proceedings

Eurosensors PARIS 2017

MDPI

Proceedings

1 Million-Q Optomechanical Microdisk Resonators with Very Large Scale Integration †

Maxime Hermouet [1,2,*], Louise Banniard [1,2], Marc Sansa [1,2], Alexandre Fafin [1,2,3], Marc Gely [1,2], Sébastien Pauliac [1,2], Pierre Brianceau [1,2], Jacques-Alexandre Dallery [4], Pierre Etienne Allain [3], Eduardo Gil Santos [3], Ivan Favero [3], Thomas Alava [1,2], Guillaume Jourdan [1,2] and Sébastien Hentz [1,2,*]

1 Department de Physique, Université Grenoble Alpes, F38000 Grenoble, France; louise.banniard@cea.fr (L.B.); Marc.SANSAPERNA@cea.fr (M.S.); alexandre.fafin@cea.fr (A.F.); marc.gely@cea.fr (M.G.); sebastien.pauliac@cea.fr (S.P.); pierre.brianceau@cea.fr (P.B.); thomas.alava@cea.fr (T.A.); guillaume.jourdan@cea.fr (G.J.)
2 CEA, LETI, Minatec Campus, F-38054 Grenoble, France
3 Matériaux et Phénomènes Quantiques, Université Paris Diderot, CNRS UMR 7162, Sorbonne Paris Cité, 75013 Paris, France; pierre.allain@univ-paris-diderot.fr (P.E.A.); eduardo.gil-santos@paris7.jussieu.fr (E.G.S.); ivan.favero@univ-paris-diderot.fr (I.F.)
4 Vistec Electron Beam GmbH, Ilmstrass 4, 07743 JENA, Germany; Jacques-Alexandre.Dallery@vistec-semi.com
* Correspondence: maxime.hermouet@cea.fr (M.H.); sebastien.hentz@cea.fr (S.H.); Tel.: +33-438-782-891 (S.H.)

† Presented at the Eurosensors 2017 Conference, Paris, France, 3–6 September 2017.

Published: 28 August 2017

Abstract: Cavity optomechanics have become a promising route towards the development of ultrasensitive sensors for a wide range of applications including mass, chemical and biological sensing. We demonstrate the potential of Very Large Scale Integration (VLSI) with state-of-the-art low-loss performance silicon optomechanical microdisks for real-world applications. We report microdisks exhibiting optical Whispering Gallery Modes (WGM) with 1 million quality factors. These high-Q microdisks allow their Brownian motion to be resolved at few 100 MHz in ambient air. Such performance shows our VLSI process is a viable approach for the next generation of high-end sensors operating in vacuum, gas or liquid phase.

Keywords: optomechanics; microdisk resonators; quality factor; whispering gallery mode; radial breathing mode; very large scale integration

1. Introduction

Nano-optomechanical resonators have attracted much interest in the last decade and have shown record displacement sensitivities [1]. On-chip cavity optomechanics has been a privileged route towards quantum studies [2] and has now become mature enough to reach a more applied realm, like mass [3] or chemical[4] sensing, as well as operation in liquid [5]. In cavity optomechanics, displacement sensitivity is proportional to optical quality factor and disk resonators are canonical objects for experimental—and optical performance demonstration [6,7]. Industrial applications however, will require reaching state-of-the-art performance with VLSI processes and packaging.

2. Fabrication

We show here silicon optomechanical microdisks fabricated in an industrial-grade clean-room on 200 mm SOI wafers (Figure 1). The fabrication process of these resonators is illustrated in Figure 2. The disks were fabricated from SOI wafers with 220 nm thick top layer. Partial silicon etching was first performed to pattern grating couplers (Figure 2a). A second lithography level was performed by Variable Shape Beam (VSB) and the optical waveguides and resonators were patterned by Induced Coupled Plasma (ICP) dry etching (Figure 2b). Resist exposure with VSB as well as the ICP process were optimized in order to minimize silicon wall roughness. Finally, disks were released using vapor HF etching (Figure 2c). Typical disk dimensions range from 2 to 20 µm in radius, with optical gaps of a few hundred nm.

On-chip light coupling is compatible with standard silicon photonics packaging and uses grating couplers. The devices are the first optomechanical resonators fabricated on 200 mm wafers with Variable Shaped Beam (VSB) lithography, allowing for both high fabrication throughput and high patterning resolution: each wafer contains more than 120,000 optomechanical devices.

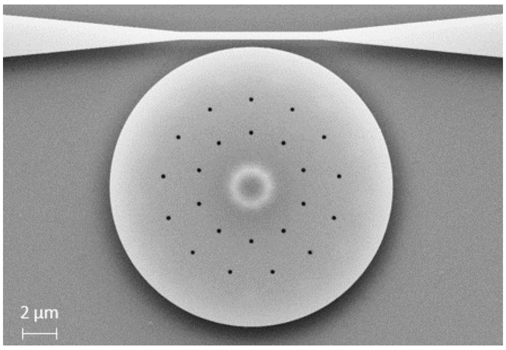

Figure 1. Scanning electron microscope image of a Si optomechanical disk with an 8 µm radius and its tapered waveguide .The black circles are release holes.

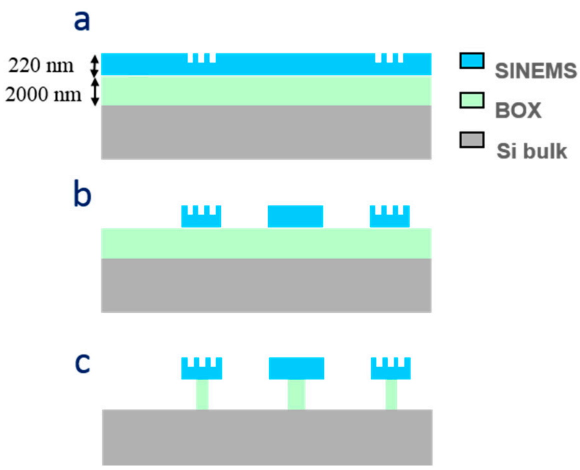

Figure 2. Fabrication process of the optomechanical devices. (**a**) Partial silicon ICP etching to pattern grating couplers; (**b**) Patterning of the optical waveguides and microdisk resonators by ICP etching; (**c**) Microdisks release using vapor HF etching.

3. Results

Our optomechanical set-up is described in Figure 3. It consists of a tunable external cavity laser (with wavelength around 1.55 µm), a fiber polarization control (FPC), a lock-in amplifier and a low-noise, variable gain photodetector (PD). The laser wavelength was swept to obtain optical spectra.

Typical examples of optical WGM close to 1.55 µm wavelength are shown in Figure 4. Most measured loaded quality factors are in the high 100,000 s, and many resonances show quality factors above 1 million. These figures are among the best measured in the literature with silicon disks of a few µm radius [6]. We attribute this to the very low silicon roughness obtained with our specifically developed lithography and etching processes.

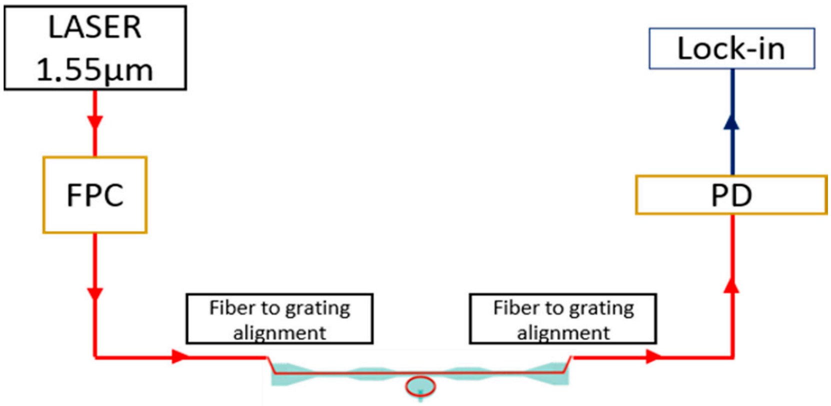

Figure 3. Schematics of the optomechanical setup.

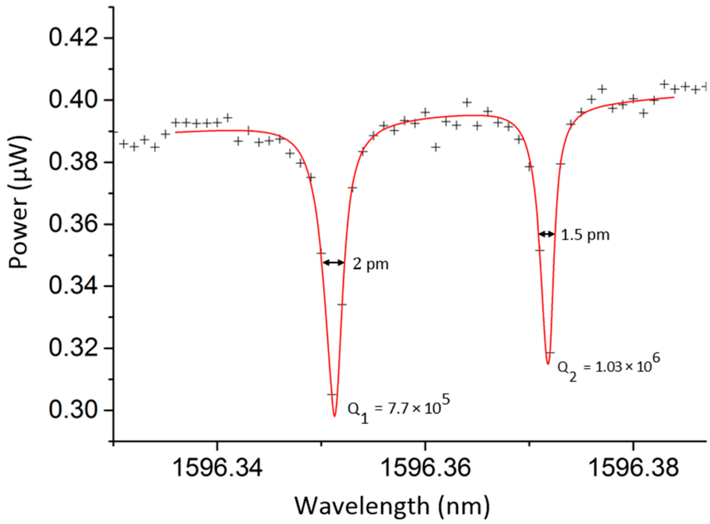

Figure 4. Narrowband transmission spectrum of an 8 µm radius disk with high loaded optical quality factor WGM doublets.

Such high-Q microdisks show a strong coupling between optical WGMs and Radial Breathing Modes (RBM). We were able to resolve the thermomechanical motion of our resonators at a few 100 MHz frequencies at ambient pressure (Figure 5).

Sufficient signal to noise ratio was obtained without the need for an optical amplifier while the optical power was kept low (100 s of nW at the device output) in order to limit thermo-optical and back-action effects. Indeed, with such high Qs, the resonator operates in the good cavity (sideband-resolved) regime: strong back-action with blue- or red-detuned operation can be expected. These results show our VLSI process is a promising route towards real-world sensors with optomechanical devices operating in vacuum, gas or liquid medium.

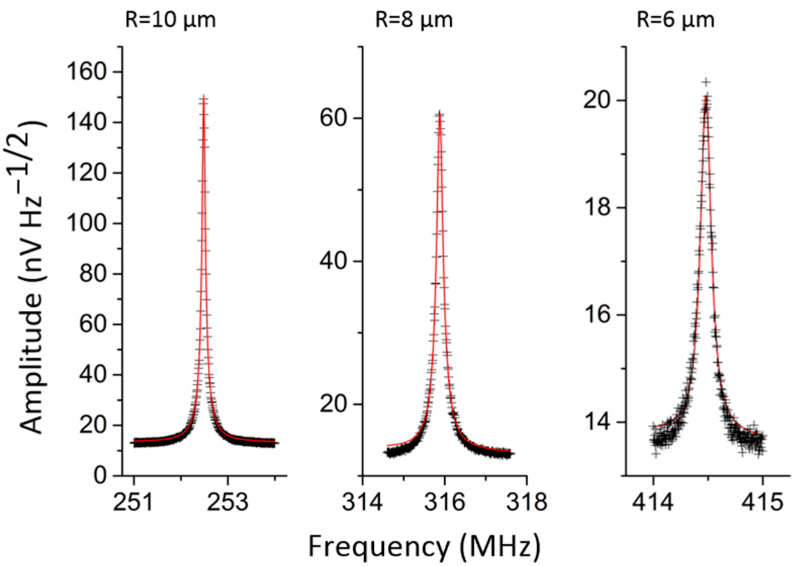

Figure 5. Thermomechanical spectra of three different disks vibrating in air. Mechanical resonances are observed at 252.5 MHz (R = 10 µm), 315.9 MHz (R = 8 µm) and 414.5 MHz (R = 6 µm) with mechanical quality factors (Q_m) of 4115, 2141 and 3778 respectively.

Acknowledgments: This work was supported by the ERC Enlightened grant, the Carnot LETI Oppladiag project and the ANR Olympia project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ding, L.; Baker, C.; Senellart, P.; Lemaitre, A.; Ducci, S.; Leo, G.; Favero, I. Wavelength-sized GaAs optomechanical resonators with gigahertz frequency. *Appl. Phys. Lett.* **2011**, *98*, 113108, doi:10.1063/1.3563711.
2. Aspelmeyer, M.; Meystre, P.; Schwab, K. Quantum optomechanics. *Phys. Today* **2012**, *65*, doi:10.1063/PT.3.1640.
3. Liu, F.; Alaie, S.; Leseman, Z.C.; Hossein-Zadeh, M. Sub-pg mass sensing and measurement with an optomechanical oscillator. *Opt. Express* **2013**, *21*, 19555, doi:10.1364/OE.21.019555.
4. Venkatasubramanian, A.; Sauer, V.T.K.; Roy, S.K.; Xia, M.; Wishart, D.S.; Hiebert, W.K. Nano-Optomechanical Systems for Gas Chromatography. *Nano Lett.* **2016**, doi:10.1021/acs.nanolett.6b03066.
5. Gil-Santos, E.; Baker, C.; Nguyen, D.T.; Hease, W.; Gomez, C.; Lemaître, A.; Ducci, S.; Leo, G.; Favero, I. High-frequency nano-optomechanical disk resonators in liquids. *Nat. Nanotechnol.* **2015**, *10*, 810–816, doi:10.1038/nnano.2015.160.
6. Borselli, M.; Johnson, T.; Painter, O. Beyond the Rayleigh scattering limit in high-Q silicon microdisks: Theory and experiment. *Opt. Express* **2005**, *13*, 1515–1530.
7. Sun, X.; Zhang, X.; Tang, H.X. High-Q silicon optomechanical microdisk resonators at gigahertz frequencies. *Appl. Phys. Lett.* **2012**, *100*, 173116, doi:10.1063/1.4709416.