

A Two Tip MEMS Array Nanopositioner for High Throughput STM

Emma Fowler and S. O. Reza Moheimani, *Fellow, IEEE*

Abstract—Though widely used for research, the scanning tunneling microscope (STM) has not been adopted as a commercial nanofabrication tool due to its low scan speed and throughput. One of the key contributors to the STMs sluggishness is the piezoelectric nanopositioner (piezotube) it employs to move the tip over the sample. The bulkiness of the piezotube limits the system bandwidth to 1 kHz, restricting achievable scan speeds. This paper presents a design for a micro-electromechanical system (MEMS) nanopositioner for the STM that replaces the piezotube with a piezoelectric actuator that has an order of magnitude higher bandwidth. To further increase the STMs throughput, this design also features two integrated tips that streamline fabrication with a batch process. The proposed MEMS design is shown to achieve $5.7\ \mu\text{m}$ of displacement in the Z-axis and have a first in-plane resonance of 15.8 kHz. The design is experimentally tested by establishing a stable tunneling current with each STM tip individually and concurrently on a graphite sample in ambient conditions.

I. INTRODUCTION

STM is an imaging technique largely credited with exposing atomic-level phenomena and giving rise to the field of nanotechnology [1], [2]. It has become an indispensable tool in disciplines ranging from molecular biology to semiconductor manufacturing, and is most commonly used to capture topographic images of conductive surfaces [2]. The STM tip can manipulate individual atoms, making it expertly suited to nanolithography, where a single layer of resist is patterned with angstrom-level resolution [3]. The precision of the STM sets it apart from other forms of microscopy [4], and has led to the fabrication of atomic devices [5]–[8] and examinations of quantum quandaries that are unable to be explored with other tools [9], [10].

Common optical microscopes amplify visible light through a lens, but the STM works by scanning using a piezotube scanner to move a tiny, single-atom sharp tip made of tungsten (W) over a conductive sample with a three-degree-of-freedom (3-DOF) in ultra-high vacuum (UHV) conditions. When the tip and sample are sufficiently close and a voltage is applied across them, a quantum tunneling current is established. The tunneling current is exponentially dependent on the distance separating the tip and sample, so it is extremely sensitive to vibrations, 60 Hz noise, and variations on the sample surface. To control the tunneling current, a feedback loop is created with a proportional-integral (PI) controller to regulate the tip-sample separation in the Z-axis as the tip moves across the sample. By keeping the tunneling current at a user-defined setpoint, measurements of the variations in tunneling current can be used to reconstruct topographic images of the surface variations with sub-nanometer resolution [11].

The unmatched resolution of the STM has not been enough to secure it a place in the quickly moving commercial nanofabrication industry, in large part because the STM is exceedingly slow to use. Tools like electron-beam lithography are more ubiquitous in fabrication because they can achieve much higher speeds than the STM [12], [13], though they are quickly reaching practical resolution limits [3]. For the STM, the bulkiness of the piezotube combined with the mass of the STM tip is enough to cap the system bandwidth in the Z-axis to 1 kHz [14], [15], which severely limits the throughput and resistance to mechanical vibrations. The inherent nonlinearities of piezoelectric actuators, like hysteresis [16], further impede STM performance by making it immensely difficult to achieve high-resolution images [17]. The large size of the piezotube also prevents parallel tip operation. To achieve the biggest improvement in the throughput of the STM, a design where multiple electrostatic tips can operate in parallel is the necessary next step.

To increase the scan speed of the STM, researchers have proposed flexure-guided [18]–[21] and dual-stage piezopositioners [22] as alternatives to the piezotube. The substantial size of these designs and the difficulty implementing them in high-throughput fabrication have stopped them from becoming widespread in STMs [23]. The overriding bulkiness of piezopositioners has led to many flexure-guided nanopositioners being miniaturized with microfabrication processes [24]–[27] to offer a smaller footprint and larger bandwidths. The smaller size of these MEMS nanopositioners also makes them ideal for potential array configurations [28], [29]. Regardless of their potential benefits, the majority of MEMS STM nanopositioners suffer from slow Z-axis dynamics, thereby limiting their scan speed.

This paper proposes a design for a STM MEMS nanopositioner array with two tips and electrostatic comb-drive actuators. This design leverages the higher bandwidths achievable via electrostatic actuation with parallel imaging through two STM tips to realize a substantial increase in potential scan speeds and throughput. Previous attempts at designing multi-tip STM arrays [30], [31] have failed to incorporate scalable electronics and individual actuation mechanisms for each tip. The MEMS design proposed here builds on the single-tip STM nanopositioner shown in [32]–[34] and the single-tip STM nanopositioner with an integrated Silicon (Si) tip shown in [35], [36]. This design is expanded to multiple tips, each with its own Z-axis actuation and electrical isolation. The advantages of this design are multi-fold: it incorporates batch process STM tips, electrical isolation via oxide bridges, distinct Z-axis actuation for each tip, and extendable control electronics. The device is designed such that it offers a ten-fold increase in

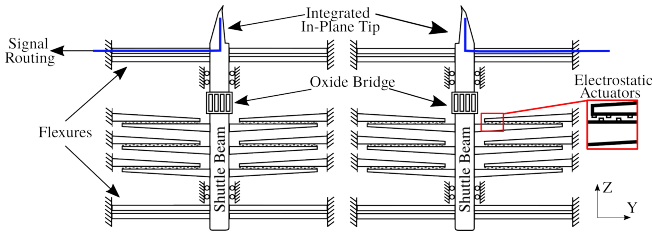


Fig. 1. A simple overview of the two-tip MEMS nanopositioner design showing examples of the in-plane tips, oxide bridge isolation, flexures, and comb-drive electrostatic actuators. Not all device features are shown in the overview.

the STM Z-axis bandwidth and is a direct replacement for the Z-axis functionality of the piezotube without changing any interior STM components. The design is verified by establishing tunneling current with each STM tip on a graphite sample.

The paper continues by first discussing the design constraints and specifications in Sec. II and then walks through the microfabrication process in Sec. III. The characterization results for the two-tip array are discussed in Sec. IV and the real-time tunneling current achieved with each tip is shown in Sec. V before ending with the conclusion in Sec. VI.

II. DEVICE CONSTRAINTS AND DESIGN

A schematic overview of the device is shown in Fig. 1. The nanopositioner is composed of two tips, each connected to a shuttle beam suspended by compliant flexures. Instead of a post-process approach, the tips are integrated into the device fabrication in a batch process, so that all tips across the wafer are made at the same time with identical dimensions. To isolate the tips from the Z-axis actuation, an oxide bridge is placed near the end of the shuttle beam, between the tip and the electrostatic actuators. The flexures that suspend the shuttle beam are designed to be stiff enough to prevent the shuttle beam from moving in the Y-axis, while the out-of-plane stiffness of the device is designed to be higher than that of the Z-axis to prevent mechanical vibrations. The electrostatic actuators are oriented in the Z-axis so that the device can directly replace the Z-axis functionality of a conventional piezotube. Unlike a previously published single-tip device [35], this array utilizes electrostatic comb drives to make the device more compact. The following subsections go into the device design in more detail.

A. Physical Constraints

To replace the Z-axis of the STM piezotube, the MEMS nanopositioner design has to fit two tips in the space defined by an STM tip holder. In the commercial STM of interest for this work, the tips are mounted on a vertical tip holder composed of a gold plate with an outer diameter of 6 mm. This tip holder is then placed on the piezotube for tip positioning. While maneuvering the tip inside the STM at UHV conditions, the tip holder is positioned in a tip carrier that has a limiting height of 4.5 mm. Therefore, the total design dimensions should be no larger than 6 mm $\times$ 4.5 mm in the Z direction for two tips.

B. STM Tip

An ultra-sharp, conductive STM tip is crucial for high-resolution STM images. The conductivity of the tip allows for electron tunneling when the tip is between 0.5 nm and 5 nm away from a conductive sample. Other MEMS nanopositioners for the STM have favored post-process tips [32], [33], [37] of W, platinum (Pt), or gallium arsenide (GaAs). These designs utilize a Focus ion beam (FIB) deposition process to attach pre-made tips or to grow tips via deposition; this process is serial in nature and unduly prolongs the fabrication process. For an array nanopositioner, attaching many tips serially is impractical and cumbersome. This design utilizes the integrated Si tip process found in [35] that uses a batch process to etch all STM tips at once.

The in-plane Si tips are fabricated through anisotropic wet etching of highly doped Si [38]. This method has been shown to reliably produce Si tips with a radius of 40 Å. A detailed schematic of the Si tip geometry can be seen in [35]. The tips in the design are made from a Silicon-on-insulator (SOI) wafer in the $\langle 100 \rangle$ orientation. The intersection of three planes forms a tip of length L with tunable parameters t , device layer thickness, and θ , the angle that the tip deviates from the $\langle 110 \rangle$ direction. The photolithography process defines the angle θ . The tip apex length is calculated from [35]:

$$L = \frac{1}{\sqrt{2} \tan \theta} \quad (1)$$

The doping of the Si wafer highly affects the conductivity of the Si tip; for the wafer used here, the doping is 0.001 – 0.005 Ω cm, N-type.

There exists a natural tradeoff between tip length L and sharpness. As the tips become longer, they are more susceptible to vibrations, which can lower the resolution of an STM image. However, as the tip angle narrows in pursuit of a single-atom apex, the tips necessarily become longer. For this work, $t = 19 \mu\text{m}$ and $\theta = 15^\circ$ were chosen. Different tip angles were investigated early in the fabrication qualification process, but it became too difficult to get each of the two tips to comparable lengths as they became longer. The integrated tip fabrication stops naturally when the etching process hits an oxide, which allows sharp tips to be formed uniformly across the wafer. Images captured with a Scanning electron microscope (SEM) showed that the bulk of the tips on the wafer reached a sharpness of less than 15 nm; those that did not etch properly were due to microfabrication irregularities. More details on the fabrication process will be outlined in Sec. III.

C. Electrical Isolation

Both the STM tip and actuators are in the same device layer for this design, negating the need for a double SOI fabrication process. To include two tips on the same device, the design must include electrical isolation between each STM tip and its corresponding actuation. The in-plane nature of the Si tips makes it possible to use a single SOI wafer and integrate the electrical isolation in the same layer as the tip. To do this, the oxide bridge method from [35] is used; in this method, the

shuttle beam is composed of two separate Si bodies connected by a completely oxidized structure. A detailed schematic of the oxide bridge geometry can be seen in [35].

This isolation method uses the wet thermal oxidation process to thoroughly oxidize a Si structure that connects the actuation to the tip; after thermal oxidation is complete, the Si structure has been entirely replaced by an insulator, SiO₂. The oxide bridge process starts with a grid of Si beams, each 2 μm wide and 20 μm long, etched into the device layer in a three-by-eight pattern. The beams are fully oxidized in a furnace with the wet oxidation process, which consumes the Si and increases the beam thickness to 4.4 μm. For added strength, the bridge beams are then covered in 2 μm of low-stress, conformal low pressure chemical vapor deposition (LPCVD) oxide. To expose the device layer again for subsequent fabrication steps, the oxide layers are selectively etched back, leaving only the completely oxidized bridge. Clamped-clamped beam flexures are put on either side of the oxide bridge to ensure that it does not fail when under force while imaging. The actuators are also designed to only be in one direction so that the oxide bridge is under compressive stress during operation.

D. Actuation Method

To avoid the inherent nonlinearities of piezoelectric actuation, electrostatic comb-finger actuators are used in this MEMS array design. These actuators offer a high bandwidth, high resolution, low creep, and increased surface area compared to parallel-plate actuators, which is important for getting the two on-chip STM tips reasonably close together. Excluding the effect of fringing fields, the electrostatic force and corresponding input voltage of a comb-drive actuator are related by [39]:

$$F_e = \frac{n\epsilon h}{g} V^2 = k_z z \quad (2)$$

where n is the number of comb-fingers, ϵ is the permittivity of the medium, h is the thickness of the fingers, g is the gap between the fingers, V is input voltage, k_z is the stiffness in the Z direction, and z is the shuttle beam displacement in the Z direction. For this design, the finger thickness $h = 20 \mu\text{m}$ and the desired stroke for each tip is set to $z = 5 \mu\text{m}$. A mechanical stopper is also implemented at the bottom of each shuttle beam to prevent large displacements.

E. Stiffness

There will always be a slight imbalance in comb-finger lengths and widths on either side of a MEMS shuttle beam due to fabrication imperfections. This can lead to lateral pull-in instability, where electrostatic forces perpendicular to the direction of motion become unbalanced and cause neighboring fingers to come in contact [40]. The in-plane stiffness k_z in Eq. 2 therefore becomes critical to prevent lateral movement of the shuttle beam. The device stiffness needs to be high enough to ensure the desired bandwidth of 10 kHz and to decrease susceptibility to vibrations and thermal noise while scanning. The stroke $z = 5 \mu\text{m}$ of the device is also dependent on the device stiffness, which sets the actuation voltage. For

the STM of interest, the actuation voltage must be less than 120 V.

The dynamics of a MEMS comb-drive actuator can be modeled as a spring-mass damper system [39], [41], [42], where the cumulative stiffness of the suspension elements of the device adds up to determine the overall device stiffness. Suspension elements that are compliant in the direction of motion (the Z-axis in this case) and stiff in the orthogonal directions are the design goal. The design criteria for this two-tip nanopositioner led to a conservative calculation of the device stiffness at 300 N/m from Eq. 2. A combination of clamped-clamped beam flexures and serpentine flexures are used to achieve the requisite device stiffness. The stiffness of a clamped-clamped beam flexure in-plane (Z) is calculated as [39]:

$$k_{ccz} = 2Ebh/L \quad (3)$$

where E is Young's modulus, b is the beam width, h is the beam thickness, and L is the length of one beam segment. Serpentine flexures were chosen to supplement the clamped-clamped beams because they provide higher stiffness in a smaller lateral area. The total stiffness provided by serpentine flexures can be calculated by breaking one serpentine beam down into an equivalent series of crab-leg flexures and summing their stiffness in series. The equation for in-plane (Z) stiffness for crab-leg flexures is calculated as [39]:

$$k_{crabz} = \frac{12E_z I_2}{L_2^3} \left(\frac{L_1 I_2 + 2L_2 I_1}{2L_1 I_2 + L_2 I_1} \right) \quad (4)$$

where E is Young's modulus, I_1 and I_2 are the second moments of inertia for segments of the crab-leg flexures, and L_1 and L_2 are the lengths of segments of the crab-leg flexures. The crab-leg flexures are added in series to get the total serpentine flexure stiffness [43]. For this design, the shuttle beams (for each tip) have two serpentine flexures and six clamped-clamped beam flexures. The number of comb-fingers, their thickness, and their overlap are optimized to hit the targeted stroke of 5 μm and the stiffness of 300 N/m.

Thermal noise is also a limiting factor in scanning probe microscopy designs. Undue thermal noise can excite mechanical resonances of the nanopositioner and may cause pull-in instability. The lightly damped nature of MEMS nanopositioners makes the impact of thermal noise especially critical; runaway noise can cause too much lateral drift for pull-in or in-plane drift and crash the tip, deteriorating the system performance. For a conventional oscillator, thermal noise can be written as [44]:

$$\bar{x}_{th} = \sqrt{\frac{k_b T}{k}} \quad (5)$$

where k_b is the Boltzmann constant, T is temperature, and k is spring stiffness. If k is increased, the thermally induced vibrations $\bar{x}_{th}$ will be proportionately decreased, but increasing k too large also means a larger actuation force F_e , and therefore more comb-fingers, is required. To satisfy both constraints, finite element analysis (FEA) simulations are done to optimize the stiffness of the clamped-clamped beams and the number of meanders of the serpentine beams. In these simulations, the in-plane Z-axis stiffness is obtained to be 371 N/m, and the

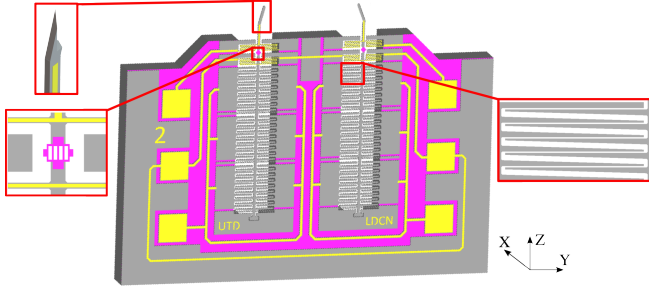


Fig. 2. A CAD rendering of the two-tip MEMS nanopositioner showing an etched tip, oxide bridge isolation, and electrostatic actuation. The actuators are rendered as parallel-plates in the software because the comb-fingers protruding from the plates are too small to be rendered.

out-of-plane stiffness in the Y-axis is obtained to be 500 N/m.

F. Finite Element Simulations

The two-tip MEMS nanopositioner is designed in CoventorWare software using the discussed device constraints. The computer aided design (CAD) model evaluated by the software measures 4.4 mm in height and 6 mm in length with a thickness of $19\mu\text{m}$. The design is composed of two tips separated by 1.5 mm with mirrored actuators and electrical isolation; each tip is connected to a shuttle beam measuring 2.7 mm in length, 4 serpentine flexures and 12 clamped-clamped beam flexures with 6 sets of eight comb-drives, each with comb-fingers measuring $2\mu\text{m}$ in width and separated by $2\mu\text{m}$. A summary of the relevant device measurements is shown in Table I.

TABLE I
MEASUREMENTS OF THE MEMS DEVICE COMPONENTS

Feature Type	Length (μm)	Width (μm)	Small Base (μm)	Large Base (μm)
C-C Flexure	300	4.3		
Serp. Flexure	300	10		
C-C Flexure w/ Routing	300	8		
Serp. Flexure w/ Routing	300	14		
Actuator Arm	285	-	20	30
Shuttle Beam	2753	40		
Tip	153	-		

The dynamic response of the MEMS nanopositioner is fully described by its natural frequencies and mode shapes since it is a distributed parameter system. FEA is used to obtain the first four mode shapes of the device, which are located at 17.7 kHz, 38.6 kHz, 46 kHz, and 49 kHz (Fig. 3). These mode shapes are in good alignment with the design requirements and show an increase in the STM bandwidth by a factor of ten. There is no danger of exciting unwanted out-of-plane resonances while scanning because successive modes are several kHz apart.

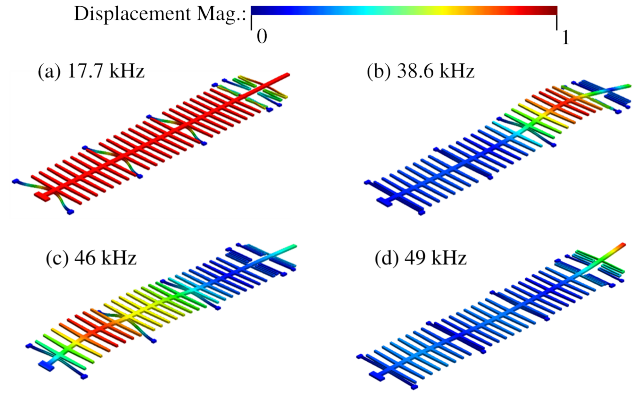


Fig. 3. Simulated mode shapes of the MEMS two-tip nanopositioner using Coventor software: (a) first mode, (b) second mode, (c) third mode and (d) fourth mode.

For comb-drive actuators, sideways instability originating from unbalanced comb-finger forces on either side of the shuttle beam limits the maximum allowable displacement of the nanopositioner. FEA is used to get an estimate of the travel range of the two-tip nanopositioner in the Z-axis before lateral pull-in occurs; the static response of the device while under electrostatic actuation is shown in Fig. 4a. The simulation shows that the tips will displace $5.8\mu\text{m}$ in the Z direction before sideways instability occurs at 124 V. This is within the design constraints, which aim to have a displacement of $5\mu\text{m}$ within 120 V.

The resonance of the nanopositioner in the Z-axis while under electrostatic actuation is also simulated. The superposition of a 20 V DC signal with a small-amplitude AC signal is applied to the nanopositioner actuators as the frequency is swept from 10 Hz to 50 kHz. The simulation assumes squeezed film damping between the actuators. The frequency response under these conditions is shown in Fig. 4b. The simulation shows that the first resonance occurs at 17.7 kHz with a dynamic range of approximately 40 dB; this is a typical response for a lightly damped MEMS device. The MEMS nanopositioner will be used in an STM under UHV conditions, so the same simulation was carried out under 10^{-10} Torr pressure and plotted in Fig. 4b. The comparison of the UHV and in-air simulations shows that the dynamic range of the nanopositioner will increase by approximately 14 dB under UHV pressure.

III. MICROFABRICATION

The MEMS nanopositioner design starts with a highly doped SOI wafer ($0.001 - 0.005\Omega\text{cm}$, N-type, $\langle 100 \rangle$ orientation) with a $20\mu\text{m}$ device layer, $2\mu\text{m}$ BOX layer, and a $490\mu\text{m}$ handle layer (Fig. 5a). The first part of the fabrication process is to build the oxide bridge for electrical isolation by etching a series of trenches down to the BOX layer with the DRIE process (Fig. 5b). The oxide bridge is then completely oxidized with wet thermal oxidation at 1100°C (Fig. 5c) and then reinforced by the deposition of a $2\mu\text{m}$ layer of conformal LPCVD oxide (Fig. 5c as well). The oxide layers are then

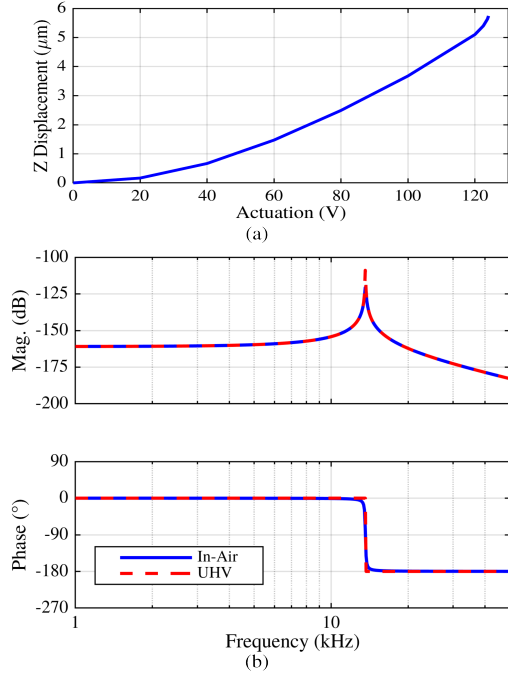


Fig. 4. Simulated characteristics of the two-tip MEMS nanopositioner using Coventor software: (a) static response and (b) frequency response in-air and under UHV pressure conditions.

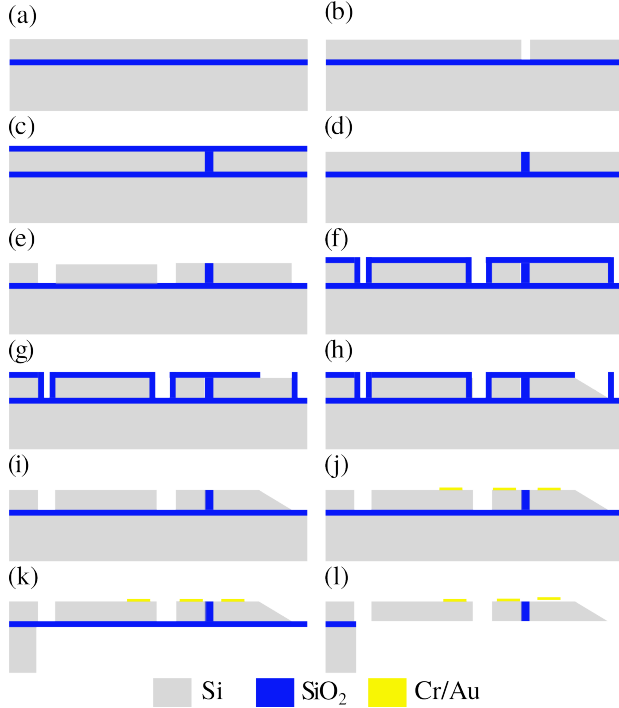


Fig. 5. An overview of the fabrication process for the nanopositioner: (a) SOI wafer, (b) formation of oxide bridge body, (c) thermal oxidation and LPCVD oxide deposition for the oxide bridge, (d) RIE of oxide layers, (e) DRIE of device layer, (f) deposition of sacrificial oxide layer, (g) RIE to form oxide openings for Si tips, (h) Si wet etch, (i) stripping of sacrificial oxide, (j) electrode deposition, (k) DRIE of handle layer and (l) RIE of BOX layer to release device.

selectively etched back with the RIE process to expose the device layer and form the oxide bridge shape.

Next, the shuttle beam, flexures, comb-drives, and bonding pads are formed with the DRIE process (Fig. 5e). The length of the Si tip body is also formed during this step with an angle of $\theta = 15^\circ$ with respect to the Si $\langle 110 \rangle$ crystallographic plane. The next steps start the process of forming the in-plane tips with a short dry oxidation at 1100°C , followed by the deposition of a $2\text{ }\mu\text{m}$ sacrificial LPCVD oxide mask (Fig. 5f) to cover the entirety of the tip body. Next, an opening is made in the sacrificial oxide with the RIE process to serve as a mask for the formation of the Si tips (Fig. 5g). The tips are then anisotropically wet etched with a 45% KOH solution (Fig. 5h), and the sacrificial oxide layers are removed with a buffered oxide wet etch solution (Fig. 5i).

The process finishes by depositing a stack of 20 nm Cr and 300 nm Au with a sputtering process followed by lift-off (Fig. 5j). The handle layer of the SOI wafer is then patterned and etched back to the BOX layer with a DRIE process (Fig. 5k). The BOX layer is then etched away with a RIE process to release the device (Fig. 5l). Fig. 6 shows SEM images of the fabricated nanopositioner, including the tips, oxide bridge, and comb-finger actuators.

IV. DEVICE CHARACTERIZATION

After fabrication, the displacement, frequency response, mode shapes, and feedthrough capacitance of the nanopositioner are empirically measured to ensure that they conform to the design constraints. This section describes this characterization.

A. Static Response

The displacement curve for the nanopositioner is found experimentally to determine the required voltage for the desired Z-axis stroke. A Polytec-MSA-100-3D laser doppler vibrometer (LDV) is used to generate a 1 Hz triangular waveform that is cascaded into a voltage amplifier before being applied to the electrostatic actuators. The LDV concurrently measures the Z-axis displacement for the corresponding actuation voltage and plots the trend, seen in Fig. 7a. The measured results show that the shuttle beam displaces $5.5\text{ }\mu\text{m}$ at 116 V for the right tip and $5.7\text{ }\mu\text{m}$ at 112 V for the left tip on the same device. This result aligns closely with the simulated results, with slight discrepancies due to fabrication tolerances. The static response experiments were not conducted to the full 120 V because it is the maximum voltage rating for the STM used in this application, so it would not be practical to run the actuators at the system's limits.

B. Frequency Response

The frequency response of the STM nanopositioner was also measured in ambient conditions with the LDV and displayed in Fig. 7b. An input voltage with a 10 V offset is generated by the LDV, and the frequency response is measured from the input voltage to the tip displacement along the Z-axis. The measured frequency response shows that the first resonant frequency of

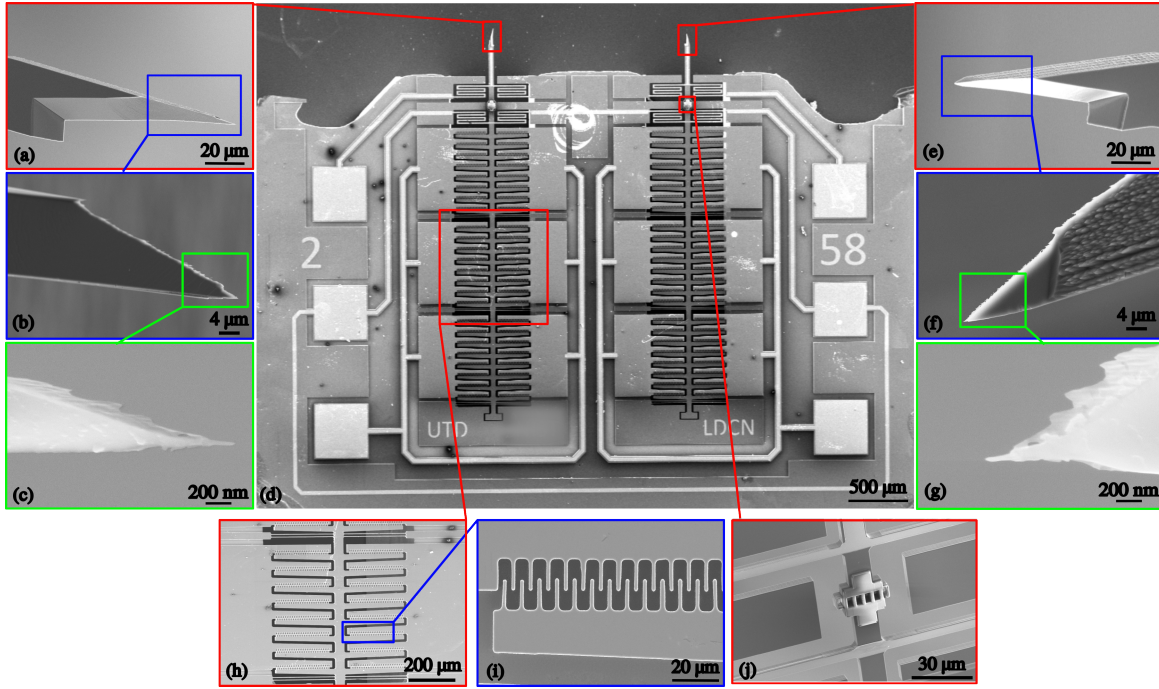


Fig. 6. SEM images of the fabricated two-tip MEMS nanopositioner: (a) the oxide bridge, (b), one section of the comb-finger actuators, (c) a close up of one pair of the comb-finger actuators, (d) the full device, (e) one of the etched Si tips, (f) a close-up view of the tip, (g) the tip apex.

the nanopositioner occurs at 15.6 kHz for the right tip and 15.8 kHz for the left tip, which is roughly 2 kHz lower than simulated due to fabrication tolerances. The simulation also did not account for all sources of damping that were present in the experiment, like the internal damping of the material. The dynamic range of the fabricated device is comparable to the FEA simulations at 50 dB. To characterize the first mode dynamic response of the system, a second-order transfer-function model $G_m(s)$ was fitted to the frequency response of the right side of the device:

$$G_m(s) = \frac{0.5636}{s^2 + 243.7s + 9.674 \times 10^9} \quad (6)$$

C. Mode Shapes

The first four mode shapes of the device were measured in ambient conditions and are depicted in Fig. 8. To measure the mode shapes, a series of predefined points is placed on the surface of the nanopositioner along the comb-drives. These points are then scanned using the LDV and the frequency response is measured at each point, sweeping from 100 Hz to 60 kHz to encompass the predicted mode shape frequencies. The measured mode shapes are: 15.6 kHz, 32.16 kHz, 43.85 kHz, and 46.16 kHz. The experimental mode shapes in Fig. 8 are in good agreement with the simulated mode shapes in Fig. 3. The slightly lower measured modes can be attributed to fabrication tolerances.

D. Cross-Coupling

Having the sensing and actuation signals placed close together on the same substrate gives rise to electrical cross-coupling, where the device layer can overlay the actuation

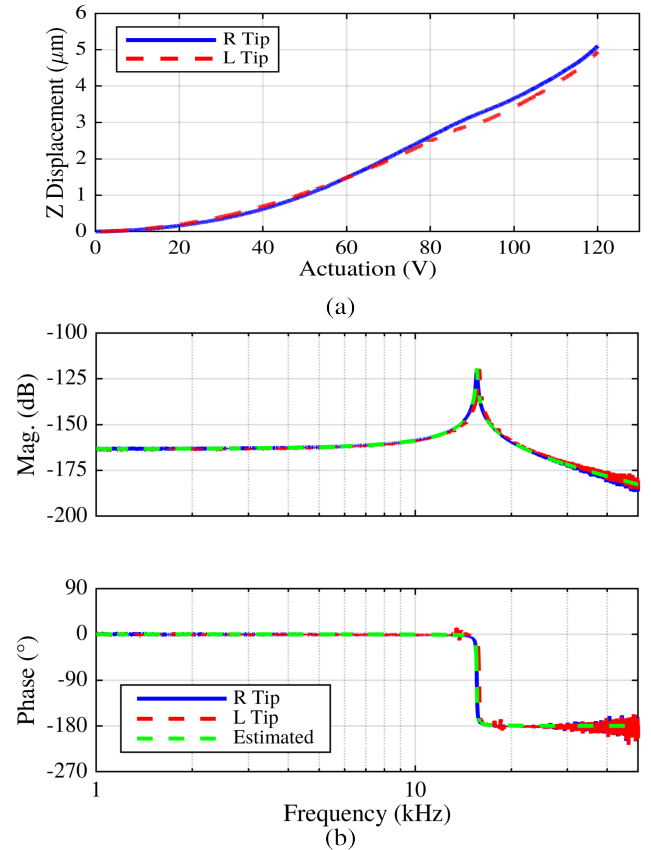


Fig. 7. Measured displacement characteristics of the MEMS nanopositioner right and left tips: (a) static response and (b) frequency response in-air with a fitted transfer function.

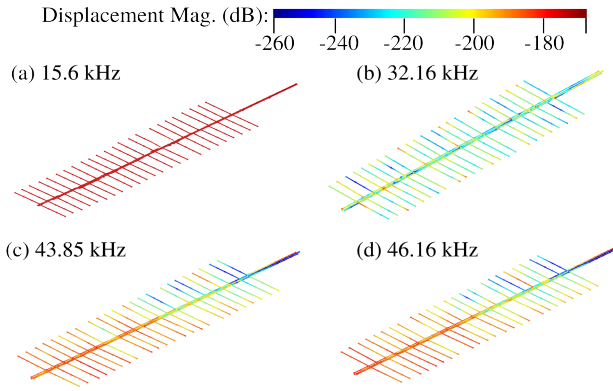


Fig. 8. The mode shapes of the MEMS nanopositioner measured using a LDV: (a) first mode, (b) second mode, (c) third mode and (d) fourth mode.

signal on the sensor output. This effect is also referred to as electrical feedthrough, and is modeled as a capacitor between the actuation and sensing outputs. This is an important effect to mitigate, especially for STM, as the tunneling current amplitude is in the nano-ampere range and a strong feedthrough signal can corrupt the delicate current.

The feedthrough capacitance and impedance between sensing and actuation were measured with an impedance analyzer. The measurements show that the capacitance is less than 11 pF and the impedance is less than 200 M Ω . The impedance was also measured between the actuation and sensing for opposite tips to ensure there isn't a significant impedance to overcome between sides; the impedance across the device was measured to be less than 400 M Ω . No adverse effects on the tunneling current measurements are expected from the feedthrough effect since the capacitance and impedance have resonant frequencies well beyond the bandwidth of the STM.

The mechanical cross-coupling between the two halves of the nanopositioner was calculated using an LDV. To quantify the coupling, the frequency response was measured in four configurations: from left sensing to left actuation, from left sensing to right actuation, from right sensing to right actuation, and from right sensing to left actuation. The results showed that the frequency responses on the same side of the device matched the results shown in Fig. 7. Measurements that crossed the device were lost completely in the noise floor of the voltage amplifier of the LDV, signifying no strong mechanical coupling between left and right sensing or actuation.

V. EXPERIMENTS

To determine the capabilities of the two-tip MEMS nanopositioner to work in an STM, the device is tested in ambient conditions by establishing tunneling current on a highly ordered pyrolytic graphite (HOPG) sample. This section details the experimental setup and the closed-loop architecture that controls the tip-approach mechanism, and concludes with the tunneling current results.

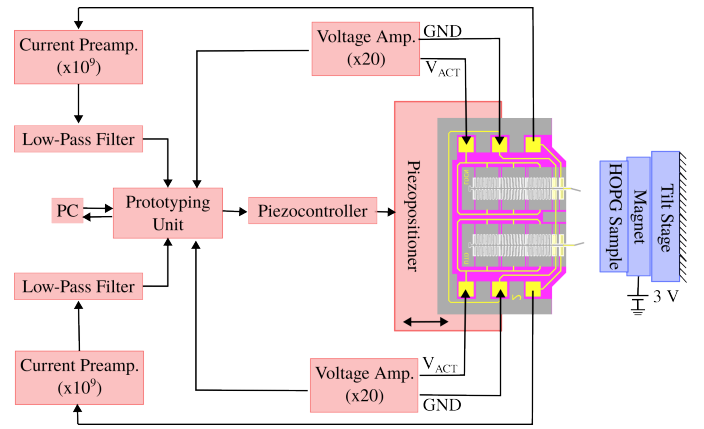


Fig. 9. A schematic of the experimental setup for establishing tunneling current with the two-tip array in ambient conditions.

A. Experimental Setup

To establish tunneling current with two tips in air, the MEMS device is mounted on a custom printed circuit board (PCB) that is fastened to a 3-DOF piezopositioner (P-363.3CD, Physik Instrumente) for coarse movement in the Z-axis. The piezopositioner is driven by a digital piezocontroller in closed-loop mode (E-536.3CH, Physik Instrumente). The fine Z-axis movement is realized by the comb-finger actuators of the MEMS device. A rapid prototyping unit (MicroLabBox, dSPACE) operating at a 80 kHz sampling frequency is used to regulate the tip-sample distance and run the approach process. The sample is a HOPG sample magnetically clamped in a vertical positioner with 3 V applied across it. The sample is fastened to a tilt stage so the sample orientation can be adjusted to compensate for potentially out-of-plane tips. The tips are virtually grounded at the input of the current preamplifier, and a tunneling current setpoint of 0.3 nA is maintained by the prototyping unit.

To measure the tunneling current from each tip, a two-channel, low-noise current preamplifier (HF2TA, Zurich Instruments) is used to amplify the current with a gain of 1 V/nA. A low-pass filter is used after the current preamplifier to filter out 60 Hz noise in the delicate current measurements. The command signal generated by the prototyping unit passes through a voltage amplifier with a fixed gain of 20 (A400DI, FLC Electronics) to drive the electrostatic MEMS actuators for each tip. Fig. 9 shows a schematic of the experimental setup.

B. Closed-Loop Architecture

After the tips have approached the sample and established tunneling current, a feedback loop in the prototyping unit produces a control command to maintain the current at a setpoint of 0.3 nA. The structure of the feedback loop is shown in Fig. 10. The control command $u(t)$ from the prototyping unit is amplified by the voltage amplifier $G_{AMP}(s)$ to drive the nanopositioner $G_M(s)$, with a separate control command being sent to the actuation for each tip. The control command regulates the tip-sample distance δ to maintain tunneling current; the tip-sample distance is approximately equal to the barrier thickness, which includes the initial distance between

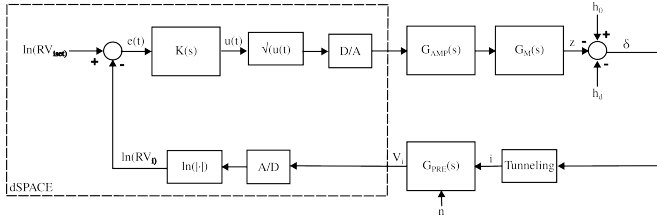


Fig. 10. A schematic of the closed-loop feedback control loop used to establish tunneling current for each tip. The controller $K(s)$ is an integrator, and a square-root function is used to linearize the quadratic relationship between displacement and actuation voltage.

tip and sample h_0 , displacement z , and disturbances h_d . The tunneling current is related to δ by [45]:

$$i = \sigma V_b e^{-1.025\sqrt{\varphi}\delta} \quad (7)$$

In this equation, σ is a constant that encompasses the material properties of the tip and sample, V_b is the bias voltage of the sample, and φ is the barrier height. The nano-ampere current i from each tip is converted to a measurable voltage V_i by the current preamplifier $G_{PRE}(s)$. The gain of the preamplifier R is set to 1 V/nA, subject to measurement noise n . Due to the exponential relationship between current and the tip-sample gap δ , a natural logarithm must be implemented in the feedback loop of the prototyping unit:

$$\ln(Ri) = \ln(R\sigma V_b) - 1.025\sqrt{\varphi}\delta \quad (8)$$

The logarithm of the current $\ln(RV_i)$ is subtracted from the setpoint $\ln(RV_{i\text{set}})$ to obtain an error signal $e(t)$. The error signal is fed into an integrator $K(s)$ to generate the control command $u(t)$. The integrator is realized with a continuous-time representation due to the high sampling frequency, with an integrator gain K_i of 0.5:

$$K(s) = \frac{K_i}{s} \quad (9)$$

Finally, a square root function must be applied to the control command to account for the quadratic relationship between displacement and voltage in electrostatic actuators before the signal is converted and sent to the voltage amplifier.

C. Results

Two sets of voltage and current setpoints are used for this experiment to ensure that the two-tip array can operate under a variety of typical STM conditions. The two setpoints used for the in-air tunneling current experiments were 0.3 nA and 3 V, and 0.5 nA and 1 V. Fig. 11 and Fig. 12 show the tunneling current established and maintained simultaneously by the left and right tips at 0.3 nA and 0.5 nA. With each current setpoint, the array nanopositioner can maintain tunneling for approximately 2 minutes for each tip before the tips are retracted individually. Due to slight variations in tip length, the left tips approach before the right tips in both figures. The root mean square (RMS) error between the current and the setpoint for the left tip is 0.16 nA and for the right tip is 0.18 nA, predominantly due to drift in the in-air setup. A final set of approach results was also obtained with different

tunneling current and bias voltage set points on the two halves of the device in Fig. 13. Here, the left tip had a current set point of 0.6 nA with a bias voltage of 1 V, and the right tip had a current set point of 0.4 nA and a bias voltage of 3 V. This result proves that the tips are able to maintain separate current set points for 2 minutes each before the tips are individually retracted. The same observations on coupling and power spectral density are present here. The RMS error between the current and the setpoint for the left tip is 0.22 nA and for the right tip is 0.25 nA, which is within the expected variance for tunneling current. The approach experiments were performed multiple times with multiple array nanopositioners without crashing any tips.

Because the two tips approached the sample at different times, significant observations on the electrical cross-coupling between the tips can be made. In Fig. 11, the left tip approaches first at 20 seconds and the right tip approaches 40 seconds later, at 1 minute. Monitoring the tunneling current signal of the right tip from 20 seconds to 1 minute shows that there is no current signal until the right tip approaches on its own. The control command plot of the right tip verifies this observation, as the control command signal does not peak until the right tip approaches on its own. Large electrical coupling would cause the right control command to compensate for the tunneling current of the left tip before the right tip has landed, but this is not the case here. The same observation can be made for the left tip from approximately 2 minutes to 3 minutes, when the left tip has retracted, but the right tip is tunneling. The tunneling current and control command signals do not show any feedthrough from the right tip while the left tip is retracted. Fig. 12 mimics the behaviors shown in Fig. 11. These observations indicate that there is no significant electrical coupling between the two halves of the array nanopositioner.

The power spectral density plots of the tunneling current in Fig. 11 and Fig. 12 show a primarily flat response, which is attributed to white noise. The plots also display a low-frequency roll-off from flicker noise due to charge trapping in the MEMS device [46]. The high-frequency attenuation from the current preamplifier cutoff frequency is not visible in the power spectral density plots because the bandwidth of the current preamplifier exceeds the limits of the plot.

VI. CONCLUSION

This work presented the first individually actuated, batch processed two tip MEMS array for the STM. The design utilizes an in-plane Si tip and comb-drive actuators to realize a large stroke and high displacement. The device is intended to be integrated into commercial STM systems by replacing the small-scale Z-axis movements of the piezotube; after fabrication, the device is measured to have a stroke nearly twice as large as a piezotube and a bandwidth beyond 15 kHz. Verification of the MEMS array is performed by establishing tunneling current with both tips concurrently in ambient conditions on an HOPG sample.

The primary advantage of the two-tip nanopositioner is that it opens opportunities for highly parallel STM nanopositioner

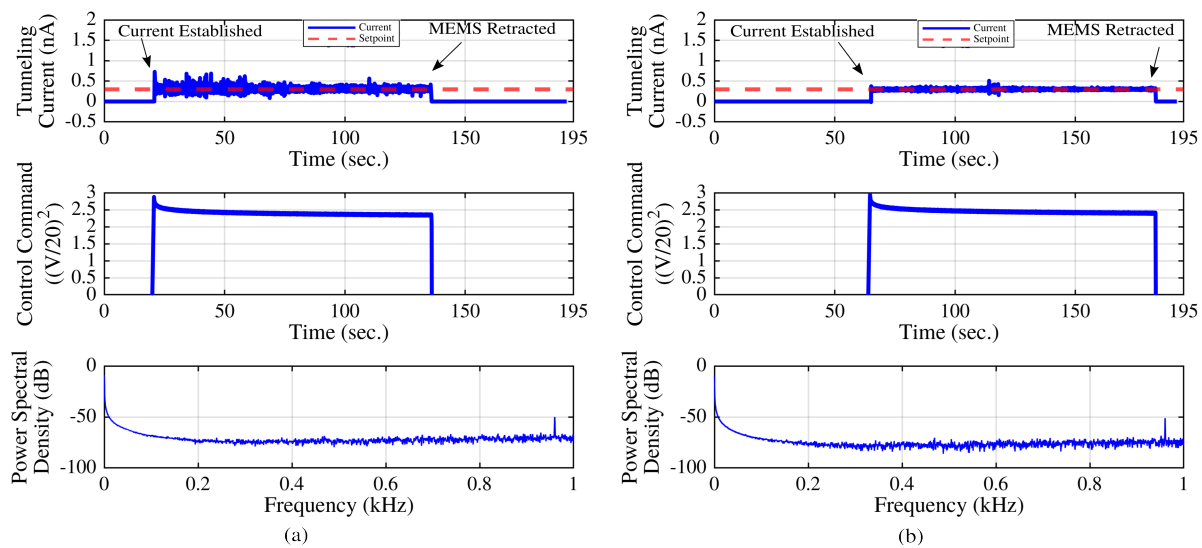


Fig. 11. Tunneling current for both tips in the array when approaching the HOPG sample together at a current setpoint of 0.3 nA and a bias voltage of 3 V: (a) the left tip with Z-command signal and power-spectral density, and (b) the right tip with Z-command signal and power-spectral density.

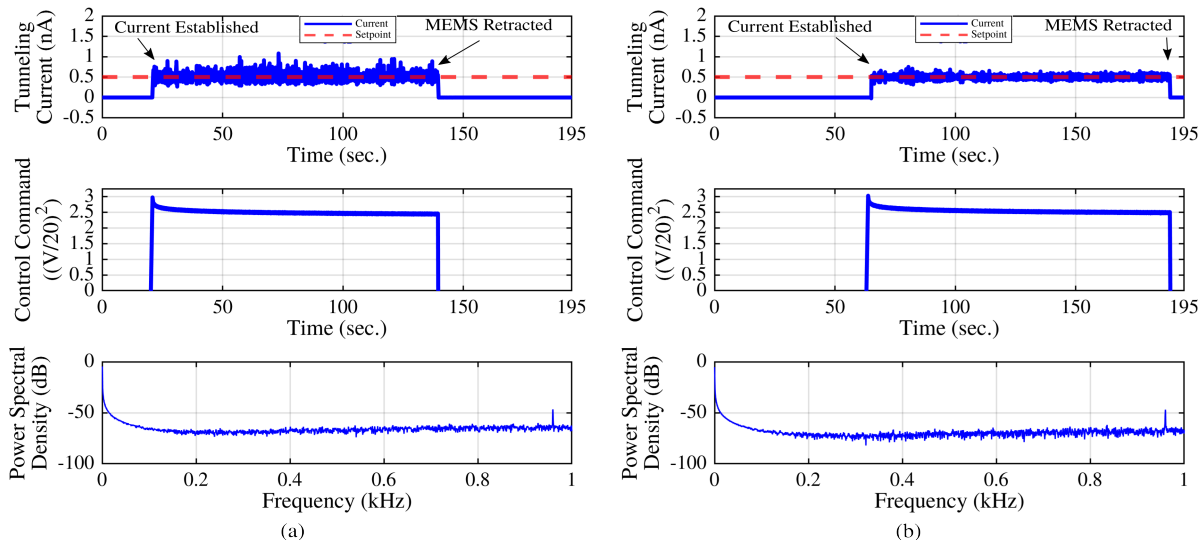


Fig. 12. Tunneling current for both tips in the array when approaching the HOPG sample together at a current setpoint of 0.5 nA and a bias voltage of 1 V: (a) the left tip with Z-command signal and power-spectral density, and (b) the right tip with Z-command signal and power-spectral density.

designs through its in-plane tip and efficient comb-drive actuation; scalable nanopositioner designs are paramount for increasing STM throughput and patterning speeds. Future work will involve incorporating the array into a commercial STM under UHV conditions for tandem imaging and lithography.

REFERENCES

- [1] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, "Surface Studies by Scanning Tunneling Microscopy," *Phys. Rev. Lett.*, vol. 49, pp. 57–61, Jul 1982.
- [2] G. Binnig and H. Rohrer, "Scanning Tunneling Microscopy," *Surface Science*, vol. 126, no. 1, pp. 236–244, 1983.
- [3] J. N. Randall, J. H. G. Owen, J. Lake, and E. Fuchs, "Next Generation of Extreme-Resolution Electron Beam Lithography," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, vol. 37, no. 6, p. 061605, 10 2019. [Online]. Available: <https://doi.org/10.1116/1.5119392>
- [4] Y. Sugimoto, Y. Nakajima, D. Sawada, K.-i. Morita, M. Abe, and S. Morita, "Simultaneous AFM and STM Measurements on the Si(111)-(7 × 7) Surface," *Phys. Rev. B*, vol. 81, p. 245322, Jun 2010. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevB.81.245322>
- [5] J. Lyding, "UHV STM Nanofabrication: Progress, Technology Spin-Offs, and Challenges," *Proceedings of the IEEE*, vol. 85, no. 4, pp. 589–600, 1997.
- [6] Y. Ling, Z. Wang, W. Wang, T. Zhang, and W. Xu, "A Perspective to STM Manipulation at the Atomic Scale," *Applied Physics Letters*, vol. 127, no. 7, p. 070502, 08 2025. [Online]. Available: <https://doi.org/10.1063/5.0270784>
- [7] S. Rubel, M. Trochet, E. E. Ehrichs, W. F. Smith, and A. L. de Lozanne, "Nanofabrication and Rapid Imaging with a Scanning Tunneling Microscope," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, vol. 12, no. 3, pp. 1894–1897, 05 1994. [Online]. Available: <https://doi.org/10.1116/1.587664>
- [8] G. M. Shedd and P. Russell, "The Scanning Tunneling Microscope as a Tool for Nanofabrication," *Nanotechnology*, vol. 1, no. 1, p. 67, jul 1990. [Online]. Available: <https://doi.org/10.1088/0957-4484/1/1/012>
- [9] L. Bi, K. Liang, G. Czap, H. Wang, K. Yang, and S. Li, "Recent Progress in Probing Atomic and Molecular Quantum Coherence with Scanning Tunneling Microscopy," *Progress in Surface*

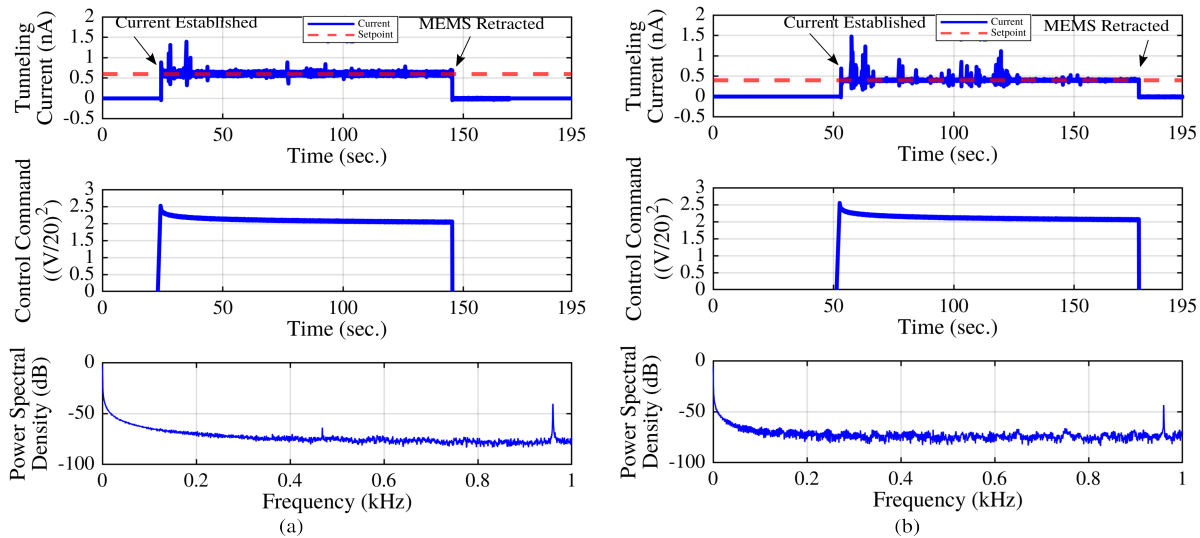


Fig. 13. Tunneling current for both tips in the array when approaching the HOPG sample together at a current setpoint of 0.6 nA and 1 V on the left tip and 0.4 nA and 3 V on the right tip: (a) the left tip with Z-command signal and power-spectral density, and (b) the right tip with Z-command signal and power-spectral density.

- Science, vol. 98, no. 1, p. 100696, 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0079681622000442>
- [10] F. Trixler, "Quantum Tunnelling to the Origin and Evolution of Life," *Current Organic Chemistry*, vol. 17, no. 16, pp. 1758–1770, 2013.
- [11] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, "7 × 7 Reconstruction on Si(111) Resolved in Real Space," *Phys. Rev. Lett.*, vol. 50, pp. 120–123, Jan 1983. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.50.120>
- [12] J. N. Randall, J. W. Lyding, S. Schmucker, J. R. Von Ehr, J. Ballard, R. Saini, H. Xu, and Y. Ding, "Atomic Precision Lithography on Si," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, vol. 27, no. 6, pp. 2764–2768, 2009. [Online]. Available: <https://avs.scitation.org/doi/abs/10.1116/1.3237096>
- [13] V. R. Manfrinato, L. Zhang, D. Su, H. Duan, R. G. Hobbs, E. A. Stach, and K. K. Berggren, "Resolution Limits of Electron-Beam Lithography toward the Atomic Scale," *Nano Letters*, vol. 13, no. 4, pp. 1555–1558, 2013, pMID: 23488936. [Online]. Available: <https://doi.org/10.1021/nl304715p>
- [14] F. Tajaddodianfar, S. O. R. Moheimani, J. H. G. Owen, and J. N. Randall, "On the Effect of Local Barrier Height in Scanning Tunneling Microscopy: Measurement Methods and Control Implications," *Review of Scientific Instruments*, vol. 89, no. 1, 2018.
- [15] F. Tajaddodianfar, S. O. R. Moheimani, and J. N. Randall, "Scanning Tunneling Microscope Control: A Self-Tuning PI Controller Based on Online Local Barrier Height Estimation," *IEEE Transactions on Control Systems Technology*, vol. 27, no. 5, pp. 2004–2015, 2019. [Online]. Available: <https://doi.org/10.1109/TCST.2018.2844781>
- [16] Y. Cao and X. B. Chen, "A Survey of Modeling and Control Issues for Piezo-electric Actuators," *Journal of Dynamic Systems, Measurement, and Control*, vol. 137, no. 1, p. 014001, 08 2014. [Online]. Available: <https://doi.org/10.1115/1.4028055>
- [17] E. Anguiano, A. I. Oliva, and M. Aguilar, "Optimal Conditions for Imaging in Scanning Tunneling Microscopy: Theory," *Review of Scientific Instruments*, vol. 69, no. 11, pp. 3867–3874, 11 1998. [Online]. Available: <https://doi.org/10.1063/1.1149191>
- [18] G. Schitter, K. J. Astrom, B. E. DeMartini, P. J. Thurner, K. L. Turner, and P. K. Hansma, "Design and Modeling of a High-Speed AFM-Scanner," *IEEE Transactions on Control Systems Technology*, vol. 15, no. 5, pp. 906–915, 2007.
- [19] T. Ando, N. Kodera, T. Uchihashi, A. Miyagi, R. Nakakita, H. Yamashita, and K. Matada, "High-speed Atomic Force Microscopy for Capturing Dynamic Behavior of Protein Molecules at Work," *e-Journal of Surface Science and Nanotechnology*, vol. 3, pp. 384–392, 01 2005.
- [20] Y. K. Yong and S. O. R. Moheimani, "Design of an Inertially Counterbalanced Z-Nanopositioner for High-Speed Atomic Force Microscopy," *IEEE Transactions on Nanotechnology*, vol. 12, no. 2, pp. 137–145, 2013.
- [21] S. P. Wadikhaye, Y. K. Yong, and S. O. R. Moheimani, "A Serial-Kinematic Nanopositioner for High-Speed Atomic Force Microscopy," *Review of Scientific Instruments*, vol. 85, no. 10, p. 105104, 10 2014. [Online]. Available: <https://doi.org/10.1063/1.4897483>
- [22] A. J. Fleming, "Dual-Stage Vertical Feedback for High-Speed Scanning Probe Microscopy," *IEEE Transactions on Control Systems Technology*, vol. 19, no. 1, pp. 156–165, 2011.
- [23] J. N. Randall, J. H. G. Owen, J. Lake, R. Saini, E. Fuchs, M. Mahdavi, S. O. R. Moheimani, and B. C. Schaefer, "Highly Parallel Scanning Tunneling Microscope Based Hydrogen Depassivation Lithography," *Journal of Vacuum Science & Technology B*, vol. 36, no. 6, p. 06JL05, 10 2018. [Online]. Available: <https://doi.org/10.1116/1.5047939>
- [24] M. Maroufi, A. G. Fowler, and S. O. R. Moheimani, "MEMS for Nanopositioning: Design and Applications," *Journal of Microelectromechanical Systems*, vol. 26, no. 3, pp. 469–500, 2017.
- [25] E. C. M. Disseldorp, F. C. Tabak, A. J. Katan, M. B. S. Hesselberth, T. H. Oosterkamp, J. W. M. Frenken, and W. M. van Spengen, "MEMS-based High Speed Scanning Probe Microscopy," *Review of Scientific Instruments*, vol. 81, no. 4, p. 043702, 04 2010. [Online]. Available: <https://doi.org/10.1063/1.3361215>
- [26] S. Akamine, T. Albrecht, M. Zdeblick, and C. Quate, "Microfabricated Scanning Tunneling Microscope," *IEEE Electron Device Letters*, vol. 10, no. 11, pp. 490–492, 1989.
- [27] M. Mita, H. Kawara, H. Toshiyoshi, J. Endo, and H. Fujita, "Bulk Micromachined Tunneling Tips Integrated with Positioning Actuators," *Journal of Microelectromechanical Systems*, vol. 14, no. 1, pp. 23–28, 2005.
- [28] M. Bulut Coskun, M. Baan, A. Alipour, and S. O. R. Moheimani, "Design, Fabrication, and Characterization of a Piezoelectric AFM Cantilever Array," in *2019 IEEE Conference on Control Technology and Applications (CCTA)*, 2019, pp. 227–232.
- [29] T. Kim and J. J. Gorman, "A 3-DOF MEMS Motion Stage for Scanning Tunneling Microscopy," in *2022 IEEE 35th International Conference on Micro Electro Mechanical Systems Conference (MEMS)*, 2022, pp. 470–472.
- [30] Y. Tang, Y. Zhang, G. K. Fedder, and L. R. Carley, "A Dual Probe STM Imaging System and a Low Noise Switched-Capacitor Transimpedance Amplifier," *IEEE Sensors Journal*, vol. 13, no. 8, pp. 2984–2992, 2013.
- [31] M. Leeuwenhoek, R. A. Norte, K. M. Bastiaans, D. Cho, I. Battisti, Y. M. Blanter, S. Gröblacher, and M. P. Allan, "Nanofabricated Tips for Device-Based Scanning Tunneling Microscopy," *Nanotechnology*, vol. 30, no. 33, p. 335702, may 2019. [Online]. Available: <https://doi.org/10.1088/1361-6528/ab1c7f>
- [32] A. Alipour, M. B. Coskun, and S. O. R. Moheimani, "A High Bandwidth Microelectromechanical System-Based Nanopositioner for Scanning Tunneling Microscopy," *Review of Scientific Instruments*, vol. 90, no. 7, p. 073706, 2019.

- [33] A. Alipour, S. O. R. Moheimani, J. H. G. Owen, E. Fuchs, and J. N. Randall, "Atomic Precision Imaging with an On-Chip STM Integrated into a Commercial UHV STM System," *Journal of Vacuum Science & Technology B*, vol. 39, no. 4, 2021.
- [34] A. Alipour, E. Fowler, S. O. R. Moheimani, J. H. G. Owen, and J. N. Randall, "Atomic-Resolution Lithography with an On-Chip Scanning Tunneling Microscope," *Journal of Vacuum Science & Technology B*, vol. 40, p. 030603 (5pp), 2022.
- [35] A. Alipour, M. B. Coskun, and S. O. R. Moheimani, "A MEMS Nanopositioner with Integrated Tip for Scanning Tunneling Microscopy," *IEEE Journal of Microelectromechanical Systems*, vol. 30, no. 2, pp. 271 – 280, 2021.
- [36] A. Alipour, E. Fowler, S. O. R. Moheimani, J. H. G. Owen, and J. N. Randall, "Atom-Resolved Imaging with a Silicon Tip Integrated into an On-Chip Scanning Tunneling Microscope," *Review of Scientific Instruments*, vol. 95, no. 3, pp. 033703–7pp, 2024.
- [37] J. Nunes, G. and N. M. Amer, "Atomic Resolution Scanning Tunneling Microscopy with a Gallium Arsenide Tip," *Applied Physics Letters*, vol. 63, no. 13, pp. 1851–1853, 09 1993. [Online]. Available: <https://doi.org/10.1063/1.110654>
- [38] R. Ried, H. Mamin, B. Terris, L.-S. Fan, and D. Rugar, "6 – MHz 2 – N/m piezoresistive atomic-force microscope cantilevers with IN-CISIVE tips," *Journal of Microelectromechanical Systems*, vol. 6, no. 4, pp. 294–302, 1997.
- [39] R. Legtenberg, A. W. Groeneveld, and M. Elwenspoek, "Comb-Drive Actuators for Large Displacements," *Journal of Micromechanics and Microengineering*, vol. 6, no. 3, p. 320, sep 1996. [Online]. Available: <https://doi.org/10.1088/0960-1317/6/3/004>
- [40] B. Borovic, F. L. Lewis, A. Q. Liu, E. S. Kolesar, and D. Popa, "The Lateral Instability Problem in Electrostatic Comb Drive Actuators: Modeling and Feedback Control," *Journal of Micromechanics and Microengineering*, vol. 16, no. 7, p. 1233, may 2006. [Online]. Available: <https://doi.org/10.1088/0960-1317/16/7/017>
- [41] S. I. Moore, M. B. Coskun, T. Alan, A. Neild, and S. O. R. Moheimani, "Feedback-Controlled MEMS Force Sensor for Characterization of Microcantilevers," *Journal of Microelectromechanical Systems*, vol. 24, no. 4, pp. 1092–1101, 2015.
- [42] M. Bulut Coskun, S. Moore, S. O. R. Moheimani, A. Neild, and T. Alan, "Zero Displacement Microelectromechanical Force Sensor Using Feedback Control," *Applied Physics Letters*, vol. 104, no. 15, p. 153502, 04 2014. [Online]. Available: <https://doi.org/10.1063/1.4871380>
- [43] N. Duong, N. Chien, D. Hieu, and H. Chu, "Performance Analysis of Serpentine Springs Compliant to Out-of-Plane Oscillation," *Journal of Theoretical and Applied Mechanics*, pp. 91–101, 12 2021.
- [44] P. R. Saulson, "Thermal Noise in Mechanical Experiments," *Phys. Rev. D*, vol. 42, pp. 2437–2445, Oct 1990. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevD.42.2437>
- [45] B. Voigtländer, *Part III: Scanning Tunneling Microscopy and Spectroscopy*.
- [46] J.-F. Ge, M. Ovadia, and J. E. Hoffman, "Achieving Low Noise in Scanning Tunneling Spectroscopy," *Review of Scientific Instruments*, vol. 90, no. 10, p. 101401, 10 2019. [Online]. Available: <https://doi.org/10.1063/1.5111989>