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Nondestructive gap dimension estimation of electrostatic MEMS resonators from electrical measurements

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ABSTRACT

This paper proves that critical geometric dimensions of a capacitive resonator can be estimated from nondestructive electrical measurements. In particular, the gap between the electrodes at rest is precisely determined. The imperfect verticality of flanks introduced by defects of the manufacturing process is also quantified. The presented approach is especially interesting compared to time-consuming observations with conventional microscopy techniques (optical, SEM,...) which are complex to automate. Furthermore, it is the first available nondestructive way to determine the fabrication defects coming from imperfect etching processes such as DRIE. After presenting the theoretical developments, experimental characterization is performed on a fabricated capacitive comb drive resonator. The estimated parameters are compared to optical microscope observations. Our method paves the way to novel reverse-engineering techniques, simultaneously combining process control and system characterization.

1. Introduction

MEMS fabrication techniques include several processes which may induce defects affecting the overall performance of the device [1]. Some of these defects, such as stiction or particle contamination, may obstruct the motion of the movable part and are thus quite easy to detect with self-test, built-in test or final electrical test [1–3]. However, many defects are reportedly undetectable with standard electrical test and require specific individual control of each device with expensive and time-consuming methods. For example, optical microscopy, scanning electron microscopy (SEM) or atomic force microscopy (AFM) can give very valuable information about the geometric defects of the cross-section, etching profile or bottom side of electrodes [4]. Unfortunately, this observation usually requires breaking the springs suspending the resonator [5]. Moreover, measuring the dimensions of a cross-section of a few micrometers on a MEMS resonator is a quite complicated task with a limited precision (instrument- and user-dependent) [5], thus time-consuming and hard – if possible – to automate. In addition to this, microscope observations must be combined with other techniques like interferometry to deduce the natural frequency and damping of the [6–8].

Contrary to microscope observations, electrical measurements are already a fast routine test for quality control and process monitoring since they provide access to useful system-level parameters and are easy to automate. In energy harvesters, such measurements are required to find out the maximum power and bandwidth provided by the system when subject to a

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mechanical actuation [9]. In resonant sensors, electrical measurements are useful to characterize and/or predict and optimize the phase noise characteristics of an electromechanical oscillator [10]. Amongst electrical methods, several ways exist to determine the characteristics of a linear or nonlinear MEMS resonator [11] as well in the time domain [12] than in the frequency domain [13,14]. However, no work has yet proven that even geometric process-induced defects of a MEMS resonator can be estimated from electrical measurements.

In this paper, we prove that critical geometric information about the structure of a MEMS resonator can be extracted from nondestructive electrical measurements. In particular, characteristics of the gap between the electrodes are estimated. Among these characteristics, we characterize the process-induced imperfect verticality of the flanks obtained by a deep reactive ion etching (DRIE) process. The parameter estimation is performed on a manufactured gap-closing comb drive MEMS resonator polarized with an external source and actuated by a shaker. Nonlinear parameter estimation is performed on a double-sided gap closing resonator model including squeeze-film damping and a nonlinear electrostatic force. The actual dimensions of the resonator are verified through optical microscopy and compared to the estimated values.

2. Device under study

2.1. Structure of the MEMS moving part

The device under study is a gap-closing comb drive resonator. Its structure is depicted in Fig. 1. The structure is attached to the ground frame with linear springs which are not represented here. The electrode length is written L (as defined in Fig. 1). G is the gap between the electrodes at rest and M is an additional mass.

It is originally designed to exhibit a first resonance frequency around 125 Hz. All the geometric characteristic of the design are summed up in Table 1.

2.2. Fabrication process

The fabrication of the device consists of 6 main steps which are schematically depicted in Fig. 2. A clean room process for silicon on borosilicate glass (SOG) wafer has been developed. First, a spin-coating of positive photoresist is performed followed by ultraviolet (UV) lithography. Next, a 200 μm layer of Si is etched by deep reactive ion etching (DRIE). After that, the wafer is diced and the device is released using a wet etching solution of HF/HCl in 10:1 vol ratio for avoiding the re-deposition of non-solvable in HF borosilicate constituents [15]. Further, the Cr/Al layer of 20 nm/200 nm respectively, is evaporated on the surface of the device in order to form electrical contacts. Finally, the wire bonding is performed and the additional tungsten mass had been placed on the moving part of the resonator to decrease the resonant frequency.

3. Model of the gap closing comb-drive energy harvester

3.1. Ideal case

In this section, we focus on an electromechanical resonator made of a proof mass M suspended by linear mechanical springs of total mechanical stiffness K. The cross-section of its electrodes is first supposed to be perfectly rectangular, as depicted in Fig. 3.

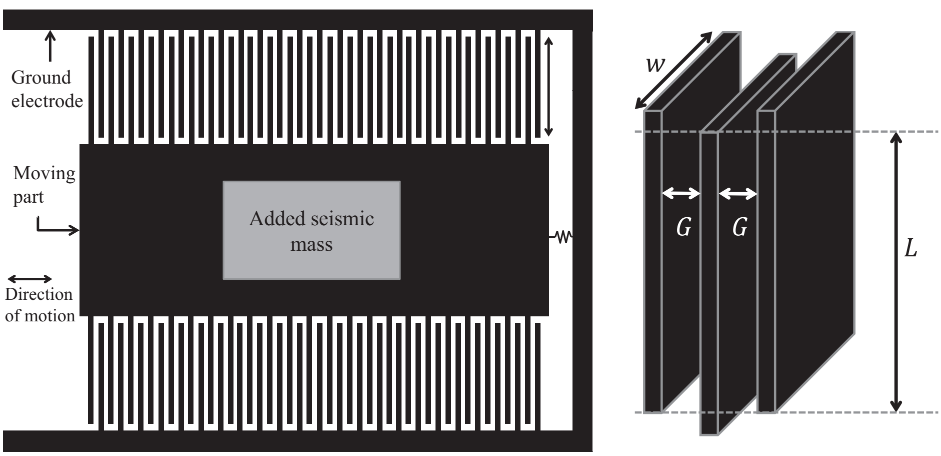

Fig. 1. Structure of the gap-closing comb-drive resonator (left). Zoom on three teeth of the comb drive structure (right).