National Institute of Standards & Technology

Certificate

Standard Reference Material® 2059

Photomask Linewidth Calibration Standard

Serial Number Sample

This Standard Reference Material (SRM) is a chrome-on-quartz photomask intended primarily for use in calibrating optical microscopes used to make dimensional measurements on antireflecting chromium integrated circuit photomasks, and supersedes SRM 473 *Optical Microscope Linewidth Standard* [1]. SRM 2059 consists of patterns of clear and opaque isolated lines with nominal dimensions ranging from 0.25 µm to 32.0 µm and line-spacing (pitch) patterns ranging from 0.5 µm to 250 µm (see Figure 1). These patterns are on a nominal 152.4 mm × 152.4 mm × 6.35 mm (the industry standard 6.0 in × 6.0 in × 0.25 in) quartz substrate.

Certified Values: Certified values are given for isolated linewidths (both clear and opaque) and center-to-center line-spacings for one of the eight repeated patterns on the SRM as indicated by the pattern number given as the final digit of the serial number. All measurements were averaged over the central 2 µm of each feature (at the horizontal fiducial line, also 2 µm wide to aid in tool setup), and the certification applies only to that portion of the feature. The certified values and their uncertainties are given in Tables I and II.

Expiration of Certification: The materials used for this SRM, primarily quartz and chrome, are inherently stable. Consequently the certification of SRM 2059 is valid indefinitely, within the measurement uncertainty specified, provided the SRM is handled and stored in accordance with the instructions given in this certificate (see “Instructions for Use”). Periodic recertification is not required; however, this certification will be nullified if the SRM is damaged, contaminated, or modified.

Maintenance of Certification: NIST will monitor representative samples from this SRM lot over the period of its certification. If substantive changes occur that affect the certification, NIST will notify the purchaser. Registration (see attached sheet) will facilitate notification.

The overall preparation of this SRM was under the direction of J. Potzick.

The underlying theory and the optical equipment used in the certification of the NIST photomask SRMs were developed and initially constructed by D. Nyyssonen of the NIST Precision Engineering Division. Dr. Nyyssonen's model of optical image formation in the microscope has been significantly improved by M. Davidson [2–4] of the Spectel Research Corp., and this model was used in calibrating this SRM. A wholly independent optical imaging model developed by E. Marx of NIST was used to verify these modeling results.

The equipment for automation of the measurement process was subsequently designed, constructed, and programmed by J.E. Potzick, M. Pedulla, and M.T. Stocker of the NIST Precision Engineering Division.

Measurements and data reduction were provided by M.T. Stocker and J.S. Jun of the NIST Precision Engineering Division. Atomic force microscope (AFM) measurements were provided by R.G. Dixson of the NIST Precision Engineering Division. Nien-Fan Zhang of the NIST Statistical Engineering Division provided statistical support. R. Larrabee and R. Silver provided additional advice and occasional encouragement.

The support aspects involved in the issuance of this SRM were coordinated through the NIST Measurement Services Division.

Michael T. Postek
Precision Engineering Division

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Certificate Issue Date: 13 November 2006

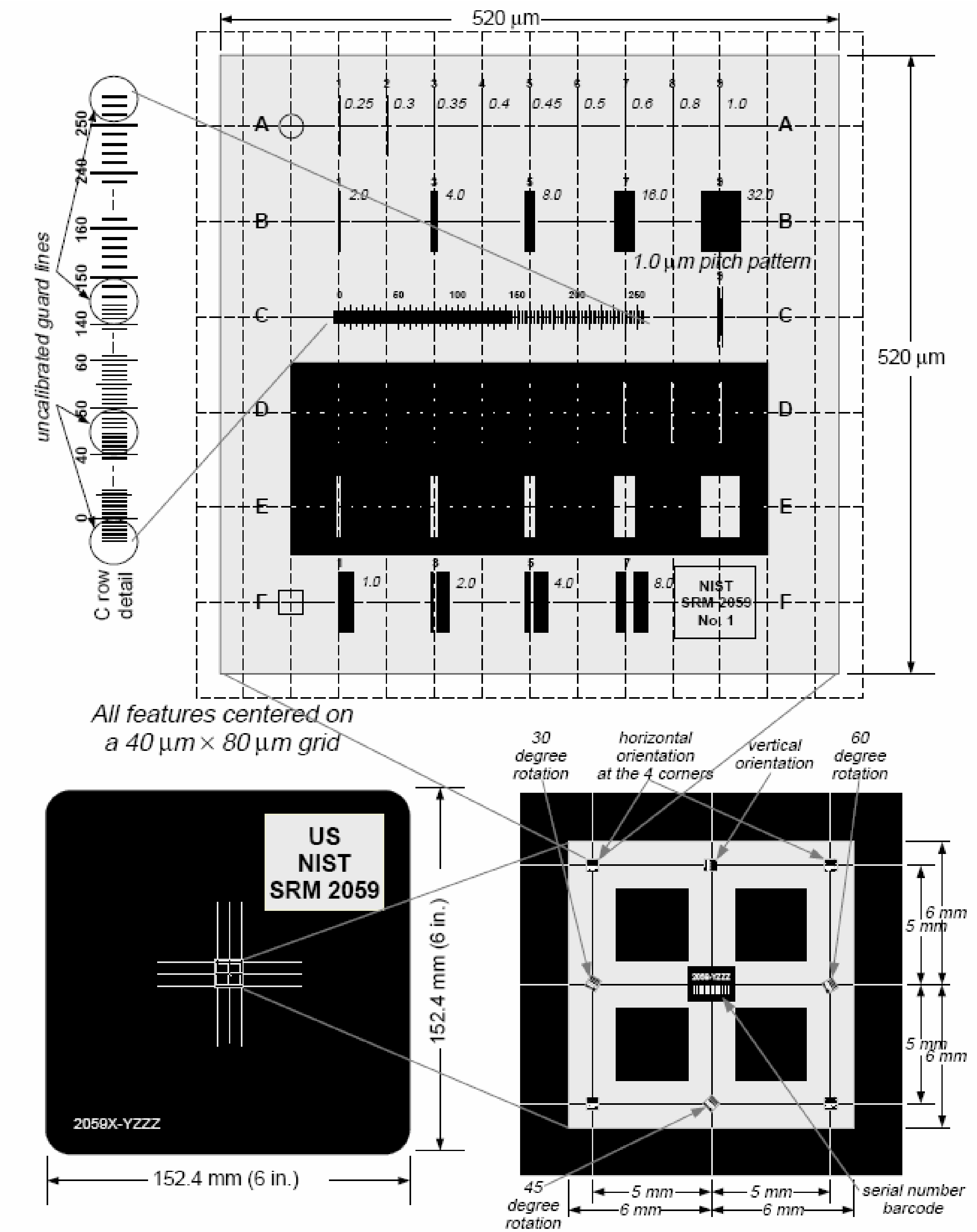

Figure 1. Chrome side view of SRM 2059.

Table I. Isolated Lines and Spaces and Pitch Pattern C9[a]

Calibration Data for SRM 2059

Photomask Linewidth Standard

Serial Number 2059-Sample, Pattern No. 1
Calibrated October 6, 2004

2059-Sample-1 8-29-05

Linewidth	***A1***	***A2***	***A3***	***A4***	***A5***	***A6***	***A7***	***A8***	***A9***
Nominal (µm)	0.250	0.300	0.350	0.400	0.450	0.500	0.600	0.800	1.000
***Measured* (µm)**	**0.172**	**0.238**	**0.294**	**0.346**	**0.386**	**0.440**	**0.535**	**0.723**	**0.923**
Uncertainty (*nm*)	13.6	13.4	13.5	13.8	13.4	13.3	14.0	14.2	14.1
	B1		***B3***		***B5***		***B7***		***B9***
Nominal (µm)	2.000		4.000		8.000		16.000		32.000
***Measured* (µm)**	**1.906**		**3.903**		**7.897**		**15.898**		**31.884**
Uncertainty (nm)	21.4		25.2		23.4		23.39		24.4
Pitch	***C1***								***C9***
Nominal (µm)	(b)								1.000
***Measured* (µm)**	**(b)**								**1.000**
Uncertainty (nm)	(b)								2.8
Spacewidth	***D1***	***D2***	***D3***	***D4***	***D5***	***D6***	***D7***	***D8***	***D9***
Nominal (µm)	0.250	0.300	0.350	0.400	0.450	0.500	0.600	0.800	1.000
***Measured* (µm)**	**0.283**	**0.339**	**0.417**	**0.453**	**0.534**	**0.586**	**0.701**	**0.897**	**1.100**
Uncertainty (*nm*)	17.6	16.1	15.3	17.3	15.5	16.3	18.7	15.8	15.0
	E1		***E3***		***E5***		***E7***		***E9***
Nominal (µm)	2.000		4.000		8.000		16.000		32.000
***Measured* (µm)**	**2.090**		**4.102**		**8.111**		**16.105**		**32.103**
Uncertainty (nm)	24.2		24.1		22.1		22.7		21.0

[a]Every pitch and isolated line feature on this SRM was measured at least 8 times on the NIST UV Microscope. The nominal and measured values of all of the calibrated lines and spaces are listed above, in micrometers. The expanded (2σ) calibration uncertainty for any linewidth or spacewidth feature is less than 26 nanometers.

[b]Values for the C1 pitch pattern are in Table II.

Table II. Pitch Pattern C1[a]

Calibration Data for SRM 2059

Photomask Linewidth Standard

Serial Number 2059-Sample, Pattern No. 1

Calibrated October 5, 2004

2059-Sample-1 *8-29-05*

Nom	Meas	Unc	Nom	Meas	Unc	Nom	Meas	Unc	Nom	Meas	Unc
µm	µm	nm	µm	µm	nm	µm	µm	nm	µm	µm	nm
0.0	0.000	0.0	28.0	27.993	5.0	81.0	80.376	6.0	137.0	136.376	7.1
0.5	0.498	1.5	28.5	28.494	5.2	82.0	81.379	6.4	138.0	137.380	6.0
1.0	1.000	2.6	29.0	28.993	4.6	83.0	82.377	6.8	139.0	138.378	5.3
1.5	1.497	3.1	29.5	29.498	5.0	84.0	83.378	7.8	140.0	139.381	5.8
2.0	2.000	2.7	30.0	29.994	4.9	85.0	84.376	7.7	150.0	149.131	7.7
2.5	2.494	2.9	30.5	30.496	5.3	86.0	85.376	8.0	152.0	151.130	8.3
3.0	2.997	4.0	31.0	30.997	6.0	87.0	86.375	7.6	154.0	153.129	8.4
3.5	3.495	4.1	31.5	31.498	6.6	88.0	87.379	7.2	156.0	155.129	7.4
4.0	3.998	4.1	32.0	31.997	6.9	89.0	88.383	7.3	158.0	157.126	7.7
4.5	4.499	4.1	32.5	32.495	6.6	90.0	89.379	6.9	160.0	159.123	7.5
5.0	4.998	4.3	33.0	32.993	6.0	91.0	90.375	6.2	162.0	161.126	7.7
5.5	5.495	4.6	33.5	33.494	6.0	92.0	91.374	6.6	164.0	163.126	7.5
6.0	5.998	3.9	34.0	33.994	5.7	93.0	92.376	7.0	166.0	165.131	6.6
6.5	6.495	3.6	34.5	34.495	5.3	94.0	93.377	7.5	168.0	167.126	6.7
7.0	6.996	3.9	35.0	34.997	4.9	95.0	94.378	8.2	170.0	169.123	8.9
7.5	7.495	3.6	35.5	35.500	4.9	96.0	95.380	8.0	172.0	171.125	8.4
8.0	7.996	4.0	36.0	35.998	5.1	97.0	96.377	7.7	174.0	173.123	7.7
8.5	8.495	4.7	36.5	36.496	5.8	98.0	97.381	7.4	176.0	175.124	9.3
9.0	8.996	4.8	37.0	36.995	6.2	99.0	98.380	7.9	178.0	177.127	9.4
9.5	9.498	4.9	37.5	37.495	6.7	100.0	99.379	7.5	180.0	179.125	8.6
10.0	10.001	4.3	38.0	37.995	6.9	101.0	100.378	6.5	182.0	181.125	8.3
10.5	10.498	3.4	38.5	38.495	6.7	102.0	101.379	6.7	184.0	183.126	8.9
11.0	10.997	3.9	39.0	38.995	6.2	103.0	102.373	7.1	186.0	185.122	9.4
11.5	11.496	4.2	39.5	39.497	6.0	104.0	103.375	6.5	188.0	187.125	9.8
12.0	11.999	4.3	40.0	39.995	5.9	105.0	104.377	6.7	190.0	189.125	9.7
12.5	12.492	5.0	50.0	49.378	5.9	106.0	105.378	6.6	192.0	191.124	9.7
13.0	12.996	4.9	51.0	50.378	6.1	107.0	106.374	6.3	194.0	193.125	9.5
13.5	13.492	5.2	52.0	51.377	6.4	108.0	107.377	7.3	196.0	195.122	9.9
14.0	13.994	5.2	53.0	52.378	6.4	109.0	108.378	7.0	198.0	197.124	10.1
14.5	14.491	5.6	54.0	53.379	6.5	110.0	109.377	6.5	200.0	199.124	10.0
15.0	14.994	5.5	55.0	54.375	6.0	111.0	110.376	6.7	202.0	201.122	10.0
15.5	15.493	5.8	56.0	55.375	6.3	112.0	111.376	7.0	204.0	203.126	9.1
16.0	15.994	6.1	57.0	56.379	6.0	113.0	112.376	6.7	206.0	205.129	8.9
16.5	16.493	6.7	58.0	57.377	5.8	114.0	113.377	6.4	208.0	207.125	7.8
17.0	16.997	6.6	59.0	58.377	6.1	115.0	114.375	6.6	210.0	209.125	8.5
17.5	17.498	6.6	60.0	59.377	6.5	116.0	115.373	6.1	212.0	211.129	9.1
18.0	17.998	6.4	61.0	60.380	6.8	117.0	116.372	6.6	214.0	213.126	8.5
18.5	18.494	5.8	62.0	61.377	7.1	118.0	117.377	6.3	216.0	215.123	8.5
19.0	18.995	5.4	63.0	62.378	6.5	119.0	118.376	6.3	218.0	217.125	9.1
19.5	19.497	5.6	64.0	63.377	7.1	120.0	119.378	6.4	220.0	219.124	9.4
20.0	19.995	6.4	65.0	64.374	8.4	121.0	120.376	6.3	222.0	221.122	9.4
20.5	20.499	6.6	66.0	65.375	8.4	122.0	121.381	6.3	224.0	223.125	9.5
21.0	20.999	6.3	67.0	66.378	8.1	123.0	122.378	7.2	226.0	225.122	9.4
21.5	21.493	5.9	68.0	67.375	8.0	124.0	123.373	6.9	228.0	227.125	8.4
22.0	21.994	5.9	69.0	68.373	8.2	125.0	124.377	7.2	230.0	229.125	9.3
22.5	22.494	6.4	70.0	69.377	8.2	126.0	125.378	7.0	232.0	231.123	9.6
23.0	22.997	6.4	71.0	70.376	7.8	127.0	126.378	7.0	234.0	233.127	9.5
23.5	23.495	6.1	72.0	71.375	7.6	128.0	127.376	7.8	236.0	235.124	8.6
24.0	23.991	5.8	73.0	72.379	6.8	129.0	128.378	8.3	238.0	237.124	8.7
24.5	24.495	5.4	74.0	73.379	7.6	130.0	129.375	7.5	240.0	239.126	9.4
25.0	24.995	5.5	75.0	74.378	8.9	131.0	130.373	8.0	242.0	241.121	9.7
25.5	25.493	5.4	76.0	75.377	8.8	132.0	131.373	7.2	244.0	243.125	9.5
26.0	25.993	5.8	77.0	76.373	7.9	133.0	132.375	7.2	246.0	245.125	9.8
26.5	26.498	5.9	78.0	77.377	7.5	134.0	133.375	8.2	248.0	247.123	10.3
27.0	26.998	6.0	79.0	78.374	6.8	135.0	134.378	8.3	250.0	249.124	11.0
27.5	27.497	5.6	80.0	79.372	6.8	136.0	135.374	8.6			

[a]Every line on Pattern C1 was measured at least 11 times on the NIST UV Microscope. The nominal and measured positions of the C1 lines relative to the "0" line are listed in micrometers, along with their expanded calibration uncertainties (2σ), in nanometers.

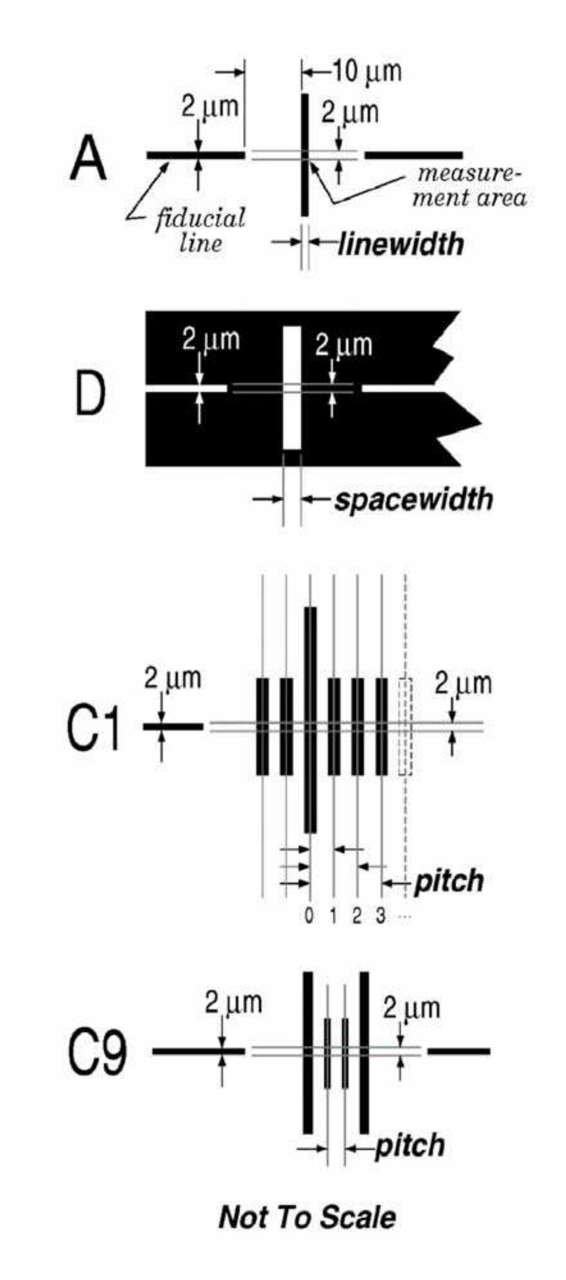

Figure 2. Linewidth, spacewidth, and pitch measurands. The features in Row F were not calibrated.

INSTRUCTIONS FOR USE

The linewidth, spacewidth, and pitch measurands are defined in Figure 2. Pitch measurements are center-to-center to avoid possible confusion from inverting or reversing the image in a microscope. The patterns in Row F have not been calibrated.

Only one of the eight replicated patterns is certified at NIST, as noted in Table I. The user is advised to transfer these calibrations to one or more of the other patterns on this mask for routine use, as insurance against damage to the certified pattern.

Use of this SRM in a scanning electron microscope is not recommended; the SRM may become contaminated, the material profile may be altered and charging and edge effects may invalidate the measurement.

Handling and Storage: Care must be exercised when handling this SRM. Avoid touching the surface with the microscope objective lens while setting up or focusing. Only non-abrasive and non-corrosive cleaning techniques should be used, as abrasives and acids can alter the line edges. When not in use, SRM 2059 should be stored in the photomask case supplied or equivalent.

Certification Technique: All measurements for certification were made with the NIST Ultraviolet (UV) Microscope Optical Linewidth Measurement System [5], which is a photometric transmission microscope with a scanning stage and displacement measuring interferometer. Except for the setup and removal of the photomasks, the entire calibration process is automated. The performance of the system is assessed before and after each calibration by measuring features on a control photomask. These control measurements include center-to-center spacing of line pairs that have been independently traced to the NIST Linescale Interferometer. Feature widths below ~2 µm were referenced to AFM measurements on the control mask, as described below.

Linewidths are determined from the image profile (image intensity vs. position across a feature). The algorithm for locating the position on the image profile of the feature edge is derived from a mathematical model of the optical microscope and is based on the theory of partial coherence imaging [6–10]. Because the relative brightness of an image profile at this edge position is a function of the physical and optical properties of the imaged object (the line), the calibration of a linewidth measurement system, by using this SRM, is valid only for measuring artifacts with physical and optical properties similar to the specific SRM used.

Calibration Procedure for SRM 2059: The scale of the UV Microscope (for both pitch and feature width) was calibrated using SRM 2800 *Microscope Magnification Standard* [11], traceable to the NIST Linescale Interferometer [12]. The line and space features on SRM 2059 were calibrated using a combination of AFM and optical microscope measurements; each technique was used where it has the lower measurement uncertainty.

All of the isolated linewidth and spacewidth features 8 µm and below on the control mask were measured by both techniques, creating a kind of "Rosetta Stone" of AFM and optical values for the same features. These pairs of measurements tended to diverge for features less than 1 µm and coincide for features greater than 2 µm. From these data, AFM equivalents of the optical values were derived and used for all subsequent measurements on all the photomasks:

$$AFMeq = m\,AFM + (1 - m)\,Optical, \qquad (1)$$

where $m = 1/\left[e^{(X-1.5)/2} + 1\right]$ is the AFM weighting factor, and x is the feature width in micrometers. Thus, every feature was measured optically on the UV Microscope, but the smaller line and space features were referenced to the AFM measurements.

Linewidth and Spacewidth Calibration Uncertainty: The measurements on this SRM are traceable to the definition of the meter through the NIST Linescale Interferometer. Some of the uncertainty components are listed in Tables III and IV. These include repeatability and scale factor uncertainty, as well as parametric components

$$\sigma_{P_i} = \left(\partial LW / \partial P_i\right)\sigma\left(P_i\right), \qquad (2)$$

where ($\partial LW / \partial P_i$) is found using the optical imaging model and perturbing the parameter P_i . The terms in Table III are included as "Other Terms" in Table IV. The various uncertainty components σ_1, σ_2, σ_{P1}, σ_{P2}, etc., are weighted by m or ($1{-}m$), as appropriate, and combined as described in reference 13 to yield the expanded uncertainties, U, in Tables I and II:

$$U = 2\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_{P1}^2 + \sigma_{P2}^2 + \ldots} \qquad (3)$$

The factor 2 is the "coverage factor" and ensures there is a 95 % probability that the true value lies within the range *Measured Value* ± *U*.

Differential Uncertainty: The difference between two linewidth or spacewidth values on the same mask is useful for characterizing the linearity of a linewidth measuring instrument. The uncertainty of this difference, U_{diff}, has fewer components than the uncertainty of a single feature width because feature-to-feature parameter differences like Cr n and k, illumination and objective numerical apertures (NAs), etc., are negligibly small (i.e. these parametric uncertainties are correlated). The largest components are optical-to-AFM, repeatability, and defocus effects. These uncertainties are listed in Table IV as "Differential Unc":

$$U_{diff} = \sqrt{\left(\frac{U}{2}\right)^2 - u_{corr}^2} \qquad (4)$$

For SRM 2059, it has been observed empirically that:

for spaces ≤ 1 µm, $U_{diff}/U \approx 0.8$
for lines ≤ 1 µm, $U_{diff}/U \approx 0.7$
for lines and spaces > 1 µm, $U_{diff}/U \approx 0.3$

The uncertainty of the difference between two lines or spaces on a single mask is then represented by the following equation:

$$U(x_1 - x_2) = \sqrt{U_{diff}(x_1)^2 + U_{diff}(x_2)^2} \qquad (5)$$

These uncertainties are listed in Table IV as "Differential Unc."

Chrome Edge Runout: The average chrome edge profile of all the features on the control mask, measured by AFM, is shown in Fig. 3. Feature-to-feature variations were small compared to the average profile. The chrome edge is taken here to be the "halfway up" point, which differs from the "halfway out" point by 0.6 nm. Thus the "halfway out" linewidth is 1.2 nm smaller than reported in Table III, and the "halfway out" spacewidth is 1.2 nm greater.

If the cross section is considered to be rectangular, then the edge can be assumed to lie anywhere within the 7.74 nm runout shown in Figure 3, with left and right edges mirror-image correlated, and the linewidth at the "halfway out" point. Then the feature width uncertainty will be as described in references 13 and 14 as "Rectangular Edge Unc." See the references for a discussion of the relation between edge runout and linewidth uncertainty. Both U_{diff} and U_{rect} are expanded (2σ) uncertainties.

$$U_{rect} = 2\sqrt{\left(\frac{U}{2}\right)^2 - 2^2 + \frac{4}{3}(Cr\ edge\ runout)^2} \qquad (6)$$

$$= 2\sqrt{\left(\frac{U}{2}\right)^2 + 8.71^2}$$

C1 Pitch Patterns: The center-to-center distance between any line and the “0” line in pattern C1 is given in Table II, along with its expanded uncertainty. The uncertainty can be summarized as

$$U_{C1} < 1.455\ \mathrm{Ln}(x) + 4\ \mathrm{nm} \qquad (7)$$

where x is in micrometers for any unit of SRM 2059. The lines not listed in Table II are guard lines, intended to balance proximity effects in printing and measuring, and are not calibrated.

Table III. Length-Independent Uncertainty Components

Source	Value (nm)
Weighted	
Model Convergence	0.97
Model Uncertainty	3.00
Wavelength	0.01
Data Low Pass Filter	0.88
Data Convergence	3.00
Sampling Aperture	1.70
Cr Edge Runout	2.00
Unweighted	
Unassigned	2.00

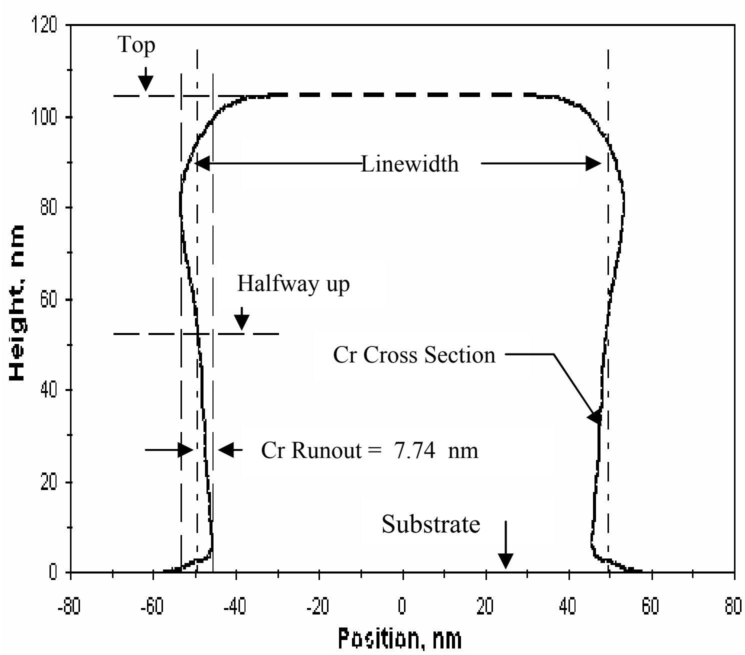

Figure 3.   Chrome sidewall profile and line edge definition.

Table IV. Width-Dependent Line and Space Uncertainty Component

(Typical values, not for this serial number, in nm unless otherwise indicated.)

Line ID	***A1***	***A9***		***B9***	***D1***	***D9***		***E9***
Species	**LINE**	**LINE**	**LINE**	**LINE**	**SPACE**	**SPACE**	**SPACE**	**SPACE**
Nominal Feature Width (µm)	**0.25**	**1.00**	**1.50**	**32.00**	**0.25**	**1.00**	**1.50**	**32.00**
	AFM 1σ Width Uncertainty (nm)							
AFM	5.02	5.39	5.83	64.19	5.02	5.39	5.83	64.19
AFM Scale	0.20	0.48	0.56	1.17	0.20	0.48	0.56	1.17
Optical-to-AFM	4.28	4.28	4.28	4.28	5.98	5.98	5.98	5.98
AFM Contribution	6.61	6.90	7.26	64.35	7.81	8.06	8.37	64.48
Weighted AFM	**6.59**	**6.37**	**3.63**	**0.00**	**7.80**	**7.45**	**4.19**	**0.00**
AFM Weight (m)	1.00	0.92	0.50	0.00	1.00	0.92	0.50	0.00
	Optical 1σ Width Uncertainty (nm)							
Optical Scale	0.20	0.48	0.56	1.17	0.20	0.48	0.56	1.17
Chrome *n*	7.35	7.65	7.74	8.40	8.17	8.10	8.08	7.93
Chrome *k*	2.01	2.22	2.28	2.74	2.68	1.60	1.28	1.10
Illum NA	8.66	6.28	5.58	0.32	11.43	8.21	7.27	0.17
Obj NA	2.99	3.60	3.79	5.15	34.51	3.00	2.65	2.50
Residual Defocus	0.23	0.25	0.25	0.25	0.31	0.25	0.25	0.25
Focus Correction Unc	0.51	1.96	1.26	3.39	0.36	0.56	1.05	1.25
Optical Contribution	13.00	12.10	11.78	11.95	37.71	13.10	12.43	9.93
Weighted Optical	**0.03**	**0.92**	**5.89**	**11.95**	**0.07**	**0.99**	**6.21**	**9.93**
***Repeatability* (nm)**	**1.24**	**2.82**	**2.04**	**5.71**	**0.63**	**1.00**	**3.09**	**2.58**
***Other Terms*[(a)]**	5.15 2.00	4.77 2.00	2.58 2.00	0.00 2.00	5.15 2.00	4.77 2.00	2.58 2.00	0.00 2.00
	Expanded 2σ Uncertainty (nm)							
Expanded Uncertainty (U)	**13.43**	**14.09**	**14.47**	**26.58**	**15.66**	**15.20**	**16.25**	**20.65**
Differential Unc (same mask)	**9.04**	**11.19**	**7.21**	**13.48**	**12.08**	**11.95**	**9.43**	**6.20**
Rectangular Edge Unc	**21.99**	**22.76**	**22.65**	**32.03**	**23.76**	**23.46**	**24.16**	**27.31**

[(a)]Refer to the terms in Table III.

REFERENCES

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APPENDIX

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