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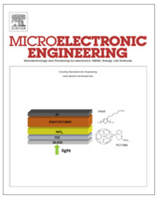

Piezoelectric sensing of electrothermally actuated silicon carbide MEMS resonators

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ABSTRACT

The influence of piezoelectric sensor design on electrothermally actuated micro-electro-mechanical (MEMS) resonators performance (resonant frequency and Q factor) has been investigated. Silicon-carbide double-clamped beam resonators have been fabricated with platinum electrothermal actuator and lead–zirconium–titanate piezoelectric sensor on the top of the beam. The fabricated devices differ only in the piezoelectric sensor length, while other dimensions and technological parameters are the same. The 200 μm long devices resonate between 0.6 and 1.1 MHz with Q factor in air up to 410, and can be tuned up to 300,000 ppm using relatively low DC bias voltages (2–6 V). The transmission frequency response measurements have shown that the devices, actuated in the same operating conditions, with shorter piezoelectric sensor resonate at higher frequencies with higher Q factors. However, the wider frequency tuning range has been obtained with devices with longer piezoelectric sensor integrated and positioned closer to the center of the beam.

1. Introduction

Micro-electro-mechanical systems (MEMS) resonators are a potential alternative to filter components and quartz crystal currently used in high-end electronic systems due to their small size and low operating voltages [1]. Among all transduction techniques for electrical induction of mechanical vibrations, major advantages of electrothermal actuation include simple fabrication process, low actuation voltages and impedance matching. Several electrothermally actuated MEMS resonators have been reported in literature, showing high resonant frequencies, high quality (Q) factors and wide frequency tuning ranges [2–5]. Silicon carbide (SiC) is one of the most promising materials for the development of high efficient MEMS resonators due to its excellent mechanical properties [6]. In addition, high thermal conductivity makes it particularly suitable for electrothermal actuation purposes.

Practical implementation of MEMS resonators requires electrical sensing of mechanical vibrations. Recently, we have demonstrated the piezoelectric sensing of an electrothermally actuated and tuned MEMS resonator [5]. The use of piezoelectric transduction for electrical sensing enables stronger electromechanical coupling and better impedance matching compared to the alternative electrostatic transduction [7]. In addition, the fabrication process for the piezoelectric transducers can be controlled better than the electrostatic case, since the stringent nanometric control of the electrode-to-resonator gap spacing is not required. However, the design of the piezoelectric transducer on top of a resonator can significantly affect the resonant performance.

In this work, piezoelectric sensors with different dimensions have been integrated on the top of SiC double-clamped beams (bridge structure) for the study of the influence of piezoelectric sensor design on device performance. By performing two-port measurements of devices' transmission frequency response, the resonant frequency, Q factor and frequency tuning range as a function of the piezoelectric sensor length have been investigated. Q factor and frequency tuning range dependences on the piezoelectric sensor length have been studied under different DC bias conditions, while resonant frequency dependence has been studied under equilibrium conditions.

2. Transductions principles and device operation

Electrothermal actuation is a transduction mechanism based on the Joule heating and thereby thermal expansion of a material. The structure of our devices is bimorph meaning that a heating Pt layer (electrothermal actuation electrode) is deposited on an 3C–SiC layer. By applying a voltage across the electrothermal electrode,

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electric current is dissipated through the electrode resistance. The generated heat induces a temperature gradient within the structure leading to the thermal expansion of the entire structure and therefore to a mechanical strain. The mechanical strain is enhanced by using two materials with different thermal expansion coefficients [8]. Due to square relationship between dissipated power and voltage, the application of an actuation voltage with only AC component and the frequency f_{AC} can drive a device into resonance if the value of f_{AC} is equal to the half of the structure's natural frequency f_0 ($f_{AC} = f_0/2$) [9]. In order to drive a device into resonance using the actuation frequency equal to the structure's natural frequency ($f_{AC} = f_0$), the actuation signal should contain both AC and DC components.

Piezoelectricity has been used as a transduction technique for electrical sensing of our devices' operation. Piezoelectricity refers to the property of a material to become electrically polarized when subjected to mechanical strain. In our devices, the piezoelectric layer is placed on the top of the 3C–SiC beam. When the device is electrothermally driven into resonance, the beam vibrates in vertical direction inducing mechanical strain in the top piezoelectric layer. As a consequence, an alternating voltage with a frequency equal to the frequency of the mechanical vibrations can be detected across the piezoelectric material of the output port.

3. Experimental details

3.1. Device design

The devices have been designed as a two-port double-clamped beam resonator with the beam length of 200 μm and width of 50 μm. The electrothermal actuator has been designed with two platinum (Pt) arms, parallel to the longer side of the beam, connected by a perpendicular arm (u-shaped layout). The electrothermal actuator length is 67 μm (a third of the beam length), the arms' width is 20 μm and the spacing between arms is 3 μm. The strong electromechanical coupling offered by the electrothermal transduction allows the structure to be driven efficiently into vibration by positioning the electrothermal actuator close the beam's root, leaving enough area on the other side of the beam for the piezoelectric sensor. The piezoelectric sensor is formed from a lead–zirconium–titanate (PZT) layer sandwiched between two Pt layers. PZT has been used due to its high piezoelectric coefficient, so that the electromechanical coupling in the sensing part is enhanced [7]. Fig. 1 shows a scanning electron micrograph of one of the fabricated devices, and the top and the side view schematics of the designed devices.

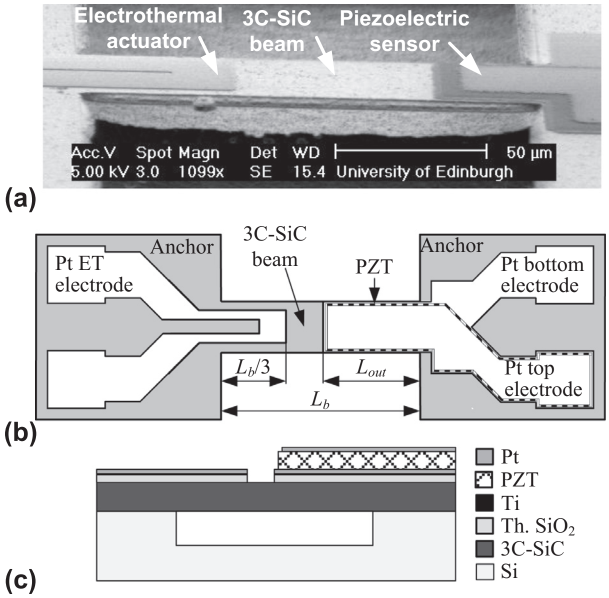

Fig. 1. SEM image (a), top (b) and side (c) view schematics of the double-clamped 3C–SiC beam resonator, with the electrothermal actuator and piezoelectric sensor on top of the beam.

3.2. Fabrication

The fabrication process consists of three major phases: all layers deposition, electrodes forming and the beam forming. The all layer deposition phase starts with a 2 μm thick 3C–SiC epilayer grown on 4 in. Si wafer [10]. A 100 nm thick silicon dioxide (SiO_2) passivation layer has been grown thermally and a 10 nm thick titanium (Ti) adhesion layer has been deposited on top of the SiO_2. The Pt/PZT/Pt stack has been deposited with thicknesses of 100/500/100 nm, respectively [11]. In the second phase, the electrodes have been defined photolithographically. The Pt and Ti layers have been dry etched while the PZT has been wet etched [12]. After patterning the electrodes, a 3 μm thick SiO_2 layer has been deposited for masking the 3C–SiC layer. The 3C–SiC beam shape has been patterned photolithographically and the exposed SiO_2 has been dry etched. Afterwards, 3C–SiC beam has been etched and released with inductively-coupled-plasma [13] and XeF_2 chemical etching.

3.3. Measurement setup

The fabricated devices have been tested with a RF probe station and the transmission frequency response has been measured by an HP 8753C vector network analyzer. Signal-ground (SG) probes have been used and two-port short-open-load-through (SOLT) calibration has been performed before starting the measurements. The devices under test have been directly connected to the network analyzer without any external interface electronics. In order to perform electrothermal actuation and resonant frequency tuning, the AC signal applied with the network analyzer has been superimposed to a DC voltage provided by an external stabilized DC power. The bottom metal contact of the output electrode has been grounded, while the top metal contact has been used for piezoelectric sensing. All measurements have been performed in air, at room temperature and pressure.

4. Results and discussion

Testing of the devices has been performed by measuring the transmission frequency response in atmospheric conditions (Fig. 2a). The devices under test differ only in the piezoelectric sensor length, while other dimensions and technological parameters are the same. In order to perform a comparative study, the devices measured in this work have been taken from the same die (0.7 cm^2) and therefore fabrication related differences such as film thicknesses have been minimized.

4.1. Piezoelectric port length influence on resonant frequency

The resonant frequency measured as a function of the piezoelectric sensor length is shown in Fig. 2b. Resonant frequencies in the range of 0.85–1.05 MHz have been measured for the devices actuated with input signal power of 10 dBm and DC bias voltage of 3 V. By decreasing the piezoelectric sensor length from 125 μm to 25 μm, the resonant frequency increases by ~20 kHz (~24,000 ppm). The observed increase of the resonant frequency as the piezoelectric sensor length decreases can be attributed to the decrease of the structure's effective mass. The resonant frequency of a multi-layer bridge resonator is proportional to ratio