Lecture 3:

2006 Term Project Review

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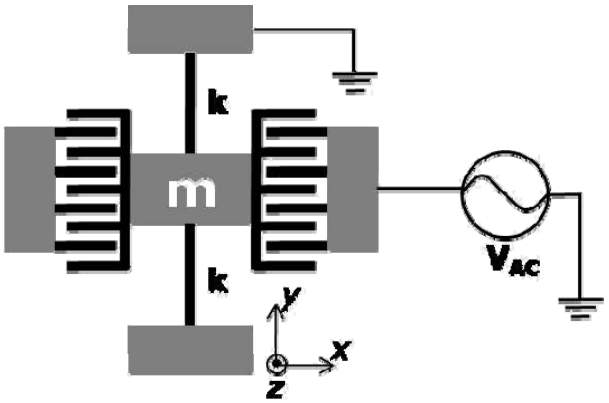
Project Goals & Design Constraints

- Design a resonator to resonate at exactly 10 kHz
  - Atmospheric pressure
  - Resonate at 10 kHz ± 0.5 kHz
  - Low actuation voltage

- Design Constraints
  - Die size: 4mm X 4 mm
  - Lithography, etch constraints: 4 um (line and space)
  - Minimize the footing phenomenon
  - Resonance frequency: 10 kHz ± 0.5 kHz
  - Actuation voltage: The lower, the better

Measurement Considerations

- Why use biased AC voltage?



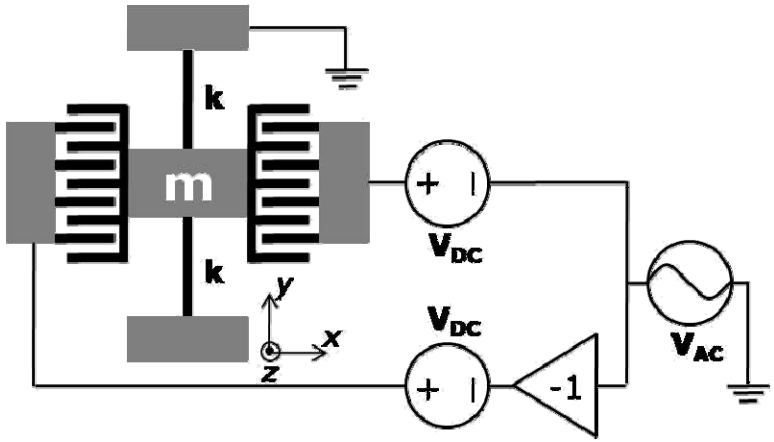
[Only AC voltage]

$$F \propto V^2$$

$$F \propto V_{AC}{}^2 = V_{AC\_MAX}{}^2 \cos^2 \omega t$$

$$F \propto (1 + \cos 2\omega t)$$

→ DC term & 2ω term remains



[Biased AC voltage]

$$F \propto V^2$$

$$F \propto [(V_{DC} + V_{AC})^2 - (V_{DC} - V_{AC})^2]$$

$$F \propto V_{DC} V_{AC} = V_{DC} V_{AC\_MAX} \cos \omega t$$

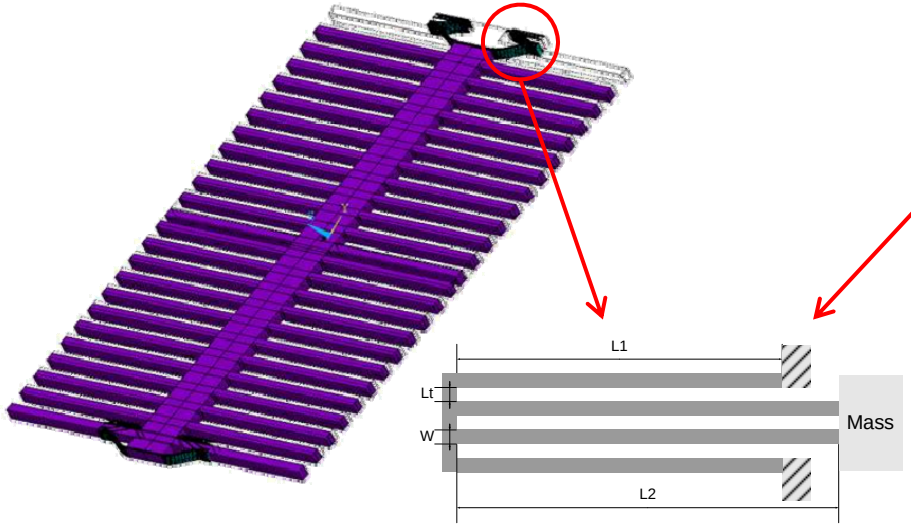
$$F \propto \cos \omega t$$

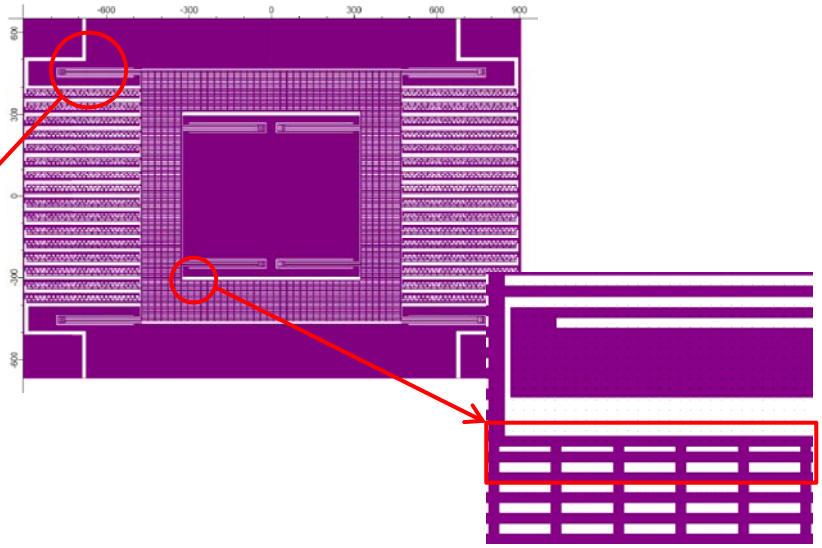
2006 Design Summary

	#	1		2	3	4	5		6	7	8		9	10	11
	Type	**#1**	**#2**	**#1**	**#1**	**#2**	**#1**	**#2**	**#1**	**#1**	**#1**	**#2**	**#1**	**#1**	**#1**
spring design	type	folded -flexure	folded -flexure	folded -flexure	folded	folded	folded -flexure	folded -flexure	folded	folded	folded	folded	folded -flexure	folded	guided -end
	spring constant [N/m]	396	206.4	429.93	178	30.6	729	1978	2112	625	94.6	109.6	24.1	654	108.7
mass design	Mass [kg]	1.00E-07	4.70E-08	1.09E-07	5.19E-08	9.02E-09	1.29E-07	3.51E-07	4.01E-07	1.58E-07	2.20E-08	2.30E-08	6.13E-09	1.71E-07	2.75E-08
target frequency	**[kHz]**	**10.02**	**10.55**	**10.00**	**9.32**	**9.27**	**11.96**	**11.95**	**11.60**	**10.00**	**10.40**	**11.00**	**9.98**	**9.85**	**10.00**

result	**actuation**	o	x	o	x	x	x	o	x	x	o	o	o	o	o
	actuation frequency [kHz]	9.5	-	9.2	-	-	-	9.8	-	-	9.8	10	10.1	9.9	10
	applied voltage	24V (DC) 16V (AC)	-	12.5 (DC) 5V (AV)	-	-	-	9V (DC) 8.5V (AC)	-	-	24V (DC) 16V (AC)	40V (DC) 32V (AC)	- (DC) 10.1(AC)	28V (DC) 5V (AC)	4.8V (DC) 5V (AC)

Comb Resonator Design 1





DC Voltage	24 V
AC Voltage	16 V
Natural Frequency	9.1 kHz ~ 10.1 kHz
Remarks	# of spring : 4

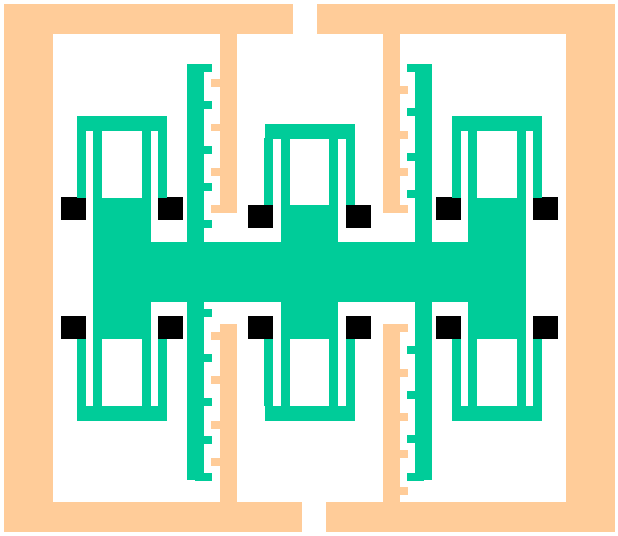
[Design 1]

DC Voltage	-
AC Voltage	-
Natural Frequency	-
Remarks	# of spring : 8

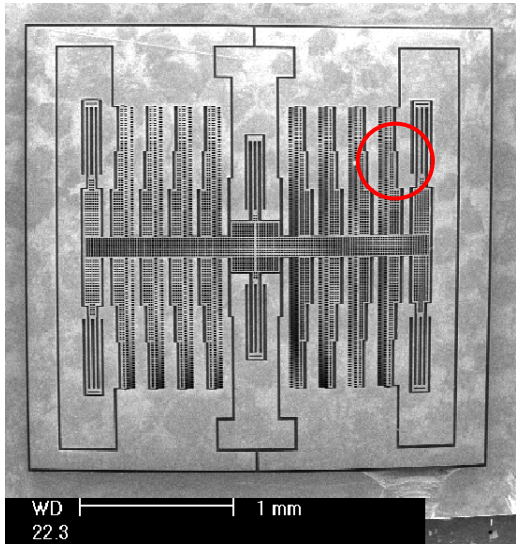
[Design 2]

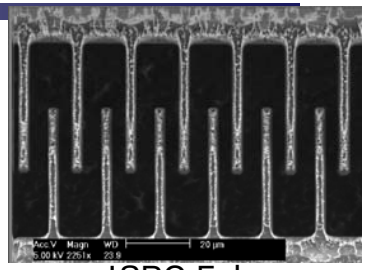
• Too small etch hall → Release failure

Comb Resonator Design 2

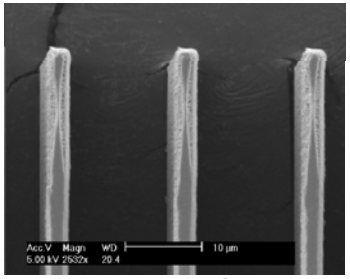


[Layout]





ISRC Fab.



KETI Fab.

[SEM Image]

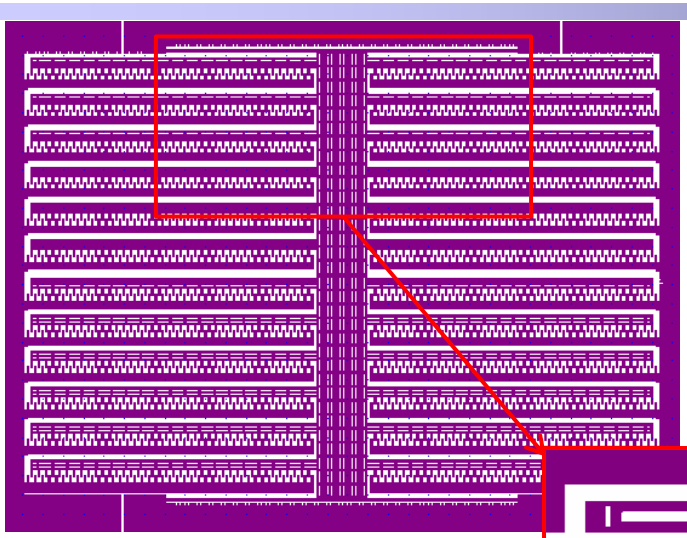
DC Voltage	12.5 V
AC Voltage	5 V
Natural Frequency	ISRC: 9.2 kHz KETI: 9.9 kHz
Remarks	Spring width : 5um (ISRC Fab., KETI Fab.)

• Less footing effect → More accurate frequency

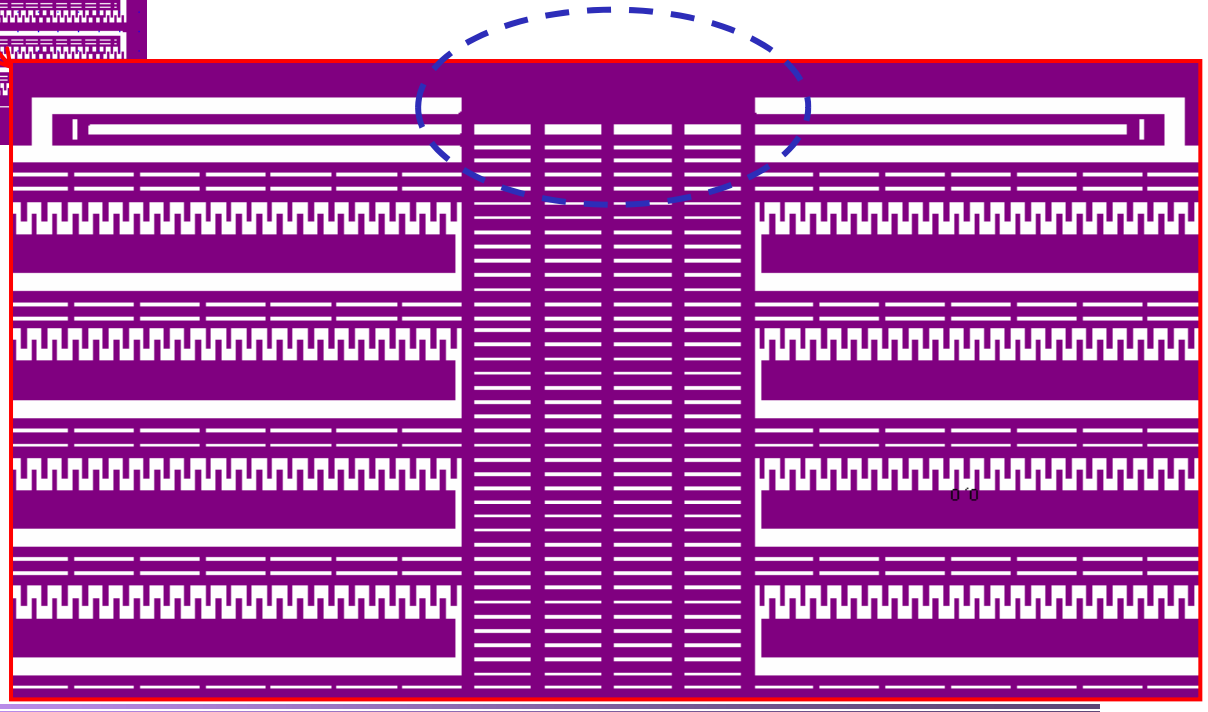
DC Voltage	12.5 V
AC Voltage	5 V
Natural Frequency	ISRC: 7.5 kHz
Remarks	Spring width : 10um (ISRC Fab.)

• Footing effect → Frequency spec out

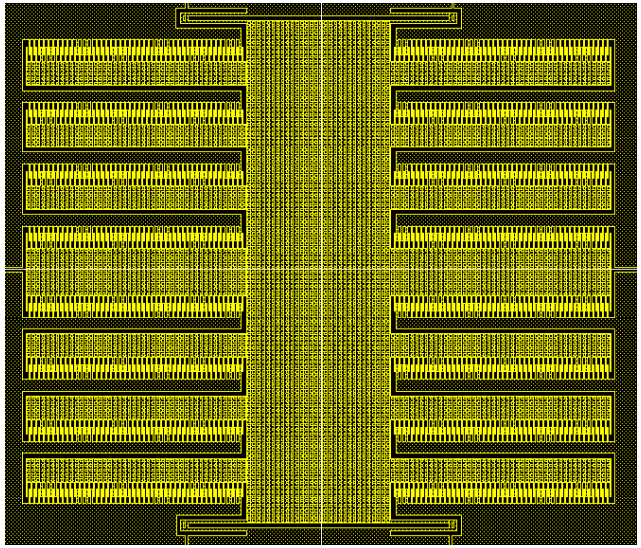
Comb Resonator Design 3



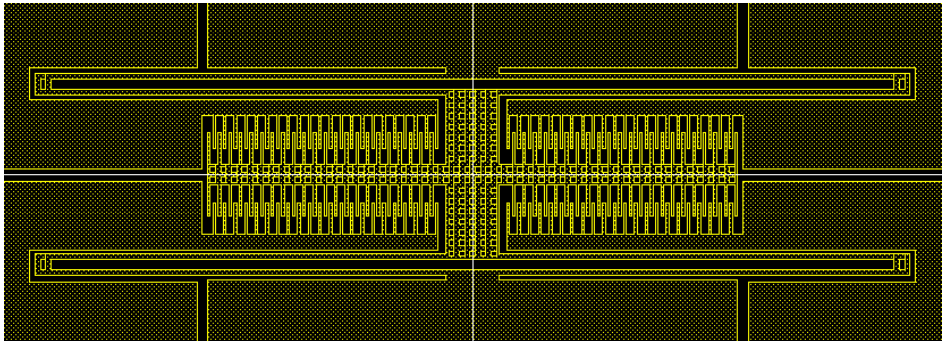
[Layout]



Comb Resonator Design 4



[Design 1]



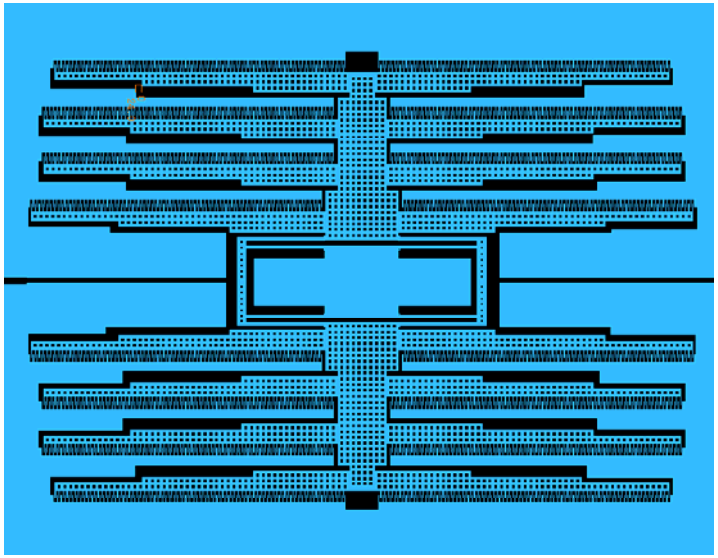
[Design 2]

DC Voltage	20 V
AC Voltage	15 V
Natural Frequency	8.3 kHz
Remarks	Design 2/ISRC Fab.

DC Voltage	15 V
AC Voltage	10 V
Natural Frequency	9.27 kHz
Remarks	Design 2/KETI Fab.

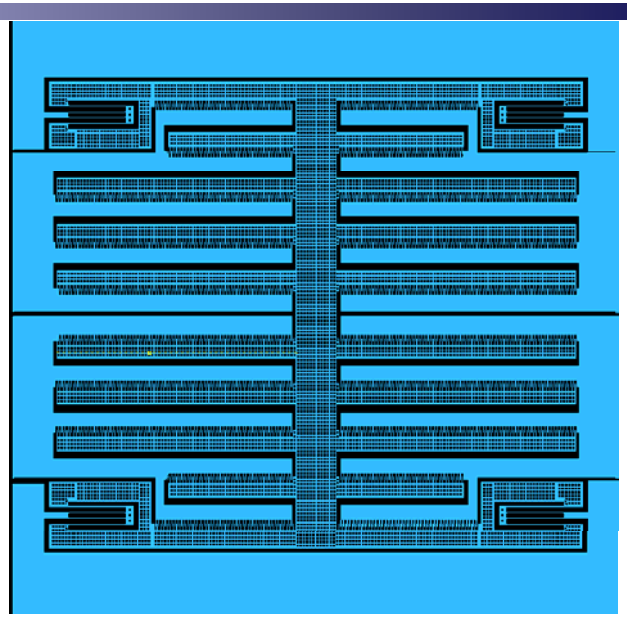
• Footing & Under cut difference → Spring & Mass difference → Frequency difference

Comb Resonator Design 5



DC Voltage	-
AC Voltage	-
Natural Frequency	-
Remarks	1st mode: Z-axis 2nd mode: X-axis

[Design 1]

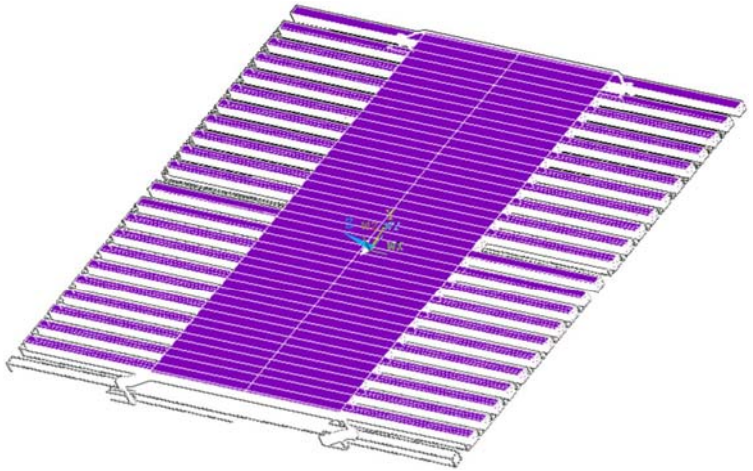


DC Voltage	9 V
AC Voltage	8.5 V
Natural Frequency	9.85 kHz
Remarks	-

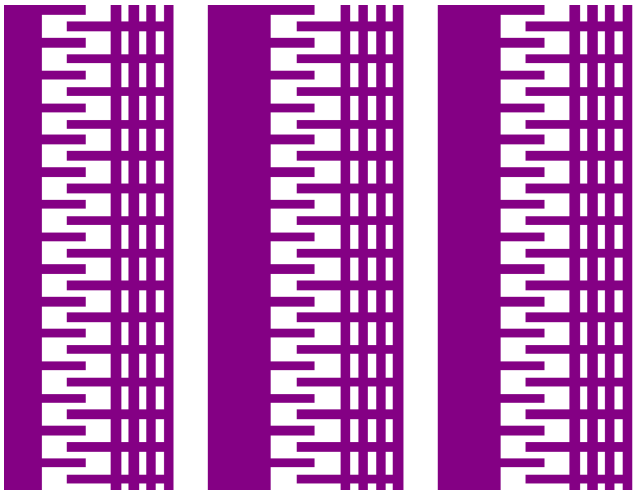
[Design 2]

• All spring is close each other → Wrong actuating mode

Comb Resonator Design 6



[Layout]



[Comb Design]

DC Voltage	-
AC Voltage	-
Natural Frequency	-
Remarks	Designed Freq.: 9.475 kHz

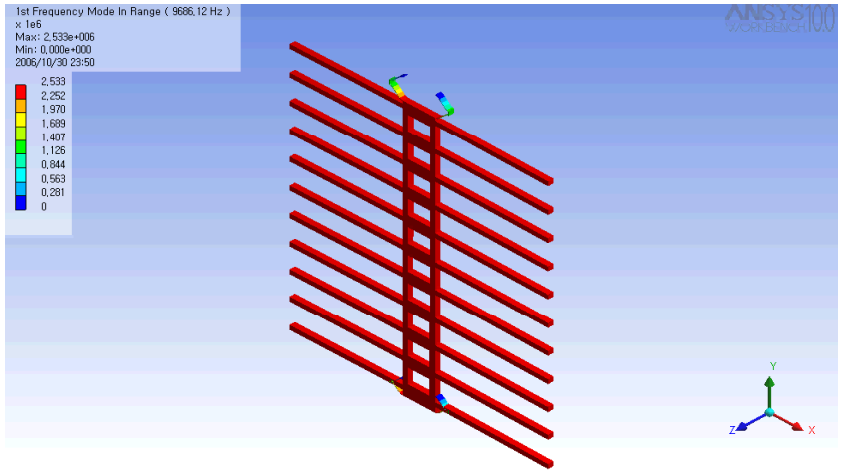
[Design 1]

DC Voltage	-
AC Voltage	-
Natural Frequency	-
Remarks	Designed Freq.: 10.01 kHz

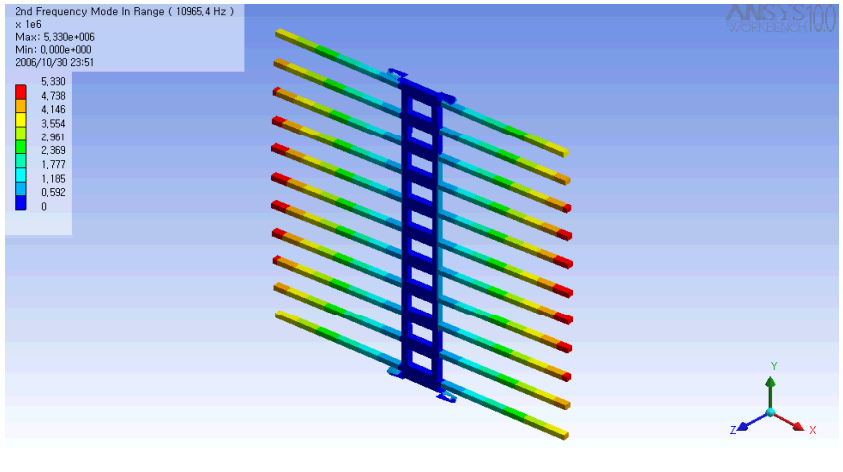
[Design 2]

- Two beams are close etch other → Electrostatic force problem
- Large mass & short spring

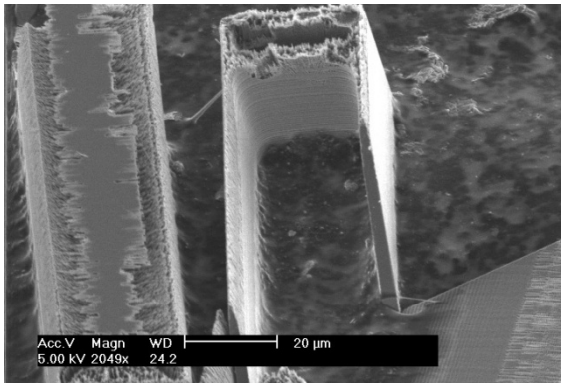
Comb Resonator Design 7

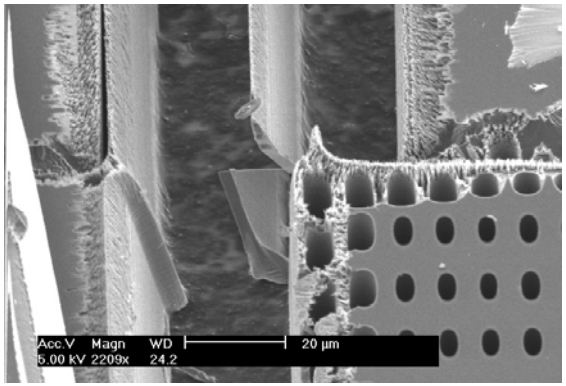


[1st mode: 9.69 kHz]



[2nd mode: 10.97 kHz]

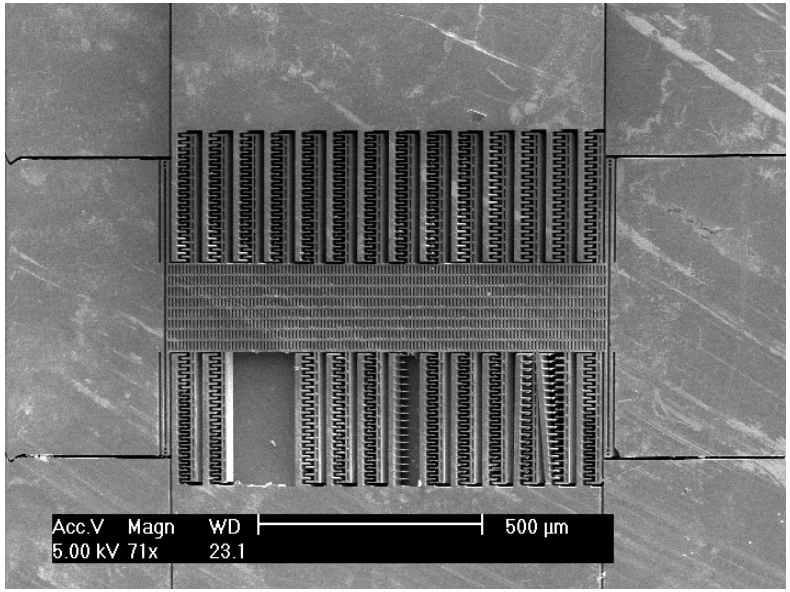


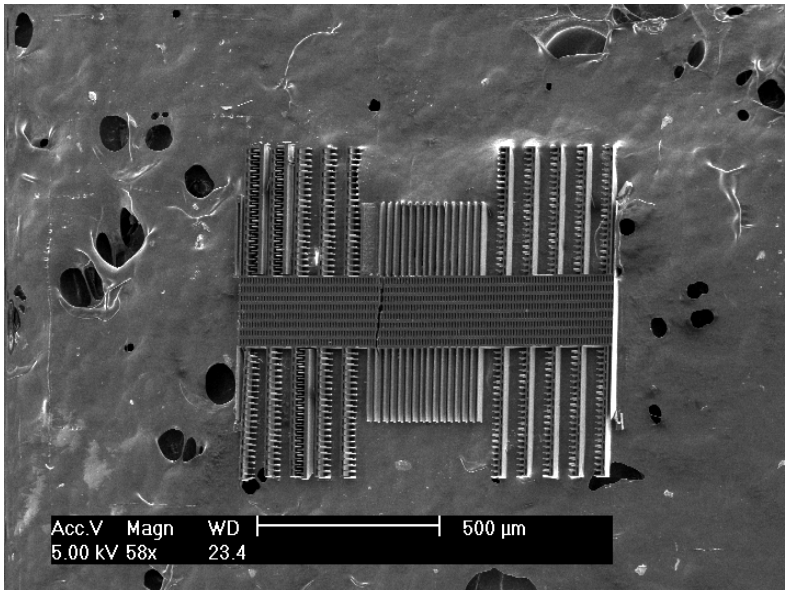


[SEM Image]

- Two modes are close etch other → Wrong actuating mode
- Cleaning problem after release → Particle under the structure

Comb Resonator Design 8





DC Voltage	24 V
AC Voltage	16 V
Natural Frequency	9.7 kHz ~ 10.3 kHz
Remarks	No Tuning

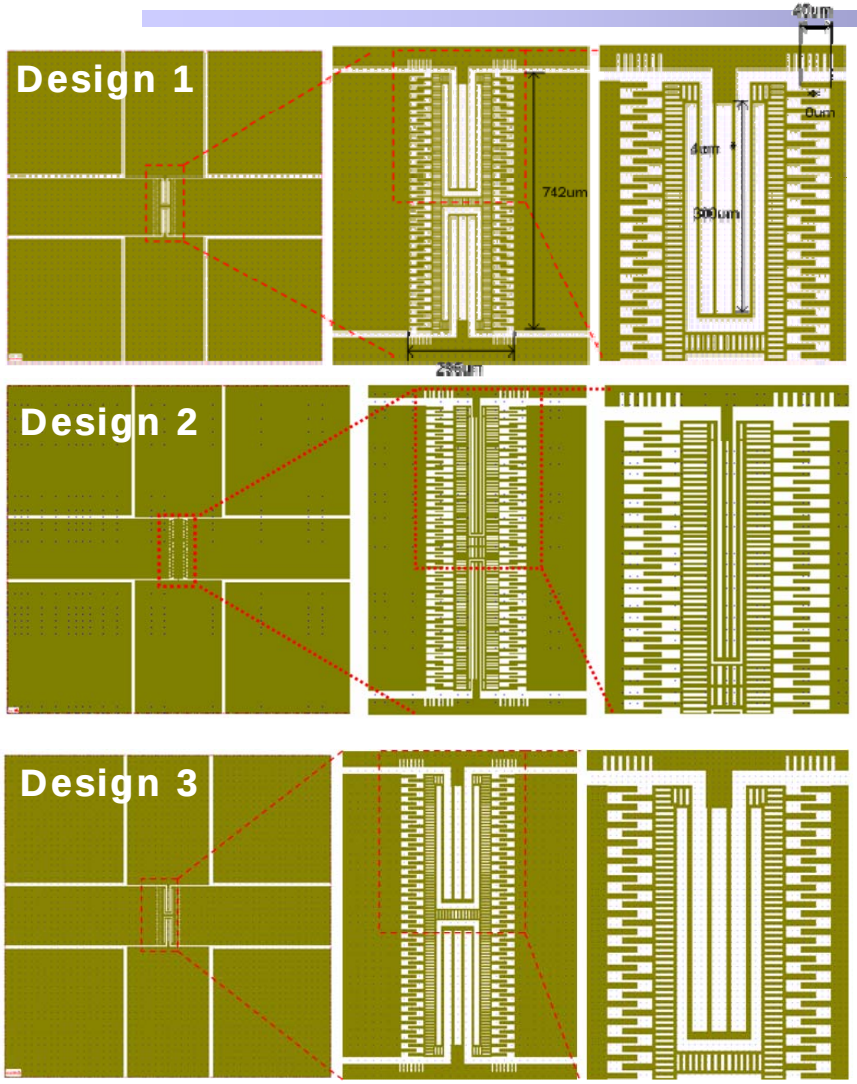
[Design 1]

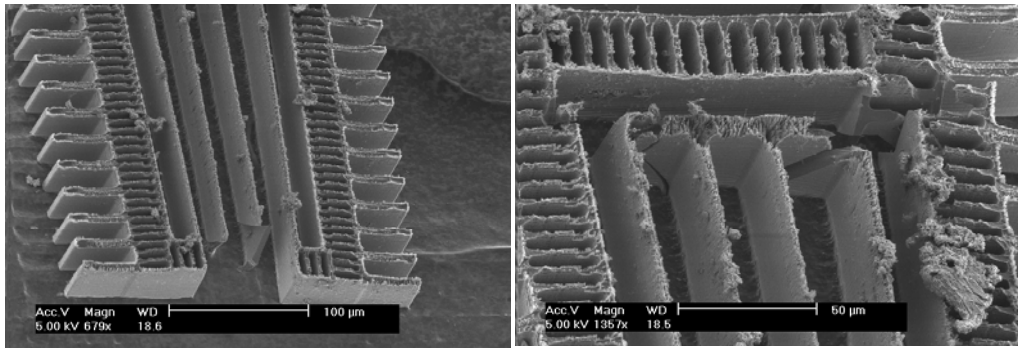
DC Voltage	40 V
AC Voltage	32 V
Natural Frequency	10 kHz
Remarks	Tuning Voltage : 0 V

[Design 2]

• Using the negative stiffness effect for natural frequency control

Comb Resonator Design 9



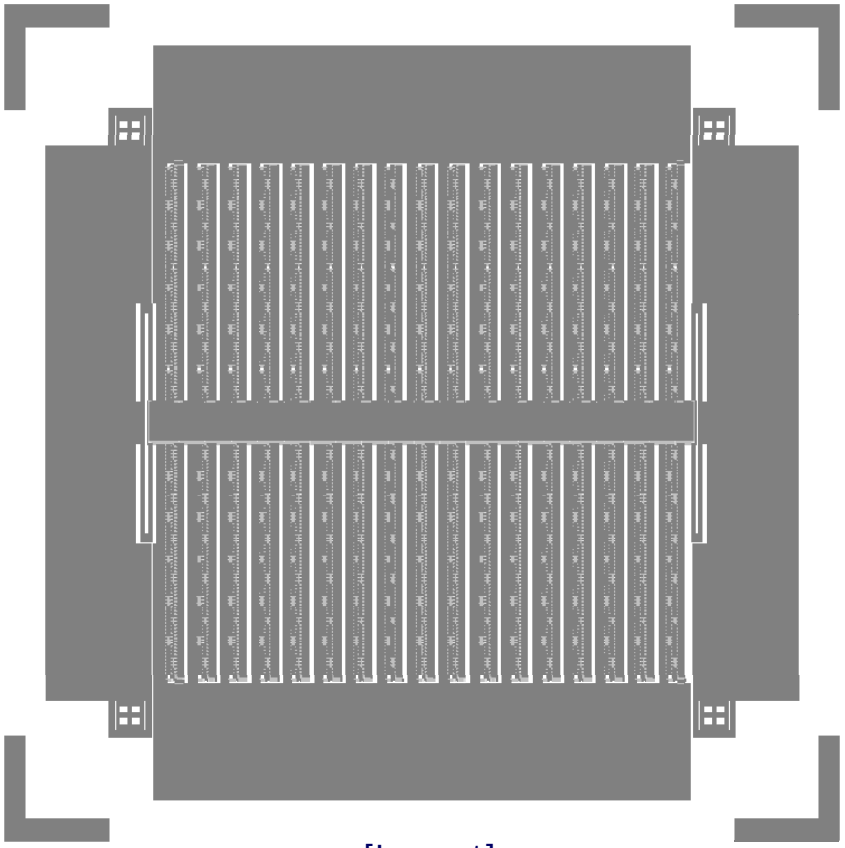


[SEM Image]

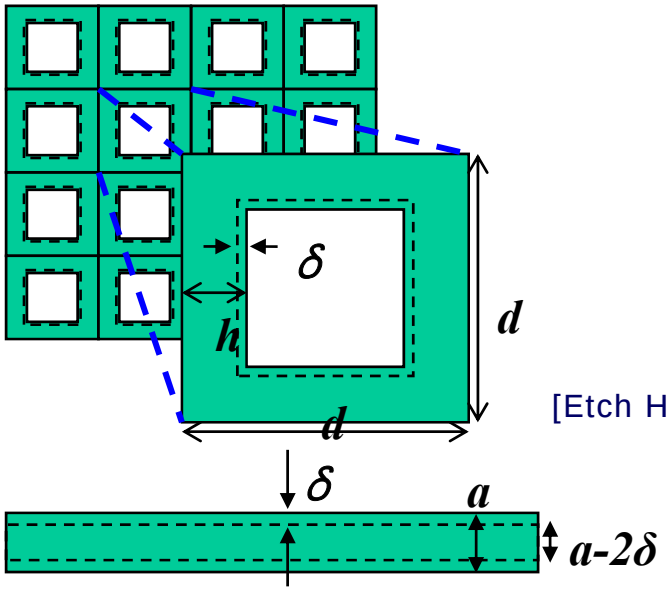
	Design 1	Design 2	Design 3
Input Voltage	2.5 V	2.5 V	20 V
Natural Frequency	8.1 kHz	10 kHz	9.0 kHz
Remarks	Size (um^2) [742 X 296]	Size (um^2) [742 X296]	Size (um^2) [742 X 296]

• Simple design is good for estimation.

Comb Resonator Design 10



[Layout]



[Etch Hole]

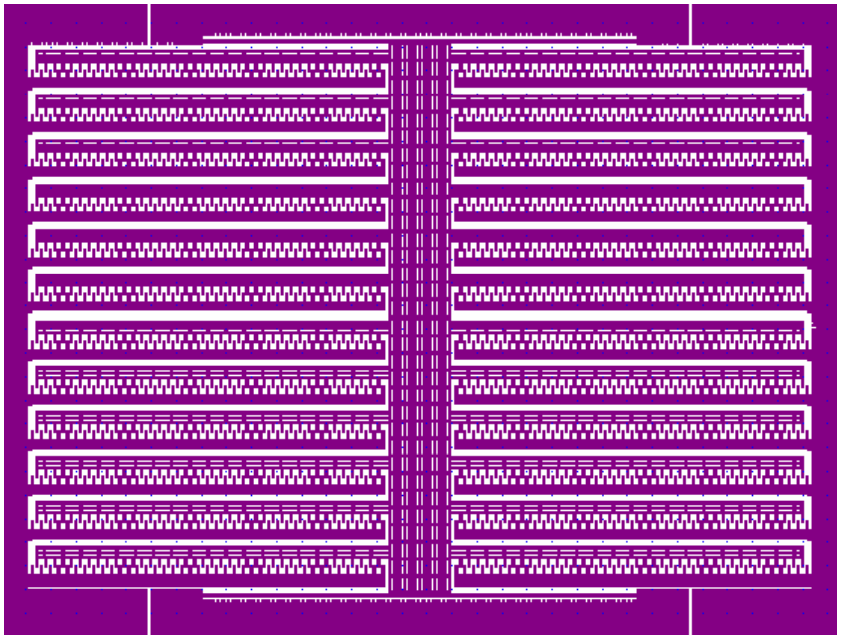
[Spring width]

- Under cut compensation

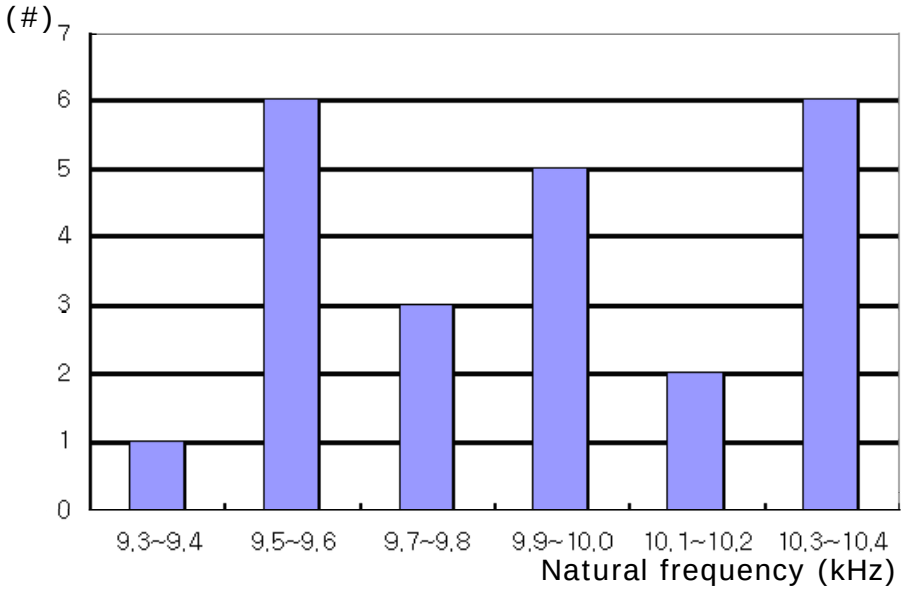
→ Robust design

DC Voltage	35 V	28 V
AC Voltage	5 V	5 V
Natural Frequency	9.3 kHz	9.9 kHz
Remarks	Spring width: 15 um	Spring width: 20 um

Comb Resonator Design 11



[Layout]



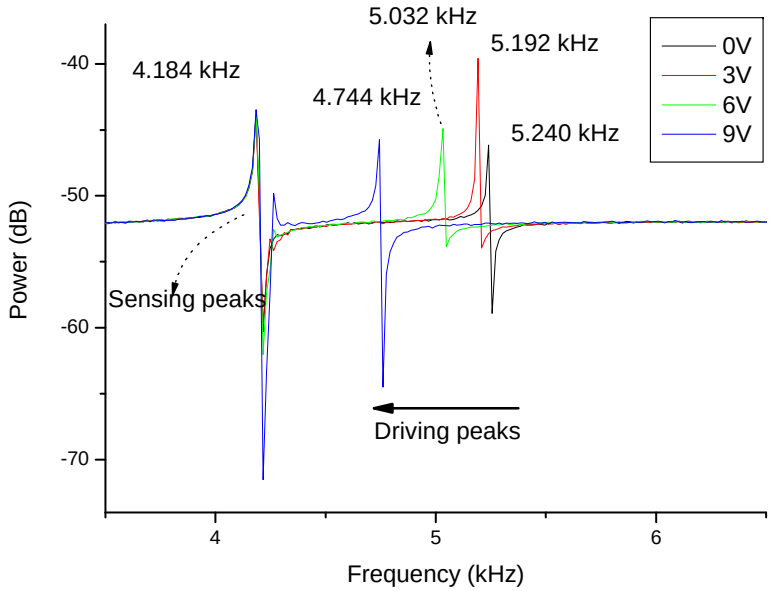
[Result]

- Many samples → 10 kHz sample
- Histogram

DC Voltage	4.8 V
AC Voltage	5 V
Natural Frequency	10 kHz

Conclusions & Q/A

- Layout Design with Fabrication error compensation
  - Etch lag phenomenon, Footing effect, etc
- Release
  - Anchor design issue
- Simple design
- Negative Stiffness Effect
  - Can control frequency by applying voltage



Example of negative stiffness effect

ref) Nam-kuk Kim, "Decoupled Gyroscope Using Actuating Frequency Tunable Comb," M.S. Thesis, 2008.2