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on Sensors and Applications

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Assessment of micromechanically-induced uncertainties in the electromechanical response of MEMS devices

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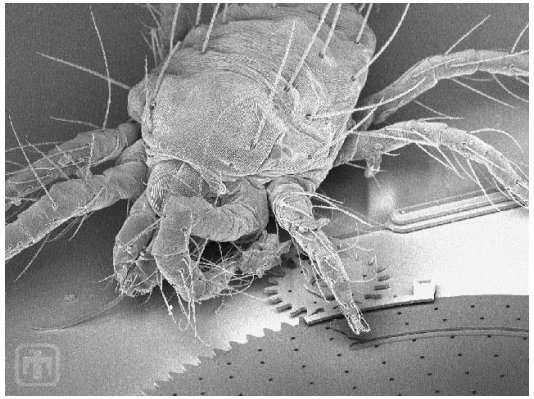
Motivation

❖ MicroElectroMechanical Systems (MEMS)

miniaturization and reliability



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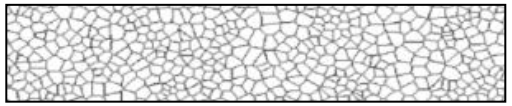
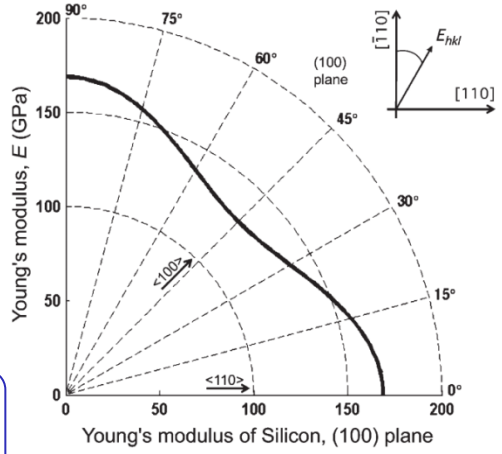
- ❖ **Polysilicon** a popular material in MEMS fabrication
- ❖ **Anisotropic crystalline** material whose material properties depends on the **relative orientation** to the crystal lattice
- ❖ **Characteristic length** of mechanical components can be compared to the size of grains

❖ Morphology & crystal lattice orientation



Sources of uncertainties in device static/dynamic response



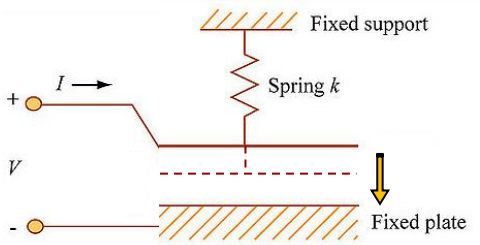
Hopcroft,M.A.,et.al.,"What is the Young Modulus of Silicon?", *JMEMS*,2010

- ❖ As **the Characteristic length** of mechanical components decreases the effects of fabrication inaccuracies emerge

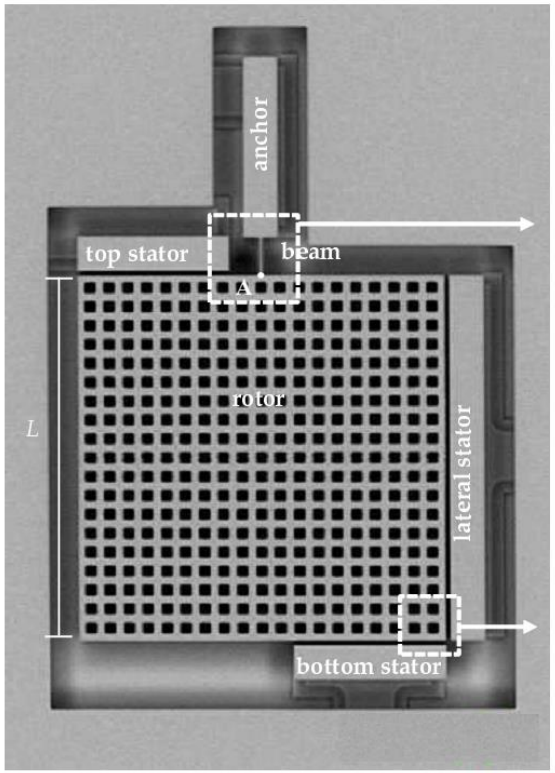
❖ Type & amplitude of these fabrication imperfections

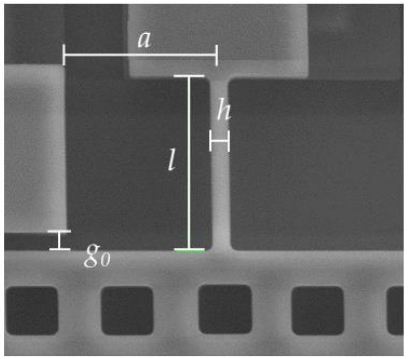
Experiments design

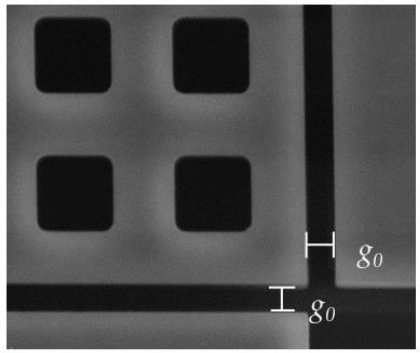
- Electrostatic actuation/sensing
- Microcantilever
- 4 testing configurations in a simple design



Actuation
- Rotational capacitors
- Lateral capacitor



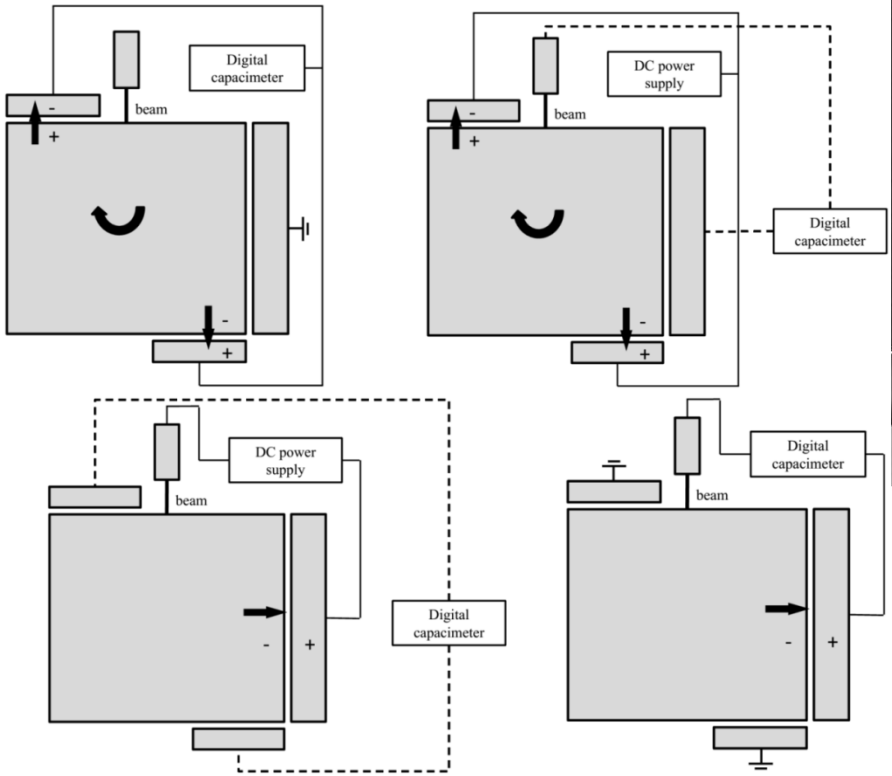


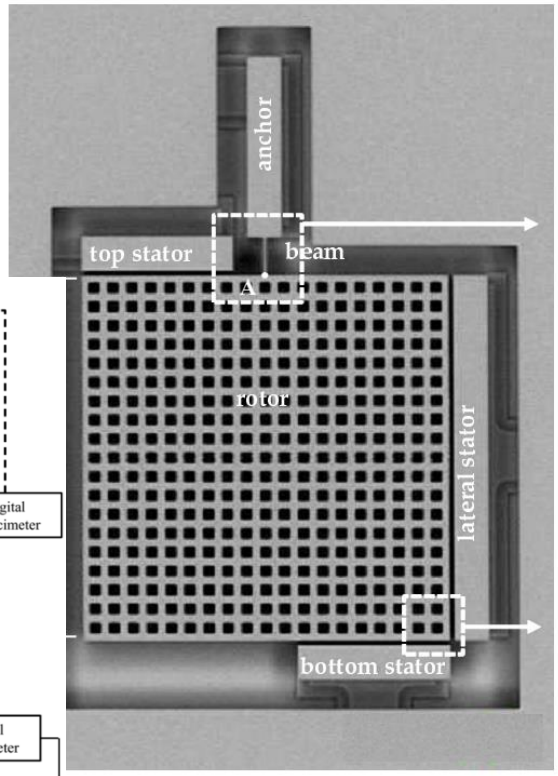


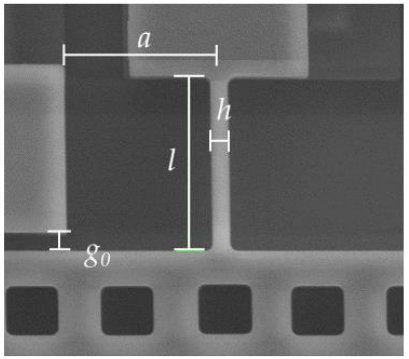
Designed gap	$g_0 = 2$ μm
Designed beam thickness	$h = 2$ μm
Beam length	$l = 20$ μm

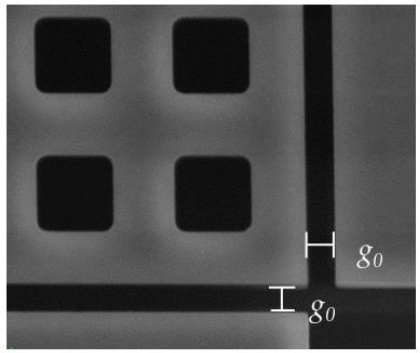
Experiments design

- Electrostatic actuation/sensing
- Microcantilever
- 4 testing configurations in a simple design







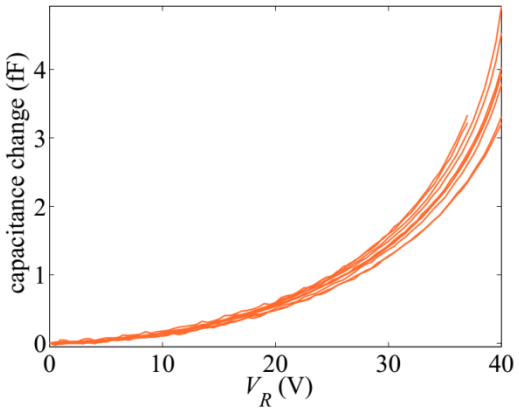


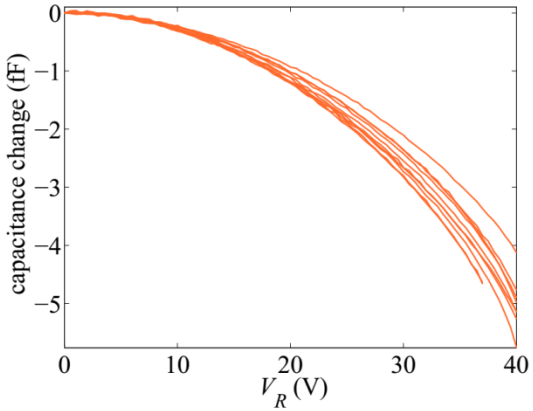
Designed gap	$g_0 = 2\ \mu m$
Designed beam thickness	$h = 2\ \mu m$
Beam length	$l = 20\ \mu m$

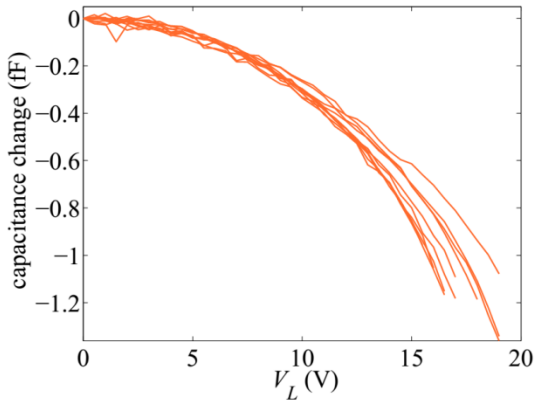
Experiments

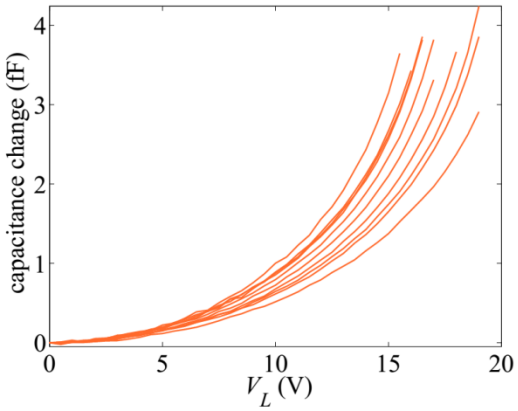
- 10 specimens are tested
- Capacitance changes in order of few fF

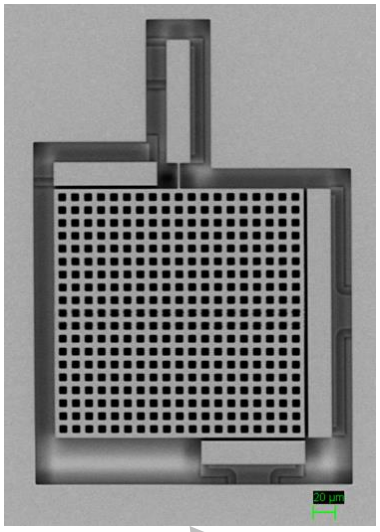
$l = 20\ \mu m$

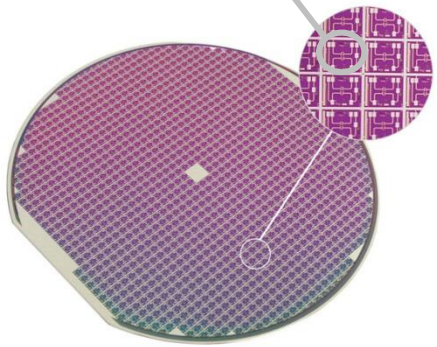












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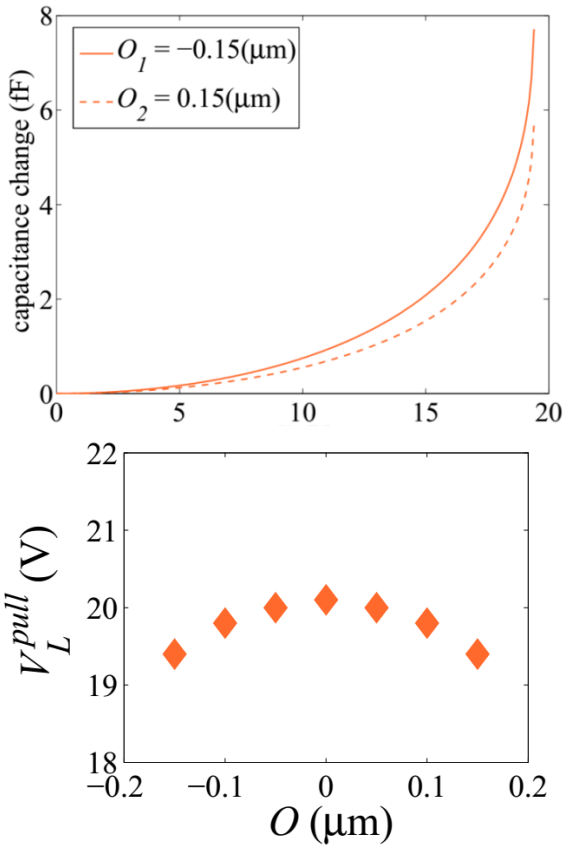
Scattering of electromechanical reseponses

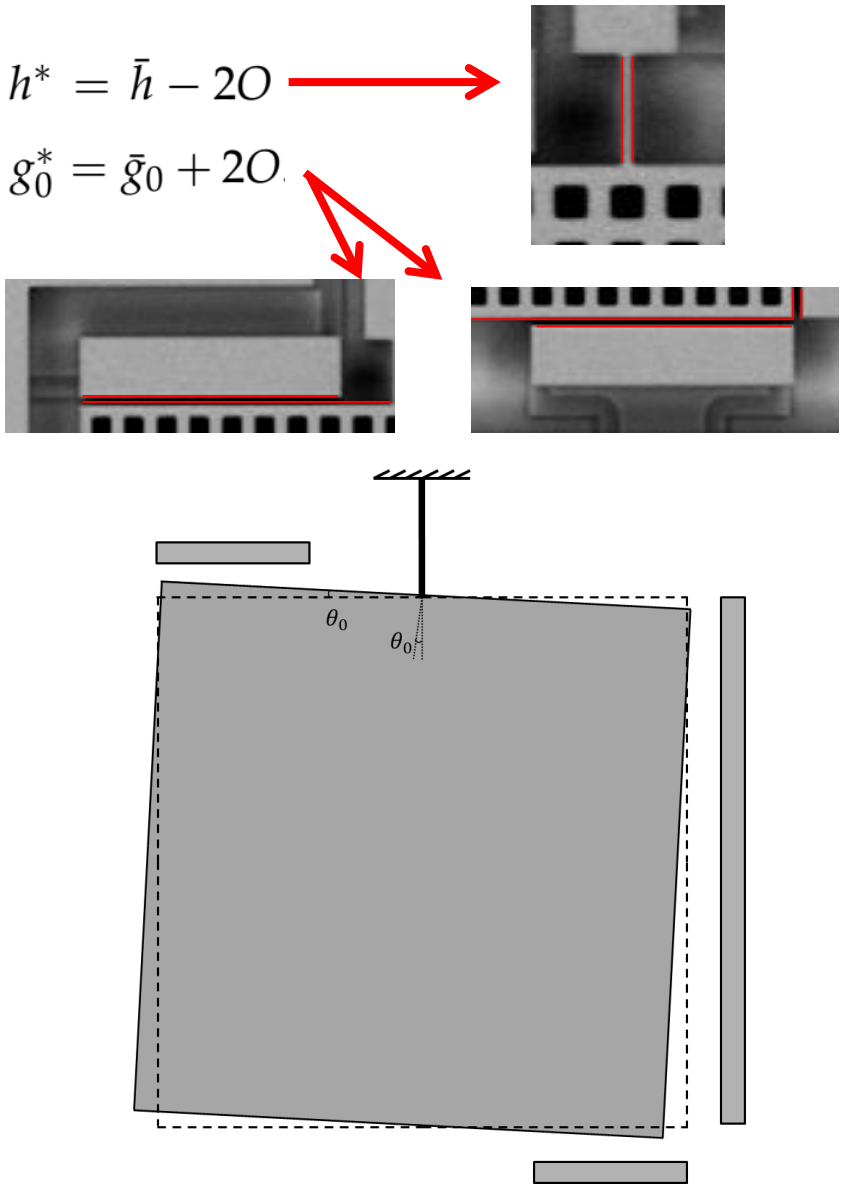
Formulating uncertainty sources

- Formulating the problem
  - Young's modulus, E
  - Overetch, O
  - Initial rotation, θ_0



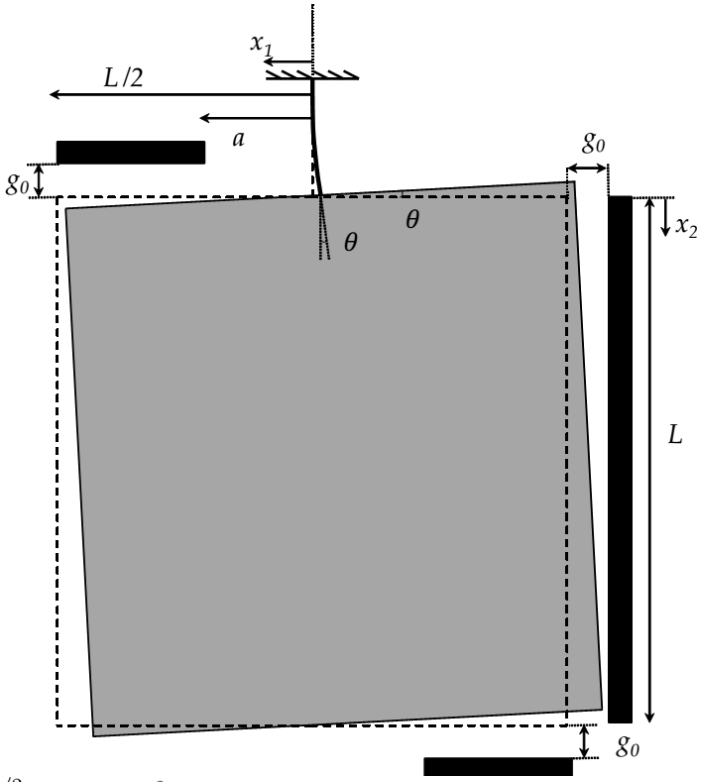
$$h^* = \bar{h} - 2O$$

$$g_0^* = \bar{g}_0 + 2O$$



Analytical modelling

- Assumption: negligible electric fringe field , perfect anchor



Euler Bernoulli

$$\begin{Bmatrix} F(l) \\ M(l) \end{Bmatrix} = \frac{EI}{l^3} \begin{bmatrix} 12 & -6l \\ -6l & 4l^2 \end{bmatrix} \begin{Bmatrix} u^E(l) \\ \theta^E(l) \end{Bmatrix}$$

Timoshenko

$$\begin{Bmatrix} F(l) \\ M(l) \end{Bmatrix} = \frac{EI}{l^3} \begin{bmatrix} 12 & -6l \\ -6l & 4l^2 \end{bmatrix} \begin{Bmatrix} u^T(l) - \frac{\Omega l^3}{EI} F(l) \\ \theta^T(l) \end{Bmatrix}$$

$$\Omega = \frac{E}{G\kappa_s} \left(\frac{l}{r}\right)^{-2} \qquad r = \sqrt{I/A_s}$$

Electrostatic potential

$$\mathbb{E} = \frac{1}{2} c V^2$$

Unit electrostatic force

$$f = \frac{\epsilon V^2}{2g^2}$$

Unit capacitance

$$c = \frac{\epsilon}{g}$$

Similar expressions for capacitance changes at two sets of capacitors

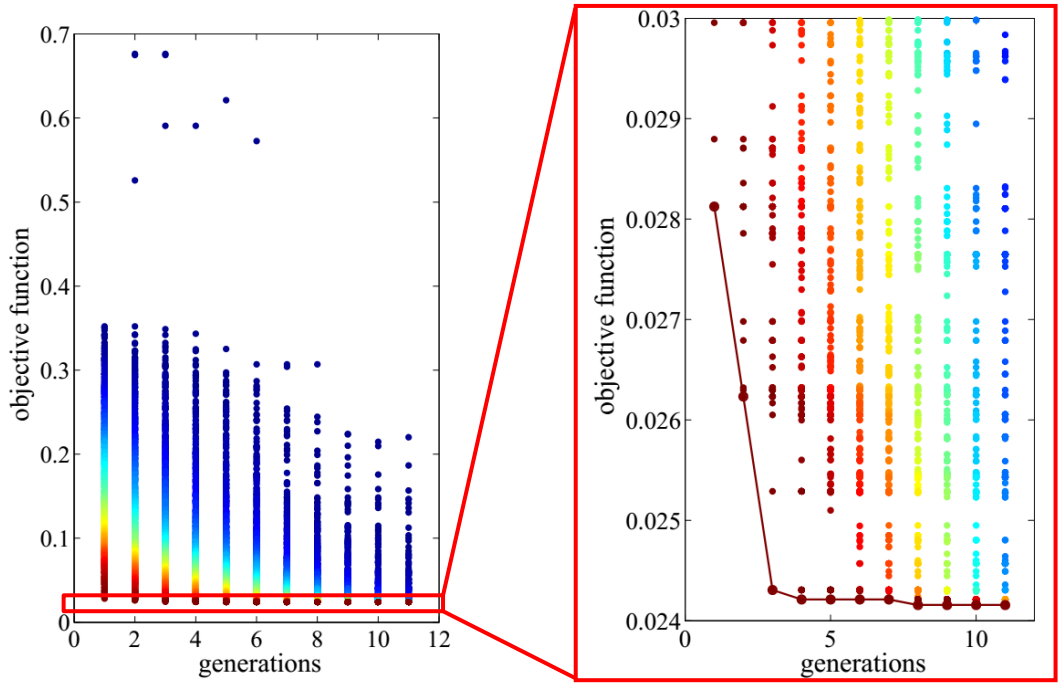
$$M_R = -2 \int_a^{L/2} \frac{\epsilon w V_R^2}{2(g_0 + x_1 \sin\theta)^2} x_1 \, \mathrm{d}x_1$$
$$= \frac{\epsilon w V_R^2}{\sin^2\theta} \left(\frac{a \sin\theta \log(g_0 + a\sin\theta) + g_0 \log(g_0 + a\sin\theta) + g_0}{g_0 + a\sin\theta} - \frac{g_0 \log\left(g_0 + \frac{L}{2}\sin\theta\right) + \frac{L}{2}\sin\theta \log\left(g_0 + \frac{L}{2}\sin\theta\right) + g_0}{g_0 + \frac{L}{2}\sin\theta} \right)$$

$$M_L = \int_0^L \frac{\epsilon w V_L^2}{2(g_0 - u - x_2 \sin\theta)^2} x_2 \mathrm{d}x_2$$
$$= \frac{\epsilon w V_L^2}{2\sin^2\theta} \left(\frac{g_0 - u}{g_0 - u - L\sin\theta} + \log(-g_0 + u + L\sin\theta) - \log(-g_0 + u) - 1 \right)$$

Parameter identification
Genetic algorithm

- Parameter identification using a genetic algorithm
- Population of 5000 individuals, and 11 generations
- Two actuation types for cross-validaiton

$$S(\mathbf{x}) = \|\mathbf{h}(\mathbf{x}) - \mathbf{y}\| \rightarrow S(\mathbf{x}) = \left\| \frac{|(\mathbf{h}_R(\mathbf{x}) - \mathbf{y}_R)|_1}{n \max(\mathbf{y}_R)} + \frac{|(\mathbf{h}_L(\mathbf{x}) - \mathbf{y}_L)|_1}{m \max(\mathbf{y}_L)} \right\|$$



- Formulating the problem
  - Young's modulus, E
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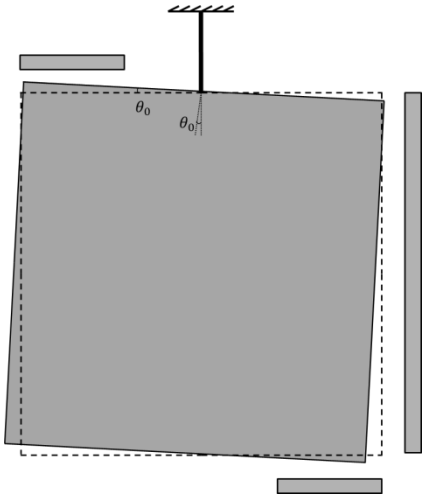


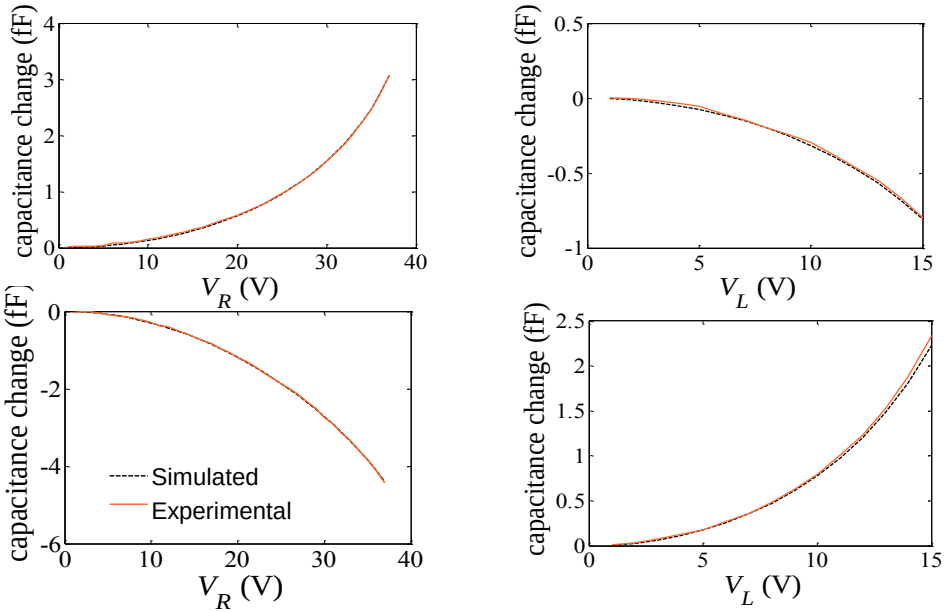
Parameter identification
Genetic algorithm

	O (μm)		θ_0 (milliradian)		E (GPa)	
Specimen #	through V_R	through V_L	through V_R	through V_L	through V_R	through V_L
1	-0.10	-0.05	0.08	0.34	134.6	131.6
2	-0.09	-0.02	-0.15	0.07	147.6	137.7
3	-0.09	-0.13	-0.31	-0.30	150.8	153.2
4	-0.12	-0.07	-0.01	-0.05	149.5	130.7
5	-0.09	-0.10	-0.55	-0.56	149.5	141.8
6	-0.07	-0.07	-0.42	-0.85	161.5	144.2
7	-0.10	-0.10	0.07	0.41	130.3	134.3
8	-0.12	-0.06	0.12	0.46	134.0	130.2
9	-0.04	-0.05	0.91	1.00	131.1	135.5
10	-0.06	-0.12	0.52	0.53	132.2	142.6

Consistent estimations

Inconsistent estimations

Introducing three uncertain parameters into the model enhaced the parameter estimation process with respect to the previous work*



*Mirzazadeh R., Ghisi A., Mariani S., "Assessment of polysilicon film properties through on-chip tests", Proceedings of Sensors and Applications, November 2015.

Conclusion

Concluding remarks:

- An on-chip testing device is designed in order to characterize the main features of MEMS fabricated by polycrystalline materials with cross-validation capability.
- Experimental evidence on the scattering of micro beams electromechanical response when their characteristic length shrinks.
- Analytical coupled-field models are provided for electrostatic MEMS. Appropriate models can be developed for other MEMS devices similar to what has been proposed in this work.
- Material and geometrical parameters of the devices have been characterized through genetic algorithm.

Possible future developments

- Adopting numerical models such as FEM for more sophisticated modelling of the device.
- Employing probabilistic tools (such as Bayesian inference based methods) for parameter identification to allow for measurement errors

References:

- Mirzazadeh, R., Eftekhar Azam, S., Mariani, S.: Micromechanical Characterization of Polysilicon Films through On-Chip Tests. Sensors, 16, 1191, 2016.
- Mirzazadeh R., Ghisi A., Mariani S., "Assessment of polysilicon film properties through on-chip tests", Proceedings of Sensors and Applications, November 2015.
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- Hopcroft M. A., Nix W. D., Kenny T. W.: What is the Young's Modulus of Silicon? J Microelectromech Syst 19: 229-238 2010.