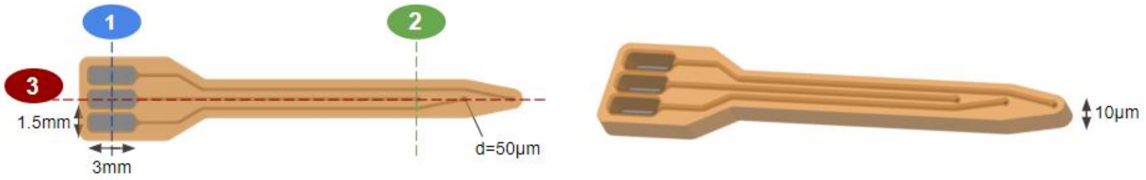
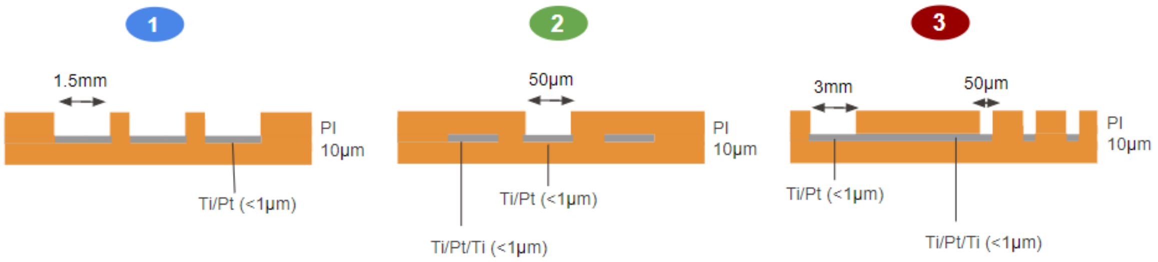
Exercise set 2 - Microfabrication and mechanics

Exercise 1 – Microfabrication of a neural implant

You want to create a flexible probe with embedded microelectrodes (50µm diameter) for acute and chronic neural recordings. The microelectrodes are made out of platinum (Pt) and encapsulated in polyimide (PI). The overall probe's geometry is depicted below.



a. Draw the device cross section along lines 1, 2, and 3. Assume the top and bottom encapsulation have the same thickness. What is a typical thickness of the metal layer(s)?



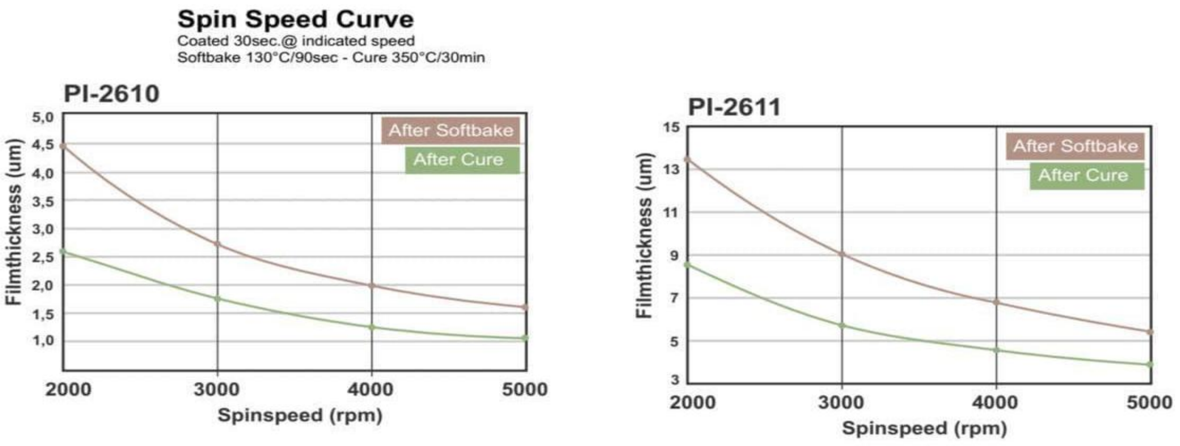
Remember: These diagrams are not drawn to scale (and almost never are).

The total thickness of the metal stack is less than 1 µm. Typically, a thin titanium layer is used as an adhesion layer between the main conductive metal, in this case platinum, and the encapsulation, which here is polyimide. Since it serves as an adhesion layer, the titanium thickness is much less than that of the platinum. A representative configuration is Ti/Pt/Ti with respective thicknesses of 25 nm/150 nm/25 nm. While the titanium layers mainly serve adhesion purposes and their thickness is generally fixed, the thickness of the platinum can be adjusted according to the specific design requirements of the device, such as the width and length of the conductive tracks. Thicker platinum would give less resistive tracks, although mechanical and cost constraints should be considered.

b. We start with a Ti-Al-coated Si wafer, where Ti-Al is a sacrificial layer that will be dissolved at the end of the process to release the finished flexible probe from the Si carrier. Outline the steps of the process flow you would use to fabricate the implant in a cleanroom. Provide the thickness of every layer (PI, Pt, photoresist).

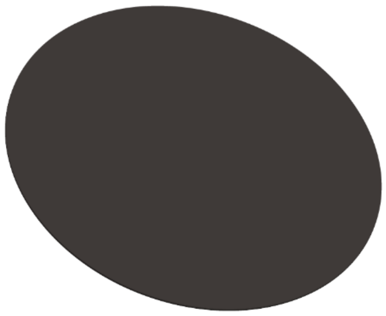
Below you have the different polyimides and photoresists that you can use:

- Photoresists: ECI3027 (4 µm) and AZ10XT (12 µm)
- Polyimide: PI-2610 and PI-2611 (see curves below and choose the spin speed to attain your chosen thickness)



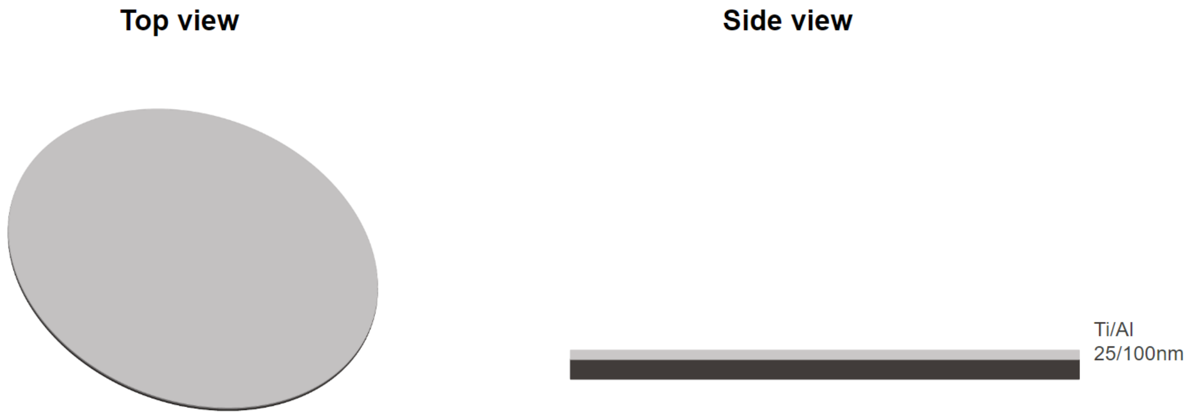
1. **Si wafer.** A 10 cm silicon (Si) wafer is used as a carrier substrate.

Top view

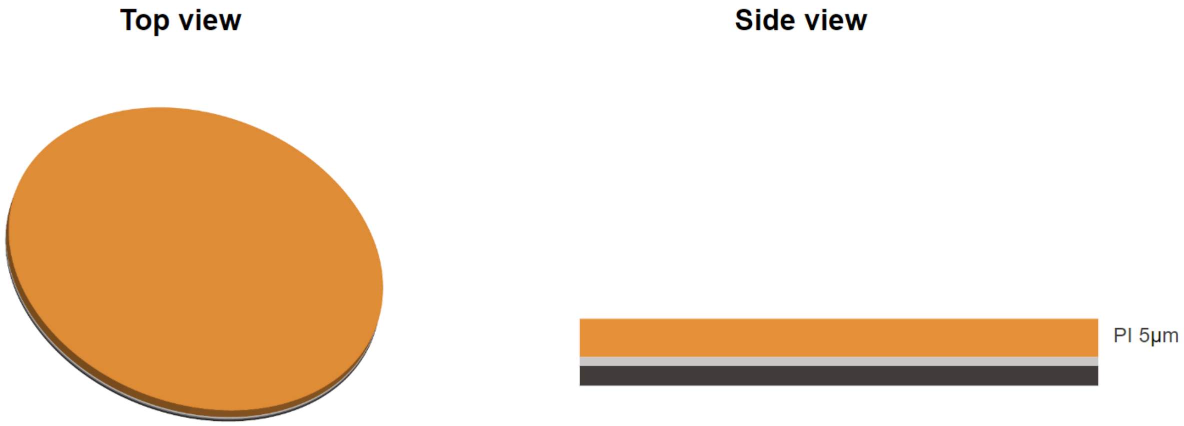


Side view

2. **Sacrificial layer.** The sacrificial layer is applied by sputtering 25nm of titanium (Ti) followed by 100 nm of aluminium (Al). The Al layer acts as the sacrificial layer that will be removed once the fabrication will be completed, therefore allowing the device to be released from the wafer. Titanium is used as an adhesion layer between Al and Si. At CMi, you can purchase wafers with this step already completed.

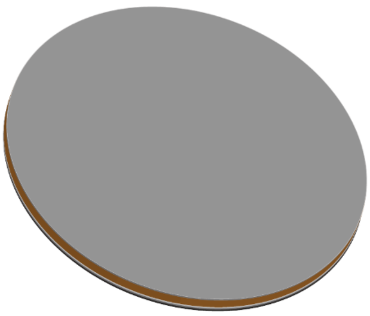


3. **Substrate (bottom encapsulation).** We spin coat 5µm of polyimide as the bottom encapsulation layer (PI-2611, 3500 rpm). Consider the thickness after curing to define the needed spin coating speed. After spin coating, the polyimide undergoes a soft bake (70C for 3 min and 110C for 3 min) and a hard bake process (350C for ~3h in N2 environment).



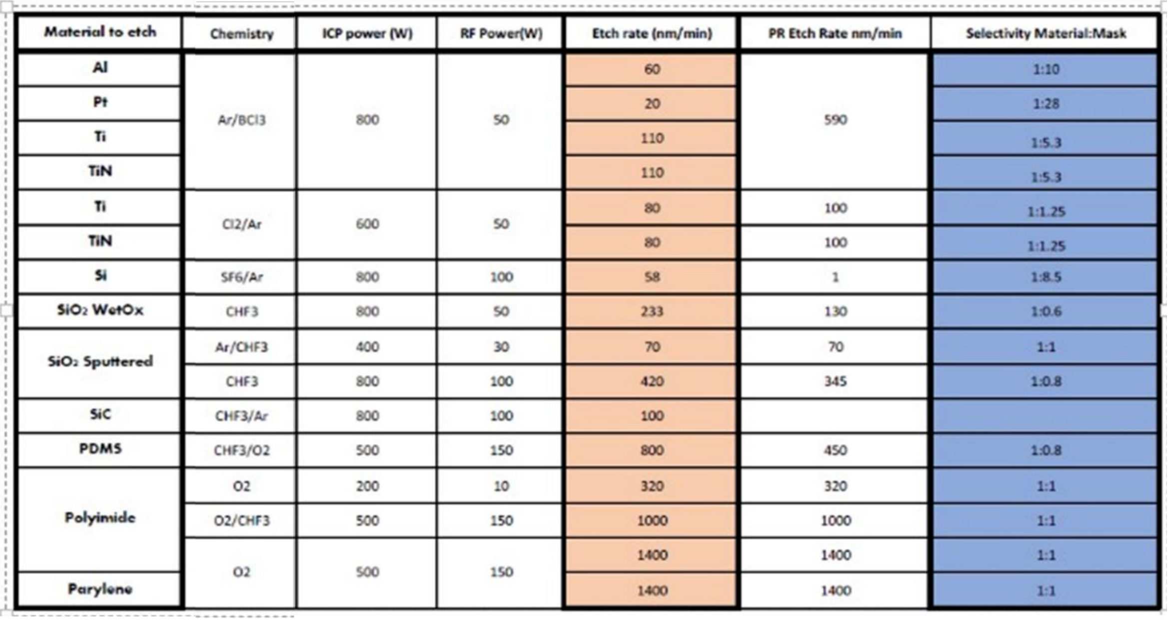
4. **Metallization.** We sputter 25nm of titanium (Ti), then 150 nm of platinum (Pt), and finally another 25nm of titanium (Ti). Platinum is a good, stable (not very reactive) conductor, while titanium serves as an adhesion layer to ensure good adhesion of the metal to the top and bottom polyimide layers.

Top view



Side view

5. **Definition of the tracks, electrodes and pads.** We spincoat, expose and develop a photoresist layer. Normally, you would calculate the amount of photoresist (PR) required based on a table, like the following:



Material to etch	Chemistry	ICP power (W)	RF Power(W)	Etch rate (nm/min)	PR Etch Rate nm/min	Selectivity Material:Mask
Al	Ar/BCl3	800	50	60	590	1:10
Pt				20		1:28
Ti				110		1:5.3
TiN				110		1:5.3
Ti	Cl2/Ar	600	50	80	100	1:1.25
TiN				80	100	1:1.25
Si	SF6/Ar	800	100	58	1	1:8.5
SiO_2 WetOx	CHF3	800	50	233	130	1:0.6
SiO_2 Sputtered	Ar/CHF3	400	30	70	70	1:1
	CHF3	800	100	420	345	1:0.8
SiC	CHF3/Ar	800	100	100		
PDMS	CHF3/O2	500	150	800	450	1:0.8
Polyimide	O2	200	10	320	320	1:1
	O2/CHF3	500	150	1000	1000	1:1
	O2	500	150	1400	1400	1:1
Parylene				1400	1400	1:1

To etch 150 nm Pt @20nm/min = 7min30sec

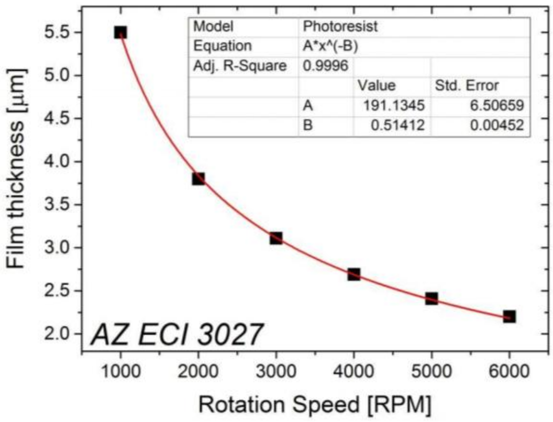
To etch 50 nm Ti @110nm/min = 27 seconds

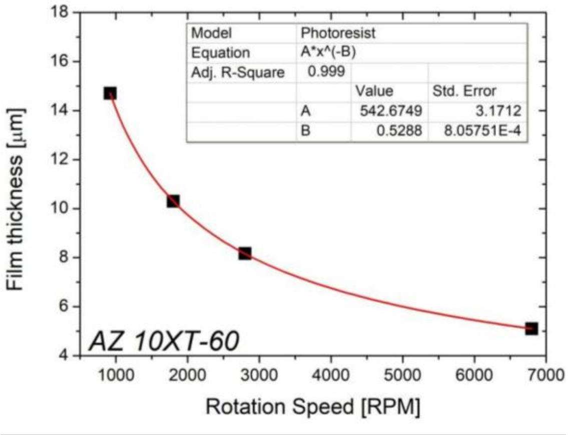
= ~8 minutes of etching

PR etch rate with Ar/BCl3 chemistry = 590 nm/min

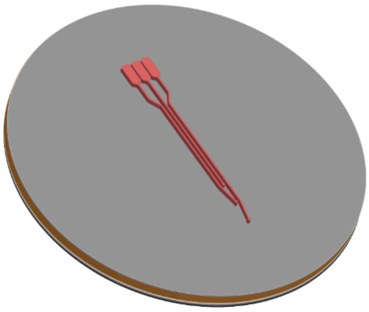
➔ 590 nm/min * 8 minutes = **4.72 µm of PR required**

- ➔ You would likely use 5.5 µm of ECI3027 (more than 4.72 µm, for safety; and the maximum thickness attainable with ECI3027, see spin-curve charts below).
- ➔ Between the options of 4 µm of ECI3027 and 12 µm of AZ10XT (as given in this exercise), you would need to choose 12 µm of AZ10XT.





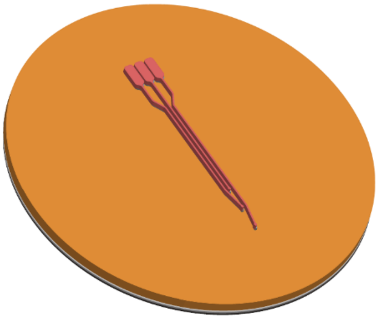
Top view



Side view

6. **Definition of the tracks, electrodes and pads.** We dry etch the exposed Ti/Pt/Ti stack (and also etch the PR). Possible options:
   a. Reactive ion etching (RIE, chemical + physical) with Ar+BCl_3
   b. Ion beam etching (IBE, purely physical) with Ar only.

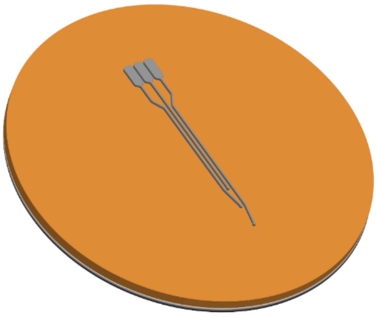
Top view



Side view

7. Strip the photoresist (with acetone/IPA or remover). Wash in DI water and dry with N2.

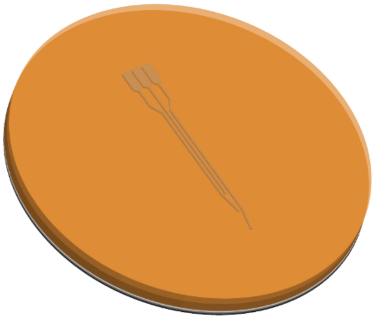
Top view



Side view

8. **Superstrate (top encapsulation).** We spin coat another 5µm layer of polyimide for electrical insulation.

Top view



Side view

9. **Definition of the device outline and opening of the electrodes and pads.** We spin coat, expose and develop a photoresist (PR) layer on the wafer. This PR needs to survive the etching of 5 + 5 = 10 µm of polyimide. Based on the etch rates of O2 gas in the table above,

   To etch : 10 µm polyimide @1000 nm/min = **10 minutes**

   To etch : 25 nm Ti @ 110 nm/min = **14 seconds**

   PR etched during Pi etch : 10 minutes * 1000 nm/min = **10 µm**

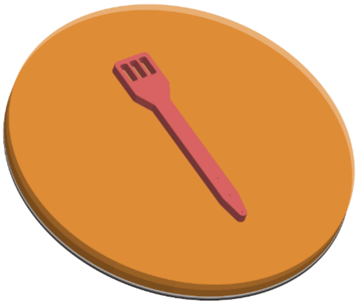
   PR etched during Ti etch: 14 seconds * 590 nm/min = **134 nm**

   ➔ 10.134 µm of PR are required

   ➔ This can be approximated more simply by noting that the ratio of etching rates of PR and Pi = 1:1 (the Ti layer is very thin and etches very quickly)

   ➔ For safety, we would likely choose something like **12 µm of AZ10XT** for our photoresist

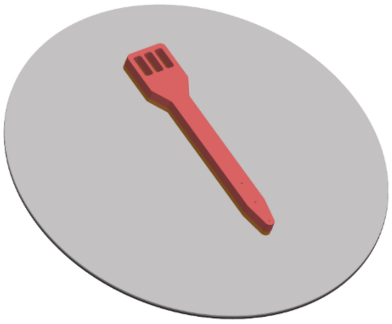
Top view



Side view

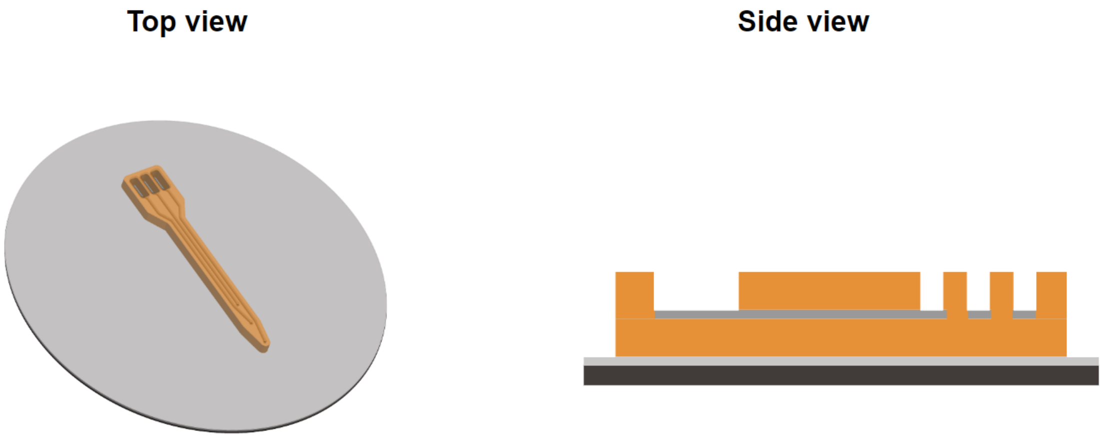
10. **Definition of the device outline and opening of the electrodes and pads.** We dry etch the polyimide (Pi) layer (possibility: O_2 RIE), then etch the titanium layer to expose the platinum electrodes (possibility: either Ar+BCl_3 RIE, or Ar IBE). Because Ti oxidizes, it is not as effective of an electrode material and is therefore removed here (exposing the Pt below). Note that the electrodes would be exposed for a portion of this etching step (after etching the 5 µm thickness of the top polyimide (Pi) encapsulation, we continue to etch for another 5 µm thickness of Pi). This is not a big problem since the chemistry used for etching Pi (O_2) does not etch Ti.

Top view

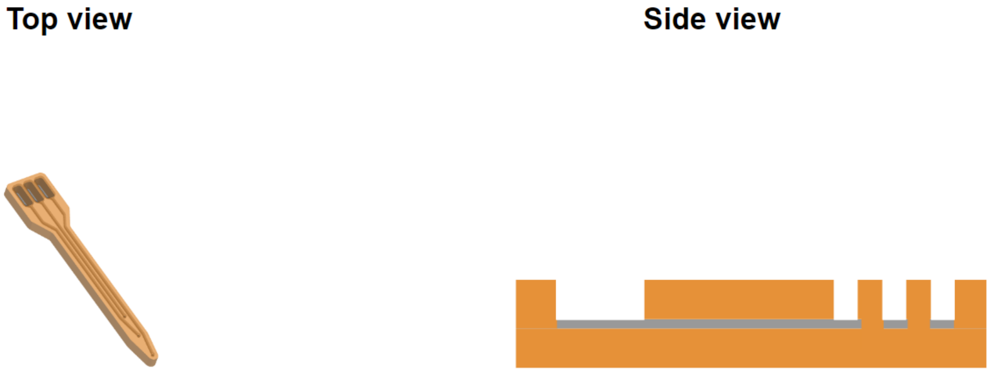


Side view

11. Strip the photoresist (with acetone/IPA or remover). Wash the wafer with DI water and dry with N2 gun.



12. **Release of the device from the wafer.** We release the device from the wafer using anodic dissolution of aluminium (https://ieeexplore.ieee.org/document/1416914).



Exercise 2 – Bending strain and the neutral plane

Relevant Young's moduli (E):

E(polyimide) = 2.5 GPa

E(platinum) = 170 GPa

a. A 10 μm thick polyimide foil is rolled on a 1-mm-diameter tube. What is the bending strain on the top surface of the foil (farthest away from the tube)?

R = 0.5 mm + 0.01 mm = 0.501 mm

$$\epsilon = \frac{h}{2R} = \frac{10\times10^{-3}mm}{2\times0.501mm} = 0.00998 = \text{~}\mathbf{1\%}$$

You can see that including the thickness of the film in the calculation of R does not considerably change the value of strain.

b. A 150-nm-thick layer of platinum is patterned on the top of that same polyimide film, forming electrodes, tracks, and pads. What is the bending strain on the top surface of the platinum layer if the whole stack (polyimide+platinum) is bent around the same 1-mm-diameter tube conforming to the bottom surface of the stack? (Assume the blanket layer formulas hold)

$$z_{NA} = \frac{\sum_k E_k t_k z_k}{\sum_k E_k t_k} = \frac{E_{Pi} t_{Pi} z_{Pi} + E_{Pt} t_{Pt} z_{Pt}}{E_{Pi} t_{Pi} + E_{Pt} t_{Pt}}$$

$$= \frac{(2.5GPa \times 10\mu m \times 5\mu m) + (170GPa \times 0.150\mu m \times 10.075\mu m)}{(2.5GPa \times 10\mu m) + (170GPa \times 0.150\mu m)} = 7.56\ \mu m$$

$$y_i = 10.150\ \mu m - 7.56\ \mu m = 2.59\ \mu m$$

$$\epsilon = \frac{y_i}{R} = \frac{2.59\ \mu m}{500\ \mu m + 10\ \mu m + 0.150\ \mu m} = 0.0051 = \mathbf{0.51\%}$$

c. When the stack is bent in this way, does the top surface or bottom surface of the platinum experience more stress? (top Pt surface = away from the polyimide, exposed to air; bottom Pt surface = buried in the stack, in contact with the polyimide)

The surface farther from the neutral plane will experience more stress, which in this case is **the top surface of the Pt**.

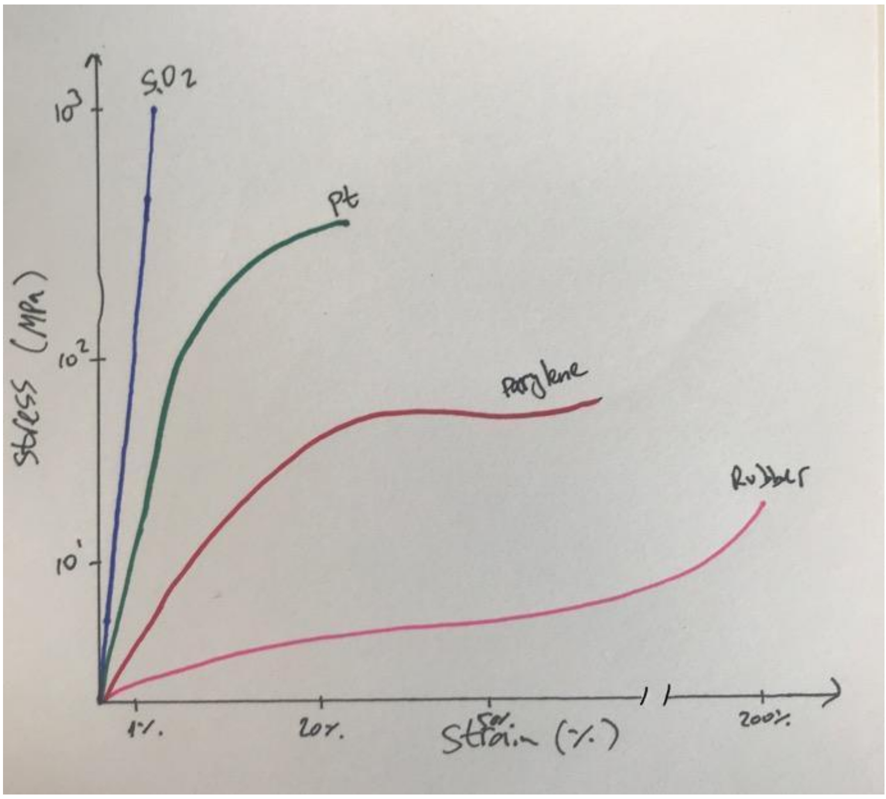
d. Assume the critical strain of platinum is 1%. What is the smallest diameter tube around which you could bend the polyimide+platinum stack without fracturing the platinum? (Assume the blanket layer formulas hold)

$$R_{min,i} = \frac{y_i}{\epsilon_{crit,i}} = \frac{2.59}{0.01} = 259\ \mu m$$

$$D = \mathbf{518}\ \mu m$$

Exercise 3 - Stress and strain

Draw the stress-strain relationship for the following materials: rubber, platinum, parylene and silicon dioxide (SiO_2). Provide the units of the x-y axes and order-of-magnitude estimates for Young's moduli in the elastic regimes.



SiO_2: Highest modulus, strongest, lowest failure strain, brittle

Pt: High modulus, small plastic deformation region

Parylene: Polymer, elastic + plastic deformation, ductile

Rubber: Elastomer, very low modulus, high elastic deformation, high failure strain