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Microresonator Frequency Control and Stabilization Using an Integrated Micro Oven

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ABSTRACT

The high Q of micromechanical resonators operated in vacuum gives them strong potential for use as frequency references and as signal processing elements. The application range for such devices would be greatly enhanced by convenient means for frequency tuning and stabilization against temperature variations. In this paper, we report on a micro-oven technique for controlling and stabilizing μresonator center frequency, in which a μresonator is suspended above a microplatform, which is in turn suspended above a silicon substrate, and the resonator frequency is adjusted by changing its temperature via on-platform heating resistors. Since the platform is thermally isolated from the substrate, power requirements are on the order of only milliWatts, and thermal time constants are on the order of milliseconds.

I. INTRODUCTION

Due to their high quality factors when operated under vacuum, micromechanical resonators have strong potential for use as frequency references in electronic systems. Polysilicon folded-beam electrostatic-comb driven resonators typically have Q's in the range of 50,000 under 10 mTorr pressure, and in excess of 100,000 for pressures in the tens of microTorr [1]. Such a high Q element, when embedded in a positive feedback loop, can realize an oscillator with phase jitter noise stability approaching that of quartz crystal oscillators. In addition, high Q micromechanical resonators have potential as on-chip signal processing devices with frequency selectivity better than present integrated filtering technologies [1, 2].

The above applications share the simultaneous need for frequency tunability and frequency stability with respect to temperature. Frequency-pulling for capacitively excited resonators via adjustment of resonator dc-bias has been reported previously [3, 4]. Although convenient, this pulling technique is effective only for resonator designs for which the variation of drive capacitance with displacement of the resonator is nonlinear. Thus, resonators that use electrostatic comb-drive to enhance linearity cannot benefit from this technique. In addition, for some signal processing applications, it desirable to hold the resonator dc-bias fixed, since the dc-bias determines the transfer function gain of the device [1, 5].

In this paper, we discuss an alternative frequency tuning method that takes advantage of the temperature coefficient of the resonator. This technique utilizes a micro-oven, in which a resonator is fabricated on a thermally isolating microplatform equipped with heater and sense resistors, and its frequency is varied by controlling the platform temperature via feedback electronics. The resonance frequency can not only be made variable through temperature control, but can also be stabilized via the feedback control electronics. In other words, the temperature coefficient of the center frequency is reduced. Depending on the isolating platform design, power requirements for this micro-oven approach can be in the range of only milliWatts—orders of magnitude lower than that for oven-control methods used for macroscopic crystal oscillators (1 to 10 Watts [6]).

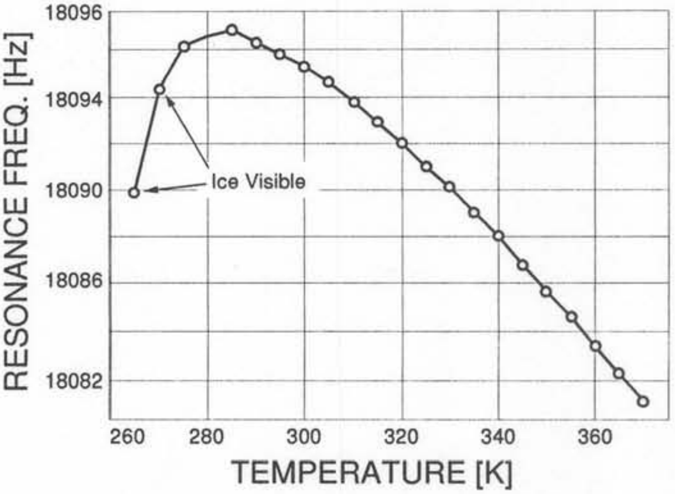

Fig 1. Measured frequency versus temperature plot for a folded-beam μresonator. The turning point at lower temperatures is due to ice forming on the resonator.

II. MICRO-OVEN CONTROL

The range of frequencies controllable by a micro-oven technique is dependent upon the temperature coefficient, TC_{f_r}, of the resonator's center frequency and on the range over which the temperature can be varied with acceptable power consumption. A measured plot of frequency versus temperature for a folded-beam μresonator is presented in Fig. 1. From the data, TC_{f_r} is found to be -10 ppm/°C from 20°C to 100°C. This TC_{f_r} compares with those for AT cut quartz crystals [6], thus, further enhancing the potential of μresonators as frequency references. The value -10 ppm/°C implies that the temperature coefficient of the Young's modulus, given to first order for a folded-beam resonator by $TC_{f_r} = \frac{1}{2}(TC_E + TC_h)$, is near -23 ppm/°C for *in situ* phosphorous-doped LPCVD polysilicon, deposited at 610°C. Since this value is considerably smaller than a previously reported number [8], we state it tentatively, until a more systematic study of the factors determining TC_{f_r}, such as packaging stress due to thermal expansion mismatches, is available.

Although the small TC_{f_r} indicated by Fig. 1 provides the advantage of better frequency stability, it also widens the required temperature range for an oven-control system designed to tune the frequency. To achieve a wide temperature range with minimal power dissipation, heat loss must be minimized via thermally isolating the μresonator from the surrounding substrate. An overhead schematic of the micro-oven control system is presented in Fig. 2. Here, a polysilicon μresonator is suspended above a nitride platform, which in turn, is suspended above the substrate via long, thin struts. The suspending struts, which can be polysilicon or a poly/nitride sandwich, provide thermal isolation of the platform from the substrate, as well as conductive interconnect between these media. These struts are folded in order to relieve post fabrication compressive stress, preventing pos-

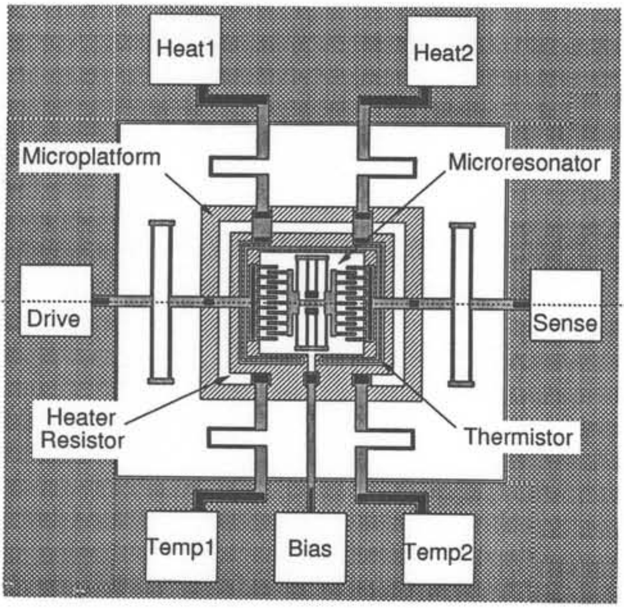

Fig 2. Overhead schematic view of the micro-oven control system, showing a μresonator situated on top of a nitride platform, which in turn, is suspended above the substrate. The platform is attached to the substrate via long, thin beams, which provide thermal isolation from the substrate.

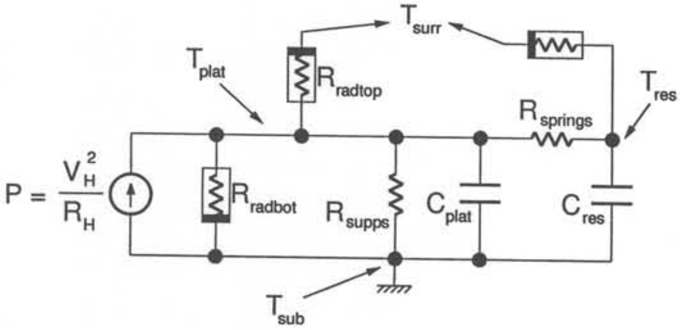

Fig 3. Equivalent thermal circuit schematic for the micro-oven control system of Fig. 2.

sible buckling of the platform. Devices on the platform include the μresonator, plus two polysilicon resistors, which serve to heat the platform and sense its temperature.

The main concern in design of such a microplatform is the degree of thermal isolation achieved, since this dictates the power required to sustain a given temperature and the time required to change it [7]. Since the μresonator is normally operated in vacuum, thermal loss through convection can be neglected. Thus, power and transient information can be attained using a simple lumped-parameter model where the supporting struts are represented by equivalent thermal resistances (thermal C neglected), the platform and resonator shuttle are modeled with thermal capacitors (thermal R neglected), and loss due to radiation is modeled via nonlinear thermal resistors, as shown in Fig. 3. The expression for conductive thermal resistance is given by [9]

$$R_{thermal} = \sum_{j=1}^{m} \left[\sum_{i=1}^{n} k_i (A_i / l_j) \right]^{-1}, \tag{1}$$

where k_i is the thermal conductivity of the i^{th} layer, A_i is the cross sectional area of the i^{th} layer, and l_j is the length of the j^{th} beam in the support strut. Thermal capacitance can be found using [9]

$$C_{thermal} = \sum_{i=1}^{n} \rho_i V_i c_{pi}, \tag{2}$$

where ρ_i is the density of the i^{th} layer, V_i is the volume of the i^{th} layer, and c_{pi} is the specific heat of the i^{th} layer.

Finally, two components of radiative thermal loss must be considered: one component for the top surface of the μplatform where heat radiates to free space; and one for the bottom surface, for which there is significant thermal reflection with the silicon substrate just 2 μm below. Top surface radiation can be modeled by [9]

$$P_{radtop} = \sigma A_{top} \varepsilon_{pSi} (T_{plat}^4 - T_{surr}^4), \tag{3}$$

where P_{radtop} is the power radiated from the platform at temperature T_{plat} to the surroundings (room or enclosed probe station compartment) at temperature T_{surr}, A_{top} is the top surface area, ε_{pSi} is the thermal emissivity for polysilicon, and σ is the Stefan-Boltzmann constant. ε_{pSi} is used since the top of the platform is mostly polysilicon (resistors, ground plane, and resonator). The bottom polysilicon surface and polysilicon-coated substrate may be approximated as infinite parallel planes, for which radiative thermal loss from the μplatform is given by [9]

$$P_{radbot} = \frac{\sigma A_{bot} (T_{plat}^4 - T_{sub}^4)}{2/\varepsilon_{pSi} - 1}, \tag{4}$$

where P_{radbot} is power, A_{bot} is the bottom surface area, and T_{sub} is the substrate temperature.

The total steady-state power dissipation required to maintain a constant temperature T_{plat} on the platform is given by (refering to Fig. 3)

$$P = \frac{T_{plat} - T_{sub}}{R_{supps}} + P_{radtop} + P_{radbot}, \tag{5}$$

where T_{sub} is the substrate temperature and R_{supps} is the parallel combination of the thermal resistances of all the supporting struts. Again, refering to Fig. 3, the thermal time constants by which the platform and resonator temperatures may be adjusted can be approximated by

$$\tau_{plat} \approx R_{supps} C_{plat} \tag{6}$$

$$\tau_{res} \approx R_{supps} C_{plat} + R_{springs} C_{res} \tag{7}$$

Using typical dimensions for the micro-oven control system (total platform strut lengths of 320 μm, platform dimensions of 300 x 400 μm^2, 67 μm resonator spring lengths), and assuming that the struts and microplatform are composed of a 1 μm-thick silicon-rich nitride sandwiched between two layers of polysilicon (4000 Å- and 2 μm-thick), the expected power requirement and thermal time constants to maintain a platform/resonator temperature of 120°C are $P = 1.4$ mW, $\tau_{plat} = 21$ ms, and $\tau_{res} = 41$ ms. Note that the required power and warm-up time are several orders of magnitude smaller than those required by similar oven-control methods applied to crystal oscillators (1–10 W and about 30 minutes [6]), and herein lies a major incentive for miniaturizing frequency-stable, crystal-based oscillators.

III. MICRO OVEN FABRICATION

The fabrication sequence for the micro oven utilizes surface micromachining procedures, exclusively, and is summarized in Fig. 4. The process starts with an *in situ* phosphorous-doped LPCVD of polycrystalline silicon (for a conductive substrate ground plane) immediately followed by a 2 μm-thick layer of phosphosilicate glass (PSG, 8% phosphorous), which serves as the sacrificial layer for the silicon-rich nitride platform. The PSG is then patterned to define the platform anchor points (Fig. 4(a)).

Next, a polysilicon/silicon-rich nitride/polysilicon sandwich of layers is deposited via LPCVD in thicknesses of 4000Å/1μm/4000Å. The top layer of polysilicon is patterned to form bonding pads, the μresonator ground plane, and the heating and sensing resistors. The nitride platform and supporting beams are then patterned into both the silicon-rich nitride layer (LPCVD at 835°C with 5:1 SiH_2Cl_2:NH_3) and bottom film of polysilicon using an SF_6-based plasma etch (Fig. 4(b)). The bottom layer of polysilicon is in electrical contact with the substrate and serves as a conductive shield preventing electrostatic attraction between platform devices and the substrate which tends to pull the platform down.

Next, a second sacrificial PSG layer is deposited and patterned to define the microstructure anchors. In situ phosphorous-doped polysilicon is then deposited 2μm-thick to serve as the microstructural layer. The polysilicon is deposited doped for consistency with the MICS

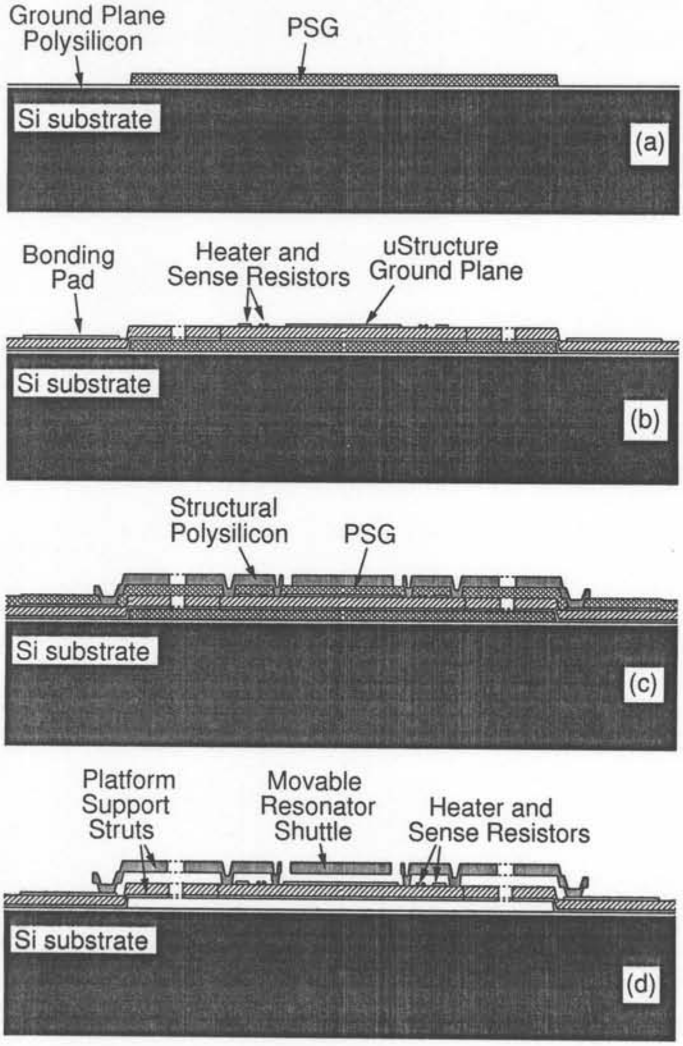

Fig 4. Micro oven fabrication process. (Cross sections taken through the line indicated in Fig. 2.)

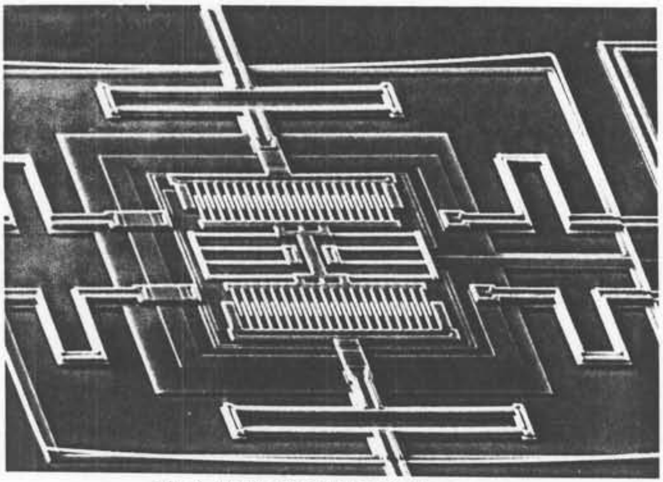

Fig 5. SEM of a fabricated micro-oven.

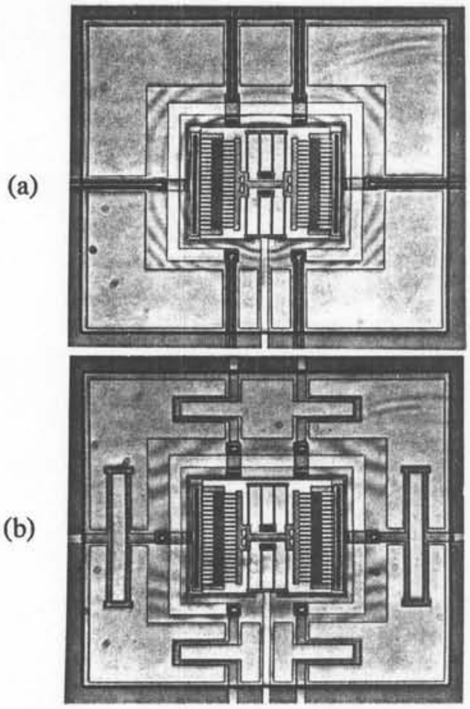

Fig 6. Photomicrographs of microplatforms suspended by (a) straight beams; and (b) folded-beams. The concentric rings on the platform of (a) indicates post-fabrication compressive stress, which is partially relieved via folded-beams in (b).

process, which combines CMOS and micromachining technologies and is capable of realizing a completely monolithic μresonator oscillator [10]. The structural polysilicon is patterned to form the resonator (Fig. 4(c)), then rapid thermal annealed (RTA'ed) for 1 minute at 1100 °C to relieve overly compressive residual stress in the polysilicon caused by an excessive amount of phosphorous in the lattice and between grains. Even after the anneal, clamped-clamped beams with lengths over 200 μm are buckled. However, folded-beam resonators remain unbuckled because most of the residual strain is released in this structure.

After RTA, suspended structures are released via a sacrificial PSG etch using 48.8 wt. % hydroflouric acid (Fig. 4(d)). Since the HF is highly concentrated, the release etch takes less than 3 minutes, even for 300x400 μm^2 platforms suspended only 2 μm above the substrate.

IV. EXPERIMENTAL RESULTS

Figure 5 shows an SEM of the fabricated micro-oven. Figure 6 shows angled-light photomicrographs of two microplatforms, one suspended by folded beams, another by straight beams. The concentric circular rings on the straight-beam platform are visible even under direct light, and they clearly indicate buckling due to compressive stress. Ripples are fewer and farther apart for the folded-beam suspended platform and can only be seen under angled light, indicating partial stress relief via folded beams.

By applying a voltage across the on-platform heating resistor (1150 Ω), the temperature of the platform and resonator may be adjusted. Figure 7 presents a plot of resonance frequency versus applied heating voltage, comparing experiment with prediction based on the theory of Section II and physical constants taken from [11]. Note that for a 1% change in center frequency, only 5 V need be applied to the heater resistor, which corresponds to 22 mW of power and a platform temperature over 750°C. The measured $\tau_{plat} = 20$ ms.

Frequency stabilization through feedback control was then demonstrated using the feedback circuit shown in Fig. 8 In this scheme, the voltage V_{th} is initially low and causes the amplifier to supply current to the heating resistors. As the temperature rises, the thermistor (a polysilicon resistor of 12 kΩ) resistance increases, causing V_{th} to rise to the optimum value V_{ref}, where the feedback loop attempts to stabilize V_{th}. The bias temperature of the system is, thus, set by V_{ref}. For purposes of maximizing frequency stability, this temperature is chosen at the point of minimum TC_{f_r}.

Unfortunately, there is no turning point or zero slope point in the frequency versus temperature plot of Fig. 1 where the system can be biased for maximum stability. Rather, TC_{f_r} stays relatively constant along the whole curve (from 300 to 370 K), so any elevated bias temperature in this range would be as good as another for oven-stabilization tests; in this report, we chose 160°C. The frequency versus temperature curve under micro-oven stabilization using the circuit of Fig. 8 is shown in Fig. 9. The TC_{f_r} is now only 2 ppm/°C. Again,

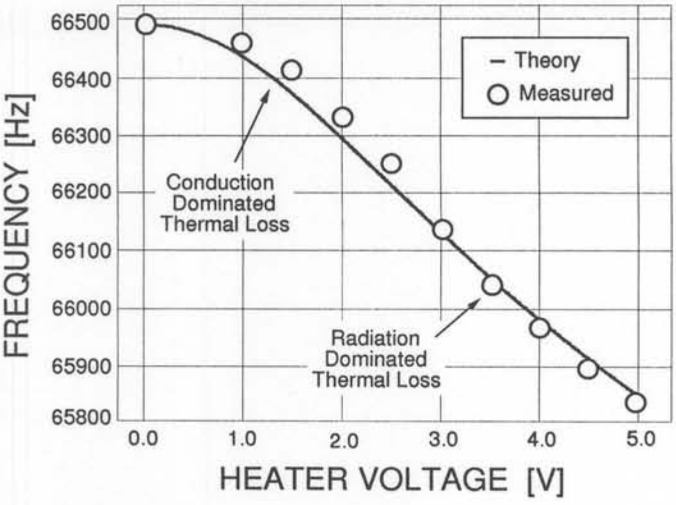

Fig 7. Plot of resonance frequency vs. voltage applied to the heater resistor on the microplatform.

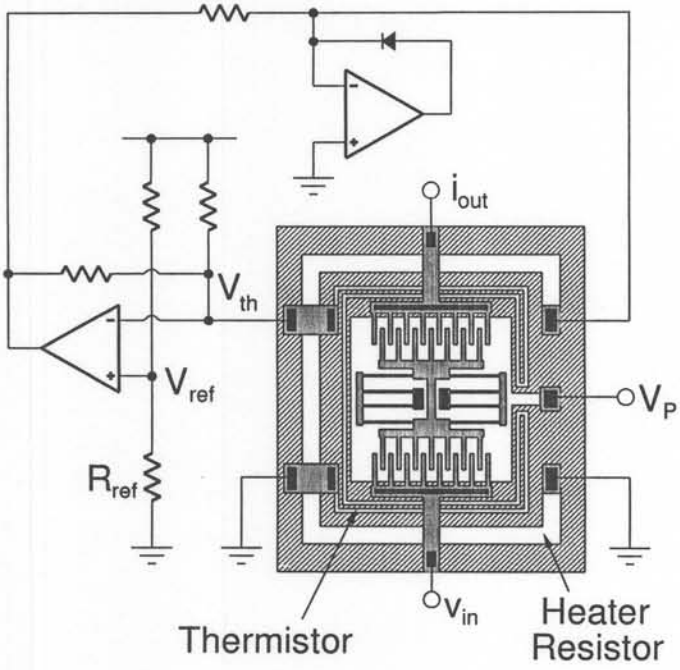

Fig 8. Feedback circuitry for stabilizing the temperature of the microplatform.

a much smaller TC_{f_r} might be achieved through μoven-control if the resonator can be designed to have a turning point or zero slope point at which the temperature may be biased.

V. CONCLUSIONS

Due to the large volume required for thermal insulation, the long warm-up time needed (around 30 minutes), and the excessive power requirements (1–10 Watts), there has been a tendency to avoid oven control techniques for *macroscopic* crystal oscillators, and rather, use circuit compensation techniques, which are less effective than oven control [6]. However, as have been discussed, orders of magnitude improvement in power dissipation and thermal time constant can be obtained through micro-miniaturization. Because of this, oven control of a frequency reference becomes much more practical on a micron scale, and an oven-controlled μresonator oscillator becomes a much more viable approach for achieving a stable, completely monolithic frequency reference, for use in sensors or in signal processing environments.

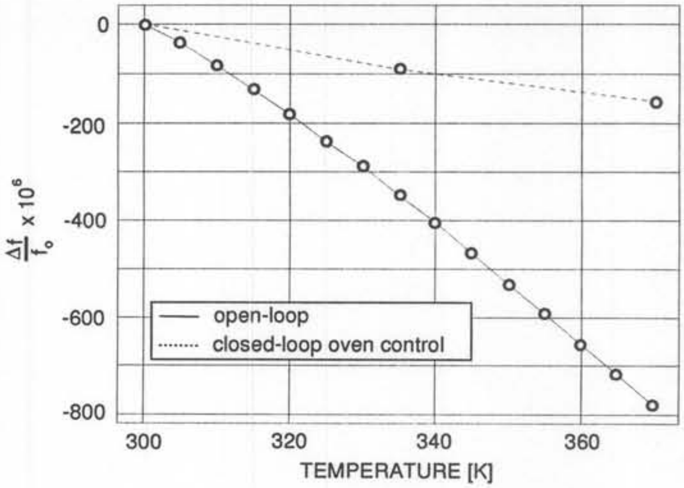

Fig 9. Plot of ppm change in resonance frequency vs. temperature for a μresonator on a thermally isolating μplatform, comparing the case where on-platform controlling resistors are unused to that where resistors are connected in an active temperature controlling feedback loop.

VI. ACKNOWLEDGEMENTS

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References

[1] C. T.-C. Nguyen, "Quality Factor Control for Micromechanical Resonators," *Technical Digest*, IEEE International Electron Devices Meeting, San Francisco, California, Dec. 13-16, 1992, pp. 505-508.

[2] L. Lin, C. T.-C. Nguyen, R. T. Howe, and A. P. Pisano, "Micro electromechanical filters for signal processing," *Technical Digest*, IEEE Micro Electromechanical Systems Workshop, Travemünde, Germany, pp. 226-231, Feb. 4-7, 1992.

[3] R. T. Howe, "Resonant microsensors," *Technical Digest*, 4th International Conference on Solid-State Sensors and Actuators, Tokyo, Japan, June 2-5, 1987, pp. 843-848.

[4] M. W. Putty, "Polysilicon resonant microstructures," M.S. Thesis, Dept. of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Mich., September, 1988.

[5] W. C. Tang, C. T.-C. Nguyen, M. W. Judy, and R. T. Howe, "Electrostatic-comb drive of lateral polysilicon resonators," *Sensors and Actuators*, **BA21-A23**, 1990, pp. 328-331.

[6] M. E. Frerking, *Crystal Oscillator Design and Temperature Compensation*. New York: Van Nostrand Reinhold, 1978.

[7] M. A. Huff, S. D. Senturia, and R. T. Howe, "A thermally isolated microstructure suitable for gas sensing applications," *Technical Digest*, IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, South Carolina, June 6-9, 1988, pp. 47-50.

[8] H. Guckel, *et al*, "The mechanical properties of fine-grained polysilicon: the repeatability issue," *Technical Digest*, IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, S.C., June 1988, pp. 96-99.

[9] J. P. Holman, *Heat Transfer*, 6th Edition. New York: McGraw-Hill, 1986.

[10] W. Yun, R. T. Howe, and P. R. Gray, "Surface micromachined, digitally force-balanced accelerometer with integrated CMOS detection circuitry," *Technical Digest*, IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, South Carolina, June 22-25, 1992.

[11] C. H. Mastrangelo, "Thermal Applications of Microbridges," Ph.D. Dissertation,, Dept. of Electrical Engineering and Computer Sciences, University of California at Berkeley, Dec. 1990.