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Theoretical analysis of the atomic force microscopy characterization of columnar thin films

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Abstract

In this paper, the theoretical analysis of the influence of finite linear dimensions of an atomic force microscope tip on profiles of the upper boundaries of columnar thin films and their statistical quantities is performed. This analysis is based on a numerical evaluation of the main statistical quantities, i.e. the standard deviations of the heights and slopes, one-dimensional distributions of the probability density of heights and slopes and power spectral density function, corresponding to a simulated columnar structure of the thin films. It is shown that the strongest misrepresentation of the measured profiles of the upper boundaries of the columnar films originates in the cases when the linear dimensions of the columns are smaller or comparable with the linear dimensions of the tip. Further, it is shown that using a surface reconstruction procedure one can correct (improve) the boundary profiles and their statistical quantities partially. The results of this analysis enable us to perform rough estimation of the errors achieved within atomic force microscopy studies of the real columnar thin films. Moreover, these results allow to estimate the corrections of the statistical quantities mentioned above to be obtained using the surface reconstruction. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The structure of the upper boundaries of thin films exhibiting a columnar structure (e.g. dielectric films prepared by miscellaneous technologies) are often studied using atomic force microscopy (AFM) (see, e.g. Refs. [1–3]). This structure influences the properties of the columnar thin films in a significant way. For example, the optical properties of these films are strongly influenced by this structure (see, e.g. Refs. [1,4, 6–8]. By means of AFM measurements, one can determine the values of quantitative characteristics describing the structure of the upper boundaries of the columnar thin films. The tops of the columns namely form a certain statistical roughness (see, e.g. Refs. [1,5]) that can be characterized by the known statistical quantities such as the RMS

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values of the heights and slopes, correlation function, power spectral density function (PSDF), etc. In consequence of finite dimensions of the tips of atomic force microscopes the values of the statistical quantities characterizing the boundary roughness caused by the columnar structure can be misrepresented considerably (see, e.g. Ref. [1]). Several procedures enabling us to respect the finite dimensions of tips in quantitative AFM studies of various objects whose linear dimensions are comparable with the dimensions of these tips have been developed (see, e.g. Refs. [9–11]). Because of the fact that the linear dimensions of the boundary roughness corresponding to the columnar structure are mostly comparable to the tip dimensions one can use the procedures mentioned for estimating the misrepresentation of the AFM results concerning this surface roughness.

In this paper, we shall deal with the theoretical analysis concerning the influence of the tip dimensions on the values of the main statistical quantities characterizing the surface roughness of the upper boundaries of the columnar thin films based on the following stages (see also Fig. 1):

1. The columnar structure of thin films is simulated by a simple theoretical model of growing these thin films corresponding to their deposition. Further, the values of the statistical quantities of this simulated structure are determined.
2. Using the dilation algorithm given by Villarrubia [9] an AFM image of the upper boundary for the columnar structure originated is simulated for a chosen AFM tip geometry.
3. The values of the statistical quantities are determined using the data corresponding to this image, i.e. using the data corresponding to the structure influenced by the tip dimensions (uncorrected structure).
4. Using the surface reconstruction described by Villarrubia [9] (algorithm referred as "erosion") the tip effect on the boundary is partially corrected.
5. The values of the statistical quantities corresponding to the corrected structure of the boundary are determined.
6. The values of the statistical quantities concerning the corrected structure are compared with the values of the same statistical quantities evaluated for simulated and uncorrected structures.

Using this theoretical analysis, one can estimate errors of the statistical quantities describing the upper boundaries of the columnar thin films originating within the AFM characterization of the different columnar films in practice.

2. Simulation of the columnar thin film growth

For the simulation of the growth of the columnar thin films the simple $(2+1)$-dimensional algorithm based on Monte Carlo procedure was employed. Moreover, a shadowing model was included into this procedure.This means that the procedure used was similar to those presented in the different papers dealing with simulating sputter deposition of the thin films (see, Refs. [12,13]). Within the procedure the upper boundary between the ambient and film is described by a height function $\zeta(x,y)$ for a chosen time, where x and y denote the Cartesian coordinates corresponding to the system placed into the mean plane of the upper boundary of the film. The simulation was performed on the grating of $N \times N$ $(N = 400)$ points. The periodic condition, e.g. the condition $\zeta(x,y) = \zeta(x+N, y+N)$, was utilized. A particle was placed in a random position above the boundary and then this particle was incident onto the boundary under a certain direction chosen according to a given distribution function of their falling onto the boundary. Upon striking the boundary, the particle sticked at the point of impact. However, if the particle hitted the side of a column, it slided straight down until if hitted the boundary again. Further, with a certain probability it was ensured that the sticked particle could be translated into an adjacent lower position at the boundary. In this way, a limited diffusion of the particles along the boundary was allowed. Note that the distribution function of the directions of the particles falling on the boundary was chosen in the form of the cosine distribution (this distribution corresponds to the simplest situation concerning the sputtering process, i.e. it corresponds to neglecting a mutual interaction of the falling particles). It should be pointed out that the other distribution functions of the directions were tested. However, for the other distributions, similar results were obtained for the structure of the upper boundaries. After the simulation procedure the columnar structure was scaled into the dimensions corresponding to usual columnar structures and linear dimensions of typical AFM images. In Fig. 2, the example of the cross-section of $(2+1)$-dimensional columnar structure achieved using the procedure described is plotted. For our analysis, we used the same columnar structure that was scaled in three different ways. We then achieved the three different relations between the linear dimensions of the tip on the one hand and the linear dimensions of this columnar structure on the other hand. The advantage of this approach consists in the fact that the forms of the statistical quantities of the original simulated columnar structure will be identical in all the three different cases of the relations between the tip dimensions and this columnar structure.

3. Definitions of the statistical quantities employed for the analysis

In this section, mathematical formulae defining the statistical quantities employed within our theoretical analysis are introduced.

1. The RMS value of the heights of irregularities σ:

$$\sigma^2 = \int_{-\infty}^{\infty} z^2 w(z)\,\mathrm{d}z = \lim_{S\to\infty} \frac{1}{S} \int\int_S \zeta^2(x,y)\,\mathrm{d}x\,\mathrm{d}y, \tag{1}$$

where $w(z)$ denotes the one-dimensional distribution of the probability density of the random function $\zeta(x,y)$, S represents the magnitude of the area of the columnar structure in the (x,y) plane and z denotes the values of the heights of the irregularities of the columnar structure.

2. The RMS value of the slopes of the irregularities $\tan^2\alpha_0$:

$$\tan^2\alpha_0 = \int_{-\infty}^{\infty} z'^2 w(z')\,\mathrm{d}z' = \lim_{S\to\infty} \frac{1}{S} \int\int_S \zeta'^2(x,y)\,\mathrm{d}x\,\mathrm{d}y, \tag{2}$$

where

$$\zeta'(x,y) = \frac{\partial\zeta(x,y)}{\partial x} \quad \text{or} \quad \frac{\partial\zeta(x,y)}{\partial y}, \tag{3}$$

$w(z')$ represents the one-dimensional distribution of the probability density of the random function $\zeta'(x,y)$ and z' represents the values of function $\zeta'(x,y)$.

3. The power spectral density function $W(K)$:

$$W(K) = W(K_x,K_y) = \frac{1}{2\pi} \int_0^{\infty} \tau B(\tau) J_0(\tau K)\,\mathrm{d}\tau, \tag{4}$$

where $K = \sqrt{(K_x^2 + K_y^2)}$, K_x and K_y denote the components of the wave vector of the harmonic component of a certain spatial frequency of the boundary roughness, J_0 represents the Bessel function of the zeroth order, $B(\tau)$ denotes the correlation function of the roughness and τ is the distance between the two points $[x_1,y_1]$ and $[x_2,y_2]$ ($\tau_x = x_2 - x_1$, $\tau_y = y_2 - y_1$, and $\tau = \sqrt{\tau_x^2 + \tau_y^2}$).

The mathematical definition of function $B(\tau)$ is given in many monographs (e.g. in Ref. [14]).

It should be pointed out that the foregoing definition formulae correspond to function $\zeta(x,y)$ describing the continuous stationary isotropic and ergodic stochastic process. Moreover, these formulae are true for function $\zeta(x,y)$ having the mean value equal to zero. The main statistical quantities σ, $\tan(\alpha_0)$, $w(z)$, $w(z')$ and $W(K)$ defined above can be used for theoretical investigations mentioned in Section 1 because they strongly influence some physical and other properties of the columnar thin films (e.g. optical properties).

4. Measurements of the statistical quantities using AFM

Within measuring the statistical quantities using AFM, the values of heights are determined in certain points of the (x, y) plane. Thus, within the AFM analysis, the following equations for determining these statistical quantities must be employed:

1. $$\sigma^2 = \frac{1}{NM} \sum_{j=0}^{M} \sum_{i=0}^{N} z_{ij}^2, \tag{5}$$

   where N and/or M is the number of the columns and/or rows corresponding to a concrete AFM scan.
2. $$\tan^2 \alpha_0 = \frac{1}{(N-1)M} \sum_{j=0}^{M} \sum_{i=0}^{N} z_{ij}'^2,$$
   $$\text{where } z_{ij}' = \frac{z_{i+1,j} - z_{ij}}{h}, \tag{6}$$

   where h represents the distance between the two points in the (x, y) plane used to calculate the values z_{ij}'.
3. In practice, it is more advantageous to use function $W_1(K_x)$ instead of function $W(K)$ defined by Eq. (4). This function $W_1(K_x)$ is given as follows:

   $$W_1(K_x) = \int_{-\infty}^{\infty} W(K_x, K_y)\, \mathrm{d}K_y. \tag{7}$$

   The values of $W_1(K_x)$ can be calculated by the fast Fourier transform, i.e.

   $$W_1(K_x) = \frac{2\pi}{NMh} \sum_{j=0}^{M} |\hat{P}_j(K_x)|^2, \tag{8}$$

   where $\hat{P}_j(K_x)$ is the Fourier coefficient of the jth row, i.e.

   $$\hat{P}_j(K_x) = \frac{h}{2\pi} \sum_{k=0}^{N} z_{kj} \exp(-\mathrm{i}K_x kh). \tag{9}$$

Functions $w(z)$ and $w(z')$ must be calculated using the following formulae:

$$w(z) = \frac{\mathcal{N}(z, \delta z)}{NM\, \delta z} \tag{10}$$

and

$$w(z') = \frac{\mathcal{N}(z', \delta z')}{(N-1)M\, \delta z'}, \tag{11}$$

where function $\mathcal{N}(z, \delta z)$ and/or $\mathcal{N}(z', \delta z')$ represents the number of the values of z_{ij} and/or z_{ij}' lying within the interval $\langle z - \delta z/2, z + \delta z/2 \rangle$ and/or $\langle z' - \delta z'/2, z' + \delta z'/2 \rangle$.

5. Processing of the simulated data

It is known that some artifacts (systematic errors) arise in AFM measurements of all fine structures [15–17]. The main artifact concerns the "tip convolution" due to the fact that the tip exhibits finite linear dimensions (i.e. the tip has not an ideal form represented by the δ-function). This effect causes a misrepresentation of the data describing a profile of the fine structure studied (e.g. the upper boundaries of the columnar thin films). The lateral dimensions of all the fine objects investigated including the roughness corresponding to the columnar structure are enlarged. Thus, the values of the statistical quantities characterizing the boundary roughness of the columnar films investigated must be misrepresented too. One must therefore correct this artifact in a suitable way.

For this purpose, two algorithms described by Villarrubia were employed in this paper. The first Villarrubia's algorithm (dilation) enables us to include the influence of the finite dimensions of the tip on the profile of the upper boundary of the columnar thin film measured, i.e. it enables us to construct the boundary profile measured using an AFM tip. The latter Villarrubia's algorithm (surface reconstruction) enables us to perform a certain correction of the measured (dilated) profile. A schematic diagram showing the boundary profiles obtained using the Villarrubia's algorithms is shown in Fig. 1.

For the purposes of our theoretical analysis we chose a model of the standard pyramidal contact AFM tip. The apex radius was equal to 10 nm (see Fig. 2).

Note that we examined the different forms of the tips (e.g. square-based pyramidal contact tip, triangle-based non-contact tip, sharpened tip etc.).

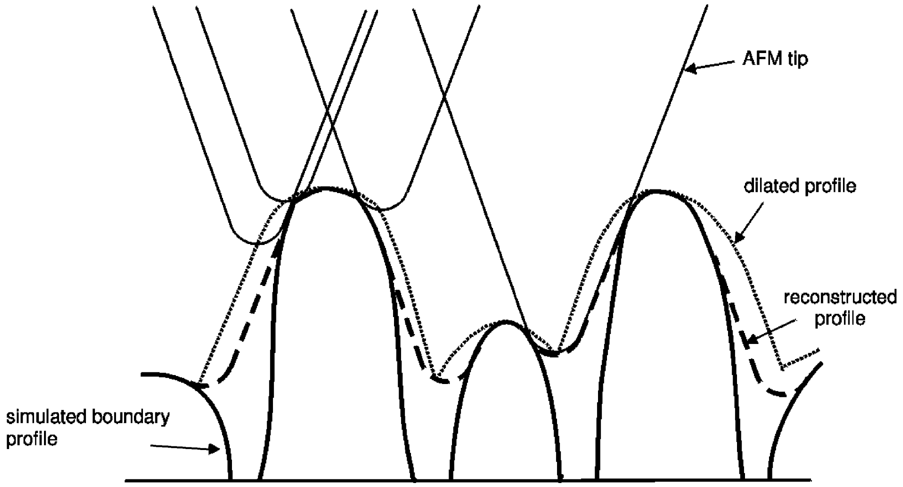

Fig. 1. Schematic diagram expressing the influence of the tip on measuring the profile of the upper boundary and improvement of this profile measured using the correcting algorithm employed.

We found that the results of our theoretical analysis were the same for all the tips from the practical point of view. This was caused by the fact that only the apexes of the tips mentioned influenced our results because of very small linear dimensions of the columnar structures studied (the dimensions of both the columns and pores were comparable with the tip radii). The tip apex radius equal to 10 nm was selected because this value was nearly identical with the values employed within the experimental AFM studies of the real columnar thin films (e.g. HfO_2 films). The values of the apex radii of the tips used in our experiments were determined using "blind tip estimation" algorithm described by Villarrubia [9].

6. Results and discussion

In Fig. 2, one can see the parts of the cross-sections of the boundaries of the three columnar films mutually differing in the linear dimensions (i.e. the cross-sections of the "fine", "medium" and "coarse" boundaries). From this figure it is evident that the misrepresentation of the measured profile is the largest one for the columnar structure with the smallest linear dimensions. Further, it is clear that for increasing the linear dimensions of the columnar structure the profile misrepresentation is reduced. However, even for the largest linear dimensions of this structures certain parts of the profile cannot be reached by the tip apex so that a certain misrepresentation of the boundary profile remains. Thus, one can state that the AFM data corresponding to the heights of the irregularities of the boundary profile of the columnar thin films are misrepresented more or less in principle. The measure of this misrepresentation is strongly dependent on the mutual relationship of the linear tip dimensions and linear columnar structure dimensions. It is necessary to point out that the measure of the foregoing profile misrepresentation is mainly given by the relation between tip apex radius and column lateral dimensions (see, Fig. 2). From Fig. 2, it is also seen that the profile corrected by the Villarrubia's surface reconstruction algorithm is evidently closer to the real (simulated) profile than the profile measured (misrepresented using dilation). In some places, both the corrected and measured profiles are practically identical. However, the differences between both these profiles take place for certain parts of the simulated profile. This is given by the fact that for these parts of the profile no information is obtained (these parts are mostly identical with the pores of the columnar structure).

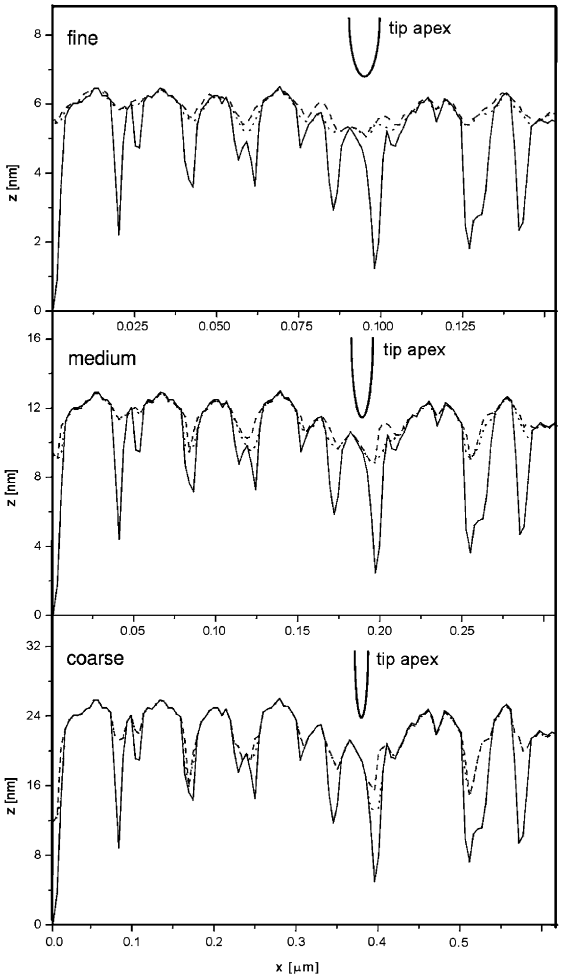

Fig. 2. Cross-sections of the three simulated upper boundaries of the columnar films. i.e. the "fine", "medium" and "coarse" boundaries, corresponding to the different relationships between the linear dimensions of tip and columns: (—) simulated profile, (- - - -) misrepresented (dilated) profile, (....) reconstructed profile.

Within these parts of the simulated profile any point of the apex of the tip does not touch this profile and so no information is contained in the AFM measurements about them (this statement is true for any correcting procedure). There is an algorithm enabling us to find the places on the rough surfaces (boundaries) that cannot be touched by the tip with the given geometry in a single point (see, Ref. [9]). Thus, in these places the profile of the rough surface (boundary) cannot be determined unambiguously. This algorithm allows to construct the "certainty map" showing the places that cannot be corrected using an "surface reconstruction" algorithm. Note that in Fig. 2, the tip apexes appear to be the parabolic ones because of the scales of both the coordinate axes (the z-axis and x-axis) are different (the z-axis has the nanometric scale and the x-axis has the micrometric scale).

Below the influence of both the Villarrubia's algorithms on the main statistical quantities mentioned above is quantitatively presented. In Fig. 3, one can see the one-dimensional

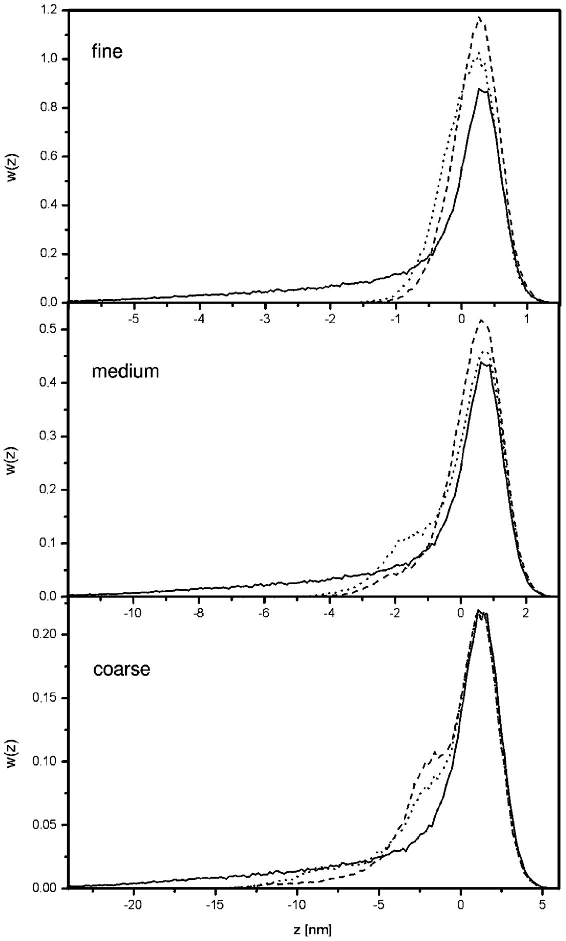

Fig. 3. Dependences of $w(z)$ corresponding to the "fine", "medium" and "coarse" boundaries: (—) simulated profile, (- - - -) misrepresented (dilated) profile, (....) reconstructed profile.

distributions of the probability density of the heights $w(z)$ for the three profiles plotted in Fig. 2. In Fig. 3, the curves of $w(z)$ corresponding to the simulated profile (boundary), measured (dilated) profile and corrected (reconstructed) profile are related to the mean value of the heights of the simulated profile put equal to zero (this operation is performed because of the simpler illustration). From this figure it is evident that the values of $w(z)$ for the highest values of the height z are practically the same for all the three profiles which is caused by the fact that the parts of the profiles corresponding to these values of z are touched by the top of the apex of the tip. The values of $w(z)$ corresponding to the measured (dilated) profile belonging to smaller values of z are influenced more or less by the tip. Further, it is clear that using the correcting Villarrubia's algorithm one can correct these values of $w(z)$ in a partial way. It is seen that for the smallest values of z the values of $w(z)$ are not equal to zero only for the simulated profile. In accordance with the profiles presented in the foregoing Fig. 2, this corresponds to the parts of the simulated profile that cannot be reached by the tip.

In Fig. 4, the one-dimensional distributions of the probability density of the slopes $w(\alpha)$ corresponding to the three boundary profiles are plotted. Note that function $w(\alpha)$ is related to function $w(z')$ (the values of z' are replaced by the corresponding values of the slope angles α). From this figure, it is clear that only for the simulated boundary profile the values of $w(\alpha)$ are different from zero for the relatively great values of the slopes represented by the values of angle α. Further, it is evident that the values of $w(\alpha)$ corresponding to the reconstructed profile come near to the values of $w(\alpha)$ belonging to the simulated profile again. Note that the values of $w(\alpha)$ differing from zero are limited by the certain value α_1 of the slope angle α depending on the relationship between the tip apex radius and linear dimensions of the columns (this statement is apparent from Figs. 2 and 4). It should be pointed out that even for the slope angles smaller than the threshold angle α_1 the forms of $w(\alpha)$ corresponding to the measured and corrected profiles are deformed in comparison with $w(\alpha)$ for the simulated profile. In Fig. 4, the curves of $w(\alpha)$ corresponding to the positive angles α are only plotted because it was found that the functions $w(\alpha)$ were symmetric ones owing to value $\alpha = 0$.

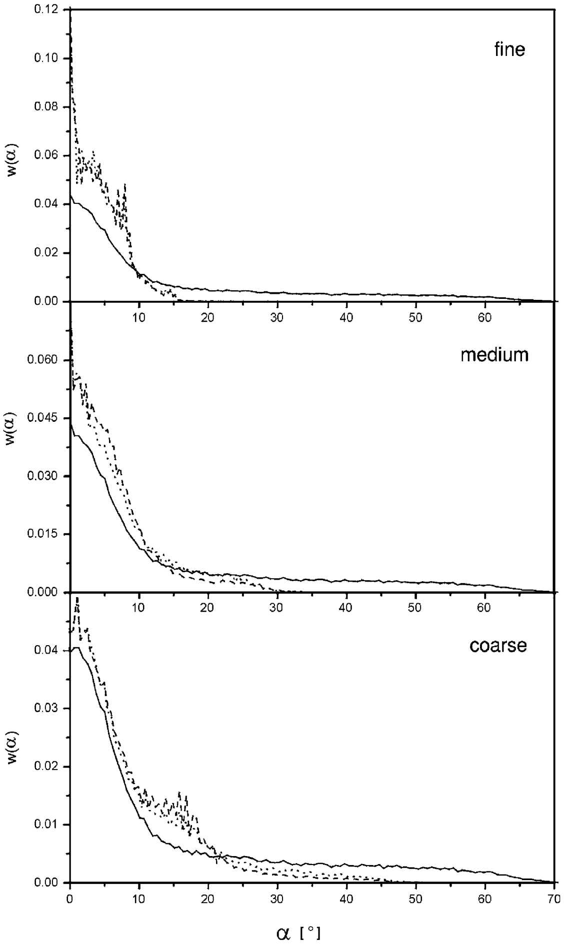

Fig. 4. Dependences of $w(\alpha)$ corresponding to the "fine", "medium" and "coarse" boundaries: (—) simulated profile, (- - - -) misrepresented (dilated) profile, (....) reconstructed profile. Note that the quantity z' is replaced by the corresponding slope angle α.

In Table 1, the RMS values of the heights and slope angles of the three individual profiles mentioned above belonging to the three different boundaries studied, i.e. to the "fine", "medium" and "coarse" boundaries, (see Fig. 2) are summarized. One can see that both the RMS values, i.e. σ and α_0, are strongly reduced in comparison with

Table 1
The values of σ and α_0 corresponding to the "fine", "medium" and "coarse" boundaries of the columnar structure calculated using Eqs. (5) and (6)

Boundary	α_0 (deg)	σ (nm)
Fine:		
Original	22.47	1.382
Dilated	5.40	0.366
Reconstructed	5.47	0.405
Medium:		
Original	22.47	2.763
Dilated	8.414	0.999
Reconstructed	9.387	1.210
Coarse:		
Original	22.47	5.526
Dilated	11.82	2.732
Reconstructed	12.97	3.159

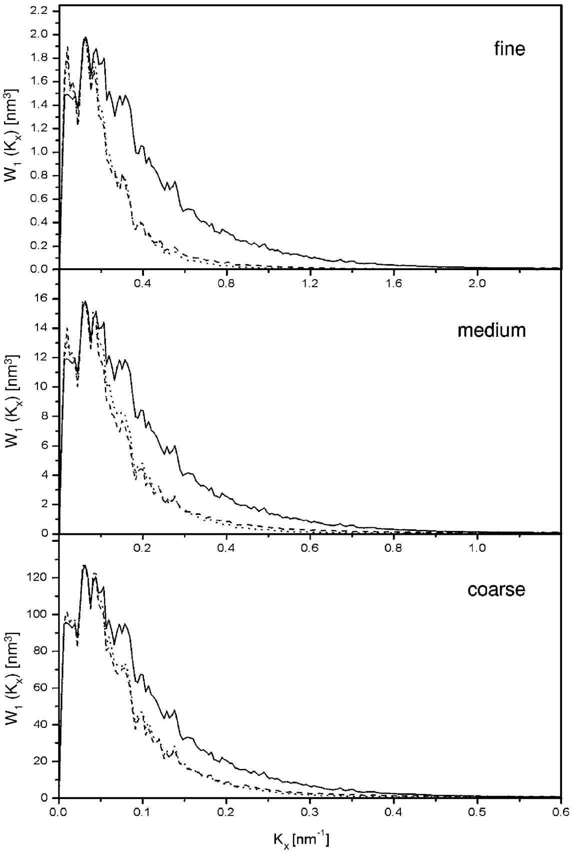

Fig. 5. Dependences of $W_1(K_x)$ corresponding to the "fine", "medium" and "coarse" boundaries: (—) simulated profile, (- - - -) misrepresented (dilated) profile, (....) reconstructed profile.

the values of these quantities corresponding to the simulated profile. The Villarrubia's surface reconstruction algorithm increases these RMS values clearly. However, from Table 1, it is implied that the values of σ and α_0 of the corrected boundary profiles are considerably different from those corresponding to the simulated (original) boundary profiles for all the three boundaries under investigation. This statement is true for the finest boundary (i.e. for the "fine" boundary) in particular. Thus, it is clear that the true values of σ and α_0 of the boundary roughness due to the columnar structure of the thin films differ from those determined using the AFM analysis in the relevant way in spite of including the surface reconstruction algorithm. This fact must be taken into account in AFM studies of the real columnar thin films in practice.

In Fig. 5, the power spectral density functions of the three boundaries studied, i.e. the "fine", "medium" and "coarse" boundaries, are plotted. It is evident that the influence of the tip on the measured boundary profile is enormous for all the three boundaries. Moreover, it is seen that the surface reconstruction algorithm does not enable us to improve the values of the PSDF of the measured profiles in a substantial way. The values of the PSDF of both the measured and corrected profiles corresponding to the higher values of K_x (i.e. higher values of the spatial frequencies) are totally suppressed. The threshold of this suppressing again depends on the relationship between the apex radius and linear dimensions of the columns. Thus, one can state that the values of the PSDF are influenced by the finite linear dimensions of the apex of the tip in the strongest way with regard to the other statistical quantities studied here.

Note that the correlation function corresponding to PSDF denoted as $W_1(K_x)$ can be determined by the Fourier transform of this PSDF (in practice the fast Fourier transform is mostly employed for this purpose).

It is evident that the results and conclusions similar to those presented here can be expected at measuring the upper boundaries of real columnar thin films taking place in practice. This statement can be supported by the fact that the simulated columnar thin films employed for our analysis are rather similar to the real columnar thin films. This statement is illustrated using Figs. 6A and 7A. In Fig. 6A, the AFM image of the upper boundary of the columnar structure of a chosen HfO_2 thin film measured by the atomic force microscope Topometrix Accurex II L is presented (note that the linear dimensions of the tip apex used was approximately identical with that chosen within our theoretical analysis). The measured (dilated) upper boundary of the columnar thin film corresponding to the "coarse" boundary of the simulated columnar structure is introduced in Fig. 7A. In Fig. 6B and/or Fig. 7B, the "certainty map" of the upper boundary of the HfO_2 thin film and/or the simulated columnar thin film is presented.

One can see that the similarity of both the structures is evident. This means that the results of the theoretical analysis carried out in this paper allow to estimate errors originating at the AFM statistical analysis of the real columnar thin films, i.e. these results and conclusions can enable us to estimate roughly the errors of the basic statistical quantities originated at AFM measurements of the upper boundaries of the columnar thin films taking place in practice. For example, using the procedures and results described here one can estimate the suppression of the higher spatial frequencies for the given dimensions of the tip apex used for determining the PSDF of the upper boundaries of these real columnar thin films. This is given by the fact that the true PSDF of the HfO_2 film is misrepresented by the chosen tip apex approximately in the same way as the PSDF corresponding to "coarse" structure which is supported by Figs. 6 and 7. This conclusion is obviously true for the remaining statistical quantities taken into account here.

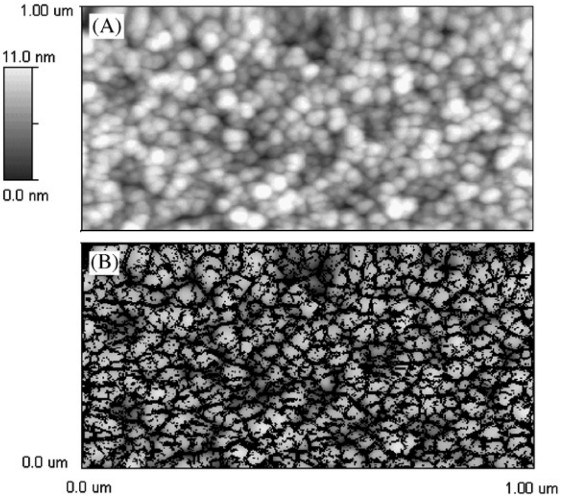

Fig. 6. A: The AFM image of the upper boundary of the selected HfO_2 thin film prepared by vacuum evaporation (thickness of this film is equal to 180 nm). B: The certainty map of the same part of the boundary of the HfO_2 film.

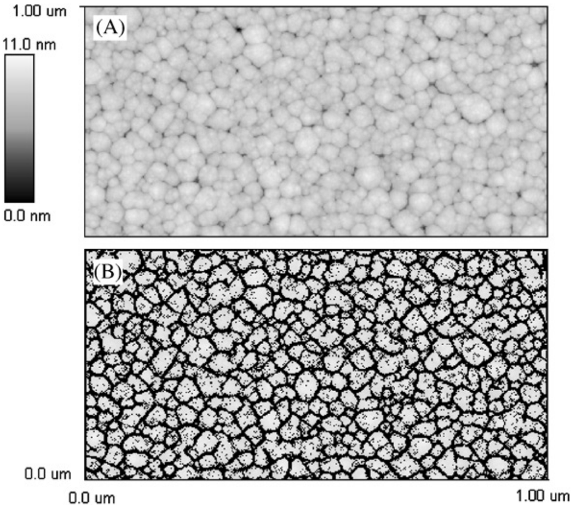

Fig. 7. A: The image of the misrepresented (dilated) upper boundary of the simulated columnar structure ("coarse" structure). B: The certainty map of the same part of the dilated boundary.

7. Conclusion

In this paper, the theoretical analysis enabling us to study the influence of the finite linear dimensions of the apex of the AFM tip on measuring the upper boundaries of the columnar thin films was performed. It was shown that the tip influence on the values of the basic statistical quantities characterizing the upper boundaries of the columnar thin films, i.e. σ, α_0, $w(z)$, $w(\alpha)$ and $W_1(K_x)$, is relatively strong. This statement is especially true for the thin films with the fine columnar structure, i.e. the films exhibiting the columnar structure characterized with the linear dimensions of the columns and pores smaller or comparable with the linear dimensions of the apex of the tip. Further, in this paper, it was shown that using the correcting procedures it was possible to correct the values of the statistical quantities in a partial way (here the surface reconstruction described by Villarrubia was used). This correcting algorithm was the least effective for the values of PSDF. It should be noted that the interpretation of the values of the PSDF evaluated for the upper boundaries of the columnar thin films by AFM can thus be very problematic. This statement is true for the remaining statistical quantities in a smaller measure. Moreover, it could be emphasized that the quantitative influence of the tip dimensions on the values of the statistical quantities studied here depends considerably on the relationship between the tip linear dimension and column linear dimensions.

The practical meaning of this theoretical analysis consists in the numerical evaluation of the tip influence on the values of the basic statistical quantities employed in practice for characterizing the upper boundaries of the columnar thin films. The results of this analysis can enable us to perform rough estimation of the errors achieved within AFM studies of the real columnar thin films. Further, these results allow to estimate the corrections of the statistical quantities mentioned above to be obtained using the correcting procedures (e.g. the Villarrubia's surface reconstruction algorithm).

In conclusion, it is further necessary to point out that using AFM one can determine the values of the statistical quantities corresponding to the "effective" microroughness of the upper boundaries of the columnar thin films. It is evident that the difference between this "effective" microroughness and true one depends on the mutual relationship between the linear dimensions of the AFM tip apex and linear dimensions of the columns and pores of the films investigated. In spite of this fact, it is however helpful to measure the statistical quantities characterizing the microroughness of the upper boundaries of the columnar thin films using AFM because even the statistical quantities of the "effective" microroughness give a useful information about the columnar structures of the films under study from the point of view of their spatial structure (geometry). Moreover, it is also necessary to point out that the results of the AFM measurements of the statistical quantities characterizing the columnar roughness achieved with different experimental conditions (e.g. with the different tip apexes) have to be compared very carefully. Without a detailed specification of the conditions of these measurements it is very problematic to perform this comparison.

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