NOVA

University of Newcastle Research Online

nova.newcastle.edu.au

Maroufi, Mohammad; Ruppert, Michael G.; Fowler, Anthony G.; Moheimani, S. O. Reza
“Design and control of a single-chip SOI-MEMS atomic force microscope”, Published in
Proceedings of the 2017 American Control Conference (ACC). (2017)

Available from: <http://dx.doi.org/10.23919/ACC.2017.7963386>

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Accessed from: <http://hdl.handle.net/1959.13/1348369>

Design and Control of a Single-Chip SOI-MEMS Atomic Force Microscope

Mohammad Maroufi¹, Michael G. Ruppert², Anthony G. Fowler¹, and S. O. Reza Moheimani¹

Abstract—This paper presents a novel microelectromechanical systems (MEMS) implementation of an on-chip atomic force microscope (AFM), fabricated using a silicon-on-insulator process. The device features an XY scanner with electrostatic actuators and electrothermal sensors, as well as an integrated silicon microcantilever. A single AlN piezoelectric electrode is used for simultaneous actuation and deflection sensing of the cantilever via a charge sensing technique. With the device being operated in closed loop, the probe scanner is successfully used to obtain $8\mu\text{m} \times 8\mu\text{m}$ tapping-mode AFM images of a calibration grating.

I. INTRODUCTION

The atomic force microscope (AFM) is one of the primary instruments used by researchers to perform nanoscale object and material analysis. The AFM fundamentally consists of a microcantilever with a sharp probe tip that is scanned by a nanopositioner over the surface of a sample. By measuring the intermolecular forces between the microcantilever's probe tip and the surface of the sample, the instrument is able to obtain topography information and material properties with nanometer or sub-nanometer resolution.

To date, the AFM has conventionally been implemented as a macroscale system. The in-plane positioning of the AFM's microcantilever is typically performed using piezoelectric tube scanners or flexure-guided nanopositioners [1], while the microcantilever's deflection is usually measured using the optical beam deflection (OBD) method [2]. High-end commercial AFMs often provide the ability to perform high-speed scanning with sub-nanometer resolution, however their relatively high cost of purchase and the size of the required hardware installation tends to restrict their use to laboratory-based applications.

More recently, microelectromechanical systems (MEMS) technology has allowed the development of microscale nanopositioners that can provide mechanical positioning abilities that are comparable to those of conventional macroscale nanopositioners while occupying a significantly smaller footprint [3]. The use of MEMS technology also provides a number of other advantages, including batch manufacturability, much lower fabrication costs, and potentially higher operating bandwidths [4]. In previous work we have successfully

demonstrated the use of silicon-on-insulator (SOI)-based MEMS nanopositioners as the scanning stage of an AFM (e.g. [5], [6]). The next logical step is the development of a fully microfabricated AFM, i.e. a nanopositioner equipped with an AFM probe, which has the potential to provide significant improvements in cost and portability and may greatly expand the device's range of suitable applications. While a CMOS-MEMS approach to single-chip AFM was demonstrated in [7], the device's use of electrothermal actuation potentially places a number of restrictions on the device's performance, particularly in terms of its operating bandwidth and power consumption.

A single-chip MEMS AFM requires a microcantilever with integrated actuation and sensing abilities, as the commonly used piezoelectric stack actuator at the base of the cantilever and the OBD sensor are not directly transferable to a microfabricated implementation. Cantilever actuation methods that are compatible with MEMS devices include, but are not limited to, resistive thermal actuation [8] or via a piezoelectric layer [9], and potential sensing techniques include capacitive [10], piezoresistive [11], and piezoelectric [12] sensing. Out of these methods, piezoelectric transduction provides the greatest potential to act as both an actuator and a sensor using a single electrode [13].

This paper introduces a MEMS probe scanner that represents a novel SOI-MEMS implementation of an on-chip AFM. Building on previous work [14], the device uses electrostatic actuators to position a central stage along the X and Y directions. The implementation of electrothermal displacement sensors allows for closed-loop position control of the stage. A silicon microcantilever designed for tapping-mode AFM is integrated with the stage, with an aluminum nitride (AlN) piezoelectric self-sensing actuator providing out-of-plane deflection of the cantilever. Through the use of a high-side charge sensing implementation motivated by previous work [15], the piezoelectric transducer is able to simultaneously measure the cantilever's deflection. By adding a tip to the end of the microcantilever through a post-fabrication step, the probe scanner is successfully used to obtain tapping-mode AFM images of a calibration grating.

II. PROBE SCANNER DESIGN AND FABRICATION

The mechanical structure of the MEMS probe scanner is shown in Fig. 1, which is obtained using an optical microscope and a scanning electron microscope (SEM). A stage with dimensions of $2315\mu\text{m} \times 650\mu\text{m}$ is incorporated at the center of the device, while a two-section microcantilever is fabricated at its upper edge. The probe scanner

¹Mohammad Maroufi, Anthony G. Fowler and S. O. Reza Moheimani are with the Department of Mechanical Engineering, The University of Texas at Dallas, Richardson, TX 75080 USA. Mohammad.Maroufi@utdallas.edu, Anthony.Fowler@utdallas.edu, Reza.Moheimani@utdallas.edu

²Michael G. Ruppert is with the School of Electrical Engineering and Computer Science, The University of Newcastle, Callaghan, NSW, 2308, Australia. Michael.Ruppert@uon.edu.au

Fig. 1. SEM and optical images of the probe scanner. In the close-up views, the main parts of the device are presented.

is implemented using the standard SOI-based PiezoMUMPs fabrication process provided by MEMSCAP [16] using an SOI wafer with a $10\mu\text{m}$ -thick device layer.

The in-plane displacement of the stage along the X and Y axes is achieved by using a parallel kinematic mechanism. Along the X axis, electrostatic actuators are implemented on both sides of the stage, enabling it to have a bidirectional displacement range. In this direction, two sets of electrostatic actuators are also used to obtain a higher actuation force, while alleviating potential in-plane rotation of the stage. The actuation force of each set of electrostatic actuators on either side is transferred to the stage via shuttle beams and tethering beams. Another actuation mechanism including a shuttle beam with dimensions of $1851\mu\text{m} \times 200\mu\text{m}$, tethering beams, and electrostatic actuators is incorporated on the bottom side of the stage, rendering unidirectional displacement along the Y direction.

Clamped-clamped beams are used as the mechanical flex-

ures for the X axis and also for the realization of the tethering beams. However, as the Y axis has a relatively large unidirectional displacement range, folded beam flexures are used [6]. It is expected that these flexures show higher linearity in comparison with the clamped-clamped beams.

A double-sectioned microcantilever is implemented on the top side of the stage to be used as an AFM probe. The dimensions of the cantilever at its wider section are $380\mu\text{m} \times 240\mu\text{m}$ and at the narrower part are $260\mu\text{m} \times 40\mu\text{m}$. A $0.5\mu\text{m}$ -thick AlN layer is deposited on the wider section of the cantilever. The piezoelectric properties of the AlN are exploited for the actuation of the cantilever and sensing its out-of-plane deflection. A sharp tip is added to the fabricated probe scanner using a focused ion beam (FIB) system (FEI Nova NanoLab 200). By the use of this fabrication method, achieving high-resolution, high-aspect-ratio AFM tips is possible [17]. Using platinum, a stepped support structure with a total height of approximately $9\mu\text{m}$ is initially fabricated, followed by the deposition of a tip with $1.5\mu\text{m}$ length and a diameter of approximately 40nm . In the close-up view in Fig. 1 the deposited probe tip is shown.

In order to provide an electrical connection to the cantilever's piezoelectric transducer, long beams with dimensions of $2.3\text{mm} \times 25\mu\text{m}$ are used on either side of the stage. As the silicon layer is doped and the entire mechanical structure is connected to the electrical ground, a thin layer of silicon oxide is used as the insulation layer on these beams. Their width is minimized while considering the restrictions imposed by the fabrication process due to the deposition of both insulating and aluminum layers. Serpentine structures are used at the anchor point of the routing beams to reduce their in-plane stiffness along the Y direction.

The in-plane displacement of the stage along each axis is measured using electrothermal sensors as shown in the close-up view in Fig. 1. Each electrothermal sensor comprises two slender silicon beams with dimensions of $44\mu\text{m} \times 2\mu\text{m}$. A heat sink is incorporated as a part of each shuttle beam in proximity to the heaters with an air gap of $2\mu\text{m}$. The heat transfer rate between the heaters and the heat sink is a function of their overlap area. Hence, the heat transfer rate changes as the heat sink moves parallel to the heaters. This leads to opposing variations in the heaters' temperature and consequently opposite variations in their electrical resistance [18]. A transimpedance circuit (shown in more detail in [19]) is used to translate the electrical resistance changes of the heaters to a varying output voltage.

III. XY-NANOPositioner CHARACTERIZATION

The static and dynamic behavior of the X and Y axes of the stage are characterized, while the electrothermal sensors are active with a 5V bias voltage. As the device features electrostatic actuators on both sides along the X axis, a linear actuation mechanism can be implemented for this direction [19]. In this method, the actuation signal is applied to the electrostatic actuators with opposite polarities while superimposed on a 35V DC bias voltage. As discussed in

Fig. 2. The stage's displacement and the electrothermal sensors' outputs versus actuation for the (a) X and (b) Y axes.

[19], the quadratic behavior of the electrostatic actuators can be highly linearized using this method.

A. Static Response

The in-plane mechanism of the device is characterized in both the time and frequency domains. A low-frequency triangular signal is applied to both axes, while their displacements are measured using a Polytec MSA-100-3D Micro System Analyzer (MSA). In Fig. 2, the in-plane displacement for both axes is shown as a function of the actuation signal. Both axes demonstrate a displacement range of more than $10\mu\text{m}$. The displacement along the X axis is not precisely linear, which is most likely due to the nonlinearities in the stiffness of the flexures and possible asymmetries in the device's structure along the X axis. The well-understood quadratic behavior of the electrostatic actuators can be seen in Fig. 2. The outputs of the electrothermal sensors, which are recorded simultaneously, are also presented in the same figure. Using the sensors' output and the stage displacement, the calibration factors for the sensors are obtained and reported in Table I.

TABLE I
THE CALIBRATION FACTORS AND THE RESOLUTION OF THE
ELECTROTHERMAL SENSORS IN BOTH AXES.

	X axis	Y axis
Calibration factor ($\text{V}/\mu\text{m}$)	0.468	0.285
1σ -Resolution (nm)	5.2	7.6

Fig. 3. The frequency response of the stage displacement and electrothermal sensors along the X and Y axes.

B. Dynamic Response and Identification

Fig. 3 shows the frequency response of the device along the X and Y axes, which is obtained using the MSA. The first resonance modes along the X and Y axes are located at 2.85 kHz and 2.77 kHz, respectively. The frequency responses of the X and Y sensors are simultaneously obtained and are also presented in Fig. 3. As is visible, the sensors fully capture the dynamics of the system within a bandwidth of about 5 kHz.

Using the least squares method in the frequency domain, the transfer functions from the actuation signal to the sensor output are identified for both axes in (1) and (2) within a bandwidth of 5 kHz.

$$G_x(s) = \frac{-9.02 \times 10^{-5}s + 2.42}{3.25 \times 10^{-9}s^2 + 8.81 \times 10^{-7}s + 1} \quad (1)$$

$$G_y(s) = \frac{-2.87 \times 10^{-5}s + 0.89}{3.38 \times 10^{-9}s^2 + 4.68 \times 10^{-7}s + 1} \quad (2)$$

The resonance modes of the probe scanner and the microcantilever are further studied by applying a wide-band periodic chirp to the piezoelectric transducer on the microcantilever. The MSA is used to measure the out-of-plane displacement amplitude of the device at many points across the moving structure in order to obtain the mode-shape for each resonance frequency. This test allows for the determination of a suitable operating frequency for tapping-mode AFM, which is characterized by a large displacement at the tip while inducing negligible motion in other parts of the stage. As shown in Fig. 4, the resonant mode located at approximately 200 kHz satisfactorily meets these criteria.

C. Noise and Resolution

The output noise of the electrothermal sensors is characterized in the time domain. The noise is recorded with a sampling frequency of 781 kHz over a time period of 12.8 s. As an anti-aliasing filter, two second-order low-pass filters (Stanford Research SR560 Low-Noise Voltage Preamplifier) with a cutoff frequency of 100 kHz are incorporated in series. The resolution of the sensors can be calculated by obtaining

Fig. 4. The mode shape of the probe scanner at approximately 200kHz, which is suitable for use in tapping-mode AFM imaging.

the root mean square (rms) value of the sensors' noise and converting it to the corresponding displacement using the sensors' calibration factors obtained in Section III-A. The resolution of the sensors are reported in Table I.

IV. CANTILEVER DEFLECTION ESTIMATION

By sputtering a piezoelectric layer on top of the microcantilever section of the probe scanner, a transducer with inherent self-sensing capabilities is obtained. The transfer function from actuation voltage $V(s)$ to tip displacement $D(s)$ is well described by a sum of n second order modes [20]

$$G_{dv}(s) = \frac{D(s)}{V(s)} = \sum_{i=1}^n \frac{\alpha_i \omega_i^2}{s^2 + \frac{\omega_i}{Q_i} s + \omega_i^2} + D, \quad (3)$$

where each second order term is characterized in terms of the resonance frequency ω_i , quality factor Q_i , and gain α_i . The first four dominant modes of the microcantilever are highlighted in the measured frequency response shown in Fig. 5a.

Conversely, when the piezoelectric transducer is subjected to mechanical strain, a charge is produced on the surface of the material which can be electrically modeled as a strain dependent voltage source $V_p(s)$ in series with the piezoelectric capacitance C_p [13]. The transfer function from actuation voltage to charge $Q(s)$ can be found to be [21]

$$G_{qv}(s) = \frac{Q(s)}{V(s)} = C_p + C_p \sum_{i=1}^n \gamma_i G_{dv,i}(s). \quad (4)$$

From (4) it can be concluded that an estimate of the cantilever deflection can be obtained by measuring the charge while the piezoelectric layer is actively driven by a voltage source if the feedthrough part associated with C_p can be canceled.

A self-sensing charge amplifier configuration is employed in order to estimate the cantilever deflection while simultaneously using the same piezoelectric layer for actuation. As the piezoelectric layer shares a common terminal with the electrical network of the rest of the MEMS device, the charge signal has to be measured on the same electrode where the actuation signal is applied. The sensor circuit that realizes

Fig. 5. Magnitude frequency response (—) and identified model (---) of the probe scanner measured with the OBD sensor highlighting the first four dominant flexural modes. (b) Magnitude frequency response (—) and identified feedthrough model (---) of the probe scanner measured with the charge sensor. (c) Magnitude frequency response of the M4 mode measured with the OBD sensor (—) and charge sensor before (---) and after feedthrough cancellation (·····).

this task is similar to the design in [15] with a switched sense impedance and piezoelectric device. Within the bandwidth of interest, the transfer function of the sensor is a first order lead-lag element but additional parasitic components in the electrical path add higher order dynamics. The measured charge transfer function is shown in Fig. 5b along with an identified second order model of the feedthrough part. It can be clearly seen, how the feedthrough heavily swallows the dynamics around the major resonance frequencies M1-M4.

In order to recover the motional signal from the sensor output, a feedforward compensator is implemented on a Field Programmable Analog Array (FPAA) (Anadigm, AN221E04). The implemented second order biquadratic filter is used to cancel the feedthrough around the mode of interest (M4). As can be seen in Fig. 5c, the mechanical resonance is recovered from the feedthrough resulting in an increase in dynamic range from 0.03dB to around 19dB. While a well matching response between charge and optical sensor is obtained in the vicinity of the resonance frequency, the higher order nature of the feedthrough part results in deviations further away from the mechanical resonance.

V. CONTROL AND TRACKING

In order to use the probe scanner for AFM imaging, the raster scanning method is used. The scanning trajectory is obtained by applying a 1Hz triangular signal to the X axis while the Y axis follows a slow ramp.

Fig. 6. The schematic of the feedback controller implemented for the X and Y axes.

Fig. 7. Tracking performance of the stage's (a) X axis following a 1 Hz triangular signal and (b) Y axis following a ramp signal.

Various parameters such as high-frequency contents of the reference signal, external disturbances, and nonlinearities in the X and Y axes can deteriorate the tracking performance of the probe scanner in open loop. Thus, in order to improve the tracking performance, an integral action feedback controller is implemented along both axes as schematically depicted in Fig. 6. As shown in Fig. 2, the relationship between the actuation signal and the sensor output is nonlinear for both axes, hence, look-up tables are used for both axes to linearize the system. The gain (K_i) is chosen to be 120 for both axes and the controller is implemented at a sampling rate of 40 kHz on a digital signal processing system (dSPACE MicroLabBox).

The tracking performance of the device along the X and Y axes is shown in Fig. 7a and b, respectively. The rms value of the tracking error in the X axis is 76.4 nm and for the Y axis is 21.5 nm. A significant component of the error along the X axis, however, is due to a time shift between the sensor output and reference, which does not affect AFM imaging quality. By compensating for the time shift, the tracking error is reduced to about 7.8 nm.

Fig. 8. The experimental set-up implemented to use the probe scanner for AFM imaging. (a) A commercial AFM with a custom-made external PCB for signal conditioning. (b) The probe scanner fixed to a PCB. (c) Close-up view of the probe scanner used within the AFM. The AFM's laser is shone on the probe scanner to highlight its position.

VI. TAPPING-MODE AFM IMAGING

A. Experimental Setup

For AFM imaging, the MEMS probe scanner is fixed using an adhesive and wire-bonded to a printed circuit board (PCB), which provides the piezoelectric sensing circuitry and signal routing for the XY actuators and sensors. Subsequently, the PCB with the MEMS device is mounted on a custom-made 3D-printed probe holder designed to be used in a commercial AFM (AFMWorkshop, TT-AFM). Photos of the experimental setup are shown in Fig. 8. Throughout the AFM experiments, the internal z-axis stepper motor of the commercial AFM is exploited as the approach mechanism. An external lock-in amplifier (Zurich Instruments, HF2LI) with integrated function generator is used to drive the cantilever and to acquire the imaging signals via a MATLAB script. We image a silicon NT-MDT TGZ3 calibration grating with periodic features of heights $h \approx 500$ nm at a cantilever free-air amplitude of $A_0 \approx 130$ nm and at an imaging setpoint of 60%.

B. AFM Imaging

AFM images have been obtained for an image size of $8 \mu\text{m} \times 8 \mu\text{m}$ with the lateral XY axes tracking raster scan trajectories at a frequency of 1 Hz in open loop and closed loop, respectively. In order to close the Z-axis feedback loop, the OBD sensor of the commercial AFM and the integrated charge sensor are used interchangeably. As can be clearly seen in the 2D topography images shown in Fig. 9, with the XY axes operating in open loop, significant distortion is visible in the AFM image. By employing integral controllers for both the X and Y axes, the distortion is largely eliminated. Note that the AFM images are generated without the sensor signals which implies that any distortion created by the scanner movement directly translates into image artifacts. Also visible is the comparable scan quality when employing the self-sensing charge measurement instead of the optical measurement. However, some triangular artifacts can be

Fig. 9. Topography in 3D and 2D and error image measured with (a), (c), (e) OBD sensor and XY axes in open-loop (OL) and (b), (d), (f) with charge sensor and XY axes in closed-loop (CL).

observed in the charge topography images and amplitude images at the downward edge of the features, which is believed to be due to a deterioration of the cantilever's tip throughout the tests. In future work, research will focus on manufacturing an integrated tip. This is believed to mitigate the degradation of the tip and consequently increase the probe scanner's durability.

VII. CONCLUSION

A MEMS on-chip atomic force microscope is proposed for use in tapping-mode AFM imaging. The device contains an in-plane stage and features a microcantilever with a piezoelectric layer as the AFM probe. Electrostatic actuators are implemented for both axes, providing a maximum travel range of $10\mu\text{m}$ along either direction. To measure the in-plane displacement of the device, electrothermal sensors are employed. The device is manufactured using a silicon-on-insulator MEMS fabrication process. After characterization, a feedback control system is implemented for both axes to improve the tracking performance of the system in both axes. The out-of-plane actuation of the cantilever is performed using a single piezoelectric actuator. The cantilever is actuated at one of its resonance frequencies and a high-side charge sensor is used to estimate the deflection signal from the piezoelectric signal. The imaging performance of the MEMS AFM is successfully examined using a calibration grating.

REFERENCES

- [1] Y. K. Yong, S. O. R. Moheimani, B. J. Kenton, and K. K. Leang, "Invited review article: High-speed flexure-guided nanopositioning: Mechanical design and control issues," *Review of Scientific Instruments*, vol. 83, no. 12, p. 121101, dec 2012.
- [2] G. Meyer and N. M. Amer, "Novel optical approach to atomic force microscopy," *Appl. Phys. Lett.*, vol. 53, no. 12, pp. 1045–1047, 1988.
- [3] X. Liu, K. Kim, and Y. Sun, "A MEMS stage for 3-axis nanopositioning," *Journal of Micromechanics and Microengineering*, vol. 17, no. 9, pp. 1796–1802, sep 2007.
- [4] S. Bergna, J. J. Gorman, and N. G. Dagalakis, "Design and modeling of thermally actuated MEMS nanopositioners," in *2005 ASME International Mechanical Engineering Congress and Exposition*, Orlando, USA, nov 2005, pp. 1–8.
- [5] A. G. Fowler, A. N. Laskovski, A. C. Hammond, and S. O. R. Moheimani, "A 2-DOF electrostatically actuated MEMS nanopositioner for on-chip AFM," *Journal of Microelectromechanical Systems*, vol. 21, no. 4, pp. 771–773, 2012.
- [6] M. Maroufi and S. O. R. Moheimani, "A 2DOF SOI-MEMS nanopositioner with tilted flexure bulk piezoresistive displacement sensors," *IEEE Sensors Journal*, vol. 16, no. 7, pp. 1908–1917, apr 2016.
- [7] N. Sarkar, R. R. Mansour, O. Patange, and K. Trainor, "CMOS-MEMS atomic force microscope," in *Transducers '11*, Beijing, China, jun 2011, pp. 2610–2613.
- [8] G. E. Fantner, W. Schumann, R. J. Barbero, A. Deuschinger, V. Todorov, D. S. Gray, A. M. Belcher, I. W. Rangelow, and K. Youcef-Toumi, "Use of self-actuating and self-sensing cantilevers for imaging biological samples in fluid," *Nanotechnology*, vol. 20, no. 43, p. 434003, 2009.
- [9] P.-F. Indermühle, G. Schürmann, G.-A. Racine, and N. de Rooij, "Fabrication and characterization of cantilevers with integrated sharp tips and piezoelectric elements for actuation and detection for parallel AFM applications," *Sensors and Actuators A: Physical*, vol. 60, no. 1-3, pp. 186 – 190, 1997.
- [10] T. Goddenhenrich, H. Lemke, U. Hartmann, and C. Heiden, "Force microscope with capacitive displacement detection," *J. Vac. Sci. Technol. A*, vol. 8, no. 1, pp. 383–387, 1990.
- [11] M. Tortonese, R. C. Barrett, and C. F. Quate, "Atomic resolution with an atomic force microscope using piezoresistive detection," *Appl. Phys. Lett.*, vol. 62, no. 8, pp. 834–836, 1993.
- [12] T. Itoh and T. Suga, "Development of a force sensor for atomic force microscopy using piezoelectric thin films," *Nanotechnology*, vol. 4, no. 4, p. 218, 1993.
- [13] M. G. Ruppert and S. O. R. Moheimani, "A novel self-sensing technique for tapping-mode atomic force microscopy," *Rev. Sci. Instrum.*, vol. 84, no. 12, p. 125006, 2013.
- [14] A. G. Fowler, M. Maroufi, and S. O. R. Moheimani, "A silicon-on-insulator microelectromechanical systems probe scanner for on-chip atomic force microscopy," *Review of Scientific Instruments*, vol. 86, no. 4, p. 046107, 2015.
- [15] M. G. Ruppert and S. O. R. Moheimani, "Novel reciprocal self-sensing techniques for tapping-mode atomic force microscopy," in *Proc. 19th IFAC World Congress*. Cape Town, South Africa: IFAC, 24–29 August 2014, pp. 7474–7479.
- [16] A. Cowen, G. Hames, K. Glukh, and B. Hardy, *PiezoMUMPs Design Handbook*, revision 1.3 ed., 2014.
- [17] I. Utke, P. Hoffmann, and J. Melngailis, "Gas-assisted focused electron beam and ion beam processing and fabrication," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, vol. 26, no. 4, p. 1197, 2008.
- [18] B. Krijnen, R. P. Hogervorst, J. W. van Dijk, J. B. C. Engelen, L. A. Woldering, D. M. Brouwer, L. Abelmann, and H. M. J. R. Soemers, "A single-mask thermal displacement sensor in MEMS," *Journal of Micromechanics and Microengineering*, vol. 21, no. 7, 2011.
- [19] M. Maroufi, A. Bazaei, and S. O. Reza Moheimani, "A High-Bandwidth MEMS Nanopositioner for On-Chip AFM: Design, Characterization, and Control," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 2, pp. 504–512, March 2015.
- [20] M. G. Ruppert and S. O. R. Moheimani, "Multimode Q control in tapping-mode AFM: Enabling imaging on higher flexural eigenmodes," *IEEE Transactions on Control Systems Technology*, vol. 24, no. 4, pp. 1149–1159, July 2016.
- [21] —, "High-bandwidth multimode self-sensing in bimodal atomic force microscopy," *Beilstein Journal of Nanotechnology*, vol. 7, pp. 284–295, 2016.