# Advances in optomechanical force sensors

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***Abstract* - Mechanical elements are successfully employed as force sensors in various devices. The sensors have reached impressive sensitivity of few nN/sqrt(Hz), but the quest for even more sensitive sensors is still on. The capability of sensing a single bacteria stuck to the sensor's surface in few seconds would provide unprecedented possibilities in various fields. Even in physics such sensitive sensors could be used in search for the elusive constituents of the dark sector. A possible interaction of either dark energy or dark matter with the sensor could be detected. A characterisation of an optimised sensor element will be presented along with it's properties.**

***Keywords – force sensor; optomechanics; dark sector; characterization***

## I. INTRODUCTION

The need for measurement of ever tinier forces is probably as old as human history. The first great achievement in the field is more than two centuries old and is due to H. Cavendish who first measured the force of gravity between two masses in the laboratory. A century later L. Eötvös further improved the technique and the sensitivity of the apparatus. These measurements relied on the torsion balance method where a beam is suspended on a thin wire and the differences in the horizontal force perpendicular to the beam acting on its ends is detected as a rotation. Usually, the rotation is observed as a deflection of a light beam reflecting from a mirror attached to the beam itself.

Since then, with advances in manufacturing of sensors and readout devices there is a constant improvement in the sensitivity of the force sensors. The torsion balance technique is not the most sensitive and mostly used measurement method. Nowadays there is a plethora of devices and techniques which are used in force measurements. The possibilities range from tiny cantilever beams used in Atomic Force Microscopes where the change in either their displacement or resonant frequency corresponds to a measured force, over Quartz Crystal Microbalances where a change in resonant frequency is proportional to applied force, to piezoelectric crystals where a voltage proportional to the force acting on the crystal is generated. Each of these systems has advantages and disadvantages and their field of application is based on them.

It turns out that force sensors can be used also in searches for the constituents of the Dark Sector, i.e. Dark Matter (DM) and Dark Energy (DE) [1] which could answer the questions about the still largely unknown composition of the universe. Nowadays, the observations of the Cosmological Microwave Background by various experiments show that only 5% of the Universe's content is the ordinary baryonic matter [2]. The rest is either DM which was introduced to explain the anomalous rotational velocities of the stars around galactic centres [3] or DE which should account for the accelerated expansion of the Universe [4]. An experiment where detection of DE candidate particles by sensing the force exerted by their interaction with a force sensor was performed at CERN [5]. Since their interaction with the sensor depends on the density of the material from which it is made, tests have been performed at the University of Rijeka with different coatings applied to the sensor surface. In this work, a force sensor based on a thin silicon nitride membrane produced by Norcada and modified at the University of Rijeka is presented.

## II. MEMBRANE CHARACTERIZATION

The proposed force sensor is a 2x2 $mm^2$ square membrane 50 nm thick and supported by 200 $\mu m$ silicon frame. Its fundamental resonant frequency can be calculated by using the expression

$$f = \frac{\sqrt{2}}{2L}\sqrt{\frac{T}{\rho t}}\,. \quad (1)$$

Here L is the side length, T the tension related to inplane stress ~ 1 GPa, $\rho$ density of the membrane material and t its thickness. When the numbers for that particular membrane are used $f \sim 2 \cdot 10^5$ Hz is obtained which is less than percent from the measured value.

In order to enhance its sensitivity to DE particles order of ten nanometres of high-density coating was applied on a membrane [6]. If the same equation is used to estimate the frequency of the coated membrane where only the density and the thickness are changed the result is more than 40 kHz off the measured value of $f \sim$ 70 kHz. Obviously, the oversimplified model from the previous equation is accused

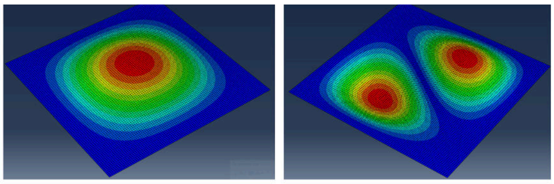


*Fig. 1. The first (a) and second (b) eigenmode of a prestressed silicon nitride membrane with a thin platinum layer.*

source of the discrepancy and a full finite element simulation was performed to obtain a theoretical value of the frequency.

A modal analysis of the composite silicon nitride membrane with dimensions 2x2 mm and thickness 50 nm was performed. A layer of platinum 13.3 nm thick was considered as an added mass of uniform distribution. The Young's modulus of silicon nitride was 270 GPa, Poisson ratio 0.27 and specific mass density 3180 kg/m$^3$. The specific mass of platinum was 21460 kg/m$^3$.

The membrane was prestressed with inplane stress of 1 GPa. The finite element analysis was performed in Abaqus 6.14 and the model consisted of 10000 S4R finite elements. Standard modal analysis with included prestress effects was performed.

First two modes are given in Fig. 1. The first eigenvalue equals 118.6 kHz while the second one is 187.5 kHz. Such kind of eigenmodes are expected in the case of square membranes.

Again the result is off from the measured value and in order to understand the discrepancy the properties of the membrane's coating were further investigated. The membrane coated with the same process parameters as the one used in the measurements was further investigated. The thickness and distribution of the coating was studied with Scanning Electron Microscope and an ellipsometer.

The thickness of the layers was determined using JEOL JSM-7800F field emission SEM instrument from the cross-sectional SEM images recorded at the working distance (WD) of 2 mm, by collecting the secondary electrons with the electron beam acceleration voltage of 12 kV. The overview of the resulting cross-section can be seen in Fig. 2. The surface of a 45 nm thick silicon nitride membrane is coated with rather uniform Pt thin film of approximately 13.5 nm.

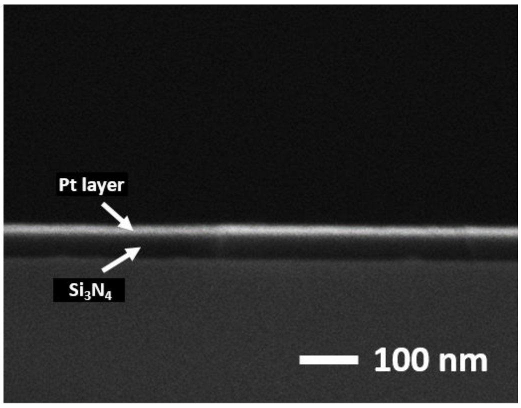


*Fig. 2. Cross section of the membrane's frame. The Si frame (bottom) and silicon nitride and platinum layers can be seen.*

It's interesting that the silicon nitride is almost transparent in the picture, but since these materials are used as sample holders for electron or X ray microscopy applications this is hardly surprising. As a confirmation of these results also an ellipsometric measurement of the thickness was performed. This method is interesting also for future application since it is non-invasive and it can be used on membranes that will be used in force sensing setups.

Variable angle spectroscopic ellipsometry (VASE) was applied for the experimental determination of the thickness of the two layers (Si3Ni4, Pt). The ellipsometric spectra measured for the sample in the wavelength range 400 – 1000 nm, at three angles of incidence (45°, 50°, 55°), are presented in Fig. 3. The thickness of the layers was determined by fitting the Fresnel's equations for a model of stratified optical layers, comprising crystalline Si/$Si_3N_4$/Pt/air (from the semi-infinite substrate to the medium), and by applying the dielectric functions for the three involved materials (Si,$Si_3N_4$,Pt) as reported in the Sopra database [7] while $\tilde{\varepsilon} = 1 + 0 \cdot i$ for air at all wavelengths. The modelled ellipsometric angle spectra are presented in Fig. 3. as solid lines, and the best fit thicknesses of the $Si_3N_4$ and Pt layers are 45.5 nm and 13.5 nm, respectively.

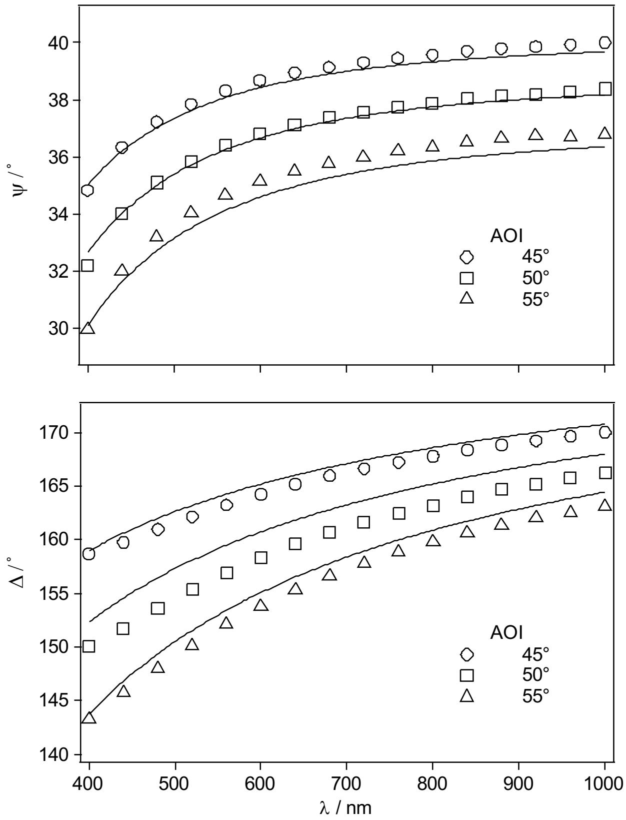


*Fig. 3. VASE ellipsometric angles spectra measured for the crystalline Si/Si3N4/Pt/air sample at room temperature at three different angles of incidence. Solid lines represent the best fit VASE spectra obtained by the model, with the fitted thicknesses of 45.5 nm and 13.5 nm for the $Si_3N_4$ and Pt layer, respectively. The measurements were performed with a nulling ellipsometer (EP4, Accurion GmbH).*

From the thickness' measurements and the model used in finite element analysis it is clear that for the full understanding of the membrane's mechanical properties the influence of the added layer on the value of the prestress should be considered and a more elaborate model should be used.

## III. Optical Measurements

The oscillations of the membrane are measured by the Michelson interferometer where the mirror in one arm is replaced by the membrane. The output of the interferometer is read out by the optical homodyne technique. The signal is digitized and stored on a personal computer where it is analysed. The analysis consists of performing a Fourier transform on the time series, and subsequently performing a least-squares fit of the peaks with a Lorentzian

$$A(\omega) = \sqrt{\frac{1}{m}\frac{2k_BT}{\left(\omega^2-\omega_0^2\right)^2+(D\omega)^2}}. \qquad (2)$$

In theory useful information is contained in every parameter of the fit, but for the purpose of this work only the resonant frequency $\omega_0$ will be used since only relatively few external causes are expected to influence it. It is noteworthy that no external excitation other than connection to the thermal bath is needed to excite

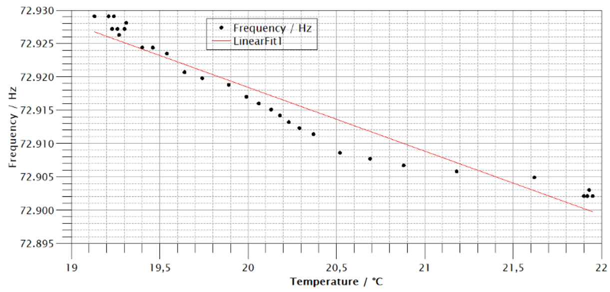


*Fig. 4. Dependence of the frequency on the room's temperature. A change of about 10 Hz per degree Celsius is observed.*

membrane's oscillation. From Eq. 2 it can be seen that the bath temperature has an influence on the amplitude of the peak but not on its frequency. However, the measurements show a dependence of the resonance's frequency on the temperature (Fig. 4).

The observed frequency dependence on the temperature is attributed to the changes in the material properties. Further investigation included the influence of the pressure in the vacuum chamber on the frequency. The results shown in Fig. 5 do not show a clear dependency and are not conclusive.

Basically, a correlation between the pressure and frequency is suspected but there is no explanation about the origin of the effect. The working hypothesis is that the additional molecules provide an additional viscous damping which contributes to the frequency change. Further investigation of the effect is planned, and a dedicated setup is under construction.

After checking the influence of the most obvious outside factors to the frequency change, the more interesting calibration was performed, the response of the membrane to the influence of the external force. Due to its fragility and sensitivity the external force was provided as

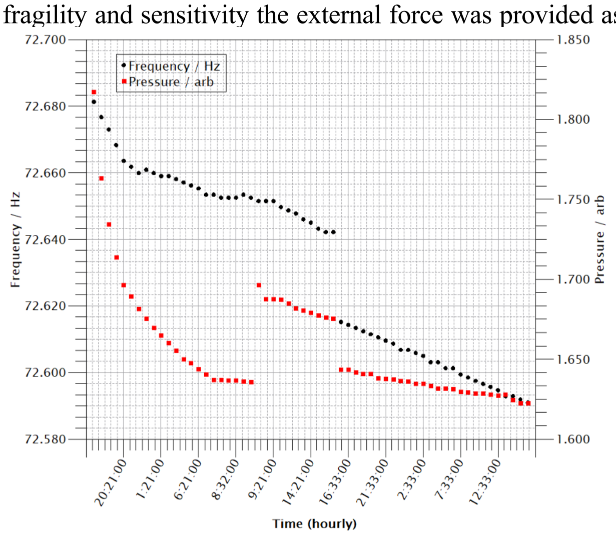


*Fig. 5. Resonant frequency as a function of pressure in the vacuum chamber. Two zones can be observed. Initial where a correlation between pressure and frequency value can be seen, and the following one where the pressure is not changing significantly but the frequency is nevertheless decreasing. In the middle a discontinuity in both observables can be seen which remains unexplained.*

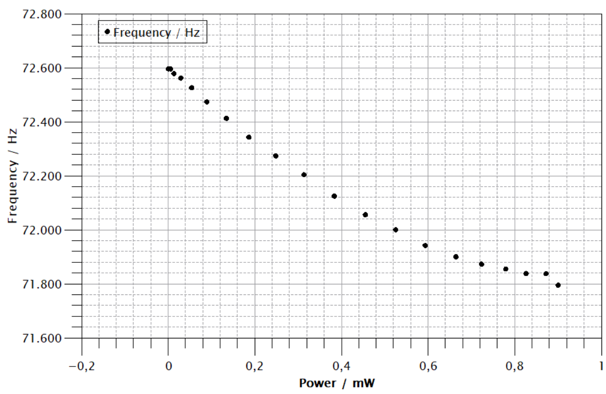


*Fig. 6. The dependance of the frequency on the incident light power. There is almost a kHz change for a mW.*

a light beam of constant intensity. The results are shown in Fig. 6. The origin of the frequency change can reside in two different causes. One is change in temperature. Here we must bear in mind that the absorptance of 50 nm thick layer of silicon nitride covered with a platinum layer ~ 10 nm thick can reach 0.70 at $\lambda = 633$ nm used for illumination. And the other is the radiation pressure i.e., force that is pushing the membrane. If the first possibility is the cause, from calibration a change in effective temperature of the oscillating mode of almost100 ℃ corresponds to nearly 1000 Hz change in the resonant frequency. The other possibility would mean that the same change in frequency is caused by approximately 10 pN force.

## IV. Conclusion

In this work a development of a force sensor based on a thin silicon nitride membrane coated with a layer of high-density metal is described. The simulation results, characterization and calibration measurements and simulation are reported. The results hint to a sensitivity of ~ 10 fN force which is remarkable result. However, further measurements and simulations have yet to establish this hypothesis. The possibilities to confirm the sensitivity include use of other forces, from gravitational to Casimir force. For example, by inclining the membrane from the vertical positions a component parallel to the normal to its surface and proportional to its mass should cause a change in frequency. In any case, a device with interesting properties has been developed and there is an ongoing work on its characterization.

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