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On-Chip Assessment of Scattering in the Response of Si-Based Microdevices

micromachines

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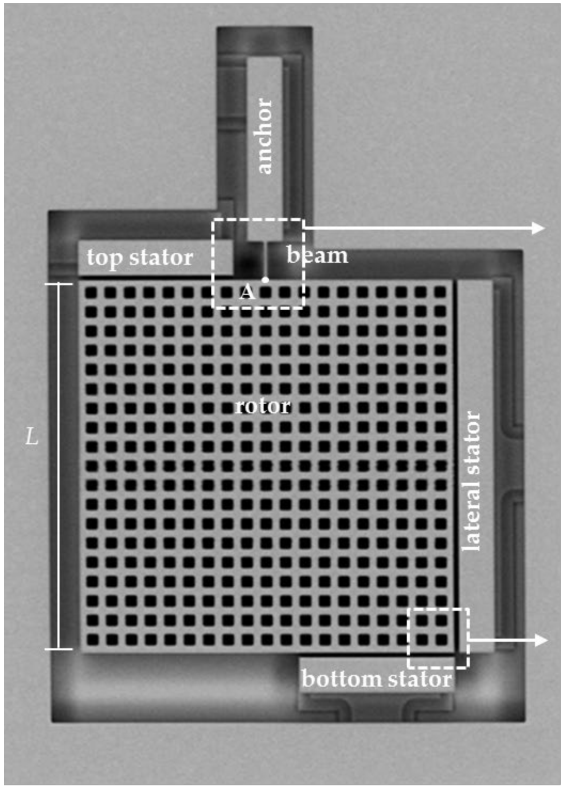
On-Chip Assessment of Scattering in the Response of Si-Based Microdevices



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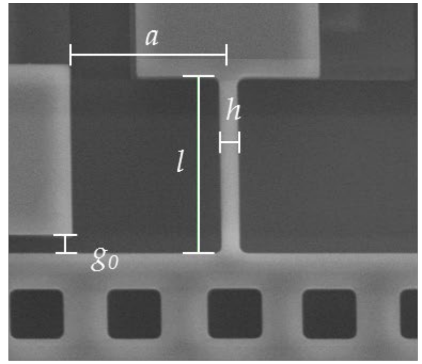

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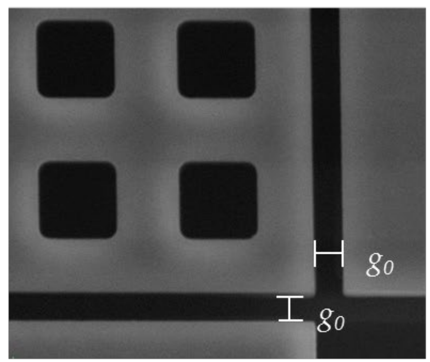

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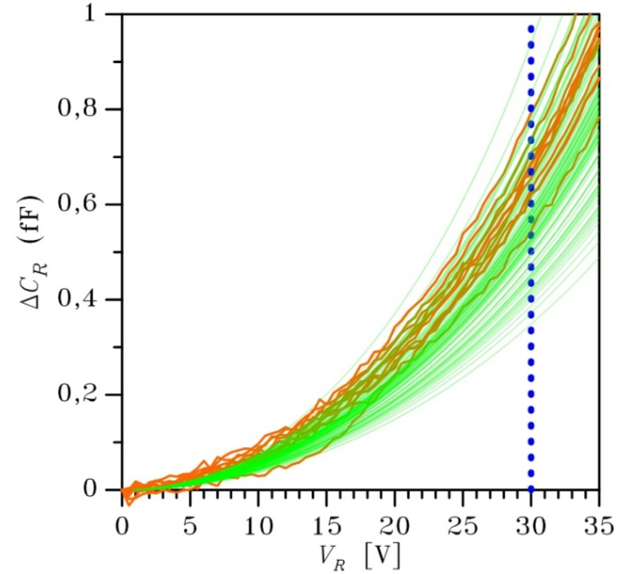
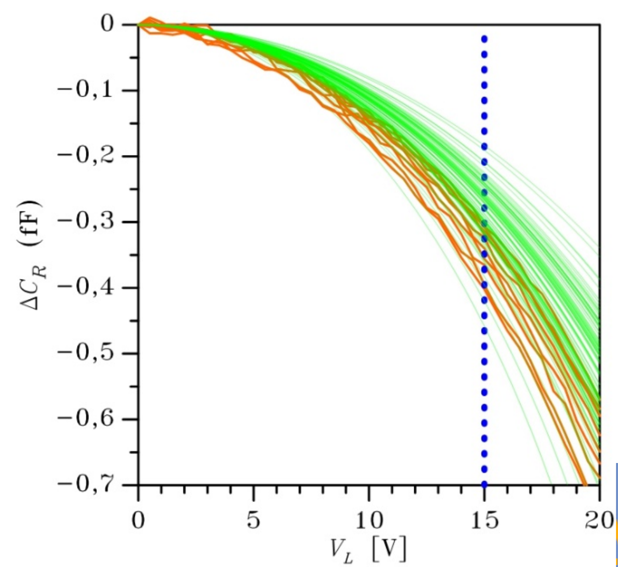


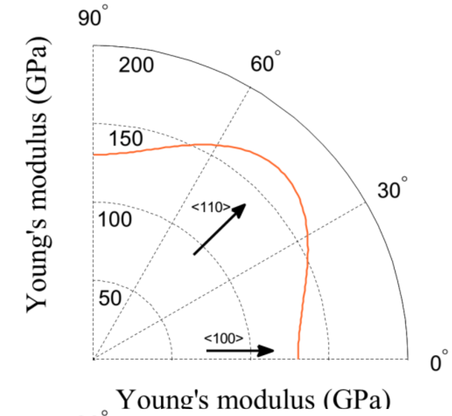


Abstract: The response of micromachines to the external actions is typically affected by a scattering, which is on its own induced by their microstructure and by stages of the microfabrication process. The progressive reduction in size of the mechanical components, forced by a path towards (further) miniaturization, has recently enhanced the outcomes of the aforementioned scattering, and provided a burst in research activities to address issues linked to its assessment. In this work, we discuss the features of an on-chip testing device that we purposely designed to efficiently estimate the two major sources of scattering affecting inertial, polysilicon-based micromachines: the morphology of the silicon film constituting the movable parts of the device, and the etch defect or overetch induced by microfabrication. The coupled electro-mechanical behavior of the statically determinate movable (micro)structure of the on-chip device has been modelled via beam bending theory, within which the aforementioned sources of scattering have been accounted for through local fluctuating fields in the compliant part of the structure itself, namely the supporting spring. The proposed stochastic model is shown to outperform former ones available in the literature, which neglected the simultaneous and interacting effects of the two mentioned sources on the measure response.
The model can fully catch the scattering in the C-V plots up to pull-in, hence also in the nonlinear working regime of the device.

Keywords: polysilicon; micromechanics; stochastic effects.

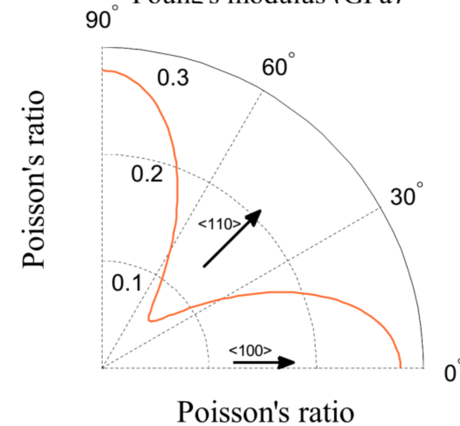
Uncertainties at the micro scale due to grain morphology

❖ Polysilicon (film) is one of the most used materials for MEMS.

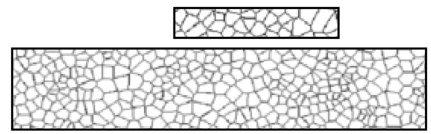


❖ Silicon is an **anisotropic crystalline** material whose material properties depend on the **relative orientation** with respect to the crystal lattice orientation.

❖ Due to miniaturization, the **characteristic size** of structural components can be comparable to the size of grains.



❖ Morphology & crystal lattice orientation



Sources of uncertainties affecting the device static/dynamic response

❖ As **the characteristic size** of components decreases, on the same order of the fabrication tolerances, relative importance of the fabrication inaccuracies increases.

❖ Type & amplitude of the fabrication inaccuracies

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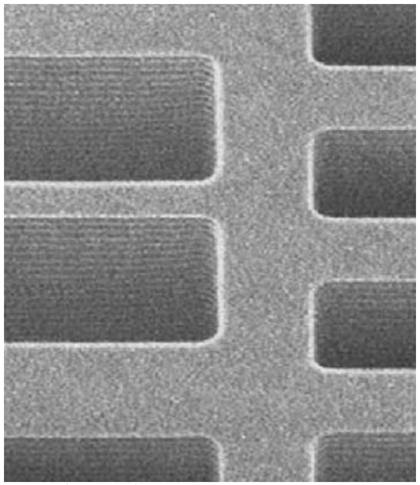
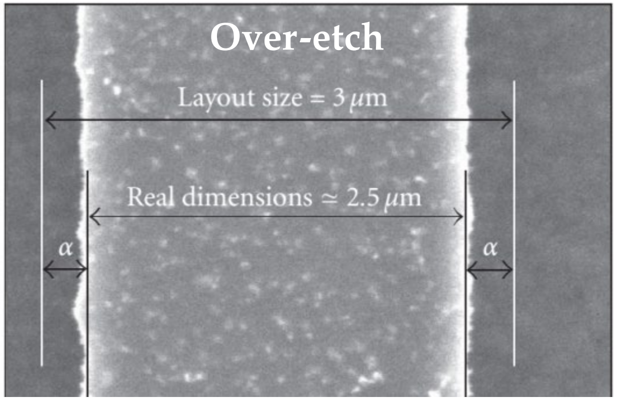
Uncertainties at the micro scale due to micro-fabrication

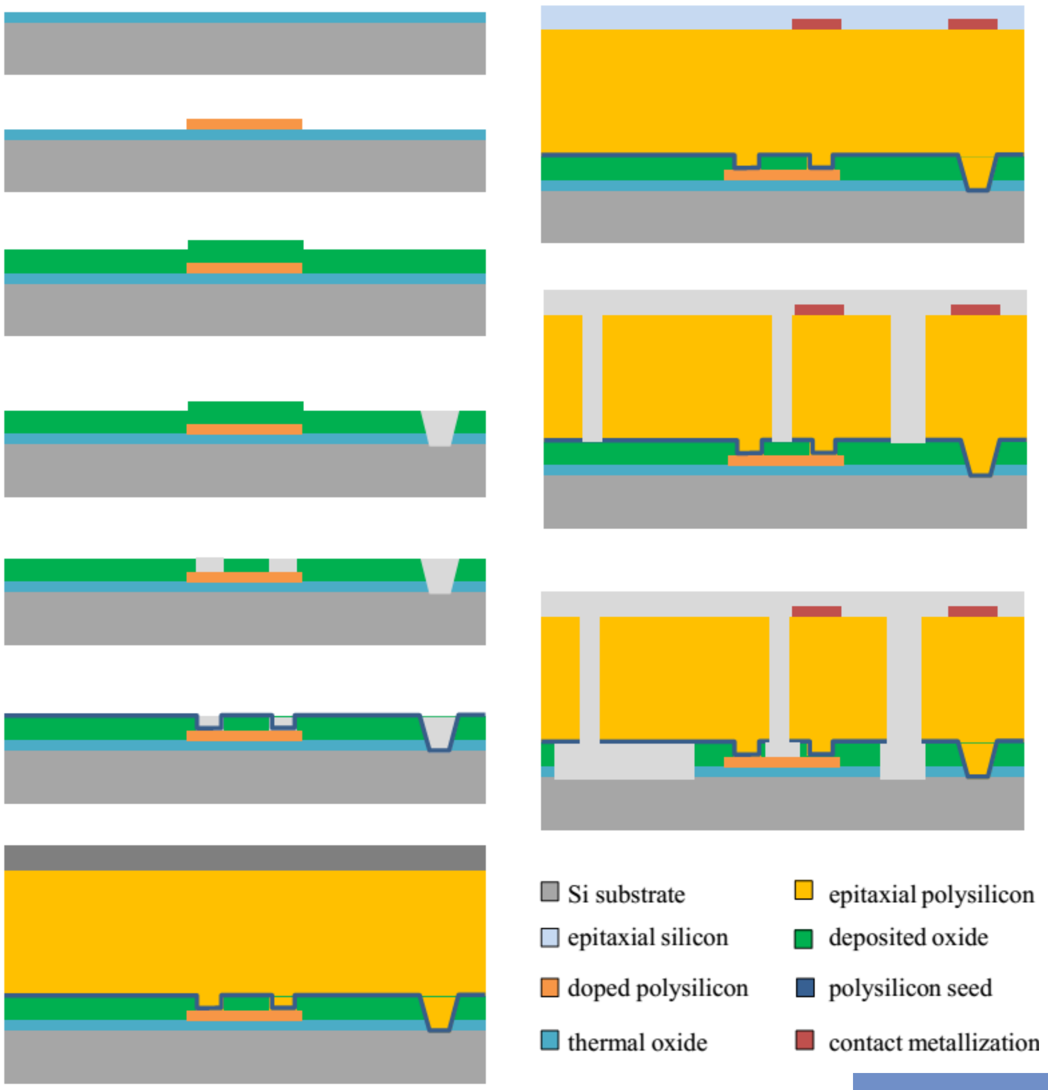
- MEMS fabrication includes several stages of chemical processes
- Components are formed by **etching** of silicon layers



Corigliano et al., 2004



Rocha et al., 2008



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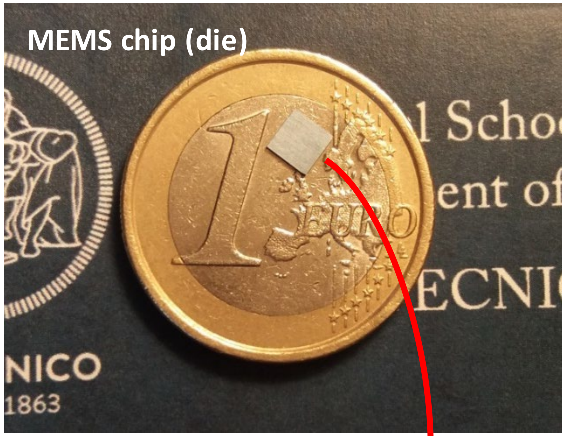
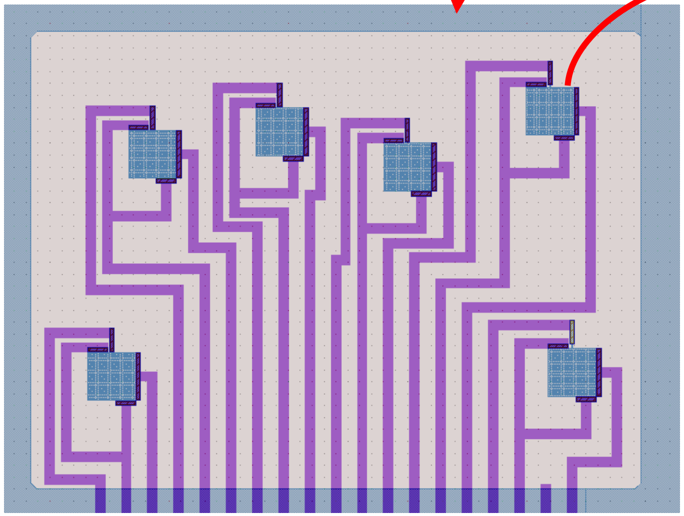
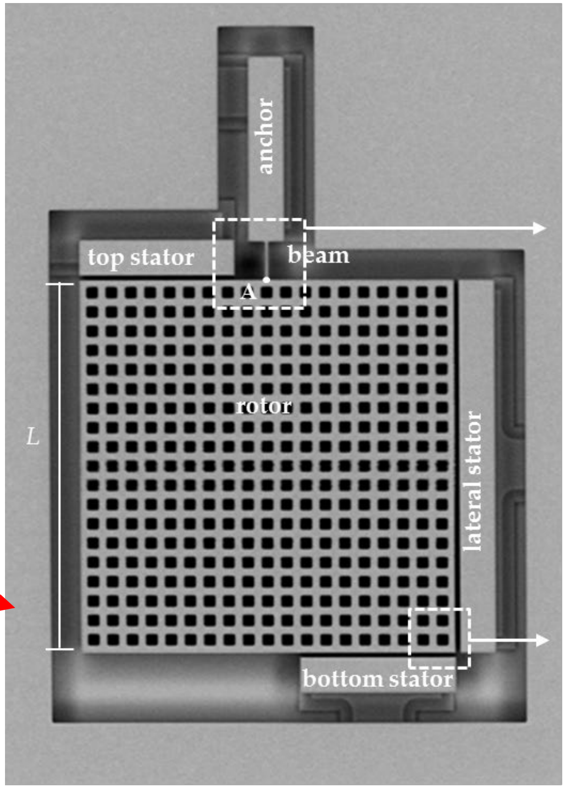
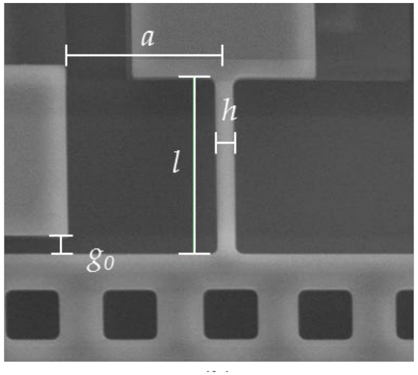
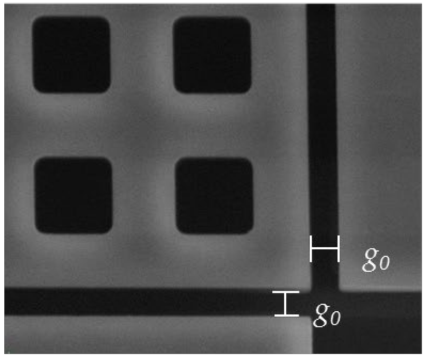
On-chip testing device to assess the scattering induced by micromechanical features for polysilicon films











beam length (l)	20,10 μm
beam width (h)	2 μm
out-of-plane film thickness (w)	22 μm
initial gap at capacitors (g_0)	2 μm
a	17 μm
L	200 μm

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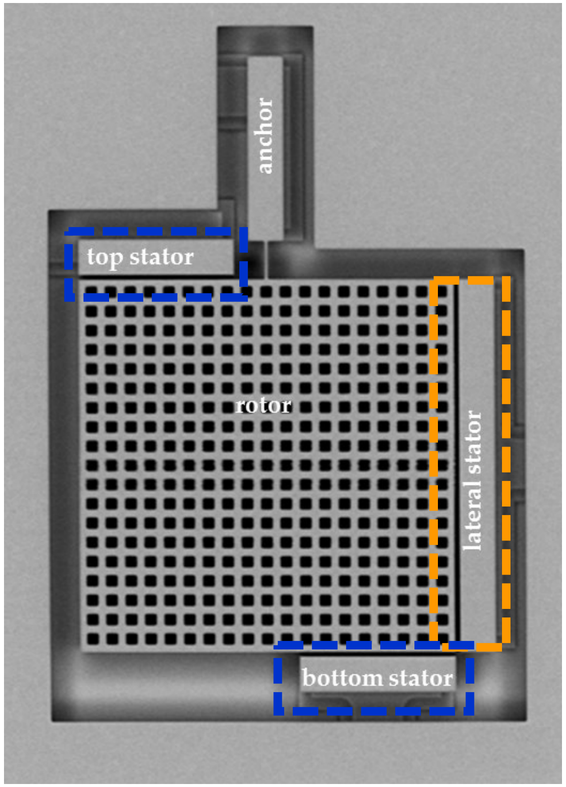
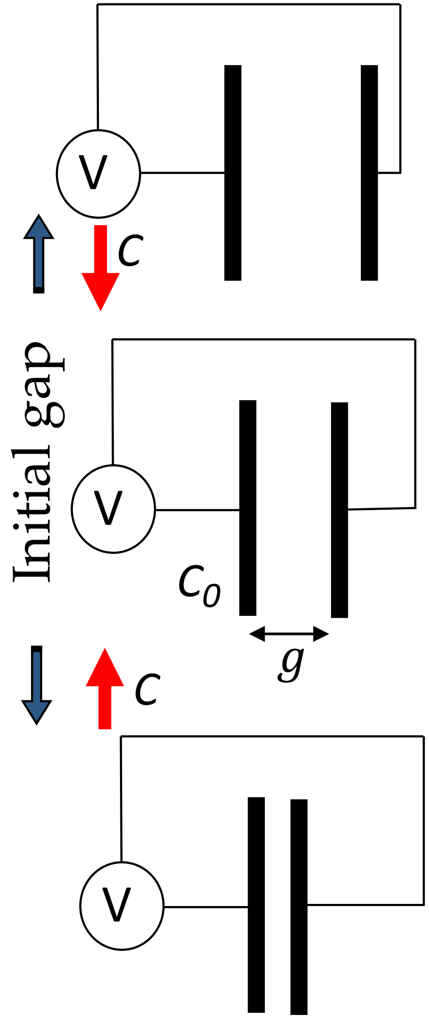
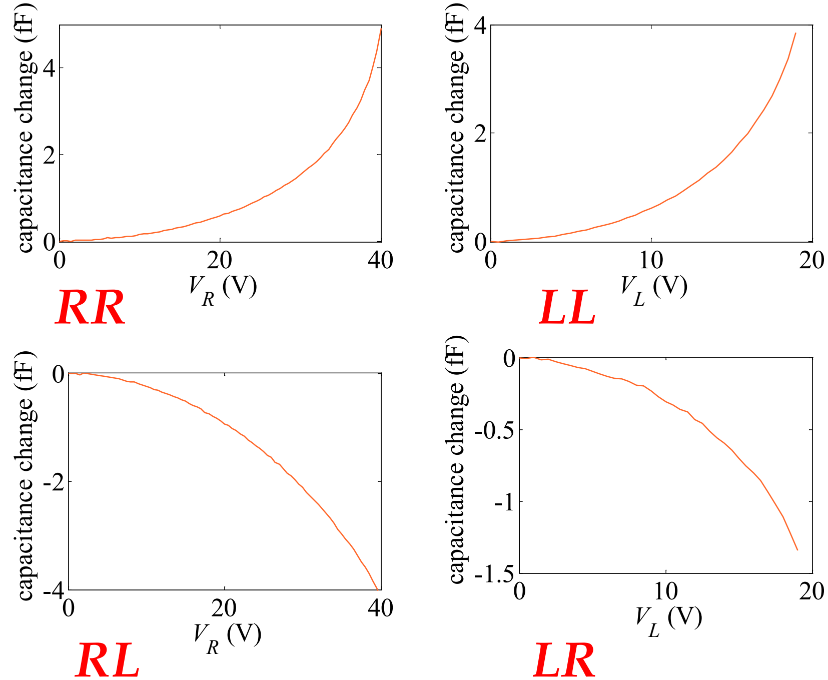
On-chip testing device: actuation and sensing configuration (redundancy of data)

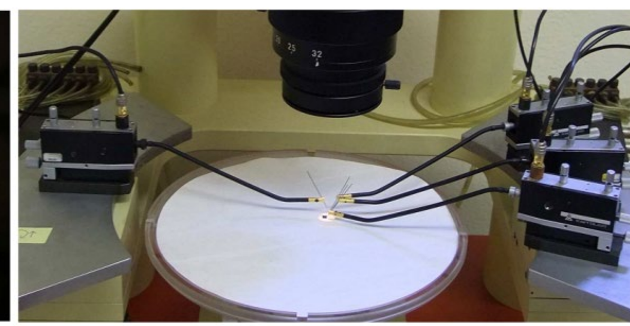


$$C = \frac{\epsilon A}{g}$$

$$F = \frac{\epsilon A V^2}{2g^2}$$







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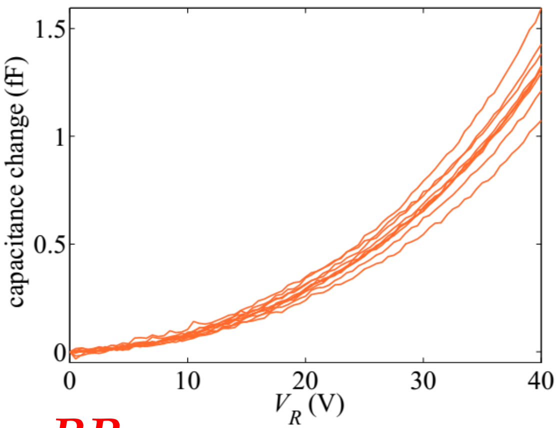
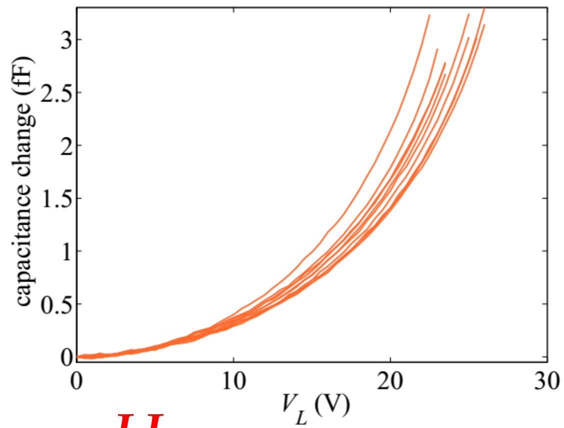
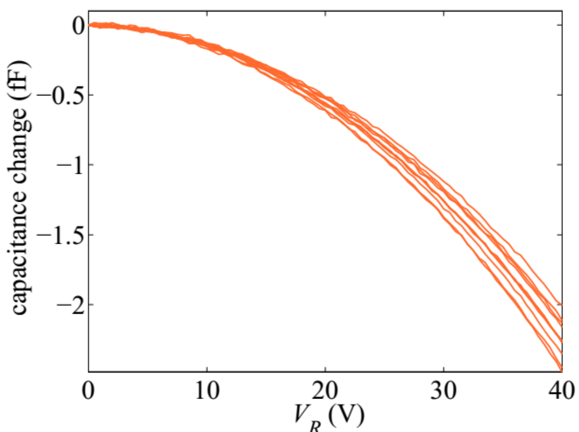
On-chip testing device: scattering in the experimental data\10



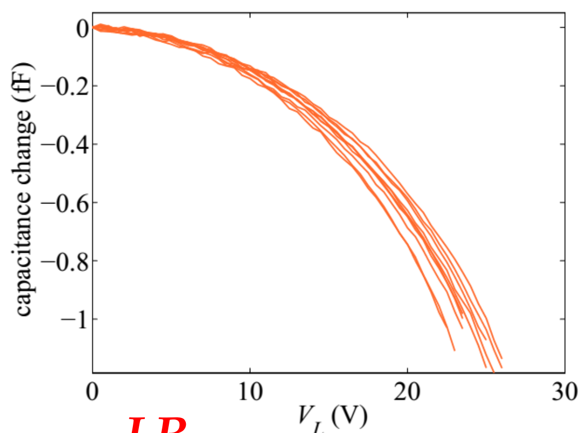
RR



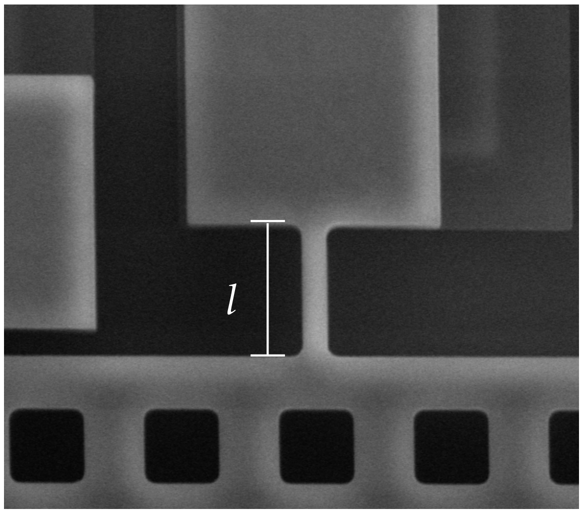
LL



RL

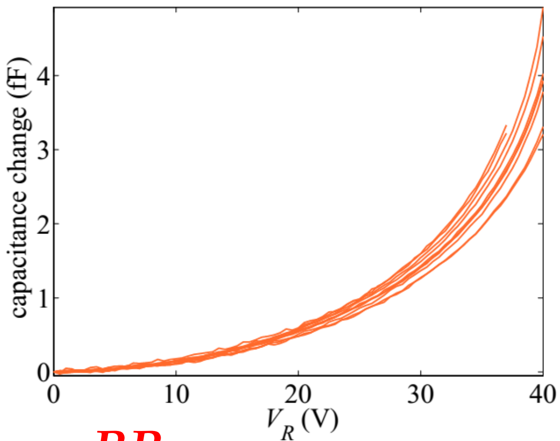


LR

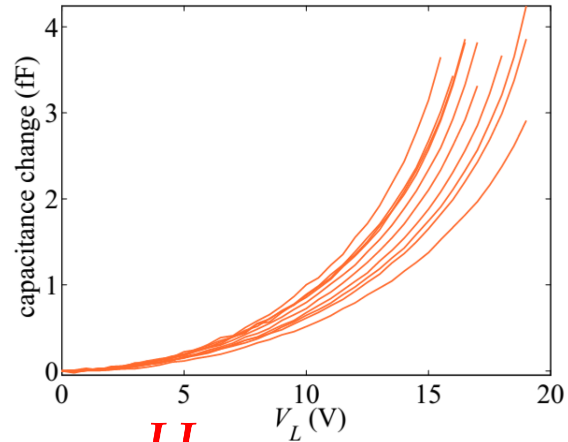


$l = 10\ \mu m$

On-chip testing device: scattering in the experimental data\20



RR



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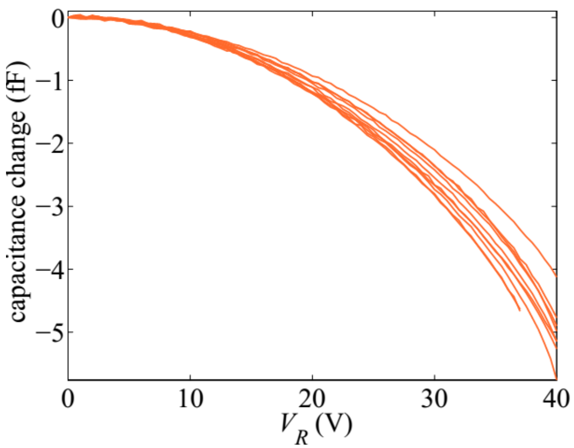
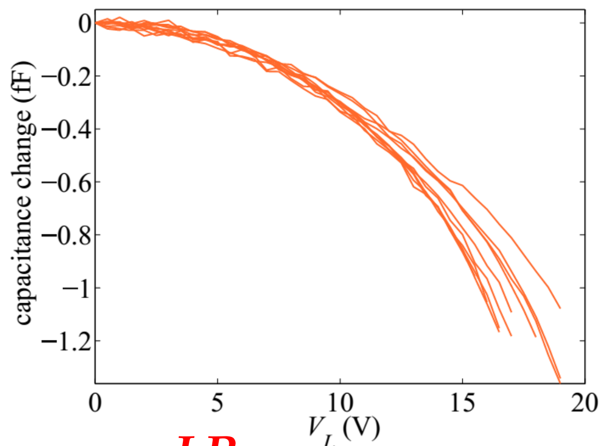
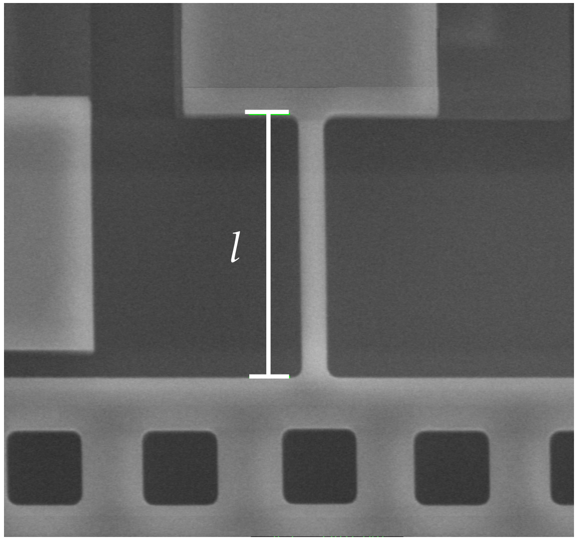


RL



LR



$l = 20\ \mu m$

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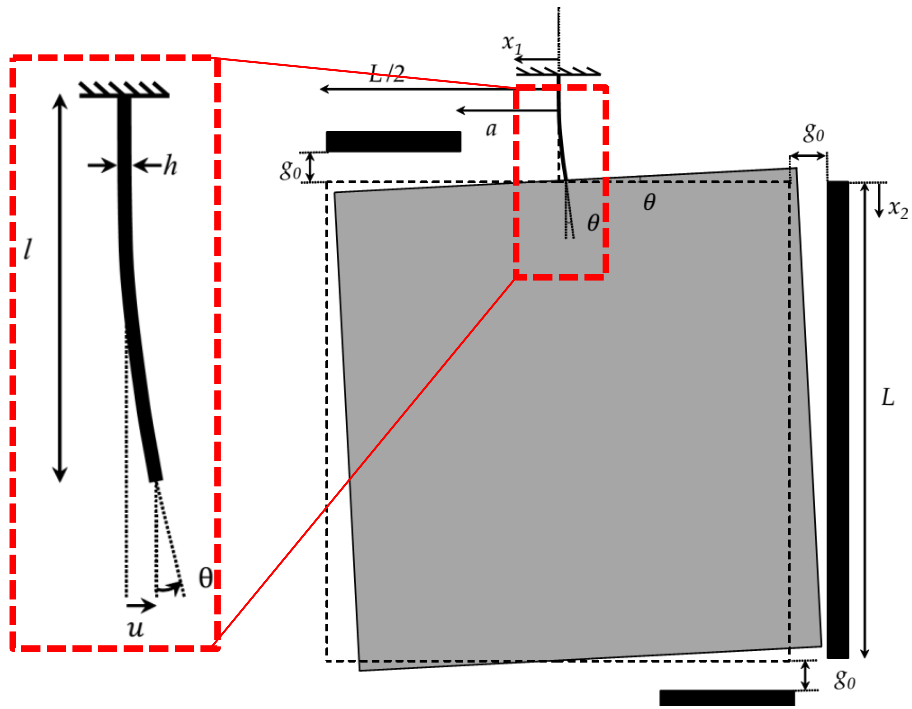
Analytical modelling: Mechanical domain

Assumptions:

- Cantilever beam subjected to the end load
- Mass bulk to be rigid
- Small displacements (linearized kinematics)
- Perfect anchor



Via Bernoulli-Euler beam bending theory, the relation between (generalized) forces and displacements at the beam tip reads:

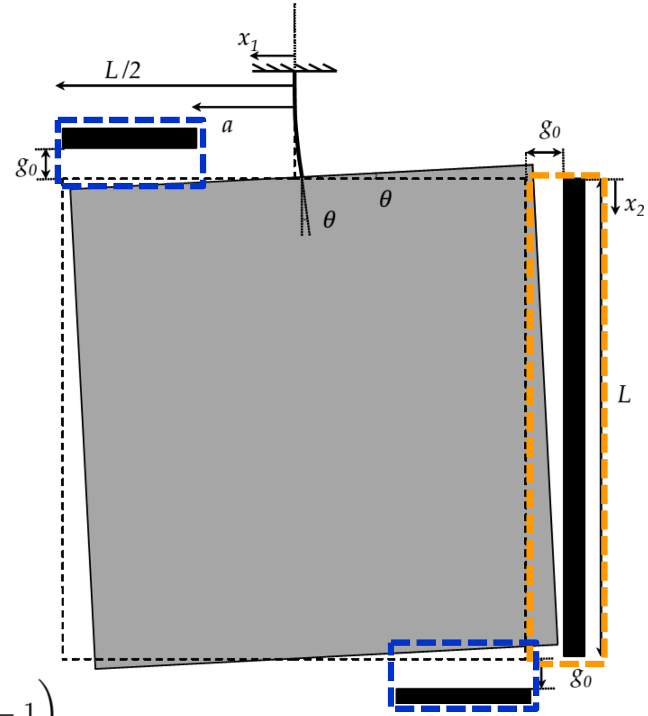
$$\begin{Bmatrix} F(l) \\ M(l) \end{Bmatrix} = \frac{EI}{l^3} \begin{bmatrix} 12 & -6l \\ -6l & 4l^2 \end{bmatrix} \begin{Bmatrix} u^E(l) \\ \theta^E(l) \end{Bmatrix}$$

where stiffness and cross-section properties are random variables.

Analytical modelling: Electric domain

Assumptions:

- neglecting fringe field effects
- electric domain deformation at the top and bottom capacitors to be identical



Unit electrostatic force

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

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

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

Unit capacitance

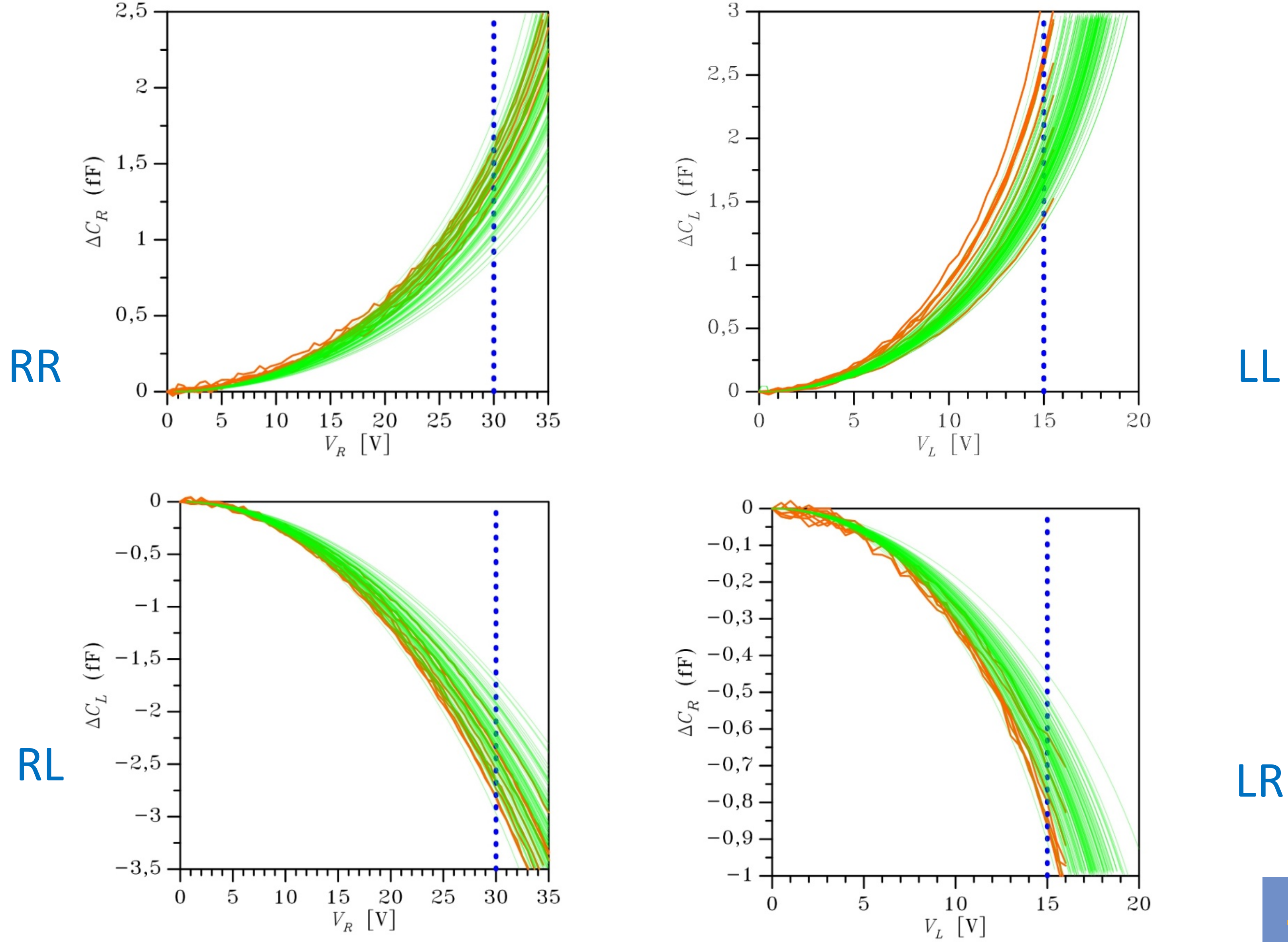
$$c = \frac{\epsilon}{g}$$

$$g_R = g_0 + x_1\sin\theta$$
$$g_L = g_0 - u - x_2\sin\theta$$

$$C_R = 2\int_a^{L/2} \frac{\epsilon w}{g_0 + x_1\sin\theta} dx_1$$
$$= \frac{2\epsilon w}{\sin\theta}\left(\log\left(g_0 + \frac{L}{2}\sin\theta\right) - \log(g_0 + a\sin\theta)\right)$$

$$C_L = \int_0^L \frac{\epsilon w}{g_0 - u - x_2\sin\theta} dx_2$$
$$= \frac{\epsilon w}{\sin\theta}\left(\log(-g_0 + u) - \log(-g_0 + u + L\sin\theta)\right)$$

Results: assessment of scattering in the data



$L = 20$ µm

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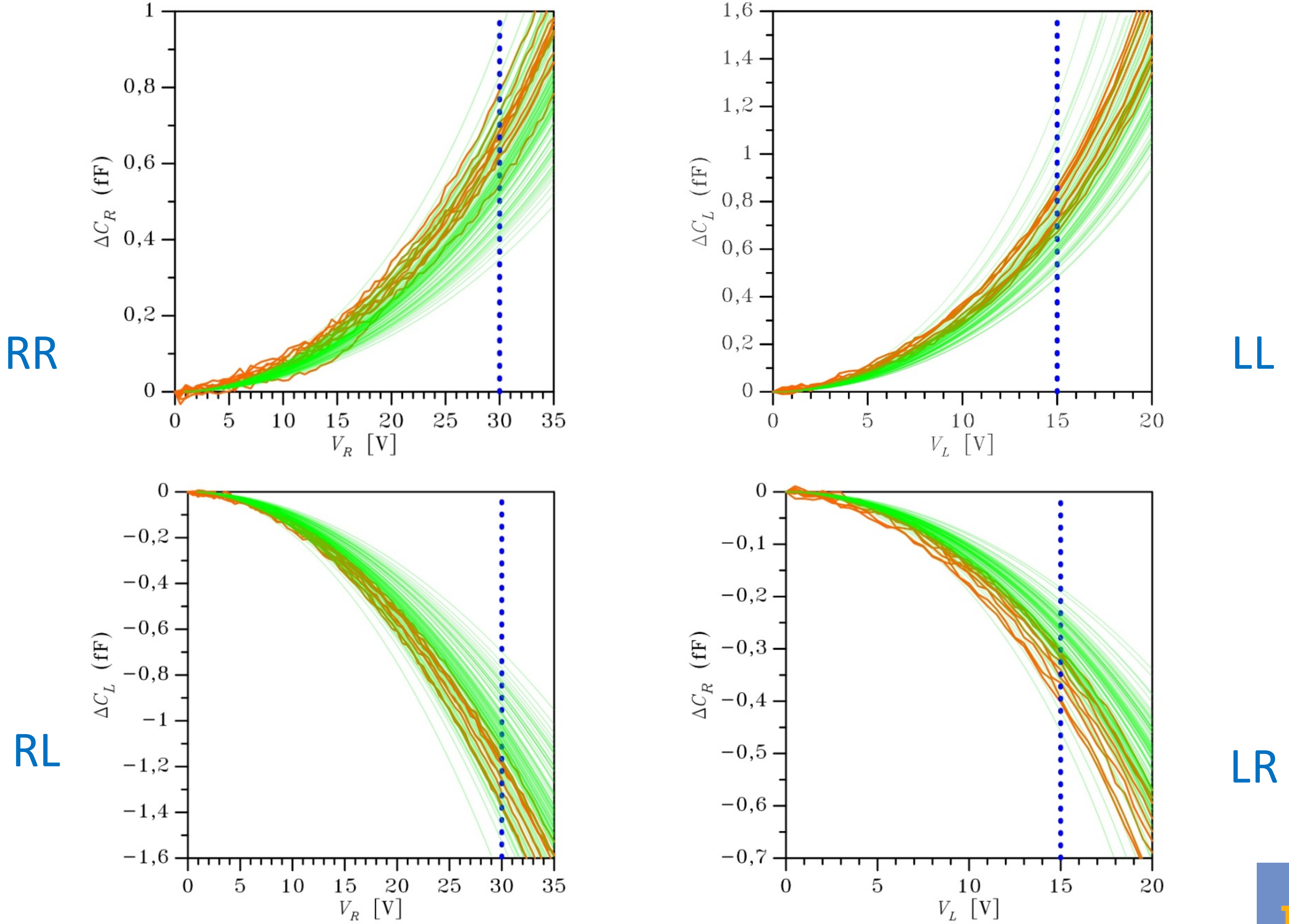
Results: assessment of scattering in the data
(orange lines are experimental curves; green lines are analytical curves)



$L = 10\ \mu\text{m}$

Conclusions

Main results:

- Experiments evidence the emerge of **uncertainties** due to material properties variation and fabrication inaccuracies as the MEMS **dimensions shrink**.
- **Material properties** at structural components with dimensions comparable to the grain size should not be considered **deterministic**.
- **Uncertainty** ***quantification*** for the present device has been carried out through estimation of the unknown parameters governing the uncertainties.
- **A beam bending-based coarse grained stochastic formulation** has been proposed to account for the film morphology- and overetch-governed scattering in the mechanical properties and device response to the external stimuli.

Possible future developments:

- Experimental campaign to allow for a larger variety of beam geometries.
- Bayesian model class selection to be carried out using POD-kriging TMCMC approach.
- Optimization of a neural network architecture to attain even more accurate results regarding the scattering.

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