Microfabrication of large area high-stress silicon nitride membranes for optomechanical devices

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AIP Advances, 2016, 6, 065004

iQUOEMS Erice conference
04 August 2016

UNIVERSITÀ DEGLI STUDI DI TRENTO
INFN Istituto Nazionale di Fisica Nucleare
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Università degli Studi di Firenze
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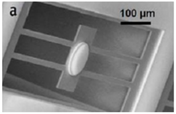
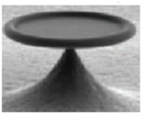
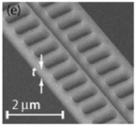
Motivation

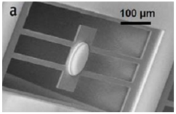


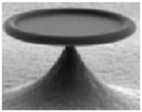



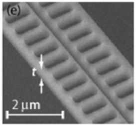
see e.g. *Aspelmeyer, Kippenberg, Marquardt*, RMP 86 1391 (2014)

- low-loss mechanical resonators for optical cavities
- SiN membranes

Motivation







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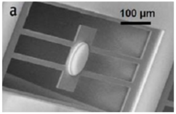
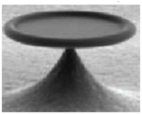
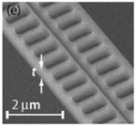




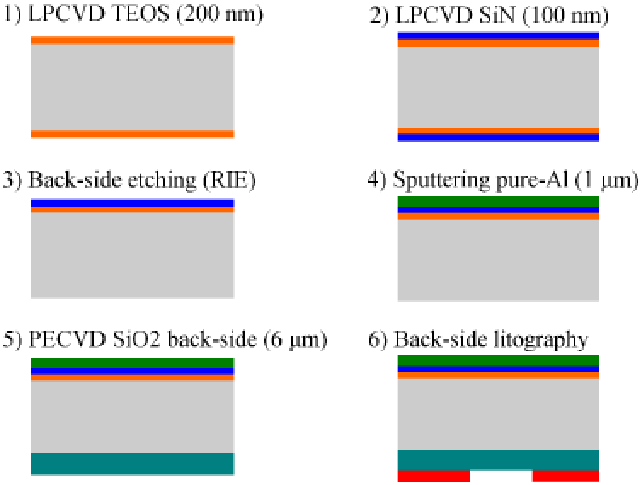


see e.g. *Aspelmeyer, Kippenberg, Marquardt*, RMP 86 1391 (2014)

- low-loss mechanical resonators for optical cavities
- SiN membranes

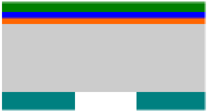
- freely selectable shape
- controlled high internal stress

Microfabrication process

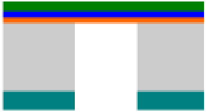


Microfabrication process

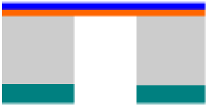
7) Back-side dry etching (SiO2)



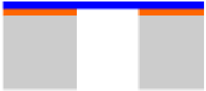
8) DRIE silicon etching



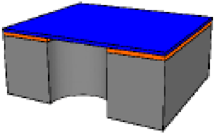
9) Pure-Al wet etching (PES)



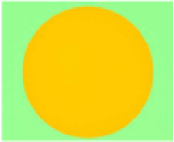
10) TEOS wet etching (HF)



11)

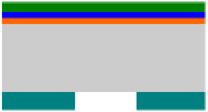


12)

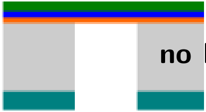


Microfabrication process

7) Back-side dry etching (SiO_2)

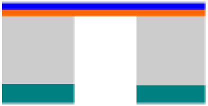


8) DRIE silicon etching



no KOH etching!

9) Pure-Al wet etching (PES)



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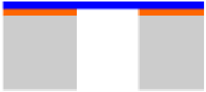

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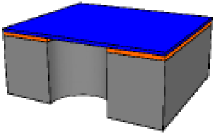

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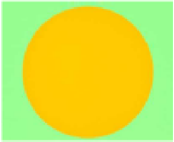
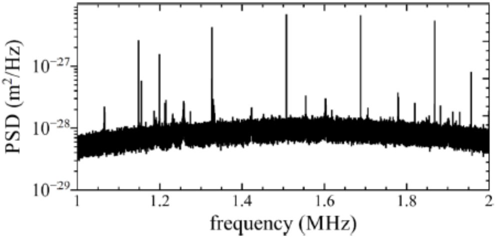


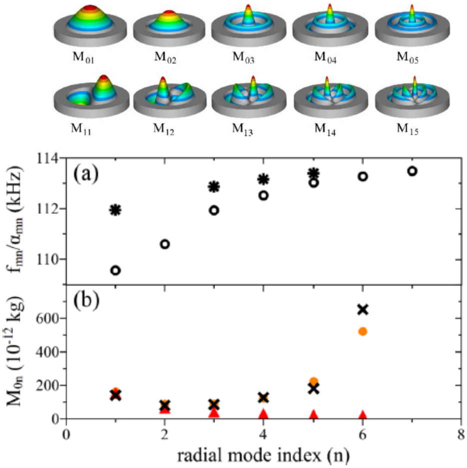
Resonance frequencies of circular membranes

- resonance frequencies

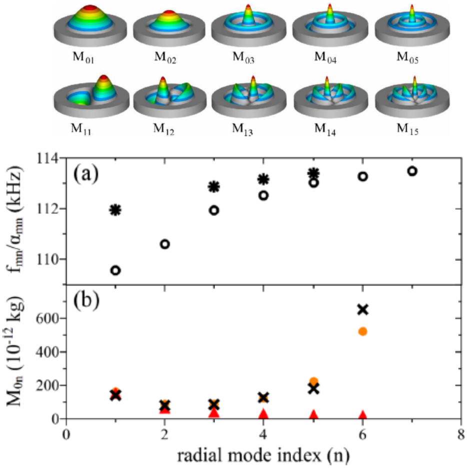
$$f_{mn} = f_0 \alpha_{mn}, \quad f_0 \equiv \frac{1}{2\pi R}\sqrt{\frac{\mathcal{T}}{\rho}}, \quad J_m(\alpha_{mn}) = 0$$



Resonance frequencies of circular membranes

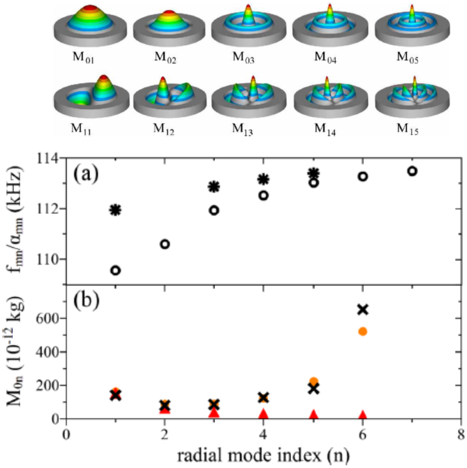


Resonance frequencies of circular membranes



$$f_0^{\mathrm{exp}} \simeq 114\ \mathrm{kHz}$$

Resonance frequencies of circular membranes



$f_0^{\text{exp}} \simeq 114$ kHz

$R = 0.75$ mm
$\mathcal{T} = 1$ GPa
$\rho = 3200$ kgm^{-3}

$f_0 = 118.6$ kHz

Effective mass

- effective mass dependent on modal index
  - pointlike readout:

$$M_{0n} = M J_1^2(\alpha_{0n})$$

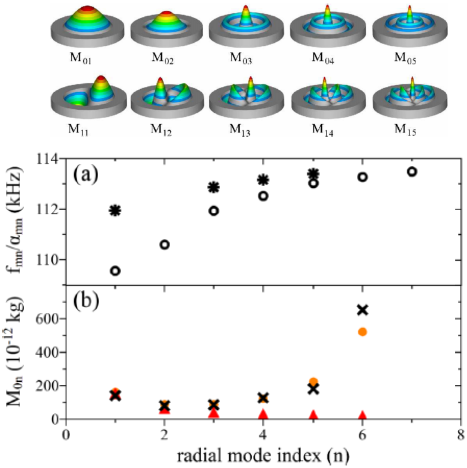
  - Gaussian readout:

$$M_{0n} = M \left(\frac{J_1(\alpha_{0n})}{\frac{4}{w^2} \int J_0(\alpha_{0n} r/R) \exp\left(-\frac{2r^2}{w^2}\right) r dr} \right)^2$$

- experimentally obtained from the areas of the thermal peaks

$$A_{0n} = \frac{kT}{M_{0n}(2\pi f_{0n})^2}$$

Effective mass



Q-factor

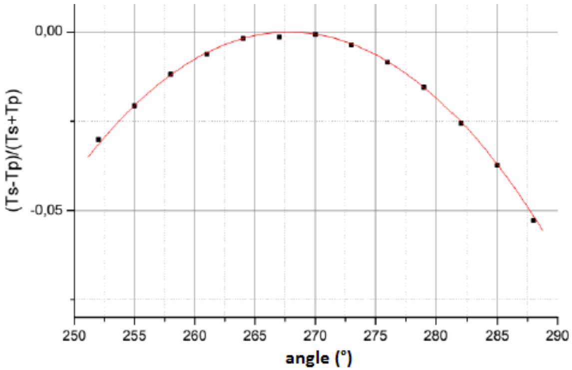
- at room temperatures ranging from few thousands to 2×10^5
- at cryogenic temperatures globally higher:

$R = 0.75$ mm, 5 mm side frame — $Q_{max} = 0.65 \times 10^6$ @ 8 K

$a = 1$ mm, 5×20 mm^2 frame — $Q_{max} = 1.3 \times 10^6$ @ 13 K

Optical properties of circular membranes

$$L_d = 97.27 \pm 0.01 \text{ nm}$$
$$n_R = 2.0210 \pm 0.0005 \ @ \ \lambda = 1064 \text{ nm}$$



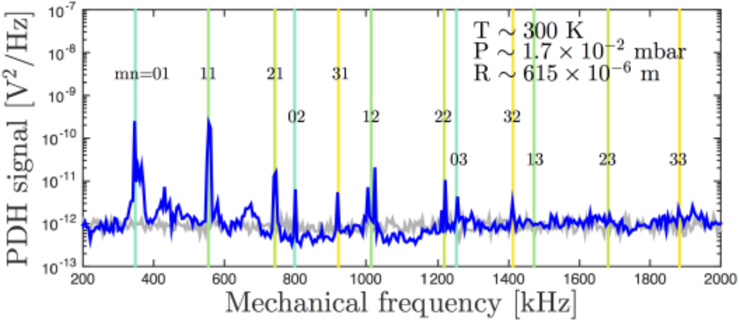
Optical properties of circular membranes

$\Rightarrow |r_d|^2 = 0.355 \pm 0.002$

- reflection and transmission coefficients of the membrane, $\beta \equiv nkL_d$

$$r_d = \frac{(n^2-1)\sin\beta}{2in\cos\beta + (n^2+1)\sin\beta}$$
$$t_d = \frac{2n}{2in\cos\beta + (n^2+1)\sin\beta}$$

Optical properties of circular membranes



$f_{01} \sim 348.5$ kHz

Finesse measurement

- cavity resonance shift

$$\delta\Omega_c(z) = \frac{c}{L}\left\{(-1)^{\left\lfloor \frac{n_M k^0_{mnp} L_d}{\pi} \right\rfloor} \arcsin\left[(-1)^p \sqrt{\mathcal{R}(k^0_{mnp})}\cos(2k^0_{mnp}z)\right] - \right.$$

$$\left. -\beta(k^0_{mnp}) - \left(\frac{n_M k^0_{mnp} L_d}{\pi}\right)\pi \right\}$$

see e.g. *Biancofiore et al.*, PRA 84, 033814 (2011)

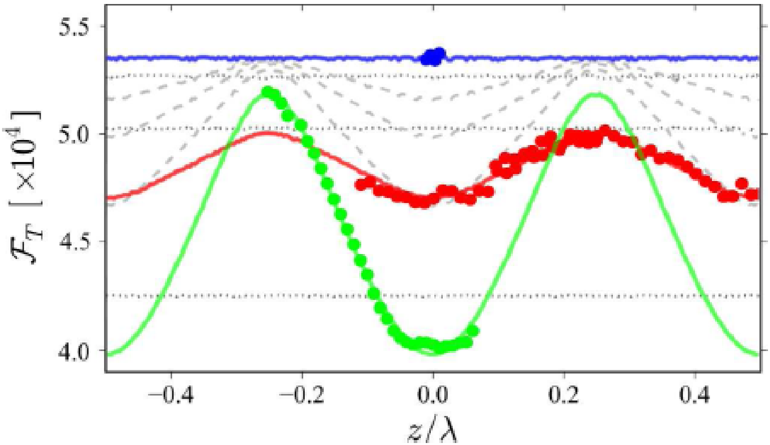
- additional loss channel

$$\kappa(z) = \kappa_0 + \kappa_1(z) \quad \text{where} \quad \kappa_1(z) = \mathrm{Im}\left\{\delta\Omega_c(z)\right\}$$

$$\Rightarrow \quad \frac{1}{\mathcal{F}_T} = \frac{1}{\mathcal{F}} + \frac{2}{\pi}\left|\mathrm{Im}\left(\frac{L\delta\Omega_c(z)}{c}\right)\right|$$

- ringdown technique, $\mathcal{F}_T = \pi c\tau/L$, $\tau = 1/\kappa$

Finesse measurement



Finesse measurement

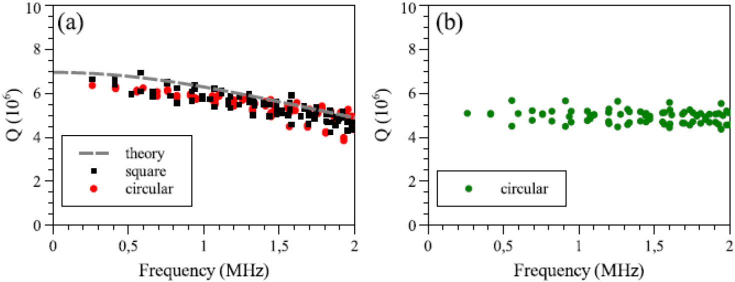
- optical roughness $\sigma_{opt} \Rightarrow \sqrt{\exp\left[-(2k\sigma_{opt})^2\right]}$
- $L_d = 97$ nm, $n_R = 2.021$, $L = 9.03$ cm, $\lambda = 1064$ nm, $\mathcal{F} = 53500$

- $n_I = (1.97 \pm 0.08) \times 10^{-6}$
- $\sigma_{opt} = (287 \pm 4)$ pm

- Norcada 1 mm side, 50 nm thickness membrane: $n_I = (1.0 \pm 0.01) \times 10^{-5}$, $\sigma_{opt} = (280 \pm 10)$ pm

Thank you!

Auxiliary slides



$$M_i = \frac{\tilde{M}_i}{\Theta^2_{i,j,l}}$$

where

$$\tilde{M}_i = A_i L_d \rho,$$

$$A_i = \int_0^R r dr \int_0^{2\pi} d\theta \phi_i(r,\theta)^2,$$

$$\Theta_{i,j,l} = \int_0^R r dr \int_0^{2\pi} d\theta \phi_i(r,\theta) \tilde{T}_j(x,y) \tilde{T}_l(x,y),$$

with, e.g.,

$$\tilde{T}_j = \frac{H_p(\sqrt{2}x/w_0) H_r(\sqrt{2}y/w_0)}{w_0\sqrt{\pi 2^{p+r-1} p! r!}} \exp\left(-\frac{x^2+y^2}{w_0^2}\right)$$