Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 87 (2014) 1597 – 1600

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the § edition of the conference series

Piezoelectrically actuated linear resonators on ring-shaped suspensions for applications in MEMS phase-sensitive gyroscope

S. Gorelick*, J.R. Dekker, B. Guo, H. Rimminen

VTT Technical Research Centre of Finland, Tietotie 3, Espoo, P.O.BOx 1000, FI-02044 VTT, Finland

---

Abstract

Excitation of linear resonators by means of thin aluminium nitride piezoelectric films processed on annular (ring-shaped) flexures was investigated. The in-plane resonance modes at 8-45 kHz frequencies with quality factors >10^4 were measured for both single (uni-directional) and double (bi-directional) in-plane degree of freedom devices in vacuum. Annular springs have different spring constants for different directions of deformation allowing efficient decoupling of orthogonal modes in bi-directional symmetric devices. The primary application of the bi-directional resonators is in orbiting-motion MEMS gyroscopes that rely on phase-shift detection induced by external angular rates. To investigate the feasibility of differential piezoactuation for generation of motion in uni- and bi-directional devices by means of thin piezoelectric films processed on supporting annular springs, MEMS resonators were modelled, designed, fabricated and electrically characterized.

Peer-review under responsibility of the scientific committee of Eurosensors 2014

Keywords: piezoactuation; differential piezoactuation; annular spring; ring-shaped spring; MEMS; MEMS gyroscope; aluminium nitride

---

1. Introduction

In a linear MEMS gyroscope a proof mass is excited to vibrate in the drive direction and angular rates are deduced from displacements induced by Corilios force in the direction orthogonal to both the drive and angular rate axes. MEMS gyroscopes typically rely on electrostatic actuation, however narrow gaps and considerable DC-bias voltages are needed to generate sufficient forces and displacement amplitudes. Piezoactuation is an attractive

---

* S. Gorelick, VTT Technical Research Centre of Finland, Tietotie 3, Espoo, P.O.Box 1000, FI-02044 VTT, Finland. Tel.: +358 440820 306; fax: +358 20 7227012.
E-mail address: sergey.gorelick@vtt.fi

Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.532

alternative because the inherent electromechanical coupling is stronger, and no DC-bias or narrow gaps are required. Furthermore, the piezoelectric actuators can be processed directly on top of mechanical supporting flexures thus reducing the form factor of the device. Using differential piezoactuation (Fig. 1a), similar to that used in Si tuning forks [1], linear motion in the wafer plane can be achieved. While piezoactuation can replace electrostatic actuation in traditional MEMS gyroscopes with one axis used for driving and the orthogonal axis used for sensing Coriolis displacements, a promising method to improve the performance of a MEMS gyroscope is to drive both identical and orthogonal modes into resonance with harmonic excitations having π/2 rad phase difference. In such a drive configuration the proof mass performs a motion along a circular path about its centre of mass. External rotation of such a resonance system modifies its mechanical response which is manifested as a phase-shift that is nearly proportional to the angular rate [2]. The device, therefore, can operate as a phase-sensitive gyroscope with potentially greater sensitivity and simplified read-out electronics compared to conventional MEMS gyroscopes relying on amplitude-signals. In this study we explored both with finite element method (FEM) simulations and experimentally the feasibility of excitation of linear resonators suspended by annular springs with aluminium nitride (AlN) piezoactuators processed on top of them (Fig. 1c and Fig. 2a,b). The results of this study are important for understanding the design trade-offs in the phase-sensitive piezo-gyroscope.

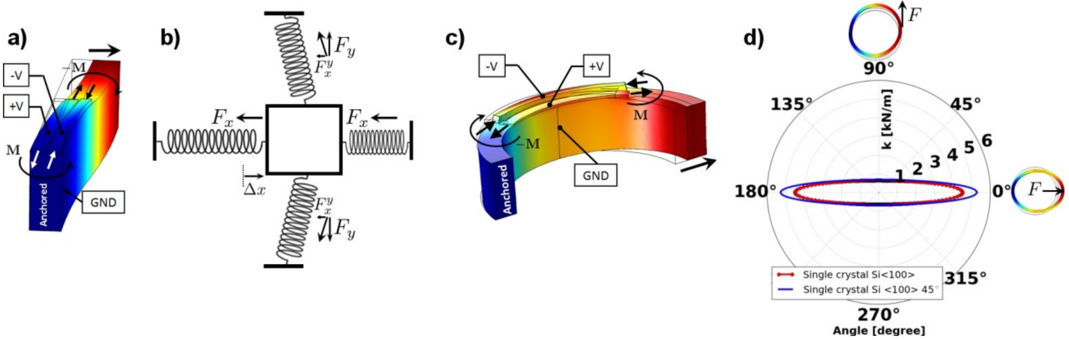

Fig. 1. (a) Differential in-plane actuation of a Si beam is achieved by applying voltages V of different polarity across a pair of piezolayers processed on the beam. The piezoelectric effect is equivalent to opposite forces applied at the boundaries of the piezolayers resulting in force couples and bending moments M. (b) Displacement Δx of a proof mass along X-axis in a two degrees of freedoms system results in spring deformation of the orthogonal Y-mode. This results in the "parasitic" restoring force F_x^y along the X-axis in addition to the primary restoring force F_x. (c) Differential thin-film in-plane piezoactuation of a semi-annular Si flexure due to the force couples by applying voltages V of opposite polarity to the corresponding piezolayers. (d) Simulated angle-dependent spring constant of a Si annular spring (external radius 200 μm, beamwidth 20 μm) for different orientation of the spring with respect to the crystal axis.

2. Spring design

Schematic presentation of a bi-directional system that can be driven along two in-plane orthogonal directions is shown in Figure 1b. The system is compliant in both orthogonal directions such that, e.g., deflection along the X-axis results in deformation of the Y-mode's springs and coupling of the modes. A solution to reduce the coupling is to isolate the modes by frame structures [3], however, matching the resonance frequencies and vibration amplitudes is challenging in such designs. Designs invariant to rotation by 90° simplify matching of the resonance frequencies of the orthogonal modes. The actuation of a single mode in bi-directional devices (Fig. 1b) causes "shear" deformation of the springs of the orthogonal mode. This "shear" deformation introduces additional restoring forces F_x^y that should be smaller than the primary restoring force F_x to avoid excessive coupling of the orthogonal modes. Conventional spring designs (e.g., meander or U-beams) are, however, considerably stiffer along the orthogonal ("shear") than in stretch/compression and, hence, are not suitable for supporting the orbiting motion of the proof mass about its centre-of-mass. A more suitable spring shape for this purpose is a curved beam such as semi-annulus (Fig. 1c). Annular or semi-annular beams' compliance has pronounced dependence on the direction of deformation [4]. From simulation results shown in Fig. 1d, the primary spring constant associated with the stretch/compression (deforming force 0° with respect to the primary vibration mode) is a factor of ~7 larger compared to the secondary "shear" spring constant (deforming force 90° with respect to the primary vibration mode), when the primary deformation is along the [100]-crystal axis. Due to the anisotropy of silicon [5], the mode decoupling can be improved by realigning the devices with respect to the crystal axis. Thus, rotating the spring by 45° in the wafer plane (primary deformation is along the [110]-crystal orientation) increases the ratio of the primary and secondary spring constants by >10% to ~7.8, further decoupling the orthogonal modes. The shape of the beams can be further optimized to reduce the mode coupling even more.

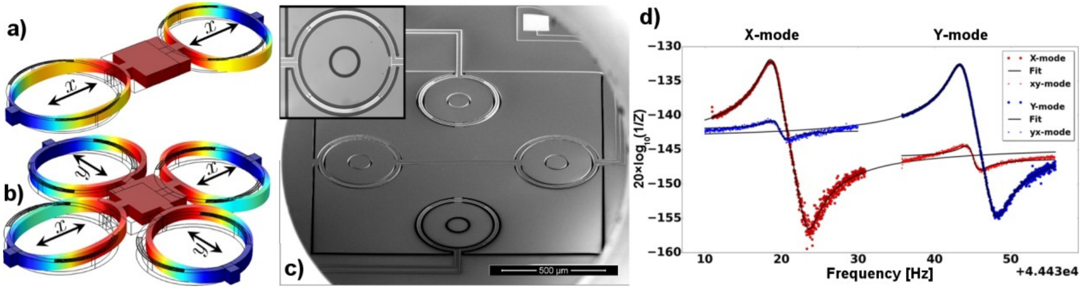

Fig. 2. Simulated resonance modes of linear resonators consisting of a proof mass suspended on annular springs with piezoactuators processed on top of the springs (a) uni-directional device with mode along the X-axis, (b) bi-directional device with two orthogonal modes along the X- and Y-axis. (c) SEM image of a processed bi-directional device with inset showing a magnified annular spring with piezoactuators. (d) Vacuum measurement of frequency response of X- and Y-modes separately with equivalent circuit parameters fit. The resonance frequencies of both modes are separated by 25 Hz. Due to the high Q-factor of both modes ($\sim 20\times10^3$) Y-resonance is excited when X-mode is driven (xy-mode) and vice versa, X-mode is excited when Y-mode is driven (yx-mode).

3. Device characterisation

Several design variations of uni- and bi-directional test devices having different beamwidth (14, 22 µm) and annulus external radius (200, 300 µm) were fabricated using cavity-silicon-on-insulator (c-SOI) technology in 50-µm thick device layers (Fig. 2a-c). The 1-µm-thick patterned AlN layers were sandwiched between patterned Al or Mo electrodes. The electromechanical performance of the devices can be assessed from admittance-frequency response and corresponding fits of equivalent circuit: R_m, L_m and C_m (motional resistance, inductance and capacitance, respectively), and C_0 static capacitance of the AlN films. The measured resonance frequencies of all the devices were typically in good agreement (±4%) with the analytical or simulated values. The quality factors Q $>2\times10^4$ in vacuum (10^{-2} mbar) and >300 in air were observed for all the device designs. Detailed performance characteristics of the uni- and bi-directional design with the annular spring's external radius of 200 µm and beamwidth of 22 µm are presented in Table 1 and discussed in greater detail below.

Since the piezoelectric films can be used simultaneously both for motion excitation and its sensing, the values of transduction factor η (force generated per applied 1V AC-voltage) and electromechanical coupling k^2 (ratio of stored mechanical to input electrical energy) are important for design evaluation. The following AlN material properties were assumed in the simulations to verify the devices performance: stiffness matrix components C_{11}=360, C_{13}=C_{44}=120 GPa; piezoelectric coupling matrix components e_{31}=-0.58, e_{33}=1.55 C m^{-2}; relative permittivity ε=9. These material properties are comparable with the values for thin-film AlN in literature [6 and Refs. therein]. The transduction factor 1.41 µN/V was derived from FEM simulations by finding the equivalent force that generates the same deformation for 1V of applied voltage. Since the mechanical inductance and proof mass of the system are related as $L_m = m/\eta^2$, the transduction factors of the measured resonators can be derived from the frequency response and geometric proof mass (Table 1). The agreement between η derived experimentally and from simulations is 65% for the uni-directional and 60% for the bi-directional designs, respectively. The discrepancy can be partially attributed to non-idealities in the fabricated devices, partially to the uncertainties in the material properties, and partially to the simplified geometry used in simulations neglecting complex particularities of the actual three-dimensional geometry of the beams with processed top and bottom metals, AlN and SiO_2 isolation layers. Nevertheless, the observed η is substantial, considering that an electrostatic comb drive needs >200 of 2-µm-gaps and 20 V DC-bias to produce a similar actuation force amplitude of 1 µN due to 1V AC-drive.

Results of the equivalent circuit parameters fit of the bi-directional device correspond to the measurement shown in Fig. 2d. Due to the 25 Hz separation of *X*- and *Y*-modes, their independent excitation leads also to observable excitation of the orthogonal modes at their corresponding frequencies (*xy*- and *yx*-modes in Fig. 2d). This result indicates that cross-coupling exists between the primary modes e.g. due to the mass disbalance, or the actuation force has a component in the orthogonal direction. The "parasitic" transduction of the orthogonal modes is, however, considerably weaker (Table 1). The modes are clearly resolved at 25 Hz separation due to their relatively high Q-factors. The modes separation can be reduced by decreasing the Q-factor, e.g., by increasing the air pressure, thus forcing the system to operate at a single resonance frequency. High Q-factors and relatively large transduction factors derived from the measurements make the bi-directional devices suitable for orbital motion generation and operation as phase-sensitive piezogyroscopes.

Table 1. Vacuum measurements (10^{-2} mbar) with corresponding resonance frequencies f_0, quality factors Q and equivalent circuit parameters ($R_mL_mC_m$-C_0) fit to uni-directional design (only one resonant X-mode) and bi-directional design performance (X-, Y-modes, Xy- and Yx-modes, Figure 2d). The proof masses of the uni- and bi-directional devices were 1.52×10^{-7} and 2.13×10^{-7} kg, respectively. The electromechanical coupling k^2 was defined as $\pi^2/8\ C_m\ (C_0 + C_m)^{-1}$. The transduction factor η was derived from the proof mass and motional inductance as $(m/L_m)^{-½}$.

	f0 [Hz]	C_0 [fF]	R_m [MOhm]	L_m MHn]	Cm [$\times10^{-17}$ F]	Q	k^2 [$\times10^{-4}$]	η [µN/V]
X	**48679**	**237**	**3.310**	**0.180**	**5.94**	**16600**	**3.10**	**0.918**
Xx	**44449**	**220**	**4.170**	**0.286**	**4.48**	**19200**	**2.51**	**0.860**
Xy	44474	220	50.77	4.814	0.26	26500	0.18	0.210
Yy	**44474**	**233**	**4.690**	**0.289**	**4.42**	**17200**	**2.34**	**0.847**
Yx	44449	233	42.36	4.000	0.32	26300	0.14	0.230

4. Conclusion

Differential in-plane actuation by means of AlN piezoelectric films processed directly on top of annular 50-µm-thick Si beams was studied both experimentally and using FEM simulations. Resonance modes with quality factors $>2\times10^4$ at expected frequencies for both uni- and bi-directional devices were characterized by measuring frequency response of the devices' electrical admittance. High Q-factors and transduction factors up to 1 µN/V make the proposed differential piezoactuators processed on top of annular springs suitable for supporting orbiting motion and operation in phase-sensitive gyroscope.

Acknowledgements

This contribution was developed within the scope of the CATHRENE project EM4EM (CA 310; Electromagnetic Reliability of Electronic Systems for Electro Mobility) which is funded by TEKES (Finnish Funding Agency for Technology and Innovation) by funding decision 40471/11. The responsibility for this publication is held by authors only. The content of the manuscript is patent pending.

References

[1] C. Muller, J. Baborowski, A. Pezous, M.-A. Dubois, Experimental evidence of thermoelastic damping in silicon tuning forks, Proceedia Chemistry 1 (2009) 1395-1398.

[2] M. Dalal, A.N. Shirazi, W.K. Sung, G. Casinovi, F. Ayazi, Novel read-out scheme for MEMS vibratory gyroscopes based on signal phase shift, Solid-State Sensors, Acuators and Microsystems Worshop (2012) 328-331.

[3] C. Acar, A. Shkel, MEMS vibratory gyrocopes, Springer, 2009, ISBN 978-0-387-09535-6, pp. 78-80.

[4] W.C. Young, R.G. Budynas, Roark's Formulas for Stress and Strain, Seventh Edition, McGraw-Hill 2002, Chapter 9.

[5] D. Kwak, J. Kim, S. Park, H. Ko and D.-I. Cho, *Why is (111) Silicon a better mechanical material for MEMS*, from http://www-mtl.mit.edu/researchgroups/mems-salon/sriram_Si-111-better.pdf

[6] A.V. Sotnikov, H. Schmidt, M. Weihnacht, E.P. Smirnova,. T.Yu. Chemekova, Yu.N. Makarov, Elastic and piezoelectric properties of AlN and $LiAlO_2$ single crystals, IEEE Transactions on ultrasonic, ferroelectrics and frequency control 57 (2010) 808-811.