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Experimental investigation of temperature and relative humidity effects on resonance frequency and quality factor of CMOS-MEMS paddle resonator

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ABSTRACT

This paper reports an experimental approach to analyse the performance of an externally actuated CMOS-MEMS paddle resonator with proof mass. The surface morphology test of the device is performed with the help of field emission scanning electron microscopy (FESEM), before and after the reliability tests. The effects of temperature variation on the resonance frequency response of the fabricated CMOS-MEMS resonator is analysed under the variation of temperature from 25 °C to 80 °C inside a custom made environmental chamber at a constant relative humidity (32%RH). In the next step, the variation in the quality factor of the MEMS resonator is studied under the effect of varying temperature. Finally, the resonance frequency behavior is analysed under the variation of relative humidity from 32%RH to 90%RH at a constant temperature of 25 °C. The device is found to be eroded and there are some wastes of humidity on it. A total change of 6.9 Hz in resonance frequency is recorded from 25 ° C to 80 °C. The drop in the resonance frequency of the MEMS device is found to be 137 MHz/°C with the rise in temperature. Under the temperature variation from 25 °C to 80 °C, the quality factor is found to be nonlinear. A total change of 1.3 Hz in the resonance frequency is observed from 32%RH to 90%RH. The resonance frequency is found to be −21.8 MHz/RH% with an increasing humidity level.

1. Introduction

MEMS, being a diversified field of microelectronics, has been identified as one of the most promising technologies of modern engineering. Rapid developments in the field of MEMS technologies have resulted in power efficiency, low cost and smaller sized devices. At present, microsystem technology is involved in a wide range of applications; starting from health care to consumer electronics, industrial to defense usage, and many more, all featuring MEMS devices. A large numbers of MEMS devices are designed and proposed every year, however, only a handful of them have been able to claim successful commercialisation [1], therefore, producing a reliable MEMS device is still a challenge in spite of the global recognition of these devices.

Temperature and relative humidity are the adverse environmental factors for MEMS devices in terms of their performance. Mostly silicon and other metals, like aluminum and gold, are used in the fabrication of MEMS devices. These materials are sensitive to temperature and humidity that cause a substantial variations in the physical characteristics of these devices whilst operating in an ambient environment. The effects of temperature are significant at the micro level and influence the performance of MEMS devices. The functional deviation in these devices is usually found due to the thermomechanical coupling. Whilst relative humidity may cause high condensation of moisture on the surface of a MEMS structure, the increase in the relative humidity results in a higher concentration of water vapors that grows the thickness of the oxide layers on the surface [2]. This oxide layer can initiate the rate of corrosion in material. Being used in an extensive range of applications, MEMS devices need to be operated in varying temperatures and humidity levels that tend to degrade its performance. Therefore, it is essential to investigate the performance variations of MEMS under these conditions.

Many aspects of MEMS resonators are being studied, such as temperature stability, long term stability and quality factor. In [3], a temperature induced frequency shift of −0.24 ppm/°C was demonstrated by utilizing a stiffness-compensated temperature-insensitive micromechanical resonators. In [4], temperature coefficients of resonance frequency of about 5 Hz/°C (4 ppm/°C) and 210 Hz/°C (170 ppm/°C) with and without temperature compensation were observed, experimentally. Similarly, a temperature drift reduction from 2400 ppm to 240 ppm for a 4 MHz CMOS-

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MEMS resonator over a temperature range of 90 °C was observed in [5]. Moreover, a temperature coefficient of the resonance frequency equivalent to 0.020 ppm/°C vibrating in flexural mode was exhibited by a composite resonator [6]. The resonator reported in [7] showed a quadratic temperature coefficient of the resonance frequency of −20 ppb/°C in the tunable temperature range of −55 °C to 125 °C. The stability of the resonance frequency for MEMS resonators was investigated for both long-term operation and temperature cycling [8]. The resonance frequency of this encapsulated resonator was measured at the temperature of 25 °C for >9000 h, the uncertainty in the resonance frequency recorded was 3.1 ppm. The resonator has been tested in varying temperatures for 680 temperature cycles, claiming that the resonator can be used for long term operation under a large number of temperature cycles. Bulk acoustic wave resonators illustrated a better frequency drift of 0.1 ppm/month, ensuring that the long term stability can be achieved in MEMS resonators [9]. The temperature instability of the CMOS-MEMS resonator was derived through a comprehensive analytical model by embedding a metal block [10]. Temperature dependent Young's modulus and the quality factor of the CMOS-MEMS composite layer were modelled and investigated, experimentally [11]. The quality factor of the micro resonator in atmospheric air was thoroughly investigated to find the effects of temperature on the quality factor in microresonators [12]. They reported that in a highly humid environment ≅>90%RH, the quality factor can be 50% larger at 100 °C compared to 10 °C. Whereas, in dry air quality factor can be 10% lower at 100 °C compared to 10 °C. Reference [13] reported that the MEMS resonator can be designed to have a strong or weak dependency of the quality factor on temperature. Furthermore, they observed a sensitivity of 1% change in the quality factor per degree rise in temperature.

According to the demand of modern age MEMS devices are expected to be low power, compact and of small size. These features can be achieved by combining MEMS with CMOS technology. Different CMOS-MEMS resonators for various applications have been fully studied, and the effects of temperature variation on resonance frequency of the CMOS-MEMS dogbone resonator was studied in [14] and found to be −12.53 ppm/°C. A mere-metal free-free CMOS-MEMS resonator was demonstrated in [15] and a change of $\delta f/f_0$ vs. temperature was found to be −358.3 ppm/°C. The effect of temperature on the quality factor of the CMOS-MEMS double ended tuning fork resonator was reported in [16] and the quality factor variation trend was found to be nonlinear. The effect of the relative humidity on the resonance frequency of the CMOS-MEMS clamped-clamped beam resonator was covered in [17] and variation in the resonance frequency was found to be −3.5 kHz/RH%. These aforementioned CMOS-MEMS resonators are high resonant devices, however, if the geometry of the CMOS-MEMS resonator is changed and is operated at a low resonance frequency (~kHz), then the way temperature and relative humidity variations affect the resonance frequency and the quality factor of the CMOS-MEMS devices need to study. That is why, the effects of temperature and relative humidity on the resonance frequency and the quality factor of a low resonant CMOS-MEMS paddle device is studied in this article. The rest of the paper is organized as follows. Mathematical explanation of resonance frequency and quality factor of CMOS-MEMS are given in Section 2. Fabrication of CMOS-MEMS device and environmental chamber is described in Section 3. Experimental setup and equipments used in the experimental analysis are described in Section 4. Results and discussion are explained in Section 5. Finally, Section 6 concludes this study.

2. Mathematical explanation

2.1. Effects of temperature on resonance frequency

Basic equation for resonance frequency of the CMOS-MEMS paddle resonator is expressed as:

$$f_r = k_m \sqrt{\frac{E(ave)}{\rho(ave)} \frac{t_{b,com}}{L_{b,com}^2}} \tag{1}$$

k_m represents the modes of vibration whereas the parameters, such as $E(ave)$, $\rho(ave)$, $t_{b,com}$ and $L_{b,com}$, are the collective Young's modulus, average density, composite thickness and length of the CMOS-MEMS resonator, respectively.

The resonance frequency is determined through (1) at ambient temperature T_0 and variation in resonance frequency at temperature T is calculated as [18]:

$$\frac{f_r(T)}{f_r(T_0)} = [1 + K(T - T_0)] \tag{2}$$

2.2. Effects of relative humidity on resonance frequency

The effect of relative humidity on resonance frequency at constant temperature is given as:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m_r + \Delta m_{watervapor}}} \tag{3}$$

where m_r is the mass of resonator, $\Delta m_{watervapor}$ is the mass of water vapors. The increasing level of the relative humidity decrease the resonance frequency.

2.3. Effects of temperature and quality factor

The variation in temperature affects the quality factor of the CMOS-MEMS resonator in two different ways, (i) increase in the temperature reduces the quality factor (Q) and can be expressed as:

$$Q_i = \frac{k_m \sqrt{\frac{E(ave)}{\rho(ave)} \frac{t_{b,com}}{L_{b,com}^2}}}{\Delta(f_r)_{-3db}} \tag{4}$$

(ii) dependence of the quality factor on internal and external damping factor, the expression for the quality factor under different damping values is given as [19]:

$$Q_{ii} = \frac{1}{2\left(\frac{3\pi\mu + 3/4\pi W_{(proofmass)}\sqrt{2\rho_a \mu \omega_n}}{2\rho_b T_{(proofmass)} W_{(proofmass)} \omega_n}\right)} \tag{5}$$

where μ is the viscosity of the air, $W_{(proofmass)}$ is the width of the proof mass, $T_{(proofmass)}$ is the thickness of the proof mass, ω_n is the angular frequency, ρ_a is the density of the air and ρ_b is the density of the material of which CMOS-MEMS resonator is fabricated.

2.4. Effects of relative humidity on quality factor

The increase in the relative humidity decreases the resonance frequency and decrease in the resonance frequency decreases the quality factor, meantime the relative humidity increases the viscus damping.

$$Q = \frac{\frac{1}{2\pi}\sqrt{\frac{K}{m_r + Deltam_{watervapor}}}}{\Delta(f_r)_{-3db}} \tag{6}$$

Increase in the viscous damping increases the bandwidth of the resonance frequency which also contributes to the decrease in the quality factor.