Neural Interfaces

NX-422

Manufacturing of Neural Interfaces

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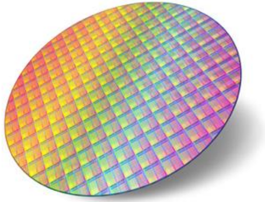
Neuro-X Institute

Neural Interfaces manufacturing

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

Man-made vs biological materials

steel



silicon

elastic bands

jello cubes

E 100GPa 1GPa 1MPa 1kPa

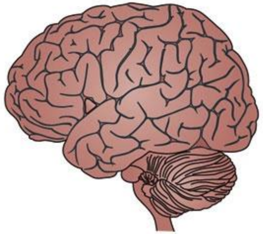
bone

©123rf.com

skin

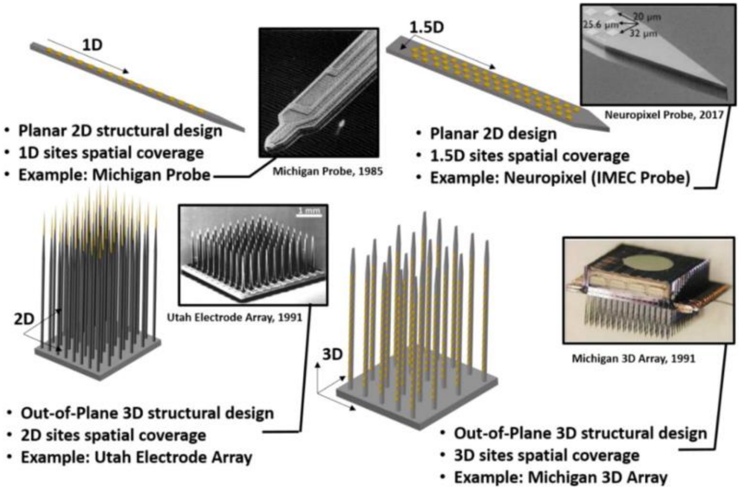
©123rf.com

brain



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

Flexible neural interfaces

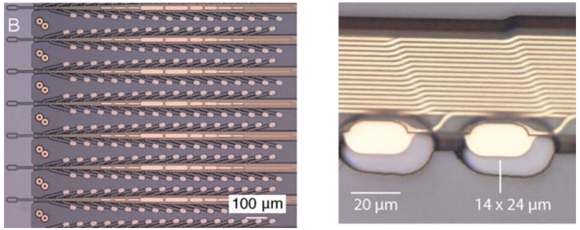


- Planar 2D structural design
- 1D sites spatial coverage
- Example: Michigan Probe

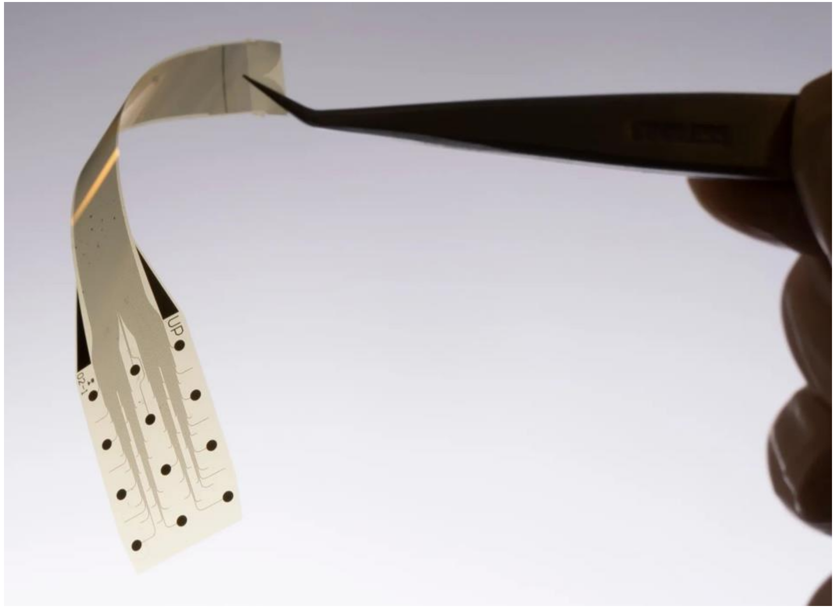
- Planar 2D design
- 1.5D sites spatial coverage
- Example: Neuropixel (IMEC Probe)

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

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

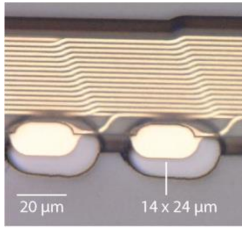


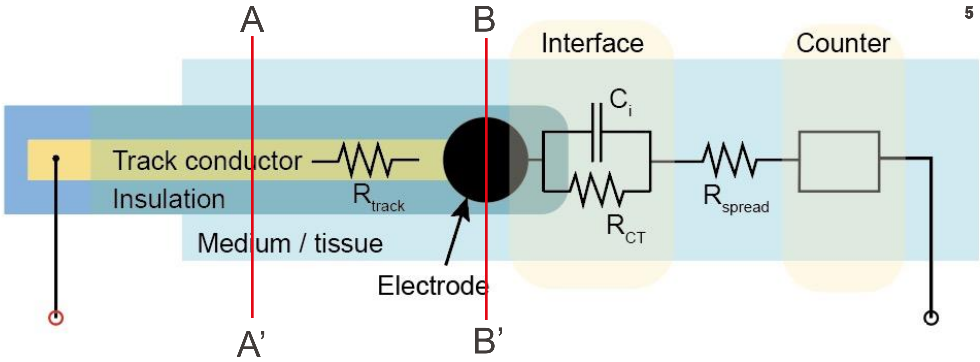
Neuralink



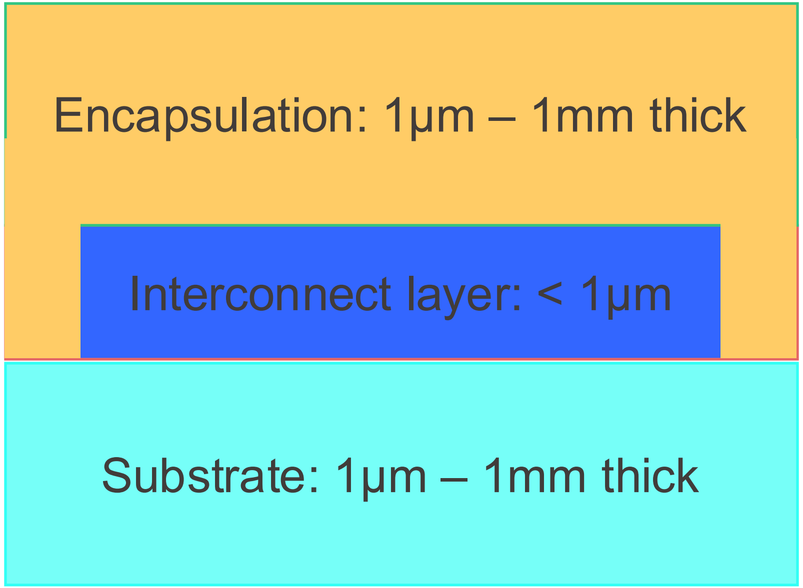
graphene electrodes
InBrain - Spain

Flexible implantable interfaces





A-A'

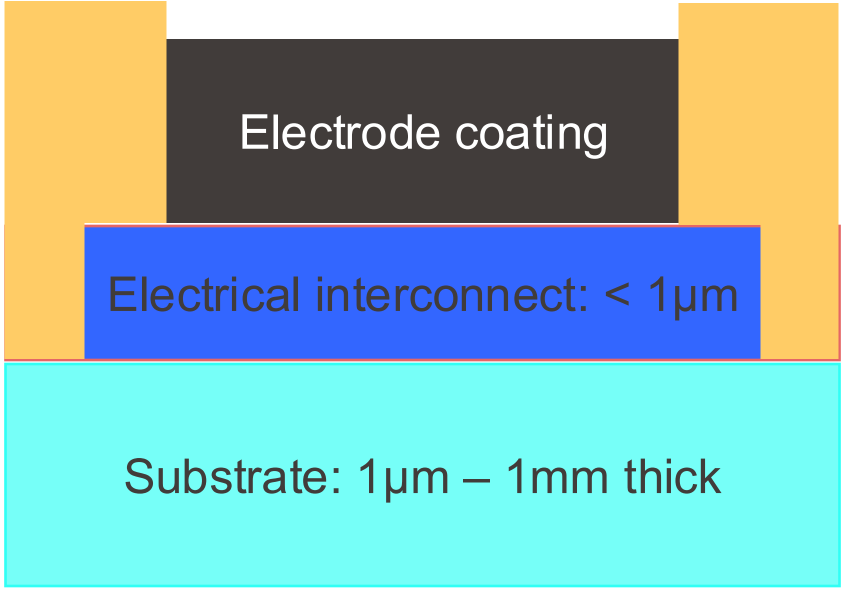


Encapsulation: 1µm – 1mm thick

Interconnect layer: < 1µm

Substrate: 1µm – 1mm thick

B-B'



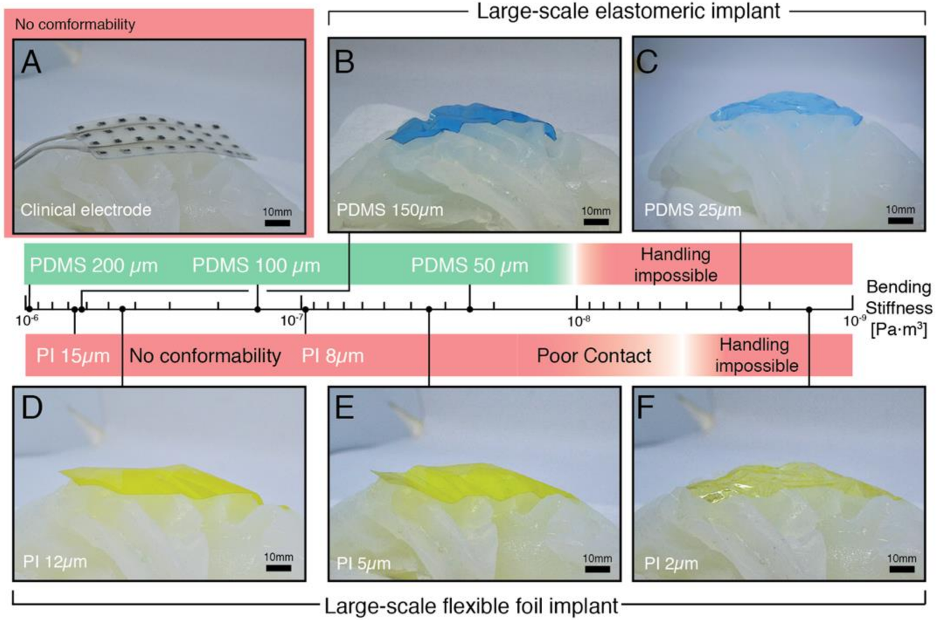
Electrode coating

Electrical interconnect: < 1µm

Substrate: 1µm – 1mm thick

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

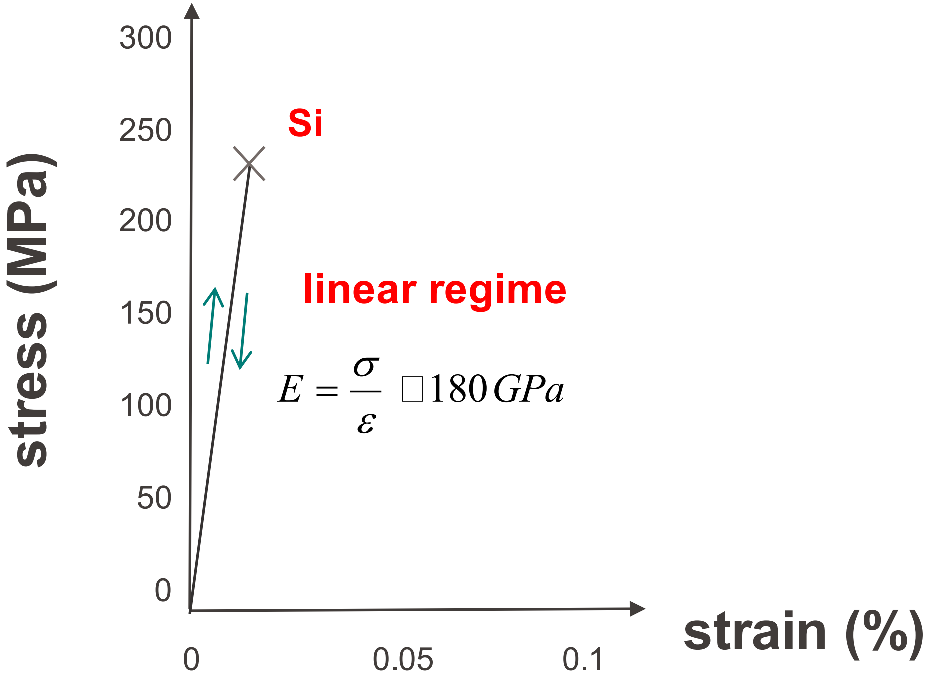


Fallegger et al., 2020, submitted

Thin = flexible

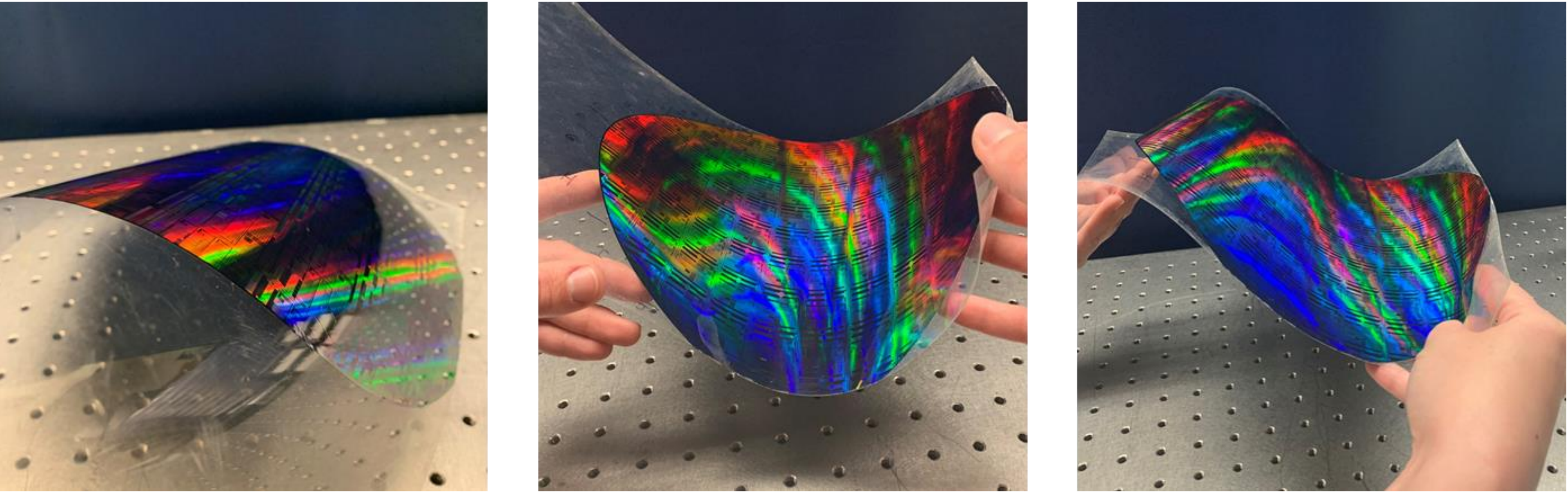
cellulose

http://www.paperonweb.com/



$$E = \frac{\sigma}{\varepsilon} \square 180\, GPa$$

Thinned silicon is flexible



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

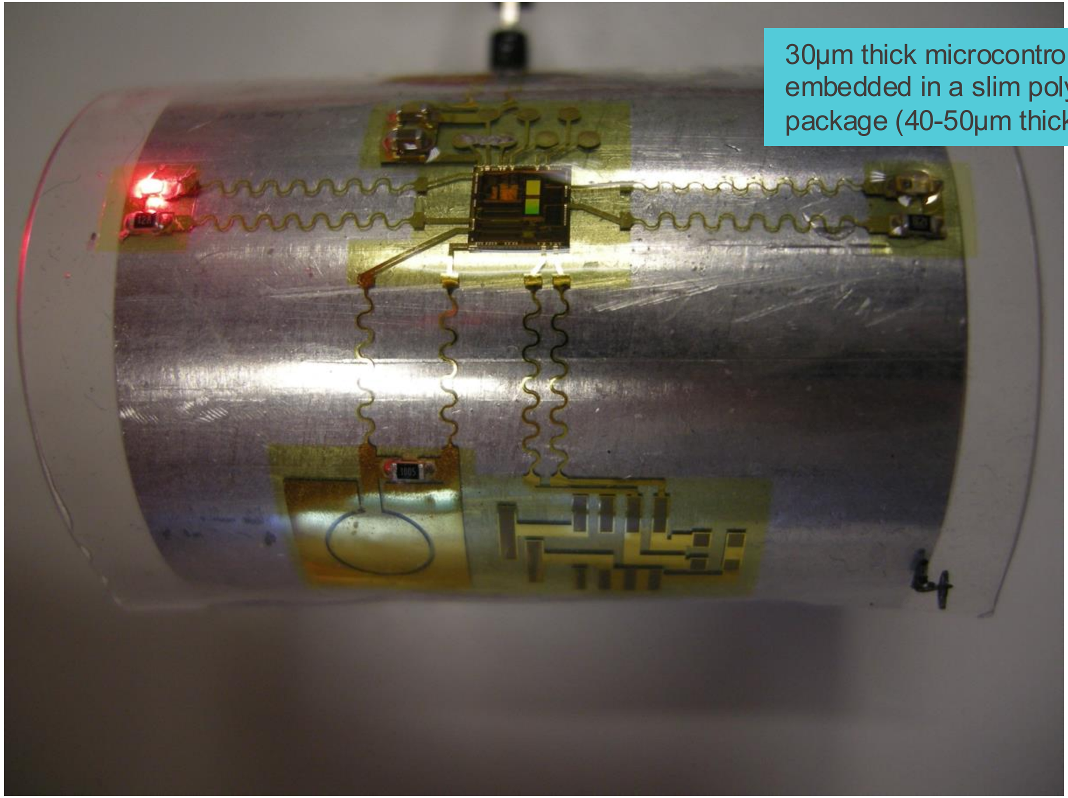
Remember the flexural rigidity formula

$$D = \frac{\boxed{E}\,\boxed{h}^3}{12(1-\nu^2)}$$

elastic modulus

thickness

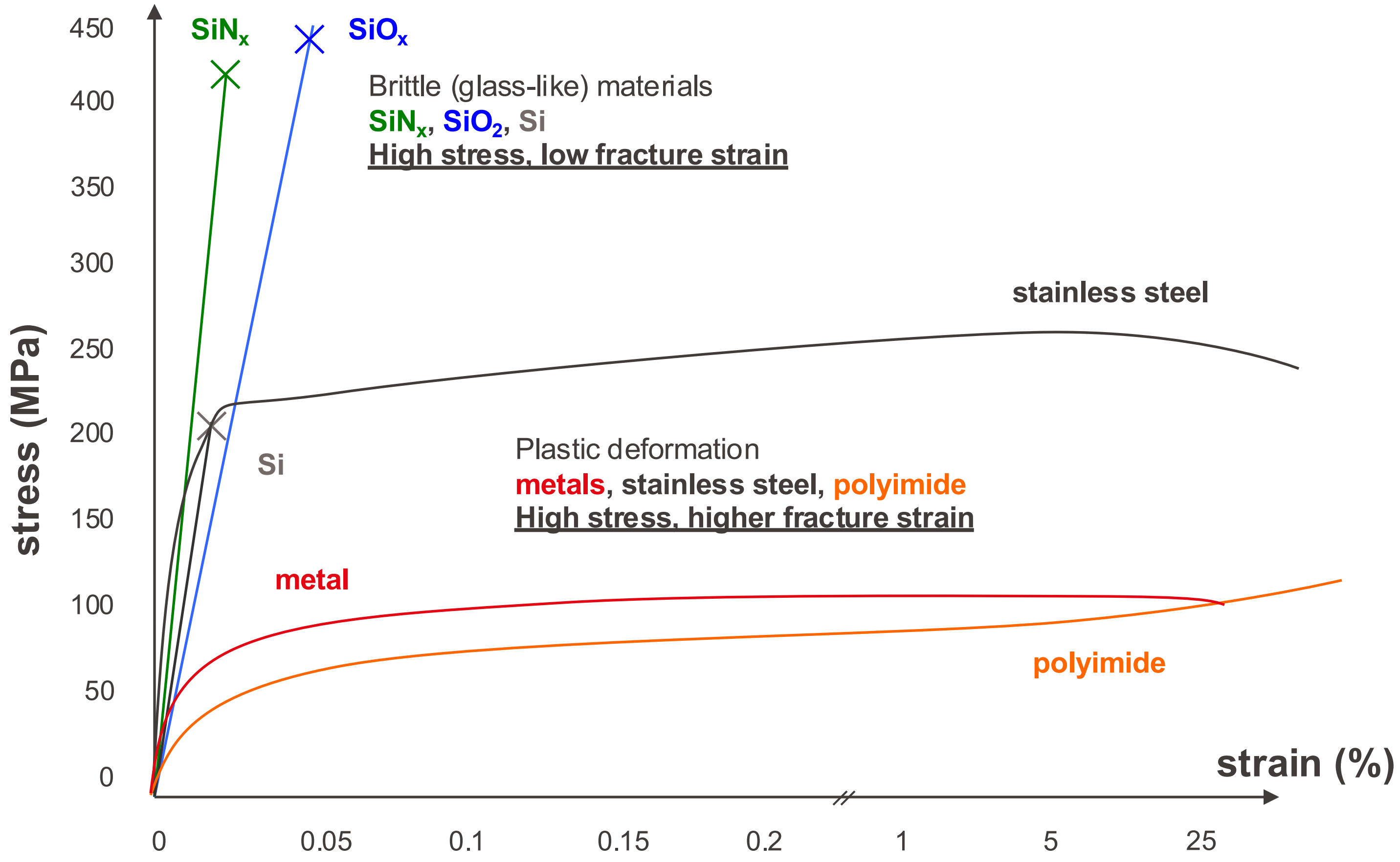
Ultra-thin flexible chip



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

IMEC, 2012 ESTC Conference

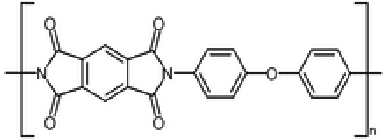
Typical stress(strain) responses



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>

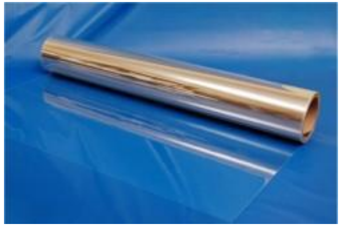
Polyimide films



Kapton©

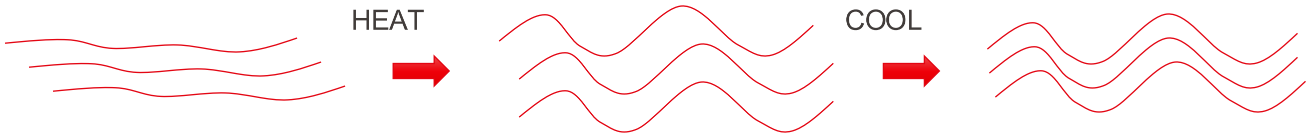
- **Imide-based polymer**
  - Imide: 2 acyl groups bonded to nitrogen
- **Thermoplastic**
  - Available as a foil
  - Spinnable as an uncured resin
  - Can be photosensitive

- **Good thermal and mechanical stability**
  - Young's modulus: ~2.5 GPa
  - CTE: 20 – 60 ppm/°C
- High resistance to solvents and weak acids



Thermoplastics

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



cold and hard polymer

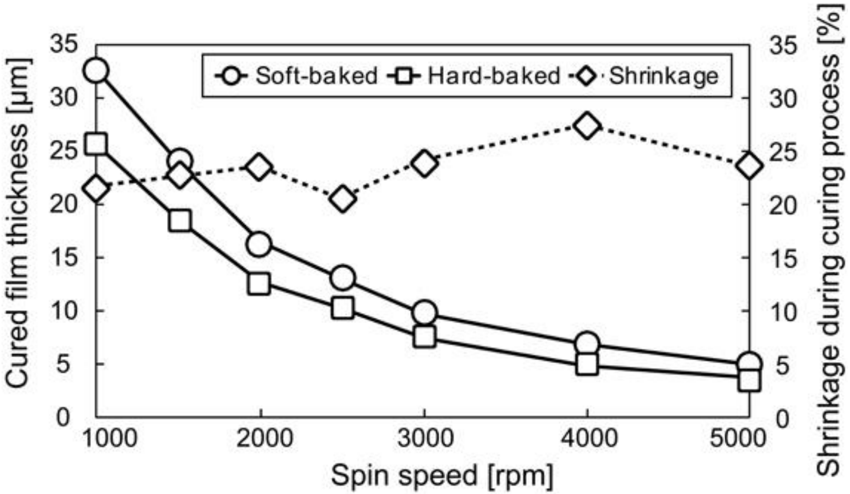
hot and malleable polymer
→ new shape

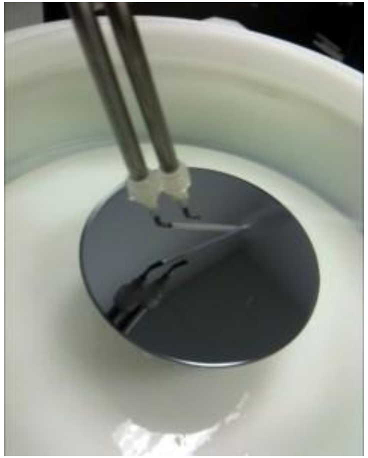
cold and hard polymer
preserving the new
shape

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

Forming a polyimide film

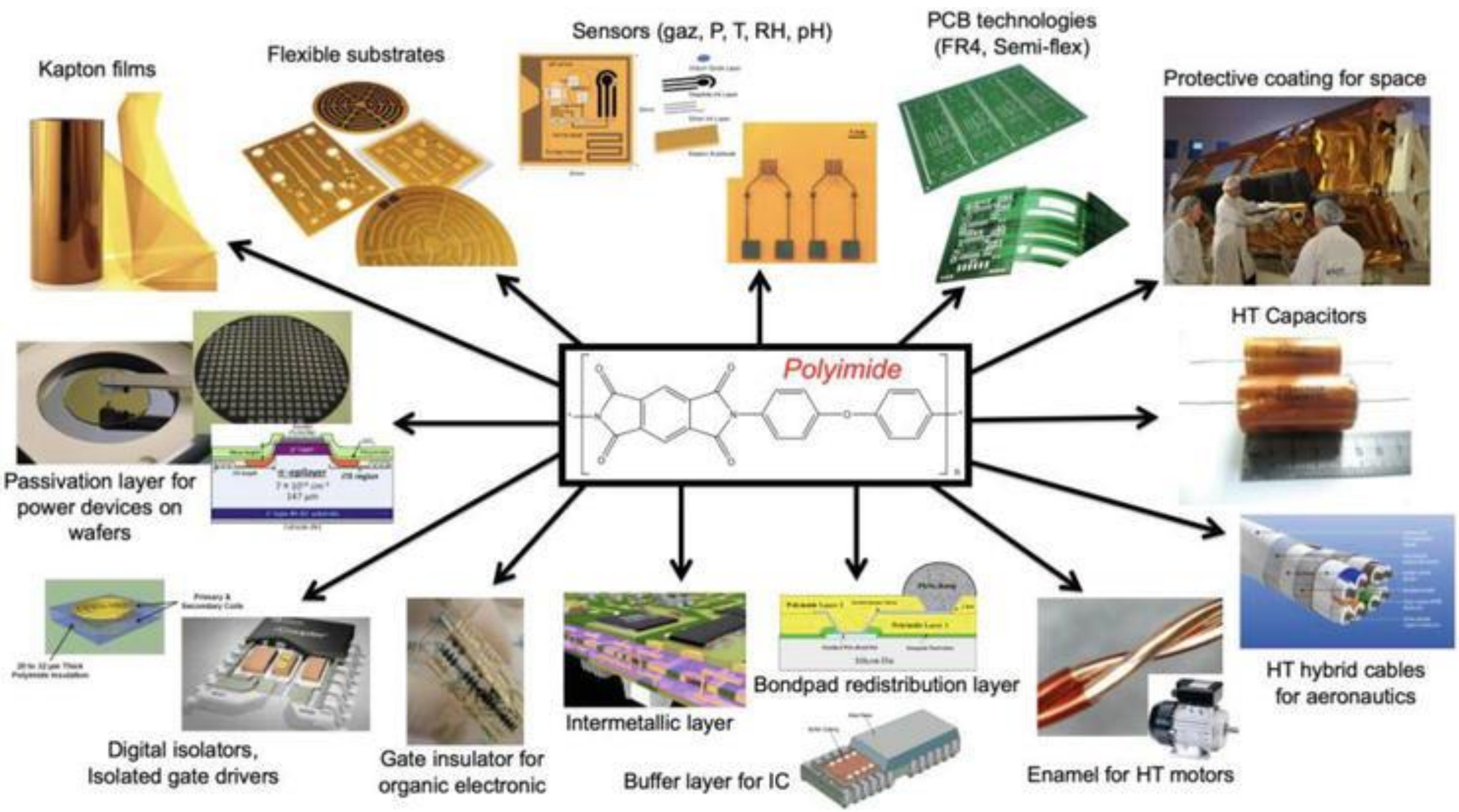
- 1. clean the rigid carrier e.g. a silicon or glass slide
- 2. spin-coat polyimide
  - Spin speed → thickness
  - Ramps → uniformity and edge beads
  - Soft bake





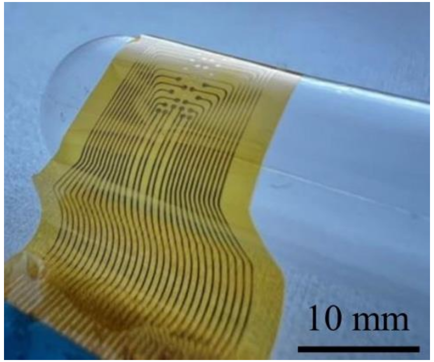
Kato et al, Front. Neuroeng. 2012 https://doi.org/10.3389/fneng.2012.00011

Polyimide applications



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

Critical strain when bending



Saghir et al 2025

- The critical strain is the maximum applied strain before mechanical fracture
- For a single, homogeneous foil (thickness *h*)

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

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

Critical strain

- For stacks:
- Strain in a layer = distance from **neutral axis/plane (NA, NP)** divided by radius.
- Where is the neutral plane? → z = distance

$$z_{\mathrm{NA}} = \frac{\sum_k E_k t_k \, z_{k,\mathrm{centroid}}}{\sum_k E_k t_k}$$

"Centroid" = midline

- So that distance from NA is

$$y_i = \left| z_{\mathrm{surface},i} - z_{\mathrm{NA}} \right|$$

- And critical strain is

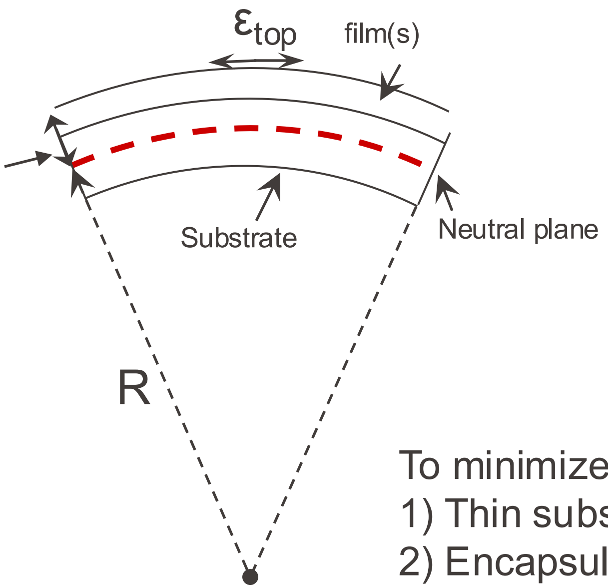
$$\varepsilon_i = \frac{y_i}{R}$$

$$R_{\mathrm{min},i} = \frac{y_i}{\varepsilon_{\mathrm{crit},i}}$$

Bending a film-on-substrate stack

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

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



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

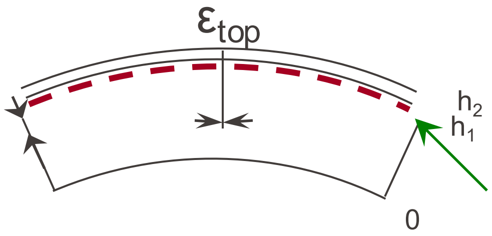
To minimize the strain use:
1) Thin substrate
2) Encapsulation
3) Compliant substrate

Bending a film-on-substrate stack

Compliant substrates $E_f \square d_f \square E_s \square d_s$

Distance from top to neutral plane

$$d < \frac{d_f + d_s}{2}$$



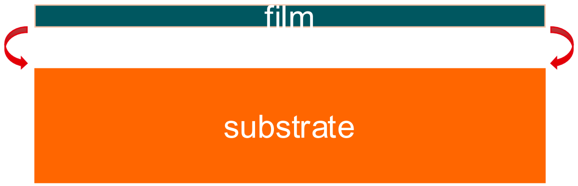
Shift upwards of the neutral plane

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.

Mechanical design of flexible thin-film devices



Young’s modulus, thickness

Film: E_f, d_f

Substrate: E_s, d_s

$E_f \cdot d_f \ll E_s \cdot d_s$	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
$E_f \cdot d_f \gg E_s \cdot d_s$	The film dominates, The substrate complies with it	Ex. Film on rubber

Critical strain - example calculations

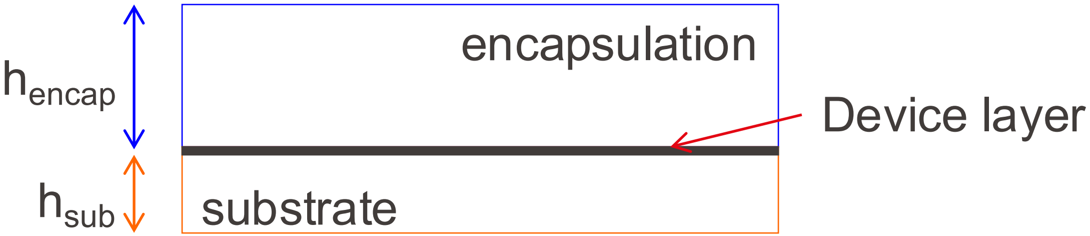
What is the minimum radius of curvature in these systems?

- **PET foil**, t=50 µm, $\varepsilon_{crit} = 2\%$
    - → R_{min}= 50µm / (2×0.02) =1.25 mm
- **Cu-on-PI stack**: 50 µm PI and 18 µm Cu (standard flex PCB). E_{PI} = 2.5GPa, E_{cu} = 110 GPa. $\varepsilon_{crit} = 0.3\%$
    - → Neutral plane: z = [110 x 18 x 9 + 2.5 x 50 x (18+25)] / [110 x 18 + 2.5 x 50] µm ~ 11 µm
    - NP lies inside Cu.
    - → R_{min}≈ 11 µm / 0.003 ≈ 3.7 mm

Design tips

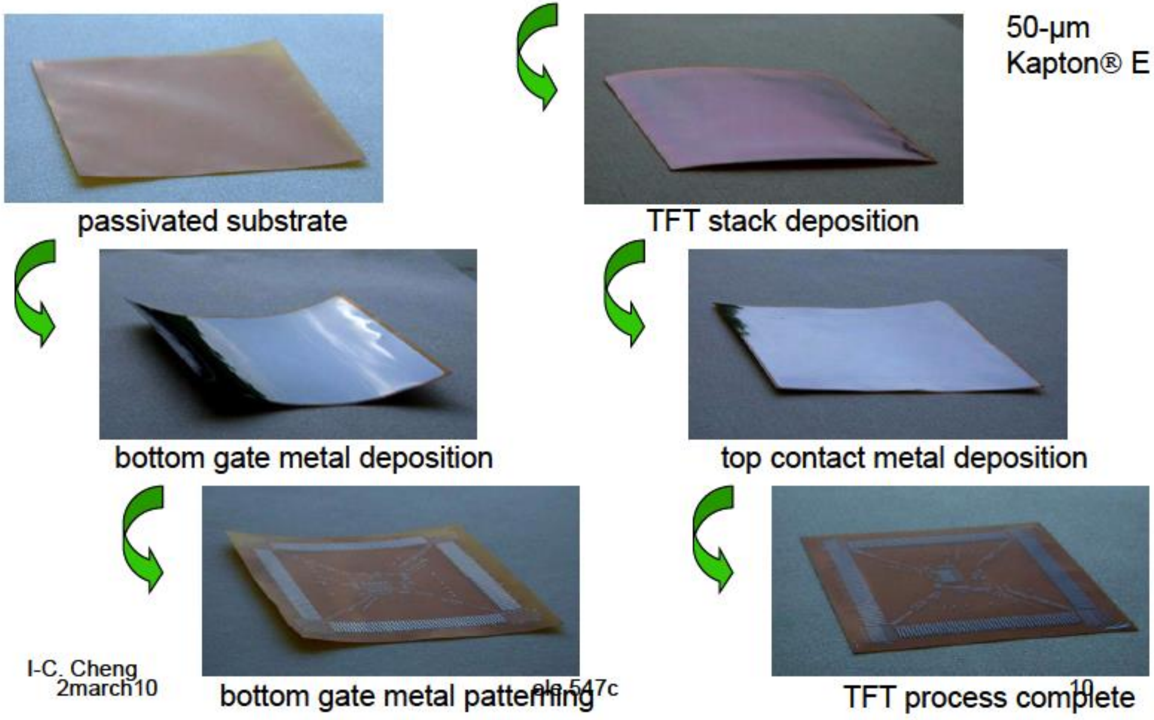
- Design the device layer near the **neutral plane** (e.g. use a symmetric encapsulation);
- Fatigue and plasticity: for repeated bending, use a lower effective ε_{crit}.

Placing devices in the neutral plane



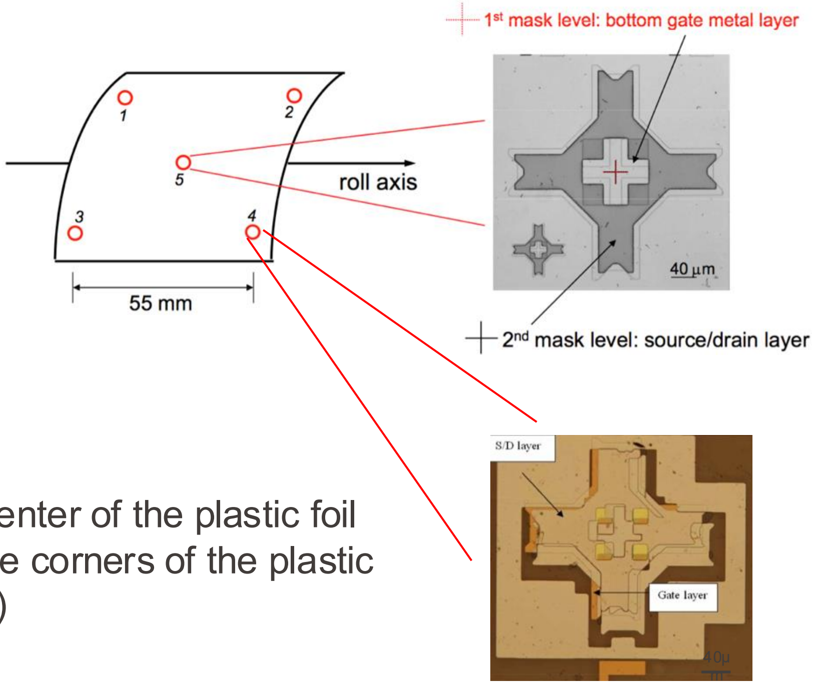
Design rule: place the device layer at the neutral surface

Stress → Curvature during manufacturing



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

Can cause 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

Thin-film metals

- Electrical conductors

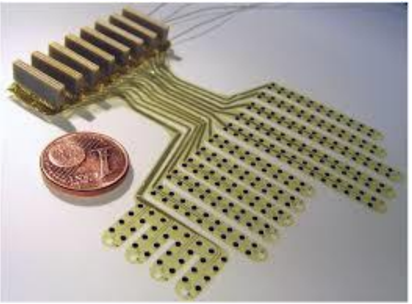
  - **Physical properties**

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

  - **Processability**
    - Deposition
    - Patterning

Interconnect resistance

Flexible ECoGs
T. Stieglitz's lab



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

material	Resistivity [Ω/cm] for bulk	Resistivity [Ω/cm] for THIN film (from literature)
Ag	~1.59μΩ.cm	~ 5 – 40 μΩ.cm
Au	~2.44μΩ.cm	~ 2.5 – 200 μΩ.cm
Pt	~10.6 μΩ.cm	~10 – 30 μΩ.cm

Numbers change with **thickness, continuity/percolation, grain size, roughness, adhesion / wetting layers, and post-anneals!!!!**

Microfabrication

Option 1

- Prepare the carrier substrate
- Deposit the metal film
- Pattern the metal film

Option 2

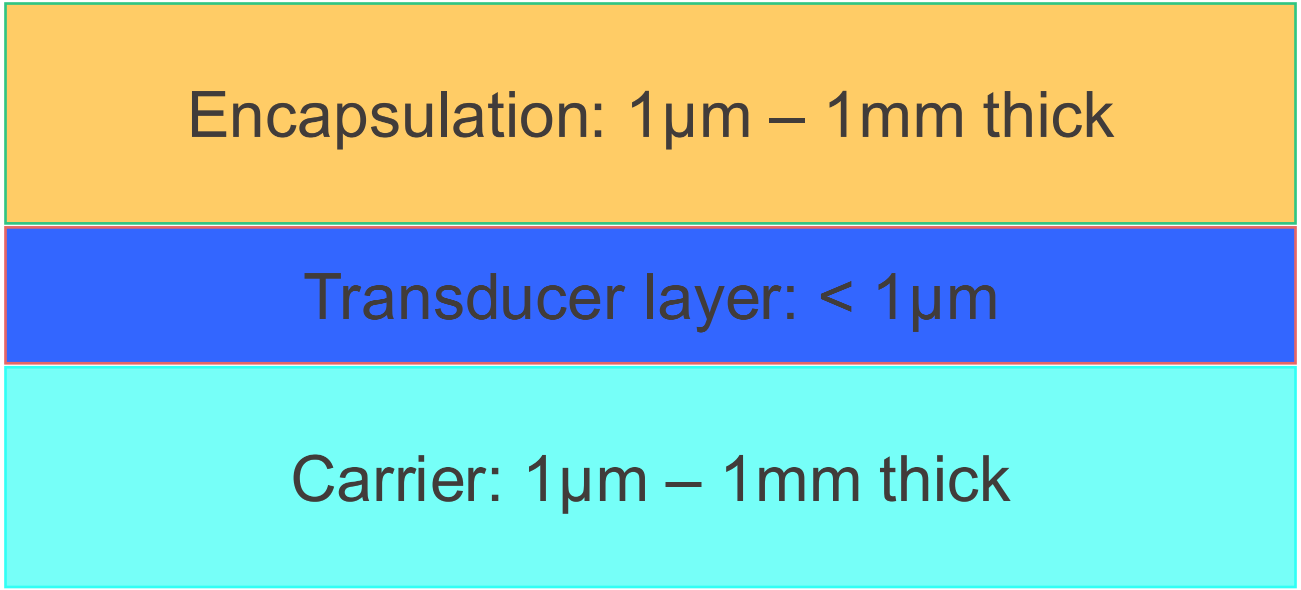
- Prepare the carrier substrate
- Pattern a masking film
- Deposit the metal film
- Remove the masking film

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 strip
   Wet process
6. Substrate release
   Wet or mechanical process

Encapsulation



Encapsulation: 1µm – 1mm thick

Transducer layer: < 1µm

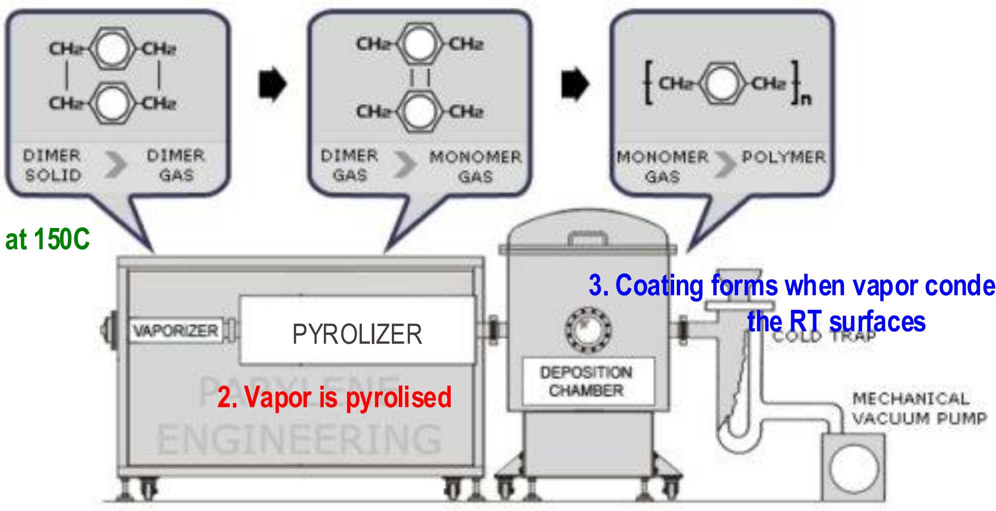
Carrier: 1µm – 1mm thick

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



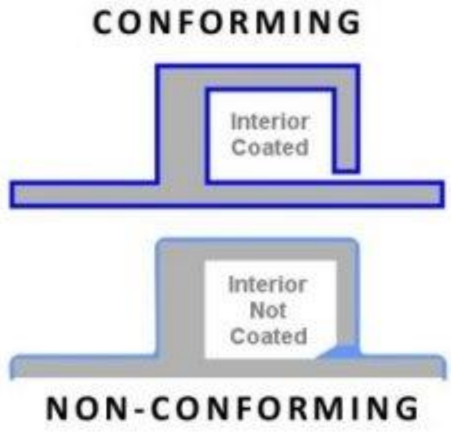
1. Sublimation at 150C

2. Vapor is pyrolised

3. Coating forms when vapor condenses on the RT surfaces

www.paryleneengineering.com

Parylene: conformal coating

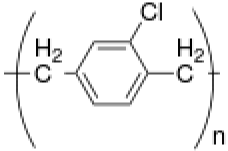


Conformal
Pin-hole Free
Thermal Stress Free (Cureless Coating)

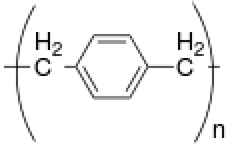
Unconformal
Thin on the Edges and Corners
Thermal Stress (100 to 150 Degree's C)

Types of parylenes

- Parylene C → standard compound



- **Parylene N → biomed. applications**



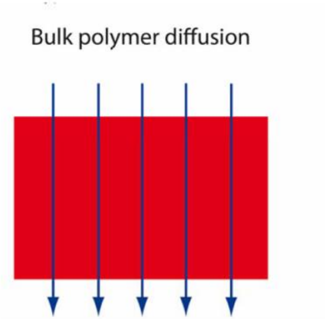
- Parylene D → higher temperature applications
- Parylene HT → high temperature and UV exposure stability

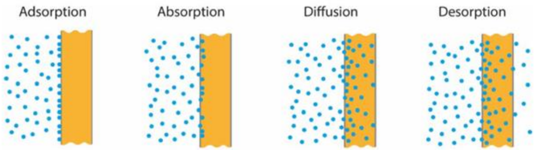
Parylene properties

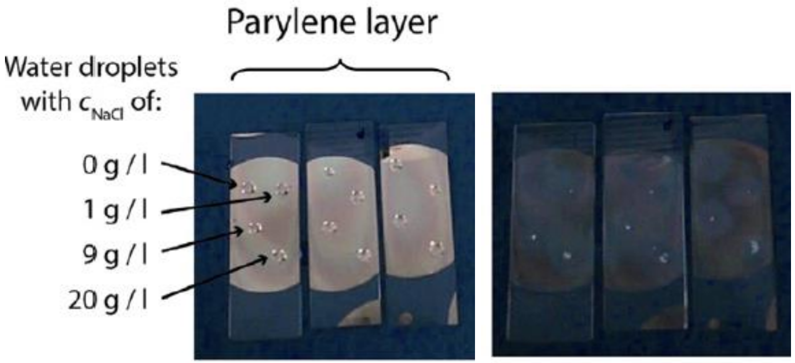
- **Mechanical properties**
  - Young’s modulus: 0.5GPa – 2.75GPa
  - Low stress coating that does not form sites prone to crack initiation
- **Thermal stability**
  - CTE: **35 – 70** ppm/℃
- **Optical properties**
  - Transparent and colorless in the visible range
  - Autofluorescence – limited

Hermeticity

Permeation process







t = 0

t = 8h

Test : Calcium mirror test

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

Surface and Coatings Technology (2014), 255, 124129

WVTR
Thin Film Encapsulation

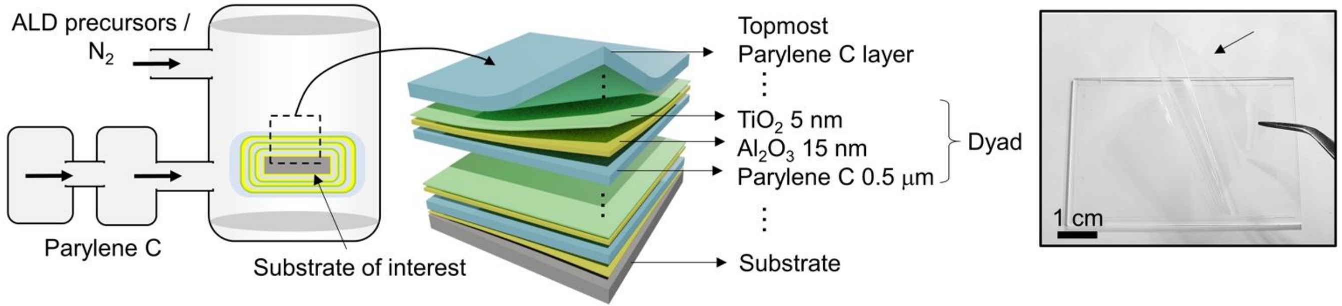
- Stable operation of flexible electronic devices
  - >10,000 h requires **$10^{-3} \leq \mathrm{WVTR} \leq 10^{-6}\ \mathrm{g\ m^{-2}\ d^{-1}}$**
  - Even more constraining for implantable devices

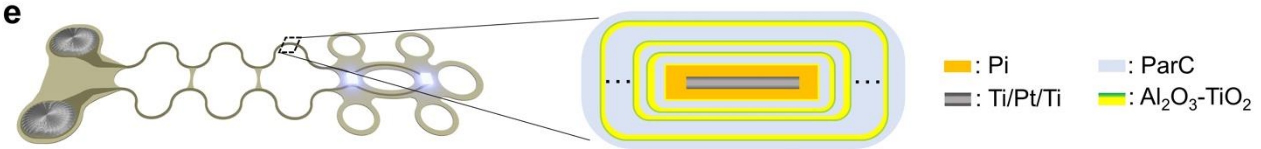
- Thermoplatics

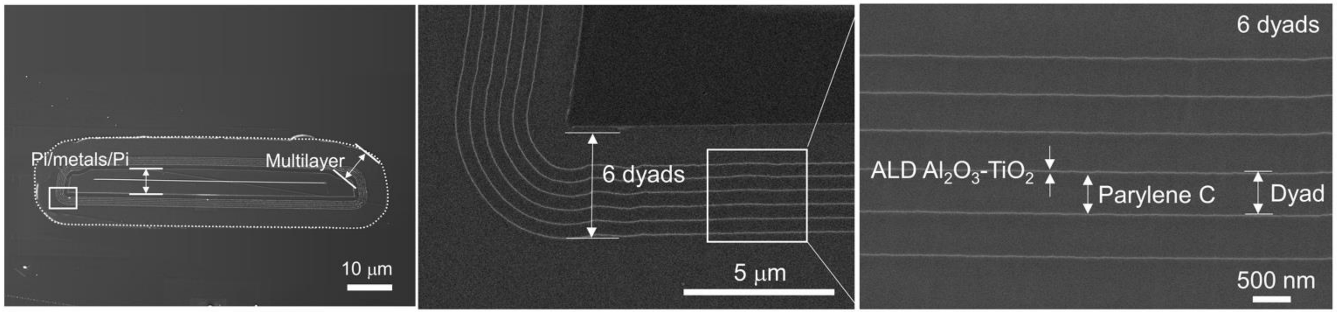
- Single-layered barrier films
  - e.g. SiO_x, SiN_x, SiC_x, SiO_xN_y, SiO_xC_y, Al_2O_3, AlO_xN_y, ZrO_2, TiO_2, MgO, ZnO, SnO_2
  - relatively high $10^{-1} \leq \mathrm{WVTR} \leq 10^{-3}\ \mathrm{g\ m^{-2}\ d^{-1}}$

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

Organic/inorganic multilayer encapsulation

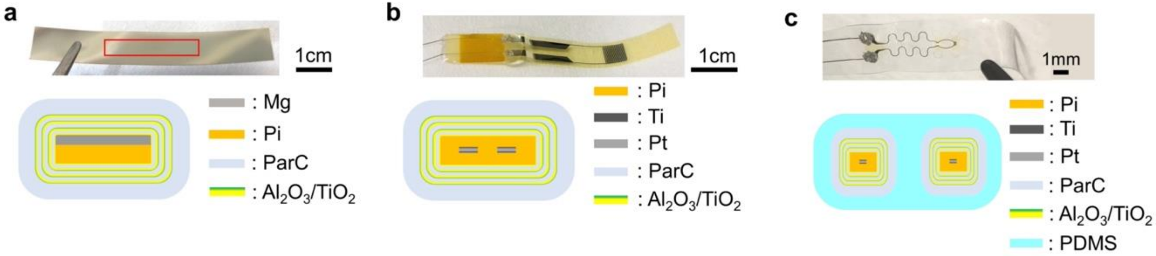






K. Kim et al., Small, 2021, https://doi.org/10.1002/smll.202103039

Lifetime evaluation



Mg test

IDE: Inter-digitated electrodes

OE: micro-LED

The 10-degree rule

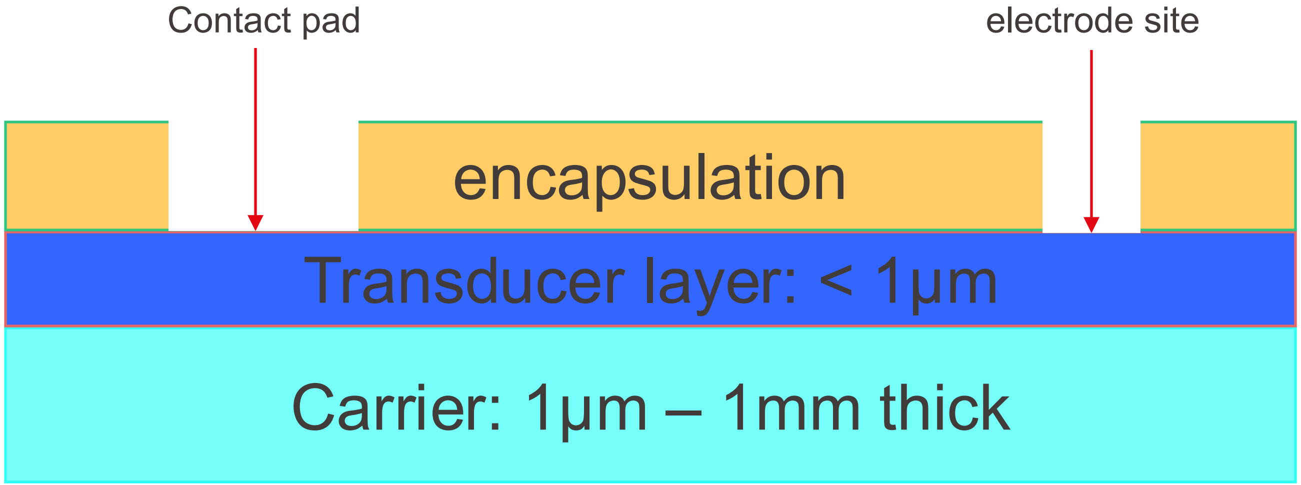
- For **thermally activated** failure/degradation mechanisms, a 10 °C rise in temperature roughly doubles the reaction rate → time to failure halves.
- Conversely, drop 10 °C and lifetime roughly doubles.

- Derived from the Arrhenius model of reaction rates $\propto e\hat{}(-E_a/kT)$

- **Acceleration factor: $AF \approx 2 \hat{}\ [(T_2 - T_1) / 10°C]$**
- **For implants: $T_1 = 37°C$**

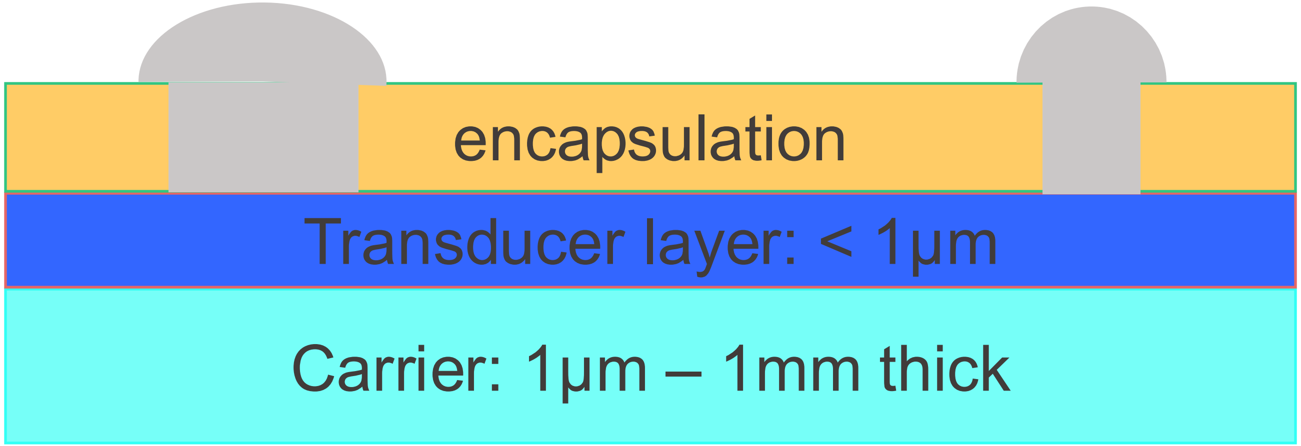
- Remember: A gross approximation, but often (over)used. Depends on the actual degradation mechanisms (how many?), E_a of the reactions, changes in the surrounding environment, etc.

Encapsulation patterning



Conductive coating

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



Materials and technologies recap’

material	properties		
polyimide	Form factor	Resin foil	Spin-coating + curing (350C, h, N2 env)
		thickness	10-100um
	Hermeticity	limited	
Orange thermoplastic	E	2.5 GPa	Plastic deformation, strain > 5%
	CTE	20-60 ppm/C	
	Electrical insulation	3 (dielectric constant)	Use as substrate and/or encap.
	etch	Dry etching (O2) Wet etching (KOH)	Laser micromachining
	Non toxic		

Materials and technologies recap'

material	properties		
Parylene	close to PI		
	Elastic modulus	~2-3GPa	
	processing	CVD (chem. vapor dep. At room temperature)	Conformal, 3D
	Optical prop	Transparent in the visible range	
	CTE	~35 ppm/C	
	Dielectric constant	~2.65	
	patterning	Dry O2 based etching	

Materials and technologies recap’

material	properties		
Silicon (crystalline)	semiconductor	wafer	
	Critical strain	0.05%	brittle
	Elastic modulus	140GPa	
	processing	Transfer printing	
	Optical prop	Opaque (vis range)	
	CTE	2.6-3.3 ppm/C	
	Dielectric constant	11.7	
	patterning	RIE (F-based) Wet etching (KOH, HF)	

EPFL

Materials and technologies recap'

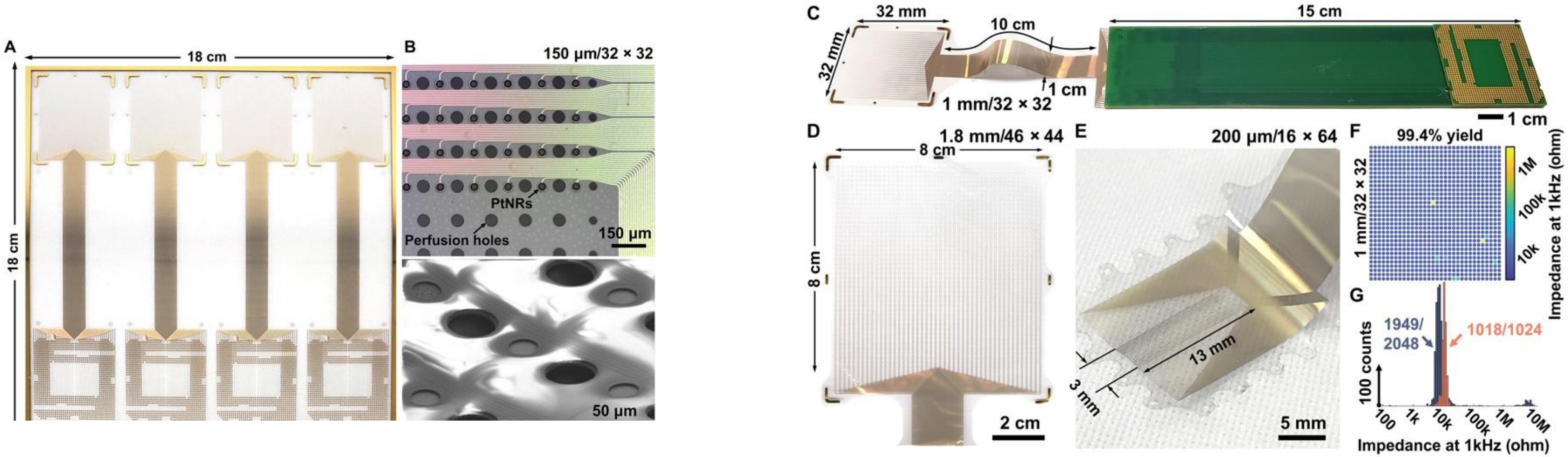
material	properties		
platinum	metal		100-300nm
	Ductile material	Plastic deformation	
	Electrical resistivity	~10 – 30 µΩ.cm (thin-film)	
	Young modulus	170 GPa	
	Deposition technique	Sputtering, evaporation	Thin film
		Electroplating (electrode only)	porous
	Etching	Wet etching Dry etching, ablation Lift-off	
	Needs an adhesive layer		

Materials and technologies recap’

material	properties		
Silicone	elastomer	Highly viscous before crosslinking	
	Elastic modulus	10 kPa – 10 MPa	
	processing	spin-coating Injection molding	Curing in air from RT to 150C
	Optical prop	Transparent (vis. range)	
	CTE	300 ppm /C	
	Dielectric constant	2	
	patterning	RIE (F based) Laser micromachining	

Thin film electrode arrays

- 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



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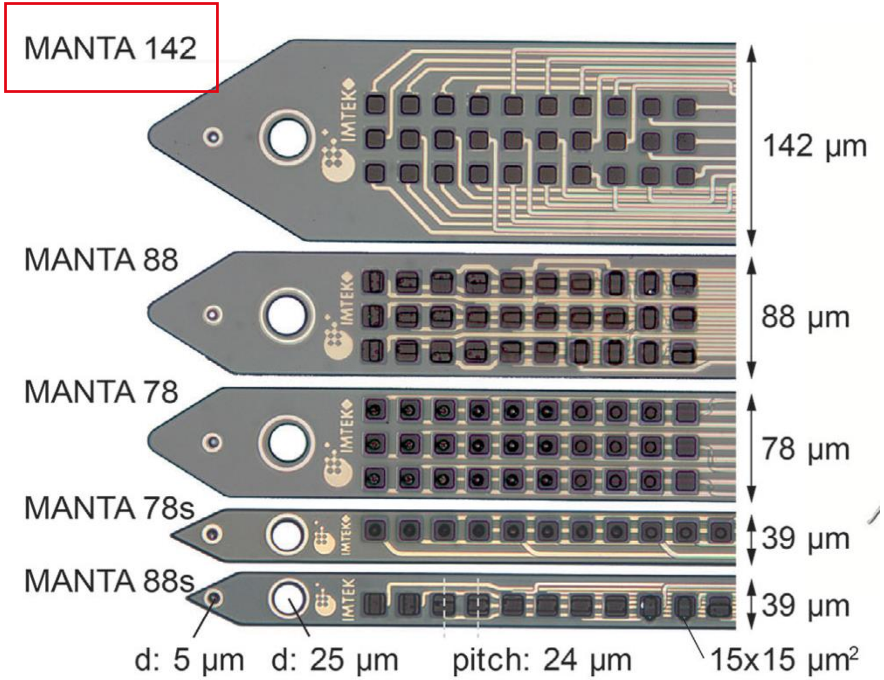
Polyimide based shank with high density electrodes

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



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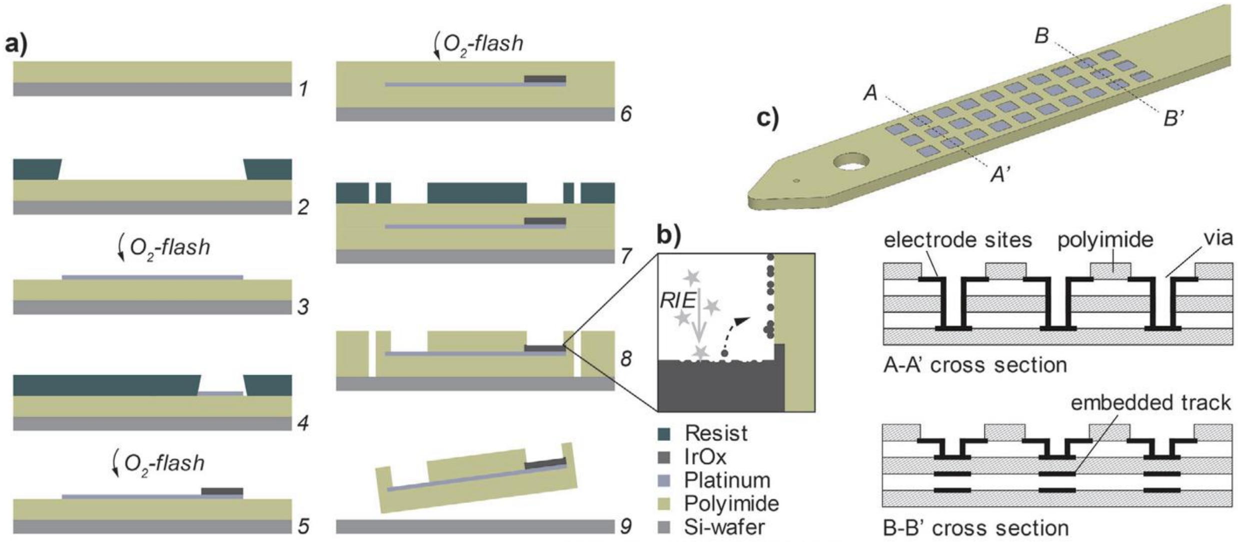
Polyimide based shank with high density electrodes



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Polyimide based shank with high density electrodes

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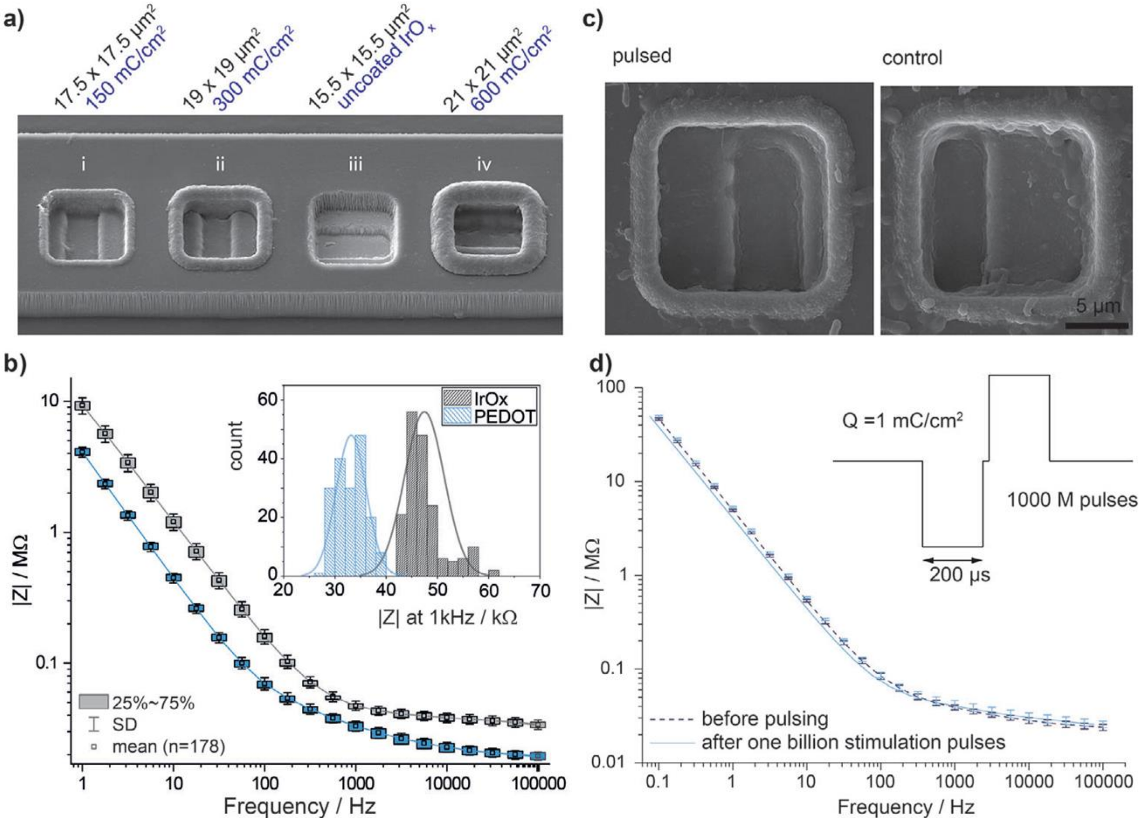
MANTA probes were fabricated by advancing ***standard PI fabrication*** *protocols to a multilayer design, comprising ultimately* ***5 PI and 7 metallization layers*** *in a probe of* ***10 µm thickness****.*

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.

Polyimide based shank with high density electrodes

Electrode characterization



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Summary

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

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