Advanced Topic in MEMS (06-88-552-01-2016W)

Non-contact type RF MEMS Switch for Radar applications

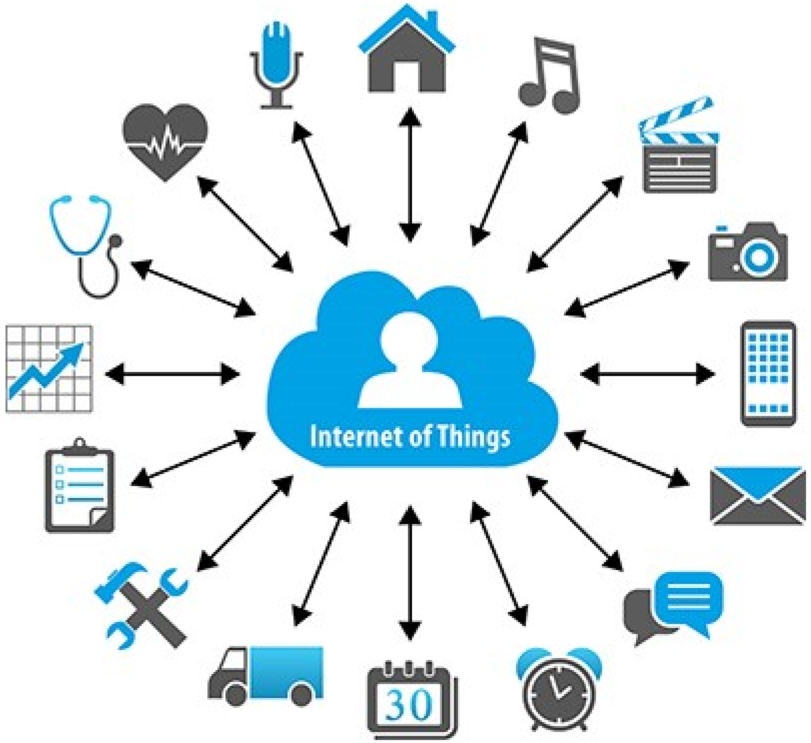
Instructor: Dr. Sazzadur Chowdhury

Presented by:

Parvathi Shenoy Kasargod -104213203

Introduction

- ✓ IoT is expected to reach trillions of dollars by 2020.
- ✓ Where size of the device plays an important role in many applications.
- ✓ Micro ElectroMechanical Systems (MEMS) is gaining tremendous popularity in IoT.
- ✓ Our project deals with the design of MEMS switches.

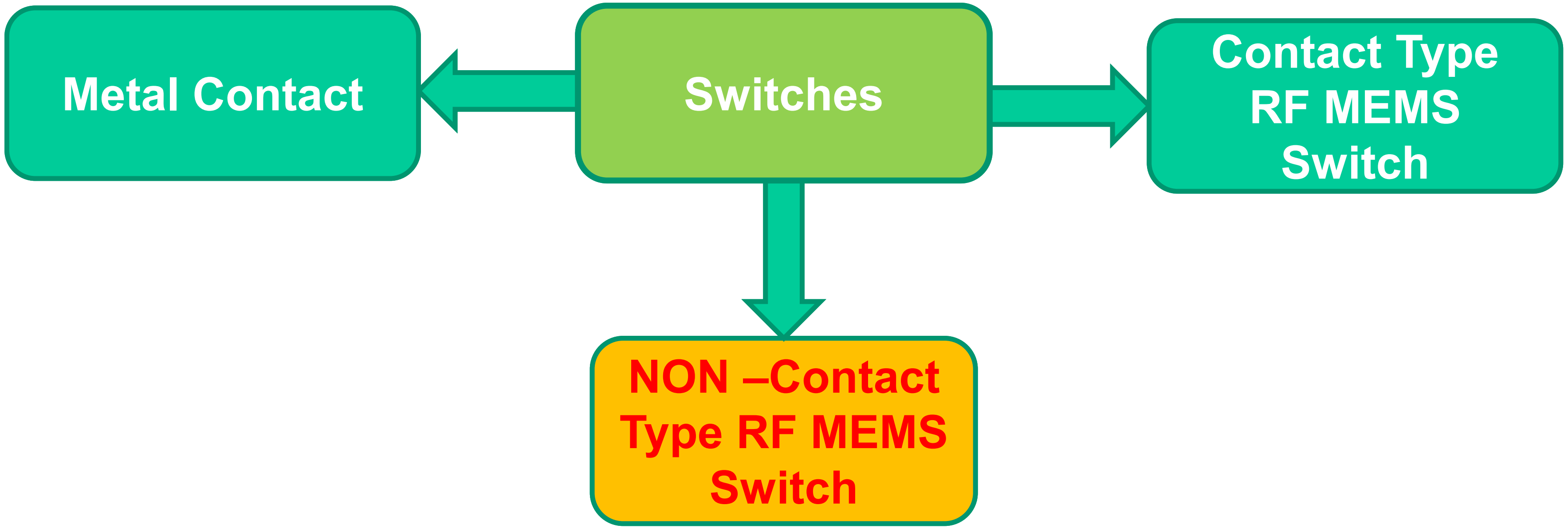


Comparison of Switches

Characteristic	**PIN diode (IN4001)**	**FET (BF862)**	**MEMS SWITCH**
Area	50mm	1.1mm	0.9mm
Resistance	1-5Ω	1-5Ω	0.5Ω
Insertion Loss (dB)	0.7	0.8	0.29
Isolation (dB)	15	20	30.1
Power Consumption	LOW	LOW	VERY LOW

Switches

- Micro welding
- Increase Contact Resistance



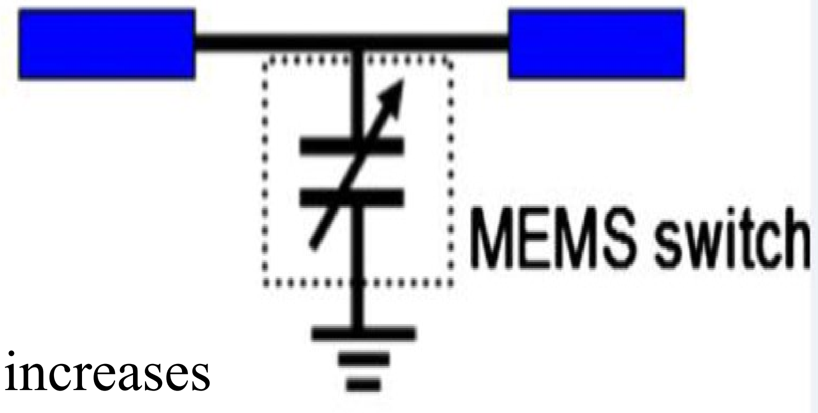
- Stiction
- Charge Injection
- Charge Trapping

Variable capacitor structures containing small air gap

Principle Of Operation

- **ON State**

  In ON state, when variable capacitors are not actuated, input signal passes from input port to output port



- **OFF State**

  In OFF state, When actuation voltage is applied capacitance increases providing a low impedance RF path to the ground. This prevents the signal to reach the output port.

OFF State

Actuation voltage applied to the comb drive

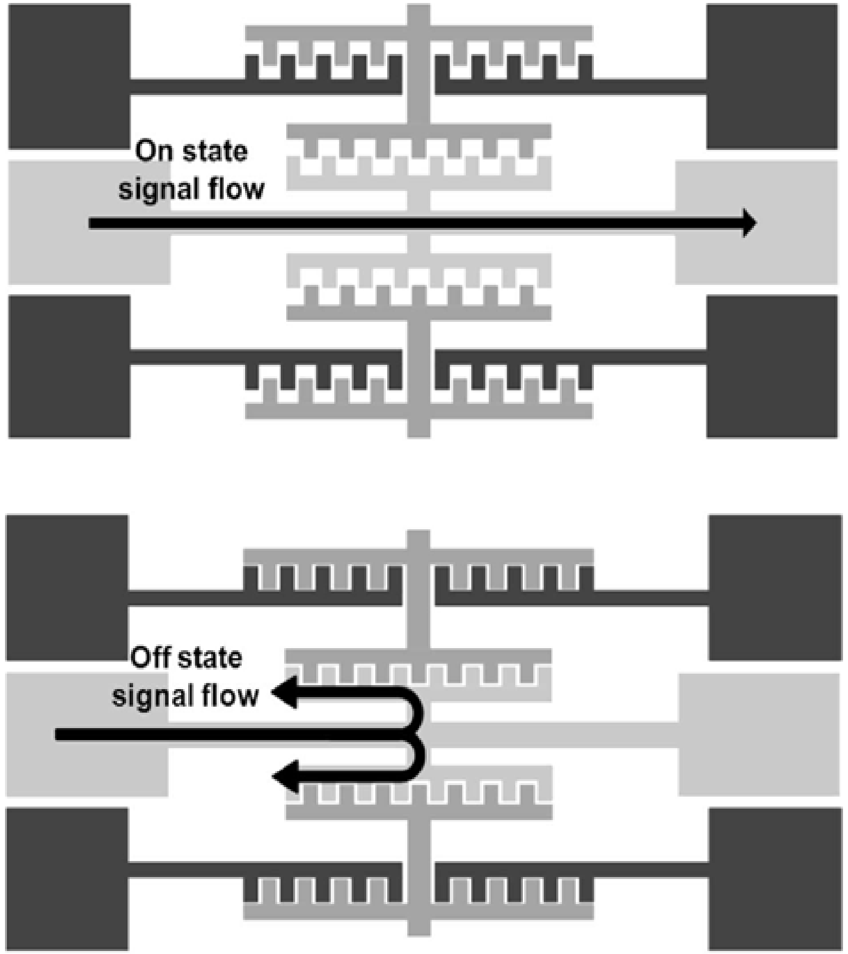
↓

Gap between the comb fingers reduced

↓

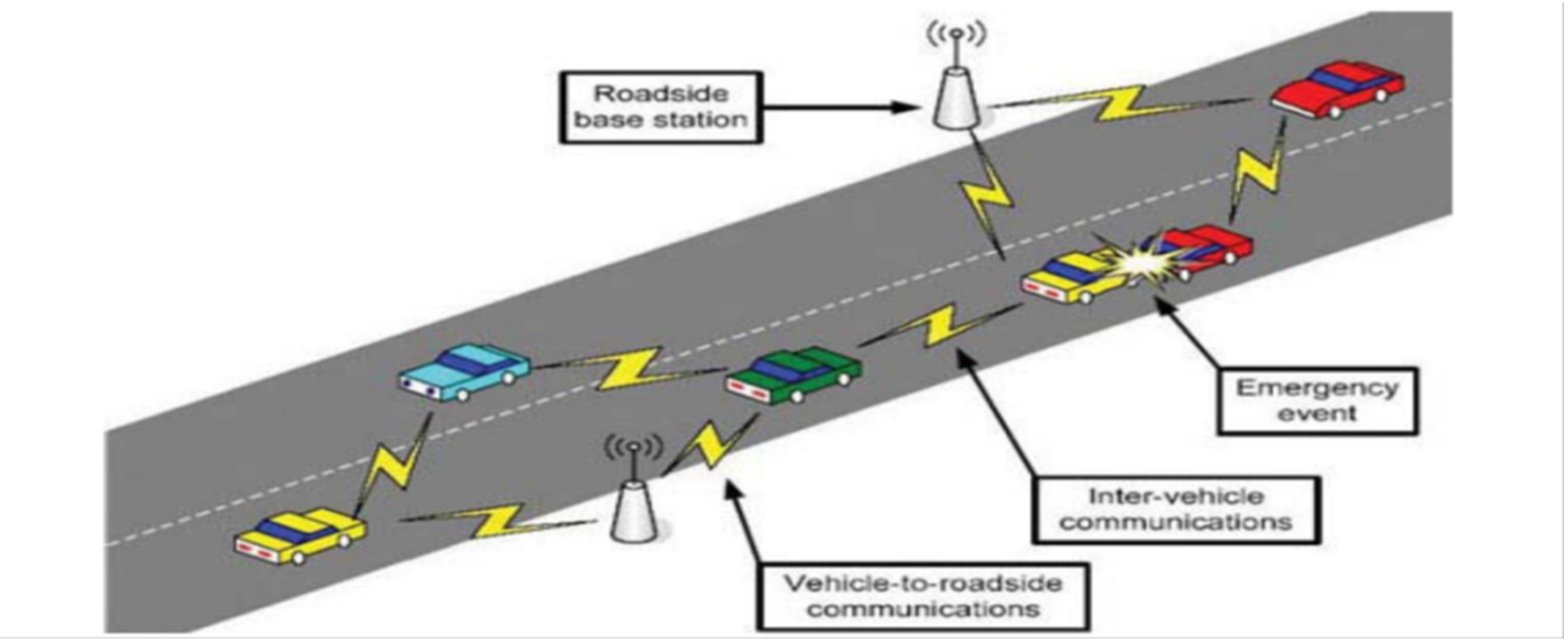
Capacitance increase

$$X_C \downarrow = \frac{1}{J\omega C \uparrow}$$



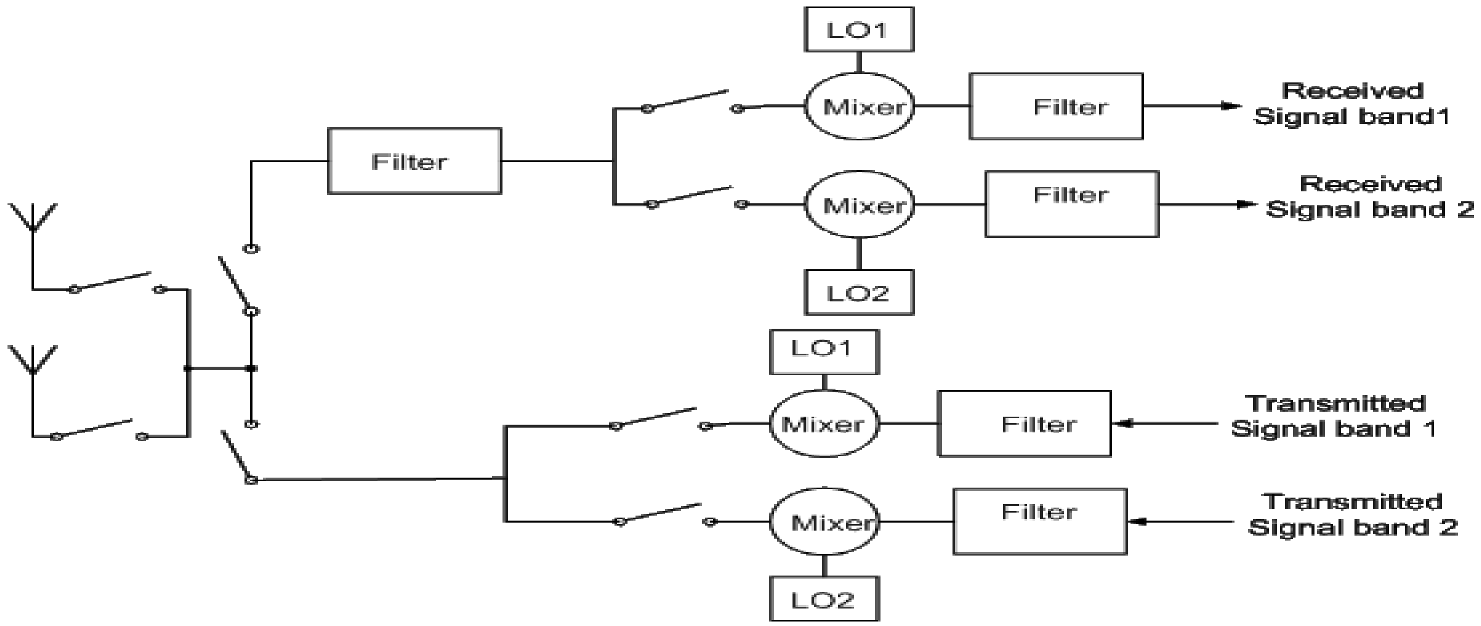
Target Application

- Our project application deal's with 24GHz frequency which has allocated a band name of super high frequency **(K band)**, which mainly finds application in Radars .
- Our switch design finds its application in intelligent transportation system.



Communication Between Road Side Base station and Vehicles

MEMS switches can be used in base station to increase reliability



Base Station Tx/Rx block diagram

Mathematical Modeling

ON State

- $Z_{in} = Z_{out}$ Impedance matching (Maximum signal transfer)

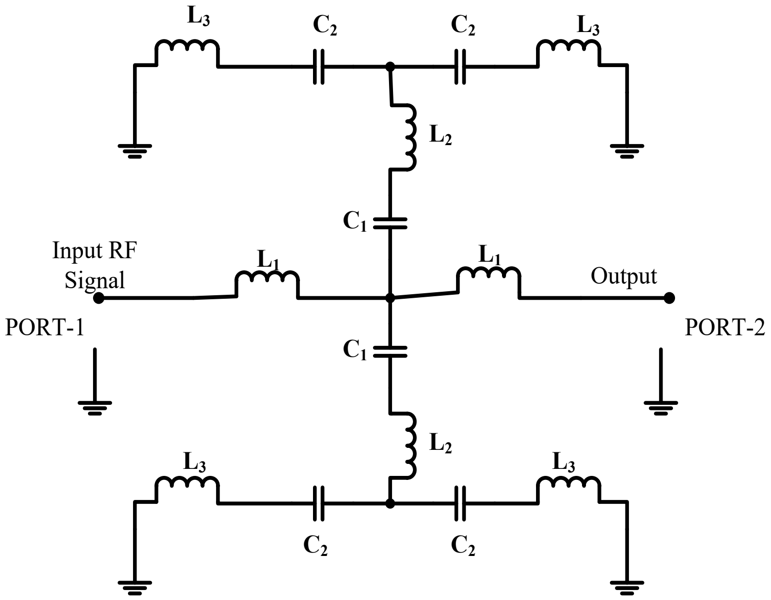
$$j\omega L_1 + \frac{(j\omega L_1 + Z_0)(J\omega L_{eq} + \frac{1}{j\omega C_{eq}})}{j\omega(L_1 + L_{eq}) + \frac{1}{j\omega C_{eq}} + 50} = 50 \qquad (1)$$

$$-2\omega^2 L_1 L_{eq} + \frac{2L_1}{C_{eq}} - \omega^2 L_1^{\,2} = 2500 \qquad (2)$$

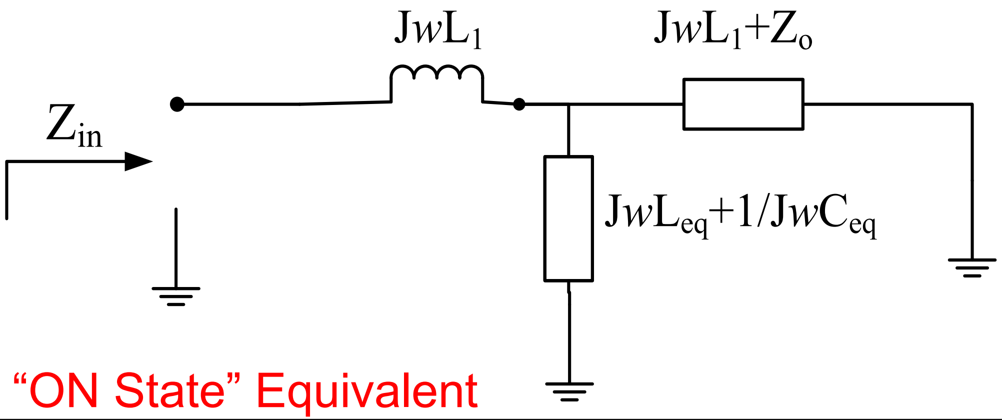
Where ,

$$L_{eq} = \frac{1}{2}L_2 + \frac{1}{4}L_3$$

$$C_{eq} = \frac{4C_1C_2}{C_1 + 2C_2}$$

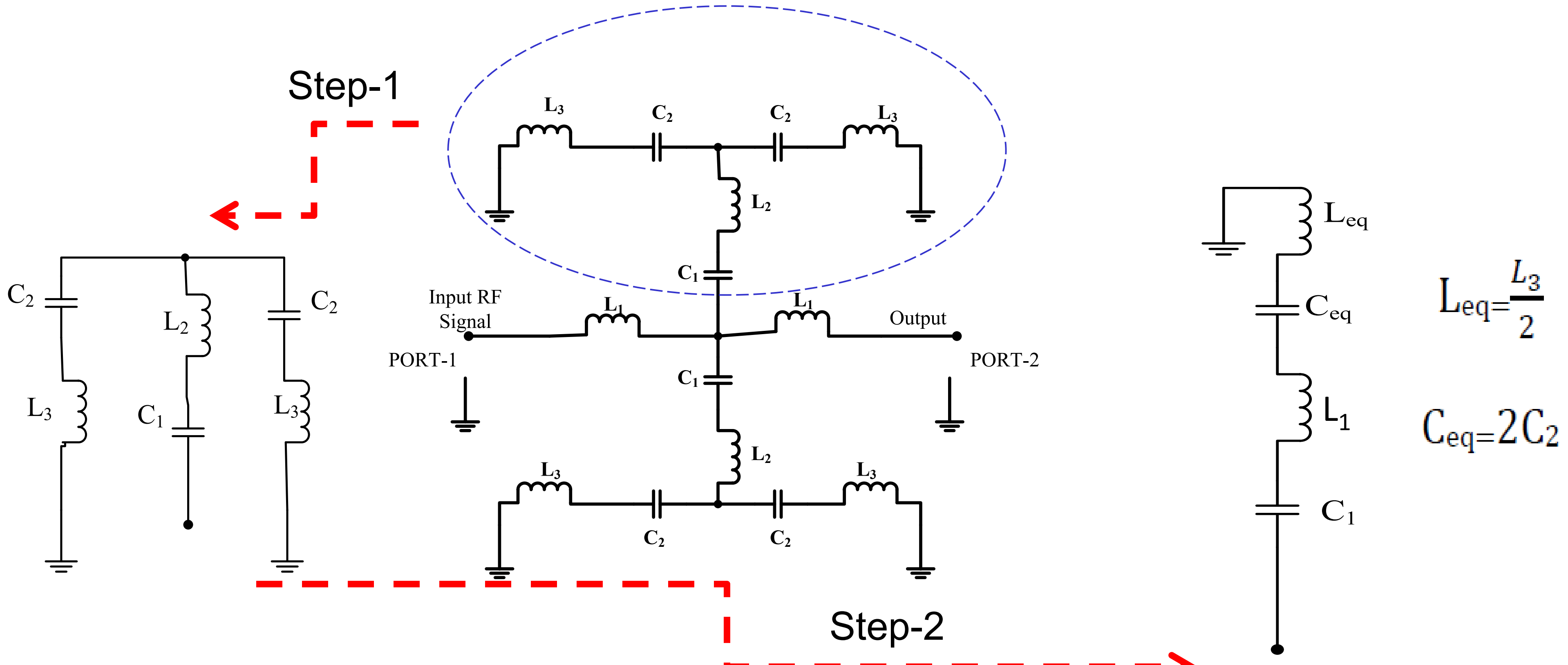


Lumped Circuit model



“ON State” Equivalent

OFF State



During OFF state, signal chooses to flow through low impedance path (two symmetrical parts) one of which is highlighted in the

$$j\omega(L_{eq}+L_2)+\frac{1}{j\omega(C_{eq}+C_1)}=0 \quad (3)$$

$$\frac{C_1+2C_2}{C_1C_2(L_3+2L_2)}=2.27395*10^{22} \quad (4)$$

Mathematical Modeling

ON State

$$-2\omega^2 L_1 L_{eq} + \frac{2L_1}{C_{eq}} - \omega^2 L_1^{\ 2} = 2500 \qquad (5)$$

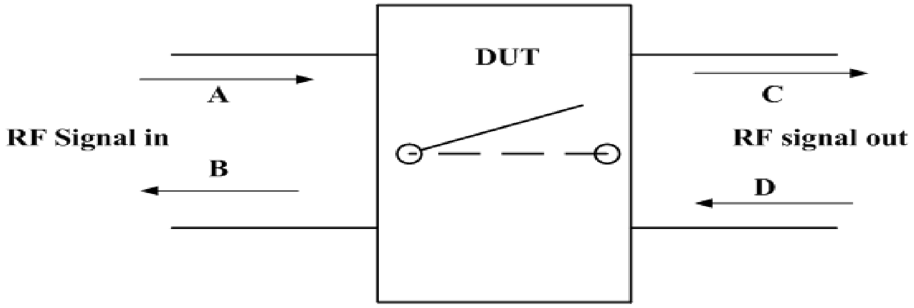
OFF state

$$\frac{C_1 + 2C_2}{C_1 C_2 (L_3 + 2L_2)} = 2.27395 * 10^{22} \qquad (6)$$

Parameter	ON State	OFF State
L1	0.19nH	0.19nH
L2	0.22nH	0.19nH
L3	0.19nH	0.19nH
C1	43.1fF	366fF
C2	130fF	158fF

S –Parameters

Insertion Loss: When the switch is in ON state . It is expected that the entire signal flows from port 1 to port 2. But in reality a part of the signal is lost . This loss is termed as insertion loss.



$$\text{Transmission Coefficient} = \frac{C}{A} = S_{21}$$

$$S_{21} \text{ in decibels} = 20log(S_{21})$$

$$\text{Insertion loss} = -20log(S_{21})$$

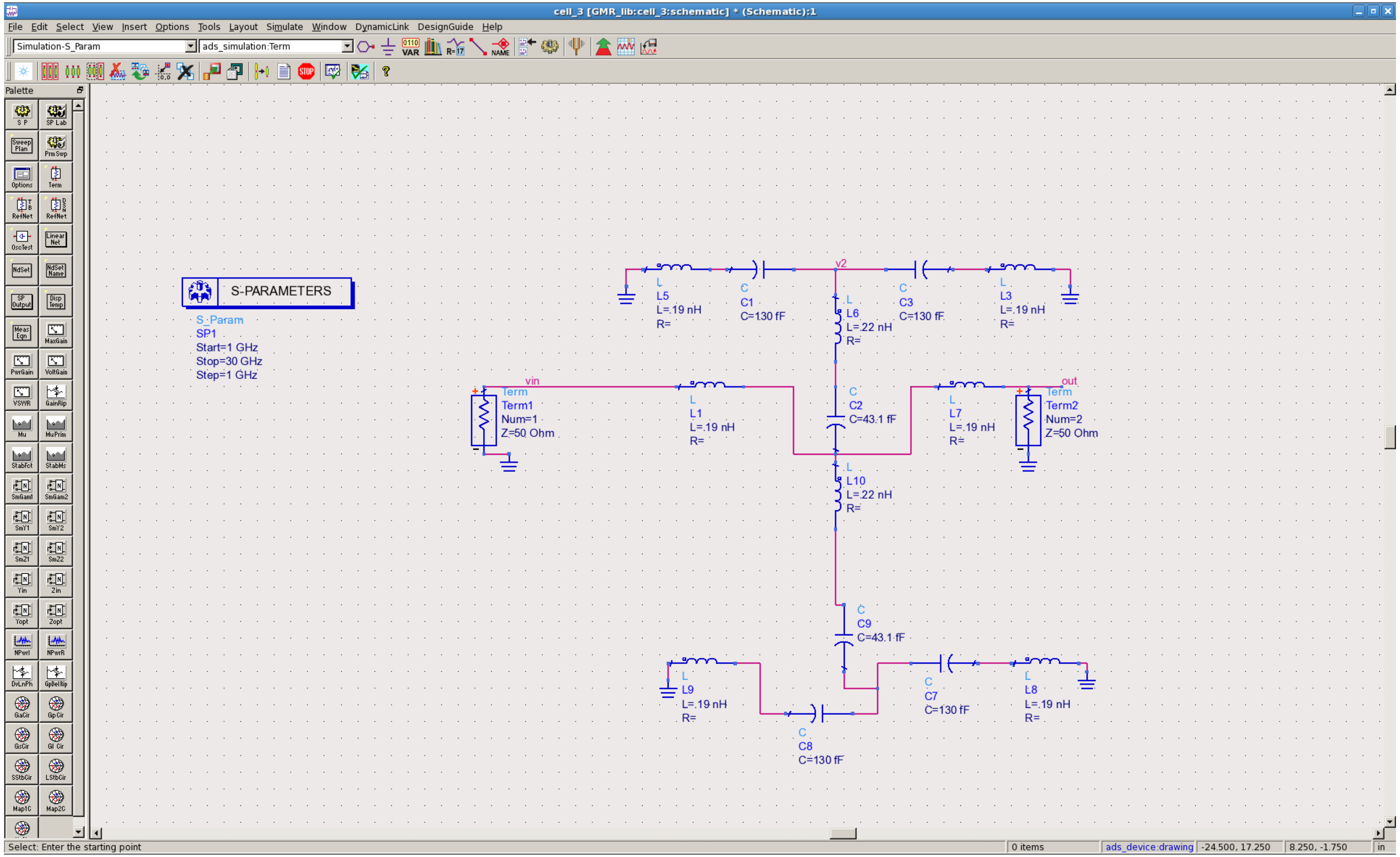
Isolation Loss: When the switch is in OFF state. It is expected that no signal flows from port 1 to port 2. But in reality a part of the signal is transmitted. This loss is termed as isolation loss.

$$\text{Transmission Coefficient} = \frac{C}{A} = S_{21}$$

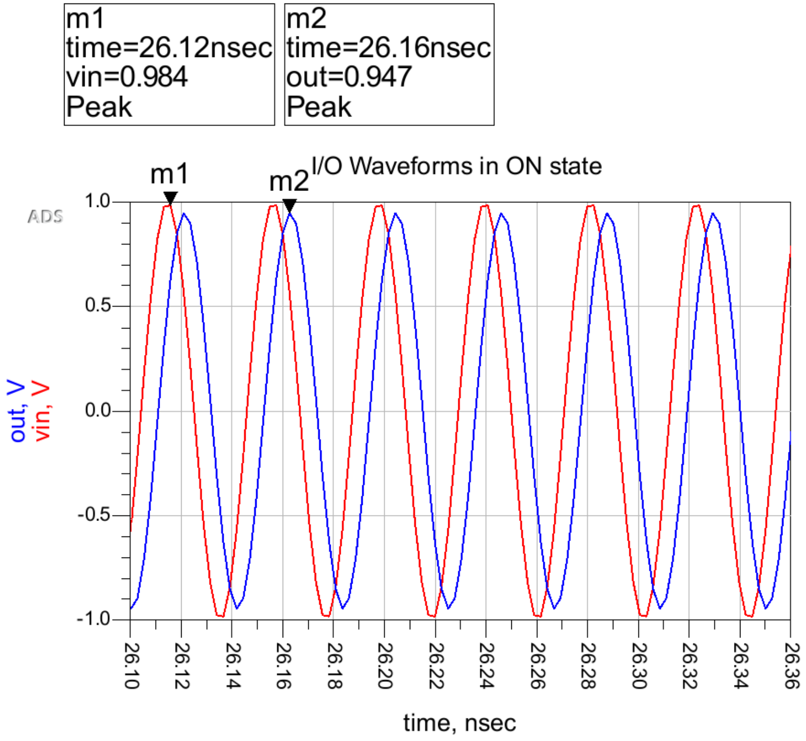
$$S_{21} \text{ in decibels} = 20log(S_{21})$$

$$\text{Isolation loss} = -20log(S_{21})$$

ON STATE

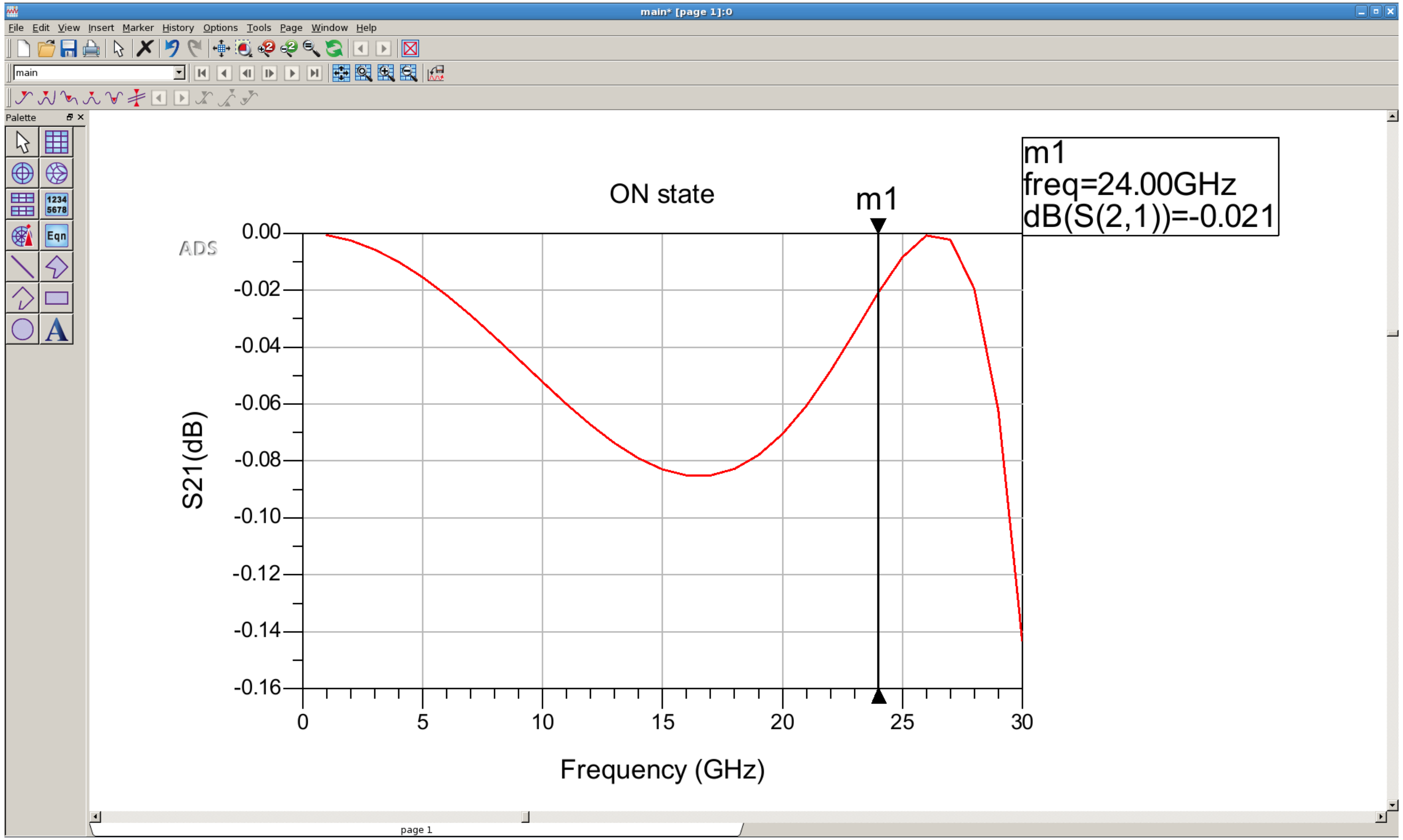

cell_3 [GMR_lib:cell_3:schematic] * (Schematic):1
S-PARAMETERS
S_Param
SP1
Start=1 GHz
Stop=30 GHz
Step=1 GHz
v2
L5
L=.19 nH
C1
C=130 fF
L6
L=.22 nH
C3
C=130 fF
L3
L=.19 nH
vin
Term1
Num=1
Z=50 Ohm
L1
L=.19 nH
C2
C=43.1 fF
L7
L=.19 nH
out
Term2
Num=2
Z=50 Ohm
L10
L=.22 nH
C9
C=43.1 fF
L9
L=.19 nH
C8
C=130 fF
C7
C=130 fF
L8
L=.19 nH
Select: Enter the starting point

ON State

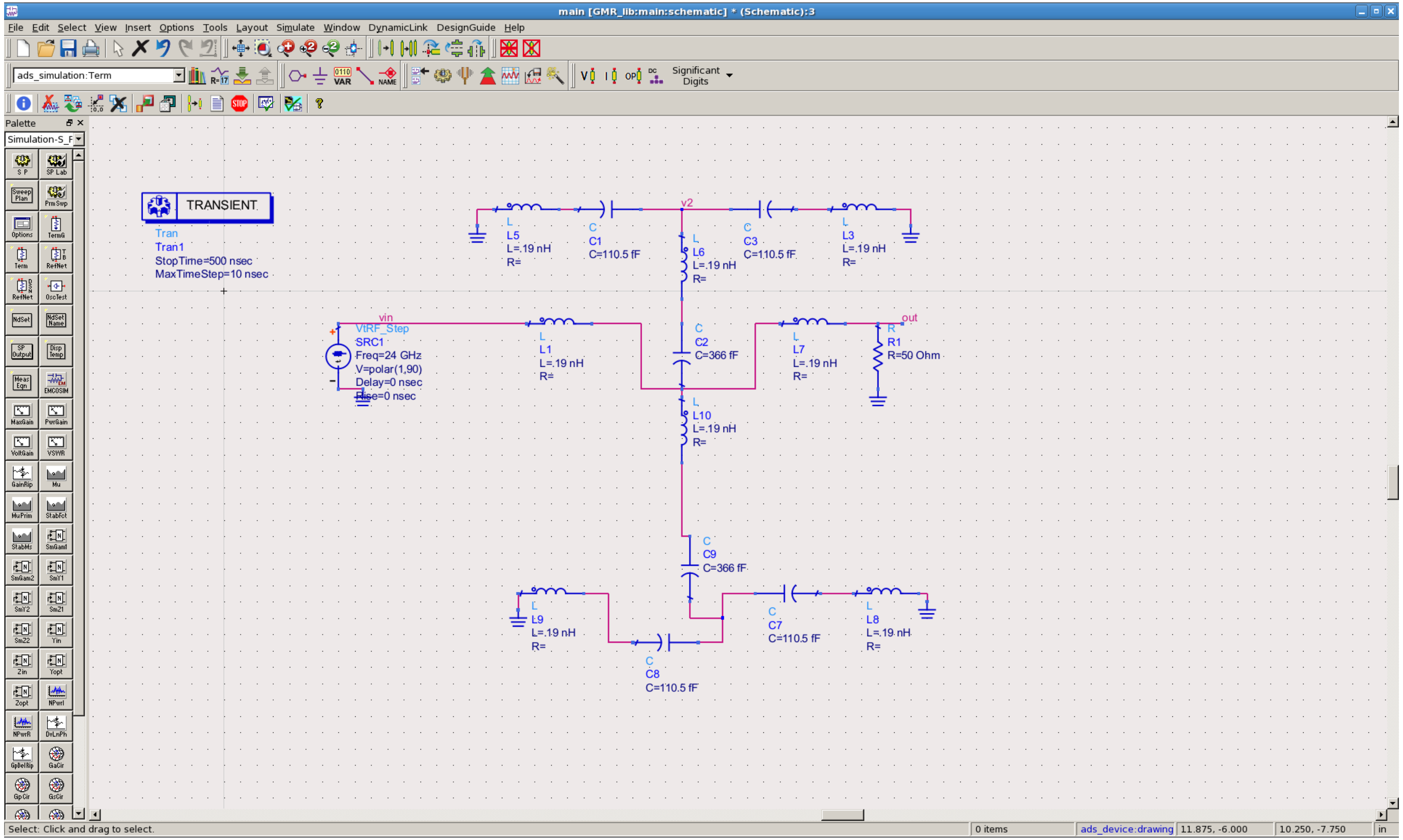


96.23% of the input signal is allowed to reach the output port in the "ON" state of operation of the switch

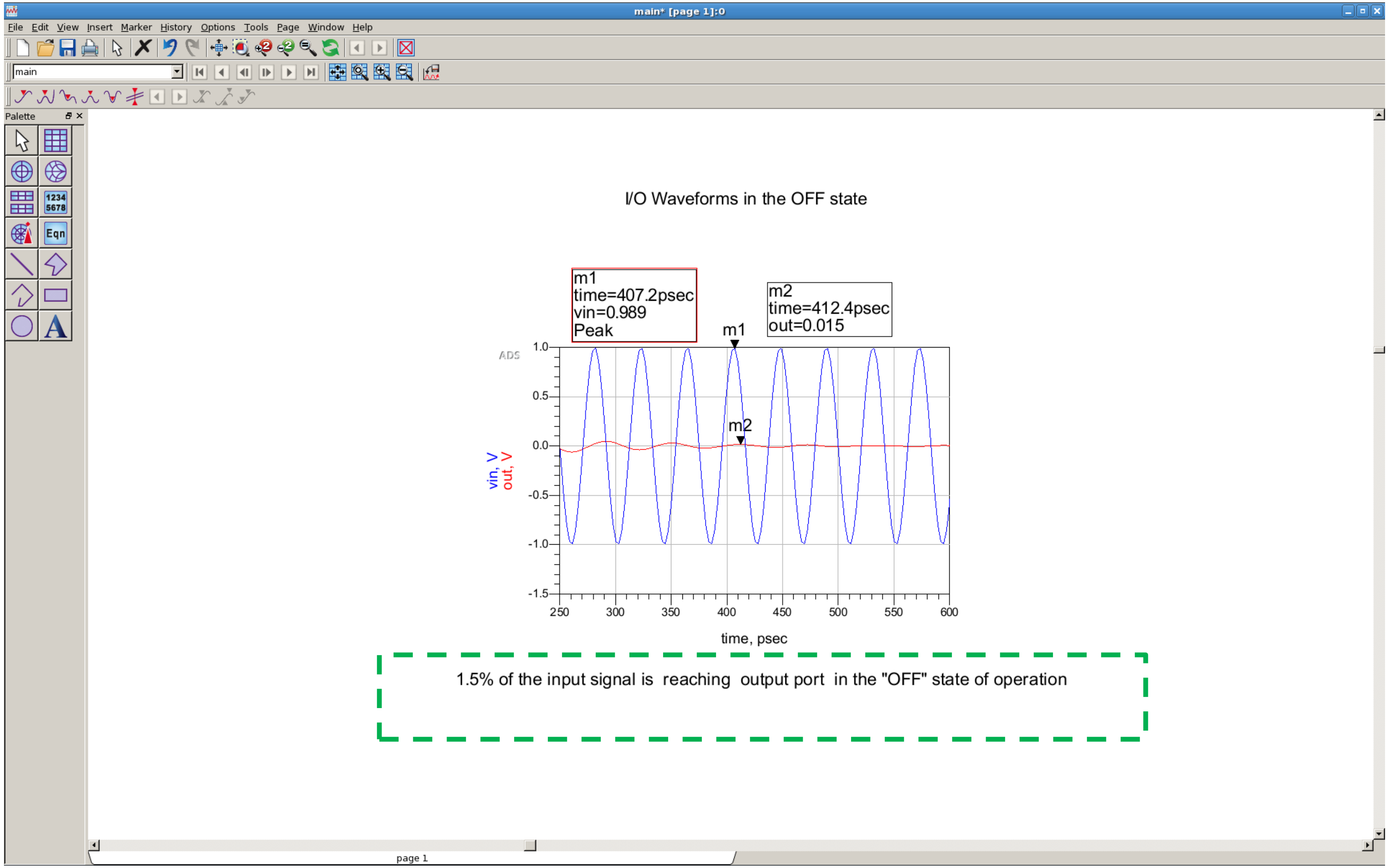
ON STATE


main* [page 1]:0
File Edit View Insert Marker History Options Tools Page Window Help
Palette
ON state
m1
m1
freq=24.00GHz
dB(S(2,1))=-0.021
ADS
S21(dB)
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
0
5
10
15
20
25
30
Frequency (GHz)
page 1

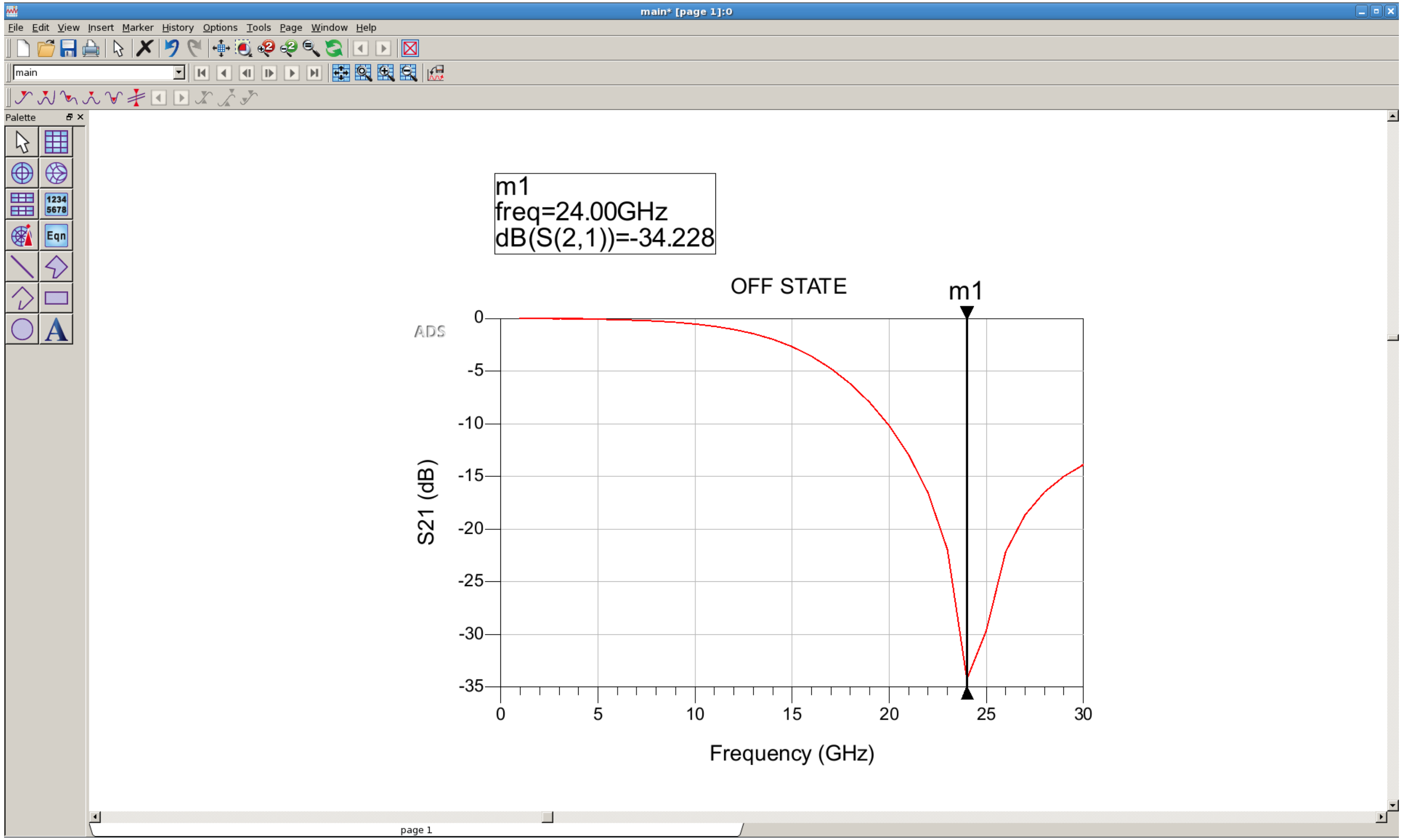
OFF State


main [GMR_lib:main:schematic] * (Schematic):3
TRANSIENT
Tran
Tran1
StopTime=500 nsec
MaxTimeStep=10 nsec
vin
VtRF_Step
SRC1
Freq=24 GHz
V=polar(1,90)
Delay=0 nsec
Rise=0 nsec
v2
L5 L=.19 nH R=
C1 C=110.5 fF
L6 L=.19 nH R=
C3 C=110.5 fF
L3 L=.19 nH R=
L1 L=.19 nH R=
C2 C=366 fF
L7 L=.19 nH R=
out
R1 R=50 Ohm
L10 L=.19 nH R=
C9 C=366 fF
L9 L=.19 nH R=
C8 C=110.5 fF
C7 C=110.5 fF
L8 L=.19 nH R=
Select: Click and drag to select.
0 items
ads_device:drawing
11.875, -6.000
10.250, -7.750

OFF State


main* [page 1]:0
I/O Waveforms in the OFF state
m1
time=407.2psec
vin=0.989
Peak
m2
time=412.4psec
out=0.015
vin, V
out, V
time, psec
1.5% of the input signal is reaching output port in the "OFF" state of operation

OFF State


main* [page 1]:0
File Edit View Insert Marker History Options Tools Page Window Help
main
Palette
m1
freq=24.00GHz
dB(S(2,1))=-34.228
OFF STATE
m1
ADS
S21 (dB)
0
-5
-10
-15
-20
-25
-30
-35
0
5
10
15
20
25
30
Frequency (GHz)
page 1

Target design specifications

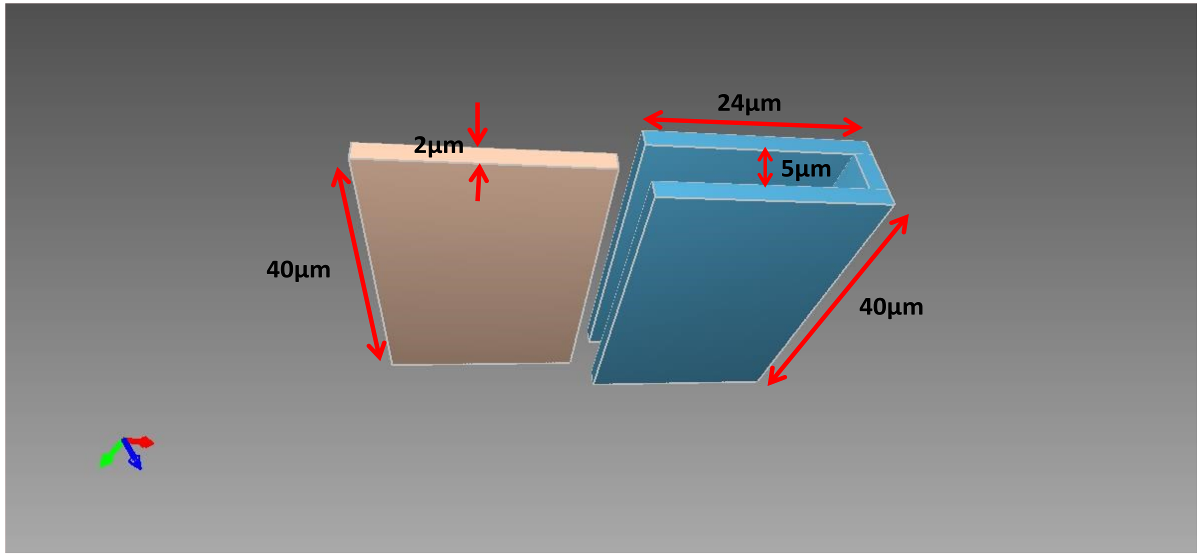
Switch size		1.1mm × 0.9 mm	
CPW line width		40μm	
CPW line length		780 μm	
Characteristic impedance		50 μm	
Comb finger length		C1	24 μm
		C2	37 μm
Comb finger Width		C1	2 μm
		C2	2 μm
Comb finger thickness		40 μm	
Air gap between comb fingers		C1	1.5 μm
		C2	3 μm
Air gap between substrate and Switch		30 μm	
Frequency		24GHz	
Anchor Size		30 μm	
Substrate height		50 μm	
Folded Flexure beam	L	357μm	
	W	5 μm	
	t	40 μm	

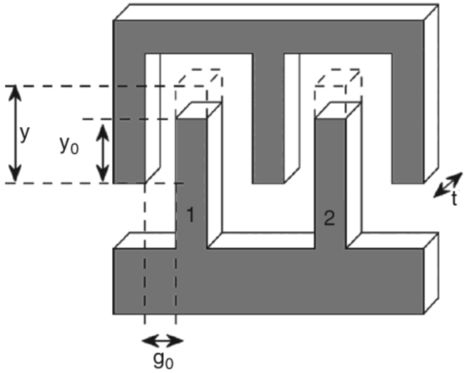
Comb drive actuator design (C1)

- Capacitance between two metal plates with one stator and one rotor is given as:

$$C = \frac{2n\varepsilon t(y + y_0)}{g}$$

- So for Capacitor C1 having overlap gap (y) of 7µm and gap (g) between fingers is 1.5µm and thickness (t) is 40µm with 110 comb fingers in rotor side, the capacitance obtained was 366fF (OFF state).





$$C1 = 366fF$$
$$220C1 = 366fF$$
$$C1 = 1.66fF\ for\ each\ finger\ (OFF\ state)$$

$$C1 = 43.1fF$$
$$220C1 = 43.1fF$$
$$C1 = 0.1959fF\ for\ each\ finger\ (On\ state)$$

Comb drive actuator design (C2)

- Capacitance between two metal plates with one stator and one rotor is given as:

$$C = \frac{2n\varepsilon t(y + y_0)}{g}$$

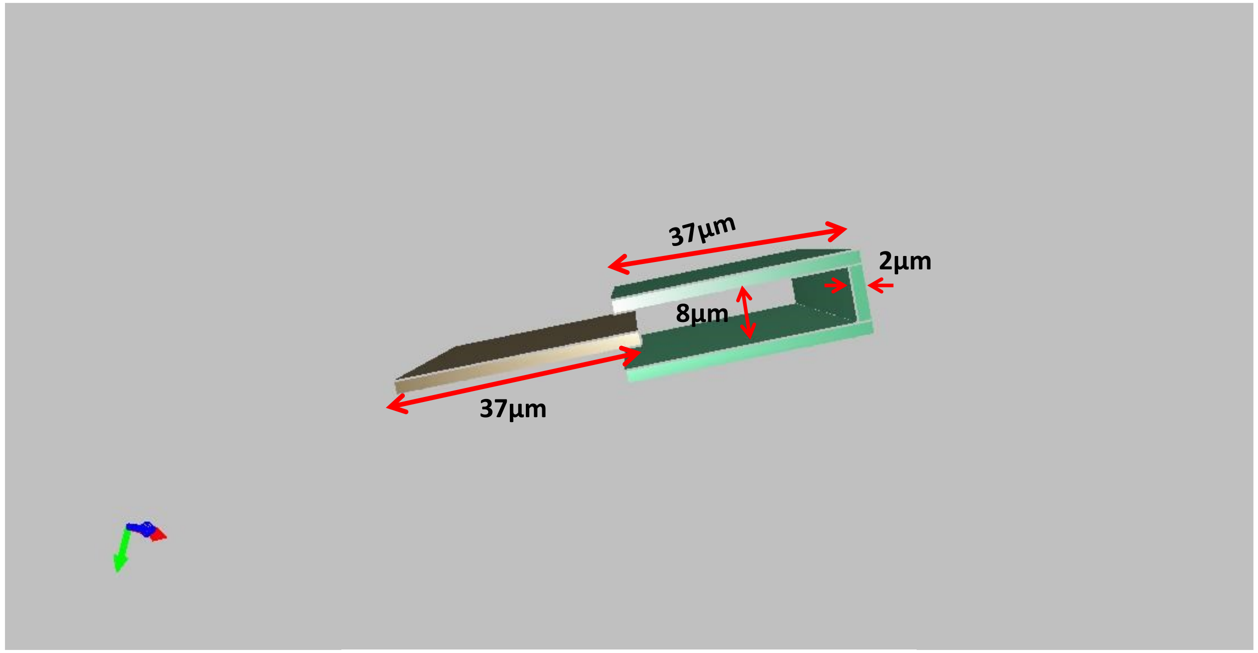
$$71C2 = 130fF$$

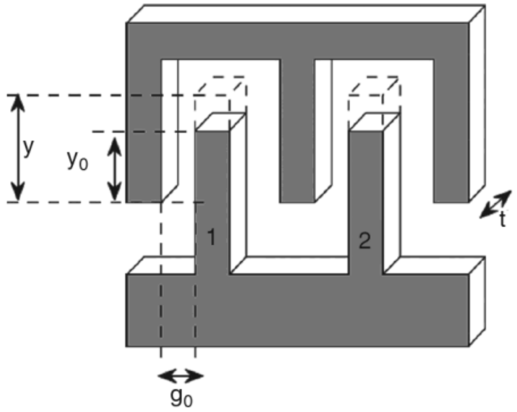
$$C2 = 1.83fF\ (ON\ state)$$

- While in OFF state, rotor comb drive makes displacement of 10µm. Which produced capacitance of C2=158fF

$$71C2 = 158fF$$

$$C2 = 2.22fF(OFF\ state)$$

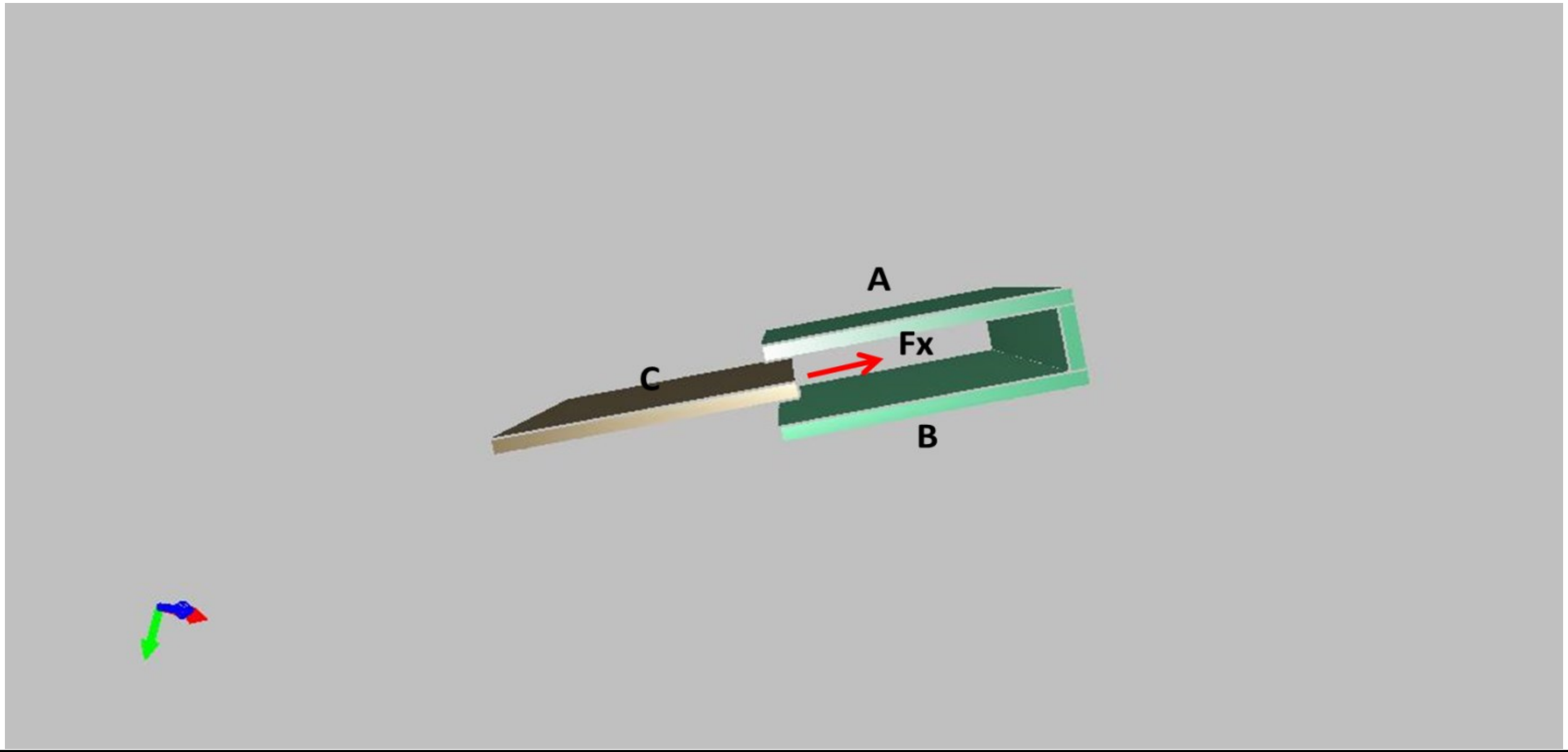




Lateral electrostatic force

$$F_{el} = \frac{1}{2}\frac{\partial CV^2}{\partial y} = \frac{n \in_o tV^2}{g}$$

- To increase the electrostatic force, we can increase actuation voltage (V) or reduce the gap between fingers or increase the number of comb fingers.



Displacement calculation of comb drive

- Under equilibrium condition,

$$F_{el} = F_k = K(y - y_0)$$

- So we can calculate the displacement of comb drive as,

$$(y - y_0) = \frac{F_{el}}{K}$$

$$y = y_0 + \frac{n\in_0 tV^2}{Kg}, \quad \text{where } K = 2Et(\frac{W}{L})^3$$

- After implementing dimensions of comb drive and folded flexure beam, we got the displacement y=10µm.
- These gives us the capacitance of C1=366fF and C2=158fF that is enough to divert the RF signal produce low impedance path.

Target values obtained

Parameter	ON State	OFF State
C1	43.1fF	366fF
C2	130fF	158.5fF

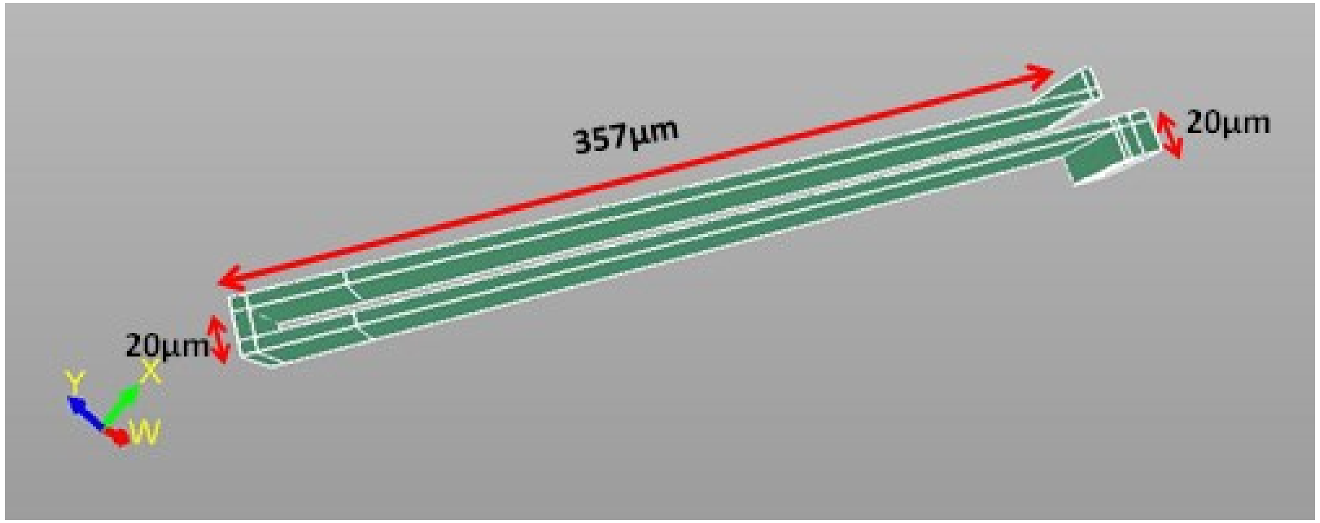
Spring designing parameters

- Stiffness of the spring was measured from the given equation:

$$K = 2Et(\frac{W}{L})^3$$

- To make the spring stiffer, width (W), Young's modulus and thickness of spring should be increased, but stiffer spring will higher restoring force resulting in less displacement.
- We determined a suitable values of all parameter to attain our desired displacement of 10μm, which gives $K = 37.02\ \frac{N}{m}$.

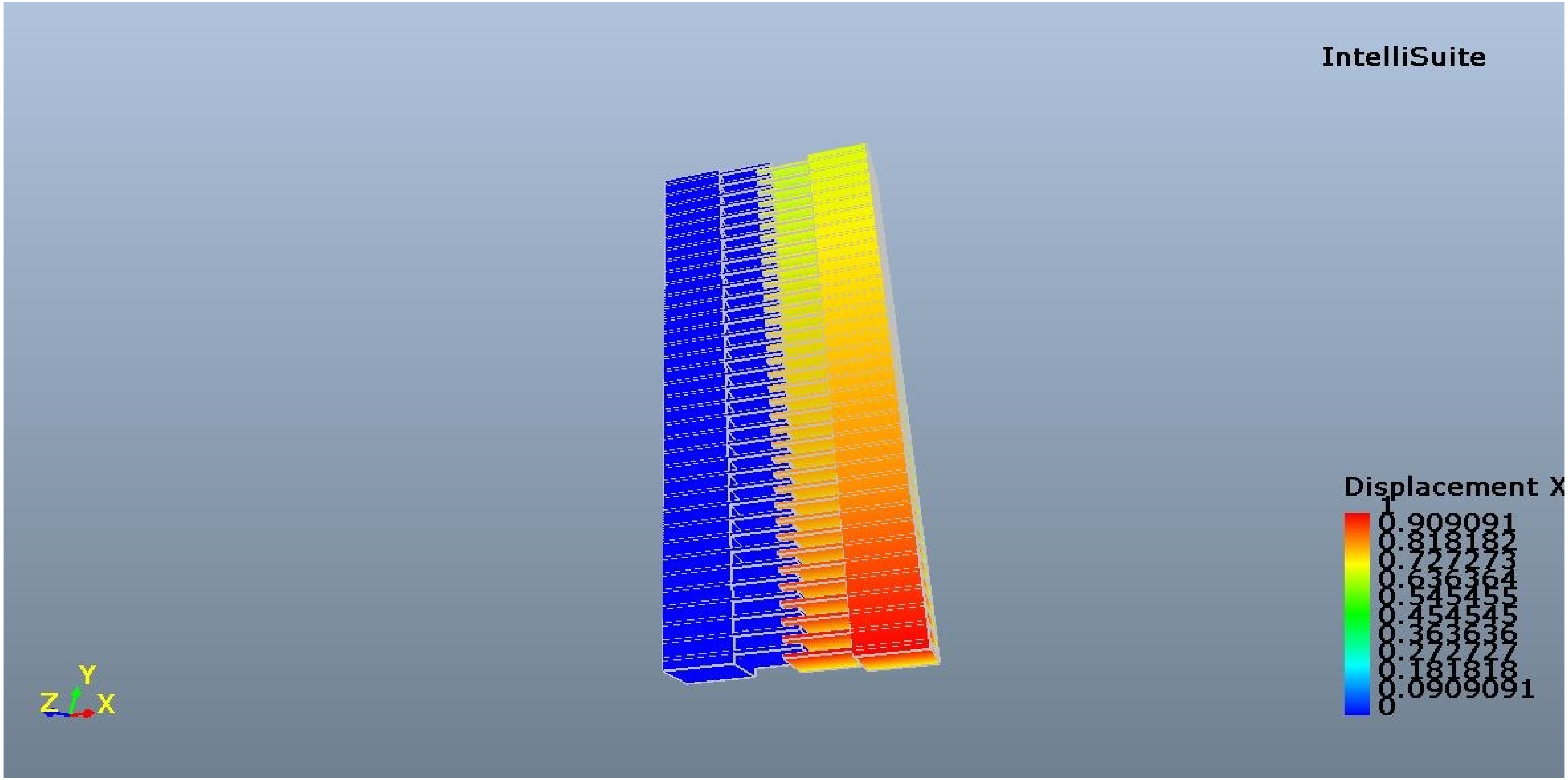
Folded Flexure beam	**L**	**357μm**
	W	5 μm
	t	40 μm



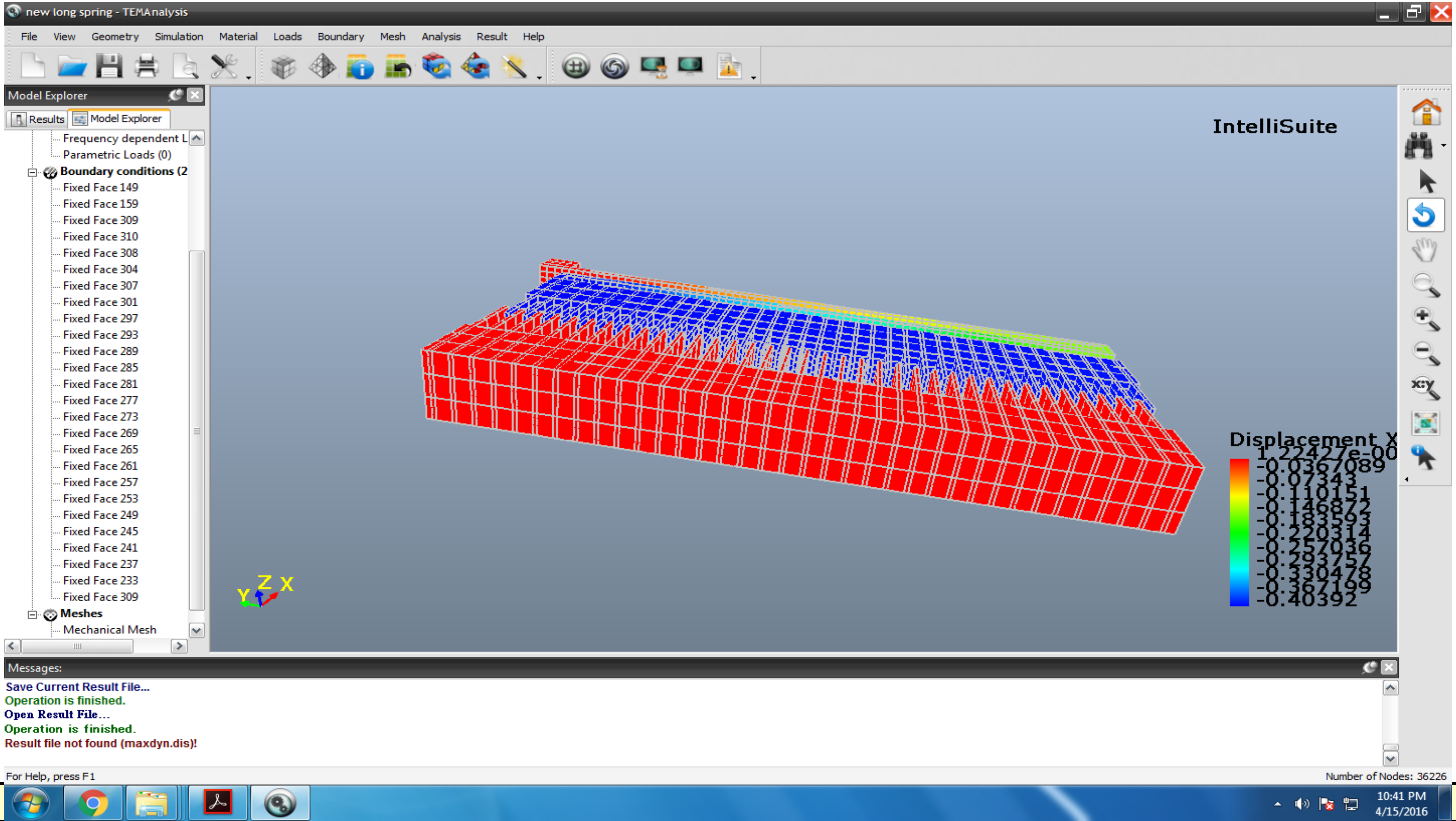
Comparison of different types of springs

Parameters	Fixed –Fixed	Crab leg	Folded flexure beam
Voltage(V)	130	130	130
Displacement (µm)	0.92	1.156	2.85
Force (N)	0.0050	0.0052	0.0056
Capacitance (pF)	326	328	352

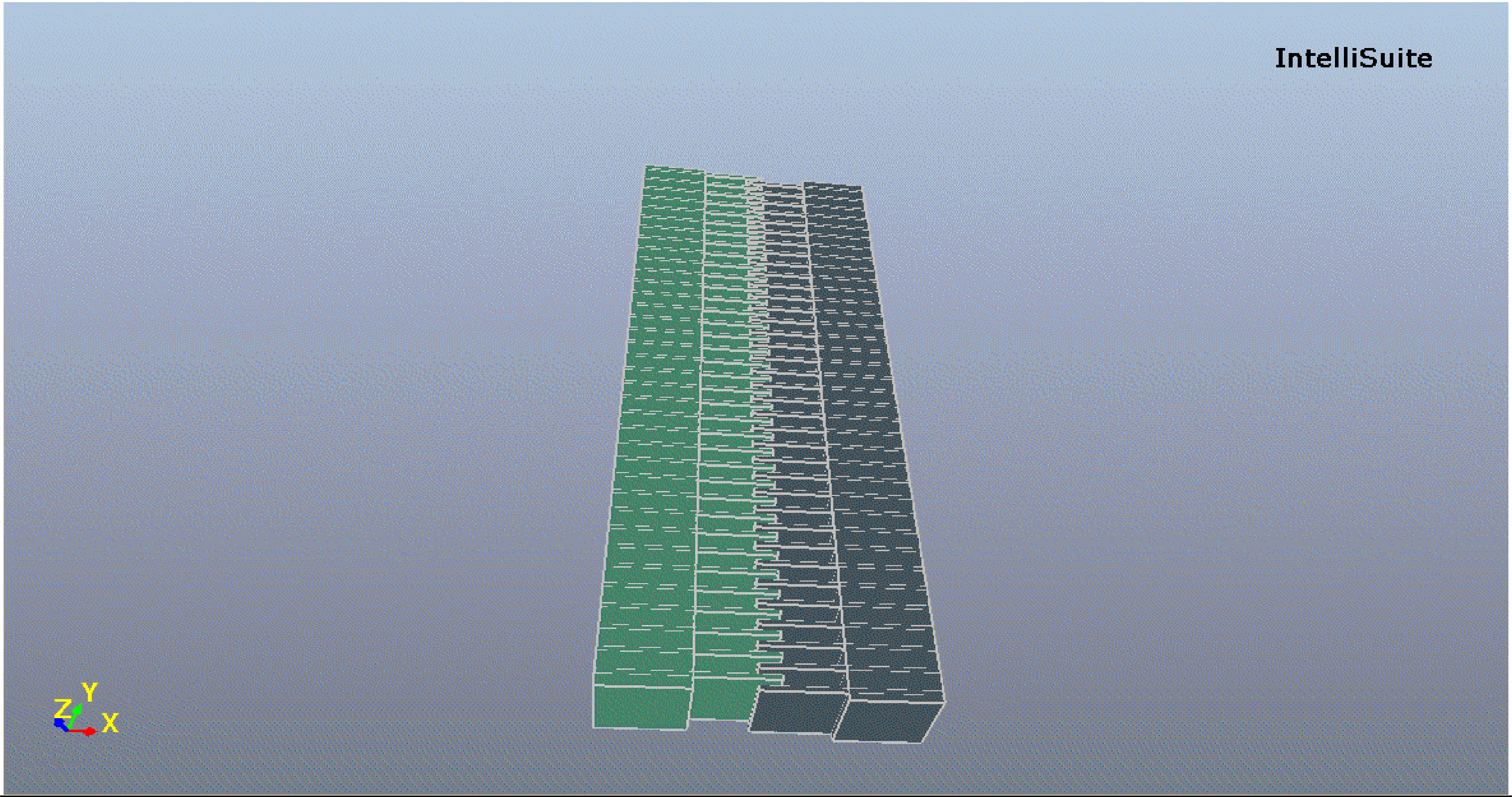
TEM analysis of comb drive without spring



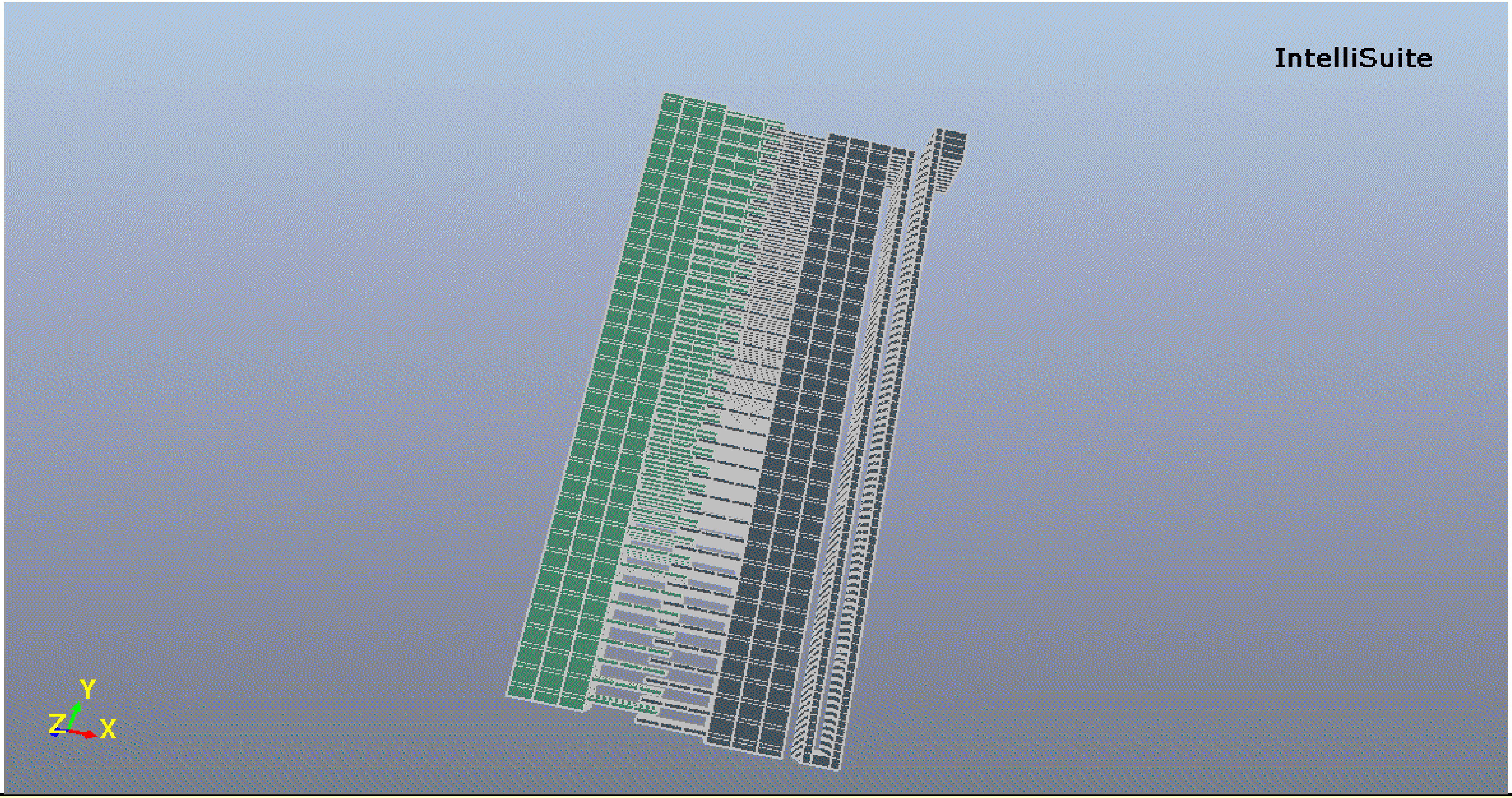
TEM analysis of comb drive with spring



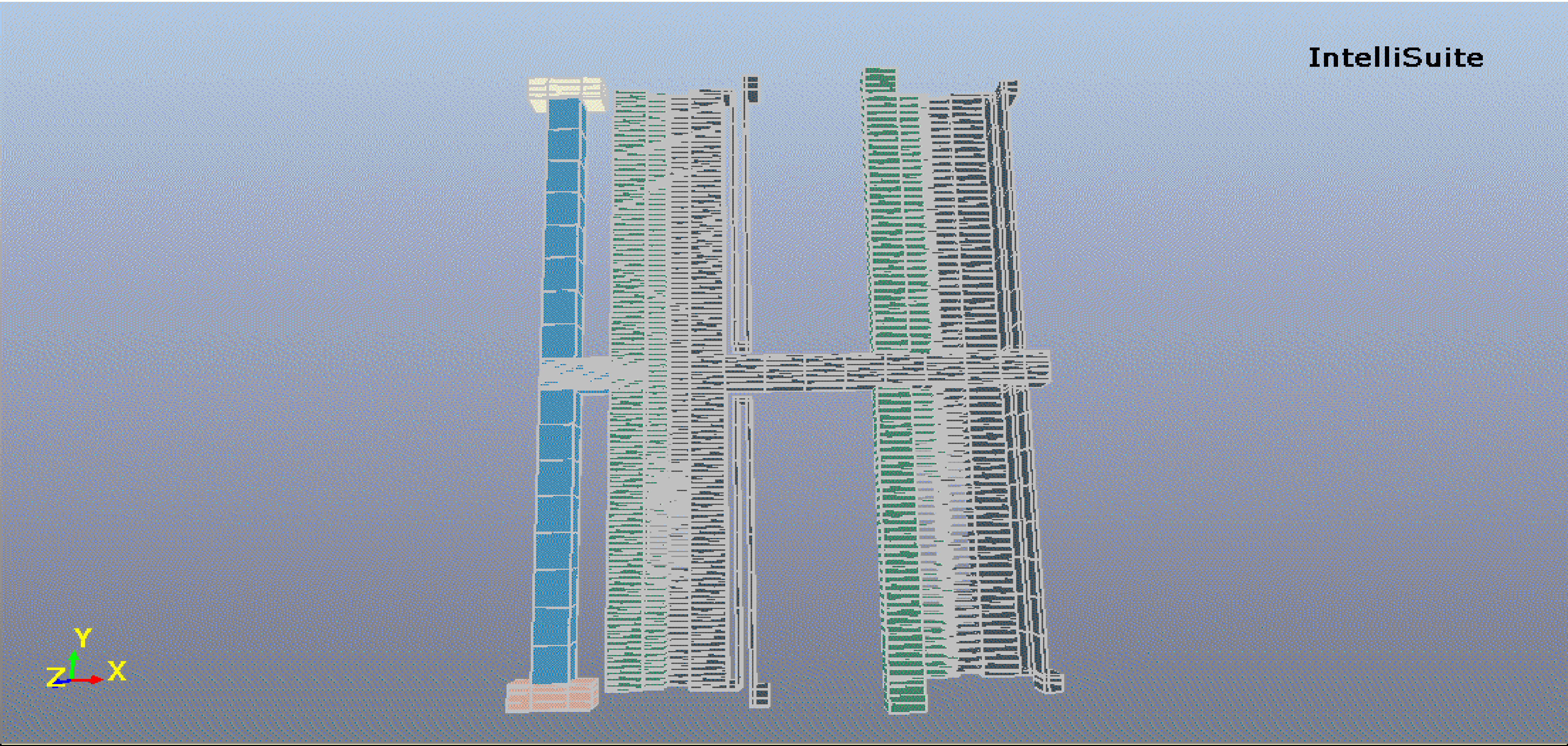
Animation of Comb drive without spring



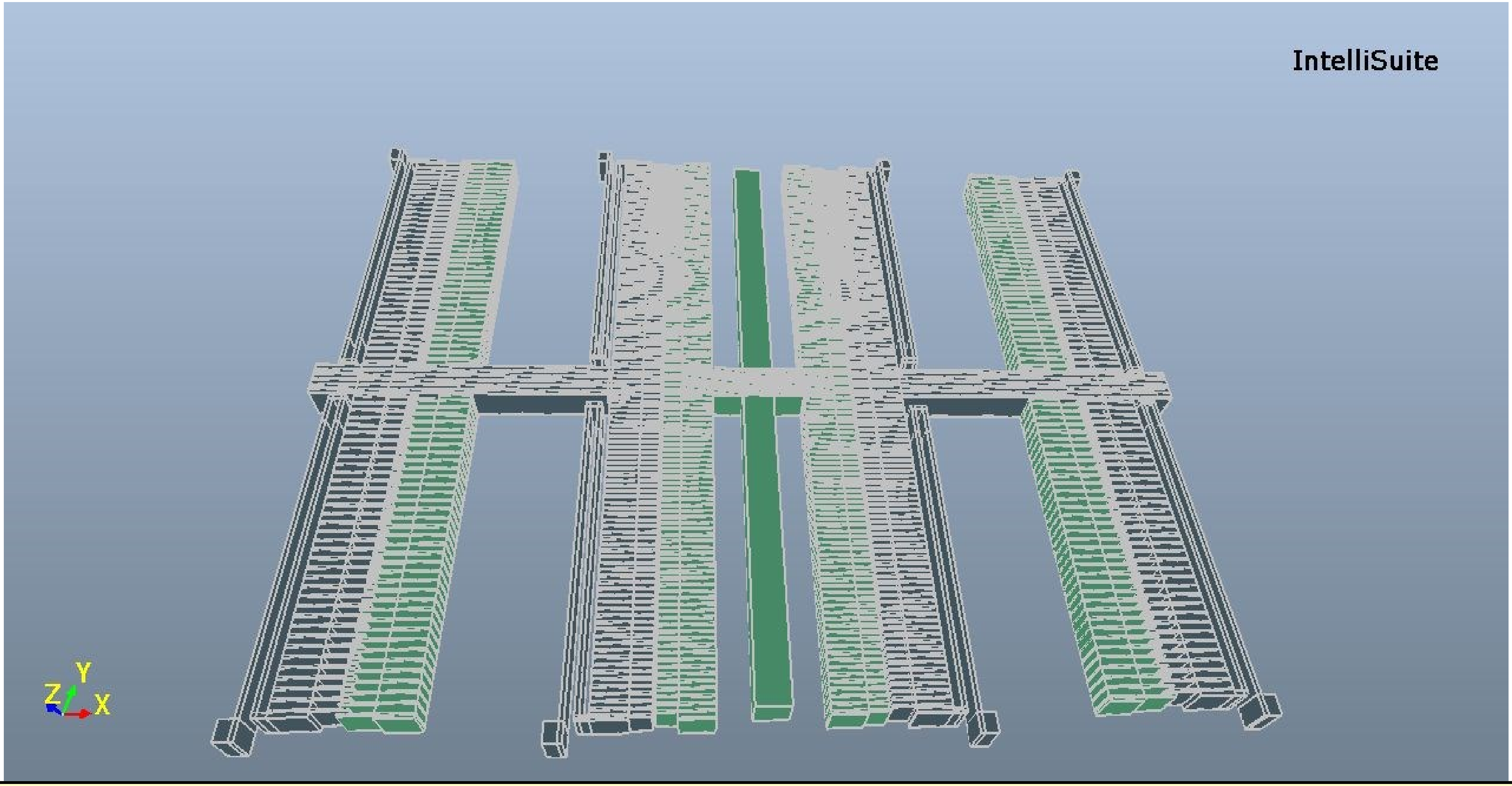
Animation of Comb drive using spring



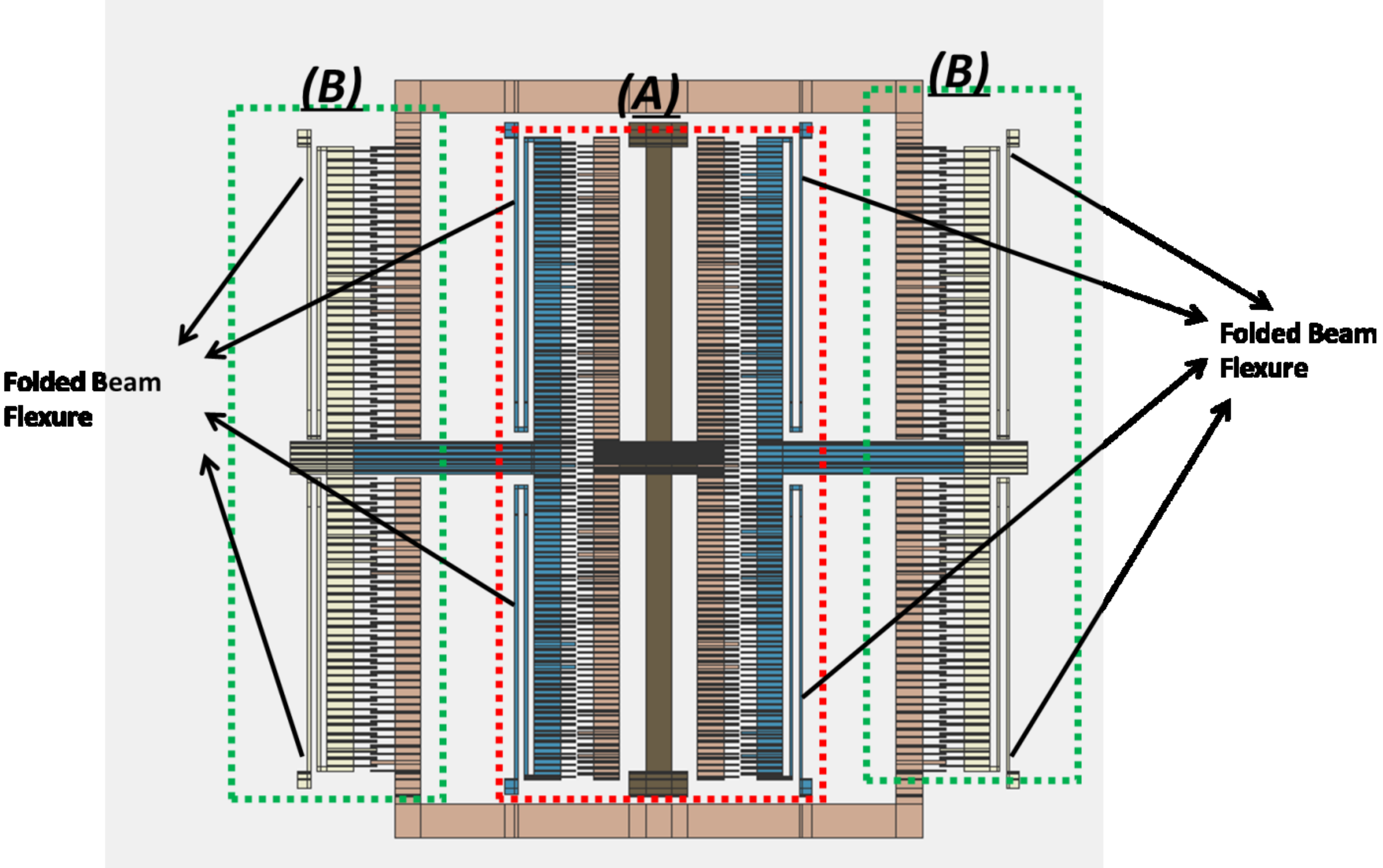
Animation of comb drive actuator



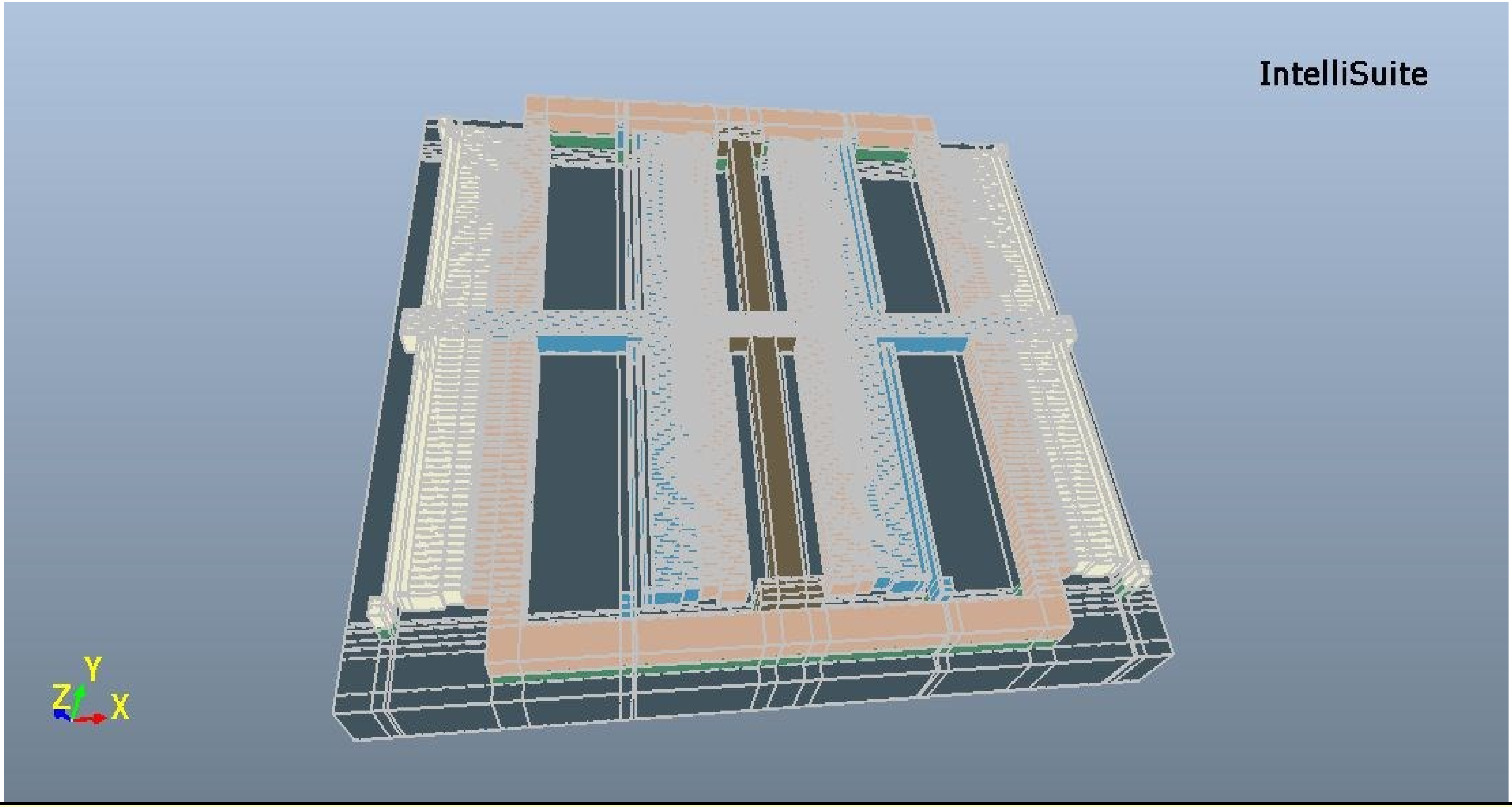
Complete comb drive structure



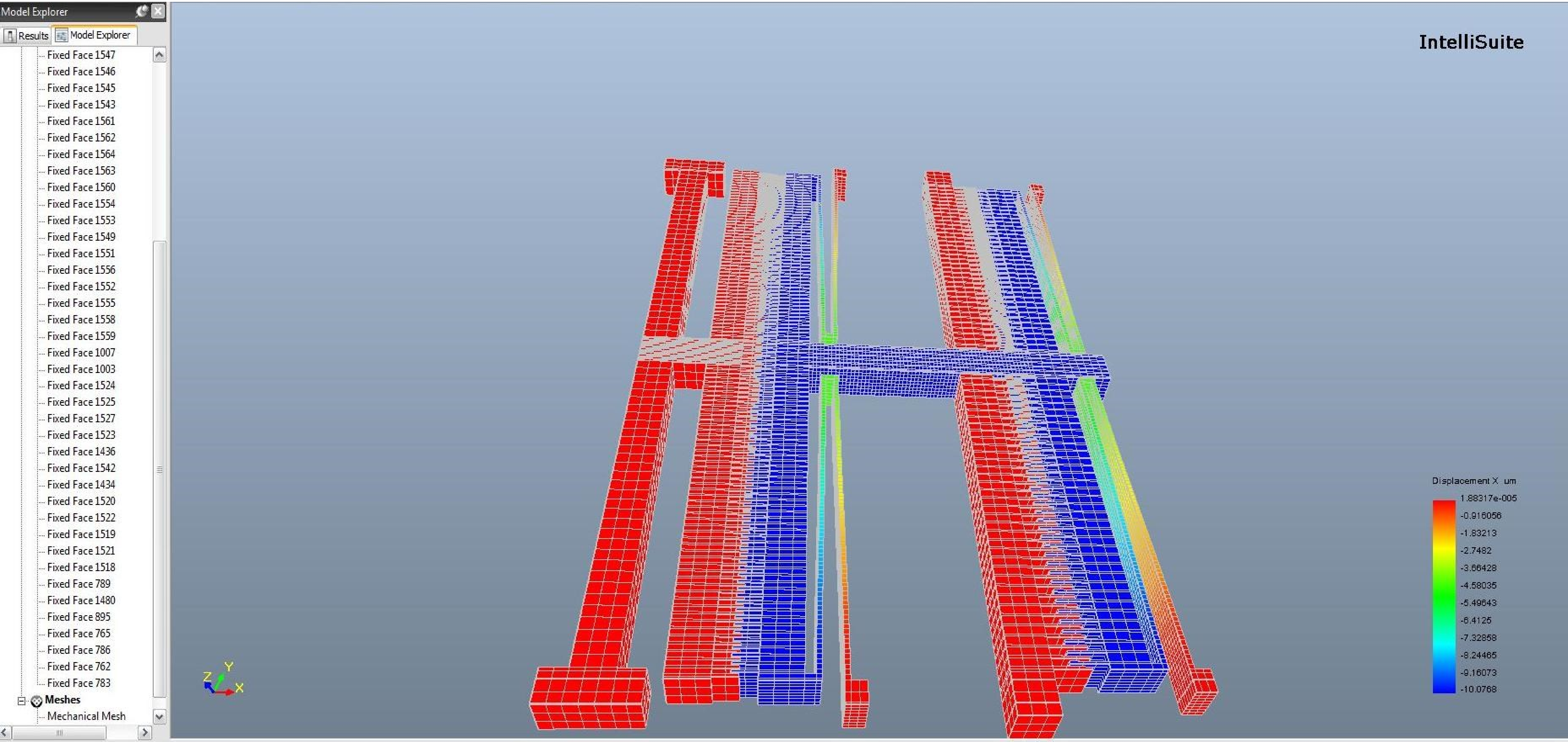
Schematic diagram of non-contact RF switch



Complete model of switch design



Displacement obtained from TEM analysis



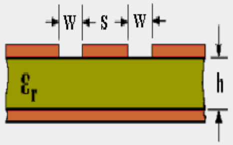
Substrate thickness Calculation

Substrate material (High Resistivity Silicon): 11.6
Width of the gap : 0.32 mm
Width of the signal line: 0.09 mm
Characteristic impedance: 50 Ohm

Thickness of the dielectric : 0.1013 mm

Coplanar Waveguide With Ground Characteristic Impedance Calculator

The characteristic impedance (Z_0) of coplanar waveguide with ground or microstrip lines with signal side ground plane can be calculated using the active calculator or the formulas at the bottom of the page.



Where ε_r= Relative Dielectric Constant

W = Width of gap

S = Width of track

h = Thickness of dielectric

Enter the ε_r of the PCB:	11.6					
Enter the width of the track:	0.09	mm				
Enter the width of the gap:	0.32	mm		Effective Dielectric Constant (ε_{eff}):	8.005	
Enter the thickness of the dielectric:	.1013	mm		Characteristic Impedance (Zo):	50	Ohms

Reference : http://chemandy.com/calculators/coplanar-waveguide-with-ground-calculator.htm

Material Selection

- **High Resistivity Silicon (HRS)**: Normal silicon wafer substrate resistivity ranges typically span from 5 Ω.cm to 30 Ω.cm. But for applications operating at GHz frequency range, the resistivity of silicon wafer should be very high.
- HRS satisfies the requirements of RF applications:
    1. Low RF noise
    2. Good linearity
    3. High breakdown voltage
    4. Better thermal conductivity
- At frequencies higher than 1GHz, the skin depth induces high RF losses. So, we choose HRS silicon with resistivity 2000 Ω.cm.

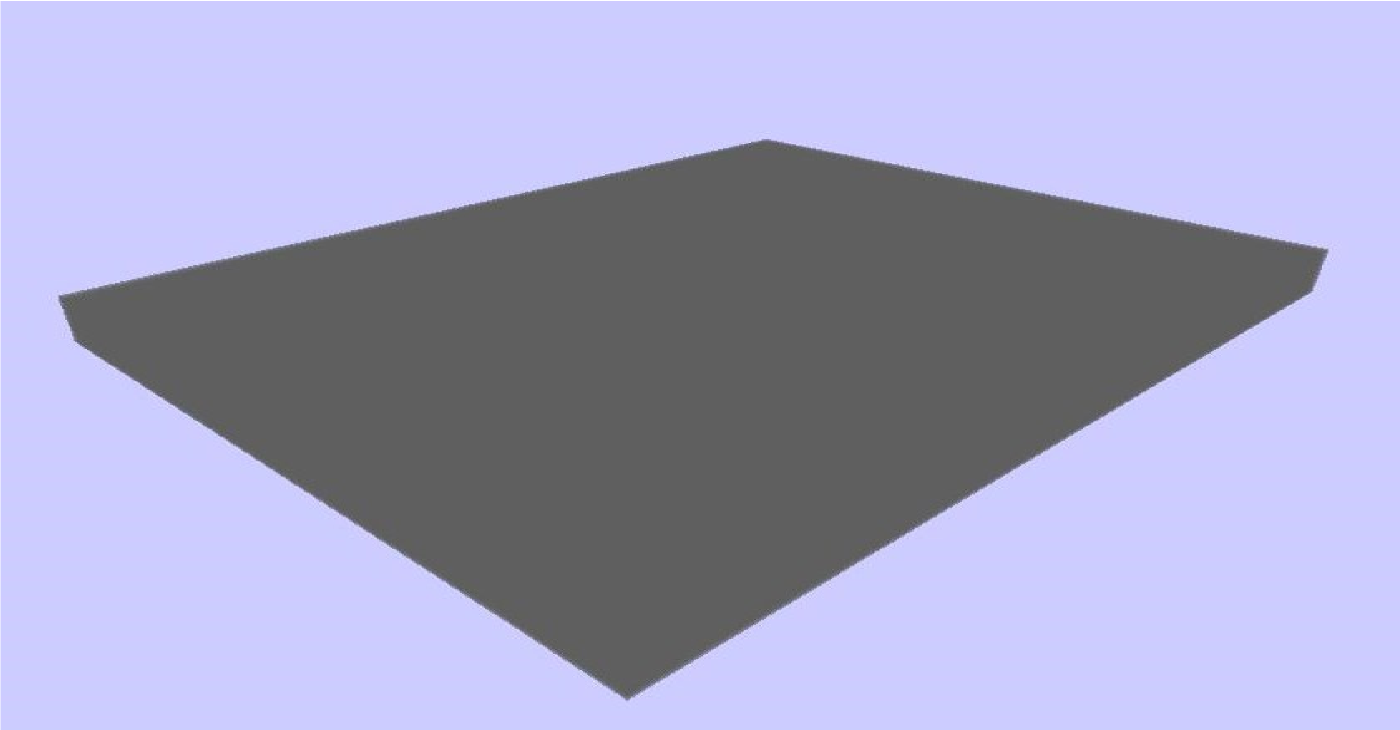
Material Selection

- Silicon nitride and silicon dioxide are used as insulation layers between electrode and the substrate.
- Low stress nitride layer increases the mechanical strength of the released HRS comb structure.
- Tetraethylorthosilicate (TEOS) oxide layer is used as hard mask for Reactive ion etch (RIE).
- Polysilicon is used as sacrificial layer to realize the airgap and also used as a structural material due to its good electrical and mechanical properties.
- Ag, Au, Cu and Al are most conductive metals. We choose Cu as a conducting part of the structure due to its high conductive property and high melting point.

Fabrication Process Flow

Step 1:

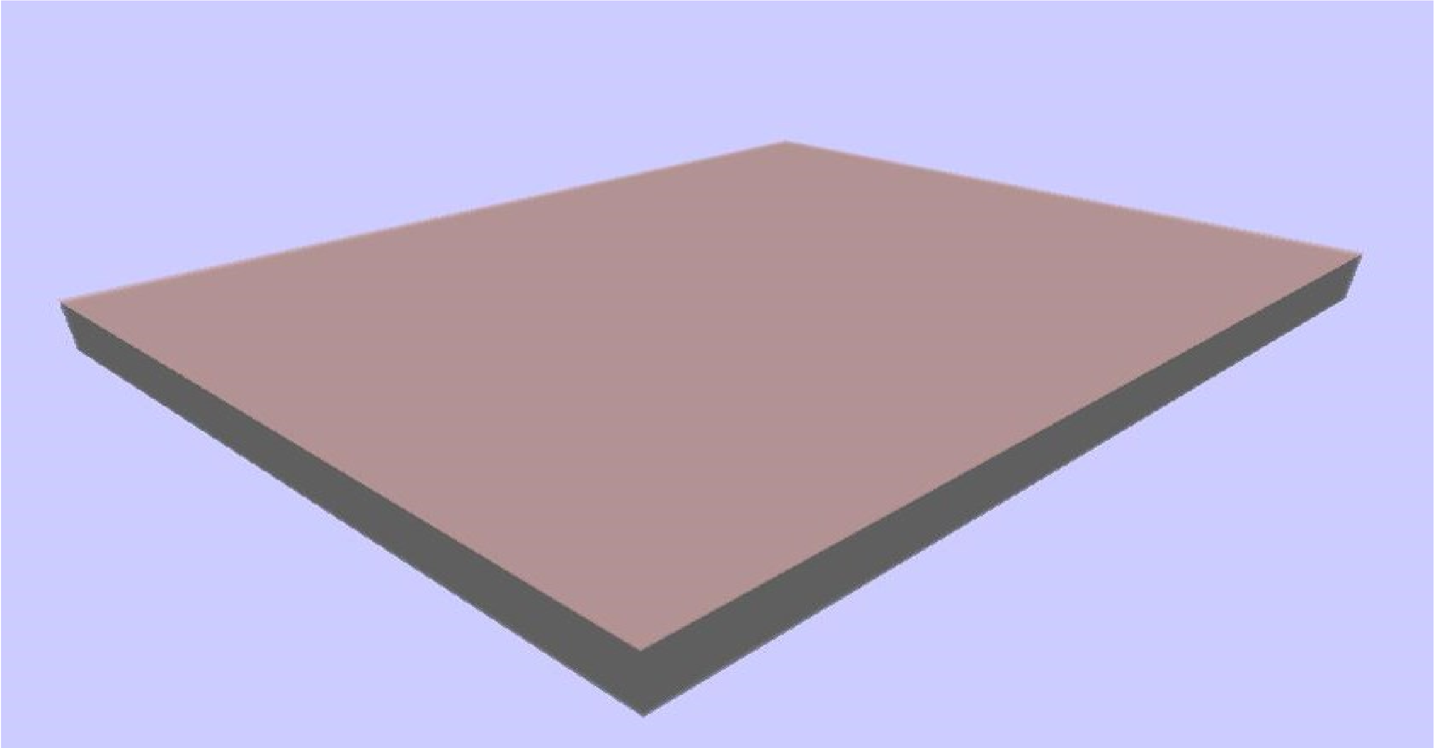
Definition of HRS wafer of thickness (101.3+5 =106.3 μm)
Resistivity: 2000 Ω-cm.



Fabrication Process Flow

Step 2:

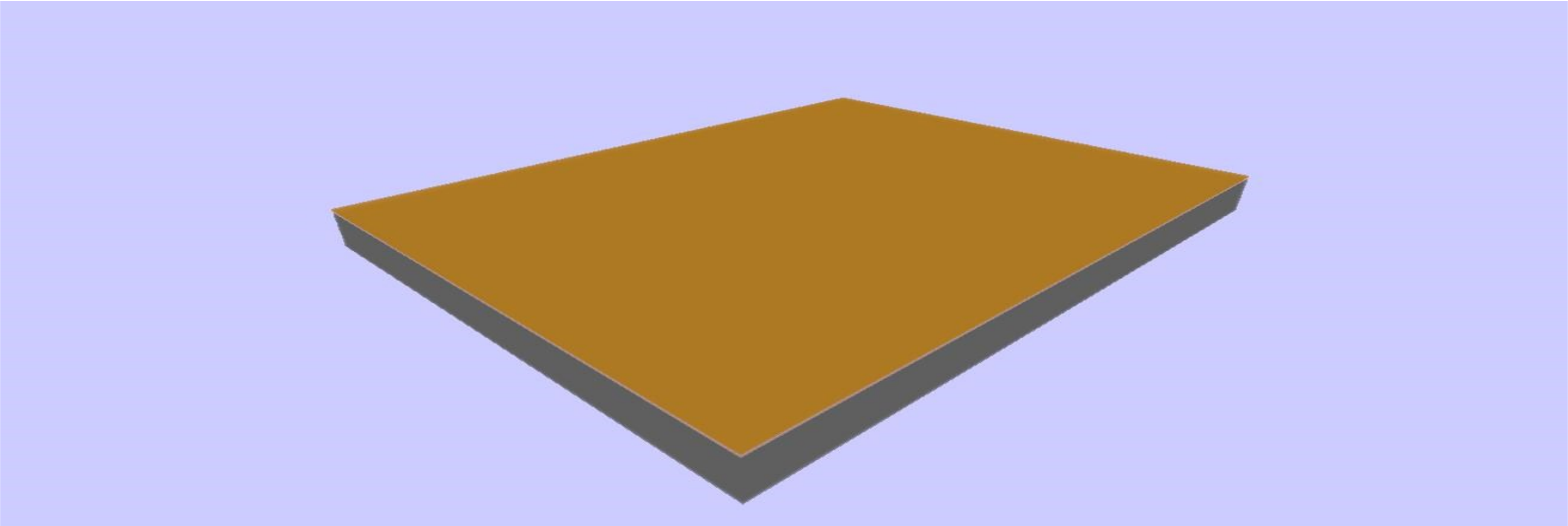
- Deposition of Plasma-enhanced chemical vapor deposition Tetraethylorthosilicate oxide layer.
- Serves as hard mask for Reactive ion etch (RIE).
- Insulation layer between substrate and electrode.



Fabrication Process Flow

Step 3:

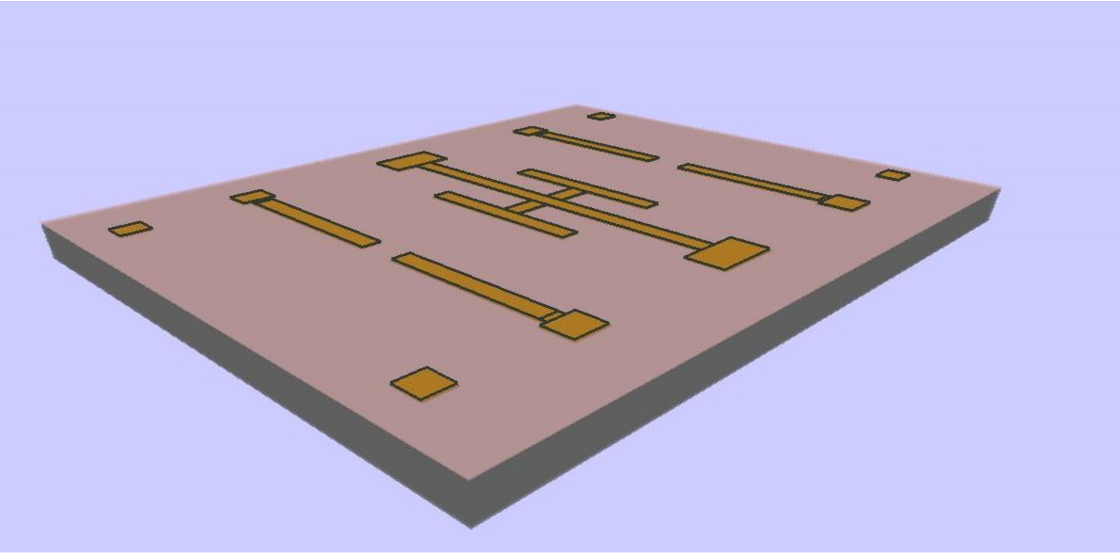
- Deposition of Photoresist (PR-S1800) as a part of Photolithography.
- Lithography in MEMS context is typically the transfer of a pattern to a photosensitive material by exposing to a radiation source.
- A PR is a material which change its physical properties when exposed, so the pattern get transferred to the material exposed.

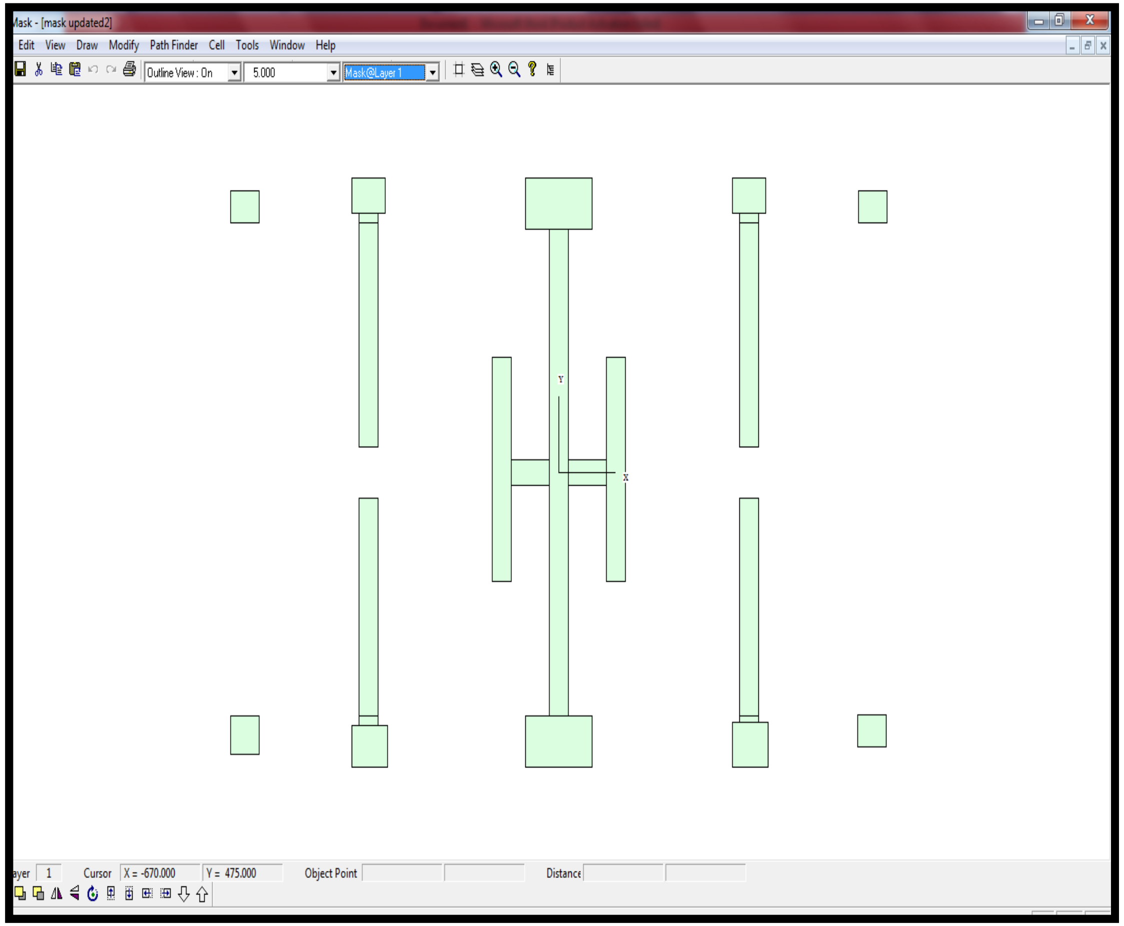


Fabrication Process Flow

Step 4:

- Exposing the PR layer to the Ultra Violet (UV) radiation.
- Need to specify the layer of the mask file to be patterned.

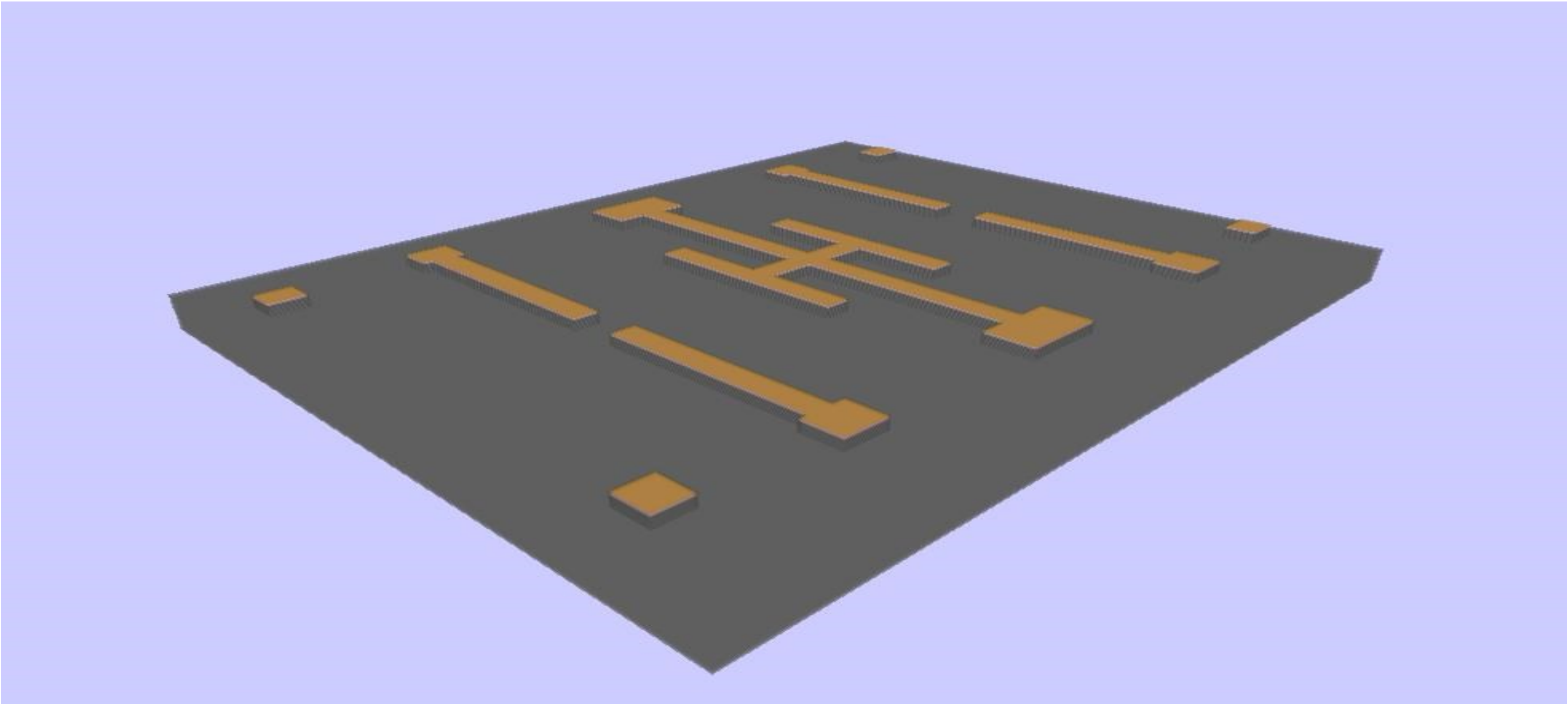




Fabrication Process Flow

Step 5:

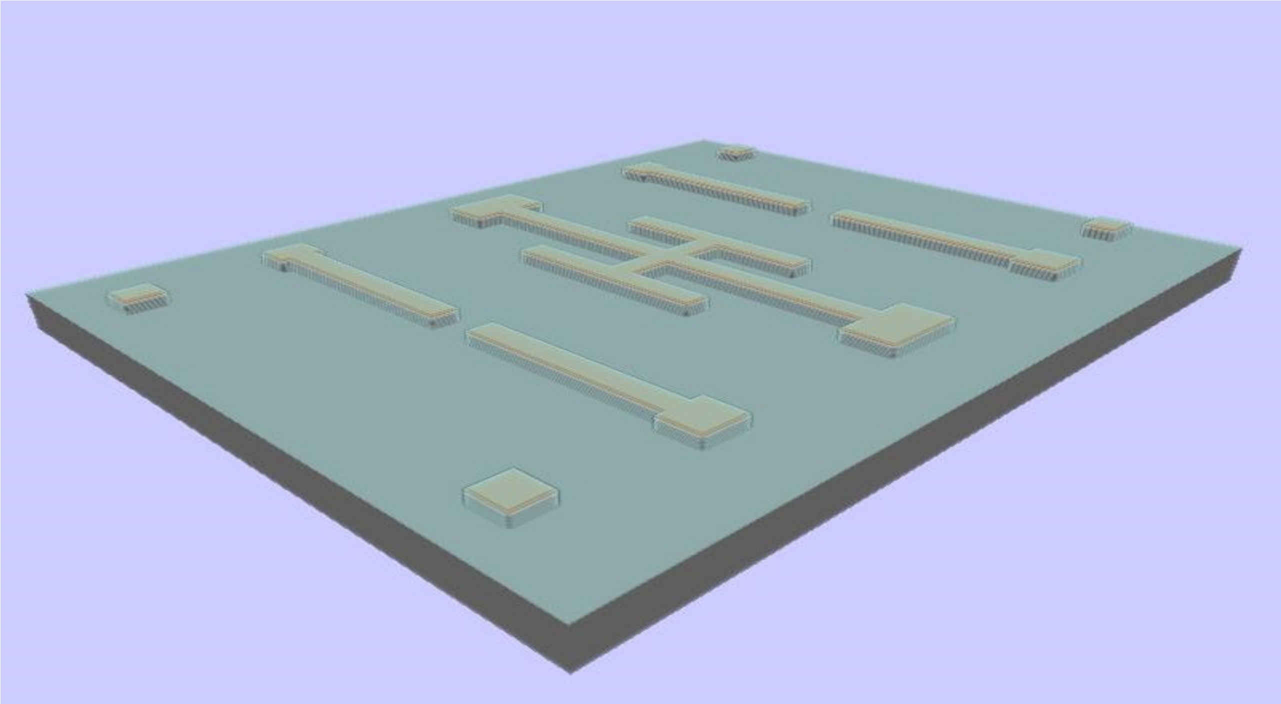
- Etch the HRS silicon, to realize the electrodes using Reactive Ion Etch.
- Partial Etching: When Partial etching is selected, we can specify the value of etching depth(t_etch), in our design t_etch is equal to 5 µm.



Fabrication Process Flow

Step 6:

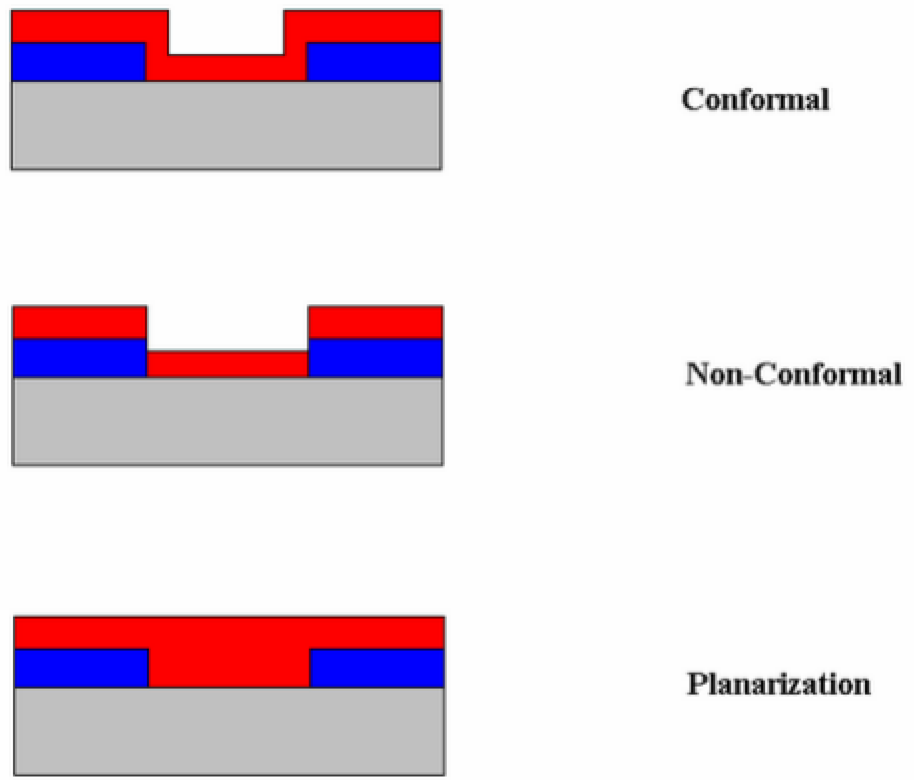
- Silicon Nitride (Si_3N_4) is deposited using PECVD technique.
- Conformal Deposition



Deposition Techniques

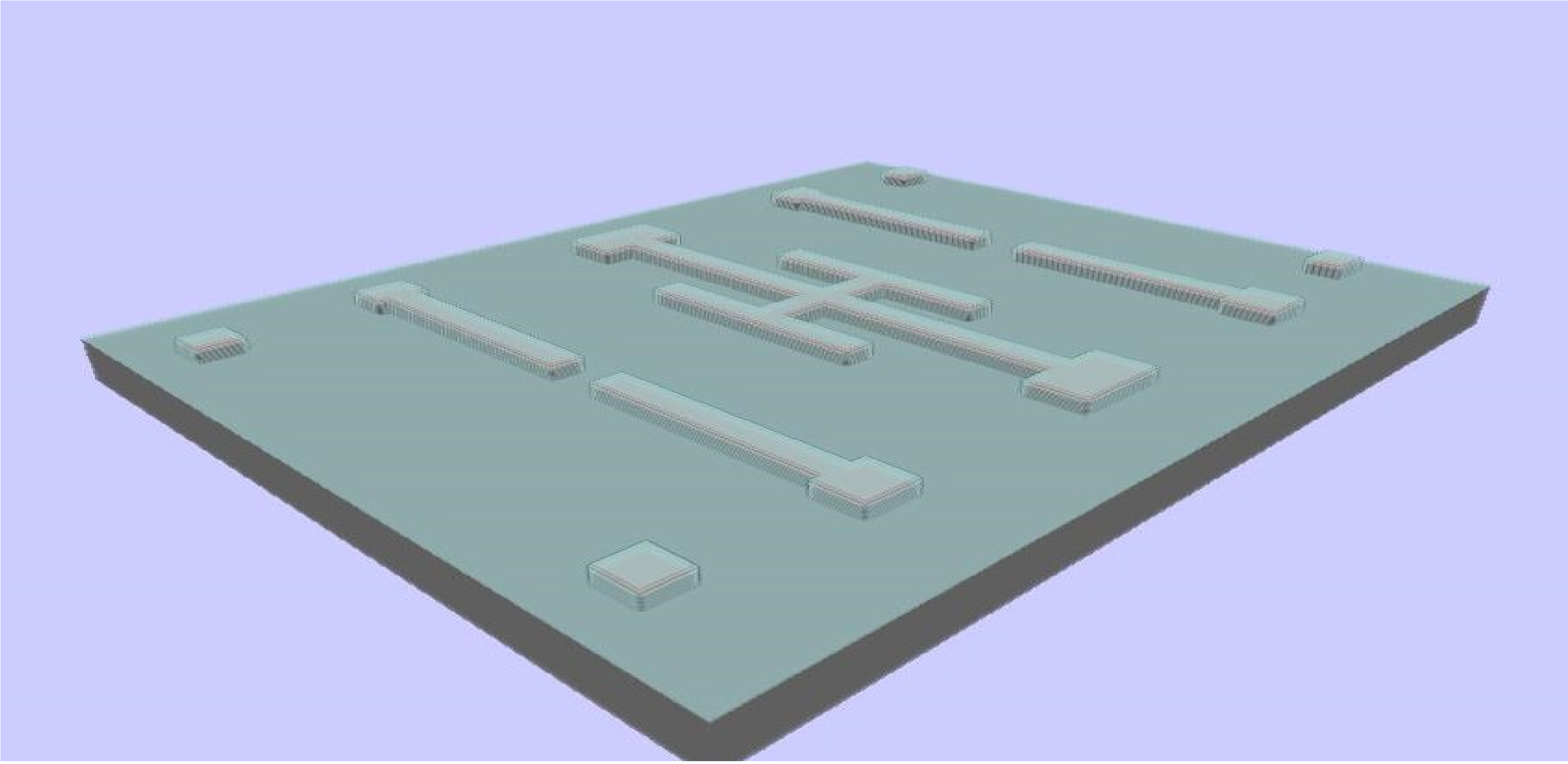
Types of Deposition processes in IntelliFab:

- Conformal: Continuous sidewalls.
- Non-Conformal: Breaking sidewalls.
- Planarization: The top surface of the deposited material will be flat despite the topography of the layers beneath it



Fabrication Process Flow

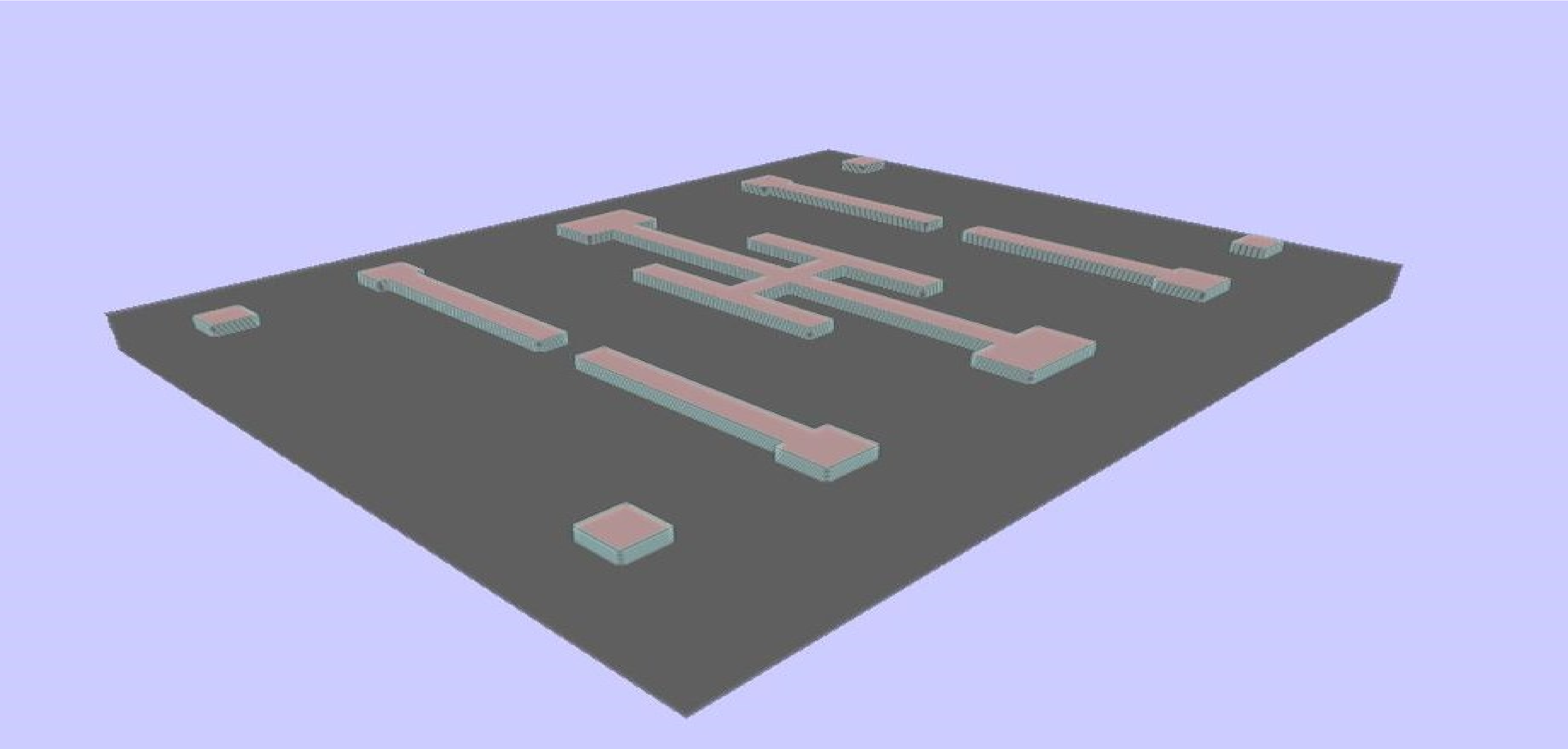
Step 7:
Etch photoresist.



Fabrication Process Flow

Step 8:

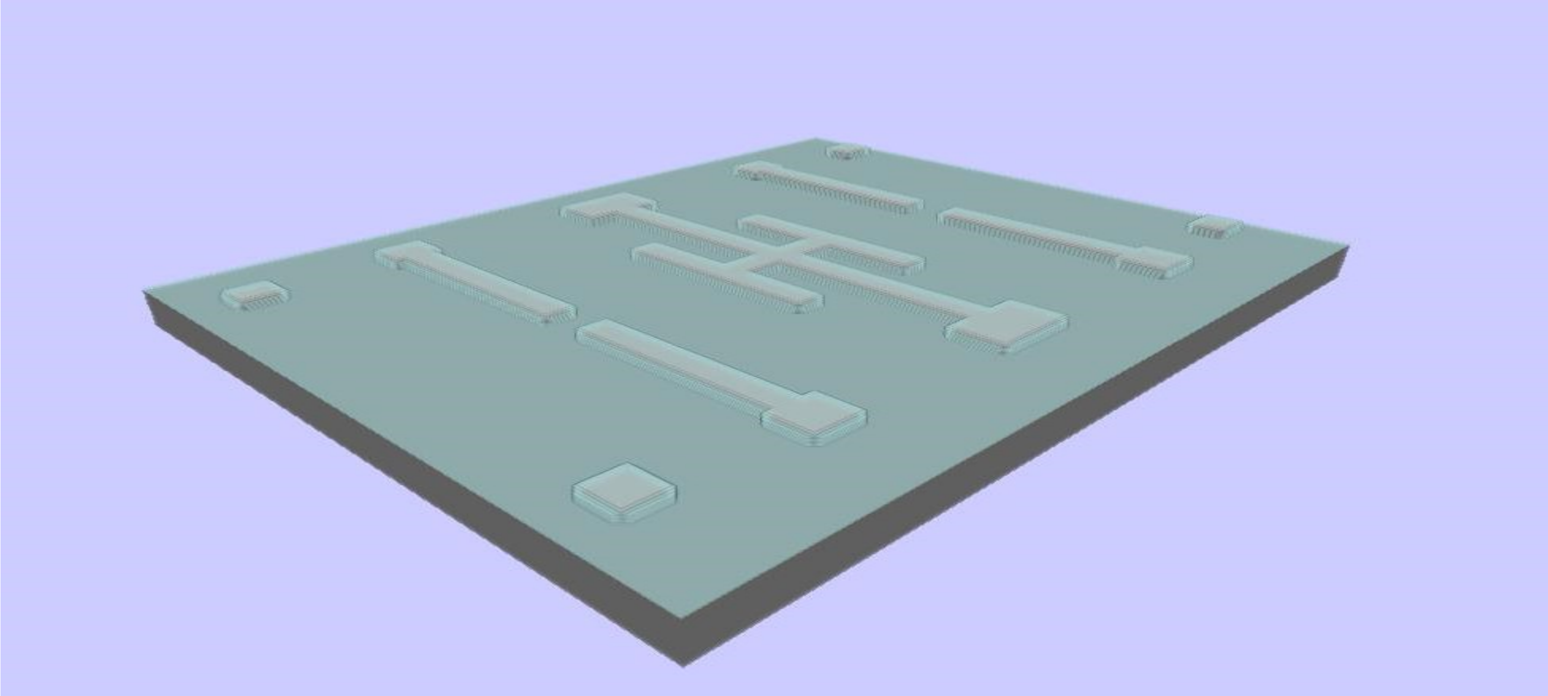
Etch Si_3N_4



Fabrication Process Flow

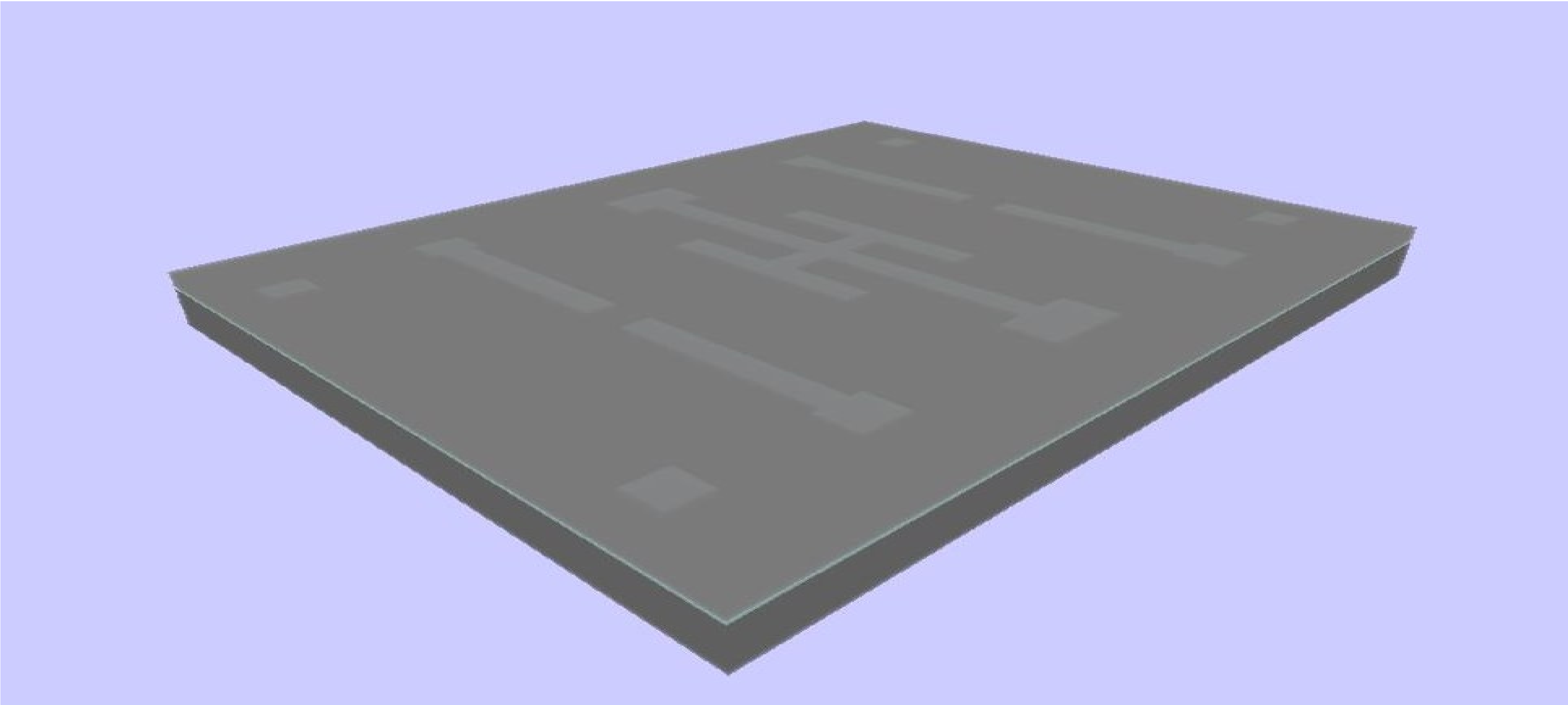
Step 9:

- Deposition of polysilicon.
- Type: Planarization



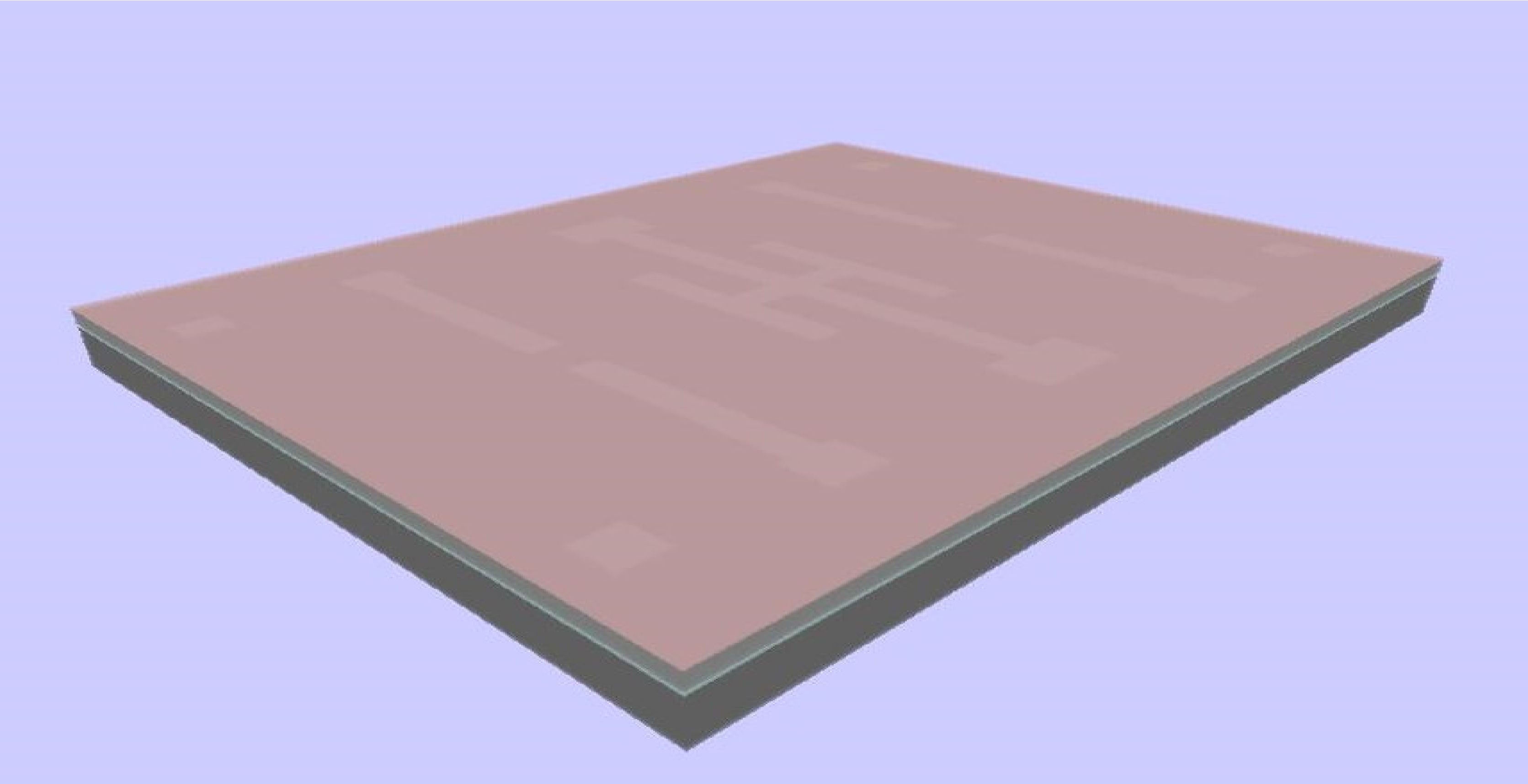
Fabrication Process Flow

Step 10:
Deposition of Si_3N_4



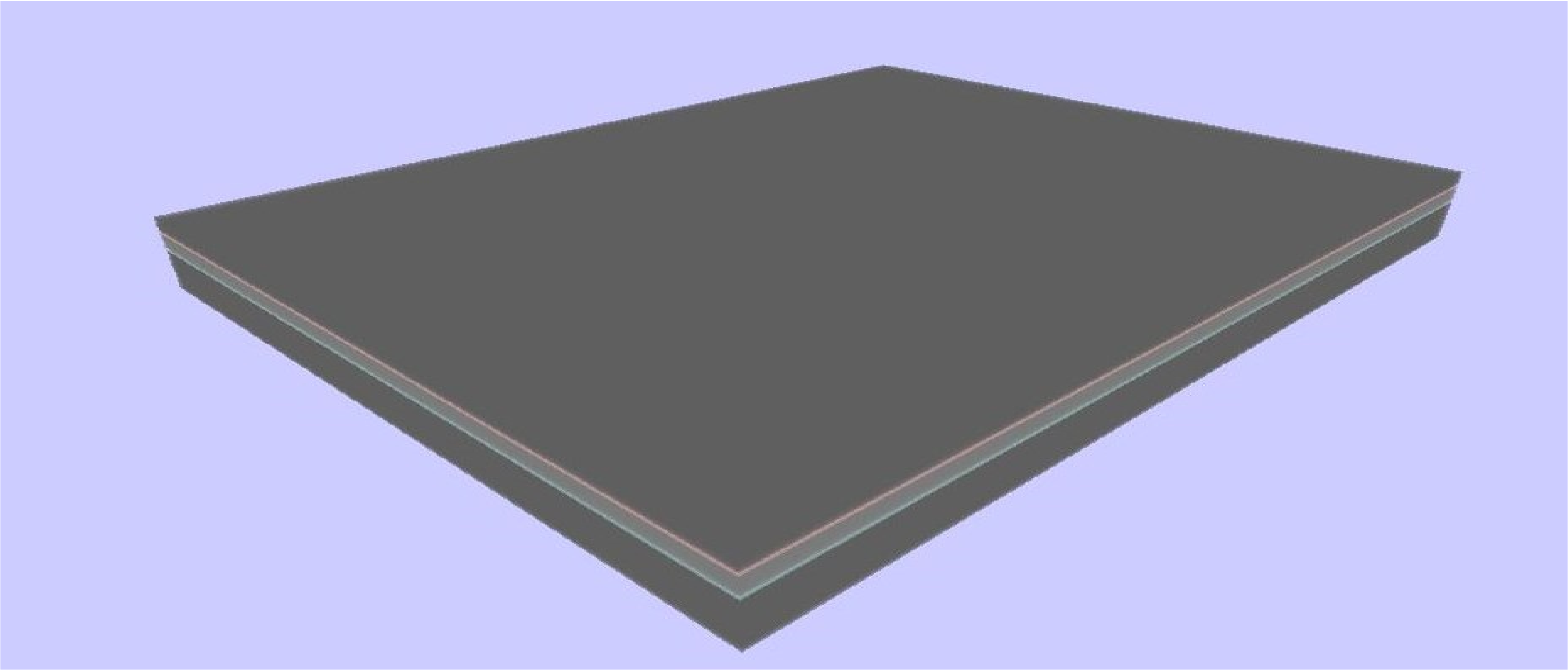
Fabrication Process Flow

Step 11:
Deposition of Sio2



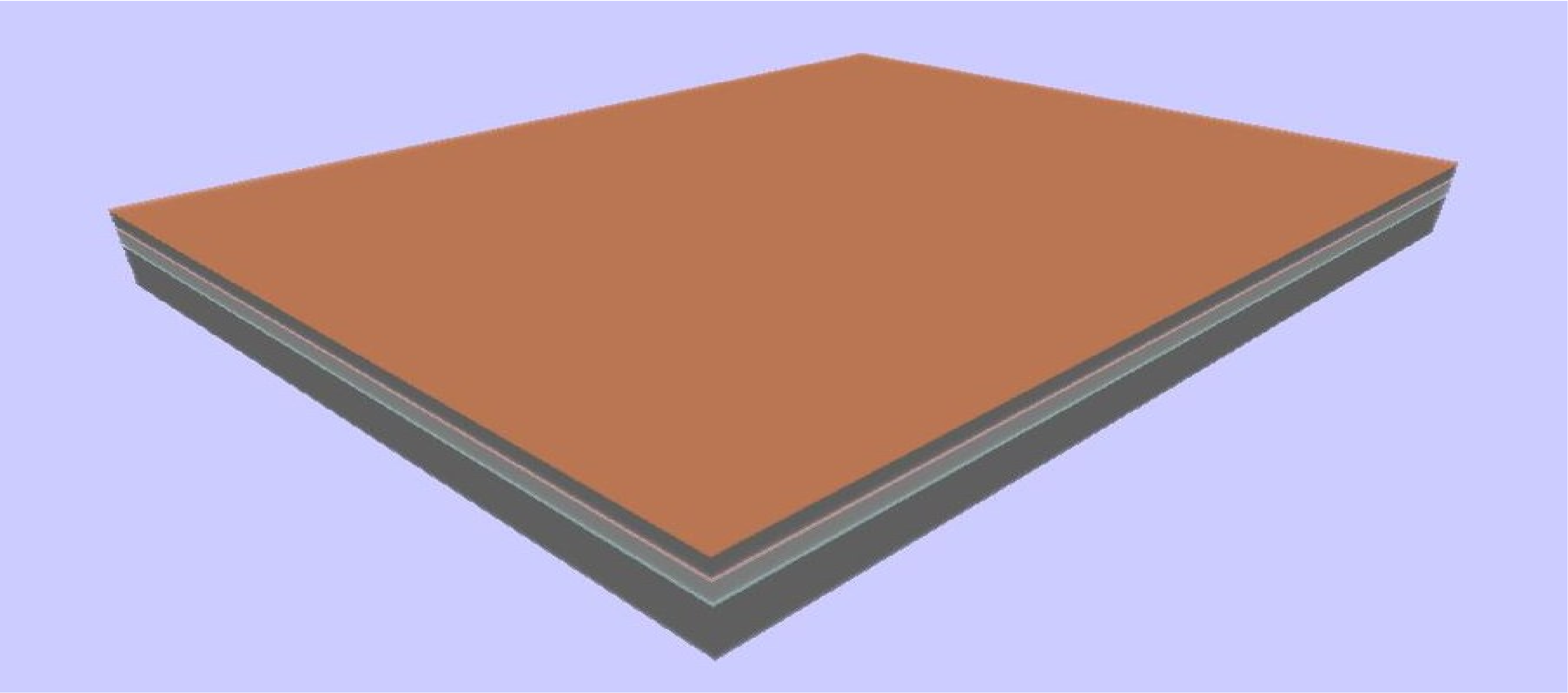
Fabrication Process Flow

Step 12:
Deposition of HRS



Fabrication Process Flow

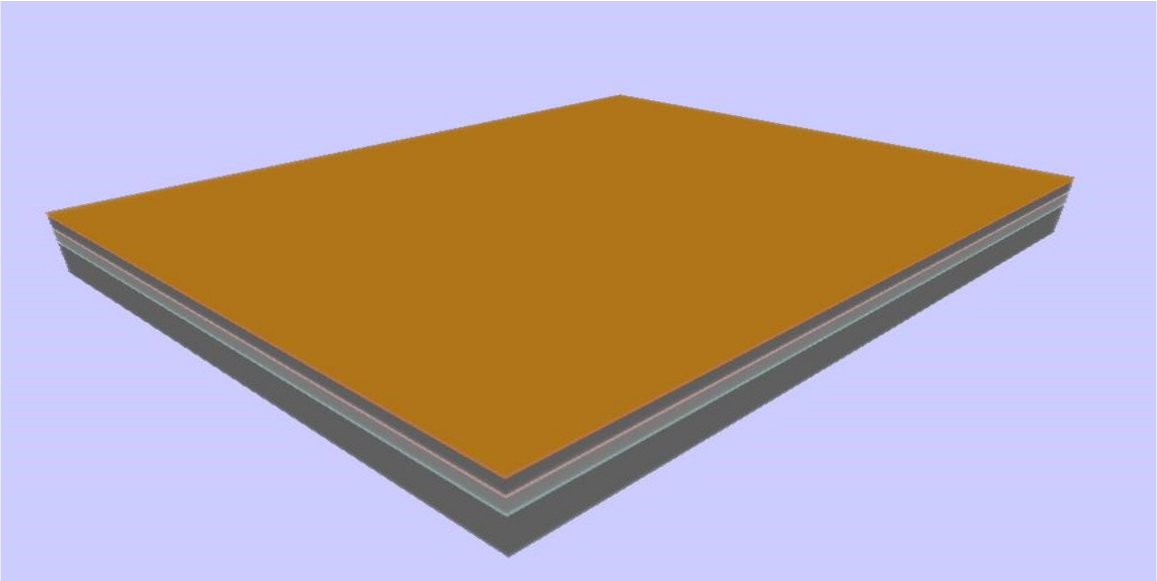
Step 13:
Deposition of metal layer

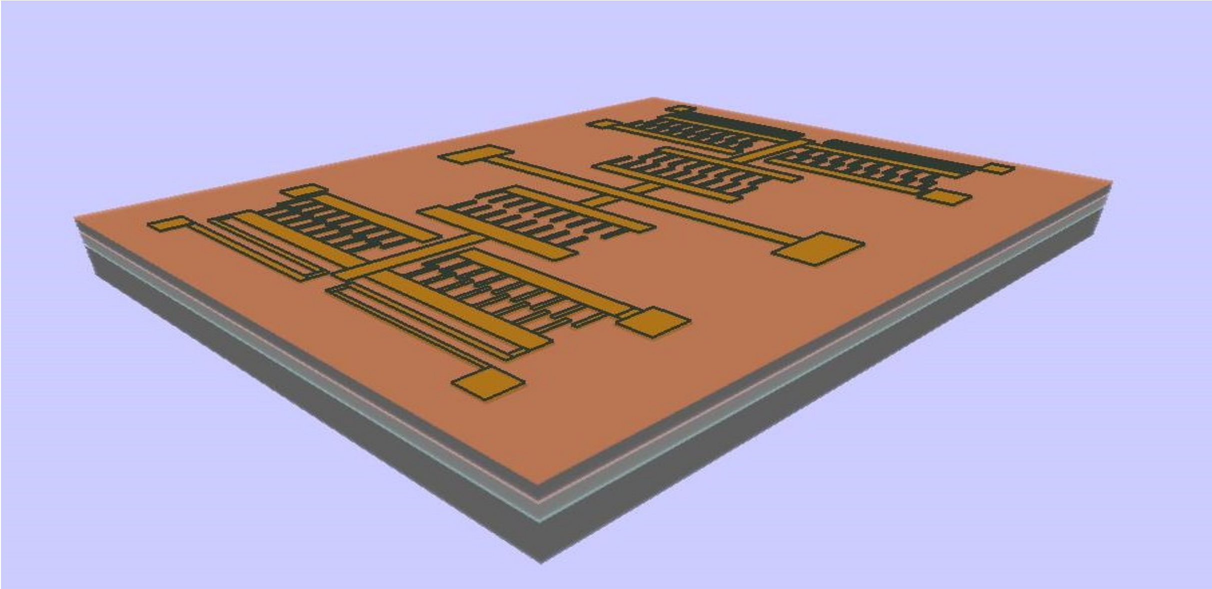


Fabrication Process Flow

Step 14&15:

Deposition of Photo Resist and exposure of UV radiation, to pattern the mask layer 2.

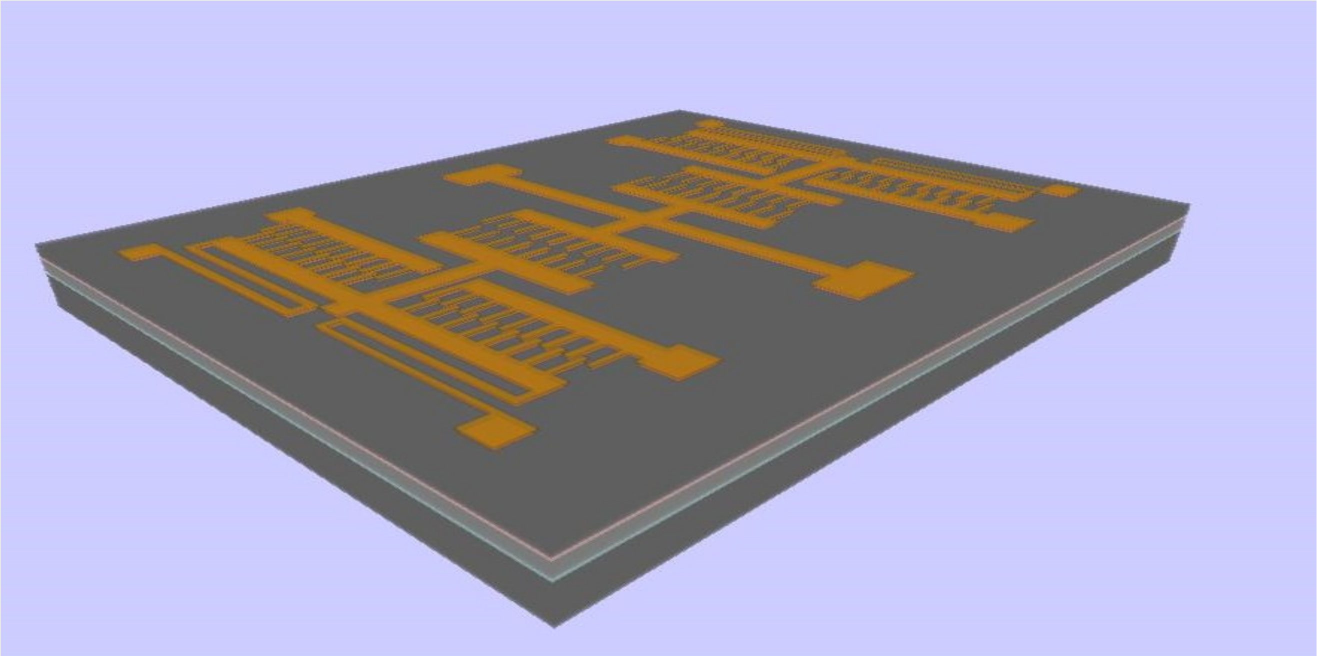




Fabrication Process Flow

Step 16:

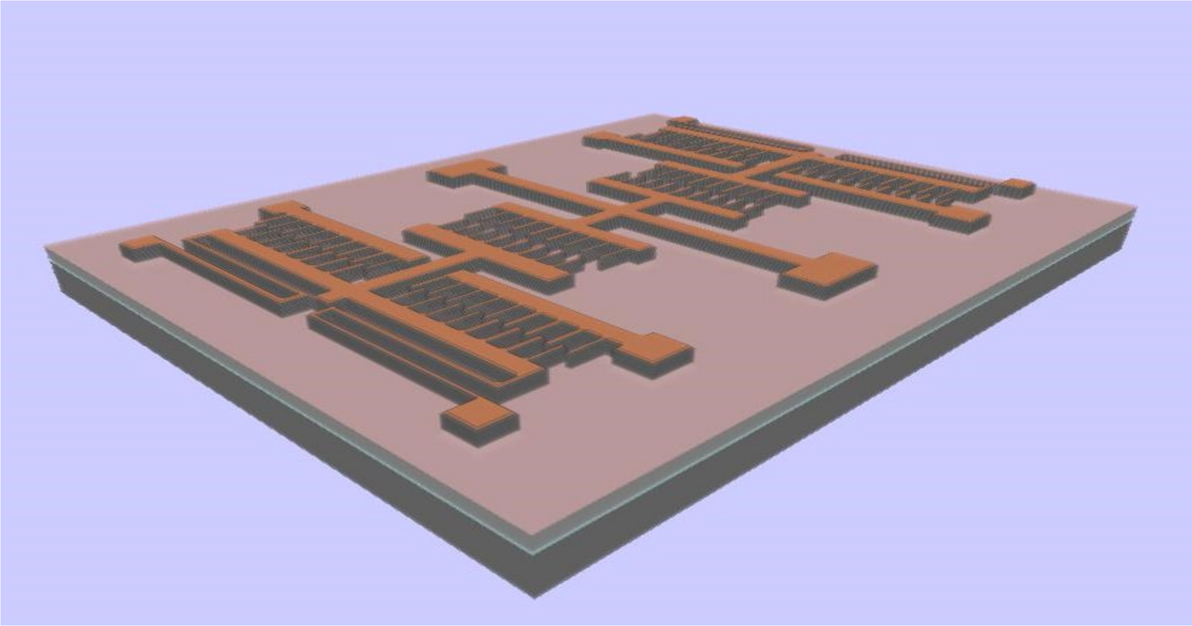
- Before etching Photoresist, etch the copper layer so that a layer of 4 μm is deposited only on the comb structure.
- As whole structure is realized using HRS ,which has high resistivity→ Low conductivity, so as to make comb structure conductive, a metal layer is deposited.

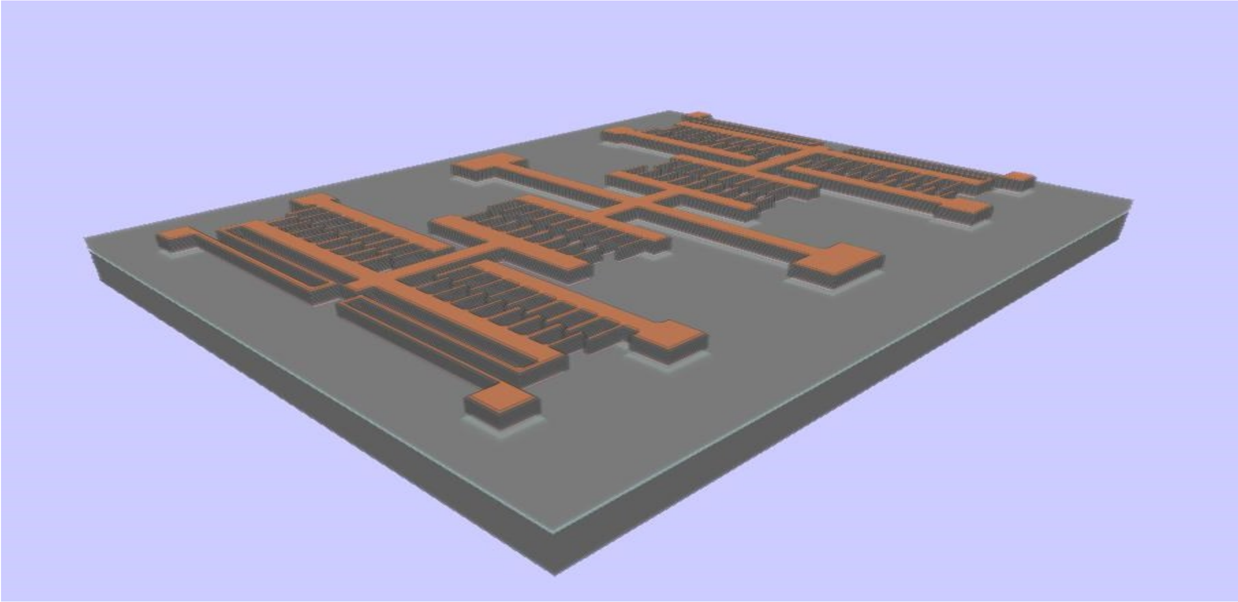


Fabrication Process Flow

Step 17-step 20:

After that Silicon layer, polysilicon, silicon nitride and polysilicon are etched to realize the pattern transferred from the photolithography of mask layer 2

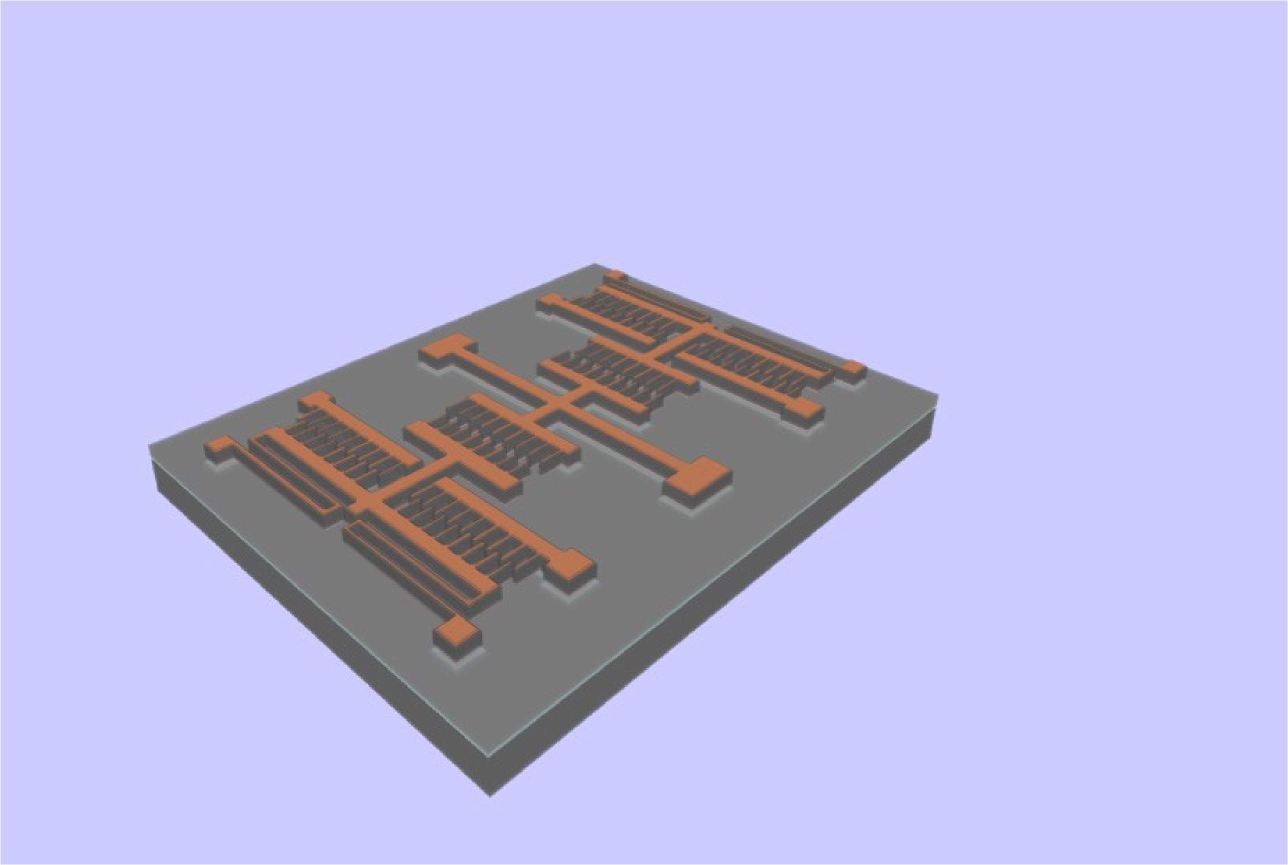




Fabrication Process Flow

Step 20:

- Etching of photoresist



Summary of work done

- We started our project by mathematical modelling of the switch, by considering the conditions to be satisfied during ON and OFF states of switch.
- From analytical model we calculated the capacitance of variable capacitor required to allow (ON state) and Block (OFF state) signal.
- We used these analytical results in Advanced Digital System (ADS) and observe the performance of switch by calculating insertion, isolation and return loss.
- Analytically calculated values are proved to be correct for obtaining good performance.
- Then we mathematically calculated the dimensions of comb drive fingers and spring dimensions to achieve the capacitance value obtained from ADS.
- From mathematical model, displacement of 10μm is required to obtain the enough capacitance so as to block the signal in OFF state.
- We carried out frequency analysis in Intellisuite TEM module to calculate the displacement and the obtained result is 10.0768 μm.
- Our analytical result is in good agreement with Intellisuite simulation result.
- Then we carried out the fabrication process in IntelliFab.

Conclusion

- We compared the designed Non-contact switch parameters with contact RF switch Available in the market (SPDT 24 GHz RF MEMS switch TT1224).

Parameters	Available switch	Designed Switch
[redacted]	[redacted]	[redacted]
Insertion	0.4dB	0.021 dB
[redacted]	[redacted]	[redacted]
Switch size	3.8mm× 5.1mm	1.1mm × 0.9 mm

- In our design we use 100 volts to generate a displacement of 10 µm, but practically it is not efficient, as power consumption is very high.
- But, voltage can be reduced by inserting additional comb structures to the existing system as shown in [4].
- Non-contact RF switch based on variable capacitance principle, is capable of replacing Contact based RF switch and also offers good performance.

Thank you
Any Questions ?