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Effect of Tip-sample angle on Atomic Force Microscopy Images

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It is know known that the incline angle of the cantilever may cause the error of AFM images [1]. According to Fu's research in Ref. 2, the error of the height of the critical dimension (CD) line could be 2% if the obliquity angle of the sample changes by 0.1°. However, no interpretation for the significant error has been given yet, therefore, we are trying to prove that the angel between tip and sample surface directly responses for the error. The effect of the tip-sample angle is theoretically formulated and analyzed. A blind scan region is also obtained which is finally verified by experiments. Note that the van der waals force, perpendicular to the sample surface, is the dominant force between the tip and the sample surface, whereas the friction force F_f is parallel to the sample surface [3]. We define the angle θ between the tip axis and the sample surface as the tip-sample angle. The sum forces acting on the tip can be decomposed into the forces parallel (F_P) and vertical (F_V) to the long axis of the cantilever, as shown in Fig. 1. We can obtain $\varphi_P = C_P \cdot F_P$, $\varphi_V = C_V \cdot F_V$, $\varphi_{sum} = \varphi_P + \varphi_V$, where φ_P, φ_V are the bending angles separately generated by parallel and vertical forces, and φ_{sum} is the total bending angle. For rectangular cantilevers, we can easily obtain the compliances C_P=$12hL/Ewt^3$, $C_V = 6L^2/Ewt^3$, where E is the elastic modulus, L, w, t, and h are the length, width, thickness and tip height of the cantilever, respectively. Finally, the bending angle can be given as $\varphi_{sum} = C_V \cdot F_{vdW}(-\mu\cos\theta + \sin\theta) - C_P \cdot F_{vdW}(\mu\sin\theta + \cos\theta)$. If we assume that the sample surface is a perfectly slide surface where μ=0, we have $F_{vdW} = \varphi_{sum} / (C_V \sin\theta - C_P \cos\theta)$. The $F_v dW$ has a functional relationship with the d. And for AFM images, we have $M_{hi} = S_{hi} + d$, where M_{hi} and S_{hi} are the measured and real height at each point i. In Fig. 1, we also have $\theta = 90° - (\alpha + \beta + \gamma)$. We can know from the derivation formulae for F_{vdW} that error will take place if $\theta \neq 90°$. Especially, when $(C_V \sin i - C_P \cos\theta) \leq 0$, we can obtain that the cantilever would not bend upwards ($\varphi_{\mathrm{sum}} \leq 0$), however, the atomic force $F_v dW$ changes. Consequently, touch will appear between the tip and sample surface, and the sample will be raised by the PZT to keep the total bending constant (φ_{sum}>0). Finally, false images will be acquired. We define the region of angles $\theta \in [0, \tan\text{-}1(C_P/C_V)]$ as blind scan region.

The analytical results are given in Fig. 2, where the upper two show the relationship between the angle θ and tip-sample distance (solid), and the set-point value of tip-sample distance (dashed) d_0 = 0.083nm; the lower two give the error of the tip-sample distance at each angle. We can find that error is infinite at the angle of 4.96°, and the blind scan region should be [0°, 4.96°]. However, we can also find that when $\theta \in (4.96°, 34.4°] \cup [155.5°, 180°]$, the tip-sample distance $d \leq 0$. In the regions, the inter-atomic force could not make the bend unchanged, and touch also appears between tip and sample surface, hence, the sample must be raised largely to keep the bend unchanged. So the blind scan region should be expanded as $\theta \in [0°, 34.4°] \cup [155.5°, 180°]$, and big error could be acquired when AFM works in blind scan region. When AFM works in the region of (34.4°, 155.5°), the tip-sample distance changes from 0 to d_0. If the real height of the sample $S_{hi} >> d_0$, the influence could be ignored in this region. Typically, there's no error at the angle of 90°.

The measurement was carried out on a TGF11 and a TGZ02 from Mikromasch with a NanoScope III Dimension 3100. A rectangular cantilever CSC17/AIBS was utilized. We use one scan to obtain the error instead of using the image. The results of the TGF11 sample are plotted in Fig. 3, The error is about 10nm on three planes, 140 nm on the left slope, and 30-40nm on the right slope. On the left slope, the tip-sample angle is 23.4°, and it belongs to the blind scan region, and the angles of 79° and 133.7° are far from the region, therefore, the error on the left slope is much larger than the others, which shows good agreement with the analysis. The results of the TGZ02 sample are given in Fig. 4. It is indicated that the error is small on the planes and very large on the sidewalls. However, the error on the sidewalls is not caused by the tip-sample angle. Because the sidewall slope of the sample exceeds the cone angle of the probe, it is not the tip, but the sidewall of the probe that contacts with the sidewalls of the sample, and this effect is called tip convolution effect [4, 5], which mainly causes the error of the sidewalls here. The error on the planes is much larger than the analytical results at the angle of 79°. This is because the friction force cannot be completely eliminated even we have slowed down the scan rate, and the friction force may make the error bigger. The error is different on the planes of the two samples, and this may be because the set-point value of inter-atomic forces F_{vdW0} of the two samples are different, which causes the different value of the friction force.

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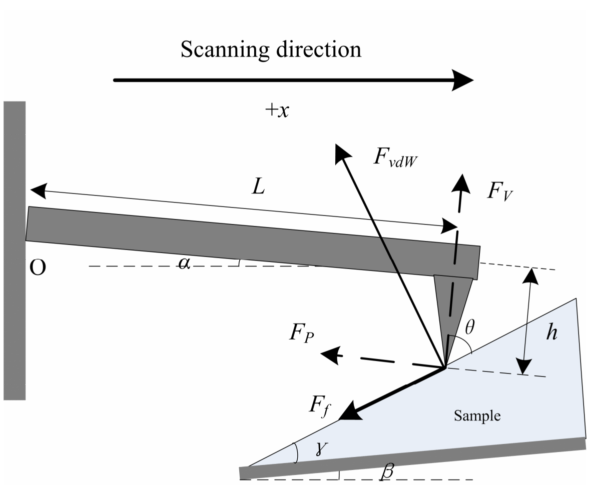

FIG. 1. Schematic diagram and force analysis for the working condition of the AFM cantilever

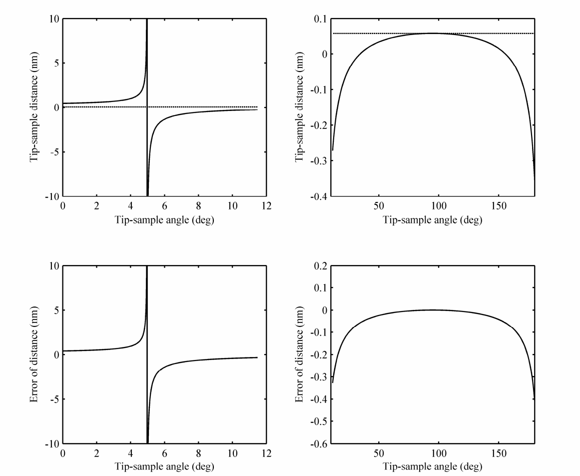

FIG. 2. Analytical results for the effect of tip-sample angle on imaging error.

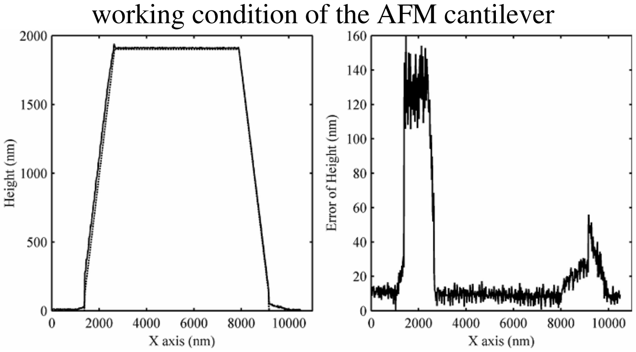

FIG. 3. Measuring results of sample TGF11.

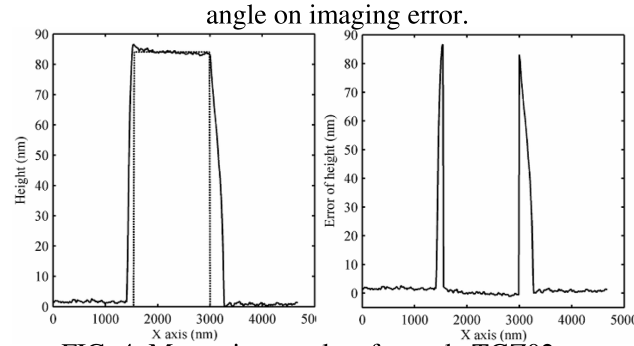

FIG. 4. Measuring results of sample TGZ02.

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