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Roadmap for Traceable Calibration of a 5-nm Pitch Length Standard

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ABSTRACT

Production of objects with 5 to 25 nm width or pitch requires metrology with picometer-scale accuracy. We imaged a new 70-nm pitch standard by AFM and made it traceable to the international (SI) meter. We describe data capture and analysis procedures that produce metrology-quality results from general purpose AFMs and SEMs. We suggest that traceable pitch standards are most useful when the expanded uncertainty (k=2, 95% confidence) is less than ±1.33% for single pitch values and ±0.5% for mean pitch. We show a projected chain of comparisons (roadmap) leading to a 5-nm pitch standard with expanded uncertainty of 52 pm (1.04%) for single values and 16 pm (0.32%) for the mean value, significantly better than the target.

Keywords: Traceability, microscope calibration, atomic force microscopy, pitch, period, measurement uncertainty, technology roadmap, multiple feature measurement.

1. INTRODUCTION

Consumer products with critical dimensions less than 100 nm are now pervasive. On February 1, 2010, Intel and Micron Technology announced the production of 25-nm NAND flash memory devices in sample quantities, with volume production expected by June 30.[1] Research and development of progressively smaller devices continues. A large part of that research is directed at optimizing performance by controlling the size, shape and position of nanometer-scale features. Microscopy, mainly SEM and AFM, is heavily used to measure the devices. This paper discusses the magnification calibration standards and the picometer-scale accuracy that are needed to support that work.

Among people who purchase and use traceable calibration standards, everyone understands that the calibrated value is very important. For example, when calibrating a microscope's magnification with a pitch standard, it is obvious that the pitch has to be smaller than the smallest scan size to be calibrated. But not everyone appreciates that the uncertainty of the calibrated value is also important. This uncertainty limits the uncertainty of all subsequent measurements. In order to specify the required uncertainty, we consider some possible applications for standards with 70-nm or smaller pitch.

Measuring Critical Dimensions in semiconductors is very challenging. According to the International Technology Roadmap for Semiconductors (ITRS) 2009 edition, MPUs (microprocessor units) in volume production in 2009 had these characteristics: Metal 1 half-pitch = 54 nm, gate length in resist = 47 nm and physical gate length = 29 nm. The 3σ tolerance for Gate CD Control here is 3.0 nm, using a standard formula (10.3% of the CD).[2]. The "Gauge maker's Rule" states that the gauge should be at least 3x and preferably 10x more precise than the process limits.[3] In the ITRS, this rule is stated more carefully, using P/T, the ratio of gauge uncertainty to process tolerance. The Metrology portion of the roadmap uses P/T = 0.1 wherever possible and P/T = 0.2 for very challenging measurements, such as CD measurement. Thus, it requires that the 3σ uncertainty for the Wafer CD metrology tool is 0.6 nm. This is about 2% of the measured value.[4]

The data storage industry has different challenges, related to the need to have a pickup head track a physical path with nanometer-scale precision while a disk is rotating at a linear velocity of several meters/second. Optical disk (e.g. Blu-Ray) and magnetic hard disk drives use removable and non-removable media, respectively. In optical disks, the data are laid out on a spiral path. A 'track' is one turn of the spiral and the track pitch is the radial distance between the centerlines of adjacent tracks.[5] Average (mean) pitch is specified in order to achieve the desired data capacity and pitch variation is tightly controlled to assure that a random disk will play when placed in a random drive. Track pitch variation is specified as a range that is often interpreted as ±3σ.[6] For optical disks, 3σ is typically 3-4% of the mean pitch (DVD: mean 740 nm, range +-30 nm[7]; Blu-Ray: mean 320 nm, range +-10 nm[8]; 4th generation: mean 100-150 nm. In magnetic hard disks, the data are laid out on concentric cylinders (tracks). What is called "track pitch variation" for optical disks is called "write to write track misregistration" for traditional, unpatterned magnetic disks. Because the magnetic hard disks are not intended to be interchangeable between drives, the specification is looser: 3σ is typically 10-20% of the mean pitch.[9] However, the mean pitch is much smaller than for optical disks and already was < 100 nm for existing disk drives in 2009. Pre-patterned magnetic disks are planned to have track pitch < 25 nm so that a 3.5" disk can store > 1 terabyte per side. Such disks are expected to have to have similar tolerances.

Recapitulating, for measurements of Gate CD in semiconductors, the industry roadmap specifies a 3σ uncertainty of 10.3% for the CD itself and a gauge uncertainty of 2%, based on P/T < 0.2. In the disk industries, there are no guidelines specifying gauge uncertainty. For optical disks, the 3σ tolerance for track pitch is 3-4%. A reasonable gauge uncertainty requirement would be 3σ < 1% at 100 nm. Existing microscopes and the 70-nm pitch grating described below meet the calibration requirement. No further decrease in optical disk track pitch is expected beyond the 4th generation. For magnetic disks, the 3σ tolerance for track pitch is 10-20%. A reasonable gauge uncertainty requirement would be 3σ < 3% . Considering the requirements for semiconductors and magnetic disks, we suggest that the gauges should be able to measure individual pitch values of a pitch standard with 3σ < 2%.. Likewise, we suggest that traceable calibration standards should have expanded uncertainty (k=2, 95% confidence) < 1.33% for single pitch values and < 0.5% for mean pitch.

In the semiconductor industry, the key gauges for Gate CD are specially designed CD-SEMs and CD-AFMs. In the data storage industry, the key gauges are general purpose AFMs and SEMs, whose design emphasizes image clarity (high resolution and contrast) and convenience more than accuracy. In this paper, we show what results can be achieved using a commercial, general purpose AFM that is available in more than 1000 labs worldwide. We have not modified the AFM hardware or software and there is nothing extraordinary about the scanning conditions we use. But we do capture numerous calibration images and follow a particular method of offline analysis.

2. MATERIALS AND METHODS

The work reported here involves a pitch comparison between two types of calibration specimens. One ("test specimen") is a 70-nm pitch 1-dimensional grating (Silicon oxide lines on Si, Advanced Surface Microscopy model 70-1DUTC). The other ("calibration standard" or "transfer standard") is a 144-nm pitch 2-dimensional grid (Al bumps on Si, Advanced Surface Microscopy model 150-2DUTC.).

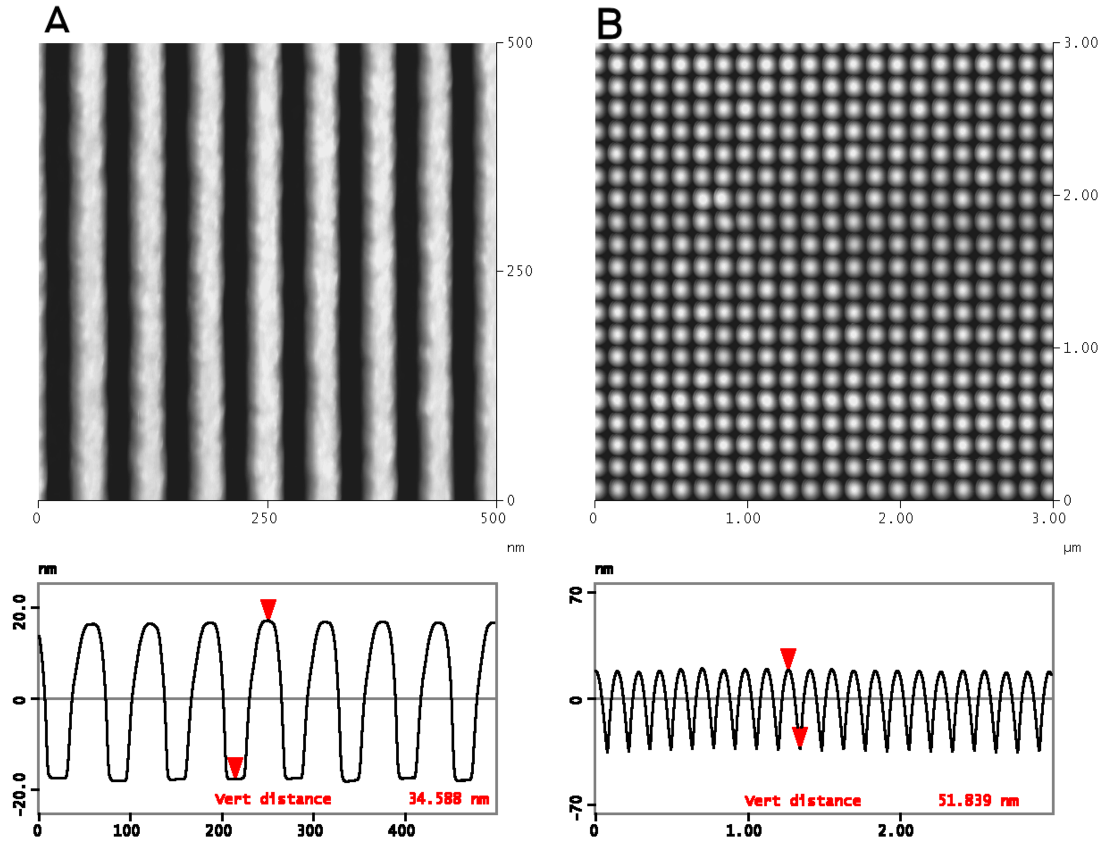

Figure 1. AFM height images of the 70-nm 1D grating (A) and the 144-nm 2D grating (B). The graphs are height profiles made by averaging all scan lines. The ridge height for the 1D grating was 35 nm and the bump height for the 2D grating was 88 nm. The average height of the columns of bumps was 52 nm.

Physikalisch-Technische Bundesanstalt (PTB) previously made a traceable measurement of the mean pitch of the 144-nm grating using optical diffraction.[10] In the current work, we used AFM measurements to provide a traceable value for the mean pitch of the 70-nm grating. The key steps in our traceability path were:

PTB pitch value for 150-2DUTC --> AFM height images of 150-2DUTC yield a calibrated length scale --> AFM height images of 70-1DUTC yield calibrated pitch measurements.

2.1 Data Capture using Atomic Force Microscopy

We used a general purpose, commercial AFM. It includes a PC, NanoScope® IIIA controller and Dimension 3100 microscope (Veeco Metrology/Digital Instruments). The scanner was calibrated to factory specifications and operated open loop in air at ambient conditions. The AFM can operate in TappingMode™ or contact mode and our prior experience with other gratings indicates that the two modes give similar precision. In this work, we performed two runs on a single test specimen. During a 4-month interval between runs, the specimen was measured in two national standards labs, NMC/A-STAR in Singapore and NIST in the USA. In run 1, we used contact mode, capturing 3x3 µm height images with 512x512 pixels at a scan rate of 5 Hz, with rounding 0.1. Rounding means that the scanner actually moves 110% of the nominal scan size on the fast axis, but captures data only for the middle 100%. The captured data avoids the turnaround oscillations that occur for scan rates > 3 Hz and some of the image stretching seen at the start of scan at all scan rates. In run 2, we used TappingMode™, capturing 3x3 µm height images with 512x512 pixels at a scan rate of 1.5 Hz, with rounding 0.1.

The standard used to calibrate the AFM was a specimen of Model 150-2DUTC whose pitch was calibrated previously at PTB: (143.931 ± 0.015) nm.

Both specimens, i.e. the calibration standard and the test specimen, were placed in the AFM at the same time. Each was independently rotated so that the pitch features to be measured were parallel to the slow scan axis within 1°. Sample tilt relative to the XY plane of the scanner was < 0.5°. We measured pitch on the "Y" axis of the 150-2DUTC specimen. For the calibration standard, where the pattern covers the entire 4x3 mm die, 12 spots were selected on 1 mm centers on a grid spanning the central 3x2 mm. For the test specimen, where the pattern covers a 1.2x0.5 mm region at the center of a 3x4 mm die, 11 spots were selected on a regular pattern consisting of alternate rows of 2 spots and 1 spot. Each spot was previewed using the AFM's optical microscope and if defects were found, we moved 20-50 µm to a better spot. A 'programmed move' sequence was set up so that the AFM would automatically move to a spot, engage to the surface, capture the image, withdraw and move to the next spot. The measurement sequence was arranged so that images of the test specimen were interleaved between images of the calibration standard. Fig. 2 shows the spot layout and sequence of measurements.

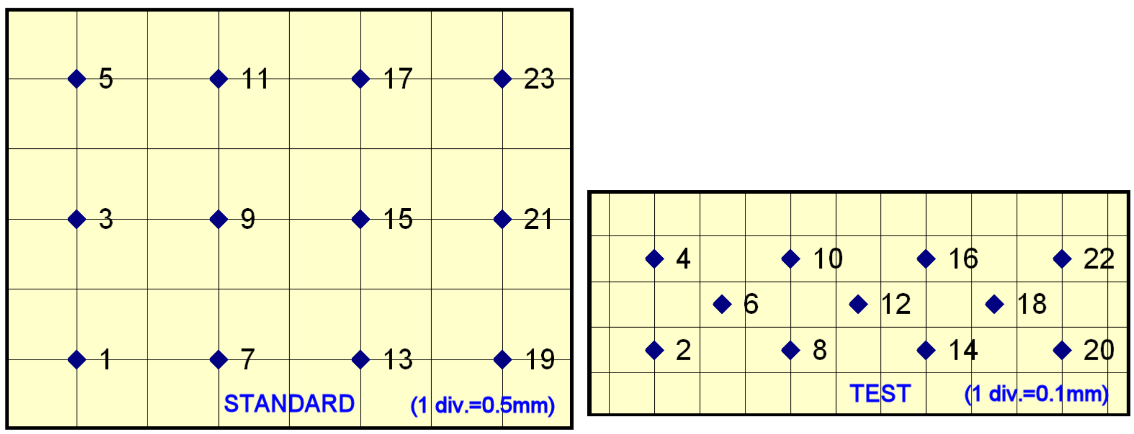

Fig. 2. Points are the nominal spot locations on the calibration standard and the test specimen. The numbers are the sequence of captured images. The first image is at "1" on the Standard, the second is at "2" on the Test, and so on.

3. RESULTS

We analyzed the height images using Advanced Surface Microscopy's DiscTrack Plus™ software. In a given run of the software, we measured the pitch using one test specimen image and two images of the calibration standard, one captured before and one captured after the test image, for example image 2 was calibrated using images 1 and 3. This procedure ("interleaved calibration") increases accuracy by correcting for short term drift in the AFM's magnification and it increases precision by using redundant calibration data. Fig. 3 shows the AFM images used for the analysis of Run 2, Data Set 8.

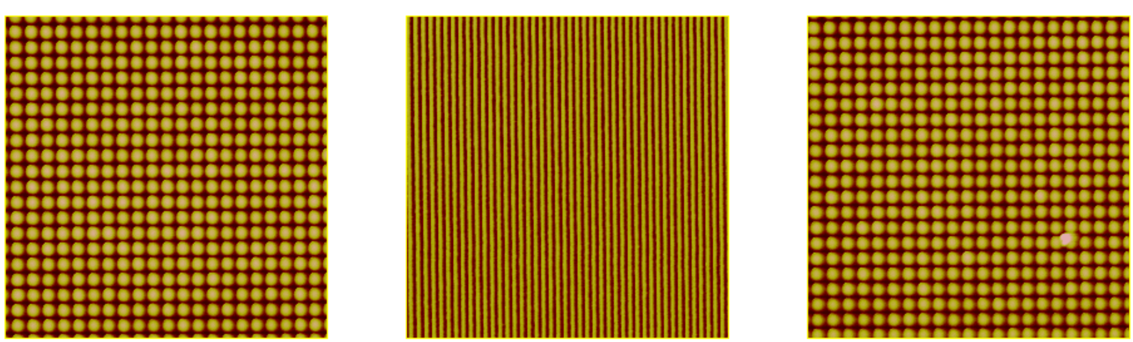

Fig. 3. Tapping mode AFM height image of 70-nm test specimen bracketed by images of the 144-nm standard. 3 µm scans.

The measurements were made according to procedures described in detail elsewhere[11, 12, 13] and summarized here. The software computes an average height profile Z(x) by averaging all scan lines. Peaks on the height profile correspond to ridges or columns of bumps (e.g., see fig. 1B). The centroid of each peak is its position. The difference of successive positions is an individual pitch value. No microscope is perfect and figure 4A shows there is a significant non-linearity in the image: apparent pitch values are large at the left side of the image (start of scan) and decrease towards the right. Because the image distortion is reproducible from one scan to the next, one can correct this systematic effect in the offline analysis. Using a 5th-order polynomial fit of pitch vs. position in the calibration images, the software computes a new length scale that corrects for average magnification error and non-linearity. The corrected length scale is then applied to the feature position data from the test image to produce a set of corrected pitch values. For this data set, calibration reduced the standard deviation by almost 7x and removed a bias of 3.2% in the mean value (see inset table in the figure).

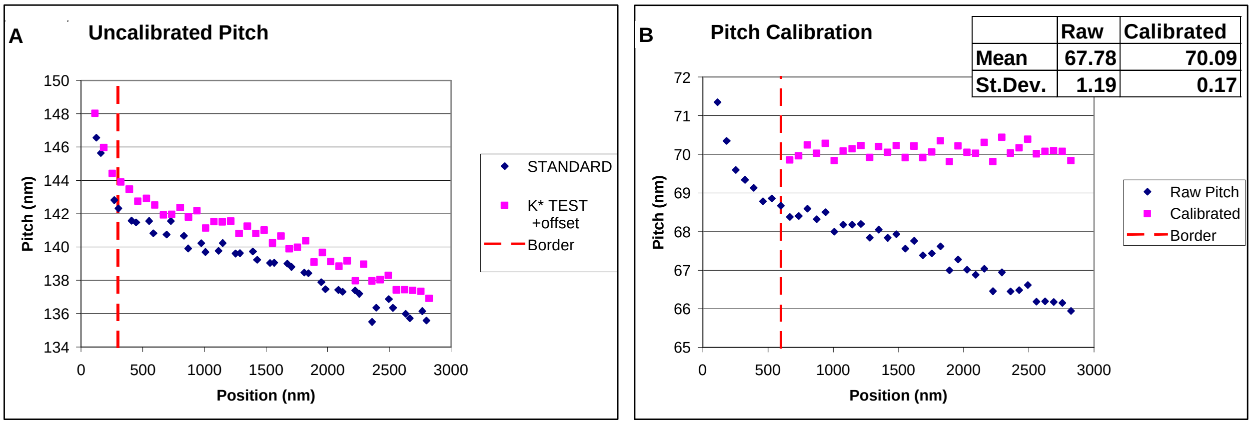

Fig. 4. Pitch results for one data set. A: Raw pitch as a function of position in the image. Points labeled "Standard" are pitch values measured in the calibration images captured before and after the test specimen image. Points labeled "K * Test + Offset" are (re-scaled) pitch values from the test image. The two curves were approximately parallel. B: Raw and calibrated pitch for the test specimen. The dashed vertical lines indicate data exclusion borders. Because the AFM nonlinearity is hard to correct at the start of scan, we exclude pitch results from the leftmost 20% of the test image and from the leftmost 10% of the calibration images.

For each data set, we computed descriptive statistics, such as mean and standard deviation, and pooled them to obtain overall results for each run. The mean pitch differed by only 0.019 nm, or 19 pm (picometer), between the two runs. This difference was not statistically significant. See Table 1 and figure 5.

Table 1. Pitch results (in nm) for the 70-nm pitch grating. SD = standard deviation (1σ).

	Run 1					Run 2			
Data Set	Count	Mean	SD	SD of Mean		Count	Mean	SD	SD of Mean
1	34	70.05	0.17	0.03		34	70.12	0.17	0.03
2	34	70.07	0.17	0.03		34	70.10	0.15	0.03
3	33	70.02	0.14	0.02		34	70.09	0.12	0.02
4	34	70.01	0.18	0.03		34	70.08	0.13	0.02
5	34	70.08	0.20	0.04		34	70.11	0.14	0.02
6	34	70.09	0.25	0.04		33	70.08	0.15	0.03
7	34	70.12	0.17	0.03		34	70.07	0.10	0.02
8	35	70.13	0.16	0.03		33	70.09	0.17	0.03
9	35	70.08	0.22	0.04		34	70.05	0.19	0.03
10	34	70.05	0.28	0.05		34	70.09	0.15	0.03
11	34	70.07	0.21	0.04		33	70.11	0.12	0.02
Overall	375	70.071	0.202	0.011		371	70.090	0.147	0.006

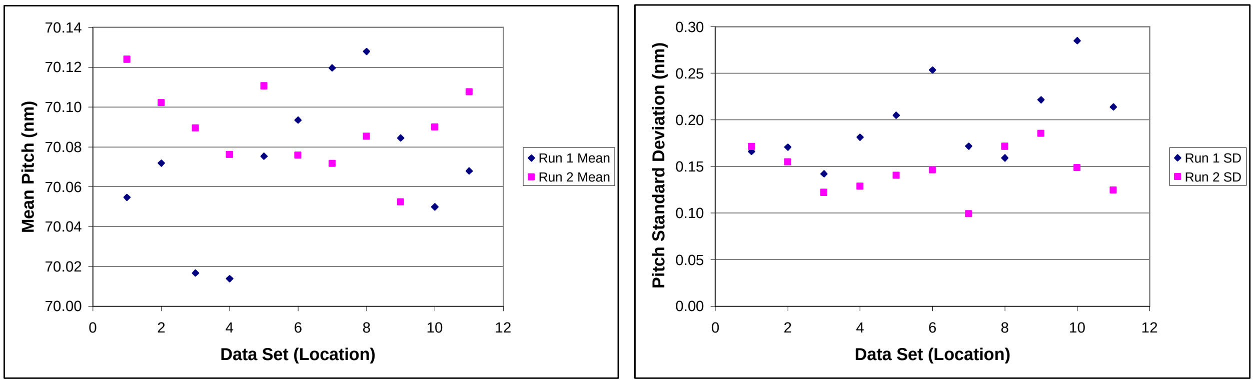

Figure 5. Mean pitch and standard deviation of single pitch values in two runs. Each data set corresponds to a specific location in the patterned area, but the very small scan size means it is very unlikely that corresponding scans in the two runs actually overlapped.

4. MEASUREMENT UNCERTAINTY

4.1 Measured errors (type A).

Magnification error and image nonlinearity are by far the largest errors present in the original data. We used an Analysis of Variance (ANOVA)[14] calculation to partition the overall variation into two components, called the "within group" and "between group" variances. A natural grouping of the data is by test image (or data set). Then, the "within group" variance is the variance of individual pitch values within each image relative to the mean value for that image, averaged over all images. The "between group" variance refers to the variance of mean pitch values for each image relative to the overall mean. The ANOVA result showed that there was no statistically significant difference between images in each run. This is consistent with the impression of random variation given by the graph of mean pitch values in fig. 5. This means that the interleaved calibration method has successfully corrected for average magnification error. The random variation of pitch values vs. position within each image, as shown in fig. 4, indicates that the length scale correction method has successfully corrected for the image nonlinearity. Therefore, we have corrected these effects as fully as is reasonably possible.

An alternative view of randomness comes from comparing two different estimates of the standard deviation of the overall mean. Estimate 1 is simply the standard deviation of the mean of the 11 mean values in each data set. Estimate 2 comes from dividing the single value standard deviation by SQRT(N), where N = 375 or 371 in runs 1 and 2. As shown in Table 1, the overall standard deviation of the individual pitch values was 0.20 nm (run 1, contact mode) and 0.15 nm (run 2, tapping mode). The overall standard deviations of the mean of means were 11 and 6.2 pm for runs 1 and 2, respectively. We compare these values with the "estimate 2" values, 10.4 and 7.6 pm. The corresponding values agree within 20%, indicating that the observed variation is mainly random. The random effects include surface and edge roughness, local pitch variation in the test specimen (whether intrinsic or due to debris on the surface), error in the corrected length scale, tip shape changes and AFM noise.

4.2 Unmeasured errors (type B)

Some sources of error are automatically minimized by the repetitive motion that occurs when scanning an AFM image.

-For our AFM, the piezo creep and frame drift rate can be on the order of 0.5 nm/sec, based on observing skew angles up to 1° for a 10 µm image scanned in 5-6 minutes. The relative error in apparent pitch is the ratio of drift speed to tip speed. We measure pitch on the fast scan axis. With a scan rate of 5 Hz and a scan size of 3000 nm, the tip speed is 30,000 nm/sec. The ratio is 0.0017%. This would change individual and mean pitch values by the same amount, ca. 1.2 pm. At a scan rate of 1.5 Hz, this effect would be 3.9 pm.

-Piezo hysteresis between the trace and retrace directions shifts peaks significantly, but we make all measurements using the same scan direction, so we discount this effect. Variation in hysteresis is included in the measured random variation of pitch values.

-Imperfect tracking and reproduction of the surface distorts the height profile. While this affects apparent widths and angles, it should not affect pitch measurements, so long as the distortion is consistent from feature to feature. There are several sources of inconsistency in the distortions caused by imperfect tracking and reproduction. Tracking errors generally appear as reduced angle on the downward side (relative to scanning direction) of slopes in the image. This produces an asymmetry artifact that can cause differences in height to lead to different measured positions. Features that are similar to the slopes of the AFM tip are another source of error. Small variations in slope can create regions where the image is accurately reproduced and regions where tip shape effects alter the observed feature shape.[15] These variations can lead to variation in measured feature position. In normal operation, tips and scan conditions are chosen to minimize these effects. Residual errors are included in overall random measurement errors.

Other sources of error are persistent.

-Rotation and tilt of the specimen means that the ridges or bump columns would not be exactly perpendicular to the AFM fast scan direction. We control absolute rotation and tilt to be less than 1° and 0.5°. When the values are different for the calibration and test specimens, they affect pitch by a cosine factor, amounting at most to 0.015% and 0.004%, respectively. If the calibration standard is rotated or tilted more than the test specimen, this would decrease the reported pitch of the test specimen, and vice versa. An error of 0.015% is 10.5 pm at 70 nm. This effect gives a constant bias within a given run and contributes to a run to run reproducibility error when specimens are replaced.

-The stated uncertainty of the 150-2DUTC mean pitch is 7.5 pm (0.0052%).

-Temperature dependence is discounted because the calibration standard and the test specimen both use silicon substrates and because both are measured under the same environmental conditions.

Table 2. Summary of the AFM uncertainty budget.

Input Quantity	Factor, if proportional to pitch	Contribution to Pitch Uncertainty for single pitch values (nm)	Contribution to Pitch Uncertainty for mean pitch(nm)
Run 1			
Random error in measured data	0.2883%	0.2020	0.0110
Pitch uncertainty of 144 nm standard (expanded uncertainty = 0.015 nm)	0.0052%	0.0036	0.0036
Sample rotation difference (cos(1 degree))	0.0150%	0.0105	0.0105
Sample tilt difference (cos(0.5 degree))	0.0040%	0.0028	0.0028
Piezo creep and frame drift (see text)	0.0017%	0.0012	0.0012
Resulting uncertainty of pitch value (nm), 1 sd		0.2023	0.0159
K=2 uncertainty		0.4047	0.0318
Run 2			
Random error	0.2096%	0.1469	0.0076
Pitch uncertainty	0.0052%	0.0036	0.0036
Sample rotation difference	0.0150%	0.0105	0.0105
Sample tilt difference	0.0040%	0.0028	0.0028
Drift	0.0056%	0.0039	0.0039
Resulting uncertainty of pitch value (nm), 1 sd		0.1474	0.0143
K=2 uncertainty		0.2947	0.0286

Run	1	2
Pitch (nm)	70.071	70.09
Count	375	371
SD (single pitch), nm	0.202	0.147
SD of overall mean (estimate 1)	0.0110	0.0062
SD of overall mean (estimate 2)	0.0104	0.0076
AFM scan rate	5	1.5
image size (nm)	3000	3000
tip speed (nm/s)	30000	9000
drift speed (nm/s)	0.5	0.5

Notes: SD = standard deviation. The uncertainty in mean pitch due to random error is taken as the greater of estimates 1 and 2. Values are presented with 4 decimal places for clarity, but it is understood that uncertainties have at most two significant figures.

As shown in the table, the expanded uncertainties for our AFM results were: for single pitch values ± 0.40 nm in run 1 and ±0.29 nm in run 2; for mean pitch ±32 pm for run 1 and ±29 pm for run 2.

Because the combined uncertainty is computed as the root mean square of the individual components, we assess the importance of each uncertainty component by computing its square, i.e. its contribution to variance.

Table 3. Relative variance of the uncertainty components for single pitch and mean pitch.

	Single Pitch	
Input Quantity	Contribution to Variance as % of total	
	Run 1	Run 2
Random error in measured data	99.7%	99.3%
Sample rotation difference (cos(1 degree))	0.27%	0.51%
Pitch uncertainty of 144 nm standard (expanded uncertainty = 0.015 nm)	0.03%	0.06%
Piezo creep and frame drift (see text)	0.003%	0.07%
Sample tilt difference (cos(0.5 degree))	0.02%	0.04%
Resulting uncertainty of pitch value (nm), 1 sd	100.0%	100.0%

	Mean Pitch	
Input Quantity	Contribution to Variance as % of total	
	Run 1	Run 2
Random error in measured data	47.5%	28.4%
Sample rotation difference (cos(1 degree))	43.6%	53.9%
Pitch uncertainty of 144 nm standard (expanded uncertainty = 0.015 nm)	5.3%	6.5%
Piezo creep and frame drift (see text)	0.5%	7.4%
Sample tilt difference (cos(0.5 degree))	3.1%	3.8%
Resulting uncertainty of pitch value (nm), 1 sd	100.0%	100.0%

For single pitch values, only the random error was important. For mean pitch values, the two most important components were the measured standard deviation of the mean and the cosine error due to sample rotation. The path for reducing the uncertainty of the mean value is clear: measure and control the sample rotation better and capture more pitch measurements.

5. DISCUSSION

The results presented above show that our method of using a transfer standard to calibrate a test specimen is very accurate. This claim of accuracy has been verified in two separate experiments. In 2007, the 144-nm pitch 2D grating was measured by optical diffraction at PTB, the national standards lab of Germany, and by AFM in our lab, with reference to a 292-nm pitch standard. The average pitch values agreed within 0.023% (or 33 pm). This value was less than our uncertainty due to random effects, indicating that unknown effects that might cause bias were small.[10] In 2009, the 70-nm pitch grating discussed here was measured in two national standards labs, NMC/A-STAR in Singapore and NIST in the USA. Detailed results will be presented later showing that all three labs' results for mean pitch agreed within a few parts in 10,000.[16]

We believe that any high-quality, general purpose SEM or AFM may be capable of providing metrology at this level when combined with our method of systematic data capture and image analysis. A necessary requirement is short-term measurement precision, within single images. We test this by imaging a calibration grating and measuring the image with our purpose-built calibration and measurement software. We have done this for several AFMs and SEMs using calibration gratings whose pitch values cover 3 orders of magnitude, from 2000 down to 35 nm. In each case, the image or set of images contained enough pitch periods (>15) so that we could use self-calibration to correct image nonlinearity. We then computed relative pitch variation (standard deviation/average pitch). See figure 6.

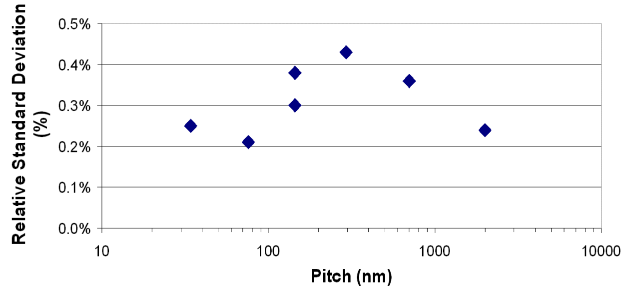

Figure 6. Relative precision of pitch measurements in AFM and SEM images of gratings with pitch from 35 to 2000 nm.

The relative standard deviation was in the range 0.22-0.43% for all pitch values from 35 to 2000 nm. This result is important because at 0.5% relative Standard Deviation for single Pitch values, it is practical to get relative uncertainty of mean < 0.05% in a short data run (N=100).

Once a grating has been measured in the traceable process described above, it is no longer just a test specimen but instead can be used as a calibration standard itself. We anticipate that traceable calibration standards will be needed at pitch values that decrease by a factor of about 2 at each step. Traceability can be achieved in either of two ways: by measurement in a "first-principles" traceable microscope or by using a transfer standard, as in our work. We now present a metrology roadmap that applies the transfer standard method to measure patterns down to 5 nm pitch. The steps along the road are as follows: a 144-nm standard calibrates 70-nm (accomplished in this work). The 70-nm standard calibrates a 35-nm standard. 35-nm calibrates 20, 20 calibrates 10, and 10 calibrates 5. At each step in the chain, one would capture a data set consisting of multiple images of the current and new standards, just as shown above. The measured data would include >300 independent pitch measurements of the new standard. The resulting accuracy can be predicted by applying the uncertainty model described above, along with the assumption that the relative standard deviation of single pitch measurements is 0.5%. This assumption is plausible based on experience to date (see fig. 6). Under this assumption, random variation will contribute 0.03% (1 σ) to the uncertainty of the new standard's mean pitch value. Additional error components include the uncertainty of the current standard's mean value and the other instrumental factors discussed in detail above.

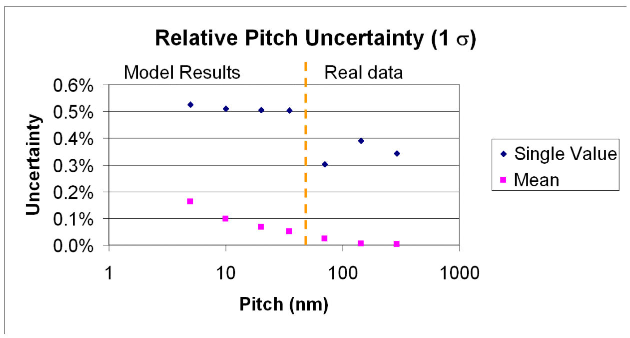

Figure 7. Actual and modeled uncertainties (k=1) of existing and future calibration standards.

Figure 7 shows the results for three calibration standards produced so far (292, 144 and 70 nm) and projected uncertainties at 35, 20, 10 and 5 nm. We expect that the uncertainty (k=1) of the 5-nm pitch standard will be 8 pm (1σ) for the mean value and 26 pm (1σ) for single values. These uncertainties easily meet the target given above (1σ = 12.5 and 50 pm, respectively). It is interesting to note that different sources of uncertainty become important at the smallest dimensions. For example, drift dominates the uncertainty of the mean value at 5 nm. Even if the 10 nm transfer standard were perfect (0 uncertainty), the 5 nm mean uncertainty would be reduced only a little bit, to 6.5 pm.

In describing the calibration roadmap, our purpose has been to show that one can proceed with confidence, knowing that the measurement procedures and mathematical methods have been substantially worked out. We do not minimize the challenges of producing the calibration specimens themselves or the tools to image them. We are presently looking for patterns with pitch < 40 nm. If you are making such patterns and can provide samples, please contact the authors.

6. CONCLUSIONS

We briefly reviewed requirements for accuracy in length measurements for semiconductors, optical disks and magnetic disks. The pitch calibration standards used to calibrate measuring microscopes should have expanded uncertainty (k=2, 95% confidence) < ±0.5% for mean pitch and < ±1.33% for single pitch values. We used a common general purpose AFM and a traceable 144-nm pitch transfer standard to make traceable measurements of a 70-nm pitch standard. We applied purpose-built analysis software to correct for significant magnification errors present in the as-captured images. In two separate runs using contact mode and tapping mode, we found mean pitch of 70.071 and 70.090 nm. Our error budget yielded expanded uncertainties of 0.030 nm for the mean and 0.35 nm for single values, which are 0.043% and 0.50% of the pitch. Based on this success, we defined a roadmap for traceable calibration of smaller pitch specimens, leading to a 5-nm pitch standard whose expanded uncertainties are expected to be 16 pm for the mean and 26 pm for single values, which are 0.32% and 1.04% of the pitch. This is better than the target accuracy.

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