Slope Measurements with a Stylus Profiler

KLA-Tencor HRP-Series and P-Series Profilers

Introduction

The measurement of slope via stylus profilometry is affected by many factors, and it is important to understand them in order to make the most accurate measurements possible.

Background

What are the different factors that can affect the accuracy of a slope measurement? It is important that the sample surface plane (relative to which the slope(s) will be measured) is normal to the stylus shank when the stylus is in the raised position. This relative positioning ensures that a flat surface will appear flat, rather than sloped, and can be adjusted via the Mechanical Leveling function.

The motion of the stylus arm, which bends in a vertical arc, is automatically accounted for in the initial configuration of the instrument. In addition, scan recipe parameters should be set such that slope measurements are not compromised: (1) the sampling rate must be high enough to provide an adequate number of data points in the region of interest; (2) the scan speed must be slow enough to avoid the stylus losing contact with the surface; and (3) the noise filter must be less than the horizontal spatial frequencies encountered in the slope region. The geometry of the sample itself is also important. If a trench is narrow, the stylus tip may not reach the bottom and slope measurements will be erroneous. This effect is called Groove Width Loss and is discussed in the Reference Manual under Theory of Operation: *Stylus Geometry*. The geometry of the stylus tip plays a critical role in slope measurement and will be the focus of this discussion.

Note: Due to its slightly different geometry, the DuraSharp stylus will not be included in this discussion.

Definitions

In the profiler software, slope is defined with respect to the horizontal leveling plane, measured in degrees. Measured from left to right, a downward slope has a negative value, and an upward slope has a positive value. The stylus geometry, shown in Figure 1, is assumed to consist of a symmetric cone truncated in a sphere of radius R. The KLA-Tencor styli are specified by their radius and included cone angle. In Figure 1, the included cone angle is defined as θ.

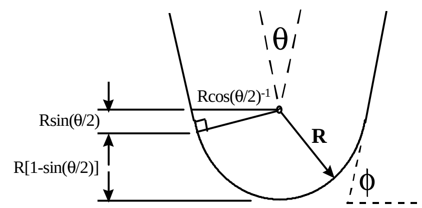

Figure 1. Stylus geometry, where R is the tip radius, and θ is the included cone angle.

From Figure 1, it can be seen that the slope of the stylus cone, as measured from the horizontal, is equal to a constant value of $\phi = 90° - (\theta/2)$ for a height above the surface greater than $R[1-\sin(\theta/2)]$. Below this height, the tip geometry changes from conical to spherical, and the tip slope ϕ is variable and height-dependent, as shown in Figure 2. The relationship between the height above the surface, h, and the tip slope, ϕ, is as follows:

$$h = R(1-\cos\phi), \text{ so that}$$

$$\phi = \cos^{-1}[1-(h/R)]$$

Measurement Limitations

For a given sample, its slope ψ can be measured accurately when $\phi > \psi$. However, at the top of a step, the sample touches the tip along the bottom edge of the tip, where the tip slope ϕ(h) is shallow. This means that the measured sample slope ψ at a

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distance h below the top surface of the step will always be equal to the tip slope ϕ(h) where the sample touches the tip at a distance h above the bottom of tip, as shown in Figure 3. This relationship is true as long as the tip slope ϕ(h) is less than the sample slope ψ.

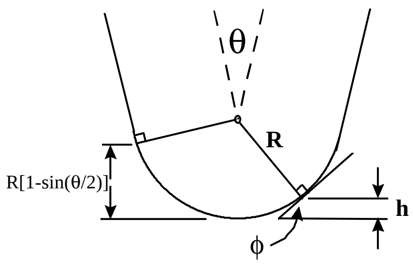

Figure 2. The slope of the stylus tip ϕ, is height-dependent when h < R[1-sin(θ/2)].

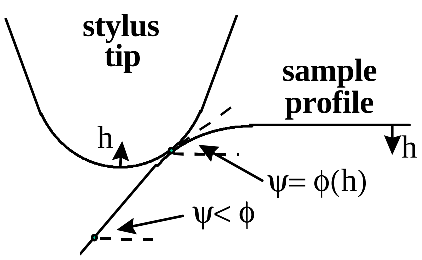

Figure 3. The tip and sample touch at a point that is a distance h below the top of the step and a distance h above the bottom of the tip. At this point, the sample slope ψ reflects the tip slope ϕ(h). Measurement of sample slope ψ is accurate whenever ϕ(h) > ψ.

An example of the effects of the stylus tip geometry on slope measurements is shown in Figure 4. The sample's step thickness is t, and the stylus radius is R. Profiles using different radius/thickness ratios are represented by the broken lines. As R decreases with respect to t, there will be regions of constant slope on either side of the step. If ϕ(h) < ψ in these regions, then the constant slopes will measure equal to ϕ(h). However, if ϕ(h) > ψ, then the constant slope regions will reflect the actual sample slope ψ.

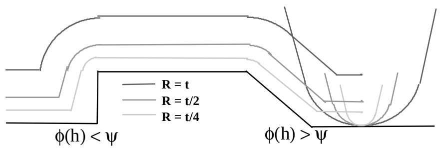

Figure 4. The measured slope on the left reflects tip slope ϕ. The measured slope on the right reflects actual sample slope.

When comparing two different sample slopes, it is important to be aware of the possibly limiting geometry of the stylus. Quantitative comparisons can be made if both slopes to be measured are less steep than the tip slope. Qualitative comparisons can be made if one slope is less than the tip slope, and the other slope is steeper. However, if both slopes to be measured are steeper than the tip slope, the measurements in both cases will reflect the tip slope, producing artificially equivalent slope measurements.

As discussed previously, where the cone and sphere meet is where the tip slope changes between its constant slope in the conical region and its variable slope in the spherical region. For KLA-Tencor's L-stylus product line for P- and HRP-Series profilers, the tip slope ϕ(h) is plotted vs. distance h below the top of a step, shown for each stylus in Figures 5a-i. This tip slope ϕ(h) variability also means that for a given step thickness equal to h, the maximum measurable sample slope ψ along a step edge will be equal to ϕ(h). Plots are labeled by nominal tip radius R(μm) and included cone angle θ(deg.). The corresponding stylus part numbers and band colors are listed in Table 1.

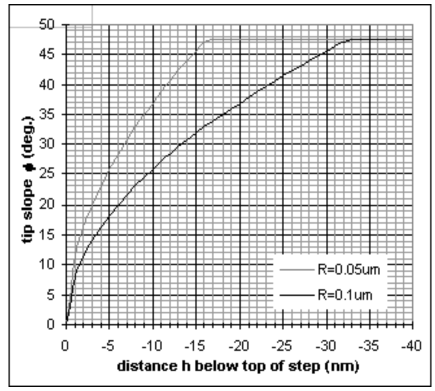

Figure 5a. Tip slope ϕ as a function of distance h, plotted for stylus R=0.05-0.1μm, θ=85°.

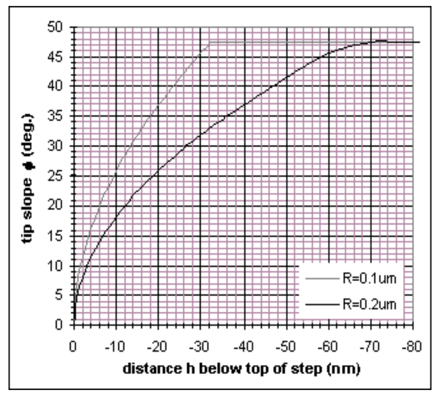

Figure 5b. Tip slope ϕ as a function of distance h, plotted for stylus R=0.1-0.2μm, θ=85°.

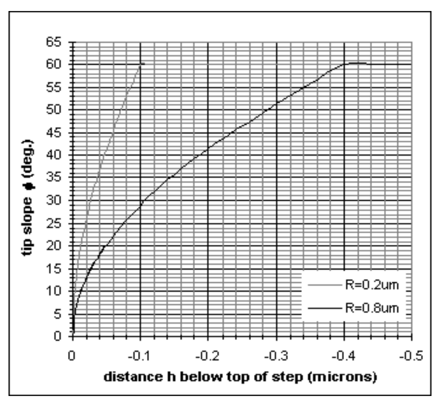

Figure 5c. Tip slope ϕ as a function of distance h, plotted for stylus R=0.2-0.8μm, θ=60°.

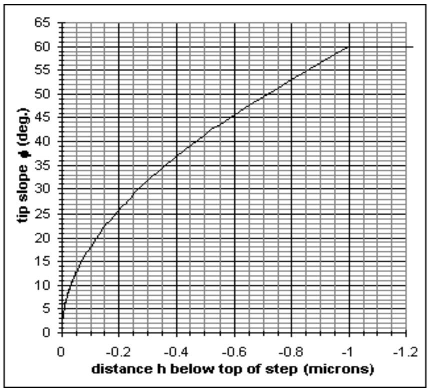

Figure 5d. Tip slope ϕ as a function of distance h, plotted for stylus R=2μm, θ=60°.

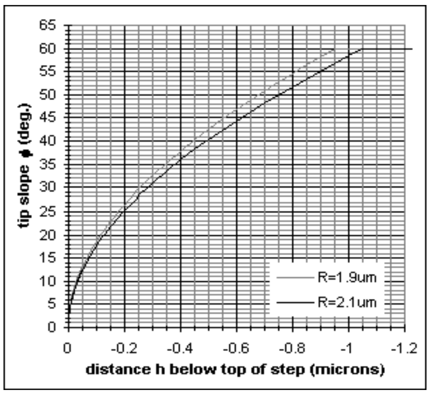

Figure 5e. Tip slope ϕ as a function of distance h, plotted for stylus R=1.9-2.1μm, θ=60°.

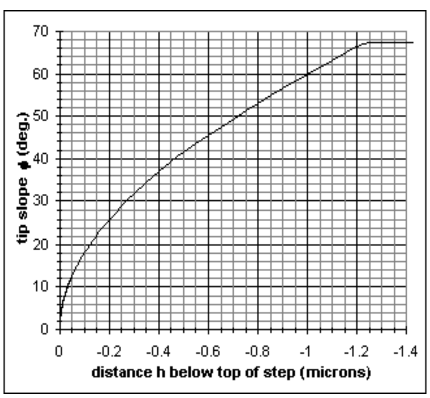

Figure 5f. Tip slope ϕ as a function of distance h, plotted for stylus R=2μm, θ=45°.

As an example, consider a step of thickness 0.4μm that has a nominal slope of 30° from horizontal. The measured slope along the step edge

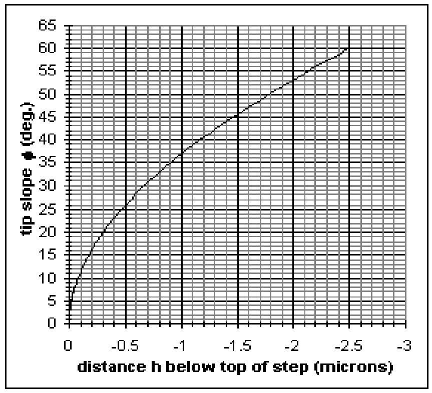

Figure 5g. Tip slope ϕ as a function of distance h, plotted for stylus R=5μm, θ=60°.

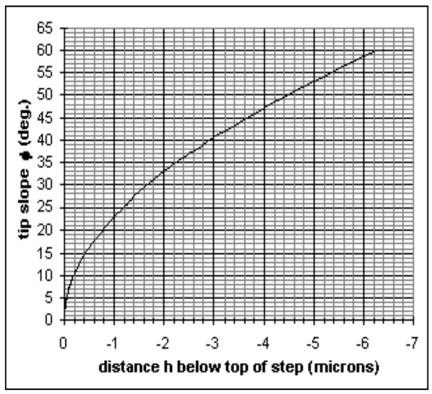

Figure 5h. Tip slope ϕ as a function of distance h, plotted for stylus R=12.5μm, θ=60°.

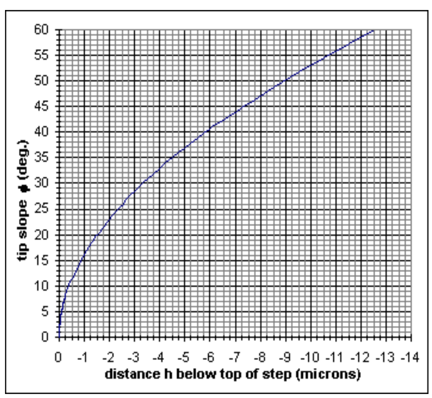

Figure 5i. Tip slope ϕ as a function of distance h, plotted for stylus R=25μm, θ=60°.

will depend on the stylus that is used. If a smaller-radius stylus is used, such as those shown in Figures 5a-f, then the maximum measurable slope on the edge will be limited by the cone angle itself. If a larger-radius stylus is used, such as those shown in Figures 5g-i, then the slope measurement will be greatest at the bottom of the step, but would still be less than 30° (23°, 14°, and 10°, respectively). On the other hand, a stylus of R ≤ 2μm would allow slope measurement greater than 30°, which would be more appropriate for this particular sample. These effects are shown in Figure 6, where the black lines represent smaller-radius styli, and the gray lines represent larger-radius styli. In this case, and also in general, the choice of stylus depends on both the stylus radius and included cone angle, which requires consideration of both the nominal step slope as well as the step thickness. Table 1 lists descriptive information about KLA-Tencor's L-shaped styli.

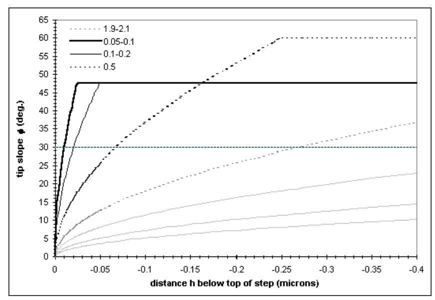

Figure 6. Tip slope ϕ as a function of distance h (0.4μm limit), plotted for all styli, where larger-radius styli are plotted in gray, and smaller-radius styli are plotted in black.

Conclusions

For the most accurate slope measurements, it is important to consider both stylus geometry and sample geometry when choosing a stylus. A small step height may require a smaller-radius stylus, but not if the step edges have a very gradual slope. The graphs presented in this Applications Note provide a reference for slope measurement limits as a function of step height, with data provided for all KLA-Tencor L styli, (DuraSharp stylus excepted). Please refer to your P- or HRP-Series Profiler Reference Manual for additional information.

P/N	Tip Radius (um)	Cone Angle (deg.)	Band Color	Max. Tip Slope (deg.)	h limit (um)
308358	25	60	Blue	60	12.5
240532	12.5	60	Red	60	6.25
217190	5	60	Yellow	60	2.5
270741	2	45	Orange	67.5	1.23
217182	2	60	Green	60	1
238203	1.9 - 2.1	60	Green	60	1
288560	0.05 - 0.10	85	Black	47.5	0.024
217212	0.1 - 0.2	85	Black	47.5	0.049
217247	0.2 - 0.8	60	Black	60	0.25

Table 1. KLA-Tencor L-stylus descriptive information. The stylus "h limit" refers to the vertical distance above the bottom of the tip where the tip slope becomes constant.

KLA-Tencor Corporation
Metrology Group
Surface Metrology Division
160 Rio Robles
San Jose, CA 95134
Tel 408-875-4200
Fax 408-875-6389
www.kla-tencor.com

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