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The influence of the electrical field on structures dimension measurement in electrostatic force microscopy mode

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Electrostatic force microscopy (EFM) is one of important tools for diagnostic of surface electric properties on micro- and nanoscale. Its usefulness can be particularly seen when the development of new devices or materials is considered and its electric behavior is to be investigated. Due to the accessibility to both the height and the electrostatic distribution in two-dimensional data matrix, one can easily correlate the topography and electric properties of the surface. It is common that experienced AFM users pay attention to the presence of artifacts, but generally only the influence of the height signal on the EFM signal is considered. In the article, the influence of the electrostatic force on the measurement accuracy of structure dimensions will be shown. Also, the way of avoiding the misinterpretation of data will be proposed.

Keywords: atomic force microscopy (AFM), electrostatic force microscopy (EFM), dimensions measurement accuracy.

1. Introduction

The development of atomic force microscopy (AFM) techniques for the last two decades allowed us to obtain information about various properties of the surface of samples. Such modes as LFM (tribology), FMM (stiffness), MFM (magnetic domain orientation), EFM (electrostatic charge distribution), SThM (temperature, thermal conductivity), and others, cover wide spectra of the properties which should be measured when new material or device is tested.

Electrostatic force microscopy (EFM) is a very popular mode with a particular application in semiconductor industry and materials science [1–4]. It is a derivative technique from the intermittent contact mode, when the scanning tip vibrating perpendicularly to the surface, touches (taps) it for a certain part of the cycle, and as a result, the reduction of the oscillation amplitude can be measured (this technique is also known as tapping mode). Detection of the amplitude is used for determination of the tip-to-sample distance. While scanning over the surface, one can gather information about the height at every point and create a map which images the shape of the scanned surface. This technique is most common due to its high resolution and low risk of surface modification [5–7]. Acquisition of information about the electrostatic charge is realized by moving the tip above the surface, where previously observed interaction between the tip and sample is no longer present, but the electrostatic interaction can still be detected. Therefore, the first pass of the tip allows us to obtain information about the height of the surface, and during the second pass the tip is raised above the surface and moves along the acquired profile. The change of the amplitude and the phase shift caused by the electrostatic interaction are observed. This procedure is known as the two-pass, or as the lift mode, technique. In order to perform such measurement, a silicon tip with a metallic layer deposited on it should be used and a cantilever should be connected electrically to the biasing circuit. After the measurement is complete, one obtains two maps: the topography of the sample and the charge distribution correlated with the topography. An example of such data set is shown in Fig. 1, where two diffusion resistors in a powered integrated circuit were scanned. Although one cannot see those resistors in the topography, and only alumina contacts and interconnections are visible, the EFM picture reveals the potential along the resistors. Moreover, the width of visualized electrostatic interaction varies along the resistors, which is caused by the voltage dropout. This example shows how valuable can be the information obtained with this method.

During analysis of the data, one should be aware of the possibility of artifacts appearing. In the EFM image (Fig. 1), one can see the brighter and darker lines along the edges of the interconnections (lower right corner), which are not the result of a local change in charge distribution, but are present due to the imperfection of the scanning process. Such artifact can be easily found where the tip is moving above the surface with imperfect distance control which results in detection errors of the electrostatic interaction. Also a change of active area of the tip scanning (the surface exposed to the interaction) can cause such an effect [8]. This is obvious for experienced users and must be taken into account. There is, however, another kind of artifacts that can be introduced into the topography data, and if undiscovered, can be used for further data processing and lead to wrong conclusions. Moreover, unlike the typical tip-caused

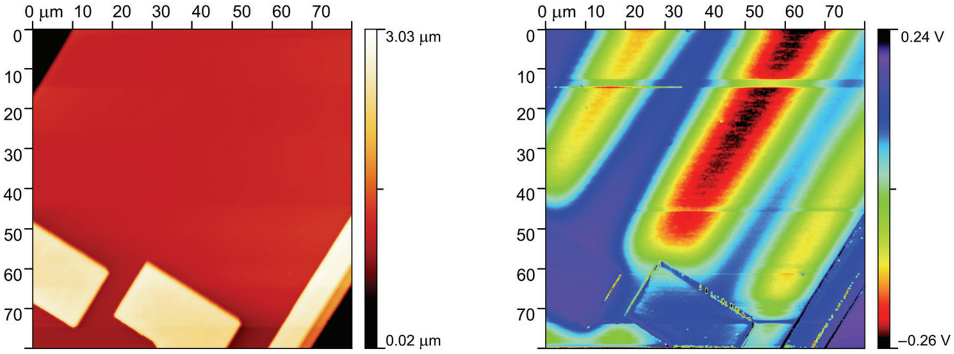

Fig. 1. An example of using EFM in detection of the current paths in the integrated circuit (topography: left-hand side; the EFM image on the right-hand side).

distortion of the surface's shape, one cannot use the advanced method of data reconstruction (blind reconstruction) [9, 10] in order to obtain the result with removed artifacts. The problem of such influence was also observed in the surface potential mapping (SPM) technique [11].

2. The influence of electrostatic field on the tip-sample interaction

The oscillating tip can detect various forces when approaches the surface in the distance of near field interaction. The principal mechanism, which is used in topography measurement, are attractive and repulsive Van der Waals forces [12]. Also the capillary forces can be observed, therefore one can obtain a map of the viscosity correlated with topography (phase shift of the oscillating tip) [13, 14]. When the cantilever is covered with conductive or magnetic material, one can also detect additional forces like the presence of electrostatic field or magnetic domains if the tip-to-sample distance

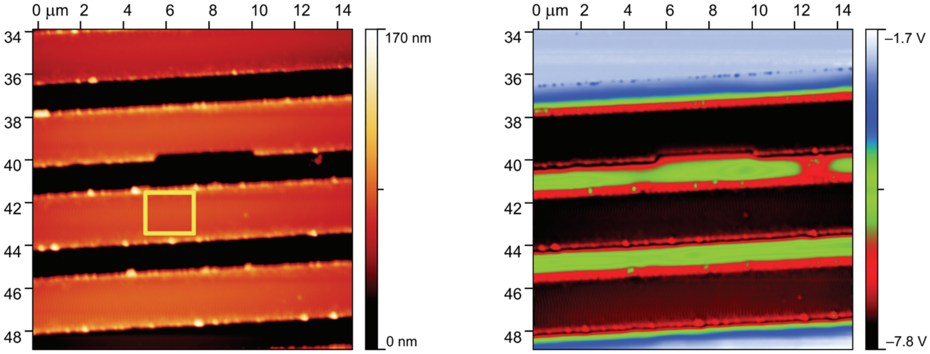

Fig. 2. The results of measurement performed on the test structure (topography: left-hand side; the EFM image on the right-hand side). Three middle alumina lines are biased at 6.1 V. This is well visible in EFM image. The height of the lines measured during the scan appears different (lines biased and unbiased).

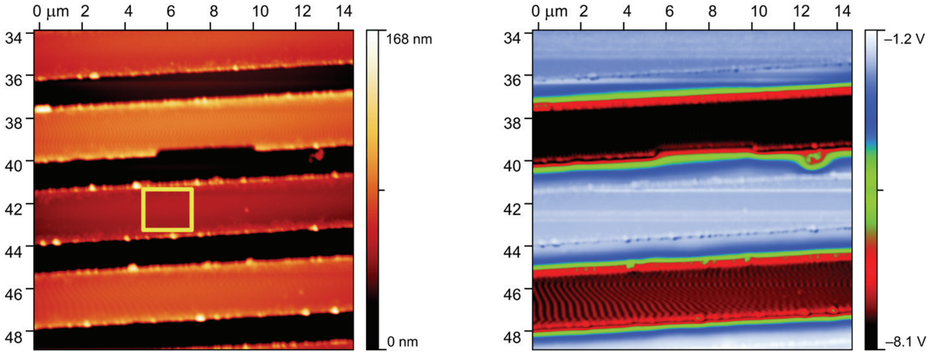

Fig. 3. The results of measurement performed on the test structure shown above (topography: left-hand side; EFM image on the right-hand side). This time every second alumina line is biased with voltage of 6.1 V. The middle line appears to be lower than the other two ones beside. This is unlike the previous scan.

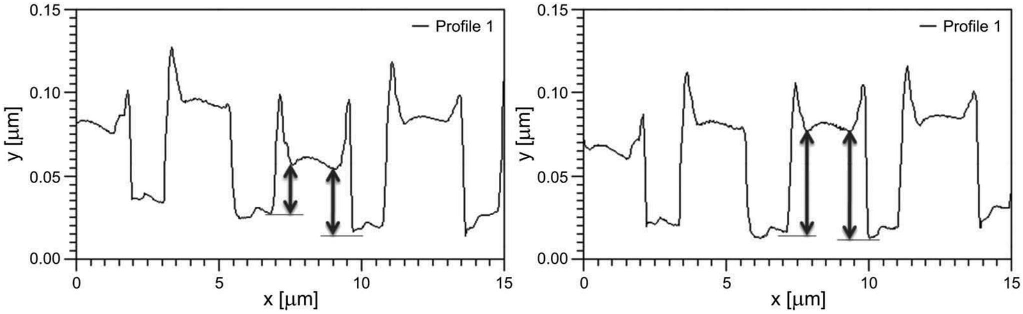

Fig. 4. Profiles taken across the topography images of Figs. 2 and 3 (left- and right-hand sides, respectively). One can clearly see differences in height of the lines.

is within the specific range. It can be, however, a source of problems, when a particular interaction disturbs detection of the other one. In such a case, artifacts can appear. Therefore one should interpret the results very carefully or perform an experiment in order to avoid such situation. When the electrostatic force is strong enough, it can act together with van der Waals forces and, during the first pass of the scanning tip, cause a change of the oscillation amplitude. The way it influences the topography measurement is shown in Figs. 2–4. The selected lines of the test structure were biased with voltage of 6.1 V.

As a next step, one of the lines of the structure was disconnected and measurement was undertaken again (Fig. 3). It can be easily noticed that the indication of the height of the line changed significantly after disconnecting. Therefore, one could assume, when performing the data analysis without careful consideration, that the lines of the structure differ in height.

In order to evaluate the change of the structure's height indication, profiles of the imaged surface of the test structure for both cases described above were made (Fig. 4). The height of each line was measured at two points (see arrows) and the data are compared in Tab. 1. One can note that the height of all lines, except the middle one, are practically the same. However, significance of the middle line's height change (3L, 3R) can be seen clearly.

The calculated difference in the height of the structure shows practically a 100% increase of the readout in the presence of electric field, which is unacceptable. Also, calculation of the surface roughness was performed within the disconnected structure area (the rectangles marked in Figs. 2 and 3) in order to show the influence

Table 1. The height of structures measured for two different bias cases.

	1R	2L	2R	**3L**	**3R**	4L	4R
h_1 [nm]	39	57	69	**29**	**39**	63	65
h_2 [nm]	38	60	66	**60**	**64**	61	63
Δ [nm]	1	3	3	**31**	**25**	2	2

Table 2. The roughness evaluation of scans measured for two different bias cases corresponding to Figs. 2 and 3, respectively.

	Case 1	Case 2
Ra [nm] (mean value of the height irregularities)	1.1	2.7
Rms [nm] (RMS value of the height irregularities: this quantity is computed from data variance)	1.5	3.0
Skew (height distribution skewness: computed from the 3rd central moment of data values)	0.0632	−0.354
Kurtosis (height distribution kurtosis: computed from the 4th central moment of data values)	0.409	−1.07

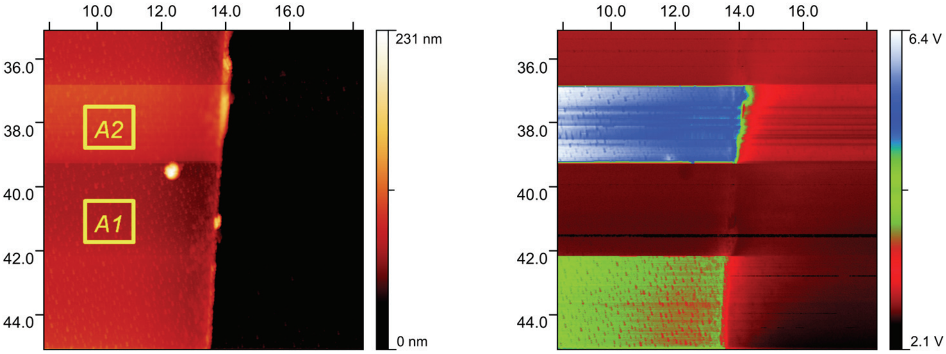

Fig. 5. Influence of electric field while the bias voltage changed during scanning. Note the horizontal stripes (topography: left-hand side; EFM image on the right-hand side).

of the electrostatic field (Tab. 2). The differences are significant, therefore one cannot use the data obtained during measurement of biased structures in order to evaluate such parameters.

Another example is presented in Fig. 5, where the bias voltage was changed during scanning. One can see the changes in EFM signal, however, horizontal stripes in the topography image can also be found. Those stripes correlate perfectly, therefore the influence of the electric field is shown very clearly. Also the elevation of the substrate can be noticed. Again, the roughness of the surface was calculated and given in Tabs. 2 and 3. Significant differences are visible. The examples presented are easy to recognize due to known or predictable surface construction. In the case of material samples or unknown structures, the distortions can be overlooked and used for evaluation of certain properties. Eventually, the results obtained would be irrelevant.

Due to dynamic interaction between the tip and the sample, the oscillation amplitude of the cantilever was changed (3, 11, 114 nm) and the approach curve (tip's oscillation amplitude versus distance) was measured for different sample bias voltages from 0 to 6 V (Fig. 6). One can see that for small amplitudes the influence caused by the electric field is much stronger than that for a relatively large amplitude. This effect

Table 3. The roughness evaluation for scans performed with different bias voltage.

	Area 1	Area 2
Ra [nm]	2.8	5.2
Rms [nm]	3.7	6.2
Skew	1.29	−0.413
Kurtosis	2.23	−0.663

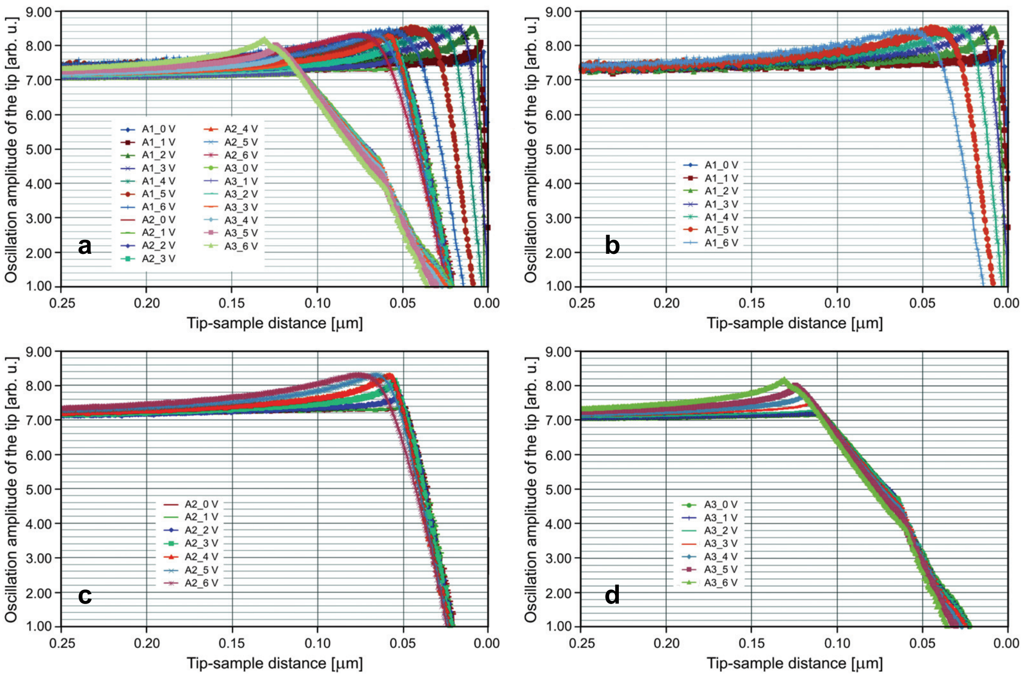

Fig. 6. The obtained approach curves, the parameter of the curves being the voltage applied to the structures. All sets together (**a**), three sets of approach curves were obtained for oscillation amplitudes: 3 nm (**b**), 11 nm (**c**), and 114 nm (**d**). Voltages applied were: 0, 1, 2, 3, 4, 5, 6 V for each set.

is due to changing the fraction of the time the tip experiences the electrostatic interaction and repulsive forces. A larger amplitude (tens or hundreds of nanometers) causes a weaker electrostatic interaction but a stronger tapping of the tip against the surface. A 30 nm shift of the approach curve for the 3 nm oscillation amplitude and 6 V bias voltage (4.5 V set point) corresponds perfectly with the structure's height increase presented in the first example.

3. The electric field's influence problem solution

In order to avoid the problem of introducing a significant influence of the electric field on the measurement result, one can use a few methods proposed below. The easiest way is to disconnect the sample from external source of power. In such a case, additional measurement should deliver reliable information about the topography, and the dimensions can be estimated within the standard uncertainty of the instrument. One must pay attention whether the internal capacitances are already discharged in order to avoid accidental influence of residual electric field.

The next method is to apply the amplitude of the cantilever oscillation at a level which would guarantee insignificant influence of the electric field during the topography measurement. The best way to confirm if one has already reached that level is to perform a few measurements with different excitation amplitudes of the cantilever. If at some point the dimensions of the structures are not changing, one can assume that the obtained data can be used for size estimation. The drawback of this method is the time consuming procedure and increased wear of the tip due to closer tapping of the tip against the surface. Also, the reduced sensitivity of the electric field during the second pass of the tip must be taken into account. This is, however, a compromise between quality of both acquired signals: the topography and electrostatic field distribution. It must be emphasized that when the topography has not been scanned correctly due to the influence of electric field, the height of the second pass is also disturbed (*i.e.*, 25 nm higher than it should be due to such an increase in the height of structure); therefore, also the electrostatic charge distribution map is convoluted significantly.

Finally, the scanning Kelvin probe microscopy (SKPM, SPM) can be used instead [4, 15–17]. This mode is based on compensation of the voltage difference between the tip and the sample, therefore the interaction caused by electrostatic field is minimized and does not have any impact on the topography measurement. The result of the measurement performed the same way as that of Fig. 5 is shown in Fig. 7. It is known, however, that this method is very sensitive, therefore one can observe distortions of the potential map, if working semiconductor devices are measured. The influence sometimes reaches the millimeter range. Moreover, the SKPM mode is not typically available in basic SPM instrument setups.

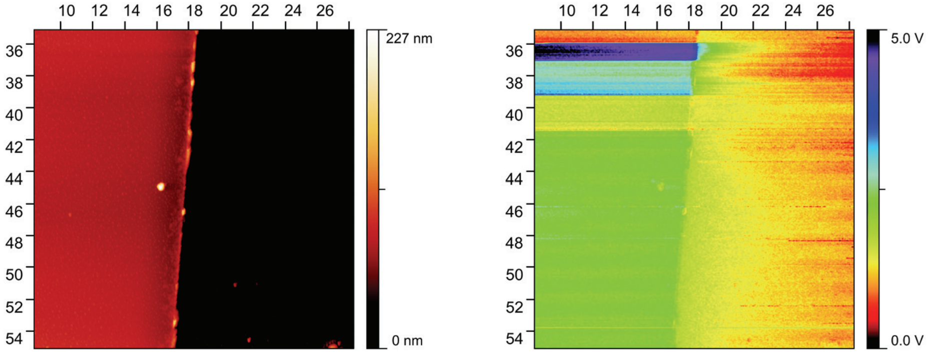

Fig. 7. The results of the SKPM measurement. The bias change during the measurement did not cause the topography distortion. The SKPM picture shows the voltage value applied to the structure.

4. Conclusions

The near-field microscopy techniques can deliver a variety of information about the scanned surface. Several modes offer different signals in order to create an image of the distribution of specific properties and the quality of the scanning process. One can, if carefully, use those signals to analyze their result. Usually, only two or three signals are considered as useful data. Therefore the source of artifacts can be overlooked and the data can appear misinterpreted. In the case of electrostatic force microscopy the influence of the topography on the EFM signal is known and taken into account. However, the opposite interaction is not so commonly taken into account, therefore it is easier to overlook its presence.

In the article, examples of possible distortions caused by the presence of electric field typical of standard electronic circuits have been presented. Also, the origin of as well as methods to avoid such problems have been described.

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