CORE
Metadata, citation and similar papers at core.ac.uk
Provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com
ScienceDirect
Procedia Chemistry 1 (2009) 1395–1398
Procedia Chemistry
www.elsevier.com/locate/procedia

Proceedings of the Eurosensors XXIII conference

Experimental evidence of thermoelastic damping in silicon tuning fork

C. Muller*, J. Baborowski, A. Pezous, M.-A. Dubois

RF and Piezo Components, CSEM, 2002 Neuchâtel, Switzerland

Abstract

Miniaturized resonators are critical components in many application fields such as sensing, communication and time reference. One critical parameter for these resonators is their quality factor. In this study, various silicon tuning fork resonators with an AlN piezoelectric actuation have been fabricated. Depending on their resonance frequency, quality factors between 10’000 and 25’000 were obtained. It is shown that for frequencies between 30 and 80 kHz thermoelastic damping (TED) is the dominant mechanism that limits the Q-factor.

Keywords: Q-factor; thermoelastic damping; silicon resonator; tuning fork; piezoelectric; Aluminum Nitride

1. Introduction

Silicon MEMS resonators are positioned as potential competitors to quartz crystal resonators. As such, they are targeting very broad application fields such as sensing, consumer electronics, communication systems and time reference. Their main advantage probably lies in their possible integration onto the silicon-based IC platforms [1]. However, to compete with the mature, well-established quartz technology, silicon MEMS resonators must first provide the same or better performances. One of the most crucial parameter is certainly the quality factor.

Energy losses can occur through different mechanisms such as air damping, energy loss at the clamping position, material loss, surface loss or thermoelastic damping. In the vacuum case, the dominating mechanism depends on the type of resonator and on the frequency range. This work is concerned with flexural beam silicon resonators working in the kHz domain. Experimental results are presented which show the dominance of the thermoelastic losses in the 30 to 80 kHz frequency range..

Many studies on thermoelastic damping have been published [2-6]. To very few exceptions, they are based on simple mechanical beams without any integrated actuation mean. In this paper, true silicon MEMS resonators with an integrated piezoelectric actuation are presented. They also differentiate from usual structures by the fact that they use an in-plane flexure mode rather than the common out-of-plane mode.

* Corresponding author. Tel.: +41-32-720-5038; fax: +41-32-720-5763.
E-mail address: claude.muller@csem.ch.

1876-6196/09 © 2009 Published by Elsevier B.V. Open access under CC BY-NC-ND license.
doi:10.1016/j.proche.2009.07.348

2. Thermoelastic damping theory

In the 1930's Zener predicted that thermoelastic losses may be a limitation to the maximum Q-factor of resonators and developed a model to quantify the phenomenon [7-9]. Basically, the principle of thermoelastic damping is the following: When a mechanical structure vibrates, there are regions where compressive stress occurs and others where tensile stress occurs, in a cyclic way given by the vibration frequency. Accordingly, compressed regions heat up and stretched regions cool down. Hence a temperature gradient is established between different regions of the system. However, to set the mechanical system in vibration, energy must be provided, leading to a non-equilibrium state having an excess of energy. Disregarding thermoelastic damping, the vibration could persist indefinitely in an elastic body that is perfectly isolated from its environment. However, local temperature gradients lead to irreversible flows of heat, which are a dissipation mechanism that attenuates the vibration until complete rest is achieved.

Consider now a resonator based on a flexural beam. When the beam bends, one side is in compression and heats up and the other is in tension and cools down. The relaxation time for the heat to travel from the hot side to the cold side depends on the thickness t of the beam and on the thermal conductivity of the material. This relaxation time corresponds to a characteristic frequency F_0 that Zener calculated to be

$$F_0 = \frac{\pi\,\kappa}{2\,\rho\,C_p\,t^2}$$

where κ is the thermal conductivity, ρ is the density and Cp is the heat capacity at constant pressure. Zener established that thermoelastic dissipation exhibits a Lorentzian behavior. The thermoelastic Q-factor is given by [2]

$$Q^{TE} = \frac{1}{2\,\Gamma(T)\;\Omega(f)}$$

where Γ(T) contains the temperature dependency as well as the material parameters dependency of Q^{TE} and Ω(f) gives its frequency dependency. Γ(T) and Ω(f) are given by

$$\Gamma(T) = \frac{\alpha^2\,T\,E}{4\,\rho\,C_p}\;, \qquad \Omega(f) = \frac{2\,f/F_0}{1+\left(f/F_0\right)^2}$$

where α is the thermal expansion coefficient, T is the temperature, E is the elastic modulus, f is the mechanical vibration frequency and F_0 is the characteristic thermal frequency.

3. Fabrication

Devices are fabricated from SOI wafers. The first step is a wet oxidation of the substrate. Then a Pt or W bottom electrode is sputter-deposited and patterned by dry etching. Piezoelectric aluminum nitride (AlN) and aluminum top electrode are sputter-deposited in one run. After top electrode patterning by dry etching, the resonators shape is formed by successive dry etching of the layers from the top surface down to the buried oxide. Finally, the devices are released by deep reactive ion etching (DRIE) from the backside. Fig. 1 shows a picture of a fabricated tuning fork.

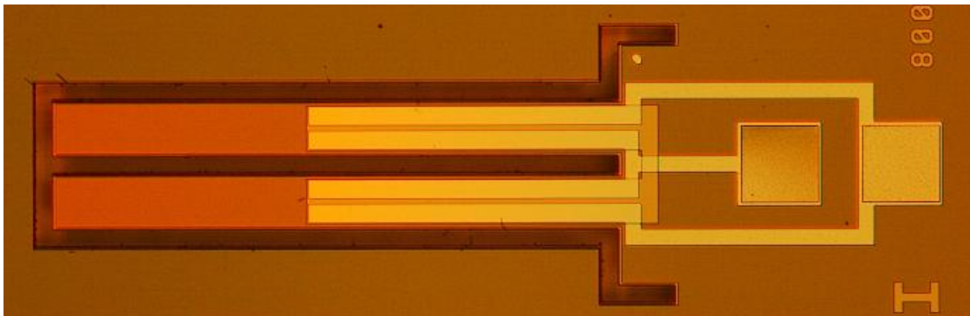

Fig. 1 Picture of a piezoelectrically actuated silicon tuning fork. Tuning fork arms are 1000 µm long and 100 µm wide.

4. Characterisation and results

The resonant frequency of the resonators was varied in two ways. In a first series, the change in resonant frequency was obtained by varying the width of the arms of the tuning fork between 26 and 200 µm. In the second series, their length was varied between 500 and 1500 µm.

Fig. 2 shows the results for the width series. Circles, triangles and crosses are measured values for different dies or wafers. Thermoelastic damping is clearly visible in the form of a dip with a minimum Q value of 8700 slightly above 50 kHz. This behavior can be fitted with the combination of a TED curve with a constant curve.

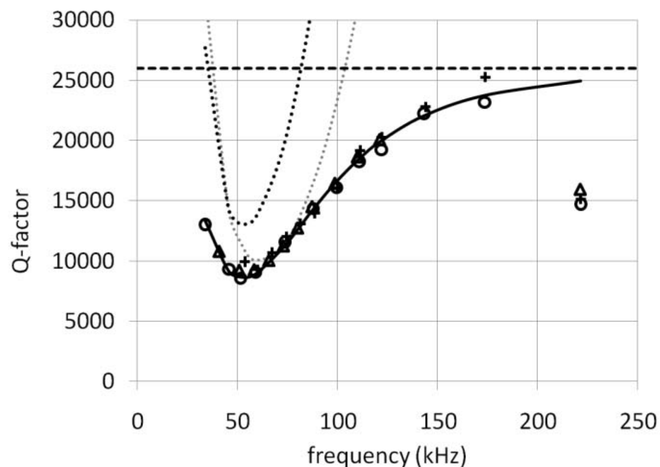

Fig. 2 Theoretical and measured Q-factor as a function of frequency for silicon tuning forks where resonance frequency variations were obtained by modification of the width of the fork arms. The dotted grey line is the TED curve calculated with material values from [4]. The dotted black line is the corrected TED curve to fit the measurement points. The dashed black line represents a constant loss at 26000. The black curve is the combination of the corrected TED curve with the constant loss. Circles, triangles and crosses are measured values for different dies or wafers.

The TED curve was calculated as follows: A first calculation was made for pure silicon beams using material values from Reference [4]. Then, F_0 was shifted by multiplying it by 0.6333, so that the position of the minimum of the calculated curve coincides with the minimum position of the measured data points. At this point, it was evident that some other losses were playing a role, lowering the measured Q-values both for the smallest frequency and for frequencies above 100 kHz. It was found that an excellent fit was obtained by assuming a constant Q value of 26000 for the other losses. Obviously, the amplitude of the thermoelastic loss had to be adapted. It was multiplied by a factor 1.3 relative to the first calculation.

The modification of the TED curve relies on the fact that, firstly material constants are not precisely known. In particular it seems logical to make the calculated and the measured minima coincide. Secondly, the measured tuning forks are not pure silicon. Oxide, piezoelectric layer and electrodes represent 25% of the volume. Vengallatore[4] showed that depending on its material nature and on its relative volume, an additional layer around the silicon beam can greatly affect both the amplitude and the frequency dependence of the thermoelastic damping.

The fit, using a constant Q value of 26000 for other losses, is surprisingly good. However, it is certainly also possible to get a good fit using a combination of powers of f and powers of 1/f. The limited frequency range in this work doesn't enable to go further in this pure mathematical analysis. Additionally, physical considerations would certainly also be helpful. The data points at 220 kHz, far away from the calculated curve, might be an indication that different phenomena are playing a role, unless these resonators have a particular problem.

Fig. 3 is the same graph as in Fig. 2, but for the length series. Calculations were performed with exactly the same values and correction factors. Again, the fit is excellent. The major difference between the length series and the width series is that in the length series only f is varied while a change in the width of the arms modifies both f and F_0.

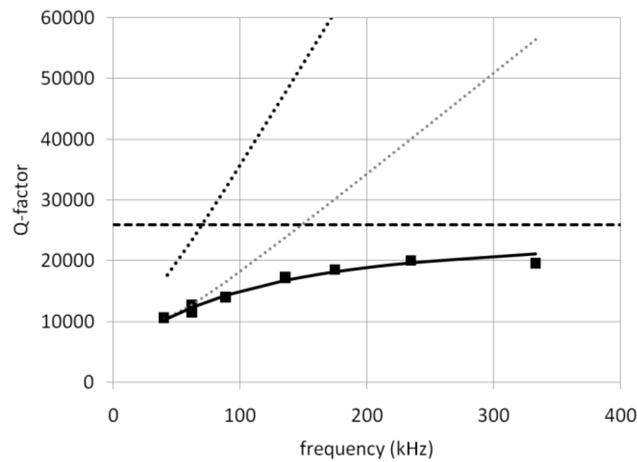

Fig. 3 Same as Fig. 2 for a series where the resonance frequency variation was obtained by modification of the length of the fork's arms.

5. Conclusion

Clear evidences of thermoelastic damping in silicon tuning fork were shown. It is particularly harmful in the 30-80 kHz range where it limits the Q factor to values around 10000. Additionally, other loss mechanisms seem to limit the Q- factor of these resonators to 26000. Further investigations should be made to understand this limitation.

6. Acknowledgments

The authors made use of the cleanroom facilities at CMI center of EPFL in Lausanne for the fabrication of the devices. The authors thank the NanoLab at EPFL and the 'Laboratoire de caractérisation et de fiabilité des microsystèmes' at CEA_LETI in Grenoble for providing the vacuum prober facilities.

References

1. C.S. Lam, "A Review of the Recent Development of MEMS and Crystal Oscillators and Their Impacts on the Frequency Control Products Industry", IEEE UFFC Ultrasonics Symposium 2008 Beijing, pp 694-704
2. T.V. Roszhart, "The effect of thermoelastic internal friction on the Q of micromachined silicon resonators", Tech. Dig. Solid-State Sens. Actuator Workshop, Hilton Head, SC, 1990, 13-16
3. R. Lifshitz and M. L. Roukes, "Thermoelastic damping in micro- and nanomechanical systems", Physical review B, Vol. 6, No 8, Feb. 2000, 5600-5609
4. Srikar Vengallatore, "Analysis of thermoelastic damping in laminated composite micromechanical beam resonators", J. Micromech. Microeng. 15 (2005), 2398-2404
5. B. Le Foulgoc et al., "Highly decoupled single-crystal silicon resonators: an approach for the intrinsic quality factor", J. Micromech. Microeng. 16 (2006), S45-S53
6. A. Duwel, R.N. Candler, T.W. Kenny, M. Varghese, "Engineering MEMS Resonators with Low Thermoelastic Damping", IEEE JMEMS, Vol. 15, No 6, 14-22
7. C. Zener, Phys. Rev. 52 (1937) 230
8. C. Zener, Phys. Rev. 53 (1938) 90
9. C. Zener, W. Otis and R. Nuckolls, Phys. Rev. 53 (1938) 100