Application of FFT transformation for correlation analysis of near field microscopy measurements

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Abstract. The near field microscopy has been a dynamically developing diagnostic method for the last two decades. The number of measurement modes and data it delivers, sometimes make it difficult for interpreting. Thereby one needs sophisticated methods of extraction to get some specific information from the obtained results. Increasing complexity of the instruments as well as a software allows to acquire several signals simultaneously and to process them in a specific way in order to receive a particular result. Two dimensional Fast Fourier Transformation (2D FFT) is one of the most important tools in the picture analysis in near field microscopy. Such tools as finding specific spatial frequencies or noise filtering are very efficient. In the article we present some results of different modes of AFM measurements, where additional signals were acquired during measurements and by performing 2D FFT with the comparison approach, specific results and information were obtained.

1. Introduction

The measurement of the physical properties of the surface in nanoscale requires specific methods and tools. One of the most popular technique in such measurements is the Atomic Force Microscopy (AFM). The principle of the method is the observation of the interaction between the surface and the scanning tip moving within the distance of few tens of nanometers from the surface (the specific distance varies with used methods). During the scanning process, the tip-sample interaction is measured and converted in a specific way. When processed, the signals measured by various sensors are acquired as X-Y data matrix, where the X and Y are spatial coordinates related to specific spot on the sample’s surface. Using such formatted data, one can visualize the results as graphs that represents certain properties of the surface. Recently more than one or two signals can be acquired with commercial or home made systems, thereby the amount of information grows radically. Despite the possibilities of main signal interpretation, a significant amount of the information about the properties of the surface can be found in other signals acquired by the instrument. For different AFM modes, particular signals can be available, in order to provide the information related to the measured phenomena. Moreover, one can also observe additional signals which are not frequently used, but appropriately interpreted can be very useful for obtaining the best possible quality. One of the data

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processing methods is two dimensional FFT (Fast Fourier Transformation), which can improve the data processing chain. By combining the various signals FFT’s, the results comparison and processing, and finally inverted FFT’s, we could improve the quality of the results as well as increase the amount of information we could receive.

2. Typical signals in AFM instruments
Typical setup allows to acquire several signals measured or generated by specific components of the instrument: scanning head, controller (including PID regulator), linearizer, lock-in detectors and so on. It must be emphasized that particular signals can be available only for certain measurement modes or they can contain different kinds of information as the configuration or setting of the instrument changes. As the principle signal, the topography information is always considered. It contains the tip or sample height value at certain point. It allows to create 2-dimensional or 3-dimensional picture of the shape of the surface. Mostly one can assume that this information correlates very precisely with the sample’s surface topography. Despite the tip’s shape influence as well as the near field interaction issues, which are commonly known and considered [1-5], the topography signal can differ significantly from the reality if the regulation process of tip-sample distance was not performed appropriately. In real conditions there is always some difference between the expected value, which mostly is called as a setpoint and the real value which generally follows the setpoint and its efficiency can be changed with the PID regulator settings. This difference between the setpoint and the real value is mostly called an error signal and it can be very helpful for adjusting the Z feedback parameters. Mostly one can observe significant values of the error signal when the tip approaches the steep slopes of objects on the surface. Thereby the information about such features is not completely lost and it also can be used for the result interpretation. Another typical signals are: cantilever deflection for LFM mode, signal amplitude and phase in dynamic modes. Also specific signals active for certain modes like EFM, MFM, SKFM, FMM, SThM and many others are acquired during the measurement and available as a piece of information about specific properties of the surface. One must be aware, that the mutual correlation of the signals should be taken into account, especially when one wants to eliminate the artefacts. Thereby the simultaneous processing of different signals can improve the interpretation process. It must be emphasized that the signals can be acquired during movement of the scanning tip forward and backward (if the scanning algorithm moves the tip back and forth in that same slow axis coordinate). This feature allows to recognize various issues connected to Z feedback settings, scanner nonlinearity or other phenomena which can be a significant source of misinterpretation.

3. Fast Fourier Transformation and Two dimensional Fast Fourier Transformation
Fourier Transformation can be described as a calculation of frequency spectrum of a signal. This method of data processing allows to reveal single frequencies which if mixed, cannot be distinguished in any other way. Thereby specific values of frequencies can be discovered or measured if necessary. Two dimensional FFT (2D FFT) is a much more complex method and it shows spatial frequencies which are responsible for the presence of the artefacts and features with certain orientation and size. The 2D FFT processing can be performed with many commercial programs [6,7] as well as free ones [8-11]. In order to obtain a specific result, one needs to choose the windowing method and the result form, thereby it is important to use appropriate settings.

Due to the planar character of the AFM measurement sampling, the 2-dimensional FFT must be applied:

\[
F(i,k) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} s(m,n) \cdot \exp\left(\frac{-j \cdot 2 \cdot \pi \cdot m \cdot i}{M}\right) \cdot \exp\left(\frac{-j \cdot 2 \cdot \pi \cdot n \cdot k}{N}\right)
\]

where \(F(i,k)\) is the point of 2-dimensional magnitude spectrum, \(s(m,n)\) is the sample of image of coordinates \((m,n)\), \(M\) and \(N\) are dimensions of the image (expressed as the number of samples). Complex elements represent pairs of sine and cosine samples of the appropriate frequency and phase.
used for correlation. Typically in AFM everyday’s practise 2D FFT can be used for certain frequency
noise filtering, deconvolution, measurement periodicity of the structures and its orientation [12-19].

4. Experimental results

As an example of a data interpretation and processing using the 2D FFT, a structure developed by
local oxidation of the silicon is shown. The results were measured with a home made combined shear
force/ emission microscope which was described elsewhere [20, 21]. Three signals were acquired with
the instrument: topography (figure 1), error (figure 3) and phase (figure 5). The topography signal
shows three sloped lines which were developed during the oxidation test procedure. The FFT picture
shows an adequate response. In the error signal one cannot distinguish typical features connected to
measured structures (visible when the regulation is not perfect), thereby we can assume that the PID
parameters were adjusted correctly and the scanning process was running without any loss of
information about the surface’s shape. However 2D FFT of error signal reveals very weak response
coherent to 2D FFT of topography signal. Although the amplitude of this response is at that same level
as noise, but is visible anyway due to its specific shape. Such a small FFT object is better visible than
the original, large shape of the object on the signal picture. Another confirmation we could obtain is
the phase picture, where the shape of developed structure is visible. Usually, a phase shift in the
dynamic AFM mode is related to a difference of mechanical (viscoelasticity) properties of the surface.
Thereby we can see that oxidized silicon differs from the silicon surface covered with native oxide.
However the signal/ noise ratio is very poor and additional comparison of topography FFT (figure 2)
and phase FFT (figure 6), where the sloped lines are coherent, allows to confirm this observation.

![Figure 1. Topography signal. The object visible in the middle was developed by a local oxidation of silicon surface.](image1)

![Figure 2. 2D FFT of topography signal](image2)

![Figure 3. Error signal](image3)

![Figure 4. 2D FFT of error signal.](image4)
Moreover, due to the fact, that the phase signal can also contain error-like response (change of the cantilever oscillation amplitude caused by imperfect tip-sample distance regulation, affects also the phase shift), one can compare signal/noise ratio in error FFT (figure 4) and phase FFT (figure 6). It can be seen clearly that the phase FFT is much stronger, therefore the obtained image is related to surface properties, not to quality of measurement process.

Another example of the analysis of several signals is the measurement performed in intermittent contact mode with Innova instrument from Veeco. Topo, Phase (PhaseImaging) and TM Deflection (containing top-bottom laser beam unbalance detected signal from the cantilever) signals were acquired. The measured object was the surface of integrated circuit. One can see, that the topography signal (figure 7) is relatively undisturbed, however the phase signal (figure 8), which is also an important source of information, contains wavy artifacts. Its presence is connected to high reflectance of the surface and high, steep features causing unwanted interference, what disturbs a detection process. Thereby we can see a combination of real and not existing objects. In order to remove them one can use the 2D FFT filtering method, however the FFT result contains complex information about the picture and it is not obvious, which area is responsible for the presence of the artifacts (figure 12).

We found out, that the TM Deflection signal contains all reflection artifacts (figure 9) and can be used as a source of information about the spatial frequencies responsible for appearance of the wavy structure. After performing 2D FFT of TM Deflection signal, we could easily recognize the areas which should be filtered in order to remove undesired features (figure 10). The artifact extracted from TM Deflection signal (figure 11) by applying FFT confirmed appropriate choice of the spatial frequencies. Finally, we applied the FFT filtering to the phase signal (figure 14).
Figure 9. TM Deflection signal.

Figure 10. 2D FFT TM Deflection signal.

Figure 11. The IFFT of selected round areas from TM Deflection 2D FFT.

Figure 12. 2D FFT of phase signal.

Figure 13. Phase signal after IFFT.

Figure 14. 2D FFT of phase signal with filtered unwanted areas.

Figure 15. Crosssection of unfiltered phase signal along line marked with “1”.

Figure 16. Crosssection of filtered phase signal along line marked with “1”.

Although the artifact was removed, another appeared instead. Nevertheless we could compare the filtered and unfiltered signals and filtering process definitively improved the quality of the result. In order to compare the results before and after filtering process, the crossections of specific profile are shown (figures 15 and 16). The amplitude and frequency of the artefact has been reduced.

5. Conclusions
As presented, the method of using other signals in order to improve the filtering process and analyze the results appeared to be useful. Also first tests of application of this method for the EFM mode were promising, where the electrostatic interaction is detected in “LiftMode”, and the detection of tip oscillation is very fragile for interference from the highly reflective surface. Currently available FFT filters allow to remove specific areas (reduce the power of signal to 0), what causes removing some artefacts, but introducing a new ones instead. In our opinion a feature, where one can modulate the power of specific frequencies would be useful, however the complexity of whole operation would increase significantly. We have also observed interesting correlations between 2D FFT’s of different signals, however further work should be performed in order to recognize its origin.

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Acknowledgments
This work was financially supported by Polish Ministry of Science and Higher Education under Grant 3 T11B 021 30.