AFM CALIBRATION FOR HEIGHT AND LATERAL MEASUREMENTS

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1. Introduction

This document presents spatial calibration measurements carried out on the two AFM instruments that are used in the Advanced Bio-engineering Laboratory (course number 83411). The older instrument is an AFM Workshop model TT-AFM, and the newer instrument is a TT2-AFM. The two instruments are very similar and are controlled with identical Labview™ based software.

2. Materials and Methods

2.1. Test targets and scanning. The following test targets were used:

(1) Budget Sensors HS20MG and HS100MG 20 nm and 100 nm height standards. The lab has a numberof these standards, and they are labeled as #1, #2, or #3, in order to specify which target was used.

(2) NT-NDT Test Grating TGT-1

(3) SiC/1.5 Silicon Carbide 1.5 nm step test target.

Generally, coarse scans were 128×128 and 0.5 Hz, while higher resolution scans were 256×256 and 0.25 Hz. Note that a raster scan is done. The scan speed and scan lines are shown for each scan. For height calibration, the Z_SENSE channel was used, becasue the Z_DRIVE signal is sensitive to hysteresis in the piezo-drive. This problem is documented here.

2.2. Data analysis. The open source Gwyddion software package was use for analysis. Unless otherwise indicated, leveling was was done in two steps. First, a plane level was done. This was good enough to easily created a mask of the background. Then a 5^{th} order polynomial fit to the masked area was used for the final leveling step. More information on this procedure can be found in the Tips and Tricks document that can be found at this link.

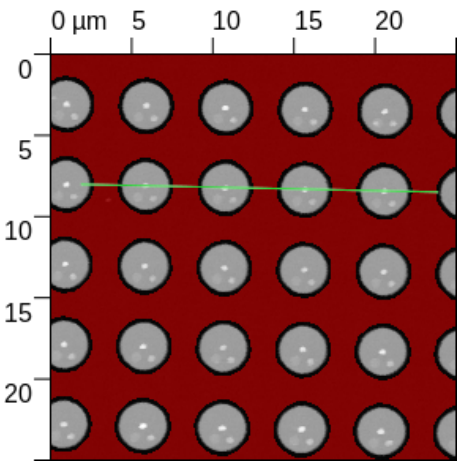
The SiC target cannot be leveled using this procedure, since it ia staircase target. For this target, leveling was done within an individual terrace, as described in Tips and Tricks.

The lattice parameters were used to check the lateral (XY) calibration. The method is described in Tips and Tricks.

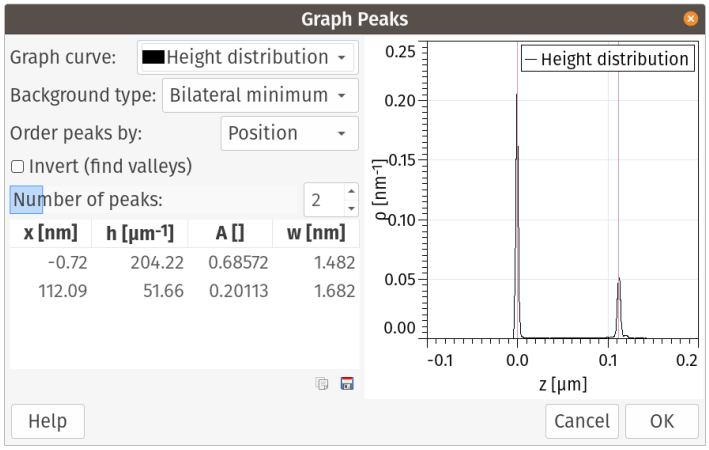
3. TT2-AFM spatial calibration

3.1. Height measurements (Z-axis). HS100MG#2 was scanned at 256 lines and 0.25 Hz, and leveled as described above. Figure 1 shows the leveled scan, and the height histogram obtained from the leveled image. The average height difference is 112.8 nm, which is within the specified 3% height accuracy of the specimen, with is specified to be 113 nm Notice that there is an undocumented spike in the center of each pedestal. This is shown in Figure 1C, and can be seen as a small peak to the right of the main peaks in Figure 1B.

We now look at an HS20MG 20 nm standard (#3),measured on the same instrument. The image, height histogram, and a line profile are shown in Figure 2. The average height difference is 19.4 nm. A similar measurement done on a 50 µm×50 µm area resulted in an average height difference of 19.5 nm. The Z_SENSE image is much noisier relative to the height that is being measured, as expected. More importantly, the error is now 19.4/21.4=0.91 (about 9% error). The TT-AFM software allows for calibration



(A)



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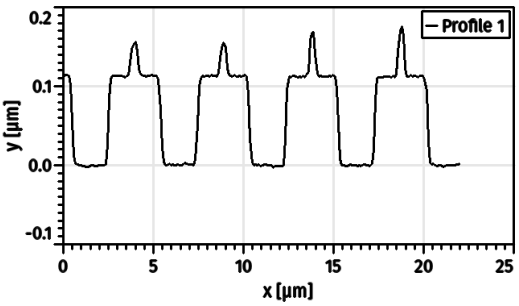
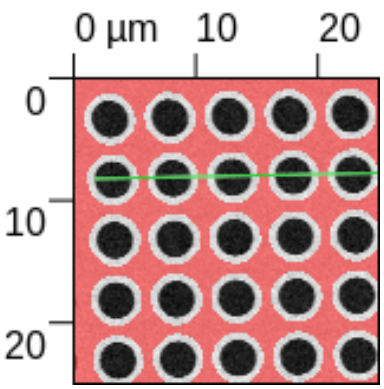


(C)

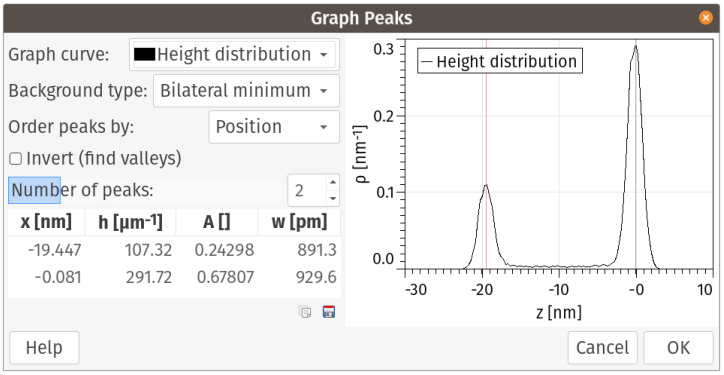
FIGURE 1. (A) Image of HS100MG#2 test target after leveling. Background mask is red. Scan parameters: Z_SENSE, 256×256, 0.25 Hz. Scan title is hs100mg2_20201-02-15_11.46.18. (B) Height histogram - the two main peaks indicate an average measured height of 112.8 nm. (C) Line profile through center of the pedestals, taken along the line shown in (A). There is an undocumented spike in the middle of the pedestals.

at a single point, and the instruments have been calibrated using the HS100MG. It would be nice to have a second degree of freedom to allow for a two point calibration.

The Z_DRIVE image acquired together with the Z_SENSE image in Figure 2, is shown in Figure 3 The signal is much less noisy, but notice that the measurements along the vertical lines differ from those along the horizontal lines. The difference is not large, and it is likely that if higher sensitivity is required, the Z_DRIVE signal must be used. In Figure 3, the green and red profiles were taken along a vertical line (profiles 3 and 2), and the blue and black profiles were taken along horizontal lines (profiles 4 and 1) . (It may be necessary to zoom in on the image to see the line labels.)



(A)



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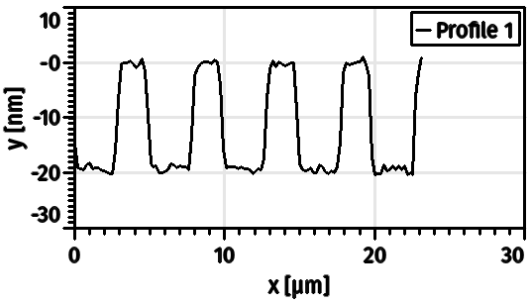
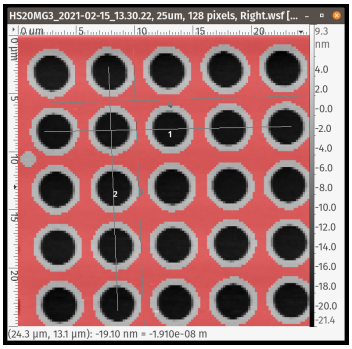
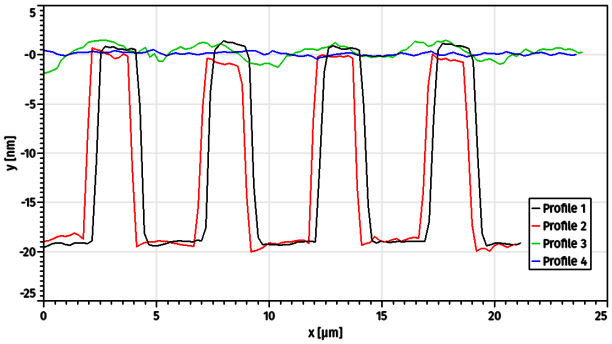


(C)

FIGURE 2. (A) Image of HS20MG#3 test target after leveling. Background mask is red. Scan parameters: 128×128, 0.25 Hz. Scan title is hs100mg2_20201-02-15_13.30.2. (B) Height histogram - the two main peaks indicate an average measured height of 19.4 nm. (C) Line profile through center of the wells, taken along the line shown in (A).



(A)



(B)

FIGURE 3. (A) Z_DRIVE image of HS20MG#3. Mask shown in red was used for to mark background for leveling. (B) Line profiles along lines shown in (A). The scan raster was horizontal.

3.2. Lateral measurements (XY-axes). Figure 4 shows the measurement of some representative lattice parameters. Table 1 lists the results. The larges absolute error is 2 nm to 79 nm, which is less than the specified lateral accuracy, which is 100 nm.

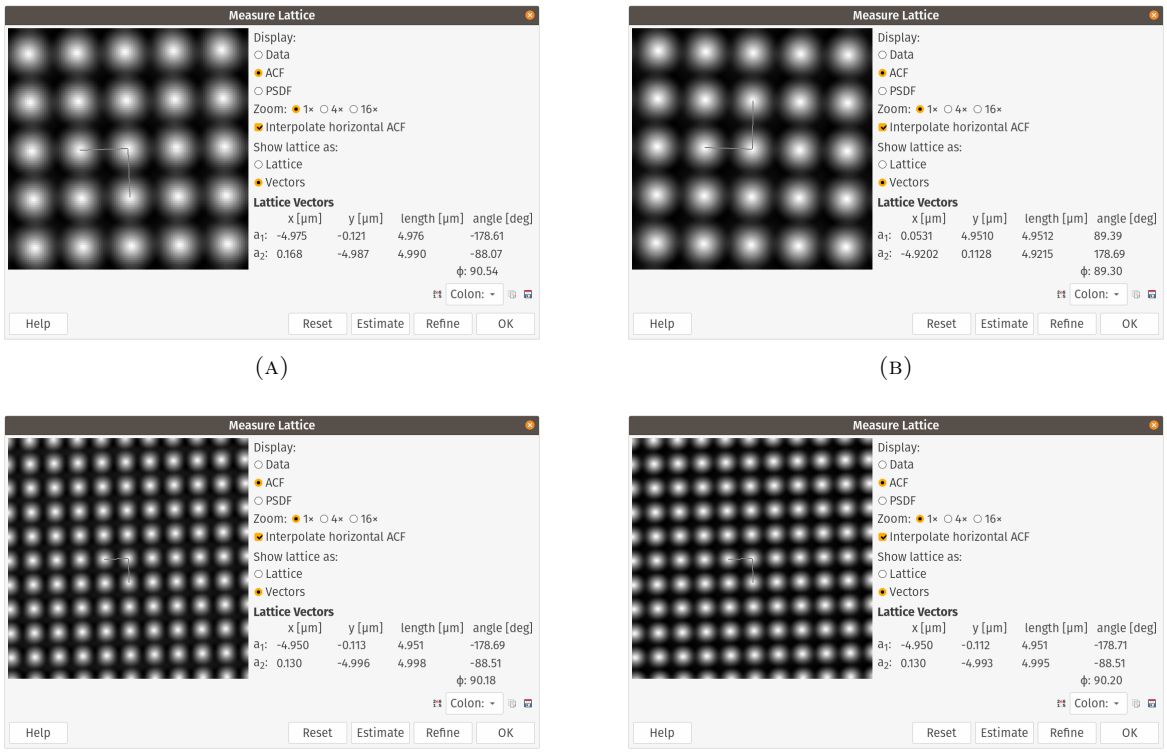


FIGURE 4. Typical output of the lattice measurement. (A) HS20MG#3, 128 lines, Z_SENSE. (B) HS100M#2, 256 lines, Z_SENSE. (C) HS20M#3 50 µm scan, Z_DRIVE. (D) HS20M#3 50 µm scan, 256 lines, Z_SENSE.

TABLE 1. Lattice Parameter Measurements from Figure 4. Distance are in µm, and angles are in degrees.

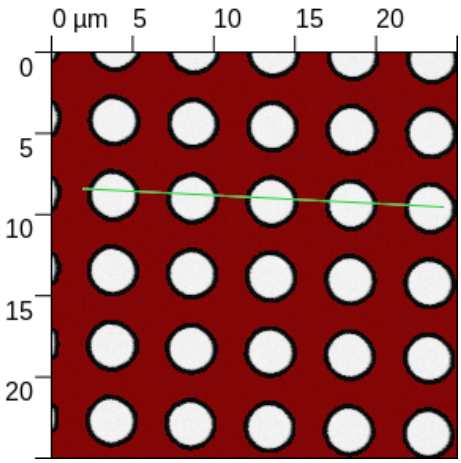
Sample	Xmeas	$\angle X$	Xpred	%error	Ymeas	$\angle Y$	Ypred	%error
HS20MG#3 Z_SENSE	4.975	1.39	4.999	0.5%	4.987	88.07	4.997	0.2%
HS100MG#2 Z_SENSE	4.920	1.31	4.999	1.6%	4.951	89.39	5.000	1.0%
HS20MG#3 Z_DRIVE (50)	4.950	1.31	4.999	1.0%	4.996	88.51	4.998	0.05%
HS20MG#3 Z_SENSE (50)	4.950	1.29	4.999	1.0%	4.993	88.51	4.998	0.1%

4. TT-AFM SPATIAL CALIBRATION

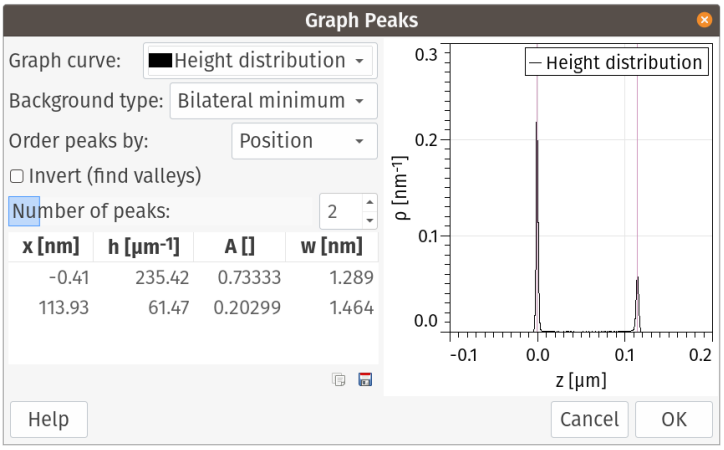
4.1. Height measurements (Z-axis). HS100MG#3 was scanned at 256 lines and 0.25 Hz, and leveled as described above. Figure 5 shows the leveled scan, and the height histogram obtained from the leveled image. The average height difference is 114.3 nm, which is within the specified 3% height accuracy of the specimen, with is specified to be 114 nm There is no undocumented spike in HS100MG#3.

We now look at an HS20MG 20 nm standard (#1),measured on the same instrument. The image, height histogram, and a line profile are shown in Figure 6. The average height difference is 19.3 nm. The Z_SENSE image is noisier relative to the height that is being measured, as expected. More importantly, the error is now 19.3/21.2=0.91 (about 9% error). Again we see that a two point calibration might be preferred.

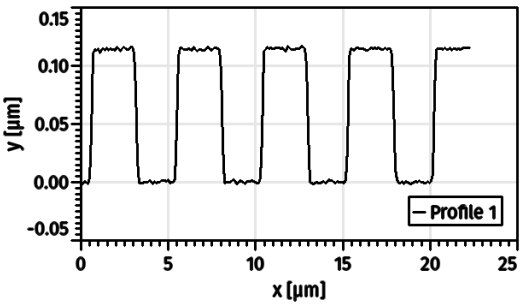
The Z_DRIVE image acquired together with the Z_SENSE image in Figure 6, is shown in Figure 7 The



(A)



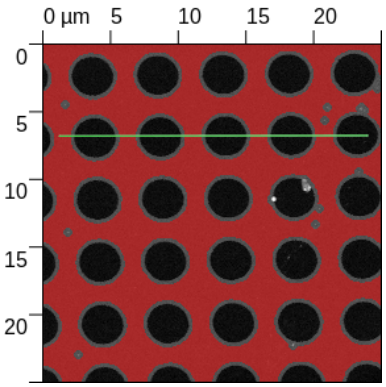
(B)



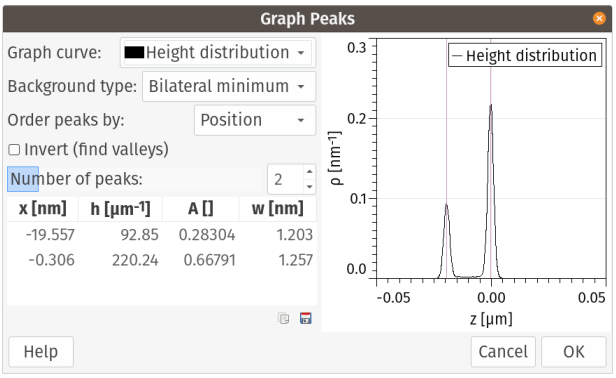
(C)

FIGURE 5. (A) Image of HS100MG#3 test target after leveling. Background mask is red. Scan parameters: Z_SENSE, 256×256, 0.25 Hz. Scan title is hs100mg3_20201-02-15_11.29.40. (B) Height histogram - the two main peaks indicate an average measured height of 114.3 nm. (C) Line profile of the pedestals, taken along the line shown in (A).

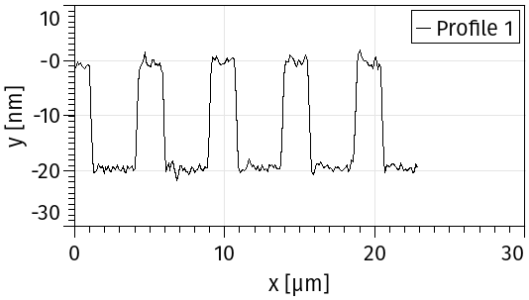
signal is much less noisy, but notice that the measurements along the vertical lines differ from those along the horizontal lines. Again, it may be necessary to zoom in to see the legend properly.



(A)

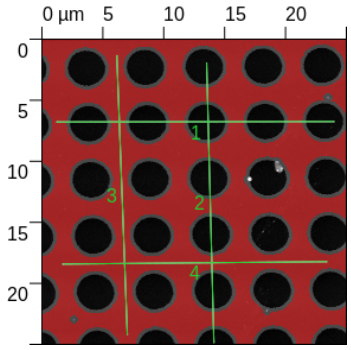


(B)

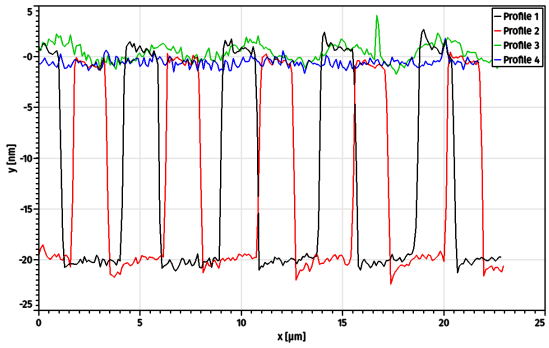


(C)

FIGURE 6. (A) Image of HS20MG#1 test target after leveling. Background mask is red. Scan parameters: 256×256, 0.25 Hz. Scan title is hs20mg1_20201-02-15_12.29.42. (B) Height histogram - the two main peaks indicate an average measured height of 19.3 nm. (C) Line profile through center of the wells was taken along the line shown in (A).



(A)



(B)

FIGURE 7. (A) Z_DRIVE image of HS20MG#1. Mask shown in red was used for to mark background for leveling. (B) Line profiles along lines shown in (A). The scan raster was horizontal.

4.2. Lateral measurements (XY-axes). Figure 8 shows the measurement of some representative lattice parameters. Table 2 lists the results. The larges absolute error is 2 nm to 79 nm, which is less than the specified lateral accuracy, which is 100 nm.

The HS100MG#3 image was also measured by taking a line profile through centers of the pedestals, and measuring the distance between five peaks, as shown in Figure 9

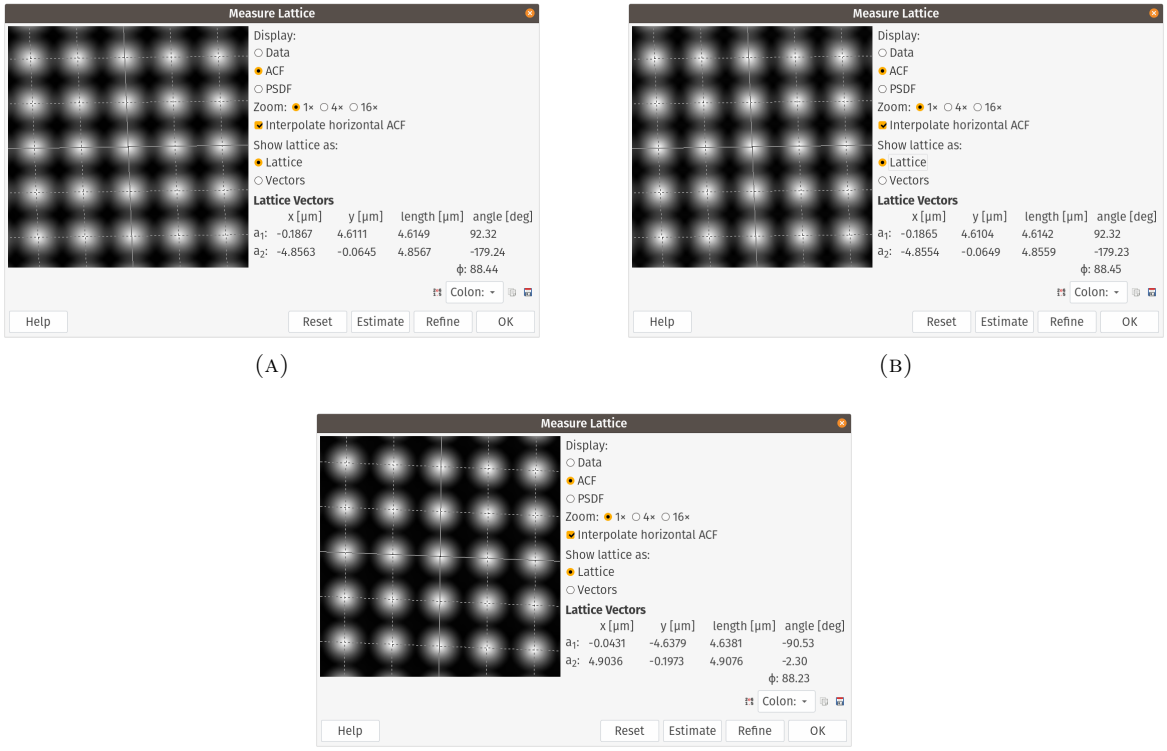
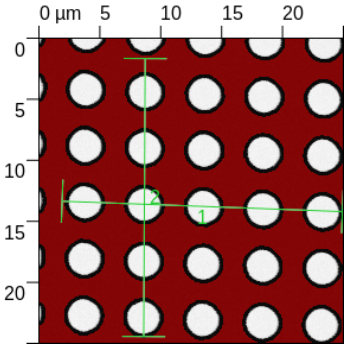


FIGURE 8. Typical output of the lattice measurement. (A) HS20MG#1, 256 lines, Z_SENSE. (B) HS20MG#1, 256 lines, Z_DRIVE. (C) HS100MG#3 , 256 lines, Z_SENSE.

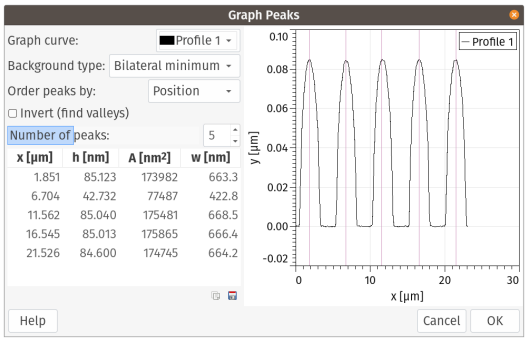
TABLE 2. Lattice Parameter Measurements from Figure 8. Distance are in µm, and angles are in degrees.

Sample	Xmeas	$\angle X$	Xpred	%error	Ymeas	$\angle Y$	Ypred	%error
HS20MG#1 Z_SENSE	4.856	0.76	5.000	2.9%	4.611	92.32	4.996	7.7%
HS20MG#1 Z_DRIVE	4.855	0.77	5.000	2.9%	4.610	92.32	4.996	7.7%
HS100MG#3 Z_SENSE	4.904	2.30	4.996	1.8%	4.638	90.53	5.000	7.2%

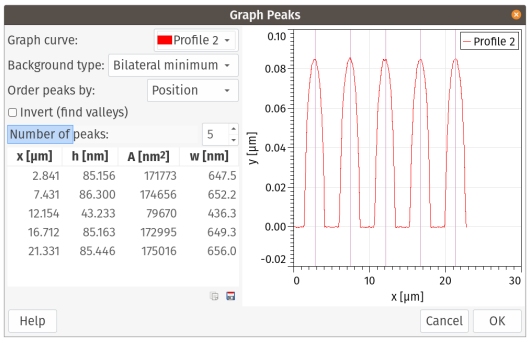
In the X-direction, the average spacing over four periods is 4.924 nm, and the deviation from the nominal value of 5 nm is 1.5%. In the Y-direction, the average over four periods is 4.623 nm, and the deviation from the nominal value is 7.6%. The absolute difference in X is in the range of 9 nm to 145 nm, which is consistent with the stated accuracy of 100 nm. The absolute difference in Y us much larger – 362 nm to 386 nm. The Y axis calibration needs to be corrected. This can be done using the X and X calibration in the control software.



(A)



(B)



(C)

FIGURE 9. Distance measurement along line profiles (A) HS100MG#3, 256 lines, Z_SENSE image. (B) Line profile 1 (horizontal), with peaks locations shown. (C) Line profile 2 (vertical), with peaks locations shown.

5. SiC/1.5 1.5 nm step height sample

Figure 10 shows image of a SiC/1.5 1.5 nm test sample, acquired on the TT-AFM, using 128 scan lines and an acquisition speed of 0.125 Hz. We note that in most images Z-HV=15 (the ful scale) but for the image in Figure 10 Z-HV=5 (1/3 of full scale, 3× sensitivity).

The terrace spacing in the Z_DRIVE image is (1.460 ± 0.027) nm, which is remarkably close to the nominal value 1.5 nm. The corresponding value measured on the Z_SENSE image is (1.614 ± 0.078) nm.

Note the difference in noise between the Z_DRIVE and Z_SENSE images that are shown in Figure 10. The RMS roughness under the masked area was measured using the "Statistical quantities" tool in Gwyddion. The RMS roughness of the Z_DRIVE image is 0.177 nm, while the RMS roughness of the Z_SENSE image is 0.869 nm. The measurement on the Z_SENSE image is only possible because the profile is averaged aver a large area (the thickness of the endcaps of the line on the images). The ZDRIVE image produces a usable line profile even without this averaging.

5.1. Effect of Z-HV. The same area was scanned with Z-HV=15, and on that image the terrace height for the Z_DRIVE image is (1.995 ± 0.067) nm. However, for the Z_SENSE image, the terrace height measurement (1.598 ± 0.076) nm. The RMS roughness for Z-HV=15 is 0.228 nm for Z_DRIVE and 0.859 nm for Z_SENSE.

The reduction of Z-HV lowers the noise on the Z_DRIVE signal, but has no effect on Z_SENSE. This is expected. Z-HV determines the range of the drive voltage, but has no effect on the output of the strain gauges.

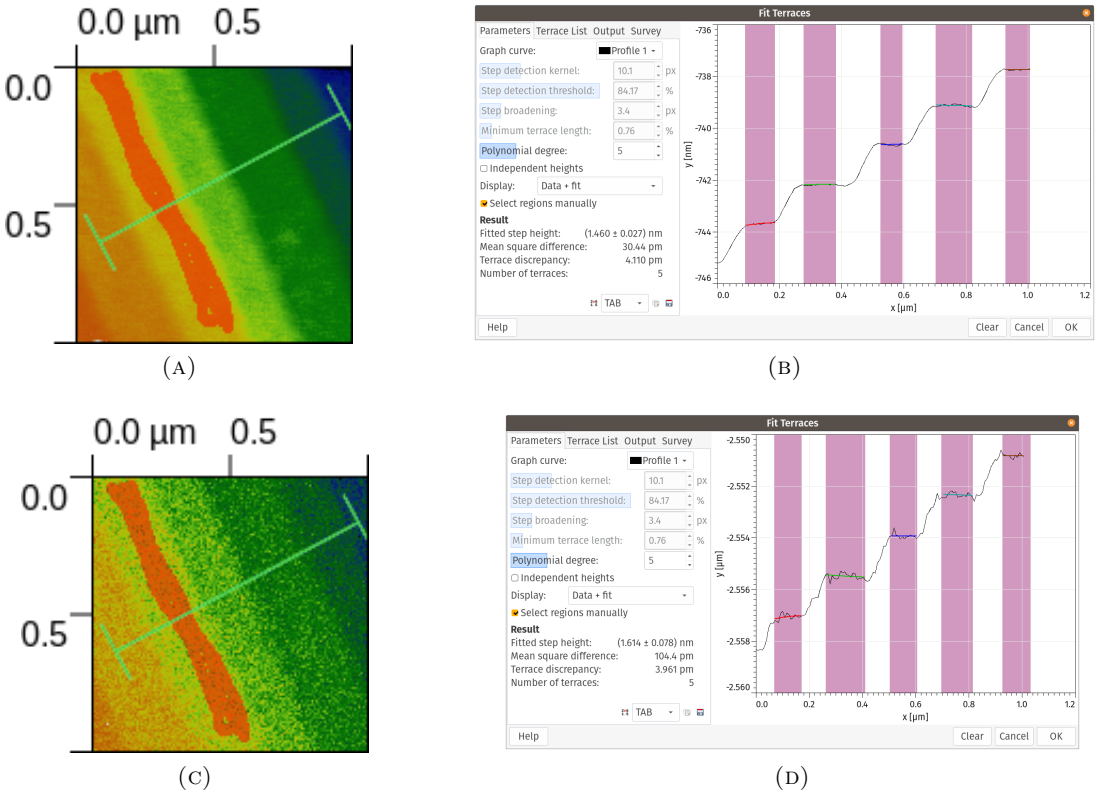


FIGURE 10. SiC/1.5 imageson TT-AFM, 128×128, 0.125 Hz, Z-HV=5. The red overlay shows the mask area that was used for leveling. (A) Z_DRIVE image (B) Terraces from the image shown in (A) (C) Z_SENSE image. (D) Terraces from the image shown in (C).

APPENDIX A. BUDGET SENSOR HEIGHT STANDARDS IN THE LAB

TABLE 3. Available Budget Sensor Height Standards

Name	Lab Label	Specified Height
HS20MG	#1	21.2 nm
	#2	21.4 nm
	#3	21.4 nm
HS100MG	#1	113 nm
	#2	113 nm
	#3	114 nm

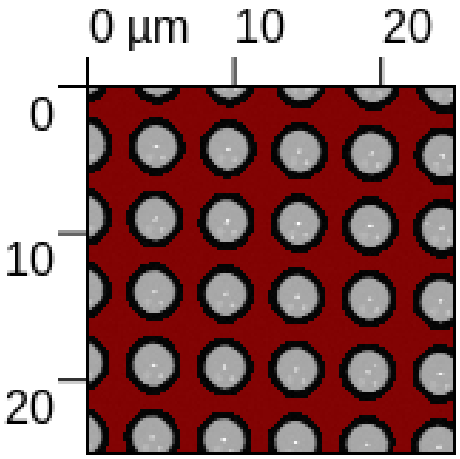
APPENDIX B. TT-AFM XY RECALIBRATION

Following the results obtained above, the Y_cal setting of the TT-AFM was corrected by 6% as follows:

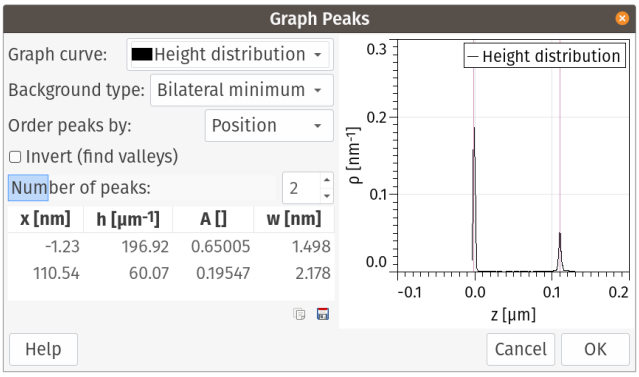
$$yCal_{new} = yCal_{old} * 0.94 \quad (1)$$

0.94 was used because additional measurements indicated a 6% error, rather than 7–8%. The results for one of the targets (HS100MG#2) appear in Figure 11.

A summary of measurements done on HS100MG#2 , HS20MG#1 appears in Table 4. The lattice parameters were not corrected for rotation, because the angle was very small (<2%), so the correction was negligible.



(A)



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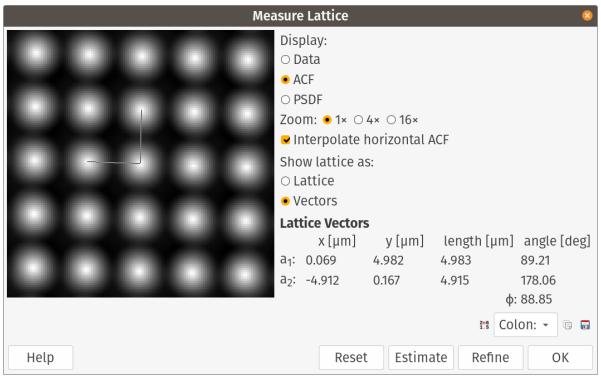

(C)

FIGURE 11. (A) Image of HS100MG#2 test target after leveling. Background mask is red. Scan parameters: Z_SENSE, 128×128, 0.25 Hz. Scan title is hs100mg2_2021-02-23_11.25.32. Nominal pitch of the area scanned is 5 µm.(B) Height histogram - the two main peaks indicate an average measured height of 111.77 nm. (C) Lattice parameters of the image shown in (A).

TABLE 4. Summary of measurements done on TT-AFM after Y_cal correction.

Sample	Nominal Pitch (µm)	X(µm)	Y(µm)	Z(nm)
HS100MG#2 pedestals	5	4.91	4.98	111.77
HS100MG#2 wells	5	4.91	4.97	113
HS20MG#1 wells	5	4.95	4.97	19.6