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Silicon nitride drum resonators with a top-gate capacitive coupling scheme

Xin Zhou^a, Srisaran Venkatachalam^a, Hao Xu^a, Alok Pokharel^a, Andrew Fefferman^b, Mohammed Zaknounge^a, and Eddy Collin^b

^a CNRS, Univ. Lille, Centrale Lille, Univ. Polytechnique Hauts-de-France, UMR 8520-IEMN, F-59000 Lille, France

^b Univ. Grenoble Alpes, Institut NEEL - CNRS UPR2940, 25 rue des Martyrs, BP 166, 38042 Grenoble Cedex 9, France

e-mail: xin.zhou@iemn.fr

Silicon nitride (Si_3N_4) based micro- and nano-electromechanical system (NEMS and MEMS) allow electrical signals to couple with a mechanical degree of freedom and give access to electrical integration on-chip. They are attractive applications of mass/force sensing and signal processing, because they offer good mechanical properties and controllable nonlinearity. In very recent years, Si_3N_4 based NEMS and MEMS have been used to build microwave optomechanical system through coupling with microwave cavities, which serve for quantum engineering and on-chip thermometry [1-2].

However, the implementation of Si_3N_4 mechanical resonators in electrical systems is particularly limited by the weak coupling with surrounding circuits due to the insulating features of the Si_3N_4 material. So far, Si_3N_4 based doubly-clamped beams are one of the simplest and widely used device structures, in which the suspended beam is covered with a thin metal layer to create the capacitive coupling with the side-gate or the bare beam is coupled with its side-gate through dielectric coupling [2-3]. This MEMS/NEMS conception leaves limited space for making trade-offs among the coupling strength, the mechanical resonance frequency and the quality factor. Therefore, there is a strong motivation to explore new types of membrane resonators for today's microelectronics and quantum engineering, with desirable features, such as scalable fabrication, large electrical coupling effects, and good mechanical properties in a wide range of temperatures.

Here, we present our recent work in developing a novel Si_3N_4 -MEMS structure in which a Si_3N_4 drum is covered with an aluminum thin film, enabling large capacitive coupling to its suspended top-gate [4]. The full MEMS structure is shown in Fig.1. The Si_3N_4 drum, which is hidden under its top-gate, is shown in Fig.2. It is released from a silicon substrate by a dry etching process. This scalable Si_3N_4 -MEMS structure is achieved through a standard top-down and ultra-clean nanofabrication process, which enables to have the quality factor $\sim 10^4$ at room temperature yielding a fQ factor (resonance frequency times the quality factor) $\sim 10^{11}$ Hz, which is comparable to the bare Si_3N_4 drum [5]. We have demonstrated the full electrical integration of our Si_3N_4 drum resonator with both microwave reflectometry and a microwave optomechanical system. The fairly good capacitive coupling allows to detect around 10 mechanical modes and to study the Duffing nonlinearity. Besides, we have also calibrated the optomechanical coupling strength between the drum resonator with a diameter $D=40\ \mu\text{m}$ and a microwave cavity, which is ~ 10 times larger than that of a typical double clamped beam structure with a similar resonance frequency. The measurement results are in good agreement with the analytical calculations.

Our experimental results demonstrated that such a kind of electromechanical resonator can provide a powerful platform for exploring mechanical resonator hybrid devices in classical and quantum domains.

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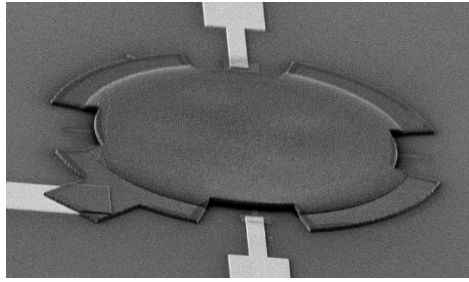


Figure 1. Scanning electron microscope (SEM) image of the final device structure, a suspended top-gate capacitively coupled to a Si_3N_4 -drum (hidden under the top-gate).

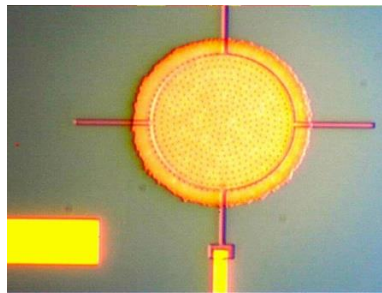


Figure 2. Optical image of the Si_3N_4 -drum, which is covered with an aluminum thin film. The drum structure is released from the silicon substrate by a dry etching process, which is performed through those small holes patterned circularly on the top of the drum by using electron beam lithography.