Towards the Inclusion of Large Area High-Stress Silicon Nitride Membranes in Opto-Mechanical devices

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The optomechanical coupling between a laser beam and a microdevice via radiation pressure is gaining interest in fundamental research in quantum-optics and wide-range applications [1,2]. Actually recent advances in micro- and nano-mechanical resonators offer great potential for precision sensing and for manipulation of the quantum state of light in a high-finesse Fabry-Perot optical cavity. One promising platform is silicon nitride (Si_3N_4) membrane resonators on silicon substrates, in which a large tensile stress (of the order of GPa) increases the Q-frequency product above 10^{13} Hz [3]. Silicon nitride resonators are used mainly in experiments with dispersive membrane in the middle (Fig.1) for detecting signature of quantum phenomena as optical cooling or ponderomotive squeezing [4]. There are a number of ongoing efforts to extend the capabilities of these resonators. We mention for instance metallized membranes, to be used in hybrid optical-microwave setups [5], and the study of intrinsic mechanical loss, to improve their mechanical performance [6]. In particular efforts are underway [7,8] to improve the overall reproducibility of membrane-based resonators, where the quality factor and the frequency can depend on the details of the sample holder. This translate into reducing: (1) radiation loss due to the *phonon tunneling*, in which the energy of membrane modes radiates into the substrate, and (2) substrate noise, in which the mechanical modes of the silicon frame limit the optomechanical performance.

In this work, we address some issues concerning the integration of SiN membranes, currently made by KOH release, with on-chip isolation systems made by DRIE. In fact the release process puts some constraints on the final shape of the membrane, because the DRIE have to be stopped tens of microns short of etching fully through the wafer, and a KOH wet etch completes the release of the membrane on the front of the wafer. Moreover the intrinsic anisotropy of the KOH silicon etching forces the production of square membranes, while circular membranes can display superior mechanical properties [9] and more complex shapes could be very useful in hybrid systems. In view of the integration of the SiN membrane in a SOI wafer with on-chip isolation [10], we developed a general fabrication procedure for free standing large area LPCVD high-stressed SiN membranes in any shape (in Fig. 2 a round shape membrane) with a good dimensional precision by using DRIE through wafer etching. With a special recipe we are able to release the free-standing membrane preserving both optical quality (in terms of cavity finesse) and its mechanical Q-factor. In the bottom table of Fig. 3, we report the quality factor of a mode of the membrane measured at room temperature and at cryogenic temperature, and in Fig. 4 we show the finesse of an optical cavity with the membrane in the middle, plotted vs the position of the membrane.

To measure the frequency and the Q-factor, we realized a Michelson interferometer with a balanced homodyne detection scheme (as shown in Fig. 3). In this set up we observed the usual limitations due to clamping issues, but Q-factor of the order of million have been measured for some modes. In comparison to commercial wet-etch SiN membranes, we have an improved the optical quality that allows finesse up to $4x10^4$. These results encourage us to go forward with the inclusion in more complex silicon devices [10,11] tailored for quantum optomechanics in the frequency band 100-500 kHz.

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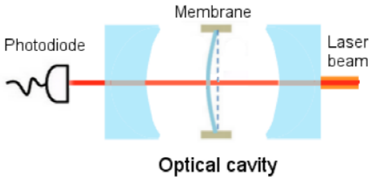

Figure 1: principle of Membrane in the Middle opto-mechanical experiment

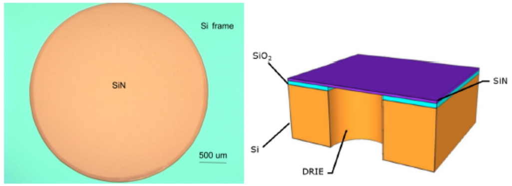

Figure 2: (left) Optical microscope image of a SiN membrane (100 nm thick, $\sigma_0 = 1$[GPa])

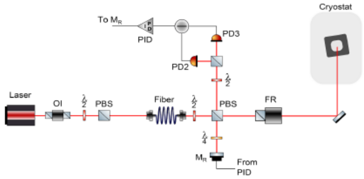

Figure 3: Michelson scheme for measuring the mechanical Q-factors reported in the table. The membrane is a round-shape membrane, diameter d = 1.5 mm thickness $L_d = 97$ nm and $\nu_0 = 119$k [Hz], $\sigma_0 = 0.92$ [GPa].

T [K]	$\nu_{m,n}$[kHz]	Q	m_e [kg]
300	969	6.5×10^4	8.5×10^{-11}
8	894	6.5×10^5	-

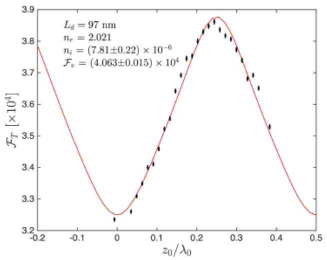

Figure 4: cavity finesse $\mathcal{F}_T$, as a function of the membrane position in the cavity. The red curve represents the best fit of the theoretical expectation. Fixed parameters of the fit are the membrane thickness Ld = 97 nm, and real part of the index of refraction $n_r = 2.021$. Parameters obtained with 95% of confidence are the imaginary part of the index of refraction $n_i = (7.81 \pm 0.22) \times 10^{-6}$, and the empty-cavity finesse of $\mathcal{F}_v \sim 4 \times 10^4$.