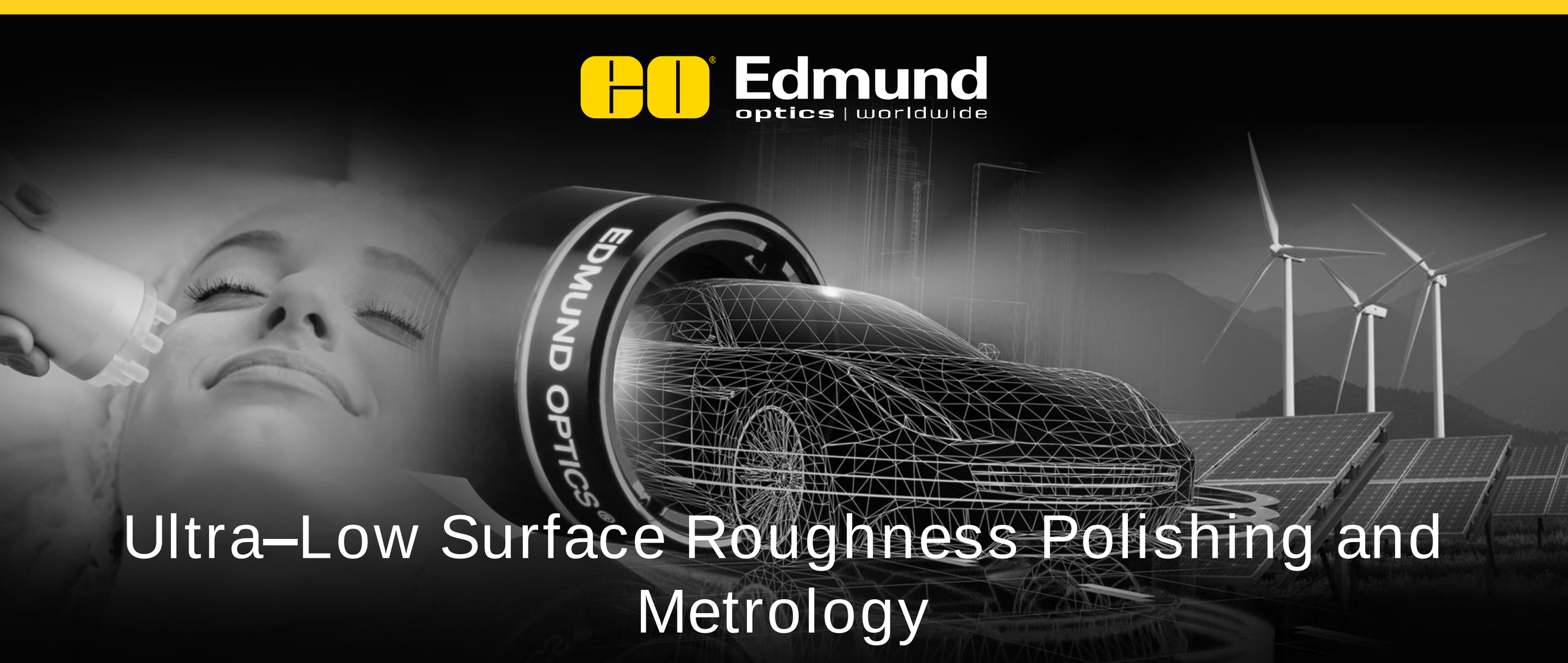


Ultra–Low Surface Roughness Polishing and Metrology

蔡斌彧 Bence Cai – 华南区客户经理

2023/09/07

Edmund Optics Company

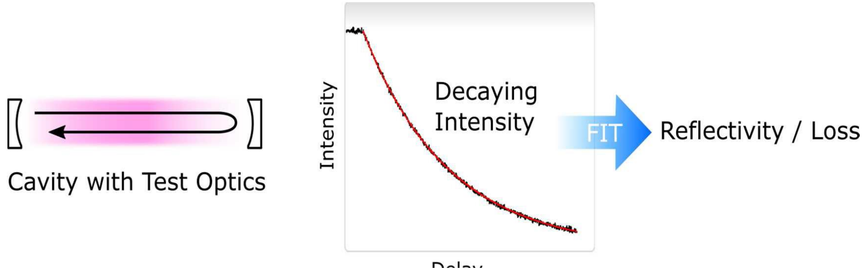
全球化的工程与制造

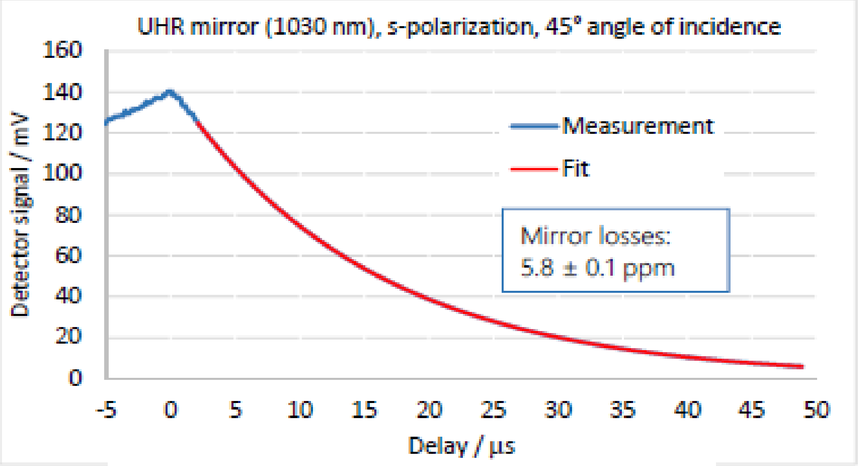
- 广为人知的产品手册
- 作为定制晶圆厂和工程解决方案的提供商，拥有超过20年的经验
- 每年内部制造超过200万个光学器件
- 亚利桑那大学的特别项目

亚埃表面对哪些市场有利？

需要光学和能量效率的应用

- 紫外线范围及以下
- 超低散射
- 高功率激光系统
- 计量系统





Images from Ultrafast Innovations GmbH

亚埃表面对哪些市场有利？

需要光学和能量效率的应用

- 紫外线范围及以下
- 超低散射
- 高功率激光系统
- 计量系统

医学的

- 眼科手术
- 成像系统

国防

- 导航系统

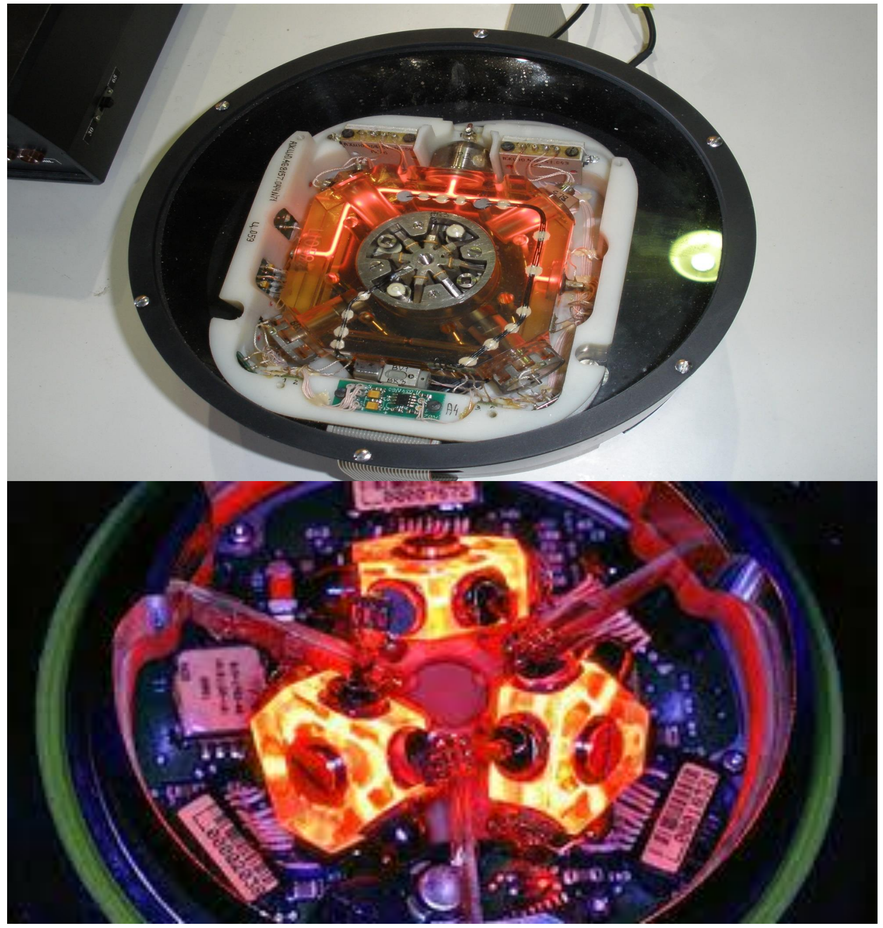
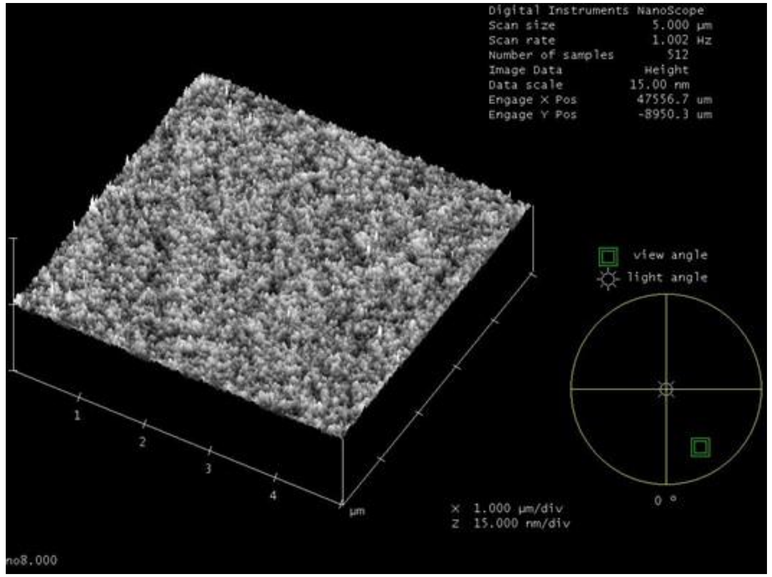
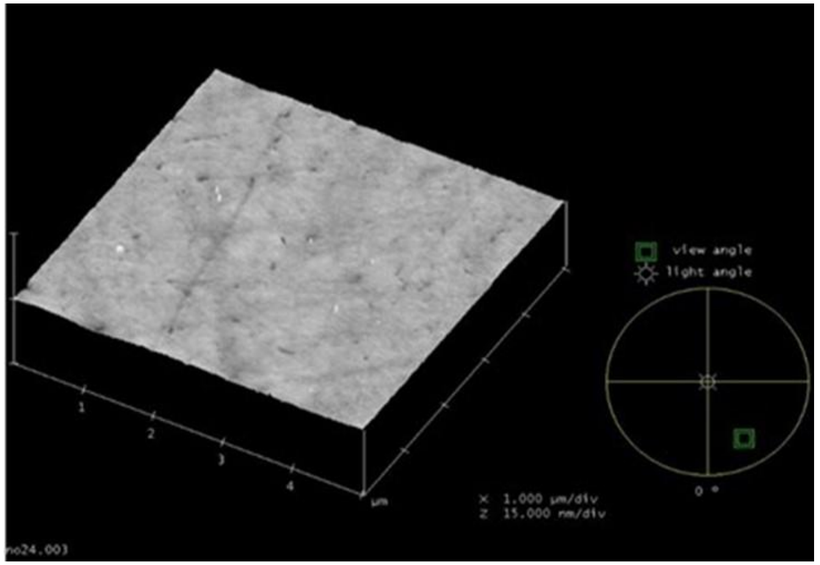
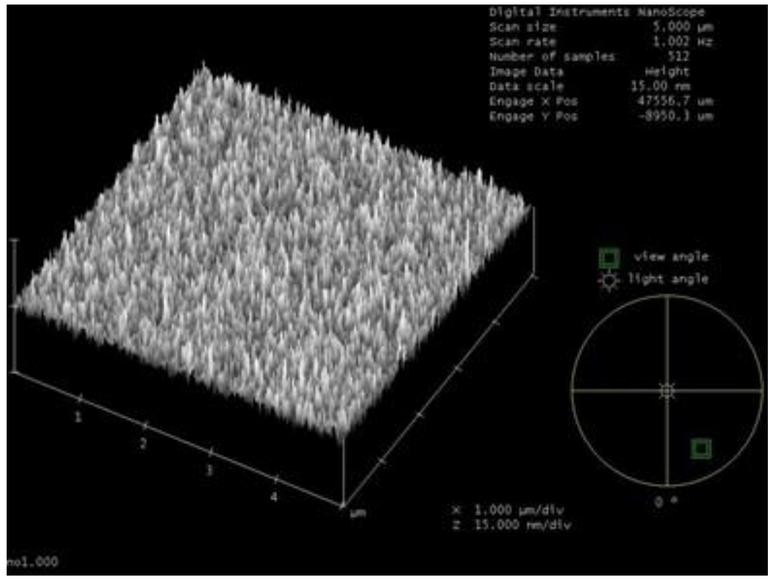


Image from FoxTrotAlpha

超低表面粗糙度







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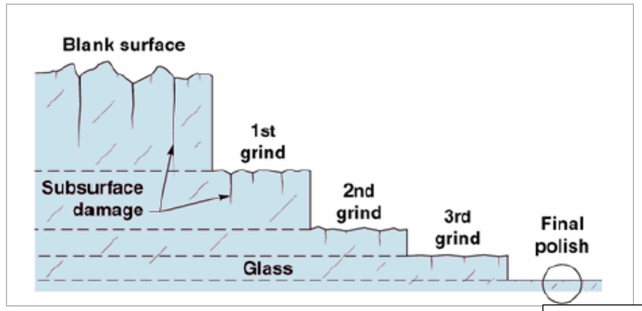
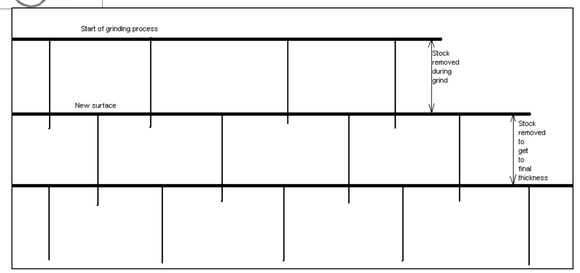
doi: 10.1117/12.2536689

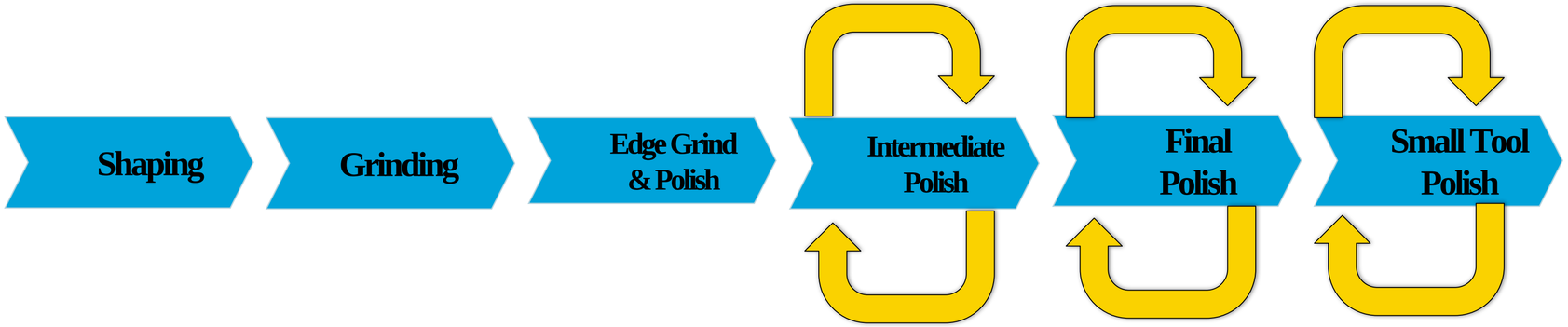
抛光基础

传统的减法抛光从表面形成开始

- 固定磨料（Blanchard 等）
- 松散磨料
- 逐渐变细的砂砾
- SSD是材料机械移除的自然结果







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doi: 10.1117/12.2536689

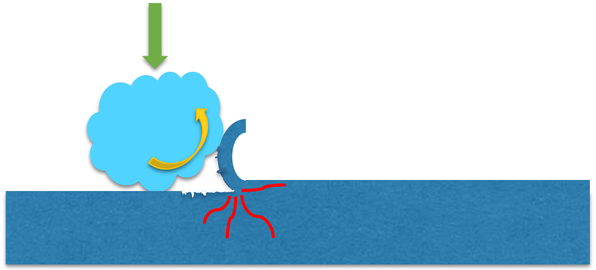
亚表面损伤层

原子级键非常强

- **抛光**颗粒具有不规则形状
- 颗粒将材料从基材上剥离

一些基材仍与剪切材料粘合

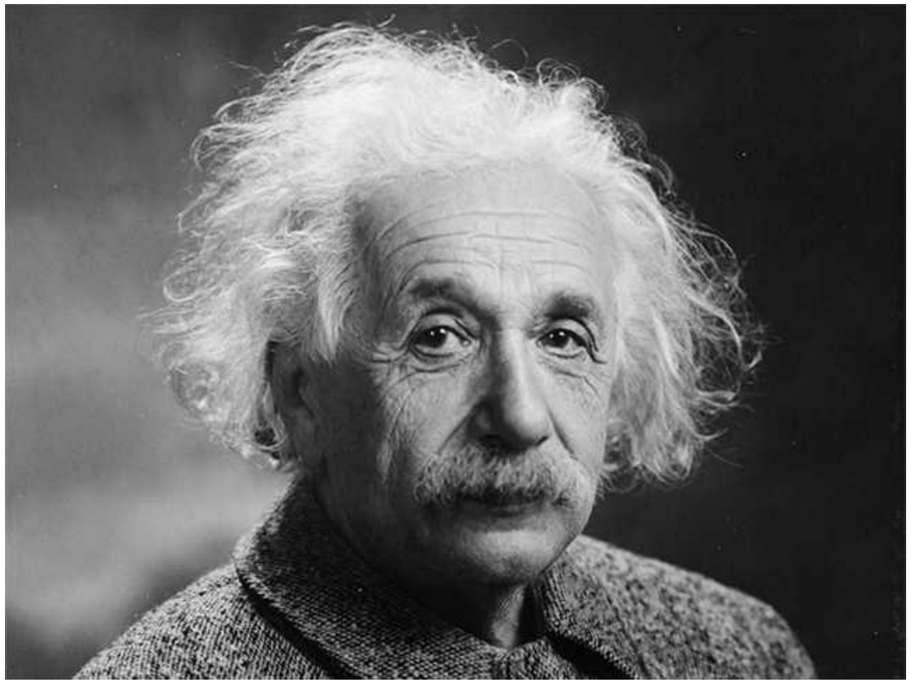
- **玻璃碎片的不**规则表面
- **玻璃上的**颗粒压力导致破裂



剪切面下方的材料移除会产生表面空隙

- **一些可**见，一些潜在（SSD）

“疯狂就是一遍又一遍地做同样的事情，期望得到不同的结果”



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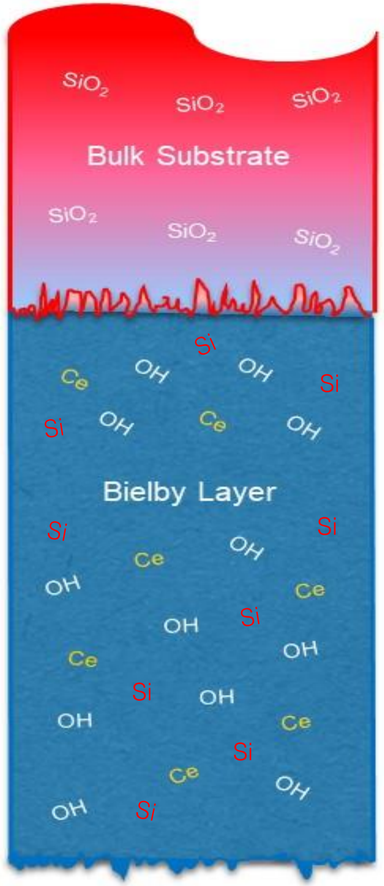
doi: 10.1117/12.2536689

抛光科学

化学机械抛光（CMP）

- **氧化**铈、氧化铝、氧化锆和二氧化硅是常见的抛**光**剂
- **水通**过打破Si-O**化学**键软化玻璃;
  - $SiO_2 + 2(H_2O) \rightarrow Si(OH)_4$
  - Si-OH **分子形成** ($Si(OH)_4$)



*<u>现实情况下：</u>**在拜**尔贝层以下的侵蚀性清除；SSD*

***<u>理想情况下：</u>材料去除**发生在改性 Si (OH) 4层**从表面去除**时*

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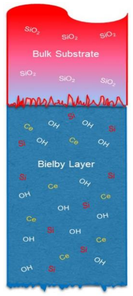
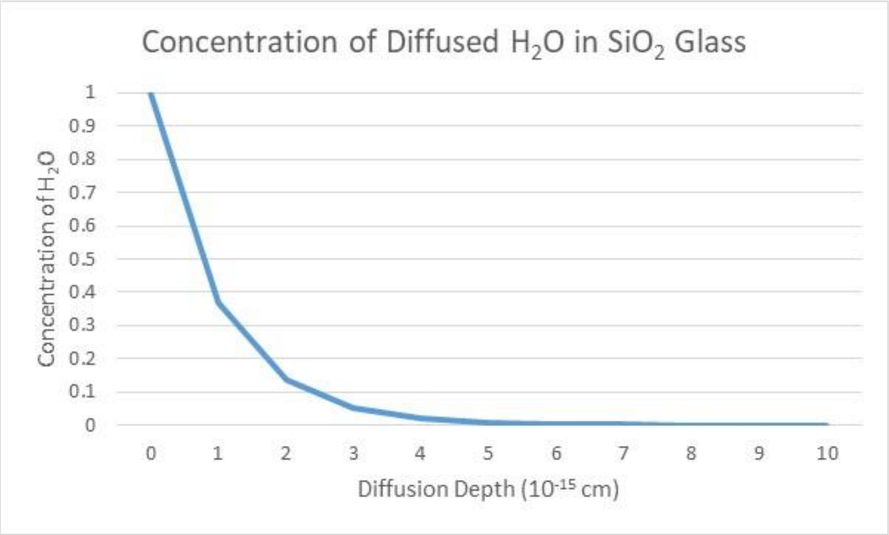
抛光科学

H2O在Sio2中的扩散

- 扩散系数估计约10 - 15 cm2 / sec * (非常低的价值)
- 扩散深度测量值0.5 nm≤d≥12.0nm **
- H2O在Si O2中的溶解度随静水压力和压应力的增加呈指数增加
- 扩散系数呈指数递减 (Lee Cook paper)





↔ 因此需要控制好浆液的浓度跟窗片上的压力

**"Diffusion of Water in SiO2 at Low Temperatures", Lanford, Doremus, et al, "Advances in Materials Characterization II", 1985, p203*

*** "Effect of Stress on Water Diffusion in Silica Glass", Nogami & Tomozawa, J of Am Cer Society, 67, 1984, p151*

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doi: 10.1117/12.2536689

超级抛光基本原理

浸没式抛光*

- 新鲜浆液的恒定输入
- 保持磨盘表面处于水化状态
- 恒定的温度
- 表面张力对空气中的污染物形成屏障
- 拜尔贝层的不间断形成
- 更高的粒子混合概率

- *对于制作出亚埃级表面至关重要*

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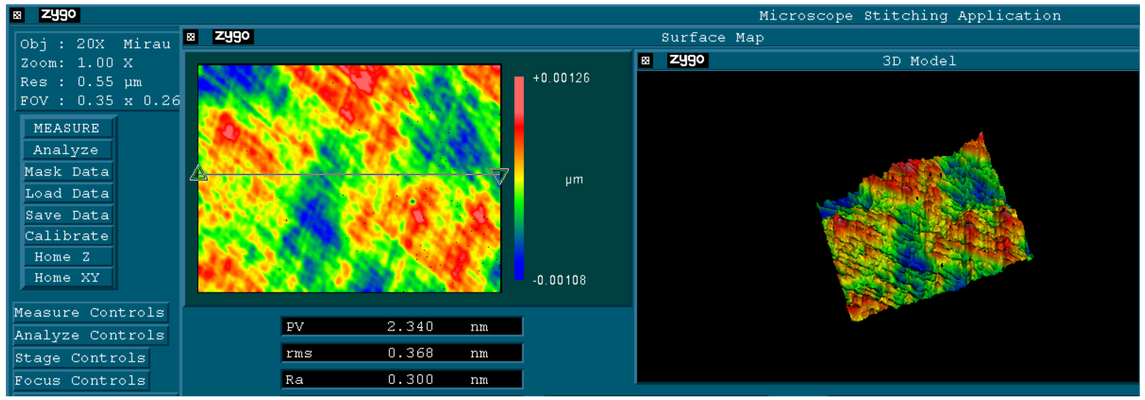
doi: 10.1117/12.2536689

超级抛光工艺对比

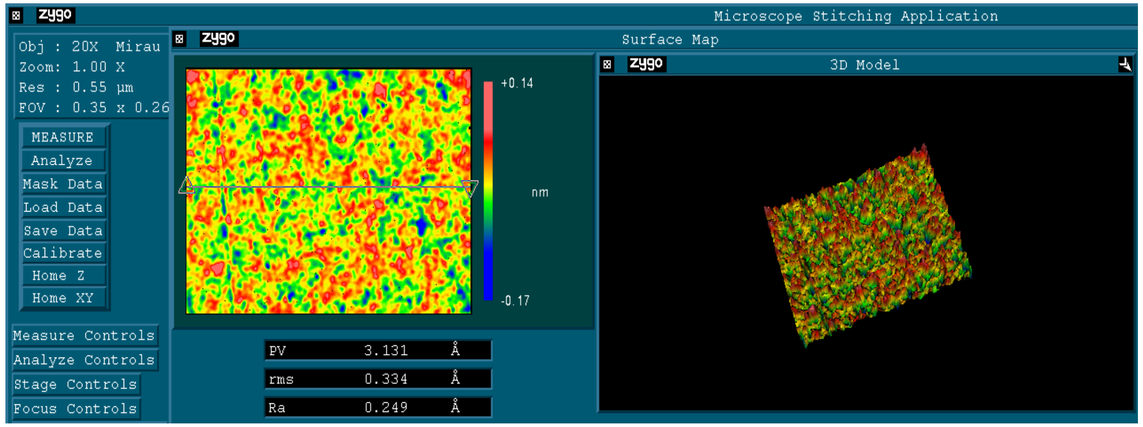
标准流程- WLI

- 颗粒穿过拜尔贝层并进入基底(0.5μm ≤ ø ≥ 1.5μm)
- **擦痕、沟槽和表面**结构的证据
- 23 Å P-V, 3 Å Ra



EOT 工艺 – WLI

- **反复去除拜**尔贝层
- 证明为随机表面结构，没有划痕或沟槽
- 3 Å P-V, 0.25 Å Ra



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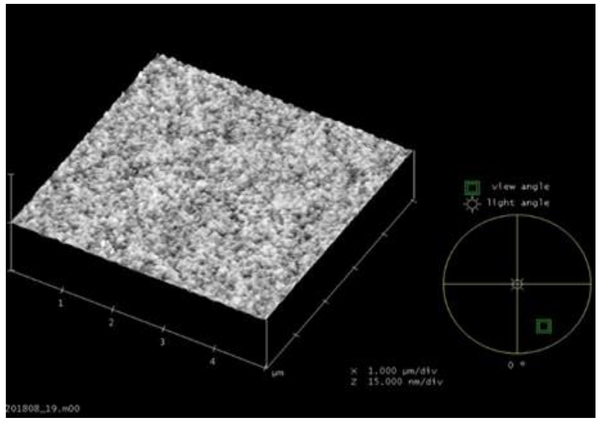
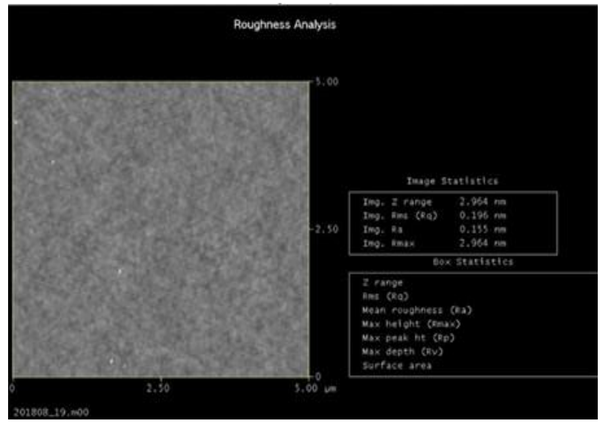
doi: 10.1117/12.2536689

超级抛光工艺对比

标准超级抛光- AFM

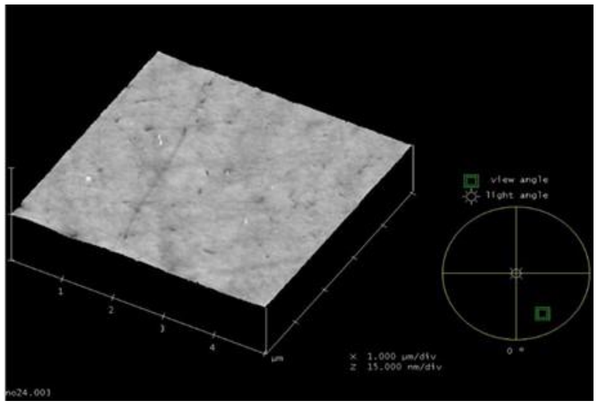
- 非常好的表面- 1.55 Å平均粗糙度
- 29.6 Å P-V
- 表面微结构依然明显

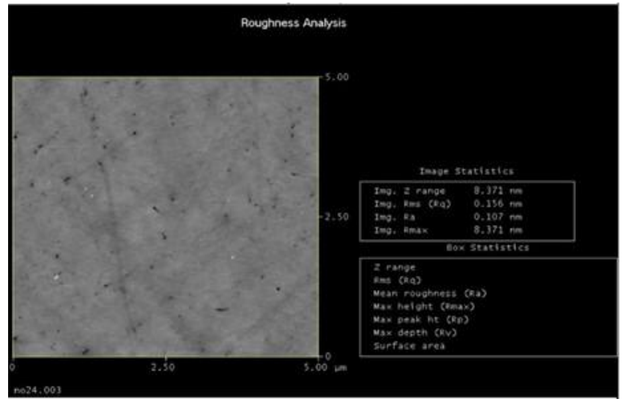




EOT 超级抛光 – AFM

- 优异的表面- 1.07 Å平均粗糙度
- 3.71 Å P-V
- 表面已被清理干净





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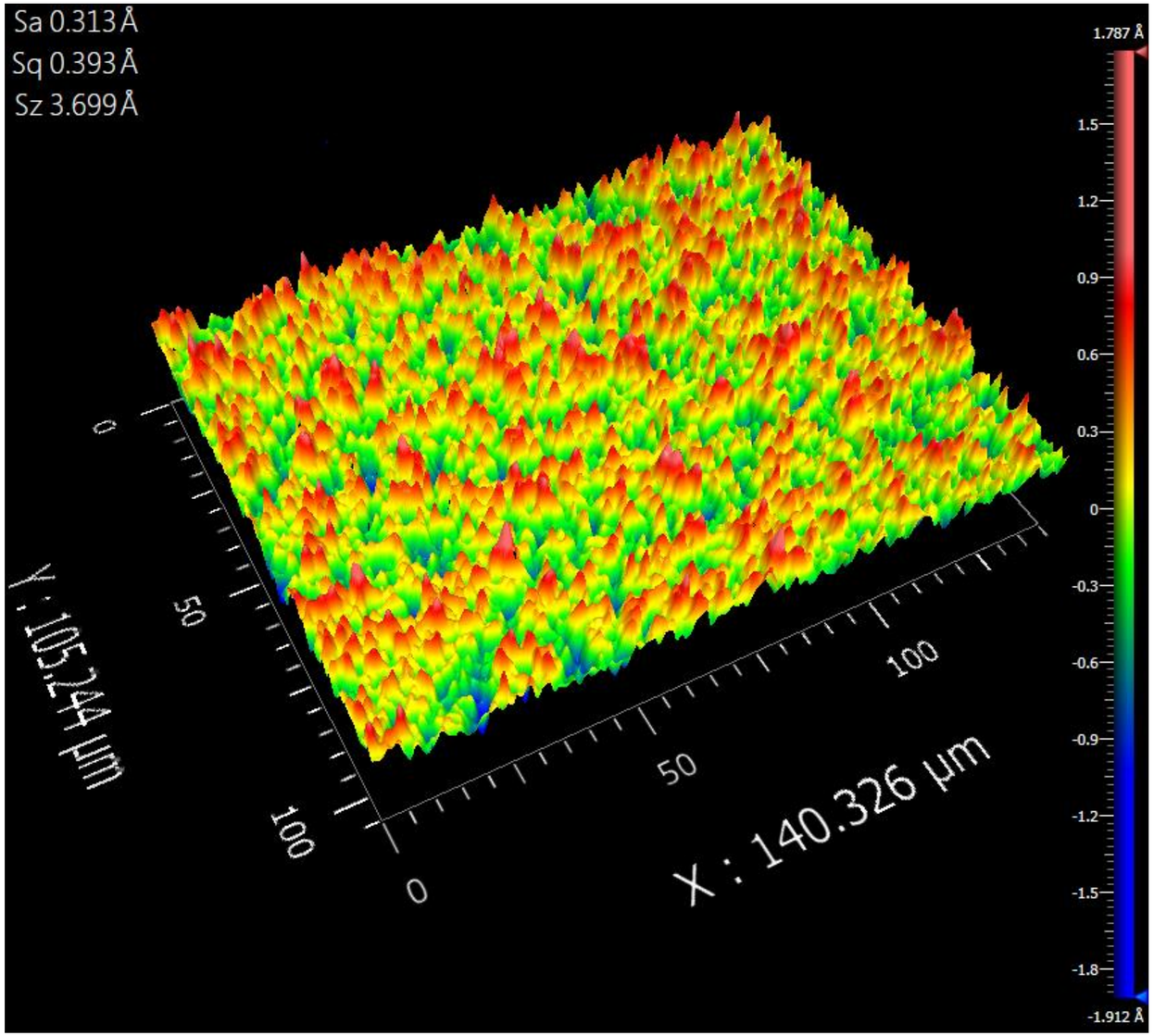
粗糙度参数

$$RMS = \sqrt{\int_{f_1}^{f_2} PSD(f)df}$$

- 需要完全定义空间频率带宽(SFB)



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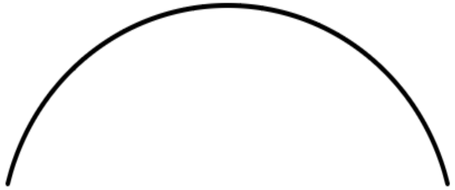
doi: 10.1117/12.2536683

空间频率组

轮廓



0.02 – 13 [mm^{-1}]

波纹度

1 – 1800 [mm^{-1}]

粗糙度

30 – 50,000 [mm^{-1}]

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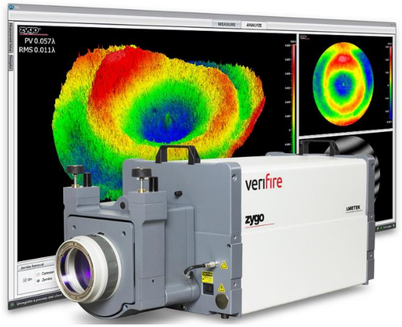
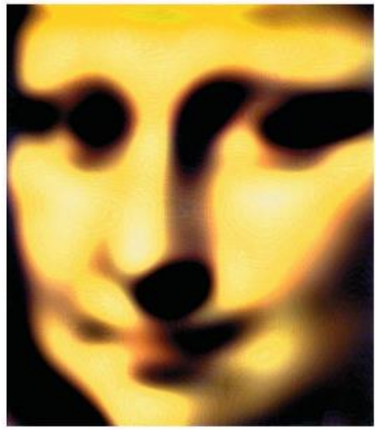
doi: 10.1117/12.2536683

标定表面特征



低空间频率



中空间频率

高空间频率

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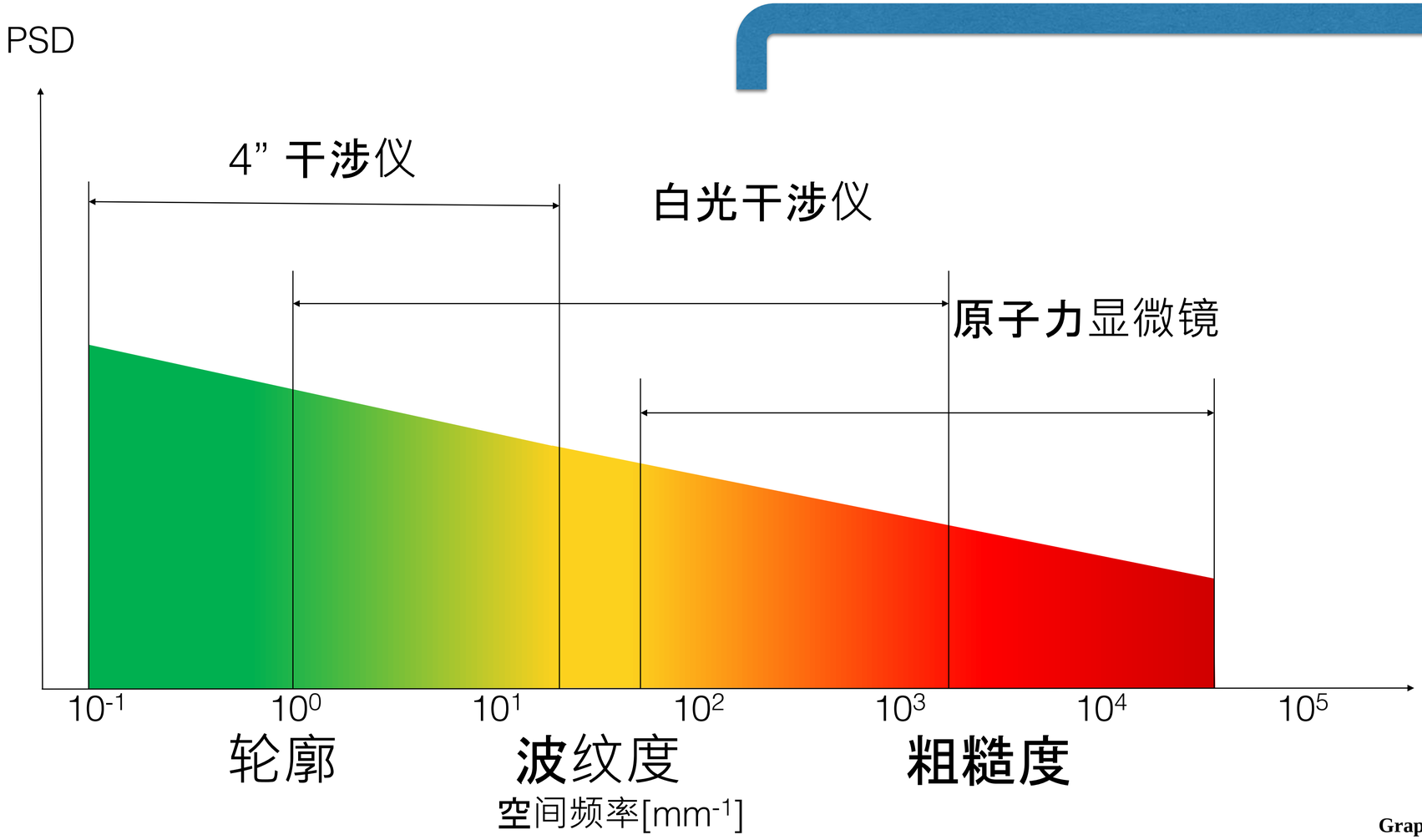
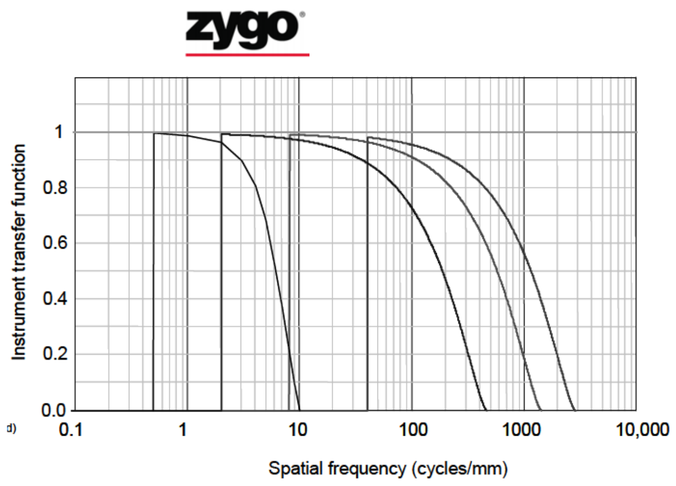
doi: 10.1117/12.2536683

仪器功能





5X，20X，100X

Graph: L. Deck, C. Evens, “High performance Fizeau and scanning white-light interferometers for mid-spatial frequency optical testing of free-form optics” SPIE (2004)

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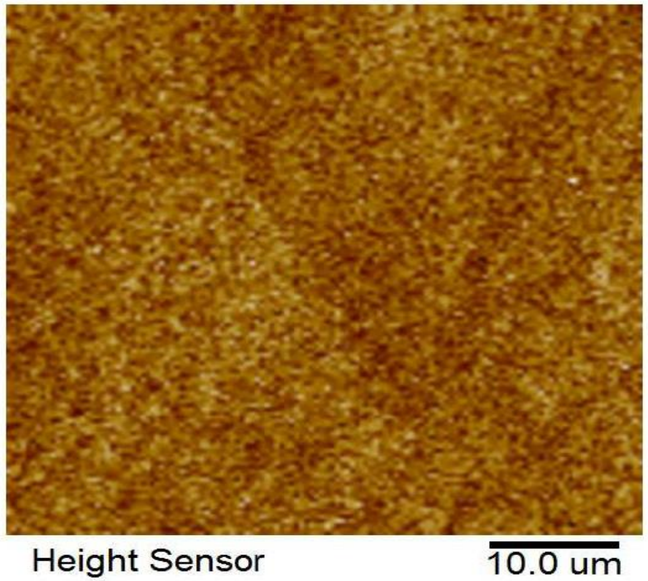
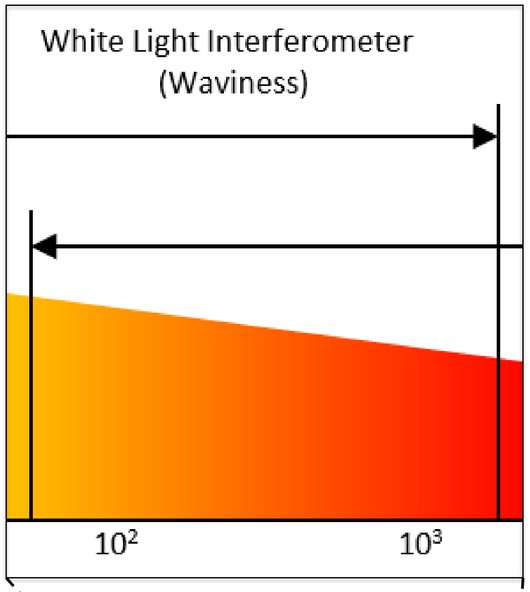
doi: 10.1117/12.2536683

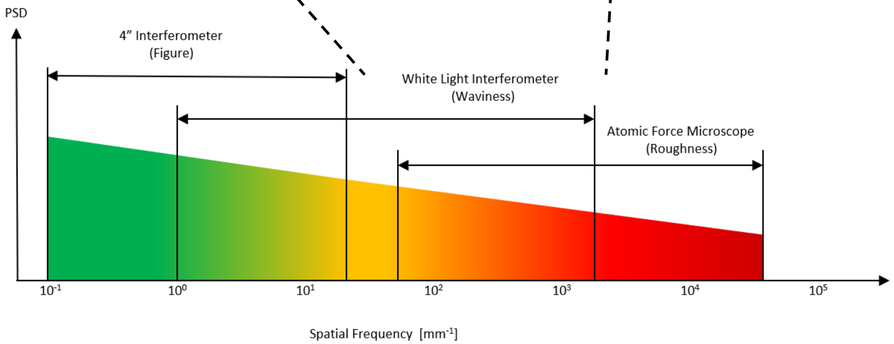
数据相关性

AFM 图

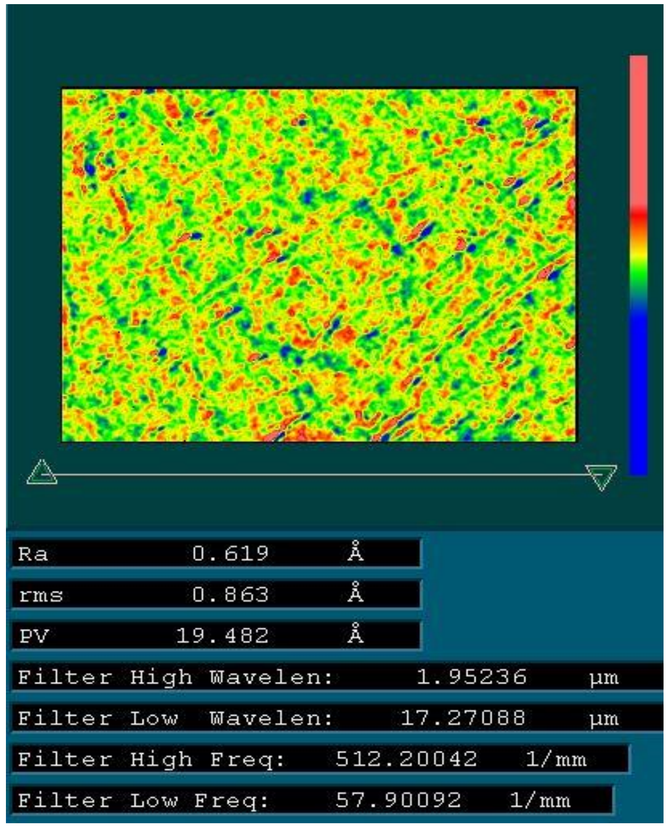


Rq: 0.72A
Ra: 0.57A





WLI 图



共同覆盖的空间频率:
60 – 512 [cycle/mm]

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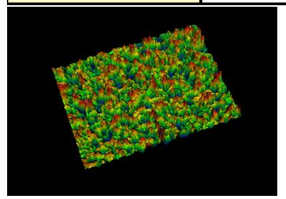
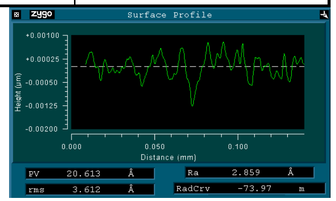
熔融石英表面

Fused Silica Incoming Material

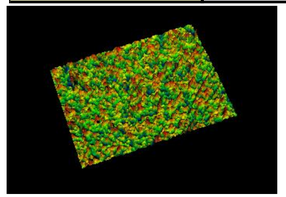
	P-V (Å)	RMS (Å)	Ra (Å)
Average	183.416	7.423	5.701
Range	2089.920	18.240	11.190
Std Dev	186.88391	2.90696	1.81687

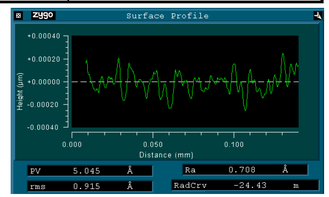


Fused Silica Final Results 2 Hr Polishing Time

	P-V (Å)	RMS (Å)	Ra (Å)
Average	7.862	0.448	0.333
Range	1.131	0.034	0.101
Std Dev	0.97763	0.02217	0.02024



熔融石英平面抛光

- 2小时抛光后达到亚埃级
- 没有可测量的SSD

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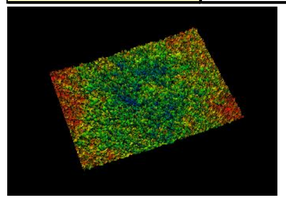
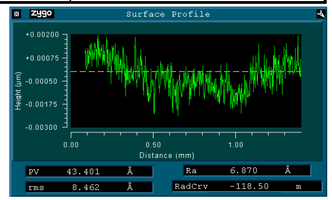
doi: 10.1117/12.2536689

N-BK7 表面

N-BK7 Incoming Material

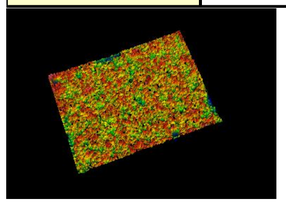
	P-V (Å)	RMS (Å)	Ra (Å)
Average	256.370	11.397	6.004
Range	538.988	17.017	1.989
Std Dev	205.748	7.484	0.671

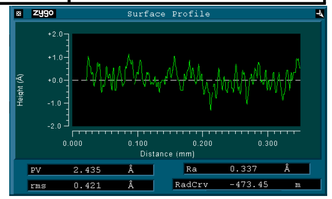


N-BK7 Final Results 2 Hr Polishing Time

	P-V (Å)	RMS (Å)	Ra (Å)
Average	15.887	1.095	0.839
Range	3.392	0.065	0.047
Std Dev	1.70506	0.03253	0.02354



N-BK7 平面抛光

- 2小时抛光后达到亚埃级
- 与熔融石英窗口片同时做表面处理
- 粗糙度Ra 值大概比熔融石英高出25%
- N-BK7 包含了 SiO_2, B_2O_3, Na_2O, Al_2O_3, 等其他元素

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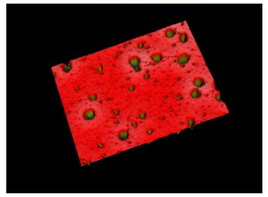
doi: 10.1117/12.2536689

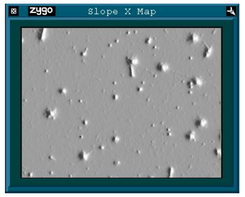
超级抛光- 硅

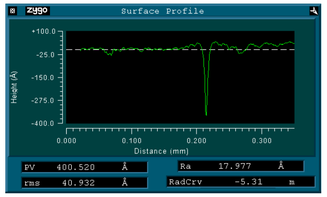
- EO 产品编号 *#68527*
- **光学**级硅平片
- 25.0mm Ø, 3.0mm CT
- **持**续抛光
- **浸没式工**艺
- 0.368 Å Ra
- 5.871 Å P-V

Incoming Material

	P-V (Å)	RMS (Å)	Ra (Å)
Average	802.180	38.217	14.581
Range	657.097	58.222	32.398
Std Dev	229.81659	21.45135	13.15213

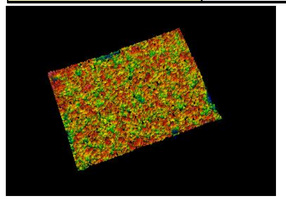


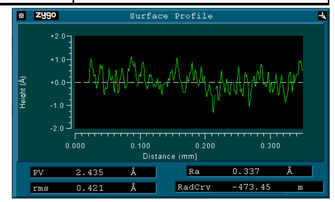




Final Results 2 Hr Polishing Time

	P-V (Å)	RMS (Å)	Ra (Å)
Average	5.871	0.483	0.368
Range	4.435	0.093	0.074
Std Dev	1.22176	0.02710	0.02125



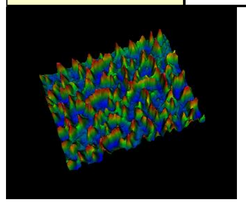


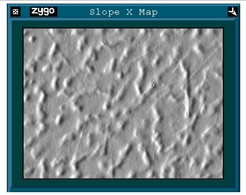
New View, 20X Mirau, 1X Zoom, BPF, FFT Fixed, 9 - 250 mm^{-1}, 10X Average, Sys Err Removed

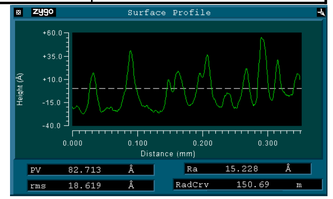
超级抛光 – 氟化钙

Incoming Material

	P-V (Å)	RMS (Å)	Ra (Å)
AVERAGE	163.835	15.502	11.729
RANGE	734.679	15.537	10.326
STD DEV	227.9093	4.3495	3.1080

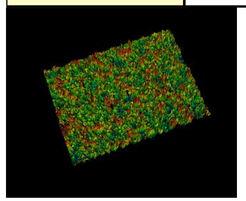


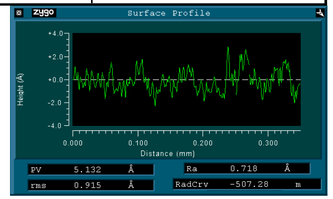




Final Results 2 Hr Polishing Time

	P-V (Å)	RMS (Å)	Ra (Å)
Average	18.274	0.964	0.713
Range	19.657	0.213	0.121
Std Dev	5.99559	0.07277	0.04265

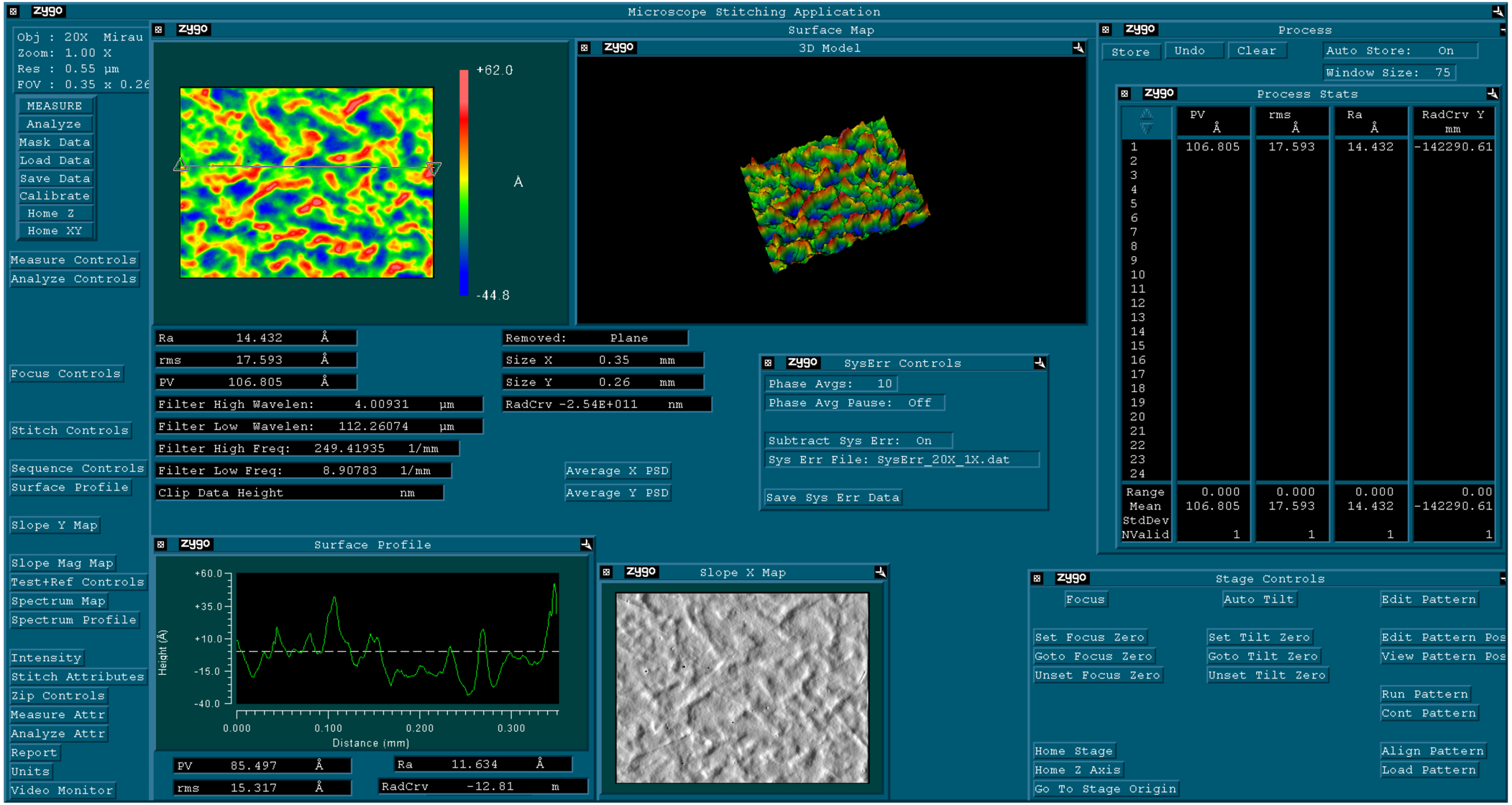




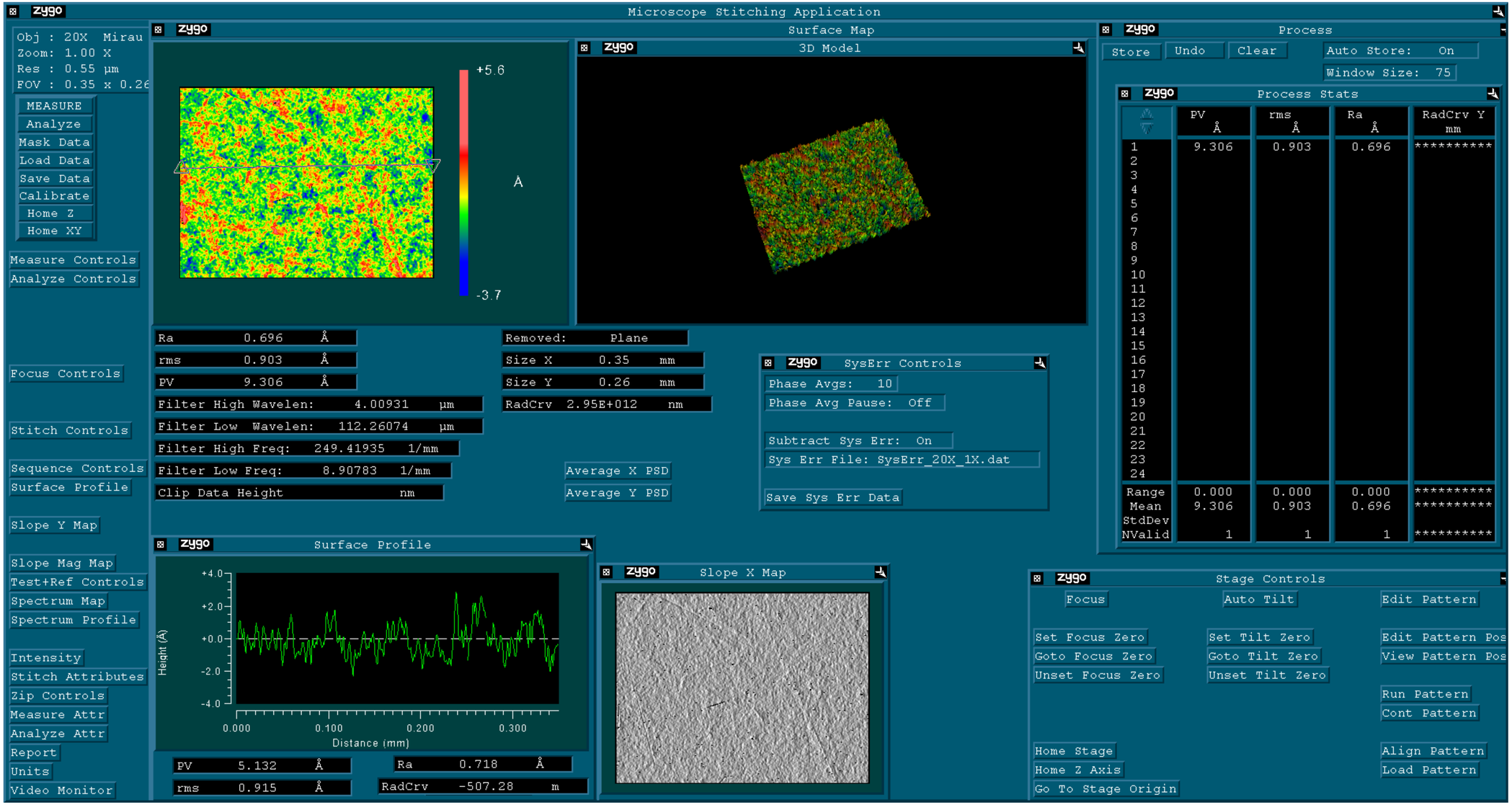
New View, 20X Mirau, 1X Zoom, BPF, FFT Fixed, 9 - 250 mm^{-1}, 10X Average, Sys Err Removed

- EO 产品编号 *#47683*
- **真空紫外**线等级CaF_2
- 25.0mm ø, 3.0mm CT
- **持**续抛光
- **浸没式工**艺
- 0.713 Å Ra
- 18.274 Å P-V

超抛前 CaF_2


Microscope Stitching Application
Obj : 20X Mirau
Zoom: 1.00 X
Res : 0.55 µm
FOV : 0.35 x 0.26
MEASURE
Analyze
Mask Data
Load Data
Save Data
Calibrate
Home Z
Home XY
Measure Controls
Analyze Controls
Focus Controls
Stitch Controls
Sequence Controls
Surface Profile
Slope Y Map
Slope Mag Map
Test+Ref Controls
Spectrum Map
Spectrum Profile
Intensity
Stitch Attributes
Zip Controls
Measure Attr
Analyze Attr
Report
Units
Video Monitor
Surface Map
+62.0
Å
-44.8
3D Model
Ra 14.432 Å
rms 17.593 Å
PV 106.805 Å
Filter High Wavelen: 4.00931 µm
Filter Low Wavelen: 112.26074 µm
Filter High Freq: 249.41935 1/mm
Filter Low Freq: 8.90783 1/mm
Clip Data Height nm
Removed: Plane
Size X 0.35 mm
Size Y 0.26 mm
RadCrv -2.54E+011 nm
Average X PSD
Average Y PSD
SysErr Controls
Phase Avgs: 10
Phase Avg Pause: Off
Subtract Sys Err: On
Sys Err File: SysErr_20X_1X.dat
Save Sys Err Data
Process
Store
Undo
Clear
Auto Store: On
Window Size: 75
Process Stats
PV Å
rms Å
Ra Å
RadCrv Y mm
1 106.805 17.593 14.432 -142290.61
Range 0.000 0.000 0.000 0.00
Mean 106.805 17.593 14.432 -142290.61
StdDev
NValid 1 1 1 1
Surface Profile
+60.0
+35.0
+10.0
-15.0
-40.0
Height (Å)
0.000
0.100
0.200
0.300
Distance (mm)
PV 85.497 Å
rms 15.317 Å
Ra 11.634 Å
RadCrv -12.81 m
Slope X Map
Stage Controls
Focus
Auto Tilt
Edit Pattern
Set Focus Zero
Goto Focus Zero
Unset Focus Zero
Set Tilt Zero
Goto Tilt Zero
Unset Tilt Zero
Edit Pattern Pos
View Pattern Pos
Run Pattern
Cont Pattern
Home Stage
Home Z Axis
Go To Stage Origin
Align Pattern
Load Pattern

超抛后 CaF_2


Microscope Stitching Application
Obj : 20X Mirau
Zoom: 1.00 X
Res : 0.55 µm
FOV : 0.35 x 0.26
MEASURE
Analyze
Mask Data
Load Data
Save Data
Calibrate
Home Z
Home XY
Measure Controls
Analyze Controls
Focus Controls
Stitch Controls
Sequence Controls
Surface Profile
Slope Y Map
Slope Mag Map
Test+Ref Controls
Spectrum Map
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Intensity
Stitch Attributes
Zip Controls
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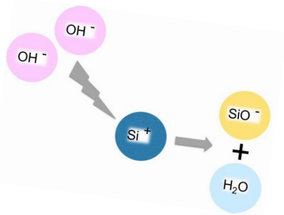
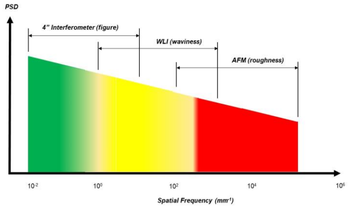
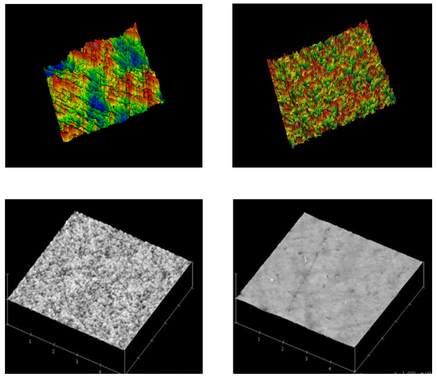
Report
Units
Video Monitor
Surface Map
+5.6
Å
-3.7
3D Model
Ra 0.696 Å
rms 0.903 Å
PV 9.306 Å
Filter High Wavelen: 4.00931 µm
Filter Low Wavelen: 112.26074 µm
Filter High Freq: 249.41935 1/mm
Filter Low Freq: 8.90783 1/mm
Clip Data Height nm
Removed: Plane
Size X 0.35 mm
Size Y 0.26 mm
RadCrv 2.95E+012 nm
Average X PSD
Average Y PSD
SysErr Controls
Phase Avgs: 10
Phase Avg Pause: Off
Subtract Sys Err: On
Sys Err File: SysErr_20X_1X.dat
Save Sys Err Data
Process
Store
Undo
Clear
Auto Store: On
Window Size: 75
Process Stats
PV Å
rms Å
Ra Å
RadCrv Y mm
Range
Mean
StdDev
NValid
Surface Profile
Height (Å)
Distance (mm)
PV 5.132 Å
rms 0.915 Å
Ra 0.718 Å
RadCrv -507.28 m
Slope X Map
Stage Controls
Focus
Auto Tilt
Edit Pattern
Set Focus Zero
Goto Focus Zero
Unset Focus Zero
Set Tilt Zero
Goto Tilt Zero
Unset Tilt Zero
Edit Pattern Pos
View Pattern Pos
Run Pattern
Cont Pattern
Home Stage
Home Z Axis
Go To Stage Origin
Align Pattern
Load Pattern

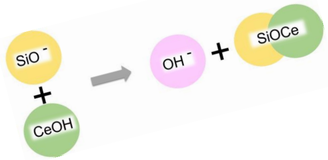
总 结

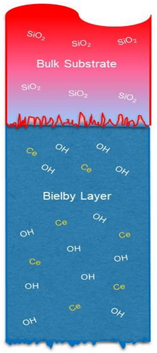
- *超抛技术高度依赖于研磨浆液化学*
- *化学主要受玻璃类型和抛光化合物的影响*
- *在比较结果时，适当的计量工具非常重要*
- *通过工艺控制可以获得去除可测量SSD的近乎完美的表面*
- *熔融石英、NBK-7、Si、CaF2均达到亚埃水平*

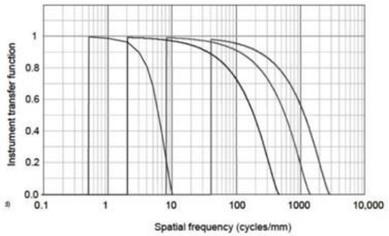












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