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Frequency stability of wafer-scale film encapsulated silicon based MEMS resonators

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Abstract

The stability of resonant frequency for single wafer, thin-film encapsulated silicon MEMS resonators was investigated for both long-term operation and temperature cycling. The resonant frequencies of encapsulated resonators were periodically measured at $25 \pm 0.1\,^{\circ}$C for >9000 h, and the resonant frequency variation remained within the measurement uncertainty of 3.1 ppm and 3.8 ppm for the two designs of resonators measured. Also, the resonators were temperature cycled for 680 cycles between $-50\,^{\circ}$C and $80\,^{\circ}$C, measuring the resonant frequency each time the temperature reached $30\,^{\circ}$C. Again, the change in resonant frequency was seen to remain within the measurement uncertainty. This demonstrates stability of resonant frequency for both long-term operation of more than a year and large number of temperature cycles, emphasizing the stability of both the resonator and the package.

Keywords: MEMS resonator; Long-term stability; Resonant frequency stability; Encapsulation

1. Introduction

Silicon based MEMS resonators are a promising technology for the replacement of quartz resonators, which are currently the dominant technology for many frequency reference applications [1]. Silicon resonators are attractive because the potential for reduced size, cost, and power consumption, as well as integration with circuitry on the same wafer. Also, integration of the resonator structure with the IC can reduce parasitic losses from higher level packaging, This integration will also lead to reduced need for higher level packaging, which is significant when considering that packaging dominates the cost of many devices.

While there have been many breakthroughs in the field of MEMS resonators [2–5], the problem of packaging has not yet been solved. The stability of the resonant frequency over time is absolutely essential for use as a frequency reference, and the frequency stability depends on the quality of the package environment. Early work investigated the long-term stability of MEMS resonators, but the measured stability was insufficient for many applications [6]. Recent work has investigated possible fatigue in thin-film silicon for both single crystal and polysilicon [7,8]; however, fatigue of thin-film silicon is not fully understood and remains controversial [9–12]. Hope has remained that silicon resonators can have sufficient stability for IC references and other applications if low-pressure, water and oxygen-free hermetic packaging is developed [9,13].

We have developed a wafer-scale encapsulation process for MEMS resonators and inertial sensors. Our wafer-scale encapsulation has several possible benefits, including high yield of devices on completed wafers, reduced package size (and therefore cost) due to the lack of a bond ring, and robustness against standard post processing techniques, such as wire bonding, die handling, and injection molding of plastic [14–16]. In addition, we show that our encapsulation process provides an effective seal against air leakage, such that it may provide excellent vacuum condition for MEMS resonators to achieve and maintain high quality factor for long-term operation [17]. Frequency stability towards acceleration and vibration have also been investigated [18]. We believe that the stability of the package environment also leads to stability of resonant frequency. This paper reports the first measured results for resonant frequency stability

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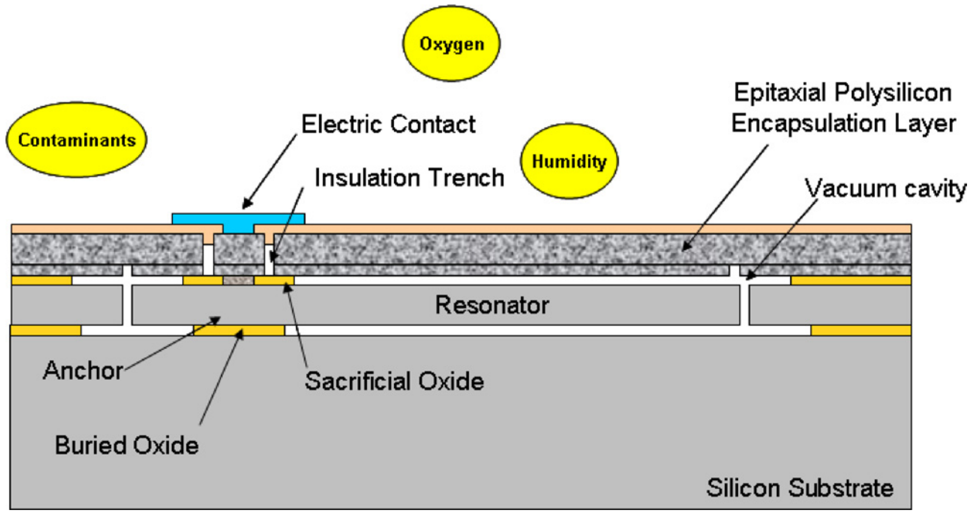

Fig. 1. The schematic for epi-seal encapsulated device. Resonator is released by HF vapor etching of sacrificial oxide, and epi-poly silicon is deposited to seal the cavity. (Not to scale.)

of silicon MEMS resonators fabricated within this wafer-scale thin-film encapsulation process.

2. Fabrication

The resonators investigated here were fabricated using a single-wafer polysilicon thin-film encapsulation process [16,17,19]. This process involves covering unreleased MEMS devices with a sacrificial oxide layer and a 2 μm-thick epitaxial polysilicon layer. The devices are released by etching the sacrificial oxide layer with a vapor-phase HF etch process through vent holes etched in the 2 μm thick silicon layer. The device is then resealed by a ∼25 μm-thick epitaxial polysilicon deposition at 950 °C and planarized via chemical–mechanical polishing (CMP). The 25 μm-thick encapsulation is etched to provide isolation for the electrical contacts, which are routed *through* the highly conductive polysilicon encapsulation. Finally, oxide and metal layers are deposited to provide electrical contact and insulation to the resonator. Fig. 1 shows a schematic of our encapsulation process and Fig. 2 shows an SEM cross-section view of the resonator used for the stability test.

The two resonator designs used in this work are electrostatically actuated and capacitively sensed (Fig. 3). Both the designs are specifically designed with a single mechanical support in the middle of the structure to minimize the possibilities of induced stress from thermal expansion of different materials or residual stress of adjacent layers. The electrostatic driving force is applied at the “Stimulus” electrodes and the resonator output is sensed through the “Response” electrodes, with a DC bias applied to the resonator structure. Temperature coefficient of resonant frequency (TCf), resonant frequency sensitivity to the environmental temperature change, is experimentally acquired as −27 ppm/°C for design A resonators and −33 ppm/°C for design B resonators respectively at room temperature. These values depend on temperature coefficient of Young’s modulus of silicon and resonator geometry. Temperature in a test cham-

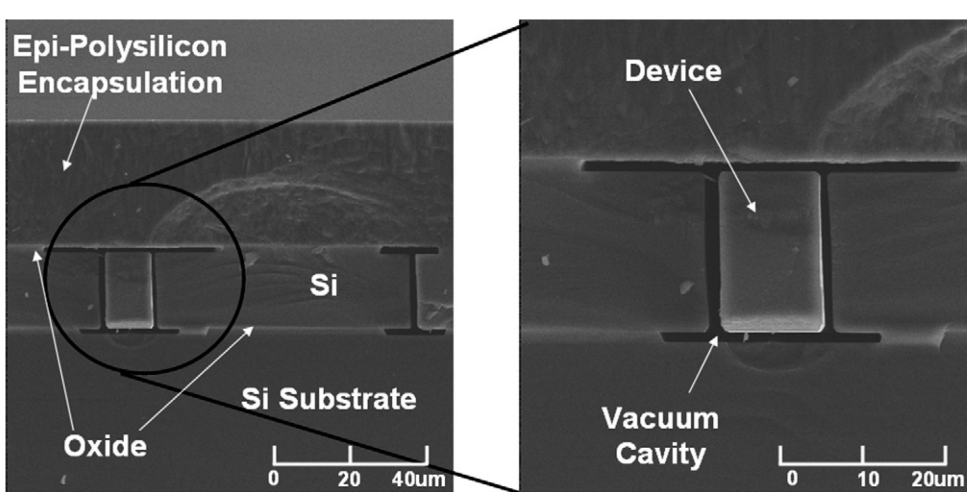

Fig. 2. SEM picture of cross-section view of the device fabricated by epi-seal encapsulation process. The polysilicon cap layer creates a hermitically sealed enclosure. The pressure in the cavity is determined to be less than 1.5 Pa [17].