Phase Standard Based on Profilometer Metrology Standard

Gregory P. Hughes*[a], Cindy Goodman[a], Gunter Antesberger[b], Stefan Burges[b], Troy Morrison[c], Alex Buxbaum[c]
[a]DuPont Photomasks Inc., 400 Texas Ave. Round Rock, TX 78764
[b]Advanced Mask Technology Center, Rähnitzer Allee 9, 01109 Dresden Germany
[c]FEI Company, 5350 NE Dawson Creek Dr. Hillsboro, OR 97124

Abstract

A NIST traceable phase[1] shift standard has been designed, fabricated, and tested on three phase shift measurement tools using different wavelengths. By using the fundamentals of NIST traceable step height, quartz index, and the understanding of the illumination optics of the Lasertec phase metrology tool, a phase standard has been created which can be used to calibrate Lasertec phase metrology tools. The pattern that is used is compatible with the recommended best practices for calibrating and measuring step heights and phase on the Lasertec tools. The mask is made with multiple depths. The three mask depths allow for the mask to be calibrated to three NIST traceable depth heights. This was done using the FEI SNP XT depth metrology tool. Since the mask format is mask based (6x250 Cr on quartz), it can be easily used on mask manufacturing metrology systems. The depths are targeted at the 180-degree phase shift for 157nm, 193nm, and 248nm lithography. The mask can be used to set targets and check the linearity of the phase metrology tools. The patterns are compatible with AFM and Profilometer depth metrology tools as well as multiple Lasertec spot sizes and shearing distances. The quartz depths are fabricated using a wet quartz etch process. The wet etch minimizes the quartz roughness and removes that error source from the metrology. The pattern is also arrayed so that multiple sites can be used to confirm the metrology and the prime measurement site could be changed if there was a suspicion of pattern damage or contamination.

Introduction

Every metrology tool needs to be controlled and if possible controlled to a standard. Figure 1 shows an example of a Lasertec MPM 248 in uncontrolled and controlled mode. In this case the control is most needed when the source light is changed even though the tool is wavelength controlled. But control does not mean that that one tool will read the same value as another tool. Figure 2 shows the results of 5 Lasertec tools reading 3 different masks. Although all of the tools are in control to their own control masks, they differ tool to tool. This variation can be brought into control (as shown on the right side of Figure 2) by sharing control masks between tools (in this case at different manufacturing sites), but it does not mean that there is control between similar tools at different mask vendors. This is best accomplished with a NIST calibration mask (as it is done for CDs). Unfortunately one does not exist, but using a NIST calibrated quartz step mask with an understanding of the Lasertec optics, a NIST traceable phase[1] calibration vehicle has been created.

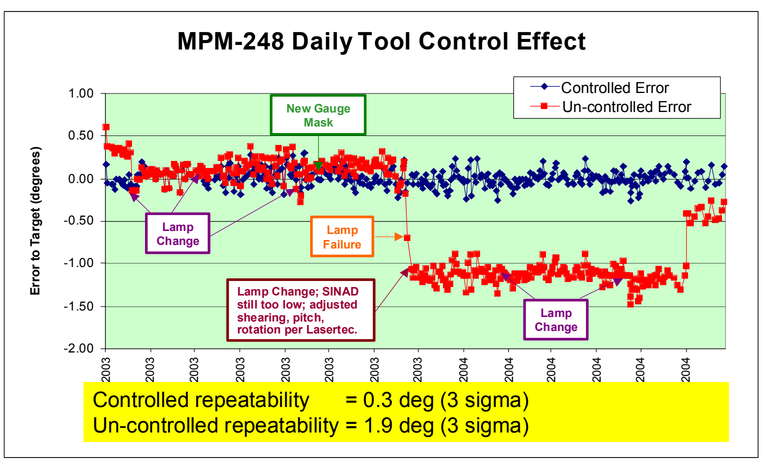


Fig. 1 Lasertec MPM 248 tool control. Red line shows the events that can cause the tool to shift its readings of a control sample. The Blue line shows the response of a well-controlled tool even when the tools nominal reading is changing.

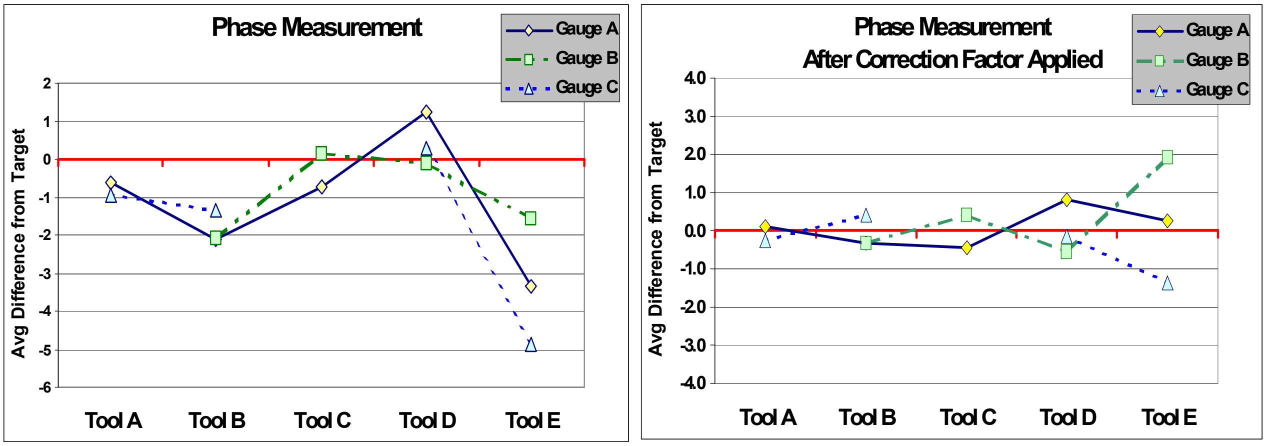


Fig. 2 Lasertec phase tool control of multiple tools across multi ple sites. The left chart is before across site control and the right chart is after applying control to a company set of company phase standards.

Physics of the Phase from Depth Standard

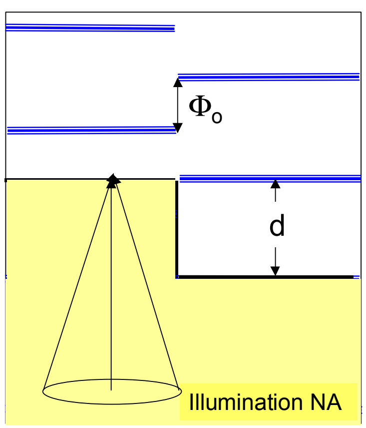
Obtaining a calibrated phase shift from a known height difference is similar to an Alternating Phase Shift mask. The phase shift is caused by the difference in the phase paths across the step. In each case the phase path is the distance traveled (in waves) (d/λ) times the index of refraction of the media. Thus for quartz step height the phase path difference is

$$\text{Phase Difference} = d*n/\lambda - d/\lambda = \theta/360$$

The phase path is quartz minus the phase path in Air with an index n=1.

This equation works well for light at normal incidence but when the light is coming from an angle the path length is not d. Thus when this concept is used with a Lasertec phase metrology tool the integrated path length of the illumination NA needs to be accounted for. This correction is "m" in the equation[2] in Figure 3.

Figure 3 shows the use of this relationship with a mask with three step heights (nominally 120, 180, and 240 nm) in quartz. The step heights were measured in depth and in phase with both a 248nm Lasertec and a 365nm Lasertec. In each case the phase was converted to a depth using the corrected relationship and solving for depth. The calculated depth agrees very well with the measured step height as shown in Figure 3 by the average difference in depth for each Lasertec system.



Normal Incident Illumination Phase Shift

$(\Phi_o \text{ deg}/360) = d/[\lambda/(n-1)]$

Incidetn NA Adjusted Phase

$\Phi = \Phi o * m$

$m = (1+(1/4n)*(NA)^2)$

		d = (Φ/m/360)*λ/(n−1)	
Target	Depth (AFM)	**248.4**	**365**
NA		0.31	0.21
m=(1+(1/4n)*(NA)^2)		1.0159	1.0075
index	n	1.508433	1.47454
120nm	123.1	122.6	123.1
180nm	180.7	180.7	180.6
240nm	241.2	241.3	240.2
Average Depth Difference		**-0.1**	**-0.4**
Ave Stdev		0.36	0.55

Fig. 3 Shows the relationship between the step height and phase as measured on a Lasertec system. The table shows the phase and calculated results from three different depths and their relationship to the measured depth.

Errors associated with determining a Phase Standard from a NIST traceable depth measurement

Figure 4 shows the calculation of the phase from a known depth and the error calculation of the uncertainty in the determined phase value. The dominant contribution to the error is the determination of the error in the NIST traceable depth. Typically this is about 1% of the measurement depth[3]. The wavelength of the illumination is tuned in the Lasertec tools and the index of quartz is well known. The error in the determination of "m" is based on a 10% error in the value of the Illumination NA of the Lasertec systems.

Phase from NIST Depth d_t

Φo= Phase of Normal Incident Wave

$\Phi o=(d_t*360)/\{\lambda/(n-1)\}$

$\Phi=\Phi o*m$ - Measured adjusted for Incident NA

$m=(1+(1/4n)*(NA)^2)$

Error in Phase

$\Delta\Phi/\Phi = \Delta d/d + \Delta\lambda/\lambda + \Delta n/n + \Delta m/m$

=1% + 0.1% + 0.001% + 0.3%

Fig. 4 Shows the determination of the phase from a step height d. The step height and all of the other terms in the equation are NIST traceable values. Given the uncertainty in the equation components, the uncertainty in phase is determined as shown.

Calibration Mask Description

A phase calibration standard mask has been designed as shown in Figure 5. The standard format is that of a 6x250 Cr on quartz photomask so that all of the normal mask holding stages will work with it. The mask consists of a 5-chip array for evaluating phase in the four corners and center of the mask. Each array is composed of a labeled 10x10 array of calibration cells. The array allows the metrology engineer the opportunity to change cells if they feel that the cells have been contaminated or damaged. Each cell is composed of an array of 9 patterns. The rows have different widths to the quartz etched area and the columns have different depths. The different pattern widths are designed to allow the Lasertec to be used with different shearing conditions. The different depths are designed to be approximately 180 deg for the 157nm, 193nm, and 248nm lithography cases. The different depths also provide the opportunity to study the linearity of the metrology tools.

The mask was fabricated using standard photomask processes. The etched quartz areas were sequentially opened in a lithography process and quartz was wet etched to achieve maximum uniformity and quartz smoothness. The last step cleared the Cr from the reference areas and provided the labeling. This approach provided less than 0.5 nm across the mask depth variation and no measurable across chip depth variation. The depth metrology and the phase metrology both show about a 0.5 nm (at the 2400 Ang. Depth) pattern dependent depth variation with the wider pattern having less depth. This is best seen in Figure 6.

This mask can also be used to cross calibrate different depth metrology tools used in the photomask industry. It can serve as a single standard for AFM and profilometer tools as well as phase tools.

NIST Traceable Depth Measurements on Calibration Masks

Two calibration masks have been fabricated and measured. Figure 6 shows the results of the depth measurements. Two cells on each mask were measured (E5 and G7) at each of the 9 patterns and depths. These measurements were made multiple times to determine the repeatability of the depth metrology. The depth was measured using FEI SNP XT Stylus Nanoprofilometer™ metrology tools. Each mask was measured on two separate SNP XT production tools against three independent NIST Standard sets. Each standard set that is used to calibrate the SNP tool consists of three depth standards at nominally 25nm, 100nm, and 500nm. The black hash marks represent the individual tools 3 sigma repeatability. The red error bar represents the NIST traceable error associated with the three standards used to calibrate each tool. Note that the depth data from tool to tool does not agree within the tools repeatability, but does agree within the NIST traceable standard errors. Thus pointing out that the depth calibration is only as good as the NIST traceable standard depth. For this reason we chose to use the average of the three depth readings for our calculation of phase angle.

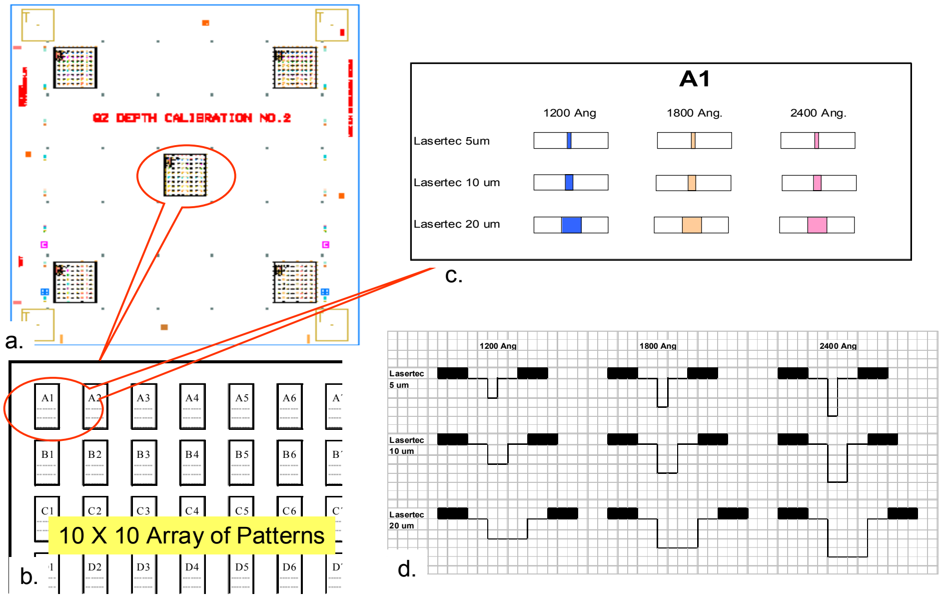


Fig. 5 a. Layout of the quartz Depth Calibration mask **b.** Detail of the calibration die (a 10 x 10 array of depth-phase patterns) **c.** Layout of the different depth patterns with trenches into the quartz at different depths and widths **d.** Cross sectional view of the layout that is shown in c.

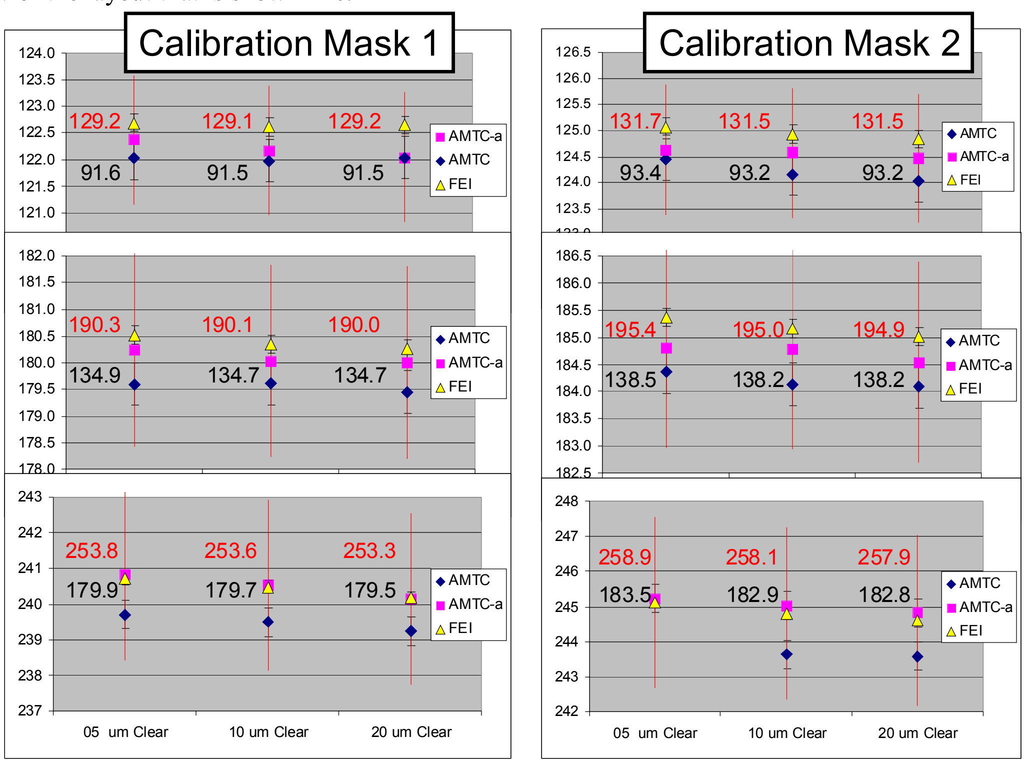


Fig. 6 Shows the depths that were measured on the calibration masks. The data from the three pattern widths show a slight variation of depth with the different patterns. Measurements were made on the masks using two separate FEI SNP XT tools and three independent sets of depth standards. The black hash marks represent the 3-sigma repeatability of the tools. The red bar represents the NIST depth uncertainty. The numbers at each point are the phase values that the Lasertec Phase Metrology tool should read (top-red - MPM 193, bottom-black MPM 248) at each pattern.

Figure 6 has the phase calculations determined from the average depth for each of the patterns. Note the two phase values, one for calibrating the Lasertec MPM 193 and one for calibrating the MPM 248 tool. Thus one standard can be used to calibrate multiple wavelength tools.

Lasertec Phase Readings vs the Quartz Calibrated Phase

Figure 7 is a plot of the Lasertec phase vs the calibrated phase determined from the average quartz depth values. This plot uses the data from the two masks and the three different Lasertec tools (2 MPM 248 and one MPM 193)

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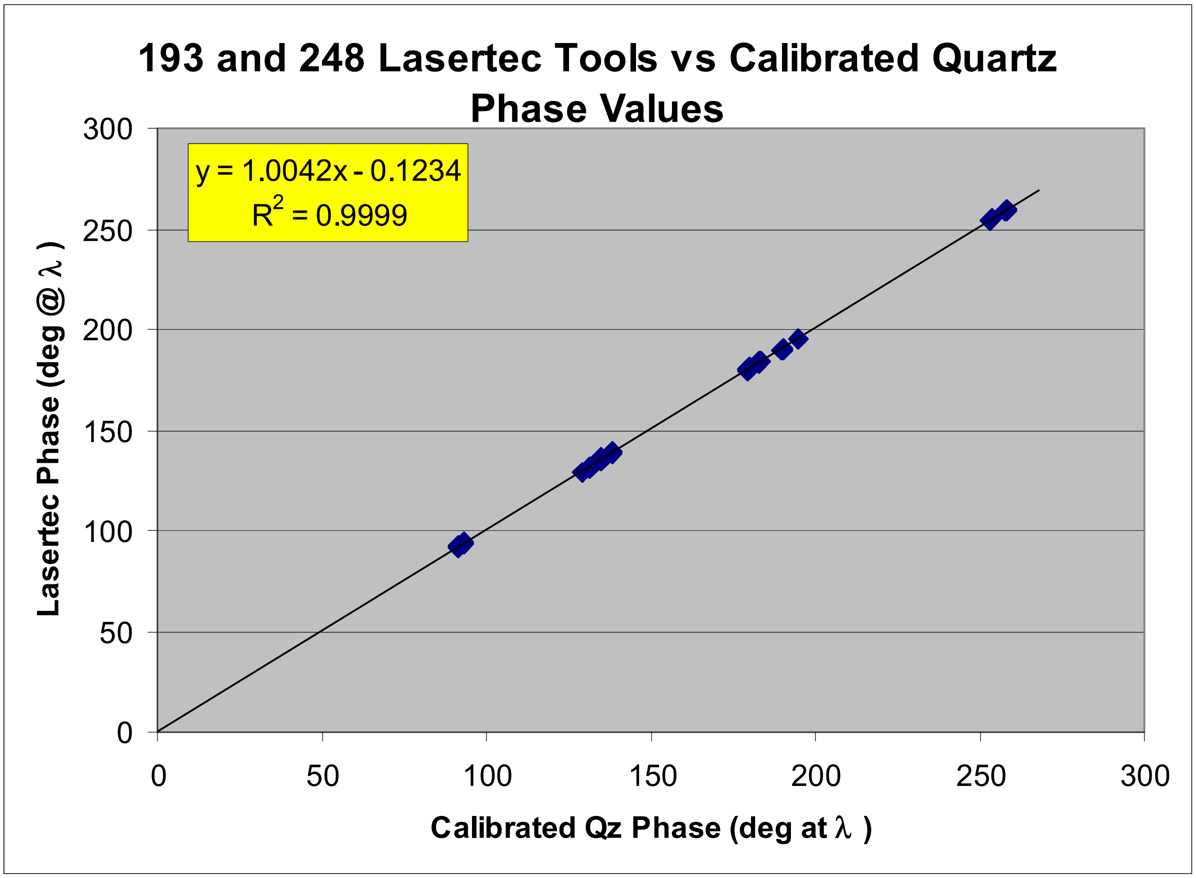

Fig. 7 Shows a plot of the Lasertec phase readings vs the Calibrated quartz phase readings. Note this includes the two masks, the 3 pattern widths, the 3 depth values and three different Lasertec tools (MPM 193 and two MPM 248s)

Figure 8 (left) shows the difference in the Lasertec phase readings vs the Calibrated phase for each of the Lasertec tools studied. The MPM 248 tools are both flat with different mean offsets vs the Calibrated depth. The MPM 193 tool shows a slight slope response.

Lasertec Calibration Approaches

Three different Lasertec calibration approaches have been studied. The first approach uses a best-fit slope to the data forcing the Y intercept to zero (Figure 8 right). The slope to calibrate each Lasertec tool was determined using the Calibration Mask 1 (solid points). The calibration slope was then used on the control mask. This approach works well with the tool's design because a calibration slope can be loaded into the Lasertec software. The results are good for the MPM 248 tools (3 sigma in phase about 0.8 deg), but the variation with depth on the MPM 193 tool causes this error to double.

The second approach is to use a linear fit to the data, allowing the Y intercept to have a value. Figure 9 right shows the results of this fit. The Y intercept for the MPM 248 tools is small as one would expect from the previous data, while the MPM 193 tool shows a Y intercept of –1.9 deg. Using this approach the 3-sigma variation of the control mask is under 0.7 deg for all tools. This is probably the best type of calibration because it provides a good fit over a large range of phase values. Unfortunately the tool data would need to be post processed in order to use this type of fit since the Lasertec software does not provide for a linear calibration with a Y intercept.

The third approach is a best-fit slope for the phase data at 180 degrees. Figure 9 right shows this type of fit. This approach is good for all tools for phase values around 180 degrees (3 sigma of the control masks are all under 0.7 deg). This method is valid for the typical mask maker's use of the tool where the target phase is 180 degrees and it is compatible with the Lasertec software.

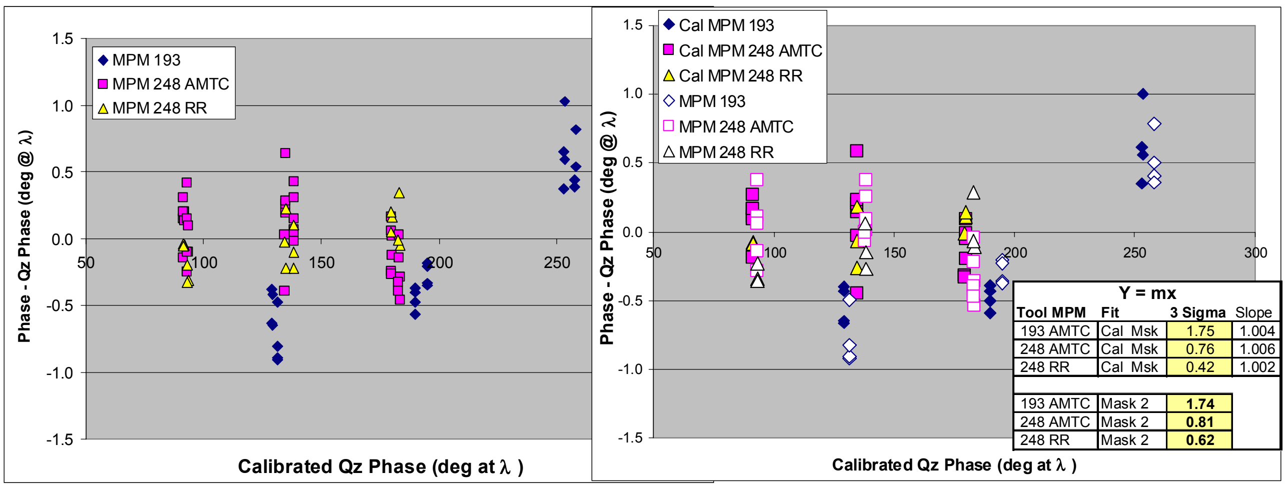

Fig. 8 Left) Shows the phase difference between the Lasertec values and the Calibrated quartz phase readings for three different Lasertec tools (MPM 193 and two MPM 248s). Right) Shows the results of a slope calibration of the Lasertec tools to the calibration mask (solid patterns). The open boxes are the results from the measurements of mask two on the calibrated Lasertec tools. The 3-sigma deviations are similar to the calibration fits.

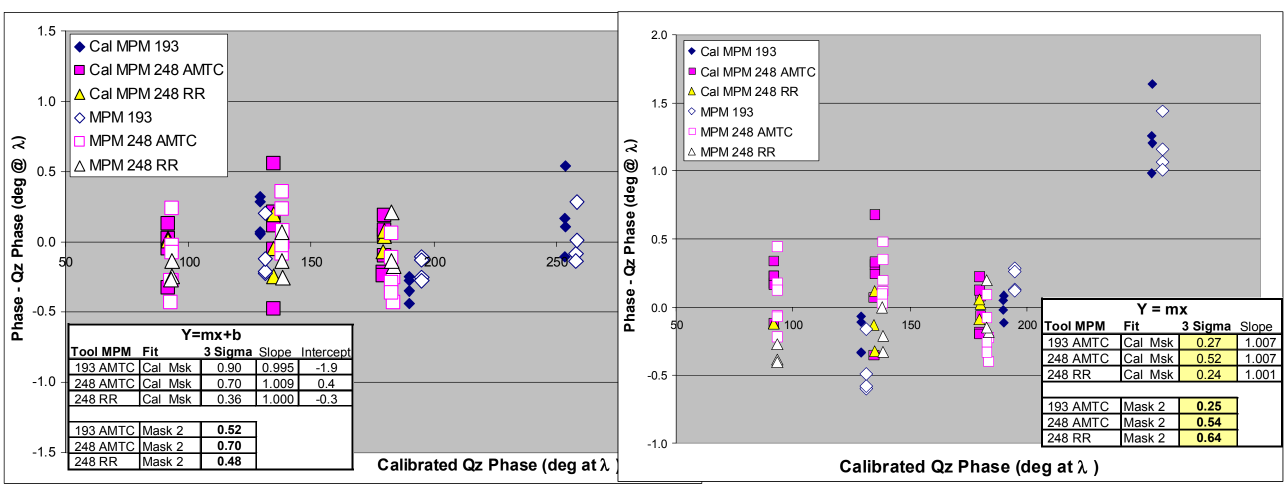

Fig. 9 Left) Shows the results of a linear calibration of the Lasertec tools to the calibration mask (solid patterns). Right) Shows the results of a slope calibration of the Lasertec tools to the 180 deg points on the calibration mask (solid patterns). The open boxes are the results from the measurements of mask two on the calibrated Lasertec tools. The 3-sigma deviations are similar to the calibration fits.

Conclusions

This paper has demonstrated that both phase tool control and control to a standard is needed so that customers can receive masks that are referenced to a standard. We have shown that with the proper corrections for illumination NA, a NIST traceable phase[1] can be obtained from a NIST traceable depth standard. The uncertainty of the phase is dominated by the uncertainty in the depth standard (about 1%). By using the FEI SNP XT that is calibrated to three depth standards we have seen that three different standard groups agree to within 0.65% of each other (1.2 deg).

We have also shown that when a quartz depth phase standard is used in a linear fit, the 3-sigma residuals of a quartz control mask are less than 0.7 degrees. This value just represents the variation in the metrologies and not the NIST calibration, which still remains at the 1% value due to the depth calibration standards[3].

This NIST traceable phase standard has been implemented into the standards quality program at DuPont Photomasks. It is used to control and calibrate all of the DuPont Lasertec tools and is used as a transfer depth standard across the multiple depth metrology tools.

* Greg.Hughes@photomask.com

1) "NIST traceable phase" used in this paper is not an Official NIST term

2) Hiroshi Fujita, Hisatake Sano, Dai Nippon Printing Co.Ltd.
Haruhiko Kusunose, Hideo Takizawa, Koji Miyazaki, Naoki Awamura, Takahiro Ode, Daikichi Awamura, Lasertec Corp. "Performance of i and g-line phase-shift measurement system MPM-100"
Proc. SPIE **Vol. 2793**, p.497-512, 1996

3) MikroMasch. "Certificate of an Ultra Fine Calibrating Grating". Step Height Reference Standards: NIST 821/261141-99, NIST 821/265166-01.