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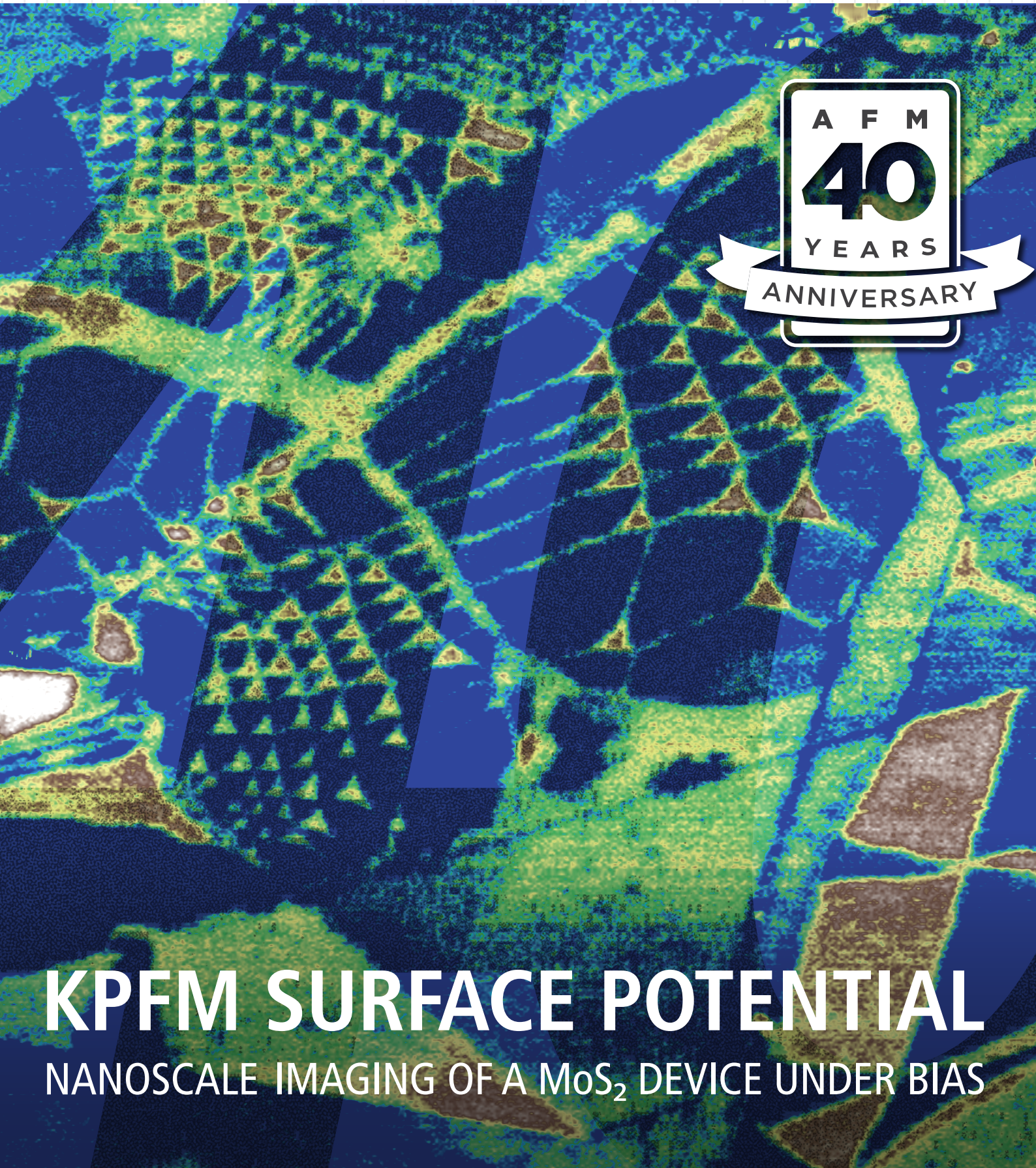


KPFM SURFACE POTENTIAL

NANOSCALE IMAGING OF A MoS_2 DEVICE UNDER BIAS

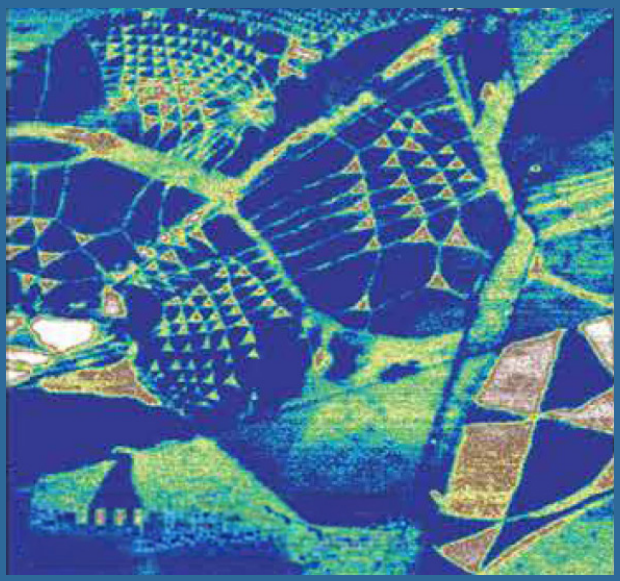
40 YEARS OF AFM: SHAPING THE NANOSCALE FRONTIER

This edition of NanoScientific marks a defining milestone: 40 years since the introduction of the atomic force microscope (AFM). In March 1986, Gerd Binnig, Calvin Quate, and Christoph Gerber published their landmark paper in Physical Review Letters, establishing a new way to measure and explore the nanoscale. Extending beyond the capabilities of the scanning tunnelling microscope, AFM enabled high-resolution imaging and characterization of virtually any surface, regardless of conductivity.

In this issue, we begin by tracing the scientific foundations and early development of AFM, followed by a tribute to Professor Calvin Quate, whose vision and leadership were instrumental in shaping the field. We then examine how AFM evolved from a laboratory innovation into a globally essential technology, supporting both scientific discovery and semiconductor manufacturing.

Looking forward, the issue highlights emerging advances such as active cantilever technologies and presents a range of cutting-edge applications across electrical, magnetic, and mechanical measurements. These contributions, many drawn from NanoScientific Symposiums worldwide, reflect both the depth and breadth of AFM today.

We also revisit the recent 40 Years of AFM celebration at Stanford, honoring the legacy of this transformative instrument while underscoring its continued role in advancing nanoscience and industry.



Cover Story: KPFM Surface Potential Image of a MoS_2 Device Under Bias

This Kelvin Probe Force Microscopy (KPFM) surface potential map of a MoS_2 device under applied bias reveals the nanoscale distribution of electrical potential across the channel. Contrast variations show the voltage drop from source to drain, highlighting local resistance and contact effects. These measurements enable direct correlation between surface potential and device transport behavior.

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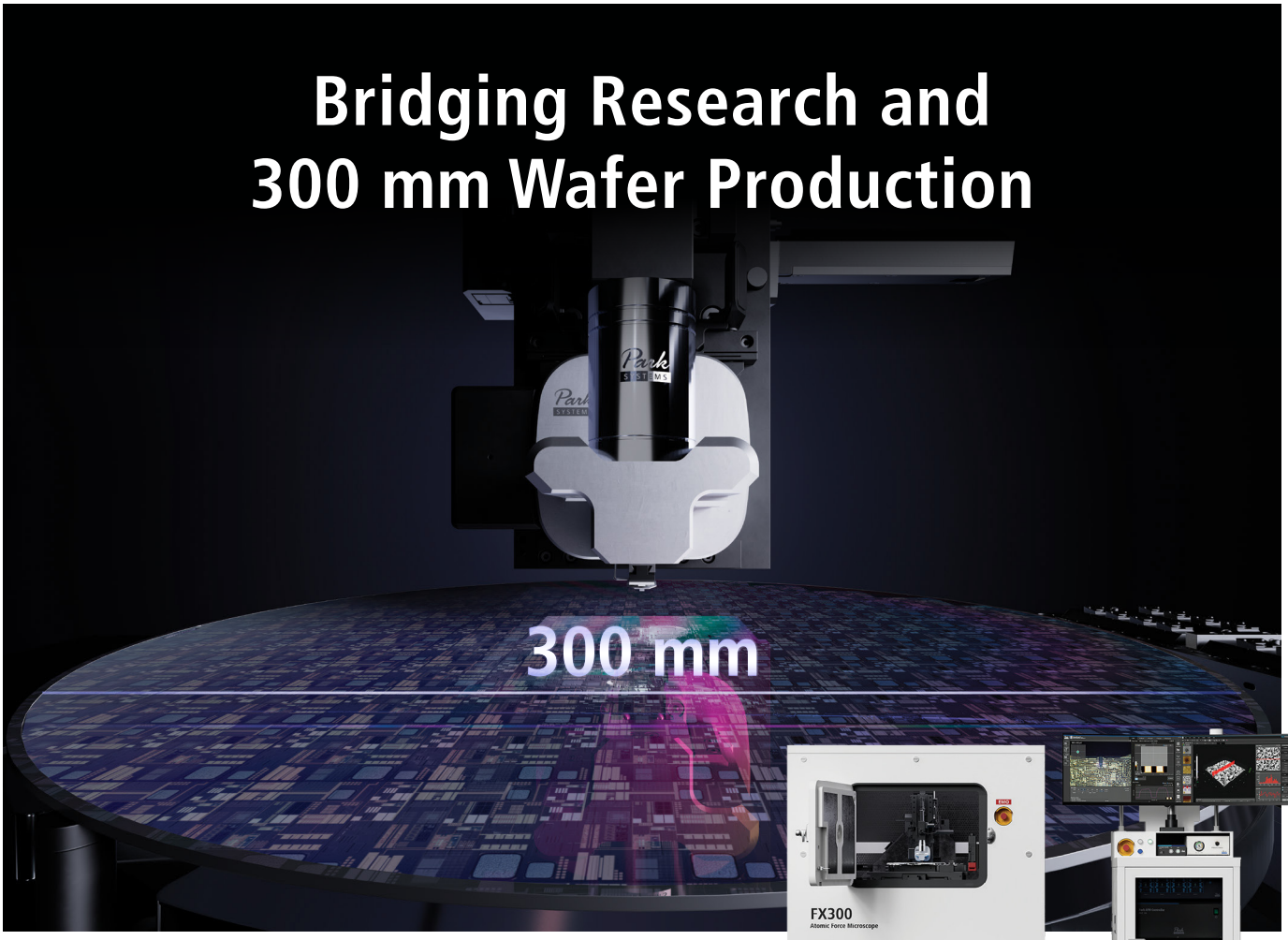
Bridging Research and 300 mm Wafer Production



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Enable smooth transition from lab research to production with the FX300, capable of measuring everything from small samples to full 300 mm wafers. Supporting a wide range of AFM modes, it empowers diverse applications from semiconductor analysis to advanced materials research.

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Park AFM-IR Spectrometers

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The Park AFM-IR Spectrometers seamlessly integrate atomic force microscopy (AFM) with photo-induced force microscopy (PiFM) technology. These innovative platforms deliver molecular vibration mapping at the nanometer scale while maintaining full AFM capabilities for comprehensive topographic, nanomechanical, electrical, and thermal analysis.

Park SYSTEMS

FROM NON-CONTACT AFM TO FUNCTIONAL NANOSCOPY

Expanding the Capabilities of Scanning Probe Microscopy

Prof. Kumar Wickramasinghe, UCI Distinguished Professor Emeritus,
Henry Samueli Endowed Chair Emeritus, University of California, Irvine, CA, USA

This article is based on a presentation delivered at the NanoScientific Symposium, Stanford University. Watch the full presentation at www.nanoscientific.org.

Introduction

Over the past four decades, atomic force microscopy has evolved from a surface imaging tool into a versatile platform for nanoscale characterization. Beyond topography, AFM now enables measurement of electrical, magnetic, thermal, and optical properties with high spatial resolution.

This transformation was driven by the need to understand functionality at the nanoscale, particularly in semiconductor manufacturing and advanced materials research. As presented by Prof. Kumar Wickramasinghe at the Stanford NanoScientific Symposium, key developments—including non-contact AFM and a range of functional scanning probe techniques—expanded AFM into a comprehensive measurement platform, laying the foundation for modern functional nanoscopy.

Early Motivation: Nanoscale Metrology

In the early 1980s, semiconductor feature sizes were approaching the limits of optical microscopy, creating an urgent need for higher-resolution metrology. Feature sizes in microelectronics and magnetic storage were approaching half a micron, and further progress would require new measurement tools capable of resolving structures an order of magnitude smaller.

At IBM Research, efforts were underway to explore scanning probe approaches that could address these emerging metrology challenges. One early concept investigated by Wickramasinghe's group was a scanning thermal microscope, in which a heated probe tip approached a cooler sample surface. Heat transfer between the tip and the sample served as an indicator of their separation. As the tip moved closer to the surface, thermal conduction increased, causing the probe temperature to drop more rapidly.

Although this technique successfully demonstrated nanoscale surface profiling on insulating materials, the spatial resolution achieved—on the order of several hundred angstroms—was insufficient for semiconductor manufacturing requirements. As device dimensions continued to shrink, resolutions of tens of angstroms were needed.

Around this time, the publication of the AFM introduced a new approach that promised significantly higher resolution and broader applicability.

Toward Non-Contact Atomic Force Microscopy

Early AFM instruments typically operated in contact mode, in which the probe tip maintained direct contact with the surface while scanning. While effective for measuring topography, contact operation could disturb or damage delicate surfaces and nanoscale structures.

To overcome these limitations, researchers began exploring methods for operating AFM without direct contact between the tip and the sample. A key step involved oscillating the cantilever near its resonance frequency while monitoring extremely small changes in its vibration behavior.

Using highly sensitive optical detection methods, including laser heterodyne probes capable of detecting minute vibrations, researchers could observe how the cantilever's oscillation changed as it approached a surface. Long-range attractive forces—primarily van der Waals interactions—alter the effective stiffness of the cantilever and cause shifts in its resonance frequency.

By monitoring these shifts and maintaining constant oscillation conditions through feedback control, the microscope could operate with the tip positioned extremely close to the surface without touching it. This approach became known as non-contact AFM, enabling stable imaging while minimizing tip wear and sample damage.

Early experiments achieved spatial resolutions on the order of five nanometers, already sufficient for many metrology applications envisioned by semiconductor manufacturers.

Engineering AFM for Manufacturing Environments

Demonstrating nanoscale imaging in a research laboratory was only the first step. For scanning probe microscopy to become useful in semiconductor fabrication, it had to be engineered into a robust and automated measurement system capable of handling large wafers with high reliability.

This presented a formidable engineering challenge. The probe tip, typically about one hundred micrometers long, must be controlled with nanometer precision while scanning across surfaces thousands of times larger than the tip itself. Maintaining stable operation under these conditions required innovations in both instrumentation and automation.

Key developments included microfabricated silicon cantilevers with integrated sharp tips, automated tip-exchange mechanisms, dual feedback control systems for maintaining stable tip–sample spacing, and robotic wafer handling systems capable of loading and positioning semiconductor wafers for measurement.

These advances made it possible to build scanning probe workstations capable of performing nanoscale measurements directly within semiconductor manufacturing environments. One early application involved diagnosing failures in integrated circuits caused by subtle variations in chemical-mechanical polishing processes. AFM measurements revealed nanoscale topographic variations that were invisible to optical inspection methods, allowing engineers to identify and correct the underlying process issues.

This transition marked an important milestone in the history of scanning probe microscopy, demonstrating that AFM could serve not only as a scientific instrument but also as a practical industrial metrology tool.

Expanding AFM into Functional Measurements

While AFM was initially used primarily for imaging surface morphology, researchers quickly realized that the probe–sample interaction could be exploited to measure many other physical properties. This insight led to the development of a wide range of scanning probe techniques capable of probing electrical, magnetic, and chemical characteristics at the nanoscale.

One important development was Kelvin probe force microscopy, which measures the contact potential difference between a conductive probe and the sample surface. By applying a compensating voltage to cancel the electrostatic force between the tip and the sample, the technique determines local variations in work function and surface potential.

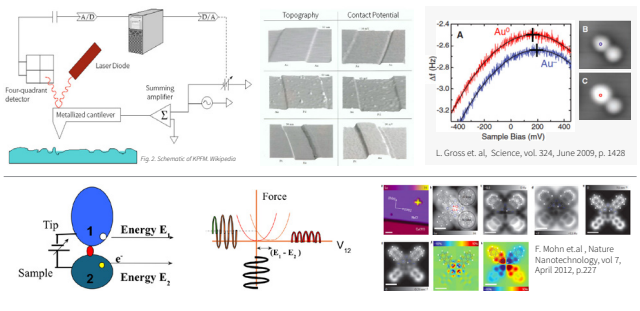


Figure 1. *Kelvin probe force microscopy (KPFM) for electrostatic measurements, illustrating nanoscale mapping of work function differences through detection of tip–sample electrostatic interactions.*

Kelvin probe measurements provide valuable information about charge distribution, electronic structure, and dopant concentration in semiconductor materials.

Another extension of AFM is magnetic force microscopy, in which a magnetized probe interacts with magnetic stray fields above a sample surface. By detecting changes in the cantilever motion caused by magnetic interactions, the microscope can map magnetic domain structures and field distributions with nanometer resolution. This capability has proven valuable in the study of magnetic storage media, nanomagnetic materials, and spintronic devices.

Scanning probe techniques also enabled nanoscale dopant profiling, allowing researchers to map variations in semiconductor doping levels that strongly influence device performance. These measurements provided new insights into the relationship between fabrication processes and electronic behavior in integrated circuits.

Optical Nanoscopy and Near-Field Techniques

Beyond mechanical and electrical measurements, scanning probe microscopes also opened new possibilities for optical characterization at spatial resolutions far below the diffraction limit of conventional microscopy.

Near-field optical microscopy achieves this by detecting electromagnetic fields in the immediate vicinity of a sample surface. Early approaches used small apertures at the end of tapered optical fibers to confine light to nanoscale regions. Later developments introduced apertureless near-field optical microscopy, in which a sharp AFM tip acts as a nanoscale antenna that scatters light interacting with the sample surface.

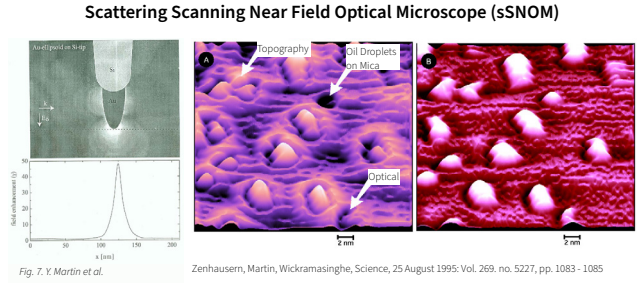


Figure 2. *Apertureless near-field optical microscopy (sSNOM) concept and performance. (Top) Localized field enhancement at a metal-coated AFM tip apex enables nanoscale optical interaction beyond the diffraction limit. (Bottom) Correlated topography and optical images of oil droplets on mica, demonstrating simultaneous structural and optical contrast at nanometer-scale resolution.*

When illuminated by a focused laser beam, the tip–sample system produces scattered light carrying information about local optical properties. Interferometric detection methods can measure the amplitude and phase of this scattered signal with high sensitivity, enabling optical imaging with nanometer-scale resolution.

These techniques made it possible to study nanoscale optical phenomena such as molecular orientation, plasmonic interactions, and phonon polaritons in advanced materials.

Photo-Induced Force Microscopy

An important extension of optical scanning probe techniques is photo-induced force microscopy (PiFM), which combines AFM with optical spectroscopy. In this method, incident light polarizes both the probe tip and the sample surface. The resulting electromagnetic interaction generates a small force that can be detected by the cantilever.

By measuring this photo-induced force while tuning the wavelength of the incident light, the microscope can obtain nanoscale infrared spectra of materials. This enables chemical identification and molecular characterization with spatial resolutions far beyond the capabilities of conventional optical spectroscopy.

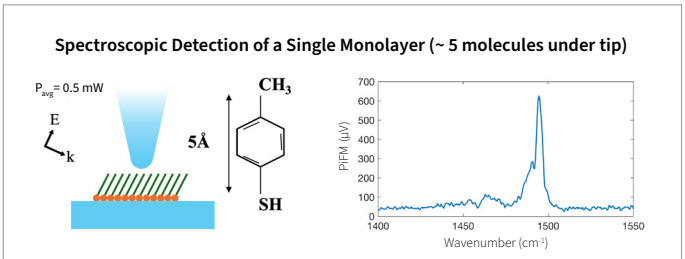


Figure 3. *Vibrational spectrum of a single molecular monolayer detected using photo-induced force microscopy (PiFM), demonstrating nanoscale infrared sensitivity with signals originating from only a few molecules beneath the tip.*

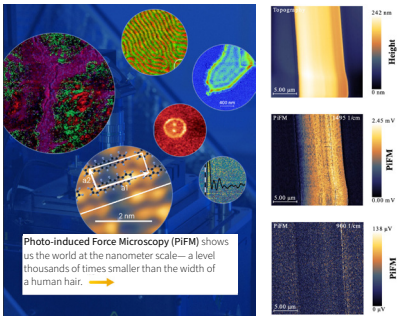


Figure 4. *Comparison of topography and PiFM images acquired on- and off-resonance, highlighting chemical contrast enabled by PiFM through selective excitation of molecular vibrational modes achieving a spatial resolution independent of the topography.*

PiFM has been used to study molecular monolayers, polymer materials, and nanoscale structures in two-dimensional materials. In many cases, the technique allows researchers to detect chemical signatures from extremely small volumes of material, approaching the sensitivity needed for single-molecule spectroscopy.

Toward Multifunctional Nanoscale Measurement

Over the past four decades, AFM has evolved into a multifunctional platform capable of measuring a wide variety of physical properties with nanometer-scale resolution. Modern scanning probe techniques can simultaneously probe surface morphology, electrical potential, magnetic fields, optical responses, and thermal behavior.

This ability to correlate multiple properties at the same location provides powerful insights into nanoscale phenomena. In semiconductor research, it enables detailed characterization of device structures and materials. In materials science, it allows researchers to study the interplay between structure, chemistry, and physical behavior at nanometer length scales.

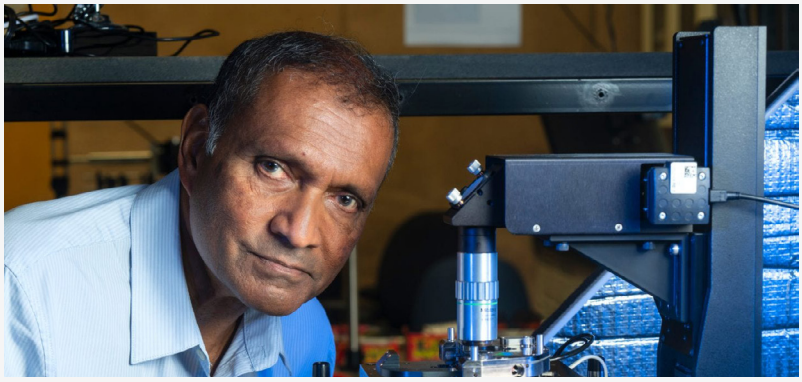
The continuing evolution of scanning probe microscopy reflects the broader trend in nanoscience toward integrated measurement platforms capable of combining multiple analytical techniques in a single instrument

Conclusion

Since its introduction in 1986, atomic force microscopy has become one of the most important tools in nanoscale science and technology. Advances in instrumentation, detection methods, and measurement techniques have transformed AFM from a simple surface imaging device into a comprehensive platform for nanoscale characterization.

As highlighted in Prof. Wickramasinghe's presentation at the Stanford NanoScientific Symposium, the early development of non-contact AFM and the expansion of scanning probe methods into electrical, magnetic, optical, and chemical measurements laid the foundation for today's multifunctional nanoscopy techniques.

Looking forward, scanning probe microscopy will continue to play a central role in advancing nanoscience, enabling researchers to explore and understand the physical properties of materials with unprecedented spatial resolution.



About Prof. Kumar Wickramasinghe

Professor Kumar Wickramasinghe is a pioneering researcher in scanning probe microscopy and nanoscale measurement science. A Distinguished Professor at the University of California, Irvine, he previously conducted influential research at IBM Research, where his group helped advance atomic force microscopy beyond surface imaging to multifunctional nanoscale characterization. His work contributed to the development of techniques such as non-contact AFM, Kelvin probe force microscopy, magnetic force microscopy, and photo-induced force microscopy (PiFM), enabling measurements of electrical, magnetic, optical, and chemical properties at nanometer and molecular scales.

THE BOLD PIVOT
An Interview with John Foster on Calvin Quate and the Birth of AFM

Forty Years After AFM: A Personal Reflection from the Stanford Lab

In 1986, the atomic force microscope (AFM) was introduced to the scientific community, transforming our ability to explore the nanoscale. At the center of that breakthrough was Professor **Calvin F. Quate**, whose bold leadership at Stanford University reshaped the trajectory of scanning probe microscopy.

By the early 1980s, Quate's laboratory was already internationally recognized for pioneering acoustic microscopy. His emphasis on mechanical scanning had pushed resolution to remarkable limits, and the group was operating at the forefront of precision imaging. Yet even at the height of that success, Quate was looking ahead. After visiting IBM Zurich and observing early work on the scanning tunneling microscope, he made a decisive move: redirecting his entire lab toward this emerging technology. That pivot would soon lead not only to Stanford's STM efforts, but to the invention of AFM — an instrument capable of imaging insulating surfaces and ultimately enabling nanoscale research across physics, materials science, biology, and semiconductor technology.

Dr. John Foster, now Chief Operating Officer of Shiftwave Inc., was a graduate student in Quate's lab during this transformative period. In this interview, he reflects on the revolutionary shift inside the lab, Quate's distinctive mentoring style, and the fearless mindset that helped bring AFM into existence and shape generations of innovators.

NS: When you joined Cal Quate's lab at Stanford, what was the atmosphere like?

Foster: It was exhilarating. By the early 1980s, the lab was leading the world in acoustic microscopy. We were pushing resolution to extraordinary levels — experiments at cryogenic temperatures, even down to millidegrees Kelvin. These were technically demanding, sometimes exotic experiments, and the expectation was clear: when we presented our work, we had to know more than anyone else in the room.

It felt like being at the top of the world scientifically. But what I didn't realize at the time was that we were already standing in the middle of a much larger revolution.

NS: Do you remember the moment when Cal decided to pivot the entire lab toward scanning tunneling microscopy?

Foster: Very clearly. Cal had visited IBM Zurich and seen the early tunneling experiments. Almost overnight, he announced that the lab would shift to STM — and soon after, AFM. That meant no more acoustic microscopy students.

We were stunned. We were doing so well. Why abandon a field where we were leaders? But Cal showed no hesitation. No backup plan. No mitigation strategy. Just bold conviction.

That decision taught me one of the most important lessons of my career: sometimes innovation requires abandoning success.

NS: How did Cal approach risk?

Foster: Fearlessly. Imagine being the most recognized figure in a field and walking away from it to pursue something uncertain. That's what he did.

He didn't overanalyze it. He didn't hedge. He simply believed in the direction and moved. From a business standpoint, that seems reckless. But from a scientific standpoint, it was visionary.

We all jumped in with him.

NS: How would you describe his mentoring style?

Foster: Unconventional. We had no formal group meetings during my four years there. Cal led with big ideas — "We're going this way now" — but he was often deliberately vague about the details.

We would leave his office unsure whether we had approval or not. Escaping without being stopped often counted as tacit approval.

If he truly disliked something, he would simply call out your name with a tone of anguish: "John…" That was it. No explanation. You had to figure out what to fix.

In hindsight, it forced us to think independently. He wasn't going to solve problems for you. You had to invent the solution yourself.

NS: STM was already revealing atomic resolution. Why push further toward AFM?

Foster: From the beginning, Cal had a vision beyond STM. STM could only image conductive surfaces. Cal wanted to scan insulating materials.

At the time, I didn't see the need. We were already seeing atoms! But he was looking ahead.

The early AFM experiments were incredibly hard — piggybacking an STM onto a cantilever just to read its motion. It was complicated and fragile. But again, Cal encouraged risk. He believed if something was worth doing, we would find a way to make it work.

And eventually, we did.

NS: The earliest AFM experiments were quite complex. Can you describe how the first implementations actually worked?

Foster: The earliest versions were incredibly complex — much more than what people might imagine today. One of the first approaches essentially involved piggybacking a scanning tunneling microscope onto a cantilever. So you had the cantilever interacting with the surface, and then an STM trying to read out the motion of that cantilever.

But STM itself was already very challenging — vibration isolation, electrical noise, ultra-high vacuum. Now we were stacking another layer of complexity on top of that. It made the whole system extremely difficult to operate.

Those early measurements were hard-won. People would spend long periods just trying to get a single line trace. It wasn't a push-button instrument by any means.

NS: What were the biggest technical challenges in making AFM a workable instrument?

Foster: There were several. First, detecting the motion of the cantilever with sufficient sensitivity was a major hurdle. The initial approaches were not very practical, which is why the optical readout became such an important breakthrough later.

Then there were the usual challenges we were already dealing with in STM — vibration isolation, environmental control, and noise reduction. All of that carried over.

But beyond the hardware, there was also the conceptual challenge. We were trying to measure forces at an extremely small scale and translate that into meaningful images. That required a lot of experimentation and intuition.

NS: Looking back, what do you think was the most critical breakthrough that enabled AFM to become widely adopted?

Foster: I would say the combination of two things: the conceptual leap and the practical implementation.

The conceptual leap was recognizing that you could image surfaces using forces rather than tunneling current — and that this would allow you to work with insulating materials.

But the practical side was just as important. Without reliable ways to detect cantilever motion and stabilize the system, it wouldn't have gone very far.

Once those pieces came together, AFM became much more than a laboratory curiosity. It became a versatile tool that could be applied across many fields.

NS: What was the lab culture like during that transition?

Foster: It was intense. We were expected to attempt experiments others considered nearly impossible. Vibration isolation, ultra-high vacuum systems, extreme precision — that was the norm.

But there was also a sense of joy. Cal loved exploration. He loved windsurfing, hiking, adventure. Even when he wasn't good at something — like windsurfing — he kept doing it because he loved it.

That mindset translated into the lab: don't be afraid of failure. Keep trying.

NS: How did Cal's influence extend beyond AFM?

Foster: Years later, when I was working on MEMS technologies, Cal introduced me to the idea of cell sorting for medical applications. He didn't tell me how to solve it. He just pointed me in the direction and said, "Go talk to this person."

He had a way of planting seeds without dictating the outcome. That conversation changed my career. Eventually, the technology that grew from those ideas is now used in major medical research facilities worldwide.

He taught us how to think boldly — not just how to build microscopes.

NS: What made Calvin Quate truly exceptional?

Foster: He wasn't driven by ego. He didn't campaign for awards. He just kept doing great things.

What made him happiest was seeing his students succeed. I never saw him more joyful than when he talked about what others had accomplished.

That's rare.

His legacy isn't just AFM. It's the mindset he instilled: take risks, pursue big ideas, and let others grow beyond you.

NS: As we mark 40 years of AFM, what lessons remain most relevant today?

Foster: The biggest lesson is courage.

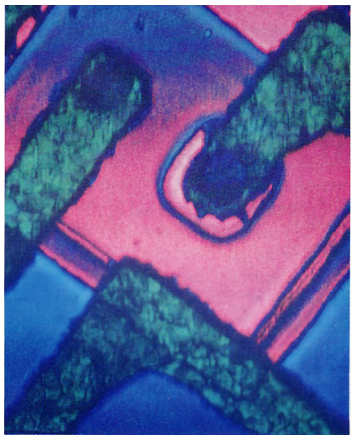
Courage to pivot.

Courage to leave a successful path.

Courage to attempt something that may fail.

AFM didn't emerge from incremental improvement. It came from bold redirection. That lesson applies just as much today as it did in 1986.

NS: Dr. Foster, thank you for sharing your reflections and for giving us a firsthand look at the vision and courage behind the birth of AFM.



Acoustic microscope image of an integrated circuit segment showing two micron aluminum conductors with sub-micron density features.

Final adjustments are made to the superfluid helium acoustic microscope cryostat before cooling.

Reunion with Prof. Cal Quate, Mrs. Quate, and former students (Foster standing in blue shirt).

FROM LABORATORY CURIOSITY TO INDUSTRIAL INFRASTRUCTURE: THE COMMERCIAL EVOLUTION OF AFM

A Founder's Perspective on Building Park Systems and Industrializing Atomic Force Microscopy

Dr. Sang-il Park, Founder and CEO, Park Systems Corp., Gwacheon, South Korea

This article is based on a presentation delivered at the NanoScientific Symposium, Stanford University. Watch the full presentation at www.nanoscientific.org.

The Dawn of a New Instrument

In the early 1980s, as scanning tunneling microscopy (STM) began revealing atomic images of silicon surfaces, a quiet revolution was taking shape at Stanford University. Under the leadership of Professor Calvin Quate, researchers were pushing beyond the limits of optical microscopy and redefining what it meant to "see" matter.

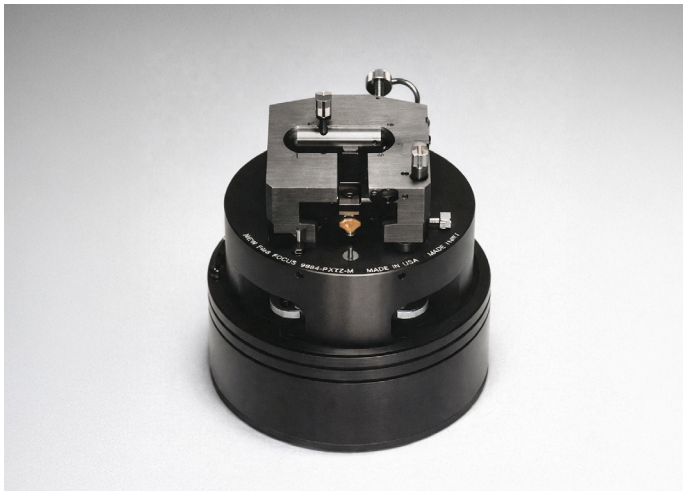
Achieving atomic resolution was not routine—it demanded patience, precision, and sometimes luck. For those who succeeded, it felt like entry into an exclusive club. Yet even at that early stage, it was clear that STM had limitations. It required conductive samples, leaving vast categories of materials beyond reach.

The breakthrough came when the idea that would become atomic force microscopy (AFM) emerged: instead of relying on tunneling current, it utilized the interaction forces between a sharp probe tip and the sample surface. This concept was realized in 1985 and formally introduced in 1986, marking the birth of AFM. This approach enabled imaging of virtually any material—conductive or insulating—at the atomic scale.

The commercialization path that followed would eventually take shape through the founding and growth of Park Systems. But at the time, AFM was still a fragile laboratory apparatus—powerful, but far from industrially ready.

The First Commercialization Wave

In the late 1980s, AFM remained largely confined to research laboratories. Commercializing such an instrument required not only engineering refinement but business conviction.



The first commercial AFM.

The early members of Park Scientific Instruments.

In 1988, I founded Park Scientific Instruments (PSI) to bring AFM into broader scientific use. In 1990, we introduced the first commercial atomic force microscope, marking the beginning of AFM's transition from a laboratory instrument to a practical research tool. Early systems brought AFM to universities and research institutes worldwide. By licensing cantilever technology developed at Stanford, we also established a reliable probe supply chain—at one point even supplying competitors.

However, early success did not guarantee stability. The early 1990s brought intensified competition from well-funded entrants. Shrinking margins and financing pressures pushed the young company to the brink of collapse. A painful restructuring followed, along with new investment and strategic partnerships that enabled survival and eventual recovery.

Those formative years revealed a central truth about scientific instrumentation: technological brilliance is necessary but insufficient. Commercial viability demands operational discipline, capital management, and long-term resilience.

By the late 1990s, consolidation reshaped the AFM landscape. Companies merged, were acquired, and reorganized. The field was transitioning from pioneering startups into structured industrial players.

The AFM industry was maturing.

A Second Beginning: Rebuilding with a New Architecture

After returning to Korea, a second venture began—initially as PSIA, later renamed Park Systems. This phase was not about repeating earlier commercialization efforts, but about rethinking AFM from the ground up.

First-generation commercial AFMs had demonstrated market demand, yet they carried fundamental technical limitations. Most relied on tube scanners—a simple solution for nanoscale positioning but prone to cross-coupling between axes. Even flat surfaces could appear distorted. For research, this was manageable. For metrology, it was unacceptable.

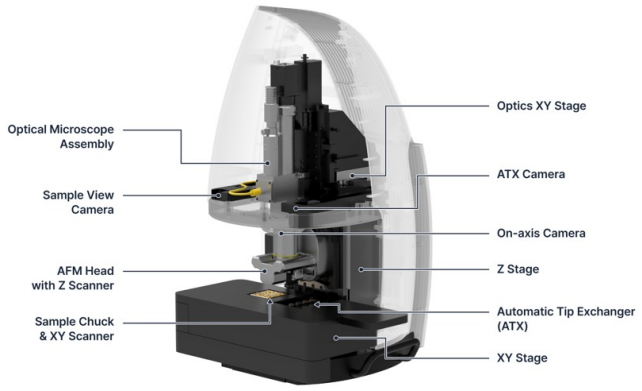
A major architectural shift emerged with the separation of XY and Z scanners, each based on flexure-guided mechanisms and stacked piezo actuators. By fully decoupling lateral and vertical motion—particularly through an independent Z scanner—this orthogonal scan design eliminated cross-talk and enabled true metrology-grade accuracy. Higher resonance frequencies further improved measurement stability and scan speed.

Equally significant was the stabilization of true non-contact mode in ambient conditions. Early systems relied heavily on tapping mode due to the difficulty of maintaining stable non-contact operation. However, tapping introduced tip wear, limiting measurement accuracy and repeatability. By refining scanner mechanics, feedback control, and system stability, it became possible to maintain operation strictly within the attractive force regime. This enabled minimal tip degradation, improving measurement reliability, particularly for high-aspect-ratio structures, soft materials, and advanced semiconductor applications.

Control theory played a central role in advancing AFM performance. By quantitatively modeling the feedback loop, the relationships among scan speed, surface slope, feedback gain, and tracking error could be clearly defined. This enabled systematic optimization of operating conditions, replacing empirical tuning with predictable and reproducible performance.

These advances enabled the transition from manually tuned instruments to increasingly automated systems. Automation was implemented at multiple levels, including probe handling, alignment, and system calibration, forming the foundation for fully automated AFM operation in both research and industrial environments:

- Pre-mounted probe carriers with encoded identification
- Kinematic mounting for repeatable positioning
- Automatic tip exchange modules
- Integrated machine vision for laser alignment



The anatomy of the Park FX40 AFM.

These developments culminated in automated AFM platforms such as the FX series, where users define scan size, resolution, and quality preference, and the system optimizes remaining parameters in real time.

AFM was evolving from a skilled-operator instrument into a robust measurement platform.

Crossing the Industrial Threshold

Transitioning AFM from a laboratory instrument to an industrial metrology tool required meeting the stringent demands of semiconductor manufacturing. These include high repeatability, system uptime, full automation, fab integration, and data traceability—requirements far beyond those of typical research environments.

At the same time, continued device scaling and the introduction of complex 3D architectures created measurement challenges beyond the capabilities of conventional optical techniques. Parameters such as line edge roughness, sidewall angles, nanoscale topography, and defect characterization required atomic-scale resolution combined with high measurement accuracy.

To address these requirements, Park Systems industrial AFMs were developed with capabilities tailored for semiconductor process control, including:

- 300 mm wafer handling
- Fully automated navigation
- SECS/GEM communication protocols
- Environmental control
- High-throughput architectures

Joint development programs with leading research institutions such as imec marked critical validation milestones. These collaborations demonstrated AFM's suitability for advanced node metrology and 3D stacking applications.

Applications expanded across semiconductor manufacturing, covering both front-end and back-end processes:

Front-End

- Surface roughness metrology
- Height, depth, width, and angle measurements
- CMP metrology
- Wafer edge (bevel) metrology
- Defect review
- Electrical conductivity measurements

Back-End

- Copper pad height metrology
- Redistribution layer (RDL) metrology
- DUV/EUV mask defect review
- Defect repair using AFM probes

These capabilities established AFM as a versatile metrology platform across multiple stages of semiconductor manufacturing.

Park NX-Wafer, an automated AFM system for in-line nanometrology.

The Rise of Park Systems Within a Consolidating Industry

The AFM industry has undergone multiple consolidation waves. Early pioneers—including Park Scientific Instruments, Digital Instruments, and TopoMetrix—were absorbed into larger metrology groups over time. Companies such as Veeco and later Bruker played significant roles in shaping the competitive landscape.

Within this evolving environment, Park Systems—rebuilt from its second founding—pursued steady expansion through technological differentiation rather than scale alone. Over the past two decades, it has grown into a global AFM manufacturer with installations in research institutions and semiconductor fabs worldwide. Today, Park Systems is widely recognized as the AFM industry leader, with approximately $150 million in annual revenue and a market capitalization exceeding $1 billion.

Public listing in 2015 marked a structural transition from entrepreneurial venture to globally recognized corporation. Strategic acquisitions broadened capabilities into adjacent nanoscale metrology domains, including ellipsometry, vibration isolation, and digital holographic microscopy.

The newly constructed Park Systems building, Gwacheon, South Korea.

The trajectory reflects not simply corporate growth, but the maturation of AFM as a cornerstone measurement technology.

Beyond Technology: The Human Dimension

Over four decades, AFM's transformation has also reflected broader lessons in leadership and purpose. Early efforts focused on invention and survival, while later experience underscored the importance of organizational culture—trust, accountability, and long-term commitment. Sustained innovation requires not only technical excellence, but also disciplined execution and clarity of purpose.

At a certain stage, financial success becomes secondary to value creation. When confronted with a major acquisition offer, the defining question was not valuation, but direction: would selling maximize value for society, or would continued innovation create greater long-term impact?

The choice was to continue building.

True entrepreneurship means creating something new and sustaining it responsibly. It requires balance—neither driven by fear nor by greed—and a long-term commitment to earning respect.

Forty Years Forward

Forty years later, atomic force microscopy has evolved from a laboratory innovation into a foundational tool for nanoscale science and semiconductor manufacturing.

Over the past four decades, continuous innovation has transformed AFM from a laboratory apparatus into a widely used scientific instrument and a critical metrology tool in semiconductor fabrication. Key technological milestones included the development of flexure-based orthogonal scan systems, reliable true non-contact operation, optimized Z-servo control, automated operation through software such as SmartScan, and fully automated semiconductor process-control AFMs. These advances enabled AFM to move beyond academic laboratories and become an essential technology for nanoscale characterization and industrial metrology.

The evolution of AFM is inseparable from the organizations that advanced it from laboratory innovation to industrial infrastructure. Park Systems represents one sustained effort to industrialize and globalize AFM while maintaining its foundation in scientific rigor and engineering precision. More broadly, AFM's evolution reflects not only advances in physics, but also engineering discipline, entrepreneurship, and long-term commitment. As device dimensions continue shrinking and advanced packaging expands, nanoscale metrology will face even greater demands, and the next forty years will require the same courage that defined the first.

Dr. Sang-il Park is the founder and CEO of Park Systems and founder and CEO of Park Scientific Instruments. He earned his Ph.D. in Applied Physics from Stanford University, where he worked in the laboratory of Calvin Quate during the early years of scanning probe microscopy. Dr. Park has dedicated his career to advancing nanoscale measurement technologies and building globally competitive instrumentation companies in atomic force microscopy.

Professor Calvin Quate and his Ph.D. student Sang-il Park.

Dr. Sang-il Park, Chairman and CEO of Park Systems.

ACTIVE AFM CANTILEVERS AND THE NEW RESEARCH THEY ENABLE

Prof. Georg E. Fantner, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

This article is based on a presentation delivered at the NanoScientific Symposium, Stanford University. Watch the full presentation at www.nanoscientific.org.

Introduction: Beyond Miniaturization

Since its introduction in 1986, the atomic force microscope (AFM) has evolved largely through advances in cantilever design and microfabrication. Early progress was driven by miniaturization, making cantilevers smaller, faster, and more precise. This strategy dramatically increased imaging speed and force sensitivity, enabling high-speed AFM and expanding the technique into liquid environments and dynamic biological systems.

However, miniaturization alone eventually encounters practical and physical limits. Extremely small cantilevers are difficult to handle and operate reliably, particularly in applications requiring larger scan ranges or stable force control. Further increases in resonance frequency yield diminishing returns when bandwidth becomes limited by the quality factor (Q) and intrinsic material losses.

In his recent presentation, Professor Georg Fantner revisits cantilever design from a different perspective: rather than focusing exclusively on size reduction, he explores how material choice, intrinsic damping, and multilayer microfabrication can fundamentally alter cantilever dynamics and enable new and enhanced measurement modalities. His work demonstrates that innovation in AFM hardware, particularly in cantilever engineering, continues to unlock new scientific capabilities, from high-speed air imaging to self-sensing detection, in-SEM correlative metrology, and even approaches toward three-dimensional tomography.

Cantilever Dynamics: Rethinking Speed and Bandwidth

In dynamic (tapping-mode) AFM, the response time of the cantilever determines imaging speed and force control. When the cantilever encounters a change in tip-sample interaction, it must transition to a new steady-state oscillation. The time required for this transition sets the imaging bandwidth.

Traditionally, bandwidth improvement has been pursued by increasing resonance frequency through miniaturization. Since the response time scales approximately with the ratio of Q factor to resonance frequency, reducing cantilever size increases frequency and therefore shortens response time.

Fantner highlights a complementary strategy: instead of only increasing resonance frequency, one can also reduce the intrinsic Q factor. Because the bandwidth scales with f_0/Q, modifying material properties to intrinsically lower Q can achieve comparable, or even superior, dynamic response without extreme miniaturization.

This shift in perspective leads directly to reconsidering the materials used in cantilever fabrication.

Polymer Cantilevers: Intrinsically Faster Dynamics

Most commercial cantilevers are fabricated from silicon or silicon nitride, materials that provide high mechanical stability and low intrinsic mechanical losses. However, these same properties contribute to relatively high Q factors, particularly in air and vacuum.

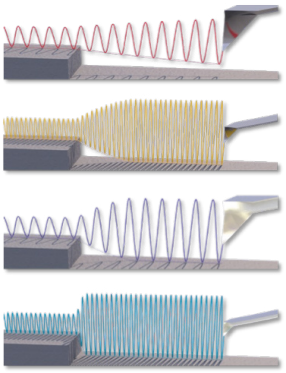


Figure 1. *The dynamic response of a cantilever depends on its resonance frequency and its Q-factor. A low resonance frequency and high Q-factor lead to a low imaging bandwidth (top: red curve). A smaller cantilever with a higher resonance frequency at the same Q-factor increases the bandwidth (yellow curve). An alternative approach is to leave the cantilever size large and reduce the Q-factor through an increase in the materials damping (purple curve). Ideally both approaches are used to create a small cantilever with high resonance frequency while retaining a low Q-factor (bottom: blue curve)*

Fantner's group investigated polymer-based cantilevers, specifically using the photodefinable epoxy SU-8. While polymers typically exhibit greater intrinsic mechanical losses, this characteristic becomes advantageous in dynamic AFM because it lowers Q and improves transient response.[1,2]

By fabricating cantilevers with identical geometries in both conventional materials and SU-8, the team demonstrated:

- Reduced Q factors in polymer cantilevers.
- Significantly improved dynamic response in air.

Small SU-8 cantilevers achieved imaging rates on the order of one image per second in air for typical scan conditions, a performance typically associated with high-speed AFM in liquid. Moreover, these improvements were achieved without sacrificing force control stability.

An important secondary benefit is gentler imaging. Faster dynamic response reduces feedback lag, enabling lower interaction forces and improved topographical fidelity. High-resolution images (e.g., 26 Megapixels acquired within practical acquisition times) demonstrate that speed enhancements translate directly into better force regulation and data quality.

Rather than simply making cantilevers smaller, Fantner's work shows that selecting materials with tailored intrinsic loss properties can fundamentally reshape AFM performance.

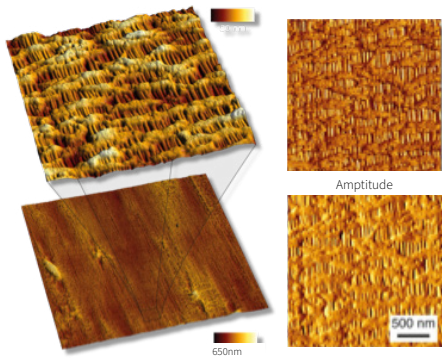


Figure 2. *A fast polymer cantilever can image large areas with high image content. The large scale 30x30 µm image showing a battery separation membrane has 8192 × 3200 pixel recorded at a surface speed of 261 µm/s. The magnified area is a digital zoom-in with 656 × 256 pixels showing the high imaging fidelity.*

Self-Sensing Cantilevers: Overcoming Optical Lever Limitations

Despite decades of innovation, the optical beam deflection method remains the dominant AFM detection scheme. While highly sensitive, optical detection introduces constraints:

- Alignment complexity.
- Space requirements.
- Incompatibility with confined geometries.
- Difficulty operating in opaque liquids.
- Limited integration with other instruments.

Self-sensing cantilevers, particularly piezoresistive designs, offer a compact alternative. However, they historically suffer from lower sensitivity.

The reason lies in what is being measured. Optical detection measures deflection or angular change, whereas piezoresistive detection measures strain. Since strain is related to curvature (the second derivative of displacement), thinning the cantilever, which lowers the spring constant and improves optical sensitivity, reduces strain sensitivity because the distance between the sensing elements and the neutral axis decreases.

Fantner's solution is a trilayer cantilever architecture[3]:

- Thin silicon nitride layers with embedded piezoresistive sensing elements.
- Thick polymer core forming the structural bulk.

By embedding sensing elements farther from the neutral axis while maintaining low spring constants through polymer compliance, the design significantly increases strain sensitivity[4].

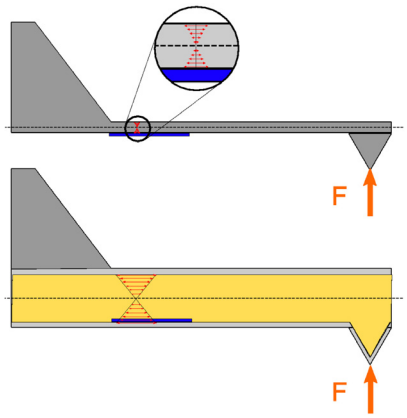


Figure 3. *In self-sensing cantilevers, the applied force is measured through the strain in a strain sensor strategically placed at the base of the cantilever. To increase the sensitivity of the strain measurement without increasing the cantilever's spring constant, Fantner uses a polymer as the main structural material of the cantilever. That way the cantilever becomes thicker without becoming stiffer. The strain sensor is then placed farther away from the neutral axis which increases the strain signal and improves the force sensitivity.*

Two-Wafer Microfabrication

Fabrication involves a two-wafer bonding process:

1. One wafer defines silicon or silicon nitride tips.
2. The second wafer carries the piezoresistive sensing elements and interconnects.
3. After high-temperature processing, a polymer core is introduced.
4. The wafers are then bonded, followed by micromachining steps to define and release trilayer cantilevers.

All sensing traces are encapsulated within the cantilever, making the device robust in liquid environments and chemically harsh conditions.

The result is a self-sensing cantilever with force noise approaching that of optical detection and operation close to the thermal noise limit.

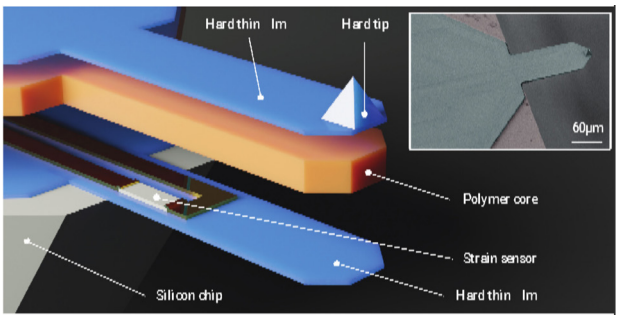


Figure 4. *Conceptual drawing of the tri-layer cantilevers, showing the polymer core (orange) sandwiched between the silicon nitride layers (blue). The strain sensors are embedded between the nitride and the polymer and are therefore hermetically sealed. Inset: SEM image of a microfabricated tri-layer cantilever.*

Actuation Integration: Toward Faster Off-Resonance Imaging

The flexibility of microfabrication enables the integration of both sensing and actuation. Fantner's cantilevers incorporate integrated actuation (e.g., electrothermal and piezoelectric), allowing direct excitation of cantilever motion[5,6].

Direct actuation reduces spurious resonances associated with external piezo excitation and can improve response speed by up to two orders of magnitude.

This capability enables rapid off-resonance imaging. In this mode, the cantilever is driven below resonance, and the tip-sample interaction is directly probed. With integrated actuation, mechanical property mapping can be performed on the order of one to two seconds per image while preserving quantitative force information.

Correlative AFM Inside the SEM

The compactness of self-sensing cantilevers enables integration into confined environments. Fantner's group developed an AFM system capable of operating inside a scanning electron microscope (SEM)[7], later commercialized in collaboration with Quantum Design.

Modern SEM chambers provide limited space above the sample, making optical detection impractical. Self-sensing cantilevers eliminate the need for laser alignment and bulky optical components.

This integration enables:

- Direct navigation to regions of interest.
- Correlative topography and mechanical mapping.
- Imaging of irregular or structured samples.

For example, the mechanical characterization of self-healing composite polymers was performed within the SEM. AFM provided nanoscale stiffness contrast across structural fibers and thermoplastic regions, information not directly accessible through SEM imaging alone.

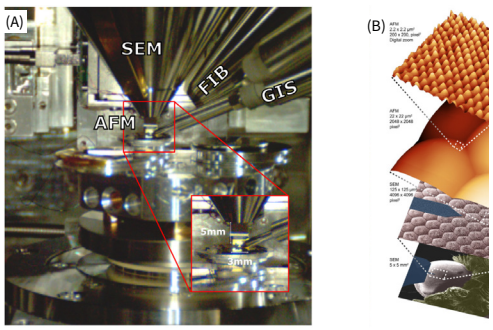


Figure 5. **(A)** *Self-sensing cantilevers enable integration of AFM into many other systems, even when space is restricted as is often the case in an SEM.* **(B)** *Correlative SEM/AFM image of a moth eye.*

Three-Dimensional AFM: Toward Tomography

AFM is inherently a surface technique. Extending it into the third dimension has long been a challenge. Fantner's solution combines AFM with focused ion beam (FIB) milling inside a dual-beam FIB-SEM instrument. Sequential slicing exposes successive surfaces, which are then imaged mechanically.

In many cases, topography changes little between slices, while stiffness mapping reveals internal heterogeneity. In rubber samples, carbon filler particles appear as stiff inclusions within a soft matrix, enabling three-dimensional stiffness mapping.

This approach extends AFM from a surface profiler toward a volumetric mechanical characterization tool.

Impact and Outlook

Fantner's work underscores a central theme: microfabrication remains a key enabling technology for AFM evolution. By rethinking materials, architecture, and integration strategies, cantilevers become multifunctional platforms rather than passive mechanical probes.

Key contributions include:

- Polymer cantilevers with intrinsically lower Q for faster air imaging.
- Trilayer self-sensing designs with improved strain sensitivity.
- Integrated actuation for rapid off-resonance imaging.
- Integration of AFM within SEM and FIB systems.
- Three-dimensional stiffness tomography.

Nearly four decades after the introduction of AFM, the cantilever remains central to innovation. Rather than being limited by physical constraints, creative microfabrication strategies continue to expand the scope of what AFM can measure, mechanically, electrically, and volumetrically.

As AFM increasingly intersects with electron microscopy, cryogenic techniques, and multimodal characterization, the cantilever evolves from a simple mechanical beam into a multifunctional nanoscale sensor.

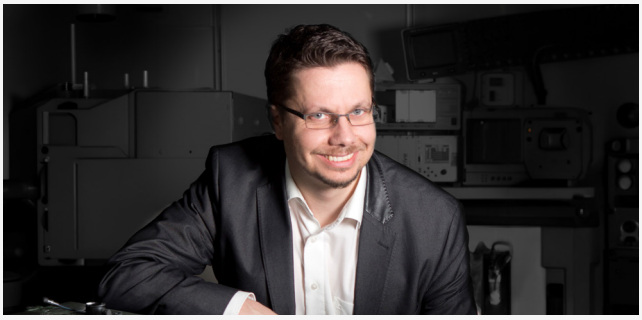
The field's future may lie not in making cantilevers smaller, but in making them smarter.

About Prof. Georg Fantner

Georg E. Fantner received his MS from the University of Technology Graz (2003) and his PhD from the University of California, Santa Barbara (2006). Following a postdoctoral position in the Biomolecular Materials Lab at the Massachusetts Institute of Technology, he joined the École Polytechnique Fédérale de Lausanne (EPFL) in 2010. He leads the Laboratory for Bio- and Nano-Instrumentation and serves as co-director of the Institute of Bioengineering.

His research focuses on developing advanced technologies for measuring and manipulating nanoscale structures, particularly atomic force microscopy instrumentation, with applications spanning materials science, nanotechnology, and the life sciences. His work has been published in leading journals including Nature, Nature Materials, Nature Physics, Nature Nanotechnology, Nature Cell Biology, Nature Microbiology, Nature Communications, Nano Letters, and Science, and has been featured in popular science publications.

Prof. Fantner is co–Editor-in-Chief of Microsystem Technologies (Springer Nature) and serves as scanning probe microscopy editor for Microscopy and Microanalysis. He holds several patents in nanotechnology and is co-founder of two nanotechnology companies. He is also active in open hardware initiatives to promote academic knowledge sharing and serves as president of the EPFL Open Science Strategic Committee and the ETH Domain Open Research Data Steering Committee.



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DECIPHERING ELECTRICAL BISTABILITY IN NANOCOMPOSITE DEVICES USING ELECTROSTATIC FORCE MICROSCOPY

Prof. Shashi Paul, De Montfort University, Leicester, United Kingdom

This article is based on a presentation delivered at the NanoScientific Forum, Université Paris-Saclay. Watch the full presentation at www.nanoscientific.org.

Introduction

The search for new electronic memory technologies remains one of the central challenges in modern electronics. As computing systems demand faster processing speeds, higher data density, and reduced power consumption, researchers continue to explore materials and device architectures capable of storing information in fundamentally different ways.

Among the many emerging approaches, nanocomposite materials consisting of insulating polymers embedded with nanoscale or sub-nanoscale bits (nanoparticles, molecules, nanoclusters, etc) have attracted considerable attention[1]. These systems can exhibit electrical bistability, meaning that the device can exist in two stable electrical states corresponding to binary information storage[2].

Electrical bistability has been widely reported in nanocomposite-based devices over the past two decades[3]. However, despite the large number of studies, the underlying mechanisms responsible for bistable switching remain widely debated. Different research groups have proposed a range of explanations, including charge trapping, filament formation, and interface effects, often even for identical material systems[4].

In work spanning more than a decade, Prof. Shashi Paul and collaborators at De Montfort University have investigated the physical origins of electrical bistability in nanocomposite devices[2, 5]. By combining device engineering with electrostatic force microscopy (EFM) measurements, their research provides insight into how internal electric fields generated by stored charges can produce bistable electrical behavior in nanocomposite structures[6, 7].

Bistability and Information Storage

In electronic memory systems/device, bistability refers to the presence of two stable states separated by an energy barrier. A system/device can flip from one state to another when sufficient energy is supplied, but once the transition occurs, the system remains in that state until another external stimulus is applied[8].

This concept forms the basis of binary memory. A simple physical representation of a bistable system is a particle in a double-well energy landscape. Each well represents a stable state. To move from one well to the other, the particle must overcome an energy barrier.

For memory devices, the stability of these states determines how long information can be stored. Ideally, a memory device should maintain its stored state for extended periods without requiring continuous energy input.

However, many conventional electronic memory technologies suffer from charge leakage or degradation over time, which ultimately limits their retention performance. This limitation has motivated research into new materials and physical mechanisms capable of supporting stable bistable behavior. Prof. Shashi Paul is seeking an immortal memory that should remain for eternity after it is written.

Nanocomposite Materials for Memory Devices

In Prof. Paul's research, a nanocomposite is defined as an admixture of polymer matrix and nano and sub-nano bits (nano-particles, nano-wires, molecules, nano-clusters, etc).

The polymer serves as an electrically insulating medium. Common examples include polystyrene, polyvinyl alcohol, polyvinyl acetate, polyvinyl phenol. These polymers exhibit low electrical conductivity and can be processed into thin films suitable for electronic devices.

Nanoparticles or molecular species are introduced into the polymer matrix to modify its electrical properties. These inclusions may be metallic, semiconducting, or molecular in nature. Their presence introduces localized sites capable of interacting with charge carriers.

Once fabricated, the nanocomposite film is typically sandwiched between two metal electrodes, forming a simple two-terminal electronic device. By applying a voltage across the electrodes, the resulting current–voltage characteristics can reveal whether bistable switching occurs.

Despite the structural simplicity of such devices, the mechanisms governing their electrical behavior can be surprisingly complex.

Early Studies of Nanocomposite Bistability

Interest in nanocomposite memory devices increased significantly following several experimental demonstrations in the early 2000s. One early example involved the organic compound Alq_3 (tris(8-hydroxyquinolinato)aluminum) and C60 embedded in Polystyrene and sandwiched between metal electrodes[3]. This study revealed hysteresis in the current–voltage response, suggesting the presence of bistable electrical states.

Another widely cited study incorporated gold nanoparticles blended with polymer materials. When this nanocomposite film was sandwiched between electrodes, the resulting device exhibited clear bistable switching behavior[6].

Following these pioneering experiments, numerous research groups began exploring nanocomposite memory devices using a wide variety of materials and fabrication approaches. However, the reported electrical characteristics varied widely.

Typical parameters reported in the literature include:

- On/off current ratios ranging from 10 to 10^9
- Retention times ranging from seconds to several weeks
- Switching endurance ranging from tens to millions of cycles

In addition, the shapes of the current–voltage curves differed considerably, with behaviors often described as N-shaped, S-shaped, or O-shaped switching characteristics[9]. Such variability suggested that the underlying mechanisms were not yet fully understood[4].

Conflicting Conduction Mechanisms

A major challenge in understanding nanocomposite bistability is the lack of agreement regarding the conduction mechanisms responsible for switching.

Even when identical materials are studied, different research groups often propose different explanations for the observed electrical behavior. These include mechanisms such as:

- Charge trapping within nanoparticles
- Formation of conductive filaments
- Interface-related conduction processes
- Space-charge-limited transport

This lack of consensus motivated Prof. Paul and his collaborators to revisit the problem from a more fundamental perspective.

Rather than attempting to interpret experimental results using existing models, their approach focused on developing a physical explanation based on first principles, beginning with the role of charge storage and internal electric fields.

Internal Electric Fields as the Origin of Bistability

A key concept emerging from this work is that excess charge within a material inevitably generates an electric field.

Charges can accumulate in several locations within a device: on material surfaces, at defect sites, within embedded nanoparticles. When these charges are present , they create internal electric fields that influence the transport of charge carriers through the device.

A simple physical analogy involves a dipole placed near a charged electrode. Depending on the orientation of the dipole, the potential distribution within the system changes. Reversing the dipole orientation produces a different potential configuration.

If a system can switch between such configurations, it can exhibit two stable electrical states, corresponding to bistability. In nanocomposite materials, nanoparticles can act as charge storage centers. Charges trapped in these nanoparticles create local electric fields that effect current flow through the device.

Investigating Charge Storage with Electrostatic Force Microscopy

To experimentally investigate charge storage in nanocomposite systems, the researchers employed electrostatic force microscopy (EFM). EFM is a scanning probe microscopy technique capable of detecting electrostatic interactions between a probe tip and a sample surface. These interactions arise from local electric fields and surface charges.

By measuring the forces acting on the probe tip, EFM can map charge distributions across a surface with nanoscale spatial resolution.

The experiments were performed using a Park Systems XE-100 scanning probe microscope, which provides multiple imaging modes suitable for nanoscale electrical characterization.

The device structures studied consisted of:

- A silicon substrate
- A silicon dioxide insulating layer
- Metal electrodes
- A nanocomposite film containing nanoparticles and, also just nano-particles

Using the AFM probe tip, charges could be locally injected into the nanocomposite/nano-particles surface. Subsequent EFM imaging allowed the researchers to observe how these charges evolved over time.

Charge Retention in Nanocomposite Systems

Initial experiments focused on determining how long stored charges remain in the nanocomposite material. EFM images revealed bright regions corresponding to localized surface charge. By repeatedly imaging the same area, the researchers observed that these charges gradually dissipated over time. In many cases, the stored charge decayed within approximately one hour.

Control experiments were also performed using pure polymer films without nanoparticles. These experiments showed that polymers themselves can also store charge temporarily, although the charge typically dissipates relatively quickly.

This finding emphasized the importance of carefully distinguishing between the roles of the polymer matrix and the embedded nanoparticles when interpreting bistability measurements.

Direct Charging of Individual Nanoparticles

To better understand charge storage at the nanoscale, the researchers conducted experiments in which individual nanoparticles were charged using the AFM probe tip. In one experiment, a collection of nanoparticles was deposited onto an electrode surface. Most of the nanoparticles formed conductive pathways connected to the electrode, but a few particles remained electrically isolated.

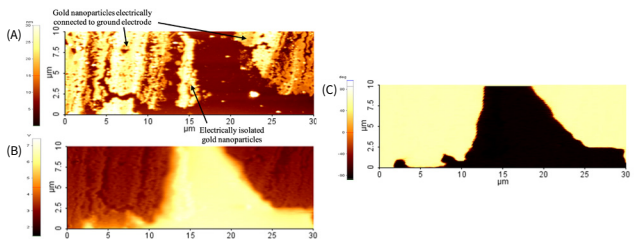

Figure 1. (A) *Topography image of the area where nanoparticle charging experiments were conducted.* (B) *EFM amplitude and* (C) *phase image when an external voltage is applied to one of the electrodes. (Source: PhD thesis (2010), Dominic Prime)*

By charging these isolated nanoparticles, as shown in Figure-1, with the probe tip and monitoring it over time, the researchers were able to directly observe charge decay on a single nanoparticle. Sequential EFM images showed that the stored charge gradually dissipated over several minutes before disappearing completely.

These measurements provided direct evidence that nanoparticles can temporarily store electrical charge, supporting the hypothesis that charge accumulation plays an important role in nanocomposite bistability.

Filament Formation and Device Variability

In some nanocomposite devices, extremely large on/off current ratios have been reported. These large switching ratios are often attributed to the formation of conductive filaments within the device.

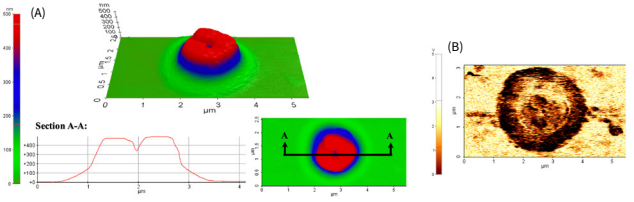

Figure 2. *3D topography and line profile of the second damage type on a nanocomposite memory device's top electrode (Non-standard colours have been used to better highlight the features).* (B) *EFM image of damaged area. This generally happened due to filamentary conduction path formation. (Source: PhD thesis (2010), Dominic Prime)*

However, atomic force microscopy imaging revealed that such filament formation often leads to high device-to-device variability. From a device engineering perspective, this variability is undesirable. Reliable memory devices must exhibit consistent switching behavior across large arrays of devices.

Therefore, while filament formation can produce large switching currents, it may represent device failure rather than a reliable switching mechanism.

A Simple Physical Model

Based on their experimental findings, the researchers proposed a simple model to explain electrical bistability in nanocomposite systems.

The model suggests that bistability occurs when:

1. Charge carriers become trapped in nanoparticles.
2. These charges generate an internal electric field.
3. The internal electric field alters the effective electric field across the device.

As a result, the device exhibits two different current levels when measured under identical external voltage conditions. These two current states correspond to the bistable states of the memory device. The retention time of the device depends on how long the stored charge—and therefore the internal electric field—can be maintained.

Conclusion

Electrical bistability in nanocomposite materials has been widely observed but remains poorly understood. Through a systematic investigation combining device fabrication and electrostatic force microscopy, Prof. Shashi Paul and collaborators have provided important insights into the physical mechanisms underlying this phenomenon.

Their work demonstrates that bistable behavior can arise from internal electric fields generated by charges stored in nanoparticles embedded within polymer matrices. Electrostatic force microscopy provides a powerful tool for directly visualizing these charge distributions and understanding their temporal stability.

Ultimately, the stability of the internal electric field determines how long information can be retained in such devices. By carefully controlling charge storage and nanoparticle distribution within nanocomposites, it may be possible to design new classes of electronic memory devices with improved efficiency and stability.

These findings highlight the importance of combining nanoscale characterization techniques with device-level analysis to fully understand the behavior of emerging electronic materials.

About Prof. Shashi Paul

Shashi Paul (SP), Professor of Nanoscience and Nanotechnology, works at the Emerging Technologies Research Centre (EMTERC) at De Montfort University, Leicester, UK. He received his degree from the Indian Institute of Science (IISc), Bangalore, India, and previously worked at the University of Cambridge, Durham University, and Rutgers University. His particular focus is on emerging electronic memory devices, batteries and solar cells, and the development of materials manufacturing processes to reduce the carbon footprint of next-generation electronic devices.

Since his teenage years, he has regarded research and teaching as a passion rather than a profession. He believes that teaching and research are like binary stars—they either exist or they do not—and that an invisible force, which cannot be seen but can be felt, is the foundation of their existence. Playing and watching cricket is also something he thoroughly enjoys.

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ELECTRICAL AFM CHARACTERIZATION OF DEVICES USING AN INTEGRATED MULTI-PROBE PLATFORM

Jay Son[1], Edward Park[1], Luna Kim[1], John Park[1], Charles Kim[1], James Kerfoot[2], Andrea Cerreta[2]
[1]Park Systems Corp., Gwacheon, South Korea [2]Park Systems GmbH, Mannheim, Germany

Introduction

As research on next-generation semiconductor devices and two-dimensional (2D) materials continues to accelerate, there is growing demand for measurement platforms capable of probing both electrical behavior and nanoscale surface properties simultaneously. Atomic force microscopy (AFM) has long been an essential tool for nanoscale characterization, providing high-resolution imaging alongside electrical and mechanical measurements[1,2]. However, advanced electrical AFM techniques—such as Kelvin probe force microscopy (KPFM), conductive AFM (C-AFM), and scanning thermal microscopy (SThM)—often require precise electrical contacts to nanoscale devices while scanning, creating significant experimental challenges[3,4].

In many laboratories, these contacts are made using external probe stations or manual probing approaches. While functional, such configurations frequently introduce complications including mechanical interference with the AFM scanner, poor reproducibility, limited placement precision, and additional mechanical loading on the sample stage. Large manipulators or external stages may also reduce stability during high-resolution AFM imaging.

To address these limitations, Park Systems and Imina Technologies have developed an integrated solution combining Park Systems AFM instrumentation with the Imina Technologies Microprobing Platform (4-Bot). In this configuration, up to four independently controlled miBot™ micro-robotic probes are mounted directly inside the AFM stage environment. Each miBot unit can be positioned with micrometer-scale precision to establish electrical contacts with the sample while maintaining full compatibility with AFM scanning.

The tungsten probes mounted on the miBot units can be connected directly to the auxiliary input/output channels of the AFM controller, enabling simultaneous source–drain biasing and electrical measurements during AFM operation. The integrated platform therefore enables multi-electrode device characterization and high-resolution nanoscale imaging within a single instrument.

This article outlines the integrated hardware configuration and demonstrates three representative applications enabled by this platform:

1. Electrical contacting of layered materials and layered material heterostructures on insulating substrates
2. In-operando nanoscale voltage mapping in lateral field-effect transistors
3. Measurement of Joule heating in nano-structured electronic devices

Together, these examples illustrate how the integrated system enables advanced electrical and thermal AFM characterization with improved flexibility and experimental control.

Integrated Hardware Platform

The experimental setup was configured by integrating a Park Systems FX200 AFM with the Imina Technologies Microprobing Platform (4-Bot). The probe station is mounted directly onto the FX200 sample chuck, allowing electrical probes to be positioned precisely near the region of interest without interfering with the AFM cantilever.

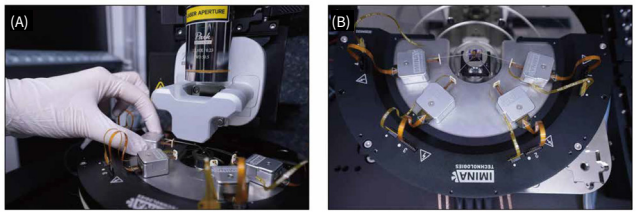

Figure 1. Integrated configuration of the Park Systems FX200 AFM and the Imina Technologies Microprobing Platform (4-Bot). **(A)** *Photograph of the Imina Technologies Microprobing Platform (4-Bot) installed inside the Park Systems FX200 AFM, and* **(B)** *top view of the integrated setup. Up to four miBot units can be placed on the sample stage without mechanical interference with the AFM head or the cantilever.*

Each miBot unit is magnetically anchored to the AFM stage, allowing rapid manual installation or removal. Up to four units can be positioned simultaneously, providing independent multi-electrode contacts for device measurements. The probes are manipulated using a dedicated positioning controller and a PC-connected control pad, which allows precise control of probe movement speed and direction.

An example configuration is shown with a device containing patterned gold electrodes placed on the FX200 stage. The AFM cantilever is first positioned near the region of interest. Tungsten probes mounted on the miBot units are then carefully aligned with the device contact pads. The alignment process is facilitated by the high-resolution optical vision system of the AFM and the intuitive operation of the Precisio™ software.

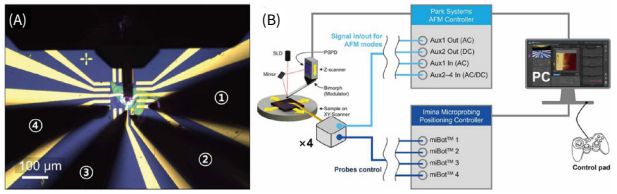

Figure 2. Multi-probe arrangement inside the Park Systems FX200 AFM, and signal & control configuration. **(A)** *Optical image of a device with patterned gold electrodes loaded into the Park Systems FX200 AFM, acquired using the built-in vision system. Four tungsten probes mounted on miBot units are positioned on the targeted electrode pads in the vicinity of the AFM cantilever, enabling AFM measurements without mechanical interference with the individual probes.* **(B)** *Schematic diagram of the operating configuration in which the probe station is integrated with the AFM system. Each miBot is connected via two separate communication lines to the AFM controller and the positioning controller, respectively. The tungsten probes mounted on the miBot units are interfaced with the Aux1 and Aux2 Out channels of the AFM controller to apply AC/DC drive signals to the device, and with the Aux1 In and Aux2–4 In channels to acquire AC or AC/DC measurement signals. Up to four miBot units can be used simultaneously and are finely positioned by the positioning controller, while a PC-connected control pad provides an intuitive interface for independent probe manipulation.*

Electrical connections are made through the AFM controller's auxiliary channels. In the configuration used in this study:

- Aux1 Out and Aux2 Out supply AC or DC drive signals to the device
- Aux1 In and Aux2–4 In acquire electrical response signals from the device

This configuration enables simultaneous electrical excitation and measurement while the AFM performs nanoscale imaging. Because

each miBot probe can be positioned independently, the system supports flexible multi-probe measurement configurations, including two-probe and four-probe device geometries.

The integrated system therefore provides a unified platform for studying nanoscale electrical behavior while maintaining stable AFM operation.

Electrical AFM of Electrically Floating Layered Materials

Layered materials (LMs) and layered material heterostructures (LMHs) have become key platforms for next-generation nanoelectronic devices. AFM-based electrical techniques such as conductive AFM and Kelvin probe force microscopy are widely used to study these materials, enabling nanoscale measurements of conductivity, potential distribution, and interfacial phenomena[5].

However, these techniques generally require reliable electrical contacts. Conventional approaches often involve lithographic patterning and deposition of metal electrodes, which can complicate sample preparation and make it difficult to study materials during intermediate fabrication stages[6].

Using the miBot microprobing system, electrical contacts can instead be applied directly to individual flakes of layered materials placed on insulating substrates.

In one experiment, a tungsten probe was positioned to contact a graphite region connected to a few-layer graphene (FLG) flake. The miBot contact served as a grounding point, preventing charge accumulation during KPFM measurements while simultaneously acting as a drain electrode during conductive AFM imaging.

To demonstrate the effect of grounding, local anodic oxidation was used to create channels that divided the FLG flake into electrically isolated regions. These channels completely separated portions of the flake from the contacted region.

AFM measurements revealed that the isolated regions developed distinct electrical potentials due to charge accumulation. In contrast, the region connected to the miBot probe remained electrically stable. Current mapping performed with C-AFM confirmed that current flow occurred only within the electrically contacted portion of the flake.

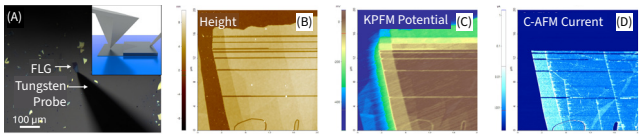

Figure 3. Contact-enabled HD-KPFM imaging and current mapping of FLG. (A) *An optical view from the FX200 camera showing a tungsten probe touching a graphite flake connected to FLG, with a schematic inset.* **(B)** *Non-contact mode height images of the FLG flake showing the height in addition to patterning achieved by anodic oxidation.* **(C, D)** *The electrical contact to the FLG enabled the acquisition of both stable single-pass HD-KPFM imaging over the contacted FLG in addition to maps of the current flow over different regions of the FLG.*

This experiment demonstrates that direct electrical contacting using miBot probes enables stable electrical AFM measurements on layered materials without the need for pre-fabricated electrodes.

Electrical Characterization of Layered Material Heterostructures

The ability to electrically contact individual flakes also enables advanced characterization of layered material heterostructures.

One example involved heterodyne Kelvin probe force microscopy (HD-KPFM) measurements of a ferroelectric superlattice formed between two parallel stacked hexagonal boron nitride (hBN) layers on a few-layer graphene substrate deposited on SiO_2.

Single-pass HD-KPFM imaging revealed nanoscale variations in surface potential associated with the ferroelectric superlattice structure. The electrical grounding provided by the miBot probe was essential for stable measurements, since the KPFM tip bias would otherwise charge the flake and cause drift in the measured potential.

A second demonstration involved contacting a graphene flake aligned with a ~25 nm thick hBN layer on a mica membrane supported by PDMS. In this case the layered structure was still on the fabrication stamp used during heterostructure assembly.

Non-contact AFM imaging combined with conductive AFM revealed a moiré pattern between the graphene and hBN layers. The ability to perform electrical characterization directly on the fabrication stamp enables researchers to verify layer alignment and interfacial properties before additional fabrication steps are performed.

This capability reduces the risk of continuing nanofabrication on misaligned structures and allows researchers to study interfaces that may later become buried during device processing.

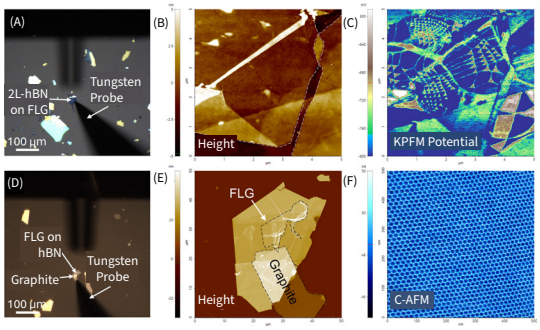

Figure 4. Contact-enabled HD-KPFM imaging and C-AFM moiré mapping of hBN/FLG heterostructures. (A,B,C) *A parallel stacked hBN homostructure on an underlying FLG on 90 nm SiO_2 exhibiting a ferroelectric superlattice was contacted by a miBot before being measured by non-contact mode height and HD-KPFM potential, again revealing the absence of charging.* **(D,E,F)** *The utility of the technique was further exemplified by contacting an FLG flake on hBN on a mica/PDMS stamp prior to non-contact mode and C-AFM imaging revealing a moiré pattern between the FLG and hBN.*

In-Operando KPFM of MoS_2 Field-Effect Devices

The integrated multi-probe platform also enables in-operando AFM measurements of operating electronic devices.

In this study, a MoS_2 thin-film device was fabricated by transferring a ~4 nm exfoliated MoS_2 flake onto a ~60 nm hBN layer deposited on a Si substrate with 280 nm thermal SiO_2. Source and drain electrodes composed of Cr/Au (10 nm/100 nm) were patterned using electron-beam lithography.

Local UV-ozone treatment was applied to selected regions of the MoS_2 channel to induce partial oxidation and modify the electronic properties of the device[7-9].

For AFM measurements, two tungsten probes mounted on miBot units were placed on the source and drain electrodes. The AFM cantilever was positioned above the MoS_2 channel to perform Kelvin probe force microscopy.

During the experiment:

- The drain electrode was held at 0 V (ground)
- The source electrode was sequentially biased at −5 V, 0 V, and +5 V

KPFM surface potential maps were acquired for each bias condition.

The measurements revealed clear bias-dependent changes in the potential distribution across the channel. Line profiles extracted from the KPFM images showed that the potential at the source electrode accurately reflected the applied bias. A nearly linear potential drop was observed along the MoS_2 channel between the source and drain contacts.

This in-operando KPFM technique enables quantitative extraction of contact resistance and analysis of potential drop distributions within nanoscale devices. By comparing measurements obtained under different bias conditions, researchers can identify spatial variations in resistance, edge-related effects, and other localized transport phenomena.

Combining KPFM imaging with electrical measurements such as current–voltage (I–V) and gate-dependent transport measurements further enables correlations between the spatial potential landscape and the overall electronic behavior of the device.

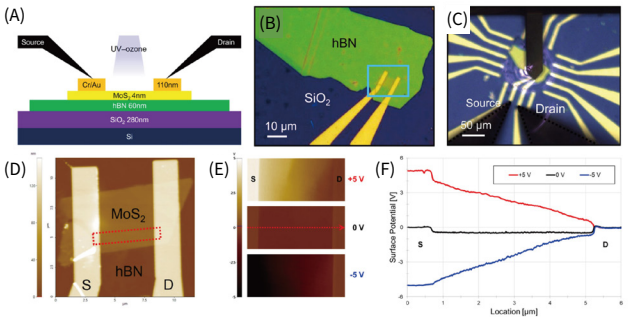

Figure 5. KPFM measurements of a UV-ozone-treated MoS_2 thin-film device under source–drain bias. **(A)** *Cross-sectional schematic of the MoS_2 thin-film device fabricated for KPFM measurements.* **(B)** *Optical microscope image of the fabricated MoS_2 thin-film device, where the blue box indicates the MoS_2 channel region used for the KPFM measurements.* **(C)** *Image acquired via the FX200 camera after loading the sample and approaching the dedicated KPFM cantilever to the device for surface potential measurements.* **(D)** *AFM height image of the MoS_2 device transferred onto the hBN layer. Gold electrodes acting as the source (S) and drain (D) are located on the left and right, respectively, and KPFM measurements were performed in the central region indicated by the red dashed box.* **(E)** *KPFM surface potential images of the MoS_2 channel acquired with a source bias equal to +5, 0 and -5 V DC (from top to bottom) and with the drain electrode held at ground (0 V).* **(F)** *Line profiles of the KPFM surface potential.*

Scanning Thermal Microscopy of Nano-Structured Devices

Beyond electrical characterization, the integrated platform also enables thermal measurements of nanoscale devices under electrical operation.

Scanning thermal microscopy (SThM) experiments were performed on nano-structured devices consisting of chains of nano-constrictions connected between large electrodes. These structures form spin Hall nano-oscillator chains[10-12].

Each device was electrically connected to top and bottom electrode pads, which were contacted using tungsten probes mounted on the miBot units. A Keithley 2636B source meter was used to inject constant DC current through the devices.

Thermal measurements were performed using the AppNano VertiSense™ SThM module with thermocouple-based AFM probes. The thermocouple voltage measured by the probe can be converted into temperature after calibration.

During the experiment, a constant 2 mA DC current was applied through the device while topography and thermal maps were acquired simultaneously.

The SThM measurements revealed localized temperature increases at the nano-constrictions. These locations correspond to regions where current density is highest, producing increased Joule heating.

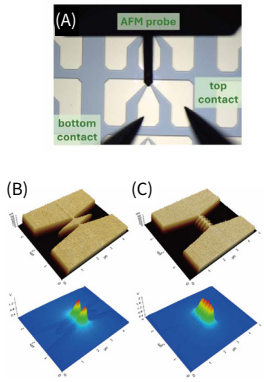

Figure 6. Thermal mapping of nano devices. **(A)** *Structures consist of a chain of nano-constrictions which are in electrical contact with a top and bottom pad, each one contacted via a needle probe.* **(B)** *Topographical map of a device with two nano-constrictions (top) and relative SThM map (bottom), where higher SThM voltage indicates a higher temperature. The same applies to* **(C)** *where a structure with five nano-constrictions was probed. For both* **(B)** *and* **(C)**, *topography was mapped by means of a PPP-MFMR probe (Nanosensors) in non-contact mode, while SThM maps were obtained using a VTP-200 probe and the VertiSenseTM setup from AppNano, with a constant current of 2 mA applied through the needles interfaced with a Keithley 2636B source meter.*

By systematically varying the injected current, researchers can observe how thermal response evolves with electrical loading. Such measurements also allow identification of non-uniformities between constrictions that may indicate increased resistance or imperfect electrical connectivity.

This approach provides direct visualization of thermal hotspots and current crowding effects in nanoscale electronic devices.

Conclusions

The integration of the Park Systems FX200 AFM with the Imina Technologies Microprobing Platform (4-Bot) provides a powerful and flexible platform for advanced electrical and thermal characterization at the nanoscale.

By enabling precise alignment of miBot-mounted tungsten probes with the AFM cantilever inside the FX200 instrument, stable electrical contacts can be established while maintaining interference-free AFM scanning. This configuration allows simultaneous device biasing, electrical measurements, and high-resolution AFM imaging.

Several application examples demonstrate the capabilities of the integrated platform:

Electrical contacting of individual layered materials and layered material heterostructures on insulating substrates

In-operando Kelvin probe force microscopy mapping of voltage distribution in MoS_2 field-effect devices

Scanning thermal microscopy visualization of Joule heating in nano-structured electronic devices

For layered materials research, the ability to electrically contact individual flakes without lithographic processing provides significant experimental flexibility. For device characterization, the system enables direct visualization of potential distributions, contact resistance effects, and thermal hotspots during device operation.

These results demonstrate that the combination of Park Systems AFM technology and the Imina Technologies microprobing platform provides an integrated solution for nanoscale electrical and thermal characterization of 2D materials and thin-film electronic devices.

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SCANNING PROBE MAGNETIC MICROSCOPY WITH MAGNETORESISTIVE MAGNETIC SENSORS

Dr. Aurélie Solignac, SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, France

This article is based on a presentation delivered at the NanoScientific Forum, Université Paris-Saclay. Watch the full presentation at www.nanoscientific.org.

Introduction

Magnetic imaging at the micro- and nanoscale is an essential tool for investigating magnetic phenomena in materials science, condensed matter physics, and nanotechnology. Beyond fundamental research, spatially resolved magnetic measurements are increasingly important in applied and industrial contexts, including the analysis of electronic circuits, magnetic nanostructures, and sensing components such as magnetic encoders used in microrobotics. In many of these cases, the goal is not only to visualize magnetic structures but to obtain quantitative maps of the magnetic field distribution with high spatial resolution and, ideally, across a broad frequency range in order to obtain more information on the magnetic properties of the material.

Scanning probe magnetic microscopy offers a powerful approach for achieving this objective by measuring the magnetic stray field emitted by a sample with a sensor scanned in close proximity to the surface. Among the various sensing technologies available, magnetoresistive sensors provide a compelling combination of sensitivity, broadband detection capability, and room-temperature operation.

This article is based on a presentation by Dr. Aurélie Solignac at the recent Europe NanoScientific Forum, describing the development of a scanning probe magnetic microscope that integrates giant magnetoresistive (GMR) sensors into flexible cantilevers for quantitative and broadband magnetic field imaging.

Magnetic Microscopy Techniques

A range of techniques is available for imaging magnetic fields at small length scales. Many of these approaches are based on scanning probe methods in which a localized sensor is scanned across the sample surface to measure the magnetic stray field.

Among the most widely used methods is Magnetic Force Microscopy (MFM). In MFM, a magnetized probe tip interacts with the magnetic field gradient above the sample surface. Changes in cantilever dynamics caused by this interaction are used to image the magnetic structure. MFM provides high spatial resolution but the technique is inherently indirect, as it measures force gradients rather than the magnetic field itself. Additionally, the magnetized probe can influence the sample due to the stray field it produces.

Another emerging technique involves nitrogen-vacancy (NV) centers in diamond. NV-based magnetometry uses a quantum defect embedded at the apex of a diamond tip as a magnetic sensor. Radio frequency (RF) excitation and optical readout of the defect allow highly sensitive magnetic measurements with excellent spatial resolution. NV sensors also offer the possibility of vector magnetic field measurements. However, the requirement for ODMR (optical detected magnetic resonance) detection increases experimental complexity and can limit measurement speed.

Scanning SQUID (superconducting quantum interference device) microscopes represent another highly sensitive approach. These systems can detect extremely small magnetic signals, but they generally require cryogenic operation and complex instrumentation.

Between these approaches lies a category of techniques based on Hall sensors and magnetoresistive sensors, which offer a balance between sensitivity, spatial resolution, and experimental simplicity.

One way to compare magnetic microscopy techniques is to examine the trade-off between magnetic field detectivity and spatial resolution. Techniques such as MFM and NV magnetometry provide high spatial resolution but typically lower detectivity. SQUID systems provide exceptional detectivity but with greater operational complexity. Magnetoresistive sensors occupy an intermediate region, combining moderate spatial resolution with robust magnetic sensitivity.

Other practical considerations also influence technique selection. These include the ability to perform quantitative measurements, measurement speed, compatibility with applied magnetic fields, and the possibility of measuring multiple magnetic field components. The potential for the probe itself to perturb the sample must also be considered.

Within this landscape, magnetoresistive sensors offer several advantages, particularly their broadband frequency response and straightforward electrical detection.

Principles of Magnetoresistive Sensing

Magnetoresistive sensors are based on the interaction between electron spin and magnetization in ferromagnetic materials. In such materials, the electrical resistance depends on the relative orientation of electron spin and the magnetization of the material. This effect forms the foundation of spintronics, a field that has transformed magnetic sensing and data storage technologies.

In a giant magnetoresistance (GMR) device, the sensor consists of two ferromagnetic layers separated by a thin spacer layer. The electrical resistance of the structure depends on the relative orientation of the magnetization in these layers. When the magnetizations are parallel, the resistance differs from the case when they are antiparallel.

To achieve stable operation, one of the layers is typically designed as a reference layer, whose magnetization remains fixed. The other layer acts as a free layer, whose magnetization rotates in response to an external magnetic field. Changes in the relative orientation of these layers result in measurable changes in electrical resistance.

Although the simplified concept involves only two magnetic layers separated by a spacer, practical devices use more complex multilayer stacks fabricated by sputtering on silicon substrates. These stacks may incorporate synthetic antiferromagnetic structures that stabilize the reference layer while minimizing stray magnetic fields generated by the sensor.

Magnetoresistive technology has reached a high level of industrial maturity. For more than three decades, GMR and TMR (tunnel magnetoresistance) sensors have been used in the read heads of hard disk drives and remain essential components in modern data storage systems. MR sensors are also widely used in automotive and industrial applications due to their robustness and reliability.

Noise and Detectivity

The detectivity of a magnetic sensor depends on both its sensitivity and its noise characteristics. In magnetoresistive sensors, a significant source of noise at low frequencies is 1/f noise.

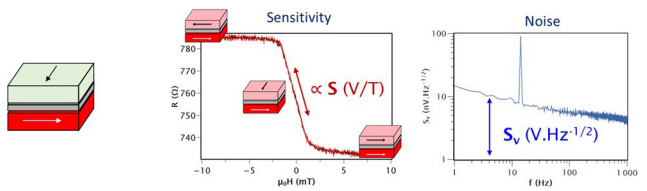

Figure 1. *Schematic of the principle of GMR structure with hard and free ferromagnetic layers. Response of the GMR: resistance versus field giving the sensitivity and noise spectral density versus frequency allowing to extract the detectivity.*

This noise component dominates measurements near DC, reducing the effective sensitivity of the sensor. However, as measurement frequency increases, the contribution from 1/f noise decreases significantly. As a result, the intrinsic sensitivity of the sensor can be fully utilized at higher frequencies.

This property gives magnetoresistive sensors an important advantage for applications that involve dynamic magnetic signals. Their ability to operate over a broad frequency range enables detection of both static and time-varying magnetic fields.

Integration into a Scanning Probe System

To use magnetoresistive sensors for magnetic microscopy, the sensor must be integrated into a probe capable of scanning the sample surface. The system presented at the NanoScientific Symposium incorporates the GMR sensor into a flexible cantilever compatible with a scanning probe microscope.

In this configuration, the cantilever performs two simultaneous measurements. The mechanical deflection of the cantilever provides topographic information, as in conventional atomic force microscopy. At the same time, the GMR sensor detects the local magnetic field generated by the sample.

Unlike conventional AFM probes, the design does not rely on a sharp tip to obtain high magnetic spatial resolution. Instead, the cantilever is oriented so that the magnetoresistive sensor itself is positioned as close as possible to the sample surface. The magnetic spatial resolution of the measurement is therefore determined primarily by the size of the sensor and the sensor–sample distance.

An important feature of this configuration is the decoupling of topography and magnetic signals. The topographic measurement is obtained from cantilever deflection, while the magnetic signal is measured electrically through the magnetoresistive sensor.

Sensor Fabrication

The fabrication of the scanning probe begins with the deposition of the multilayer magnetoresistive stack using sputtering techniques. The stack is then patterned using lithographic processes to define the geometry of the sensor and to create electrical contacts for resistance measurements.

To improve spatial resolution, nanofabrication techniques are used to reduce the lateral dimensions of the magnetoresistive element. However, reducing sensor size can increase noise levels, which may reduce detectivity. The design process therefore involves balancing spatial resolution against sensor performance.

Following sensor fabrication, additional microfabrication steps are used to create the flexible cantilever structure surrounding the sensor. The resulting probe resembles a conventional AFM cantilever but incorporates the magnetoresistive sensing element near its end.

Electrical connections are made through wire bonding to a printed circuit board that interfaces with the scanning probe microscope electronics.

Several characteristics make magnetoresistive sensors attractive for scanning magnetic microscopy. They provide high sensitivity across a wide frequency range, can be fabricated with small dimensions, and operate at room temperature. In industrial fabrication processes, sensor dimensions on the order of tens of nanometers are possible, although laboratory implementations are typically somewhat larger.

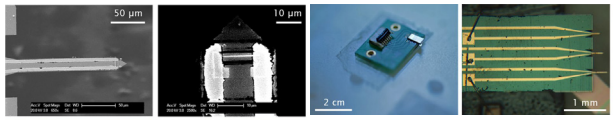

Figure 2. *NanoGMR integrated in cantilever glue and connected to a dedicated support that can be integrated into any AFM.*

Magnetic Imaging Demonstration

The capabilities of the scanning magnetoresistive microscope were demonstrated using a simple test structure consisting of a current loop. When current flows through the loop, it generates a magnetic field that can be detected by the scanning sensor.

Simultaneous measurements of topography and magnetic field were performed during scanning. The resulting images show a clear separation between structural and magnetic information.

After applying basic signal filtering, the measured magnetic field distribution was compared with simulations based on electromagnetic theory. The experimental measurements showed good agreement with the simulated magnetic field, demonstrating that the technique can provide quantitative magnetic field mapping.

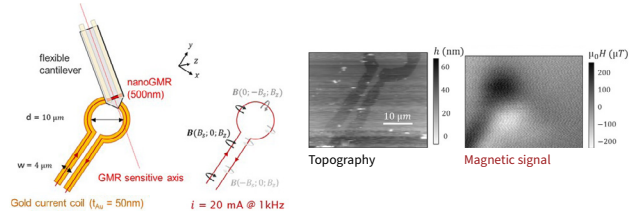

Figure 3. *A schematic of the cantilever with integrated GMR, scanning a current loop. The magnetic image of the field emitted by the loop and the topography are detected separately but simultaneously.*

Broadband Magnetic Measurements

A particularly notable feature of magnetoresistive sensors is their broadband frequency response. This capability allows magnetic signals originating from different physical phenomena to be separated in the frequency domain.

In the demonstration presented at the NanoScientific Forum, a test sample was designed to illustrate this capability. The sample consisted of a ferromagnetic rectangular structure positioned beneath a current-carrying line. The current in the line was modulated at a frequency of 1 kHz.

During scanning, the magnetoresistive sensor acquired magnetic data over a broad frequency range. Analysis of the signal revealed two distinct contributions. The DC component corresponded to the stray magnetic field produced by the ferromagnetic structure. Meanwhile, the 1 kHz component corresponded to the magnetic field generated by the alternating current in the line.

This example demonstrates how broadband acquisition allows multiple magnetic phenomena to be observed and distinguished within a single measurement.

Continued on page 25

NANOSCALE DYNAMIC MECHANICAL ANALYSIS WITH AFM AT SUB-ZERO TEMPERATURES

Jake Kim, John Kim,
Park Systems Corp., Gwacheon, South Korea

Introduction

Dynamic Mechanical Analysis (DMA) is one of the most widely used techniques for characterizing the viscoelastic behavior of polymers and elastomers. By measuring the mechanical response of a material under oscillatory loading, DMA provides critical information about stiffness, damping, and molecular mobility. These properties play an essential role in determining the performance of polymer-based materials used in applications ranging from automotive tires and sealing components to electronic packaging and coatings.

Conventional DMA techniques, however, measure the response of relatively large sample volumes. As a result, the mechanical properties obtained represent averaged behavior across the entire specimen. For many modern materials—including polymer blends, nanocomposites, and thin films—this averaging can obscure important nanoscale variations that strongly influence macroscopic performance[1].

Atomic Force Microscopy based Dynamic Mechanical Analysis addresses this limitation by combining the spatial resolution of AFM with dynamic mechanical testing. Using an AFM probe to apply oscillatory forces directly to the surface of a material enables researchers to measure viscoelastic properties with nanometer-scale precision[2,3]. This capability allows the investigation of localized mechanical responses within heterogeneous materials.

Temperature is another critical factor governing viscoelastic behavior. Many polymers undergo significant changes in mechanical response with temperature, particularly near the glass transition where materials shift from flexible, rubber-like states to rigid and brittle ones[4–6]. For applications exposed to cold environments—such as tires operating in winter conditions—understanding this temperature-dependent behavior is essential.

Recent advances in AFM instrumentation now allow dynamic mechanical measurements to be performed under controlled environmental conditions and at temperatures below 0 °C. The following examples illustrate how AFM-based DMA can provide nanoscale insight into polymer behavior while also enabling temperature-dependent measurements relevant to real-world applications.

AFM-Based Dynamic Mechanical Analysis

AFM-based DMA measures viscoelastic properties by applying a controlled oscillatory force through an AFM probe in contact with the sample surface. Unlike bulk DMA, which measures the response of the entire specimen, the AFM probe interacts with a localized region, enabling spatially resolved measurements of mechanical behavior.

During the experiment, a sharp AFM tip is brought into contact with the sample under a defined preload force. The probe is then oscillated across a range of modulation frequencies while the cantilever deflection and phase lag are recorded. From these measurements, key viscoelastic parameters can be extracted.

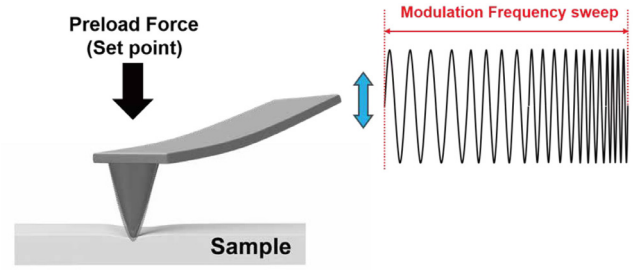

Figure 1. Schematics of Park Systems AFM-based DMA methodology. *AFM tip is brought into contact with the sample with a defined preload force (set point). The tip is oscillated while sweeping the modulation frequency, allowing measurement of viscoelastic response through cantilever deflection and phase lag.*

One important parameter is the loss tangent (tan δ), which describes the ratio of energy dissipated to energy stored during cyclic deformation. Materials with high loss tangent values exhibit greater damping and viscoelastic behavior, while materials with lower values behave more elastically.

An important advantage of AFM-based DMA is its compatibility with time–temperature superposition, a principle commonly used in polymer physics. Measurements collected at different temperatures can be shifted along the frequency axis and combined to generate a master curve. This master curve represents the material's viscoelastic response across a much broader frequency range than can be directly measured.

Such curves allow researchers to predict long-term mechanical behavior or high-frequency responses that may occur during real-world operation. The ability to construct master curves using nanoscale measurements provides a powerful bridge between localized material characterization and bulk mechanical performance.

Nanoscale Mapping of Polymer Blends

Polymer blends often exhibit complex microstructures consisting of multiple phases with distinct mechanical properties. Understanding how these phases interact at the nanoscale is critical for optimizing material performance.

To demonstrate the capabilities of AFM-based DMA, a blend of polystyrene (PS) and low-density polyethylene (LDPE) was investigated. This material forms a phase-separated structure in which PS domains are embedded within an LDPE matrix.

The same region of the sample surface was analyzed using two complementary AFM techniques: PinPoint nanomechanical mapping and AFM-based DMA. PinPoint mode provides quantitative mechanical maps including surface topography, deformation, Young's modulus, and adhesion energy[7,8].

The topographic images revealed the phase-separated structure of the polymer blend. Polystyrene formed island-like domains dispersed throughout the continuous LDPE matrix.

Mechanical property mapping showed clear contrasts between the two materials. PS domains exhibited higher stiffness and lower deformation compared with LDPE regions, consistent with their known bulk mechanical behavior. Young's modulus values for PS reached several gigapascals, whereas LDPE values remained below 1 GPa.

Adhesion measurements also revealed differences between the phases. LDPE regions showed stronger adhesive interactions with the probe, reflecting the greater chain mobility and flexibility of polyethylene compared with the more rigid polystyrene domains.

AFM-based DMA provided complementary information by mapping the viscoelastic response of the same region. The resulting loss tangent maps closely followed the morphological features observed in the mechanical measurements.

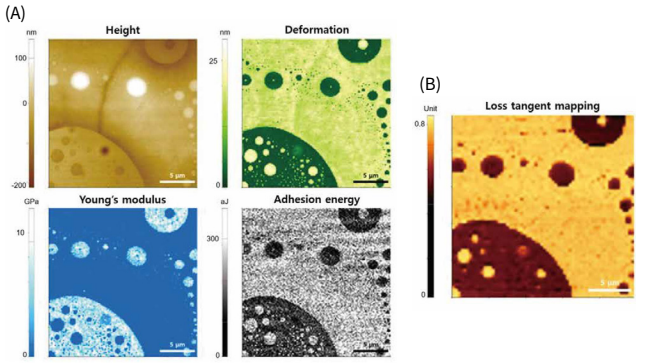

Figure 2. Complementary Nanomechanical and Viscoelastic Mapping of PS–LDPE. (A) *PinPoint nanomechanical images of PS–LDPE showing surface topography, deformation, Young's modulus, and adhesion energy.* **(B)** *Corresponding AFM-based DMA loss tangent map of the same region, highlighting local variations in viscoelasticity between PS (lower tan δ) and LDPE (higher tan δ) domains.*

PS domains exhibited lower tan δ values, indicating predominantly elastic behavior with limited energy dissipation. In contrast, LDPE regions displayed significantly higher tan δ values, reflecting greater viscoelastic damping and molecular rearrangement during oscillatory deformation.

Together, the PinPoint nanomechanical maps and AFM-based DMA measurements provided a comprehensive picture of the nanoscale heterogeneity within the polymer blend. The combination of elastic and viscoelastic mapping clearly distinguished the properties of each phase and demonstrated how local material behavior can be directly visualized.

Temperature-Dependent Viscoelastic Behavior in SBR

While nanoscale mapping reveals structural heterogeneity, many polymer applications also require understanding how mechanical behavior changes with temperature.

Styrene–butadiene rubber (SBR) is widely used in applications such as tires, seals, and gaskets because of its flexibility and durability. However, its mechanical properties are strongly temperature dependent. As temperature decreases, SBR approaches its glass transition temperature (Tg) and gradually changes from a flexible rubber to a more rigid material[9].

This transition has direct implications for applications such as winter tires, where maintaining flexibility and damping at low temperatures is essential for traction and safety.

To investigate this behavior, AFM-based DMA measurements were performed on SBR using a temperature control stage capable of regulating the sample temperature with high precision.

Experiments were conducted at five temperatures: –3 °C, 5 °C, 10 °C, 22 °C, 25 °C.

Maintaining stable experimental conditions during sub-zero measurements can be challenging because condensation can form on both the sample surface and the AFM probe. To avoid this problem, the AFM system was operated inside a controlled glovebox environment where oxygen and humidity levels were carefully regulated.

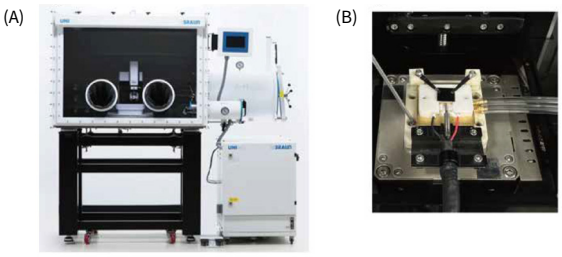

Figure 3. Low-temperature DMA Setup with Controlled Glovebox and Temperature Control Stage. (A) *Park Systems AFM integrated in a controlled glovebox for sub-zero temperature measurements, preventing condensation effects.* **(B)** *Temperature Control Stage (TCS) setup inside the AFM showing sample mounting and environmental controls for precise low-temperature DMA experiments.*

This combination of environmental control and temperature regulation enabled reliable nanoscale viscoelastic measurements at temperatures below freezing.

Loss tangent measurements collected at the different temperatures revealed clear changes in viscoelastic behavior as the material approached the glass transition. As temperature decreased, the response shifted toward higher stiffness and reduced molecular mobility.

By applying time–temperature superposition to the frequency sweep data, the individual curves obtained at different temperatures were combined to generate a continuous master curve spanning a wide frequency range.

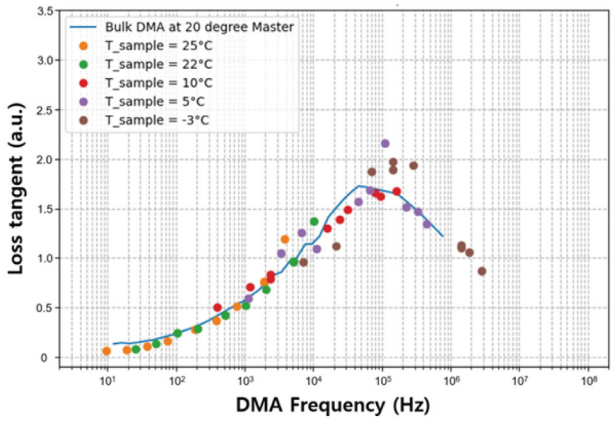

Figure 4. Loss tangent as a function of DMA modulation frequency measured on SBR at various temperatures (–3 °C, 5 °C, 10 °C, 22 °C, 25 °C). *Master curve construction via time–temperature superposition extends the viscoelastic profile beyond the directly measured range, showing strong consistency with bulk DMA master curve at 20 °C (blue line).*

This master curve extended the accessible range of viscoelastic characterization beyond the limits of direct measurement. Importantly, the AFM-derived master curve showed strong agreement with a reference master curve obtained using conventional bulk DMA at 20 °C.

The close correspondence between nanoscale AFM measurements and bulk DMA results confirms the reliability of AFM-based DMA for evaluating viscoelastic behavior. At the same time, the AFM technique offers additional advantages by enabling spatially resolved measurements of mechanical properties.

This capability is particularly valuable when studying heterogeneous materials or interfaces where local variations in mechanical response may influence overall performance.

Linking Nanoscale Structure to Material Performance

The two examples presented here illustrate how AFM-based DMA can provide valuable insight into polymer mechanics at the nanoscale.

In the PS–LDPE blend, combining nanomechanical mapping with viscoelastic measurements enabled clear identification of domain-specific differences in stiffness, adhesion, and damping behavior. These measurements demonstrate how nanoscale characterization can reveal structural heterogeneity that may influence bulk material performance.

In the SBR study, AFM-based DMA measurements performed at sub-zero temperatures allowed the construction of a viscoelastic master curve consistent with conventional bulk DMA results. This capability enables researchers to investigate polymer behavior under environmental conditions relevant to real-world applications.

The integration of temperature control and environmental stability further expands the usefulness of AFM-based DMA for studying polymers and elastomers under extreme conditions.

Conclusions

AFM-based Dynamic Mechanical Analysis provides a powerful tool for probing viscoelastic properties with nanoscale resolution. By combining the spatial precision of AFM with dynamic mechanical testing, the technique allows researchers to investigate localized mechanical behavior within heterogeneous materials.

In polymer blends such as PS–LDPE, AFM-based DMA complements nanomechanical mapping by revealing domain-specific differences in viscoelastic response. In elastomer systems such as SBR, temperature-controlled AFM-based DMA enables detailed investigation of glass transition behavior and the construction of viscoelastic master curves.

Together, these capabilities allow researchers to connect nanoscale material structure with macroscopic mechanical performance. As polymer-based materials continue to evolve in complexity and functionality, techniques capable of probing localized behavior under realistic environmental conditions will play an increasingly important role in materials development.

AFM-based DMA represents a significant step toward achieving this goal, providing a bridge between nanoscale characterization and real-world material performance.

Acknowledgements

The authors gratefully acknowledge Professor Ken Nakajima and his research group at Tokyo Institute of Technology for their support and collaboration. Their guidance in selecting representative polymer samples (PS–LDPE and SBR), along with access to laboratory facilities for AFM-based DMA measurements, was essential to this work. Their contributions to data analysis and insightful feedback significantly enhanced the quality and clarity of this study.

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Outlook

The integration of magnetoresistive sensors into scanning probe cantilevers represents an important step toward versatile magnetic microscopy systems capable of quantitative and broadband measurements.

Future developments may focus on extending the frequency range of measurements to explore dynamic magnetic properties such as magnetic susceptibility. Additional functionality could also be achieved by incorporating multiple sensors oriented along different directions, enabling measurement of multiple magnetic field components.

Further improvements may involve reducing probe-induced stray fields through optimized sensor structures or exploring alternative magnetoresistive architectures such as tunnel magnetoresistance (TMR) devices.

As magnetoresistive technology continues to advance, its integration with scanning probe microscopy is expected to provide increasingly powerful tools for nanoscale magnetic characterization across both scientific research and industrial applications.

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About Dr. Aurélie Solignac

Aurélie Solignac is a researcher at CEA, in the Nanomagnetism and Oxides Laboratory of the Department of Condensed Matter Physics. Her expertise is in the field of electronic spin sensors, magnetic imaging, thin film heterostructures and materials. Following one of the LNO's research axes, she is involved in the development and characterization of magnetoresistive sensors for various applications. She is co-leading the French magnetometry network.

NanoScientific Symposium Series Concludes, Highlighted by 40 Years of AFM Celebration at Stanford

The most recent NanoScientific Symposium Series (NSS) concluded with a global program spanning the Americas, Europe, and Asia, bringing together more than 700 participants from the international nanoscale science and metrology community. The series culminated in a landmark gathering at Stanford University—*NSS Americas: Celebrating 40 Years of Atomic Force Microscopy*, dedicated to the memory of Professor Calvin Quate.

Held at the birthplace of AFM, the Stanford symposium honored Professor Quate's scientific legacy while examining the continued evolution of AFM in modern research and industrial applications. The program featured leading pioneers and experts in the field, including H. Kumar Wickramasinghe, Thomas Albrecht, John S. Foster, Dan Rugar, Oleg Kolosov, and Helen Greenwood Hansma.

The event also reflected a unique historical continuity through the participation of Dr. Sang-il Park, Founder and CEO of Park Systems, who began his career as a graduate student in Professor Quate's laboratory during the early development of AFM. This connection—from academic invention to global industrial adoption—framed discussions that looked ahead to integrated and multimodal nanoscale metrology.

Across all regions, a consistent theme emerged: AFM is increasingly positioned as a core component within broader measurement ecosystems. Presentations explored its integration with complementary techniques such as imaging spectroscopic ellipsometry and digital holographic microscopy, enabling correlated measurements and deeper insight into complex materials and devices.

Supported by Park Systems, the symposium series continues to foster collaboration between academia and industry. Programs in Europe and Asia further highlighted the global reach of NSS. The NanoScientific Forum Europe, held in Orsay, France, focused on precision measurement and advanced characterization, while NSS Korea, hosted at Park Systems' headquarters, emphasized the connection between academic research and semiconductor manufacturing. Additional programs in India and Japan underscored the continued expansion and interdisciplinary nature of nanoscale research.

With the conclusion of this symposium cycle, NSS reinforces its role as a global platform connecting scientific heritage with emerging technologies and real-world applications. Building on this momentum, the next NanoScientific Symposium Series program is expected to be announced in March.

Park Systems Announces the Winners of the Nano Image Challenge

Park Systems' Nano Image Challenge brought together the global atomic force microscopy community to celebrate scientific innovation and the visual power of nanoscale imaging, culminating in the announcement of this year's award-winning entries.

The annual competition invited researchers, engineers, and students worldwide to submit AFM images that demonstrate both technical excellence and artistic expression. This year's submissions reflected a wide range of applications—from advanced materials and semiconductor structures to biological systems—underscoring the versatility of AFM in nanoscale characterization.

Following evaluation by an expert judging panel, winners were selected across three categories:

Scientific Value Image

Recognizing images with strong research significance and clarity of nanoscale structures

- Saroj Kumar Mishra — IIT Hyderabad
- Hu Huiji — Renmin University of China
- Rajashree Haldankar — ICFO

Aesthetic Image

Honoring visually striking and artistically compelling nanoscale imagery

- Fátima Linares, M. Dolores Molina, J. López Peñalver — Universidad de Granada
- Seong Bin Bae — Sogang University
- Yu Tang — Dalian Polytechnic University

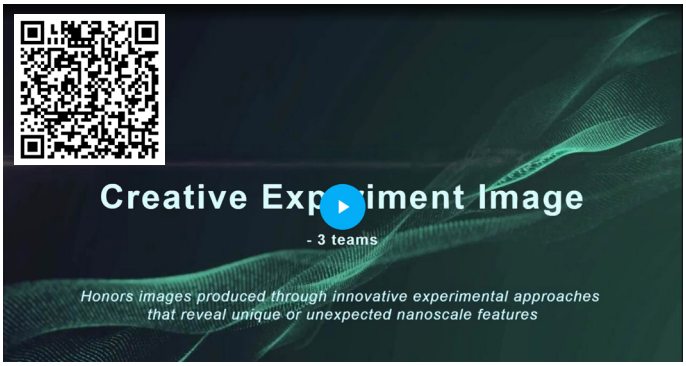
Creative Experiment Image

Highlighting innovation in imaging techniques and experimental approaches

- C.Y. Su, W.H. Cho, C.C. Kei — NCIR / NIAR
- Liang He — Zhejiang Academy of Forestry
- Puvaneswaran Chelvanathan — SERI, Universiti Kebangsaan Malaysia

The **Overall Image of the Year** was awarded to Hu Huiji of Renmin University of China, whose submission achieved the highest distinction for its combined scientific quality, creativity, and visual impact.

The Nano Image Challenge continues to showcase the intersection of science and art at the nanoscale, fostering global collaboration while highlighting the critical role of AFM in advancing research and discovery. Winning images and interviews with the awardees can be viewed by scanning the video QR code below.



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