Tech Note

Benchmarking Lateral Resolution in Dry Cryostats

Performance of attoAFM I in low- and ultra-low-vibration cryostats

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Abstract

Lateral resolution is a crucial aspect for experimentalists performing atomic force microscopy (AFM) techniques, particularly when characterizing novel materials at the nanoscale. The ability to resolve finer details is essential not only for understanding the fundamental properties of these materials but also for fostering the development of new materials with desired features. A significant challenge in achieving high lateral resolution in closed cycle (a.k.a. dry) cryostats are vibrations caused by the pulse tube. In this Note, we compare the vibrational performance of two attocube cryostats: the low-vibration attoDRY2100 and the ultra-low-vibration attoDRY2200. Topographic AFM measurements show that particles with a nominal diameter of 30 nm appear as (48 ± 5) nm in the attoDRY2100, while they appear as (30 ± 2) nm in the attoDRY2200. This apparent increase in size in the former case can be attributed to vibrations from the cryostat, whereas in the latter case the vibrations have negligible impact. Additionally, we compare the performance of the attoDRY2200 with a conventional liquid cryostat, showing the superior vibration isolation of the former cryostat by achieving a remarkable lateral resolution of ~7.5 nm.

1. Low-vibration and ultra-low-vibration cryostat

The attocube attoDRY series of closed-cycle cryostats, in particular the *attoDRY2100* and the *attoDRY2200*, provide cryogen-free solutions for low-temperature research, addressing the longstanding challenges of stability and precision in ultra-sensitive measurements. These systems eliminate the reliance on liquid helium, offering substantial advantages in operational efficiency, stability, and performance. Moreover, they represent a significant leap forward in cryogenic technology through enabling vibration levels low enough for ultra-sensitive nanoscale measurements while retaining the convenience of a closed-cycle system.

Investigating samples under variable temperatures and magnetic fields is a fundamental task in physics and materials science. The *attoDRY2100*, a versatile closed-cycle cryostat, is designed to meet these demands across a wide range of cryogenic applications, including quantum optics and magneto-optical research. Operating within a temperature range from 1.8 K to 300 K with exceptional stability, it supports magnetic fields up to ±9 T, with upgrade options to 12 T or 3D vector magnets. Its low-vibration design and 49.7 mm probe bore enable compatibility with diverse experimental setups. With efficient cooling performance, the system achieves initial cooldown times of 15 - 20 hours (up to 24 hours with a 9 T magnet) and allows for turnaround times for sample/tip exchanges within 3 - 5 hours. Fully automated control via a touchscreen, web interface, LabVIEW, or API integration ensures precise and user-friendly operation, making the *attoDRY2100* an indispensable tool for cutting-edge research.

Fig 1: The attoAFM I microscope as a common insert for both attoDRY2100 (left) and attoDRY2200 (right) cryostats.

For applications demanding an even higher level of vibration stability and precision, the *attoDRY2200* sets a new benchmark for closed-cycle cryostats. With its ultra-low vibration performance enabled by advanced damping technology, the system is designed to support nanoscale imaging and advanced quantum applications, including cutting-edge research in quantum sensing, 2D magnets, and skyrmions. Furthermore, the *attoDRY2200* combines its exceptional vibration stability with fully automated temperature and magnetic field control. Its advanced vibration isolation system efficiently decouples mechanical vibrations coming from the pulse-tube cold head, thereby ensuring exceptional stability for the microscope.

The *attoDRY2200* features a top-loading probe design with a 49.7 mm diameter probe bore. Its wide temperature range from 1.8 K to 300 K, combined with a precise magnetic field featuring various superconducting vector magnets, creates the ideal environment for studying complex materials and quantum systems. Intuitive control options, such as a touchscreen interface and versatile APIs for programmable temperature and magnetic field sweeps, enable researchers to execute complex measurement protocols with ease and precision.

A key advantage of these dry cryostats is the consistent performance of their vibration damping across the entire temperature range. Unlike traditional liquid cryostats, where vibrations typically increase at elevated temperatures due to the boiling of cryogens, the attoDRY systems maintain ultra-low vibration levels at both base and elevated temperatures. This makes them especially valuable in providing a stable environment for sensitive measurements. This consistency makes them particularly suitable for nanoscale correlative experiments and other applications where precise and stable conditions are required.

These advancements in cryostat technology enable various AFM applications, as exemplified in the following sections.

2. Lateral and vertical resolution in dry cryostats

High-resolution AFM imaging at cryogenic temperatures is crucial for studying nanoscale structures. However, achieving superior lateral resolution can be challenging, due to the vibrations induced by the cryostat and transmitted to the scanning microscope. This study compares the vibration characteristics of the *attoDRY2100* and the *attoDRY2200* cryostats and evaluates their effect on AFM lateral resolution and imaging capability.

AFM measurements were carried out using the *attoAFM I* microscope to evaluate the lateral resolution achieved in both cryostats. The microscope is equipped with fiber-based interferometric sensing for detection of the deflection of the cantilever induced by the tip-sample interaction. It also features a closed-loop scanning functionality, which provides real-time feedback of the x and y positions during imaging. This optical readout ensures accurate sample navigation by compensating for nonlinearities in the piezoelectric scanners, thereby reducing imaging distortions and ensuring accurate scan trajectories.

A gold-nanoparticles sample was used for AFM imaging. Particles with a 30 nm diameter (with size variation of ±2 nm) were chosen to be significantly larger than the tip radius of ~2 nm (*SSS-NCL* probe from *Nanosensors*) to exclude the possible effect of tip convolution. Tip convolution is an inherent limitation in AFM, arising from the finite size of the tip apex, which can distort the measured features, particularly those with sizes comparable to or smaller than the tip radius. Moreover, we employed tapping mode AFM, which minimizes lateral forces in tip-sample interactions, to further mitigate tip convolution effects and ensuring accurate dimensions in measurements.

The nanoparticles imaged in the *attoDRY2100* exhibit a diameter of ~48.0 (± 4.5) nm, with blurred edges (Figure 2a-b). In contrast, the *attoDRY2200* delivers much finer resolution, as the measured nanoparticles have the diameter of 30.19 (± 1.75) nm, with sharper edges (Figure 2c-d). The observed difference in measured diameters can be attributed to the superior vibration isolation and stability of the *attoDRY2200*. Furthermore, these results are in good agreement with the achievable inherent limit (pertaining to an infinitesimal probe size) of lateral resolution — 15 nm in *attoDRY2100* and 1 nm in *attoDRY2200* — for the *attoAFM I* microscope.

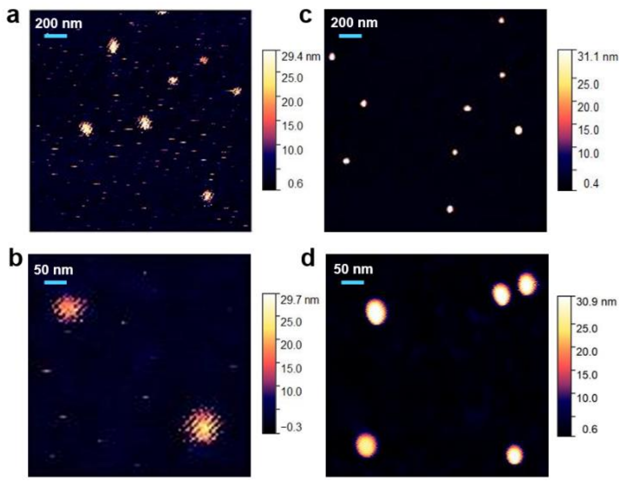

Fig 2: Tapping mode AFM images of gold nanoparticles with the nominal diameter of 30 nm, measured in attoDRY2100 (a-b) and attoDRY2200 (c-d).

We also measured the vertical (z) noise, which affects the stability of the tip-sample interaction, in both cryostats while keeping the tip in contact with the sample surface. The *attoDRY2100* exhibited z-noise levels of 130 pm rms, while the *attoDRY2200* demonstrated significantly lower z-noise of 77 pm rms (bandwidth of 195 Hz in both cases).

These results highlight the *attoDRY2200*'s superior performance, making it an ideal choice for ultra-sensitive SPM imaging, particularly for applications requiring nanoscale precision.

3. Comparison of ultra-low-vibration dry cryostat with liquid cryostat

Building on the comparison between the *attoDRY2100* and the *attoDRY2200*, it is equally important to assess how the latter compares to traditional liquid cryostats, which have long been considered the gold standard for ultra-sensitive SPM measurements, offering low-temperature environments with minimal vibrational noise. However, the emergence of closed-cycle cryostats, particularly the *attoDRY2200*, has redefined the landscape of vibration isolation and lateral resolution, challenging the supremacy of liquid cryostats even for the most sensitive SPM measurements.

To benchmark the performance of the *attoDRY2200*, conductive-tip AFM (*ct-AFM*) measurements were conducted on twisted bilayer graphene (*tBLG*), a sample known for its unique structural properties. The *tBLG* sample consists of two graphene sheets twisted by an angle of 0.8°, resulting in a moiré superlattice with a periodicity of 18 nm. The *ct-AFM* imaging clearly resolves the moiré pattern, demonstrating lateral resolution of at least 9 nm with the *attoDRY2200*. Figure 3a shows the *ct-AFM* image obtained with the *attoDRY2200*, along with a line profile above the image corresponding to a line cut through the moiré pattern, which confirms the 18 nm periodicity.

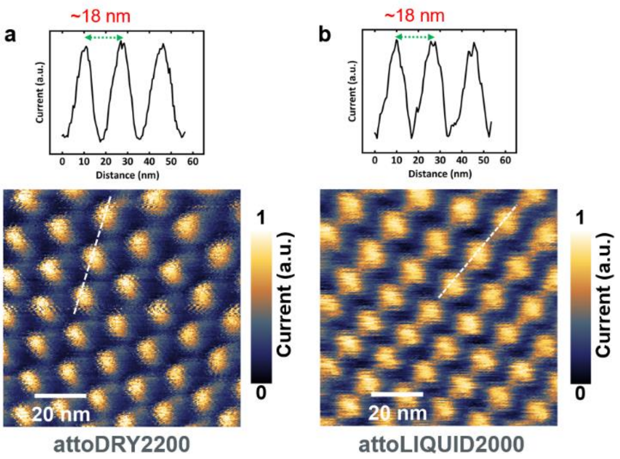

Fig 3: ct-AFM imaging of twisted bilayer graphene obtained with the dry attoDRY2200 cryostat (a) and the liquid attoLIQUID2000 cryostat (b). Line profiles above each image, corresponding to the cuts along the moiré lattice, illustrate the moiré periodicity.

To further validate the performance of *attoDRY2200*, a direct comparison was conducted with a liquid cryostat system. The results, shown in Figure 3b, from the liquid system show noticeably higher levels of noise, with the *ct-AFM* image of the *tBLG* exhibiting more significant vibrations influence. This stark contrast underscores the superior damping capabilities of the *attoDRY2200* in minimizing vibrations, hence enabling high-resolution imaging.

Quantitative analysis of the lateral vibration data from both the dry and liquid cryostats further confirms the superior performance of the *attoDRY2200* in terms of vibration isolation, as shown in Figure 4.

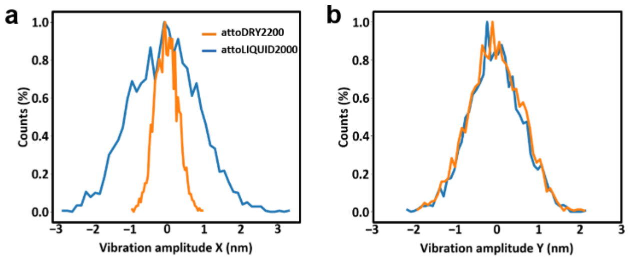

Fig 4: Lateral vibrations for the (a) x and (b) y axis measured in the dry attoDRY2200 and liquid attoLIQUID2000 cryostat.

Additionally, to demonstrate the robustness and lateral stability of the *attoDAFMRY2200*, another *ct-AFM* measurement was carried out at an elevated temperature of 70 K on monolayer graphene on hBN. The resulting *ct-AFM* images (Figure 4) reveal a well-defined moiré pattern with a superlattice constant of 15 nm and a lateral resolution of at least 7.5 nm. This underscores the cryostat's ability to maintain outstanding stability and high resolution, even under varying temperature conditions.

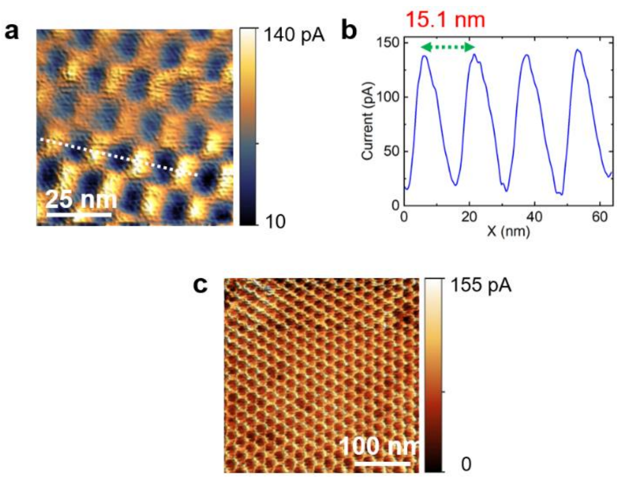

Fig 4: ct-AFM imaging of moiré superlattice in monolayer graphene on hBN. (a,c): ct-AFM image of the moiré pattern, showing detailed features of the periodic structure. (b): Line profile of the current signal corresponding to the dashed line shown in (a).

4. Conclusion

This study compares the vibration characteristics of the *attoDRY2100* and the *attoDRY2200* cryostats and evaluates their effect on AFM lateral resolution and imaging capability. We demonstrate the exceptional ability of *attoDRY2200* to achieve ultra-low noise levels and high-resolution imaging across a wide temperature range. These capabilities enable advanced research of nanoelectrical and nanomagnetic properties, where resolving intricate atomic-scale features is essential. By not only matching, but even slightly surpassing the performance of liquid cryostats, the *attoDRY2200* sets a new benchmark for ultra-sensitive SPM measurements under variable temperature and high magnetic field conditions.

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