True Non-Contact Mode

Ultimate Resolution of Atomic Force Microscopy

True Non-Contact AFM Means the Ultimate in AFM Resolution

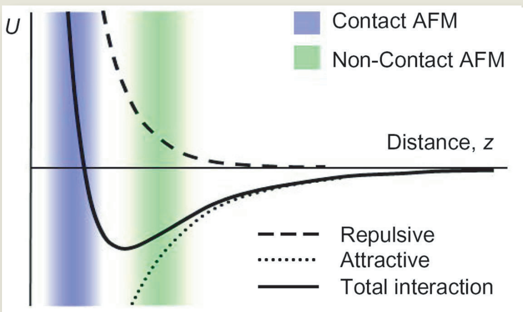
When Non-Contact AFM of the XE-series is operated with a very small tip-sample distance, even a slight deviation of tip-sample interaction force from the set point can be fatal, unlike in contact mode. This is why the tip has to be significantly far from the sample surface in conventional NC-AFM, resulting in poor resolution. It is a technically challenging task to implement NC mode with a very small tip-sample distance. Tapping imaging was initially used to avoid the difficulty of precise tip-sample spacing control. Once correctly engineered, however, NC-AFM of the XE-series provides the ultimate resolution of ambient AFM, far surpassing the capabilities of both contact and Tapping imaging (See "True Non-Contact Mode vs. Tapping Imaging" for details). Moreover, True Non-Contact AFM in the XE-series is the best means to image soft biological samples without sample degradation from either contact or tapping AFM (See "True Non-Contact AFM for soft biological samples" for details).

Introduced by the original innovators and pioneers of Atomic Force Microscope (AFM) technology after 4 years of intensive product development, the XE-series represents breakthroughs in every aspect of AFM technology (See "**Development of Crosstalk Eliminated (XE) Atomic Force Microscopy**" for details). The XE-series is the first and only AFM in the market that realizes True Non-Contact mode in every specification, not just in principle but in practice. True Non-Contact mode achieves an unprecedented tip-sample distance, combined with superb tip and sample preservation. The advantages of True Non-Contact mode enable the ultimate resolution of AFM and measurement accuracy which are without peer in the AFM industry (See "What is the Ultimate Resolution of AFM?" for details).

Non-Contact AFM: The Principle

Non-Contact AFM (NC-AFM) is one of several vibrating cantilever techniques in which an AFM cantilever is vibrated near the surface of a sample. The spacing between the tip and the sample for NC-AFM of the XE-series is on the order of tens to hundreds of angstroms. This spacing is indicated on the van der Waals curve of Figure 1 as the Non-Contact regime. There are two major forces, the static electric repulsive force and attractive force, existing between atoms a short distance apart: The static electric repulsive forces (F_{ion}) between ion cores and the static electric attractive forces (F_{el}) between valence electrons and ion cores. When the distance between the atoms at the end of the probe tip and the atoms on the sample surface becomes much shorter, the repulsive forces between them become dominant, and the force change due to the distance change becomes greater and greater. Therefore, contact AFM measures surface topography by utilizing the system's sensitive response to the Repulsive Coulomb Interactions that exist between the ion cores when the distance between the probe tip and the sample surface atoms is very small. However, as shown in Figure 1, when the distance between the probe tip and the sample atoms is relatively large, the attractive force becomes dominant. Ion cores become electric dipoles due to the valence electrons in neighboring atoms, and the force induced by the dipole-dipole interaction is the van der Waals Force. True Non-Contact AFM (NC-AFM) of the XE-series measures surface topography by utilizing this attractive atomic force in the relatively larger distance between the tip and a sample surface.

Figure 1. Interatomic force vs. distance



Because of the attractive force between the probe tip and the surface atoms, the cantilever vibration at its resonant frequency near the sample surface experiences a shift in spring constant from its intrinsic spring constant (k_0). This is called the effective spring constant (k_{eff}), and the following equation holds:

$$k_{eff} = k_0 - F' \qquad (1)$$

When the attractive force is applied, k_{eff} becomes smaller than k_0 since the force gradient F' ($=\partial F/\partial z$) is positive. Accordingly, the stronger the interaction between the surface and the tip (in other words, the closer the tip is brought to the surface), the smaller the effective spring constant becomes. This alternating current method (AC detection) makes more sensitive responds to the force gradient as opposed to the force itself. Thus, it is also applied in such techniques as Magnetic Force Microscopy (MFM) and Dynamic Force Microscopy (DFM).

A bimorph is used to mechanically vibrate the cantilever. When the bimorph's drive frequency reaches the vicinity of the cantilever's natural intrinsic vibration frequency (f_0), resonance will take place, and the vibration that is transferred to the cantilever becomes very large. This intrinsic frequency can be detected by measuring and recording the amplitude of the cantilever vibration while scanning the drive frequency of the voltage being applied to the bimorph. Figure 2 displays the relationship between the cantilever's amplitude and the vibration frequency. From this output, we can determine the cantilever's frequency.

A stiff cantilever used in True Non-Contact AFM of the XE-series typically has a relatively high resonant frequency, between 100 kHz and 400 kHz with a vibration amplitude of a few nanometers. The AFM system detects changes in the resonant frequency or vibration amplitude as the tip comes near the sample surface. The sensitivity of this detection scheme provides sub-angstrom vertical resolution in the image, as with contact AFM.

Figure 2.
Resonant frequency of a cantilever

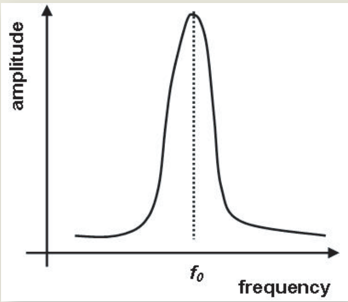


Figure 3.
Resonant frequency shift

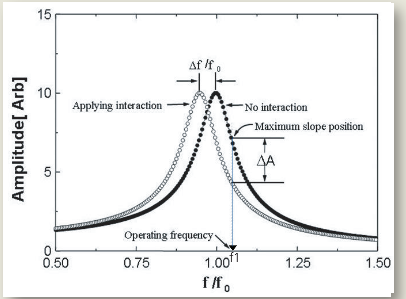
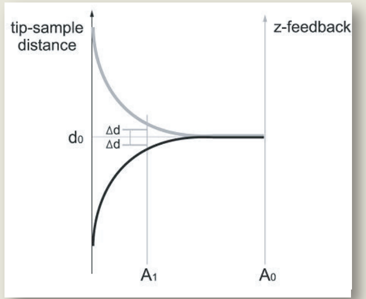


Figure 4.
Resonant frequency shift



On the other hand, the spring constant affects the resonant frequency (f_0) of the cantilever, and the relation between the spring constant (k_0) and the resonant frequency (f_0) in free space is shown as in Equation (2).

$$f_0 = \sqrt{\frac{k_0}{m}} \qquad (2)$$

As in Equation (1), since k_{eff} becomes smaller than k_0 due to the attractive force, f_{eff} too becomes smaller than f_0 as shown in Figure 3. If you vibrate the cantilever at the frequency f_1 (a little larger than f_0) where a steep slope is observed in the graph representing free space frequency vs. amplitude, the amplitude change (ΔA) at f_0 becomes very large even with a small change of intrinsic frequency caused by atomic attractions. Therefore, the amplitude change measured in f_1 reflects the distance change (Δd) between the probe tip and the surface atoms.

If the change in the effective resonance frequency, f_{eff}, resulting from the interaction between the surface atoms and the probe, or the change in amplitude (ΔA) at a given frequency (f_1) can be measured, the Non-Contact mode feedback loop will then compensate for the distance change between the tip and the sample surface as shown in Figure 4. By maintaining a constant amplitude (A_0) and distance (d_0), Non-Contact mode can measure the topography of the sample surface by using the feedback mechanism to control the Z-scanner movement following the measurement of the force gradient represented in Equation (1).

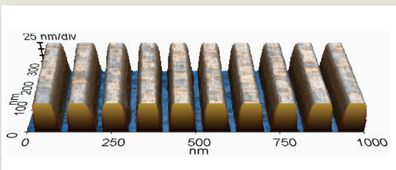


Figure 5.
True Non-Contact AFM image taken with an XE-100 of 50 nm wide, 100 nm deep trenches shown in 1:1 aspect ratio 3D rendering (1 μm scan size). True Non-Contact mode from the XE-series with high Z-servo performance can accurately trace the steep walls of the trenches.