# THE BENEFITS OF MINIATURIZATION OF AN ATOMIC FORCE MICROSCOPE

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## ABSTRACT

A single-chip Atomic Force Microscope (sc-AFM) has been developed that integrates X, Y, and Z scanners, sensors, and a sharp tip onto a single 1x1 mm CMOS-MEMS device to replace a conventional AFM. This solution leverages physical scaling laws to offer numerous benefits over conventional instruments, including reduced size (1,000x), reduced cost (100x), superior vibration immunity, and improved versatility. In addition, this small, portable system enables new applications for AFM and lowers the barrier to widespread adoption of this popular nanotechnology tool.

## INTRODUCTION

The Atomic Force Microscope was invented in 1986 using a sharp tip on a cantilever, bulk piezoelectric scanners to scan the sample, and an external sensor to measure tip deflection [1]. Over the years, the general design of the instrument has not changed significantly. Conventional AFMs continue to use large piezoelectric scanner stages for their X, Y, and Z axes, micromachined tips on silicon cantilevers for tip-sample interaction, and external laser-based sensors for measuring tip deflection. These systems are quite large and complex, with many moving parts and large mechanical paths that are susceptible to vibrations and thermal drift. More recently [2,3], all of the essential components of the AFM have been integrated onto a single CMOS- MEMS chip (Figure 1), with the ability to achieve imaging results comparable to many conventional AFMs. The sc-AFM was first commercialized by ICSPI Corp in 2016 [4]. In this paper, we present details and design considerations of CMOS-MEMS sc-AFMs discussing the benefits of AFM miniaturizations.

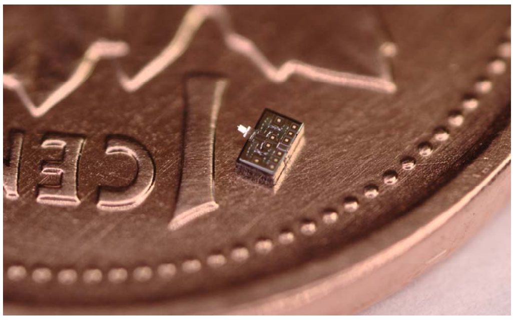

*Figure 1: An sc-AFM on a coin [2-4] .*

## THEORY AND BACKGROUND

The sc-AFM is a CMOS-MEMS device measuring approximately 1.2x0.8x0.3 mm. It comprises a number of electrothermal actuators, a cantilever with a sharp tip, and a piezoresistive strain sensor capable of measuring tip deflections. The actuators are a combination of bimorph and chevron actuators powered by resistive heaters and connected by flexures to position the tip with three degrees of freedom and sub-nanometer precision. An SEM image of an sc-AFM is shown in Figure 2.

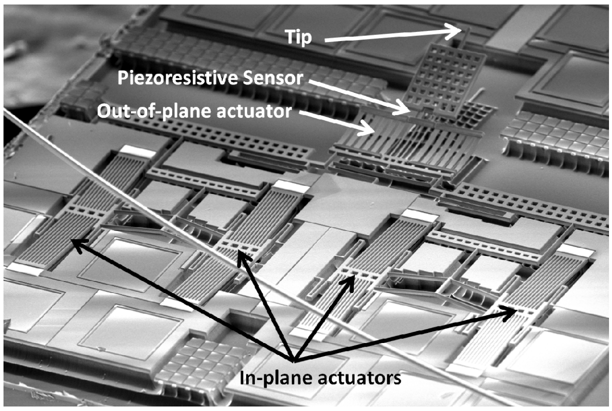


*Figure 2: SEM image of an sc-AFM.*

Multi-DOF thermal MEMS devices may suffer from thermal coupling between actuators, causing parasitic displacement, but this effect is minimized through isothermal scanner design and operation. A complementary temperature profile is applied to a pair of actuators such that a constant average temperature is maintained between them thereby suppressing local temperature variations at the sensor locations. The high work-to-volume ratio of thermal actuators enables compact sc-AFMs with large scan ranges, while isothermal operation provides ultra-precise control of the tip trajectory to generate images with sub-nanometer resolution.

The tip-sample interaction force sensor is a piezoresistive strain sensor made from the polysilicon layer of the CMOS process. The strain sensor is located at the highest stress region between the Z actuator and the tip. When the cantilever is driven at its resonant frequency, the strain sensor measures the tip oscillation amplitude, which is the process variable in the feedback loop of non-contact AFM modes. Tip-sample interaction forces shift the resonant frequency of the cantilever and change the oscillation amplitude. A controller is used to maintain a constant tip-sample distance, and the control signal then represents the sample topology.

sc-AFMs are designed in a standard 0.35 µm CMOS process and manufactured in a CMOS foundry. The CMOS chip then goes through simple post-processing steps to release the MEMS structures without requiring any additional lithography or deposition [5]. The CMOS chip first receives a maskless anisotropic oxide etch, using the top metal layer as a mask, and then a maskless isotropic silicon etch is used to release the structures, as shown in Figure 3. A scribe along the backside of the chip, directly below the base of the cantilever, allows the chip to be singulated to produce individual sc-AFM dies with cantilevers that extend beyond the edge. The CMOS-MEMS die is then bonded to the edge of a printed circuit board (PCB) and is wirebonded to the PCB to establish electrical connections.

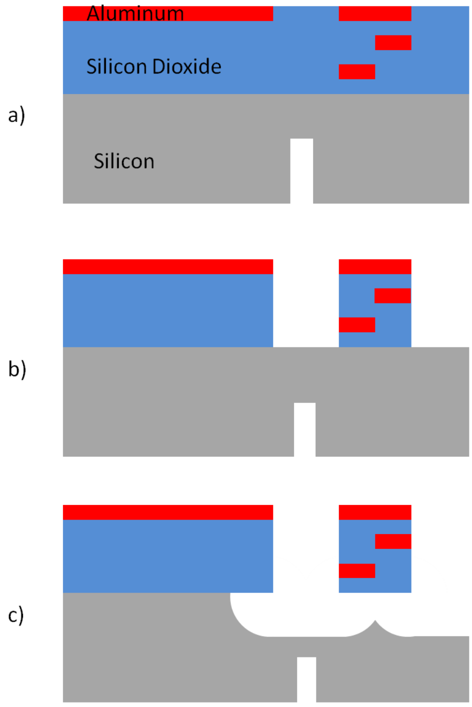


*Figure 3: The release process showing a) the unprocessed CMOS die, b) the die after an anisotropic oxide etch, and c) the die after an isotropic silicon etch.*

The PCB that carries the CMOS-MEMS AFM chip must be electrically connected to controlling electronics that can produce the signals necessary to scan the tip, measure the tip-sample interaction forces from the strain gauge, run a controller to maintain a constant tip-sample force, and transfer the resulting image data to a host computer for processing and viewing. The PCB must also be robustly affixed to a coarse approach mechanism to bring the tip into contact with the sample.

## BENEFITS OF SCALING

The miniaturization of an AFM offers many benefits. Besides the obvious space savings, there is also a significant reduction in cost, an increase in stability, an improvement in versatility, a reduction in complexity, and the potential for much higher speed. While sc-AFMs are not yet able to match the z-resolution of the best and most expensive conventional AFMs, the technology is still in its infancy and may meet or exceed the state-of-the-art upon further technology development. Table 1 compares some of the significant aspects of ISCPI Corp's sc-AFM (nGauge) [4] and conventional AFMs.

*Table 1: A comparison of some aspects of an nGauge AFM using sc-AFM technology and a conventional AFM.*

| | nGauge [4] | Conventional |
|---|---|---|
| Total Size | 0.0005 $m^3$ | ~1 $m^3$ |
| Cost | < $8,000 | > $100,000 |
| Portable | Yes | No |
| Can Place on Sample | Yes | No |
| Sensor | Integrated Piezoresistor | External Laser |
| Scanners | Integrated Electrothermal MEMS | External Piezoelectric |
| RMS noise | < 2 nm | < 0.1 nm |

The CMOS-MEMS sc-AFM itself occupies a volume of less than 1 $mm^3$. The overall system size is 0.0005 $m^3$ because of the coarse approach mechanism and the control electronics. The integration of the essential AFM components on the chip eliminates the requirement of off-chip scanners and laser-based sensors so that the supporting mechanical hardware can remain small in size. The electrical requirements are also minor since the entire device operates at CMOS-compatible voltage levels and the system can be controlled with a microcontroller. So, a complete AFM system comprising an sc-AFM, a coarse approach mechanism, and the controller occupies about the same footprint as a coffee mug. Low voltage and low power requirements also enable battery operation for a truly portable solution that is 1000x smaller than some systems.

A small system size is just one of many benefits that sc-AFMs offer in comparison with their conventional counterparts. Since the sc-AFM contains all of the components required to obtain an image, it can be integrated into a large variety of common industrial or research equipment that could benefit from nanoscale measurements. Some of these instruments include scanning electron microscopes (SEMs), probe stations, vacuum deposition chambers, lapping and polishing tools, and quality assurance assembly lines. Many of these systems are already fitted with a coarse approach mechanism and an electrical path, allowing access to the controlling electronics. This ability to customize the AFM structure will open up many new applications.

In a conventional AFM, different modes of operation may require extensive modifications in hardware. However, sc-AFMs can be designed in many different configurations, each with a conductive path to the tip, to allow many different modes that include contact, tapping, capacitive, thermal, microwave, etc, which may require minimal or no additional hardware. An added benefit of manufacturing the MEMS within a CMOS chip is the fact that driving and sensing electronics can potentially be designed on the same chip as the MEMS. Small signals will only have to travel microns instead of centimeters to the sensing electronics, thereby increasing the signal-to-noise ratio and the resolution of the measurement.

The wafer-scale CMOS manufacturing process also allows for massively parallel arrays of AFMs that will enable high throughput metrology on a large scale. While a conventional AFM's laser-based sensing system with external scanners occupy a large volume, each fully integrated sc-AFM can be fabricated in a dense array on a wafer. A single eight inch CMOS wafer can contain 30,000 AFMs that can be independently controlled with integrated electronics to yield 30,000 images. In this way, a test wafer can be imaged with nanometer precision and unprecedented coverage to identify local defects or variations in just minutes. This functionality is beyond the capabilities of conventional AFMs and has stifled their adoption in semiconductor metrology.

The stability of a system is always a major consideration when taking nanoscale measurements. The path between the tip and the sample must be mechanically stable to yield the best possible measurement results with minimal vibration and drift. A conventional AFM typically uses three separate macro-scale piezoelectric scanners as well as X, Y, and Z motorized coarse positioners. This creates a very large mechanical path between the tip and sample and renders the system susceptible to thermal drift. In addition, piezoelectric materials are known to suffer from creep and hysteresis. Moreover, the scanners and coarse positioners have relatively large masses, and possess low resonant frequencies that are easily excited by ubiquitous low frequency building vibrations. The sc-AFM, on the other hand, has integrated electrothermal scanners with high resonant frequencies that are not affected by low frequency vibrations. The scanners are also designed in an isothermal configuration that cancels out any positional shifts caused by system temperature changes. Time-lapse images taken with an sc-AFM, as shown in Figure 4, have shown that the same area of a sample can be imaged hundreds of times over 72 hours with less than 1 μm of drift and with no observable tip-wear.

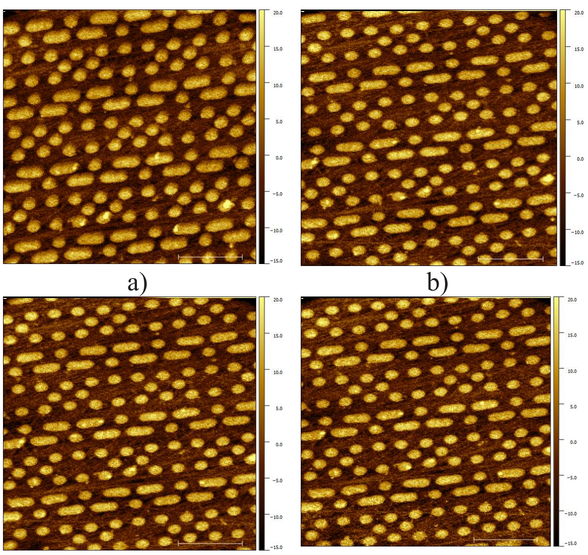

*Figure 4: Images taken with an nGauge AFM over a period of 72 hours. Out of 750 images total, these are image number a) 1, b) 250, c) 500, and d) 750.*

By integrating the entire system onto a single chip, the complexity of the system is significantly reduced to the point where a skilled operator is no longer required to operate the instrument. For example, a conventional AFM uses a laser-based position sensor requiring an intricate laser alignment process, while the integrated piezoresistive sensor of an sc-AFM requires no setup or calibration. Long-range sensors within the sc-AFM allow for a very rapid coarse approach, eliminating the need for the delicate manual approach used in most conventional systems which may lead to tip crashes. Another important feature of the sc-AFM is the ease of tip replacement. Swapping a tip in a conventional AFM system requires the user to manipulate a tiny silicon chip with tweezers which often damages the chip by mishandling or from dropping. The sc-AFM does not need to conform to this standard form factor and can instead be attached to a substrate (a carrier PCB) that can be easily handled by the user. Furthermore, if any part of the system malfunctions because of user mishandling or any other reasons, the user just needs to swap the broken sc-AFM for a new one to start with a fresh tip, sensor, and scanners.

In most conventional AFMs, the large external scanners scan the sample in X and Y while the tip moves only in Z. As the scan speed increases, the large masses of the scanners and the momentum of the sample can excite resonances and cause ringing by the rapid changes in direction during a scan, causing poor imaging results. The sc-AFM, however, leaves the sample stationary while the tiny mass of the tip is scanned in X, Y, and Z. Not only is it less likely for the system to experience ringing, but the MEMS device can be designed to operate with a lateral axis in resonance, leading to very high frequency scans and even video rate imaging.

One of the most significant benefits of the miniaturization of an AFM is the reduction in cost. sc-AFMs can be produced economically and in high volumes using wafer-scale CMOS fabrication, the same process that produces the low-cost components used in almost all electronic devices today. sc-AFMs also eliminate the costly external piezoelectric scanners, laser sensors, and controlling electronics that make conventional AFMs prohibitively expensive. This technology promises to make AFMs accessible to everyone by considerably reducing the cost of these powerful nanotechnology tools.

Conventional AFMs have been in production much longer than sc-AFMs and there are dozens of companies that produce standard accessories. AFM probes are designed with a standard shape and size and are interchangeable between different systems. There are hundreds of different types of probe, including probes designed for tapping or contact mode, conductive probes, low cost or high aspect ratio probes, and ultra sharp probes. This large selection is not currently available with sc-AFMs, and an sc-AFM tip is not interchangeable with other systems, but a multitude of sc-AFM tip options and modes are possible and will likely be offered in the future.

The maximum vertical resolution of a good conventional AFM is currently more than an order of magnitude better than an sc-AFM due to the lower noise level of the laser-based detection systems. However, it has been shown that it is possible for piezoresistive sensors to achieve similar or better noise levels in MEMS cantilevers [6]. Future optimization of the MEMS design and sensing electronics may enable similar or better imaging performance of sc-AFMs.

## RESULTS

sc-AFMs have recently been commercialized in the form of the nGauge AFM, seen in Figure 5 [4]. The system is smaller, simpler, and more affordable than most conventional AFMs, and can produce images of similar quality and resolution [3,4]. The system mounts the sc-AFM onto an automated coarse approach stage capable of positioning a sample into contact with the tip. The controlling electronics are enclosed in the backside of the stage and require only dc power and a USB connection to a host computer. The entire unit measures 70x80x90 mm.


*Figure 5: The nGauge AFM; the first commercially available instrument using sc-AFM technology.*

The nGauge AFM is capable of scanning areas up to 20x20 µm with features as tall as 10 µm with an RMS noise level of less than 2 nm. The image in Figure 6 shows terraces of highly oriented pyrolitic graphene (HOPG), acquired with an nGauge AFM in tapping mode, in air, with no additional vibration isolation.

## CONCLUSIONS

The miniaturization of atomic force microscopes offers many advantages over conventional AFMs, including improved speed, versatility, stability, complexity, size, and price. CMOS-MEMS sc-AFM technology has already demonstrated that it is reliable enough to replace conventional AFMs, and there is still plenty of room for innovation. Many new applications will be enabled by the technology, such as array operation, in-situ metrology, and even large scale tip-based nanofabrication. As a result of miniaturization and integration, this powerful nanotechnology tool is now more accessible than ever to researchers, industry professionals, students, hobbyists, and anyone who can benefit from interacting with the world at the nanoscale.

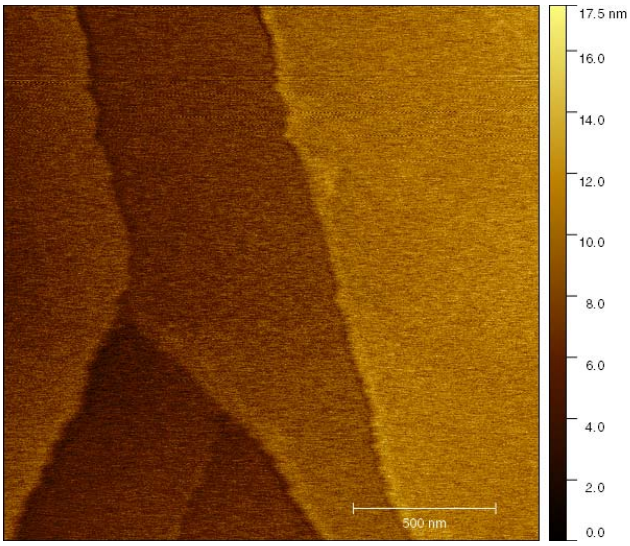


*Figure 6: 2x2 µm image of HOPG taken with an nGauge AFM.*

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Ontario Ministry of Research Innovation (MRI), Canada Foundation for Innovation (CFI), the Canadian Microelectronics Corporation (CMC) and DARPA.

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