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ASYLUM RESEARCH

Application Note

The Vero Interferometric AFM - Advances in Precision

Introduction

Interferometric Atomic Force Microscopy (AFM) detectors represent a paradigm shift in AFM design, with significant improvements in accuracy and precision. Building on the success of the Cypher IDS,[1] the Vero is the only commercial AFM to use a patented[2] Quadrature Phase Differential Interferometry (QPDI) detector,[3,4] with the vast majority of existing AFMs using detection systems based on optical beam deflection (OBD).[5,6]

This note focuses on Vero's improvement in precision over OBD-based AFMs. The benefits of Vero for improved accuracy are discussed in a separate application note.[7]

What is Precision?

Accuracy and precision are often used interchangeably but have quite different meanings in the context of scientific measurements. Accuracy is a measure of systematic error and describes how close the observed values are to the true value. Precision is a measure of random error and describes how close the observed values are to each other.

High precision is one of the hallmarks of quality for scientific instrumentation. As a measure of random errors introduced by the measurement itself, precision is therefore indicative of an AFM's ultimate measurement resolution.

Vero's QPDI Design Lowers the Noise Floor

The term “noise” can most simply be defined as unwanted signal. It was first used in this context in the early 20th century to describe the audible “static” heard in the nascent field of AM radio transmission. Similarly, “noise floor” was used to describe the threshold below which softer sounds could not be discerned. These same concepts transfer by analogy to AFM where the noise floor dictates the smallest signals that can be resolved and therefore sets the limits of measurement resolution.

One way to visualize the noise floor for a given cantilever and AFM, is to plot the cantilever’s thermal motion as a function of frequency. Figure 1 compares the OBD and QPDI thermal noise spectra for a conventional tapping mode probe showing the cantilever’s resonance at ~60 kHz and a very large difference in their respective noise floors. The Vero QPDI-based AFM typically exhibits over 10X lower noise compared to OBD-based AFMs, with a detector noise floor of <10 fm/rtHz. Indeed, in this particular example, the QPDI noise floor is 20X lower than the OBD noise floor for sub-resonant frequencies.

While OBD-based AFMs can theoretically reach the same noise floor as QPDI-based AFMs,[8] in practice this is not achievable even for the highest performing OBD-based systems. One reason is that the noise performance of OBD-based AFMs is only optimized when the laser spot size is very closely matched to the cantilever. However, even in this optimal case, the OBD detector noise floor for a high-performance AFM is still ~2.5X higher compared to the performance of the QPDI-based Vero AFM. For many typical cantilevers this OBD noise floor can be more than 20X higher.

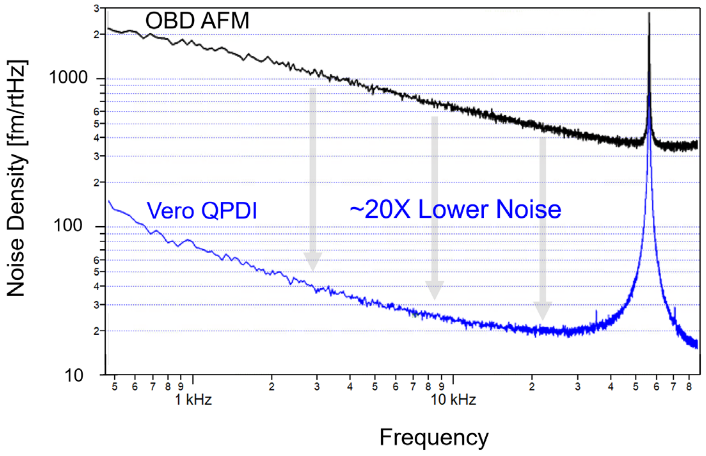
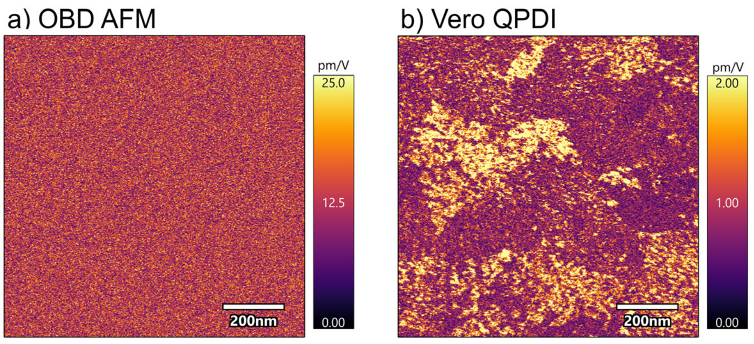


Figure 1: The thermal noise plot of an Adama Innovations AD-2.8-AS cantilever taken with the QPDI-based Vero AFM (blue) shows a noise floor that is 20X lower compared to the noise floor of the same cantilever taken with an OBD-based AFM (black).

Resolving Low-Response Piezoelectrics

The improved precision of Vero over OBD-based AFMs is advantageous in applications where the signal of interest is small relative to the noise floor. Piezoresponse force microscopy (PFM) of low-response materials is a good example of such a measurement. In this mode, an electric field is applied across the sample through a conductive cantilever and any resulting strain is measured. Low-response materials have relatively small piezoelectric coupling coefficients, meaning they have a relatively small mechanical strain for a given applied electric field. These low-response samples can have signals that are comparable to, or even below the detection noise floor.

Hafnium oxide, also known as hafnia, is an example of a low-response piezoelectric material and has garnered considerable interest in recent years as a high k dielectric and as a promising material for ferroelectric memory applications. Figure 2 shows images of the calculated piezoelectric coupling coefficient, evaluated by taking the PFM Amplitude response and dividing by the applied electrical bias. These two images were taken in single frequency PFM mode at the same sample location with the same cantilever and scan settings. The only difference between the measurements was the detector type. The data in Figure 2a was acquired using an OBD-based AFM. With hafnia being a low-response material, the PFM amplitude response signal is completely below the OBD noise floor and therefore not visible at all. This image is essentially a measure of the noise floor of the OBD detector. In comparison, the data in Figure 2b was acquired with the QPDI-based Vero AFM and the signal contrast is clearly visible because the noise floor is now more than an order of magnitude lower by comparison.


a) OBD AFM

b) Vero QPDI

Figure 2: Images of the effective piezoelectric coupling coefficient for hafnia taken with the same scan settings and calculated by dividing the piezoresponse amplitude data by the applied bias. As a low-response material, the resulting piezoresponse of hafnia is obscured by the higher noise floor of the OBD AFM but is clearly visible with Vero because of the QPDI-based Vero AFM's lower noise floor. Sample courtesy of NaMLab, Germany.

Prior to the advent of Vero with QPDI detection, the only way to image these low-response materials was to amplify the signal. One way this can be done is by using high voltage. For a sample with a given piezoelectric coupling coefficient, the larger the voltage applied across the sample, the larger the mechanical response signal relative to the noise floor. However, for some samples with either a low dielectric breakdown, or a low coercive bias, or both, as is the case with hafnia, a high-voltage bias is not an option. Another approach is to amplify the signal by operating on the cantilever's resonance. While both methods can be effective at amplifying the signal, they are also both subject to systematic errors that lower measurement accuracy. These measurement artifacts and errors result from tip-sample electrostatics, friction, and in-plane forces, as discussed in a separate application note.[7]

Height Moiré Of Twisted Bilayer Graphene

Vero's ultra-low noise performance, particularly at low frequencies, is enabled in part by the QPDI detector design.[3] Interferometry measures the interference between a reference beam positioned on a stationary surface, and a measurement beam positioned on a moving surface of interest. Since QPDI detection is a differential measurement, any "common mode" noise affecting both beams is subtracted out. Therefore, these two beams benefit from being positioned close together such that the two paths are as similar as possible. In the Vero QPDI design, the measurement beam is positioned on the cantilever while the reference beam is positioned less than 1 mm away on the cantilever chip. This enables the measurement to be largely insensitive to low-frequency vibrations and thermal drift between system components.

The benefits of the QPDI-based Vero AFM's low noise floor at DC can be demonstrated by imaging samples with very small height differences in contact mode. One particularly relevant application is imaging the moiré structure of a twisted 2D material. The moiré periodicity of a twisted 2D material can be used to determine the twist angle between layers, which can be important for tuning electrical properties. Twisted bilayer graphene, for example, exhibits superconductivity[9] when twisted at the magic angle of 1.1˚. Figure 3 shows two height images of twisted bilayer graphene acquired in contact mode at the same location, with the same cantilever, and using the same scan settings. Figure 3a was taken with an OBD-based AFM and Figure 3b with the QPDI-based Vero AFM. The moiré pattern can clearly be seen in the height image of the contact mode scan using Vero, however, this signal is buried below the noise floor in the OBD-based AFM data.

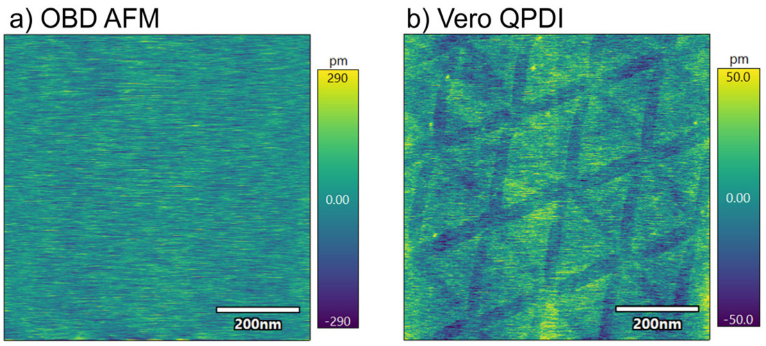


Figure 3: Contact mode height images of twisted bilayer graphene acquired with (a) an OBD-based AFM and (b) the Vero QPDI-based AFM using the same probe under identical scan conditions. The moiré pattern is clearly resolved with the QPDI-based system but is below the noise floor of the OBD AFM. Sample courtesy of Professor Lu You at Soochow University.

Conclusion

The Vero QPDI-based AFM noise floor is significantly lower than that of conventional OBD-based AFMs, resulting in higher instrument precision and resolution. Because of its unique interferometric design, the noise floor of the QPDI-based detector is no longer dependent on the size of the laser spot relative to the cantilever, as it is with OBD-based AFMs, and low-noise measurements can now easily be achieved with any cantilever. This improvement in noise performance is particularly significant for off-resonance and DC techniques, such as single frequency PFM and contact mode, as the examples in this note demonstrate. With superior measurement precision beyond the capabilities of even the best OBD-based AFMs, the Vero interferometric AFM is the next step in AFM design evolution.

References

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