TEMPERATURE HYSTERESIS IN PIEZORESISTIVE MICROCANTILEVERS

James M.L. Miller, Ze Zhang, Nicholas E. Bousse, Dusan Coso, Seid Sadat, Hyun-Keun Kwon, Gabrielle D. Vukasin, Arun Majumdar, and Thomas W. Kenny
Department of Mechanical Engineering, Stanford University, Stanford, California, USA

ABSTRACT

We observe significant temperature hysteresis in the resonant frequency and quality factor of silicon piezoresistive microcantilevers from room temperature down to 40 K. The hysteresis becomes increasingly pronounced as the support beam length is reduced from 100 μm to 30 μm, leading to over a twenty-fold difference in Q values between the temperature sweep downwards and upwards for the 30 μm support beam device. Our work suggests that temperature hysteresis is an important consideration for thermal-piezoresistive oscillators and other microelectromechanical resonators that require multiple anchor points.

KEYWORDS

Temperature Hysteresis, Quality Factor, Microcantilever Thermal-Piezoresistive Oscillator

INTRODUCTION

Thermal-piezoresistive oscillators (TPOs) and amplifiers (TPAs) have potential as real-time mass sensors for air pollution monitoring [1, 2], front-end filters for mobile communications [3], and microwave frequency references for wireless consumer electronics [4]. TPOs and TPAs utilize an effect in micro- and nanoelectromechanical (MEM/NEM) resonators known as thermal-piezoresistive pumping, whereby flowing a direct current through the device via appropriately designed thermal actuators can increase or decrease the effective damping [5, 6]. This effect can be utilized to amplify the output of gyroscopes and Lorentz-force magnetometers [7, 8], improve the bandwidth of inertial sensors [9], or filter signals in radio-frequency (RF) receivers [3]. For a sufficient direct current or constant voltage with the correct sign in the piezoresistive coefficients, the thermal-piezoresistive effect will induce self-sustained oscillations in the MEM/NEM resonator [5, 10, 11]. TPOs only require a direct current to operate, thus eliminating the feedback circuitry or external signal generators required for the other oscillator approaches [12]. Hall *et al.* demonstrated self-oscillations at 161 MHz in a dual-plate TPO with a power consumption of 20 mW [13], Li *et al.* reported on 840 kHz wing-type oscillators with 70 μW power consumption [14], and Janioud *et al.* achieved self-oscillations of a nanowire-connected pivoting resonator at 11 kHz with a power consumption of only 5 μW [11], comparable to commercial low-power MEM oscillators [15].

Progress in superconducting-qubit-based quantum computers [16, 17], quantum-noise-limited amplifiers [18, 19], and microwave-optical photon converters [20, 21] is spurring the development of a suite of on-chip cryogenic devices. One such device, the Josephson parametric oscillator (JPO), can be used to read out and manipulate qubits on-chip, reducing the number of required cryostat cables and interconnects in quantum computers [22]. JPOs still require microwave cables to supply the pump signal, and can suffer from the poor phase noise characteristic of electrical resonators.

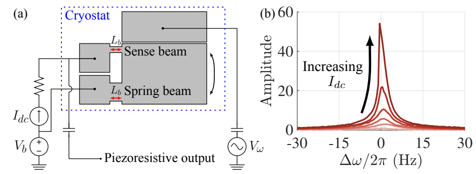

Figure 1: (a) The piezoresistive cantilevers under test. The devices are characterized in a helium cryostat, with electrical feedthroughs for the applied ac drive voltage (V_ω), the direct current (I_{dc}), the bias voltage (V_b), and the ac piezoresistive readout. (b) The measured amplitude response versus frequency offset from resonance ($\Delta\omega$) for device A, for a constant drive amplitude and increasing direct current from 2 mA to 22 mA, in 4 mA increments (light to dark red curves). The vibration amplitude is normalized so that the maximum amplitude with 2 mA of direct current is unity.

Mechanical oscillators have potential as in-cryostat signal generators for qubit manipulations, because of their excellent phase noise [23], and their amenability to nanolithography [24]. Maintaining oscillations with the thermal-piezoresistive effect could reduce the number of microwave cables even further, by generating ac signals for qubit manipulations using a relatively small number of dc feedthroughs. The prospect of using TPOs to manipulate qubits on-chip requires self-oscillation frequencies of over 1 GHz, low power consumption, and resonator stability down to cryogenic temperatures. Rapid progress is being made to increase the TPO operating frequency while reducing the power consumption [25], but to-date, little work has gone towards characterizing and optimizing the stability of TPOs over a wide temperature range. We make one step towards this goal by investigating the resonant frequency and quality factor of silicon micromechanical TPOs down to cryogenic temperatures.

EXPERIMENT AND DISCUSSION

We study silicon piezoresistive microcantilevers that are fabricated within a wafer-scale encapsulation process, as in Fig. 1(a). The base of the cantilever is split into a wide "spring" beam and a narrow "sense" beam, which enables the resonator vibrations to be measured piezoresistively by flowing a direct current through the beams, as shown in Fig. 1(b). Flowing sufficient direct current through the resonator causes it to self-oscillate at radio frequencies [5]. The resonators are mounted inside a custom closed-cycle helium cryostat, which can maintain stable temperatures down to 40 K, and the motion is monitored piezoresistively by flow-

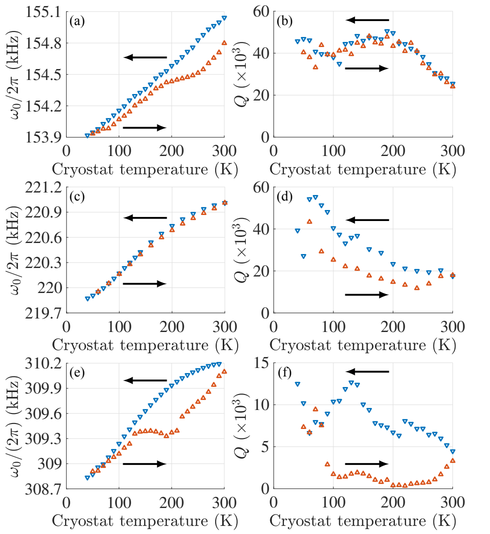

Figure 2: The measured (a, c, e) resonant frequency and (b, d, f) quality factor of (a, b) Device A, (c, d) Device B, and (e, f) Device C, for reducing cryostat temperatures (downward triangles) and increasing temperatures (upward triangles).

ing 4 mA of direct current through the device, well below the self-oscillation threshold.

We measure the temperature-dependence of the resonant frequency and Q of the microcantilevers as a function of support beam length: $L_b = 100$ μm for Device A, $L_b = 60$ μm for Device B, and $L_b = 30$ μm for Device C. Each device is characterized by reducing the temperature in steps, waiting thirty minutes for the temperature to stabilize at each step, then sweeping a drive voltage across resonance while demodulating the piezoresistive output at that frequency. The cryostat temperature is stepped from 300 K down to 40 K, then increased back to 300 K, in 10 K steps. We extract the resonant frequency and Q at each temperature step using a best-fit of the simple harmonic resonator model to the frequency response.

Figure 2 plots the measured resonant frequency and quality factor for the three devices of decreasing support beam length. We observe significant temperature hysteresis in the resonant frequency and Q of the microcantilevers that becomes more pronounced as the support beam length is reduced. The resonant frequency is consistently higher for the temperature sweep down than it is for the sweep up. The temperature hysteresis in resonant frequency is more pronounced for Device C than B, which could be due to stress relaxation in the two anchors [26]. The Q of these microcantilevers also exhibits significant temperature hysteresis as the support length is reduced. In Device C, the Q is more than twenty-fold larger at 220 K for the temperature sweep down than the temperature sweep up. This drastic change in the linewidth at a given temperature is apparent in the amplitude-frequency measurements plotted in Fig. 3. The Device C linewidths for the temperature sweep up and down are relatively comparable at 300 K, while at 220 K the peak narrows for the temperature sweep down and broadens sig-

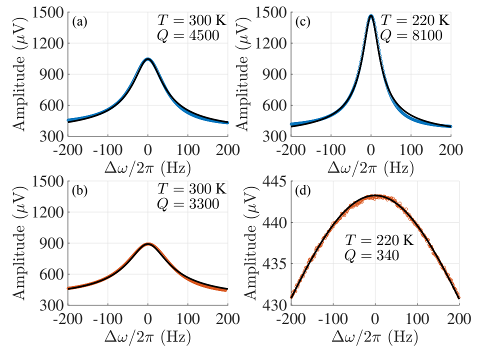

Figure 3: The amplitude-frequency measurements for Device C with overlaid best-fits, at a temperature (a, b) $T = 300$ K and (c, d) $T = 220$ K, for (a, c) reducing cryostat temperature and (b, d) increasing cryostat temperature, exhibiting Q hysteresis with temperature.

nificantly for the temperature sweep up.

Figure 4 demonstrates that this hysteresis is highly dependent on cycle count, suggesting that some kind of relaxation mechanism is at play. Successive temperature sweeps of the same device display reduced hysteresis in both quality factor and resonant frequency compared to the previous sweep. After four cycles, hysteresis in the resonant frequency is almost entirely eliminated and hysteresis in the quality factor is significantly reduced below 200 K. Repeated measurements at the same cryostat temperature over the span of several hours does not result in appreciable drift in the resonant frequency or quality factor, suggesting that any relaxation mechanism in the hysteresis has a much longer timescale. One explanation for the observed relaxation in resonator properties over multiple cycles could be relaxation of the residual stress in the support beams. For Device C, such as in Fig. 4(a), the temperature coefficient of frequency (TCF) near room temperature is positive for the temperature sweep of increasing temperature and negative for the sweep of decreasing temperature, and maintains this behavior until the fourth temperature cycle, as shown in Fig. 4(e). The TCF of highly doped silicon resonators may be negative or positive depending on the mode shape [27], but in this device, the TCF can be positive or negative at the same temperature depending on the direction of the temperature sweep.

We currently believe that the quality factor of these devices is dominated by stress-mediated anchor loss in the support beams. Measurements of other flexural-mode devices fabricated within our wafer-scale encapsulation process have shown far less device-to-device variability in pressure damping than what we observe in these devices [28]. The maximum $f \cdot Q$ product seen in these resonators, roughly 10^{10} Hz, is well below the approximate 10^{13} Hz limit expected for Akhiezer damping in silicon [29], suggesting that the Akhiezer effect can be disregarded here. While Fig. 2 shows a local maximum in quality factor near the zero thermal expansion point of silicon at 120 K for some resonators, a hallmark of thermoelestic dissipation, the maximum quality factor of the device is often seen at lower temperatures,

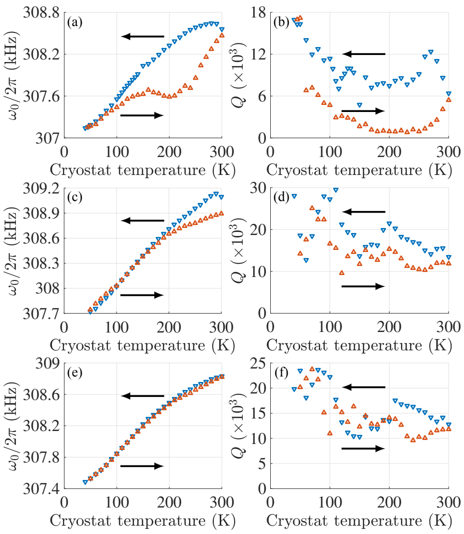

Figure 4: The measured (a, c, e) resonant frequency and (b, d, f) quality factor for additional temperature cycles with Device C, for reducing cryostat temperatures (downward triangles) and increasing temperatures (upward triangles).

suggesting that there is another limiting energy loss mechanism. We additionally observe that the magnitude and hysteresis of the quality factor of these devices is highly dependent on the length of the support beams. We hypothesize that residual stress in the structure influences the energy loss through the anchors, and that this effect becomes more pronounced in the microcantilevers with shorter, less compliant, support beams. The cycle-dependent reduction of hysteresis perhaps results from the relaxation of the residual stress in the support beams.

The piezoresistive displacement readout used to characterize these devices is inherently noisy, and limits the accuracy in determining device parameters, particularly the quality factor. The current flow through the device required for the piezoresistive readout may also contribute non-negligible Joule heating that affects the temperature of the resonator. Capacitive sensing of these devices would eliminate the Joule heating and has the potential to achieve thermomechanical-noise-limited displacement resolution [30], but is currently hindered by the parasitic capacitance and inductance inherent in our cryostat setup. Work to reduce these parastic effects and implement a low-noise capacitive readout, which would allow for a more careful characterization of the observed hysteresis, is ongoing.

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CONTACT

e-mail: jmlm, zez, nbousse@stanford.edu