

Parallel Active Microcantilevers for High-Throughput Atomic Force Microscopy

Hazhir Mahmoodi Nasrabadi, K. S. Vikrant, S. O. Reza Moheimani, Fellow, IEEE

Abstract—The limited throughput of single-cantilever Atomic Force Microscopy (AFM) motivates parallel imaging using multiple cantilevers. However, parallel imaging with passive cantilever arrays requires multiple macro-scale actuators and sensors, leading to a large system footprint, increased vibration sensitivity, and reduced imaging bandwidth per cantilever. We present an alternative approach based on active microcantilevers with integrated microscale actuators and sensors to address these limitations. We microfabricated a three-cantilever array, equipping each cantilever with a piezoelectric actuator-sensor pair for tapping-mode operation (free amplitude ≈ 100 nm near 50 kHz) and an electrothermal Z-actuator (range 10 μm , closed-loop bandwidth 100 Hz) to regulate tip-sample separation. Operating all three cantilevers in parallel, each scanned a $3\ \mu\text{m} \times 3\ \mu\text{m}$ region on two different calibration gratings at a 1 Hz line rate. The system achieved a lateral sampling of 12 nm per pixel and resolved 100 nm step features with $\leq 10\%$ height error. These results demonstrate a threefold increase in effective imaging throughput relative to single-probe AFM while maintaining high-resolution performance, highlighting the advantages of independently actuated and sensed microcantilevers for parallel AFM.

Index Terms—Active AFM cantilever, Parallel Imaging, Piezoelectric Sensing/Actuation, Electrothermal Actuation, Z Positioner, Feedback Loop.

I. Introduction

The wide-scale use of micro- and nano-scale samples in commercial products has driven the demand to increase the throughput of high-resolution imaging instruments such as Atomic Force Microscope (AFM) and Scanning Tunneling Microscope (STM) [1], [2], [3]. Among them, AFM is uniquely suited for industrial applications because it can image both conductive and insulating samples in various environments. AFM achieves its exceptional resolution by using a microfabricated cantilever with a sharp tip that raster-scans the sample surface. A feedback control loop maintains a constant tip-sample interaction force, allowing the instrument to reconstruct surface topography point by point. This direct mechanical probing provides atomic-scale spatial resolution, but the inherently serial nature of the scanning process significantly limits throughput.

Researchers have pursued two general strategies to overcome AFM's throughput limitations. The first strategy is to increase the imaging speed of a single AFM probe by enhancing the feedback loop bandwidth and using high-speed scanning techniques [4]. However, even the fastest single-probe AFMs still fall short for many industrial needs, especially for large-area inspection tasks. The alternative strategy is to operate multiple AFM probes in parallel, effectively dividing the imaging task among many tips to increase overall throughput.

Early demonstrations of parallel AFM employed arrays of conventional cantilevers, each instrumented with its own actuator and sensor. One reported system used an array of 22 passive microcantilevers operating simultaneously to boost throughput [5]. However, the system was bulky. Each AFM head, consisting of a cantilever, piezo actuator, and optical deflection sensor, occupied on the order of $60\ \text{cm}^3$, and adjacent units were spaced 20 mm apart. The large mass of each head lowered its mechanical resonance frequency, making the system more sensitive to vibrations. Additionally, the wide spacing between cantilevers left substantial gaps, requiring the sample repositioning for complete image acquisition. Furthermore, the macro-scale Z piezo actuators used to maintain tip-sample contact during imaging had a limited bandwidth of just 23–60 Hz. As a result, the system's low resonance frequency and limited Z-actuator bandwidth restricted the scanning rate to approximately 1.6 lines/s, with a pixel size of around 40 nm.

To overcome the limitations of such bulky parallel systems, microelectromechanical systems (MEMS)-based integrated cantilever arrays have been proposed. By micro-fabricating cantilevers with built-in actuators and sensors, the size and mass of the AFM head can be reduced dramatically [6], [7], [8]. These miniaturized, active-cantilever AFM systems operate at much higher resonance frequencies and are far less susceptible to vibrations than their macro-scale counterparts. However, one critical challenge remains: during topography scanning, the AFM's Z-axis actuator must accommodate height variations of several microns. On-chip piezoelectric actuators typically cannot provide such a large stroke in the Z direction [9], [10].

A major advancement in AFM technology was the development of fully integrated cantilever arrays that incorporate large-range electrothermal Z actuators on the chip itself, eliminating the need for an external Z stage [11], [12]. Ahmad et al. [11] demonstrated a four-cantilever array in which each probe featured a thermomechanical actuator for out-of-plane motion and a piezoresistive deflection sensor for self-sensing. This system achieved a significantly higher imaging speed of approximately 10 lines/s with a pixel size of ≈ 273 nm per cantilever in tapping mode, owing to its built-in thermomechanical Z actuator's high bandwidth of around 500 Hz [11]. The four cantilevers were arranged with a tight 125 μm pitch (tip-to-tip spacing), greatly reducing inter-probe separation. However, this design has two key limitations. First, the integrated Z actuator offers a motion range of only 2 μm , necessitating an external Z stage to compensate for drift and surface irregularities. Second,

it suffers from thermal coupling: the integrated heaters used for Z actuation induce temperature changes in the piezoresistive sensors, causing sensor drift and requiring careful calibration or drift compensation. In our previous work, we addressed both limitations by introducing two different Z actuators and employing a differential sensor configuration on the cantilever itself. First, we increased the Z-motion range fivefold with a closed-loop actuation bandwidth of 103 Hz, by designing an electrothermal actuator on a relatively longer cantilever [12]. Second, we minimized sensor drift by using aluminum nitride (AlN) piezoelectric transducers for both actuation and sensing. AlN piezoelectric sensors have inherently low thermal sensitivity compared to piezoresistors, and by using two sensors in a differential configuration, we further canceled out common-mode thermal drift. The AlN piezoelectric actuators provide an oscillation amplitude of ≈ 100 nm at 50 kHz, which is required for tapping-mode imaging. That prior work, however, involved only a single cantilever.

In this paper, we extend the fully integrated AFM approach to a multi-cantilever array. We present a MEMS-based AFM probe array with three active cantilevers, each integrating two types of on-chip Z actuators (piezoelectric and electrothermal) and a differential AlN piezoelectric deflection sensor. To our knowledge, this is the first multi-cantilever AFM system that combines high-bandwidth piezoelectric actuation with large-range electrothermal actuation on each cantilever. This hybrid actuation scheme enables each cantilever to respond quickly to fine variations in surface height while still accommodating height changes of several microns, all without an external Z positioner. The array was designed to address two issues in parallel operation. First, the cantilevers have well-separated resonance frequencies in the 50 kHz range to reduce mechanical cross-talk and avoid exciting each other's dynamics in tapping-mode imaging, while careful electrode routing provides electrical isolation between channels. Second, we use a low-temperature, sequential fabrication process to minimize residual stress and wafer bow. As a result, the released array is nearly planar and the tip-height mismatch is ~ 1 μ m, which is important for engaging multiple tips simultaneously.

We microfabricated the three-cantilever array and integrated it into an in-house-built AFM platform for testing. Each cantilever's piezoelectric actuator can drive a free-space oscillation amplitude of about 100 nm at its resonance frequency (49.7 kHz, 51.3 kHz, and 52.6 kHz for the three cantilevers). The co-located differential piezoelectric sensor captures the cantilever's vibratory motion. In addition, each cantilever incorporates an electrothermal actuator that provides up to 10 μ m of static deflection with a control bandwidth of 103 Hz. The compact, lightweight design of our array reduces the mass of each AFM head by orders of magnitude compared to the macro-scale system, thereby raising its mechanical resonance frequency. This higher resonance frequency greatly decreases the system's sensitivity to external vibrations. Furthermore, the integrated electrothermal actuator provides a closed-loop Z-

bandwidth of approximately 100 Hz, which is about 66% higher than that of the Z-actuator in the macro-scale parallel AFM system. In our experiments, each cantilever achieved a scanning speed comparable to the macro-scale system (1 line/s), but with approximately one-quarter the pixel size (12 nm vs 40 nm). We demonstrated this by simultaneously scanning three adjacent 3 μ m $\times$ 3 μ m regions on standard AFM calibration gratings (each with 100 nm step height and 750 nm pitch). The resulting images confirm that our parallel AFM system can accurately capture both the lateral dimensions and the vertical step heights of the sample features, with measurement errors below 10%. These results illustrate the potential of the proposed multi-probe AFM approach for high-throughput nanoscale metrology in industrial applications.

The subsequent section of this article is organized as follows: Section II describes the design of the cantilever array and the feedback loop required for tapping mode AFM imaging. Section III discusses the fabrication of the cantilever array using silicon micromachining techniques and its subsequent characterization. Section IV explains the experimental setup developed for the AFM imaging process and presents the obtained high-resolution AFM images. Finally, Section V offers the concluding remarks.

II. Design and Modeling

The schematic of the cantilever array, consisting of three cantilevers, is shown in Fig. 1a. Each cantilever in the array has a uniform thickness t and a stepped rectangular geometry, with a wider section of width W and length L , and a narrower section of width w and length l . Although the dimensions of narrower sections are identical, the wider sections have different widths and include multiple through holes that alter the equivalent mass of the cantilever, thus providing unique natural frequencies ω_0 for each cantilever. These distinct natural frequencies help reduce mechanical crosstalk between cantilevers and minimize undesired disturbances in the AFM feedback loops [13]. It is worth noting that the design can be extended to include more than three cantilevers, as the design of these cantilevers is mutually independent. However, increasing the number of cantilevers can result in increased spread in the tip height of different cantilevers and undesired cross-axis sensitivities due to fabrication errors. Therefore, an alternative is to use multiple arrays of three cantilevers to achieve the desired throughput.

The electrothermal actuators (EA), designed using serpentine aluminum tracks, are positioned on the narrower rectangular section of the cantilever to provide a larger Z-motion range [14]. The piezoelectric actuators (PA) and sensors (PS) are positioned side by side on the wider rectangular section to create a collocated configuration. Each cantilever includes two piezoelectric sensors (PS_+ and PS_-) arranged in a differential configuration to reduce noise and enhance measurement sensitivity [15].

A feedback control system is designed to operate the cantilever array in tapping mode during AFM imaging. The feedback controller employs three individual feedback

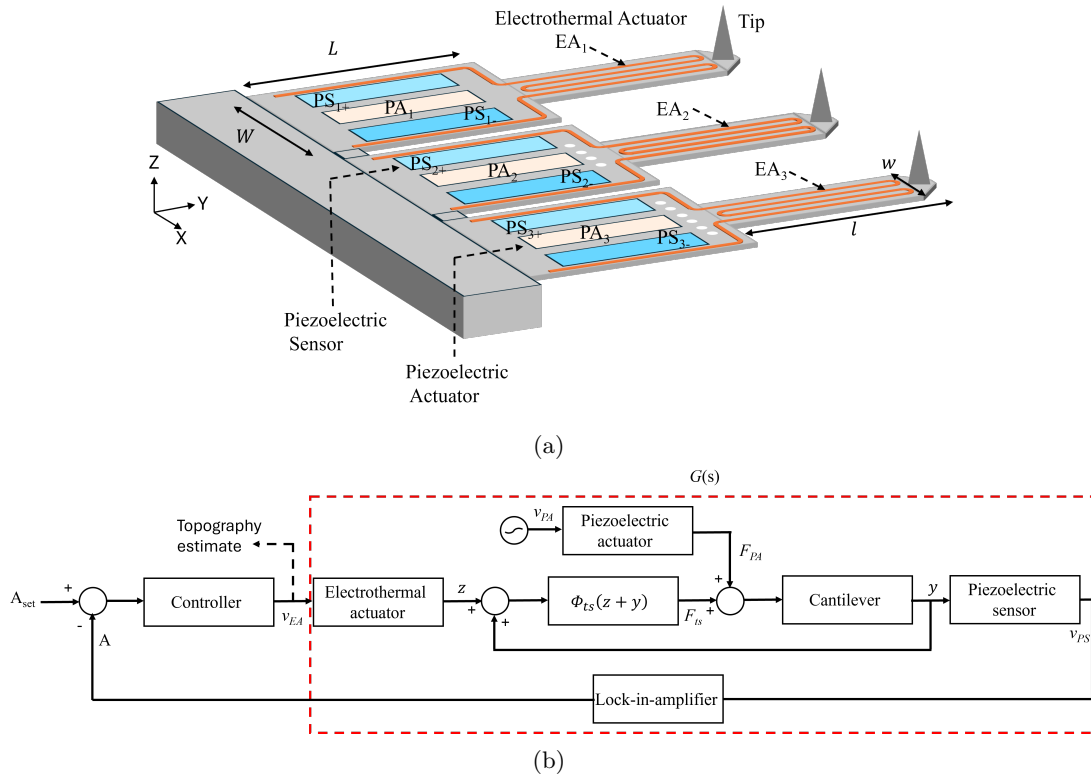


Fig. 1: (a) The schematic of the cantilever array showing the piezoelectric actuators (PA), electrothermal actuators (EA) and the piezoelectric sensors (PS). (b) The block diagram illustrating the different components required for amplitude control during tapping mode AFM imaging.

loops, one for each cantilever (see Fig. 1b). During tapping-mode AFM imaging, each cantilever in the array is oscillated with an amplitude A_0 at its respective first natural frequency using the piezoelectric actuator (PA). The resulting high-frequency Z-oscillation of the cantilever is measured by the differential piezoelectric sensor (PS₊ and PS₋). This signal is fed to a lock-in amplifier (LIA), which determines the oscillation amplitude of the cantilever. As the tip of the cantilever approaches the sample, its oscillation amplitude decreases due to the tip-sample interaction forces ϕ_{ts} . The tip-sample approach continues until the oscillation amplitude reaches a predefined set-point A_{set} , where $A_{set} < A_0$. Since variations in the sample topography alter the resultant tip-sample distance $z + y$, a controller $C(s)$, designed to regulate the oscillation amplitude at A_{set} , ensures that the tip-sample separation remains constant by moving the cantilever along the Z-axis using the electrothermal actuator. Therefore, the Z-displacement of the cantilever during AFM imaging provides precise topography information.

The transfer functions for the individual blocks shown in Fig. 1b are derived to design the controller $C(s)$, which effectively rejects low-frequency disturbances caused by the slowly varying topography. The electrothermal actuator block incorporates a square root function to generate linear displacement in response to the applied input voltage [12]. The transfer function $G_{EA}(s)$, which represents the relationship between the voltage v_{EA} applied to the

electrothermal actuator and the displacement z of the cantilever, is given by:

$$G_{EA}(s) = \frac{z(s)}{v_{EA}(s)} = \frac{k_{EA}}{\tau s + 1}, \quad (1)$$

where k_{EA} is the DC gain, and τ is the time constant that determines the bandwidth of the electrothermal actuator. Similarly, the transfer function $G_{PA}(s)$, representing the relationship between the voltage applied to the piezoelectric actuator v_{PA} and the displacement of the cantilever y , is given by [16]:

$$G_{PA}(s) = \frac{y(s)}{v_{PA}(s)} = \frac{k_{PA}\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}, \quad (2)$$

where k_{PA} , ω_0 , and Q represent the DC actuation gain, the natural frequency, and the quality factor of the cantilever, respectively, in free air. The displacements z and y were experimentally measured using a Laser Doppler Vibrometer (LDV) to obtain the above transfer functions and will be discussed in the experimental section.

Next, the transfer function $G_{PS}(s)$, representing the relationship between the voltage generated by the differential piezoelectric sensors v_{PS} due to the high-frequency voltage v_{PA} applied to the piezoelectric actuator, is given by [15]:

$$G_{PS}(s) = \frac{v_{PS}(s)}{v_{PA}(s)} = \frac{a_2 s^2 + a_1 s + a_0}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}. \quad (3)$$

where a_2 , a_1 , and a_0 are the coefficients representing the electrical feedthrough dynamics between the adjacent piezoelectric actuator and the sensor. By properly designing the measurement electronics for the differential piezoelectric sensors, the feedthrough coefficients a_1 and a_2 can be effectively canceled, resulting in accurate measurement of the dynamic motion of the cantilever [15]. It is important to note that the transfer function $G_{PS}(s)$ includes a cascaded high-pass filter due to the impedance of the measurement electronics [17]. However, this filter has been approximated as unity in Equation 3 because the gain and phase of this high-pass filter are approximately unity and zero, respectively, near the resonant frequency of the microcantilever. Since this high-pass filter has significantly smaller gain at low frequencies, the piezoelectric sensor can not measure low-frequency motion of the microcantilever. Therefore, the piezoelectric sensor is used exclusively to measure the dynamic motion of the cantilever during tapping mode AFM imaging.

Finally, the blocks enclosed within the dotted red lines in Fig. 1b can be replaced by a single block with an equivalent transfer function $G(s)$ given by the multiplication of tapping dynamics with $G_{EA}(s)$ [16]:

$$G(s) = \frac{1}{\frac{2Q}{\omega_0}s + 1} G_{EA}(s) \quad (4)$$

Using the equivalent transfer function $G(s)$, a suitable proportional-integral controller $C(s)$ is designed to effectively reject the low-frequency input disturbance, which represents the slowly changing sample's topography. The resulting output of the controller, v_{EA} provides the topography estimate.

III. Fabrication and Characterization

Integrating piezoelectric actuators (PA), electrothermal actuators (EA), and piezoelectric sensors (PS) within a single microcantilever is technically challenging due to the distinct material, thermal, and electrical requirements of each functional element. In particular, high-temperature annealing processes needed for piezoelectric thin films can adversely affect the metallization layers used in electrothermal actuators, and dense multilayer stacks increase parasitic capacitance and electrical cross-talk that degrade PS signal integrity. Similarly, residual stress and stress gradients across the stack can warp the released array, producing tip-height variation that complicates simultaneous engagement of multiple tips.

We address these risks with a sequential, low-temperature process flow; thermally robust aluminum nitride (AlN) as the piezoelectric layer; and physically separated, shielded routing for actuator and sensor electrodes to minimize coupling. This integration strategy co-fabricates PA, EA, and PS on a single chip while preserving mechanical symmetry (low tip-height spread), electrical isolation (low parasitics and cross-talk), and stable resonance characteristics.

The cantilever array was fabricated using standard silicon micromachining techniques. The fabrication process

is illustrated in Fig. 2(a-g). The process begins with a 4" SOI wafer, consisting of a 400 μm handle layer, a 1 μm Buried Oxide (BOX) layer, and a 5 μm device layer. A 500 nm thermal oxide layer is initially grown to electrically isolate the signal tracks from the cantilever body (Fig. 2(a)). Next, a lift-off process is employed to deposit a 200 nm Titanium/Platinum (Ti/Pt) bottom electrode layer (Fig. 2(b)). This is followed by the deposition of a 1 μm Aluminum Nitride (AlN) layer, which apart from aforementioned advantages, has minimal piezoelectric hysteresis compared to other piezoelectric materials [18] (Fig. 2(c)). A 200 nm Silicon Oxide (SiO_2) hardmask is then applied and patterned, which is subsequently used for etching the AlN layer. After removing the hardmask, another lift-off process is used to deposit a 1 μm top Aluminum (Al) electrode layer (Fig. 2(d)).

The cantilever structure is shaped by etching both the SiO_2 isolation layer and the Si device layer using Deep Reactive Ion Etching (DRIE) (Fig. 2(e)). A 1 μm Parylene layer is applied to protect the front side of the cantilever, while the backside undergoes complete etching, which releases the cantilevers of thickness 5 μm . Subsequently, the BOX layer is etched away, and the devices are cleaned using oxygen plasma and acetone to complete the microcantilever fabrication process (Fig. 2(f)). The final cantilever thickness after release was measured to be approximately 5 μm using SEM, consistent with the nominal device-layer thickness of the SOI wafer. Although it is possible to microfabricate the tip at the end of the microcantilever using the previously reported process, here we transferred a prefabricated tip using the Focused Ion Beam milling and welding technique for simplicity [13], [19]. Once the cantilever array is ready, the tip-transfer process, as described in [19], is carried out on each cantilever (Fig. 2(g)). The SEM image of the cantilever array after the tip-transfer process is shown in Fig. 2(h). The width w and length l of the narrower rectangular section are 70 μm and 220 μm , respectively for the fabricated micro-cantilever in the array; and the length L of the wider section is 380 μm . Minor edge protrusions observed on some cantilevers after release are attributed to localized micro-masking effects during DRIE; these features occur outside the active regions and do not affect actuation or sensing performance.

While the FIB-based tip transfer method was used in this prototype for proof-of-concept demonstration, it is not intended for large-scale implementation. Future designs will incorporate batch-compatible on-chip tip formation, such as anisotropic silicon etching or automated, high-throughput tip-transfer systems demonstrated in prior work [13], [20]. These approaches can be incorporated into the current process flow without significantly altering the cantilever geometry, enabling scalable and reproducible tip formation across large arrays.

After microfabrication, we characterized the dynamic responses of the cantilevers driven by their integrated actuators. First, we obtained the frequency response for each cantilever actuated by its electrothermal actuator.

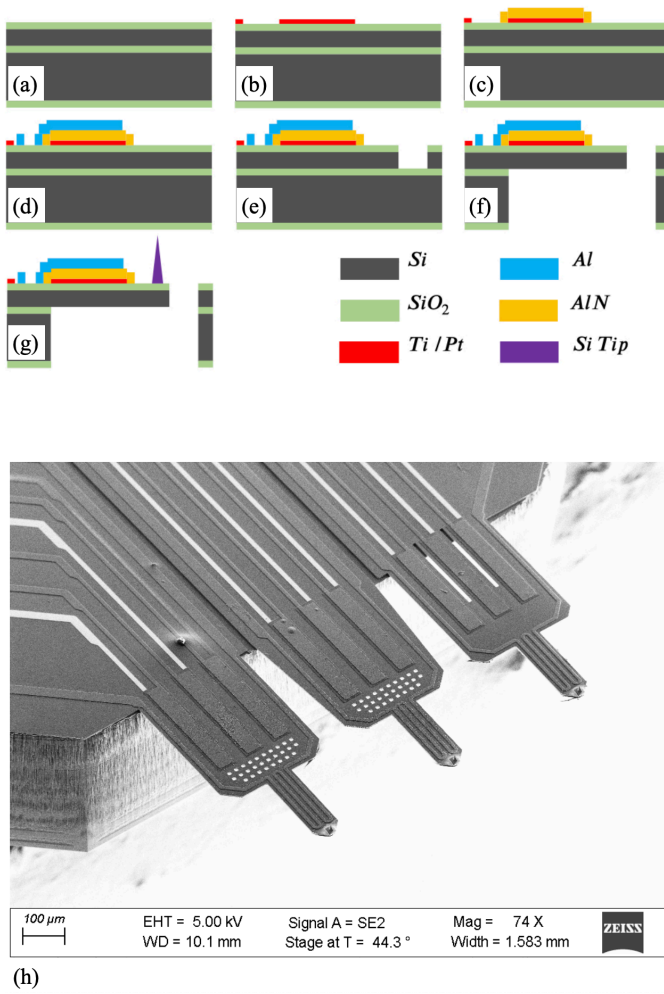


Fig. 2: (a) The 4" SOI wafer after the thermal oxide growth; (b) The deposition of the 200 nm *Ti/Pt* layer; (c) The deposition of the 1 μ m *AlN* layer; (d) Lift-off of the 1 μ m *Al* layer; (e) Frontside etch of the device layer; (f) Backside etch of the handle layer; (g) The transfer of the Silicon tip; (h) SEM image of the cantilever array after the tips are transferred.

The Z-motion of the cantilevers was measured using an LDV (MSA-100, Polytech). The measured responses are represented by their transfer functions, $G_{EA}^{ij} = \frac{z_j}{v_{EA}^i}$, as defined in Equation 1. Here, z_j represents the measured displacement of the j^{th} cantilever due to the voltage v_{EA}^i applied to the electrothermal actuator integrated with the i^{th} cantilever, where $(i, j) = 1, 2, 3$. The experimentally obtained magnitude responses $|G_{EA}^{ij}|$ are plotted in blue in Fig. 3(a). A first-order transfer function model was fitted to the measured data and used to estimate $|G_{EA}^{ij}|$. The estimated transfer function matrix $\mathbf{G}_{EA}$ is given by:

$$\mathbf{G}_{EA} \approx \begin{bmatrix} G_{EA}^{11}(s) & 0 & 0 \\ 0 & G_{EA}^{22}(s) & 0 \\ 0 & 0 & G_{EA}^{33}(s) \end{bmatrix} \quad (5)$$

where the first diagonal element is estimated to be:

$$G_{EA}^{11}(s) = \frac{9.8628 \times 10^{-7}}{0.00155s + 1}$$

The estimated diagonal elements $G_{EA}^{22}(s)$ and $G_{EA}^{33}(s)$ are almost identical to $G_{EA}^{11}(s)$ as apparent from Fig. 3(a).

The non-diagonal elements represent cross-talk and are approximated to be zero because $|G_{EA}^{ij}|_{(i \neq j)} \ll |G_{EA}^{ij}|_{(i=j)}$, as shown in Fig. 3(a).

The time constants of the electrothermal actuators, estimated from the fitted models, were 0.00155 s, 0.00156 s, and 0.00155 s. These time constants indicate that all the electrothermal actuators have a 3dB bandwidth of approximately 103 Hz. Similarly, the actuation gains of the electrothermal actuators, estimated from the fitted models, were 0.9863 $\mu\text{m/V}$, 0.9465 $\mu\text{m/V}$, and 0.9517 $\mu\text{m/V}$. The high values of low-frequency actuation gains demonstrate that electrothermal actuators can provide a large Z-motion range of $z \approx 1 \mu\text{m}$ for an applied voltage of $v_{EA} = 1 \text{ V}$ at low frequencies.

While the piezoelectric sensors offer excellent sensitivity near the resonance frequency of each cantilever, their inherent high-pass characteristics limit measurement accuracy at low frequencies. Consequently, they are primarily used for high-frequency oscillation sensing in tapping-mode operation, whereas the electrothermal actuators handle the low-frequency displacement control. The electrothermal actuators exhibit mild nonlinearity and slow thermal drift due to Joule heating; however, these effects were found to be negligible within the operating range used for our AFM imaging. The cantilevers maintained stable oscillation amplitude and Z-position during extended operation without requiring additional drift-compensation schemes. This observation indicates that the combined piezoelectric-electrothermal actuation and sensing architecture provides sufficient stability.

Next, we characterized the frequency response of the cantilevers driven by the piezoelectric actuators using the same approach. The piezoelectric actuators excite the cantilevers near their first Z-resonance frequency. The Z-motion of the cantilevers was measured using both the LDV and the integrated piezoelectric sensors. The measured frequency responses using LDV are represented by their transfer functions, $G_{PA}^{ij} = \frac{y_j}{v_{PA}^i}$, as defined in Equation 2. Here, y_j represents the measured displacement of the j^{th} cantilever due to the voltage v_{PA}^i applied to the piezoelectric actuator integrated with the i^{th} cantilever, where $(i, j) = 1, 2, 3$. The experimentally obtained magnitude responses $|G_{PA}^{ij}|$ using LDV are plotted in red in Fig. 3(b). A second-order transfer function model was fitted to the measured data $|G_{PA}^{ij}|$. The derived transfer function matrix $\mathbf{G}_{PA}$ is given by:

$$\mathbf{G}_{PA} \approx \begin{bmatrix} G_{PA}^{11}(s) & 0 & 0 \\ 0 & G_{PA}^{22}(s) & 0 \\ 0 & 0 & G_{PA}^{33}(s) \end{bmatrix} \quad (6)$$

where the first diagonal element is estimated to be:

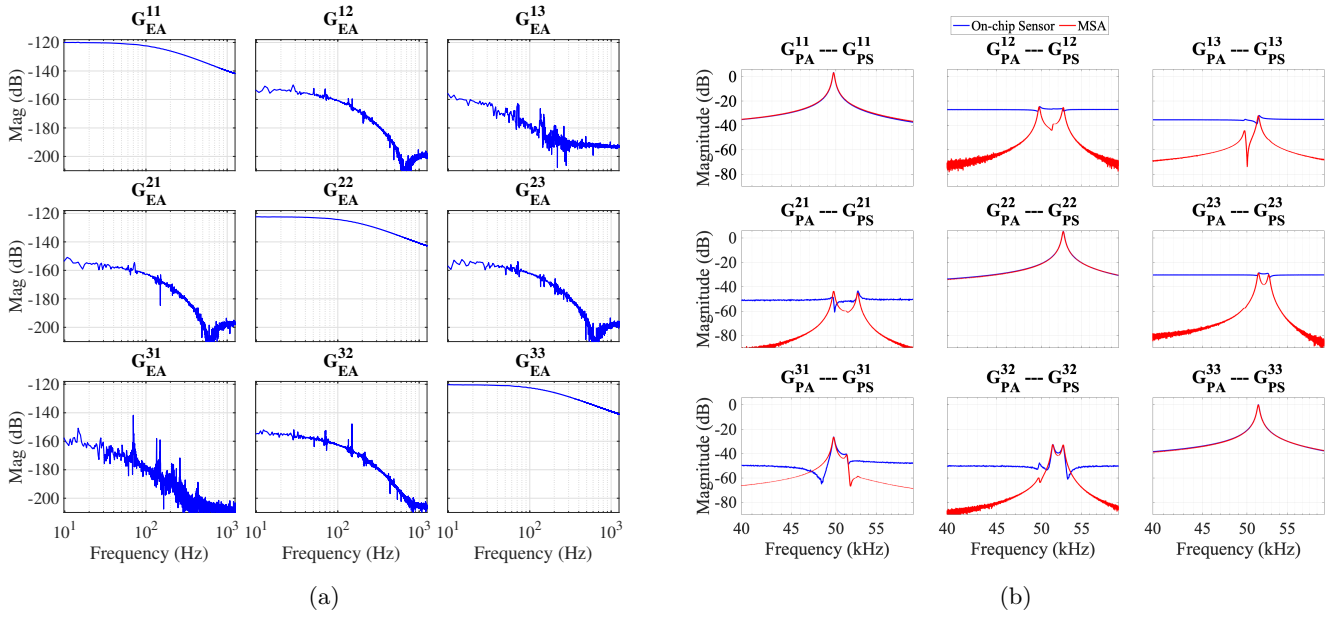


Fig. 3: The characterization of the actuators and sensor of the cantilever array. (a) Characterization of the electrothermal actuator of each cantilever in the array. The transfer function G_{EA}^{ij} represents the result of the experiment in which the electrothermal actuator in the cantilever i is actuated over a frequency range of 10 Hz to 1.25 kHz and the displacement of the cantilever j is measured using an external LDV. (b) Characterization of the piezoelectric actuator and sensor of each cantilever in the array. The transfer function G_{PA}^{ij} and G_{PS}^{ij} represent the result of the experiment in which the piezoelectric actuator in the cantilever i is actuated over a frequency range of 30 kHz to 60 kHz, and the displacement of the cantilever j is measured using both its on-chip sensor (G_{PS}^{ij} in blue) and an external LDV (G_{PA}^{ij} in red).

$$G_{PA}^{11}(s) = \frac{862.3}{s^2 + 2201s + 1.278 \times 10^{11}}$$

The estimated transfer functions $G_{PA}^{22}(s)$ and $G_{PA}^{33}(s)$ have similar characteristics to $G_{PA}^{11}(s)$ as apparent from Fig. 3(b). The natural frequencies of the three cantilevers obtained from their estimated transfer functions are 49.73 kHz, 52.65 kHz and 51.35 kHz. The estimated quality factors for the three cantilevers were 230.12, 217.82, and 212.44. The estimated DC actuation gains for the piezoelectric actuators were 6.75 nm/V, 6.87 nm/V, and 6.94 nm/V. The actuation gain at resonance for the three cantilevers are 1.7219, 1.2560, and 1.6875 $\mu\text{m/V}$, respectively. The high actuation gains at the resonance frequencies ensure that each cantilever can be oscillated with an oscillation amplitude of a few hundred nanometers and a kilohertz actuation frequency, as required for tapping mode AFM imaging. The non-diagonal elements represent cross-talk and are approximated to be zero because $|G_{PA}^{ij}|_{(i \neq j)} \ll |G_{PA}^{ij}|_{(i=j)}$ as shown in Fig. 3(b). The primary reason for the small cross-talk is the unique natural frequencies of the three cantilevers. Similarly, the measured frequency responses using the piezoelectric sensor are represented by their transfer functions, $G_{PS}^{ij} = \frac{v_{PS}^j}{v_{PA}^i}$, as defined in Equation 3. Here, v_{PS}^j represents the voltage generated by the differential piezoelectric sensors integrated with the j^{th} cantilever due to the voltage v_{PA}^i applied to the piezoelectric actuator integrated with the i^{th} cantilever, where $(i, j) = 1, 2, 3$. The experimentally

obtained magnitude responses $|G_{PS}^{ij}|$ are plotted with blue line in Fig. 3(b). A second-order transfer function model was fitted to the measured data $|G_{PS}^{ij}|$ to estimate the dynamic parameters of the cantilevers. The derived transfer function matrix $\mathbf{G}_{PS}$ is given by:

$$\mathbf{G}_{PS} \approx \begin{bmatrix} G_{PS}^{11}(s) & 0 & 0 \\ 0 & G_{PS}^{22}(s) & 0 \\ 0 & 0 & G_{PS}^{33}(s) \end{bmatrix} \quad (7)$$

where the first diagonal element is estimated to be:

$$G_{PS}^{11}(s) = \frac{3.142 \times 10^{-5}s^2 + 0.8698s + 2.201 \times 10^6}{s^2 + 2201s + 1.278 \times 10^{11}}$$

The obtained transfer function can be approximated with a pair of dominant poles as the undesired zeros are farther away from the imaginary axis in the s -plane. It is worth noting that the G_{PS} becomes identical to G_{PA} due to the reduction in electrical feed through between the piezoelectric actuators and sensors, which introduces the undesired zeros. Specifically, the use of differential piezoelectric sensors and the associated signal conditioning circuits for measuring v_{PS} has reduced the feed through and thus eliminated the undesired zeros from the measurement dynamics. Similarly, the transfer functions for the remaining two diagonal elements capture the dynamic motion of the other two cantilevers.

Again, the non-diagonal elements representing cross-talk are approximated to be zero because $|G_{PS}^{ij}|_{(i \neq j)} \ll$

$|G_{PS}^{ij}|_{(i=j)}$ as shown in Fig. 3(b). To compare the frequency responses obtained from the piezoelectric sensors and the LDV, we have plotted both the magnitude responses in Fig. 3(b). Here, the experimentally obtained magnitude responses $|G_{PA}^{ij}|$ have been multiplied by the constant scaling factor $\frac{a_0}{k_{PA}\omega_0^2}$ so that these can be compared with the frequency responses $|G_{PS}^{ij}|$ obtained using on-chip sensors. Since the measurement plots obtained from the piezoelectric sensor match perfectly with the measurement data obtained from the LDV, for $i = j$, the integrated piezoelectric sensor can be reliably used for measuring high-frequency oscillation amplitudes of the cantilevers during AFM imaging.

Using the estimated values of the quality factors and the natural frequencies, the equivalent transfer function $G^{11}(s)$ for the first feedback loops can be represented by:

$$G^{11}(s) = \frac{1}{0.001472s + 1} G_{EA}^{11}(s)$$

Similar results can be obtained for the equivalent transfer functions for the other two feedback loops. These equivalent transfer functions $G(s)$ will be used to design the controllers $C(s)$ for each feedback loop during AFM imaging.

IV. Experimental Implementation

This section describes the in-house development of the experimental set-up and its use for tapping mode AFM imaging using the micro-fabricated cantilever array. Section IV-A discusses the development of the AFM set-up, while Section IV-B explains the parallel AFM imaging using the developed AFM set-up.

A. AFM Set-up

The in-house developed AFM set-up comprises three primary components: positioning stages, driving-measurement electronics, and a prototype controller for implementing the feedback control. The AFM set-up consists of three different positioning stages for positioning the cantilever and the sample during AFM imaging (Fig. 4). A motorized stage (MTS25-Z8, Thorlabs) provides 3-axis linear motion for bringing the tips of the cantilever in contact with the sample. Additionally, a θ_x rotation stage adjusts the orientation of the cantilevers so that their tips are aligned to simultaneously touch the sample placed in the XY plane. The sample itself is mounted on a XYZ piezoelectric positioner (P-363 PicoCubeTM, PI) actuated by a piezo driver (E-536 PicoCubeTM, PI), which generates a $3\mu\text{m} \times 3\mu\text{m}$ raster scanning pattern during AFM imaging. *The nanopositioner operates in closed-loop mode using integrated capacitive sensors, which compensate for piezoelectric hysteresis and lateral drift during raster scanning.*

The drive-measurement electronics were developed to independently drive the electrothermal and piezoelectric actuators and measure the voltage signals generated by the piezoelectric sensor. Three independent voltage-controlled

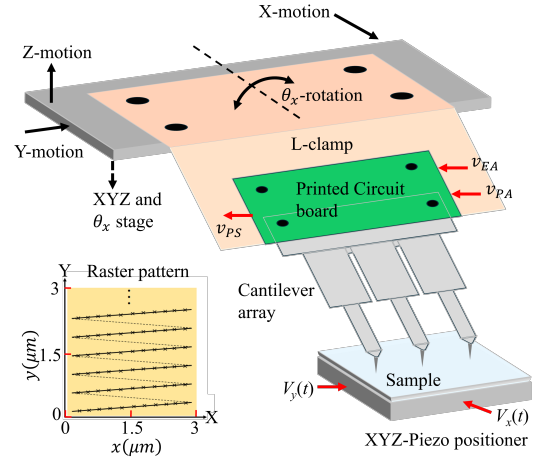


Fig. 4: Schematic showing the in-house developed AFM set-up. The raster scan pattern of the XY positioner is depicted in the bottom left.

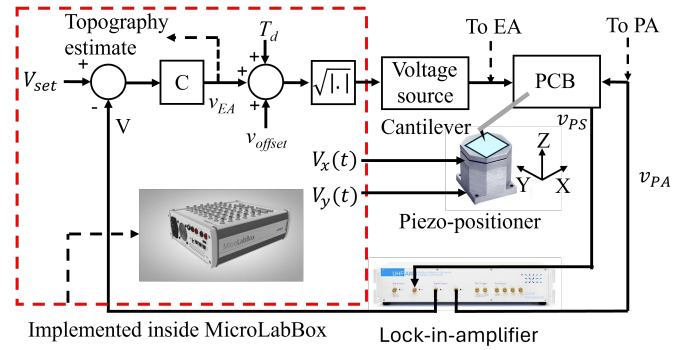


Fig. 5: The schematic showing the implemented feedback loop for tapping mode AFM imaging for a single cantilever. The portion enclosed within the dotted red box was implemented inside the prototype controller MicroLabBox.

voltage sources were developed using operational amplifiers (OPA549, TI) for driving the electrothermal actuators. These sources provide a few hundred milliamperes of currents required for electrothermal actuation. A lock-in amplifier (LIA, UHFLI, Zurich Instruments) is used to drive the piezoelectric actuators, as they require only a few milliamperes of current due to their high impedance. The differential voltage signals generated by the piezoelectric sensors are measured with a differential amplifier, which is integrated with signal conditioning circuits developed on a printed circuit board (PCB). The PCB also contains electrical tracks that connect the electrothermal and piezoelectric actuators to their respective external driving electronics.

The feedback control loop shown in Fig. 5 is implemented using a prototype controller (MicroLabBox, DSpace). The voltage signal measured from the piezoelectric sensor, v_{PS} , is fed into the LIA. The lock-in detection generated the demodulated signal, V which represents the measured oscillation amplitude A of the

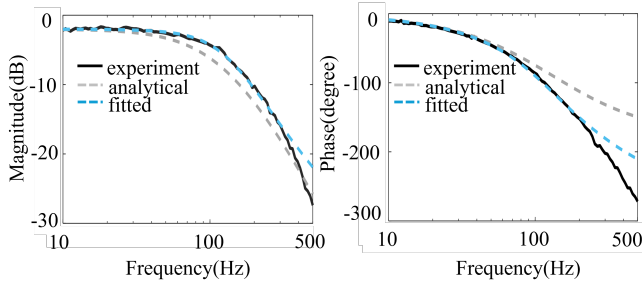


Fig. 6: Frequency response of the equivalent transfer function $G^{11}(s)$ from the experiment (solid black), the analytical model (dashed grey) and the fitted model (dashed cyan)

cantilever. The voltage V is acquired using the analog-to-digital converter of the MicroLabBox and compared with a reference voltage signal, V_{set} that represents the set-point oscillation amplitude, A_{set} . The error signal is then fed to a PI controller, $C(s) = k_P + \frac{k_I}{s}$, where k_P is the proportional gain and k_I is the integral gain. The PI controller generates an appropriate control voltage v_{EA} , which is applied to the voltage source driving the electrothermal actuator through a digital-to-analog converter. To generate a linear displacement z , the control voltage v_{EA} first passes through a block that includes an absolute function followed by a square-root function. Additionally, an offset voltage, v_{offset} is added to the controller output, allowing the cantilever to move both up and down about its initial mean Z-position [19].

To achieve high-resolution AFM imaging, we first identified the transfer function $G^{11}(s)$ using the closed-loop identification technique described in [19]. The experimentally obtained transfer function $G^{11}(s)$, shown in solid black line Fig. 6, closely matches the analytical transfer function given by Equation 4 and represented by the dashed grey line in Fig. 6. The small error is due to the unmodeled dynamics introduced in the feedback loop, which are caused by the tip-sample interaction forces, the square root operator, and the demodulation process. The complete dynamics of $G^{11}(s)$ are obtained using the fitted model represented by the dashed cyan line.

Using the fitted model $G^{11}(s)$, we selected the controller gains as $k_P = 1$ and $k_I = 750$ to effectively reject more than 98% of input disturbances T_d shown in Fig. 5 while maintaining sufficient stability margins (phase margin = 42 degrees and gain margin = 9 dB). The calculated gain and phase margins obtained from the identified transfer function confirm that the feedback loop remains well within stable operating limits. These analytical margins indicate that the PI controller provides adequate robustness against modeling uncertainties and parameter variations within the normal operating range. No oscillatory or divergent behavior was observed during imaging, further confirming that the designed control loop maintains stable and consistent performance during AFM operation. Since the voltage T_d represents the disturbance

due to slow varying topography, it was modeled as sinusoidal signals with a frequency less than 5 Hz. This controller $C(s)$ is implemented in all three feedback loops since the equivalent transfer functions $G^{11}(s)$, $G^{22}(s)$, and $G^{33}(s)$ are nearly identical.

B. AFM Imaging

First, the cantilever array was moved downward using the 3-axis motorized stage (Fig. 4). During the approach phase, the cantilevers were driven with an oscillation amplitude of $A_0 \approx 100$ nm at their resonance frequency. The approach continued until the oscillation amplitude A of each cantilever was reduced to below the reference value $A_{ref} = 80$ nm. Subsequently, the feedback controller for each loop was activated. Next, to acquire the AFM image, drive voltages $V_x(t)$ and $V_y(t)$ were applied to the piezo driver to generate a raster scan pattern (Fig. 5). Specifically, $V_x(t)$ is a fast triangular waveform with a frequency of 1 Hz and a peak-to-peak amplitude of 6 V, used to produce motion along the X-axis. In contrast, $V_y(t)$ is a slow ramp signal with a slope of approximately 23.44 mV/s and a maximum value of 6 V, used to drive the Y-axis motion. With these voltage parameters, the piezo takes 256 s to traverse $3 \mu\text{m}$ along the Y-axis, during which it completes 256 cycles of X-axis motion, each spanning $3 \mu\text{m}$. The resulting raster scanning pattern, covering an area of $3 \mu\text{m} \times 3 \mu\text{m}$, is illustrated in the bottom left of Fig. 4.

During the raster motion of the sample in the XY-plane, the tips of all three cantilevers interacted with the sample, resulting in varying tip-sample interaction forces depending on the local topography of the sample. These varying forces caused the oscillation amplitude A to deviate from the set point A_{set} . However, the designed feedback controller $C(s)$ ensured that the oscillation amplitude remained close to the set point by adjusting the Z-position of each cantilever using the electrothermal actuators. The resulting controller output directly provides the local topography of the sample. Specifically, we recorded the controller output for each of the microcantilevers as a function of the XY position of the sample during the raster scan motion. The data collected for each cantilever captures the topography information of a $3 \mu\text{m} \times 3 \mu\text{m}$ area positioned below each cantilever. For illustration purposes, the topography data captured by each cantilever was divided into 256 pixels $\times$ 256 pixels, providing a spatial resolution of ≈ 12 nm per pixel.

Figure 7 shows AFM images of a calibration grating (750-HD) with a nominal step height of 100 nm and a nominal pitch of 750 nm, acquired via simultaneous operation of three cantilevers in parallel and visualized using Gwyddion software. Specifically, Fig. 7(a-c) presents 2D AFM images acquired using the first (C1), second (C2), and third (C3) cantilevers, respectively. Similarly, Fig. 7(d-f) displays the corresponding 3D AFM images from C1, C2, and C3. The high-resolution results demonstrate the ability to simultaneously capture sample features with

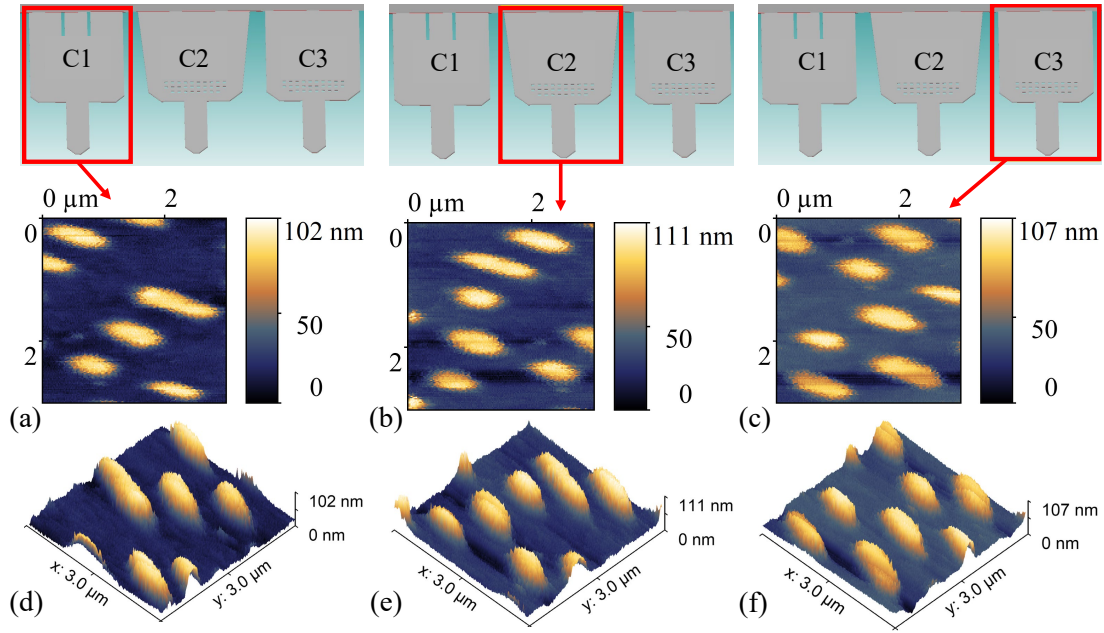


Fig. 7: 2D AFM images of a calibration grating: (a) acquired using the first cantilever C_1 ; (b) using the second cantilever C_2 ; and (c) using the third cantilever C_3 . 3D AFM images of the calibration grating: (d) acquired using C_1 ; (e) using C_2 ; and (f) using C_3 . The AFM images were acquired simultaneously by operating the cantilevers in parallel.

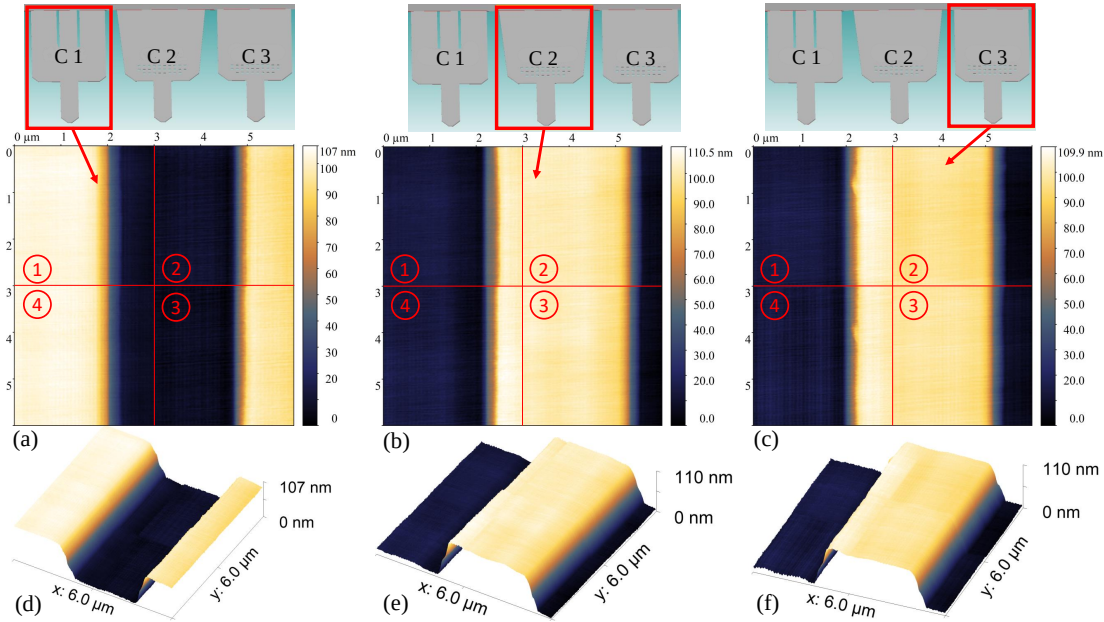


Fig. 8: Stitched 2D AFM images of a calibration grating obtained by moving the : (a) the first cantilever C_1 ; (b) the second cantilever C_2 ; and (c) the third cantilever C_3 to four different positions using the motorized XY-stage, acquiring the images at each of these positions simultaneously and finally stitching them together. Stitched 3D AFM images of the calibration grating obtained by moving : (d) C_1 ; (e) C_2 ; and (f) C_3 to four different positions using the motorized XY-stage, acquiring the images at each of these positions simultaneously and finally stitching them together.

heights up to 111 nm over a $9\mu\text{m} \times 3\mu\text{m}$ area, highlighting a threefold throughput improvement compared to a single probe AFM under identical imaging conditions.

Next, we demonstrate the process of capturing and stitching multiple AFM images to acquire features from

a large sample. For this experiment, we selected an AFM calibration grating consisting of rectangular troughs and peaks, with a pitch size of $5\mu\text{m}$. To capture one complete pitch, we first imaged an area of $3\mu\text{m} \times 3\mu\text{m}$ using all three cantilevers, as shown by the squares labelled "1"

in Fig. 8(a-c). After completing the initial imaging, the cantilever array was displaced by $3\mu\text{m}$ along the positive X-axis using the motorized stage, and AFM imaging was performed again, capturing the images in the squares labelled "2". This process was repeated by moving the cantilever array along the Y-axis and then along the X-axis again, with the AFM images captured at the positions labelled "3" and "4", respectively.

Finally, the individual images were stitched together, resulting in a lateral image of $6\mu\text{m} \times 6\mu\text{m}$, acquired using each of the three cantilevers. The stitched image captures three rectangular troughs and three rectangular peaks, with an average height difference of 107 nm. The imaging experiments in this study were performed on silicon calibration gratings to provide a well-defined and repeatable reference for validating the multi-probe feedback performance. The vertical and lateral sample features measured from both calibration grating matches with values mentioned in the datasheet with an error of less than 10 %. These results further demonstrate that the parallel imaging technique can provide large-area and high-resolution AFM images for high-throughput industrial applications.

The current implementation uses three independent, real-time feedback loops on a dSPACE MicroLabBox, each sampling at 50 kHz. The three cantilevers were intentionally given different natural frequencies to reduce mechanical cross-talk, so their plant responses $G(s)$ differ slightly. We use the same controller $C(s)$ with identical PI gains in each feedback loop. With robustness margins of 42° phase and 9 dB gain, this controller maintains the desired imaging performance across the three feedback loops (Fig. 7-8), so no re-tuning is required. The same principle extends to larger arrays: as long as added cantilevers produce $G(s)$ within this tested range, the identical controller can be reused; the only change is a roughly linear increase in computational load with channel count. In the present three-cantilever setup, total CPU utilization is $<15\%$, indicating headroom for additional channels. For larger arrays, the architecture can be scaled using parallel processing on an FPGA or a multi-core DSP to support tens of synchronized loops at comparable bandwidths.

V. Conclusion

We have demonstrated a parallel AFM system with three MEMS microcantilevers, each with independent on-chip actuation and self-sensing; this design eliminates the macroscale external actuators and sensors of earlier parallel AFM systems. The compact, low-mass probe heads raise each cantilever's resonance frequency and provide a 66 % higher Z-axis control bandwidth compared to a macro-scale 22-cantilever AFM instrument, which was limited by heavy probe heads. Operating three cantilevers in parallel, our MEMS-based AFM achieves a threefold imaging throughput increase over a single probe while maintaining high imaging resolution of 12 nm/pixel. The proposed system also builds on prior MEMS AFM

advances, such as the four-cantilever "Quattro" array, by integrating dual actuation on each cantilever. This combination of high-frequency piezoelectric and large-range electrothermal actuation provides $10\mu\text{m}$ of Z travel per tip compared to $2\mu\text{m}$ in the Quattro system without an external scanner, albeit with a five times lower Z-bandwidth. Using differential piezoelectric self-sensing, our design further avoids the thermal drift that affected Quattro's piezoresistive sensors. Finally, the architecture is modular and inherently scalable: additional cantilevers can be added on the same chip, or multiple such arrays can be operated in parallel without degrading feedback performance. Extending this approach to tens of cantilevers is feasible and, together with future enhancements to increase the on-chip Z-actuator bandwidth, will enable even greater imaging throughput in high-speed, high-throughput AFM applications.

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Hazhir Mahmoodi Nasrabadi received his B.Sc. in Electrical Engineering from the University of Tehran, Tehran, Iran in 2018. He received his Ph.D. degree in electrical engineering from the University of Texas at Dallas. His research focuses on MEMS-based active actuation and sensing systems

for AFM microcantilevers and enhancing their throughput by using them in parallel.



Vikrant Kumar Singh completed both his MTech (Research) and Ph.D. from the Indian Institute of Science, Bangalore, in 2022. During his graduate research, he extensively worked on precision actuation and measurement systems. He is currently a research scientist at the University of Texas at Dallas and is a member of the Labora-

tory for Dynamics and Control of Nanosystems (LDCN). His current research interests include self-actuating and sensing scanning probe microscopes, hybrid levitation-based precision positioners, and micro-robotics.



S. O. Reza Moheimani is a professor and holds the James Von Ehr Distinguished Chair in Science and Technology in the Department of Systems Engineering at the University of Texas at Dallas with appointments in Electrical and Computer Engineering and Mechanical Engineering Departments. He is the founding Director of

UTD Center for Atomically Precise Fabrication of Solid-State Quantum Devices and founder and Director of Laboratory for Dynamics and Control of Nanosystems. He is a past Editor-in-Chief of *Mechatronics* (2016–2021), and a past associate editor of *IEEE Transactions on Control Systems Technology*, *IEEE Transactions on Mechatronics* and *Control Engineering Practice*. He received the Industrial achievement Award (IFAC, 2023), Nyquist Lecturer Award (ASME DSCD, 2022), Charles Stark Draper Innovative Practice Award (ASME DSCD, 2020), Nathaniel B. Nichols Medal (IFAC, 2014), IEEE Control Systems Technology Award (IEEE CSS, 2009) and IEEE Transactions on Control Systems Technology Outstanding Paper Award (IEEE CSS, 2007 and 2018). He is a Fellow of IEEE, IFAC, ASME, and Institute of Physics (UK). Moheimani received the Ph.D. degree in Electrical Engineering from University of New South Wales, Australia in 1996. His current research interests include applications of control and estimation in high-precision mechatronic systems, high-speed scanning probe microscopy and atomically precise manufacturing.