Sensors and Actuators A 262 (2017) 99–107

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Fabrication and evaluation of capacitive silicon resonators with piezoresistive heat engines

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form 20 April 2017
Accepted 21 May 2017
Available online 23 May 2017

Keywords:
Silicon capacitive resonators
Piezoresistive heat engines
Thermal actuation
Electromechanical transduction
Finite element method

ABSTRACT

This work reports the design, fabrication and evaluation of capacitive silicon resonators with piezoresistive heat engines. A combination of capacitive transduction and piezoresistive actuation based on a piezoresistive heat engine in the single micromechanical resonator is proposed to achieve a low insertion loss and small motional resistance. Capacitive silicon resonators with single and multiple piezoresistive beams have been demonstrated. In these structures, resonant bodies are divided into many parts that are connected to each other by using small piezoresistive beams to enhance electromechanical transductions by the piezoresistive heat engines. When a bias voltage $V_b = 7\,\mathrm{V}$ is applied to the piezoresistive beams, the insertion loss and motional resistance of the capacitive silicon resonator with multiple piezoresistive beams are improved by 20 dB (enhanced from −68 dB to −48 dB) and 90% (reduced from 125.5 kΩ to 12.5 kΩ), respectively, in comparison to the case without a bias voltage. In addition, the tuning frequency characteristic with the piezoresistive effect is increased by 165 times over that of the structure with only the capacitive effect.

1. Introduction

Micromechanical resonators have been employed for a variety of applications [1–9]. Mass sensing with resonating ultra-thin silicon beams was demonstrated in [1,2], where the resonant frequency of an oscillating thin cantilever beam monitors a loaded mass. Timing reference applications were studied and presented in many works [3–6], where resonator structures can be used to generate clock signals in electronic systems. Microresonators are also employed for filtering applications [7–9], which can be present in radio frequency transmitter and receiver modules nowadays. To actuate and sense the motion of resonators, many transduction mechanisms, including piezoelectric [7–10], capacitive [5,6,11] and piezoresistive [12,13], have been investigated. All the above methods possess both advantages and disadvantages.

The piezoelectric technique [9], usually used for filtering applications, offers low insertion losses, but the quality factors of resonators are small and good piezoelectric materials are very important. Piezoelectric materials, such as lead zirconate titanate (PZT), aluminum nitride (AlN), or zinc oxide (ZnO), etc., are typically used; however, the deposition techniques needs to achieve high piezoelectric coefficients and low residual stress still need further improvements.

The capacitive technique, typically employed for sensing and timing references, is based on the measurement of the change in the capacitance between a sensing electrode and the resonant body. Capacitive resonators can show a high stability and low phase noise; however, their drawbacks are large motional resistances and high insertion losses that make it difficult for them to meet oscillation conditions. Methods for lowering the motional resistance presented in [14–21] utilize the reduction of the capacitive gap width [14–16], and the increase of the overlap area of the capacitance, the quality factor Q and the polarization voltage V_{DC}. Unfortunately, each of the above methods has some drawbacks. Decreasing the capacitive gap width is very effective in lowering the motional resistance; nevertheless, the fabrication of a nanogap is very difficult, and the applicable maximum polarization voltage decreases due to the pull-in phenomenon. Smaller capacitive gaps result in lower pull-in voltages that will easily cause short circuit situations. An increase in the electrode areas being utilized such as resonator arrays [4,17] and mechanical coupling [18], etc., can reduce the motional resistance, but the frequency response and Q factor of the resonators suffer from the mismatches in the resonant frequencies. To increase the Q factor, some of the methods to reduce the energy losses, including external and internal losses, have been reported, but there are material and structural limita-

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http://dx.doi.org/10.1016/j.sna.2017.05.031
0924-4247/

tions [5,19–21]. In addition, piezoresistive sensing techniques for micromechanical resonators have been studied [22,23]. Piezoresistive sensing with the thermal actuation shows a high-quality factor and low insertion loss; however, it faces a large power consumption. Besides, this technique is not appropriate for the construction of a high sensitivity products due to strong effects from environmental conditions, such as a temperature dependence. There have been some efforts to improve the piezoresistive transduction sensitivity recently [24,25]. Self-sustained oscillators without any amplifying circuitry can be achieved by piezoresistive heat engines, which are based on thermodynamic cycles. Their operation principles are as follows: due to the higher resistance of narrow piezoresistive beams over other parts of the resonator structure, the piezoresistive beams are heated up when a DC voltage is applied to the piezoresistive elements. This results in the expansion of the piezoresistive beams, which causes the resistance to increase due to the piezoresistive effect. As a result of this resistance increase, the current passing through the piezoresistive beams decreases, which also decreases the temperature of the piezoresistive beam. Thus, the piezoresistive beams are compressed and the resistance decreases due to the piezoresistive effect, resulting in an increase in the current. From this, a thermomechanical actuation power is generated by the above cycle in the piezoresistive elements. Therefore, the self-oscillators can be achieved [24].

Achieving all the aforementioned advantages in different transduction mechanisms on a single resonator is highly expected. Combined capacitive and piezoelectric transductions for high-performance silicon micromechanical resonators have been developed in [26]. An integration of a capacitive actuation and piezoresistive sensing are in micromechanical resonators has been demonstrated in [27,28].

In this research, capacitive silicon resonators with piezoresistive heat engines are proposed and examined. The piezoresistive thermal actuators are used for the excitation of the vibration to enhance the driving force. Two designs of the capacitive resonators, which consist of single and multiple piezoresistive beams, are demonstrated. The fabricated devices are evaluated and compared with each other in cases with and without the piezoresistive effect.

2. Device description

2.1. Device structure and working principle

The basic components of the proposed device's structure are schematically shown in Fig. 1. It consists of the resonant body, supporting beams, electrodes, piezoresistive beams and capacitive gaps. The resonant body is a square frame structure that is fixed at four corners of the square plate via the supporting beams. The resonant body is divided into many parts that are connected to others using the small piezoresistive beams. Four electrodes are create narrow capacitive gaps with the resonant body. The design parameters of the resonator are shown in Table 1. All structures are made of *p*-type low-resistivity single crystal silicon of 0.02 Ω cm.

Two kinds of resonator designs are presented in this work. A single piezoresistive beam at the connection areas (connecting two parts of the resonant body) is used in the device #1 (Fig. 1(a)). The resonant body of the device #1 is split into four parts that are connected to each other by the single piezoresistive beam above. This beam is placed at the center of the resonant body, as illustrated in Fig. 1. In the device #2, the multiple piezoresistive beams (10 beams) have been employed, which are located near the edges of the resonant body to enhance the vibration amplitude. Its resonant body is divided into the twelve elements, as shown in Fig. 1(b).

The operation principle of these devices is as follows: the resonator structure works in a capacitive mode, in which the output voltage results from the changes in the capacitive gap on the sensing electrode. A current controlled by a voltage source V_b is applied through the resonant body. Due to the higher electrical resistance of the narrow actuator beams than that of the other parts of the body, Joule heating mostly occurs at the actuator beams. The vibration of the resonant body is mainly caused by capacitive transduction in addition to the piezoresistive engine using the piezoresistive beams. As described previously, the temperature modulation (thermodynamic cycles consists of heating and cooling cycles) in the piezoresistive beam causes thermomechanical force. Thus, the thermodynamic cycles (thermal actuators) are possibly used for an efficient excitation of vibration with the driving force enhancement.

The resonant frequency f_0 of the fundamental mode can be calculated using the following equation.

$$f_0 = \frac{1}{2\prod}\sqrt{\frac{k_{eff}}{m_{eff}}}, \tag{1}$$

where k_{eff} and m_{eff} are the effective spring constant and mass, respectively.

The motional resistance R_m represents the mechanical loss of the vibration and can be extracted from the insertion loss as follows [11]:

$$R_m = 50\left(10^{\frac{IL_{dB}}{20}} - 1\right), \tag{2}$$

where IL_{dB} is the insertion loss of the transmission and its unit is in decibels (dB).

A thermal response time τ and frequency response f_T of the piezoresistive beams can be estimated using its thermal resistance R_T and capacitance C_T, as in the following equations.

$$R_T = \frac{l}{kwt}, \tag{3}$$

$$C_T = \rho C_{mass} lwt, \tag{4}$$

$$\tau = R_T C_T, \tag{5}$$

$$f_T = \frac{1}{2\pi\tau}, \tag{6}$$

where l, w, and t are the length, width and thickness of the piezoresistive beam, respectively. k, ρ, and C_{mass} are the thermal conductivity, density and specific heat of the silicon material, respectively.

A theoretical prediction of the resonant frequency of the proposal resonators is difficult due to the complex structures. To solve this problem, the finite element method (FEM) method is employed for the vibration mode (resonant frequency and vibration shape) and temperature distribution, as presented in the section below.

2.2. Finite element method (FEM) simulation

The FEM simulation results are shown in Fig. 2. The vibration mode (Fig. 2(a) and (b)) and temperature distribution (Fig. 2(c) and (d)) in the proposed devices are depicted. The colors correspond to total in-plane displacement (Fig. 2(a) and (b)) or temperature distribution (Fig. 2(c) and (d)), where dark red is the maximum displacement or highest temperature and dark blue is no displacement or lowest temperature. Devices #1 and #2 are vibrated at resonant frequencies of 3.16 MHz and 1.29 MHz, respectively, as the vibration mode is illustrated in Fig. 2(a) and (b). The maximum displacement is located at the center of the square resonant edges where the piezoresistive beam is placed.

The simulated temperature distribution in the designed resonators with the bias current (voltage source (V_b)) running through the resonant body via two anchors is shown in Fig. 2(c) and (d).