Integrated long-range thermal bimorph actuators for parallelizable bio-AFM applications

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***Abstract*—This paper presents the fabrication of an integrated long-range thermal bimorph actuator that controls the z-position of an AFM cantilever in liquid. Multiplied in an array, such individually actuated probes can parallelize cell force spectroscopy measurements, thereby drastically reducing the time needed per measured cell. This particular approach implicates the need for devices with an individual actuation range of more than 10 µm out of plane. In addition, any cross-talk, i.e. between actuators or between the actuator and the force sensor, must be minimized. To meet these requirements, we designed and fabricated a novel thermal bimorph actuator that was incorporated with force sensing cantilevers. To be nonhazardous to cells, the design was optimized for high thermo-mechanical sensitivity in order to keep the temperatures as low as possible. FEM simulations confirmed that the surrounding liquid constitutes a very large thermal reservoir that absorbs generated heat, leading to a highly localized temperature elevation. Suspended silicon nitride structures with platinum electrodes were micro-fabricated through standard techniques. The finalized actuator was able to displace the cantilever out of plane by about 17 µm in air. An effective passivation layer was created through a parylene deposition, allowing the actuator to function in water.**

I. INTRODUCTION

In recent years, there has been a surge of research focusing on the role of the biomechanical properties of cells in the onset and progression of human diseases [1]. For example, it has been observed that the cancerous state of a cell is coupled with significant changes of its Young's modulus and adhesion force – a fact which may be crucial in understanding metastasis formation. To quantify these changes, the AFM has emerged as an attractive metrology tool due to its high force sensitivity and harmlessness to cells. Previous works [2-3] have shown that AFM systems are able to discriminate between healthy and cancerous cells, suggesting a potential basis for diagnostics. However, as long as probing is done serially, cell by cell, the lengthy repetitions needed to gather a sufficient amount of data constitutes a bottleneck. In order to bring this research field forward, a more time-efficient approach that parallelizes measurements could prove instrumental.

Several works have high-lighted the increased time-efficiency that arrays of cantilevers working in parallel can bring, including piezoelectrically actuated AFM cantilevers [4], VLSI of 32x32 AFM cantilevers that can perform read/write/erase memory functions through thermally assisted patterning of a polymer film [5] as well as dip-pen nanolithography [6]. A proof-of-concept study implementing 2D arrays for parallel cell force spectroscopy was demonstrated by Favre et al. [7], using an interferometric readout. Loizeau et al. [8] refined the fabrication of such arrays, achieving high-density arrays with precise control of the spring constant and tip properties of each cantilever.

A disadvantage of passive cantilever arrays is that they cannot accommodate topographic differences between the points that are being probed in parallel, meaning that the height of each cell is not exactly the same. Neither can such devices correct eventual fabrication-related variations affecting the position of the tip. The result is thus that the ensemble of measurements is inhomogeneous in indentation depth and, consequently, force applied to each cell. The only way to fully resolve this is to implement individual actuation of each cantilever in the array.

In this work, we present the fabrication and characterization of arrays of individually actuated force sensing cantilevers for cell biology applications. In addition to evident requirements, such as compatibility between the actuator and the surrounding media, the device must also meet:

- A static displacement range in z of more than 10 µm. This range is necessary not only because of topography differences but also because the cell will stretch during retraction and we want to be able to separate completely before starting a new approach.
- With few degrees of margin, the structure must remain parallel. This is due to the interferometric readout method, described by Favre et al. [7].
- An efficient separation between force sensing and actuation, meaning that the behavior of the actuator is the same, even though the sample exerts forces onto the cantilever.
- The actuator should be inert to biological systems.

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- Actuators should neither cross-talk with each other, nor with the force sensors.

A careful study of the available MEMS actuation techniques led to the conclusion that thermal bimorph actuation has the best chance of fulfilling all of the above. The main challenge is to assure that the cells are not harmed by the actuator. On the positive side, thermal actuation has been used for cell imaging before by Fantner et al. [9], relying on the fact that the surrounding water works as a very large thermal reservoir that can absorb the energy dissipating from the MEMS. In this work, we investigate the potential to expand this approach to static displacement.

In order to enhance the mechanical displacement of a bimorph-actuated structure, a special configuration was proposed by Lim et al. [10], named flip-over-bimorph beams (FOBs). Actuated structures were made by Jia et al. [11]. These structures can displace out-of-plane without changing the endpoint angle. By designing a serpentine spring structure, the thermomechanical sensitivity can be enhanced while keeping a small footprint.

We modified this idea, designing a structure in which the electrode works both as a resistor that regulates the temperature and as a stress-inducing layer that causes a bending of the structure. Fig. 1 shows how four such FOBs working as actuators connect to a central platform. If a current is applied, the actuators displace the platform away from the substrate. The platform is connected to a force sensing cantilever that can be used for mechanical measurements. By narrowing the force sensing cantilever legs, the sensing and actuation can be mechanically decoupled. An optical reference structure (ORS), shown in the SEM image on fig. 2, was added to this design in order to facilitate the readout. A soft spring connects the platform to the ORS, giving a linear, attenuated displacement of the ORS with respect to the platform. The attenuation is determined by the ratio between the spring constants of the four actuator springs and the ORS spring. In cases where the cantilever moves through a distance of several wavelengths very suddenly, the ORS is designed to resolve the problem of phase ambiguity.

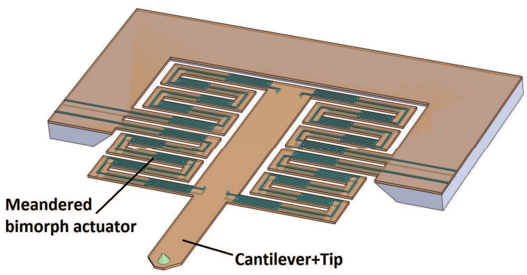

Figure 1. Schematic of the structure. Four meandered bimorph actuator springs displace the structure in z. Indicated is also the sensing cantilever and its tip.

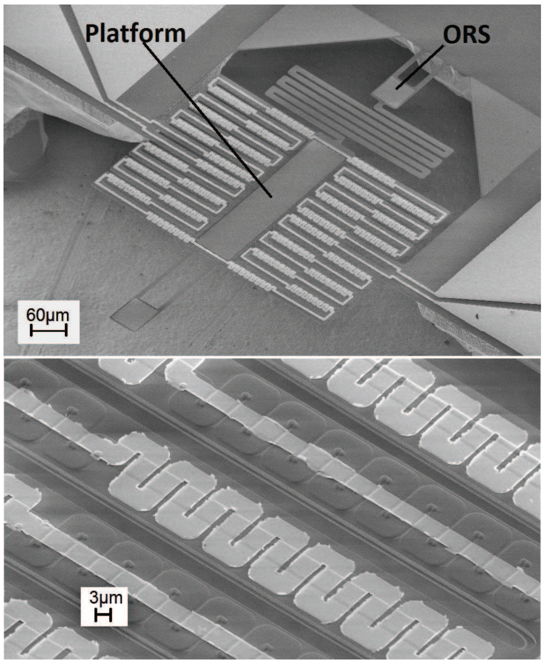

Figure 2. SEM images of the finalized device and a zoom-in of the actuator. The top-bottom alteration is revealed in the zoom-in. The optical reference structure (ORS) is indicated.

II. FABRICATION

Following the process flow shown in fig. 3, a) the process started with a double-side polished Si wafer with a SiO2 layer on one side. b) Using RIE, a back-side hard-mask of SiO_2 was patterned as preparation for the last step, i.e. the through wafer etching. In order to get a sufficient optical access, a pattern of small openings in the mask was defined that, through the RIE

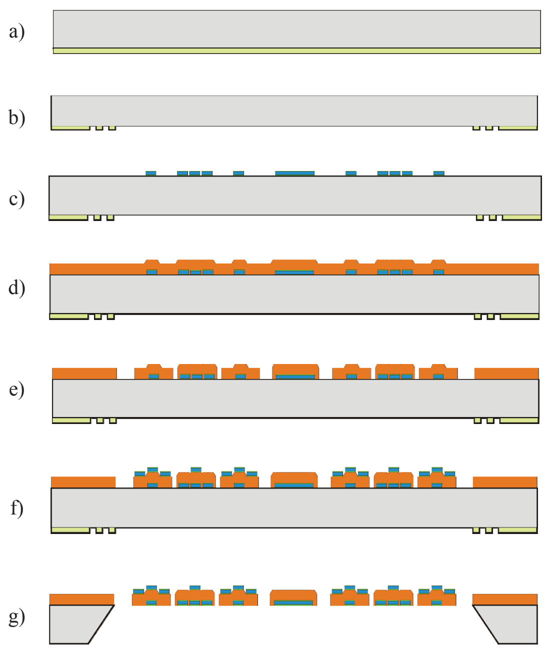

Figure 3. Process flow.

lag effect, could allow a controlled thinning of the Si in proximity to the openings during the last step. c) Subsequently, the Pt bottom electrodes (200 nm) were deposited on the front side by lift-off. d) A 1.5 µm layer of silicon nitride was deposited by PECVD and was subsequently patterned by RIE to form the different structural parts. e) Then, a 200 nm Pt top electrode layer was deposited. f) Finally, a combination of RIE and KOH was used to release the structure.

The chips were released by breaking off their fixations. Subsequently, the chip was glued to a PCB and wire-bonded. In order to passivate the electrodes, a conformal layer of parylene was deposited onto the devices.

III. RESULTS

A. *Device characterization*

SEM images of the finalized structures are shown in fig. 2. The lower image reveals the top-bottom electrode pattern alteration which is the basis for inducing a stress momentum to bend the structure in the desired direction.

The displacement range of the actuator, working in air, was measured using an optical profilometer. The results are shown in fig. 4, indicating a range of about 17 µm. The figure also shows the ORS displacement scaled by a factor 30, revealing that the mechanical coupling between the platform and the ORS is linear and attenuated as desired.

Preliminary actuation tests in water showed that the parylene could successfully passivate the electrodes.

B. *Fabrication-related results*

Fig. 5 shows the resulting slope of a test pattern aimed to thin down the silicon close to the openings. This is to allow better optical access to the device which is necessary for the readout. The image is taken after dry etching. Due to the RIE lag effect, the etch rate is higher where there is a bigger opening. The final release is done in KOH, rendering a released structure as shown in fig. 6.

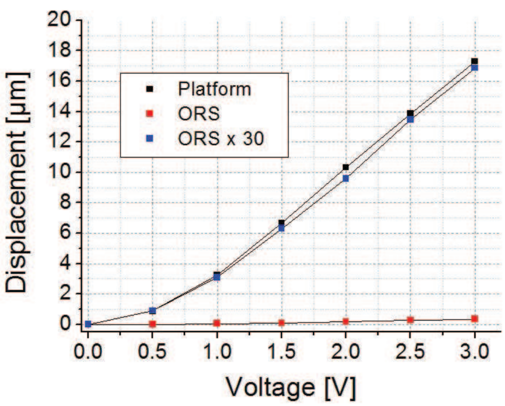

Figure 4. Vertical displacement in air as a function of applied voltage. The spring connecting the platform to the ORS attenuates the displacement by a factor 30, thus avoiding phase ambiguity in the interferometric readout.

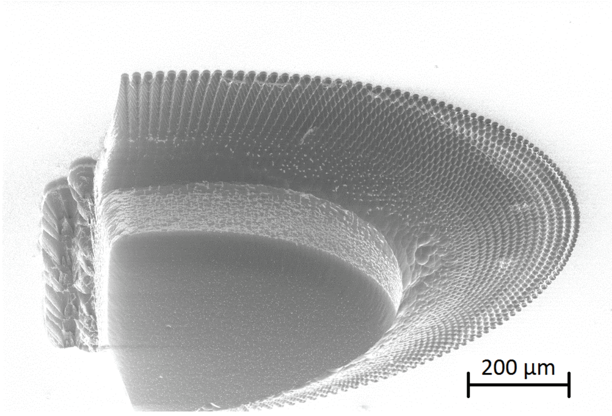

Figure 5. SEM image showing the resulted thinning of the silicon close to the main aperture. The last part is etched in KOH.

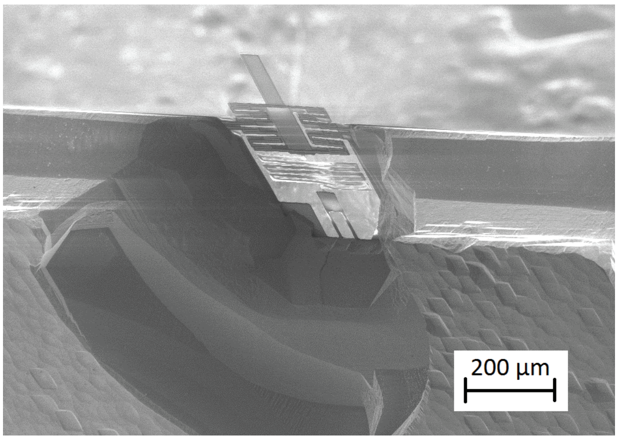

Figure 6. SEM image of a released device seen from the backside. As can been seen, the optical access angle is substantially enlarged.

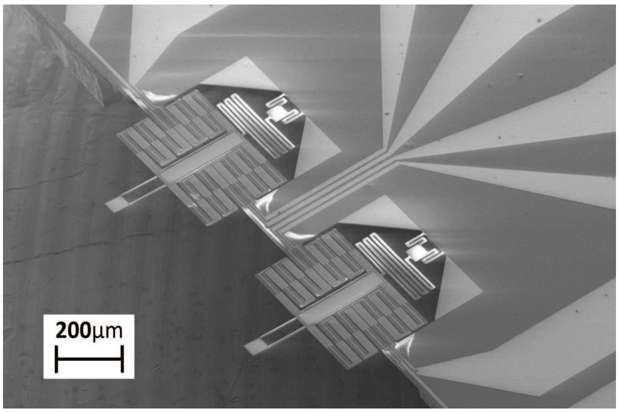

Figure 7. SEM image of a 1x2 array.

Fig. 7 shows a 1x2 array, underlining the feasibility of 1D scaling of these devices.

C. *Simulations*

FEM simulations were made to quantify the temperature elevation of the MEMS and its surroundings. A model was built featuring a single actuator spring, identical with the fabricated one, submerged in a volume of water and positioned 15 µm above a glass slide.

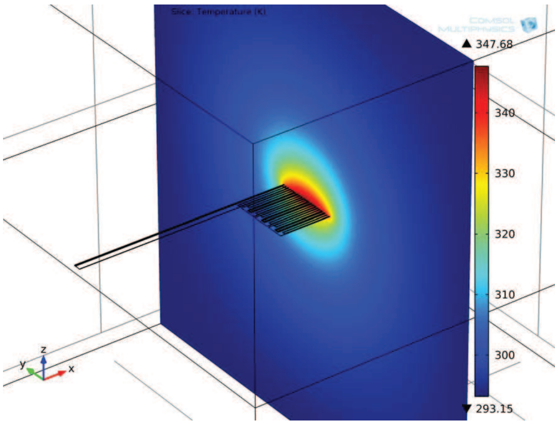

Figure 8. The yz cross-section through the actuator shows that a temperature elevation of 54.53 K was reached.

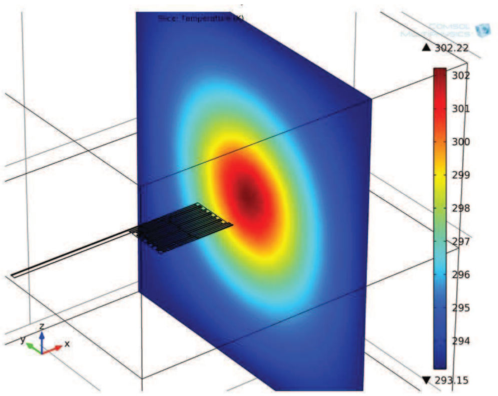

Figure 9. The xy cross-section 100 µm away from the actuator shows that the temperature elevation is much lower, 9.07 K.

A current close to the maximum withstandable was applied. The surrounding boundaries were set to 293.15 K. The model was solved using heat conduction and resistive heating physics. The result is shown in fig. 8 and 9, revealing that the electrode itself heats up by about 54 K, which through analysis can be shown to give a displacement in the correct range. 100 µm away, the temperature increase is less than 10 K. This result suggests that a "biocompatible thermal window" can be found, giving sufficient displacement without harming the cells. The result also underlines that a tip height of 20-30 µm will help substantially to thermally decouple the sample from the MEMS.

IV. CONCLUSIONS

We present the fabrication and characterization of a novel device using an integrated long-range thermal actuator to displace a force sensing cantilever. The system is conceived for bio-AFM applications. Such individually actuated devices could be parallelized in arrays in order to increase through-put.

A first generation has been successfully fabricated and characterized, reaching 17 µm of displacement in air. Throughout this displacement, the ORS follows the platform in a linear and attenuated way. Through a parylene deposition, the electrodes are passivated. A device was tested in water, confirming the functionality of this post-processing step. The next challenge is to achieve higher thermomechanical sensitivity, so that a large range is maintained in water.

A new usage of the RIE lag effect is also presented, showing how it can be used to have a controlled thinning to improve optical access.

Simulations suggest that it is possible to reach sufficiently high temperatures at the electrode in order to induce the desired displacement of about 10 µm while avoiding drastic temperature elevations at the cell level.

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REFERENCES

[1] S. Suresh, "Biomechanics and biophysics of cancer cells", Acta Biomaterialia, vol. 3, pp. 413–438, April 2007.

[2] M. Lekka, P. Laidler, D. Gil, J. Lekki, and Z. Stachura, A. Z. Hrynkiewicz, "Elasticity of normal and cancerous human bladder cells studied by scanning force microscopy", European Biophysics journal, vol. 28, pp. 312–316, January 1999.

[3] S. E. Cross, Y.-S. Jin, J., Rao, and J. K. Gimzewski, "Nanomechanical analysis of cells from cancer patients", Nature Nanotechnology, vol. 2, pp. 780-783, December 2007.

[4] S. C. Minne, G. Yaralioglu, S. R. Manalis, J. D. Adams, J. Zesch, A. Atalar, and C. F. Quate, "Automated Parallel High-Speed Atomic Force Microscopy" APL, vol. 72, pp. 2340–2342, May 1998.

[5] P. Vettiger, G. Cross, M. Despont, U. Drechsler, U. Durig, B. Gotsmann, W. Haberle, M. A. Lantz, H. E. Rothuizen, R. Stutz, and G. K. Binnig, "The 'millipede'- Nanotechnology Entering Data Storage", IEEE Transactions on Nanotechnology, vol. 1, pp. 39-55, March 2002.

[6] J. Haaheim, V. Val, J. Bussan, S. Rozhok, J. W. Jang, J. Fragala, M. Nelson, "Self-Leveling Two-Dimensional Probe Arrays for Dip Pen Nanolithography ®", Scanning, vol. 32, pp. 49–59, Jan-Feb 2010.

[7] M. Favre, J. Polesel-Maris, T. Overstolz, P. Niedermann, S. Dasen, G. Gruener, R. Ischer, P. Vettiger, M. Liley, H. Heinzelmann, and A. Meister, " Parallel AFM imaging and force spectroscopy using two-dimensional probe arrays for applications in cell biology", J. Molecular Recognition, vol. 24, pp. 446-452, May-Jun 2011.

[8] F. Loizeau, T. Akiyama, S. Gautsch, A. Meister, P. Vettiger, N. F. de Rooij, "Two-dimensional cantilever array with varying spring constants and tip radii for life-science applications", Micro Nano Lett., vol. 7, pp. 301-305, Apr 2012.

[9] G. E. Fantner, D. J. Burns, A. M. Belcher, I. W. Rangelow, K. Youcef-Toumi, "DMCMN: In Depth Characterization and Control of AFM Cantilevers With Integrated Sensing and Actuation", J. Dyn. Syst. Meas. Control-Trans. ASME, vol. 131, Nov. 2009.

[10] S. H. Lim, J. Choi, R. Horowitz, A. Majumdar, "Design and fabrication of a novel bimorph microoptomechanical sensor", JMEMS, vol. 14, pp. 683-690, Aug. 2005.

[11] K. M. Jia, S. Pal, H. K. Xie, " An Electrothermal Tip-Tilt-Piston Micromirror Based on Folded Dual S-Shaped Bimorphs ", JMEMS, vol. 18, pp. 1004-1015, Oct. 2009.