# Status of multilayer coatings for EUV Lithography

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**FOM Institute**
**for Plasma Physics**
**Rijnhuizen,**
**The Netherlands**

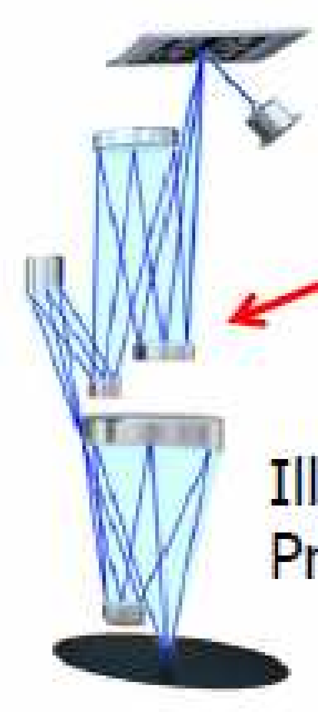
Rigaku

Maui EUVL Workshop, 14-17 June 2011

# Outline

- Introduction
- Performance versus Specifications
- Best ML performance
- ML stability
- ML coatings infrastructure
- ML for Next Generation EUVL
- Multilayer technology readiness for HVM
- Conclusion

# ASML NXE Scanner Requires 11+ ML Optics



Illuminator and
Projection optics

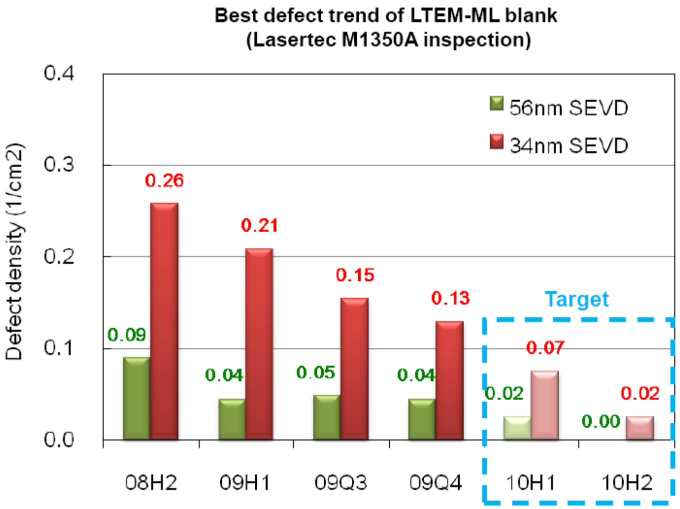
High Power Source
Collector optic

+ ML on mask blanks

# Is today's ML deposition technology ready for HVM?

- ML performance versus specification
- ML parameters to improve
  - Feasibility for improvement
- Infrastructure and capacity
  - Deposition facilities
  - Metrology
  - Substrates  suppliers

# Defects in mask blanks



Asahi Glass: 2010 Maui Workshop

**Structure**
CrN/LTEM/ML/Ru

**CTE of LTEM**

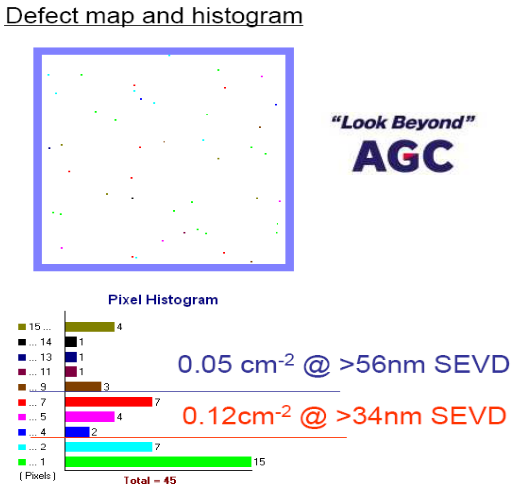
| | |
|---|---|
| Mean CTE | -3.5 ppb/K |
| CTE variation (PV) | 1.7 ppb/K |

**Substrate flatness**

| | |
|---|---|
| front | 89 nm |
| back | 76 nm |
| Blank Flatness(Bow) | 0.38 um |

**Reflectivity**

| | |
|---|---|
| Peak R | 66.2 % |
| R range(Abs.) | 0.3 % |
| centroid $\lambda$ | 13.535 nm |
| $\lambda$ range | 0.026 nm |

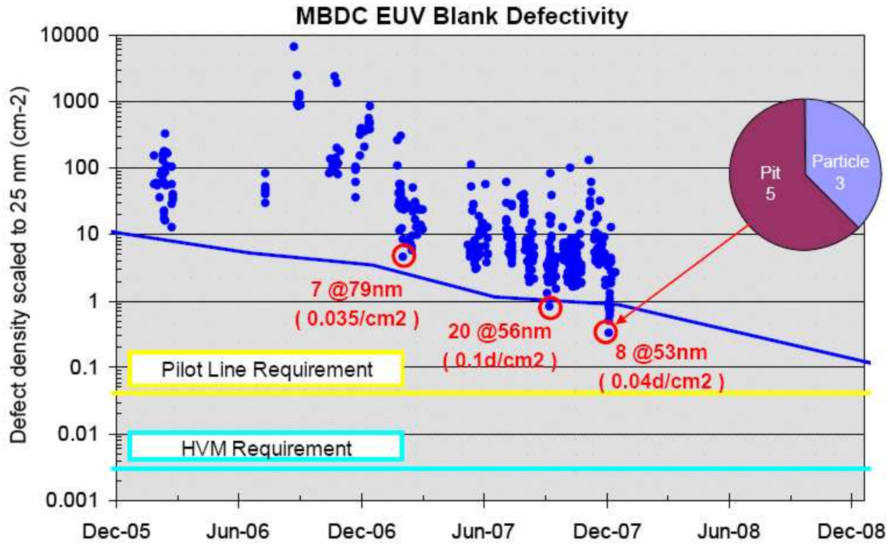


"Look Beyond"
AGC

Asahi Glass: 2010 Maui Workshop

Sungmin, et al, (Samsung Electronics) in Proc. SPIE Vol. 7969 (2011)

"Pit defects are the most dominant, accounting for on average 75% of defects observed. … The remaining 25% of the defects are due to particles deposited during the deposition process."



P. Kearney, et al., "Ion beam deposition for defect-free EUVL mask blanks," Proc. SPIE 6921, 69211X (2008)
presented by O. Wood: 2010 Maui Workshop

# Collector for NXE3100

Multilayer optics for EUV and beyond

λ = 13.5 nm

## LPP collector coating challenges

R > 65 %

λ = (13.500 ± 0.050) nm

→ Δd = 0.025 nm = 25 pm

- Diameter: > 660 mm
- Lens sag: > 150 mm
- Tilt: > 45 deg
- Weight: > 40 kg

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CYMER.

# Reflectivity radial uniformity

## Reflectivity of LPP collector mirror

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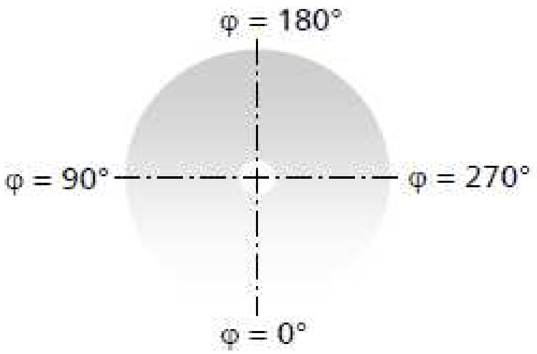
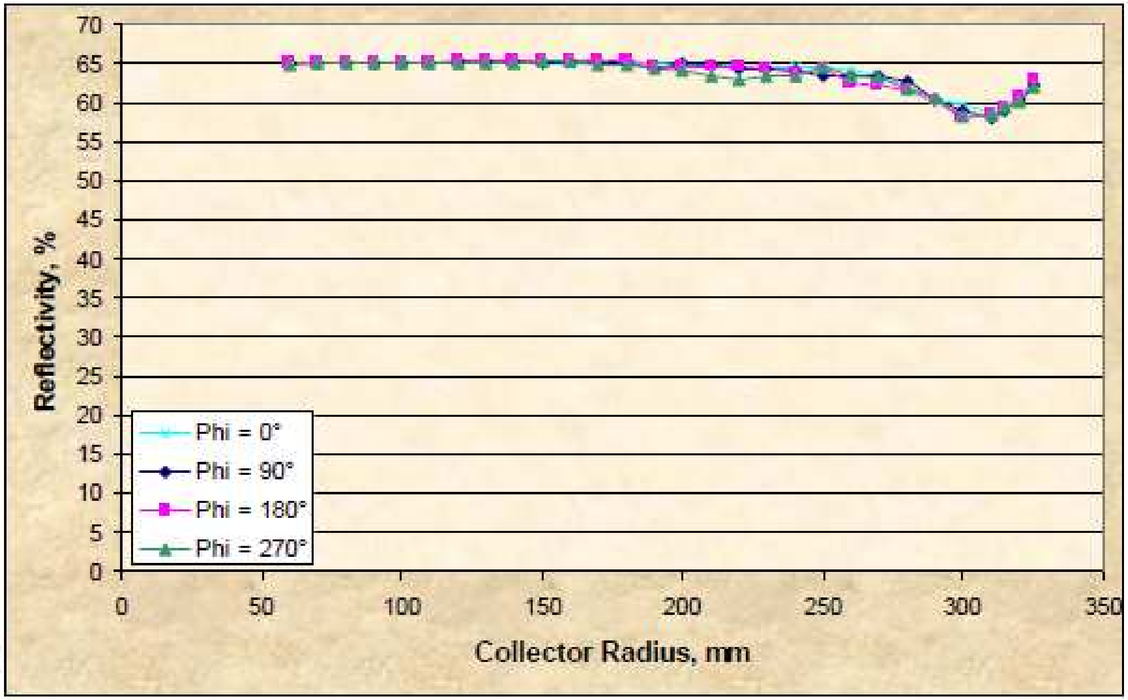


Maximum reflectance along four lines within clear aperture of collector mirror:

R ~ 65% @ r < 240 mm

R ~ 59% @ r = 250 … 320 mm

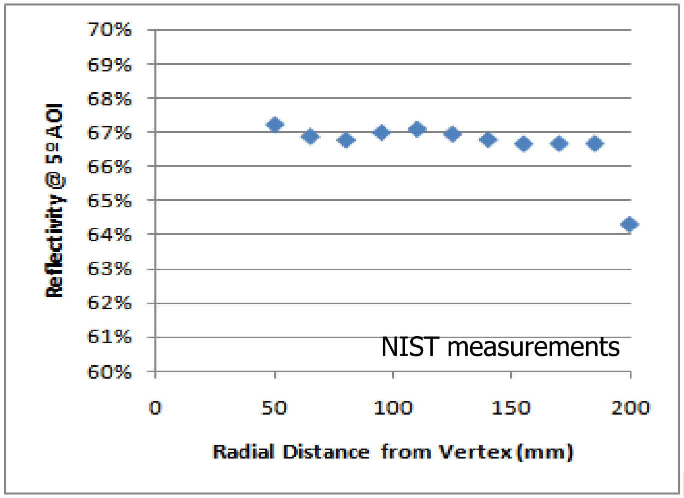


Measurements: PTB Berlin

Rigaku

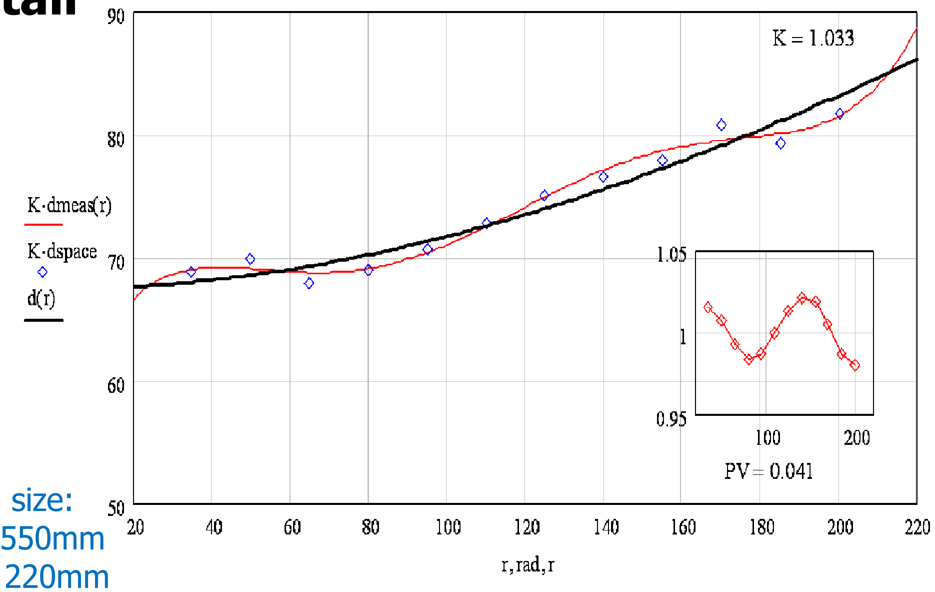
# Collector optics deposition at RIT

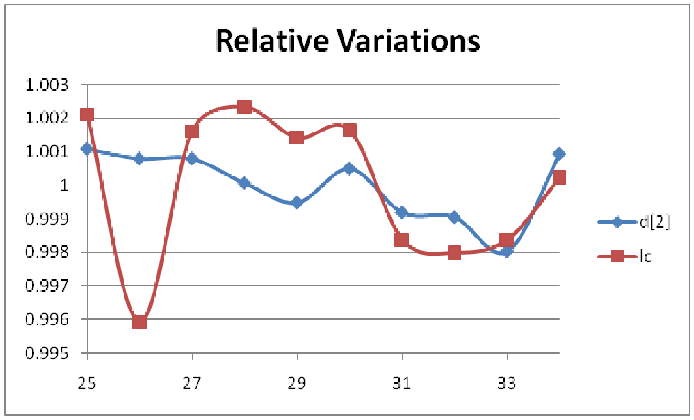
## Preliminary results: 3 weeks after install

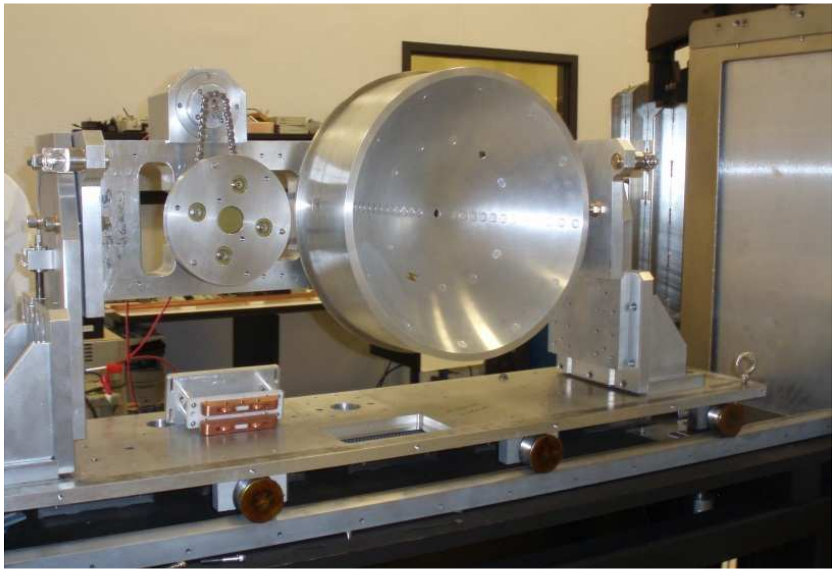


median λc ranged 13.77 @ 50mm to 13.33nm @ 200mm
total height range (sag) is 97mm
angle of surface is 13º - 49º

Maximum size:
Diameter – 550mm
Thickness – 220mm







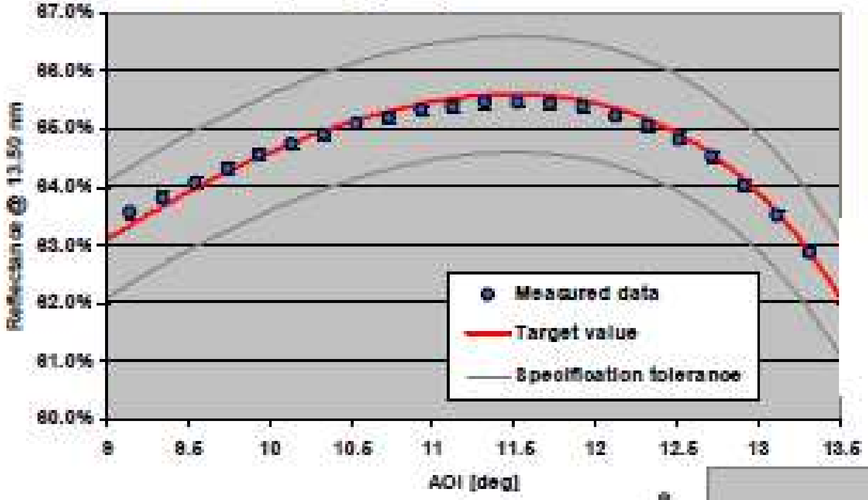
# Illuminator: Reflectivity 1

FOM Institute
for Plasma Physics
Rijnhuizen,
The Netherlands

## *Illuminator optics Alpha Demo tool*

*Highly convex illuminator element*

*Reqt. reflectivity @ used AoI +/-< 1% of target value*
*➔ 0.1% d-spacing budget*

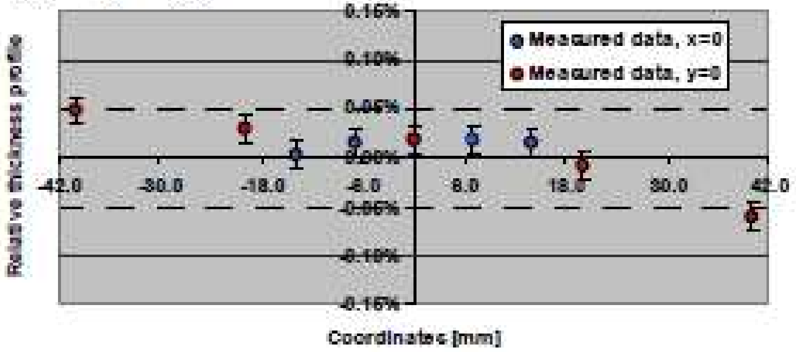


***Results deposition***

- *d-spacing within +/- 0.05%*
- *Lateral reflectivity uniformity +/- <0.5% of target value @ used AoI*

*✓Factor 2 within specification*

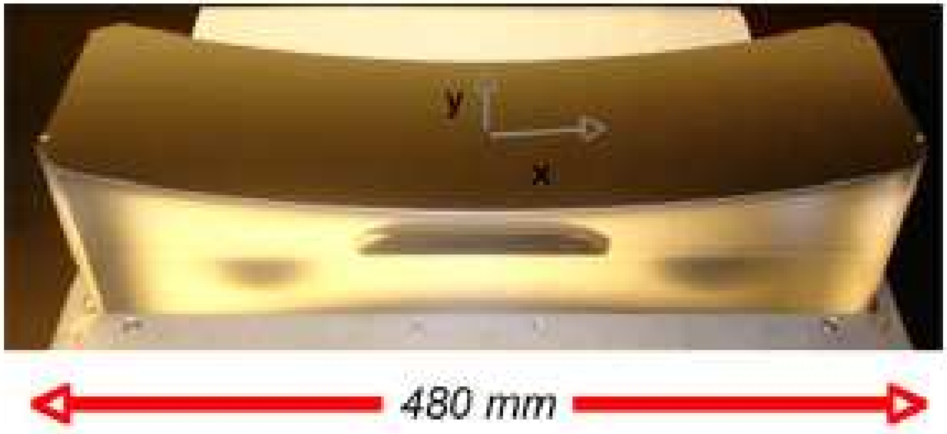
(2005)

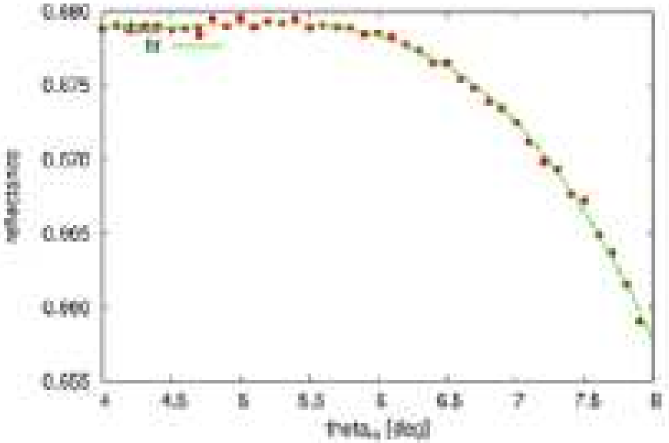


# Illuminator: Reflectivity 2

*Illuminator optics Alpha Demo tool*

**Carl Zeiss SMT GmbH**
Oberkochen
Germany





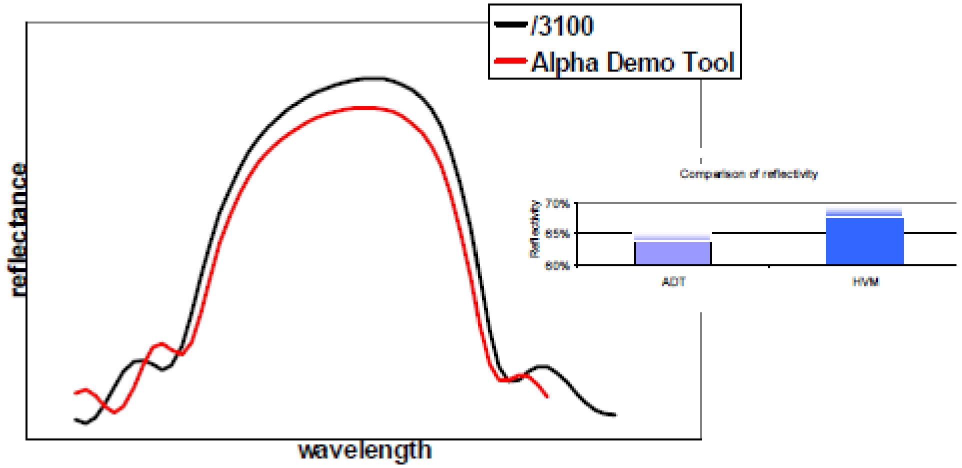
*Largest EUV ML optic to date successfully coated*

- *First real EUV optic from new large area EUV coating facility @ Zeiss*
- *Several new coating technologies successfully incorporated*
- *Lateral uniformity < 0.2%: within spec (0.3%)*
- *Reflectivity 67% (EUVR characterized)*

(2005)

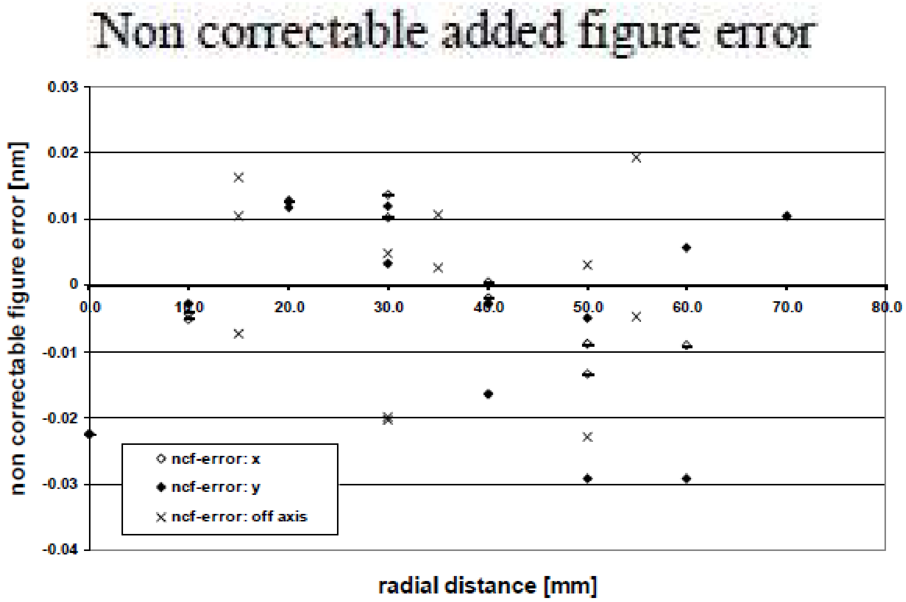
# Projection optics: towards to HVM

## Improvement since ADT



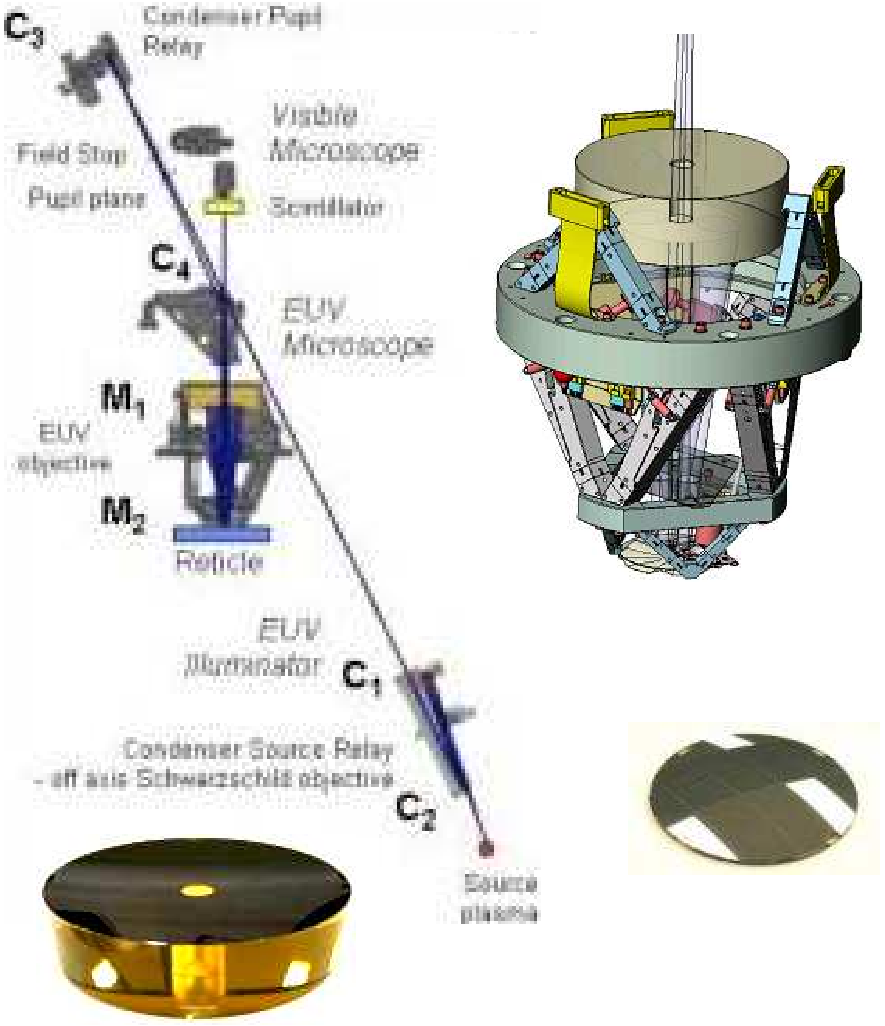
→ *69.7% Reflectance at local angle of incidence*

→ *~50% higher transmission of the PO-BOX*



*Coating added figure error less then 35 pm*
Spec is 100 pm

# Reticle Imaging Microscope (RIM, 2005)



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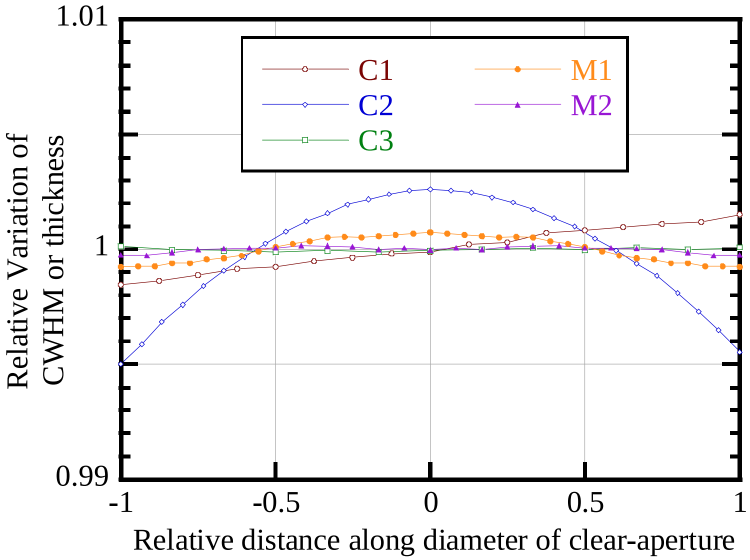
- 4 condensor (1 Ru, 3MoSi)
- 2 imaging (MoSi)
- Added Figure Error in imaging optics:
  - M1: 0.015nm
  - M2: <0.010nm



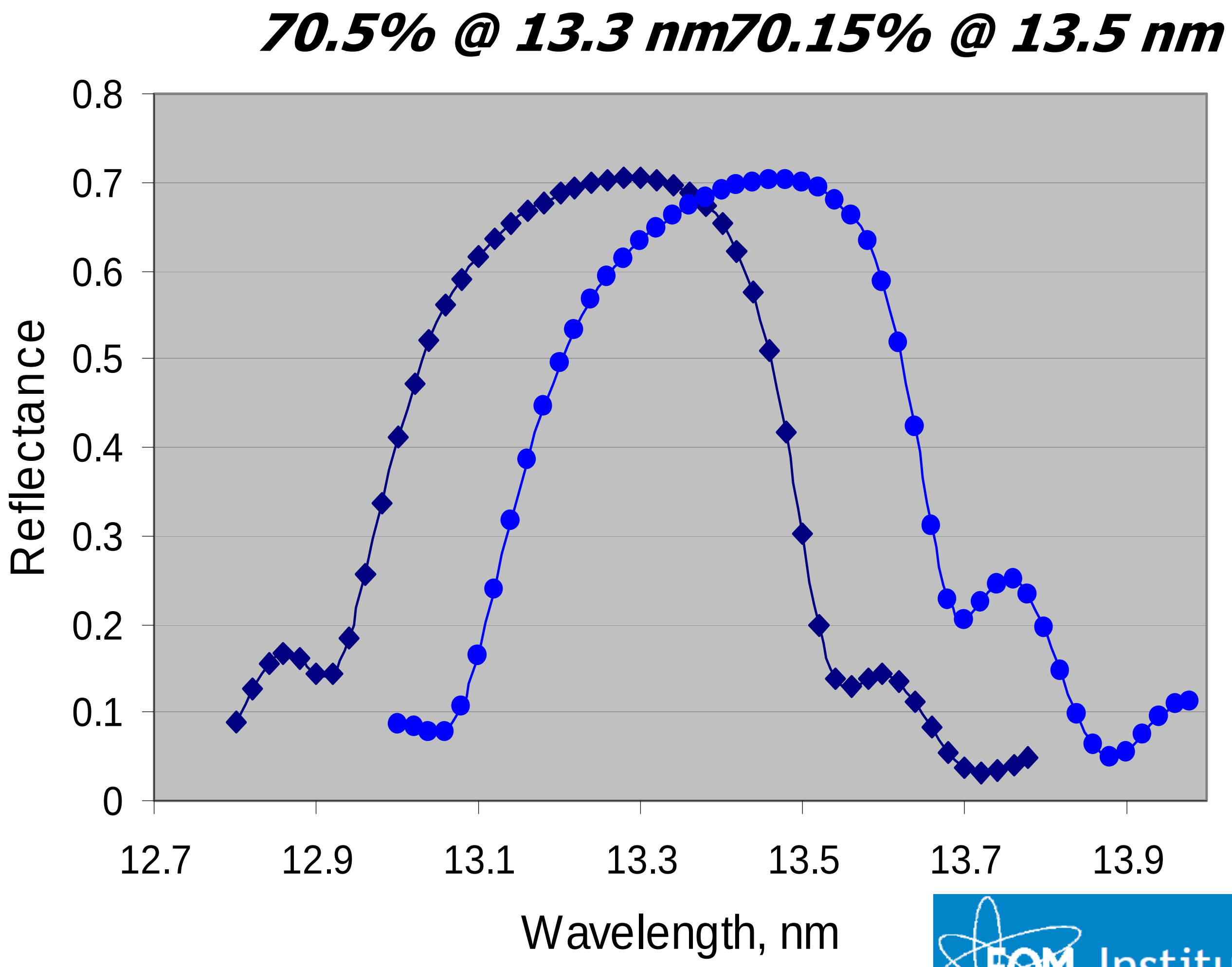
H.Glatzel et al. Characterization of prototype optical surfaces and coatings for the EUV Reticle Imaging Microscope, Proc. of SPIE, Vol. 5751 (2005), 1162 – 1169.

# Spec and achieved performance

| Application | Parameter | $\lambda_c$, nm | $\Delta\lambda_c$, nm | Rp, % | ΔRp, % | Stress, MPa | Defects, $cm^{-2}$ | Figure Error, nm rms |
|---|---|---|---|---|---|---|---|---|
| Mask blanks | Spec | ±0.030 (i) | ±0.025 (i) | ≥ 67 (a) | ±0.025 (a) | 200 (a) | < 0.003 (a) | |
| | Achieved | ±0.006 (b) | ±0.010 (b) | 67.1 (c) | ±0.025 (b) | 200-400 (b) | 0.05 at 56nm ( c) | |
| Collector | Spec | | ±0.05 (j) | | | | | |
| | Achieved | ±0.020 (j) | ±0.015 (j) | 65 (j) | ±5 (j) | | | |
| Illuminator | Spec | | ±0.014 | ≥ 67 (f) | ±1 (g) | 100 (a) | | |
| | Achieved | ±0.010 (d) | ±0.014 (e) | 69.1(f) | ±0.2 (g) | 35 (f) | | |
| Projection optics | Spec | | | ≥ 67 (f) | ±1.0 (g) | | | 0.0014 (f) |
| | Achieved | ±0.010 (d) | ±0.008 (d) | 69.1(f) | ±0.02 (g) | 35 (f) | | 0.0002 (f) |

# Best ML performance

# Maximum EUVL reflectivity - I



- *data PTB, Berlin*
- *1.5 degrees off-normal*
- *Diffusion barrier X at both interfaces*

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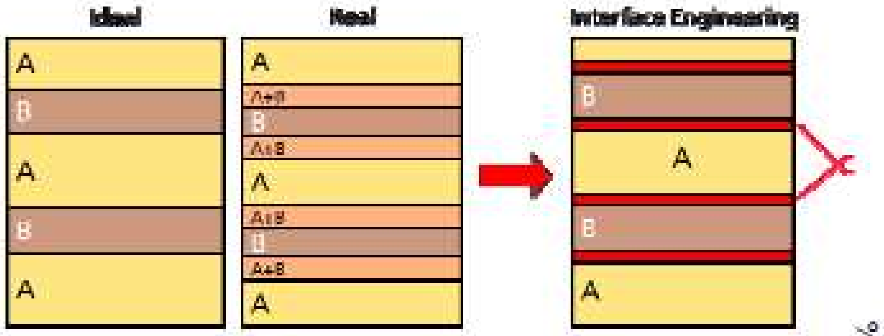
# Maximum EUVL reflectivity - II

$\lambda$ = 13.5 nm

Multilayer optics for EUV and beyond

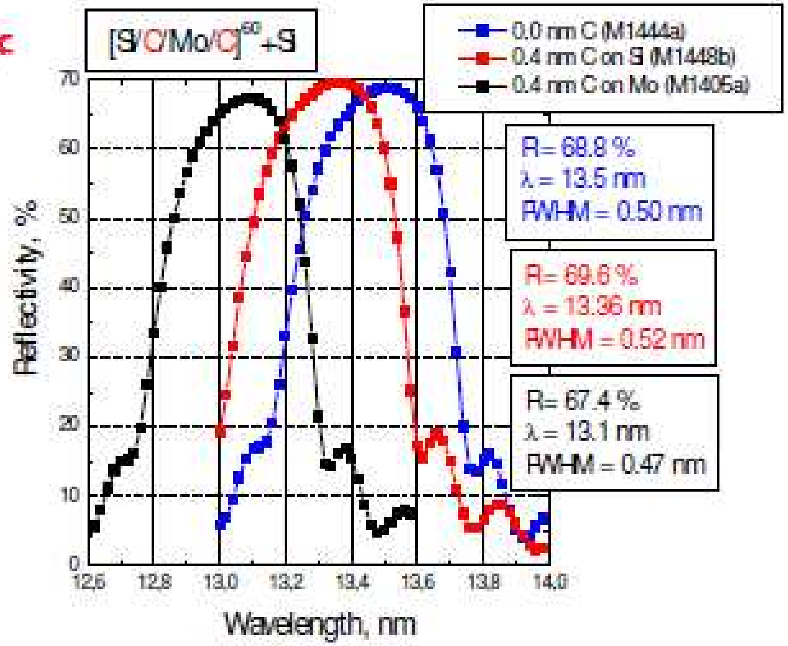
## Enhancement of Reflectivity by Interface Engineering



- Optimized Design: [Mo/Si/C]
- R (without C) = 68.8 %

**+ 0.8%**

- R (with C on Si) = 69.6 %



S. Yulin et al., "Interface-engineered EUV multilayer mirrors", MEE 83, 2006

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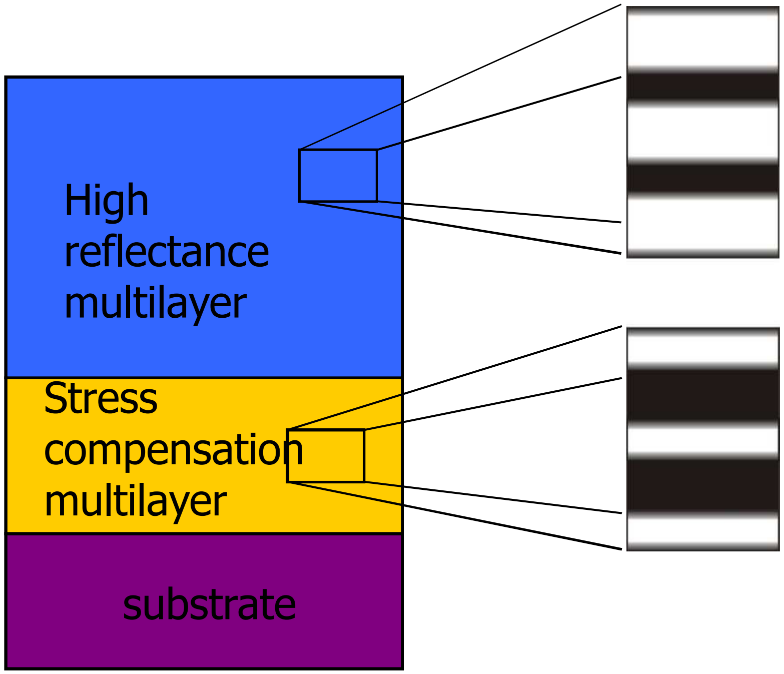
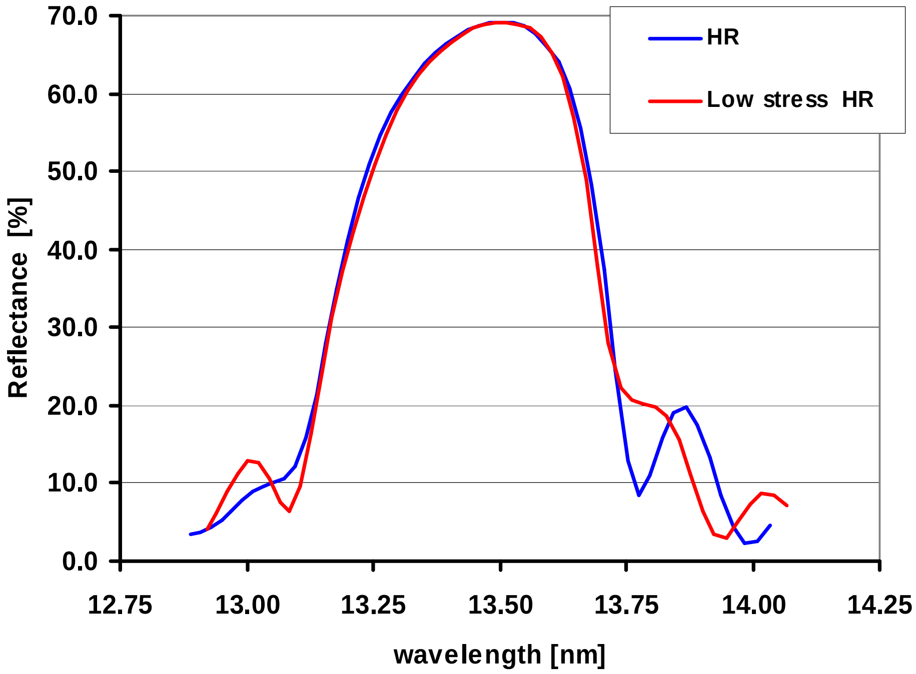
# Stress in ML coatings



P.B. Mirkarimi et al, Opt. Eng. 38, 1999

- *-200 MPa reduced to -30 MPa*



- *Stress compensation*
- *No effect on reflectance*
  *Erwin Zoethout et al, SPIE 5037, 2003*

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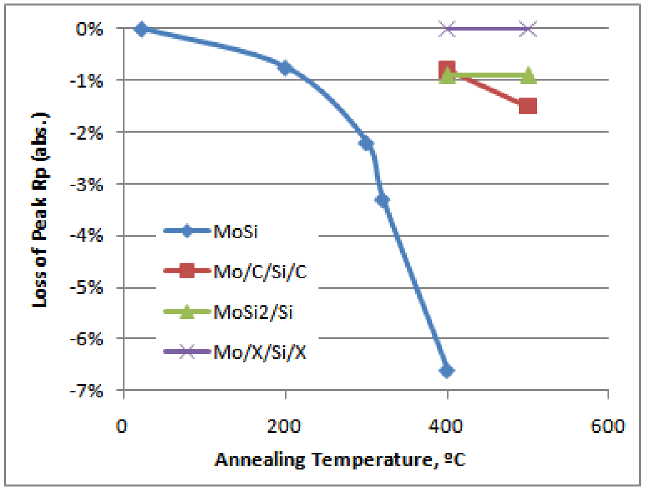
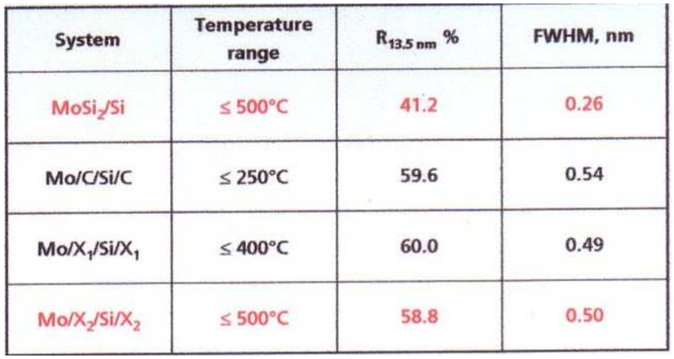
# ML stability

- Temperature stability
  - Barrier layers
- Radiation stability
  - Capping layer

# Temperature stability

## Reflectivity

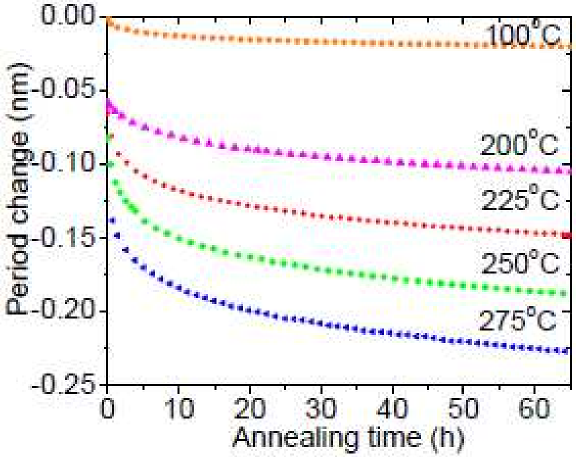




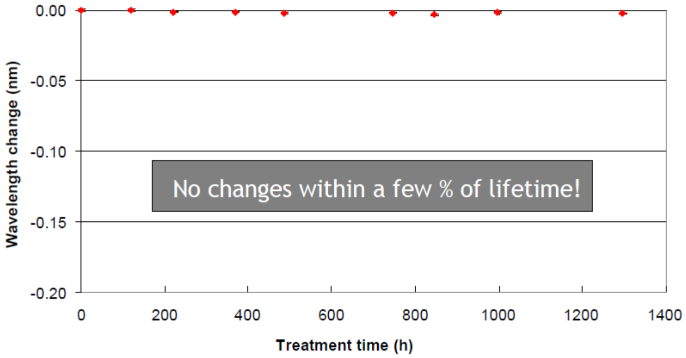
| System | Temperature range | $R_{13.5\,nm}$ % | FWHM, nm |
|---|---|---|---|
| $MoSi_2/Si$ | ≤ 500°C | 41.2 | 0.26 |
| Mo/C/Si/C | ≤ 250°C | 59.6 | 0.54 |
| $Mo/X_1/Si/X_1$ | ≤ 400°C | 60.0 | 0.49 |
| $Mo/X_2/Si/X_2$ | ≤ 500°C | 58.8 | 0.50 |

Mo/Si taken from: C. Montcalm, Eng. Opt. 40, 469 (2001)
others from: S. Yulin, SPIE 5751, 1155 (2005)

## Period



Solution: ***"Barrier stabilization"***



No changes within a few % of lifetime!

***High reflectance multilayers of EUVL HVM-projection optics***

E.D. van Hattum[1], S. Alonso van der Westen[1], P. Sallé[1], K.T. Grootkarzijn[1], E. Zoethout[1], R. van de Kruijs[1], E. Louis[1], S. Bruijn[1], J. Bosgra[1], A. Yakshin[1], G. von Blanckenhagen[2], H. Enkisch[2], S. Müllender[2], and F. Bijkerk[1,3]

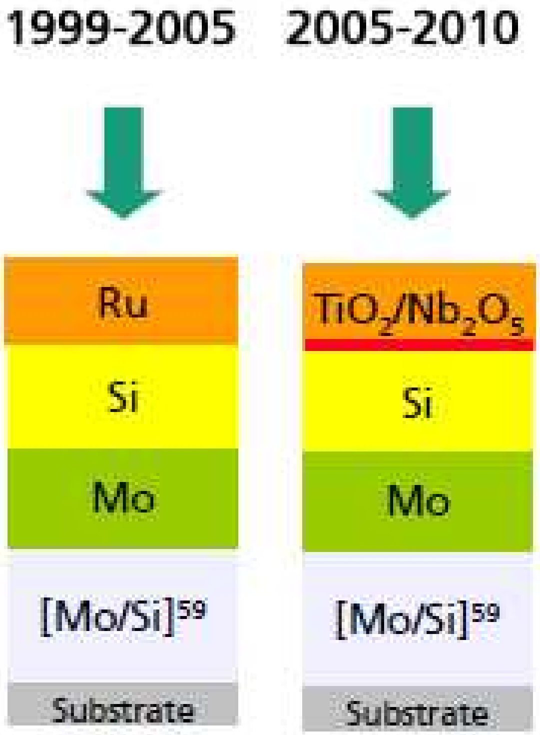
San Jose, 2010

# Radiation stability

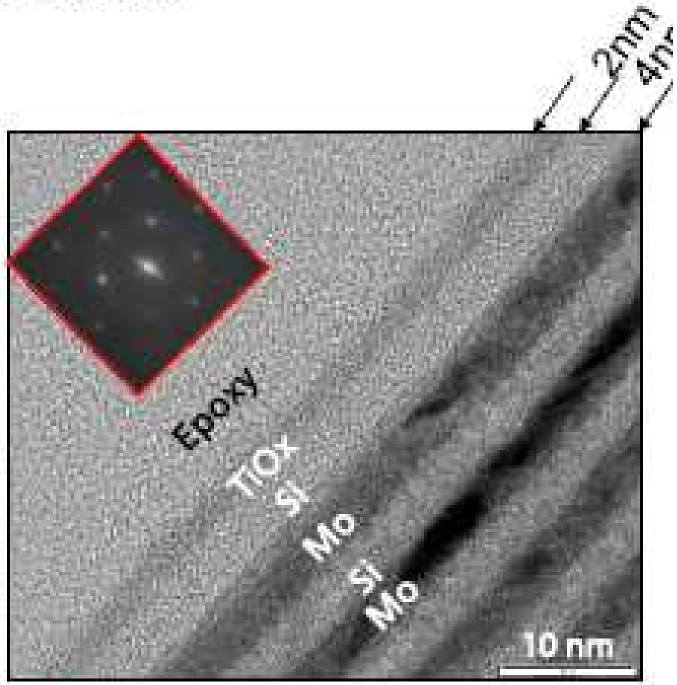
## Capping layers for EUV lithography optics protection

**Three conceptions:**

- Nobel metals (Ru, Au, Pt, Pd)
- Stable oxides ($RuO_2$, $TiO_2$, $Nb_2O_5$)
- Multilayer conception

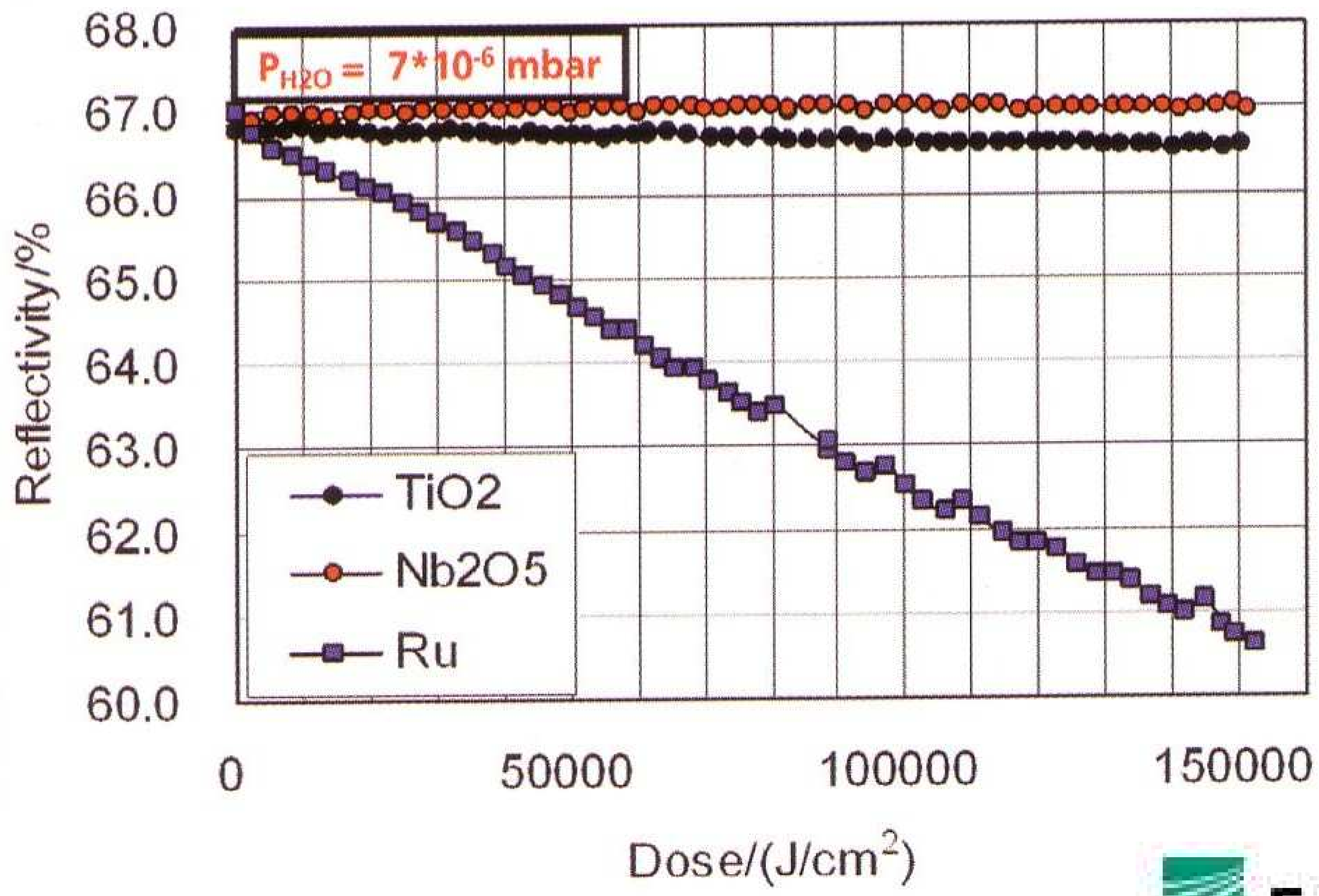


| 1999-2005 | 2005-2010 |
|---|---|
| Ru | $TiO_2/Nb_2O_5$ |
| Si | Si |
| Mo | Mo |
| $[Mo/Si]^{59}$ | $[Mo/Si]^{59}$ |
| Substrate | Substrate |



- Chemically inert to oxygen
- Good optical properties
- Amorphous structure
- Photo catalytic properties

# Radiation stability



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# Infrastructure

- Deposition facilities
- ML Performance Metrology
- Substrates

# ML deposition facilities

**Carl Zeiss SMT GmbH**
Ostalb, Region Ost-Württemberg, Baden-Württemberg
Rudolf-Eber-Str. 2
73447 Oberkochen
Germany

# EUVL multilayer coating development

**E. Louis, E. Zoethout, R.W.E. van de Kruijs, I. Nedelcu, A.E. Yakshin,**
**S. Alonso van der Westen, T. Tsarfati, and F. Bijkerk**
*FOM Institute for Plasma Physics Rijnhuizen, the Netherlands*
**H. Enkisch, G. Sipos, S. Müllender, and P. Kürz**
*Carl Zeiss SMT AG, Oberkochen, Germany*

(San Jose, 2005)

## *EUV application specific coating facility*

- Based on 'FOM coating process'
- Allows deposition of >500 mm optical diameters
- UHV conditions (4x$10^{-9}$ mbar)
- New ways of layer plasma treatment
- Improved layer thickness control (x-ray monitoring)
- Reflectance at 13.5 nm 67%
- Wavelength matching P/V 0.15%
- Lateral uniformity of periodicity P/V 0.12%

Van Loyen et al, SPIE Sta Clara (2003) ML5038-3

## *On-site EUV reflectometer*

- Up to 500 mm dia, 30 kg samples
- Reproducibility reflectance 0.5%, wavelength 0.01%

# FOM Institute
# for Plasma Physics
# Rijnhuizen,
# The Netherlands

Demounting of a batch of multilayer test samples
in one of the nSI UHV deposition systems
(photo by N. Steenkamp)

# FOM Institute Rijnhuizen

**Innovative Technologies**

Deposition equipment

Analysis equipment: High resolution, in-vacuum XPS, AES, SEM and STM

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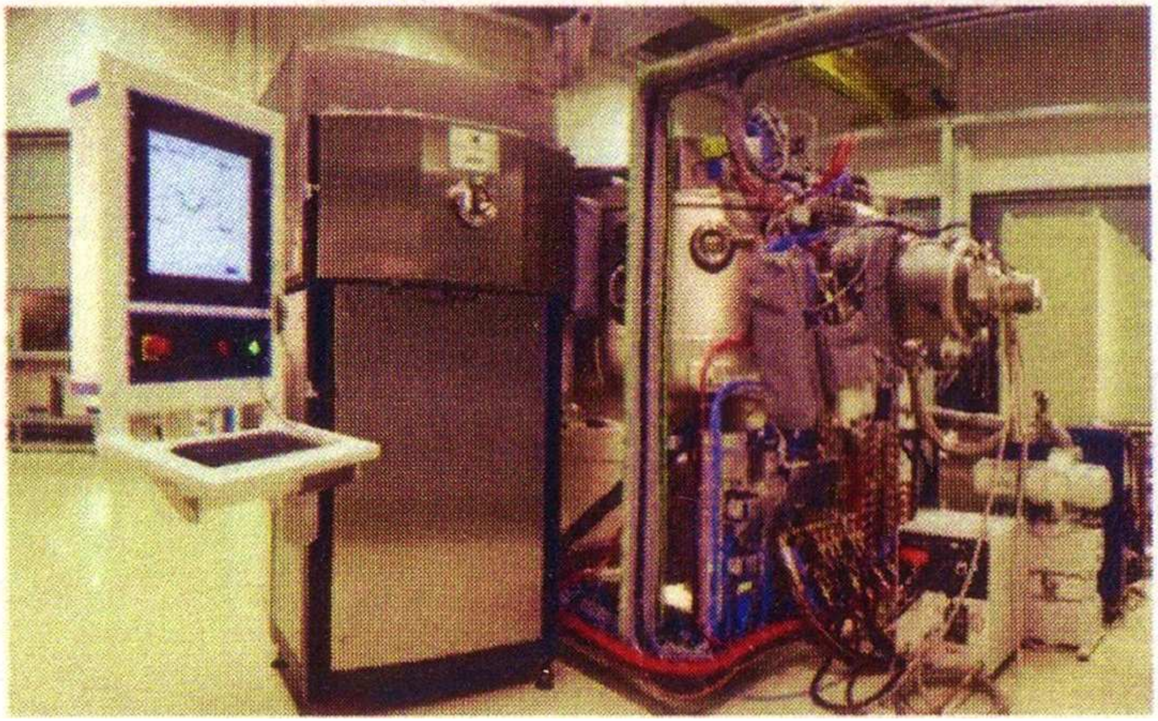
www.iof.fraunhofer.de

# Multilayer deposition

## Sputtering system NESSY-1



**Sputtering system Nessy 1**

| | |
|---|---|
| • base pressure: | $1*10^{-9}$ Torr |
| • work pressure: | 0.2 – 0.8 m Torr |
| • sample size: | D < 650 mm |
| • 4 magnetrons | dif. Barriers |
| | |
| • Thickness uniformity | 0.2% on 300 mm |
| • Reflectivity uniformity | ± 0.3 % (Mo/Si) |
| • Thickness gradient | ± 50% on 300 mm |
| • Load / unload system | |

Fraunhofer
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# Institute for Physics of Microstructures
# Russian Academy of Sciences

# IPM

## Nizhniy Novgorod
## Russia

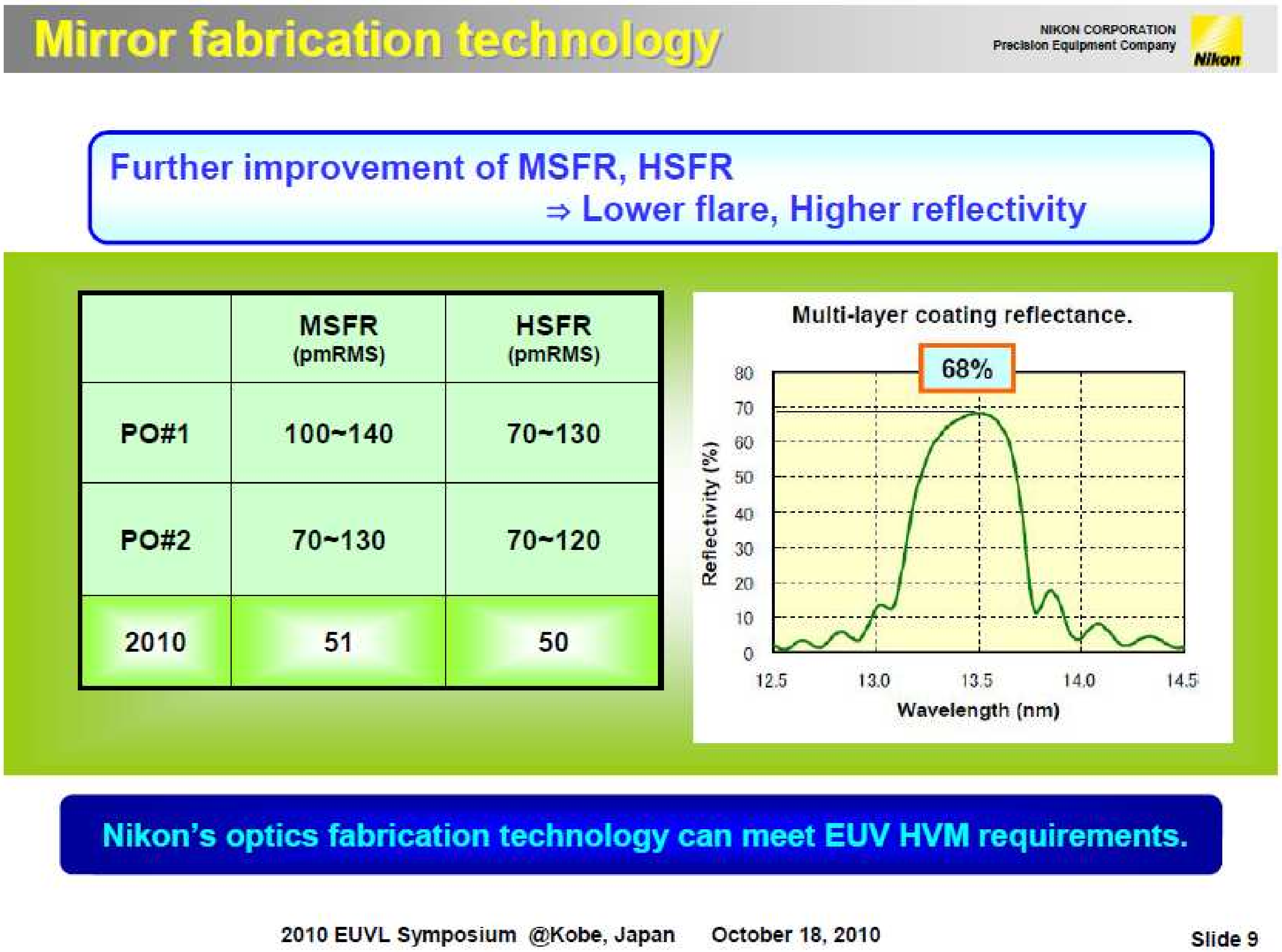
# ☐ Multilayer structures (technology; characterization)

Facility providing deposition of 6 different materials in one multilayer structure

Technological stand for deposition of MLSs by means of magnetron and ion-beam sputtering. It allows low energy ion polishing of each layer border and ion-beam assistant deposition

Reflectometer for reflectivity and transparency characterization of XEUV optics in a spectral range of 0.6 – 20 nm

Rigaku



# Mirror fabrication technology

NIKON CORPORATION
Precision Equipment Company

Further improvement of MSFR, HSFR
⇒ Lower flare, Higher reflectivity

| | MSFR (pmRMS) | HSFR (pmRMS) |
|---|---|---|
| **PO#1** | 100~140 | 70~130 |
| **PO#2** | 70~130 | 70~120 |
| **2010** | 51 | 50 |

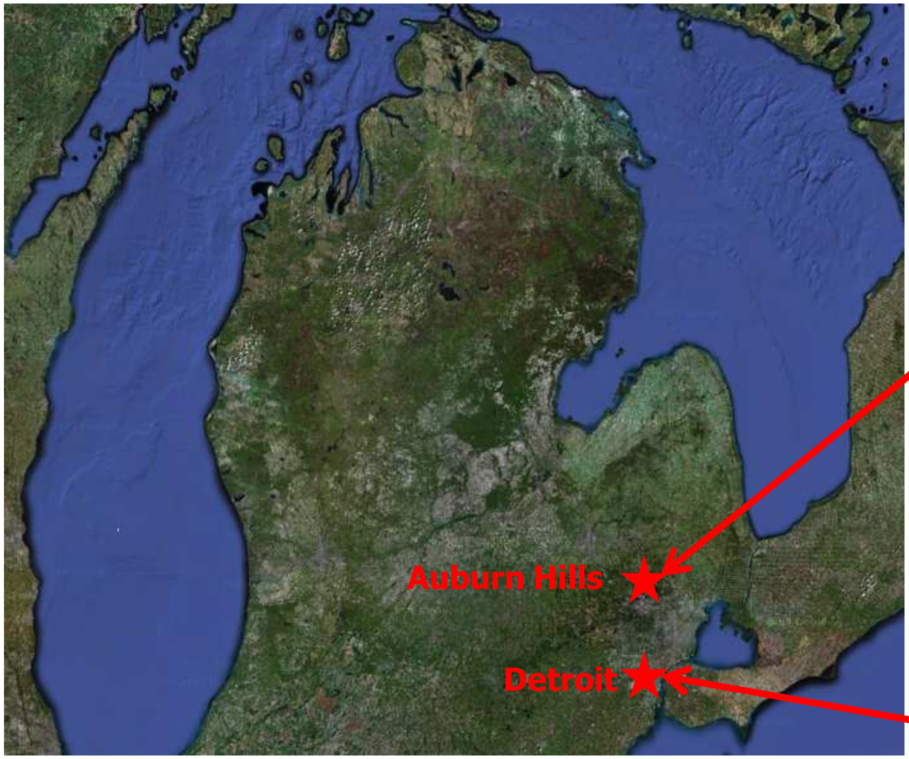
Multi-layer coating reflectance.

**Nikon's optics fabrication technology can meet EUV HVM requirements.**

2010 EUVL Symposium @Kobe, Japan October 18, 2010

Slide 9

# RIT in Auburn Hills, Michigan



RIT Facility

18 hole golf course

# RIT, Auburn Hills, USA

- **Inline Magnetron**
- **7 Carousel Magnetrons**
- **Ion Beam**
- **Class100 cleanroom with class 10 miniroom**
  - Load-locked
  - 5 planar magnetrons
  - 4 process gases
  - 500 x 1500mm carrier
  - 0.2mm accuracy

- **Wavelength Range**
  $\lambda$ = 0.2Å – 300Å
  E = 40eV – 60keV
- **Multilayer Period**
  $d_{min}$ = 10Å
- **Number of Period**
  $N_{max}$ = 1000
- **Spectral Resolution**
  $\Delta\lambda/\lambda$ = 0.2% (high-selective)
  20% (depth-graded)
- **Size**:
  ~3mm to 1.5 meter

- **Materials**
  W/Si, W/C, Ni/Ti, Ni/$B_4C$, Ni/C, Cr/C, Cr/Sc, Mo/Si, Mo/$B_4C$, La/B, V/C, Ru/$B_4C$, $Al_2O_3$/$B_4C$, SiC/Si, Si/C, SiC/C, Fe/Si, Cr/$B_4C$, Si/$B_4C$, W/$Mg_2Si$, V/$B_4C$, Ti/$B_4C$, etc.
- **Design**
  Uniform or Graded: lateral, radial, bilateral (2D)
  Depth Graded: supermirror & high-selective
  Flat or Curved
  Glancing (<1°) to Normal

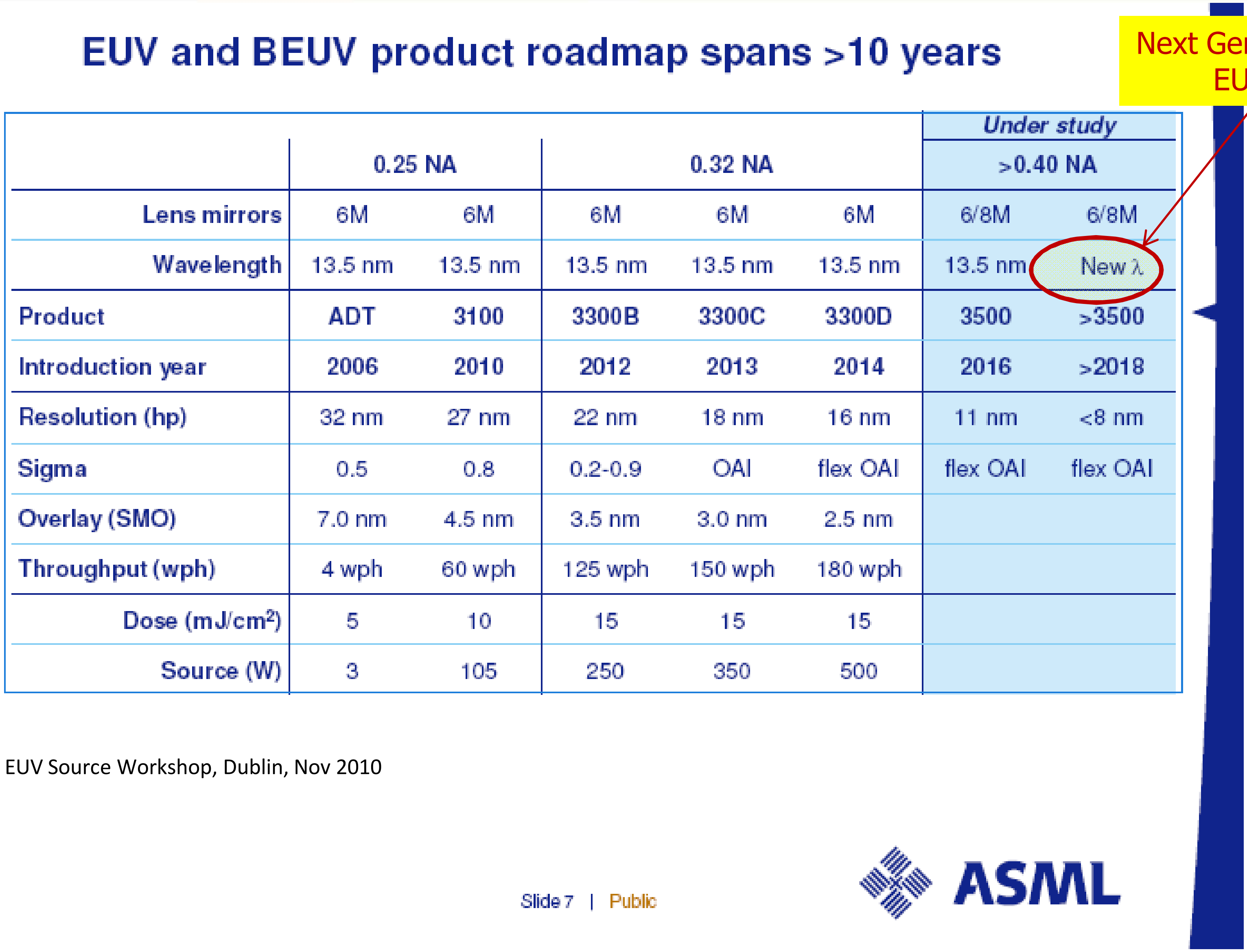
# ML reflectivity metrology

# Optics Reflectometry @ 13.5nm

- **Gullikson (CXRO) paper in SPIE 4343 (2001).** (Dmax~200mm, L~400mm)
  $\lambda_C$ precision: 0.01% $\lambda_C$ accuracy: 0.03%
  Rp precision: 0.12% Rp accuracy: 0.50%
- **S.Grantham (NIST) (2011).** (Dmax~450mm)
  median lambda uncertainty: ±0.10% ($2\sigma$) of the median
  peak reflectivity uncertainty: ±0.25% ($2\sigma$) absolute
- **F. Scholze (PTB) paper in SPIE 5751, 749 (2005).** (Dmax >660mm)
  $\lambda_C$: 0.0075% week-to-week accuracy; Rp: ±0.1% rms
  reproducibility: $\lambda c = \pm 0.0008$nm $1\sigma$ or ±0.006% $1\sigma$, Rp = ±0.11% $1\sigma$
- **New Subaru (2010).** (Dmax~200mm)
  λc: 0.004nm, R: 0.05%, fwhm: 0.001nm
- **Zeiss (2005).** (Dmax~500mm)
- **International Intercomparison (2003?)**
  $\lambda_C$: 0.03% agreement b/w CXRO/PTB; 0.029% b/w CXRO/New Subaru
  Rp: 0.13% agreement b/w CXRO/PTB; 0.05% b/w CXRO/New Subaru

# Multilayers for next generation EUVL at 6.7nm

# Next generation EUVL



## EUV and BEUV product roadmap spans >10 years

| | | | | | | Under study | |
|---|---|---|---|---|---|---|---|
| | 0.25 NA | | 0.32 NA | | | >0.40 NA | |
| Lens mirrors | 6M | 6M | 6M | 6M | 6M | 6/8M | 6/8M |
| Wavelength | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | 13.5 nm | New λ |
| Product | ADT | 3100 | 3300B | 3300C | 3300D | 3500 | >3500 |
| Introduction year | 2006 | 2010 | 2012 | 2013 | 2014 | 2016 | >2018 |
| Resolution (hp) | 32 nm | 27 nm | 22 nm | 18 nm | 16 nm | 11 nm | <8 nm |
| Sigma | 0.5 | 0.8 | 0.2-0.9 | OAI | flex OAI | flex OAI | flex OAI |
| Overlay (SMO) | 7.0 nm | 4.5 nm | 3.5 nm | 3.0 nm | 2.5 nm | | |
| Throughput (wph) | 4 wph | 60 wph | 125 wph | 150 wph | 180 wph | | |
| Dose ($mJ/cm^2$) | 5 | 10 | 15 | 15 | 15 | | |
| Source (W) | 3 | 105 | 250 | 350 | 500 | | |

Slide 7 | Public

ASML

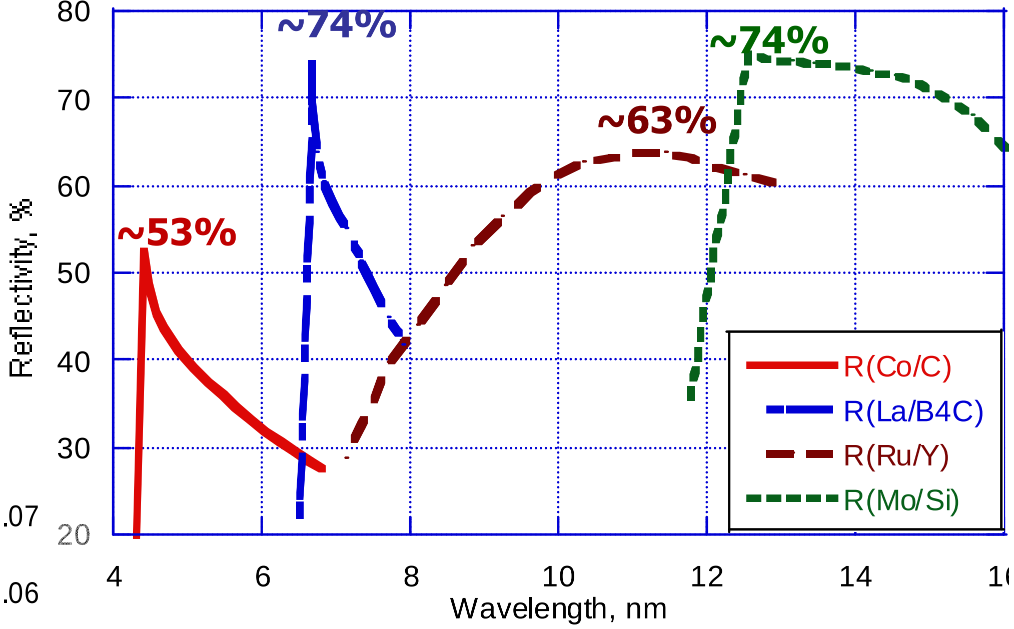
Next Generation EUVL

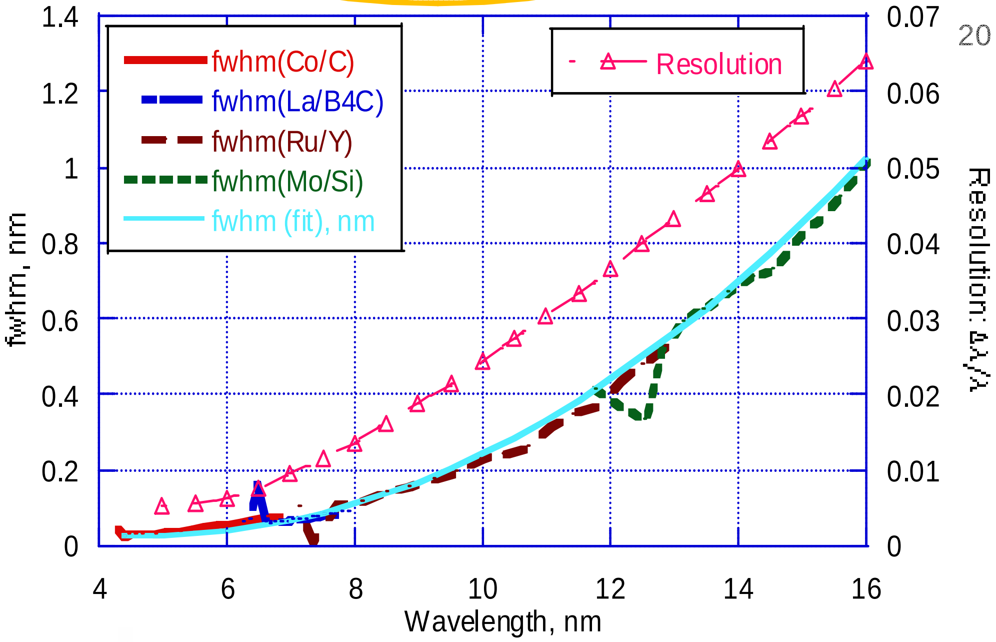
EUV Source Workshop, Dublin, Nov 2010

# Why 6.X nm: ML reflectivity

**Maximum peak reflectivity of multilayers in the wavelength range from 4nm to 16nm is expected to be at ~13.5nm and ~6.6nm**

Reflectivity





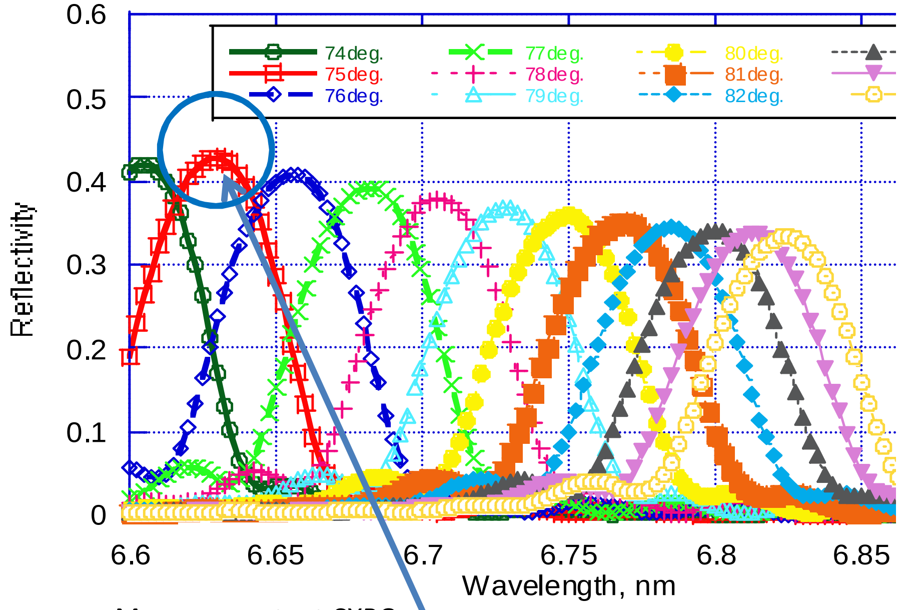
$$\Delta\lambda = 0.20523 - 0.075113\cdot\lambda + 0.0078905\cdot\lambda^2$$

**Shorter wavelength** ⇨ **Narrower reflectivity curve**

Rigaku

# Wavelength of maximum reflection

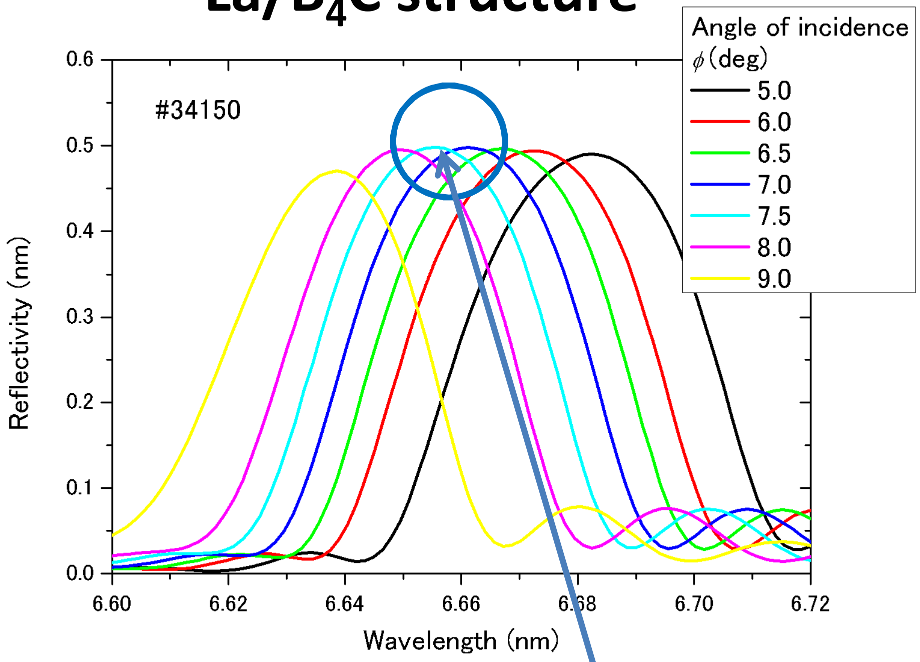
## $La_2O_3/B_4C$ structure



Measurements at CXRO,
March 2011

**R(max)=42.8% at ~6.63nm**

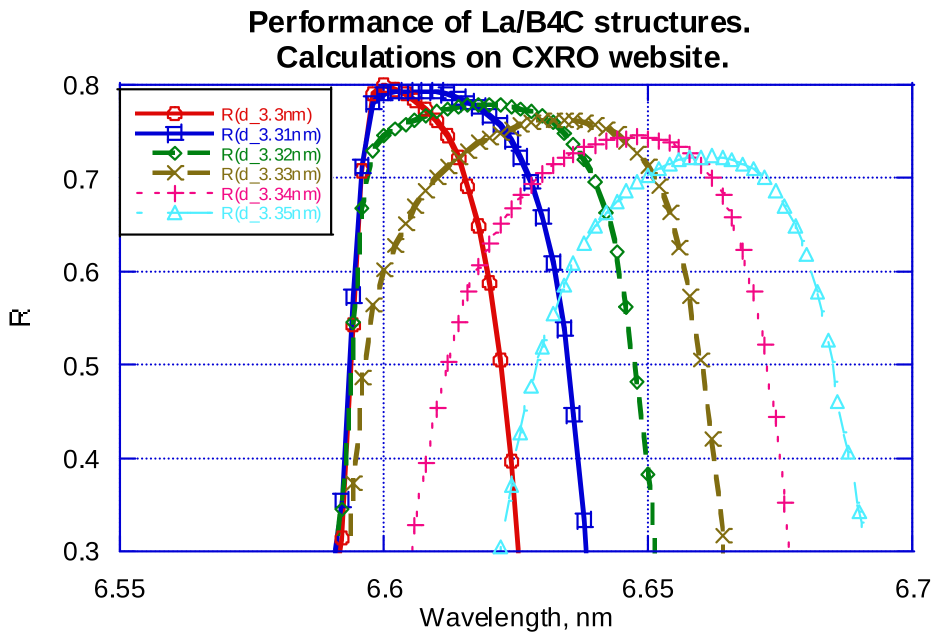
## $La/B_4C$ structure

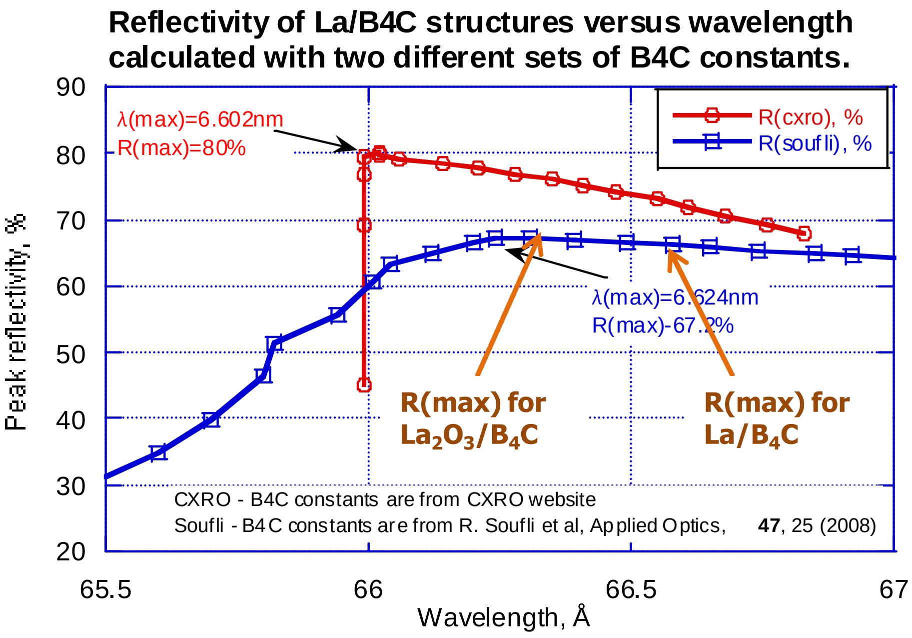


Measurements at New Subaru,
May, 2011

**R(max)=49.83% at ~6.656nm**

# Optical constants and maximum reflectivity


Performance of La/B4C structures. Calculations on CXRO website.


Reflectivity of La/B4C structures versus wavelength calculated with two different sets of B4C constants.

CXRO - B4C constants are from CXRO website
Soufli - B4C constants are from R. Soufli et al, Applied Optics, **47**, 25 (2008)

# Is today's ML deposition technology ready for HVM?

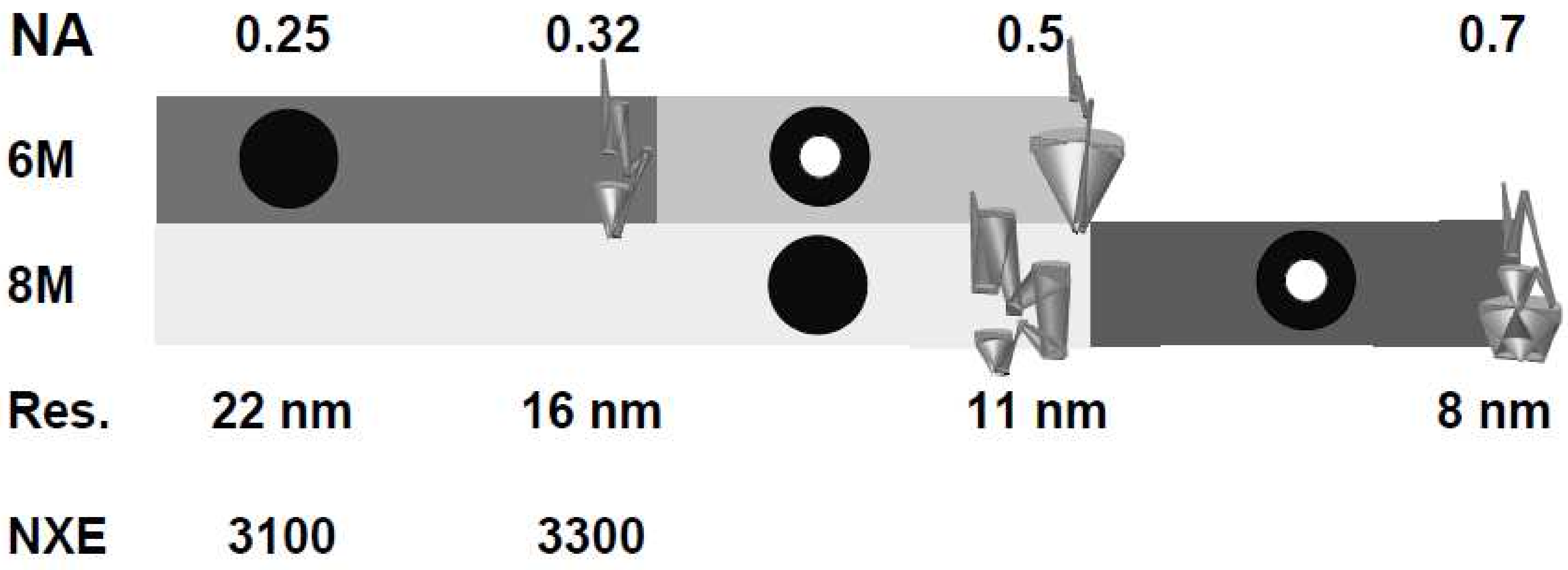
# MLO Supply Readiness – Pre-HVM (NXE3100-3300)

| Application | Coatings | Substrates |
|---|---|---|
| Collector Optics | √ | √ |
| Illumination Optics | √ | √ |
| Projection Optics | √ | √ |
| Mask Blank | √ | √ |
| Metrology Optics | √ | √ |

Largely internalized supply (with Institutional support & supply) covers small number of tool shipments; scanners, sources, limited scope for metrology tool development

# Designs for current and future tools

Solution overview:



NA 0.25 0.32 0.5 0.7

6M

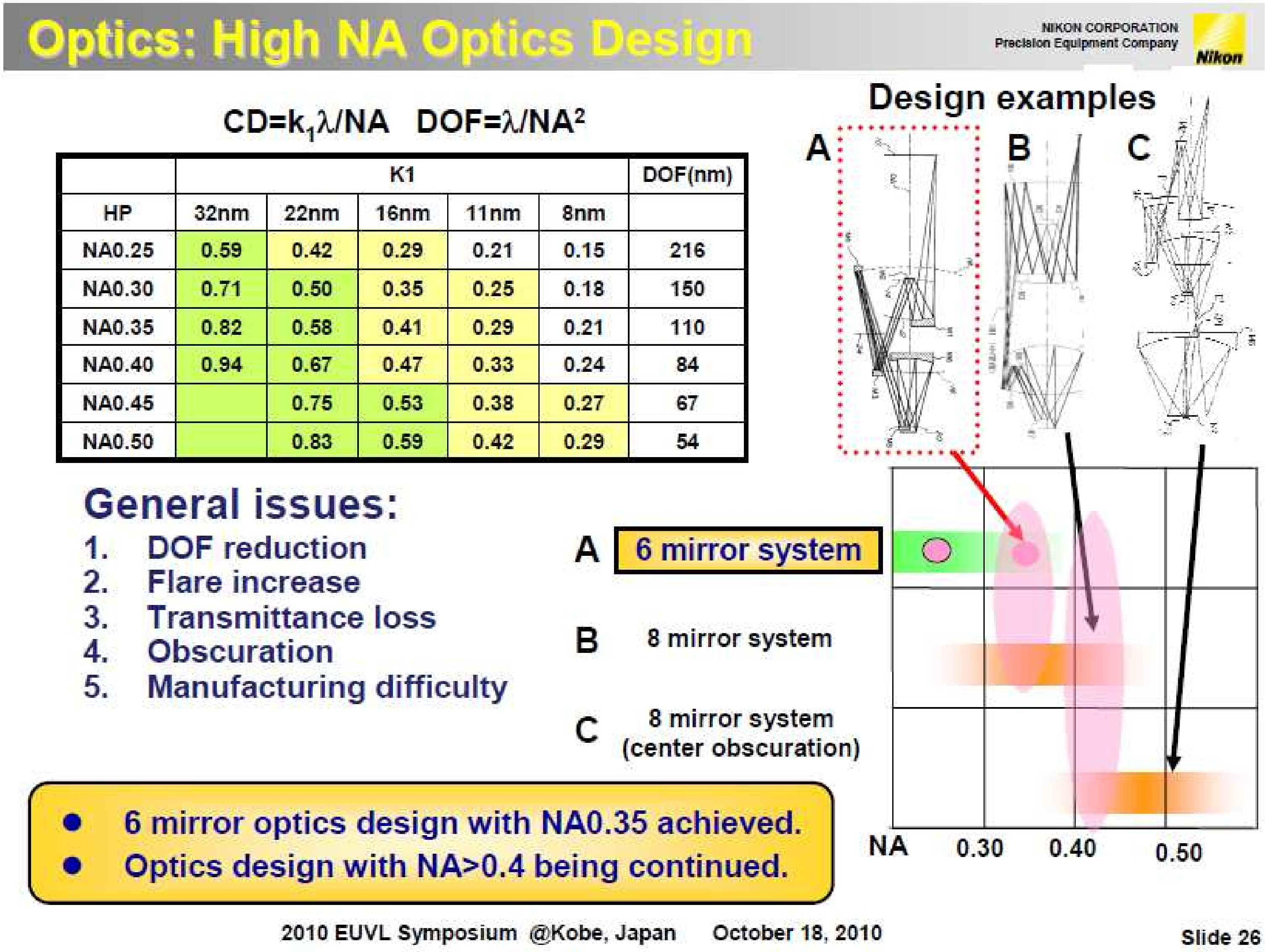
8M

Res. 22 nm 16 nm 11 nm 8 nm

NXE 3100 3300

● unobscured ◉ centrally obscured

Extreme Ultraviolet (EUV) Lithography, edited by Bruno M. La Fontaine, Proc. of SPIE Vol. 7636, 763603 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.848624



# Optics: High NA Optics Design

NIKON CORPORATION
Precision Equipment Company

$CD=k_1\lambda/NA \quad DOF=\lambda/NA^2$

| | K1 | | | | | DOF(nm) |
|---|---|---|---|---|---|---|
| HP | 32nm | 22nm | 16nm | 11nm | 8nm | |
| NA0.25 | 0.59 | 0.42 | 0.29 | 0.21 | 0.15 | 216 |
| NA0.30 | 0.71 | 0.50 | 0.35 | 0.25 | 0.18 | 150 |
| NA0.35 | 0.82 | 0.58 | 0.41 | 0.29 | 0.21 | 110 |
| NA0.40 | 0.94 | 0.67 | 0.47 | 0.33 | 0.24 | 84 |
| NA0.45 | | 0.75 | 0.53 | 0.38 | 0.27 | 67 |
| NA0.50 | | 0.83 | 0.59 | 0.42 | 0.29 | 54 |

Design examples

## General issues:

1. DOF reduction
2. Flare increase
3. Transmittance loss
4. Obscuration
5. Manufacturing difficulty

A 6 mirror system

B 8 mirror system

C 8 mirror system
(center obscuration)

- 6 mirror optics design with NA0.35 achieved.
- Optics design with NA>0.4 being continued.

2010 EUVL Symposium @Kobe, Japan October 18, 2010

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# MLO Supply Readiness – HVM (NXE3500 and beyond, + New Entrants)

| Application | Coatings | Substrates |
|---|---|---|
| Collector Optics | √a) | √a) |
| Illumination Optics | √b) | √b) |
| Projection Optics | √b) | √b) |
| Mask Blank | √c) | √c) |
| Metrology Optics | √d) | √d) |

**a) What is the required volume in HVM? When needed?**
**b) There is no published spec for higher NA optics**
**c) There are still added coating defects**
**d) There is currently no supplier of metrology tools**

# Conclusion

- MLO technology for 13.5 nm is sufficiently developed to support pre-HVM deployment(s). Deposition of higher NA optics for HVM will require further development.

- For the Next Generation EUVL, the choice of light source fuel and multilayer materials is still in R&D feasibility phase.

- The establishment of multilayer optics infrastructure based on proven low volume manufacturing is, in principal extendable and scalable to HVM.

# Acknowledgement

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# Thank you

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