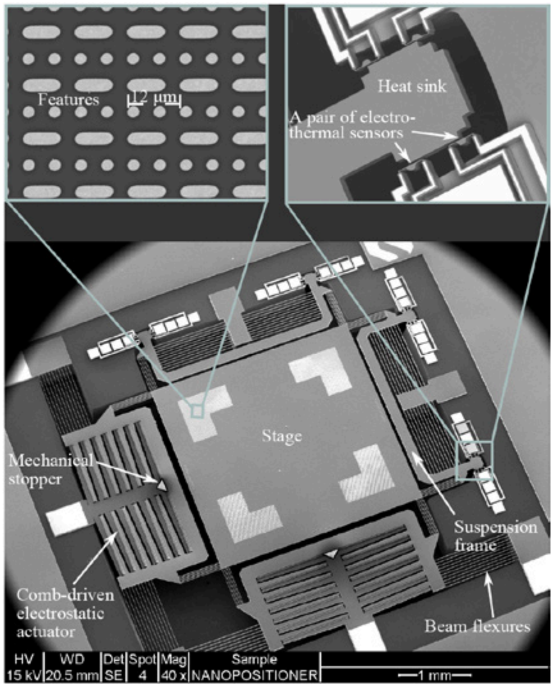
MEMS-Based Nanopositioning for On-Chip Atomic Force Microscopy

An atomic force microscope (AFM) operates by running a sharp tip, positioned at the end of a microcantilever, over a sample in a raster pattern such that a 3-D image is obtained based on the z-axis deflection and in-plane position of the tip. Typically, a laser beam is focused on the end of the cantilever, with the deflection of the reflected beam indicating the height of the cantilever and therefore the topography of the sample. The AFM is one of the most versatile methods for imaging structures at nanometer scale. The ability to operate in a non-vacuum environment gives the AFM a significant advantage over competing microscopy methods such as the transmission electron microscope (TEM) and the scanning electron microscope (SEM). Apart from imaging, the AFM is used to manipulate matter at nanometer scale and is viewed as the dominant tool in nanorobotics. The AFM's ability to image and manipulate matter at nanometer scale is entirely dependent on the use of several feedback loops. This gives rise to numerous opportunities and a significant need to apply advanced feedback control methods in AFM.

MEMS Nanopositioner

An important component of an atomic force microscope is a nanopositioner that moves the sample, relative to the probe, in a raster pattern. A typical AFM nanopositioner is a large, heavy flexure-guided mechanism machined from a solid block of steel or aluminum, with incorporated actuators and displacement sensors. The most widely used actuation technology for nanopositioning is the piezoelectric stack actuator, which can generate a large amount of force with a small stroke. These actuators suffer from nonlinearities such as hysteresis and creep, which are difficult to address using feedforward methods. Furthermore, from an electrical viewpoint, they are large capacitors that require complex and expensive low-noise, linear amplifiers for their operation. There is significant interest in moving away from using piezoelectric actuators in nanopositioning systems.

One promising approach is to develop micro-electromechanical (MEMS) nanopositioners that can function as scanning stages of future atomic force microscopes. These miniaturized systems potentially hold several advantages over conventional macro-sized nanopositioners. Qualities such as increased operating bandwidths, lower unit manufacturing costs, simpler bulk fabrication, and a much smaller packaged size mean that MEMS-based nanopositioners represent an attractive solution for many applications, particularly for atomic force microscopy.



The device shown at left is a nanopositioner fabricated using a silicon-on-insulator MEMS process. The design features integrated electrothermal sensors that enable real-time measurements of the stage displacement along the x and y directions. The scanner has two mechanical degrees of freedom, with electrostatic comb-finger actuators being used to position a 3-mm × 3-mm stage along the planar x and y directions. The mechanical design of the nanopositioner is based on a parallel-kinematic configuration, and a series of beam flexures around the perimeter of the stage are used to position the stage along the x and y axes and also to decouple the motions of the two axes. Each of the nanopostioner's electrostatic actuators features interdigitated comb fingers with dimensions chosen to maximize the force generated by the actuator for a given actuation voltage.

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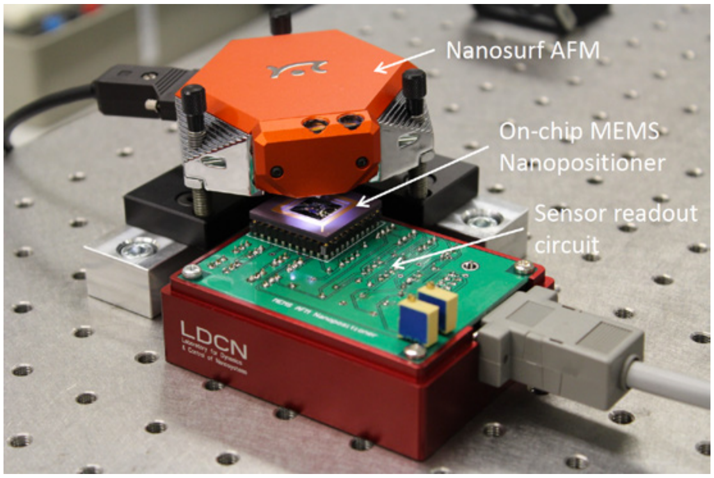
Control of MEMS-Based AFM

The Need for Feedforward and Feedback Control

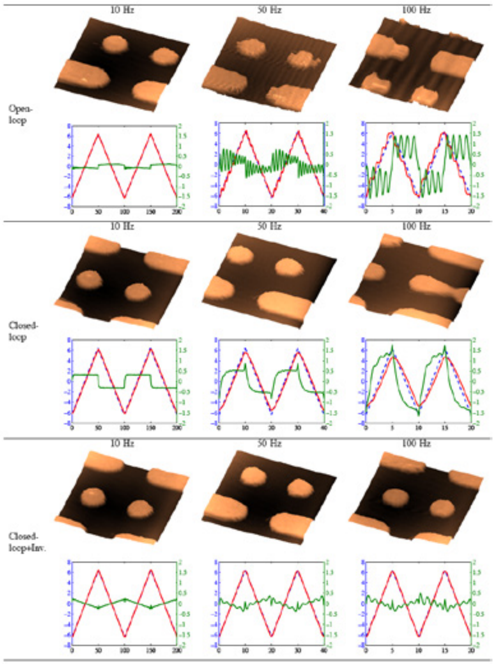
MEMS nanopositioners are typically highly resonant systems, and their high-speed operation is prone to scan-induced vibration. Therefore, to achieve the required positioning accuracies, which may be on the order of fractions of a nanometer, feedback control is essential. Sensor noise is a key issue in MEMS nanopositioners. Electrothermal displacement sensors are highly suitable for MEMS nanopositioning since they can be realized with a very small footprint; however, they suffer from flicker noise and low-frequency drift. The control system must be able to deal with these issues. The presence of cross-coupling between the two lateral axes of the nanopositioner is another contributing factor to low image quality, which can be improved by proper design of the feedback control loop. Finally, the closed-loop bandwidth achievable with a feedback controller may not be enough for high-speed scans. Thus, a feedforward controller may have to be used in addition to feedback control.



Experimental setup of the AFM and MEMS nanopositioner in a scan-by-sample mode

Benefits of Control: Experimental Results

A control system was designed and implemented on the MEMS nanopositioner. The experimental setup consisting of the MEMS scanner mounted on a printed circuit board, together with the readout circuitry and a Nanosurf EasyScan2 AFM, is illustrated in the above image. The experiments were performed in the "scan-by-sample" mode where the scan table, which is deposited with calibration features (illustrated in the SEM micrograph on the previous page), was moved in relation to the static probe. An image area of 12.7 μm × 12.7 μm was scanned at 10 Hz, 50 Hz, and 100 Hz in open-loop, closed-loop, and closed-loop with inversion-based feedforward. The figure below plots the three-dimensional topography images, the fast x-axis displacements, and tracking errors of the nanopositioner. The important role of control in improving image quality at high scan speeds is evident.



AFM scan results obtained at 10 Hz, 50 Hz, and 100 Hz in open-loop, closed-loop, and closed-loop with inversion-based feedforward. 3-D topography of the sample is plotted. The fast axis displacements (μm vs. ms) are plotted in red and tracking errors (μm vs. ms) are plotted in green. Reference signals are plotted in blue.

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