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Ultramicroscopy 96 (2003) 175–180

ultramicroscopy

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Defining the parameters of a cantilever tip AFM by reference structure

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Received 20 March 2002; received in revised form 3 December 2002

Abstract

A method of measurement and control of atomic force microscope (AFM) probe parameters is offered. The AFM real cantilever parameters are defined.

PACS: 06.30.Bp; 7.79.−v; 61.16.d; 07.05.Tp

Keywords: Atomic force microscope; AFM; Dimensional metrology; Cantilever; Tip characterization

1. Introduction

Atomic force microscope (AFM), invented in 1986 [1], has very wide applications [2,3]. The surprising simplicity of the microscope, capability of measuring in air and practically in any gas and liquid makes it indispensable both in scientific researches and in industry [2–9]. However, a number of difficulties inherent in AFM complicate its use.

The first difficulty is connected with modification of the form of investigated surfaces that occurs under the action of force of interaction of probe AFM and the surface. Such modifications occur basically while doing research on easily deformable objects (biological structures, organic materials, Langmuir–Blodgett films, etc.). Researches in such area are many (see, for example, Ref. [4]). However, for rigid objects such as those that are applied in microelectronics and nanotechnology, deformation of the surface up to a few nanometers does not play an essential role in resolutions.

The second difficulty is connected with the influence of the size and the form of the probe on the image of the researched structure. The problem of restoration of a relief of an initial surface under AFM is successfully analysed [9]. However, for this purpose, it is necessary to know the shape and dimensions of the cantilever tip of the AFM. Nowadays, there are two methods of defining parameters of a probe. One of them is measuring the dimension and shapes of the cantilever based on microphotographs (Fig. 1), obtained by scanning electron microscopes (SEM). Deficiency of this method is that while a cantilever

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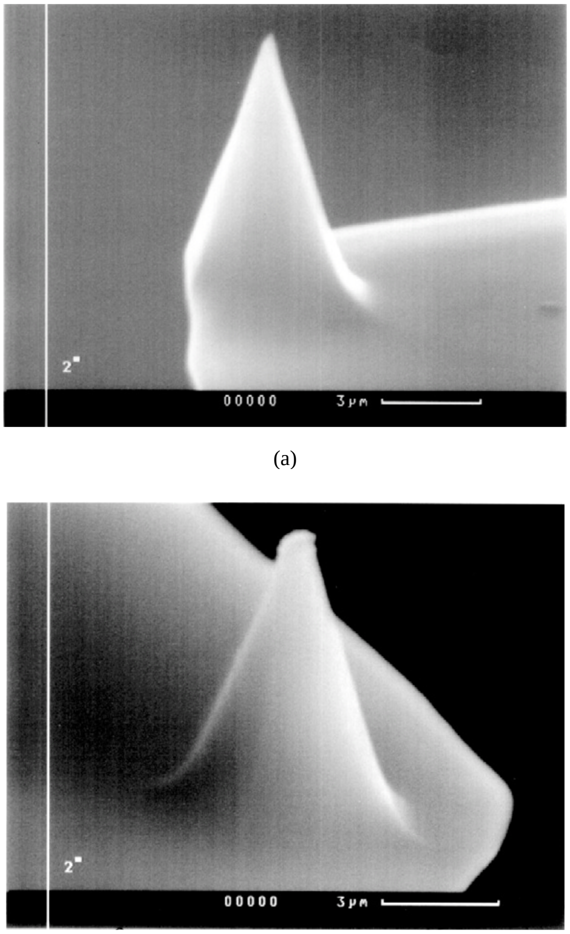
0304-3991/03/$ - see front matter
doi:10.1016/S0304-3991(03)00005-6



(a)

(b)

Fig. 1. Microphotographs made by SEM normal (a) and broken (b) tip.

is scanning, its shape and dimensions can change. These changes influence the images obtained by AFM, but defining these changes is difficult. Therefore, we have to doubt about the propriety of the supposition that shapes and dimensions of the probe are constant during measurements by AFM.

The second method is defining the form of a probe with the help of special test structures (see, for example, Refs. [5,10]). Test structures may be natural [5] (natural or artificial crystals are usually used) or specially created with the help of microelectronics or nanotechnology.

Natural test structures give an important information and this enables exclusion of a number of artifacts [3,5], but it does not allow to measure the size and form of the probe which are important for precision reconstruction of the surface [7] required for modern microelectronics and nanotechnology.

Specially created test microstructures (for example, as the ledges having a triangular structure [10]) allow measuring the true form and size of the probe. However, there is some imperfection in this method. The matter is that a probe can have a composite shape that usually presents as a pyramid or tumulus ending in a spherical surface. The radius of this sphere is the main characteristic of the probe [10]. Usually firm manufacturers of cantilevers indicate radii in the range 3–50 nm as important. It is adequate for scanning flat surfaces. For surfaces with a compound relief (for example, for microelectronic structures), these values of probe radius are inadequate.

The purpose of the present work is representation of a simple method of measurement and control of parameters of a probe of the AFM, correctly displaying the work of a microscope on difficult relief structures including that on the structures used in microelectronics and nanotechnology.

2. Theory of the method

On the basis of the method defining the parameters of a tip, there are results of geometrical model analysis of a common element of a solid surface. The surface relief presents as a ledge with a trapezoidal profile with known shapes of top u_p and lower b_p of the trapezoid basis.

It is supposed that in a working range of power effects in surface–tip system deformations, existing during scanning, are negligible small.

The cantilever has a tumulus form with a slope angle of lateral generatrix concerning a cosine axis slowly transferring into a sphere of radius R. The symmetry axis of the tip is inclined at an angle β relative to a perpendicular to the surface of the investigated sample.

The images of a ledge with a trapezoidal profile and shapes obtained by AFM signal are shown in Fig. 2. The parameters of a profile and a signal structure, and also a tip are shown in a Fig. 2. Also, it is supposed that the orthogonality of Z-scanner is ideal.

It is easy to show that there is a connection between the measured adduced sharps top U_p and lower B_p bases of a registered signal (with scaling multiplier) and known for its profile parameters U_p and B_p of a structure element described by the formulas

$$U_p = u_p + R\left(\frac{1-\sin|\psi|}{\cos|\psi|} + \frac{1-\sin|\varphi|}{\cos|\varphi|}\right), \tag{1}$$

$$B_p = b_p + R\left(\frac{1-\sin|\psi|}{\cos|\psi|} + \frac{1-\sin|\varphi|}{\cos|\varphi|}\right) + h(\mathrm{tg}|\psi| - \mathrm{tg}|\varphi|), \tag{2}$$

$$S_L = h\,\mathrm{tg}|\psi|, \tag{3}$$

$$S_R = h\,\mathrm{tg}|\varphi|, \tag{4}$$

where

$$\psi = \begin{cases} \alpha+\beta, & \alpha+\beta > \varphi, \\ \varphi, & \alpha+\beta \leqslant \varphi. \end{cases} \tag{5}$$

Implementing the condition $\alpha+\beta>\varphi$ from expressions (3) and (4), it follows that

$$S_L > s, \quad S_R = s.$$

However, more useful is the inequality

$$S_L + S_R > 2\,s, \tag{6}$$

which is valid even in the case of the Z-scanner nonorthogonality.

On implementing the condition $\alpha+\beta\leqslant\varphi$ in expression (5), formulas (1)–(4) transform to

$$U_p = u_p + 2R\frac{1-\sin|\varphi|}{\cos|\varphi|}, \tag{7}$$

$$B_p = b_p + 2R\frac{1-\sin|\varphi|}{\cos|\varphi|}, \tag{8}$$

$$S_L = S_R = s \tag{9}$$

and inequality (6) transforms to the equality

$$S_L + S_R = 2s, \tag{10}$$

which is valid in the case of the Z-scanner nonorthogonality as well as inequality (6).

Expressions (7) and (8) are suitable for defining a tip radius R. These expressions also consist of measured parameters of signals U_p and B_p and parameters of trapezoidal ledges u_p, b_p and φ known from alternative measurements.

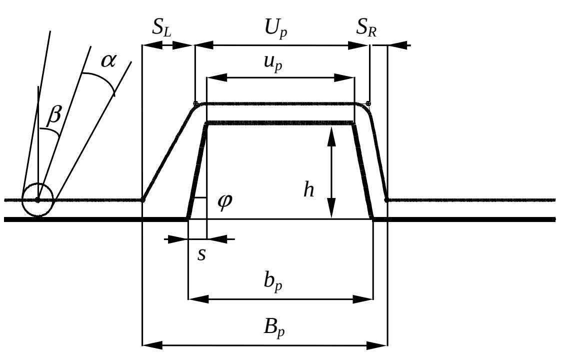


Fig. 2. The schemes of a trapezoidal ledge and AFM signal with parameters of the ledge and signal.

3. Experimental results

The step grating was used as calibration grating representing interleaving straps from silicon dioxide on silicon. This grating has a profile with shapes like a trapezoid with equal lateral sides. The SEM image of a grating cross-section and its AFM image are shown in Figs. 3 and 4. The side slope of gratings is about 40° relative to the surface normal. The height h of the step is equal to the thickness of a silicon dioxide initial film, which was measured with split-hair accuracy by the

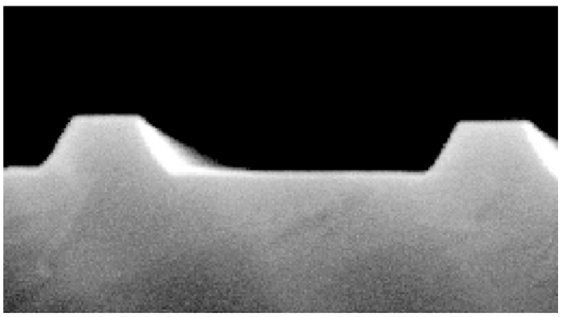


Fig. 3. Microphotograph made by SEM of a cross-section of reference step structure with a trapezoidal profile of elements.

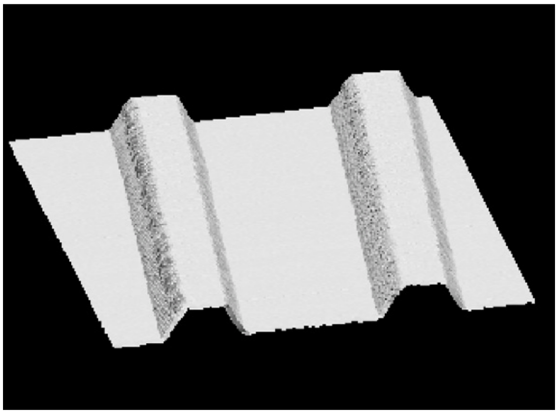


Fig. 4. The image of a step of reference structure in AFM.

ellipsometrical method [11]:

$h = 356 \pm 1$ nm.

The step of test grating was certified with split-hair accuracy by a standardized reference interferometric comparator [12]. The value of the step is

$t = 3015 \pm 6$ nm.

This value was used to define the multiplying factor of AFM and also to measure parameters of cross-section by SEM using a method specially designed for this purpose [13]. The results of these measurements were

$u_p = 492 \pm 7$ nm,

$b_p = 1059 \pm 6$ nm,

$s = 284 \pm 3$ nm,

$\varphi = 38.5° \pm 0.3°$.

Thus, all these parameters of trapezoidal cross-section of test gratings were known from alternative measurements.

The experiments defining the parameters of a tip were made by AFM P47 (NT-MDT Co. Zelenograd), which has cantilever's axis slope angle $\beta = 20°$. To except influence of a tip symmetry axis slope on a registered signal form, the test sample position is implemented so that a tip axis slope was directed along the lateral sides of silicon dioxide grating, and the scanning was done across test grating straps.

The scanning of five arbitrary selected pair ledges of test grating was done by AFM. The image of one pair ledges AFM image and the image of one of the signals are shown in Figs. 4 and 5, respectively.

The results of the measuring parameters of this cross-section are shown in Table 1. The observed difference between S_L and S_R occurred because of Z-scanner nonorthogonality. The average value is the sum of normalized projections of inclined walls of registered signals.

$S_L + S_R = 575 \pm 5$ nm.

That, within the limits of an aggregate error of measurements, coincides with the doubled projection of a lateral wall of an element measured by SEM [13]:

$2s = 568 \pm 4$ nm.

Thus equality (10) is obeyed. It indicates that in experiment the condition $\alpha + \beta \leqslant \varphi$ was executed and, therefore, it is possible to use expressions (7) and (8) to define probe's radius, whose value is given by

$R = 95 \pm 6$ nm.

The measurements executed with another cantilever have values given by

$R = 103 \pm 8$ nm.

Fig. 5. Signal form AFM from a step of reference structure.

Table 1
Parameters of signals AFM, obtained at scanning trapezoidal ledges

i	U_p (nm)	B_p (nm)	S_L (nm)	S_R (nm)
1	550 ± 5	1133 ± 8	320 ± 4	263 ± 8
2	584 ± 4	1157 ± 6	307 ± 4	269 ± 4
3	587 ± 5	1178 ± 5	319 ± 4	265 ± 2
4	593 ± 9	1158 ± 4	320 ± 4	253 ± 3
5	599 ± 4	1157 ± 4	307 ± 4	251 ± 3
Average value	583 ± 9	1157 ± 7	315 ± 3	260 ± 3

4. Discussing results

The values of radius of a tip obtained above strongly (in 5 times) exceed the data of this work [10]. However, there is no contradiction here. The matter is that the probe has a composite form. Approaching it as tumulus with hemispherical end is fair enough. It indicates good coincidence of model's forms (Fig. 2) and real (Fig. 5) signals. However the parameters of such nearing depend on structure, on which you scan. This feature (particular qualities) is illustrated in Fig. 6, where the probe is presented as cone ending by a hemisphere of radius R. At the end of the probe, there is a feature, which is also described by a part of a sphere considerably of a smaller radius ρ. It is more exact nearing of real cantilevers.

At interplay of this probe and trapezoidal ledge, the small sphere has contact only with flat surfaces of the basis of a sample and top of a ledge and practically never contact the lateral sides of a ledge. Such contact is possible only in the case the height of the structure is less than the radius of the small sphere. Therefore in physical essence radius of a small sphere characterizes a radius of a curving tip of the probe. Influence of a small sphere will exert influence on the verges shape of the upper basis of trapezoidal signals, which are left out of account in formulas (1)–(10) trapezoidal nearings of signals.

At the same time, large sphere contacts only the lateral sides of a structure and it will exert influence on cross-sectional dimensions of the ledge image. In physical essence large sphere radius characterizes interval between a probe axis and its point of tangency of a ledge lateral side of. This radius we shall call "effective".

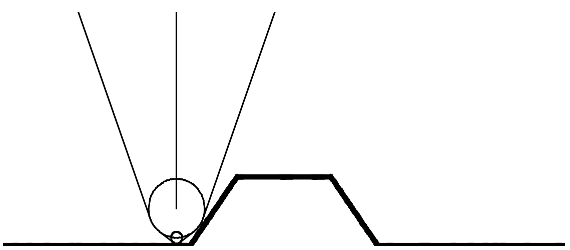


Fig. 6. The shape of a cantilever tip AFM, circumscribed by two spheres, and scheme of its contact with reference structure.

Certainly, using the method defining the shapes of the probe (for example Ref. [10]), it is possible to restore the shape of an investigated surface. However, during restoring the inverse (ill-defined) problem will be solved and this solution has poor accuracy. Besides it is useful to know the effective radius to choose the right tip, because the radius of the tip curving and the effective radius are practically irrelevant. The important tip characteristic for working on relief structures essentially (for example which are used in microelectronics) is effective radius of the probe, but not the radius of a curving tip, because only effective radius of the probe is included as amendment in measured dimensions of a structure.

5. Conclusion

Thus, the real cantilever should be characterized at least by two radii—curving radius of tip and effective radius of the probe. The first one can be defined by the method described in work [10], and the second one can be defined by the above-mentioned method. For this purpose, it is necessary to have both the reference structures, described in work [10] and the step structure with a trapezoidal profile of the elements, which allow you to measure the effective radius of the tip completed with AFM.

References

[1] G. Binning, C.F. Quate, Ch. Gerber, Phys. Rev. Lett. 56 (1986) 930.

[2] E.S. Snow, P.M. Campbell, Appl. Phys. Lett. 64 (1994) 1932.

[3] P.A. Arutyunov, A.L. Tolstikhina, Microelectronics 28 (6) (1999) 405.

[4] T.P. Weihs, Z. Nawoz, S.P. Jorviss, J.B. Pethica, Appl. Phys. Lett. 59 (1991) 3536.

[5] S.S. Sheiko, M. Moller, E.M.C.M. Reuvekamp, H.W. Zandbergen, Ultramicroscopy 53 (4) (1994) 371.

[6] M. Nagase, H. Namatsu, K. Kurihara, K. Iwadate, K. Murase, Jpn. J. Appl. Phys. 34 (1995) 3382.

[7] A.A. Bukharaev, N.V. Berdunov, D.V. Ovchinnikov, K.M. Salikhov, Microelectronics 26 (3) (1997) 163.

[8] P.A. Arutyunov, A.L. Tolstikhina, Microelectronics 26 (6) (1997) 426.

[9] L.S. Dongmo, J.S. Villarrubia, S.N. Jones, T.B. Renegar, M.T. Postek, J.F. Song, Ultramicroscopy 85 (2000) 141.
[10] V. Bykov, A. Gologanov, V. Shevyakov, Appl. Phys. A 66 (1998) 499.
[11] Yu.A. Novikov, S.V. Peshekhonov, Problems of linear measurements of microobjects in nanometer and submicron ranges, Proceedings of the IOFAN, Vol. 49, Nauka, Moscow, 1995, p. 107.
[12] V.V. Kalendin, V.N. Chernyakov, P.A. Todua, Zh. Zhelkobaev, Progress in precision engineering and nanotechnology, Proceedings of the Ninth International Precision Seminar, Vol. 1, Braunschweig, Germany, 1997, p. 138.
[13] Ch.P. Volk, Yu.A. Novikov, A.V. Rakov, Meas. Tech. 43 (2000) 346.