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Actuation Dependency of Frequency Tuning in MEMS Resonators

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***Abstract*— This letter shows that active tuning of MEMS resonators through temperature is highly dependent on the actuation mechanism used, and demonstrates the adverse effects of using substrate conductive heating characterization results to predict device's performance in their final application, where Joule heating is most likely to be used. A buckled VO_2-based SiO_2 tunable MEMS resonator is used in the study, where the thermal frequency stability or active tuning of the resonant frequency is thermally induced. The VO_2 phase transition is triggered by substrate heating and Joule heating. When using Joule heating, the increasing strain energy during the phase transition results in a monotonic increase in resonant frequency, with a maximum resonant frequency shift of 11.9%. For substrate heating, the resonant frequency shift is non-monotonic and shows a 10.6% increase followed by a 7.8% decrease. The different frequency shift patterns that are observed for two heating mechanisms can be attributed to different stress-strain responses. [2019-0256]**

***Index Terms*— Vanadium dioxide, MEMS resonators, buckling, buckling amplitude, active frequency tuning.**

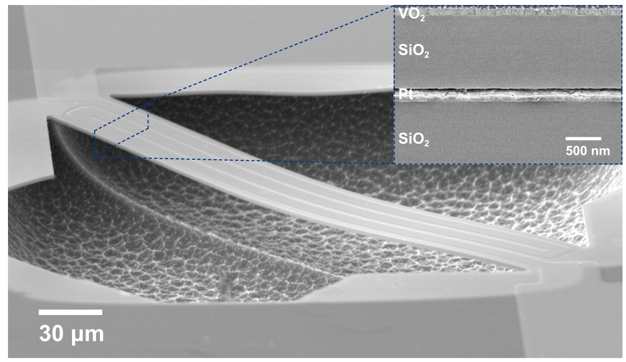

Fig. 1. SEM image of a buckled VO_2-based MEMS bridge structure.

I. Introduction

THE resonant frequency of a microelectromechanical systems (MEMS) resonator is determined by many factors such as geometry, structural material properties, stress and strain, surface roughness, etc. Many efforts have been made to stabilize the resonant frequency throughout the lifetime of MEMS resonators in order to compensate for the frequency shift caused by fabrication flaws, aging, or fluctuations in the operating environment. Thus, tunability of resonant frequencies becomes an important factor in determining the device reliability and applicability. The tuning technologies can be generally categorized into two types: passive and active tuning. Passive tuning is usually an irreversible approach, i.e. focused ion beam (FIB) technique [1] and pulsed laser deposition (PLD) method [2], which permanently shifts the resonant frequency towards the desired value. The active tuning methods, such as electrothermal tuning [3] and electrostatic tuning [4], [5], shift the resonant frequency through controllable input signals. However, the latter often requires extra tuning electrodes which complicates the MEMS structure. In an earlier work, we presented VO_2-based microstructures, which were relatively simple in fabrication and showed tuning frequencies up to 28.5% [6]. However, the reported devices consisted of bimorph structures (either silicon or silicon dioxide) with a VO_2 coating; and therefore, were not MEMS devices with integrated resistive heaters. More recently, we demonstrated integrated VO_2-based resonators for tunable band-pass filters [7], which focused on different resonator structures and tuning ranges, but never compared different heating mechanisms.

In this letter, an active frequency tuning by thermally induced stress is demonstrated on a VO_2-based MEMS coated buckled bridge. The axial stress that drives the frequency shift is generated by integrated resistive heaters or by substrate heating of the entire device. The increase in temperature triggers the insulator-to-metal transition (IMT) in the VO_2 film, which leads to a decrease in the crystal plane by $\sim 0.7\%$ along the c-axis and produces a large stress in the mechanical structure [8]. Both substrate heating and Joule heating methods are applied and result in very different tuning behaviors which reveal a strong correlation between resonant frequency and buckling amplitude.

II. Results and Discussion

The VO_2-based MEMS bridge reported in this work is 300 μm long, 40 μm wide, and 2.3 μm thick. The structure consists of a 200 nm Pt resistive heater sandwiched in between two 1 μm SiO_2 layers. The suspended structure is defined and released by reactive ion etching (RIE) and isotropic etching of the Si substrate, respectively. The residual thermal stress creates a buckling state, as shown in Fig. 1, after release. Then, a 100 nm VO_2 layer is deposited and the beam structure remains in the buckling state.

The resonant frequency is measured by the laser deflection method as described in [9] with the sample located in a vacuum below 10 mTorr. The device is wire bonded to a thermally conductive package and attached to a Peltier heater using silver paint. This configuration allows for both heating methods (substrate and Joule heating) to be used consecutively on the same device without having to move the sample from the testing set-up. A thermocouple is closely placed beside the sample in order to monitor the substrate temperature. The forced vibration of the beam is provided by a piezoelectric disk placed underneath the sample. First mode resonant

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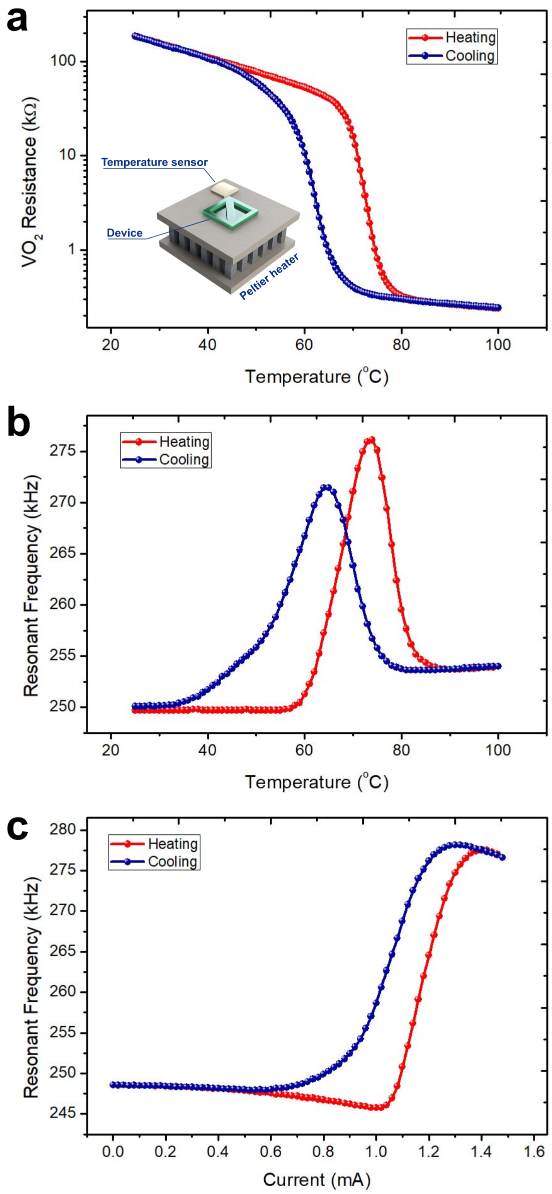

Fig. 2. Characterizations through a full heating and cooling cycle. (a) The resistance change of VO_2 film upon substrate heating and cooling. The inset shows the schematic drawing of the experimental setup. (b) Resonant frequency change of VO_2 buckled bridge upon substrate heating and cooling. (c) Resonant frequency change of VO_2 buckled bridge upon resistive heating and cooling.

frequencies are measured throughout the IMT phase transition region in a full heating and cooling cycle. The quality of the VO_2 film is verified by measuring the resistance on a 50 μm by 350 μm thin patch test site through a full heating and cooling cycle as shown in Fig. 2a. A characteristic 3 orders of magnitude drop in resistance is captured during the IMT phase transition, which starts around 68°C and spans about 15°C. Fig. 2b shows the first mode resonant frequency change as a function of temperature through substrate heating. During the phase transition, the resonant frequency first increases about 10.6% and then undergoes a decrease of about 7.8% which starts at 74°C. However, for an uncoated bridge resonator with the same structure reported in [9], the substrate heating only leads to a monotonic change of $\sim$ 0.5%. The reversibility is also demonstrated by measuring the resonant frequency on the cooling cycle. Unlike the substrate heating method, which shows a bidirectional tunability, tuning by Joule heating only shows a frequency shift of 11.9% in one direction during the phase transition. The merging heating and cooling curves at the beginning (or end) of the hysteresis loop indicate that the phase transition has not started (or has completed).

The difference in resonant frequency shift patterns can be attributed to different boundary constraints induced by two thermal activation methods. It has been shown that VO_2 coated cantilevers show much lower frequency shifts than bridge structures with similar dimensions. This is due to the stress released in the form of bending in the cantilever structure. Bridges have larger residual axial stress, which causes a larger resonant frequency sensitivity with stress [10]. According to Euler-Bernoulli beam theory, a bridge structure under a compressive axial load beyond Euler's critical load [11] $\sigma_c = -\pi^2 Eh^2/3L_{eff}^2$, where $E = 70$ GPa is the Young's modulus, $h = 2.3$ μm is the thickness, and $L_{eff} = 327$ μm is the effective beam length considering a 9% under-etching effect [7], exhibits a lateral deflection. The resonant frequency of this buckled beam increases with increasing compressive stress and decreases by applying tensile stress [12]. The relation between the axial load and the first mode resonant frequency f can be described by [13]:

$$f = \sqrt{\frac{2}{\rho_{eff} {L_{eff}}^2}(|\sigma_l| - |\sigma_c|)} \tag{1}$$

where $\rho_{eff} = 2920$ kg·m^{-3} is the effective density and $\sigma_l = \sigma_l(T) < 0$ is the temperature dependent compressive axial stress.

For a n-layer clamped-clamped beam with each layer i of different thermal expansion coefficient (TEC) α_i, σ_l can be expressed as:

$$\sigma_l = \sigma_0 + \sum_{i=0}^{n} \sigma_i + \sigma_y \tag{2}$$

where σ_0 is the residual stress at room temperature, σ_i is the stress in each layer and σ_y is the stress related to the change in L_{eff} under a bending moment. Given that σ_i is independent of other deposited layers [14] and σ_y can be related to the loaded (y) and unloaded (z) deflection amplitudes at the center as $y = z/(1 + \sigma_y/|\sigma_c|)$ [15]. Equation (2) can be rewritten as:

$$\sigma_l = \sigma_0 + \sum_{i=0}^{n} \frac{E_i}{1 - \nu_i}(\alpha_0 - \alpha_i)\Delta T + |\sigma_c|(\frac{z}{y} - 1) \tag{3}$$

where α_0 is TEC of the substrate, ΔT is the temperature change and ν_i is the Poisson's ratio. When phase transition is introduced by substrate heating, the difference in TEC among VO_2 ($\alpha_2 = \alpha$(T) [16]), SiO_2 ($\alpha_1 = 0.5 \times 10^{-6}$ 1/K), and Si ($\alpha_0 = 2.6 \times 10^{-6}$ 1/K) induces a shear stress which reduces the downward buckling amplitude [17]. Hence, two mechanisms determining the resonant frequency shift are expected here: i) the mismatch of TEC induces a compressive stress, as the second term in equation (3), which causes the increase in resonant frequency; ii) the semi-flexibility of anchors enables the decrease in buckling amplitude and therefore reduces the third term in equation (3). However, when Joule heating is used, the heat is mainly concentrated in the beam center while the anchors remain cold and the vertical deflection can be neglected. Thus, the resonant frequency shift is mostly determined by the mismatch of TEC and shows a monotonic increase as shown in Fig. 2c.

The change in the buckling amplitude can be determined by using an interferometer [18]. As shown in Fig. 3, the substrate heating results in a larger vertical displacement than the Joule heating in the phase transition region. When the phase transition starts as shown in Fig. 3a, the vertical displacement changes rapidly as a function of

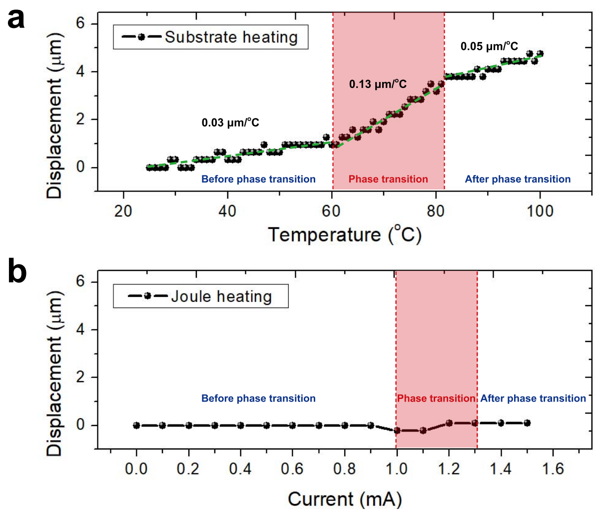

Fig. 3. Change in buckling amplitude measured by an interferometer. The y-axis shows the vertical displacement where a positive value denotes an upward deflection. (a) Vertical displacement induced by substrate heating. (b) Vertical displacement induced by Joule heating.

temperature (0.13 μm/°C). When the critical temperature is reached, 74°C in this case, the decrease in σ_y dominates over the increase in σ_i in determining the resonant frequency, and the resonant frequency starts to decrease. This observation and analysis also explain the unclear bumping phenomenon reported in [13]. When Joule heating is used, the vertical displacement in the phase transition region is only 0.32 μm, compared to 2.85 μm when substrate heating is used, as shown in Fig. 3b. In this case, the resonant frequency decrease caused by the vertical displacement is negligible, compressive axial stress continuously builds up in the longitudinal direction. This leads to a monotonic increase of the resonant frequency.

The changes in axial stress for both activation mechanisms can be estimated from equation (1). Given that the σ_c is 11.39 MPa and σ_l is 21.07 MPa at the room temperature, the Joule heating induces a compressive stress of $\sim$ 2.26 MPa during the full heating cycle. For substrate heating actuation, a compressive stress of $\sim$ 2.22 MPa is induced at 74°C, where the resonant frequency has the maximum value. Further decreasing of the buckling amplitude leads to a tensile stress of up to 1.83 MPa, therefore the net compressive stress induced at the end of transition is around 21.46 MPa.

III. Conclusion

In this work, the resonant frequency tunability of a 300 μm VO_2-based MEMS microbridge with downward buckling state is studied. The resonant frequency tuning is demonstrated by substrate and Joule heating. The results show very different tuning behaviors and ranges between the two actuation methods. Joule heating results in a monotonic 11.9% increase in the resonant frequency due to large compressive stress, which is induced by limited vertical deflections. Substrate heating presents a more flexible boundary condition, and therefore the softening effect due to large buckling amplitude change must be considered. This phenomenon leads to a non-monotonic tuning behavior in the phase transition by a 10.6% increase followed by a 7.8% decrease in resonant frequency. These results show that using substrate heating for characterizing the thermal stability or dynamic tuning range of thermally activated MEMS resonators can produce very different results than those obtained when using Joule heating.

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