Microelectronic Engineering xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Accelerated publication

Optimization of the readout of microdrum optomechanical resonators

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ARTICLE INFO

Article history:
Received 31 July 2017
Received in revised form 3 October 2017
Accepted 10 October 2017
Available online xxxx

Keywords:
Optomechanics
Optical cavities
Nanomechanics
Microspectrophotometry

ABSTRACT

Free-standing dielectric structures with a substrate underneath, as the SiN microdrums studied here, are the basis of optomechanical devices. Optimization of the optomechanical coupling is demanding in order to enhance the performance of these devices. The optomechanical coupling in the case of drum resonators critically depends on the thickness of the drum, the surface stress, the cavity length and the wavelength. Here, we develop a methodology that combines spatially multiplexed microspectrophotometry, optical modelling of the cavity and finite element method simulation of the mechanical eigenmodes that enables obtaining the properties of the optomechanical cavity and predicting the wavelength that optimizes the optomechanical coupling. By choosing this illumination wavelength we are able to spatially resolve the thermal motion of the microdrums up to the fourth mechanical mode ~20 MHz. The presented study opens the door for further optimization pathways for optomechanical detection and actuation.

Last decade has witnessed the advent of nanomechanical devices as a new platform for sensing applications in many diverse fields like physical [1,2], biological [3–5] or chemical applications [6]. In that sense, the fabrication tools developed by the semiconductor industry have paved the way for the development of different kinds of devices ranging from 1D–like resonators such as silicon nanowires [7,8] or carbon nanotubes [9] to 2D structures like suspended graphene membranes [10,11]. The ever-increasing control reached in these nanofabrication techniques has allowed remarkable milestones such as yoctogram range mass resolution [12] or single spin moment detection [2]. In these unprecedented advances, the use of new materials has played an important role, being the carbon nanotubes and graphene sheets the most promising candidates for 1D and 2D nanomechanical resonators, respectively. However, the bottom up fabrication techniques present counteracts derived not only from the quality of the structural material but also from the necessary integration. Typically, the whole electrical circuitry of the detection device must be patterned around the randomly deposited element, resulting in a costly and time-consuming process; which constitutes the main reason why top-down lithographic techniques are commonly employed these days, with silicon nitride [13,14] and MoS_2 as prominent materials [15].

As the nanofabrication techniques shrink down the size of the resonators, the read-out process becomes more complicated. Optical methods [16,17] are usually employed due to their versatility and, in principle, non-physically limited bandwidth, which is important when dealing with small oscillators with natural resonance frequencies [18] lying in the verge of 10^6 to 10^9 Hz. However, as the lateral size of the resonators approaches the illuminating wavelength, interplay between the mechanical object and the light, or optical back-action [19], arises, resulting in a new branch in the community known as optomechanics [20,21].

In this work, we present a thorough optmomechanical characterization of suspended silicon nitride membranes; the accurate measurement of the geometric and optical properties of the devices under study will allow to determine a priori the theoretical mechanical sensitivity and, therefore, the best design strategy to optimize the interferometric transduction mechanism. The optical characterization consists of the analysis of the reflectivity as a function of the illuminating wavelength; this measurement allows us accurate characterization of the thickness and the refractive index of the suspended structure. By studying the reflectivity change, we are able to calculate the mechanical displacement sensitivity of the system, which depends on the illuminating wavelength; therefore, we can anticipate that the best displacement measurement is obtained by using a red laser (632.8 nm) instead of a green laser (542 nm). This theoretical prediction was experimentally demonstrated; however, the theoretically expected mechanical resonance frequency is one order of magnitude smaller than the measured one. This discrepancy is explained in terms of the initial stress accumulated in the membrane during the fabrication process. Due to the geometrical constrains, this stress cannot be released and the membrane

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https://doi.org/10.1016/j.mee.2017.10.008

Please cite this article as: V. Pini, et al., Optimization of the readout of microdrum optomechanical resonators, Microelectronic Engineering (2017), https://doi.org/10.1016/j.mee.2017.10.008

consequently buckles. The buckling was measured by using AFM, giving us a static deformation of about 2.3 nm. Finite element simulations were employed to simulate a tense structure [22], giving a resulting value for the stress of 927 MPa. The resonance frequencies calculated by taking into account this value agree the experimental values for the first four mechanical modes.

The experimental set-up was made by means of a homemade hybrid interferometer, represented in a block diagram in Fig. 1a. By means of flip-mounts, we can use two different configurations for both the optical and mechanical characterization by choosing between two different illuminating sources: a Xe lamp for the optical characterization and a laser unit (red or green depending on the application) for the mechanical characterization. In order to carry out the optical characterization, the illumination beam coming out from the Xe lamp is directed into a monochromator that disperses the light into its constituent wavelengths. A narrow band of the dispersed spectrum passing through the exit slit of the monochromator is then collimated by a series of lenses and focused onto the testing sample by a microscope objective. The light reflected from the surface is then collected by the same microscope objective and forms an image on the surface of a CCD camera passing through a non-polarized beam splitter.

The nanofabrication of arrays of 100 nm thick silicon-nitride membranes process is performed by using standard cleanroom procedures. First, thermal oxidation was performed growing 1370 nm thick thermal oxide on a (100) silicon 6″ wafer. The oxide was then controllably etched down to a 1270 nm thickness by wet chemical etching using BHF (Buffered hydrofluoric acid). Then, a 220 nm layer of silicon nitride was deposited with LPCVD (Low Pressure Chemical Vapor Deposition). The deposited layer of silicon nitride was thicker than the final desired one to compensate the non-negligible etch rate of the hydrofluoric acid on the silicon nitride, which was calibrated prior to the device nanofabrication. After the oxide and silicon nitride deposition steps, contact UV lithography was performed following reactive ion etching (RIE) to drill the holes in the top silicon nitride layer. Finally, the plate was released by controlled etching of the silicon oxide release layer through the holes using wet hydrofluoric acid. As anticipated the wet HF etch also etches the silicon nitride plate to a thickness of approximately 100 nm.

Inset in Fig. 1b shows a topographic Atomic Force Microscopy (AFM) image of the membrane resonator (tapping mode, cantilever from Nanosensors PPP-NCH, spring constant ~42 N/m, resonance frequency ~330 kHz). The membrane is buckled up due to the accumulated stress during the silicon nitride deposition process. Since all the edges of the membrane are clamped, there is no way to release the initial stress, and the structure is buckled. The AFM characterization reveals a static deformation of 2.3 nm upwards at the center of the membrane, indicating a non-released stress of 927 MPa according to the FEM parametric study performed by sweeping the stress of the layer to fit the measured deflection.

Therefore, there are two different regions to perform the reflectivity study: the holey membrane and the silicon nitride continuous layer. The difference in between them is basically the materials forming the Fabry-Perot optical cavity. In the continuous silicon nitride layer, black dot in the optical micrograph of the inset in Fig. 2a, the two Fabry-Perot cavities are composed by the silicon nitride layer and the silicon dioxide underneath, whereas in the membrane region, red dot in the inset of Fig. 2a, the double Fabry-Perot cavity is composed by the holey silicon nitride layer and the air region. The measured reflectivity in both regions is plotted in Fig. 2a, being the solid black line the experimental reflectivity measurements on the continuous silicon nitride layer and the

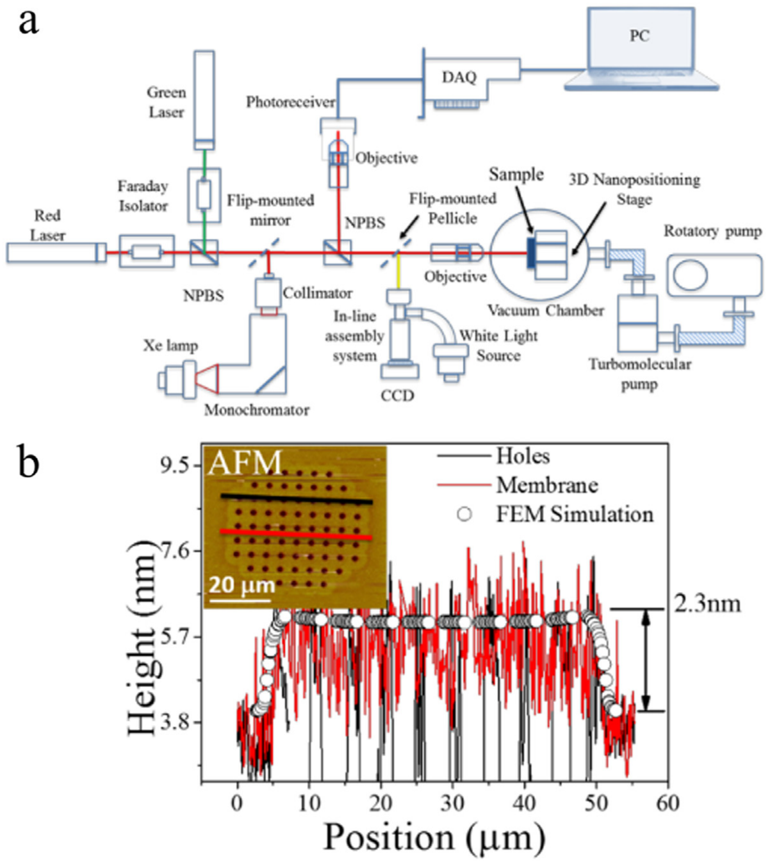

Fig. 1. a. Schematics of the experimental set-up used for the optical and mechanical characterization of the silicon membranes. b. The black curve shows the spatial profile of the topography measured with AFM over a line of holes (black line drawn in the inset); whereas the red line shows the profile avoiding the holes, along the red line drawn in the inset. The open symbols show the static deformation numerically calculated with FEM by considering an initial tensile stress of 927 MPa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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