CEPREI

A Traceable Diffraction-based Overlay Metrology Method: Target Design, Instrumentation and Analysis

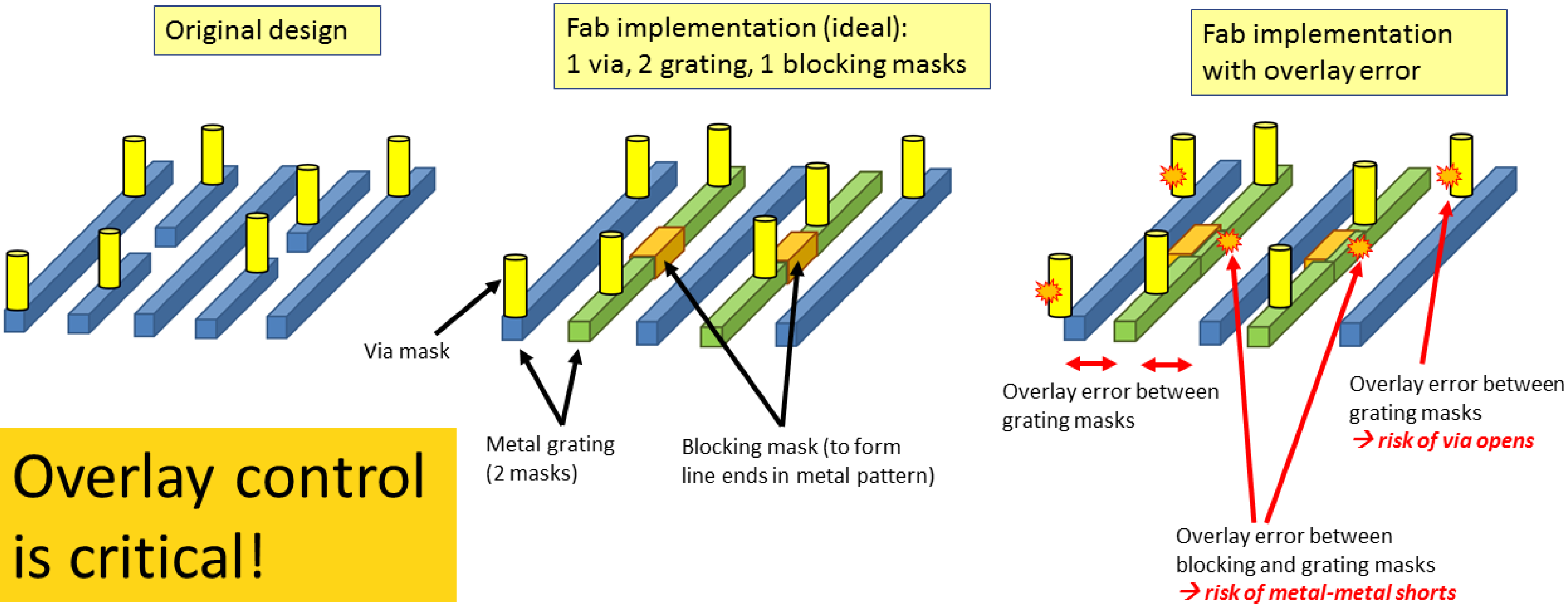
Lin Yang
Calibration and Testing Center
the Fifth Electronic Research Institute of MIIT (CEPREI)
2022.10.22

Outline

- Introduction
- Principle of traceable DBO metrology
- Design of sensitive standard sample
- Prototyping of standard apparatus
- Results and analysis
- Conclusions

Introduction

- Significance of overlay control



Original design

Fab implementation (ideal):
1 via, 2 grating, 1 blocking masks

Fab implementation with overlay error

Via mask

Metal grating (2 masks)

Blocking mask (to form line ends in metal pattern)

Overlay error between grating masks

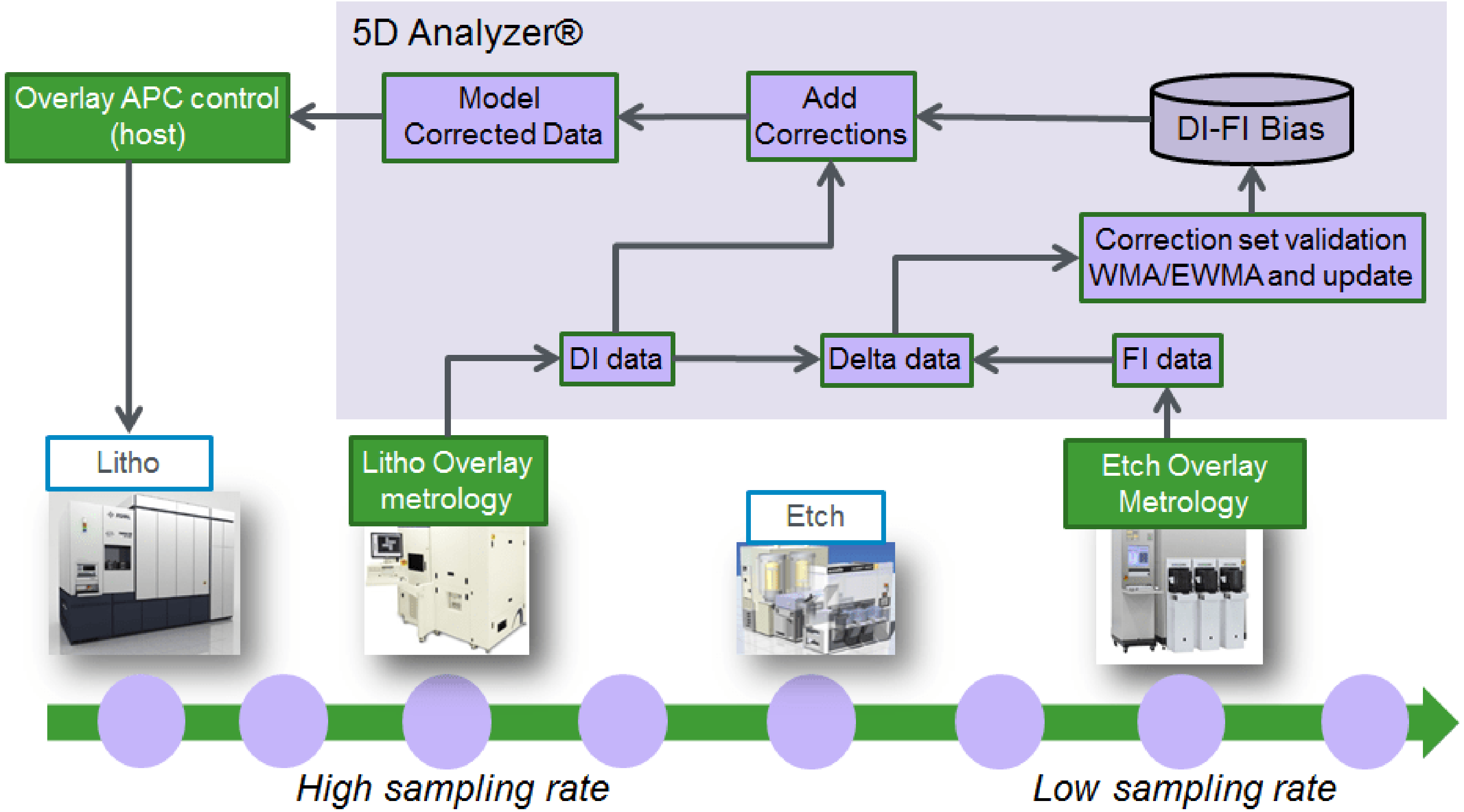
Overlay error between grating masks
→ ***risk of via opens***

Overlay error between blocking and grating masks
→ ***risk of metal-metal shorts***

Overlay control is critical!

Introduction

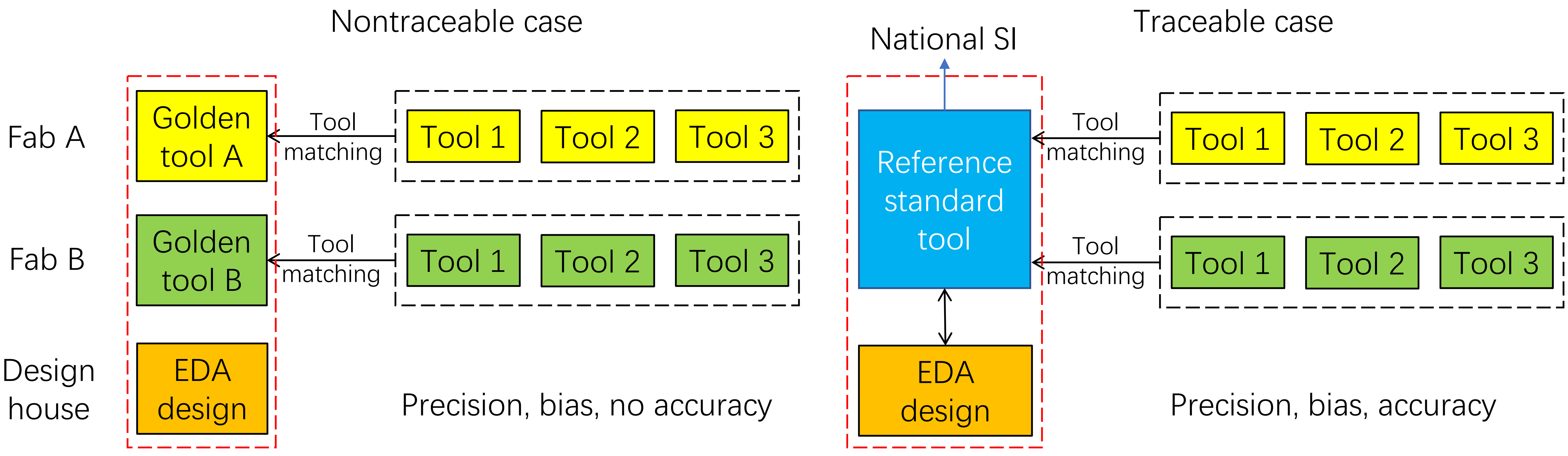
- Significance of overlay metrology



Overlay metrology is important for process monitor and control!

Introduction

- Why we need a traceable overlay metrology?



Nonuniform, incomparable

Uniform, comparable

Introduction

- Two types of overlay metrology

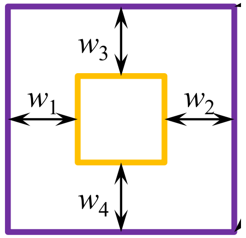
Target

Tool

Reference standard sample

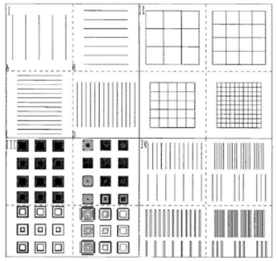
Reference standard tool

Image-based overlay (IBO)

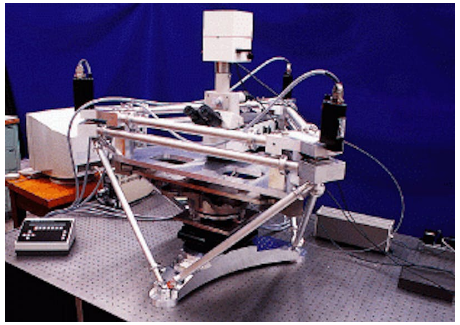


$$\Delta x = (w_1 - w_2)/2$$
$$\Delta y = (w_3 - w_4)/2$$

Traced to

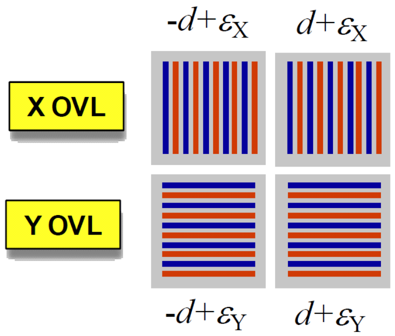


NIST SRM 5000



NIST OMT

Diffraction-based overlay (DBO)



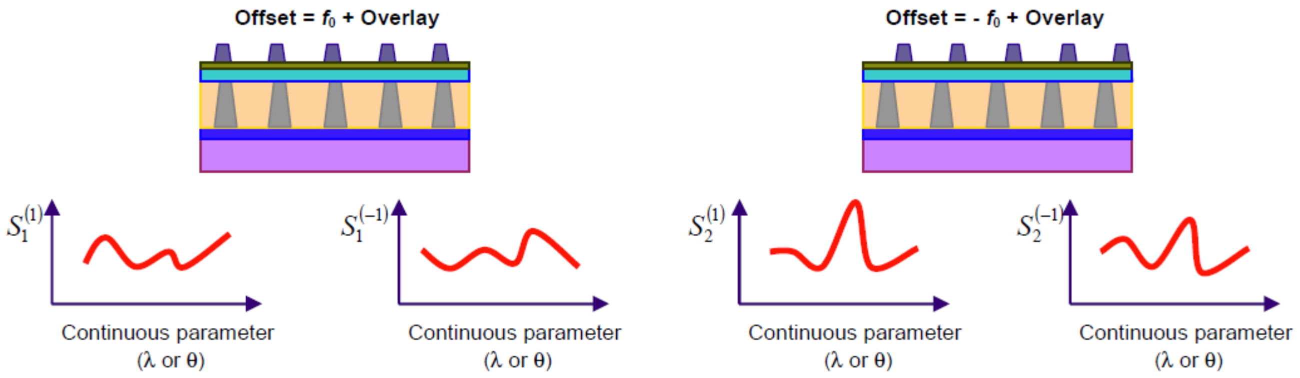
Traced to

There is no DBO reference standard!

Principle of traceable overlay metrology

- Theory of conventional DBO metrology

Target



Stacked grating structure

↓

Hard to characterize buried layers nondestructively

↓

Hard to verify by comparison

Theory

Differential signals

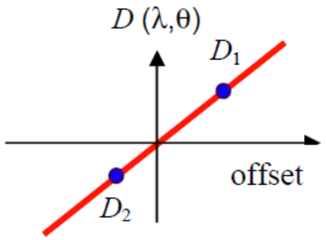
$$D_1 = S_1^{(1)} - S_1^{(-1)}$$

$$D_2 = S_2^{(1)} - S_2^{(-1)}$$

For small overlay

$$D_1 = K\left(f_0 + \text{Overlay}\right)$$

$$D_2 = -K\left(f_0 - \text{Overlay}\right)$$



$$\longrightarrow \text{Overlay} = f_0 \frac{D_1 + D_2}{D_1 - D_2}$$

Empirical calculation model

↓

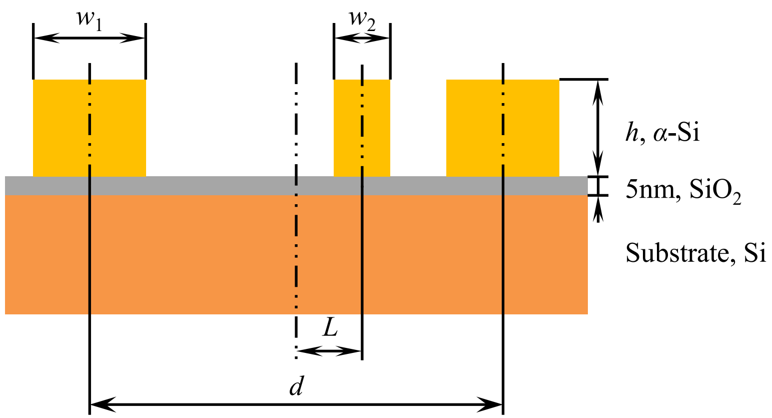
Overlay is coupled with process asymmetry (such as etch bias)

↓

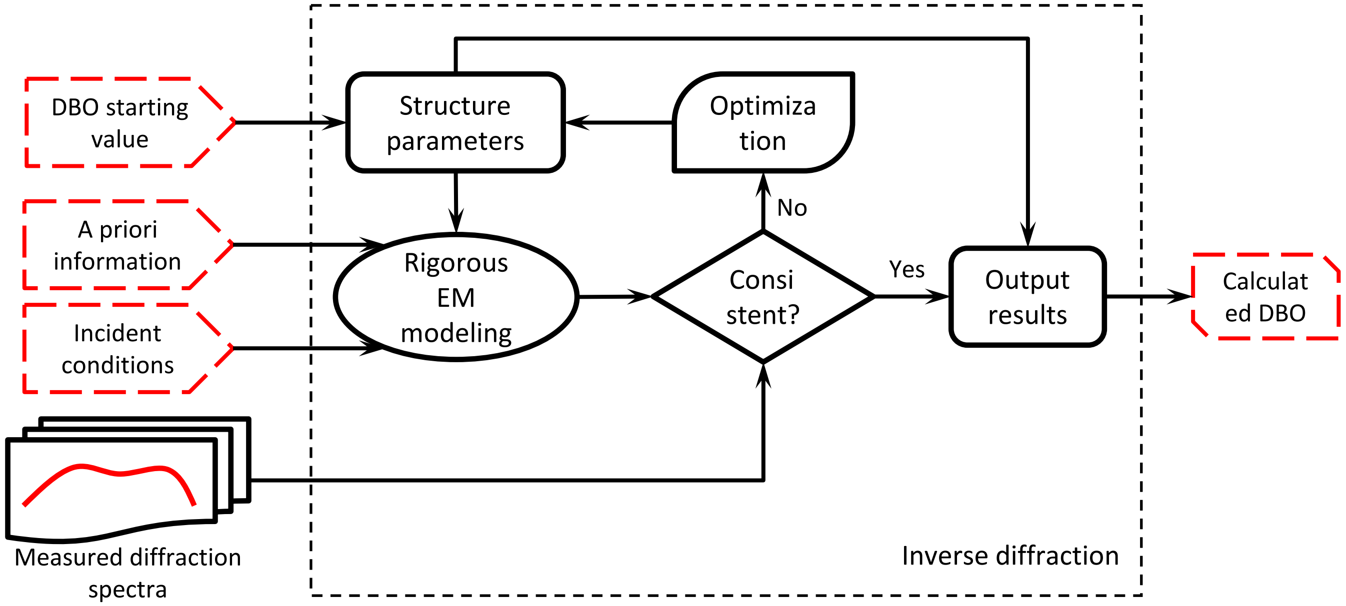
Cannot be traced to SI

Principle of traceable overlay metrology

- How to design a traceable DBO metrology method?



Monolayer grating structure


DBO starting value

A priori information

Incident conditions

Measured diffraction spectra

Structure parameters

Optimization

Rigorous EM modeling

Consistent?

No

Yes

Output results

Calculated DBO

Inverse diffraction

Rigorous calculation model

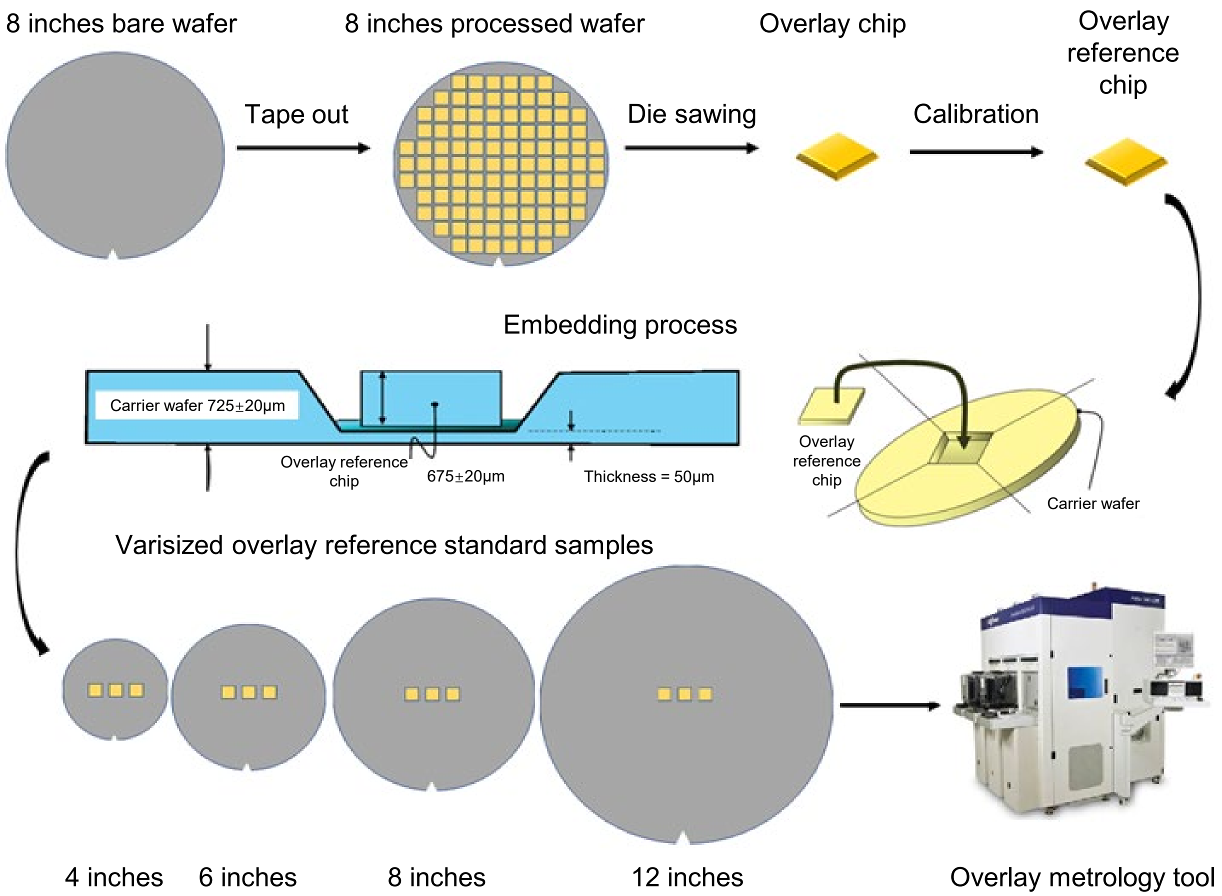
1. Can be verified by AFM nondestructively.
2. Full profile measurement, traceable to SI.

Design of sensitive standard sample

- Design of reference standard sample

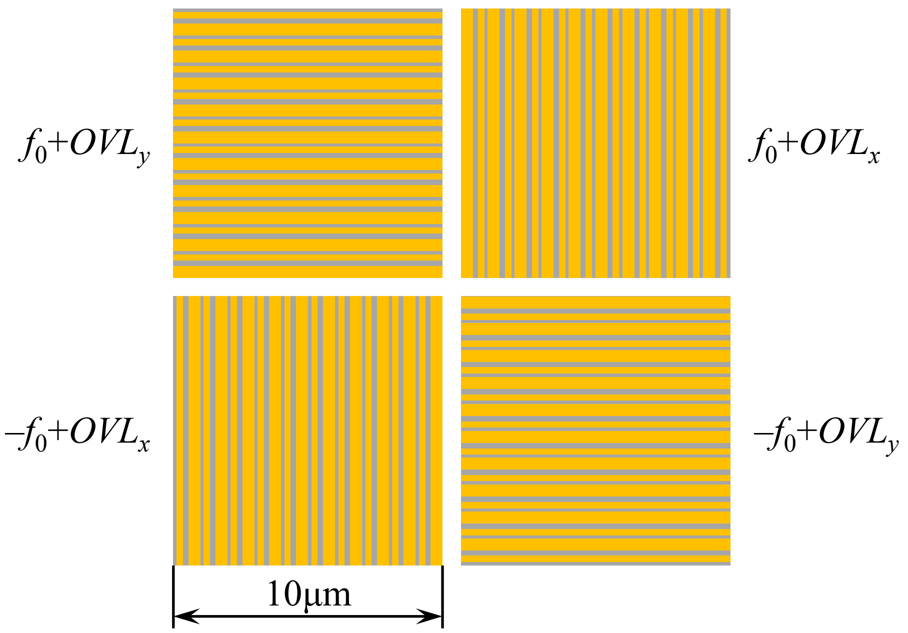
Requirements	Solutions
In application: Varisized wafers for different metrology tools	Sample should be wafer size.
In verification: Easy to measure by in-lab instruments (AFM, SEM) for comparison	Sample should be chip size.

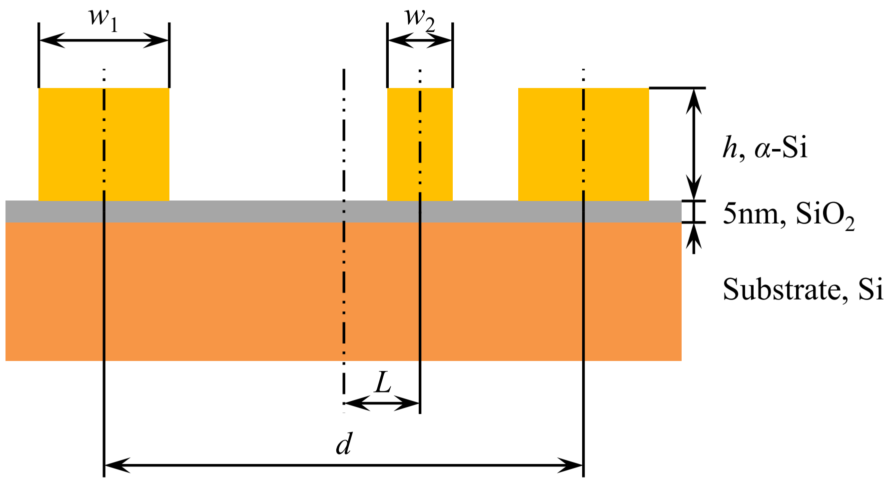
Design: **chip on wafer**



Design of sensitive standard sample

- Design of reference standard chip





- ☐ f_0：preset offset，75nm
- ☐ OVL_x：overlay on x-direction，–75nm~75nm
- ☐ OVL_y：overlay on y-direction，–75nm~75nm

Grating pitch：$d = 1\mu m$

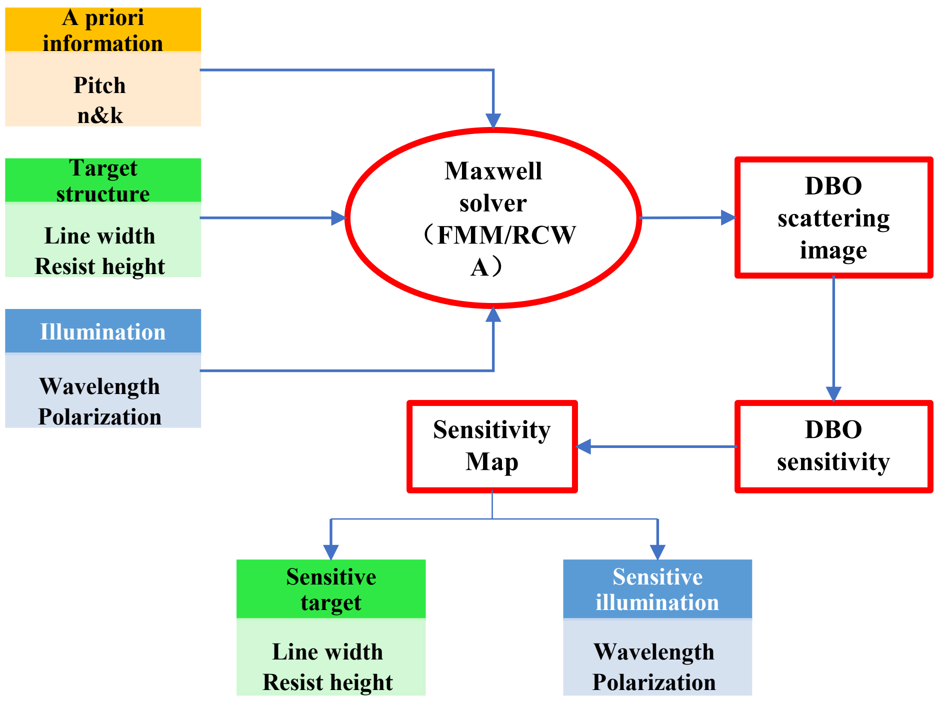
Total offset：$L = \pm f_0 + OVL_{x(y)}$

Total width：$w = w_1 + w_2$

Distribution factor：$\alpha = \frac{w_2}{w_1 + w_2}$

Design of sensitive standard sample

- Design of reference standard chip



A priori information
Pitch
n&k

Target structure
Line width
Resist height

Illumination
Wavelength
Polarization

Maxwell solver（FMM/RCWA）

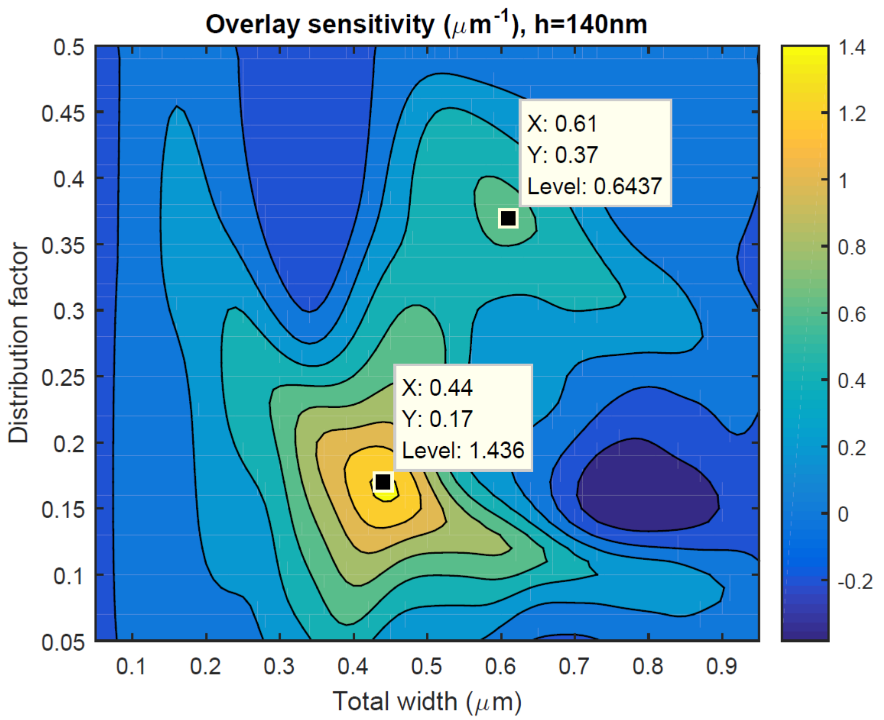
DBO scattering image

DBO sensitivity

Sensitivity Map

Sensitive target
Line width
Resist height

Sensitive illumination
Wavelength
Polarization



Optima of sensitive target:

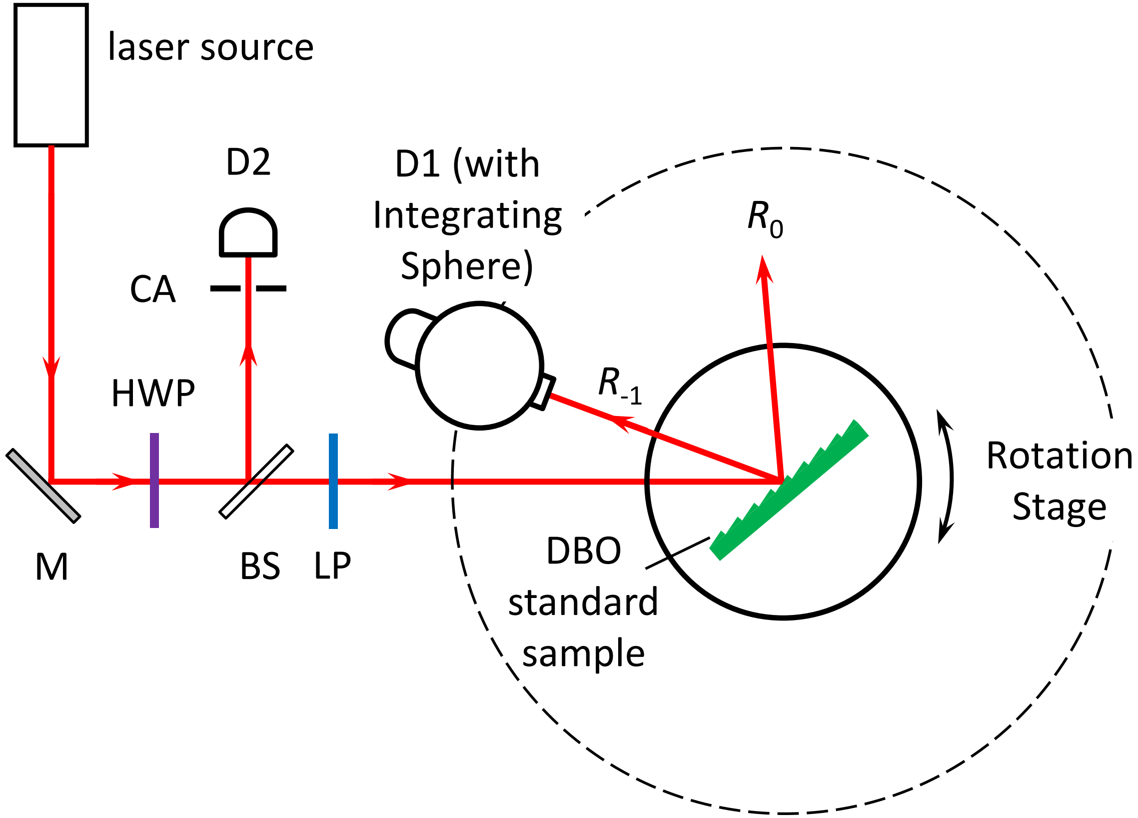
Resist height： $h = 140\text{nm}$

Line width： $w_1 = 365\text{nm}$ $w_2 = 75\text{nm}$

Prototyping of standard apparatus

- Design of standard apparatus

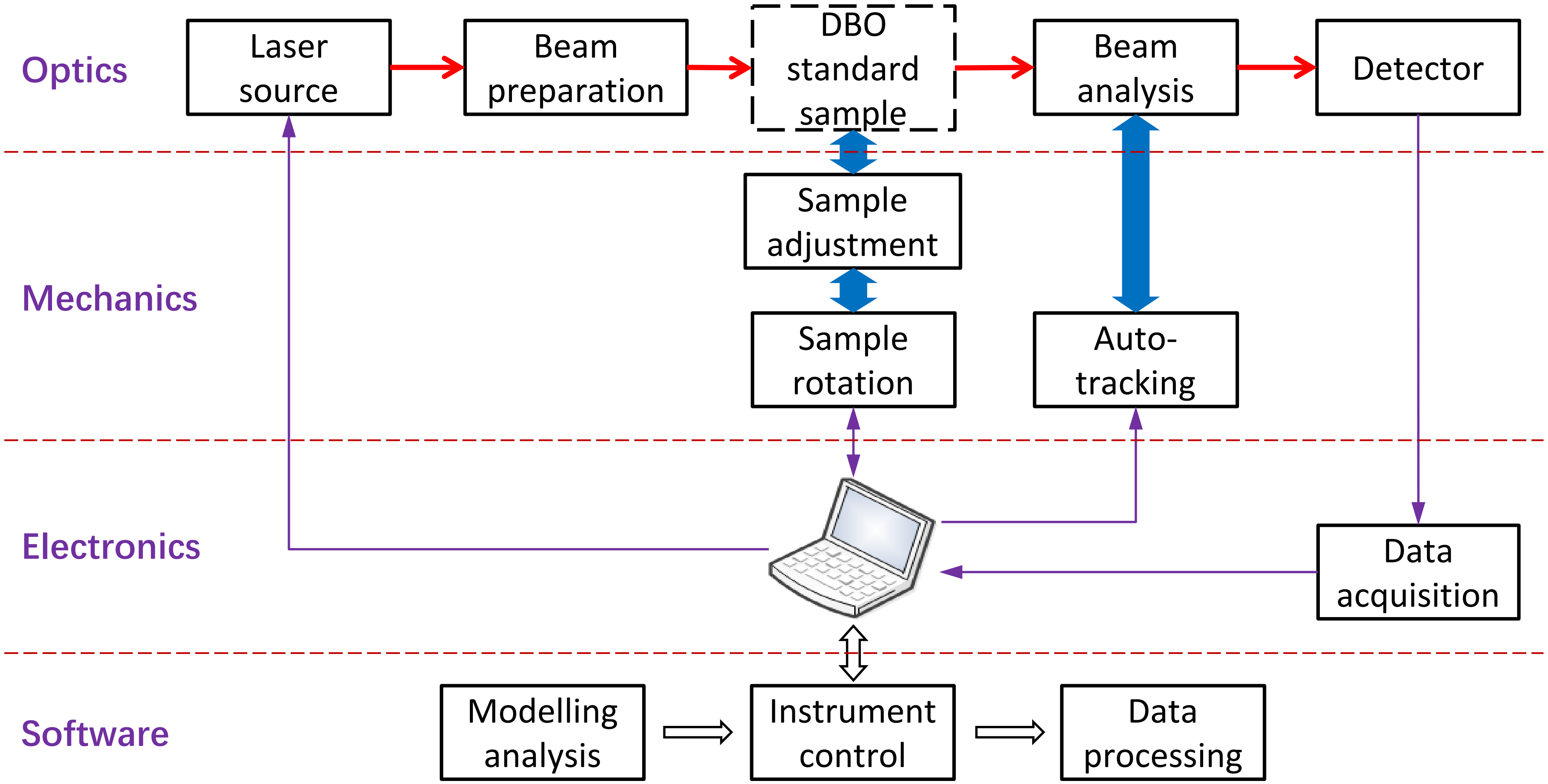
Requirements	Solutions
Traceable to national SI	✓ Subsystems can be evaluated and traced to SI separately.
Prefer high accuracy than high throughput	✓ Narrow linewidth laser is better than broadband light source. ✓ Flexible to set various configurations to obtain enough diffraction spectra.



Optics diagram of standard apparatus

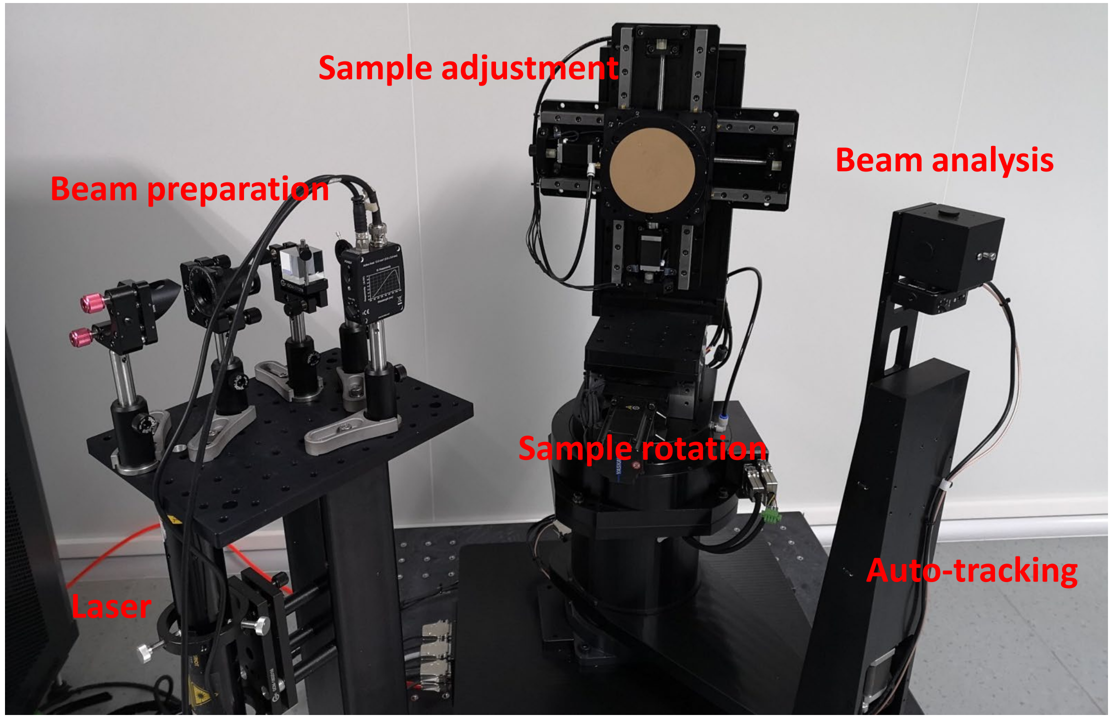
Prototyping of standard apparatus

- Schematic of standard apparatus

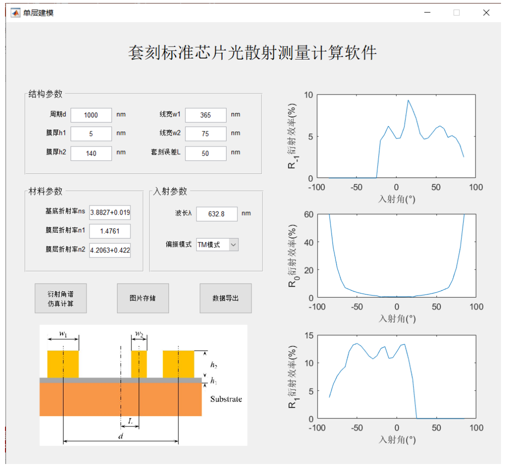


Prototyping of standard apparatus

- Prototype of standard apparatus



Hardware of standard apparatus


单层建模

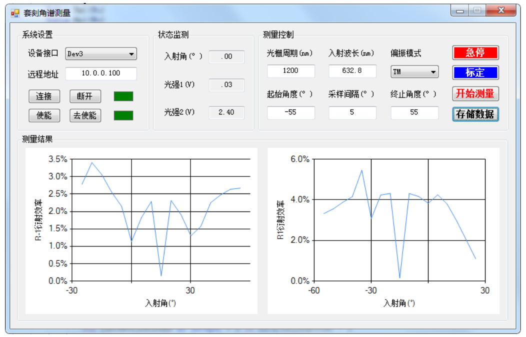
套刻标准芯片光散射测量计算软件

结构参数
周期d 1000 nm
膜厚h1 5 nm
膜厚h2 140 nm
线宽w1 365 nm
线宽w2 75 nm
套刻误差L 50 nm

材料参数
基底折射率ns 3.8827+0.019
膜层折射率n1 1.4761
膜层折射率n2 4.2063+0.422

入射参数
波长λ 632.8 nm
偏振模式 TM模式

Modelling analysis software


套刻角谱测量

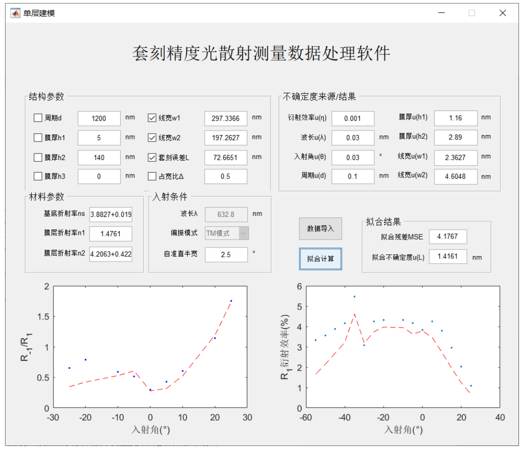
系统设置
设备接口 Dev3
远程地址 10.0.0.100

状态监测
入射角(°) .00
光强1(V) .03
光强2(V) 2.40

测量控制
光栅周期(nm) 1200
入射波长(nm) 632.8
偏振模式 TM
起始角度(°) -55
采样间隔(°) 5
终止角度(°) 55

测量结果

Instrument control software


单层建模

套刻精度光散射测量数据处理软件

结构参数
☐ 周期d 1200 nm
☐ 膜厚h1 5 nm
☐ 膜厚h2 140 nm
☐ 膜厚h3 0 nm
☑ 线宽w1 297.3366 nm
☑ 线宽w2 197.2627 nm
☑ 套刻误差L 72.6651 nm
☐ 占宽比Δ 0.5

不确定度来源/结果
衍射效率u(η) 0.001
波长u(λ) 0.03 nm
入射角u(θ) 0.03 °
周期u(d) 0.1 nm
膜厚u(h1) 1.16 nm
膜厚u(h2) 2.89 nm
线宽u(w1) 2.3627 nm
线宽u(w2) 4.6048 nm

材料参数
基底折射率ns 3.8827+0.019
膜层折射率n1 1.4761
膜层折射率n2 4.2063+0.422

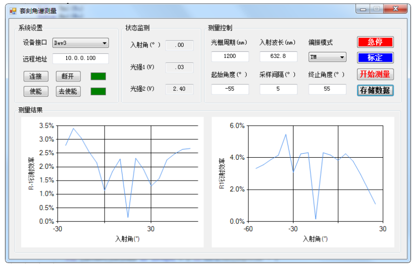
入射条件
波长λ 632.8 nm
偏振模式 TM模式
自准直半宽 2.5 °

拟合结果
拟合残差MSE 4.1767
拟合不确定度u(L) 1.4161 nm

Data processing software

Prototyping of standard apparatus

- Traceability of DBO



设备接口 Dev3

远程地址 10.0.0.100

入射角(°) .00

光强1 (V) .03

光强2 (V) 2.40

光栅周期(nm) 1200

入射波长(nm) 632.8

偏振模式 TM

起始角度(°) -55

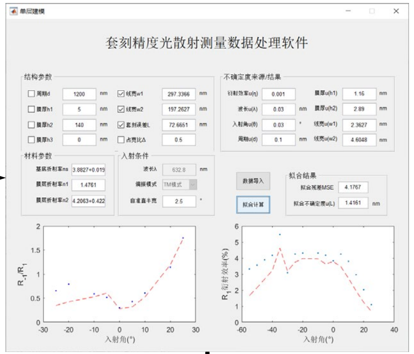
采样间隔(°) 5

终止角度(°) 55

Instrument control and spectra gathering

Measured diffraction spectra

Data processing



套刻精度光散射测量数据处理软件

☐ 周期d 1200 nm

☐ 膜厚h1 5 nm

☐ 膜厚h2 140 nm

☐ 膜厚h3 0 nm

☑ 线宽w1 297.3366 nm

☑ 线宽w2 197.2627 nm

☑ 套刻误差L 72.6651 nm

☐ 占宽比Δ 0.5

衍射效率u(η) 0.001

波长u(λ) 0.03 nm

入射角u(θ) 0.03 °

周期u(d) 0.1 nm

膜厚u(h1) 1.16 nm

膜厚u(h2) 2.89 nm

线宽u(w1) 2.3627 nm

线宽u(w2) 4.6048 nm

基底折射率ns 3.8827+0.019

膜层折射率n1 1.4761

膜层折射率n2 4.2063+0.422

波长λ 632.8 nm

偏振模式 TM模式

自准直半宽 2.5 °

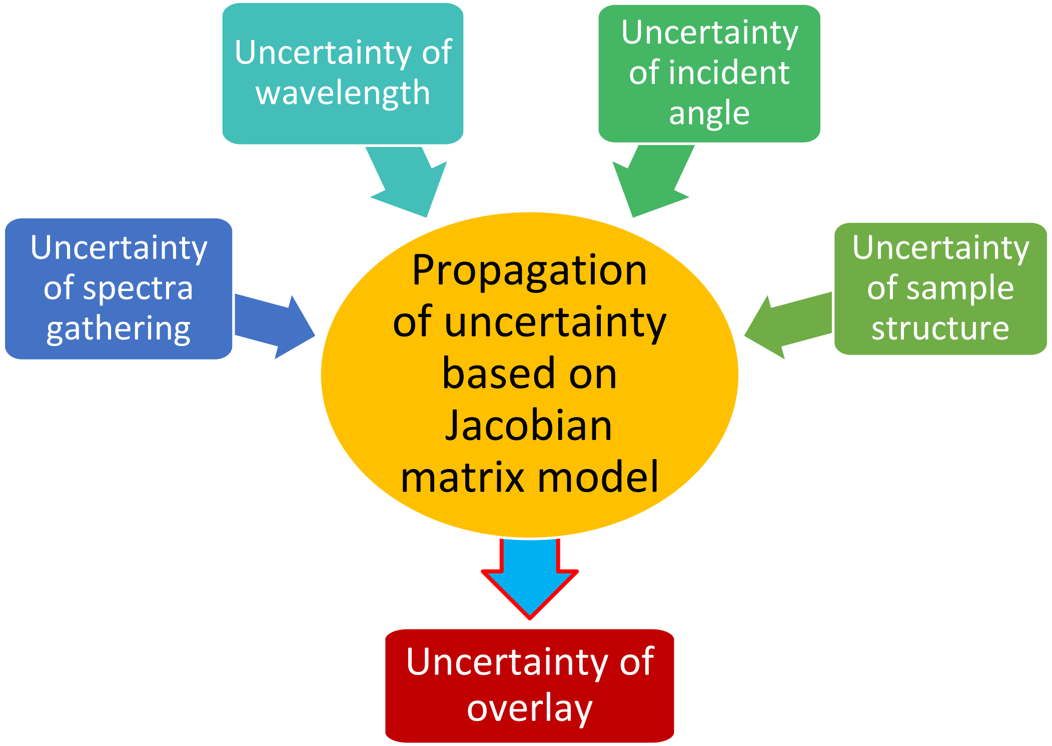
拟合残差MSE 4.1767

拟合不确定度u(L) 1.4161 nm

Uncertainty sources evaluation

Measured DBO value

DBO uncertainty



Uncertainty of wavelength

Uncertainty of incident angle

Uncertainty of spectra gathering

Propagation of uncertainty based on Jacobian matrix model

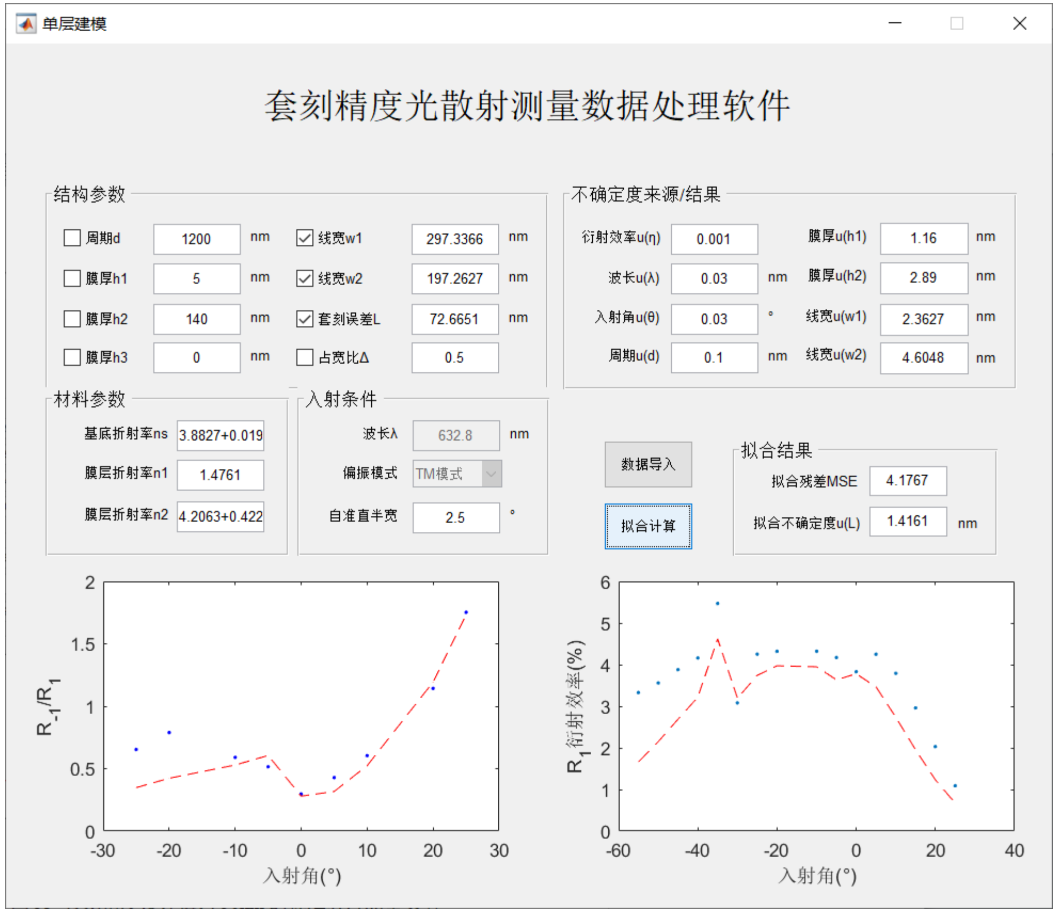
Uncertainty of sample structure

Uncertainty of overlay

$$
\begin{aligned}
\mathbf{u}^2(\mathbf{p}) &= \left\langle \delta\mathbf{p}\delta\mathbf{p}^{\mathrm{T}} \right\rangle - \left\langle \delta\mathbf{p} \right\rangle \left\langle \delta\mathbf{p} \right\rangle^{\mathrm{T}} \\
&= \left\langle \mathbf{G}_{\mathbf{p}0} \left(\delta\boldsymbol{\eta}^{\mathrm{exp}} - \mathbf{J}_{\mathbf{q}0}\delta\mathbf{q} \right) \left(\delta\boldsymbol{\eta}^{\mathrm{exp}} - \mathbf{J}_{\mathbf{q}0}\delta\mathbf{q} \right)^{\mathrm{T}} \mathbf{G}_{\mathbf{p}0}{}^{\mathrm{T}} \right\rangle \\
&= \mathbf{G}_{\mathbf{p}0} \left\langle \delta\boldsymbol{\eta}^{\mathrm{exp}} (\delta\boldsymbol{\eta}^{\mathrm{exp}})^{\mathrm{T}} \right\rangle \mathbf{G}_{\mathbf{p}0}{}^{\mathrm{T}} + \mathbf{G}_{\mathbf{p}0}\mathbf{J}_{\mathbf{q}0} \left\langle \delta\mathbf{q}\delta\mathbf{q}^{\mathrm{T}} \right\rangle \mathbf{J}_{\mathbf{q}0}{}^{\mathrm{T}}\mathbf{G}_{\mathbf{p}0}{}^{\mathrm{T}} \\
&= \mathbf{G}_{\mathbf{p}0}\mathbf{u}^2(\boldsymbol{\eta}^{\mathrm{exp}})\mathbf{G}_{\mathbf{p}0}{}^{\mathrm{T}} + \mathbf{G}_{\mathbf{p}0}\mathbf{J}_{\mathbf{q}0}\mathbf{u}^2(\mathbf{q})\mathbf{J}_{\mathbf{q}0}{}^{\mathrm{T}}\mathbf{G}_{\mathbf{p}0}{}^{\mathrm{T}} \\
&= \mathbf{u}_{\mathrm{A}}^2(\mathbf{p}) + \mathbf{u}_{\mathrm{B}}^2(\mathbf{p})
\end{aligned}
$$

Results and analysis

- Measurement of samples with nominal DBO value of 50nm



套刻精度光散射测量数据处理软件

结构参数

☐ 周期d 1200 nm
☐ 膜厚h1 5 nm
☐ 膜厚h2 140 nm
☐ 膜厚h3 0 nm
☑ 线宽w1 297.3366 nm
☑ 线宽w2 197.2627 nm
☑ 套刻误差L 72.6651 nm
☐ 占宽比Δ 0.5

不确定度来源/结果

衍射效率u(η) 0.001
波长u(λ) 0.03 nm
入射角u(θ) 0.03 °
周期u(d) 0.1 nm
膜厚u(h1) 1.16 nm
膜厚u(h2) 2.89 nm
线宽u(w1) 2.3627 nm
线宽u(w2) 4.6048 nm

材料参数

基底折射率ns 3.8827+0.019
膜层折射率n1 1.4761
膜层折射率n2 4.2063+0.422

入射条件

波长λ 632.8 nm
偏振模式 TM模式
自准直半宽 2.5 °

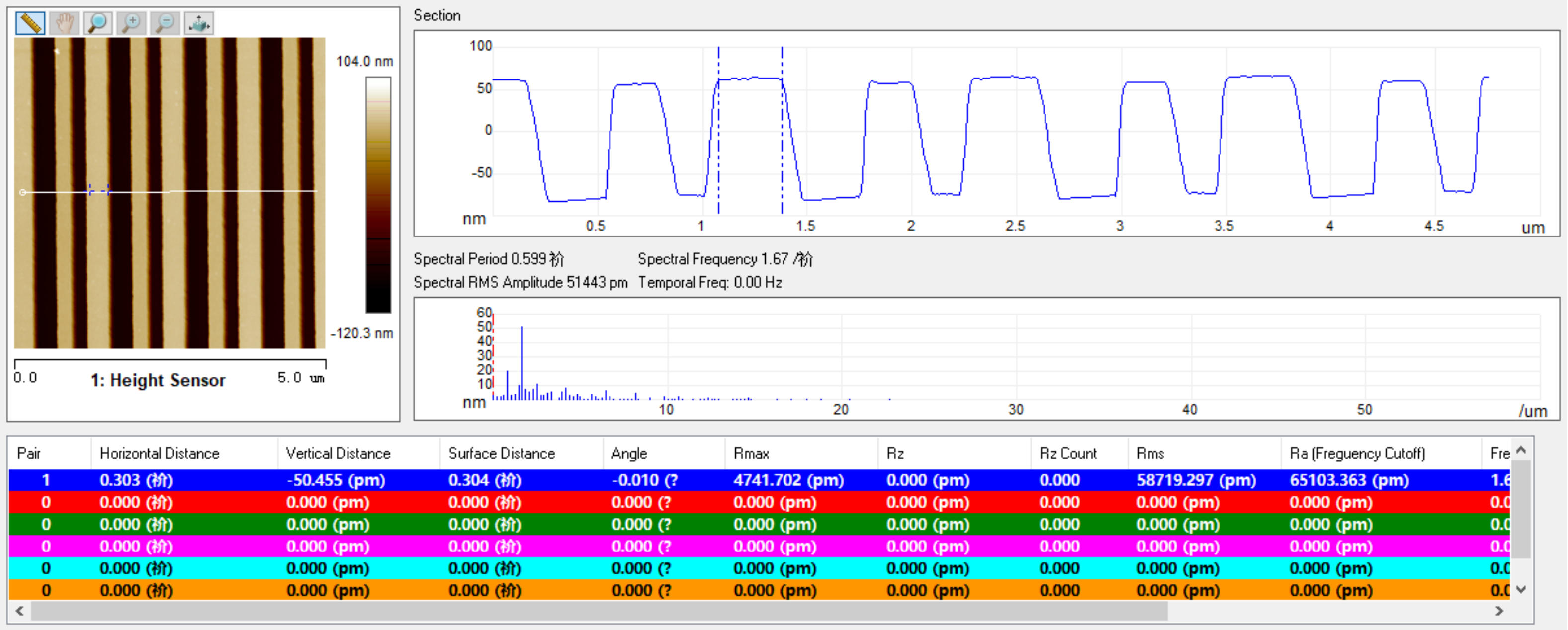
拟合结果

拟合残差MSE 4.1767
拟合不确定度u(L) 1.4161 nm

Uncertainty components	***L* [nm]**	**w_1 [nm]**	**w_2 [nm]**	**Uncertainty sources**
Type A evaluation				
Spectra gathering repeatability	0.27	0.38	0.30	0.001
Type B evaluation				
Incident angle θ	0.12	0.16	0.09	0.03°
Wavelength λ	0.01	0.03	0.02	0.03nm
Period d	0.01	0.02	0.01	0.1nm
Thickness h_1	0.44	1.82	4.49	Uniform dist., ±2nm
Thickness h_2	1.32	1.45	0.98	Uniform dist., ±5nm
Combined type B u_B	1.39	2.33	4.60	
Combined uncertainty u_c	1.42	2.36	4.60	
Expanded uncertainty U (k=2)	2.83	4.73	9.21	

Results and analysis

- Measurement of samples with nominal DBO value of 50nm



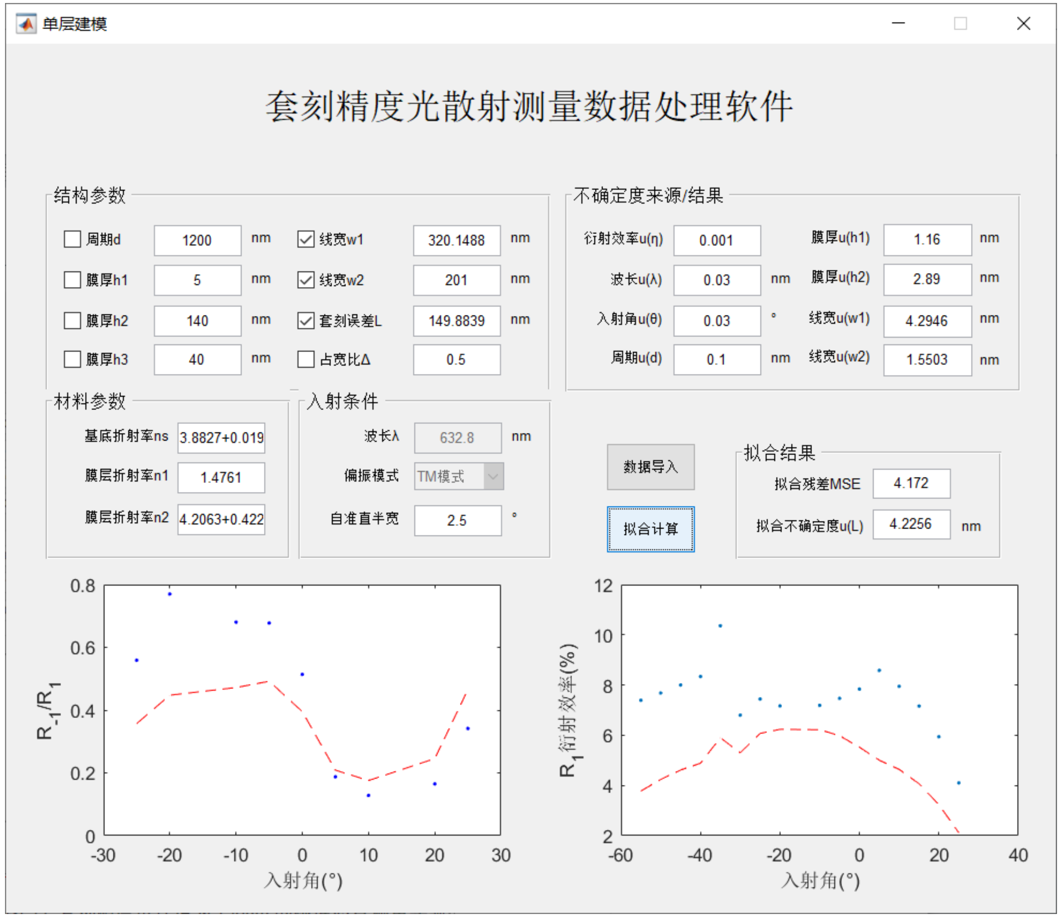
Spectral Period 0.599 祄 Spectral Frequency 1.67 /祄
Spectral RMS Amplitude 51443 pm Temporal Freq: 0.00 Hz

Pair	Horizontal Distance	Vertical Distance	Surface Distance	Angle	Rmax	Rz	Rz Count	Rms	Ra (Freguency Cutoff)	Fre
1	0.303 (祄)	-50.455 (pm)	0.304 (祄)	-0.010 (?	4741.702 (pm)	0.000 (pm)	0.000	58719.297 (pm)	65103.363 (pm)	1.6
0	0.000 (祄)	0.000 (pm)	0.000 (祄)	0.000 (?	0.000 (pm)	0.000 (pm)	0.000	0.000 (pm)	0.000 (pm)	0.0
0	0.000 (祄)	0.000 (pm)	0.000 (祄)	0.000 (?	0.000 (pm)	0.000 (pm)	0.000	0.000 (pm)	0.000 (pm)	0.0
0	0.000 (祄)	0.000 (pm)	0.000 (祄)	0.000 (?	0.000 (pm)	0.000 (pm)	0.000	0.000 (pm)	0.000 (pm)	0.0
0	0.000 (祄)	0.000 (pm)	0.000 (祄)	0.000 (?	0.000 (pm)	0.000 (pm)	0.000	0.000 (pm)	0.000 (pm)	0.0
0	0.000 (祄)	0.000 (pm)	0.000 (祄)	0.000 (?	0.000 (pm)	0.000 (pm)	0.000	0.000 (pm)	0.000 (pm)	0.0

	L [nm]	w_1 [nm]	w_2 [nm]
AFM	68.5	303	205
DBO Standard apparatus	72.7	297.3	197.3

Results and analysis

- Measurement of samples with nominal DBO value of 150nm



单层建模

套刻精度光散射测量数据处理软件

结构参数

☐ 周期d 1200 nm
☐ 膜厚h1 5 nm
☐ 膜厚h2 140 nm
☐ 膜厚h3 40 nm
☑ 线宽w1 320.1488 nm
☑ 线宽w2 201 nm
☑ 套刻误差L 149.8839 nm
☐ 占宽比Δ 0.5

不确定度来源/结果

衍射效率u(η) 0.001
波长u(λ) 0.03 nm
入射角u(θ) 0.03 °
周期u(d) 0.1 nm
膜厚u(h1) 1.16 nm
膜厚u(h2) 2.89 nm
线宽u(w1) 4.2946 nm
线宽u(w2) 1.5503 nm

材料参数

基底折射率ns 3.8827+0.019
膜层折射率n1 1.4761
膜层折射率n2 4.2063+0.422

入射条件

波长λ 632.8 nm
偏振模式 TM模式
自准直半宽 2.5 °

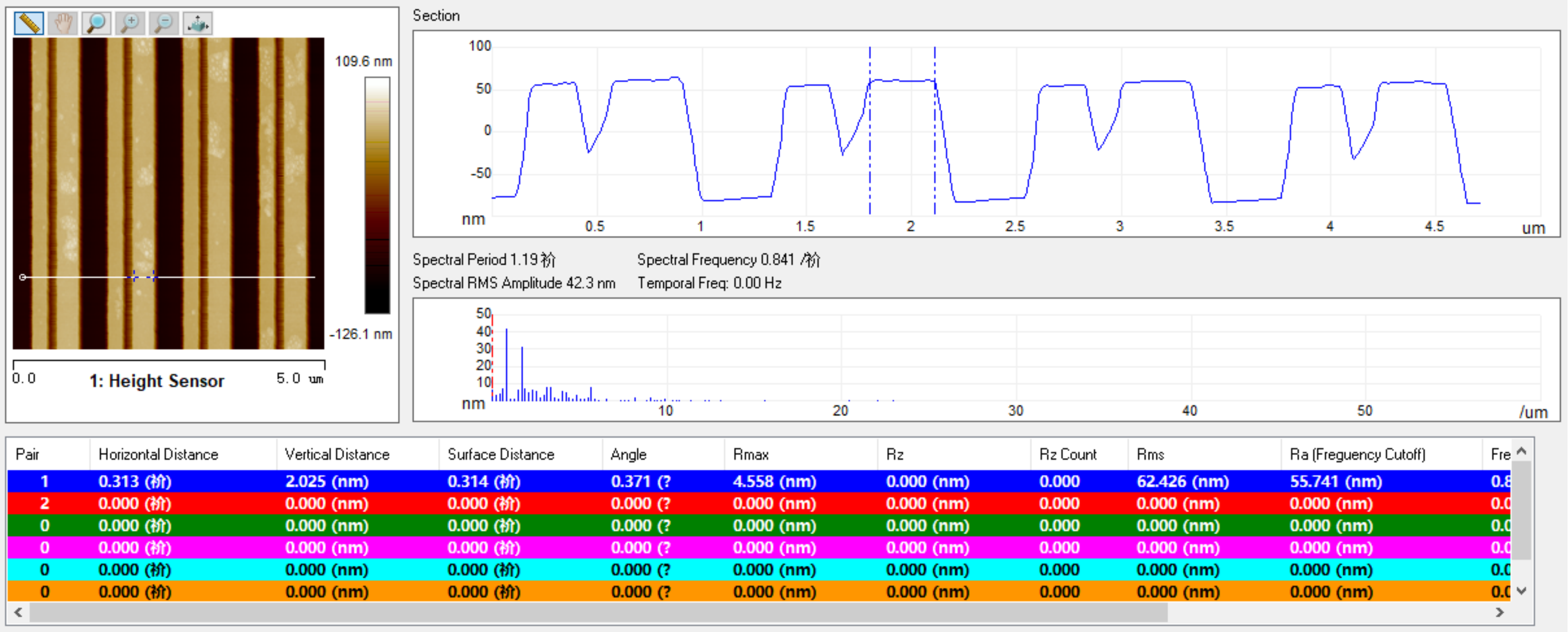
拟合结果

拟合残差MSE 4.172
拟合不确定度u(L) 4.2256 nm

Uncertainty components	L [nm]	w_1 [nm]	w_2 [nm]	Uncertainty sources
Type A evaluation				
Spectra gathering repeatability	2.20	1.44	1.29	0.001
Type B evaluation				
Incident angle θ	0.16	0.33	0.18	0.03°
Wavelength λ	0.02	0.02	0.04	0.03nm
Period d	0.02	0.01	0.04	0.1nm
Thickness h_1	3.30	3.91	0.28	Uniform dist.，±2nm
Thickness h_2	1.45	0.98	0.79	Uniform dist.，±5nm
Combined type B u_B	3.61	4.05	0.86	
Combined uncertainty u_c	4.23	4.29	1.55	
Expanded uncertainty U (k=2)	8.45	8.59	3.10	

Results and analysis

- Measurement of samples with nominal DBO value of 150nm



Spectral Period 1.19 祄
Spectral Frequency 0.841 /祄
Spectral RMS Amplitude 42.3 nm
Temporal Freq: 0.00 Hz

Pair	Horizontal Distance	Vertical Distance	Surface Distance	Angle	Rmax	Rz	Rz Count	Rms	Ra (Freguency Cutoff)	Fre
1	0.313 (祄)	2.025 (nm)	0.314 (祄)	0.371 (?	4.558 (nm)	0.000 (nm)	0.000	62.426 (nm)	55.741 (nm)	0.8
2	0.000 (祄)	0.000 (nm)	0.000 (祄)	0.000 (?	0.000 (nm)	0.000 (nm)	0.000	0.000 (nm)	0.000 (nm)	0.0
0	0.000 (祄)	0.000 (nm)	0.000 (祄)	0.000 (?	0.000 (nm)	0.000 (nm)	0.000	0.000 (nm)	0.000 (nm)	0.0
0	0.000 (祄)	0.000 (nm)	0.000 (祄)	0.000 (?	0.000 (nm)	0.000 (nm)	0.000	0.000 (nm)	0.000 (nm)	0.0
0	0.000 (祄)	0.000 (nm)	0.000 (祄)	0.000 (?	0.000 (nm)	0.000 (nm)	0.000	0.000 (nm)	0.000 (nm)	0.0
0	0.000 (祄)	0.000 (nm)	0.000 (祄)	0.000 (?	0.000 (nm)	0.000 (nm)	0.000	0.000 (nm)	0.000 (nm)	0.0

	L [nm]	w_1 [nm]	w_2 [nm]
AFM	156.5	313	196
DBO Standard apparatus	149.9	320.1	201

Conclusions

- Summary
  - Developed a traceable DBO metrology method
  - Designed a new type of DBO reference standard target and apparatus
  - Experiments show uncertainty of (3~9) nm for DBO value of (50~150) nm
- Future work
  - Design and tape out of reference samples with smaller DBO values
  - Function optimization of reference apparatus (auto loading, wafer mapping, etc.)

Thanks for attention!

Q&A

For more information:

- **CEPREI Cal: www.ceprei-cal.com**
- **CEPREI: www.ceprei.com**

- **Wechat:**

Lin Yang

CEPREI Cal