Non-contact Displacement Measurement by Dynamic Contrast Auto Focusing

Evgeniy Makagon*, Sergei Khodorov*, Anatoly I. Frenkel, Leonid Chernyak and Igor Lubomirsky

***Abstract*— A non-contact displacement system suitable for tracking slow moving surfaces with low reflectivity is demonstrated. The displacement is measured by dynamic tracking of the moving focal plane of the sample under test. The system comprises a camera, a vertical digital piezo driver and a data acquisition module. The tracking effect is achieved by continuously driving the sample with a 2µm sweep around the focal plane, simultaneously acquiring sample position and images of the part of the sample defined as a region of interest (ROI). The position of the focal plane is identified by fitting the (contrast of ROI) vs. (stage position) dependence to a Gaussian. Use of ROI provides the ability to test various regions across the object and eliminates the demand for the surface to be flat or reflective. The system is low cost, applicable to a large variety of samples and has an accuracy better than 10 nm.**

***Index Terms*— Contrast auto focusing, Displacement measurement.**

I. Introduction

Displacement measurements are of great demand for various scientific and industrial purposes [1-4]. While some methods such as push-rod dilatometry and scanning probe microscopy require a physical contact with the surface under testing, non-contact methods are often preferred for measurements of sub-mm size objects. Non-contact displacement sensing is typically based on capacitive[5, 6], inductive[7] or optical sensors. Capacitive and inductive methods work with electrically conductive surfaces, which restricts the variety of samples that can be handled by these methods. Moreover, both inductive and capacitive sensors have to be positioned in a close proximity to the surface. Hence, they may suffer from poor stability because small fluctuations of the sample temperature render the measurements inaccurate. Furthermore, both techniques are based on application of electric or magnetic field, which may be detrimental for the measurement accuracy of micro/nano electromechanical systems (M/NEMS) devices.

Optical techniques for measuring distance/displacement do not require close proximity to the sample, or a conductive surface and potentially can be very accurate. Optical sensing techniques vary widely from the simplest light intensity, optical fiber based sensors to highly complex and expensive interferometric based methods [1, 8-13]. Most optical techniques currently in use require expensive laser equipment, reflective surfaces and mechanically/thermally stable environment. The latter requirements are especially critical for slow moving surfaces because most of the thermal drift noise occurs at low frequencies. In this view, a simple non-contact method to monitor slow displacement of poorly reflective surfaces may be beneficial for a range of applications.

Recent advances in the piezoelectric-driven stages, providing highly reproducible positioning with an accuracy better than 5 nm, opened new possibilities for constructing displacement monitoring systems for MEMS. In this report, we describe a simple white light-based non-contact system operating on a dynamic focus detection principle to monitor displacement. The apparatus comprises three components: a camera, a high-accuracy vertical piezoelectric positioner (stage), and a data collection module to track the focal plane of the device under test. It does not require the surface under investigation to be reflective nor does it impose limitations on surface shape and geometry. The system can be implemented with relatively inexpensive components. It has a short stabilization time and can conduct displacement measurements of samples with <10nm resolution.

II. Description of Experimental Setup

The non-contact displacement measurement system and its components are depicted in Fig. 1 and Fig. 2. The sample (1 in Fig. 1 and inset in Fig. 2) is mounted on a XYZ piezo stage (PI-Physik Instrumente GmbH & Co) (2), equipped with manual position adjusting unit. The sample is connected to an arbitrary waveform generator (DG4102, Rigol) (3) and a high precision source measuring unit (B2901A, Keysight) (4) functioning as a multimeter. A high power resistive heating power supply and temperature controller were implemented inside the sample

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Evgeniy Makagon, Sergei Khodorov and Igor Lubomirsky are with the Department of Materials and Interfaces, Weizmann Institute of Science, Rehovot, Israel. (e-mail: Igor.Lubomirsky@weizmann.ac.il).

Anatoly I. Frenkel is with the Brookhaven National Laboratory, NY, USA and the Department of Materials Science and Chemical Engineering, Stony Brook University, NY, USA.

Leonid Chernyak is with the Department of Physics, University of Central Florida, FL, USA.

holder (PTC10, Stanford Research systems) (5). A camera (Sony IMX273 CMOS sensor 1456x1088, 12 bit, 165 f/s) (6) is mounted on a custom made microscope unit (7) equipped with a 5000K led light source (8) and a 50x, long working distance (18mm) infinity corrected objective (SLMPlan 50, Olympus)(9). Piezo stage controller (E-709 nano-positioning piezo controller, PI-Physik Instrumente GmbH & Co) (10) is connected to a multi-channel data acquisition module (DAQ-USB-6000, NI-National Instruments) (11) for real time stage position recording (C to P port connection in Fig. 1). The piezo-stage trigger is connected to the acquisition module and the camera to ensure simultaneous data recording. The whole system is mounted in a thermally insulated box to minimize temperature fluctuations.

III. Principle of Operation

The algorithm (Fig. 3) utilizes contrast-based autofocusing principle often used for static objects[14] and adds a dynamic focus-tracking capability via a continuous scan around the focal point. In order to identify the focal point of a continuously moving surface, the stage with the object of interest mounted on it, is driven back and forth in a 2 μm range around the initial focal point. The position of the piezo-stage is continuously recorded (Fig. 4a), while the camera simultaneously acquires continuous images of the object: 70 frames per 2 μm of the vertical movement of the stage. The contrast of the part of the image that is of interest for investigation is calculated for each frame from the pixel variance of the grayscale brightness. The dependence of the contrast on time is fitted to a Gaussian function, the center of which is interpreted as the focal point (0.516 ± 0.005 s, grey dashed line in Fig. 4b as an example). The dependence of the stage position on time is fitted to a linear regression, giving an exact stage position at a given time. The absolute position of the focal plane is deduced from the time, at which the Gaussian fit of the contrast reaches maximum (blue dashed line in Fig. 4b).

To obtain a reliable tracking of the sample position, the movement of the sample has to be less than 1/50 of a single sweep length (2μm). Considering the manufacture recommended stage sweep velocity of 2μm/s, the system is applicable for the objects moving slower than 0.08 μm/s. When measuring periodic signals, the best results are achieved with sampling at a frequency that is at least 50 times higher than that of the sample. For the example shown below, a 700 mHz sampling frequency was used for monitoring the sample oscillating at < 35 mHz.

The initial focal position is brought manually to the mid-range (25μm of 50 μm) of the stage and the initial focal point is roughly estimated by a fast focus detection algorithm described below. The stage is swept ≈10 μm around the manually set focal point with the step size of 50nm determining the contrast of the images at each step. The initial focus position is determined by taking the stage coordinate, at which the contrast value reached a maximum. To minimize thermal fluctuations, the system is mounted in a cabinet with inner walls covered by a foam used for sound absorption. Because of the efficient thermal insulation, the system undergoes thermal equilibration (for up to 90 min), during which the focal point may drift by up to 5μm (Fig. 5a). Once the thermal equilibrium of the measurement system with the insulating box is reached, the thermal drift has a standard deviation of 7 nm over the course of 2 h (Fig. 5b). This is despite the fact that the temperature outside the box fluctuated more than 3°.

The accuracy of the measurement strongly depends on the quality of the Gaussian fit of the "contrast – time" dependence. Most accurate results were achieved when the Gaussian profile was centered in the sweeping window, which, for the samples used for this study (see below), is 2 μm. To maintain the sweeping window centered on the focal point, each time when the focal point shifted beyond 10% of the sweeping range, the sweeping range was shifted accordingly.

During the measurements, the contrast value is calculated over a certain region of interest (ROI) of the acquired images. The size of ROI may range from tens to thousands of pixels of the image. Selection of ROI is based on two considerations. (1) With sufficiently large ROI, the points with outlying values of brightness (both low and high) are smoothed out, making the result much more reliable with respect to small area-based techniques, like interferometry or scanning probe microscopy. (2) By selecting different ROIs, different areas of the samples can be probed. Thus, the system can work with the samples exhibiting non-uniform displacement. In this view, ROI can provide an average displacement over a whole sample or probe different parts of it.

IV. Experimental Verification

The system was tested with the electro-chemo-mechanical (ECM) devices described in ref. [15]: thin film self-supported structures that are 2 mm in diameter and 2 μm thick (Fig. 2 inset). Electric bias forces the opposite surfaces (top and bottom) to undergo expansion/contraction forcing the structure to bend with a characteristic response time of ≈10 s. Bending causes maximum displacement in the center, while the edges remain clamped. Therefore, the ROI was selected in the center of the sample (150x150 pixels) (Fig. 2 inset), where the displacement was approximately uniform. Alternating electric bias of 8V at 10 mHz (red line in Fig. 6a) resulted in periodic displacement of ≈0.6 μm, easily traced by the measurement system. The magnitude of the displacement was independently verified with SPM and both values were found to be in good agreement, proving the viability of the method described above. The system remains reliable upon heating to at least 60 °C, with no significant increase in the thermal equilibration time. (Fig. 6b).

V. Conclusions

A non-contact displacement system suitable for tracking slow moving surfaces with low reflectivity is demonstrated. The displacement is measured by dynamic tracking of the moving focal plane of the sample under test. The system comprises a camera, a vertical digital piezoelectric positioner (stage) and a data acquisition module. The tracking effect is achieved by continuously driving of the sample with a 2µm sweeping range around the focal plane, simultaneously acquiring sample position and images of the sample surface. The position of the focal plane is identified according to a contrast based focus detection algorithm. The system is low cost and can be used with a large variety of samples as it does not require specific surface geometry/morphology or close proximity to the surface. Selection of a region of interest provides the ability to measure several regions at once, use selective area averaging and offers a wide dynamic range, capable of measuring displacements of 20 nm - 10 µm with the accuracy better than 10 nm.

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FIGURES

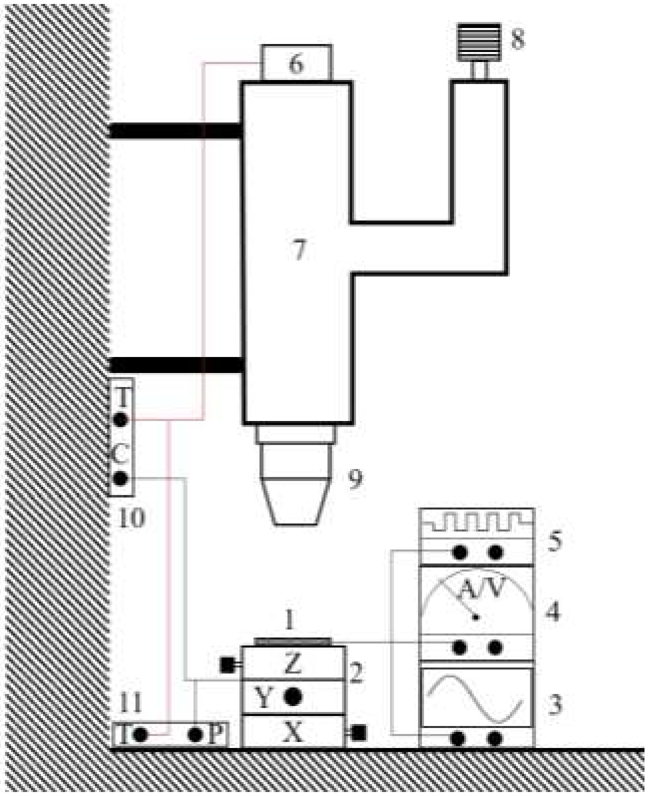

Fig. 1. Detailed scheme of the measuring system and its components. (1) Sample. (2) XYZ piezo stage with manual adjustment unit. (3) Arbitrary function generator. (4) High precision multimeter. (5) High power resistive heating power source and controller. (6) CMOS camera. (7) Microscope unit (beam splitter with a lens stack). (8) 5000K LED light source. (9) 50x objective lens. (10) Piezoelectric stage controller (T = trigger, C = comm. port). (11) Data acquisition module (T = trigger, P = position readout).

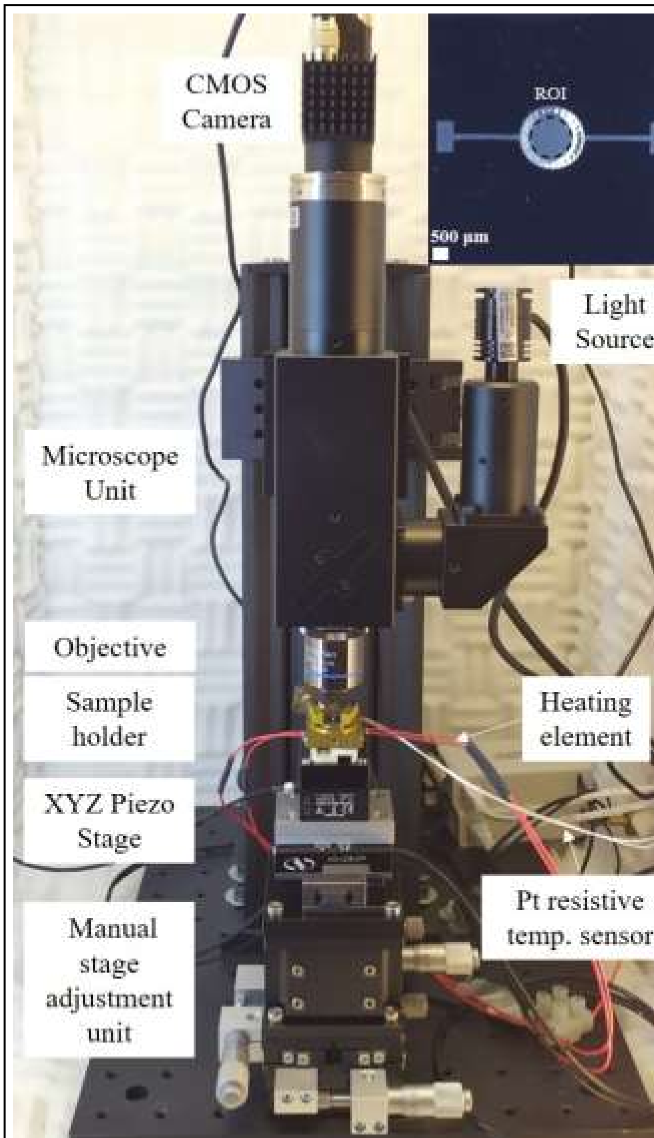

Fig. 2. Image of the measuring system with detailed description of its components. Inset: Electro-chemo-mechanical sample top surface depicting the region of interest (ROI) relevant for its measurement.

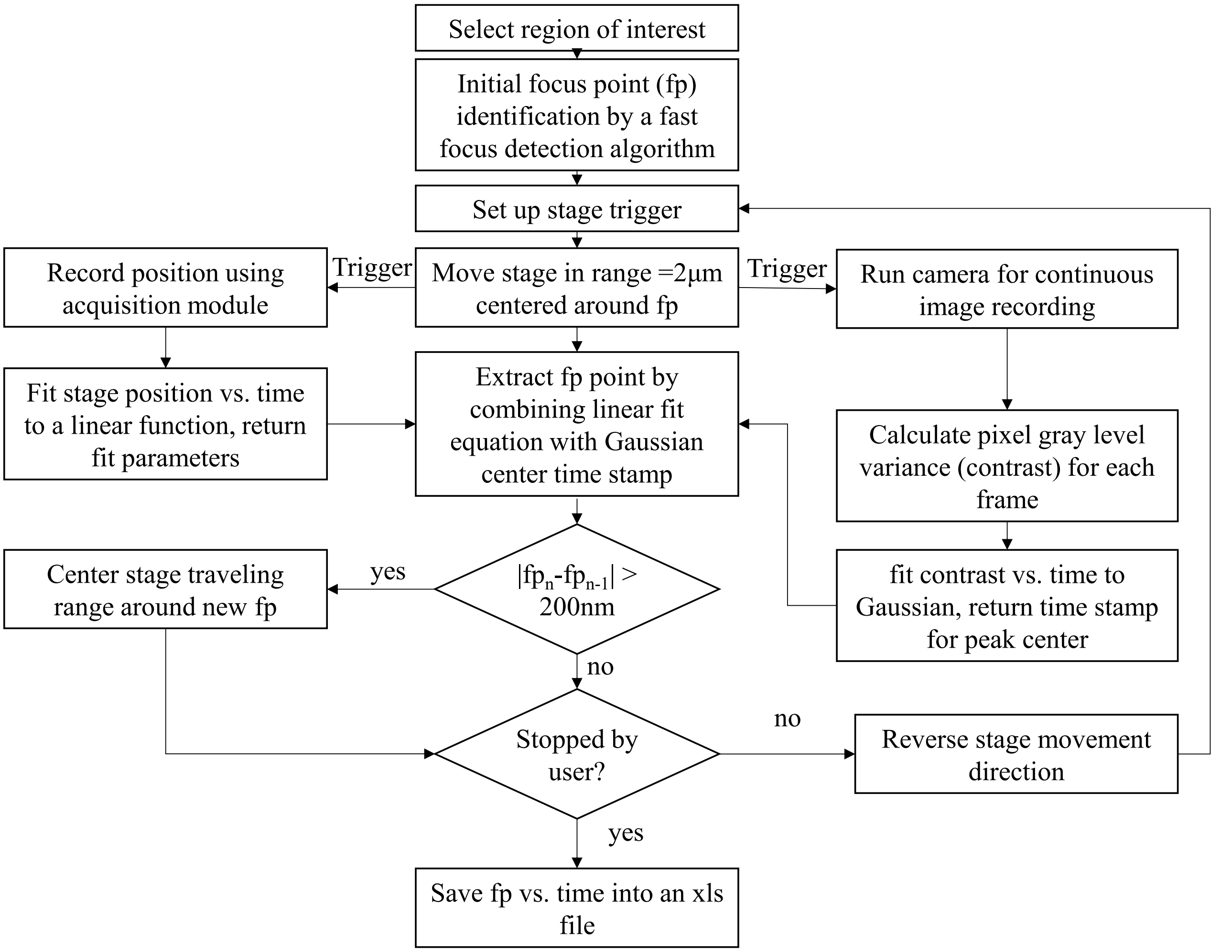

Fig. 3. Dynamic focus-tracking algorithm.

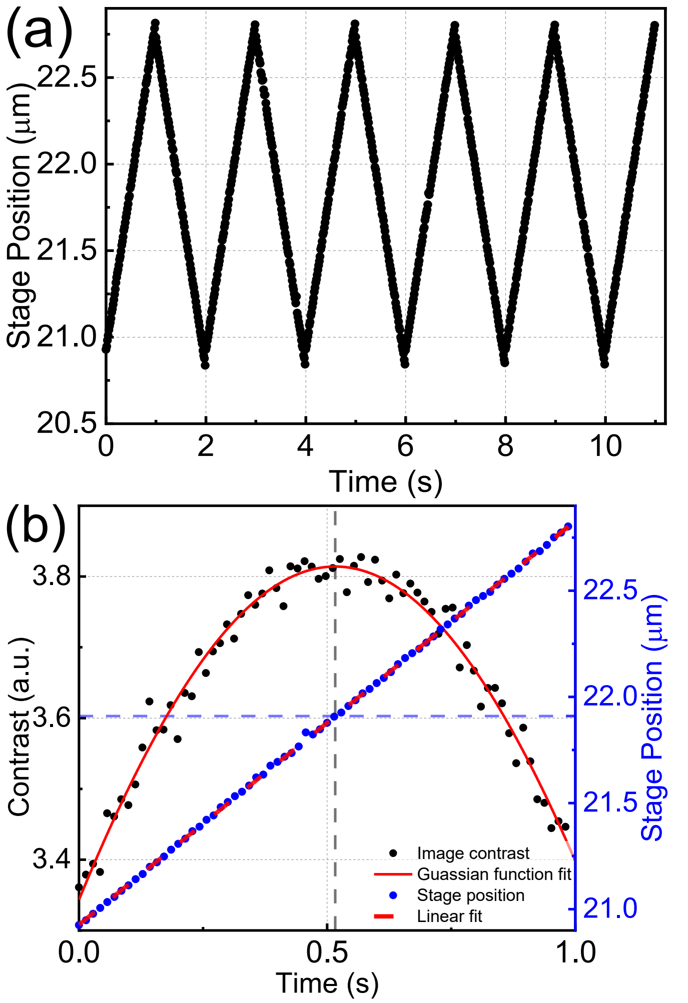

Fig. 4. Dynamic focus tracking: (a) A segment of the continuous periodic stage movement recorded by the data acquisition module. The stage is driven periodically and travels 2µm per second, during which 70 frames of the sample's surface image are recorded by the camera. The contrast of each frame is calculated. (b) Focal point detection: the position of the stage and the calculated image contrast are shown as a function of time for a single stage travel. The dependence of the contrast on time is fitted to a Gaussian function, the center of which is the time at which the focal point was identified (--). The position of the stage at the time corresponding to the center of the Gaussian (--) is deduced by fitting the dependence of stage position vs. time to a linear regression (--).

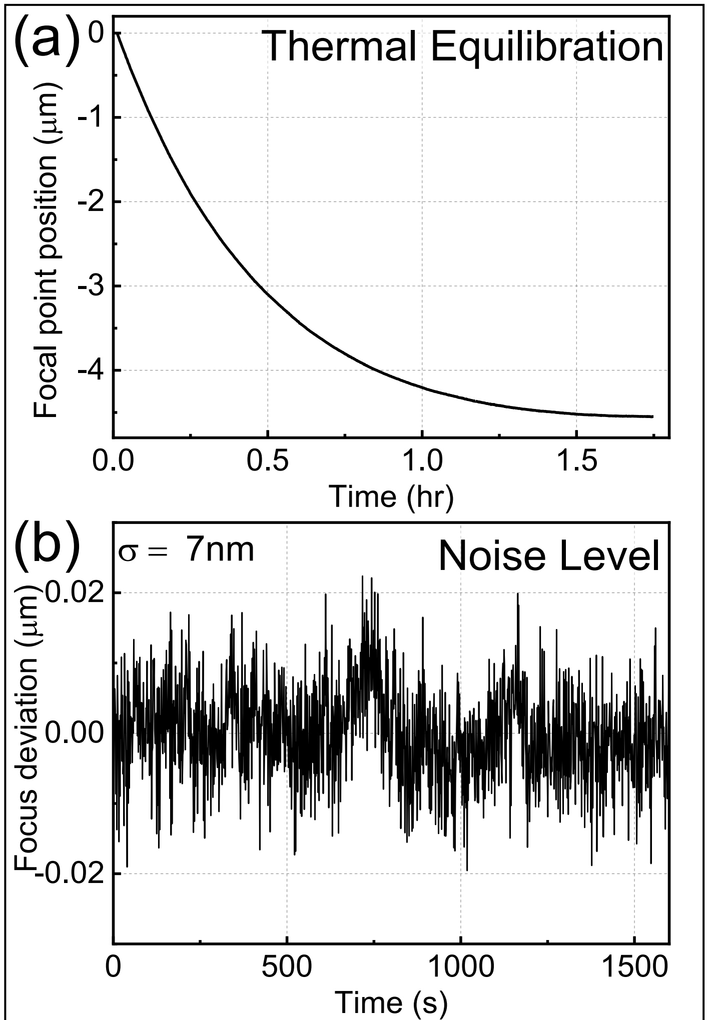

Fig. 5. Thermal equilibration and noise level: (a) Focal point position as a function of operation time. The focal point changes significantly during the first hours of operation due to equipment thermal equilibration. (b) Focal point position deviation from the mean value after equilibration period. The standard deviation of the noise is 7nm.

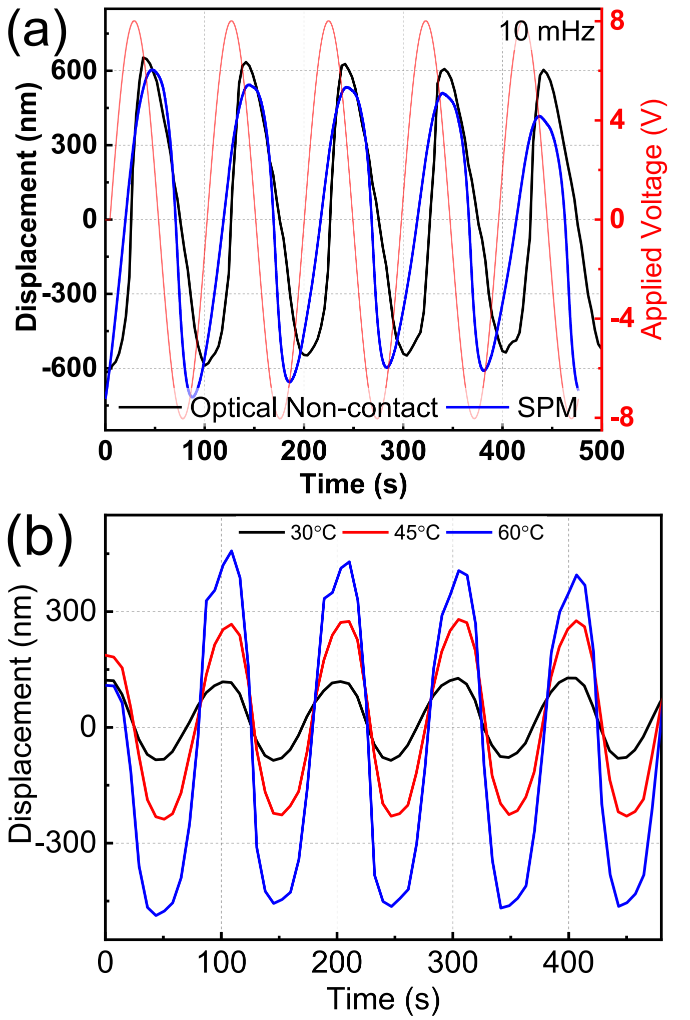

Fig. 6. Displacement measurements of electromechanical sample: (a) Room temperature measurements at 10 mHz 8V AC driving voltage (-). The non-contact dynamic autofocusing system (-) is compared to scanning probe microscopy measurements (-). (b) Temperature dependent measurements at 10 mHz 8V AC driving voltage: (-) 30°, (-) 45°, (-) 60°. Baseline subtraction was performed on all signals to allow for proper comparison.