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**THE NEW FRONTIER
OF ATOMIC RESOLUTION**

TWISTED BILAYER GRAPHENE IMAGED WITH THE PARK NX1

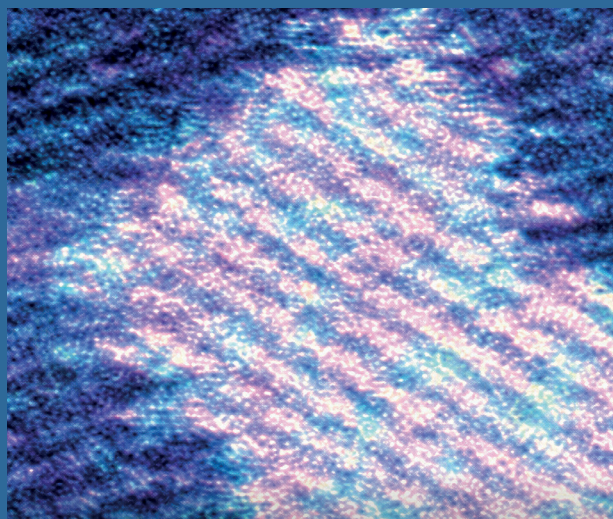
BEYOND SEEING: BUILDING THE NEXT GENERATION OF NANOTECHNOLOGY

Earlier this year, NanoScientific Vol. 30 celebrated the 40th anniversary of Atomic Force Microscopy (AFM), reflecting on four decades of innovation and the profound impact AFM has had across the physical and life sciences. In Volume 31, we shift our focus from celebrating the past to exploring the future.

The articles in this issue demonstrate how AFM continues to evolve beyond a powerful imaging tool into a platform for discovery, characterization, and nanofabrication. From Professor Franz Giessibl's perspective on the pursuit of ambient atomic resolution to advances in automated characterization of two-dimensional materials, correlative AFM-SEM workflows, and sustainable thin-film photovoltaics, each contribution highlights new ways AFM is enabling scientific progress.

This issue also showcases AFM's expanding role in emerging technologies. Next-generation perovskite color photodetectors and integrated scanning probe lithography illustrate how nanoscale metrology and direct-write nanofabrication are driving innovations in optoelectronics and advanced manufacturing. Complementing these research articles, our application notes highlight recent developments in AFM instrumentation designed to make high-performance nanoscale analysis more accessible and efficient.

Together, these contributions reflect a common direction: the future of AFM lies not only in higher resolution, but also in smarter workflows, integrated techniques, and broader applications. We hope NanoScientific Vol. 31 offers both insight into today's advances and inspiration for tomorrow's discoveries.



Cover Image: Twisted Bilayer Graphene at 2 nm Scan Size

This atomic-resolution AFM image, acquired with the Park NX1, reveals the atomic lattice of twisted bilayer graphene—a two-dimensional material whose slight rotational misalignment produces moiré superlattices responsible for remarkable electronic and quantum phenomena.

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TOWARD PRACTICAL ATOMIC-RESOLUTION AFM

An Interview with Prof. Franz Giessibl, University of Regensburg, Germany



Prof. Franz Giessibl (center, wearing a hat) with his research team

Few researchers have shaped the field of atomic force microscopy as profoundly as Prof. Franz Giessibl. From his early work with Nobel laureate Gerd Binnig during the formative years of AFM to the invention of the qPlus sensor that transformed high-resolution force microscopy, Giessibl has remained at the forefront of atomic-scale imaging for more than three decades. In this interview with NanoScientific, he reflects on the evolution of AFM, the pursuit of practical atomic-resolution imaging under ambient conditions, the challenges that still remain, and the future directions of next-generation nanometrology. He also discusses how advances in instrumentation, accessibility, and emerging technologies such as AI may shape the next era of AFM research.

NS: Looking back, what first drew you to AFM and atomic-scale measurements?

Giessibl: My research focuses on atomic force microscopy (AFM), and I have been working in this field for most of my career. I began in 1986, during my time as an exchange student at ETH Zurich. I heard about a nearby lab where a microscope capable of imaging atoms had been developed, which immediately captured my interest.

I applied for an internship at IBM Research in Rüschlikon, where I initially worked in optics. On my last day, my supervisor told me that Gerd Binnig—who would soon share a Nobel Prize with his colleague Heinrich Rohrer for their invention of the scanning tunneling microscope—was returning to Europe to establish a research group in Munich. I was asked whether I would be interested in joining him as a PhD student.

A few months later, Binnig personally called me and offered three possible research projects: building a tunneling sensor to detect gravitational waves, sequencing DNA using STM, or improving AFM to achieve true atomic resolution. At the time, AFM had been invented (1986), but it had not yet demonstrated true atomic resolution. I chose that challenge for my PhD.

NS: How did your early experience developing commercial AFM systems influence your later research?

Giessibl: Toward the end of my PhD, we were already using cantilevers from Calvin Quate's group at Stanford. Around that time, Park Scientific Instruments—the predecessor of Park Systems—had just been founded. Sang-il Park, who had worked with Quate, began commercializing STM systems and later recognized the importance of AFM.

I joined Park Scientific Instruments to develop a vacuum AFM. With the AutoProbe VP, we achieved atomic resolution on silicon using AFM for the first time. At that point, I thought many of the fundamental challenges in AFM had been solved.

I then left academia to become a management consultant at McKinsey. However, during that time, I serendipitously invented a new concept for a force sensor—the qPlus sensor—which led me back into academic research.

NS: What research principles were most important in advancing practical atomic-resolution AFM?

Giessibl: Our primary focus has always been achieving the highest possible spatial resolution. That means minimizing noise and maximizing sensitivity to extremely small forces.

We have achieved sub-ångström lateral resolution and height resolution down to about 400 femtometers (0.4 picometers). This pursuit of precision has shaped the design philosophy of our instruments.

The qPlus sensor, which I developed, is now widely used in low-temperature AFM systems. While it had not been widely applied in ambient conditions, we demonstrated in our lab that true atomic resolution is possible under ambient conditions using this approach. The NX1 represents an effort to bring this capability into a commercial system.

NS: What is most important when turning laboratory AFM concepts into reliable research instruments?

Giessibl: What I appreciated most was the ability of Park Systems to take laboratory concepts and implement them in a robust, practical way.

For example, in early systems, wiring was often a major source of failure. In our lab instruments, wires frequently broke. Park addressed this with professional engineering solutions for signal routing and system integration. These may seem like small details, but they are critical for reliability.

NS: What limitations of existing AFM systems led to the development of the NX1?

Giessibl: One major limitation was the lack of integration between high-resolution AFM and optical microscopy. Our lab-built systems

lacked a good optical interface.

Another issue was sample positioning. We used relatively crude mechanical systems, whereas the NX1 incorporates inertial drives for precise X–Y positioning, which is especially useful for locating features like graphene flakes.

NS: What are the key requirements for stable atomic-resolution imaging?

Giessibl: The most important factors are:

- Mechanical rigidity
- Thermal stability (low drift)
- Sensitive force detection
- Well-defined probe tips

For thermal stability, materials such as Kovar are used due to their low thermal expansion. Mechanical rigidity ensures that the tip–sample distance remains stable.

At low temperatures, we often use a CO molecule at the tip apex, which provides extremely high spatial resolution due to its small size and chemical inertness. A major challenge is finding an equivalent probe for ambient conditions.

NS: How do features like low noise and qPlus sensing improve atomic-scale measurements?

Giessibl: The qPlus sensor allows operation at extremely small oscillation amplitudes. This is crucial because the optimal signal-to-noise ratio occurs when the oscillation amplitude matches the interaction decay length.

For atomic-scale interactions—such as chemical bonds—the decay length is extremely short, so very small amplitudes are required. The high stiffness of the qPlus sensor enables stable operation under these conditions.

NS: What new experiments or applications could ambient atomic-resolution AFM enable?

Giessibl: There are many possibilities. One key advantage is enabling atomic-resolution measurements under ambient conditions, which is important for studying real-world processes such as corrosion.

Another exciting direction is electrochemical AFM. In our lab, we have demonstrated combined STM/AFM measurements in liquid environments. This opens the door to studying processes at solid–liquid interfaces.

Additionally, systems like the NX1 can serve as educational tools, allowing researchers and students to directly observe and understand the sensing mechanism—something that is difficult with low-temperature systems enclosed in cryostats.

NS: If ambient atomic-resolution AFM becomes practical and widely accessible, what new possibilities could emerge?

Giessibl: Ask any scientist or engineer who uses a microscope whether they would like ten times better spatial resolution, and I think almost everyone would answer yes. Improved resolution allows researchers to see details that were previously hidden, and the opportunities it creates are ultimately as broad as the scientific and engineering problems being studied. In some cases, higher resolution may provide incremental improvements by revealing finer structural details. In others, it can be transformative, enabling entirely new observations and discoveries that were simply not possible before. Whether the impact is gradual or revolutionary depends on the problem at hand, but greater access to atomic-resolution measurements under ambient conditions would undoubtedly open new possibilities across a wide range of fields.

NS: What remains the biggest challenge in ambient atomic-resolution AFM?

Giessibl: The main challenge is the probe tip.

At low temperatures, we can prepare atomically precise tips using controlled processes, such as forming a single-atom tip and attaching a CO molecule. In ambient conditions, contamination from air makes it difficult to achieve and maintain such well-defined tips.

Developing a stable, reproducible tip for ambient atomic-resolution AFM remains a major challenge.

NS: What excites you most about the future of AFM?

Giessibl: AFM is a fundamental tool for exploring the atomic building blocks of matter. Atoms are essentially stable, 13.8-billion-year-old little quantum machines, and there is still so much to learn about them.

I do not see a clear limit to what can be explored. New applications and ideas continue to emerge, and I remain optimistic about the future of the field.

NS: What do you think will be the next major breakthrough in AFM?

Giessibl: I believe one of the next major breakthroughs will be finding an ambient-condition equivalent of the CO-functionalized tip used in low-temperature AFM. CO tips have enabled some of the highest-resolution measurements ever achieved because they are exceptionally sharp and well-defined. Developing a probe with similar performance that can operate reliably in ambient environments would be a major step forward, helping bring atomic-resolution AFM to a much broader range of applications and users.

NS: How important will AI and automation become in the future of AFM?

Giessibl: AI and automation are likely to play an increasingly important role in AFM, particularly in areas that currently rely heavily on experimental experience and trial-and-error. Perhaps one of the most useful applications will be in managing the process of testing a large number of possible tip configurations. Achieving atomic resolution often depends on finding the right tip, which can require considerable experimentation. AI could help guide this search more efficiently, reducing the time needed to identify optimal tip conditions and making high-resolution AFM measurements more practical and reproducible.

NS: What will you be presenting at NanoScientific Forum Europe this year?

Giessibl: I will discuss our work in low-temperature AFM, as well as recent results using the NX1. We have only recently begun using the system, but we are already seeing promising results. I may also touch on emerging directions such as ultrafast AFM techniques.



About Prof. Franz Giessibl

Prof. Franz J. Giessibl holds the Chair of Quantum Nanoscience at the University of Regensburg, Germany, and is also a Research Professor at Kanazawa University, Japan. Widely recognized as one of the leading pioneers of atomic force microscopy, his contributions have helped advance atomic-resolution imaging and force microscopy over the past three decades. His numerous honors include the Feynman Prize in Nanotechnology, the Joseph F. Keithley Award of the American Physical Society, the Heinrich Rohrer Grand Medal, the NIMS Award, and the Materials Research Society's Innovation in Materials Characterization Award. He is a Fellow of the American Physical Society and a member of several international scientific academies and societies.

ACHIEVING SUB-ÅNGSTRÖM STABILITY IN AMBIENT ENVIRONMENTS WITH PARK NX1

Jay Son
Park Systems Corp., South Korea

Introduction

Atomic Force Microscopy (AFM) has become an essential tool for nanoscale surface characterization, enabling high-resolution analysis of surface morphology, mechanical response, and functional properties across a broad range of materials. Its ability to image both conductive and insulating samples makes AFM especially valuable for studying crystalline surfaces, two-dimensional materials, and other nanoscale structures where localized surface information is critical.

Among AFM applications, atomic lattice imaging remains one of the most technically demanding measurements. Resolving periodic structures at the atomic scale requires not only a sharp probe and optimized imaging conditions, but also exceptional mechanical stability, low noise, and minimal thermal drift. These challenges become even more significant under ambient conditions, where environmental vibration, thermal fluctuation, and instability in the tip-sample interaction can obscure atomic-scale contrast.

To achieve stable atomic lattice imaging, the AFM platform must suppress mechanical noise while maintaining stable tip-sample geometry during small-scan measurements. A rigid low-noise mechanical structure, minimized mechanical loop, and low-drift scanner architecture are therefore essential for reproducible high-resolution imaging.

Park Systems developed the NX1 to address these requirements by combining a low-noise mechanical architecture with an AFM workflow for high-resolution imaging under ambient conditions.

Please also refer to the NX1 introduction video available at: <https://bcove.video/4tlgl8M>

Overview of NX1

The NX1 is Park Systems' compact high-resolution AFM designed for stable atomic lattice imaging under ambient conditions. Developed in collaboration with Prof. Franz J. Giessibl at the University of Regensburg, the NX1 builds on the Orpheus II concept for ambient AFM operation while integrating Park Systems' beam-bounce sensing and measurement workflow.

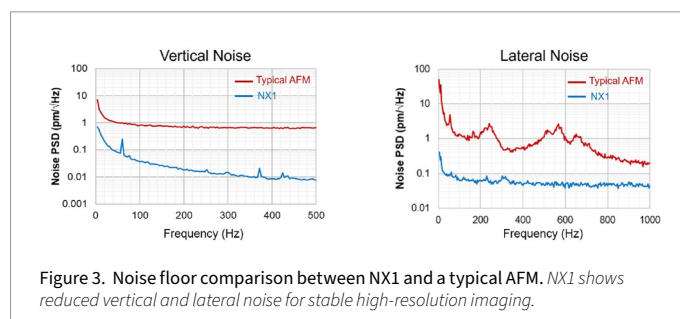
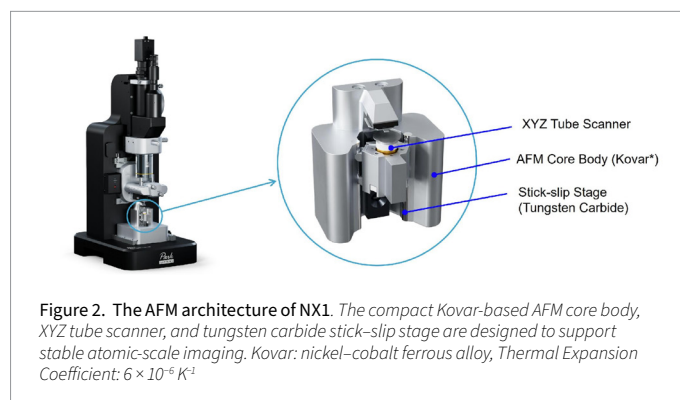
Its low-noise mechanical design, minimized mechanical loop, Kovar-based AFM core body, and precision XYZ tube scanner provide the stability required for small-scan high-resolution measurements. The system also supports both standard AFM probes and optional qPlus sensor configurations for high-resolution AFM measurements.

Figure 1 shows the NX1 with the SmartScan™ operating interface, where atomic-scale imaging results and real-time measurement signals are displayed during AFM operation.

AFM Architecture for Atomic-Scale Imaging

Atomic lattice imaging requires the AFM system to maintain highly stable tip-sample geometry during small-scan measurements. To support this requirement, the NX1 is designed with a rigid AFM architecture featuring a shortened mechanical loop between the probe and sample. By shortening and stiffening this mechanical path, the system reduces mechanical noise and improves high-resolution imaging stability.

The NX1 incorporates a Kovar-based AFM core body, a precision XYZ tube scanner, and a tungsten carbide stick-slip stage. Kovar, a nickel-cobalt ferrous alloy with a low thermal expansion coefficient, helps minimize thermal drift in the AFM core body. The XYZ tube scanner supports small-scan high-resolution imaging, while the stick-slip stage provides reliable positioning for approach and sample navigation. Together, these components establish the mechanical foundation for stable atomic-scale AFM measurements.



Low Noise Floor and Reduced Thermal Drift

The stability of the AFM platform directly influences the quality and reproducibility of atomic lattice imaging. Even small vertical or lateral noise can obscure the periodic contrast of atomic structures, particularly when imaging over scan sizes of only a few nanometers. For this

reason, the NX1 was designed to reduce mechanical noise and thermal drift through its low-noise mechanical architecture.

As shown in Figure 3, the NX1 demonstrates an order-of-magnitude reduction in both vertical and lateral noise compared with a typical AFM. The zero-scan vertical noise is reduced from 0.24 Å to 0.02 Å, while the zero-scan lateral noise is reduced from 1.40 Å to 0.04 Å. This low noise floor enables highly stable and repeatable atomic-resolution imaging under ambient conditions.

Intuitive Optical Access and Laser Beam Alignment

While the NX1 is optimized for high-resolution imaging, practical usability remains an important part of the system design. The beam-bounce detection module is separated from the AFM core body so that optical access and cantilever deflection detection can be provided without compromising the mechanical stability of the AFM core.

The NX1 uses beam-bounce deflection sensing to detect cantilever motion with high sensitivity. A superluminescent diode (SLD) provides low-coherence illumination to reduce optical interference, while laser alignment knobs allow the laser beam to be positioned on the cantilever. The reflected beam is then centered on the PSPD using steering mirror alignment knobs, simplifying the alignment process during set-up.

The system also integrates an on-axis optical microscope that provides a direct view of the sample surface and AFM probe. This optical access helps users locate the region of interest and position the probe before high-resolution AFM measurement. Software-controlled LED illumination further improves visibility across different sample types, supporting efficient sample navigation and measurement preparation.

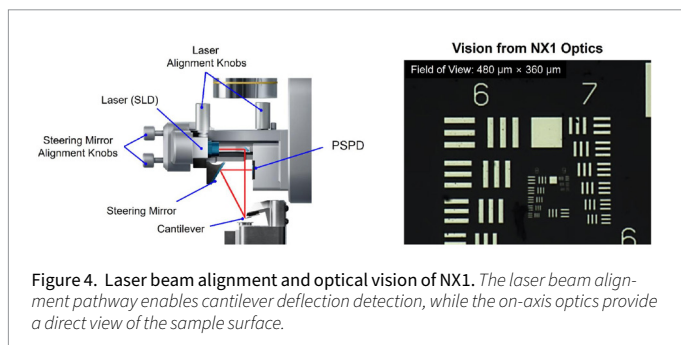


Figure 4. Laser beam alignment and optical vision of NX1. The laser beam alignment pathway enables cantilever deflection detection, while the on-axis optics provide a direct view of the sample surface.

Easy Probe Exchange and Measurement Versatility

Probe handling is an important part of practical AFM operation, particularly for high-resolution measurements where consistent probe positioning is required. Park Systems' probe holder design incorporates pre-aligned probe chip carriers and kinematic mounting points to support consistent probe positioning and simplify probe handling.

The NX1 supports both standard AFM probes and optional qPlus sensor holder configurations, allowing users to select the appropriate sensor setup depending on the measurement purpose. The optional qPlus sensor holder provides compatibility with high-stiffness quartz tuning fork sensors for measurements requiring enhanced sensitivity to short-range forces.

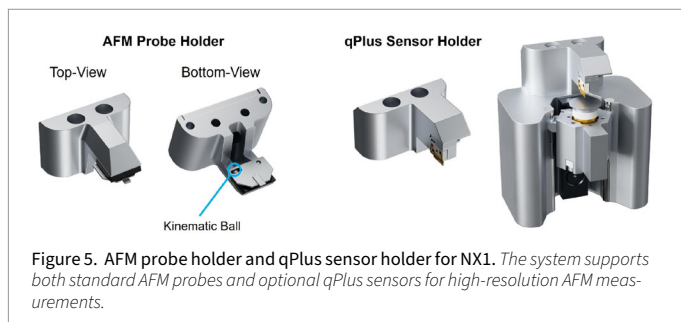


Figure 5. AFM probe holder and qPlus sensor holder for NX1. The system supports both standard AFM probes and optional qPlus sensors for high-resolution AFM measurements.

Atomic Lattice and Moiré Imaging on Two-Dimensional Materials

Atomic lattice imaging is a critical capability for evaluating crystalline surfaces and two-dimensional material systems, where local lattice periodicity, crystalline order, and moiré superlattice structures provide important information about the sample.

To demonstrate NX1 performance for these applications, four representative samples were selected: MoS₂ single crystal for LFM-based atomic lattice imaging on a layered two-dimensional semiconductor, Highly Oriented Pyrolytic Graphite (HOPG) as a reference material for FMM-based lattice imaging, and twisted bilayer graphene and WSe₂ on graphene for multi-scale FMM imaging of moiré structures.

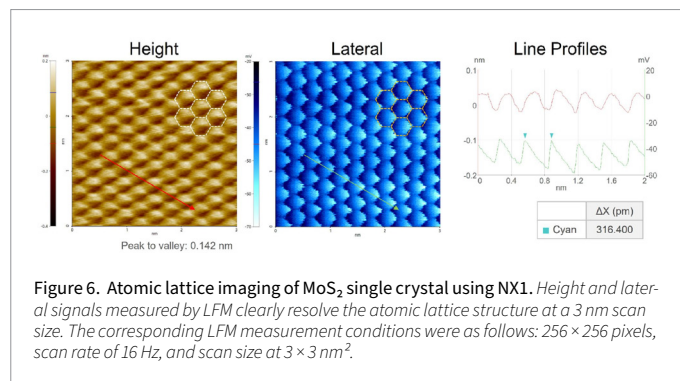


Figure 6. Atomic lattice imaging of MoS₂ single crystal using NX1. Height and lateral signals measured by LFM clearly resolve the atomic lattice structure at a 3 nm scan size. The corresponding LFM measurement conditions were as follows: 256 × 256 pixels, scan rate of 16 Hz, and scan size at 3 × 3 nm².

Figure 6 shows atomic lattice imaging of MoS₂ single crystal, a layered two-dimensional semiconductor with a hexagonal lattice structure. MoS₂ was selected to evaluate atomic periodicity on a representative 2D crystal beyond graphite-based reference materials.

The sample was measured by Lateral Force Microscopy (LFM) at a 3 nm scan size, and the atomic lattice was clearly observed in both height and lateral signals. The measured lattice spacing of 3.164 Å agrees with the reference lattice constant of MoS₂, confirming consistent atomic-scale measurement.

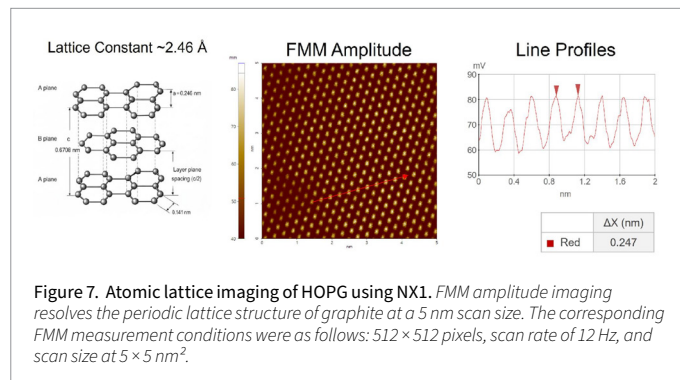


Figure 7. Atomic lattice imaging of HOPG using NX1. FMM amplitude imaging resolves the periodic lattice structure of graphite at a 5 nm scan size. The corresponding FMM measurement conditions were as follows: 512 × 512 pixels, scan rate of 12 Hz, and scan size at 5 × 5 nm².

HOPG is widely used as a reference material for atomic-scale AFM imaging because of its well-defined layered graphite structure and known lattice spacing. As shown in Figure 7, Force Modulation Microscopy (FMM) amplitude imaging of HOPG at a 5 nm scan size resolves the periodic lattice structure of graphite.

The measured lattice spacing is consistent with the reference value of graphite, demonstrating the ability of NX1 to acquire stable atomic lattice images using FMM.

Beyond direct atomic lattice imaging, the NX1 also enables multi-scale imaging of moiré structures in two-dimensional material systems. Twisted bilayer graphene and WSe₂ on graphene were selected as representative moiré systems because they contain periodic structures across different length scales.

Continued on page 10

HIGH-THROUGHPUT CORRELATED MICROSCOPY AND AUTOMATED DEVICE INTEGRATION OF 1D AND 2D MATERIALS

Accelerating Nanoscience Through Imaging Ellipsometry, Correlative Microscopy, and Machine Learning

Dr. Jack Alexander-Webber, Department of Materials, Loughborough University, UK

This article is based on his presentation delivered at the NanoScientific Forum Europe. Visit NanoScientific website to watch the full presentation: https://nanoscientific.org/on_demand

Introduction

The rapid emergence of advanced nanomaterials has created enormous opportunities for next-generation electronics, photonics, quantum devices, and sensing technologies. However, as material systems become increasingly sophisticated, one challenge continues to grow alongside them: characterization at scale.

Researchers today are no longer dealing with isolated nanoscale structures observed one at a time under a microscope. Modern nanoscience increasingly requires the ability to rapidly analyze large populations of nanoscale features while maintaining the precision necessary to understand subtle physical phenomena.

This challenge is particularly pronounced in emerging systems such as twisted bilayer graphene, transition metal dichalcogenide (TMD) heterostructures, and semiconductor nanowires, where small variations in geometry, orientation, or composition can dramatically alter electronic and optical behavior.

To address these challenges, researchers are increasingly combining imaging ellipsometry, optical microscopy, correlative imaging workflows, automated device integration, and machine learning into unified characterization pipelines capable of both nanoscale sensitivity and high-throughput analysis.

Twisted Bilayer Graphene and the Need for High-Throughput Characterization

Twisted bilayer graphene has become one of the most intensely studied material systems in modern condensed matter physics because its electronic and optical properties can change dramatically depending on the rotational angle between two graphene layers.

In conventional AB-stacked bilayer graphene, the material exhibits relatively well-understood behavior. However, introducing a rotational mismatch between the layers fundamentally modifies the electronic structure. Depending on the twist angle, researchers can observe enhanced optical absorption, altered band structures, and the emergence of strongly correlated electronic phenomena.

Practical graphene samples, however, are rarely perfectly uniform. Large-area chemical vapor deposition (CVD) growth often produces monolayer regions together with bilayer and multilayer inclusions, each potentially exhibiting different rotational domains and local optical responses.

Although conventional optical microscopy can reveal subtle color variations across these regions, the contrast is often weak and difficult to quantify reliably. This creates a major bottleneck for scalable characterization of twisted graphene systems.

Imaging Ellipsometry as a High-Throughput Optical Probe

To overcome this limitation, the researchers employed spectroscopic imaging ellipsometry, a highly sensitive optical technique capable of mapping changes in polarization across a sample surface.

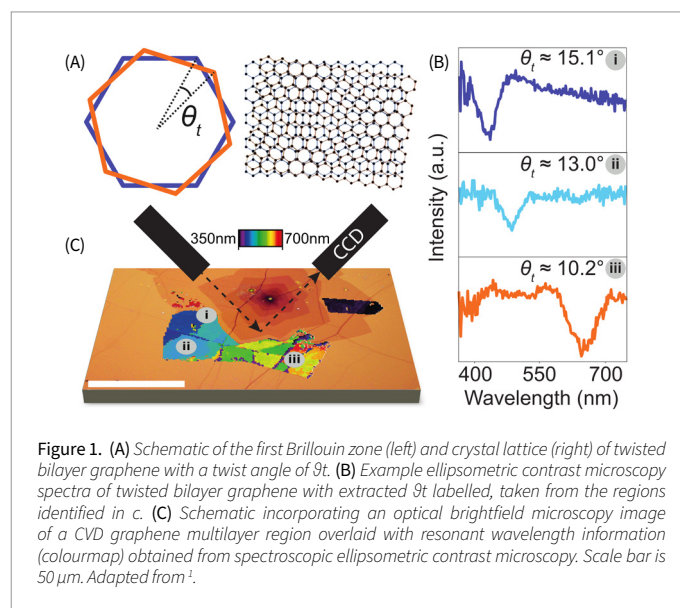
The experimental system combines a tunable wavelength light source, polarization control optics, an objective lens and camera-based imaging system to generate spatially resolved maps of optical behavior. Unlike traditional point-based optical measurements, imaging ellipsometry enables simultaneous analysis across extended sample areas.

This approach proved especially powerful for identifying subtle optical resonances associated with twisted bilayer graphene. The measurements revealed polarization-dependent resonance features that were nearly invisible in standard optical microscopy images.

These resonances originate from modifications in the electronic density of states caused by interactions between the twisted graphene layers. As the rotational angle changes, the optical absorption spectrum shifts accordingly.

By optimizing wavelength and polarization conditions, the researchers were able to maximize contrast between different graphene domains and rapidly map twist-angle variations across the sample surface¹. The wavelength-dependent optical response (Figure 1) also allowed resonance peaks to be correlated directly with graphene twist angles.

The result is a fast, non-destructive characterization method capable of probing large-area graphene samples while maintaining sensitivity to subtle electronic and optical variations.



Large-Area Mapping of 2D Semiconductor Heterostructures

The same imaging ellipsometry techniques were extended to lateral 2D semiconductor heterostructures based on transition metal dichalcogenides.

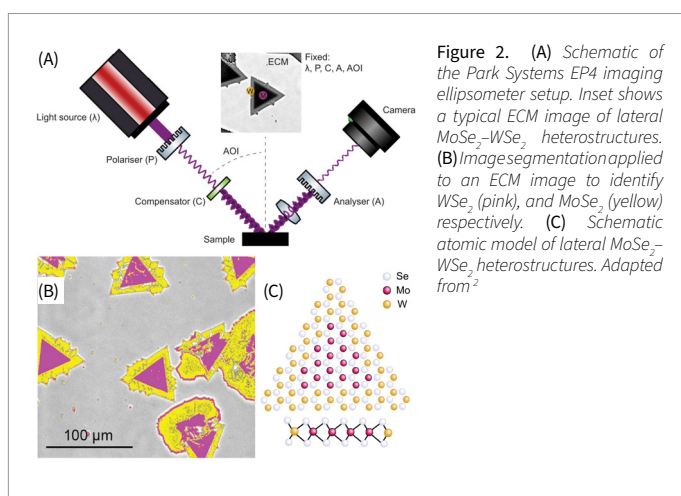
These materials are synthesized by changing growth precursors during deposition, allowing one atomically thin material to nucleate laterally from another while remaining covalently bonded at the interface. Systems discussed included combinations such as molybdenum diselenide and tungsten diselenide, as well as sulfide-based heterostructures.

Such heterostructures are particularly interesting because they can naturally form atomically thin PN junctions with useful optoelectronic behavior.

However, distinguishing adjacent material regions using conventional optical microscopy can be difficult because the intrinsic contrast is often extremely weak. The challenge becomes even greater when the materials are embedded within polymer layers or when substrate optical conditions change.

Imaging ellipsometry provides a significant advantage because both wavelength and polarization settings can be optimized specifically to enhance contrast between neighboring materials. Using these optimized conditions, researchers were able to rapidly identify material boundaries, segment different growth regions, and generate large-area statistical maps of heterostructure coverage and geometry².

Compared with slower point-based techniques such as Raman spectroscopy, the method offers a much faster approach for large-area materials analysis while still maintaining strong sensitivity to nanoscale optical inhomogeneities. These techniques can be extended to other lateral PN junctions such as those formed through selective oxidation of WSe₂^{3,4}.



Semiconductor Nanowires and Automated Device Integration

The presentation also explored semiconductor nanowires and the challenge of integrating them into scalable electronic devices.

Semiconductor nanowires are attractive for nanoscale electronics and optoelectronics because of their direct bandgap behavior, high carrier mobility, tunable geometries, and strong confinement effects. However, device fabrication workflows are often highly labor intensive.

Nanowires are typically grown vertically in dense forests before being transferred onto planar substrates for device fabrication. Researchers then traditionally identify individual nanowires manually using optical or electron microscopy before designing lithographic contacts around them⁵.

To automate this process, the researchers developed a position-encoded fiducial marker system fabricated directly onto the substrate using electron beam lithography. These markers contain spatial information that can be recognized automatically during microscopy imaging⁶.

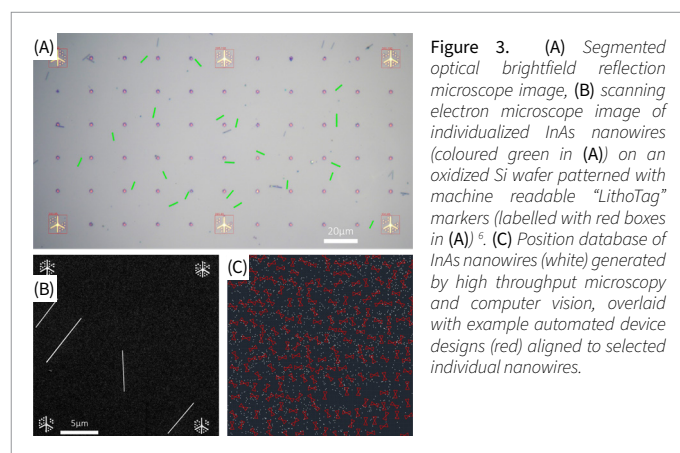
After nanowire deposition, image analysis software identifies both the fiducial markers and the nanowire positions, generating a positional database that can then drive automated lithography pattern generation.

The workflow consists of several sequential stages:

1. Nanowires are dispersed onto patterned substrates
2. Optical or SEM images are acquired

3. Fiducial markers and nanowires are automatically identified
4. Positional databases are generated
5. Lithographic electrode patterns are created automatically around selected nanowires

This approach transforms what was once a highly manual process into a scalable fabrication workflow capable of producing large numbers of nanowire devices with minimal operator intervention.



Correlative Microscopy Across Multiple Imaging Platforms

An important aspect of the workflow is the integration of multiple microscopy modalities into a unified data system.

Using fiducial markers as common spatial references, the researchers correlated information from bright-field optical microscopy, dark-field optical microscopy, scanning electron microscopy, and lithographic device maps.

Because all datasets share the same positional framework, images acquired from different microscopes—even with different magnifications or optical configurations—can be aligned automatically.

This enables researchers to combine complementary information from multiple imaging systems while dramatically simplifying navigation and targeting across large sample areas.

The resulting datasets also provide statistically meaningful insight into device behavior. By fabricating and characterizing large numbers of nanowire devices, the researchers could observe systematic relationships between threshold voltage, nanowire diameter, channel length, and device geometry.

Toward Scalable and Data-Driven Nanotechnology Research

A common theme connecting all aspects of the work is the transition of nanoscience toward increasingly automated, scalable, and data-driven research workflows.

Historically, nanoscale characterization often depended on manual image interpretation, small experimental datasets, and labor-intensive fabrication processes. As nanotechnology moves closer to practical device integration and industrial-scale manufacturing, these approaches become increasingly difficult to scale.

By integrating imaging ellipsometry, correlative microscopy, automated lithography, computer vision, and machine learning into unified workflows, researchers are building research infrastructures capable of analyzing nanoscale systems with both statistical depth and nanoscale precision.

Importantly, these methodologies are broadly adaptable beyond the specific materials discussed here. Similar approaches could play important roles in wafer-scale 2D materials manufacturing, optoelectronic device screening, quantum materials research, and future AI-assisted nanomanufacturing environments.

Conclusion

High-throughput correlated microscopy is rapidly transforming nanoscience from a largely manual discipline into a scalable, data-driven research ecosystem. By combining advanced optical characterization, automated image analysis, correlative microscopy, and machine learning, researchers are increasingly able to study nanoscale materials with both statistical depth and nanoscale precision.

As emerging materials systems continue moving toward practical device integration and industrial-scale manufacturing, automated characterization and fabrication workflows are expected to become increasingly important. The integration of microscopy, data science, and intelligent automation is not only accelerating materials research, but also reshaping how future nanoelectronic technologies may ultimately be developed, optimized, and manufactured.

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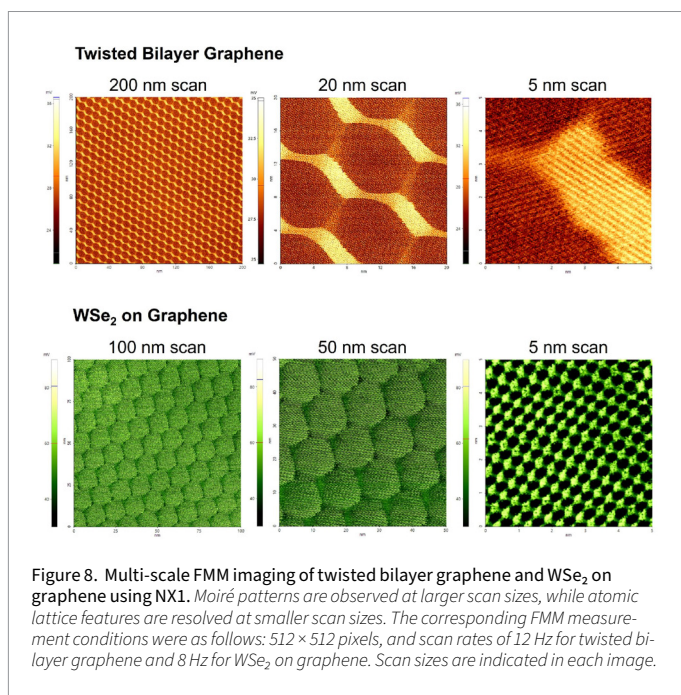
About Dr. Jack Alexander-Webber

Jack Alexander-Webber received his MSci in Physics from Royal Holloway, University of London (2009) and his DPhil in Condensed Matter Physics from the University of Oxford (2013). He joined the Electrical Engineering Division in the Department of Engineering, University of Cambridge in 2014 as a Junior Research Fellow of Churchill College. He subsequently held a Research Fellowship from the Royal Commission for the Exhibition of 1851. In 2019 Jack was awarded a Royal Society Dorothy Hodgkin Research Fellowship and now leads the Low-Dimensional Electronics Group. In 2026 Jack was appointed as a Senior Lecturer in Advanced Materials in the Department of Materials, Loughborough University.

The focus of his research is to develop a foundation of fundamental materials science and device engineering in novel electronic materials, and use the expertise and insights gained to demonstrate new (opto)electronic and quantum device concepts with enhanced performance and novel functionalities. His work has been published in leading journals including *Nature*, *Science*, *Advanced Materials*, *ACS Nano*, *Nano Letters*, *Physical Review Letters*, and *Nature Communications*, with >6000 citations to date. Jack co-authored the textbook, *Quantum Technology* (Elsevier, 2025), alongside Prof. Stefan Tappertzhofen to provide an accessible, engineering-focused introduction to the fundamentals and applications of quantum phenomena. Jack is also a co-founder of Nanomation Ltd., a startup developing scalable nanomaterial optoelectronic technologies.



Continued from page 7



Twisted bilayer graphene forms a moiré superlattice due to rotational misalignment between graphene layers, while WSe₂ on graphene forms moiré patterns due to lattice mismatch between the two materials. As shown in Figure 8, moiré patterns are observed at larger scan sizes, while atomic lattice features are resolved as the scan size is reduced, demonstrating the capability of NX1 for nanoscale-to-atomic-scale imaging of 2D material systems.

Conclusions

Advancements in AFM technology continue to expand the ability to characterize surfaces at increasingly smaller length scales, making stable atomic-scale imaging an important capability for modern materials research.

Park NX1 was developed to provide a practical high-resolution AFM platform for researchers pursuing atomic lattice imaging under ambient conditions. With its rigid low-noise mechanical architecture, minimized mechanical loop, Kovar-based AFM core body, precision XYZ tube scanner, and refined optical and probe workflow, the NX1 is designed to support stable and repeatable high-resolution measurements.

The atomic lattice and moiré imaging results presented in this note demonstrate the capability of NX1 for crystalline surfaces and two-dimensional material systems, supporting stable atomic-scale imaging under ambient conditions.

OBSERVING SAMPLES IN LIQUID USING ATOMIC FORCE MICROSCOPY

Practical Considerations for Sample Preparation and Fixation

Dr. Teiko Shibata-Seki, Research Equipment Center, Tokyo Metropolitan University

Presented at the NanoScientific Symposium Japan. Visit NanoScientific website to watch the full presentation: https://nanoscientific.org/on_demand

Introduction

Atomic force microscopy (AFM) is widely used to observe nanoscale structures and measure the mechanical and physical properties of materials. One of the important capabilities of AFM is its ability to operate under liquid environments, which allows researchers to characterize materials and biological systems under conditions closer to their natural state. However, successful AFM observation in liquid requires careful attention to measurement conditions, especially to sample preparation and fixation.

In a presentation at the NanoScientific Symposium Japan, Teiko Shibata-Seki of Tokyo Metropolitan University discussed practical approaches to observing samples in liquid using AFM. Through several examples—from polymer membranes to biological tissues and proteins—she highlighted the critical role of sample preparation and the challenges encountered when attempting stable measurements in liquid environments.

The Development of Microscopy and the Role of AFM

The history of microscopy spans approximately four centuries. Early optical microscopes achieved magnifications of only about nine times. Over the next 300 years, improvements in optical technology expanded magnification to around 1000 times. In the 1930s, the introduction of electron microscopy opened new possibilities for observing structures beyond the limits of optical instruments.

In the 1980s, scanning probe microscopy (SPM) was developed, enabling nanoscale observation of surfaces^{1,2}. In 1986, the inventors of the scanning tunneling microscope were awarded the Nobel Prize in Physics, marking a major milestone in nanoscale imaging. Since then, further innovations such as super-resolution fluorescence microscopy and cryo-electron microscopy have also received Nobel recognition.

Despite these developments, SPM techniques—including AFM—remain essential tools because they can measure not only surface topography but also properties such as friction force, electromagnetic properties, and mechanical characteristics. Their broad range of measurement capabilities ensures that they continue to play an important role in nanoscience research.

Sample Preparation as a Critical Factor

Advances in microscopy have often been accompanied by improvements in sample preparation techniques. In electron microscopy, for example, methods such as microtomy and ion milling were developed to prepare samples suitable for high-resolution observation.

Today, sample preparation is considered an independent field of research, and specialized preparation instruments are commercially available for some applications. The quality of sample preparation can strongly influence experimental outcomes.

However, sample preparation in scanning probe microscopy has historically relied heavily on the experience and intuition of the operator. Although AFM instrumentation has improved dramatically, fundamental discussions about preparation methods have been limited. As AFM

applications continue to expand, especially in liquid environments, the importance of preparation techniques has been enhanced.

Key Factors in AFM Measurements

To obtain reliable AFM data, appropriate measurement conditions must be selected. In addition to setting appropriate measurement parameters, several other factors play critical roles.

• Cantilever Selection

The cantilever must be selected according to the hardness and characteristics of the sample. When observing nanoscale materials, the radius of the AFM tip strongly affects both the resolution and the apparent size of observed structures.

• Substrate Surface Roughness

Substrate surface roughness is another important factor. If the roughness of the substrate exceeds approximately one-tenth of the size of the object being measured, it becomes difficult to identify the target object.

• Measurements in Liquid

AFM measurements in liquid introduce additional challenges. The resistance a cantilever experiences from a liquid medium is approximately 800 times greater than the resistance it experiences in air. Therefore, it becomes more difficult to stabilize the cantilever against disturbances from the liquid.

Small cantilevers are generally advantageous for measurements in liquid. For biological samples, which often require cantilevers with low spring constants, short and thin cantilevers are preferred. Advances in cantilever fabrication technology have made such probes increasingly available, enabling improved measurements in liquid environments.

Sample Fixation in Liquid

A major challenge in liquid AFM measurements is sample fixation. If a sample is not securely attached to the substrate, it may move or detach during scanning.

Several fixation mechanisms can be used depending on the sample:

- Non-specific adsorption through van der Waals interactions
- Hydrophobic interactions
- Electrostatic interactions
- Immunological reactions enabling specific adsorption
- Active adhesion in living cells
- Chemical adsorption through covalent bonding

Selecting the appropriate fixation method is essential for achieving stable imaging conditions.

Porous Polymer Membrane Study

One example presented involved a highly innovative ultrathin polymer membrane with reticular cross-linked network developed by Associate Professor Yoshimitsu Itoh of the University of Tokyo³. This research, published in *Science*, involved collaboration across multiple fields including solid-state NMR, electron tomography, MD simulations and

polymer science.

Conventional artificial porous polymers are typically mechanically weak and brittle. In this work, however, a new membrane structure was developed that is both ultralight and mechanically robust. The membrane can be produced by applying voltage to a polymer solution, forming a film approximately 77 μm thick within about two minutes.

The material also exhibits antibacterial and antiviral properties and functions as a smart material whose permeability can be switched by pH.

AFM measurements were performed on membranes formed on silicon wafers and immersed in liquid. Sample fixation relied mainly on van der Waals interactions, and detachment sometimes occurred during measurement. In some cases, the sample remained stable overnight, while in other cases the measurement had to be reattempted after detachment.

To investigate swelling behavior, the same region of the membrane was measured repeatedly in liquid. Measurements were made typically four or five times until the thickness reached a constant level.

Young's modulus was also measured. Because the contact area between the tip and the sample influences the results, the same cantilever was used for all measurements. The membranes swelled in deionized water, and their Young's modulus decreased significantly, and it decreased even more drastically in alkaline water with a pH of 10.

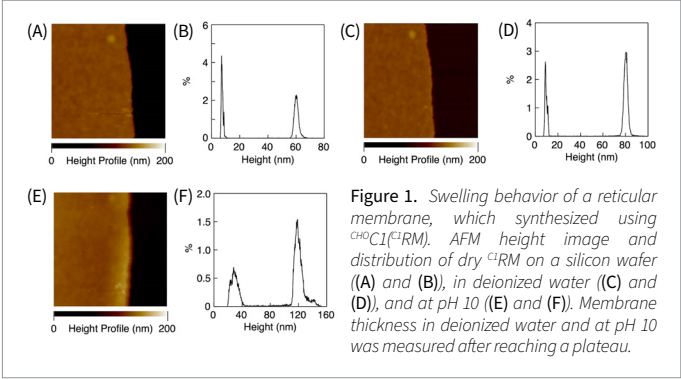


Figure 1. Swelling behavior of a reticular membrane, which synthesized using CHOCl^{TM} . AFM height image and distribution of dry CIRM on a silicon wafer ((A) and (B)), in deionized water ((C) and (D)), and at pH 10 ((E) and (F)). Membrane thickness in deionized water and at pH 10 was measured after reaching a plateau.

Parameters	Dry	Deionized water	$\text{NaOH}_{(\text{aq})}$ (pH 10)
CIRM thickness	53.2 nm	71.6 nm	59.4 nm
Degree of swelling	N/A	34.6 %	68.0 %
Young's modulus	$8.9 \pm 1.2 \text{ GPa}$	$2.9 \pm 0.1 \text{ GPa}$	$0.50 \pm 0.08 \text{ GPa}$

Table 1. Variations in thickness, degree of swelling, and Young's modulus of CIRM under different conditions.

AFM Observation of Corneal Tissue

Another example involved AFM measurements of corneal tissue. The cornea is mainly composed of three layers—epithelium, stroma, and endothelium—with a total thickness of approximately 500 μm .

Endothelial cells play a critical role in maintaining corneal function. If these cells are damaged, they do not regenerate and corneal transplantation may be required.

When attempting to observe intact corneal tissue in liquid using AFM, stable imaging was not possible because the sample moved during scanning. To address this issue, the tissue was sliced to a thickness of about 100 μm and the cut surface was fixed to glass.

This preparation allowed stable observation of both epithelial and endothelial cells. The adsorption to the glass relied mainly on van der Waals interactions, although detachment could still occur under some conditions.

The corneal cells were first observed in their native state and were subsequently treated with glutaraldehyde, a protein crosslinking agent commonly used for fixation. AFM imaging and elasticity mapping showed that longer treatment increased cellular stiffness, while histogram analysis confirmed corresponding changes in the elasticity distribution.

By examining areas where endothelial cells were absent, it was also possible to quantitatively measure the height of individual cells ⁴.

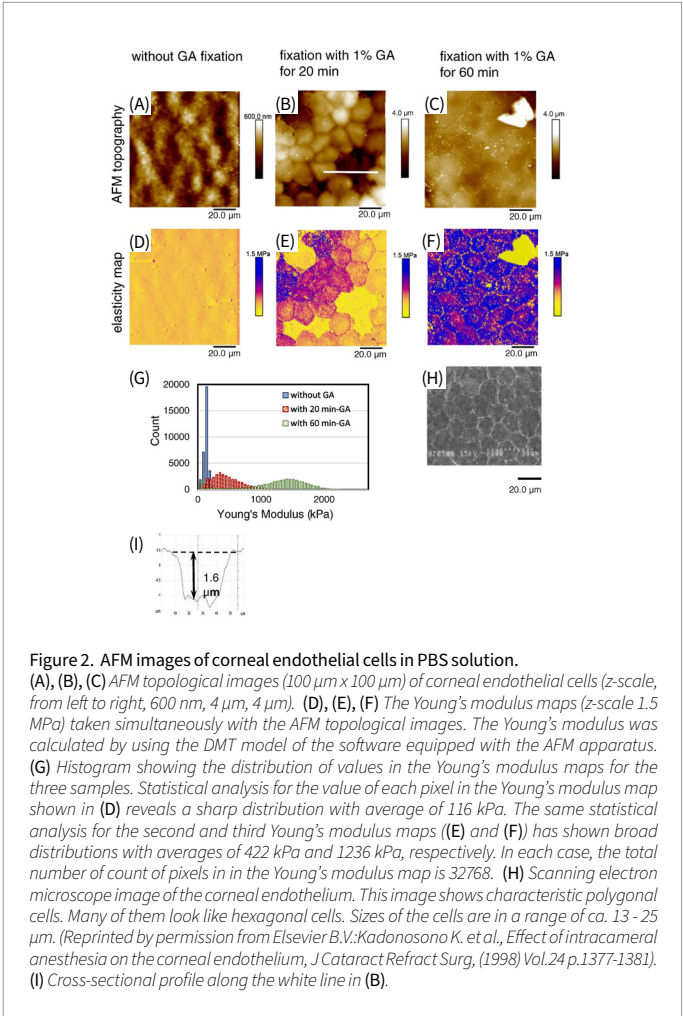


Figure 2. AFM images of corneal endothelial cells in PBS solution. (A), (B), (C) AFM topographical images ($100 \mu\text{m} \times 100 \mu\text{m}$) of corneal endothelial cells (z-scale, from left to right, 600 nm, 4 μm , 4 μm). (D), (E), (F) The Young's modulus maps (z-scale 1.5 MPa) taken simultaneously with the AFM topographical images. The Young's modulus was calculated by using the DMT model of the software equipped with the AFM apparatus. (G) Histogram showing the distribution of values in the Young's modulus maps for the three samples. Statistical analysis for the value of each pixel in the Young's modulus map shown in (D) reveals a sharp distribution with average of 116 kPa. The same statistical analysis for the second and third Young's modulus maps ((E) and (F)) has shown broad distributions with averages of 422 kPa and 1236 kPa, respectively. In each case, the total number of count of pixels in the Young's modulus map is 32768. (H) Scanning electron microscope image of the corneal endothelium. This image shows characteristic polygonal cells. Many of them look like hexagonal cells. Sizes of the cells are in a range of ca. 13 - 25 μm . (Reprinted by permission from Elsevier B.V.:Kadonosono K. et al., Effect of intracameral anesthesia on the corneal endothelium, J Cataract Refract Surg, (1998) Vol.24 p.1377-1381). (I) Cross-sectional profile along the white line in (B).

Electrostatic Interactions and Exosome Observation

Electrostatic interactions also influence adsorption behavior in liquid measurements.

Mica, commonly used as an AFM substrate, becomes negatively charged in liquid because surface ions are lost. Surface modification can therefore be used to change the electrostatic properties of the substrate.

By coating mica with polymers carrying different charges, it is possible to control the surface potential of the mica.

This method was applied to the observation of exosomes, small vesicles secreted by cells. On untreated mica, adsorption of exosomes was unstable and imaging was difficult. On positively charged polymer-coated mica, however, stable observation became possible.

In one experiment, only small particles were observed, which were more likely to adhere to the surface. When the remaining solution was transferred onto another substrate, larger particles were eventually detected. This demonstrated that AFM observations reflect what has attached to the substrate rather than the full distribution of particles present in the solution.

Protein (Cadherin) Observation

AFM was also used to observe cadherin, a protein discovered by Professor Masatoshi Takeichi that plays an important role in cell adhesion. Measurements were performed under conditions similar to physiological ones in order to observe functional structures. Cadherins were linked to another protein for fixation in petri dishes during biochemical experiments to investigate their function, and were immobilized on a hydrophobic substrate via hydrophobic interactions. Using this method, we successfully observed the direct bonding of cadherin molecules in liquid. This was consistent with a state-of-the-art model proposed by X-ray crystallography.

Cadherins function by bonding with Ca^{2+} ions. Furthermore, the cleavage of cadherin bonds upon the addition of a chelating agent was observed in real time using AFM ⁵.

Liposome Observation and Immunological Fixation

Early AFM experiments on liposomes were performed about 30 years ago, when only contact-mode AFM was available.

Initial attempts to image liposomes failed because the vesicles were swept away during scanning. The problem was solved by using antibody-based immunological fixation, which allowed the liposomes to attach securely to the substrate.

This approach led to the first successful AFM observations of liposomes in liquid. Increasing the applied load also made it possible to observe liposomes detach from the substrate and quantify adhesion forces ⁶.

AFM Observation of Living Cells

AFM can also be used to study living cells in liquid environments. Unlike passive samples, living cells remain attached through active adhesion mechanisms.

In one study, corneal epithelial cells were cultured and observed while exposed to a drug. Continuous AFM measurements showed that the cells contracted after the drug addition.

Such experiments demonstrate that AFM can provide quantitative information at the level of individual cells.

Expanding the Capabilities of Liquid AFM

AFM measurements in liquid environments present significant challenges, particularly regarding sample fixation and stability. However, as the examples described above illustrate, careful preparation and fixation strategies can enable successful observations of both materials and biological systems.

Although many practical details of sample preparation are not always described in published papers, accumulated experience has gradually expanded the range of applications for liquid AFM.

By continuing to refine preparation methods and measurement techniques, researchers can further extend the applicability of AFM to the study of nanoscale phenomena under conditions closer to their natural state.

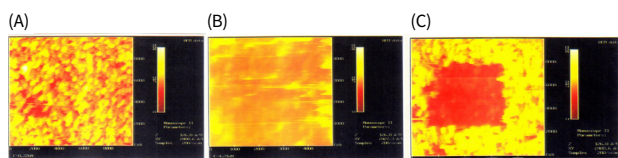


Figure 7. In-situ AFM images of liposomes on substrates taken at different load forces over the same region. Images were taken with a standard Si_3N_4 cantilever tip (spring constant of 0.12 Nm⁻¹); (A) load force was approximately 0.72 nN (scan area 10 $\mu\text{m} \times 10 \mu\text{m}$); (B) load force was approximately 4.2 nN (scan area 5 $\mu\text{m} \times 5 \mu\text{m}$); (C) load force was approximately 2.2 nN (scan area 10 $\mu\text{m} \times 10 \mu\text{m}$)

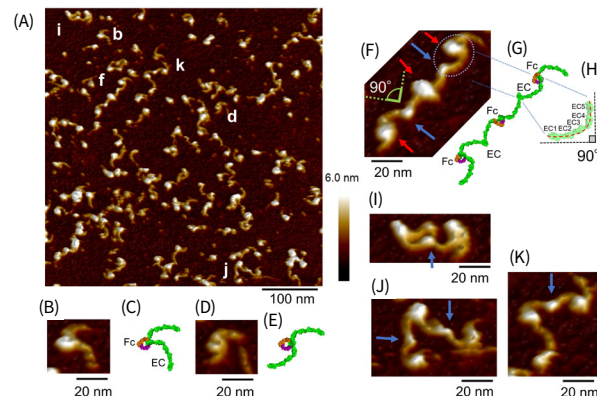


Figure 3. AFM images of E-cadherin-Fc(E-cad-Fc) molecules in a PBS solution containing 0.9 mM Ca^{2+} at room temperature and their structural models. (A) AFM image of E-cad-Fc molecules. E-cad-Fc molecules were observed in various conformations (scale bar 100 nm). (B) and (D) Magnified AFM images of E-cad-Fc monomer-like structures of the points (B) and (D) in (A) (scale bar 20 nm). (C) and (E) E-cad-Fc monomer models constructed from the AFM measurement results of (B) and (D). The orientation and tilt of the Fc domain are arbitrary due to insufficient resolution of AFM image. (F) Magnified AFM image of E-cad-Fc molecules of the point f in (A) (scale bar 20 nm). Three E-cad-Fc molecules appear trans-bonded (blue arrow) in the Extra Cellular (EC)1 domain. EC domains (blue dotted circle) and Fc domains (red arrow) are distinguishable. (G) E-cad-Fc model constructed from the AFM measurement results of (F). (H) EC domain model. The five EC domains are curved such that the long axis of EC1 is approximately perpendicular to the long axis of EC5. (I), (J) and (K) Magnified AFM images of E-cad-Fc binding structures of the molecules (H), (I) and (J) in (A) (scale bar 20 nm).

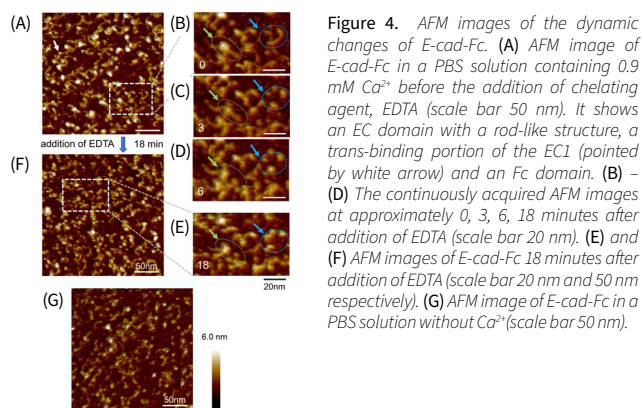


Figure 4. AFM images of the dynamic changes of E-cad-Fc. (A) AFM image of E-cad-Fc in a PBS solution containing 0.9 mM Ca^{2+} before the addition of chelating agent, EDTA (scale bar 50 nm). It shows an EC domain with a rod-like structure, a trans-binding portion of the EC1 (pointed by white arrow) and an Fc domain. (B) - (D) The continuously acquired AFM images at approximately 0, 3, 6, 18 minutes after addition of EDTA (scale bar 20 nm). (E) and (F) AFM images of E-cad-Fc 18 minutes after addition of EDTA (scale bar 20 nm and 50 nm respectively). (G) AFM image of E-cad-Fc in a PBS solution without Ca^{2+} (scale bar 50 nm).

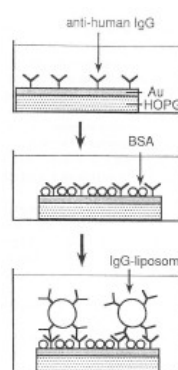


Figure 5. Schematic diagrams of sample preparation

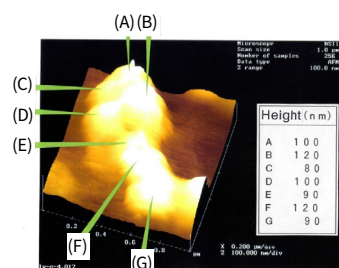


Figure 6. AFM image of liposomes in liquid taken with a standard Si_3N_4 cantilever-tip (spring constant of 0.06 Nm⁻¹), area 1 $\mu\text{m} \times 1 \mu\text{m}$.

Continued on page 22

CHARACTERIZING CTAB SURFACTANT ADSORPTION ON SINGLE NANOCUBES VIA CORRELATIVE IN SITU AFM AND SEM ANALYSIS

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Abstract

Cetyltrimethylammonium bromide (CTAB) is one of the most widely used surfactants in the aqueous synthesis of colloidal gold nanocrystals. Although essential for directing crystal growth and stabilizing nanoparticles during synthesis, residual CTAB can significantly influence nanoparticle performance in applications such as catalysis, sensing, and electrochemistry. Understanding how CTAB is distributed on individual nanoparticles under hydrated conditions is therefore critical for both fundamental studies and practical applications. In this work, a correlative microscopy approach combining in situ atomic force microscopy (AFM) and scanning electron microscopy (SEM) was used to characterize CTAB adsorption on individual gold nanocubes (Au NCs). By correlating AFM topography acquired in liquid with SEM measurements obtained from the same particles, the thickness and distribution of adsorbed CTAB were quantified at the single-particle level. Statistical analysis revealed an average CTAB thickness of 2.9 ± 2.4 nm, closely matching the theoretical molecular length of CTAB. The results demonstrate heterogeneous ligand coverage among individual nanocubes and highlight the value of in situ AFM for evaluating ligand structure and distribution under native hydrated conditions.

Introduction

Gold nanoparticles have attracted sustained interest because of their unique optical, electronic, catalytic, and physicochemical properties¹. Their applications span biomedicine, sensing, catalysis, plasmonics, and energy-related technologies. Early research focused primarily on spherical nanoparticles; however, advances in colloidal synthesis have enabled the production of nanocrystals with precisely controlled sizes, shapes, and exposed crystallographic facets^{2,4}. These developments have expanded the functional capabilities of gold nanomaterials and created new opportunities to tailor performance through structural design.

A key factor governing nanocrystal growth is the interaction between surface ligands and specific crystal facets. Surface ligands influence surface energy, regulate growth kinetics, and ultimately determine nanoparticle morphology. Among the most important of these ligands is cetyltrimethylammonium bromide (CTAB), a surfactant widely used in seed-mediated synthesis methods. CTAB has been instrumental in the development of anisotropic gold nanostructures, including nanorods, bipyramids, and nanocubes^{3,4}.

The role of CTAB extends well beyond synthesis. Residual CTAB remaining on nanocrystal surfaces can affect catalytic activity, charge transfer, interfacial accessibility, and interactions with surrounding environments⁵. Consequently, understanding CTAB adsorption is essential for optimizing nanoparticle performance. While ensemble characterization methods such as spectroscopy and scattering techniques have suggested organized CTAB layers on gold nanostructures, they do not provide direct information about ligand distribution on individual particles⁶.

To address this challenge, gold nanocubes were selected as a model system for investigating CTAB adsorption at the nanoscale. By combin-

ing the complementary strengths of AFM and SEM, a correlative measurement workflow was developed that provides detailed information about both particle geometry and surface-bound ligands. AFM offers exceptional vertical sensitivity and can operate in liquid environments where surfactant layers remain hydrated, while SEM provides high lateral resolution and accurate dimensional measurements. Together, these techniques enable characterization of CTAB adsorption on individual nanocrystals with a level of detail that is difficult to achieve using either method alone.

Experimental

Gold nanocubes synthesized through a seed-mediated growth process were used as the model system³. In seed-mediated synthesis, the morphology of a nanocrystal is determined by the relative growth rates of different crystallographic facets. By carefully controlling reaction conditions such as precursor concentration, surfactant concentration, temperature, and reaction time, specific growth pathways can be favored, enabling the formation of cubic nanocrystals dominated by {100} facets. The seed-mediated growth mechanism and resulting morphology of the well-defined gold nanocubes are illustrated by the structural diagram and baseline scanning electron micrograph in Figure 1.

In situ AFM measurements were performed under hydrated conditions using a liquid imaging configuration on a Park NX12 AFM platform. Soft tapping mode was employed with an amplitude of 5–10 nm at a resonance frequency of 25–30 kHz. A USC-F0.3-k0.3 cantilever (NanoAnd-More) with a spring constant of 0.1 N/m and an approximately 10 nm tip radius was used to achieve high topographical sensitivity in liquid^{7,9}. Scanner calibration was performed using a TGQ1 standard sample prior to imaging. The physical assembly of the liquid probe holder, its environmental sealing cover, and its configuration within the AFM scanner head are detailed in Figure 2. AFM data were analyzed using SmartAnalysis and XEI software (Park Systems)^{10–12}.

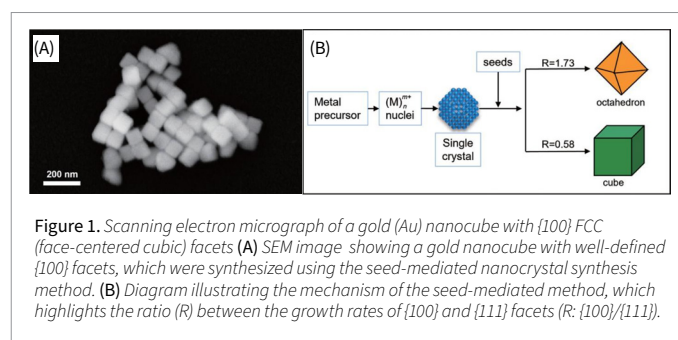


Figure 1. Scanning electron micrograph of a gold (Au) nanocube with {100} FCC (face-centered cubic) facets (A) SEM image showing a gold nanocube with well-defined {100} facets, which were synthesized using the seed-mediated nanocrystal synthesis method. (B) Diagram illustrating the mechanism of the seed-mediated method, which highlights the ratio (R) between the growth rates of {100} and {111} facets ($R: \{100\}/\{111\}$).

Accurate relocation of the same nanocrystal for both AFM and SEM measurements is a critical requirement for correlative analysis. Differences in stage geometry and sample orientation between instruments often make this process difficult. To address this challenge, a sample-position linkage system was utilized, incorporating fiducial markers and enabling coordinate transformation between Park AFM and JEOL SEM systems as shown in Figure 3. This sample-position linkage work-

flow simplified navigation to identical regions of interest, significantly improving measurement reliability across platforms.

The workflow also demonstrates the flexibility of AFM-based characterization for environmental studies. Transfer hardware designed for air-sensitive materials can be integrated with AFM and SEM platforms, enabling characterization of samples prepared under controlled conditions. Although the gold nanocubes studied here were analyzed under hydrated conditions, the approach illustrates how correlative workflows can be extended to vacuum or inert-environment investigations. The complementary transfer shuttle and vacuum-glovebox hardware configuration designed to protect air-sensitive nanomaterials during multi-instrument tracking are displayed in Figure 4.

Following AFM imaging, samples were dried under ambient conditions and coated with a thin Au/Pd conductive layer prior to SEM analysis. SEM images were acquired using an Auriga FIB-SEM microscope equipped with in-lens and Everhart-Thornley detectors operated at 20 kV accelerating voltage, a 30 μm aperture, and a 5.7–6.0 mm working distance. Line-profile analysis was performed using ImageJ (NIH).¹³ SEM imaging provided accurate lateral dimensions and high-contrast visualization of the nanocube core. These measurements served as a dimensional reference for comparison with AFM-derived topography.

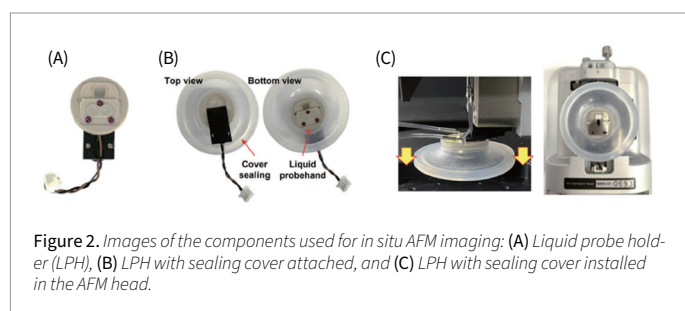


Figure 2. Images of the components used for in situ AFM imaging: (A) Liquid probe holder (LPH), (B) LPH with sealing cover attached, and (C) LPH with sealing cover installed in the AFM head.

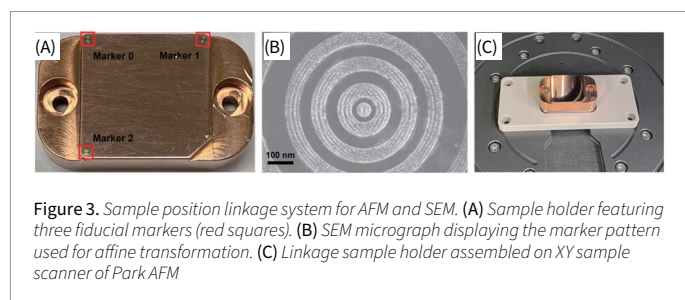


Figure 3. Sample position linkage system for AFM and SEM. (A) Sample holder featuring three fiducial markers (red squares). (B) SEM micrograph displaying the marker pattern used for affine transformation. (C) Linkage sample holder assembled on XY sample scanner of Park AFM.

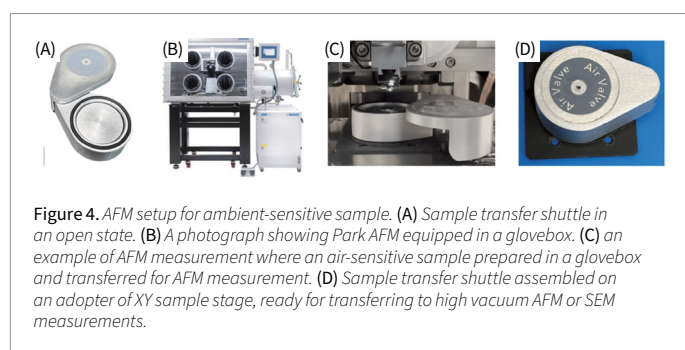


Figure 4. AFM setup for ambient-sensitive sample. (A) Sample transfer shuttle in an open state. (B) A photograph showing Park AFM equipped in a glovebox. (C) An example of AFM measurement where an air-sensitive sample prepared in a glovebox and transferred for AFM measurement. (D) Sample transfer shuttle assembled on an adapter of XY sample stage, ready for transferring to high vacuum AFM or SEM measurements.

Results and Discussion

The correlative workflow consisted of three principal stages. First, topographic information was collected from individual nanocubes while immersed in deionized water. Second, the samples were dried and prepared for SEM imaging. Finally, AFM and SEM datasets from the same nanocrystals were aligned and analyzed together. The sequential phase transitions of the experimental workflow—progressing from native in situ fluid cell characterization to conductive coating deposition and dry-state electron microscopy—are schematized in Figure 5.

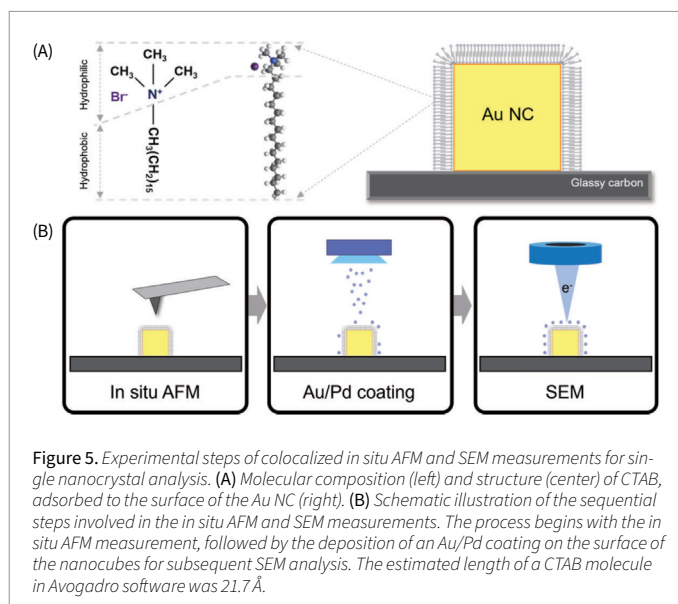


Figure 5. Experimental steps of colocated in situ AFM and SEM measurements for single nanocrystal analysis. (A) Molecular composition (left) and structure (center) of CTAB, adsorbed to the surface of the Au NC (right). (B) Schematic illustration of the sequential steps involved in the in situ AFM and SEM measurements. The process begins with the in situ AFM measurement, followed by the deposition of an Au/Pd coating on the surface of the nanocubes for subsequent SEM analysis. The estimated length of a CTAB molecule in Avogadro software was 21.7 Å.

Gold nanocubes provide an excellent model system for correlative analysis because their dimensions are expected to be nearly identical along the x, y, and z axes. SEM measurements established an average edge length of approximately 77.5 nm and confirmed that the particles exhibited near-cubic geometry. These measurements provided a dimensional baseline for evaluating differences observed in AFM data.

AFM measurements acquired under hydrated conditions revealed nanocube topography together with contributions from the surrounding CTAB layer. In one representative example, the SEM edge length of a nanocube was approximately 77 nm, whereas the AFM height measured in liquid was approximately 80 nm. The additional height is attributed to the presence of adsorbed CTAB on the top surface of the particle.

The value of the correlative approach becomes particularly evident when analyzing line profiles. SEM defines the dimensions of the nanocrystal core with high precision, while AFM captures the contribution of surface-bound surfactants. By overlaying a geometrical model derived from SEM onto AFM topography, the thickness of adsorbed CTAB can be estimated directly. This strategy enables separation of nanocrystal dimensions from ligand contributions, providing a clearer picture of adsorption behavior. A representative correlative extraction is showcased in Figure 6, highlighting the direct spatial overlay of the core nanocrystal boundaries defined by SEM onto the vertical height profile captured via fluid AFM.

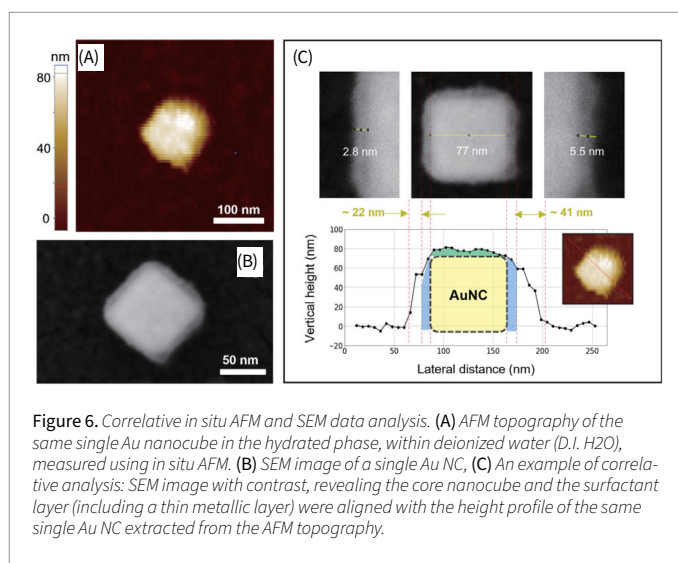


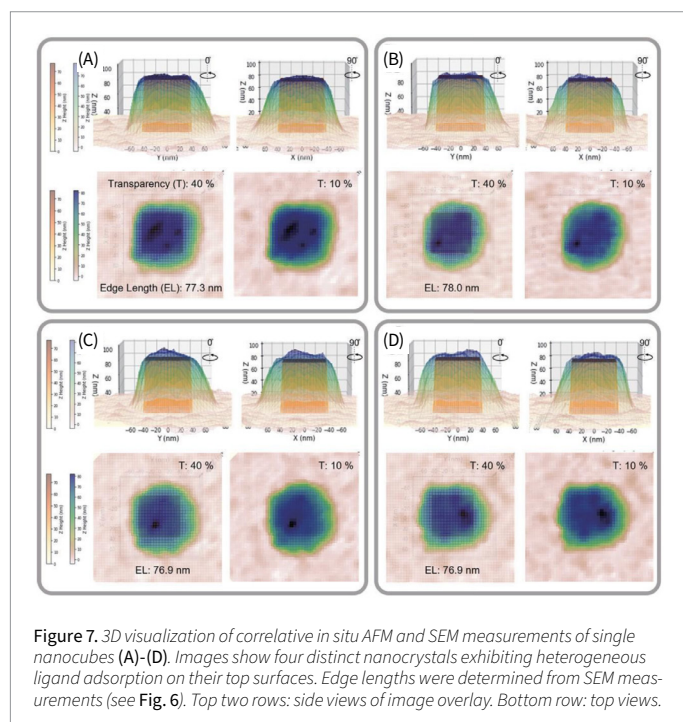
Figure 6. Correlative in situ AFM and SEM data analysis. (A) AFM topography of the same single Au nanocube in the hydrated phase, within deionized water (D.I. H₂O), measured using in situ AFM. (B) SEM image of a single Au NC. (C) An example of correlative analysis: SEM image with contrast, revealing the core nanocube and the surfactant layer (including a thin metallic layer) were aligned with the height profile of the same single Au NC extracted from the AFM topography.

Interestingly, variability in lateral CTAB dimensions was greater than variability observed in vertical measurements. Under dehydrated SEM conditions, apparent CTAB thickness ranged from approximately 2.8 to 5.5 nm. After accounting for the conductive coating, these values were broadly consistent with the 2–3 nm vertical thickness observed by AFM. Under hydrated conditions, however, AFM measurements suggested significantly larger lateral dimensions, indicating expansion and redistribution of the surfactant layer in aqueous environments.

These observations highlight the importance of evaluating ligand structure under native conditions. Surfactant layers may adopt different configurations when dehydrated, potentially leading to interpretations that do not fully reflect their behavior during operation. In situ AFM therefore provides valuable information that complements conventional ex situ characterization approaches.

Three-dimensional visualization further enhanced interpretation of the results. By combining AFM-derived topography with SEM-derived dimensions, the spatial distribution of CTAB surrounding individual nanocubes could be visualized directly. The nanocube core was represented using dimensions measured by SEM and positioned within the AFM topographic envelope. This approach enabled a realistic representation of ligand distribution on each particle.

Four representative nanocubes were analyzed in detail. Although the particles displayed similar overall dimensions, substantial differences were observed in CTAB coverage. Top-surface CTAB thicknesses ranged from approximately 1 to 5 nm. Some particles exhibited relatively uniform coverage, whereas others showed localized regions of greater thickness. These observations clearly indicate that CTAB adsorption is not identical from particle to particle, even among nanocrystals synthesized under the same conditions. The striking spatial variations in ligand distribution are mapped across individual particles using three-dimensional topographic models overlaid with volumetric geometric references in Figure 7.



The ability to visualize such heterogeneity represents a major advantage of the correlative methodology. Ensemble measurements provide average information about ligand coverage but do not reveal particle-to-particle variations. By contrast, the present approach enables direct observation of local adsorption behavior at the single-particle level.

Such heterogeneity may have important implications for nanomaterial performance. Variations in ligand coverage can influence accessibility of active sites, alter interfacial interactions, and affect catalytic or sensing behavior. Understanding these differences is therefore important when attempting to establish structure–property relationships in the nanoparticle systems.

Why Hydrated-State Characterization Matters

One of the most important outcomes of this work is the demonstration that hydrated-state characterization provides insights that may not be obtainable through conventional dry-state measurements alone. Surface ligands exist within a dynamic environment influenced by solvent interactions, molecular packing, and surface chemistry. Removing the solvent can alter these interactions and change the apparent structure of the ligand layer.

The AFM measurements performed in liquid revealed evidence of CTAB expansion and redistribution that was not apparent from SEM analysis. This observation underscores the importance of studying nanomaterials under conditions that more closely resemble their intended operating environments. For applications involving aqueous systems, measurements performed in liquid can provide a more realistic picture of ligand organization and behavior.

The findings also illustrate the value of combining complementary techniques. SEM excels at defining nanocrystal geometry, while AFM captures nanoscale topographic features associated with hydrated surface layers. When integrated into a correlative workflow, the two methods provide information that neither technique could deliver independently.

More broadly, the approach demonstrated here is applicable beyond CTAB-coated gold nanocubes. Many nanoparticle systems rely on ligands, polymers, biomolecules, or surfactants to control synthesis and functionality. The ability to characterize these surface layers directly at the single-particle level offers new opportunities for understanding and optimizing nanomaterial performance.

Statistical Analysis of CTAB Adsorption

To quantify CTAB adsorption more rigorously, statistical analysis was performed using height data extracted from the top surface of a representative nanocube. The properties of gold nanoparticles are strongly influenced by the complex interactions among their surface ligands, the surrounding solvent, and the nanoparticle core itself^{14–16}. Correlative alignment between AFM and SEM data enabled accurate definition of the nanocube geometry and isolation of the contribution arising from the surfactant layer.

A total of 76 measurements were collected from the top surface region. The nanocube height determined from SEM was subtracted from the corresponding AFM height values, producing a dataset representing CTAB thickness. The resulting distribution was analyzed using histogram and box-plot representations, with the quantified surfactant distribution, data point mapping, and corresponding statistical variance compiled visually in Figure 8.

The average CTAB thickness was found to be 2.9 ± 2.4 nm. This value agrees closely with the theoretical molecular length of CTAB, approximately 2.2 nm, estimated using molecular modeling. The agreement supports the interpretation that much of the observed surface layer corresponds to individual CTAB molecules adsorbed on the gold surface.

At the same time, the broad distribution demonstrates substantial heterogeneity in adsorption behavior. Measured thicknesses ranged from approximately 1 to 10 nm, indicating the coexistence of multiple adsorption states. Some regions appear consistent with a single molecular layer, whereas others suggest the presence of multilayer assemblies.

Continued on page 25

AFM-DRIVEN LAYER-BY-LAYER NANOSCALE FUNCTIONAL MAPPING IN CZTSSe THIN-FILM SOLAR CELLS

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Presented at the NanoScientific Symposium India. This article incorporates findings from recent published research. Visit NanoScientific website to watch the full presentation: https://nanoscientific.org/on_demand

Understanding What Limits Next-Generation Thin-Film Solar Cells

As the world accelerates its transition toward renewable energy, solar photovoltaics (PV) continue to play a central role in reducing dependence on fossil fuels while reducing greenhouse gas emissions. Although crystalline silicon remains the dominant commercial technology, researchers continue to explore alternative photovoltaic materials that can reduce manufacturing costs, improve material utilization, and rely on earth-abundant elements. Among these emerging materials, copper zinc tin sulfide/selenide (CZTSSe) has attracted considerable interest because it combines excellent optical properties with environmentally benign and low-cost constituent elements.

Unlike conventional silicon solar cells, which require wafers more than one hundred micrometers thick, CZTSSe possesses a direct bandgap and a high optical absorption coefficient, allowing nearly all incident sunlight to be absorbed within an absorber layer approximately one micrometer thick. These characteristics make CZTSSe an attractive candidate for next-generation thin-film photovoltaics.

Despite these advantages, CZTSSe solar cells have not yet achieved the efficiencies of more mature technologies such as CdTe and CIGS. Improving their performance requires a deeper understanding of how nanoscale structural and electrical properties throughout the device influence macroscopic photovoltaic performance. To address this challenge, researchers at UKM have employed a suite of advanced atomic force microscopy (AFM) techniques to perform layer-by-layer nanoscale functional mapping of CZTSSe solar cells.

Why CZTSSe?

Thin-film photovoltaic technologies offer an attractive complement to conventional crystalline silicon because they can use much thinner absorber layers while enabling lightweight, flexible, and scalable device formats. Unlike crystalline silicon wafers, which are typically around 160 μm thick, thin-film solar cells can use absorber layers of only about 1–3 μm , reducing semiconductor material use by more than 95%. This makes thin films especially relevant for applications such as building-integrated photovoltaics, vehicle surfaces, agrivoltaics, and other form factors that are difficult to realize with brittle silicon wafers¹.

Among established thin-film technologies, CdTe and CIGS have reached high levels of commercial maturity, with laboratory efficiencies above 23% and multi-gigawatt-scale production. However, each technology faces material-related concerns: CdTe involves cadmium and tellurium-related environmental or supply considerations, while CIGS depends on critical elements such as indium and gallium. Perovskites have achieved very high laboratory efficiencies, reaching 26.7% for single-junction cells, but long-term outdoor stability and lead management remain important challenges.

CZTSSe thin film solar cell (see Figure 1) is promising because it addresses some of these sustainability and scalability concerns. As a kesterite absorber based on copper, zinc, tin, sulfur, and selenium, it avoids indium and cadmium while relying largely on earth-abundant

and comparatively non-toxic elements. The related CZTS material has a direct bandgap of about 1.4–1.6 eV and an absorption coefficient above 10^4 cm^{-1} , allowing 1–2 μm films to harvest much of the terrestrial solar spectrum. Alloying sulfur with selenium to form CZTSSe further tunes the bandgap, extends minority-carrier diffusion lengths, and has enabled substantial efficiency improvements, including record CZTSSe efficiencies approaching 17%.

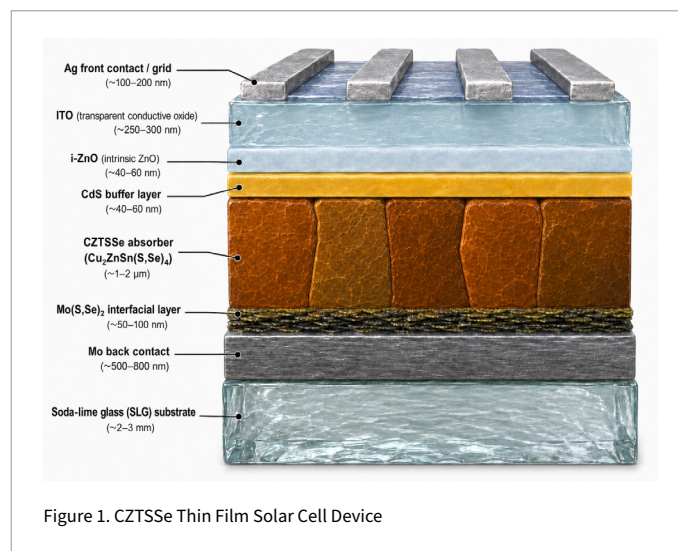


Figure 1. CZTSSe Thin Film Solar Cell Device

Despite this potential, CZTSSe still faces major scientific and engineering challenges. Its efficiency is limited by a large open-circuit-voltage deficit associated with Cu–Zn disorder, deep Sn-related defects, band-tail states, secondary phases, and recombination at grain boundaries and interfaces. The review also highlights that conventional CdS buffers can create unfavorable band alignment, while Mo back contacts may form resistive Mo(S,Se)₂ interfacial layers and promote Sn loss during selenization. These unresolved nanoscale and interfacial mechanisms make CZTSSe an important research platform for developing low-cost, earth-abundant thin-film photovoltaics with improved performance and long-term scalability.

Looking Beyond Conventional Characterization

Solar-cell performance is often evaluated through macroscopic measurements such as efficiency, open-circuit voltage, short-circuit current, and series resistance. While these measurements reveal how well a device performs, they do not explain why performance losses occur. Many of the critical processes governing charge transport happen at the nanoscale, particularly at interfaces between different layers of the solar-cell structure. Understanding these local variations requires characterization techniques capable of measuring not only surface morphology, but also electrical and photoelectrical behavior with nanometer-scale resolution.

Multimodal AFM provides this capability by combining topographical imaging with conductive and photo-conductive measurements. These techniques enable researchers to directly correlate local physical structure with functional electrical properties.

Revealing Hidden Conductivity Variations with Conductive AFM

The typical CZTSSe device consists of a glass substrate, a molybdenum (Mo) back contact, the CZTSSe absorber layer, a cadmium sulfide (CdS) buffer layer, transparent conductive oxides, and metallic front contacts. Although often viewed simply as an electrode, the molybdenum layer performs multiple functions simultaneously. It must provide excellent electrical conductivity while maintaining strong adhesion, chemical stability, moisture resistance, optical reflectance, and appropriate band alignment with the p-type absorber layer. Achieving all these requirements within a single deposited film is far from trivial.

To better understand the behavior of molybdenum back contacts, the research team investigated films deposited under different processing conditions and examined them using conductive AFM (C-AFM). Freshly deposited molybdenum films exposed to humid conditions rapidly developed native oxide layers. Conductive AFM identified localized regions of reduced conductivity associated with native molybdenum oxide formation. Conductive AFM measurements showed that these surface oxides reduced local conductivity by nearly an order of magnitude, corroborating with the Hall measurement data ².

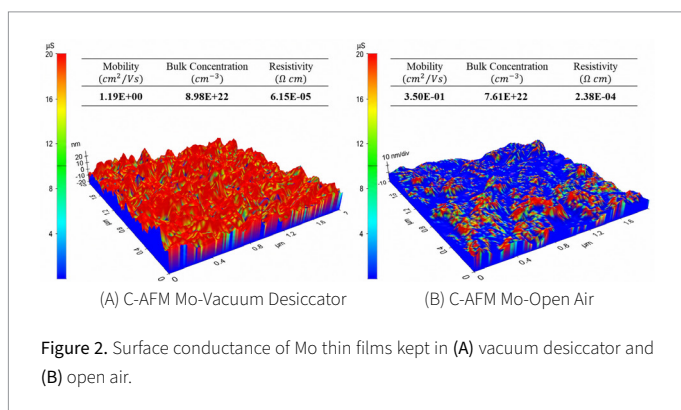


Figure 2. Surface conductance of Mo thin films kept in (A) vacuum desiccator and (B) open air.

This finding highlighted one of the key advantages of AFM-based electrical measurements: the ability to visualize local electrical heterogeneity at nanoscale resolution that may significantly affect device performance while remaining hidden in conventional bulk electrical measurements.

Engineering the Molybdenum Back Contact

An important challenge arises during sulfoselenization of the absorber layer, when sulfur diffuses into the molybdenum back contact and spontaneously forms an interfacial molybdenum disulfide (MoS₂) layer. Because this interfacial layer is not intentionally grown, its electrical properties can vary considerably, influencing band alignment and the formation of an effective ohmic contact. Simulation studies further indicated that the work function of the molybdenum back contact and the electrical characteristics of the MoS₂ interfacial layer play critical roles in determining carrier transport across the interface ³. These observations motivated a detailed nanoscale investigation using multimodal AFM.

Subsequent optimization focused on improving the molybdenum layer itself was carried out focusing on how post-deposition vacuum annealing modifies molybdenum (Mo) back contacts for CZTSSe thin-film solar cells ⁴. The vacuum-annealed Mo showed a stronger preferred crystallographic orientation, larger and more compact grains, lower surface roughness, and a much lower resistivity of 16.89 μΩ.cm compared with 61.53 μΩ.cm for the as-sputtered Mo. It also exhibited a higher work function of about 5.05 eV, compared with approximately 4.78 eV for the untreated Mo.

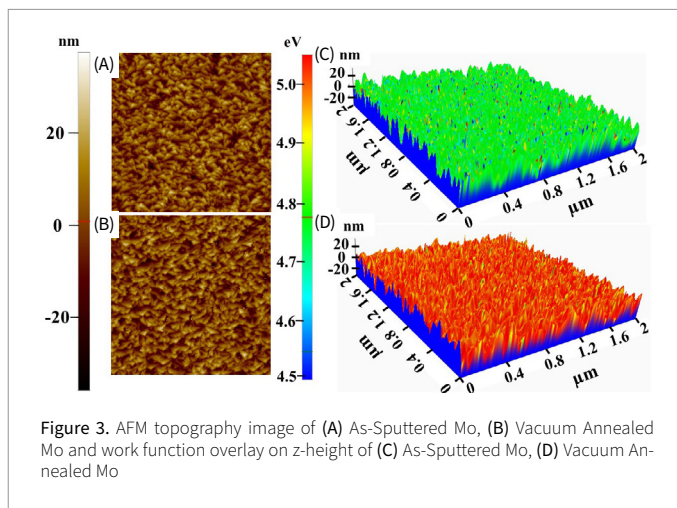


Figure 3. AFM topography image of (A) As-Sputtered Mo, (B) Vacuum Annealed Mo and work function overlay on z-height of (C) As-Sputtered Mo, (D) Vacuum Annealed Mo

These improvements also enhanced the Mo/CZTSSe interface. During selenization, the as-sputtered Mo promoted thicker and less favorable MoSe₂/Mo(S,Se)₂ interfacial formation, including mixed orientations that hindered adhesion and charge transport. In contrast, the vacuum-annealed Mo reduced interfacial layer formation and favored a more beneficial vertically aligned MoSe₂ orientation, providing a lower-resistance pathway for carrier transport. The annealing treatment also enabled sodium diffusion from the soda-lime glass substrate through the Mo layer, which enhanced the crystallinity and grain growth of the CZTSSe absorber. As a result, devices fabricated on vacuum-annealed Mo achieved a power conversion efficiency of 7.70%, far higher than the 0.71% efficiency obtained using as-sputtered Mo.

Visualizing Nanoscale Defects in the Absorber Layer

The investigation extended beyond the back contact into the CZTSSe absorber itself. Certain regions of the absorber surface exhibited unusual optical reflectivity and were selected for detailed AFM examination. Conductive AFM revealed localized defects, including pinholes and debris structures, that displayed unexpected electrical behavior. Interestingly, some pinholes that were expected to expose highly conductive molybdenum underneath showed little or no conductivity enhancement.

To understand this phenomenon, the researchers performed correlative field emission scanning electron microscopy (FESEM) analysis. The results revealed the presence of secondary phases, including tin sulfide compounds, occupying these regions. Rather than exposing the conductive molybdenum back contact as initially expected, these secondary phases altered the local electrical pathways and explained the unusual conductivity observed by conductive AFM.

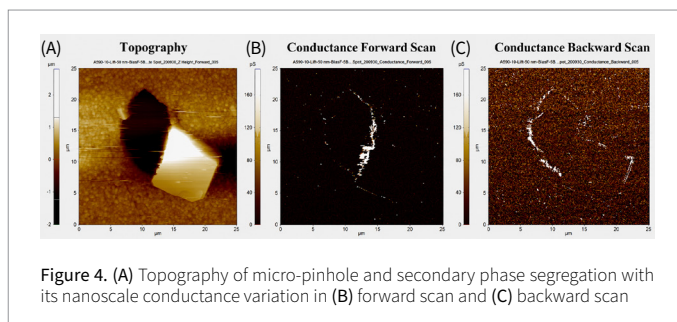


Figure 4. (A) Topography of micro-pinhole and secondary phase segregation with its nanoscale conductance variation in (B) forward scan and (C) backward scan

These observations demonstrated how local compositional variations can dramatically alter electrical transport pathways within the device, providing important clues regarding performance-limiting mechanisms.

Probing Photoresponse at the Nanoscale

The cadmium sulfide buffer layer represents another critical component of CZTSSe solar cells. Using photoconductive AFM, the research team illuminated CdS films with laser excitation while monitoring the local electrical response. Because CdS has a band gap of approximately 2.4 eV, illumination with a 405 nm laser corresponds to a photon energy of about 3.06 eV, which is above the CdS band gap. Therefore, the observed increase in conductivity under 405 nm illumination is consistent with direct photon absorption and photocarrier generation in the CdS layer.

However, measurements using longer-wavelength illumination, with photon energies closer to or below the CdS band gap, could provide additional insight into sub-bandgap photoresponse mechanisms. Such experiments may help identify band-tail states, defect-related states, or localized electronic states within the CdS thin film that could contribute to additional optical absorption pathways. These possibilities highlight the potential of photoconductive AFM for probing nanoscale photoelectrical behavior and electronic structure in semiconducting buffer layer.

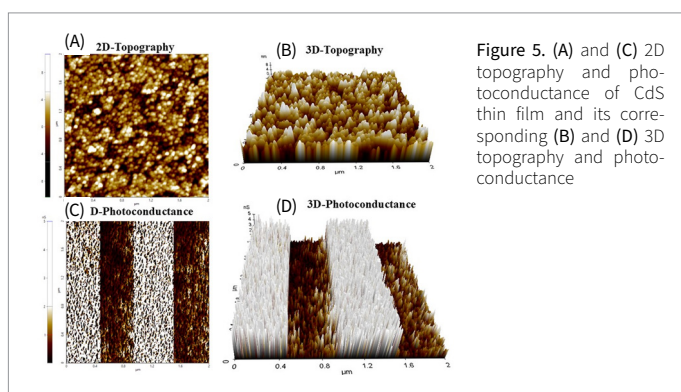


Figure 5. (A) and (C) 2D topography and photoconductance of CdS thin film and its corresponding (B) and (D) 3D topography and photoconductance

Such nanoscale photoelectrical measurements provide valuable insight into the electronic properties of thin-film photovoltaic materials that are difficult to obtain using conventional optical characterization techniques alone.

Conclusion: Toward Higher-Efficiency Earth-Abundant Solar Cells

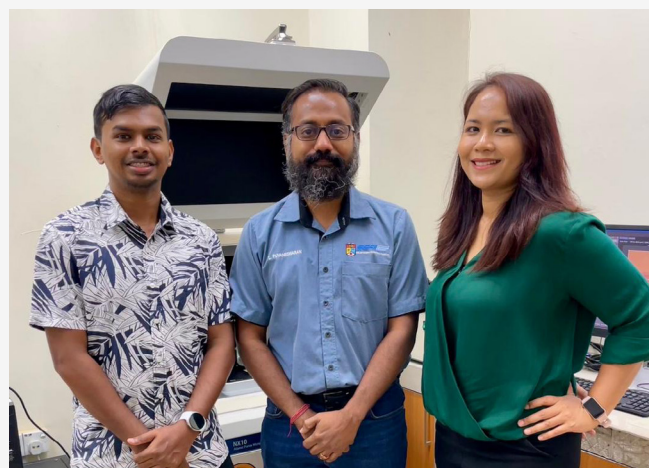
Although CZTSSe technology still trails the efficiency records achieved by silicon, CIGS, and perovskite solar cells, its combination of earth-abundant elements, low toxicity, and long-term stability continues to make it an attractive candidate for future photovoltaic applications. As photovoltaic research increasingly focuses on understanding complex material systems at ever smaller scales, nanoscale functional mapping will continue to play a vital role in bridging the gap between material properties and device performance.

The studies presented here demonstrate how advanced AFM techniques can reveal critical nanoscale processes that influence device behavior. By combining conductive AFM, photoconductive AFM, and correlative microscopy, researchers can directly relate nanoscale functional properties to macroscopic photovoltaic parameters such as open-circuit voltage, short-circuit current, and series resistance. This multimodal approach provides valuable insight into the structural and electrical origins of device performance, guiding the continued development of more efficient thin-film solar cells.

About Dr. Puvaneswaran Chelvanathan

Dr. Puvaneswaran Chelvanathan is a Senior Lecturer and Research Fellow at the Solar Energy Research Institute (SERI) and the Centre for Research Instrumentation and Management (CRIM) at Universiti Kebangsaan Malaysia (UKM). Supported by the Malaysian Public Service scholarship during his early academic path, he completed his entire higher education at UKM, earning a B.Eng. in Microelectronics (2009), an M.Sc. in Electrical, Electronic, and Systems Engineering (2012), and a Ph.D. in Renewable Energy (2016). He embarked on research into thin-film solar cell science and technology in 2008, laying a solid foundation during his doctoral research which focused specifically on developing CZTS solar cells via magnetron sputtering. Following a nearly three-year tenure as a post-doctoral research fellow at SERI, he officially joined SERI as a research fellow to lead the thin film photovoltaic research group.

Today, Dr. Chelvanathan's primary research centers on developing earth-abundant, low-cost, and highly scalable thin-film solar photovoltaic technologies capable of supporting true terawatt-scale energy deployment. As an expert in semiconductor optoelectronics, his technical pursuits bridge macroscopic device architectures with nanoscale functional mapping, making extensive use of multi-modal atomic force microscopy (AFM) and numerical simulations to eliminate performance-limiting defects. His prolific contributions to the field include extensive publication and ongoing investigation into emerging PV materials, such as perovskites, CZTSSe, and CIGS heterostructures, positioning his laboratory as a vital contributor to next-generation green energy solutions.



From left to right: Yoganash, Dr. Puvaneswaran Chelvanathan, Puteri.

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SEEING MORE WITH LESS LIGHT

Vertically Stacked Perovskite Photodetectors Could Transform the Next Generation of Color Cameras

Based on "Vertically stacked monolithic perovskite colour photodetectors" by Sergey Tsarev et al., Nature 642, 592–598 (2025).

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Nearly every digital camera, from smartphones to scientific imaging systems, relies on a technology that has changed surprisingly little over the past two decades. While image sensors have become smaller, faster, and more sensitive, they still depend on tiny color filters placed over individual pixels to distinguish red, green, and blue light. These filters make color photography possible, but they also create one of the greatest inefficiencies in modern imaging by blocking much of the light before it ever reaches the sensor.

Researchers at ETH Zürich and Empa have now demonstrated an entirely different approach that could fundamentally change how cameras capture color. Instead of using passive filters that discard unwanted wavelengths, they developed a vertically stacked photodetector in which each layer naturally absorbs a different portion of the visible spectrum. Built from thin films of lead-halide perovskites, the prototype simultaneously improves light utilization, color fidelity, and spatial resolution while eliminating many of the limitations that have accompanied conventional color sensors for decades.

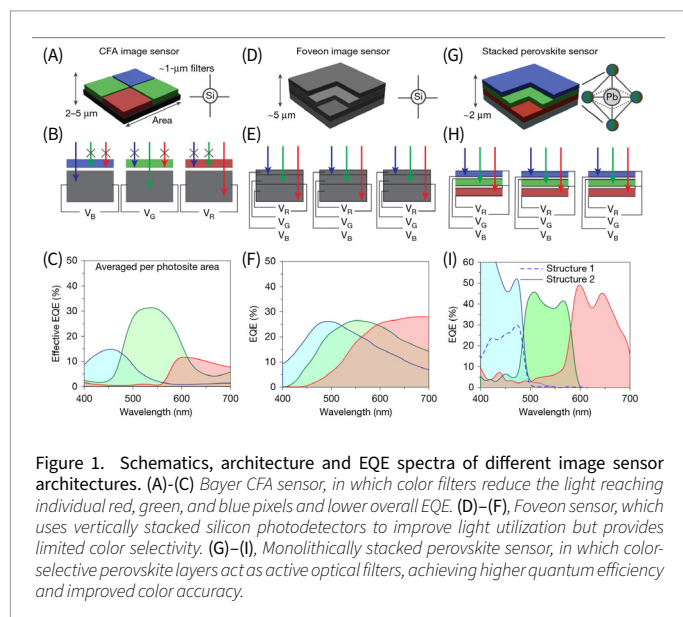


Figure 1. Schematics, architecture and EQE spectra of different image sensor architectures. (A)–(C) Bayer CFA sensor, in which color filters reduce the light reaching individual red, green, and blue pixels and lower overall EQE. (D)–(F) Foveon sensor, which uses vertically stacked silicon photodetectors to improve light utilization but provides limited color selectivity. (G)–(I), Monolithically stacked perovskite sensor, in which color-selective perovskite layers act as active optical filters, achieving higher quantum efficiency and improved color accuracy.

Why Today's Cameras Waste So Much Light

Conventional digital cameras use what is known as a Bayer color filter array (CFA). Each pixel is covered by either a red, green, or blue filter, allowing only that color to reach the underlying silicon detector while absorbing the remaining wavelengths. Every group of four pixels contains two green pixels, one red pixel, and one blue pixel, roughly mimicking the sensitivity of the human eye.

Although this architecture has proven remarkably successful, it comes with unavoidable compromises. Since each filter blocks approximately two-thirds of the incoming light, only a fraction of the available photons actually contribute to the image. The remaining light is simply lost as heat. In addition, because every pixel measures only one color, sophisticated image-processing algorithms must estimate the missing color information from neighboring pixels through a process known as demosaicing. While modern software performs this task impressively well, interpolation inevitably reduces image sharpness and can introduce

artifacts such as false colors and moiré patterns, particularly in scenes containing fine textures.

These limitations become increasingly important in applications where every photon matters, including low-light photography, fluorescence microscopy, astronomy, biomedical imaging, and machine vision.

Learning from Earlier Stacked Sensors

The idea of stacking photodetectors is not entirely new. Sigma's Foveon image sensor attempted to solve many of the shortcomings of Bayer filters by placing three silicon photodiodes vertically within each pixel. Because blue light is absorbed near the surface of silicon while longer wavelengths penetrate deeper, the three layers collect different portions of the visible spectrum without requiring external color filters.

In theory, this allows every pixel to capture full-color information.

In practice, however, silicon is not naturally color selective. Its absorption changes gradually with wavelength, causing substantial overlap between the red, green, and blue channels. This overlap complicates color reconstruction and requires significant computational correction to produce realistic images. Although Foveon sensors eliminate many of the interpolation artifacts associated with Bayer filters, they have never achieved widespread adoption because of these challenges.

Why Perovskites Offer a Better Solution

Lead-halide perovskites have emerged as one of the most exciting classes of semiconductor materials over the past decade. Much of their appeal comes from the fact that their optical properties can be precisely tailored simply by adjusting their chemical composition. By changing the ratio of iodine, bromine, and chlorine within the crystal structure, researchers can tune exactly which wavelengths each material absorbs.

This capability makes perovskites ideally suited for vertically stacked color detectors. Rather than depending on the gradual absorption profile of silicon, each perovskite layer can be engineered to respond primarily to one region of the visible spectrum.

In the new device, the uppermost layer absorbs predominantly blue light, the middle layer detects green wavelengths, and the bottom layer captures red light. Because each layer acts as both an optical filter and a photodetector, incoming photons are converted directly into electrical signals instead of being discarded by passive filters. The result is a far more efficient use of the available light.

Building Three Photodetectors into One Pixel

Transforming this elegant concept into a working device required overcoming several significant fabrication challenges. Depositing one perovskite layer using conventional solution-processing techniques typically dissolves the layer beneath it, making multilayer structures extremely difficult to manufacture.

The research team solved this problem by depositing all perovskite absorber layers using vacuum co-evaporation. This technique produced smooth, pinhole-free films while preserving the integrity of the underlying layers. Each color-sensitive layer was combined with transparent electrodes, charge-transport materials, and dielectric spacers to form three independent photodiodes stacked vertically within a single photosite.

Cross-sectional electron microscopy clearly revealed the highly ordered multilayer architecture, with each functional layer carefully integrated into a structure only a few micrometers thick.

Capturing Nearly Twice as Much Useful Light

One of the most impressive achievements of the new sensor is its ability to utilize incoming light much more efficiently than conventional color cameras.

The researchers measured external quantum efficiencies of approximately **50% for the red channel, 47% for the green channel, and 53% for the blue channel**. When averaged across an entire photosite, the stacked architecture achieved nearly twice the effective light utilization of a conventional Bayer color-filter array because very little of the incoming light is intentionally discarded.

In practical terms, this means more photons contribute directly to image formation. Improved photon efficiency can translate into brighter images, reduced exposure times, lower image noise, and improved performance under dim illumination—all highly desirable characteristics for scientific instruments as well as consumer cameras.

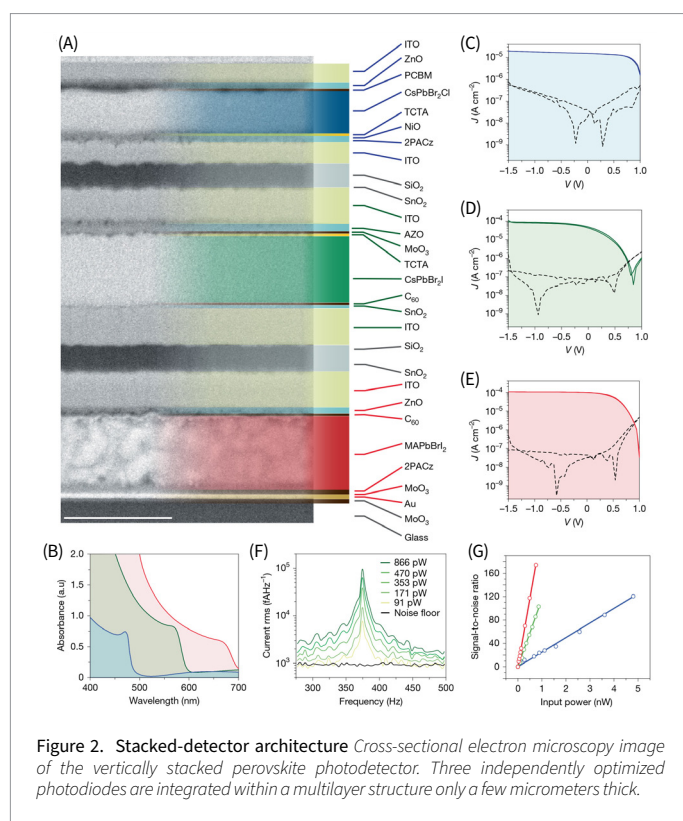


Figure 2. Stacked-detector architecture Cross-sectional electron microscopy image of the vertically stacked perovskite photodetector. Three independently optimized photodiodes are integrated within a multilayer structure only a few micrometers thick.

Reproducing Colors More Faithfully

Capturing more light is only valuable if colors remain accurate. To evaluate this aspect of performance, the researchers used a standard Macbeth ColorChecker, a calibration target widely employed throughout photography and imaging science.

Each colored patch reflects a carefully characterized spectrum of light. By illuminating the chart and recording the responses from each of the stacked detector layers, the researchers reconstructed the colors and compared them with internationally accepted color standards.

After calibration, the sensor achieved a color difference of $\Delta E = 3.8$ in the CIELAB color space, outperforming both conventional Bayer sensors and Foveon-type architectures. More importantly, only modest computational correction was required because the perovskite layers already possess strong intrinsic wavelength selectivity. Unlike silicon-based stacked sensors, where significant overlap exists between color channels, the perovskite device naturally separates red, green, and blue light before any software processing begins.

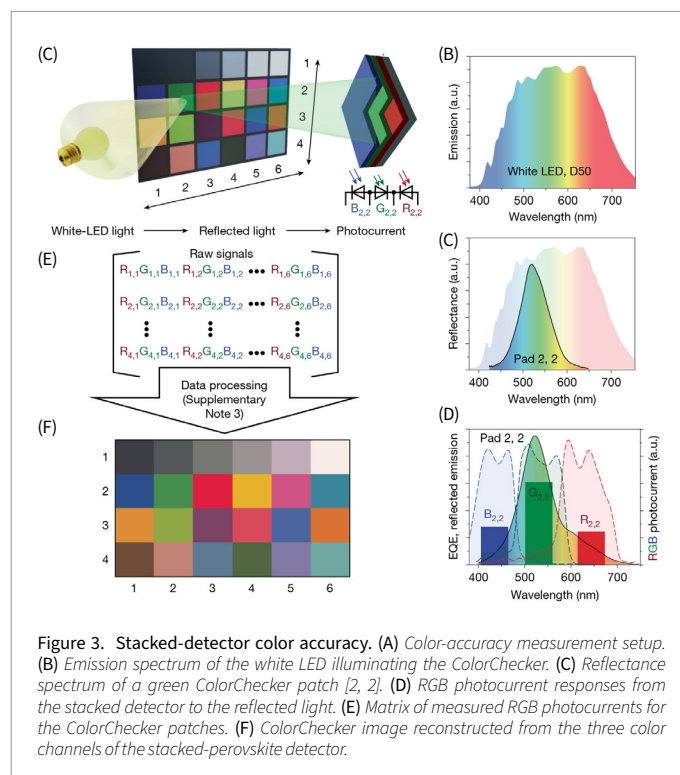


Figure 3. Stacked-detector color accuracy. (A) Color-accuracy measurement setup. (B) Emission spectrum of the white LED illuminating the ColorChecker. (C) Reflectance spectrum of a green ColorChecker patch [2, 2]. (D) RGB photocurrent responses from the stacked detector to the reflected light. (E) Matrix of measured RGB photocurrents for the ColorChecker patches. (F) ColorChecker image reconstructed from the three color channels of the stacked-perovskite detector.

Eliminating the Need for Demosaicing

Perhaps the greatest conceptual advantage of the vertically stacked design is that every pixel independently records complete color information. Since no interpolation is required, the entire demosaicing process disappears.

To demonstrate this benefit, the researchers fabricated prototype detector arrays and compared their imaging performance with simulated Bayer sensors. Images reconstructed using Bayer sampling showed the expected interpolation artifacts and reduced spatial resolution, whereas the stacked detectors produced cleaner images with improved preservation of fine detail.

Although the current prototypes contain relatively small arrays, the experiments clearly demonstrate the fundamental advantage of recording all three color channels at every pixel location.

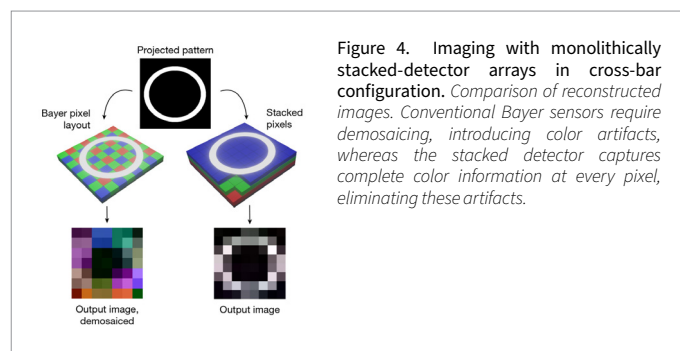


Figure 4. Imaging with monolithically stacked-detector arrays in cross-bar configuration. Comparison of reconstructed images. Conventional Bayer sensors require demosaicing, introducing color artifacts, whereas the stacked detector captures complete color information at every pixel, eliminating these artifacts.

Smaller Cameras with Better Performance

The advantages of perovskites extend beyond image quality alone.

These materials possess exceptionally high optical absorption coefficients, allowing visible light to be absorbed within films only a few hundred nanometers thick. Traditional silicon sensors generally require much thicker absorbing regions to collect the same amount of light.

Such compact detector structures could eventually enable thinner image sensors, shorter optical paths, and simpler lens designs. Smartphone cameras, wearable devices, endoscopes, and compact scientific instruments could all benefit from reduced size while maintaining—or

even improving—image quality.

The vertical architecture also provides additional design flexibility. Because the spacing between detector layers can be engineered, future devices may even compensate for chromatic aberration within the optical system itself, reducing another long-standing source of image degradation.

Beyond Consumer Photography

Although consumer cameras provide the most familiar example, the potential applications of vertically stacked perovskite detectors extend much further.

Modern scientific imaging increasingly depends on extracting the maximum amount of information from extremely limited numbers of photons. Fluorescence microscopy, biomedical diagnostics, astronomy, industrial inspection, robotics, and autonomous vehicles all require sensors capable of distinguishing subtle spectral differences while maintaining high sensitivity.

Perovskites offer an additional advantage because their absorption characteristics can be precisely engineered over a broad wavelength range. Future generations of these detectors could therefore move beyond conventional RGB imaging toward multispectral or hyperspectral cameras capable of distinguishing colors and spectral signatures that are invisible to today's sensors.

Ensuring Quality at the Nanoscale

Surface morphology is an important consideration in the fabrication of vertically stacked optoelectronic devices, where nanoscale roughness and defects can affect interfaces between successive layers. As part of the material characterization, the researchers used a Park Systems NX10 AFM operating in non-contact mode with AC160TS cantilevers to examine the surface morphology of the perovskite films. AFM measurements were performed over $2 \times 2 \mu\text{m}$ scan areas, complementing the optical, electrical, and electron microscopy techniques used to characterize the materials and completed devices.

Looking Ahead

Despite its impressive performance, the technology remains at the research prototype stage. Commercial implementation will require significant advances in multilayer lithography, high-density pixel fabrication, vertical electrical interconnects, long-term environmental stability, and integration with conventional CMOS image sensor electronics. Nevertheless, none of these challenges appears fundamentally prohibitive, and the rapid pace of progress in perovskite optoelectronics suggests that many could be overcome in the coming years.

For decades, digital cameras have accepted the loss of most incoming light as an unavoidable consequence of color imaging. This work challenges that assumption by demonstrating that vertically stacked, color-selective perovskite photodetectors can simultaneously improve photon efficiency, color accuracy, and spatial resolution while eliminating the need for conventional color filters and demosaicing algorithms. The prototype achieved external quantum efficiencies approaching 50% across all three color channels and demonstrated a calibrated color accuracy superior to today's mainstream sensor technologies.

As materials engineering, device fabrication, and sensor integration continue to mature, vertically stacked perovskite photodetectors could represent one of the most significant advances in digital imaging since the introduction of the Bayer color filter itself. From smartphones and scientific instruments to autonomous systems and machine vision, the next generation of cameras may ultimately capture more light, reproduce colors more faithfully, and reveal details that today's image sensors simply cannot see.

Reference

<https://doi.org/10.1038/s41586-025-09062-3>

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About Dr. Teiko Shibata-Seki

After graduating from the Department of Agricultural Chemistry, Faculty of Agriculture at Hokkaido University, Teiko Shibata-Seki joined Mitsubishi Kasei Corporation (now Mitsubishi Chemical). From the early days of SPM technology beginning with STM, she has been engaged in this field for more than 30 years. In particular, she focused on applications to biological materials and explored techniques for “observing” samples in liquid environments, achieving, for example, the world's first AFM observation of liposomes in liquid.

At Veeco (now Bruker Japan), she gained extensive experience as an application engineer measuring a wide variety of samples. After receiving her Ph.D. in Engineering from Tokyo Institute of Technology (now Tokyo Science University), she pursued applications in the field of regenerative medicine. At the Biomaterials Center for Regenerative Medical Engineering, the Foundation for Advancement of International Science, she used AFM in liquid to clarify the time-dependent changes in the Ca-dependent structure of cadherin, a cell adhesion protein. Subsequently, at the National Institute for Materials Science (NIMS), she used FM-AFM to investigate solid–liquid interfacial structures of glycans, which are one of the key factors in cellular differentiation.

Currently, she works at the newly established Research Equipment Center at Tokyo Metropolitan University, where she is responsible for the operation and management of X-ray diffraction instruments, contributing to research support.

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TUNING ELECTRIC FIELD AND VIBRATION FOR AFM-BASED NANOPATTERNING

Mohammad Alshoul, Xincheng Wang, Zimo Wang, and Jia Deng
Binghamton University, NY, USA

Based on "Investigation of Experimental Parameters in the Electric Field and Mechanical Vibration Integrated AFM-Based Nanopatterning on PEDOT," *Manufacturing Letters*, Vol. 41, 2024, pp. 546–557. Adapted under the Creative Commons Attribution 4.0 License.

Atomic force microscopy is best known as a powerful tool for imaging and characterizing surfaces at the nanoscale. However, the ability of an AFM probe to interact directly with a material also makes the technique attractive for nanomanufacturing. By controlling the motion, force, and electrical properties of the probe, AFM systems can be used to create nanoscale structures without the masks and complex processing infrastructure required by many conventional lithography techniques.

Researchers at Binghamton University have investigated an approach that combines an electric field with controlled mechanical vibration to improve AFM-based nanopatterning. Their study focuses on PEDOT:PSS, a conductive polymer widely investigated for applications in organic electronics, sensors, electromagnetic shielding, and optoelectronic devices. Using a systematic design-of-experiments approach, the researchers examined how applied voltage, patterning speed, and vibration trajectory affect the dimensions of nanoscale trenches produced in PEDOT:PSS films.

The results demonstrate that these parameters can be used as complementary controls over feature width and depth. In particular, the trajectory of the mechanical vibration strongly influences both the dimensions of the resulting structures and the range of conditions under which successful nanopatterning can occur.

AFM as a Nanomanufacturing Platform

High-resolution nanofabrication is essential for technologies including microelectromechanical and nanoelectromechanical systems, photonics, sensors, and emerging organic electronic devices. While established lithography methods can create extremely small structures, AFM-based approaches offer several advantages for research and specialized manufacturing. They are maskless, directly programmable, and capable of modifying selected areas of a surface with nanoscale precision.

Mechanical nanomachining can be performed by using an AFM probe as a nanoscale cutting or scratching tool. Introducing vibration into this process can further improve machining performance. Previous research has shown that vibration-assisted nanomachining can reduce machining forces and probe wear while enabling more complex two- and three-dimensional structures.

Electric fields provide another mechanism for controlling nanoscale material modification. When an electrical bias is applied between a conductive AFM probe and a sample, highly localized interactions can occur near the probe apex. Combining this electrical effect with mechanical vibration creates a hybrid nanopatterning process in which multiple parameters can be adjusted to control the resulting structures.

The Binghamton University researchers sought to better understand these interactions by quantitatively examining how electrical voltage and patterning speed behave under different vibration trajectories.

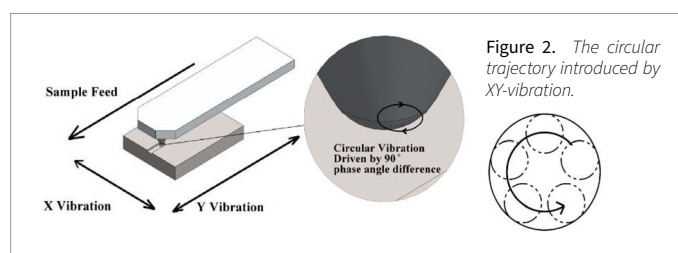
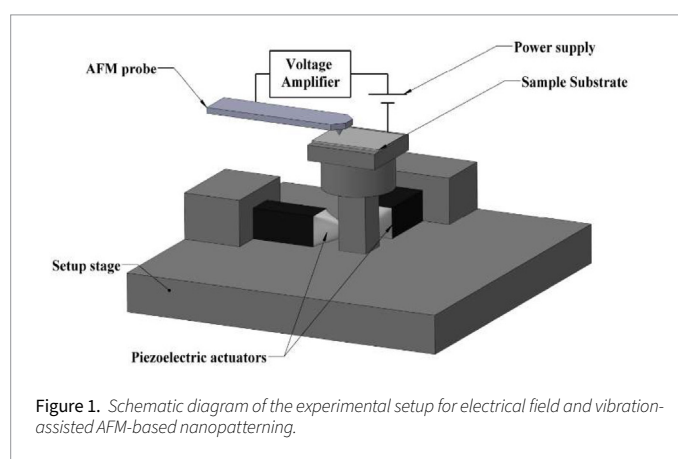
Creating Controlled Vibration Trajectories

The experiments were conducted using a Park Systems XE7 AFM equipped with a low-stiffness conductive contact probe having a nominal tip radius of 35 nm and a spring constant of 0.11 N/m. The probe was connected to a voltage source to establish the electrical potential required for electric-field-assisted lithography.

The researchers also developed a custom nanolithography stage incorporating two piezoelectric actuators oriented along the X and Y axes. By controlling the signals supplied to these actuators, the sample could be subjected to different vibration trajectories during patterning.

Two configurations were investigated. In the first, both X- and Y-axis actuators were driven with sinusoidal signals separated by a 90° phase difference, producing a circular vibration trajectory. In the second configuration, only the Y-axis actuator was used, generating a reciprocating motion.

The vibration frequency was maintained at 2 kHz with an amplitude of 0.2 Vpp, while the normal force was fixed at 2 nN. The researchers then varied two primary processing parameters: the applied voltage and the patterning speed.



The test material consisted of a 65-nm-thick PEDOT:PSS film spin-coated onto a highly doped silicon substrate. Before lithography, the film exhibited an average root-mean-square surface roughness of approximately 0.439 nm, providing a relatively smooth surface for evaluating the resulting nanoscale features.

Using Experimental Design to Identify Key Parameters

Rather than changing one variable at a time, the researchers used design of experiments, or DOE, together with analysis of variance to determine which parameters had statistically significant effects on the fabricated structures.

For circular XY vibration, patterning was performed at speeds of 0.25 and 1.25 $\mu\text{m/s}$ and applied voltages of 0.5, 1.0, and 1.5 V. A separate experiment using Y-axis vibration included an intermediate speed of 0.5 $\mu\text{m/s}$ because the highest speed did not consistently produce patterns at lower voltages.

The resulting structures were evaluated in terms of two key dimensions: trench depth and trench width. This allowed the researchers to distinguish how each process parameter influenced material removal vertically and laterally.

The analysis revealed that voltage, speed, and vibration trajectory do not affect these dimensions equally. Instead, their relative importance changes depending on how the sample is vibrated during patterning.

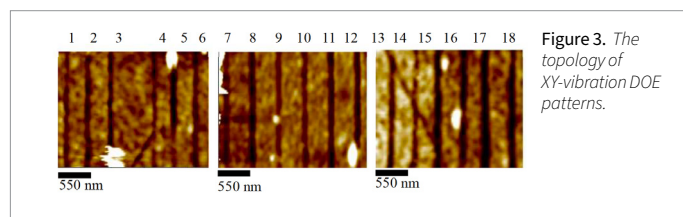


Figure 3. The topology of XY-vibration DOE patterns.

Circular Vibration Expands the Processing Window

Using circular XY vibration, the researchers produced trenches approximately 3.5 to 8 nm deep and 90 to 172 nm wide.

For trench depth, patterning speed produced the strongest statistical effect, followed by voltage and the interaction between voltage and speed. Increasing voltage generally increased the depth of the features, while increasing patterning speed tended to reduce it. This behavior indicates that the time available for the electrically assisted interaction between the probe and material plays an important role in determining how deeply the surface is modified.

Trench width behaved somewhat differently. Voltage was the only parameter identified as having a statistically significant effect on width in the XY-vibration experiment. Higher voltages generally produced wider features, while the effect of speed was less significant.

The circular trajectory also provided an important practical advantage: it enabled successful nanopatterning across a broader range of operating conditions. Combinations of relatively high speed and low voltage that could still produce structures with XY vibration sometimes failed entirely when only Y-axis vibration was used.

The researchers suggest that this difference may arise not only from the additional mechanical motion but also from the way the circular trajectory distributes the electric field along the path of the probe. As a result, circular vibration can enhance material modification and allow pattern formation under conditions that are less effective with reciprocating motion.

Single-Axis Vibration Enables Narrower Features

The Y-axis vibration experiments produced generally smaller features. Measured trench depths ranged from approximately 3.3 to 5.3 nm, while widths ranged from about 55 to 160 nm.

In this configuration, voltage became the dominant factor controlling trench depth. Unlike the XY-vibration results, speed did not show a statistically significant effect on depth over the successfully patterned conditions.

Voltage also had the strongest influence on trench width, although speed contributed significantly as well. Increasing voltage produced wider features, while increasing speed generally reduced their width.

The narrower trenches demonstrate a potential advantage of single-axis vibration when smaller lateral dimensions are required. However, this benefit comes with a more restricted processing window. At the highest tested speed of 1.25 $\mu\text{m/s}$, low and intermediate voltages frequently failed to produce measurable patterns. Successful patterning at this speed generally required a higher applied voltage.

This suggests that vibration trajectory can be selected according to the desired manufacturing objective. Circular XY vibration provides stronger and more robust material modification, while reciprocating Y-axis vibration can be advantageous when narrower and shallower structures are preferred.

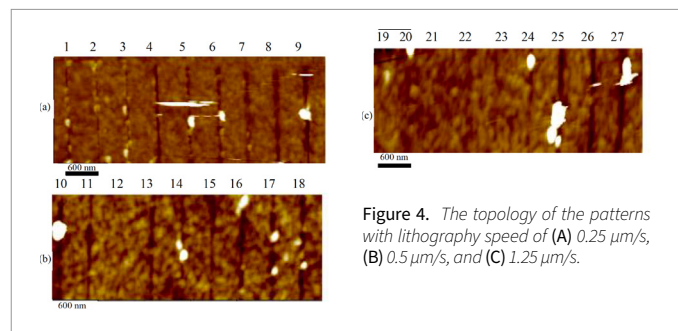


Figure 4. The topology of the patterns with lithography speed of (A) 0.25 $\mu\text{m/s}$, (B) 0.5 $\mu\text{m/s}$, and (C) 1.25 $\mu\text{m/s}$.

Vibration Trajectory Emerges as a Critical Control

To directly compare the two approaches, the researchers combined the experimental datasets and introduced the number of vibration axes as an additional factor in the statistical analysis.

The results showed that vibration axis had the largest statistical effect on both trench depth and width. For depth, the vibration trajectory was followed in importance by voltage and speed. For width, vibration axis again produced the strongest effect, followed by voltage.

This finding highlights an important aspect of vibration-assisted AFM nanomanufacturing: vibration should not be viewed simply as an auxiliary method for reducing machining forces. The geometry of the vibration itself can serve as a fundamental process parameter.

Adding X-axis motion to Y-axis vibration transforms the probe trajectory from reciprocating to circular. This increases lateral interaction with the material and consequently tends to produce wider and deeper structures. At the same time, however, the circular motion improves the ability to generate patterns at higher speeds and lower voltages.

The choice of trajectory therefore introduces a controllable trade-off between feature dimensions and processing capability.

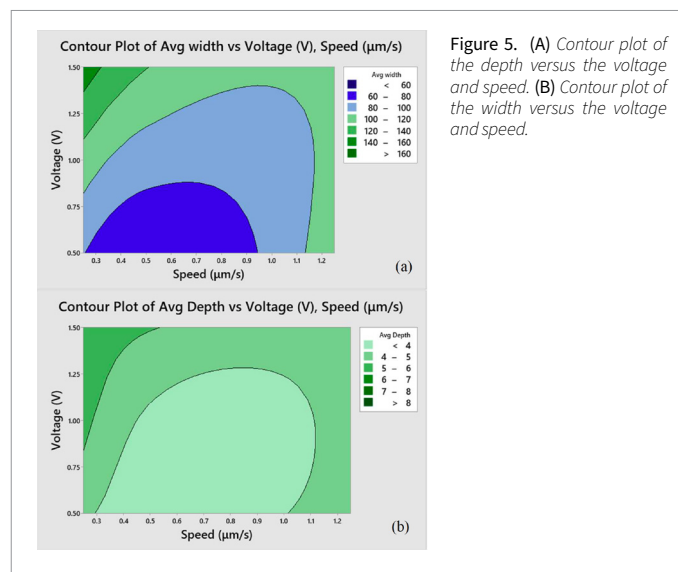


Figure 5. (A) Contour plot of the depth versus the voltage and speed. (B) Contour plot of the width versus the voltage and speed.

Toward More Predictable AFM Nanofabrication

The study demonstrates that combining electric fields with mechanical vibration provides a flexible approach for controlling AFM-based nanopatterning of conductive polymer films. Rather than relying on a single machining parameter, the process can be tuned through the coordinated adjustment of voltage, speed, and vibration trajectory.

For circular XY vibration, voltage primarily controls feature width while speed plays a particularly important role in determining depth. For single-axis Y vibration, voltage becomes the dominant factor for both dimensions. Most significantly, the vibration trajectory itself strongly affects the overall geometry of the resulting structures and determines which combinations of speed and voltage can successfully produce patterns.

These findings provide a clearer framework for selecting AFM nanopatterning conditions according to the desired feature geometry. Applications requiring stronger material modification or a broader operating range may benefit from circular vibration, while single-axis vibration may be better suited to producing narrower and shallower trenches.

More broadly, the work illustrates how AFM can evolve beyond its traditional role as a characterization instrument. By integrating precise probe control with electrical and mechanical excitation, the same fundamental platform used to observe nanoscale surfaces can also be used to manufacture structures on them.

Continued from page 16

The statistical analysis reinforces observations obtained from the three-dimensional visualizations. Rather than forming a perfectly uniform coating, CTAB exhibits significant local variation across the nanocube surface. These findings emphasize the importance of characterization methods capable of probing individual particles and local surface environments.

More broadly, the results demonstrate how correlative AFM–SEM analysis can bridge the gap between molecular-scale surface information and nanoparticle-scale structural characterization. The approach provides quantitative measurements while preserving spatial information regarding ligand distribution and organization.

Conclusions

This study demonstrates a practical correlative microscopy strategy for investigating surfactant adsorption on individual nanocrystals. By combining in situ AFM measurements performed under hydrated conditions with SEM measurements acquired from the same particles, CTAB adsorption on gold nanocubes could be characterized with high spatial precision.

The methodology leverages the complementary strengths of both techniques. The sample-position linkage system between the Park AFM and JEOL SEM platforms enabled reliable acquisition of highly colocalized datasets from identical nanocrystal locations. AFM provides sub-nanometer sensitivity in the vertical direction and enables measurements in liquid environments where ligands remain hydrated. SEM supplies accurate dimensional information and high lateral resolution, allowing the nanocrystal core to be defined precisely. Together, these capabilities enable detailed characterization of nanoscale surface layers that would be difficult to evaluate using either technique alone.

Correlative analysis revealed heterogeneous CTAB coverage across individual nanocubes and among different particles. Statistical evaluation yielded an average CTAB thickness of 2.9 ± 2.4 nm, in good agreement with the theoretical molecular length of CTAB. The observed distribution suggests the coexistence of both monolayer and multilayer adsorption states.

The results highlight the importance of studying ligand behavior under native hydrated conditions. Differences between hydrated and dehydrated environments can influence interpretation of surface structure and ultimately affect understanding of nanoparticle performance. The

As nanomanufacturing increasingly requires flexible methods for prototyping and fabricating functional materials, such hybrid AFM approaches could provide valuable capabilities for organic electronics, MEMS and NEMS, sensors, and other nanoscale devices where precise control of surface geometry is essential.

Reference

<https://doi.org/10.1016/j.mfglet.2024.09.070>

correlative AFM–SEM workflow presented here therefore provides a valuable framework for investigating ligand adsorption, ligand removal, and nanoscale surface interactions in a wide range of nanomaterial systems.

By enabling direct visualization and quantification of surface-bound ligands at the single-particle level, this approach contributes to a deeper understanding of nanocrystal surface chemistry and offers a broadly applicable strategy for future nanomaterials research.

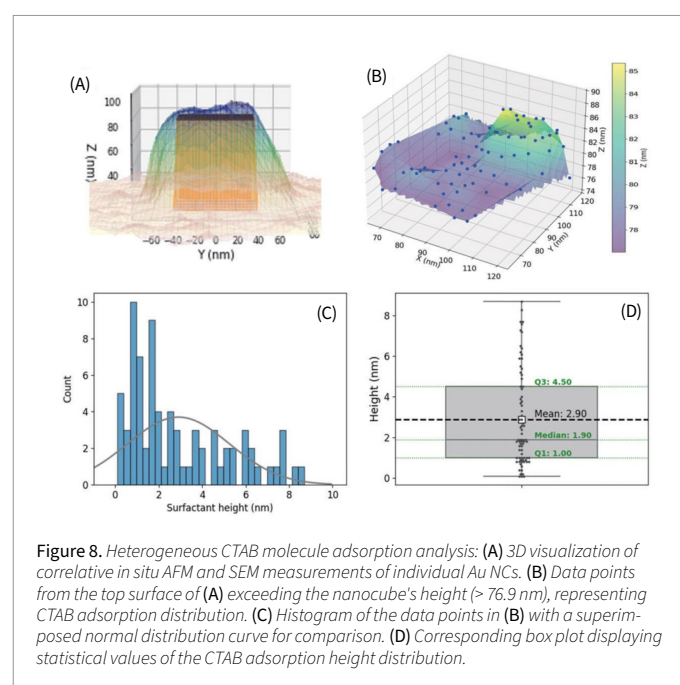


Figure 8. Heterogeneous CTAB molecule adsorption analysis: (A) 3D visualization of correlative in situ AFM and SEM measurements of individual Au NCs. (B) Data points from the top surface of (A) exceeding the nanocube's height (> 76.9 nm), representing CTAB adsorption distribution. (C) Histogram of the data points in (B) with a superimposed normal distribution curve for comparison. (D) Corresponding box plot displaying statistical values of the CTAB adsorption height distribution.

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Park Systems Launches NX1: Bringing Atomic Resolution to Everyday Laboratory Environments

Park Systems has introduced the NX1, a new atomic force microscope (AFM) designed to deliver atomic-resolution imaging under ambient laboratory conditions. Developed in collaboration with Prof. Franz J. Giessibl of the University of Regensburg, the system transforms a research prototype into a commercial instrument, enabling a level of performance that has traditionally required ultra-high vacuum environments.

The NX1 is based on the Orpheus II research platform developed by Prof. Giessibl's group, which demonstrated that true atomic-resolution imaging could be achieved in air. Park Systems refined this concept into a fully engineered commercial instrument, combining the original thermally stable Kovar-based mechanical architecture with the company's expertise in precision manufacturing, automation, and long-term instrument reliability.

One of the NX1's defining characteristics is its exceptionally low mechanical noise floor, supported by a rigid, compact structure and a minimized mechanical loop. These design features help reduce vibration, thermal drift, and environmental disturbances that typically limit atomic-scale imaging under ambient conditions. The result is stable, repeatable measurements capable of resolving atomic lattices without the need for specialized vacuum systems.

Beyond imaging performance, the NX1 emphasizes ease of operation. Automated laser alignment, simplified probe exchange, an on-axis optical microscope, and compatibility with multiple AFM operating modes make the system accessible to a broader range of researchers while maintaining the precision required for advanced nanoscience investigations. Optional support for qPlus sensors further expands its capabilities for specialized applications.

The launch represents an important milestone for atomic force microscopy. By making atomic-resolution imaging practical in standard laboratory environments, the NX1 lowers the barriers to studying surfaces and interfaces at the atomic scale. Researchers working in quantum materials, semiconductors, catalysis, nanomaterials, and surface science can now perform routine atomic-scale characterization with greater convenience and accessibility, opening new opportunities for both fundamental research and advanced materials development.



The Park NX1 Atomic Force Microscope, designed for atomic-scale imaging in ambient conditions.

Park Systems and imec Launch Joint Development Program for Next-Generation Semiconductor Metrology

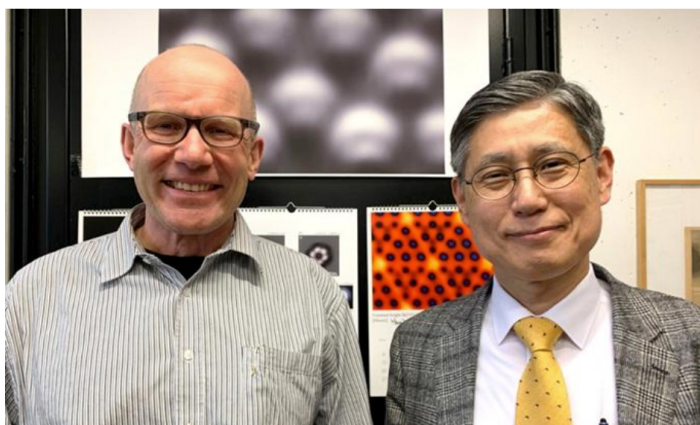
Park Systems has announced a new Joint Development Program (JDP) with imec, one of the world's leading semiconductor research and innovation centers, to develop advanced metrology solutions for next-generation semiconductor manufacturing. The collaboration will focus on the increasingly demanding measurement challenges associated with advanced 3D packaging, heterogeneous integration, and future logic technologies.

As semiconductor devices continue to evolve beyond traditional transistor scaling, advanced packaging technologies—including chiplets, hybrid bonding, and complex three-dimensional architectures—require measurement techniques capable of accurately characterizing features at the nanometer scale. Through the partnership, imec will provide research samples based on its advanced packaging and logic technology roadmaps, enabling Park Systems to evaluate and further develop measurement solutions under realistic process conditions.

Unlike collaborations centered on a single instrument, the program will leverage Park Systems' expanding metrology portfolio. In addition to its industry-leading atomic force microscopy (AFM) systems, the company will evaluate complementary technologies including White Light Interferometry (WLI), Imaging Spectroscopic Ellipsometry (ISE), and Digital Holographic Microscopy (DHM). Together, these techniques provide a more comprehensive characterization workflow for increasingly complex semiconductor structures.

The two-year agreement also includes Park Systems' participation in imec's Industrial Affiliation Program (IIAP) for 3D System Integration, strengthening collaboration with researchers working at the forefront of semiconductor technology development. The partnership reflects the industry's growing recognition that future manufacturing advances will depend not only on new device architectures but also on equally sophisticated measurement capabilities.

For Park Systems, the JDP represents another step in expanding beyond traditional AFM into a broader nanometrology platform. By combining multiple complementary measurement technologies with imec's world-class semiconductor research infrastructure, the collaboration aims to accelerate the development of metrology solutions that can support the next generation of high-performance computing, artificial intelligence, memory, and advanced packaging technologies.



(Left to right) Prof. Franz J. Giessibl (University of Regensburg) and Dr. Sang-il Park (Founder & CEO, Park Systems)

Industry's Leading Automated AFM for In-Line Metrology Solutions



Park NX-Wafer

NX-Wafer is an advanced atomic force microscope designed for seamless integration into semiconductor fabrication environments. Leveraging Park Systems' proven AFM technology, NX-Wafer delivers reliable nanoscale measurement capabilities with full compliance with SEMI standards and complete automation. Widely adopted by major semiconductor manufacturers worldwide, NX-Wafer has established a proven legacy in semiconductor metrology.



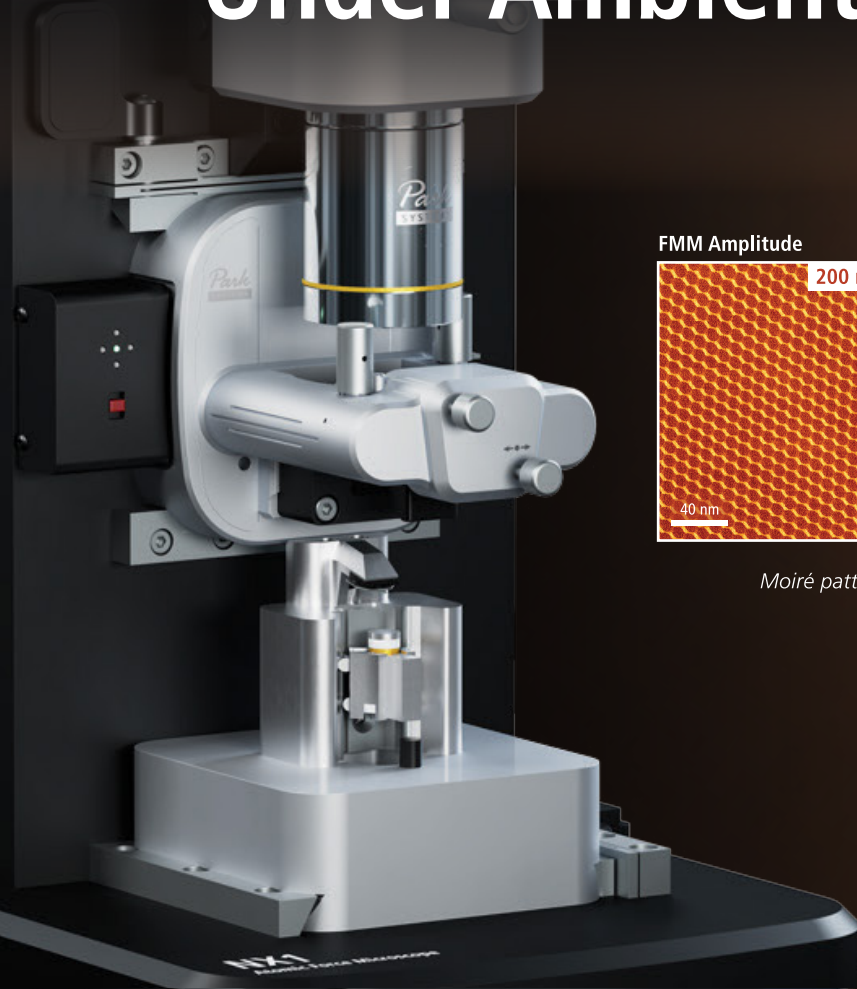
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- Low noise atomic force profiler for more accurate CMP profile measurements
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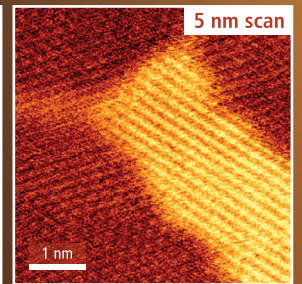
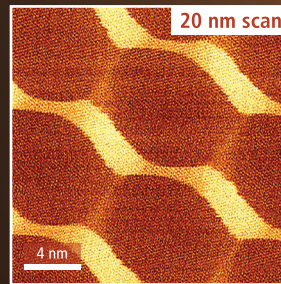
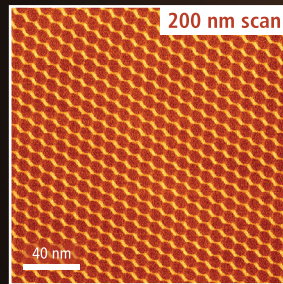
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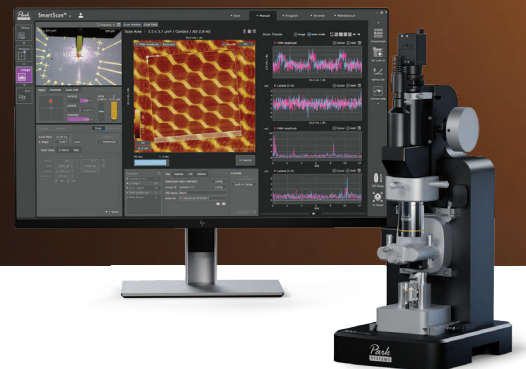
Atomic Resolution AFM. Under Ambient Conditions.



FMM Amplitude



Moiré patterns and atomic lattice resolved in twisted bilayer graphene.



Park NX1

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Resolve atomic lattices, moiré structures, and other nanoscale features across a wide range of advanced research applications, enabling next-generation scientific discovery.

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Easy probe exchange, automatic laser alignment, an on-axis optical microscope, and support for multiple AFM modes and optional qPlus sensors simplify operation while providing the flexibility to support a broad range of current and future research applications.



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