Lecture 23:

2008 Term Project Review

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Project Goal

- 1st order natural frequency: 4 kHz ~ 6 kHz
- 2nd order natural frequency:
  - About 0.45 kHz ~ 0.55 kHz than 1st order natural frequency
- Accuracy of frequency is most important
- Large displacement & Low voltage also necessary

Project summary

Calculated result

#			1		2	3	4	5		6	7	8	9	10
type			#1	#2	#1	#1	#1	#1	#2	#1	#1	#1	#1	#1
spring design	type		serpentine	serpentine	serpentine	guided end	folded	serpentine	serpentine	serpentine	guided end	guided end	guided end	serpentine
	number of spring	x-axis	4	4	12	8	4	4	4	4	8	8	6	8
		y-axis				8	4				8	8	6	
	spring constant	x-axis [N/m]	152.3	-	105.7	196.0	130.3	21.6	21.6	34.5	37.0	95.3	56.1	8.4
		y-axis [N/m]	193.2	-	127.0	256.0	140.8	26.8	26.8	38.5	43.5	115.4	68.1	10.2
mass design	mass [kg]		6.06E-07	-	9.90E-08	2.07E-07	1.28E-07	8.81E-08	9.81E-08	1.33E-07	3.52E-08	9.66E-08	3.72E-07	6.81E-08
1st mode frequency	[Hz]		5047	-	5200	4897	5070	4984	4723	5127	5160	4999	4784	5000
2nd mode frequency	[Hz]		5684	-	5700	5597	5340	5552	5261	5416	5590	5501	5271	5499
frequency difference	[Hz]		**637**	**-**	**500**	**700**	**270**	**568**	**538**	**289**	**430**	**502**	**487**	**500**

Project summary (cont'd)

ANSYS simulation result

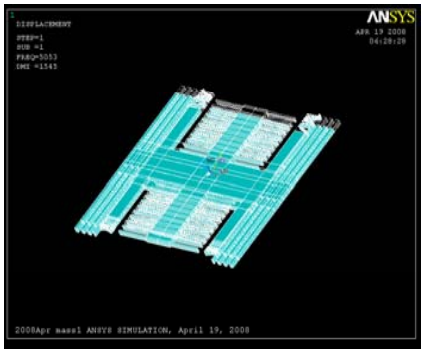
#		1		2	3	4	5		6	7	8	9	10
type		#1	#2	#1	#1	#1	#1	#2	#1	#1	#1	#1	#1
1st mode frequency	[Hz]	5053	4512	5456	4970	5080	4963	4726	5268	5163	5025	4930	4980
2nd mode frequency	[Hz]	5502	5030	6043	5170	5360	5460	5223	5619	5621	5527	5510	5650
frequency difference	[Hz]	**449**	**518**	**587**	**200**	**280**	**497**	**497**	**351**	**458**	**502**	**580**	**670**

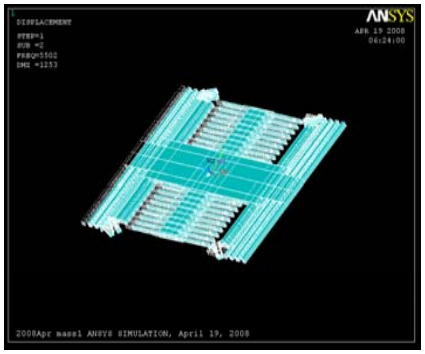
Measurement result

#		1		2	3	4	5		6	7	8	9	10
type		#1	#2	#1	#1	#1	#1	#2	#1	#1	#1	#1	#1
1st mode frequency	[Hz]	4500	4100	5020	5450	4520	4200	-	4385	4220	4880	4424	5030
2nd mode frequency	[Hz]	4970	4600	5550	5950	4560	4700	-	4903	4620	5380	4929	5530
frequency difference	[Hz]	**470**	**500**	**530**	**500**	**40**	**500**	**-**	**518**	**400**	**500**	**505**	**500**
distance/ voltage	[um/V]	0.033	0.033	0.067	0.033	0.027	0.120	-	0.076	0.053	0.008	0.112	0.080

2008 Project review #1

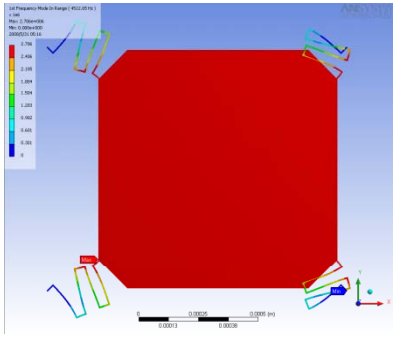
Type #1

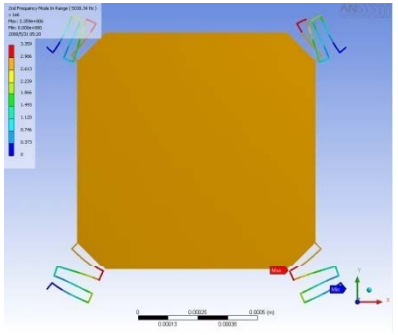




1st mode　　2nd mode

Type #2





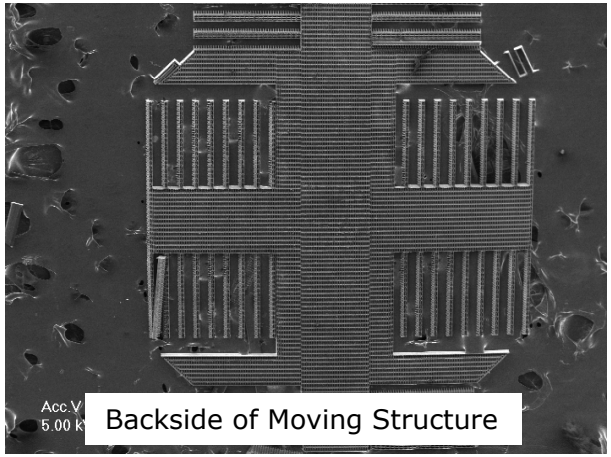
1st mode　　2nd mode

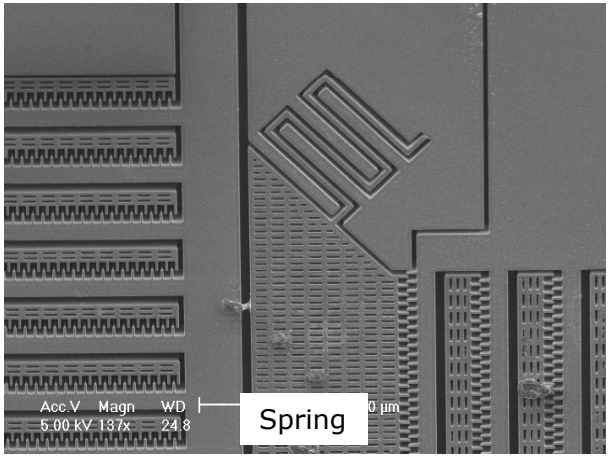
- **Comparison between Hand-calculated / ANSYS-simulated / Measured Result**

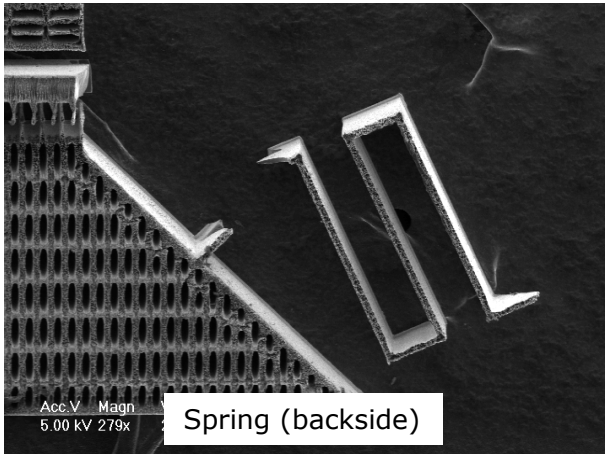
	1st mode calculated frequency	2nd mode calculated frequency	Calculated difference
Design #1	5749 Hz	5105 Hz	644 Hz
Design #2	-	-	-
	1st mode Simulated frequency	**2nd mode Simulated frequency**	**Simulated difference**
Design #1	5053 Hz	5502 Hz	451 Hz
Design #2	4512 Hz	5030 Hz	518 Hz
	1st mode measured frequency	**2nd mode measured frequency**	**Measured difference**
Design #1	4500 Hz	4970 Hz	470 Hz
Design #2	4100 Hz	4600 Hz	500 Hz

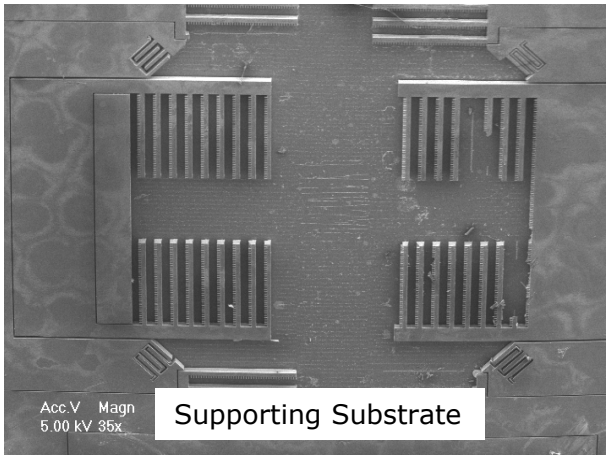
2008 Project review #1 (cont'd)

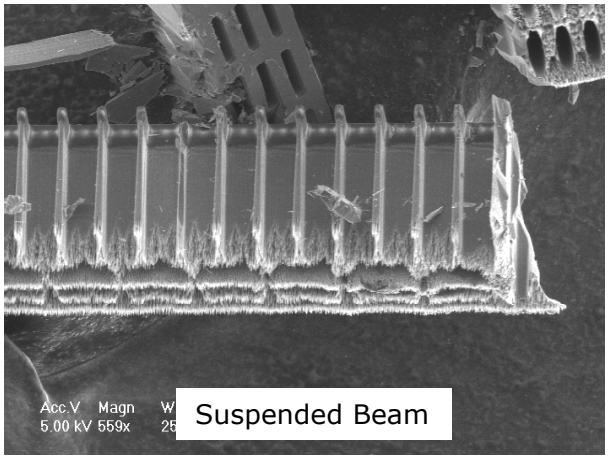
- **SEM image of Fabricated Results**





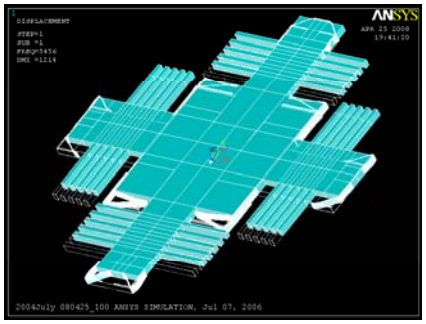




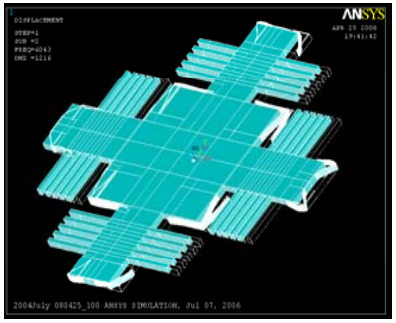


2008 Project review #2

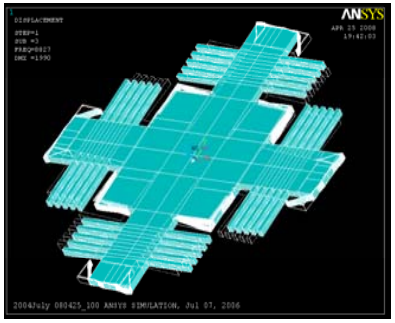
• **Modal Analysis Results**



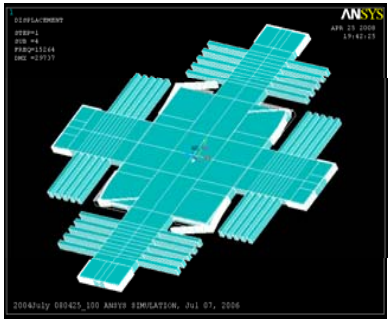
1st mode



2nd mode



3rd mode



4th mode

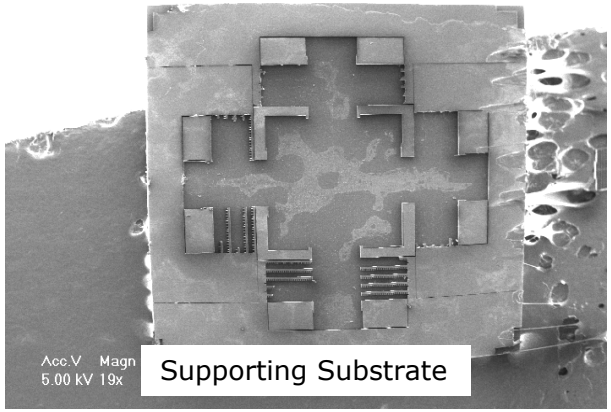
	1st mode	2nd mode	3rd mode	4th mode
Frequency (f)	5456 Hz	6043 Hz	8827 Hz	15264 Hz
Movement	y-axis	x-axis	Θ	Z-axis

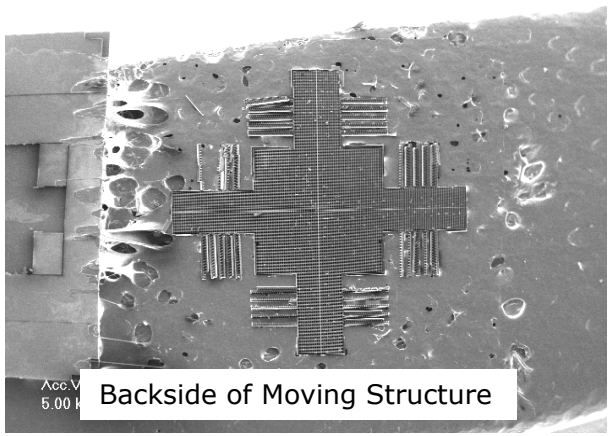
• **Comparison between Hand-calculated / Measured Result**

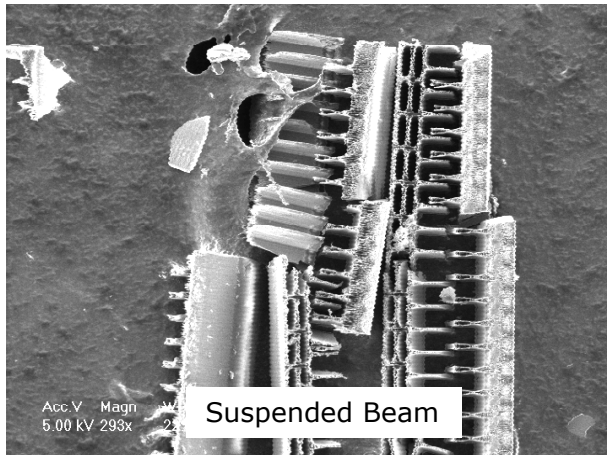
Type		Undercut	Mass	Resonant frequency	Stiffness	Driving voltage (displacement)
Design		0.3 μm	79 μg	X: 5.40 kHz Y: 5.80 kHz	X: 94.3 N/m Y: 112.3 N/m	70 V (4 μm)
Fabricated device	Device #1	0.4 μm	~74 μg	X: 5.02 kHz Y: 5.55 kHz	X: 73.6 N/m Y: 90.0 N/m	60 V (~4 μm)
	Device #2	0.4 μm	~74 μg	X: 4.40 kHz Y: 4.82 kHz	X: 56.5 N/m Y: 67.8 N/m	55 V (~4 μm)
	Device #3	0.4 μm	~74 μg	X: 4.85 kHz Y: 5.30 kHz	X: 68.7 N/m Y: 82.1 N/m	90 V (~4 μm)

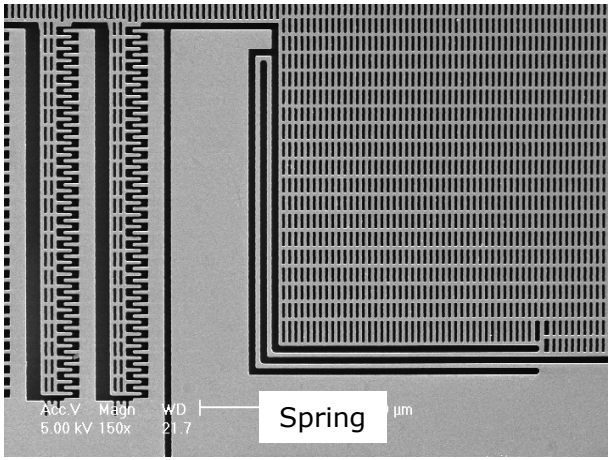
2008 Project review #2 (cont'd)

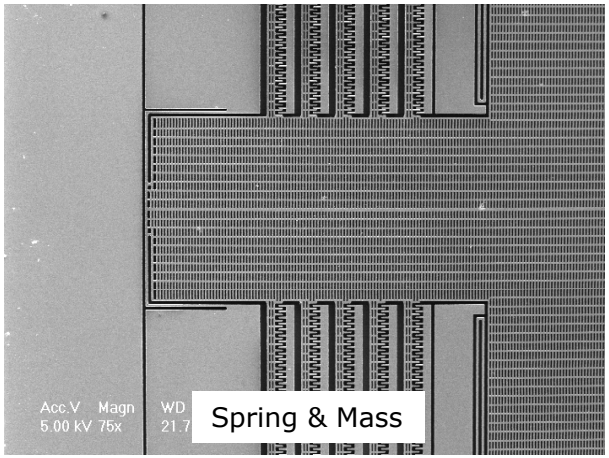
- **SEM image of Fabricated Results**





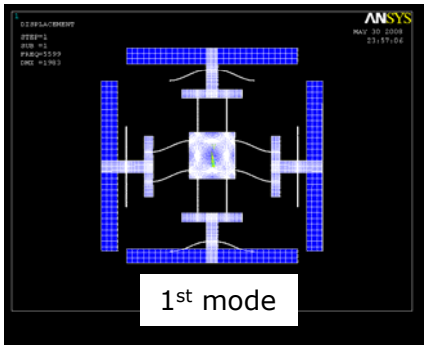


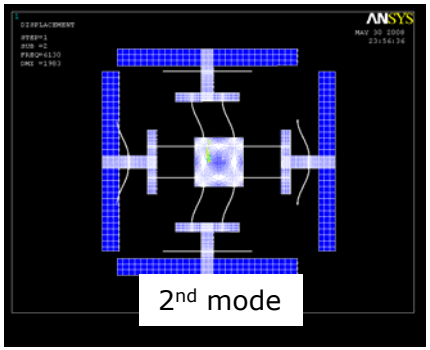


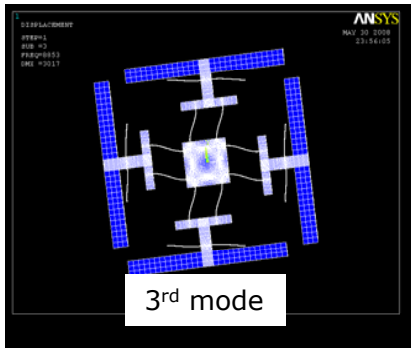


2008 Project review #3

- **Modal Analysis Results**







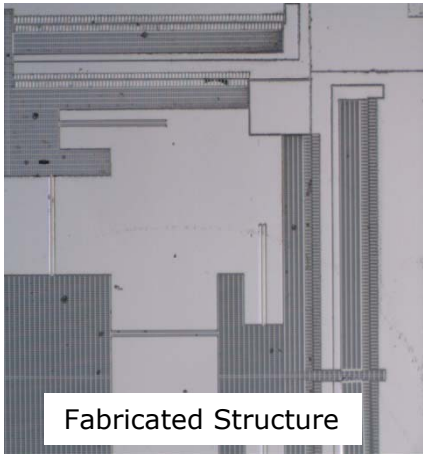
	1st mode	2nd mode	3rd mode
frequency	5561 Hz	6087 Hz	8853 Hz

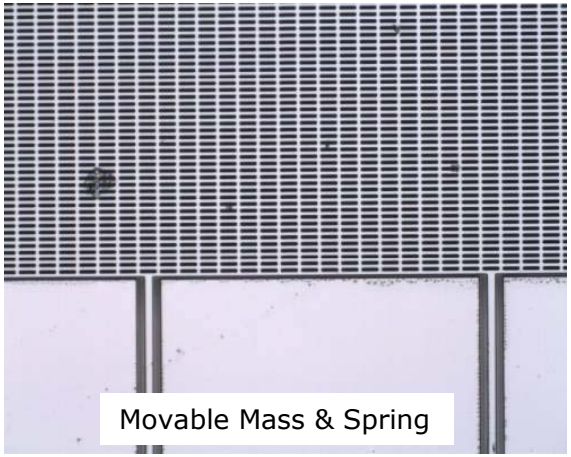
- **Comparison between Hand-calculated / Measured Result**

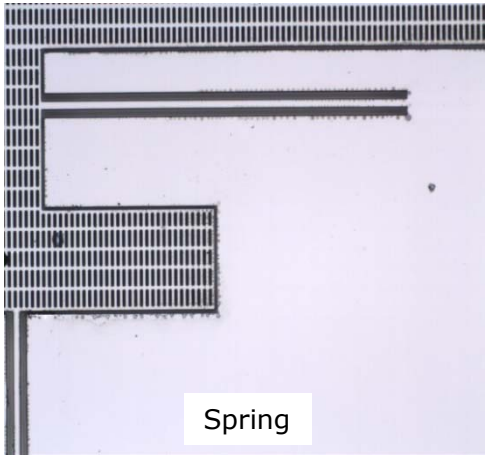
	design	fabricated	measured
Mass (kg)	2.47E-07	2.51E-07	-
spring constant_x (N/m)	39.36	45.76	-
spring constant_y (N/m)	32.8	38.15	-
frequency_x (Hz)	5679	6081	5950
frequency_y (Hz)	5184	5552	5450

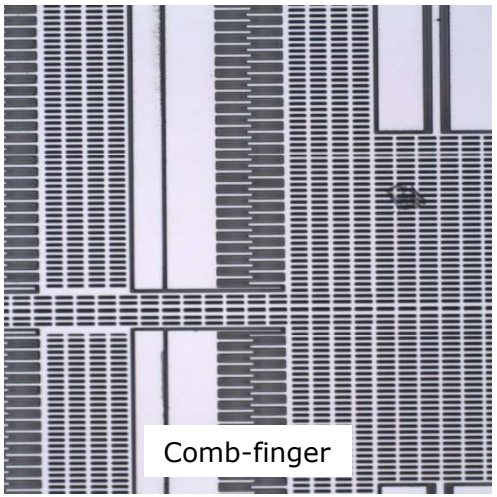
2008 Project review #3 (cont'd)

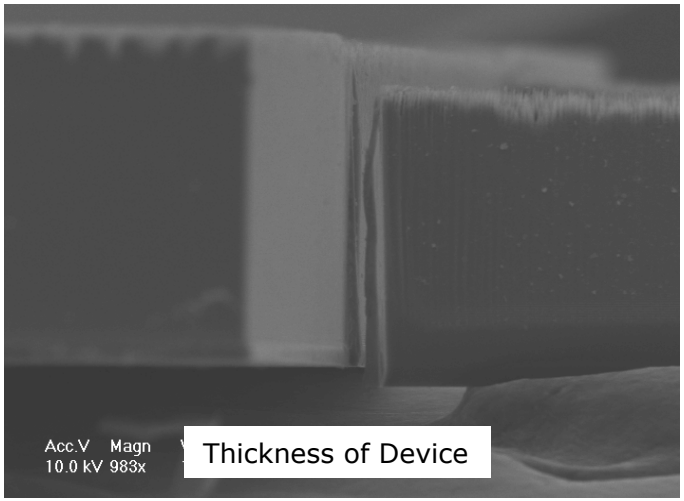
- **SEM image / Microscope image of Fabricated Results**





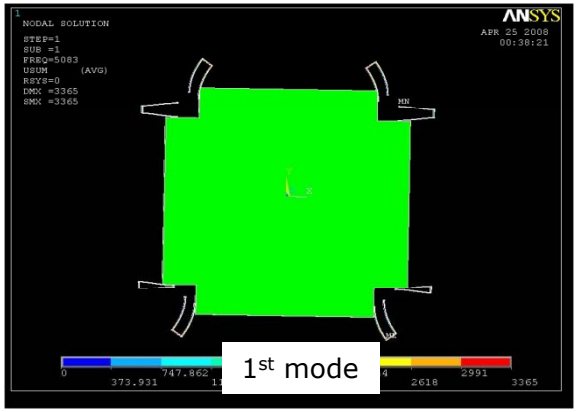


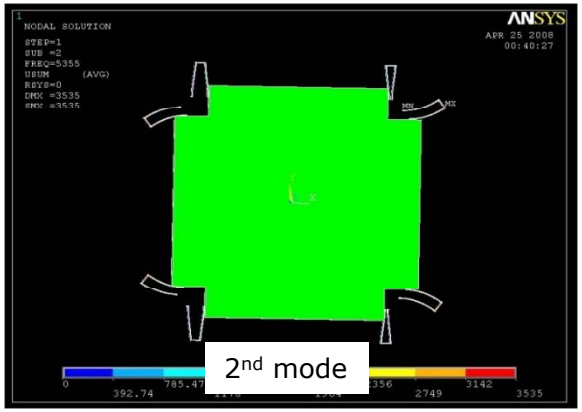


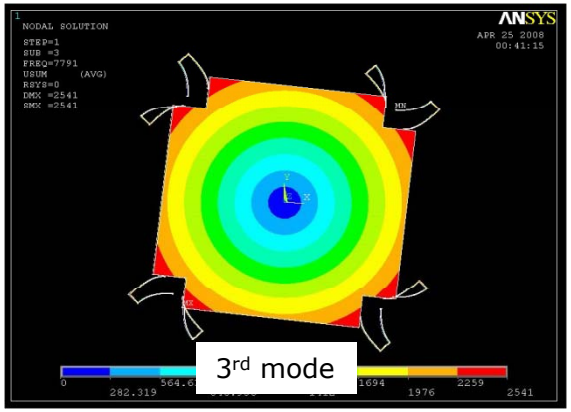


2008 Project review #4

- **Modal Analysis Results**







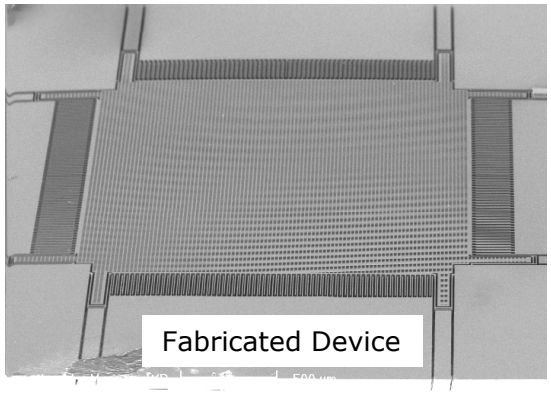
Mode	Resonant frequency [kHz]	
	Design	Simulation result
1st mode natural frequency	5.07	5.08
2nd mode natural frequency	5.34	5.36
3rd mode natural frequency	-	7.79

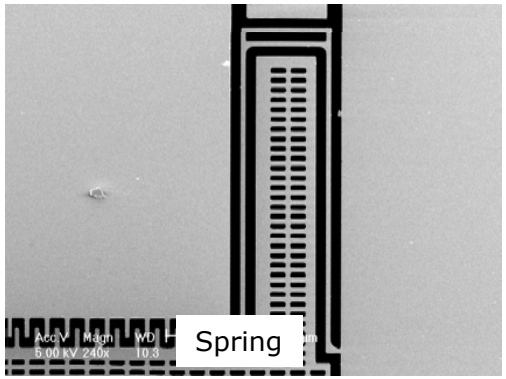
- **Comparison between Hand-calculated / Measured Result**

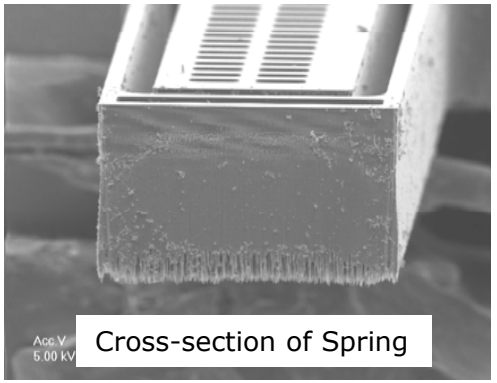
Parameters		Design	Fabrication	Measurement
Mass		3.15e-7 kg	3.20e-7 kg	
k	k_x	354.00 N/m	238.81 N/m	
	k_y	319.72 N/m	217.08 N/m	
f_r	f_x	5.34 kHz	4.35 kHz	4.56 kHz
	f_y	5.07 kHz	4.16 kHz	4.52 kHz

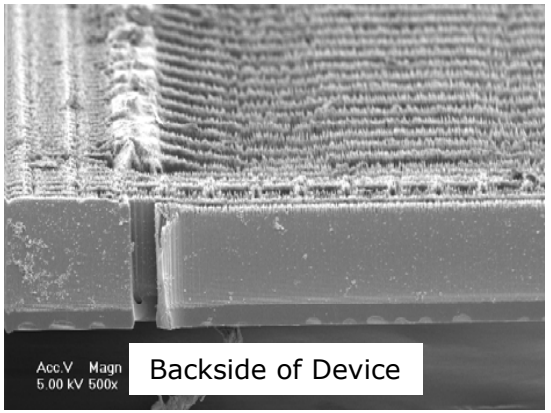
2008 Project review #4 (cont'd)

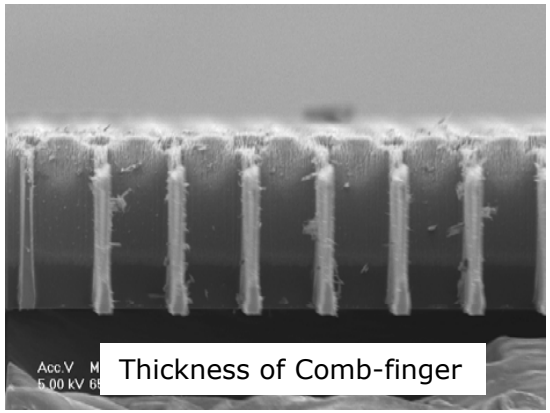
- **SEM image of Fabricated Results**

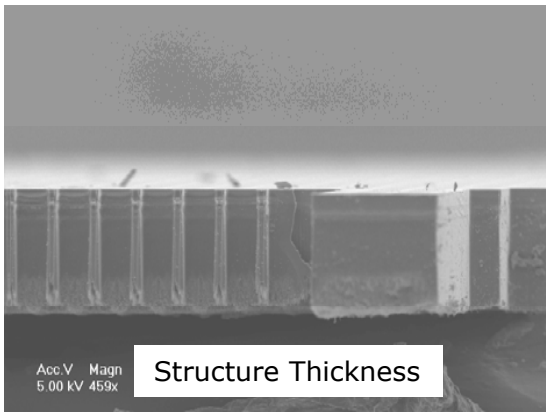






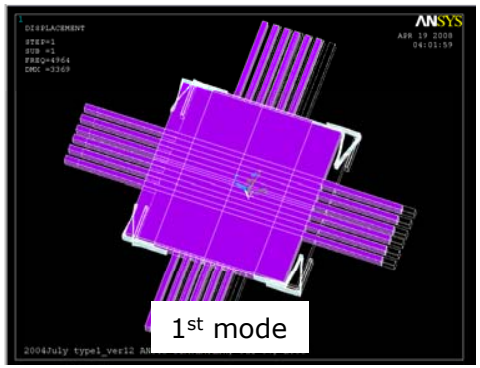


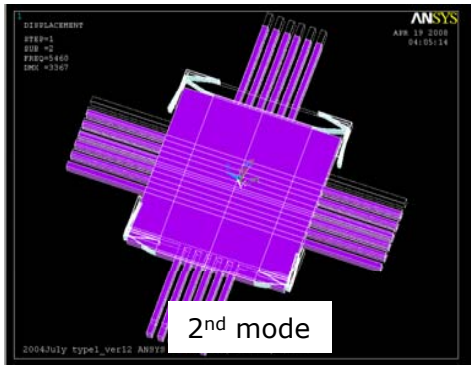


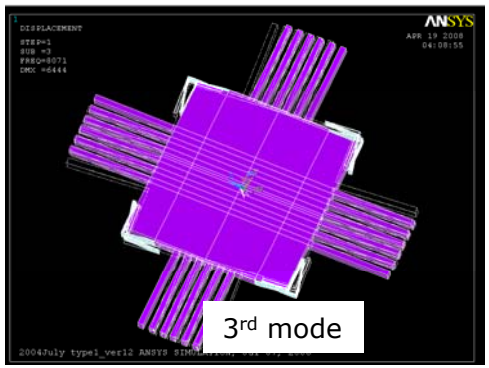


2008 Project review #5

• **Modal Analysis Results**







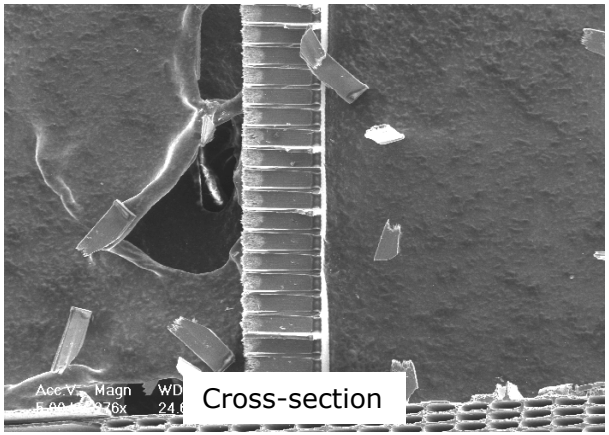
Mode	Resonant frequency [kHz]	
	Design	Simulation result
1st mode natural frequency	4.95	4.963
2nd mode natural frequency	5.50	5.460
3rd mode natural frequency	-	8.070

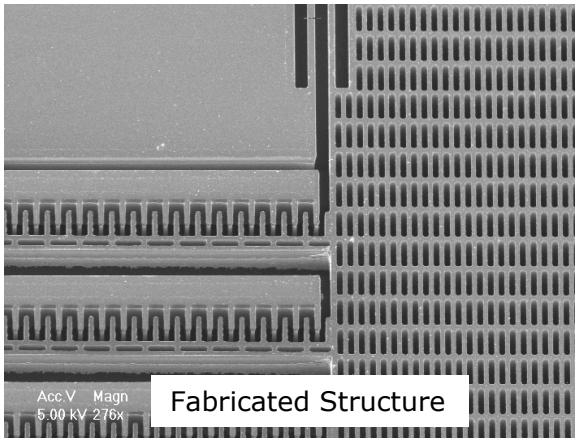
• **Comparison between Hand-calculated / Measured Result**

Parameters		Design	Fabrication	Measurement
Mass		8.81e-8 kg	8.7e-8 kg	-
k	k_x	86.4 N/m	75.6 N/m	-
	k_y	107.2 N/m	91.5 N/m	-
f_r	f_x	4.98 kHz	-	4.2 kHz
	f_y	5.52 kHz	-	4.7 kHz

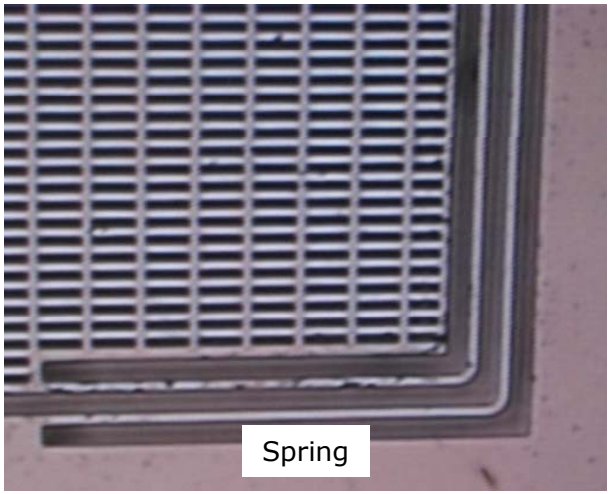
2008 Project review #5 (cont'd)

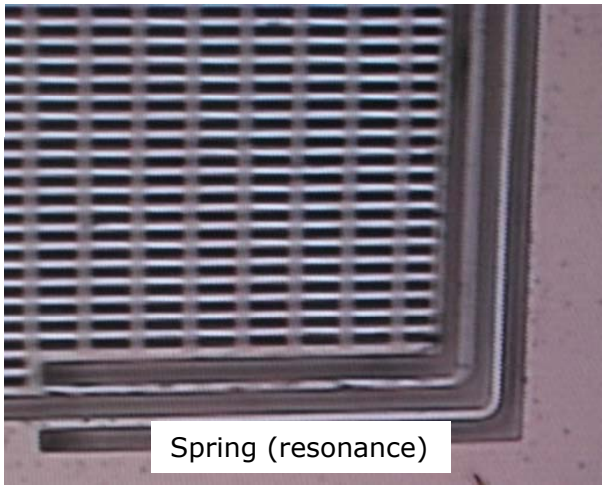
- **SEM image of Fabricated Results**

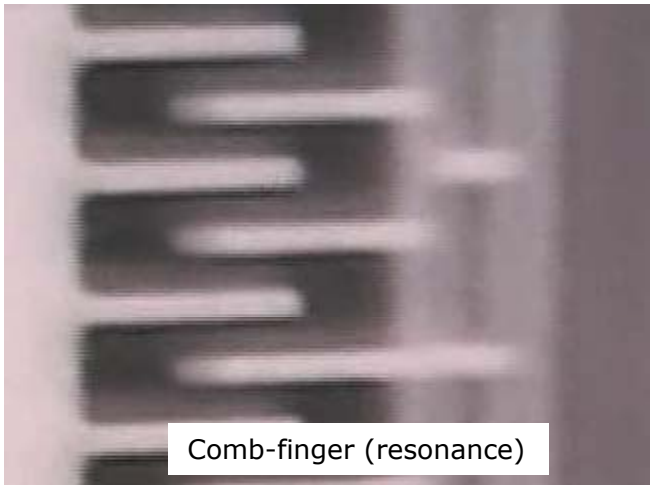




- **Microscope image (resonance)**

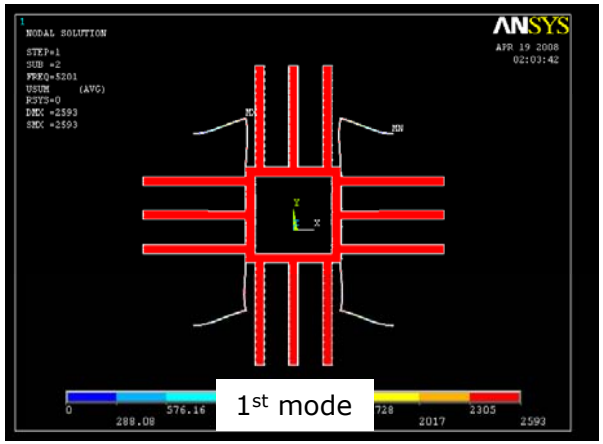


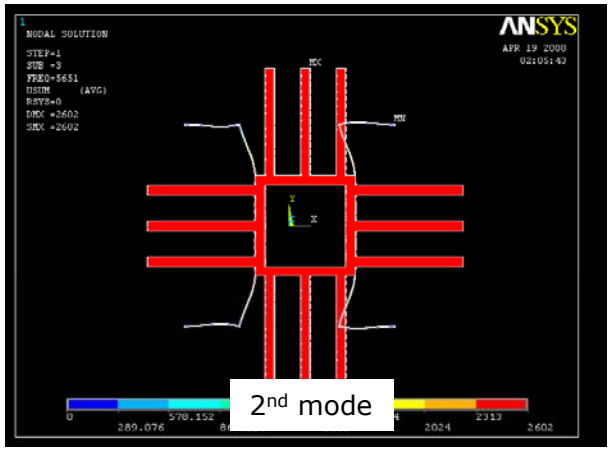




2008 Project review #6

- **Modal Analysis Results**





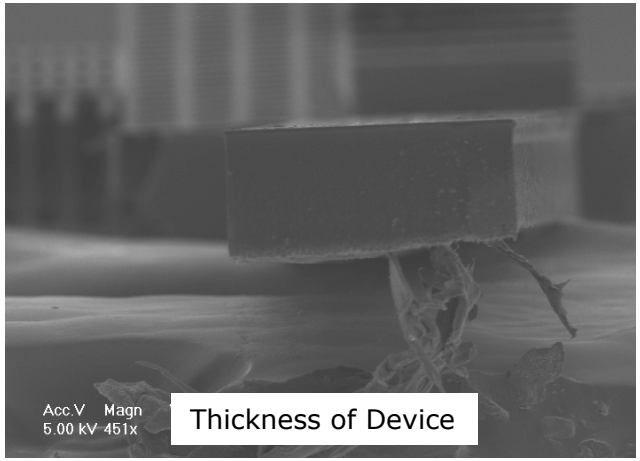
	Design	Simulation
Resonance frequency(y direction)	5.127 kHz	5268 kHz
Resonance frequency(x direction)	5.416 kHz	5619 kHz

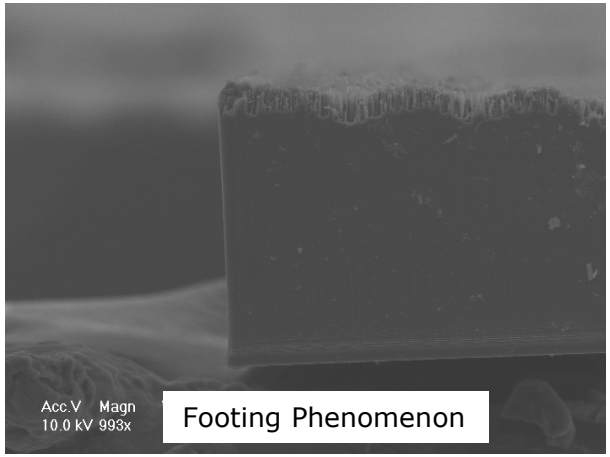
- **Comparison between Hand-calculated / Measured Result**

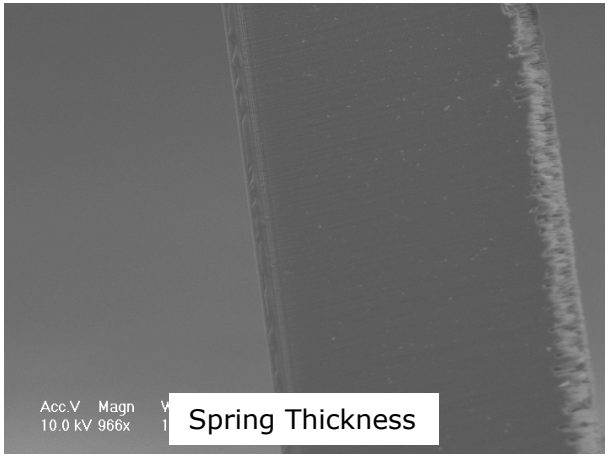
	After Fabrication	Measurement result
Spring width	10 μm	9.283 μm
Thickness of spring	57.9 μm	54~57 μm
Thickness of mass	57.9 μm	56~58 μm
Resonance frequency(x direction)	5.619 kHz	4.702 ~ 5.130kHz
Resonance frequency(y direction)	5.268 kHz	4.240 ~ 4.605kHz

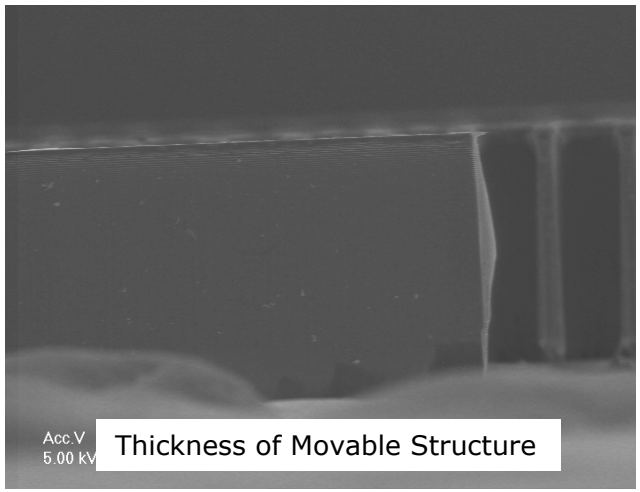
2008 Design review #6 (cont'd)

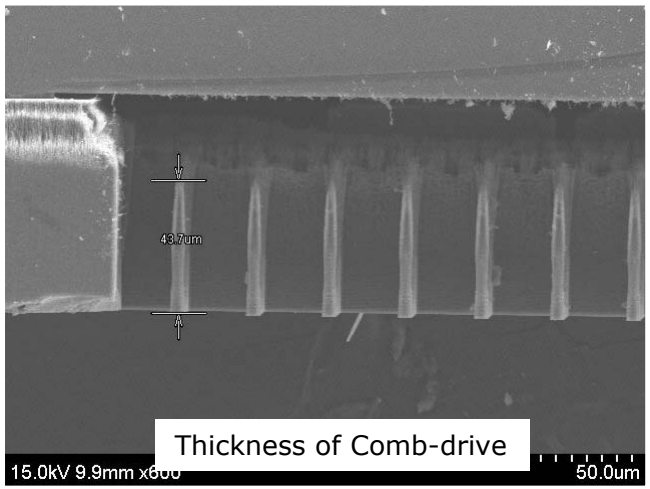
- **SEM image of Fabricated Results**





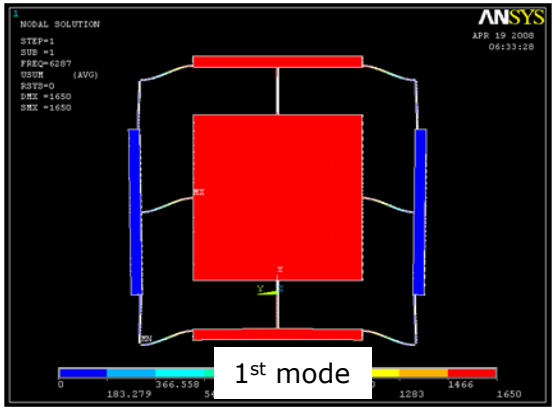


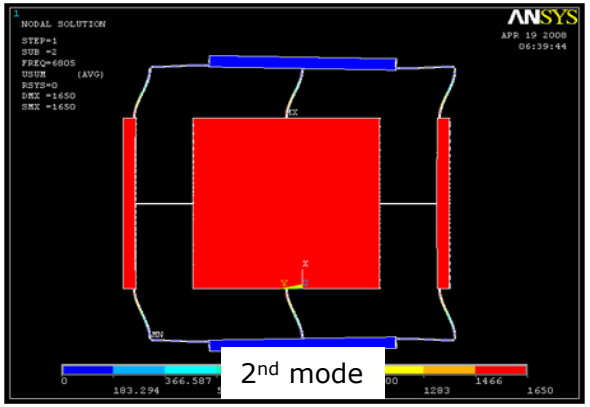


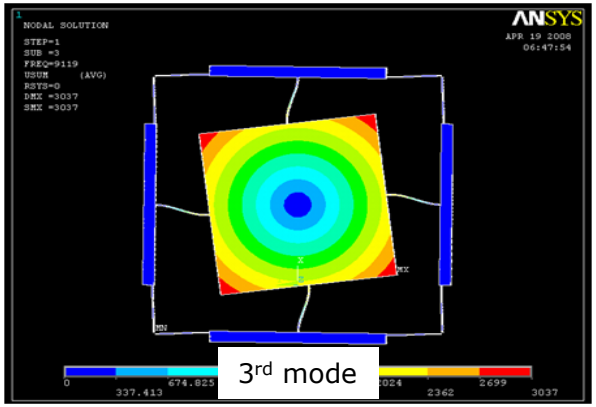


2008 Design review #7

• **Modal Analysis Results**







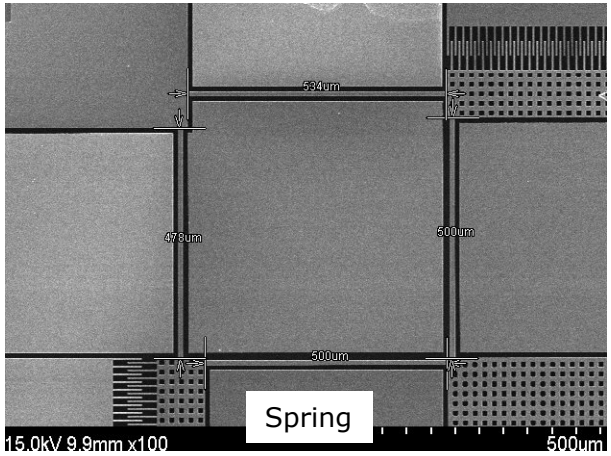
Target frequency	Calculation	Simulation
Y-axis resonant frequency	5.16 KHz	5.16 KHz
X-axis resonant frequency	5.59 KHz	5.62 KHz

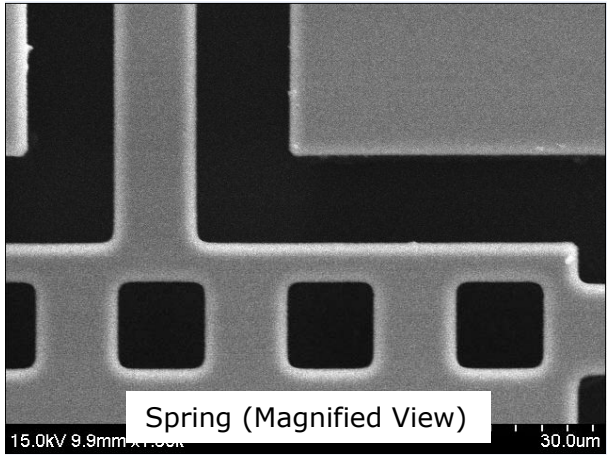
• **Comparison between Hand-calculated / Measured Result**

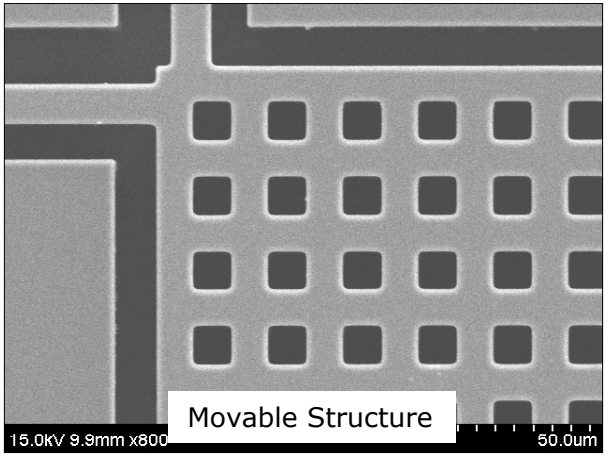
Parameter	Design[um]	Fabrication[um]
Mass thickness	65.0	60.0~61.0
Spring thickness	65.0	55.0~56.0
Comb thickness	65.0	52.0~55.0
Resonance frequency	5.59, 5.16 KHz	4.62, 4.22 KHz

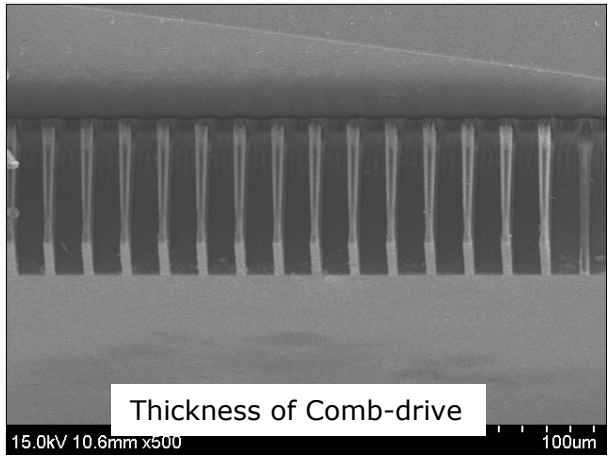
2008 Project review #7 (cont'd)

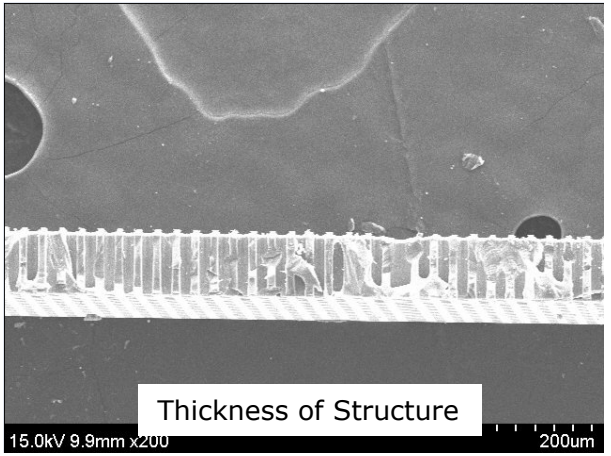
- **SEM image of Fabricated Results**





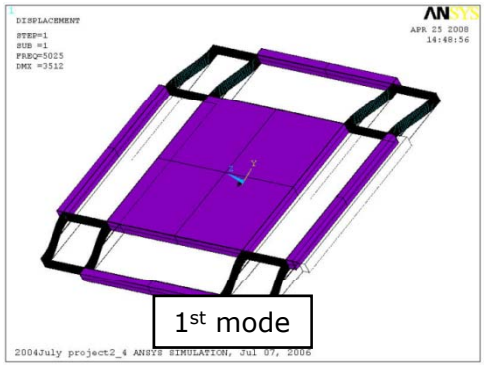


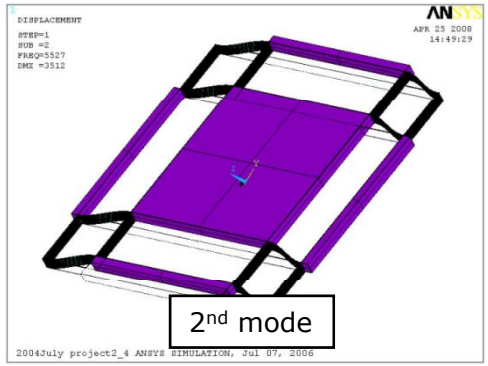


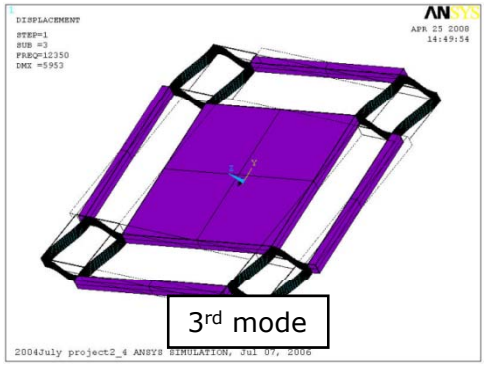


2008 Project review #8

- **Modal Analysis Results**







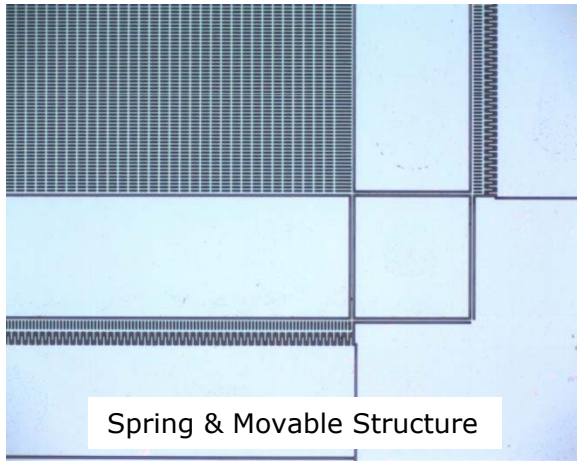
	1st mode	2nd mode	3rd mode	4th mode
Simulation freq.	5.025 kHz	5.527 kHz	13.285 kHz	37.17 kHz
Target freq.	5 kHz	5.5 kHz	-	-
Movement	X-axis	Y-axis	Θ	-

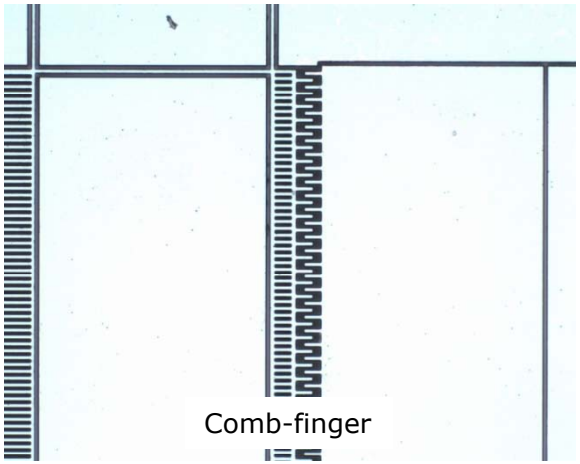
- **Summarized Result**

		Resonant freq.	DC+AC maximum actuation voltage	Actuation displacement
1st mode	Result	4.88 kHz	180 V	1.5 um
	Expectation	5.025 kHz	182.7V	1 um
	error	0.145kHz (3%)	2.7V (1.5%)	50%
2nd mode	Result	5.38 kHz	250V	2um
	Expectation	5.527 kHz	200V (25%)	2um
	error	0.147 kHz (2.7%)	50V (25%)	0%

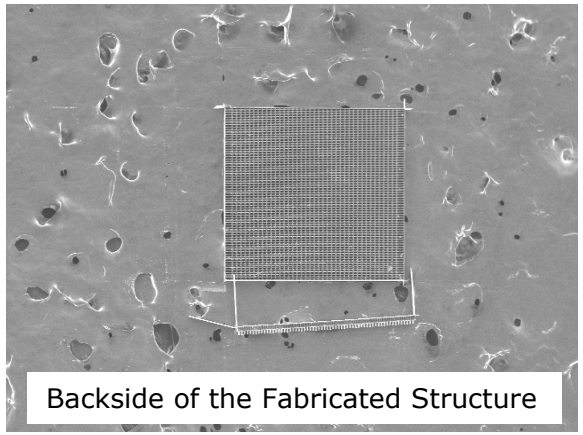
2008 Project review #8 (cont'd)

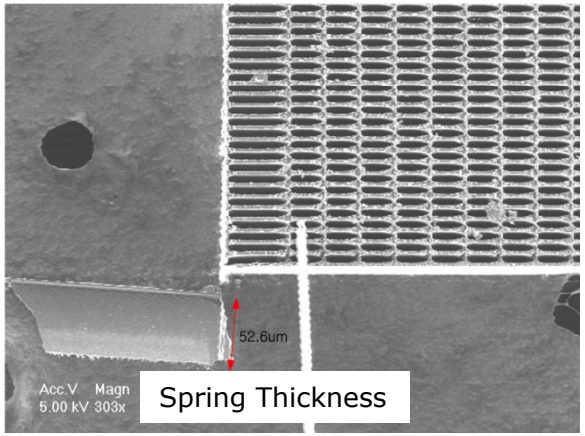
- **Microscope image of Fabricated Results**


Spring & Movable Structure


Comb-finger

- **SEM image of Fabricated Results**

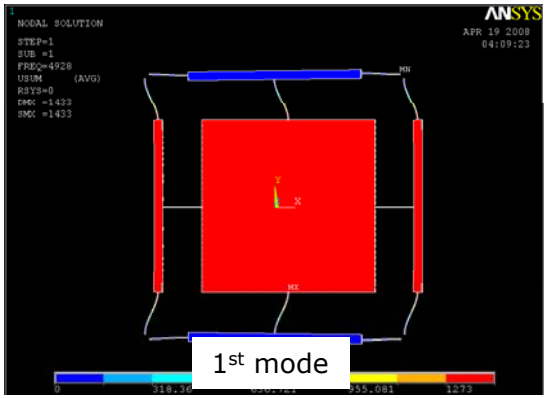

Backside of the Fabricated Structure



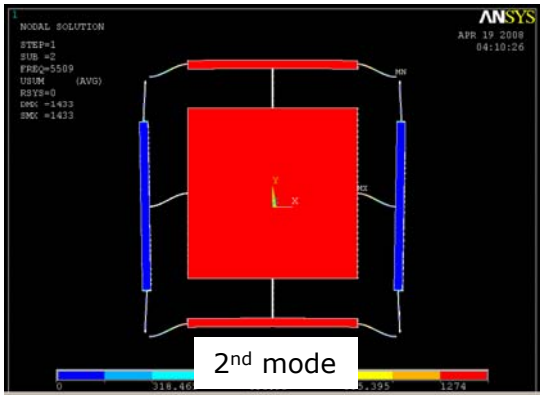
Spring Thickness

2008 Project review #9

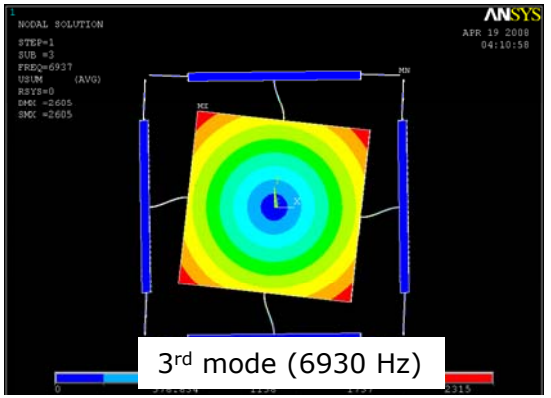
• **Modal Analysis Results**



1st mode



2nd mode



3rd mode (6930 Hz)

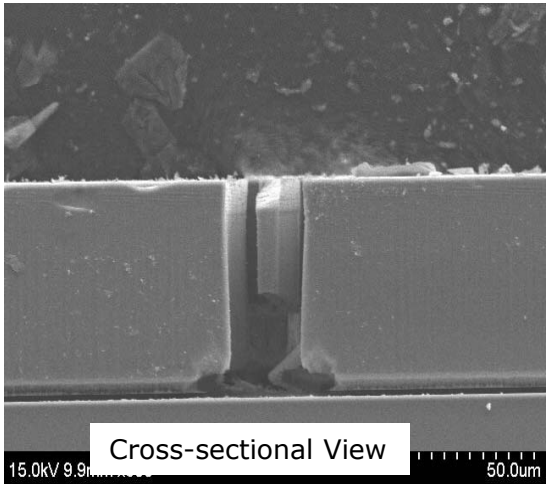
	Design	Simulation	Error(%)
Mass(kg)	3.723E-07	3.89E-07	4.5
f_{rx} (Hz): 1st mode	4784	4982	4.0
f_{ry} (Hz): 2nd mode	5271	5509	4.3
Difference of resonant frequency(Hz)	487	527	7.5

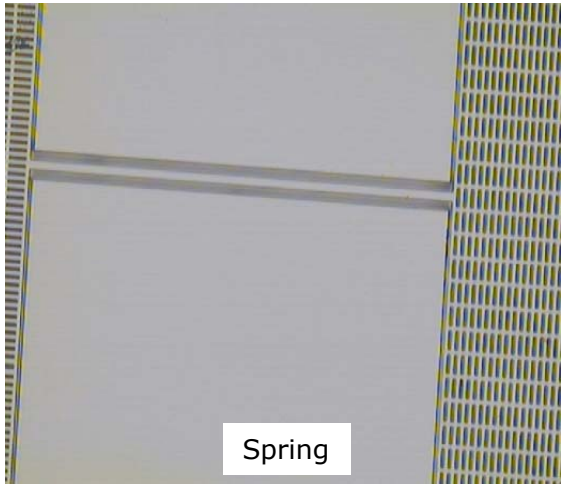
• **Summarized Result**

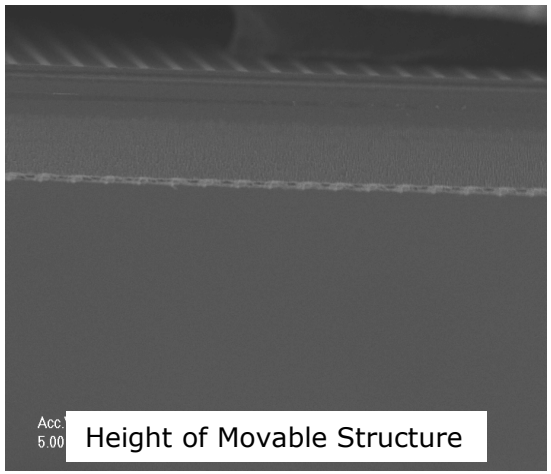
Device number		1	2	3	4	5	6	7	8	9	10
frequency (Hz)	X axis	4890	4980	4950	5070	4910	4640	5060	4950	4950	4890
	Y axis	4370	4480	4450	4570	4400	4140	4510	4440	4420	4360
difference(Hz)		520	500	500	500	510	500	550	510	530	530

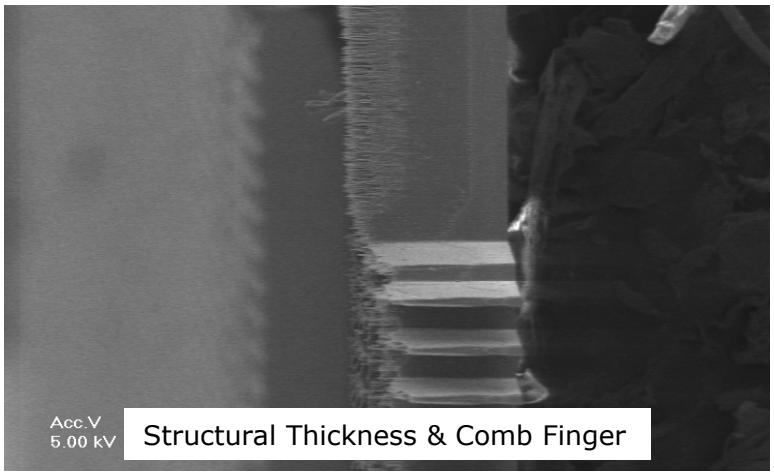
2008 Project review #9 (cont'd)

- **SEM image of Fabricated Results**



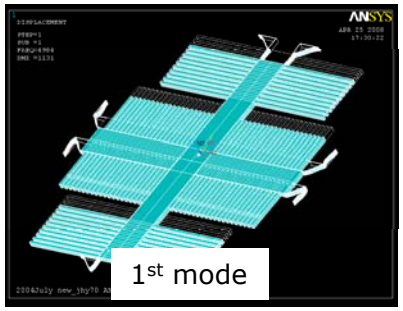


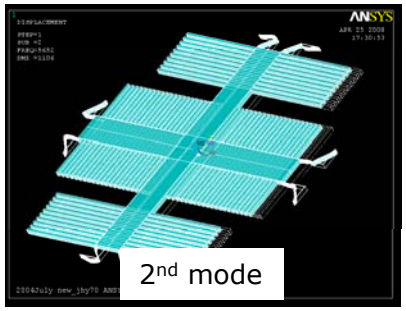


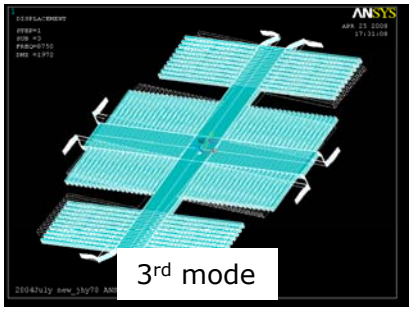


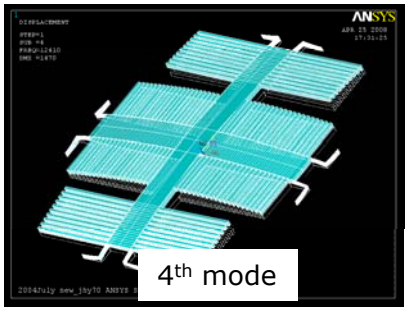
2008 Project review #10

• **Modal Analysis Results**









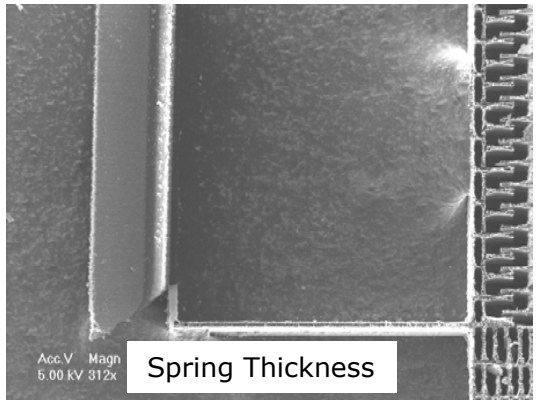
	1st mode	2nd mode	3rd mode	4th mode
Frequency (f)	4985 Hz	5652 Hz	8750 Hz	12410 Hz
Movement	y-axis	x-axis	Θ	Z-axis

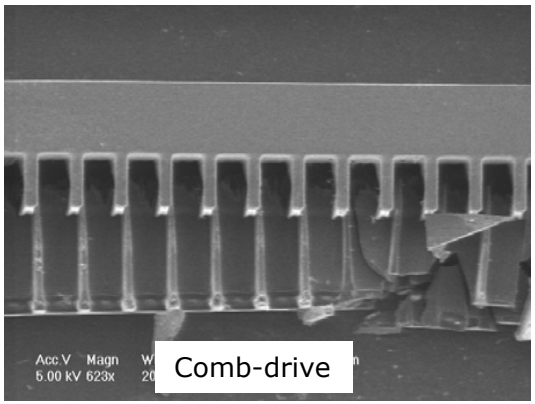
• **Summarized Result**

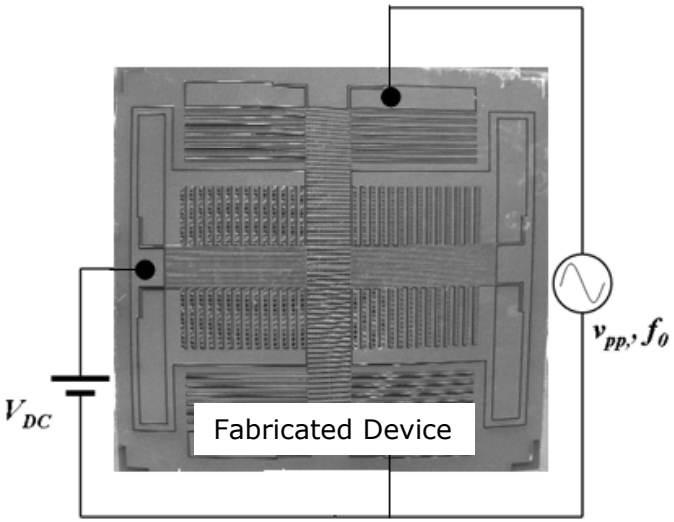
	Design		Fabrication	
Mass (kg)	6.81e-8		6.56e-8	
Stiffness (N/m)	77.62	64.74	79.13	65.72
Resonance Frequency (k Hz)	**5.50**	**5.01**	**5.59**	**5.07**

2008 Project review #10 (cont'd)

- **SEM image of Fabricated Results**







- **Microscope image of Fabricated Results**