The NanomechPro™ Toolkit: Nanomechanical AFM Techniques for Diverse Materials

Nanoscale mechanical properties are a key consideration in many applications. Oxford Instruments Asylum Research offers a variety of complementary AFM techniques in our **NanomechPro**™ **Toolkit** that let you measure everything from cells to ceramics. This collection can accurately evaluate a wide range of nanomechanical behavior including viscoelastic properties, adhesive forces, and hardness. The multiple techniques offer greater flexibility for different applications and allow deeper insight through comparison of results.

Introduction

Nanoscale mechanical properties impact the behavior and performance of countless materials and help inform both our theoretical understanding of these materials and their development for commercial applications. Examples can be found in many disciplines, for instance in materials science, where elastic modulus affects the reliability of nanoporous dielectric films in semiconductor devices, and in biology, where relations have been observed between viscoelastic damping and the metastatic potential of cancer cells. As we continue to learn more about the critical role of nanomechanics, our need for techniques that more fully measure nanoscale mechanical properties grows in importance. The atomic force microscope (AFM) has powerful capabilities for nanomechanical characterization due to its inherent spatial resolution and force sensitivity. However, the sheer diversity of materials' properties prevents any single AFM technique from providing the most relevant or accurate data for every application. The NanomechPro Toolkit was developed to address this issue. It contains a collection of AFM techniques that meet a broad spectrum of nanomechanical characterization needs (Table 1).

	Techniques in the NanomechPro Toolkit	Elastic Modulus Range	Loss Modulus / Loss Tangent	Acquisition time (256×256 image)	Advantages	Disadvantages
QUASISTATIC MODES	**Force Curves / Force Volume Mapping**	●●●●●●●○○ 1 kPa – 1 GPa	No	~3 hr (6 Hz ramp rate)	Many indentation models supported, including Hertz / Sneddon, Derjaguin-Müller-Toporov (DMT), Johnson-Kendall-Roberts (JKR), Oliver-Pharr	Impractically slow at higher pixel density
	Fast Force Mapping	○●●●●●●●● 10 kPa – 100 GPa	No	~9 min (300 Hz ramp rate) (1 kHz for Cypher)		Slower than dynamic modes
	Force Modulation Imaging	○○○●●●●○○ 1 MPa – 1 GPa	Dissipation, but not directly *tan δ*	~4 min (1 Hz line rate)	Can measure response at fixed frequencies over a wide range	Currently only qualitative analysis in Asylum software
DYNAMIC MODES	**Bimodal Dual AC Imaging**	●●●●●●●●● 1 kPa – 100 GPa	No	~10 s (20 Hz line rate using small cantilevers)	Rapid and simple. Can provide enhanced contrast and resolution vs. phase imaging	Only qualitative contrast. Can be difficult to interpret.
	Phase Imaging	●●●●●●●●● 1 kPa – 100 GPa	No	~10 s (20 Hz line rate using small cantilevers)	Rapid and simple	
	Loss Tangent Imaging	●●●●●●●●● 1 kPa – 100 GPa	Yes	~10 s (20 Hz line rate using small cantilevers)	Rapid and simple. Quantifies loss tangent, simplifying interpretation of phase data	Quantifies only loss tangent when used without full AM-FM Mode
	AM-FM	○○●●●●●●● 100 kPa – 100+ GPa	Yes	~10 s (20 Hz line rate using small cantilevers)	Rapid and simple. Measures both *E′* and *tan δ*	Currently only supports Hertzian contact mechanics
	Contact Resonance	○○○○○○●●● 1 GPa – 100+ GPa	Yes	~4 min (1 Hz line rate)	Measures both *E′* and *E″*	Currently only supports Hertzian contact mechanics

Table 1: Comparison of techniques as implemented by Asylum Research in the NanomechPro Toolkit. The approximate elastic modulus range of applicability is shown for each mode, where the dots represent orders of magnitude in storage modulus E′ from 1 kPa to 100 GPa. Image acquisition times are given for readily achievable scan or ramp rates and assume the use of small cantilevers for techniques based on tapping mode. Actual speeds may be faster or slower depending on many factors. Note that AM-FM and Contact Resonance modes are the only techniques listed that can quantitatively measure both the elastic response (E′) and viscous response (loss modulus, E″ or loss tangent, tan δ).

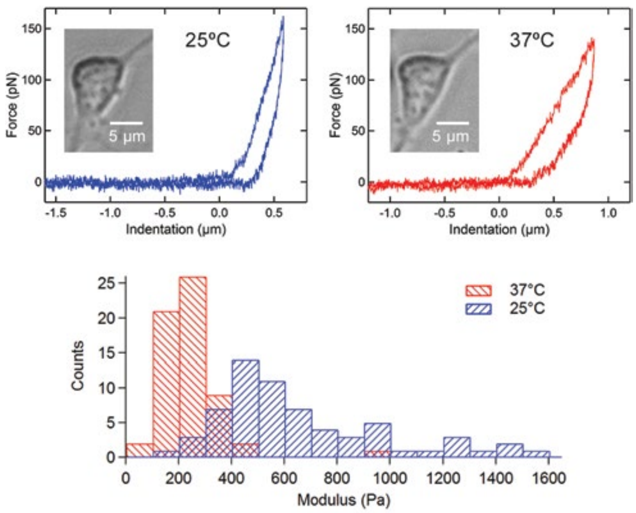

Figure 1: Force mapping experiments on chemically unmodified, live cortical neuronal cells to investigate the variation of elasticity with temperature. (top) Example force curve of a cell at 25°C (left) and 37°C (right). The inset images show optical micrographs of the cell. (bottom) Histograms of cell elastic modulus obtained from 16 µm × 16 µm force maps. Significant differences in modulus are observed from 25°C (blue) to 37°C (red). Experiments performed in liquid on the MFP-3D AFM with the BioHeater temperature stage. Adapted from Ref. 2.

Techniques in the NanomechPro Toolkit measure a range of mechanical quantities including elastic properties (e.g., contact stiffness, Young's modulus, storage modulus E'), viscous properties (e.g., contact damping, loss modulus E'', loss tangent $\tan\delta$), adhesive and van der Waals forces, and hardness. Techniques range from simple qualitative tools to more sophisticated quantitative methods so that you can choose the best approach for a given application. Results from different techniques on the same sample provide complementary information for enhanced accuracy and cross-checking. As Table 1 on the previous page shows, methods in the NanomechPro Toolkit are applicable to virtually any material: everything from compliant cells and gels with modulus of only a few kPa to stiff metals and ceramics of hundreds of GPa. Many techniques can also operate with small cantilevers, enabling accurate measurements at higher speed and lower noise.

Here we discuss several key techniques in the NanomechPro Toolkit available on both the Cypher and MFP-3D family AFMs. Techniques are considered either quasistatic (near-DC or low frequency) or dynamic (higher frequency) depending on the frequency of cantilever actuation and the cantilever's characteristic resonant frequency. Interpretation of quasistatic data for material properties is better known. However, recent advances show exciting progress for highly sensitive, quantitative measurements with dynamic modes.

Force Curves and Force Volume Mapping

Force curves are a well-known quasistatic method to probe surface forces.[1] When used in nanomechanical experiments, they provide quantitative data on elastic modulus, hardness, and adhesive and van der Waals forces. Force curves are most sensitive when the cantilever spring constant roughly matches the stiffness of the tip-sample contact. Thus, they are best suited to biological and polymeric materials with elastic moduli of up to a few gigapascals, if standard commercial cantilevers are used.

Force curves are acquired by lowering the base of the AFM cantilever until the tip makes contact with the sample. This motion continues, and the tip deforms or indents the sample until a trigger threshold is reached, such as base displacement or cantilever deflection. The cantilever is then withdrawn until the tip loses contact with the sample. The measured cantilever deflection versus Z sensor position during this load-unload cycle is converted to a force curve with measurements of the cantilever sensitivity and spring constant. Figure 1 shows examples of force curves acquired on cortical neurons.

Force curves can also be acquired in 2D arrays called force maps or force volumes. One force map can provide multiple images of different properties measured simultaneously, such as elastic modulus, adhesion, and height. The user specifies the number of array points and the location and size of the region of interest. Each force curve is saved separately for individual analysis.

Although valuable for measuring elastic modulus, conventional force curve methods do not directly quantify the sample's viscous properties. Modifications to the basic force curve technique are required for this purpose. For example, creep compliance and stress relaxation measurements can be performed by inserting a hold interval of constant force between the load and unload segments.[3] Similarly, adding a low-amplitude AC modulation (~5-200 Hz) during the hold segment enables quantitative measurements of storage and loss modulus.[4]

Oxford Instruments Asylum Research AFMs for Force Curves and Force Mapping

- Force measurements on all Oxford Instruments Asylum Research AFMs are limited only by Brownian (thermal) motion. Combined with its ultra-low-noise Z sensors, this means that both axes of force curves are measured with the highest possible sensitivity and accuracy.
- GetReal™ is a proprietary software feature that, with a single click, automatically calibrates the cantilever spring constant and deflection sensitivity.
- The open architecture of the control software on all Asylum AFMs provides exceptional versatility for custom experiments, and enables advanced force measurements with powerful capabilities.

Fast Force Mapping Mode

Force volume mapping is a powerful technique for correlating functional and structural information. However, it is inconveniently slow. To address this problem, Oxford Instruments Asylum Research offers Fast Force Mapping Mode, which can acquire force curves at pixel rates up to 300 Hz on MFP-3D Infinity™ AFMs, and 1kHz on Cypher family AFMs. Using a continuous motion from pixel to pixel, instead of disjointed steps, Fast Force Mapping Mode can capture a complete array of force curves in just a few minutes. For example, a 256×256 image of standard force curves takes over 18 h to acquire at 1 s per pixel. By contrast, it takes less than 10 min with Fast Force Mapping Mode. Such dramatically reduced acquisition times enable images with higher pixel density, for improved lateral resolution. Figure 2 shows an image of 1024×1024 pixels, acquired with Fast Force Mapping Mode on a polymer blend sample, where features as small as approximately 10 nm are resolved.

In Fast Force Mapping Mode, the entire force curve for each image pixel is captured and saved with no hidden data manipulation. Realtime and offline analysis models can be applied to calculate modulus, adhesion, and other properties. Models are fully accessible for user inspection or modification, if desired. Fast Force Mapping Mode is applicable to samples with a modulus ranging from approximately 10 kPa to over 100 GPa, depending on the choice of cantilever.

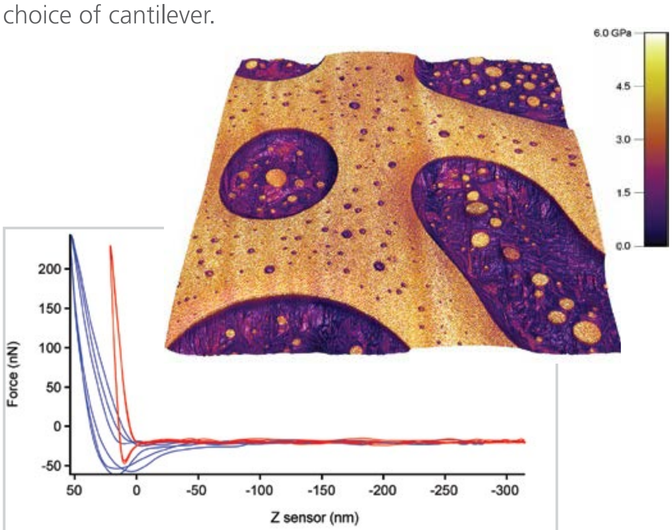

Figure 2: (top) Elastic modulus overlaid on topography for a polystyrene (PS)-polycaprolactone (PCL) blend. Imaged with Fast Force Mapping Mode on the MFP-3D Infinity AFM. Image size 4 µm. The 1024×1024 pixel image would be impractically slow to obtain with conventional force volume techniques. As expected from bulk literature values, PS regions (yellow) have higher modulus (~3 GPa) than PCL regions (purple, ~350 MPa). (bottom) Examples of complete force curves acquired during imaging in Fast Force Mapping Mode. The curves on PS have higher slope than those on PCL, indicating higher modulus.

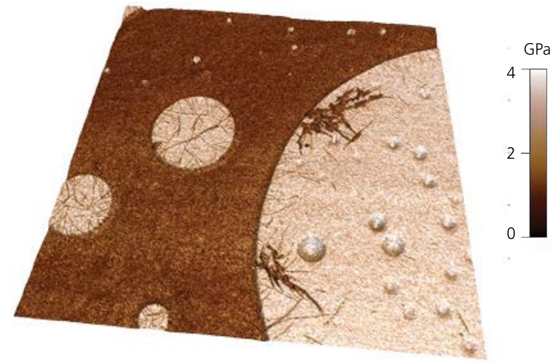

Figure 3: Polystyrene-polypropylene polymer blend thin film imaged using Fast Force Mapping mode. Elastic modulus is shown on 3D topography, 6 µm scan.

Figure 3 shows elastic modulus overlaid on topography for a polystyrene (PS)-polypropylene (PP) polymer blend spin casted onto silicon. Imaged with Fast Force Mapping Mode on a Cypher AFM with 512×512 pixels and a scan size of 6 µm. The force curves were taken with an amplitude of 80 nm and were measured at 1 kHz. Notably, every single force curve (deflection vs. height sensor) was collected for the image. Though a modulus image is calculated and displayed in real-time, the underlying force curve may be readily reanalyzed with other contact mechanics models (e.g. Hertz, Sneddon, DMT, JKR, Oliver-Pharr, see next page for details). In this case, the Hertz model was used assuming a punch-shaped indenter. Compared to the PS-PCL blend shown in Figure 2, the modulus of PS and PP are much closer together (~3 GPa and 2.4 GPa, respectively). Despite the relatively small difference, the contrast is still very clear.

Phase Imaging

Since its first demonstration in the late 1990s,[9] tapping mode with phase imaging[10,11] has become a valuable technique because it often provides contrast between different sample components. The phase response depends not only on the sample's mechanical properties (how the material stores elastic energy and dissipates viscous energy), but also on other dissipative forces and operational parameters. Depending on operating conditions, the contrast can even invert; although this complicates its interpretation, phase imaging remains widely used because it is so simple to measure.

Force Modeling

Quantitative data on mechanical properties, including elastic modulus, hardness, and adhesion, are obtained from AFM force curves by fitting the experimental data to a model for the tip-sample contact.[8] The diversity of materials and possible experimental conditions means that no single model can correctly apply to all samples. For this reason, Oxford Instruments Asylum Research software provides a variety of analysis models that offers user-friendly flexibility and convenience. Various parameters in each model can be modified from the main software interface. In addition, the software's open architecture makes all routines accessible for customization, if desired.

Models that are preprogrammed in Oxford Instruments Asylum Research software include:

- Hertz/Sneddon: This popular model allows the user to choose from several tip shapes including hemisphere, cone, and flat punch. It assumes that the tip-sample interaction is linearly elastic and does not include the effects of adhesion or other surface interactions.
- Johnson-Kendall-Roberts (JKR): The JKR model is used when there is strong adhesive contact between the tip and sample, in addition to the elastic interaction. Adhesion effects are included inside the contact area only. JKR is applicable in cases where the tip radius is relatively large compared to the indentation depth, for instance with relatively compliant materials.
- Derjaguin-Müller-Toporov (DMT): The DMT model is useful for samples that have weak but detectable adhesive forces. Attractive interactions such as adhesion are included outside the contact area only. DMT tends to be most useful for stiffer samples with low adhesion and when the tip radius is relatively small compared to the sample indentation depth.
- Oliver-Pharr: This model is used when the indentation process causes permanent, plastic deformation to the sample.

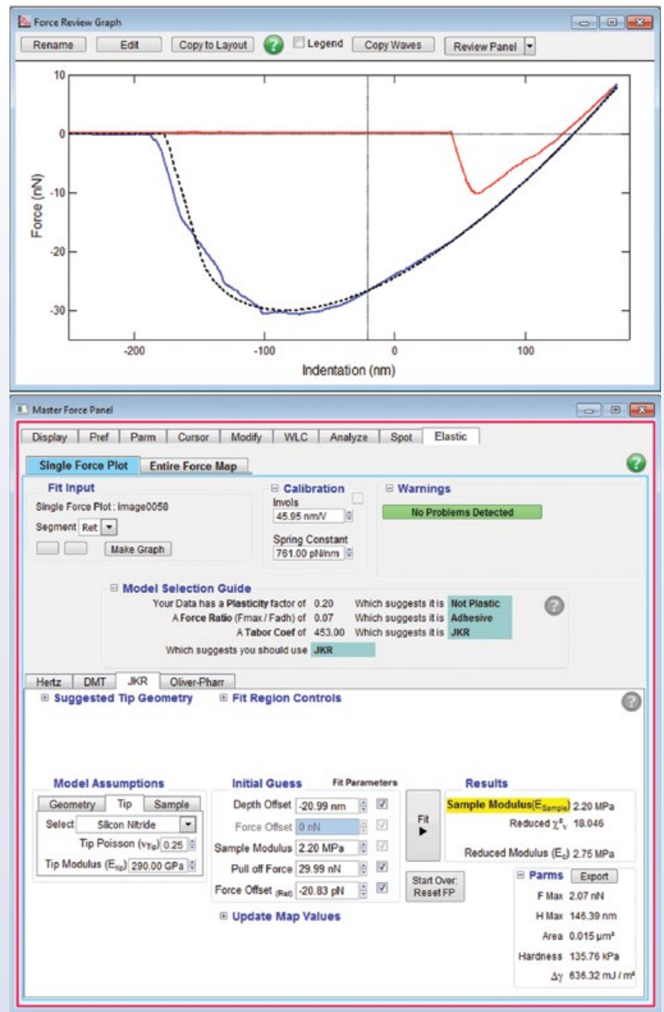

Figure 4: Example of force curve modeling with Asylum Research software. The top window shows a force curve acquired on a silicone elastomer gel. The applied force versus sample indentation is shown for both the extend (red) and retract (blue) segments of the cantilever loading-unloading cycle. The bottom window shows the extensive features of analysis software on all Asylum AFMs. As suggested by the Model Selection Guide (center of panel), a JKR fit was applied. The resulting fitted values are displayed in the bottom right of the analysis panel and are used to generate the black dotted line on the force curve.

Figure 4 illustrates the powerful capabilities for force curve analysis available in Oxford Instruments Asylum Research software. As seen in the figure, the software contains an exclusive model selection guide to evaluate various parameters, including plasticity index, force-to-adhesion ratio, and Tabor coefficient. The selection guide helps users determine the most appropriate mechanical model for their data. For example, if tip-sample adhesion is present, the software will alert the user that the Hertz model is not appropriate. The calculated selection parameters are always displayed to allow informed decisions.

Bimodal Dual AC™ Imaging

It has been determined that higher-order cantilever modes provide enhanced sensitivity to material composition. This discovery resulted in the development of bimodal AFM, in which two resonant frequencies of the cantilever are excited simultaneously.[12,13] In bimodal AFM, the first, or lower mode, operates the same as regular tapping mode. The amplitude of the cantilever is used as the feedback error signal to obtain topography, and the phase provides material contrast. In Bimodal Dual AC, a technique patented by Asylum Research, a second, higher-order cantilever resonance is driven simultaneously with the first mode; its amplitude and phase response are also measured. As shown in Figure 5, bimodal amplitude and phase images can provide enhanced contrast and spatial detail relative to conventional phase imaging. However, as with phase imaging, the contrast in bimodal images can be difficult to interpret, although, as qualitative data channels, they can be very useful.

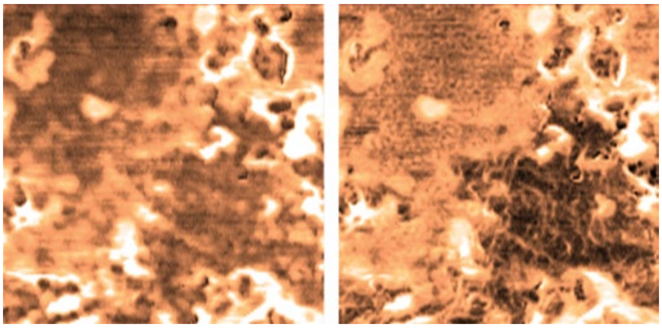

Figure 5: Bimodal Dual AC images of (left) mode 1 phase and (right) mode 2 phase for a tire sample. The sample contained a blend of several rubbers as well as carbon black and silica. The higher-mode image shows increased contrast and finer detail. Scan size 500 nm; data scale in both images is 43°. Imaged with the Cypher S AFM.

Loss Tangent Imaging

Recently, the concept of loss tangent has been applied to phase contrast.[14] The loss tangent $\tan \delta = E''/E'$ considers elastic energy and viscous dissipation jointly instead of treating them independently. It is measured in AFM experiments from the ratio of dissipated energy to stored energy per cycle of the tip's periodic deformation. These quantities are determined from the amplitude and phase response in standard tapping mode and are independent of tip-sample contact area in the linear viscoelastic limit.[15] As a ratio, the loss tangent alone does not distinguish whether contrast is due to storage or loss modulus variations. It can often differentiate sample components in cases where topography or phase cannot. Due to attractive forces and dissipative processes, such as adhesion and plasticity, AFM measurements are an upper bound on the material's actual loss tangent. Nonetheless, loss tangent imaging provides useful estimates with which to assess viscoelastic materials, as seen in Figure 6.

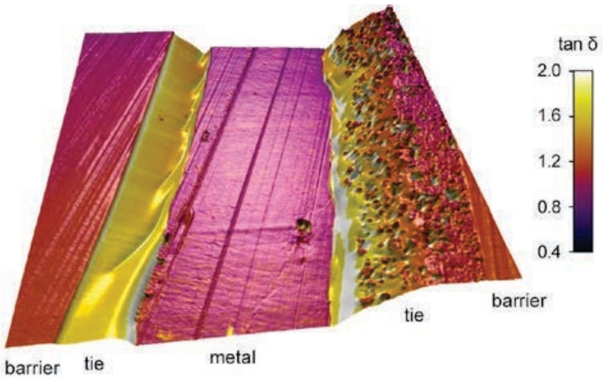

Figure 6: Image of loss tangent tan δ for a commercial coffee packaging bag in cross-section. Sample features including vapor barriers, "tie" layers, and a metal layer are clearly distinguished. Scan size 15 μm. Imaged with the Cypher S AFM.

AM-FM Viscoelastic Mapping Mode

In addition to loss tangent imaging, further progress has been made toward quantitative interpretation of bimodal amplitude and phase measurements in terms of the sample's nanomechanical properties. Exlusive to Oxford Instruments Asylum Research, AM-FM Viscoelastic Mapping Mode was developed employing bimodal AFM principles for quantitative mapping of viscoelastic properties. Its range of applicability spans a remarkable six orders of magnitude in storage modulus (from hundreds of kPa to over 100 GPa), making it a highly versatile technique. Information from AM-FM Mode includes storage modulus, contact stiffness, loss tangent, and loss modulus.[16] A material's viscoelastic response provides valuable information in many applications, since it can strongly influence practical considerations, such as impact resistance and toughness.

Like Bimodal Dual AC Imaging, AM-FM Mode uses tapping mode operating simultaneously at two different cantilever mode frequencies. The lower mode operates with amplitude modulation (AM) feedback and measures cantilever amplitude and phase. The amplitude yields a topography image, while the amplitude and phase together determine the loss tangent, as described above. However, in AM-FM Mode, the higher mode operates with frequency modulation (FM) feedback and

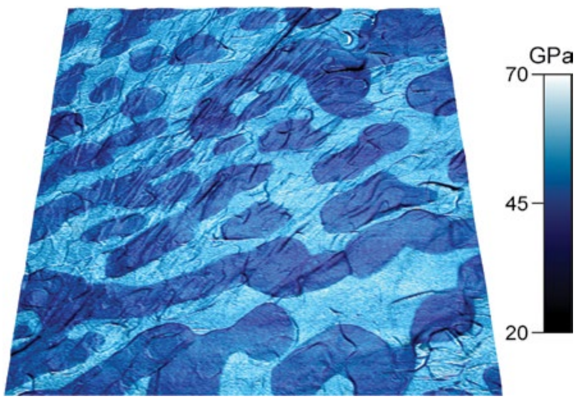

Figure 7: Elastic modulus overlaid on topography of a tin/lead alloy solder. Tin-rich (lighter) and lead-rich (darker) regions can be identified. Scan size 8 μm. Acquired in AM-FM Mode on the Cypher S AFM at 1.5 Hz line scan rate with blueDrive™ photothermal excitation.

measures cantilever frequency and amplitude. Frequency is a sensitive probe of sample stiffness or elasticity, so that raw frequency images are a quick way to obtain qualitative contrast. Quantitative results are obtained with a model for tip-sample contact and calibration measurements on a sample of known modulus. Because the amplitude of the higher mode is always much lower than for the lower mode, it does not interfere with feedback and scanning.

Because AM-FM Mode works like tapping mode, it has all the advantages of tapping mode, including fast scanning, high spatial resolution, and gentle forces. As a scanning technique, it is much faster than methods based on individual force curves and doesn't deform samples as much as force curves or contact methods, such as contact resonance and force modulation imaging (see below). An example of AM-FM Mode on a metallic solder sample is shown in Figure 7.

Contact Resonance Viscoelastic Mapping

Contact resonance is another dynamic mode that enables high resolution, quantitative imaging of both elastic storage modulus and viscous loss modulus.[17,18] It is particularly well suited to materials with moderate to high modulus (approximately 1-200 GPa). In this mode, a cantilever vibrational resonance is excited while the tip is in contact with the sample. Quantitative property data is derived from measurements of the frequency and quality factor of the contact resonance peak. The peak frequency varies monotonically with the sample's elastic stiffness, while the quality factor of the peak changes depending on the sample's viscous damping.

Asylum AFMs for Dynamic Nanomechanical Modes

- For phase and loss tangent imaging, GetStarted™ software automatically sets tapping mode parameters and minimizes setup time on MFP-3D Infinity AFMs.
- When performed on Cypher family AFMs with small cantilevers, AM-FM Mode provides quantitative nanomechanical property mapping at much higher speeds than any other technique.
- With Asylum's exclusive Bimodal Dual AC™ Mode, software controls enable simultaneous excitation at two frequencies with independent drive amplitudes. The detected photodiode signal is processed simultaneously by two lock-in amplifiers to measure the phase and amplitude at both frequencies.
- Dual AC™ Resonance Tracking (DART) and Band Excitation (BE) are proprietary Asylum techniques for imaging in Contact Resonance Mode. DART captures both resonance frequency and quality factor while operating at normal imaging rates, or even at fast scanning rates with small cantilevers on the Cypher AFM. BE records the full resonance spectrum, making it a complementary technique to confirm DART results or to apply more complex analysis models.
- Asylum's exclusive ModeMaster™ software feature makes working with dynamic modes faster and easier. It automatically configures the software and guides you through the experiment. For techniques like AM-FM Mode and Contact Resonance Mode, the software panel assists in both setting up the measurement and performing calibrations with a reference sample of known modulus. This lets you start making measurements with well-established methods, but without the full complexity.
- Cantilever spring constants are calibrated easily and accurately with GetReal software, free on all Asylum AFMs. Spring constant values are needed, for example, to measure absolute contact stiffness with AM-FM Mode and absolute applied force in Contact Resonance Mode.

Quantitative nanomechanical imaging with contact resonance requires detecting the resonance peak while the tip scans in contact mode. Although simple in concept, this can be challenging in practice because the peak changes continuously with sample mechanical properties. A variety of hardware and software approaches have been implemented to meet this challenge. Figure 8 shows an example of Contact Resonance Mode imaging on a patterned thin film on silicon.

Like other techniques mentioned here, Contact Resonance Mode can be operated with either minimal calibration for fast, qualitative imaging or can be calibrated with a material of known properties for more quantitative results. Both Contact Resonance Viscoelastic Mapping Mode and AM-FM Viscoelastic Mapping Mode provide quantitative data on viscoelastic properties, so it can be valuable to compare results directly. Contact resonance techniques can also be performed much faster than force curve mapping and are more sensitive on very stiff materials.

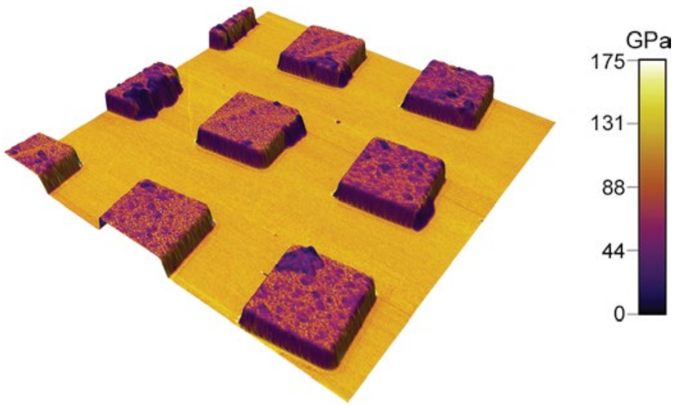

Figure 8: Elastic modulus map overlaid on topography for a patterned titanium film on silicon. Acquired in DART Contact Resonance Mode with blueDrive™ photothermal excitation on the Cypher AFM. Scan size 25 µm. Note the ability of Contact Resonance Mode to provide strong contrast between two materials with very high modulus.

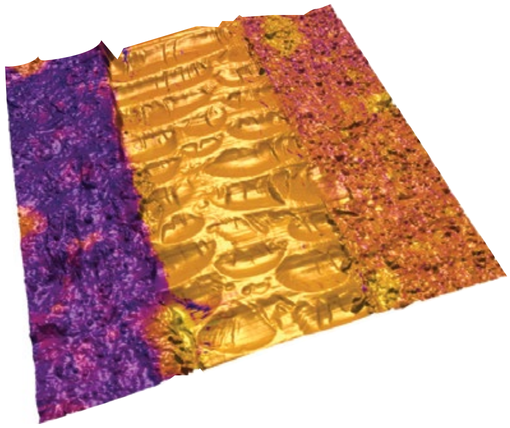

Figure 9: Force modulation amplitude overlaid on topography for a polymer sandwich. The sample contained layers of (left to right) Viton fluoroelastomer, epoxy, and ethylene propylene diene monomer rubber (EPDM). The difference in hardness between Viton® (Shore A 78) and EPDM (Shore A 58) is clearly resolved.

Force Modulation Imaging

Force modulation was one of the earliest AFM techniques developed for qualitative imaging of nanomechanical properties.[19,20] It is particularly well suited to relatively compliant samples (modulus less than about 1 GPa) such as polymers and biomaterials. Like contact resonance, force modulation is performed with the tip in contact mode while a very low amplitude, vertical modulation is applied. However, in force modulation the drive frequency is intentionally far away from, and usually much lower than, the cantilever contact resonance. Force modulation uses the idea that a compliant sample deforms more than a stiff sample for the same force applied by the tip. Differences in sample deformation, and therefore contrast in elasticity, are reflected in the relative amplitude of the cantilever deflection during scanning. Differences in viscous damping or dissipation are indicated by the phase lag of the cantilever deflection relative to the excitation source. Figure 9 contains an example of force modulation imaging on a multilayer polymer sample.

Models have been developed to interpret force modulation data in terms of storage modulus and loss tangent, but quantitative measurements have traditionally been hampered by non-optimal excitation sources. However, Asylum Research provides actuators with much flatter frequency response and higher bandwidth than previously available (see sidebar), offering exciting new possibilities for force modulation. The actuators make force modulation measurements possible over a wide range of frequencies with high amplitudes. This will not only provide increased and often different mechanical contrast in many applications but will also enable accurate measurements of frequency-dependent mechanical properties.

Summary

Knowledge of nanoscale mechanical properties can be critical to understanding a material's behavior and performance. The diversity of advanced material systems means that no single AFM technique can provide accurate, detailed information for every need. The NanomechPro Toolkit contains a variety of techniques so that you can choose the best approach for a given application, on virtually any material. This allows you to measure a wide range of properties, including elastic stiffness, loss and storage modulus, viscous damping, adhesion, and hardness. Different modes, including several available only on Cypher and MFP-3D family AFMs, probe different types of mechanical response to provide complementary information. Contact Asylum Research to explore how techniques in the NanomechPro Toolkit can benefit your research.

Oxford Instruments Asylum Research AFM Actuators

Dynamic modes, including AM-FM Viscoelastic Mapping Mode and Contact Resonance Viscoelastic Mapping Mode, place demands on the excitation source that are more stringent than standard tapping mode. For instance, they may require very high bandwidth or very uniform frequency response; because of this, several alternatives to the cantilever holder's piezoelectric actuator are available to meet these needs.

For contact resonance AFM and high-frequency force modulation, proprietary sample actuators deliver the best performance commercially available. They are highly damped so that small deviations from an ideal, frequency-independent drive are unlikely to interfere with quantitative measurements. A frequency response up to ~10 MHz means they are especially valuable for contact resonance experiments.

For AM-FM Mode and Bimodal Dual AC Imaging, where the tip only contacts the sample a fraction of the time, sample actuation is not suitable. In addition, it is not always possible to actuate the sample in Contact Resonance Mode or frequency modulation, for instance with a large or oddly-shaped sample or when a heating stage is used. For cases like these, Asylum offers AM-FM Probe holders. Based on the same technology as sample actuators, they provide output signals over a wide frequency range with relatively flat response.

Another approach for all dynamic modes is to actuate the cantilever directly. blueDrive™ (see figure 8) offers a photothermal laser excitation option for Cypher family AFMs and provides exceptionally clean, stable actuation. Replacing mechanical actuation with this option leads to a response that is nearly ideal: flat, linear, high bandwidth, and operable in air or liquid.

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