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Strain sensing on steel surfaces using vacuum packaged MEMS resonators

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Abstract

The paper presents a technology for strain sensing on steel using resonant MEMS packaged in vacuum. For this purpose, a custom sensor fabrication technology and a novel vacuum packaging technique have been developed. The MEMS sensors have been fabricated by surface micromachining of thick (15 μm) Silicon On Insulator substrates with heavily doped handle layers (ρ = 0.005 Ω cm). Using this process, Double-Ended Tuning Fork (DETF) parallel-plate resonators with reduced coupling gaps (less than 1 μm) have been fabricated, using a high-performance Deep Reactive Ion Etching performed on submicrometer features realized by near-UV lithography combined with a maskless line narrowing technique. The devices have been bonded to a thin steel bar by epoxy glue, packaged in vacuum and tested by applying strain to the bar, showing good tolerances to packaging parasitics, measurement reversibility, and strain sensitivity of 10 Hz/με.

Keywords: Strain sensing, steel, MEMS resonators, vacuum packaging

1. Introduction

In recent years, resonant MEMS [1] have been proposed as a novel way to perform strain sensing on structural materials. Despite demonstrating the potential for ultra-high strain resolution [2], most results published so far reported measurements on resonators in which an axial force is generated by an electrostatic actuator integrated on-chip [1], [3]. Only very recently, testing results on a silicon resonator bonded on an automotive halfshaft and operated in air have been reported [4]. Although all these results are very promising, in order to utilize resonant MEMS for strain sensing effectively, improvements still need to be achieved in fabrication technology, packaging and bonding to structural materials.

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In this work some of these problems have been addressed. In particular, a novel technology has been developed for fabricating high performance resonant sensors with electrostatic actuation, with particular concern to obtaining high feedthrough immunity for the devices (see Section 2). A Double-Ended-Tuning-Fork (DETF) resonator fabricated with the proposed process has been bonded on a thin steel bar with epoxy glue and tested under applied strain in vacuum. The shift of the mechanical resonance frequency peak of the resonator has been measured in open-loop while applying a tensile load to the support bar and related to the strain produced on the bar itself, independently measured with a commercial piezoresistive strain gauge (Section 3).

2. Device Fabrication

The fabrication process (Fig. 1) was based on surface micromachining of thick SOI substrates (15 μm) with heavily doped handle and device layers (ρ = 0.005 Ω cm). The fabrication started with the patterning of a SiO_2 mask on the SOI device layer by Reactive Ion Etching (RIE, step 2 in the figure). A polysilicon layer was then deposited on the patterned features by LPCVD (Low-Pressure-Chemical-Vapour-Deposition) and completely oxidized in order to shrink the gaps of the original mask features (steps 3, 4). This enables electrode coupling gaps scaled below 1 μm with large aspect ratios, which is a very important feature to decrease the device motional resistance and consequently obtain good feedthrough immunity in the strain sensing application.

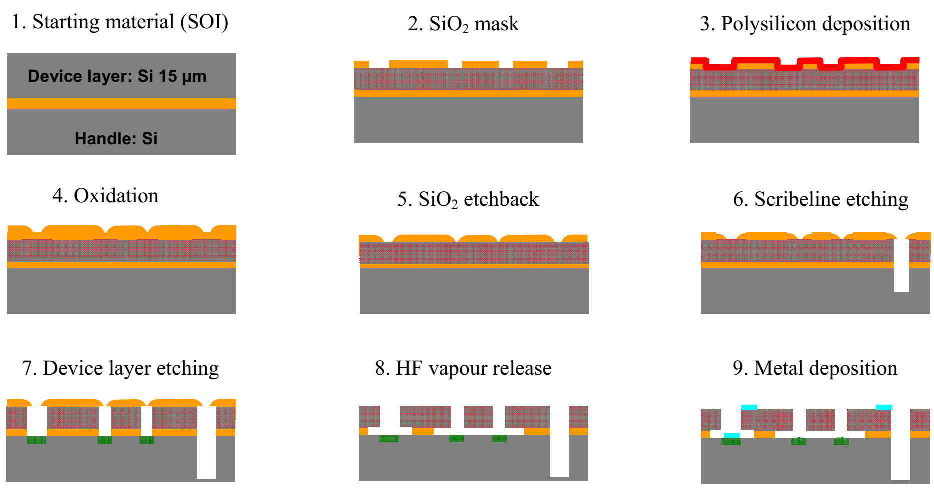

Fig. 1. Process flow used for the fabrication of the DETF resonators.

Figure 2 shows an optical micrograph of a DETF resonator (Fig. 2)fabricated in this process. The DETFs have parallel-plate electrodes with coupling gaps scaled down to 0.8 μm and thicknesses of 15 μm, obtained with a high-performance DRIE (Deep Reactive Ion Etching) process on the submicrometric features realized by the gap narrowing procedure described (see also [5] for a thorough description of the fabrication process). The resonators have been tested in open loop yielding high Q factors (up to roughly 50,000 in vacuum environment at pressures around 3 mTorr), and low feedthrough, with resonant frequency in the range 300-500 kHz, depending on the geometric design.

For the strain sensing experiment, a parallel plate DETF resonator with tine length of about 300 μm, electrode coupling gap around 1 μm and resonance frequency of roughly 438 kHz (see Fig. 2) was selected. The resonator was contacted by wire bonding after being glued on the test steel bar using vacuum epoxy glue (Torr Seal from Varian).

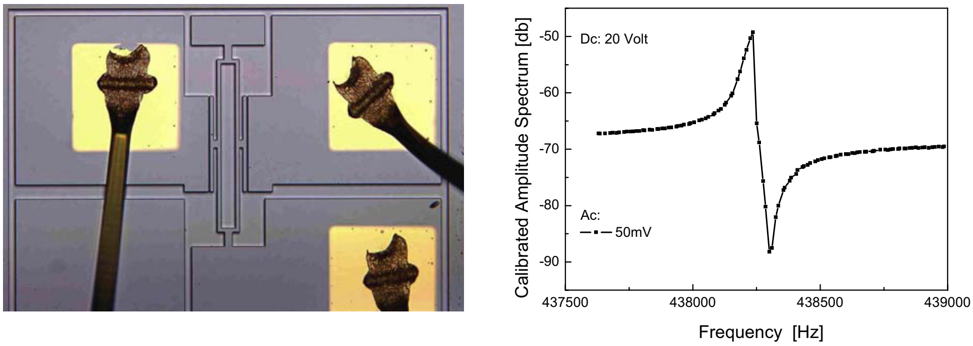

Fig. 2. DETF sensor prototype (left) and open-loop measurement on sensor (right)

3. Testing

In the tests, the resonator chip, once bonded on the steel test bar, was vacuum packaged using the technique reported in [6]. All the measurements shown in the following were performed using a dynamic vacuum setup with a vacuum level of roughly 3 mTorr, by applying a DC bias voltage on the fixed electrodes of the resonator and connecting to ground both the handle layer of the SOI device and the steel bar. A typical result of open-loop characterization on the packaged device with no strain applied is reported in Fig. 2 (DC bias 20 V, AC input signal 50 mV). Due to the high-aspect ratio gaps and the effect of the heavily doped handle layer used as a ground plane, the resonator shows low feedthrough capacitance and clear resonance peaks (about 16 dB in height above the baseline), with resonance frequency around 438 kHz and Q factor above 20,000 in vacuum.

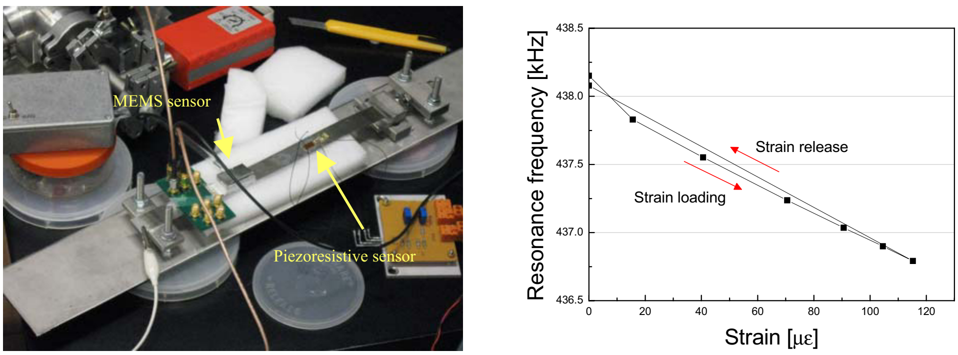

Fig. 3. Test setup (left) and resonance frequency versus strain measurement on sensor (right).

The strain sensing capabilities of the resonators were tested using the setup reported in Fig. 3. The steel test bar (to which the packaged MEMS sensor is attached) is connected to a mechanical setup for tensile load testing. In the setup, the thin test bar was fixed to a thicker steel block using anchors connected by screws, that when tightened apply a graded tensile force to the bar. The applied strain was measured by using a second strain sensor (a piezoresistive strain gauge from Vishay) also fixed on the bar beside the MEMS device (see Fig. 3), using a Wheatstone bridge configuration to acquire the sensing signal. During the bar loading, the signal from the piezoresistive strain sensor was recorded in order to evaluate the applied strain, and, simultaneously, the open-loop resonator response was measured. After the measurements, the strain level measured on the bar using the commercial sensor was correlated with the shift of the mechanical resonance peak induced by the bar loading.

The results are shown on the graph of Fig. 3, in which the resonance frequency shift is plotted versus the measured strain. As may be observed, the strain-resonance response is fairly linear and reversible, with sensitivity around 10 Hz/με, and demonstrated to be repeatable across several loading cycles. An imperfect measurement reversibility was observed for strain levels close to zero, which might be due to the poor control low strain levels on the mechanical setup used, in which only tensile loads could be applied to the slender test bar.

4. Conclusions

Strain sensing on a steel surface using vacuum packaged MEMS resonators was demonstrated for the first time. A DETF MEMS sensor realized by SOI micromachining was employed in the measurements, using vacuum packaging and adhesive bonding of the sensor on a test steel bar. The resonance frequency shift induced by tensile loading was correlated to the applied strain on the bar, independently measured, yielding a fairly linear and reversible strain-resonance response curve, with a sensitivity around 10 Hz/με. Thanks to the low feedthrough and reduced motional resistance of the MEMS technology implemented, the resonance peak height measured on the packaged resonator was about 16 dB, showing a very good tolerance to packaging-induced parasitics and proving that the adopted MEMS technology used can be suitable to implement close-loop strain dependent oscillators.

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