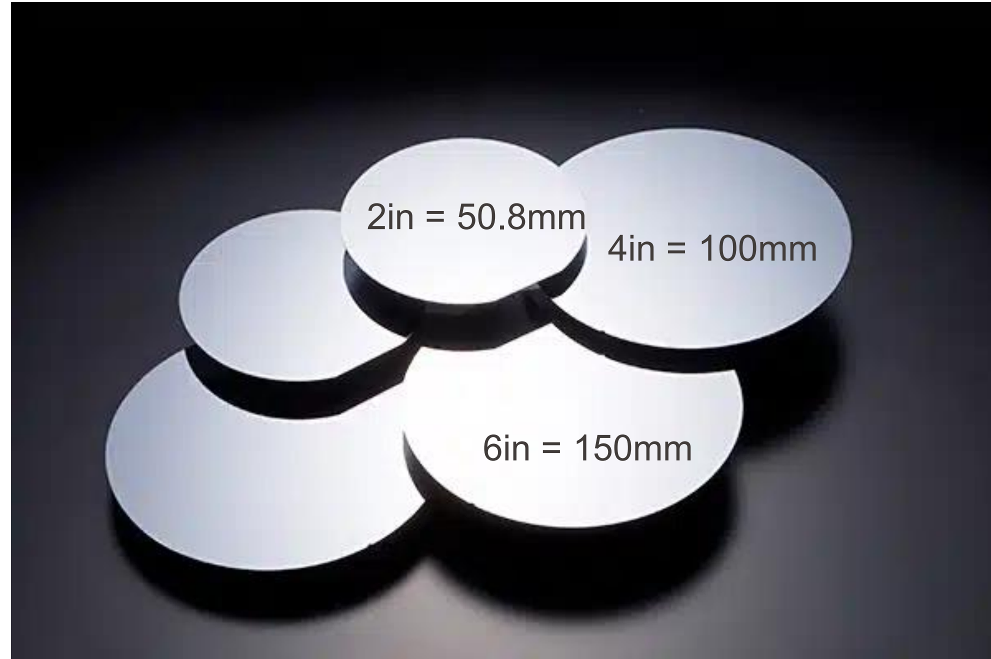
graphene electrodes
InBrain - Spain

Soft ECoG – EPFL / Neurosoft Bioelectronics

# Silicon wafers



- diameter: 2in – 12in
- *12in: modern semicond. fab.*
- thickness: 275 - 1’000 µm
- flatness
- orientation flat and notch
- *(100) or (111) orientation*
  *(anisotropicity in some properties)*



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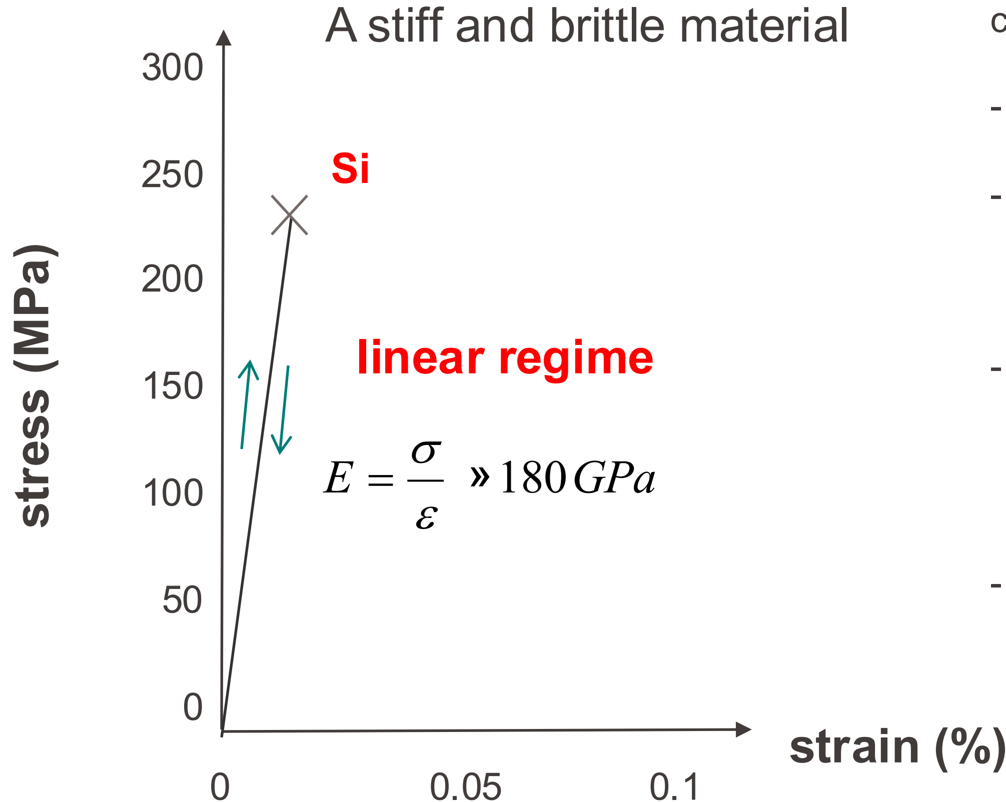
# Silicon






"Inherited" from µ-electronics because of the CMOS capabilities

- Excellent control over the mechanical properties.
- **Thermal stability:** High melting point and good thermal conductivity make it robust through high-temperature steps (oxidation, diffusion, anneals).
- **Surface chemistry control:** Surfaces can be precisely cleaned, passivated, and functionalized; $Si/SiO_2/Si_3N_4$ stacks are well understood for adhesion and protection.
- **Scale & cost:** Abundant material, mature equipment and supply-chain. Decades of CMOS know-how transfer directly to MEMS.

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# Silicon-based neurotechnology



1D

- Planar 2D structural design
- 1D sites spatial coverage
- Example: Michigan Probe

Michigan Probe, 1985

1.5D

20 µm
25.6 µm
32 µm

Neuropixel Probe, 2017

- Planar 2D design
- 1.5D sites spatial coverage
- Example: Neuropixel (IMEC Probe)

2D

1 mm

Utah Electrode Array, 1991

- Out-of-Plane 3D structural design
- 2D sites spatial coverage
- Example: Utah Electrode Array

3D

Michigan 3D Array, 1991

- Out-of-Plane 3D structural design
- 3D sites spatial coverage
- Example: Michigan 3D Array

https://doi.org/10.1101/2021.01.24.427975

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# The Utah array

a. **Backside dicing**
→ 10x10 0.5mm deep matrix

b. **Glassing**

c. **Grinding**

d. **Back-side metallization**
→ Pt/TiW/Pt sputtering

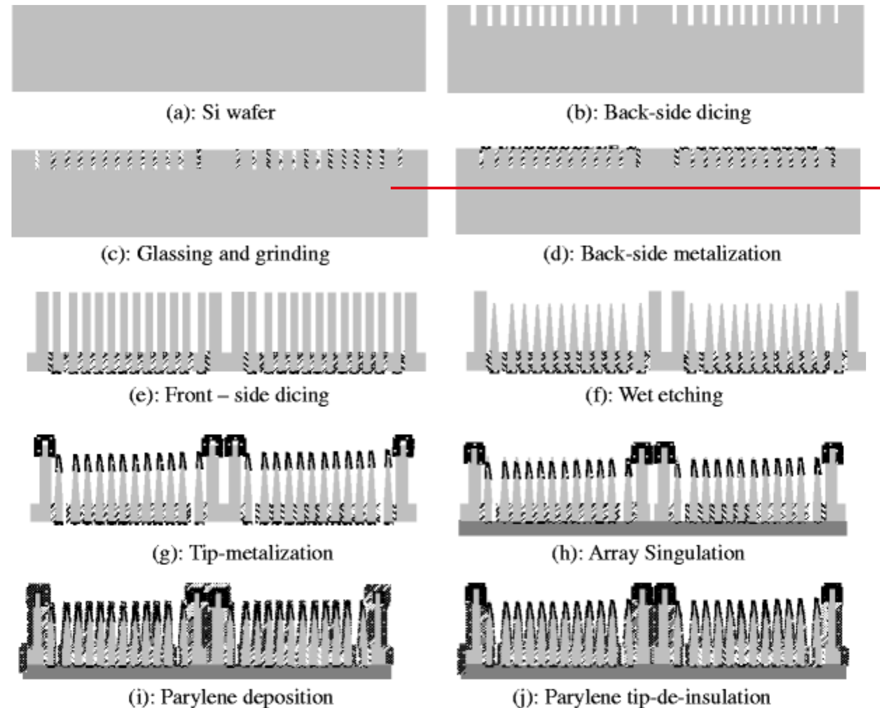
e. **Front-side dicing**
→ 1.5mm deep columns

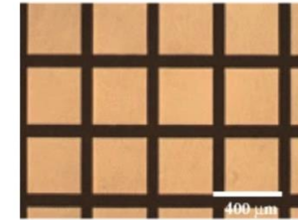
f. **Wet etching**
→ HF:$HNO_3$ (1:19 ratio)

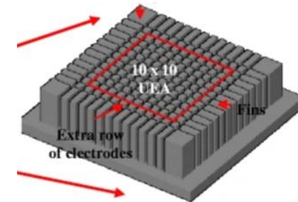
g. **Tip metallization**
→ sputtered Ti/Ir then lift-off

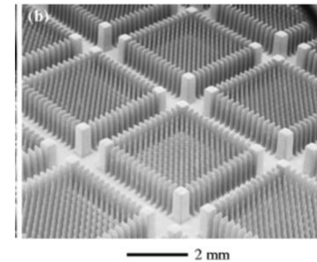
i. **Parylene deposition**
→ LPCVD, 3μm thick

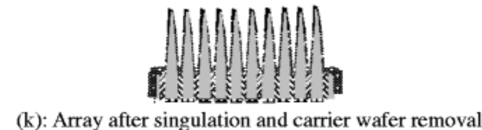
j. **De-insulation**
→ oxygen plasma etching, 30-350μm length



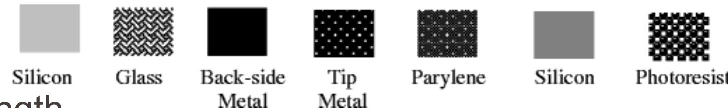



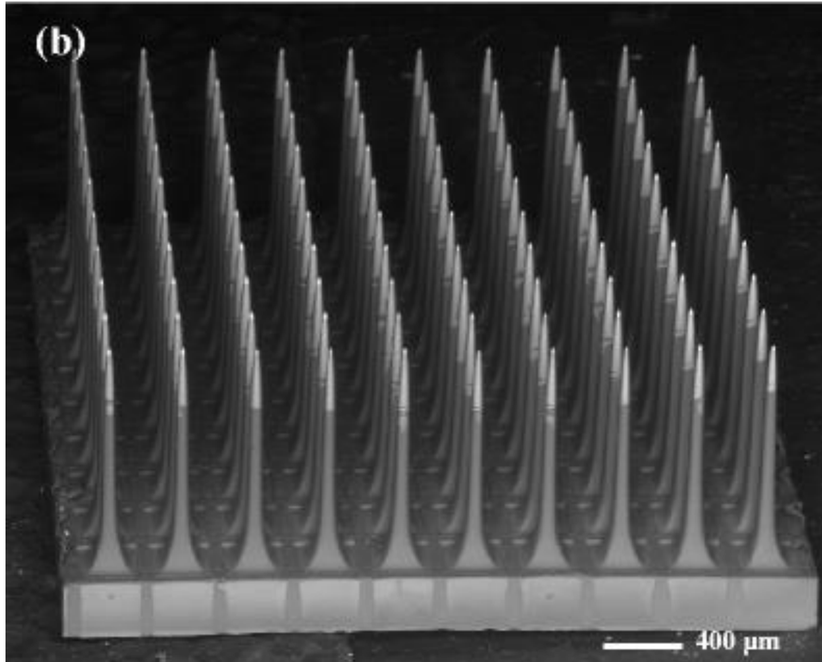
(k): Array after singulation and carrier wafer removal



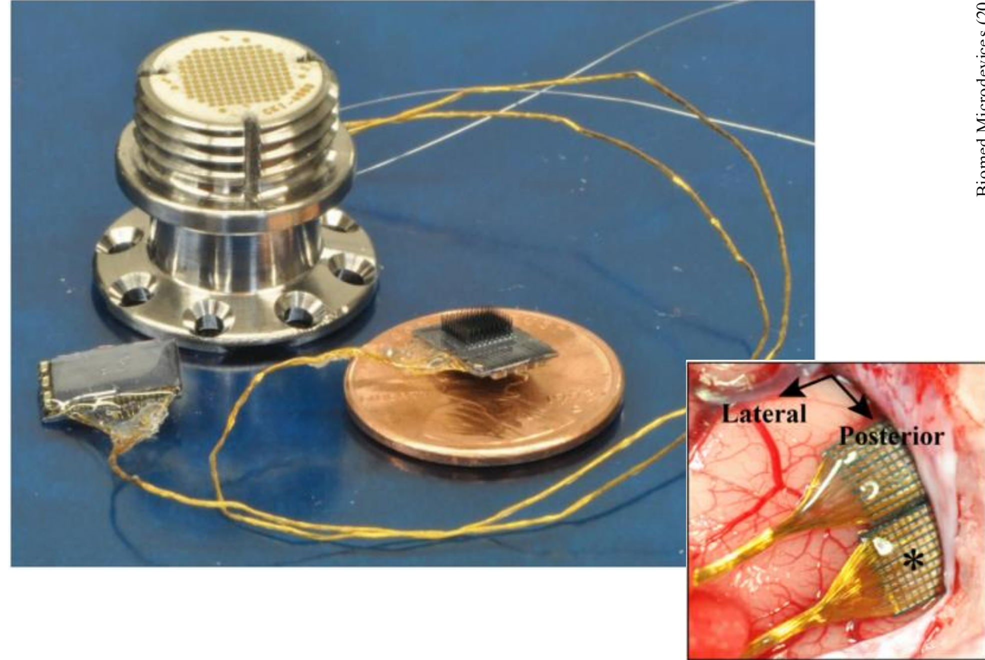

Biomed Microdevices (2010) 12:79

# The Utah array






Biomed Microdevices (2010) 12:797–807




Xianzong Xie *et al* 2014 *J. Neural Eng.* **11** 026016

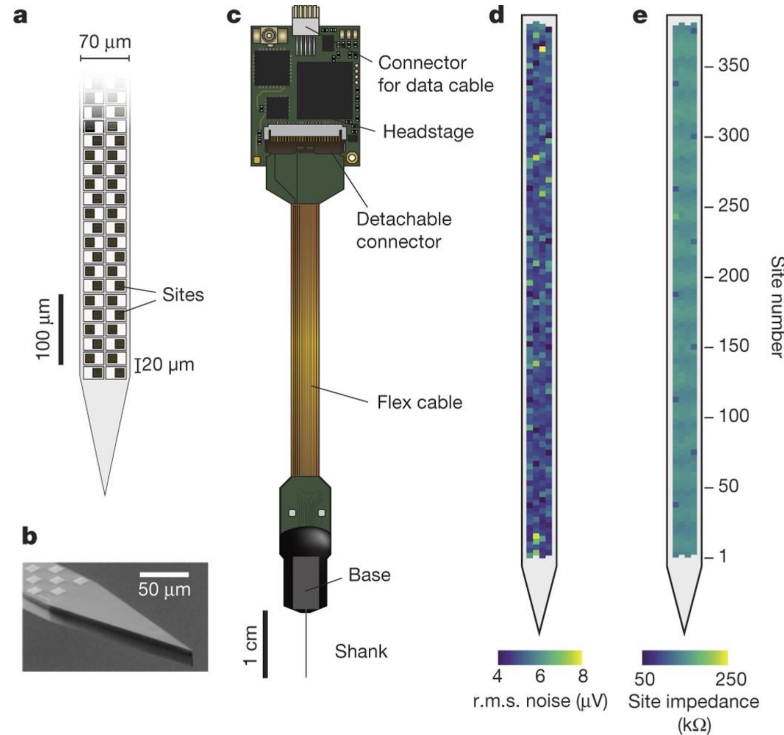
# Use in brain-computer-interface

# The Neuropixel: Active silicon probe



IMEC

User-programmable switches that allow the recording channels to address 384 of the **960 total sites** simultaneously
130nm CMOS technology



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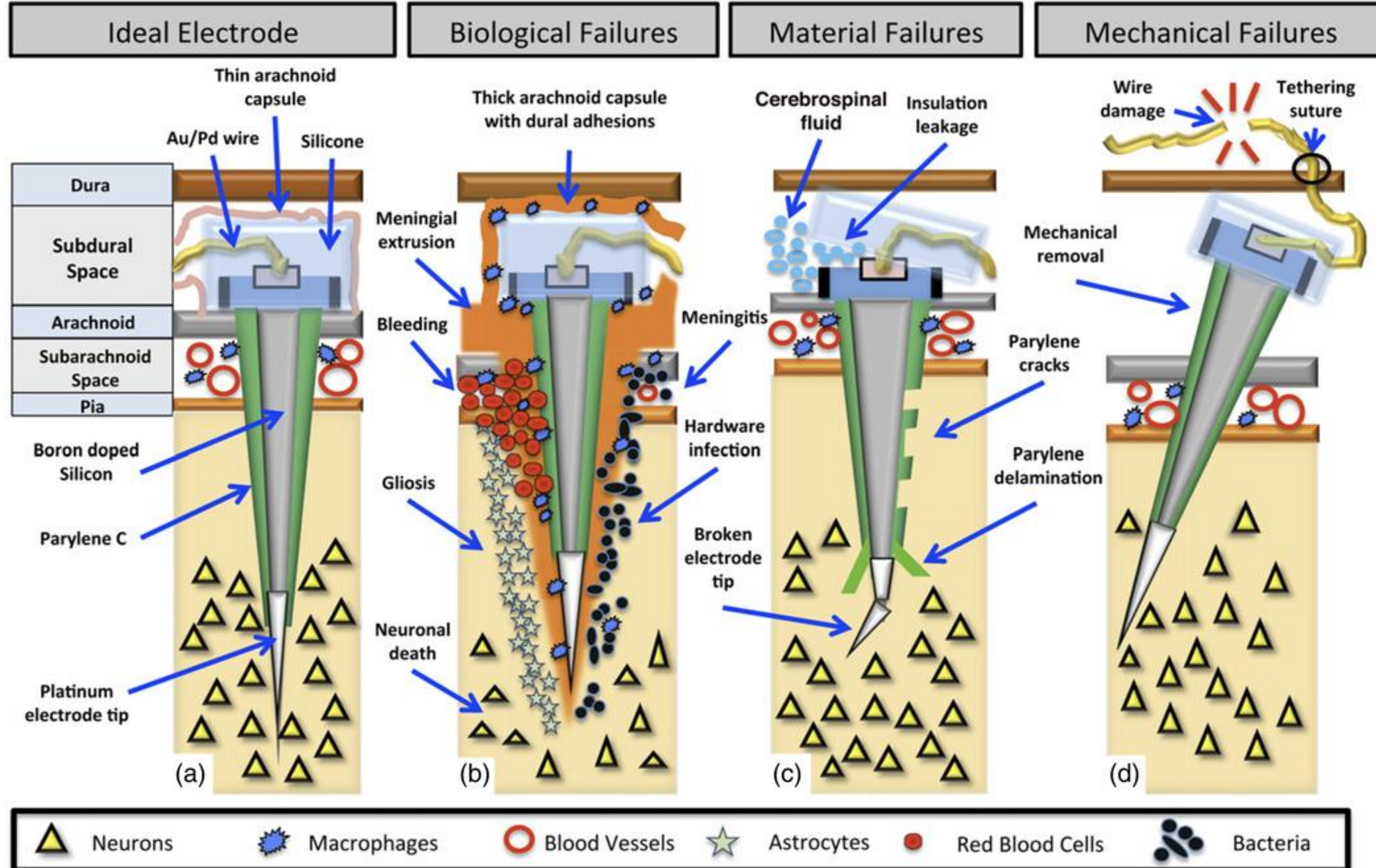
# Damage to implant






doi: 10.1088/1741-2560/10/6/066014

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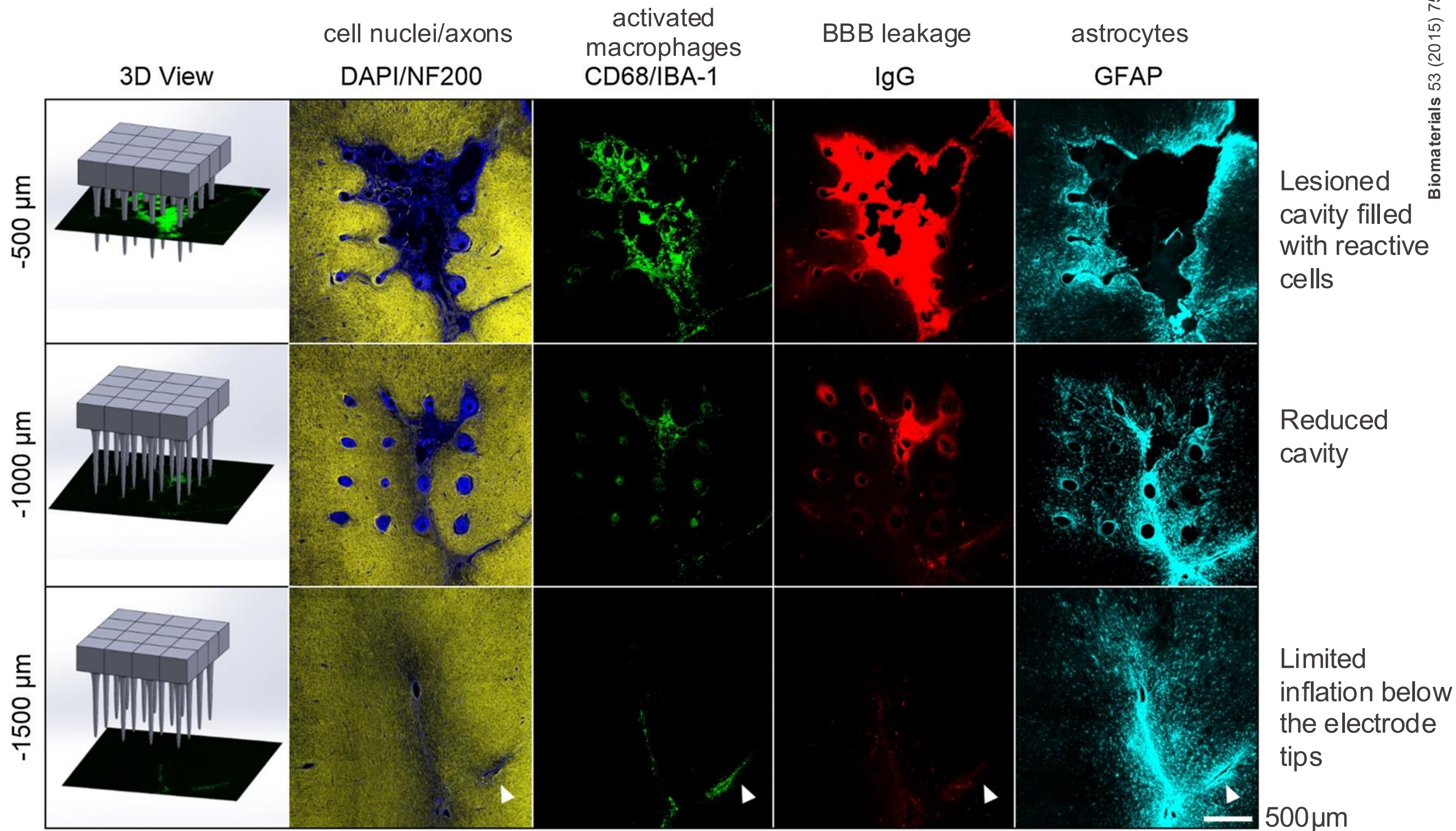
# Damage to brain tissue

4x4 Si shanks,
1mm long,
400µm apart
1.2x1.2 mm²

Timepoint: 4w



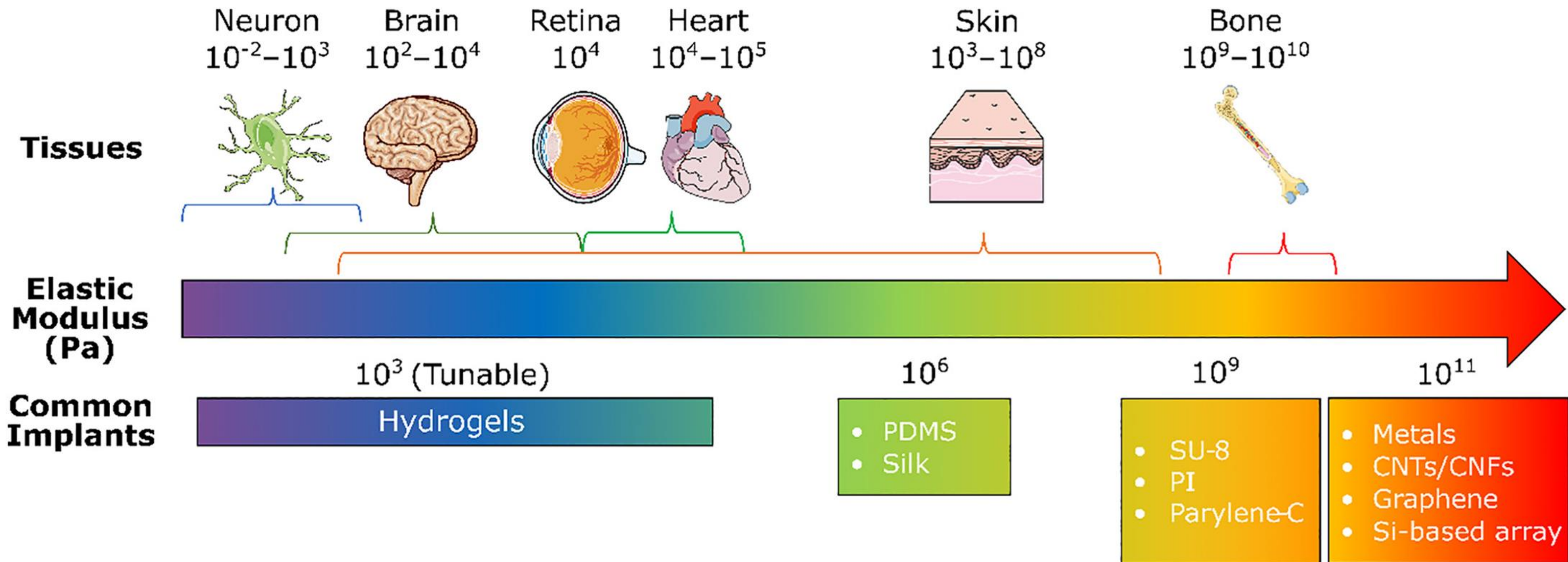

Lesioned cavity filled with reactive cells

Reduced cavity

Limited inflation below the electrode tips

Biomaterials 53 (2015) 753-762

# Man-made vs biological materials



# Flexible neural interfaces



1D
- Planar 2D structural design
- 1D sites spatial coverage
- Example: Michigan Probe

Michigan Probe, 1985

1.5D
- Planar 2D design
- 1.5D sites spatial coverage
- Example: Neuropixel (IMEC Probe)

Neuropixel Probe, 2017

25.6 µm
20 µm
32 µm

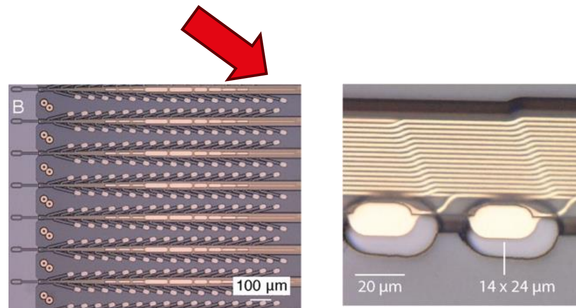
2D
- Out-of-Plane 3D structural design
- 2D sites spatial coverage
- Example: Utah Electrode Array

Utah Electrode Array, 1991

1 mm

3D
- Out-of-Plane 3D structural design
- 3D sites spatial coverage
- Example: Michigan 3D Array

Michigan 3D Array, 1991

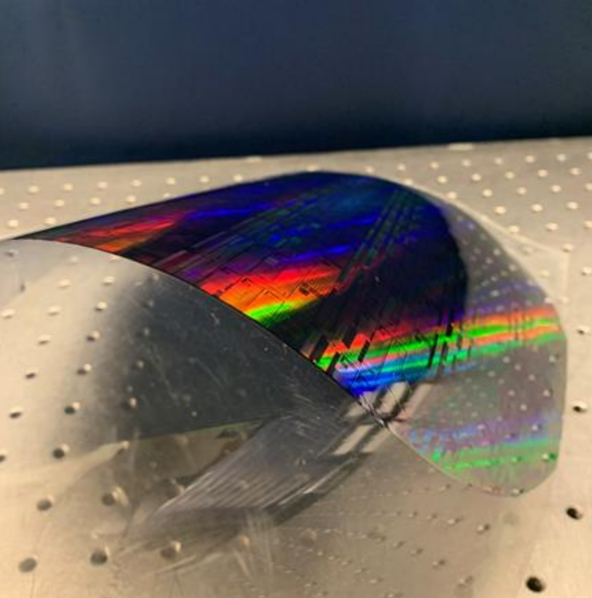


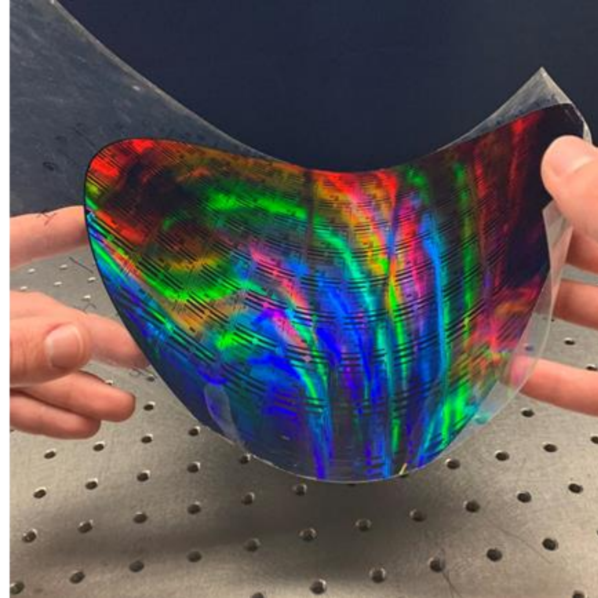

Neuralink

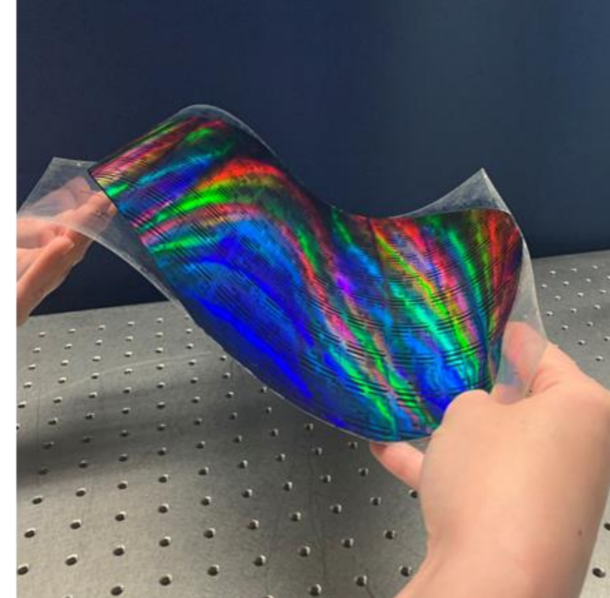
Graphene electrodes
InBrain - Spain

# Thinned silicon is flexible









https://doi.org/10.1038/s41598-024–61055-w

Flexural rigidity formula

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

$E$: elastic modulus

$h$: thickness

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# Typical stress - strain curves

stress (MPa)

450
400
350
300
250
200
150
100
50
0

$SiN_x$

$SiO_x$

Brittle (glass-like) materials

**$SiN_x$, $SiO_2$, Si**

**<u>High stress, low fracture strain</u>**

stainless steel

Si

Plastic deformation

**metals, stainless steel, polyimide**

**<u>High stress, higher fracture strain</u>**

metal

polyimide

strain (%)

0 0.05 0.1 0.15 0.2 1 5 25

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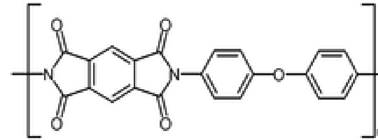
# Polyimide films

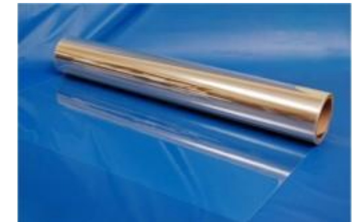




Kapton©

- **Imide-based polymer**
  - Imide: 2 acyl groups bonded to nitrogen
- **Thermoplastic**
  - Available as a foil
  - Spinnable 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



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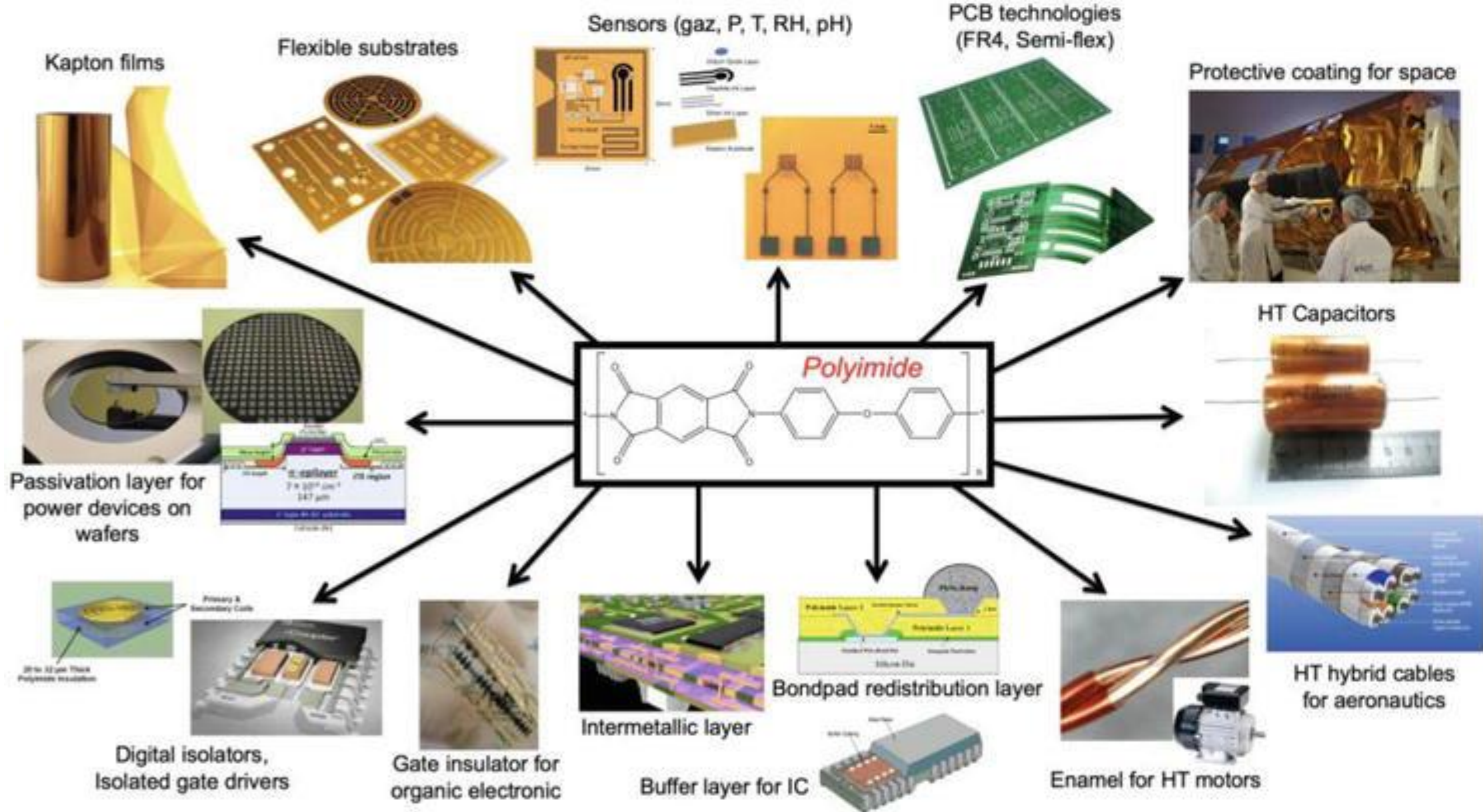
# Polyimide applications




S. Diaham. Polyimide in Electronics. DOI: 10.5772/intechopen.92629

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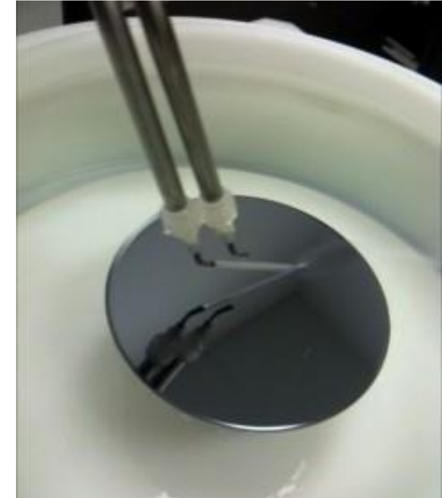
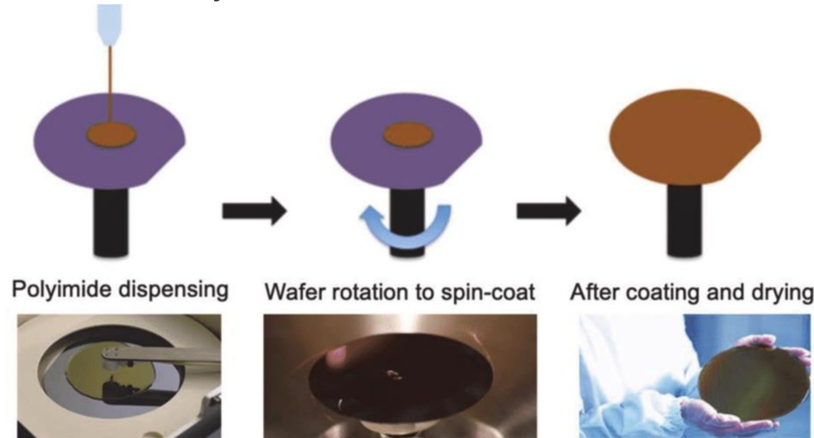
# Forming and processing a thin polyimide film

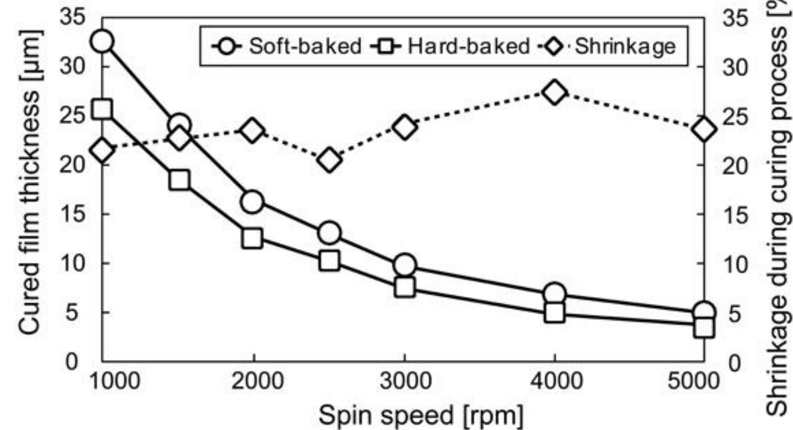


- 1. Clean the rigid carrier e.g. a silicon or glass slide
  - Apply adhesion promoter (optional)
- 2. Spin-coat liquid polyamic acid (precursor to polyimide)
  - Spin speed → thickness (1 – 20 µm typically)
  - Ramps → uniformity and edge beads
- 3. Soft bake (remove solvent)
- 4. Hard bake (aka curing, imidisation: *polyamic acid → polyimide)*
  - *Up to 300-400°C, often in N atmosphere*
  - Robust, thermally stable film



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

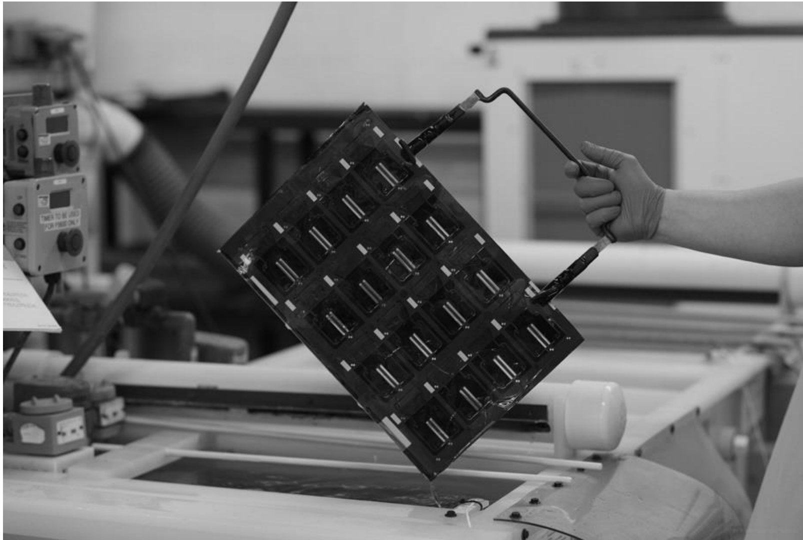


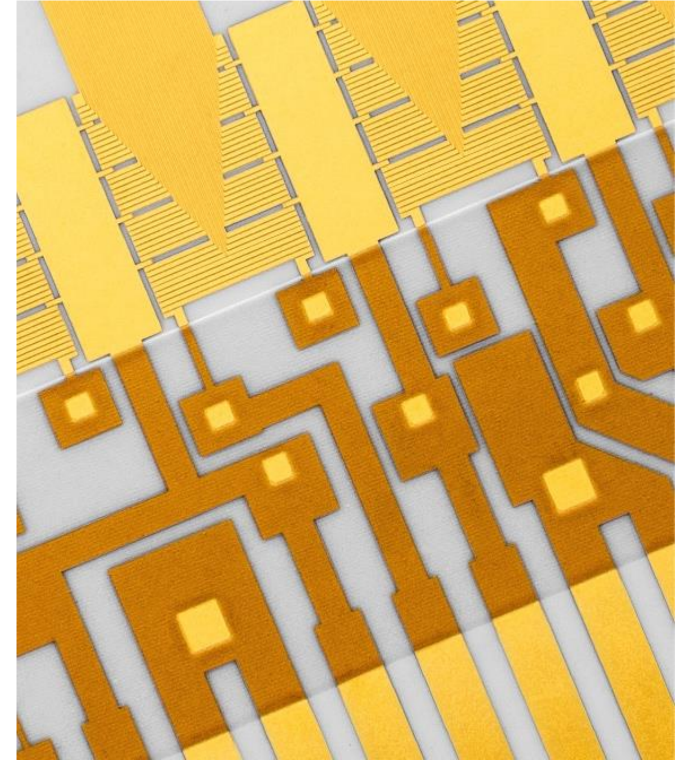



# Forming and processing a thin polyimide film



- 5. Photolithography (positive or negative photoresist)
- 6. Patterning typically by **oxygen plasma RIE**
  - Photoresist as a mask: ~1:1 etch ratio
- 7. Photoresist strip (oxygen plasma (careful) or solvent)





https://techetch.com/blog/prototyping-your-products-parts-with-polyimide-film-etching/

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# Thin-film metallization on polyimide

1. Spin-coat the substrate polymer (PI)
   *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 strip
   *Wet process*
6. Substrate release
   *Wet or mechanical process*

# Device release from Si carrier: the final step

Example materials and processes:

- Aluminium sacrificial layer, etch-release process by anodic dissolution:
  - Al **sacrificial layer** under polyimide devices
  - Al biased as **anode (2-20V)** oxidizes to **$Al^{3+}$** and dissolves ($Al \rightarrow Al^{3+} + 3e^{-}$)
  - Al dissolves from edges/access windows; device lifts-off from carrier wafer

- $SiO_2$ sacrificial layer, etch-release process by wet HF:
  - High selectivity (PI unattacked)

→ **Many release processes possible, but the device stack typically restricts the choice to very few options**

# Lift-Off

Mask

Si

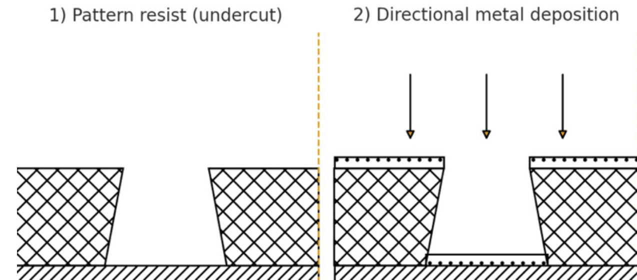
PR

thin film

DOI:10.51847/7tmarkoorg

Figure 1. Lift-off process

→ Avoids etching step (no need to stack compatibility check)
→ Requires careful photoresist profiling and ~directional (non-conformal) thin-film deposition



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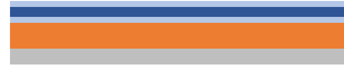
# Thin-film Pt on flex PI: general process flow

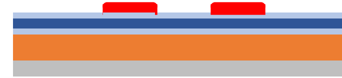


1. Polyimide spincoating on Si wafer / release layer + curing

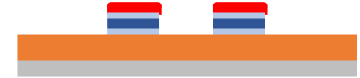
2. Ti/Pt/Ti sputtering



3. PR coating and patterning (photolithography)



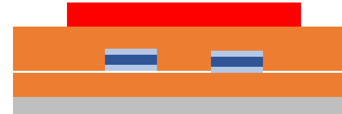
4. Ti/Pt/Ti etching (IBE)



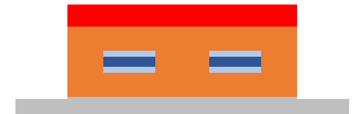
5. PR stripping

6. Polyimide spincoating + curing

7. PR coating and patterning (photolithography)

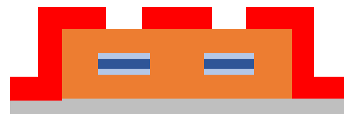


8. Polyimide etching (DRIE)

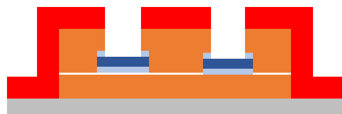


9. PR stripping

10. PR coating and patterning (photolithography)



11. Polyimide etching (DRIE) + Ti etching (IBE)



12. PR stripping

Si | Polyimide | Ti | Pt | PR

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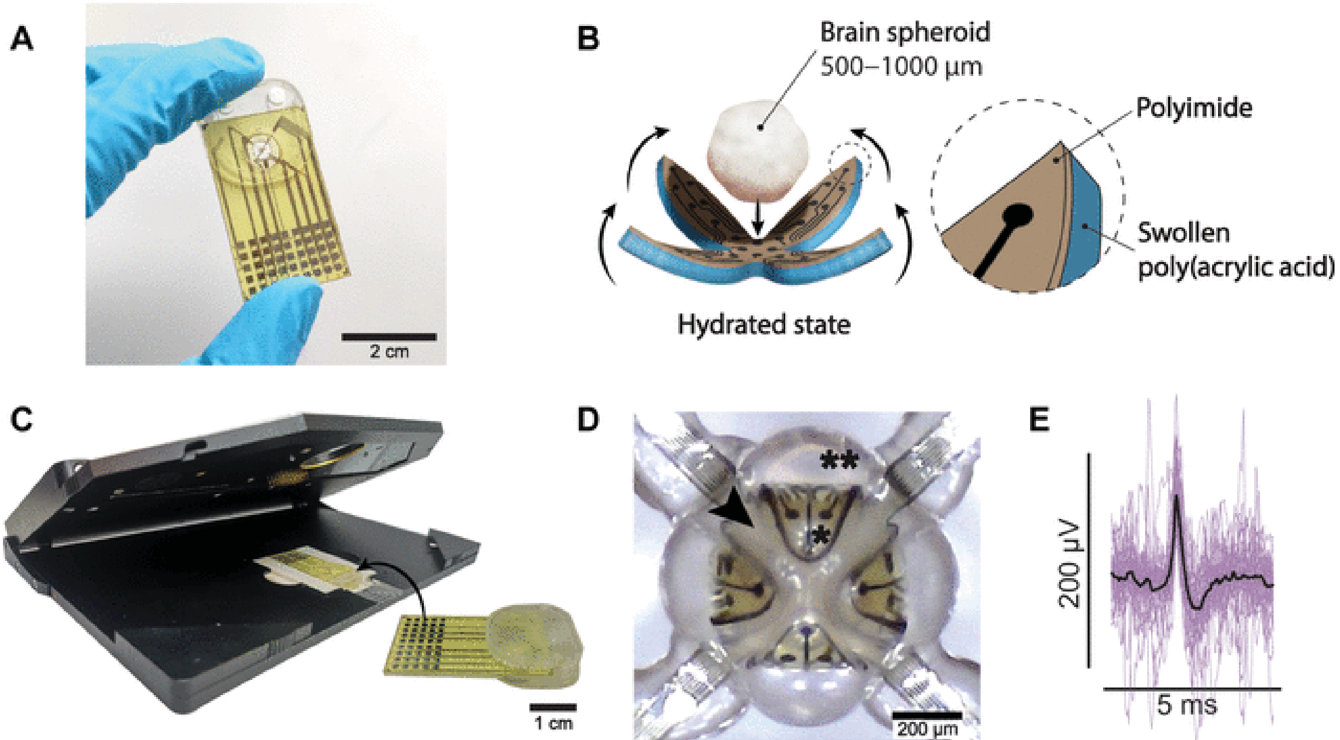
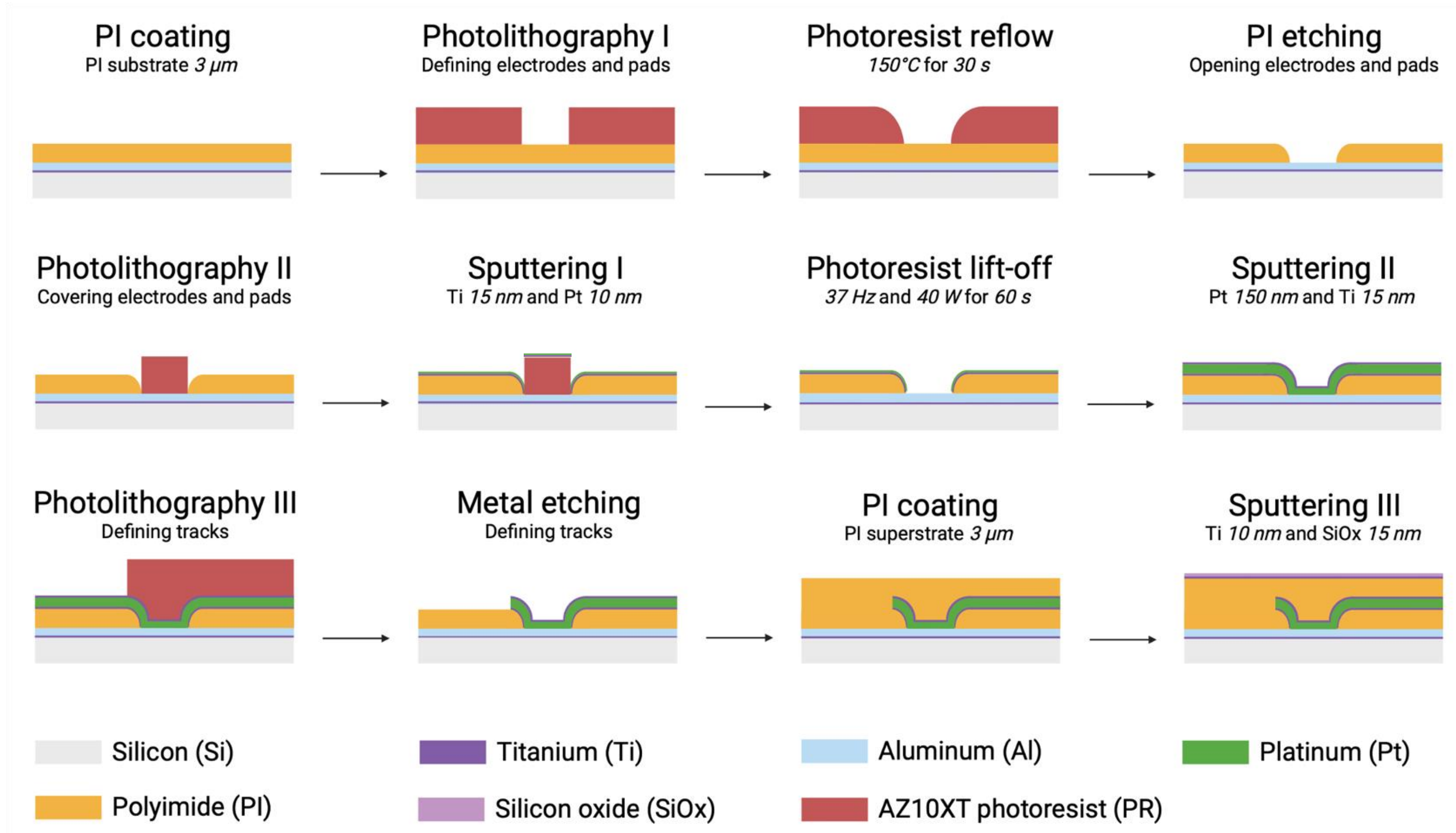
# Case study: the e-flower

- You want to graft a hydrogel to a polyimide-based device to actuate it. How can you design a process flow?

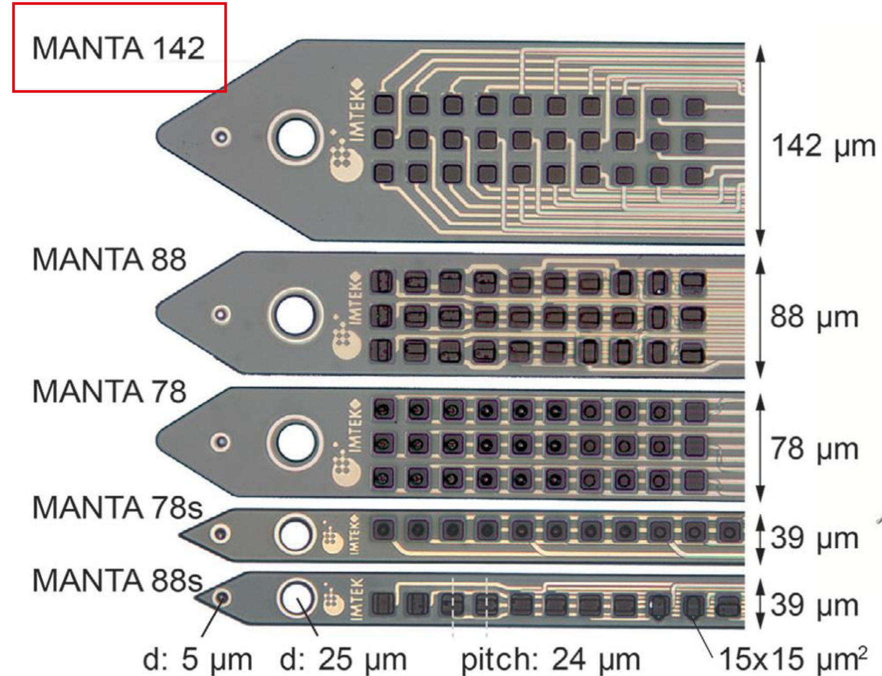


# Example process flow: the e-flower PI device



# Polyimide based shank with high density electrodes

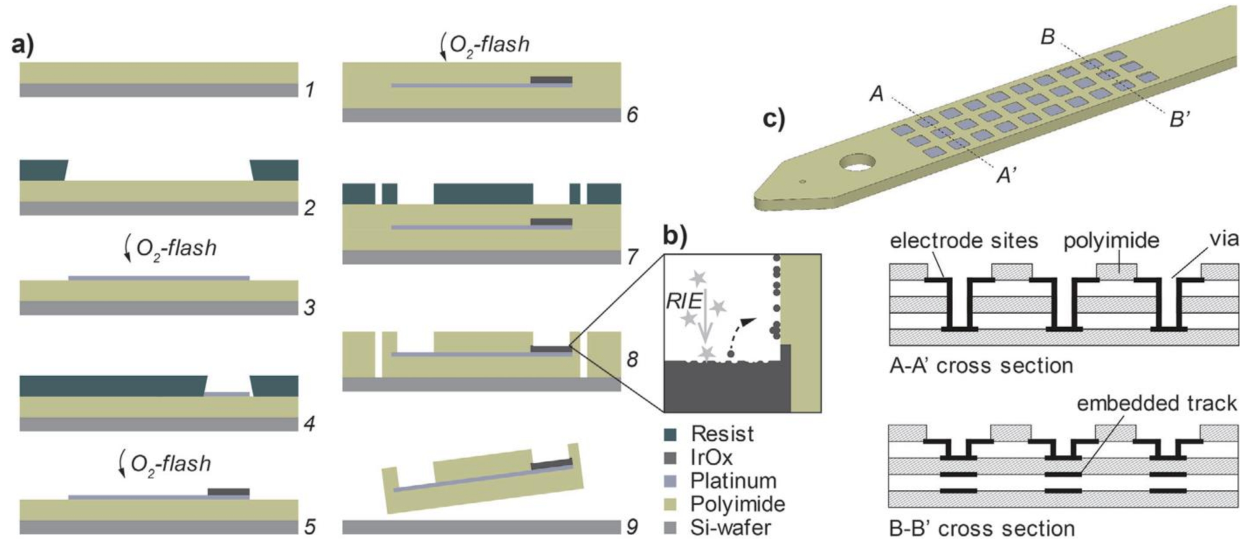
Analyse the photos.
Propose the list of materials.
Prepare cross-sections.
Propose a process flow.




Adv. Sci. 2023, 10, 2207576

# Polyimide based shank with high density electrodes

Adv. Sci. 2023, 10, 2207576



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# Polyimide based shank with high density electrodes



Adv. Sci. 2023, 10, 2207576

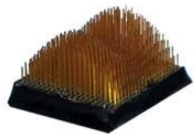
*MANTA probes were fabricated by advancing **standard PI fabrication** protocols to a multilayer design, comprising ultimately **5 PI and 7 metallization layers** in a probe of **10 µm thickness**.*

*First a **2µm thin layer of PI** (U-Varnish S, UBE corporation) was spincoated onto a carrier wafer and cured at 450°C under nitrogen atmosphere (YES- 450PB8-4PB/E, Yield Engineering Systems Inc.).*
***A liftoff-resist** (AZ5214E, MicroChemicals GmbH) was subsequently used to pattern the first **Pt layer** (100 nm, static evaporation, Univex 500, Leybold).*
*Prior to the **metal deposition**, the PI-surface was activated in an O2-plasma (30 s at 100 W, STS-RIE) to ensure stable adhesion between the layers.*
*After another O2-plasma treatment, this metal layer was insulated with **a second PI layer** (2 µm), which was then partially opened by reactive ion etching using an O2-plasma (100 W, STS-RIE) and a resist mask (AZ9260, MicroChemicals GmbH) to define the **first set of vias**.*
*A **second Pt-layer** was afterward deposited (following again an O2-plasma treatment and using the same parameters as previously described) to define the tracks and electrodes in the second metallization plane.*
*The **electrode sites** were additionally coated with a sputtered iridium oxide (**SIROF**) layer (800 nm, 100 W, 15 sccm O2, Univex 500, Leybold) using again a **lift-off resist** to define the electrode geometry.*
*The **same process steps** (O2-plasma, Pt + SIROF-deposition, and PI-insulation) **were repeated twice** to build up a total stack of **5 PI layers with 4 Pt-metallization planes** and three SIROF layers.*
*The topmost PI-layer was finally patterned using RIE to realize simultaneously the electrode openings above the SIROF sites, to open the Pt-pads for solder interconnection at the backend of the probe, as well as to define the overall outline of the probe.*
*For further use and characterization, probes were individually peeled off from the carrier wafer.*

# Beyond flexible

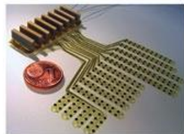
**Hard interfaces** | **Soft interfaces** | **Dynamic interfaces**

Tungsten microwire array: ~200 GPa

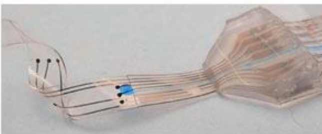


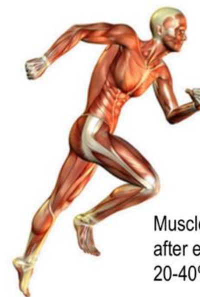
Silicon Utah array: ~150 GPa

Thin polyimide array: ~5 GPa

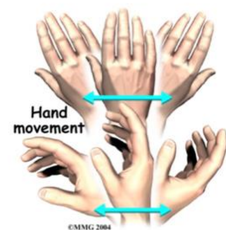


Electronic dura: ~1 MPa





Muscle expansion after exercise: 20-40% vol.




Multi-axial movements

*E* — 100 GPa — 1 GPa — 1 MPa — 1 kPa

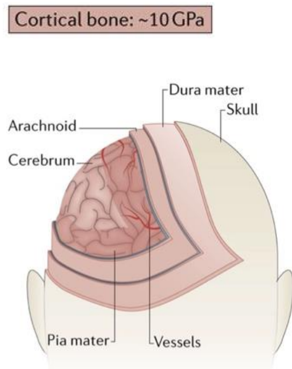
- Biological tissue
- Neural implants

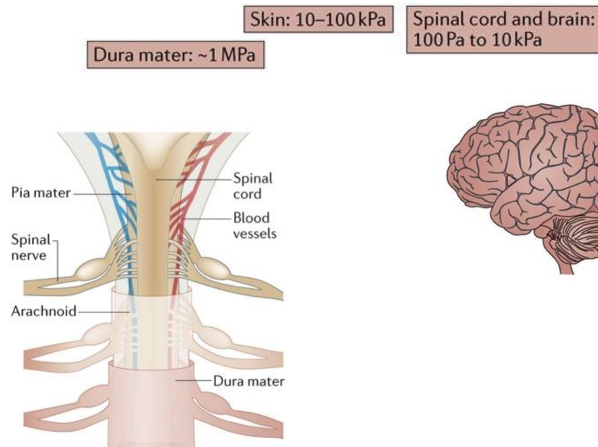
Cortical bone: ~10 GPa

Dura mater: ~1 MPa

Skin: 10–100 kPa

Spinal cord and brain: 100 Pa to 10 kPa



Stevens Institute of Technology, NJ, USA

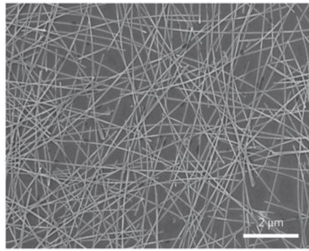
Nature Reviews Materials | 2016

# Engineering stretchable conductors

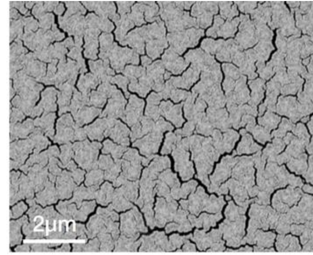


Laurine Kolly

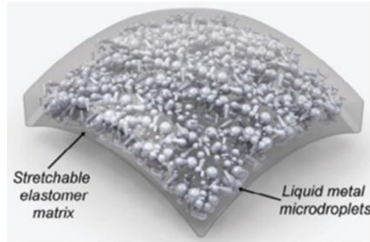
## Instrinsic stretchability




Composite of AgNW and elastomer [1]

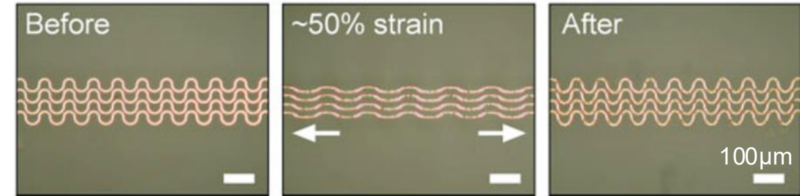



Micro-cracked gold on PDMS [2]

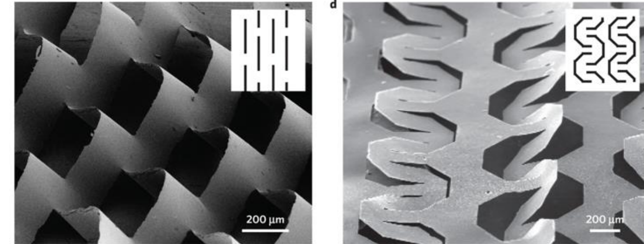



Liquid metal [3]

## Stretchability by design




Serpentines [4]




Periodic cuts (kirigami) [5]



[1] J. Liang et al. (2013), [2] I. R. Minev et al. (2015), [3] N. Matsuhisa et al. (2019),
[4] D. S. Gray et al. (2004), [5] T. C. Shyu et al. (2015)

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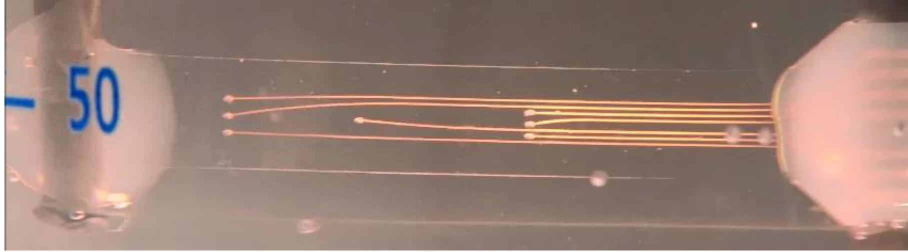
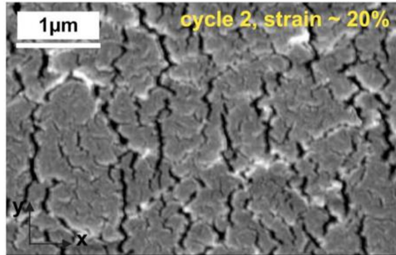
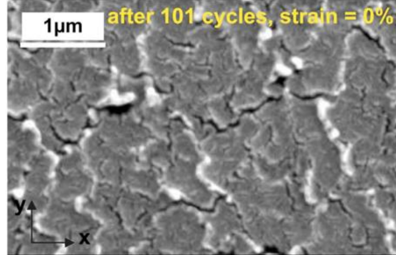
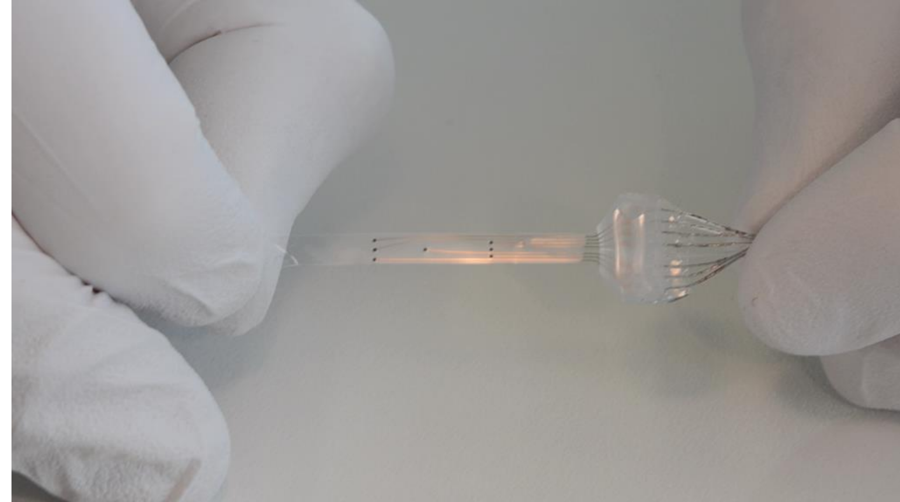
# Engineering elasticity

## Engineering reversible deformation in thin-film conductors



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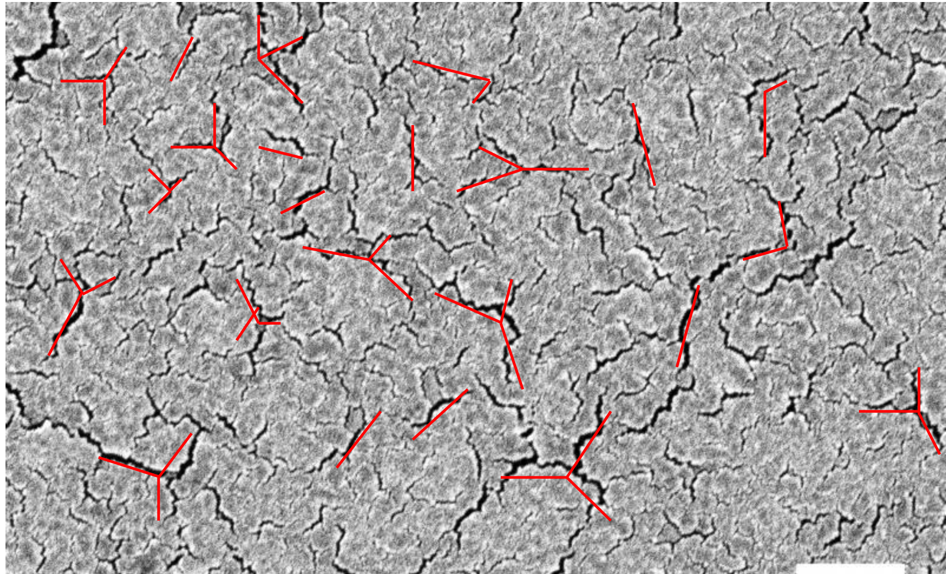
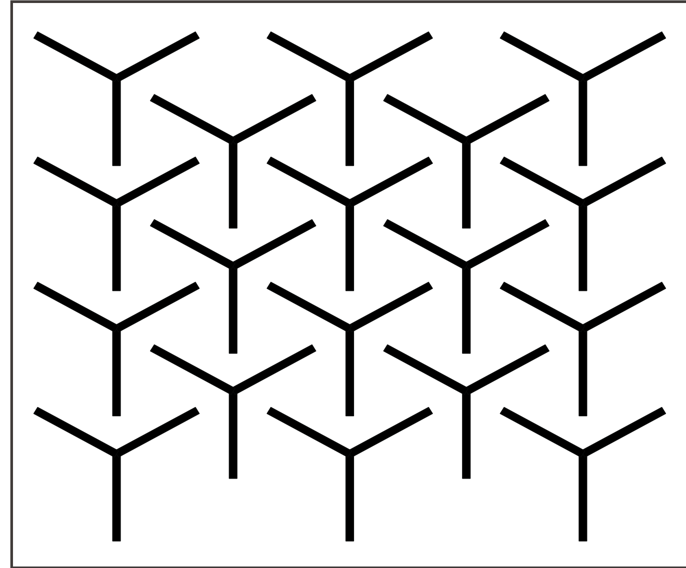
# Engineering elasticity

Naturally occurring phenomenon



Microstructured patterns



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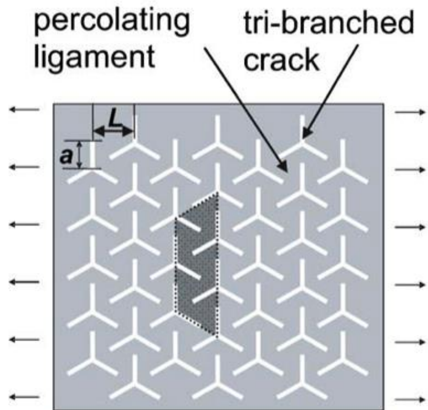
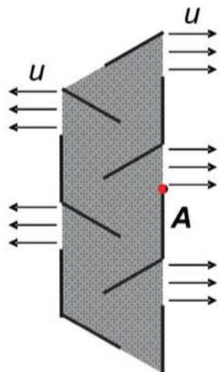
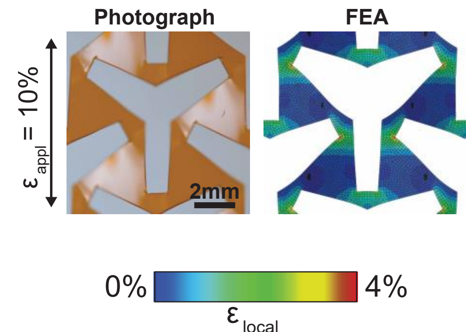
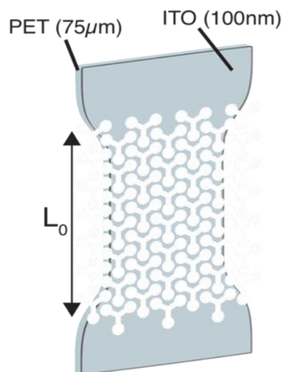
# Kirigami approach





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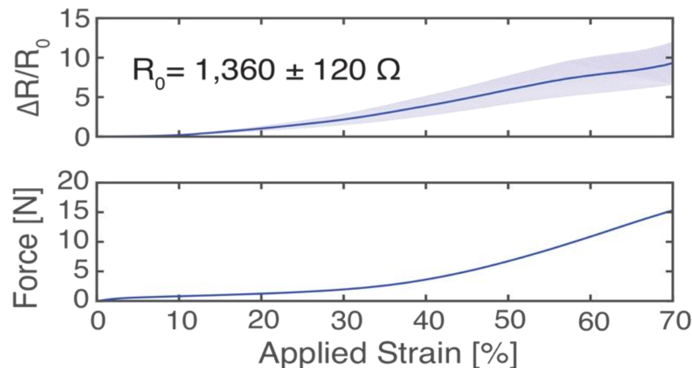
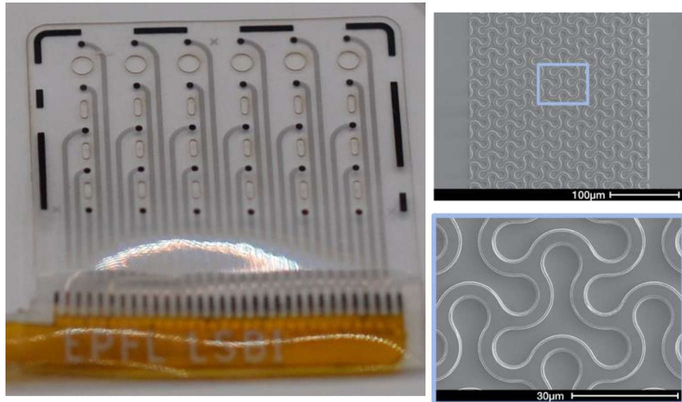
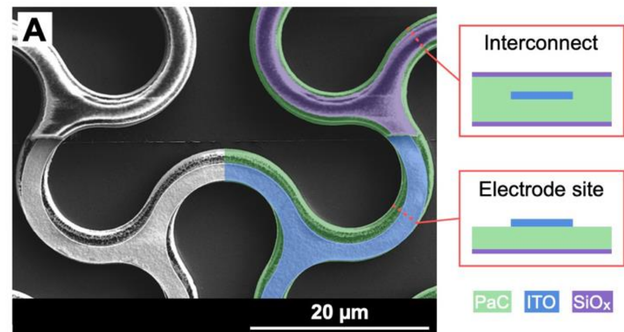


# Process flow: Kirigami-inspired neurotechnology




1. **Ti/Al deposition** — Sputtering 50/200nm
2. **SiOx/Ti deposition** — Sputtering 25/5nm
3. **Polyimide coating** — Spin-coating 1µm
4. **Ti/Pt/Ti deposition** — Sputtering 25/100/25nm
5. **PR coating & patterning** — 10XT-07 0.7µm
6. **PR reflow**
7. **Metal etching** — IBE

Si | Ti | Al | SiOx | PI | Pt | PR

Courtesy of L. Kolly, LSBI

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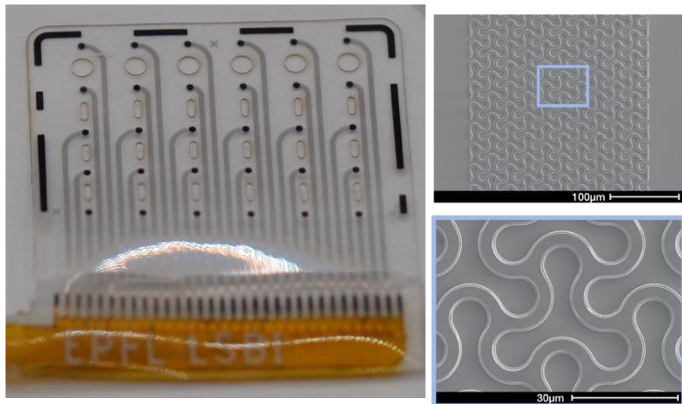
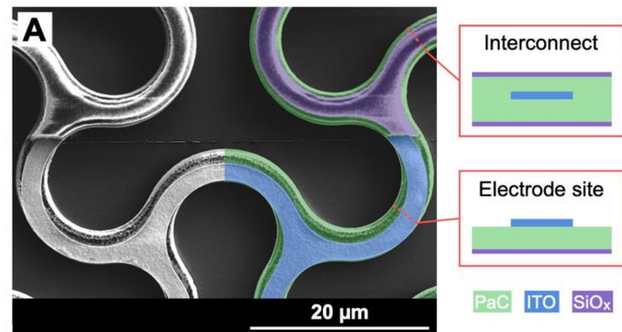
# Process flow: Kirigami-inspired neurotechnology

(numbering should continue from previous slide)




**1 — Polyimide coating**
Spin-coating 1µm

**2 — Ti/SiOx deposition**
Sputtering 5/25nm

**3 — PR coating & patterning**
ECI3027 4µm

**4 — Etching encapsulation**
CHF3/He + O2 RIE

**5 — PR coating & patterning**
ECI3027 4µm

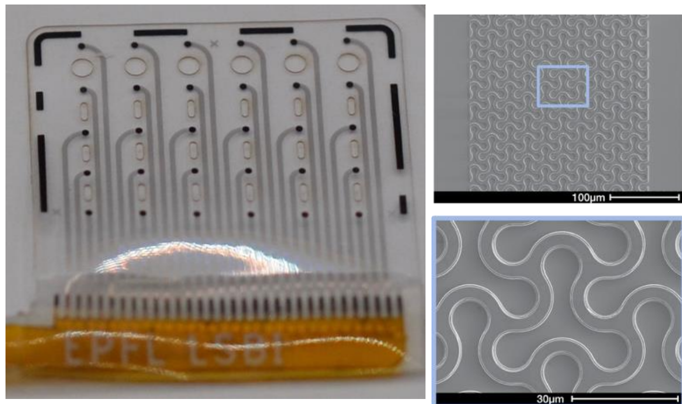
**6 — Contacts opening**
RIE + IBE

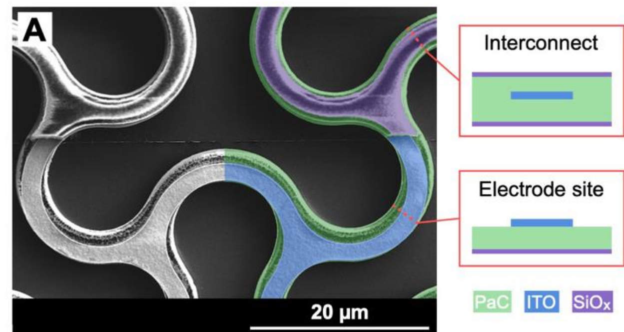
Si | Ti | Al | SiOx | PI | Pt | PR

Courtesy of L. Kolly, LSBI

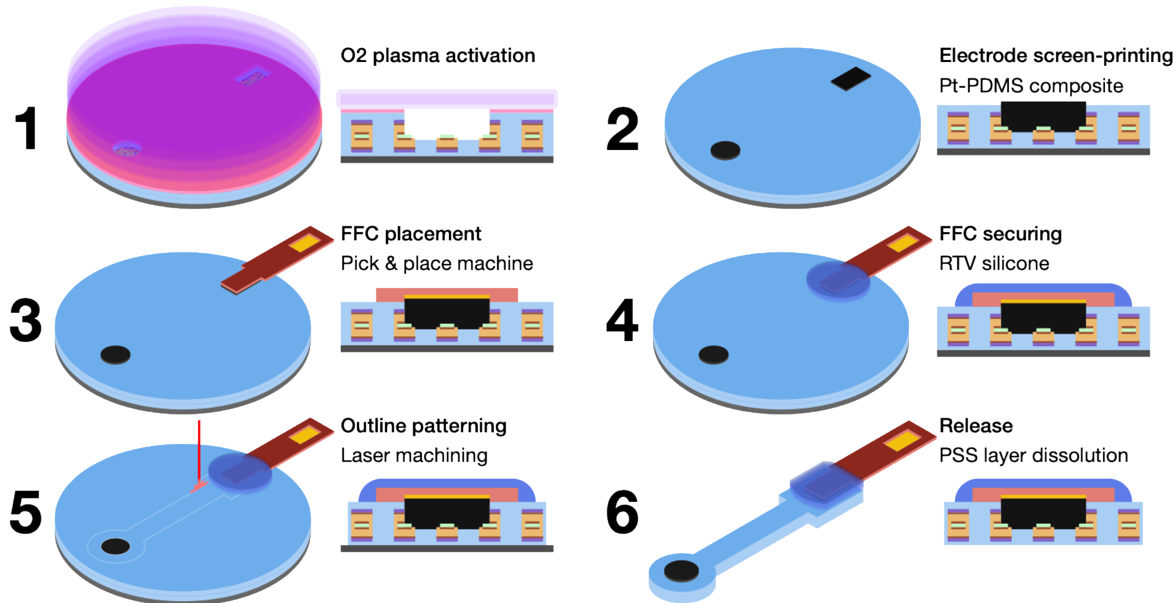
# Process flow: Kirigami-inspired neurotechnology

(numbering should continue from previous slide)



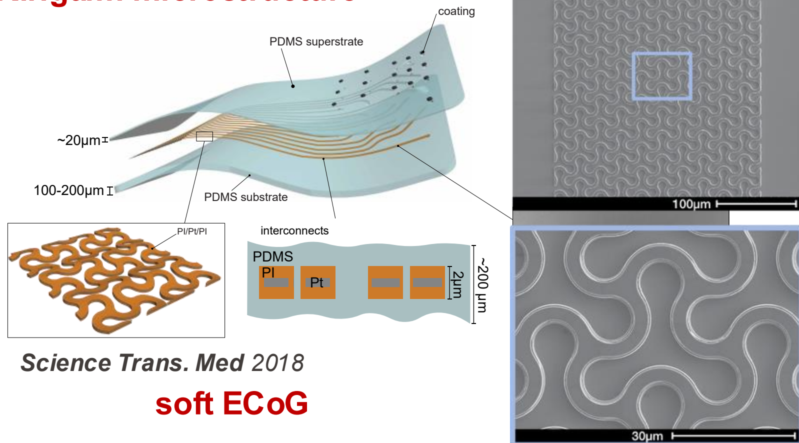

## Some skipped steps: silicone encapsulation bonding to PI



Courtesy of L. Kolly, LSBI

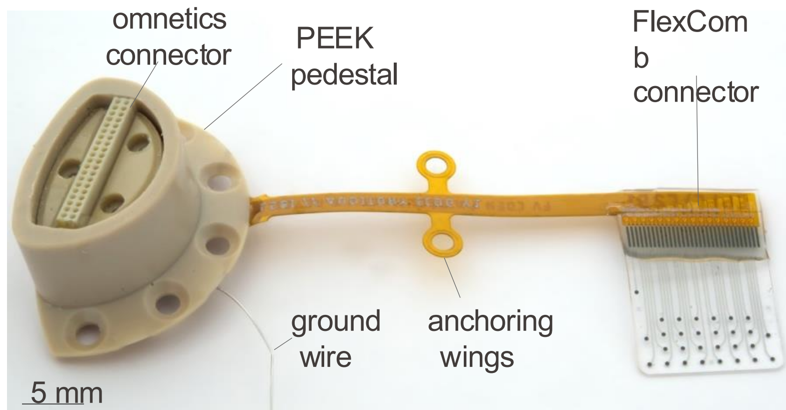
# → Compliant implants

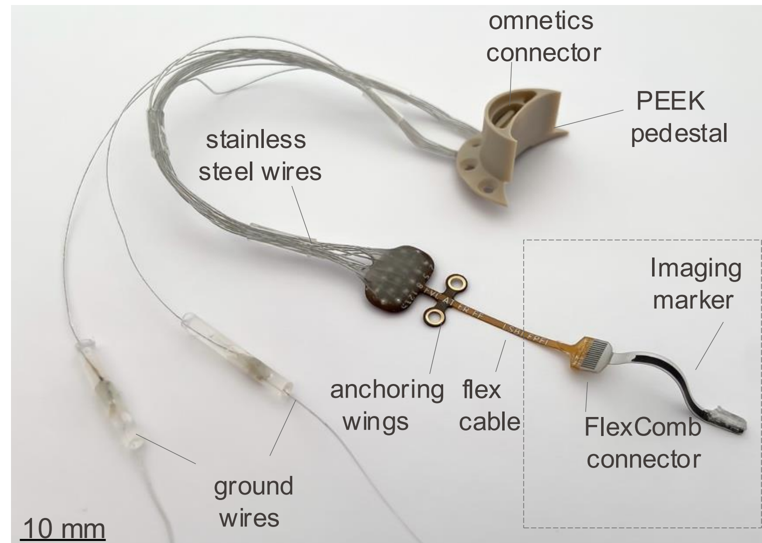
## Kirigami microstructure



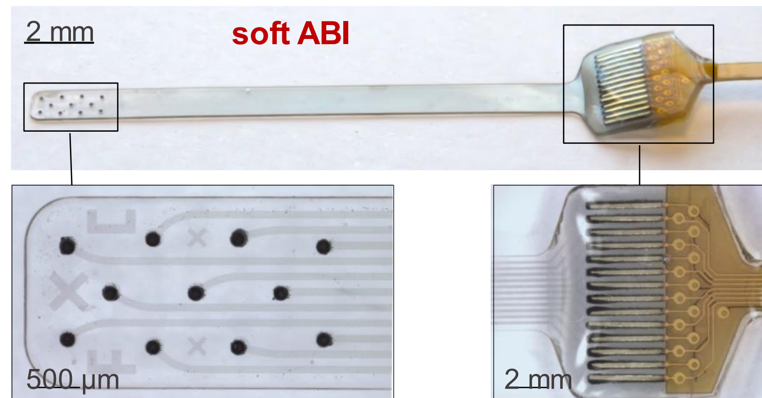

*Science Trans. Med* 2018

## soft ECoG




## soft ABI




A. Trouillet*, E. Revol* et al, 2025 Nat. Biomed. Eng.

EPFL



# Take-home messages

- Silicon is a material of choice for microfabrication
- We can borrow the same technological framework and apply it to processing on plymers. Silicon acts as carrier for processing only.
- We leverage microfabrication to manufacture flexible devices (based on thin polymer foils, typified by polyimide)
- We can apply microstructuring (Kirigami) to further introduce elasticity
- We have shown applications in neuroelectronic interfaces, but many other domains benefit from compliant microtechnology