2020

MEMS Project

DESIGN OF A MICRONEEDLE WITH A THERMAL ACTUATOR

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Problem Definition

Micro needles are widely used in the medical field. Designing a micro needle for surgery was one of the goals of the course and its design was partly described. To design the microstructure of this micro needle many properties were considered, such as Bio compatible, not brittle, no buckling and fracture in the load, no impurity in the thin layer (causing crack growth in the layer) and no covalent bonds during fabrication in the bottom layers, etc. In addition, also the ability of the needle to detect the stone and automatically and defect it after the stone has been identified. Sensing & Actuation should replace a previous micro electro mechanical structure so that the operation in this project students should use thermal actuators.

A. Micro Needle Design

By considering problem demands such as biocompatible material, not being brittle, no buckling and fracture and etc. and by reviewing studies done before about biocompatible materials and their application, **Tantalum** seems to be a suitable material for micro needle and the actuator.[1]

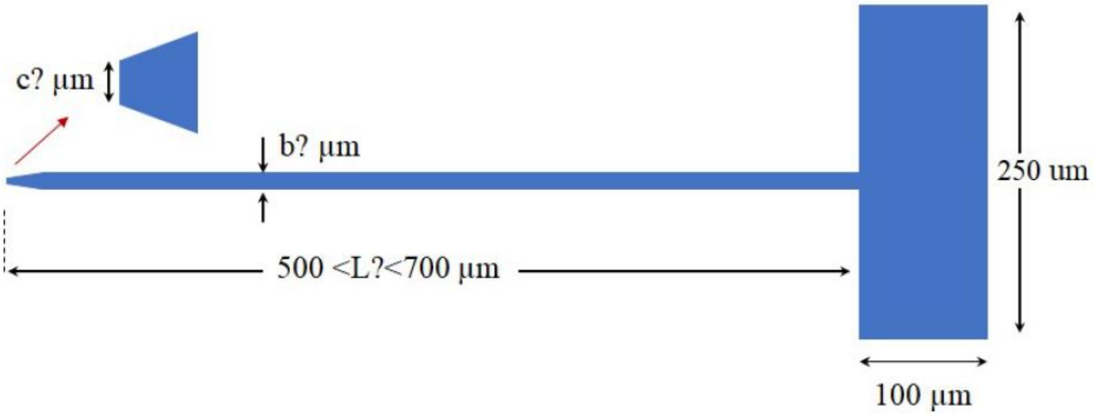
Tantalum mechanical properties:

Table 1

Young's modulus	E (GPa)	186
Yield strength[2]	σ_y(MPa)	900
Density	ρ (kg/m^3)	16690
Poisson ratio	1	0.34
Thermal diffusivity[3]	$\propto_T \ (\frac{m^2}{s})$	24.37 * 10^ (-6)
Electrical resistivity	ρ (Ω.m)	131*10^ (-9)

The stress at which the kidney stone deflects is σ = 5Mpa, we design the needle based on this stress and apply buckling and yielding studies to the needle with the necessary constraints.

Naming is based on the following shape:



We also extend the following relationships by considering the thickness t and the tip height d:

$$\sigma_{max} = 5\ Mpa$$

$$F = c \times t \times \sigma_{max}$$

$$it\ must\ be\ considered : \frac{\sigma_y}{\sigma_{max}} > 1$$

$$P_{cr} = \frac{\pi^2 \times E \times I}{le^2} \quad , \quad le = 2 \times l \quad , \quad I = A \times r^2$$

$$I_{xx} = \frac{1}{12} \times b \times t^3 = A \times {r_x}^2 \quad thus \quad r_x = \frac{t}{\sqrt{12}}$$

$$I_{yy} = \frac{1}{12} \times t \times b^3 = A \times {r_y}^2 \quad thus \quad r_y = \frac{b}{\sqrt{12}}$$

The larger the value of $\frac{l_e}{r}$, the greater the degree of buckling around which axis occurs.

$$P_{cr} = \frac{\pi^2 \times E \times A}{(\frac{l_e}{r})^2}$$

In order to obtain analytical relationships $\frac{l_e}{r} > 100$, we consider that we do not have to use empirical relationships in buckling analysis.

We also consider the micro needle length L = 500μm.

$$\sigma_{max} \times c \times t < P_{cr}$$

We drive the micro needle parameters as follow:

$t = 0.5 \times b$
$c = 0.5 \times b$
$d = 0.5 \times b$

$$F = \sigma_{max} \times 0.5b \times 0.5b = 0.25 \times \sigma_{max} \times b^2 = \frac{5}{4} \times b^2 \times 10^{-6}$$

$$r_x = \frac{0.5b}{\sqrt{12}}, r_y = \frac{b}{\sqrt{12}}, \qquad \frac{le}{r_x} > \frac{le}{r_y} \text{ so buckling occurs about x axis}$$

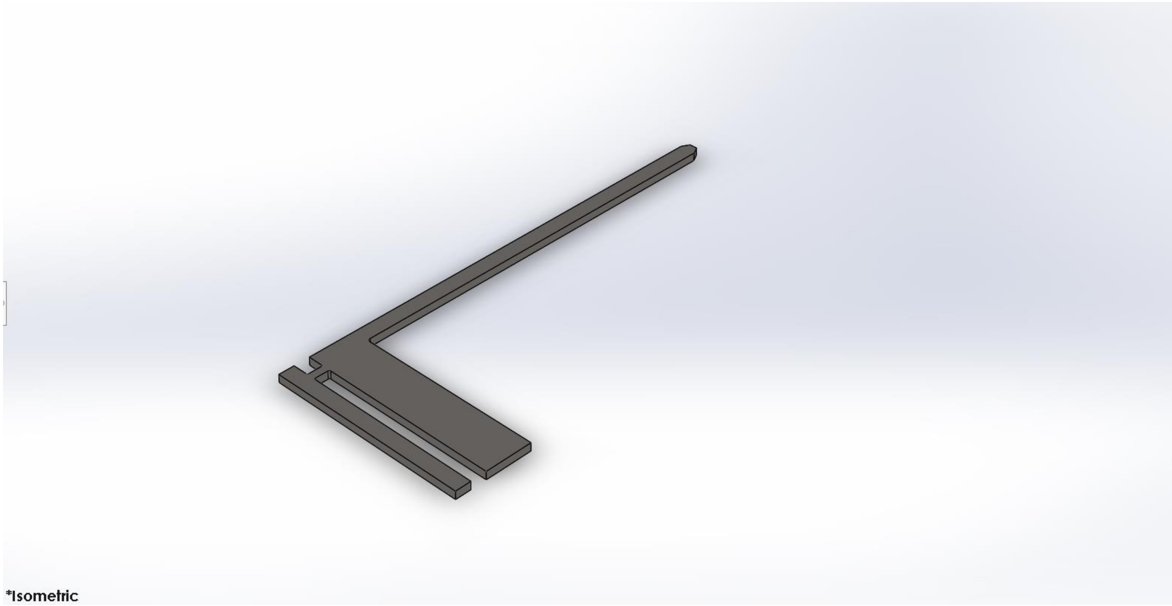
$$\frac{le}{r_x} > 100 \quad so \quad \frac{2l}{\frac{0.5b}{\sqrt{12}}} > 100 \ , L = 500\mu m \quad thus \quad b < 20\sqrt{12}\ \mu m$$

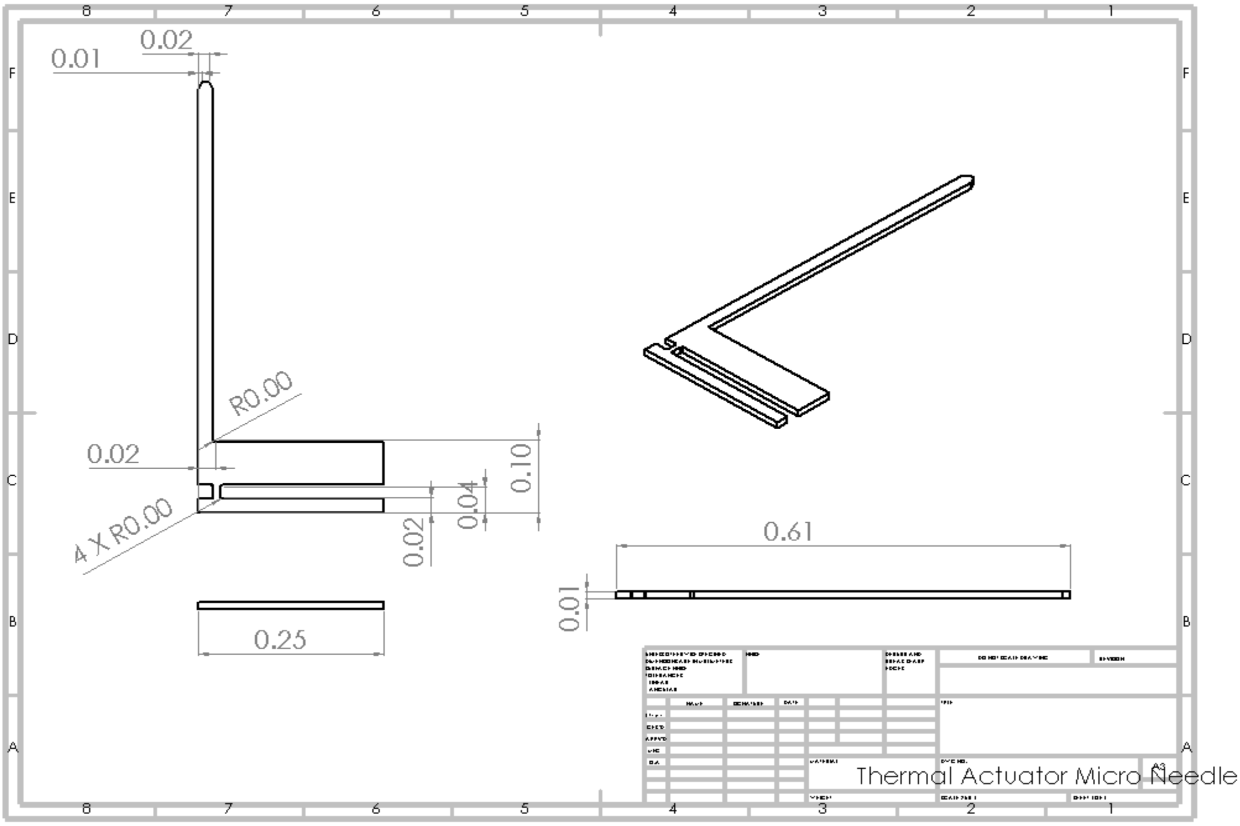
$$also \quad F < P_{cr} \quad thus \quad b > 0.045\mu m$$

By dividing by two sets of values b, we consider the value for b:

$$b = 20\mu m \ \ thus \qquad t = c = d = 10\ \mu m$$

We also implement the CAD design (SolidWorks) by extracting the needle dimensions. This needle is rigidly attached to the actuator as shown in the following three-dimensional and two-dimensional views of the system:





$$A_h = 20 \times 10 = 200\mu m^2 \qquad A_c = 60 \times 10 = 600\mu m^2$$

$$\rho_h = 2(20 + 10) = 60\mu m \qquad \rho_c = 2(60 + 10) = 140\mu m$$

$$\bar{y} = \frac{\sum A_i y_i}{A_i} = \frac{100 \times 10 + 600 \times 70}{200 + 600} = 53.75\mu m$$

$$I_1 = \frac{10 \times 20^3}{12} = 6666.66\mu m^4 \qquad I_2 = \frac{10 \times 60^3}{12} = 180000\mu m^4$$

$$d_1 = 53.75 - 10 = 43.75\mu m \qquad d_2 = 70 - 53.75 = 16.25\mu m$$

$$A_h \times {d_1}^2 = 382812.5\ \mu m^4 \qquad A_c \times {d_2}^2 = 158437.5\ \mu m^4$$

$$\bar{I} = I_1 + A_h \times {d_1}^2 + I_2 + A_c \times {d_2}^2 = 727916.66\mu m^4$$

Neutral axis distance with D:

$$D = 20 + \frac{60}{2} + \frac{20}{2} = 60\mu m$$

$\boldsymbol{L = 250\mu m}$, **length of actuator**

Body Temperature:

$\boldsymbol{T_{amb} = 37℃ \; or \; 310k}$

It should be noted that the temperature difference in the Actuator creates a tension modeled with a pure Momentum, this stress must be less than the yield stress:

$$\sigma = E\alpha_T(T_c - T_h)$$

$$\boldsymbol{\sigma < \sigma_y \quad thus \quad E \propto_T \Delta T < 138Mpa \quad thus \quad \Delta T < 198.55 ℃ \; or \; k}$$

Using the obtained equations for the deflection and temperature of the Hot Arm and the Cold Arm:

$$T_h = \frac{A_h}{h_{conv}\mathcal{P}_h \rho L^2}\left(\frac{A_c}{A_h + A_c}\right)^2 e^2 + T_{amb}$$

$$T_c = \frac{A_c}{h_{conv}\mathcal{P}_c \rho L^2}\left(\frac{A_h}{A_h + A_c}\right)^2 e^2 + T_{amb}$$

$$\omega(x) = \frac{D\alpha_T A_h e^2 x^2}{2h_{conv}\rho L^2 I}\left[\frac{A_h}{P_h}\left(\frac{A_c}{A_h + A_c}\right)^2 - \frac{A_c}{P_c}\left(\frac{A_h}{A_h + A_c}\right)^2\right]$$

All of the above statement variables are available except the value of the applied voltage to the Actuator, also taking into account x = L.

Using the code (MATLAB) below, we will find the desired voltage by consider three things:

1. The deflection should be less than 500µm
2. The temperature difference ΔT is <198.55 ℃ or k.
3. T_h should be below the melting temperature of nickel which is about 3290 K.

$$\boldsymbol{h_{conv.} = 20000\frac{w}{m^2k}}$$

```
clc; clear; close all
```

Initializing

Mechanical Properties for Tantalum

```
E = 186e9; %Young's modulus
sigma_y = 900e6;  %Yield strength
alpha = 24.37e-6; %Thermal diffusivity
rho = 131e-9; %Electrical resistivity
h_conv = 20000; %Convection Coefficient
l = 250  ; % Needle length
D = 60;
width = 10;
hight_h = 20;
hight_c = 60;
% e = 12e-3; % Actuation volatage;
T_amb = 310; % Body temprature
```

Calculation

```
Ah = width*hight_h; % Hot arm area
Ac = width*hight_c; % Cold arm area
Ph = 2*(hight_h+width);
Pc = 2*(hight_c+width);
y_bar = (Ah*0.5*hight_c+Ac*(D+0.5*hight_h))/(Ac+Ah);
Ic = (1/12)*width*hight_c^3; % Cold arm Second moment of area
Ih = (1/12)*width*hight_h^3; % Hot arm Second moment of area
dh = y_bar-0.5*hight_h;
dc = 0.5*hight_h+D-y_bar;
I = Ih+Ah*dh^2+Ic+Ac*dc^2; % Second moment of area
deltaT = sigma_y/(E*alpha); % Difference between cold and hot temp
Rh = rho*l/Ah*10^6;
Rc = rho*l/Ac*10^6;
```

Max allowed e

```
for e = 0:0.000001:1
    Th = (Ah/(h_conv*Ph*rho*l^2))*((Ac/(Ah+Ac))^2)*e^2*10^6+T_amb;
    Tc = (Ac/(h_conv*Pc*rho*l^2))*((Ah/(Ah+Ac))^2)*e^2*10^6+T_amb;
    deltaTA = Th-Tc;
    if deltaTA >= deltaT
        break
    end
end
w = ((D*alpha*Ah*(e^2))/(2*h_conv*rho*I))...
    *((Ah*(Ac/(Ah+Ac))^2)/Ph-(Ac*(Ah/(Ah+Ac))^2)/Pc);
```

Print

```
fprintf('Actuator Voltage is: %f\n',e)
fprintf('Difference between cold and hot temp is: %f\n',deltaT)
fprintf('Rh is: %f\n',Rh)
fprintf('Rc is: %f\n',Rc)
fprintf('Th is: %f\n',Th)
fprintf('Tc is: %f\n',Tc)
fprintf('deltaTA is: %f\n',deltaTA)
fprintf('w is: %f\n',w);
```

```
Actuator Voltage is: 0.142234
Difference between cold and hot temp is: 198.551895
Rh is: 0.163750
Rc is: 0.054583
Th is: 541.647070
Tc is: 343.092439
deltaTA is: 198.554631
w is: 0.000002
```

Published with MATLAB® R2019a

$$R_h = \rho \times \frac{L}{A_h} = 131 \times 10^{-9} \times \frac{250}{200} \times 10^6 = 0.163750\ \Omega$$

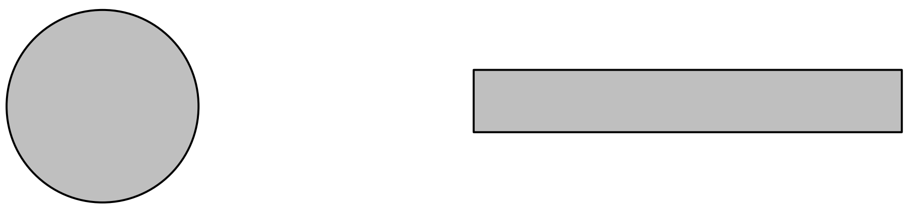
$$R_c = \rho \times \frac{L}{A_c} = 131 \times 10^{-9} \times \frac{250}{600} \times 10^6 = 0.054583\ \Omega$$

B. Functionality

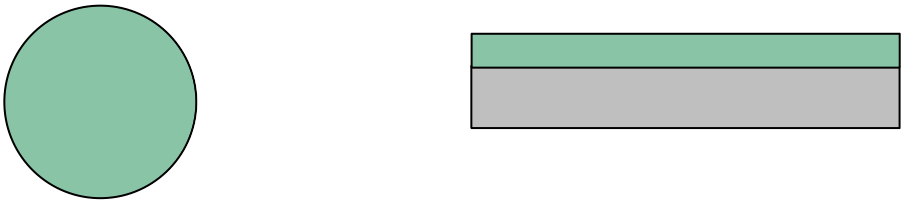
When the micro needle closes to the kidney stone (the needle is squeezing the stone), the needle bent inward. By placing a plate with electric charge in front of another plate (hot arm) we form a capacitor, so as the plates of this capacitor get closer and closer to each other we notice that the needle hits the stone and is compressing it, so we accurately distance the needle from the rock and apply voltage to the Actuator. As the hot arm warms, it bends towards the cold arm, causes the needle to deflect and push the rock to a certain pressure. Since the voltage is alternating, hot arm has the opportunity to cool down and returns to its original state. By repeating this process and applying periodic force, fatigue phenomenon happens and the stone becomes defected. Therefore, needles can move forward and progress. As we have seen, the displacement is small, so we apply a high frequency to compensate for this, thus crushing the stone.

C. Fabrication Process

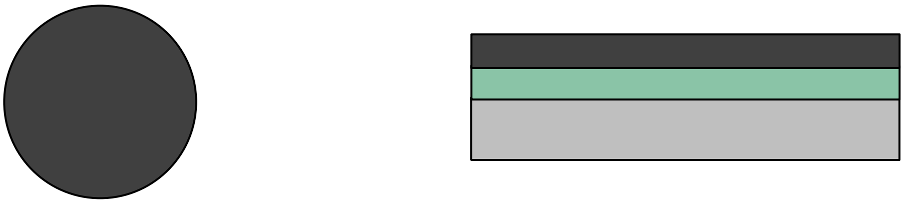
1. Silicon P-type<100> is used as substrate



We use a negative PR to increase the tantalum adhesion on the substrate. The reason for using negative PR rather than positive is that it can be deposited in greater thickness. Therefore, a negative PR of 20 μm thick (about the thickness of tantalum because the sacrificial layer is to be removed by lift-up method) is spin-coated onto the substrate.

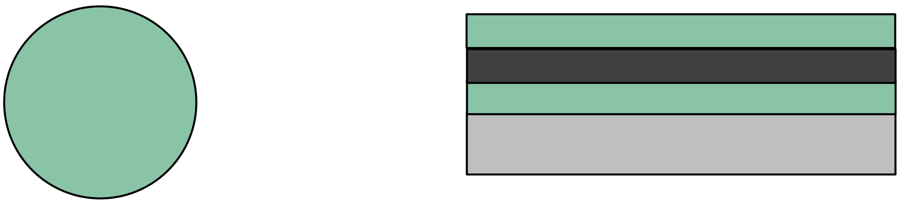


We now intend to deposit tantalum with the thickness of 10 micro meters, we could also use sputtering because we could have relatively good control over the thickness, however deposition can occur at lower temperatures and doesn't damage the PR. Therefore, we deposit tantalum.

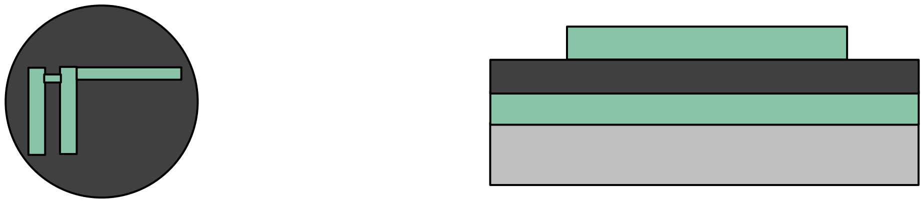


Lithography: For creating the shape of the micro needle we use lithography process.
The mask shape is blow:

Spin coating is done on the tantalum layer:

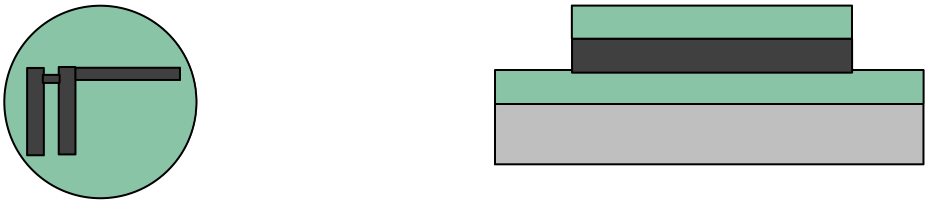


In negative PR: places get UV light remain therefore:

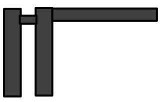


Now we need to do Etching, remove the extra tantalum and keep the under the mask area, and also select the PR so that the etch rate is very low compared to the nickel. We set the PR spin on the nickel, which is selectivity.

For etching we use RIE:

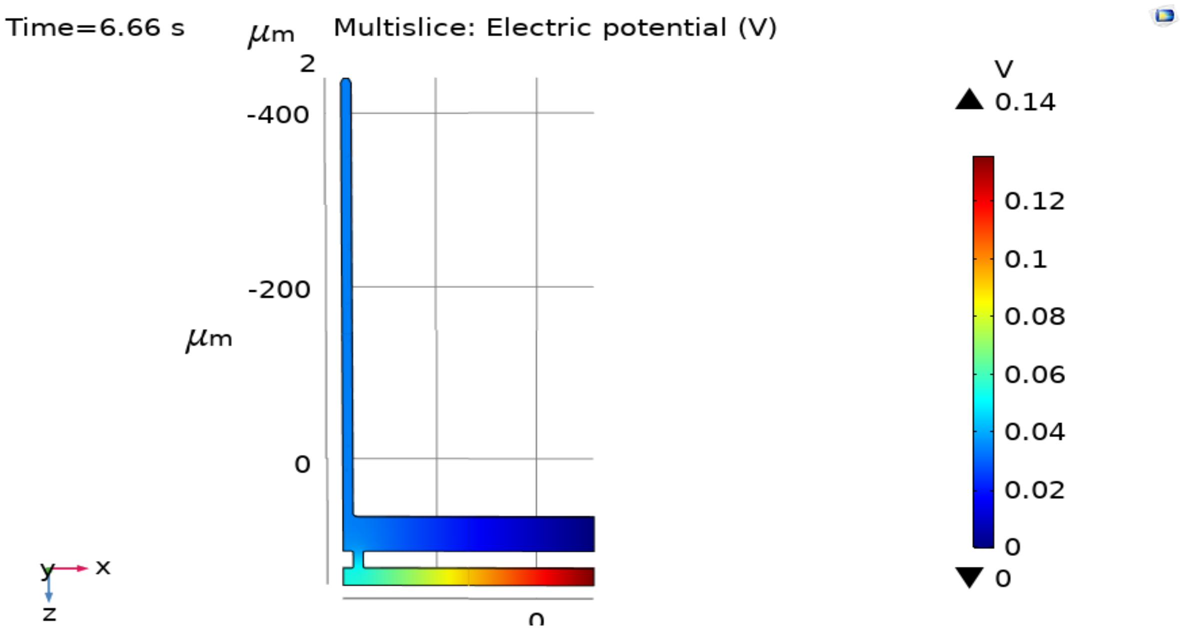


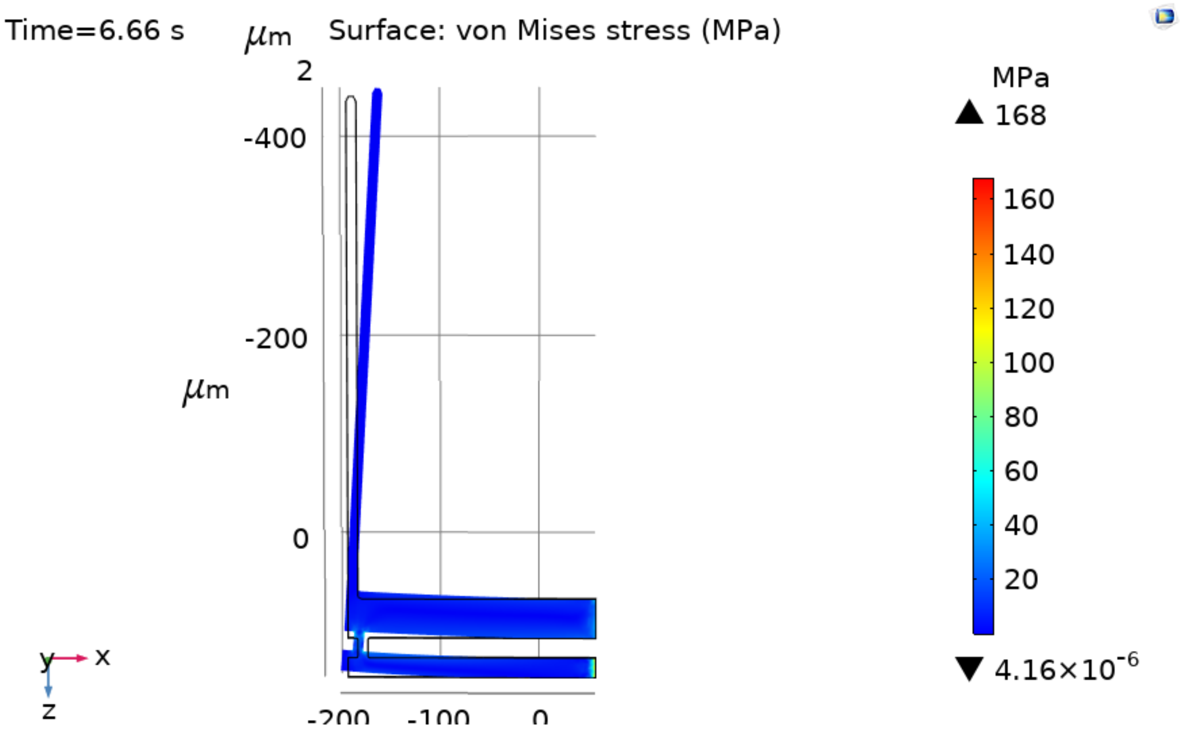
We have now obtained the actuator which is clined to the bottom of the PR nickel, with the Lift Up, remove the PR and remove the nickel from the substrate.



D. Simulation (COMSOL Multiphysics)

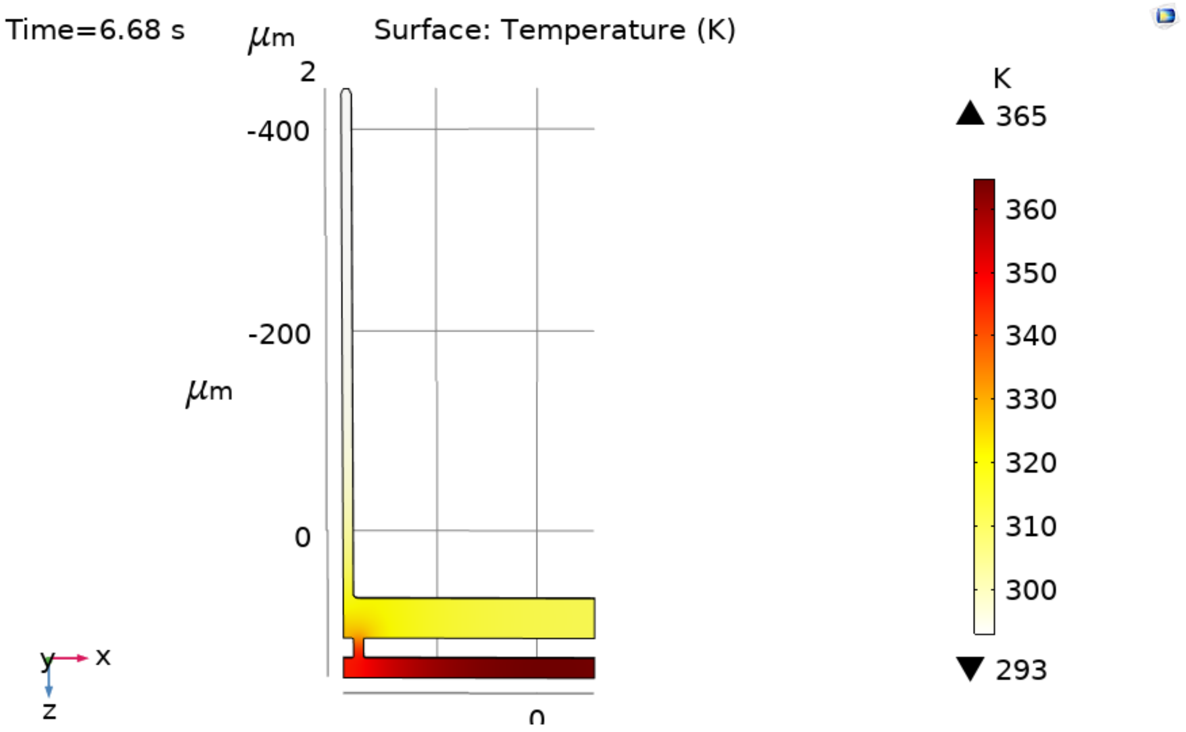
In order to evaluate out analysis, we have used FEM technique using COMSOL Multiphysics 5.4 software to verify our results. In this section, we modeled the process in the software, and analyzed the actuator behavior by thermal, electrical and mechanical coupling over a 2-minute period. Due to the studies done in Design part, the voltage used in simulation is equal to 14 mV with a frequency of $200\left[\frac{rad}{s}\right]$. Results are shown below:





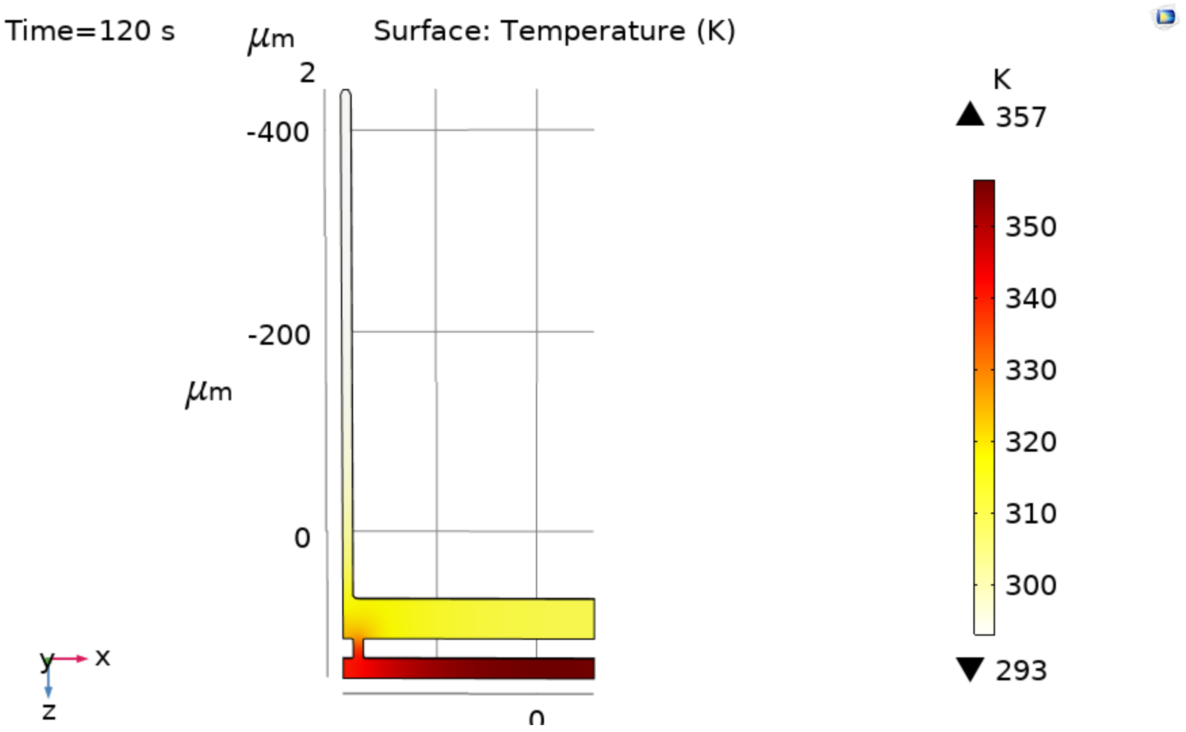
As you see the maximum stress is 168 MPa which is much less than 900 MPa.

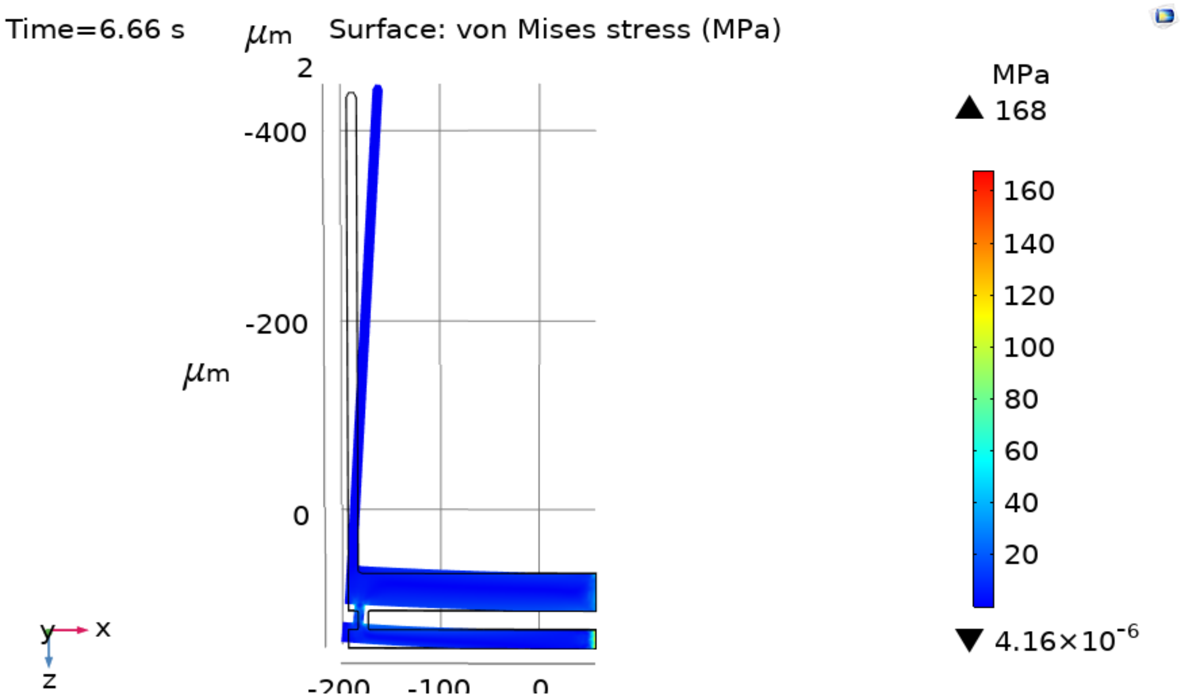
Maximum temperature:



As we can see the maximum temperature of COMSOL results is much less than calculations done before. Therefore, our model will work properly.

After 2 minutes we got:





Stress video is attached

References

[1] M. C. Tanzi, S. Farè, G. Candiani, M. C. Tanzi, S. Farè, and G. Candiani, "Biomaterials and Applications," *Advanced Materials Research*, vol. 506. Academic Press, pp. 199–287, 01-Jan-2012, doi: 10.1016/b978-0-08-101034-1.00004-9.

[2] AZoM, "Tantalum (Ta) - Properties, Applications," 2013. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=9287. [Accessed: 26-Jan-2020].

[3] I. V. Savchenko and S. V. Stankus, "Thermal conductivity and thermal diffusivity of tantalum in the temperature range from 293 to 1800 K," *Thermophys. Aeromechanics*, vol. 15, no. 4, pp. 679–682, Dec. 2008, doi: 10.1007/s11510-008-0017-z.