High aspect ratio spiral resonators for process variation investigation and MEMS applications

Middelburg, L.M.; Mansouri, B. El ; Van Zeijl, H.W.; Zhang, G.Q.; Poelma, R.H.

DOI
10.1109/ICSENS.2017.8233945

Publication date
2017

Document Version
Accepted author manuscript

Published in
Proceedings of IEEE Sensors Conference 2017

Citation (APA)
Middelburg, L. M., Mansouri, B. E., Van Zeijl, H. W., Zhang, G. Q., & Poelma, R. H. (2017). High aspect ratio spiral resonators for process variation investigation and MEMS applications. In *Proceedings of IEEE Sensors Conference 2017* (pp. 1-3). IEEE. https://doi.org/10.1109/ICSENS.2017.8233945

High Aspect Ratio Spiral Resonators For Process Variation Investigation and MEMS Applications

L.M. Middelburg[1], B. El Mansouri[1], H.W. van Zeijl[1], G.Q. Zhang[1], R.H. Poelma[1]
Delft University of Technology: Electronic Components, Technology and Materials, dept. of Microelectronics[1]
Mekelweg 4, 2826CD, Delft, The Netherlands
[1]l.m.middelburg@tudelft.nl

***Abstract*— In this work a method is described to investigate process variations across a wafer. Through wafer MEMS spiral resonators were designed, simulated, fabricated and characterized by measuring the eigenfrequency and corresponding mode shapes. Measuring the eigenfrequency and resulting spectral behavior of resonators on different locations on the wafer was performed by using an optical measurement setup. Two laser beams were used where one is modulated by the periodic movement of the center mass of the resonator. One of the beams is reflected back from the modulated resonator and this beam hits a photo diode. Variations in light intensity due to movement of the resonator is providing a measurement signal correlated to movement. Preliminary measurements showed that measured eigenfrequencies are in correspondence with the simulations within a range of 0-10% deviation.**

Keywords—MEMS; Resonators; DRIE etching; bulk micromachining; process variations

I. Introduction

Process variations can have an adverse effect on the expected operational performance of the designed MEMS devices. ‘Process variation at every step in a process flow is an intrinsic part of life in the microfabrication world’, which results in the fact that ‘real process steps do not make exact replicas of the features on a mask’ [1]. Process variations are apparent in steps ranging from lithography to depositions, to etching and will result in variations over the entire wafer. These can result in deviations from the desired behavior of the processed devices. More research is dedicated on characterizing the mechanism causing these variations, for example R.H. Poelma *et al.* on thin film characterization using electrostatic pull-in [2]. A simple method is considered, which could be used to measure process variation in nanoscale film thickness over the wafer. The process flow considered in this work concerns bulk micromachining using deep reactive ion etching (DRIE), one of the most important processing steps in the fabrication of MEMS and microsystems [3]. Process variation of interest for this work are mainly deviations in lateral direction of through wafer etched structures. To quantify these variations a spiral resonator has been designed and fabricated. In this work we quantify DRIE process variations by measuring changes in the resonance frequency induced by beam width variations over the wafer.

II. Design of the Spiral Resonator

The designed MEMS resonator has a spiral like structure to achieve a long effective beam length and a relatively small footprint.

TABLE I. DESIGN PARAMETERS OF THE RESONATOR

Figure		Value
Height	h	500 µm
Beamwidth Spiral	w	20 µm
Length of the entire spiral spring	L	183.84 mm
Number of turns		17
Center mass	m_c	0.996 mg
Resulting spring constant	k	0.017
Material		Anisotropic Silicon
Expected out of plane frequency		20.85Hz

Optical microscopy can be used to quantify resonance frequency, the resonance frequency is low enough to be captured by camera and human eye. The spiral structure will function as a coiled up spring with a mass at its center. The starting material for fabrication is single crystal double side polished silicon wafer with 500um wafer thickness. Table 1 lists the design dimensions, whileFig. 1 Fig. 1 shows the spiral-spring / mass system.

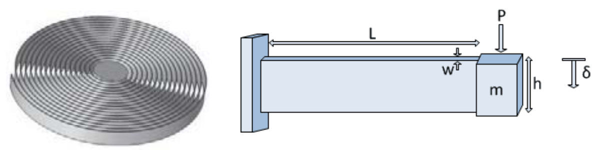

Fig. 1. The designed mass/spring system and the straight beam approximation

The uncoiled spiral beam is approximated by a straight beam as shown in Fig. 1. The out-of-plane deflection of the beam is given by eq. 1, where I is the second moment of inertia.

$$\delta = \frac{PL^3}{3EI}; \quad I = \frac{wh^3}{12} \qquad (1)$$

The spring constant is then given by,

$$k = \frac{P}{\delta} = \frac{Ewh^3}{4L^3} \qquad (2)$$

FEM simulations were performed to calculate the resonance frequency for multiple mode shapes. The first Eigen frequency is 29.436 Hz and the corresponding mode shape is depicted in Fig. 2, in which it can be noted that the center mass is displaced in the x,z-plane, thus in the wafer plane (in-plane). At 30.448 Hz the mode shape is found in which the center mass is oscillating orthogonal to the wafer plane (out-of-plane), see Fig. 2.

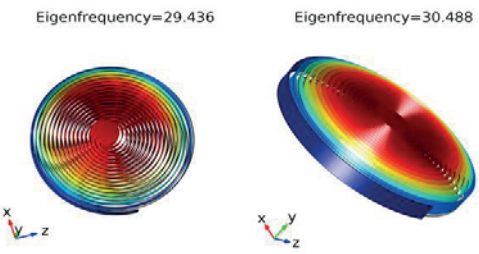

Fig. 2. The first and third mode shapes corresponding to respectively Eigen frequencies of 29.436 Hz and 30.488 Hz.

III. FABRICATION

First a silicon oxide layer is deposited on each side of the 500 µm double side polished wafers, where the front layer is used as hard mask for the Deep Reactive Ion Etching (DRIE) process step while the backside layer is used as an etch stopping layer. An additional aluminum layer is used at the backside to prevent helium leakage in case of cracks in the oxide landing layer. After the DRIE step was performed, the aluminum layer at the backside was removed by RIE etch step to release the resonator. The silicon oxide layers were removed by hydrofluoric acid (HF) vapor. During the processing, the sag of the center mass can be useful as a preliminary indication for the process variations. This sag can easily be measured using an regular microscope focusing on either the wafer or the center mass.

IV. MEASUREMENTS AND CHARACTERIZATION

The resonators were characterized using a spectrum analyzer, a mechanical shaker and an optical read-out setup. The spectrum analyzer provides a source signal to a current source driving a mechanical shaker. This shaker forces a mechanical excitation with a certain frequency on the wafer with the resonators. The movements of the resonators are detected using an optical measurement setup, based on two interacting light beams resulting in a varying shadow effect. The photodiode detects the laser beam reflected by the resonator and sends the signal to a network analyzer. The light intensity detected varies due to the movement of the resonator mass which results in variations of the measured signal.

The optical setup uses a laser at a wavelength of 633 nm where the beam passes through a beam splitter. One beam is received by the photodiode via a mirror, whereas the other beam is modulated by the resonator under test. The light beam which is incident on the center mass of the resonator will be modulated by the motion of this center mass and reflected back towards the photodiode sensor. Depending on the position of the surface of this center mass during movements, the reflected light beam will either be aligned with the unmodulated light beam, or will be shifted resulting in not being detected by the photodiode. The photodiode will therefore measure a varying light intensity, depending on the position of the reflecting center mass of the resonator. When the resonator starts to oscillate according to the excitation signal, the amplitude of the movement of the center mass will increase dramatically and the incident light beam will be modulated to a larger extend. In the current experiment we estimate that the displacement is too large so the setup is not operating in an interferometric mode. The current signal measured by the photodiode is converted to a voltage and fed-back to the spectrum analyzer, after which the transfer function is determined (| Received Signal/Source|). Averaging among 6 measurements was used to reduce the effect of noise. Considering the goal of investigating process variations, the measurement time in the order of tenths of minutes can be seen as reasonable.

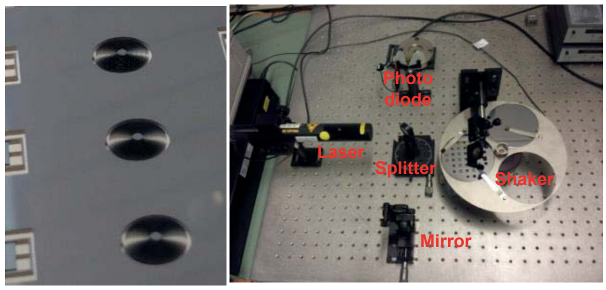

Fig. 3. The realized spiral resonator an the optical measurement setup to characterize the resonators.

TABLE II. MEASUREMENT EQUIPMENT

Device	Make,model
Spectrum Analyzer	HP 4395A
Power amplifier shaker	Brüel & Kjaer 2718
Mechanical shaker	Brüel & Kjaer 4810
Laser	Melles Griot
Wavelength	633 nm
Photodiode	Osram Silicon PIN BPX61
Current amplifier	Stanford Research Systems SR570

A. *Measurement Results and discussion*

When characterizing the devices, the excitation signal from the spectrum analyzer is swept from 10 Hz up to 150 Hz. The amplitude of the bode plot is shown in Fig. 4. Note that the absolute value of this transfer function is strongly determined by the settings of the power amplifier, the type of photodiode and laser and the configuration of the current amplifier, and therefore has less value in absolute sense. The main information of interest is in the spectral information, thus the position of the peaks.

The result for the transfer function is shown in Fig. 4. The first main peak in the amplitude is located at a 26.78 Hz and 27.78 Hz for device 1 and 2 respectively. A comparison for the frequencies for the first, fourth, fifth and sixth mode shapes is included in table TABLE III. What is notable from this table is that the first three Eigen frequencies are within 1 Hz of difference from each other, which implies that the k/m ratio in plane and out of plane are for this operation region similar. Considering that the excitation signal is swept in step of 0.5 Hz, it will limit the spectral resolution. Furthermore can it be expected that the peak in the transfer function at about 27 Hz is a 'combined' oscillating mode, the first three modes merge and are detected as one peak, because the first three modes fall within 1Hz bandwidth.

The resonator in this work was designed as a first iteration where the first three modes are close to each other. In some applications this phenomena is called veering (near crossing) where two vibration modes get close to each other using electrothermal and electrostatic actuation to form a band pass filter [4].

TABLE III. COMPARISON EIGEN FREQUENCIES

Mode	Simulation	Measured	
		Device 1	*Device 2*
1st	29.436	26.78	27.78
2nd	30.102	-	-
3rd	30.448	-	-
4th	36.116	39.8	40.56
5th	94.924	93.9	96.66
6th	101.2	103.2	103.2

In this work this is not the intended effect as an existing design was used for this work. Next to this, the first and second modes are in-plane while the third mode is in the out of plane direction. The movements are orthogonal which suggests that the stiffness in-plane and out-plane are similar where the difference in frequency could be attributed to the changing mass distribution due to the resonator beam movement. In future work a next iteration will be fabricated where the vibration frequencies will be designed for to be far from each other.

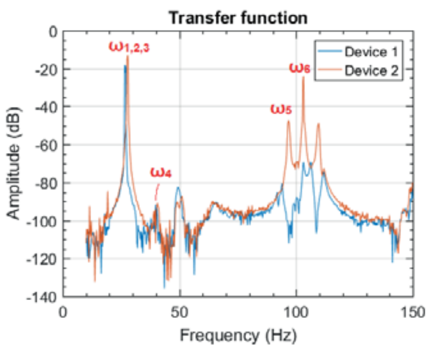

Fig. 4. The transfer function of the measurement of two resonators

B. Sensitivity Analysis

The main goal of this work is to link a difference in Eigen frequencies for different resonators to a variation in the lateral dimension of the beamwidth, caused by a variation in the etching step. The height of the beam is fixed to the wafer thickness and a possible variation in beamlength can be neglected, taking into account the total length of the beam being in the centimeter range. This leaves the mass and the width w of the beams as the main process variations parameters, which will influence the resonance frequency. The sensitivity can be obtained by revisiting the analytical derivations. Calculating the Eigen frequency from a beam with certain stiffness k and a mass m yields the following equation (4), where m_{eq} stands for the equivalent mass. This 'equivalent mass' actually consists of the mass of the beam itself and the center mass (5).

$$\omega = \sqrt{k/m} = \sqrt{\frac{Ewh^3}{4L^3 \cdot m_{eq}}} \quad (4)$$

$$m_{eq} = m_{beam} + m_{center} = \rho_{Si} hLw + \rho_{Si} hr^2\pi \quad (5)$$

$$\omega(\Delta w) = \sqrt{\frac{E(w+\Delta w)h^3}{4L^3\left(h\rho_{Si}\left(\pi(r+\Delta W)^2 + \frac{1}{2}L(w+\Delta w)\right)\right)}} \quad (6)$$

The Eigen frequencies were determined for a lateral width process variation Δw ranging from -10 µm to 10 µm and for geometrical values and the Young's Modulus according to an out-of-plane movement using MATLAB. Afterwards the derivative of this function was determined to derive the linearized sensitivity. The sensitivity around the operating point of $\Delta w = 0$ is equal to 0.10 Hz/µm, which is equivalent to 10 µm/Hz.

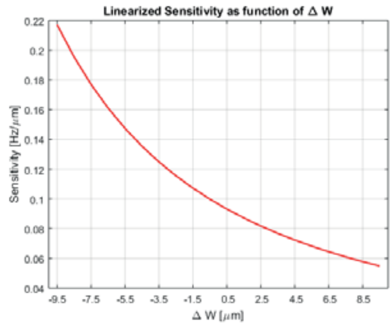

Fig. 5. The first derivative of formula (6) as linearized sensitivity

CONCLUSION

In this work a simple resonator was designed, simulated and fabricated. After which a measurement setup is described to identify the mechanical spectral behaviour. The two measurements showed that measured Eigen frequencies are in correspondence with the simulations within a range of 0-10% deviation. From the results it can be concluded that the mechanical structures and the measurement setup can be used to extract information on process variation, mainly the width of through wafer etched structures in the lateral direction. Based on the analytical model a sensitivity analysis was performed using MATLAB, which resulted in a linearized sensitivity of 10 µm/Hz. Future work includes measurements of all realized devices in order to determine the process variation over the wafer and to verify the quantification of the sensitivity. For example by measuring different beam widths under the microscope as reference values. The information can then be used to correct for process variations during processing, which results in a refined process control allowing for better design to fabrication process flow.

REFERENCES

[1] Senturia, S. D. (2007). Microsystem design, Springer Science & Business Media.

[2] Poelma, R. H., H. Sadeghian, S. P. M. Noijen, J. J. M. Zaal and G. Q. Zhang (2011). "A numerical experimental approach for characterizing the elastic properties of thin films: application of nanocantilevers." Journal of Micromechanics and Microengineering 21(6): 065003.

[3] Zhou, Z., Z. Wang and L. Lin (2012). Microsystems and nanotechnology, Springer, pp.317.

[4] Hajjaj, A. Z., M. A. Hafiz and M. I. Younis (2017). "Mode Coupling and Nonlinear Resonances of MEMS Arch Resonators for Bandpass Filters." 7: 41820.