DOI 10.5162/SMSI2025/C5.3

Optomechanical Gas Pressure Sensing over Broad Pressure and Temperature Ranges

Christoph Reinhardt[1], Hossein Masalehdan [2], Sandy Croatto [1], Lea Stankewitz [1,2], Alexander Franke [2], Moritz Kunze [1,2], Jörn Schaffran [1], Nils Sültmann [2], Axel Lindner [1], Roman Schnabel [2],
[1] Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[2] Institut für Quantenphysik (IQP) & Zentrum für Optische Quantentechnologien (ZOQ), Universität Hamburg, 22761 Hamburg, Germany
christoph.reinhardt@desy.de

Summary:
This paper presents novel optomechanical gas pressure sensors featuring a chip-scale mechanical resonator with ultra-low intrinsic loss, read out via an optical interferometer. In a recent experiment using a free-space optical Michelson interferometer, we demonstrated a single sensor with an unprecedented 10-decade measurement range from 10^{-7} to 10^{3} mbar. After providing a brief overview of our ongoing efforts to extend this range further towards lower pressures, we present developments of a compact, portable version of the sensor, using an optical fiber-based readout. We demonstrate this sensor's functionality over a broad temperature range from 77 K to 300 K.

Keywords: Gas Pressure Sensor, Interferometer, Nanomechanics, Vacuumtechnology, Cryogenics

Introduction

Chip-scale oscillating membranes have recently been shown to offer outstanding capabilities for gas pressure sensing. The demonstrated features are enabled by the membranes' ng-scale mass and ultra-low intrinsic loss, which are fully leveraged by measuring their oscillations using an optical interferometer.

In a recent study, we demonstrated such an optomechanical gas pressure sensor with an unprecedented measurement range, spanning 10 orders of magnitude [1]. Furthermore, a sensor for direct pressure measurements, independent of gas type, has been realized [2]. Work conducted at the National Institute of Standards and Technology (NIST) has demonstrated optomechanical pressure sensors with a total measurement uncertainty of $\sim 1\%$ [3], making them suitable as primary pressure sensors.

In this work we present our current efforts toward two main goals for optomechanical gas pressure sensors. First, we aim to extend the measurement range towards lower pressures, reaching into the ultra-high vacuum regime ($< 10^{-8}$ mbar). Second, we are developing a compact and portable version of the sensor that is applicable in typical vacuum setups. To this end the free-space optical readout is being replaced with an optical fiber interferometer.

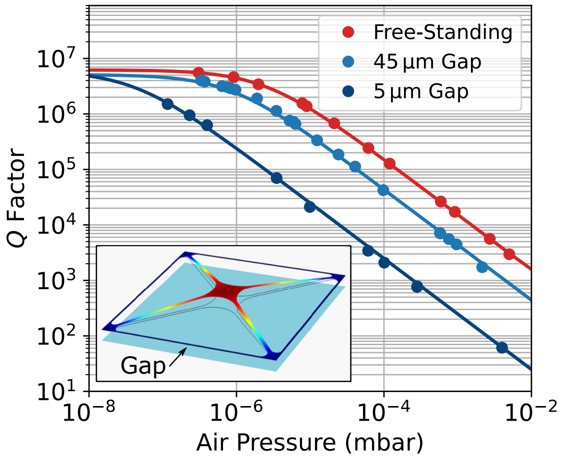

Fig. 1: Pressure dependency of the mechanical quality factor for three different trampoline pressure sensors. The inset shows a simulated oscillation mode profile of a mm-sized device, which forms a μm-scale gap with a neighboring surface.

Squeeze-Film Pressure Sensor

In Ref. [1], we present a single optomechanical gas pressure sensor covering a measurement range from 10^{-7} to 10^{3} mbar. The sensor's measurement principle relies on a pressure-dependent frictional force exerted on the oscillating membrane by impacting gas particles. This is reflected by a pressure-dependent mechanical quality factor Q, which, in the free molecular flow regime, is given by

$$Q = \left[Q_{\mathrm{in}}^{-1} + \xi \left(\frac{f \rho h}{P} \sqrt{\frac{\pi^3 k_{\mathrm{B}} T}{8m}} \right)^{-1} \right]^{-1}, \qquad (1)$$

with intrinsic quality factor Q_{in}, resonance frequency f, mass density ρ, and thickness h of the membrane, as well as pressure P, temperature T, and particle mass m of the gas. The additional parameter ξ is explained in the following.

To extend the measurement range further toward lower pressures, we exploit squeeze-film damping. The inset of Fig. 1 shows a schematic of the corresponding setup. Here, a silicon nitride trampoline membrane (details provided in Fig. 1 of Ref. [1]), comprising a central pad suspended by four tethers, is installed parallel to a neighboring surface, with a $\mu\mathrm{m}$-scale gap in between. As the membrane oscillates, gas is shuttled in and out of the gap, which increases the pressure sensitivity compared to a free-standing membrane, used in the first generation of the sensor.

The red points and curve in Fig. 1 represent the measured and modelled pressure sensitivity of the free-standing trampoline, respectively (adapted from Fig. 4 of Ref. [1]). In the corresponding model function (Eq. 1), $\xi = 1$. Results for the novel squeeze-film sensor are represented by light and dark blue points and curves for 45 $\mu\mathrm{m}$ ($\xi = 4$) and 5 $\mu\mathrm{m}$ ($\xi = 62$) gaps, respectively. Compared to the free-standing trampoline, the onset of the pressure sensitivity for the squeeze-film sensor with a 5 $\mu\mathrm{m}$ gap is shifted to about sixty times lower pressure values. Overall, the relative deviation between data and respective model is within $\pm 15\,\%$.

Compact & Portable Pressure Sensor with Optical Fiber Readout

As the first step toward realizing a universally applicable version of our optomechanical pressure sensor, we replaced the free-space optical components with fiber optics. Figure 2(a) shows a schematic of the setup, where light from a laser, including an optical isolator, is split such that 90 % are directed onto photodiode 1, for monitoring laser stability, and 10 % to the membrane sensor, which reflects a fraction of this light back onto photodiode 2. The output voltages of the photodiodes are measured with a lock-in amplifier. Figure 2(b) shows a schematic of the sensor's key components, an optical fiber pointed at an oscillating square membrane. The membrane's oscillation is measured via amplitude modulation of the reflected light, which results from interference of the part directly reflected at the fiber tip and the part reflected by the membrane back into the fiber. Panel (c) shows a photograph of the membrane, suspended from a periodically patterned silicon chip (for suppressing the coupling to the support structure).

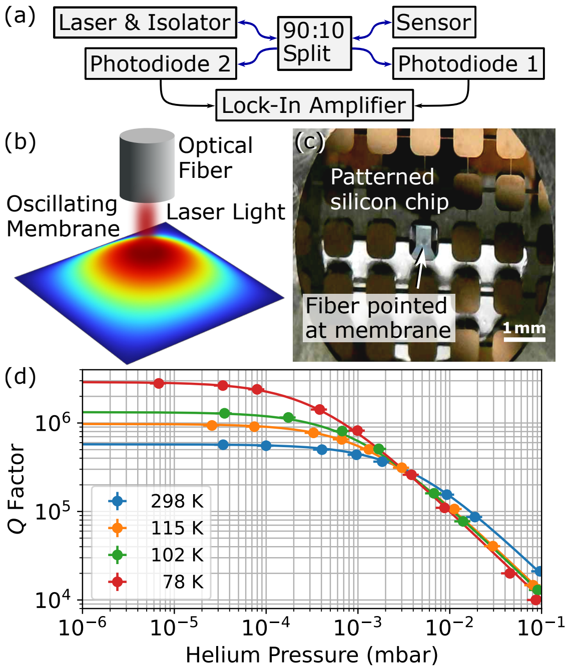

Fig. 2: Optomechanical gas pressure sensor with fiber-based readout setup (a) and key sensor components (b). (c) Photograph of the square silicon nitride membrane, suspended from a periodically patterned silicon chip. (d) Helium pressure dependence of the mechanical quality factor at different temperatures.

We measured the dependency of the sensor's mechanical quality factor on the surrounding helium pressure, inside a liquid nitrogen dipper cryostat. Figure 2(d) shows the results, at four different temperatures, where the data points are shown together with the corresponding model functions (Eq. 1, $\xi = 1$), each represented by a curve of the same color. The relative deviation between each data set and its corresponding model function is within $\pm 15\,\%$, as obtained for the squeeze-film sensor (presented above). The observed fivefold increase in the intrinsic quality factor from $Q_{\mathrm{in}} = 6 \times 10^5$, at 298 K, to $Q_{\mathrm{in}} = 3 \times 10^6$, at 78 K, follows the general trend for silicon nitride membranes.

Conclusion

We demonstrate that exploiting squeeze-film damping in optomechanical gas pressure sensors expands their measurement range to pressures sixty times lower than an otherwise identical sensor without squeeze-film damping. Furthermore, we developed a compact, portable optomechanical pressure sensor with fiber-optic readout. This sensor is compatible with cryogenic temperatures, where it provides an extended measurement range compared to room temperature, due to a fivefold increase in its intrinsic mechanical quality factor.

References

[1] C. Reinhardt, H. Masalehdan, S. Croatto, A. Franke, M. B. Kunze, J. Schaffran, N. Sültmann, A. Lindner, R. Schnabel, Self-Calibrating Gas Pressure Sensor with a 10-Decade Measurement Range, *ACS* Photonics, 11(4), 1438-1446 (2024); doi: 10.1021/acsphotonics.3c01488

[2] M. Salimi, R. V. Nielsen, H. B. Pedersen, A. Dantan, Squeeze film absolute pressure sensors with sub-millipascal sensitivity, *Sensors and Actuators A: Physical*, 374, 115450 (2024); doi: 10.1016/j.sna.2024.115450

[3] O. R. Green, Y. Bao, J. R. Lawall, J. J. Gorman, D. S. Barker, Accurate, precise pressure sensing with tethered optomechanics, *arXiv preprint* arXiv:2409.00256 (2024); doi: 10.48550/arXiv.2409.00256