Hollow Cantilevers with Holes

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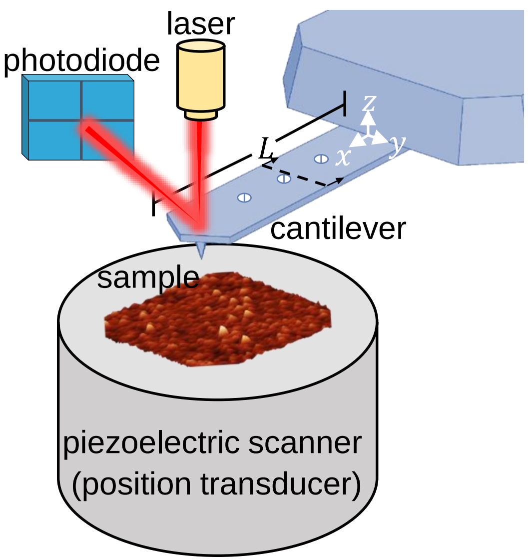
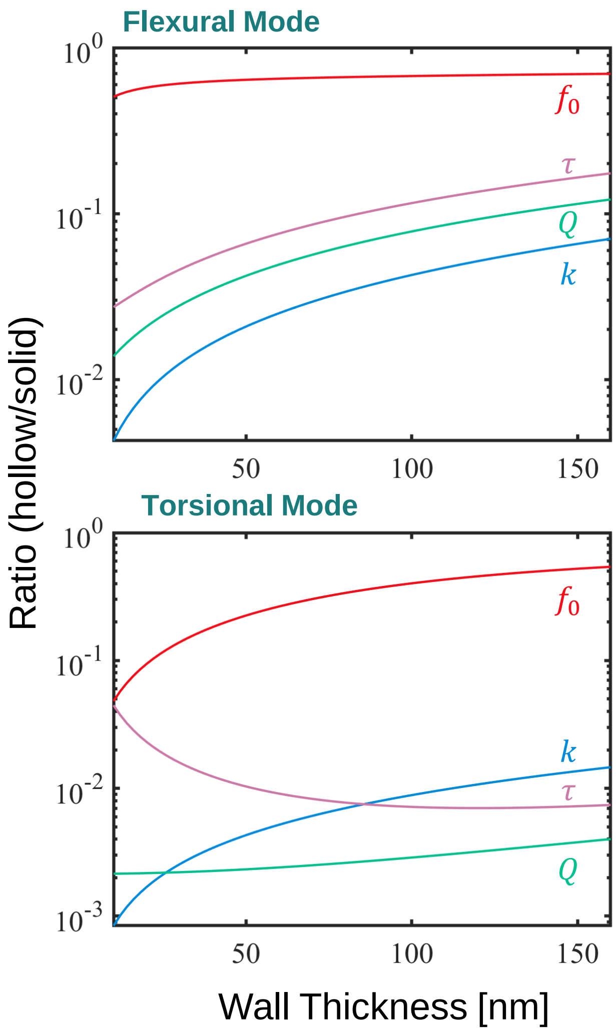
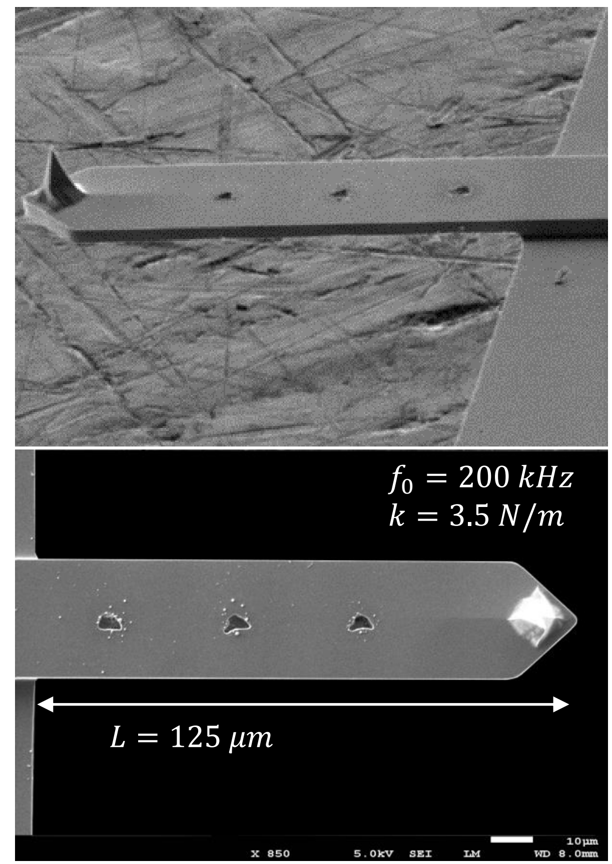






Abstract

Hollow AFM Cantilever with Holes

Since its invention, atomic force microscopy (AFM) has enhanced our understanding of physical and biological systems at sub-micrometer scales. As the performance of AFM depends greatly on the properties of the cantilevers, many works have been done to improving cantilevers by means of modifying their geometries via lithography [1] and ion-beam milling [2,3] that primarily involved opening areas on the cantilever’s face, resulting in high resonant frequency, low spring constant, and low hydrodynamic damping. Similar improvements were achieved using a hollow beam cantilever with nanoscale wall thickness [4]. In fact, the combination of these two approaches (in-plane opening and hollow beam) can result in unique metamaterial structures with tunable properties [5], but it has not been explored for AFM application.

In this work, we explore the hollow AFM cantilevers with in-plane modifications. We accomplished this by (1) taking a commercial solid silicon cantilever, (2) making a different number of holes on the face using pulsed laser micromachining, and (3) coating them with alumina using atomic layer deposition and etching the internal silicon that results in a hollow probe with holes. We present the effects of these modifications on the cantilever’s resonant frequency, quality factor, and spring constant in air. This work provides an insight into strategies for tuning cantilever’s properties for both flexural and torsional modes.

Keywords: Atomic force microscopy (AFM); flexural resonance; torsional resonance; hollow cantilever

Reference:

[1] Nilsen, M.; Port, F.; Roos, M.; Gottschalk, K.-E.; Strehle, S. Journal of Micromechanics and Microengineering 2019, 29, (2), 025014.

[2] Bull, M. S.; Sullan, R. M. A.; Li, H.; Perkins, T. T. ACS Nano 2014, 8, (5), 4984-4995.

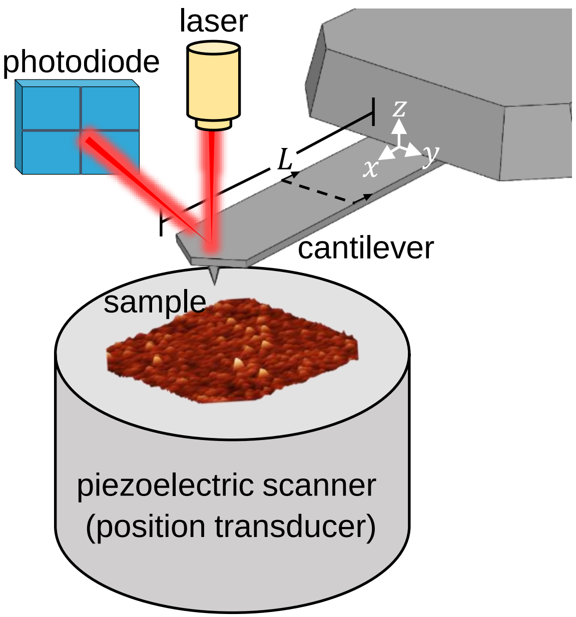
[3] Hodges, A. R.; Bussmann, K. M.; Hoh, J. H. Review of Scientific Instruments 2001, 72, (10), 3880-3883.

[4] Cha, W.; Nicaise, S.; Lilley, D.; Lin, C.; Bargatin, I. Solid-State Sensors, Actuators and Microsystems Workshop, Hilton Head Island, South Carolina, 2018; Transducer Research Foundation: Hilton Head Island, South Carolina, pp 232-233.

[4] Lin, C.; Nicaise, S. M.; Lilley, D. E.; Cortes, J.; Jiao, P.; Singh, J.; Azadi, M.; Lopez, G. G.; Metzler, M.; Purohit, P. K.; Bargatin, I. Nature Communications 2018, 9, (1), 4442.

Atomic Force Microscopy (AFM)

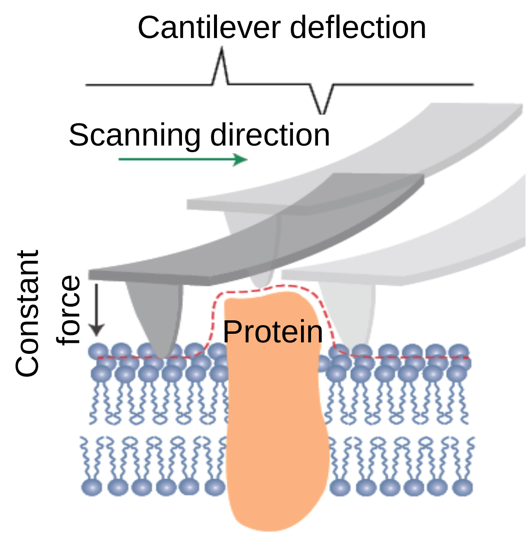
AFM Mechanism



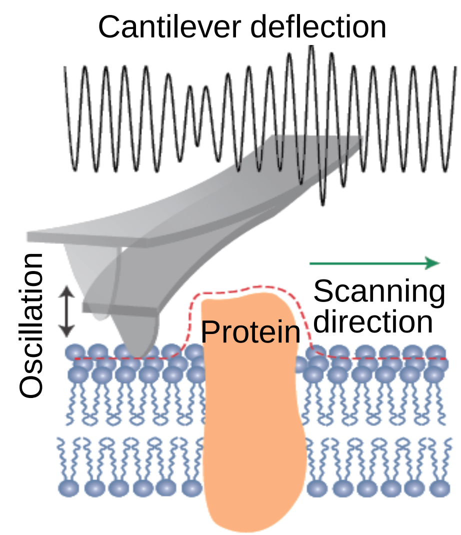
- Measures forces between probe tip and sample surface
- Optical lever system measures deflection of cantilever

AFM Operation

Contact Mode



Dynamic Mode



Dufrêne *et al.*, *Nature Nanotech.* (12) 2017

- Cantilever tip in direct contact with sample
- Sample and/or tip has high risk to be damaged

- Cantilever vibrates at or near resonant frequency
- Tip interact with sample minimally, and has lower risk to cause damage

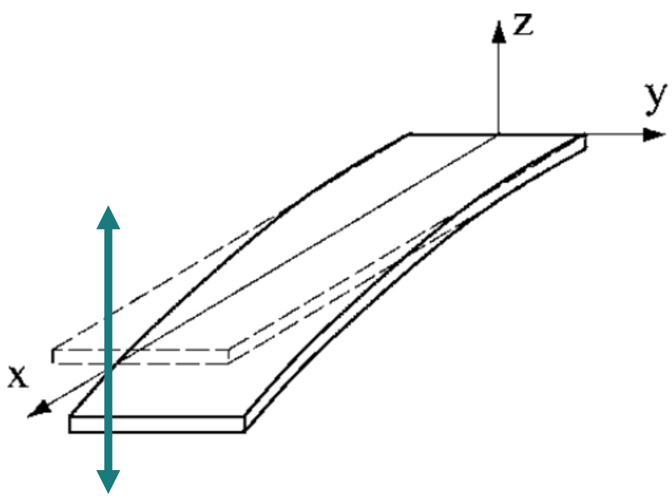
AFM Vibration Modes & Challenges

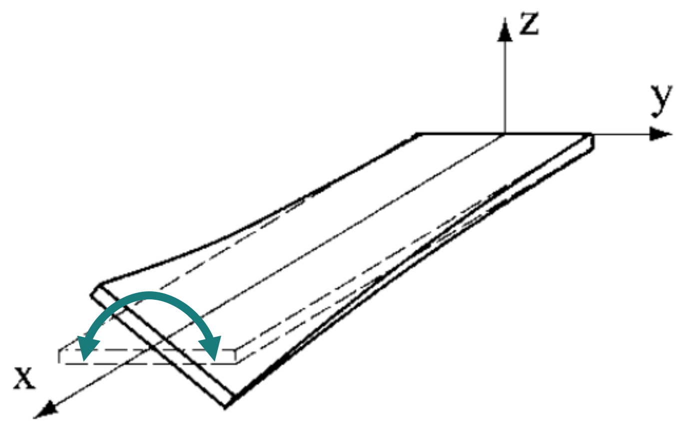
Flexural Mode

- Cantilever vibrate vertically
- Vertical force measurement, topographic imaging

Torsional Mode

- Cantilever twists
- Friction force measurement, high-frequency measurement, phase imaging





Song & Bhushan, *Appl. Phys.* (99) 2006

Challenges

- Slow response of cantilever requires long time
- Conventional probes can damage soft samples

Improving AFM Cantilever & Objectives

Faster Imaging

- Ring-down Time (characteristic response time)

$$\tau = \frac{Q}{\pi f_0}$$

Q: quality factor
f_0: resonant frequency

Softer Cantilever

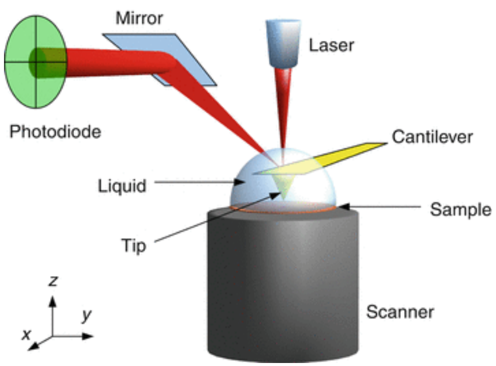
- Spring Constant

$$k = \frac{3EI}{L^3}$$

E: Young's modulus
I: cross-sectional moment of inertia
L: cantilever's length

AFM in Liquid

- Increased damping reduces Q

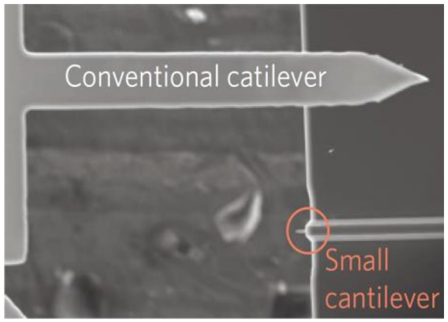


Hoogenboom, *Encycl. of Nanotech.* 2012

- Not applicable to air environment

Small Cantilever

- Shorter cantilever increases f_0

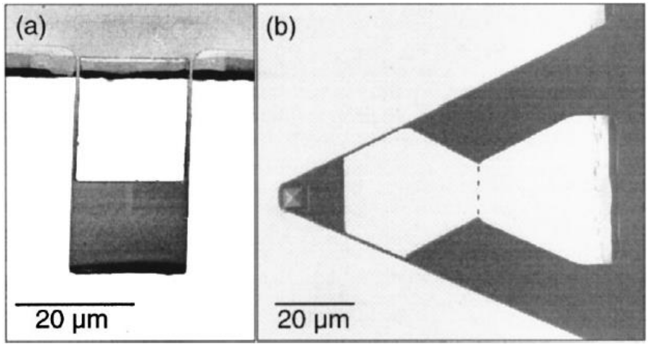


Dufrêne *et al.*, *Nature Nanotech.* (12) 2017

- Increases spring constant
- Optically difficult to detect

Micromachined Cantilever

- Low k and high f_0
- Increased force sensitivity



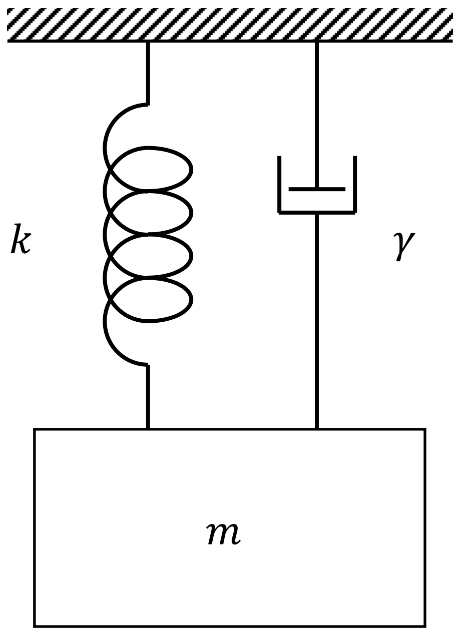
Hodges *et al.*, *Rev. Sci. Inst.* (72) 2011

- Increased Q

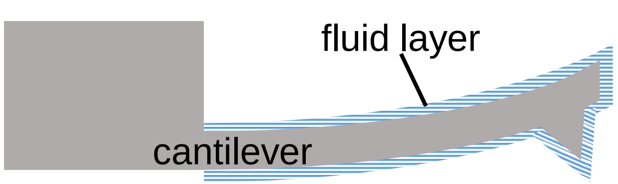
Objectives

- **Cantilever with high f_0, low Q, and low k**

Theory: Resonance Properties



m : effective mass
k : effective spring constant
γ: damping coefficient



- Ring-down time

$$\tau = \frac{Q}{\pi f_0}$$

- Resonant frequency (f_0)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

- Quality factor (Q)

$$Q = \frac{2\pi f_0 m}{\gamma}$$

Lowering cantilever mass:

$f_0\uparrow \quad Q\downarrow \quad \tau\downarrow$

- Hydrodynamic loading

$$\gamma = \frac{\pi^2}{2}\rho_f W^2 L f_0 \Gamma_{im}$$

Scaling cantilever down:

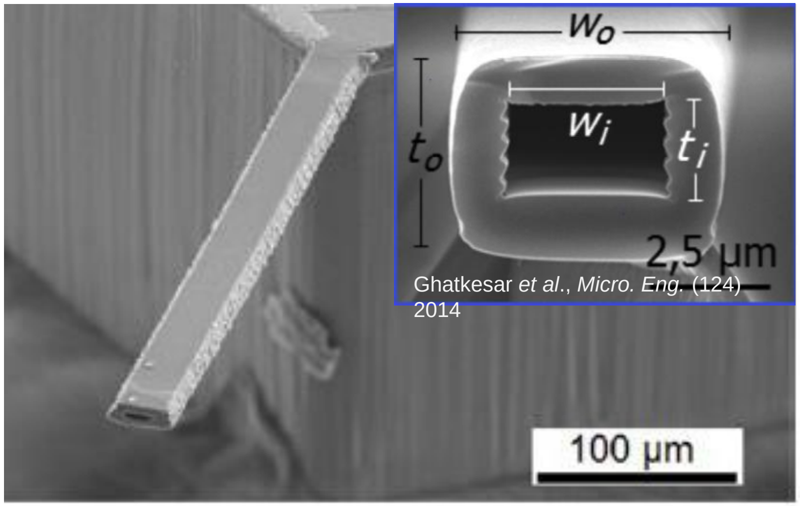
$Q\uparrow \quad \tau\uparrow$

L, W: length and width of cantilever
ρ_f: density of fluid
Γ: hydrodynamic function

Sader., *Jour. App. Phys.* 1998

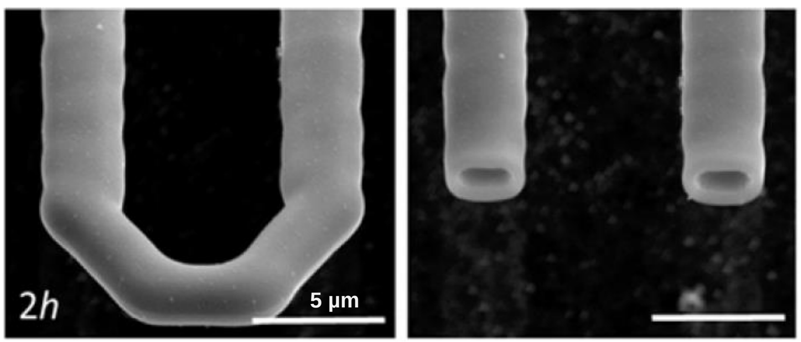
Reducing Mass: Hollow Cantilever

Hollow Cantilever



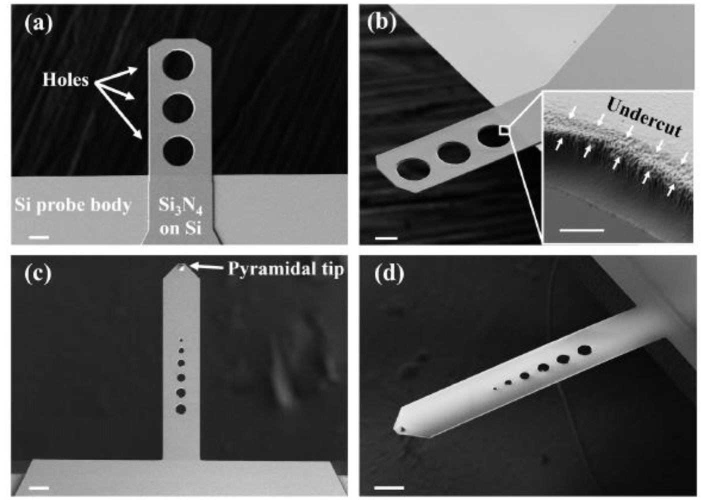
Ghatkesar *et al*., *Micro. Eng.* (124) 2014

Martinez *et al*., *J. Micromech. Microeng.* (26) 2016

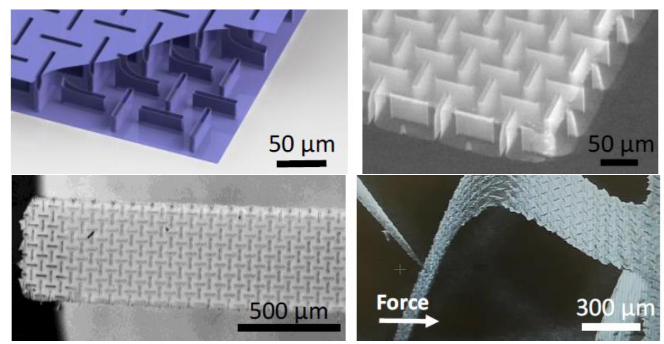


Kim *et al*., *Nano. Lett.* (16) 2016

Patterned Cantilever



Nilsen *et al*., *J. Micromech. Microeng.* (29) 2019



Lin, Bargatin *et al*., *Nat. Comms.* 2018

Objectives

- **Use these two approaches to improve AFM cantilevers**

Fabrication Process

Top View | **Side View**

(1) Solid silicon cantilever

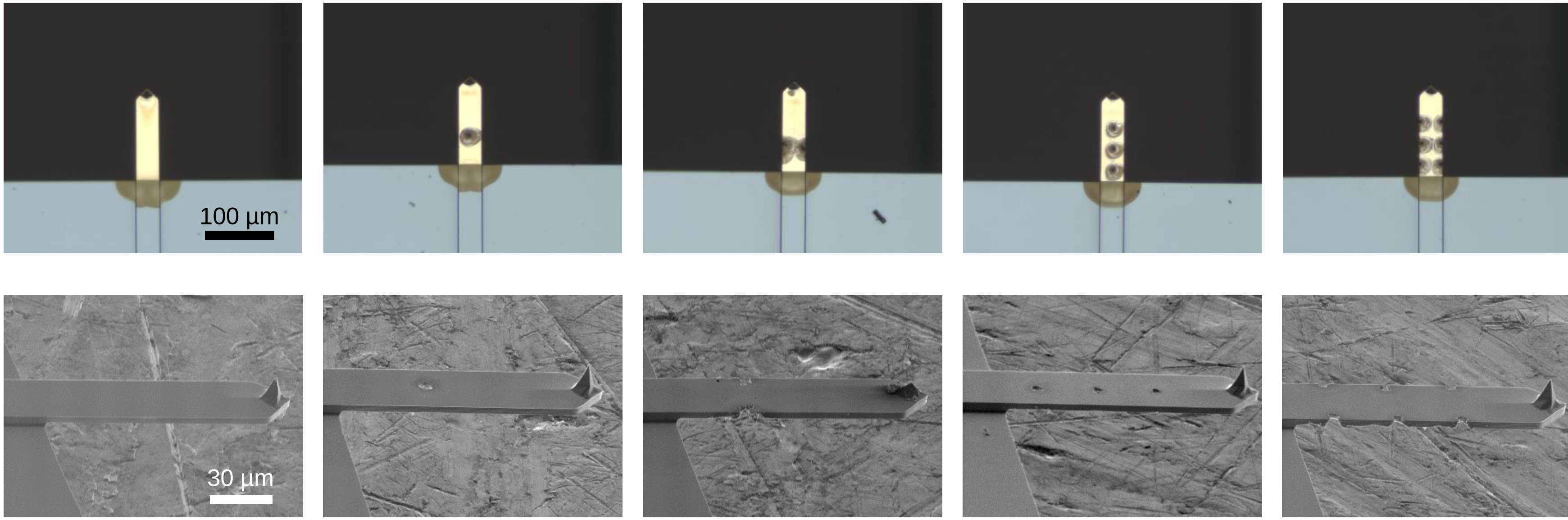
(2) Drill through-holes with laser micromachining

(3) Deposit Al_2O_3 with atomic layer deposition (ALD)

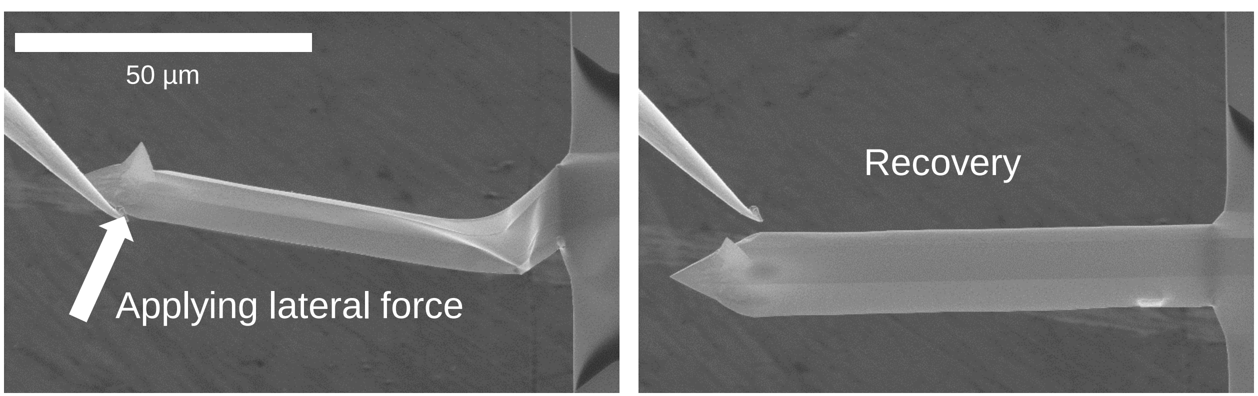
(4) Etch internal silicon mold with XeF_2

Fabricated Hollow Cantilever with Holes

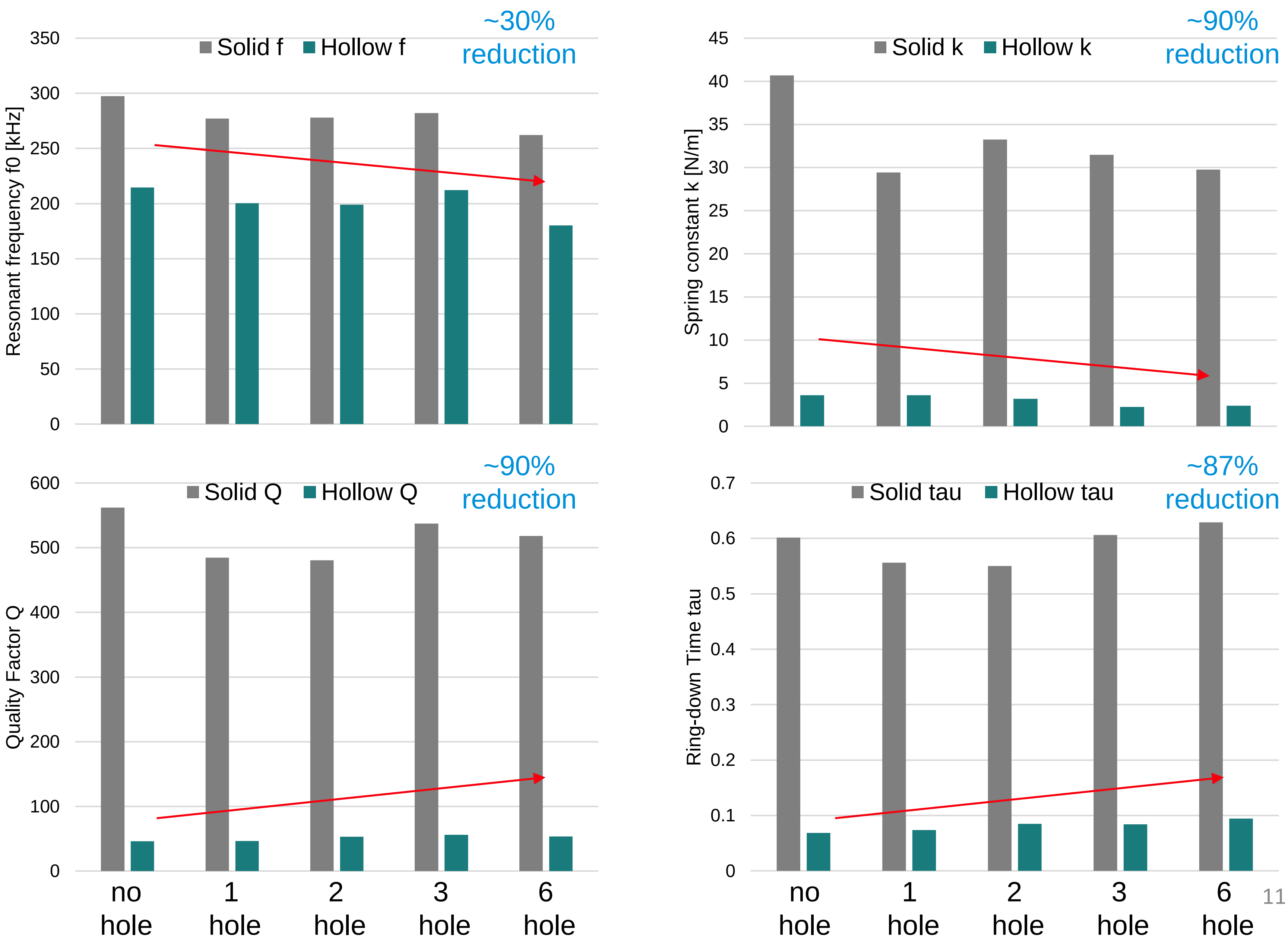
No Hole | 1 Hole | 2 Holes | 3 Holes | 6 Holes



Robustness



Preliminary Experimental Result (Flexural)



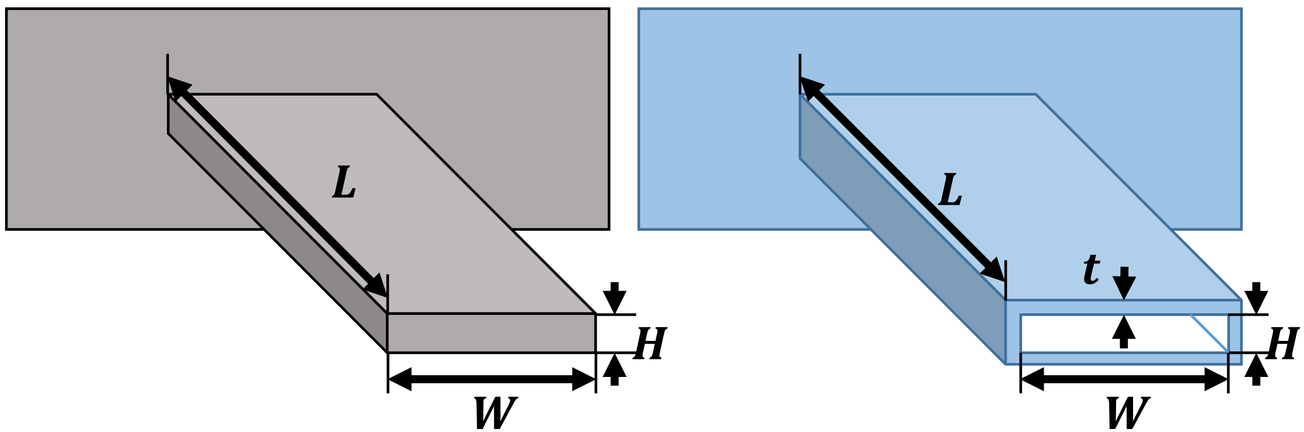
Theory: Hollow Beam Geometry

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

$$k = \frac{3EI}{L^3}$$

E: Young's modulus of cantilever material

I: moment of inertia

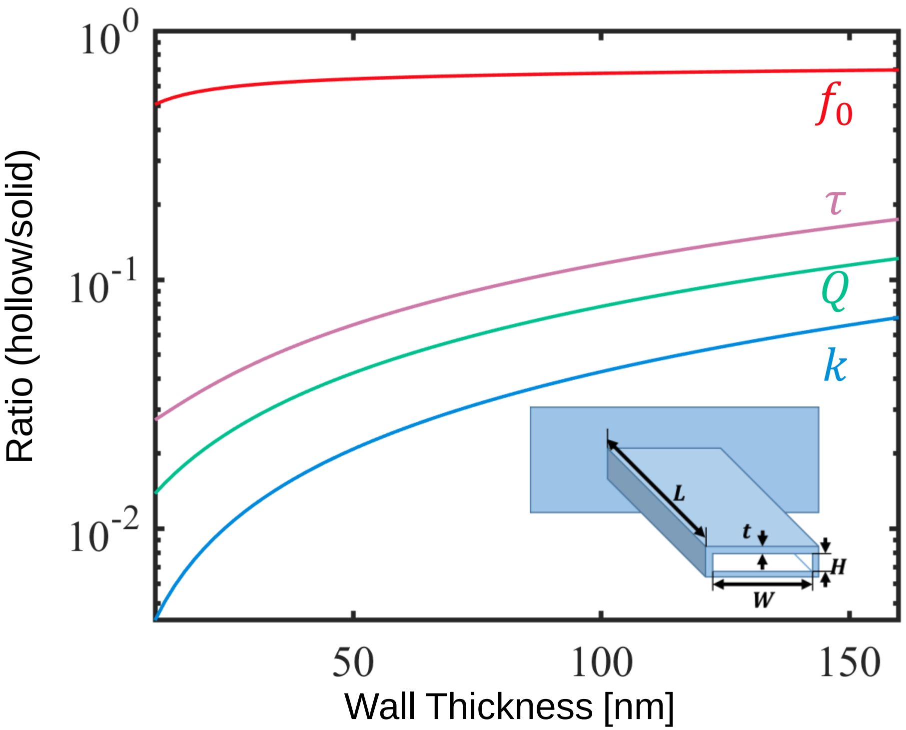


	Solid	Hollow
Moment of Inertia (I)	$\frac{1}{12}WH^3$	$\frac{1}{6}H^3t(1+3\frac{W}{H})$
Effective cantilever density (ρ)	Cantilever material → ρ_c	Fluid → $\rho_f + 2\rho_c\left(\frac{1}{W}+\frac{1}{H}\right)t$
Torsion Constant (J)	$\frac{WH}{12}(H^2+W^2)$	$\frac{2W^2H^2t}{W+H}$

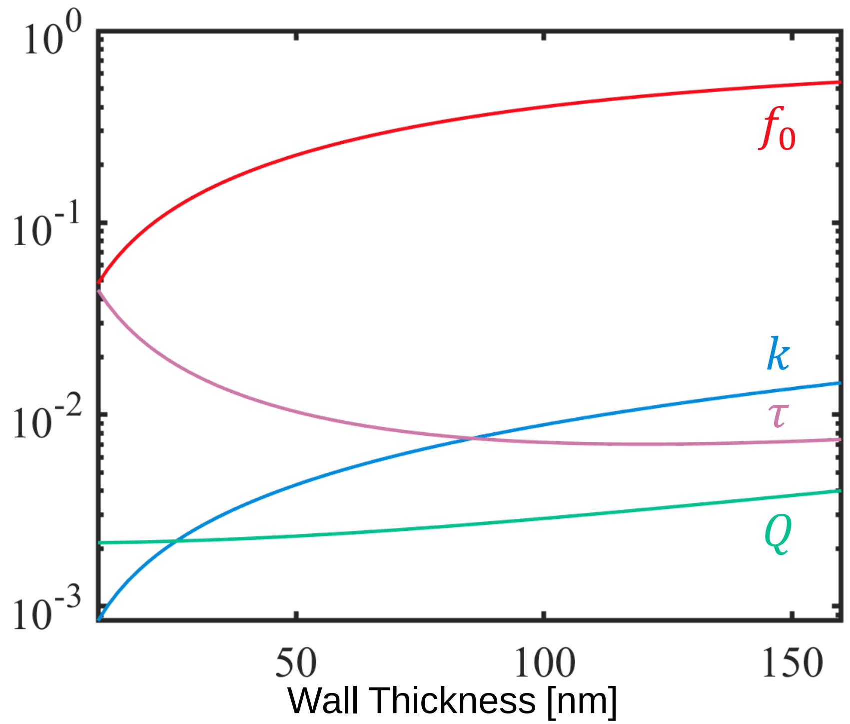
Thickness dependence

Theory: Hollow Beam Cantilever

Flexural Mode



Torsional Mode

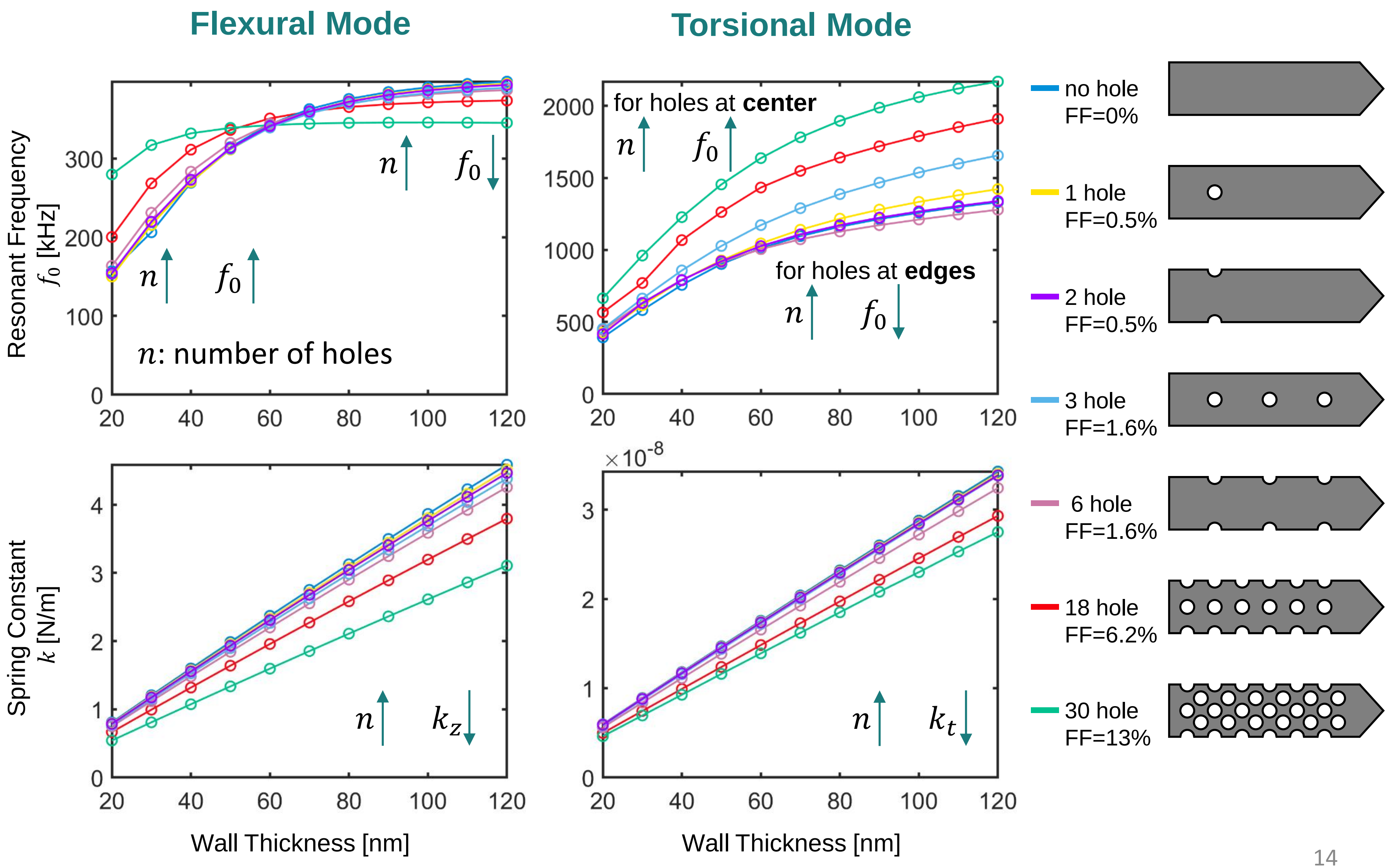


*Equations used to derive these plots can be found in the supplementary slide at the end

- Hollow beam cantilevers with nanoscale walls have properties that depends on thickness (**tunability**)

Simulation: Hollow Cantilever with Holes

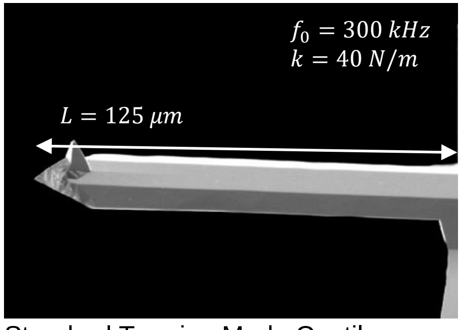
- Simulation results show f_0 and k varies with wall thickness and number of holes



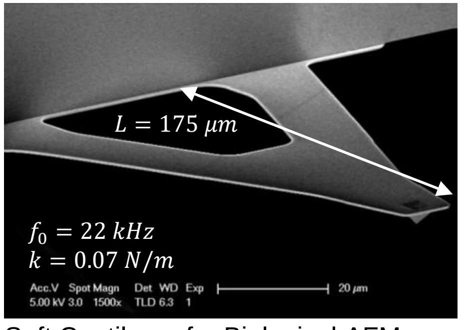
Conclusion & Future Work

Conclusion

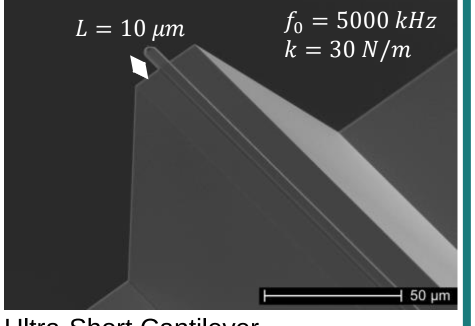
- High f_0 and low k in both flexural and torsional mode
- Tunability based on wall thickness and number of holes
- Potential benefits for dynamic biological samples



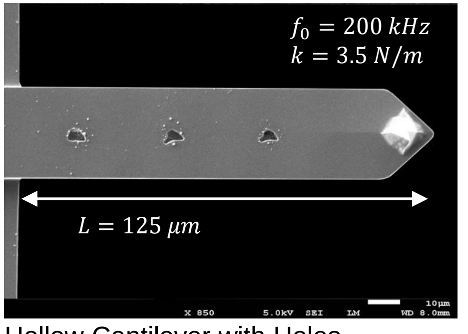
Standard Tapping Mode Cantilever (Nanoworld NCH)



Soft Cantilever for Biological AFM (Bruker MLCT-BIO)



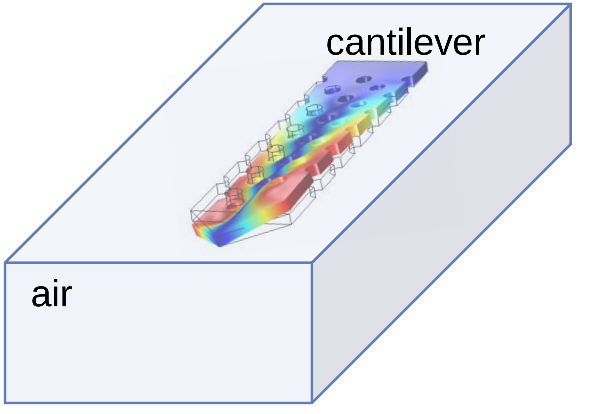
Ultra-Short Cantilever (Nanoworld USC-F5-k30)



Hollow Cantilever with Holes

Future Work

- Viscous fluid damping simulation
- Torsional mode measurements



Acknowledgments & Reference

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- Special thanks to:
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Thank You.

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Supplementary Slides

Theory: Hollow Beam Cantilever

	Flexural	Torsional
Vacuum Resonant Frequency $f_{0(v)}$	$\frac{1.758}{\pi L^2}\sqrt{\frac{EI}{\rho_c A}}$	$\frac{1}{4L}\sqrt{\frac{GJ}{\rho_c I_p}}$
Damped Resonant Frequency $f_{0(f)}$	$f_{0(v)}\sqrt{\frac{1}{1+\left(\frac{\pi\rho_f W}{4\rho_c H}\right)\Gamma_{re}}}$	$f_{t(v)}\sqrt{\frac{1}{1+\left(\frac{\pi\rho_f b^4}{8\rho_c I_p}\right)\Gamma_{re}}}$
Quality Factor Q_f	$\frac{\frac{4\rho_c H}{\pi\rho_f W}+\Gamma_{re}}{\Gamma_{im}}$	$\frac{\frac{8\rho_c I_p}{\pi\rho_f b^4}+\Gamma_{re}}{\Gamma_{im}}$
Spring Constant k	$\left(\left(k_{bending}\right)^{-1}+\left(k_{shear}\right)^{-1}\right)^{-1} = \left(\frac{1}{\left[\frac{H^3Et}{2L^3}\left(1+3\frac{W}{H}\right)\right]}+\frac{1}{\left[\frac{GA}{L}\right]}\right)^{-1}$	$\frac{GJ}{L}$

- Thin-Walled Hollow Cantilever:

$$I = \frac{(W+2t)(H+2t)^3}{12} - \frac{bh^3}{12} \approx \frac{1}{6}H^3t\left(1+3\frac{W}{H}\right) \qquad (t \ll W, H)$$

$$\rho_c \approx \frac{([(W+2t)(H+2t)-WH]\rho_{alumina})}{WHL} = \frac{(H+W)}{WHL}t\rho_{alumina} \qquad (t \ll W, H)$$

$$A = (W+2t)(H+2t) \approx WH \qquad (t \ll W, H)$$

$$J = \frac{4t[(W+t)(H+t)]^2}{2(W+H+2t)} = \frac{2t(W+t)^2(H+t)^2}{W+H+2t} \approx \frac{2W^2H^2t}{W+H} \qquad (t \ll W, H)$$

$$I_p \approx \frac{(W+2t)(H+2t)t(W+H+4t)}{3} \qquad (t \ll W, H)$$

Sader, *J. App. Phys.* (84) 1998;
Green & Sader, *J. App. Phys.* (92) 2002;
Green *et al.*, *Rev. Sci. Inst.* (75) 2004