Mapping the invisible

Correlating electric properties on the nanoscale with automated Atomic Force Microscopy

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Fig. 1 The FX200 AFM is shown in its acoustic enclosure next to the workstation.

Atomic Force Microscopy (AFM) enables high-resolution analysis of nanoscale properties essential for next-gen technologies. The Park FX200 automates multimodal AFM workflows – CAFM, KPFM, PFM – allowing correlative measurements of topography, conductivity, work function, and piezoelectricity on identical sample regions. Demonstrations on 2D materials highlight its power to reveal emergent phenomena.

Tomorrow's high-tech innovations are defined by functionality at the nanoscale. Materials used in disruptive technologies such as neuromorphic computing and quantum optics increasingly exhibit functional properties – like conductivity, magnetism, and ferroelectricity – that emerge at the nanoscale. A detailed understanding of how these materials behave in devices requires techniques capable of revealing a range of physical properties, including conductivity, work function, and piezoresponsive effects – all closely tied to local structure. This ongoing trend toward miniaturization demands analytical tools with matching resolution and the flexibility to probe multiple parameters simultaneously.

Atomic Force Microscopy (AFM) has become a cornerstone in this field, offering nanometer-scale resolution and the ability to measure a diverse array of physical properties. The basic principle of AFM relies on a cantilever – an ultrafine, flexible beam equipped with a tip only a few nanometers wide. When forces act on the tip, the cantilever bends proportionally. Tracking these deflections allows to map topography and visualize van der Waals interactions and Pauli repulsion at the atomic scale.

Beyond simple topography, AFM becomes even more powerful when conductive probes and applied voltages are introduced. For example, by scanning the tip in contact with the sample while applying a bias and measuring current through a conductive material, local conductivity can be imaged with high precision. This mode is known as conductive AFM (CAFM) [1].

In Kelvin Probe Force Microscopy (KPFM), a conductive tip oscillates above the sample while an AC bias is applied. The resulting periodic variations in electrostatic interactions reveal local work function differences, which are mapped simultaneously with topography [2, 3].

When an AC bias is applied in contact mode, ferroelectric materials undergo periodic expansion and contraction beneath the tip. Piezo Force Microscopy (PFM) detects local mechanical deformation caused by piezoelectric effects, providing insight into ferroelectric materials and polarization domains [4].

Each of these techniques yields valuable data, but traditional AFMs often require hardware changes – such as probe replacement or the

Fig. 2 In this close-up of the AFM, the AFM head can be seen in the center above a wafer sample. On the left side are the two cantilever cassettes, which can hold up to 16 different cantilevers.

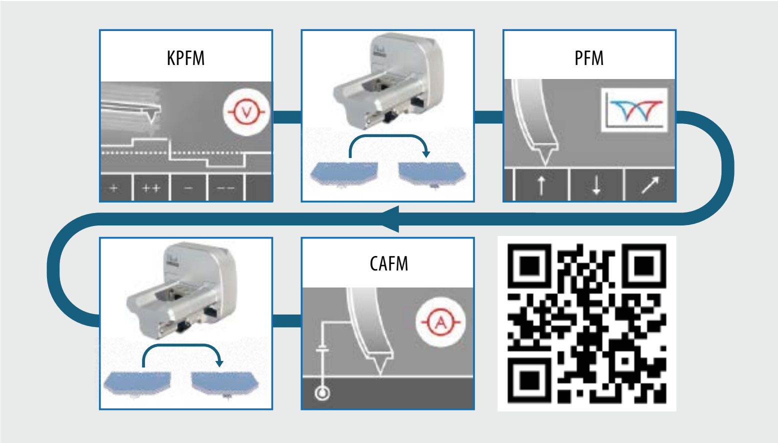

Fig. 3 With this exploratory measurement recipe, a KPFM image is captured and then the cantilever is replaced. After a subsequent PFM measurement and a second tip change, a CAFM image follows. The QR code leads to a video showing the automated tip change of the FX200 and the simple creation of recipes.

integration of external lock-in or current amplifiers – when switching between modes. This process can be tedious, risky for delicate cantilevers, and makes revisiting precise sample locations on the micrometer scale challenging when no clear reference markers are available.

Overcoming barriers

To address the barriers to realizing fully correlative and automated AFM, Park Systems has introduced the FX 200 (**Fig. 1**). The FX 200 represents a new generation of fully automated, large-sample research AFMs designed to help researchers investigate a wide range of functional properties at the nanoscale in a correlative and scalable manner. Its stage accommodates 200 mm wafers or multiple smaller samples, with precise motorized alignment ensuring accurate positioning. The system can switch between up to 16 cantilevers stored in dual cassettes without manual handling (**Fig. 2**), reducing the risk of damage and accelerating image acquisition. An integrated sample overview camera enables recipe-based imaging across multiple locations, allowing seamless transitions between different cantilevers and modes – from basic topography measurements to advanced characterization techniques (see below). This streamlined workflow makes correlative measurements significantly more practical and reliable, even when analyzing multiple physical properties on identical regions of interest.

A compelling demonstration of such correlative capabilities involves 2D materials – stacks of atomically thin layers such as graphene, hexagonal boron nitride (hBN), and transition metal dichalcogenides (e.g., MoS_2, WSe_2). When vertically stacked, these materials can exhibit moiré patterns caused by slight lattice mismatches and rotational offsets between layers. These patterns

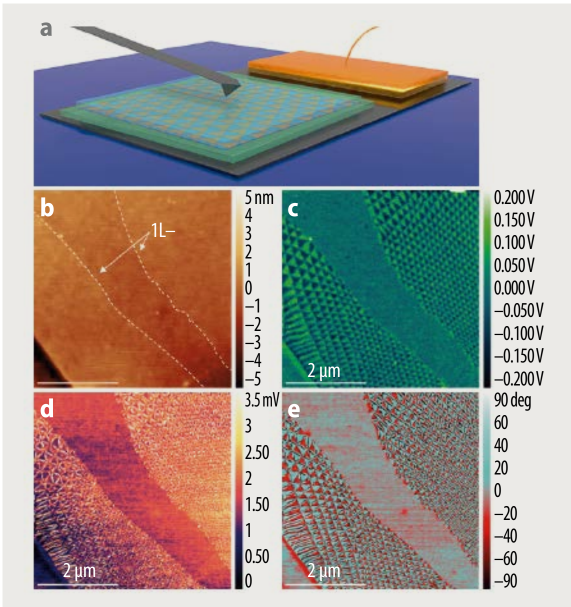

Fig. 4 Exemplary measurements on ferroelectric hBN structures (sample in a): Two hexagonal boron nitride layers are stacked with a slight twist angle and placed on a thin graphene layer atop a silicon wafer, with the graphene contacted via a gold spot. In the topography image (b), the boundaries of an hBN monolayer embedded between two double layers are outlined. The local surface potential (c), recorded using heterodyne KPFM, reveals a triangular moiré pattern on the double layers. The amplitude channel of the PFM image (d), acquired in Dual Frequency Resonance Tracking (DFRT) mode, illustrates the local strength of ferroelectric polarization. Panel (e) shows the corresponding phase image from the DFRT-PFM measurement, with colors indicating domain orientation.

give rise to emergent electronic, optical, and mechanical properties that may pave the way for future sensors, transistors, and memory devices in next-generation electronics.

Using the Park FX200, we conducted KPFM (**Fig. 3**) and PFM measurements on 2D materials, specifically targeting the same region of a ferroelectric superlattice at the interface of two twisted hBN flakes on graphene. The results revealed triangular domains in both the KPFM and PFM images, attributed to different stacking registries of hBN modulated by interlayer angle and local strain. The study employed heterodyne KPFM (HD-KPFM), an advanced technique that enhances both spatial resolution and potential sensitivity compared to the commonly used amplitude-modulated KPFM [5].

Corresponding polarization domains were visible in both the amplitude (magnitude of polarization) and phase (direction of polarization) channels of the PFM images, which were recorded using Dual Frequency Resonance Tracking (DFRT) PFM. This advanced mode significantly improves sensitivity in ferroelectric measurements.

Notably, regions of the vertical structure separated by an additional monolayer hBN step edge showed no moiré pattern, confirming a direct link between stacking order and emergent nanoscale phenomena. The measurements shown in **Fig. 4** were performed using the same cantilever, highlighting the FX200's ability to rapidly switch between modes.

Summary

As device fabrication trends increasingly favor miniaturization and multifunctionality – such as in multiferroic systems – correlating electrical and mechanical properties at the nanoscale becomes essential. AFM-based techniques like CAFM, KPFM, and PFM offer powerful insights, but traditional hardware limitations have often made multimodal, correlative studies difficult.

The Park FX200 overcomes these challenges through full automation, large-sample compatibility, multimode operation, and advanced imaging capabilities such as HD-KPFM. Demonstrations on 2D materials show how the system enables researchers to link topography, work function, and piezoelectric responses on the exact same region with minimal user intervention.

With these advances, the FX200 transforms AFM from a delicate laboratory tool into a robust, automated platform poised to accelerate discoveries in nanoscience and nanotechnology.

[1] *J. Kerfoot* and *V. V. Korolkov*, Moiré imaging with conductive atomic force microscopy, https://tinyurl.com/4edj6ks9

[2] A Comparative Study of KPFM Techniques: Highlighting the Advantages of Heterodyne Detection, https://tinyurl.com/mrysw6wv

[3] *J. P. Pineda* et al., Electrical Characterization of Semiconductor Device Using SCM and KPFM Imaging, https://tinyurl.com/2jetfk9t

[4] *J. Kim* and *C. Jung*, Dual Frequency Resonance Tracking-Piezoresponse Force Microscopy, https://tinyurl.com/45p924dd

[5] *A. Axt* et al., Beilstein J. Nanotechnol. **9**, 1809 (2018)

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