Improved subsurface AFM using photothermal excitation

Maarten E. v. Reijzen, Mehmet S. Tamer, Maarten H. v. Es, Martijn v. Riel, Aliasghar Keyvani, Hamed Sadeghian, Marco v. d. Lans

Netherlands Organization for Applied Scientific research, TNO, Delft, the Netherlands;

ABSTRACT

In this paper, we present an AFM based subsurface measurement technique that can be used for overlay and critical dimensions (CD) measurements through optically opaque layers. The proposed method uses the surface elasticity map to resolve the presence and geometry of subsurface structures. To improve the imaging performance of the AFM based subsurface measurements, we made use of photothermal excitation of the AFM cantilever together with a frequency modulation scheme. The experimental results show a significant improvement in the quality of the image, which leads to a more accurate and reliable CD and overlay measurement.

Keywords: AFM, subsurface imaging, frequency modulation, photothermal excitation, critical dimensions and overlay metrology.

1. INTRODUCTION

According to International Roadmap for Devices and Systems, one of the key challenges for metrology and process control at front-end-of-line semiconductor fabrication is the ability to see through optically opaque layers.[1,2] By the advent of 3D structures such as FinFETs and 3D NANDs, ongoing miniaturization of the circuits, and use of new materials, the conventional optical and e-beam based imaging techniques are facing physical limitations in inspecting the new IC components. For some of today's applications an overlay error should be measured by looking through layers that are opaque for a large range of the electromagnetic wave spectrum. One of the possible options to overcome some of these challenges is the subsurface Atomic Force Microscopy (AFM).[3] Recent developments in AFM have enabled its application for measuring the subsurface features based on their effect on local mechanical properties at the surface.[4] Presence of a subsurface structure changes the local effective elasticity and damping characteristic of the surface, and such a change can be measured using an AFM. Researchers have reported many different techniques for measuring these changes in mechanical properties of the surface.[4–10]

A common but loose description of all these techniques is that one can "touch and feel" the subsurface features through their effect on the (visco)elasticity of the surface. Typically, a microcantilever with a nano-scale sharp tip is brought into contact with the surface of the sample and is scanned over the surface, while its dynamic properties are monitored. Because the sample constitutes a boundary condition for the cantilever, the dynamic properties of the cantilever depend on the local mechanical properties of the sample. In cases where the presence of the subsurface structures change the effective local elastic or dissipation properties of the surface, a subsurface image of the sample can be captured even if the top layer(s) is/are optically opaque. Although there are discussions and ongoing research about the origin of the contrast mechanism, and the technique is far from being quantitative, mapping the (differences in) mechanical properties with sufficient contrast already enables applications such as critical dimensions and overlay measurement*.

A usual way of obtaining subsurface images is to track the resonance frequency of the cantilever while in contact with the surface. For example, a shift in contact resonance frequency of the cantilever indicates a change in local stiffness of the surface, which is indicative of a subsurface feature. This contact resonance frequency is normally measured indirectly using an amplitude modulation scheme, ultrasound enhanced amplitude modulation, or directly via frequency modulation technique. One main challenge regarding all these techniques is that the measured FRF of the whole system including cantilever, actuator and sample or cantilever mount, is very

a.keyvanijanbahan@tudelft.nl

*Depending on the specific technique and the sample that is used, researchers attribute the achieved contrast to different mechanisms such as elasticity, friction, and ultrasound wave scattering.[4,5]

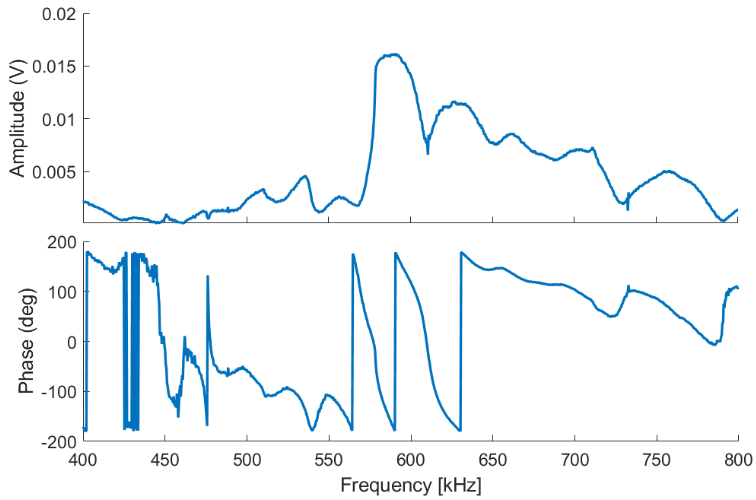

Figure 1. The frequency response function of a commercially available cantilever (Nanotools NCHAu) in contact with the surface of a flat silicon sample measured using a bottom excitation scheme. A piezoelectric actuator is coupled to the sample through a liquid media, and the deflection of the cantilever is measured using an optical beam deflection technique.

different from a single degree of freedom resonator. This makes it ambiguous to exactly pinpoint the contact resonance frequency of the cantilever. For example, van Es *et al.* presented a technique in which the amplitude of a high-frequency excitation signal is modulated at the contact resonance of the cantilever and is applied to the contact area via a piezoelectric actuator. The actuator is placed underneath the sample and is acoustically coupled to the sample via a liquid or fatty media (hereafter referred to as bottom excitation). Fig. 1 shows the frequency response of the cantilever-sample couple excited using bottom excitation. The resulting FRF shows more than one peak in the amplitude signal and the phase behavior is highly ambiguous. Although such an imperfect FRF is still usable with the amplitude modulation technique, it does not allow for frequency modulation because of a complicated and non-uniform phase behavior. Moreover, it is not guaranteed that the frequency corresponding to the largest amplitude also corresponds to the exact contact resonance point. As the amplitude channel in Fig. 1 suggests, there might exist multiple poles and zeros (resonance and anti-resonance frequencies) all very close to each other. In fact, experimental results suggest that the most sensitive frequency to the elasticity of the surface does not necessarily coincide with the peaks in Fig. 1. This makes it time consuming to optimize the frequency for the highest sensitivity and to set up the experiment. Similar FRFs are also achieved by so-called top excitation where the piezoelectric actuator is coupled to the cantilever chip.

The dynamic behavior seen in Fig. 1 does not purely reflect the dynamics of the cantilever in contact with the sample, rather a combination of the acoustic coupling between the sample and the actuator, dynamics of the actuator and dynamics of the cantilever. Therefore it is tedious (if not impossible) to perform any quantitative measurement. In this paper, we suggest the use of photothermal excitation which provides a much cleaner FRF. Together with a frequency modulation technique, this brings reproducible quantitative subsurface AFM measurements one step closer. To realize this idea, we first bulit a demonstrator and tested the FRF and imaging performance of the method. Second, we implemented the idea in a commercial AFM using a custom made add-on. Finally, we tried to improve the performance of the system by costumizing the cantilever to improve its sensitivity to thermal actuation. The remainder of this paper is organized as follows. First the photothermal excitation technique is discussed in the following section. Then the implementation of the technique in a commercial AFM is presented in section 3, followed by optimization of the cantilever in section 4. As the last part, the frequency modulation technique is discussed which is implemented on a commercial AFM system with an optimized cantilever and the custom made photothermal excitation add-on.

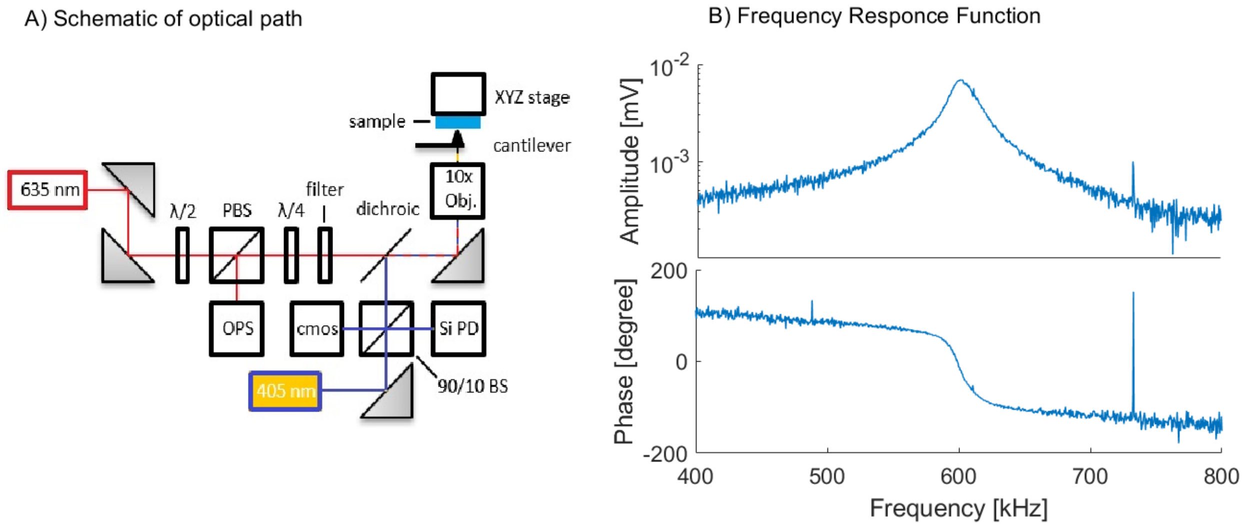

Figure 2. A) Schematic representation of the home-built AFM system with photothermal excitation technique. B) Frequency response function of the cantilever (the same cantilever as Fig. 1) while in contact with the surface of a flat silicon sample measured using photothermal excitation.

2. PHOTOTHERMAL EXCITATION

In the photothermal excitation method, the AFM cantilever is exposed to a 405 nm laser beam with a modulated power, while its deflection is measured using a laser with a longer wavelength (635nm or 830nm). The cantilever absorbs some of the 405nm laser power as heat which causes a fluctuation in its temperature. Since the cantilever has a bilayer structure (due to its metal coating layer), the changes in its temperature cause stress between the layers with different expansion coefficients which consequently bends the cantilever. The fluctuation in the 405nm laser power power modulates the thermal stress which excites the cantilever. This technique has already been suggested as an excitation mechanism for tapping mode AFM both in air and liquid environments.[11–13] However, its performance in exciting the contact resonance modes of the cantilever was not tested yet.

In order to test the proposed excitation method in contact resonance mode, we built a dedicated AFM system using off-the-shelf components. A schematic view of the home-built system is presented in Fig. 2 A) The system is composed of a stack piezoelectric XYZ-scanner to scan the sample relative to the cantilever probe, a commercially available SPM controller (High speed SPM controller from Anfatec) to control the cantilever sample distance, and an optical setup to allow for excitation and deflection measurement of the cantilever. The optical path consists of two laser diodes, one for measurement of the cantilevers deflection (Thorlabs LP635-SF8, 635 nm) and one for excitation (Thorlabs LP405-SF30, 405 nm). The optical path from both lasers is combined using a dichroic mirror, after which it is focused upon the cantilever through a 10x objective (Mitutoyo). A high bandwidth (40 MHz) optical position sensor (Maypa OPS) is used to measure the deflection of the cantilever. As shown in Fig. 2 B) with this technique, a very clean amplitude and phase signal can be captured. Since the proposed techniques provides a more clean FRF, one can use a Phase Lock Loop (PLL) to quantitatively measure the resonance frequency of the cantilever and perform a frequency modulated experiment which was very elusive with acoustic excitation techniques.

In order to test the subsurface imaging performance of the proposed method, we glued an overlay alignment marker sample to the XYZ scanner of the home-built AFM. The sample (same sample as the one presented in[3]) consists of a rigid substructure with 50 nm deep trenches. The sample is covered with a photoresist layer which is 30 nm in the shallowest part and consists of 60 nm high features aligned with those on the rigid substructure. Fig. 3 shows the surface and subsurface images of the overlay alignment sample captured using the photothermal excitation and SSURFM modulation technique.[4] As it can be seen, the buried trenches that are not visible in

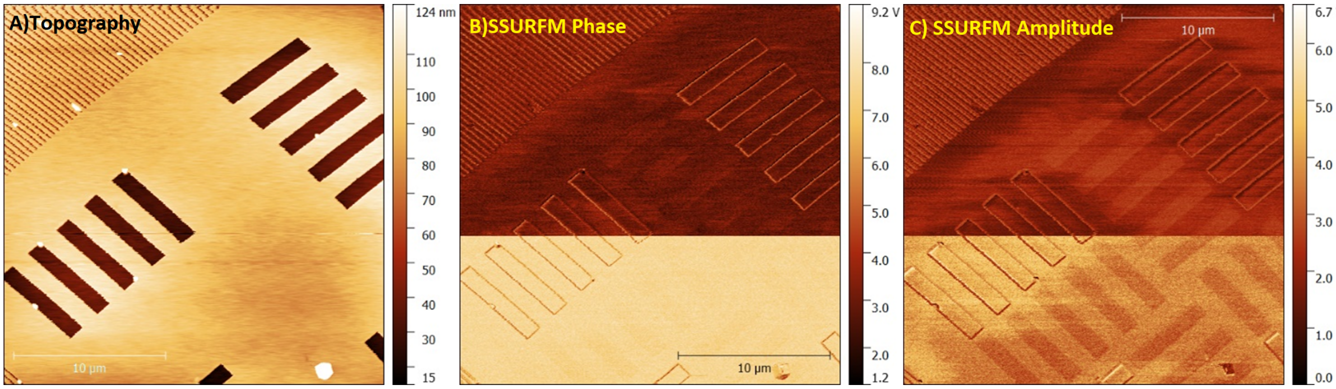

Figure 3. Surface and subsurface images of the overlay alignment sample, measured using SSURFM technique.[4] A) Topography, B) Phase of the demodulated OPS signal, C) Amplitude of the demodulated signal of the OPS. The carrier frequency was kept constant at Fc=20 MHz, and the modulation frequency was changed roughly midway during the scan (as indicated by the change of color in the amplitude and phase picture), where Fmod1=1.8 MHz and Fmod2=2 MHz for the first and second part of the scan, respectively. Pictures were taken at a scan rate of 4 lines/second and an applied force of 160 nN.

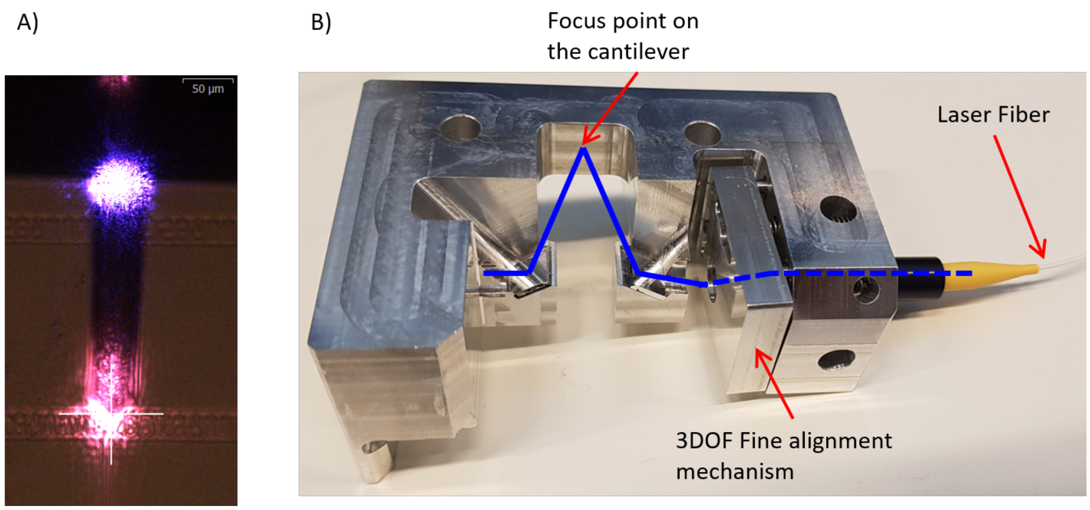

Figure 4. Photothermal excitation add-on for a commercial AFM. A) Blue and infrared lasers on the cantilever B) The laser steering mechanism for blue laser.

the topography of the sample, are clearly visible in the amplitude channel. Tamer *et al.* suggested that this combination of the surface and subsurface images can be used to determine the overlay error.[3]

3. IMPLEMENTATION

In order to implement the photothermal excitation laser on a commercial AFM system (NX20 from Park systems), we designed and realized the add-on system shown in Fig. 4. In this system, the 405nm excitation laser is focused on the base of the cantilever and the location of the laser spot is adjusted on the cantilever so that the response amplitude of the cantilever is maximized. We used a commercially available (LP405-SF30 - 405 nm from Thorlabs) laser source as the excitation laser which requires a threshold current of 30 mA and typical power-to-current slope of 0.4 W/A. Therefore, we applied a DC current of 35 mA and added a sinusoidal voltage source to the laser driver to modulate the laser power. We used a commercially available Lock-in amplifier (UHFLI 600 MHz, 1.8 GS/s from Zurich instruments) to drive the laser source, determine the amplitude and the phase of the deflection signal, and eventually lock to the resonance frequency of the cantilever using a built-in PLL. The outputs of the lock-in amplifier (and the PLL) are provided back to the AFM system as auxiliary inputs to generate the subsurface images synchronously with the topography images.

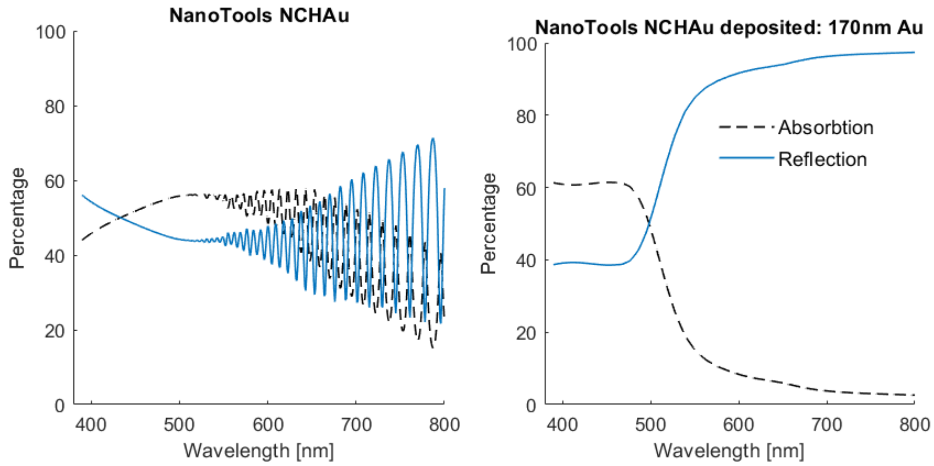

Figure 5. Absorption and reflection spectrum of a commercially available cantilever, before and after deposition of 170nm of gold coating layer calculated using the toolbox of Filmetrics based on Fresnel equations.[14] The original NCHAu cantilever has a 10 nm reflective gold coating layer that creates an optical cavity and causes the fluctuation in absorption spectra. The thicker gold layer eliminates this effect.

4. OPTIMIZATION OF THE CANTILEVERS

For subsurface AFM using the photothermal excitation, it is important to maximize the dynamic component of the force applied to the surface. A practical adjustment that can be done to improve the performance of the cantilever is to apply a coating layer on the back side of the cantilever. A suitable choice of material and thickness of this coating can maximize the dynamic forces applied to the surface.

From theoretical studies, considering a modified Kirchhoff-Love plate theory, it can be concluded that an equivalent force of the thermomechanical bilayer bending effect scales with F as:

$$F \propto \left(\frac{h_1 h_2}{h_1^2 + h_2^2 + 2h_1 h_2}\right)\left(\frac{E_1\alpha_1}{1-\nu_1} - \frac{E_2\alpha_2}{1-\nu_2}\right) \tag{1}$$

where h, E, α and ν refer to thickness, Young's modulus, thermal expansion ratio, and the Poisson ratio of each of the layers, respectively, and indexes 1 and 2 refer to the cantilever and the coating material. According to this equation, one can increase the thermomechanical force by increasing the thickness of the coating layer up to the thickness of the cantilever itself. Obviously, a difference between the thermal expansion ratio, elasticity, and Poisson ratio of the two materials is also essential. For photothermal excitation, it is also very important that most of the applied blue laser is absorbed in the cantilever, and not reflected. A good candidate for coating the silicon cantilevers which has a distinct thermal expansion coefficient from silicon, can increase the absorption of blue laser, reduce the absorption of the infrared laser, and easily found in any cleanroom is gold. Fig. 5 shows the effects of coating a layer of 170 nm gold on a commercial cantilever. Since gold absorbs shorter wavelengths and reflects the longer ones, it has a positive effect on the total performance of the cantilever for the photothermal excitation technique.

The added gold layer on the cantilever improves both the power absorption and the thermomechanical properties of the cantilever. Fig. 6 compares the FRF of single-side coated, double-side coated, and the bare cantilever.

As can be seen, coating the cantilever with gold increases the amplitude because of two reasons; i) thermomechanical and ii) absorption. If we only coat one side of the cantilever, both the thermomechanical effect and the improved absorption characteristic of the gold layer helps to increase the amplitude. However, if we coat both sides of the cantilever the second gold layer, partly counteracts with the thermechanical effect of the top layer which reduces the.

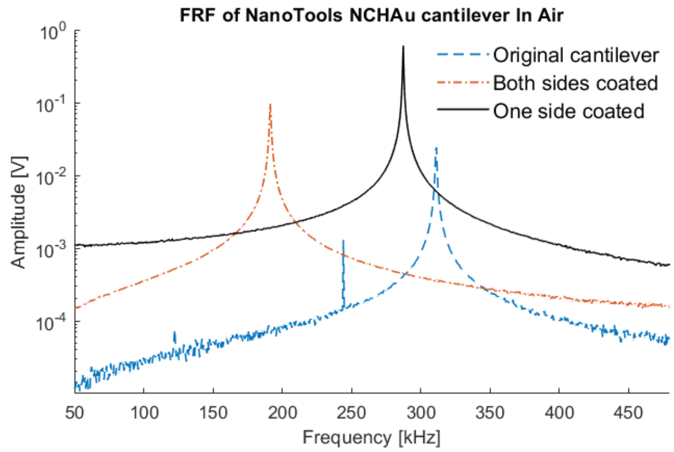

Figure 6. Changes in frequency response function of a commercially available cantilever (blue-dashed), by adding gold layer (red and black). In one case the gold layer added only to one side (black-solid) and for an other case, both sides of the cantilever is coated with gold (red-dash dotted).

It is also interesting to see that the added layer of gold increases the modal mass of the cantilever and reduces its resonance frequency, while the added stiffness is not as prominent as the added mass. This is due to the ratio between density and young modulus of gold as compared to silicon.

5. FREQUENCY MODULATION

One major challenge in amplitude modulation based techniques is the correct choice of the excitation frequency. As can be seen in Fig. 3, the contrast and sensitivity of the subsurface signals are highly dependent on the excitation frequency. If the excitation frequency is too far away from the contact resonance frequency of the cantilever the sensitivity of the system to the subsurface features reduces. Moreover, as the contact resonance frequency gets away from the excitation frequency, the amplitude drops which consequently reduces the signal-to-noise ratio (SNR).

In order to have maximum SNR for every pixel of the image, the frequency modulation scheme can be used. In the frequency modulation technique, a PI controller changes the excitation frequency of the cantilever to minimize the deviation from the resonance frequency. In this way, every pixel of the image is captured while the cantilever is at resonance, hence the highest SNR and sensitivity is guaranteed. The standard indicator of deviation from the resonance frequency is the phase of the motion of the cantilever. Using a PI controller to adjust the excitation frequency according to the phase, one can generate a map of the contact resonance frequency of the sample, which unlike the amplitude or phase, is a quantitative measurement of the influence of subsurface features on the surface.

Due to the presence of multiple resonances and anti-resonance frequencies (poles and zeros), extracting any useful information from the phase signal of a cantilever which is excited with top or bottom acoustic excitation is very elusive (if not impossible). However, this problem is resolved by using the photothermal excitation technique. As shown in Fig. 2 B), the phase of the cantilever is a clean and uniformly reducing function of the excitation frequency which enables a stable frequency modulation experiment.

Fig. 7 depicts the advantage of using the frequency modulation with photothermal excitation technique over state of the art subsurface techniques. Here, the resonance frequency histogram and cross-section of a subsurface image of a photoresist sample with subsurface trenches is shown. As can be seen, using the photothermal excitation technique in combination with frequency modulation, the subsurface features can be resolved with much better SNR.

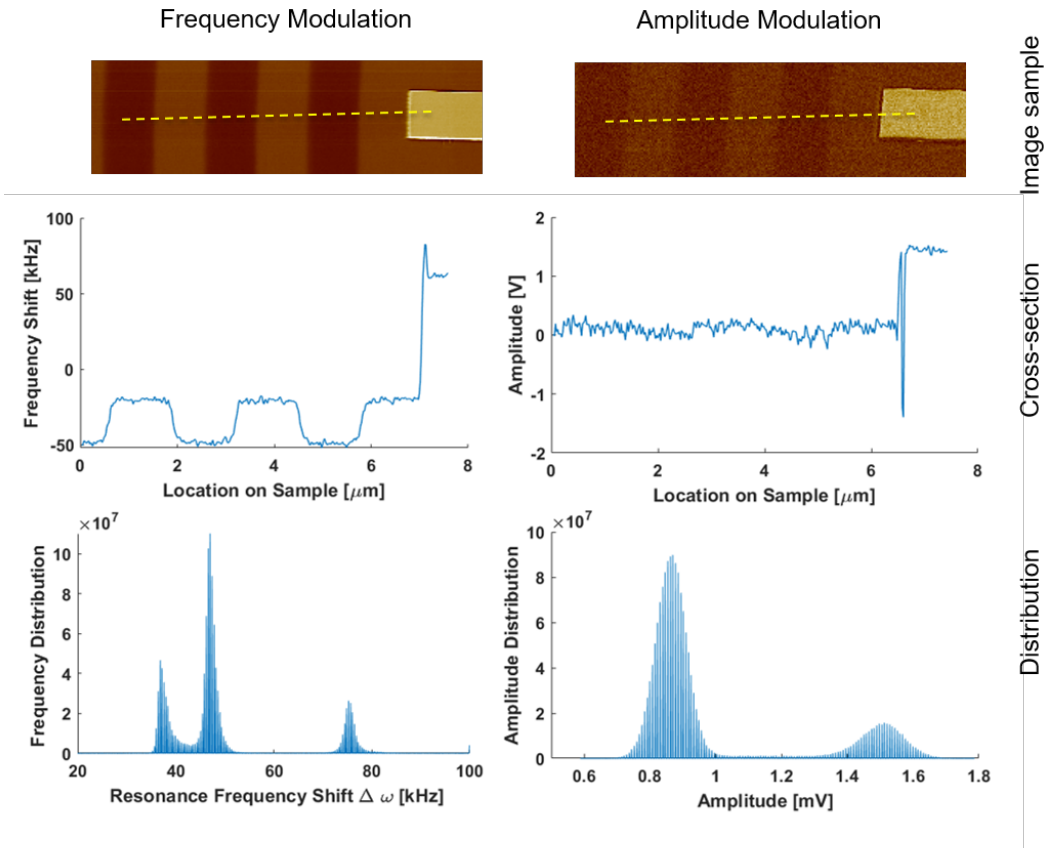

Figure 7. Comparison of frequency modulation with amplitude modulation. The yellow dashed line in the image samples shows the location of the cross-section. As compared to the FM mode, the statistical distribution and cross-section of the AM method do not clearly show the subsurface features due to the lack of signal to noise ratio.

6. CONCLUSION

In this paper, we presented the use of a photothermal excitation technique for subsurface measurements using atomic force microscopy. The use of photothermal excitation resolves the ambiguity of the frequency response functions which is one of the most important problems for application of atomic force microscopy as a subsurface metrology tool. Doing so, the photothermal excitation technique also enables the use of the frequency modulation technique which provides a much better signal to noise ratio as compared to the state of the art subsurface AFM techniques, besides being a quantitative measure. We have successfully implemented the proposed technique on a home-built AFM as well as a commercially available AFM system. It has also been shown that the performance of the proposed system can be even improved further by optimizing the cantilevers.

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