EUVリソグラフィの課題

兵庫県立大学
高度産業科学技術研究所
極端紫外線リソグラフィ研究開発センター
渡邊健夫

概要

1．半導体市場動向と半導体国際ロードマップ

2．EUVリソグラフィの露光波長

3．EUVリソグラフィの歴史

4．EUVリソグラフィの課題
　　レジストの線幅バラツキの低減

5．Beyond EUVL

6．まとめ

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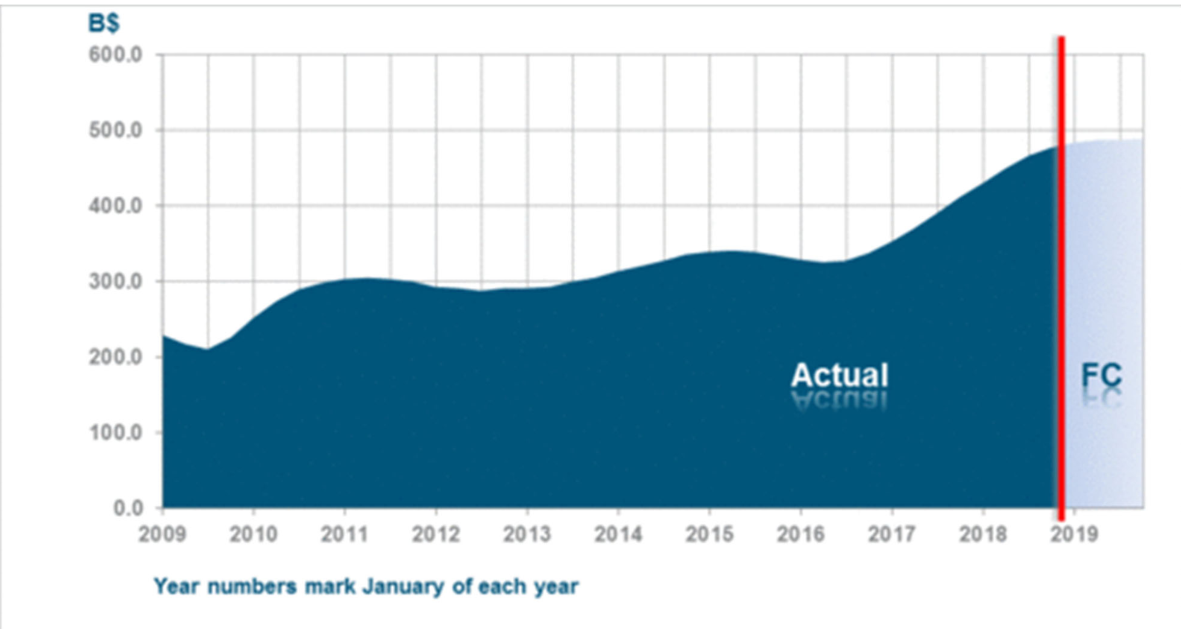
WSTS（WORLD SEMICONDUCTOR TRADE STATISTICS：世界半導体市場統計）
加盟：半導体メーカは45社
Market was up 13.7% in 2018 to US$468.8 billion, an all-time high.
The year 2019 is forecasted to be down 3.0% to US$454.5 billion.



WSTS Forecast Summary

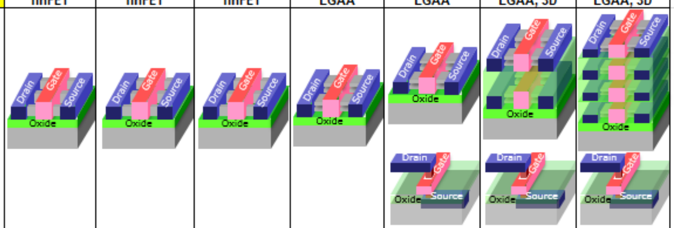
By replacing the Q4 2018 forecast figures with Q4 2018 actual results, the forecast of the annual growth rates is updated from the 2018 Fall Forecast, published on November 27, 2018.

Autumn 2018 - Q4 Update	Amounts in US$M			Year on Year Growth in %		
	2017	2018	2019	2017	2018	2019
Americas	88,494	**102,997**	**97,021**	35.0	16.4	-5.8
Europe	38,311	**42,957**	**42,824**	17.1	12.1	-0.3
Japan	36,595	**39,961**	**40,351**	13.3	9.2	1.0
Asia Pacific	248,821	**282,863**	**274,350**	19.4	13.7	-3.0
Total World - $M	412,221	**468,778**	**454,547**	21.6	13.7	-3.0
Discrete Semiconductors	21,651	**24,102**	**24,776**	11.5	11.3	2.8
Optoelectronics	34,813	**38,032**	**38,611**	8.8	9.2	1.5
Sensors	12,571	**13,356**	**13,899**	16.2	6.2	4.1
Integrated Circuits	343,186	**393,288**	**377,261**	24.0	14.6	-4.1
Analog	53,070	58,785	61,083	10.9	10.8	3.9
Micro	63,934	67,233	68,513	5.5	5.2	1.9
Logic	102,209	109,303	112,109	11.7	6.9	2.6
Memory	123,974	157,967	135,557	61.5	27.4	-14.2
Total Products - $M	412,221	**468,778**	**454,547**	21.6	13.7	-3.0

Note: Numbers in the table are rounded to whole millions of dollars, which may cause totals by region and totals by product group to differ slightly.

IRDS 2018 Device, PPA, and Ground Rules Roadmap for Logic Devices

YEAR OF PRODUCTION	2018	2020	2022	2025	2028	2031	2034
	G54M36	G48M30	G45M24	G42M21	G40M16	G40M16T2	G40M16T4
Logic industry "Node Range" Labeling (nm)	"7"	"5"	"3"	"2.1"	"1.5"	"1.5"	"1.5"
IDM-Foundry node labeling	i10-f7	i7-f5	i5-f3	i3-f2.1	i2.1-f1.5	i2.1-f1.5	i2.1-f1.5
Logic device structure options	FinFET	finFET	finFET LGAA	LGAA	LGAA VGAA	3DVLSI VGAA	3DVLSI VGAA
Mainstream device for logic	finFET	finFET	finFET	LGAA	LGAA	LGAA, 3D	LGAA, 3D



LOGIC DEVICE GROUND RULES	2018	2020	2022	2025	2028	2031	2034
Mx pitch (nm)	40	36	32	24	20	16	16
M1 pitch (nm)	36	32	30	21	20	20	20
M0 pitch (nm)	36	30	24	21	16	16	16
Gate pitch (nm)	54	48	45	42	40	40	40
L_g: Gate Length - HP (nm)	20	18	16	14	12	12	12
Lg: Gate Length - HD (nm)	22	20	18	14	12	12	12
Channel overlap ratio - two-sided	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Spacer width (nm)	8	7	6	6	6	6	6
Contact CD (nm) - finFET, LGAA	18	16	17	16	16	16	16
Contact CD (nm) - VGAA							
Device architecture key ground rules							
FinFET pitch (nm)	32.0	28.0	24.0				
FinFET Fin width (nm)	8.0	7.0	6.0				
FinFET Fin height (nm)	40	50	60				
Footprint drive efficiency - finFET	2.75	3.82	5.25				
Lateral GAA lateral pitch (nm)				22.0	20.0	20.0	20.0
Lateral GAA vertical pitch (nm)				18.0	16.0	14.0	14.0
Lateral GAA (nanosheet) thickness (nm)				7.0	6.0	5.0	5.0
Number of vertically stacked nanosheets				3	3	4	4
LGAA width (nm) - HP				25	20	15	10
LGAA width (nm) - HD				15	11	6	6
LGAA width (nm) - SRAM				7	6	6	6
LGAA total height (nm)				53	48	57	57
Footprint drive efficiency - lateral GAA - HP				4.80	4.59	5.52	5.00
Device effective width (nm) - HP	88.0	107.0	126.0	192.0	156.0	160.0	120.0
Device effective width (nm) - HD	88.0	107.0	126.0	132.0	102.0	88.0	88.0
Device lateral pitch (nm)	32	28	24	22	20	20	20
Device height (nm)	40.0	50.0	60.0	53.0	48.0	57.0	57.0
Device width (nm) - HP	8	7	6	25	20	15	10
Device width (nm) - HD	8	7	6	15	11	6	6
Device width (nm) - SRAM	8	7	6	7	6	6	6

Acronyms used in the table (in order of appearance): FDSOI: Fully-Depleted Silicon-On-Insulator (FDSOI), LGAA: Lateral Gate-All-Around-Device (GAA), VGAA: Vertical GAA, 3DVLSI: Fine-pitch 3D logic sequential integration.

Difficult Challenges 2019 Draft V2

Next Generation Technology	First Possible Use in Mfg.	22Feature Type	Device Type	Key Challenges	Required Date for Decision making
EUV Single Patterning	2018	22 to 24 nm hp CH/Cut Levels back end metals at 18nm hp LS	"7nm" Logic Node	-Pellicle -Actinic mask patterned mask inspection -Resist speed combined with LER and Stochastics -shot noise	Product Evaluation Completed
EUV Double Patterning	2022	12nm hp LS	"3nm" Logic Node	-Tolerance, EPE, and Overlay	2021
EUV high NA	2025	10.5nm hp LS	"2.1nm" Logic Node	-Stitching of two mask patterns -Shot noise	2024
EUV new wavelength	2028 ?	8nm hp LS ?	"1.5nm" Logic Node	-EUV source power -Resist material -Actinic blank and patterned mask inspection	2030
NanoImprint	2019	20 nm lines and spaces 20 to 30nm contact holes	3D Flash Memory	-Defectivity -Overlay -Master Template fabrication and inspection <20nm -Defect repair -Mass-production capacity	Product Evaluation Completed
DSA (for pitch multiplication)	2022	Contact hokes/cut levels for logic. Possibly nanowire patterning	"3nm" Logic Node	-Pattern Placement -Defectivity and defect inspection -Design -3D Metrology	2021

Work in Progress: Not for Distribution

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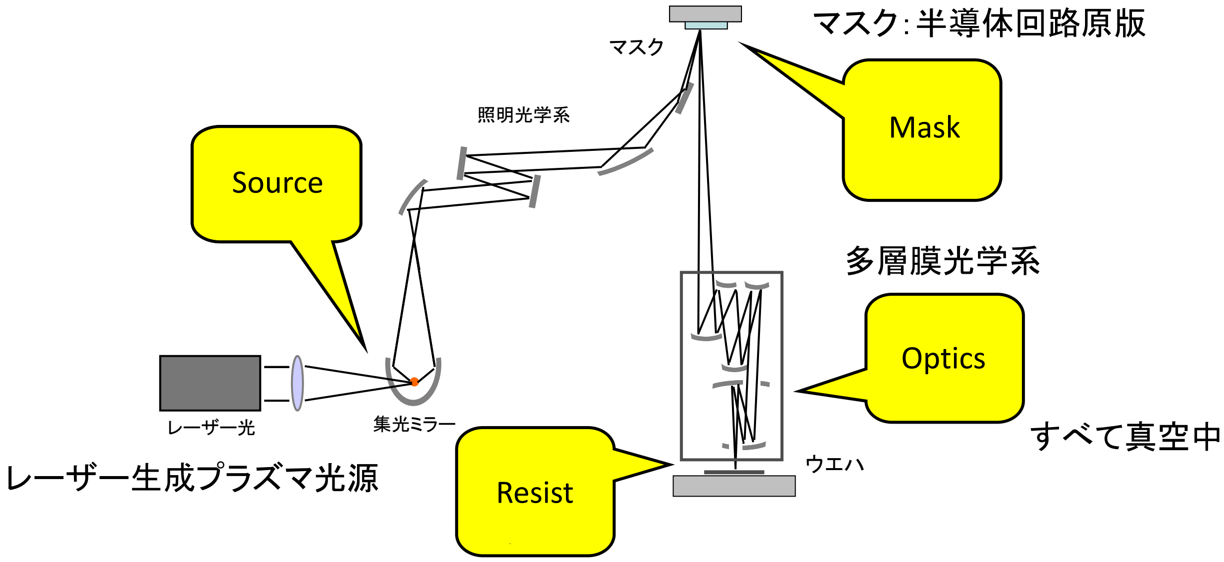
EUVリソグラフィー装置の構成概要



オランダ:ASML社
NXE, HVM tool

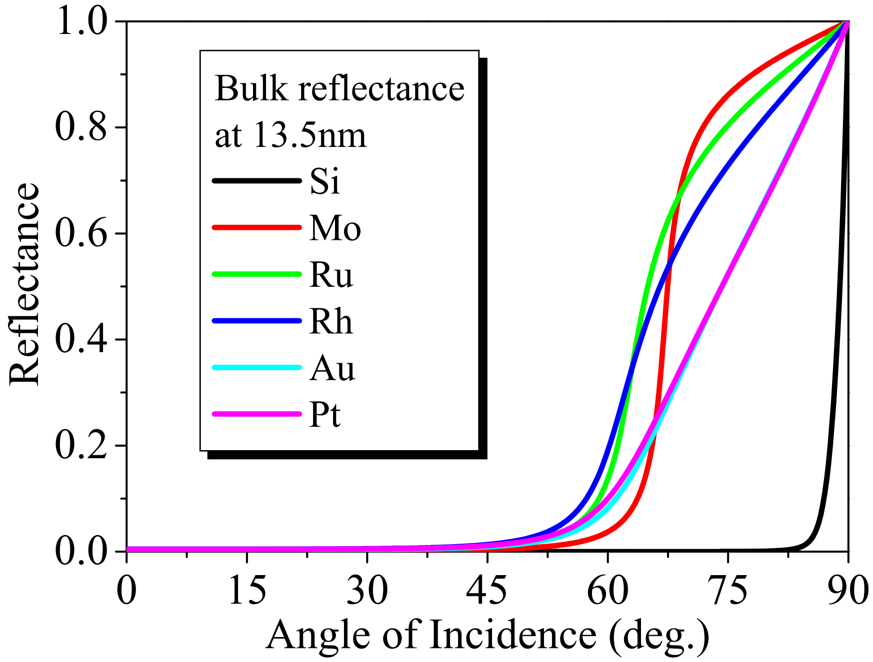
2019年度Samsung, TSMC
EUVリソグラフィーによる半導体量産

光学素子はすべて多層膜でコーティングされている。
- 照明光学系4枚
- マスク1枚
- 結像光学系6枚

11枚

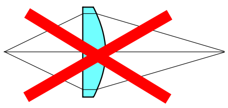
背景：軟X線とその利用

EUV領域における反射率の入射角依存性

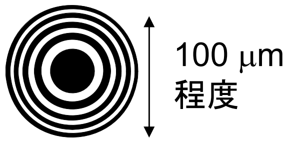


単層膜の直入射反射率は0.1%以下で、光学系の構築に工夫が必要

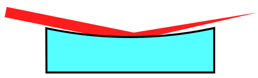
背景：軟X線光学系の比較



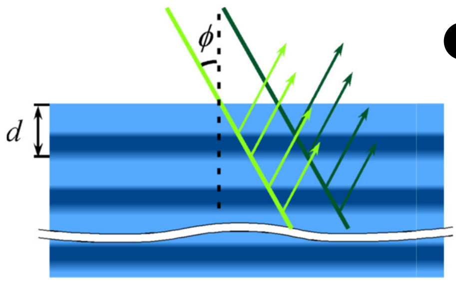
● 屈折光学系は原理的に使えない。
物質の屈折率≈1



● 回折を利用したゾーンプレート
ペンシルビームの放射光に適しているが、視野が数µmと狭く、回折効率が低い。
集光には適している。



● 全反射を利用した斜入射光学系
大きな開口数と低収差は両立が難しい。

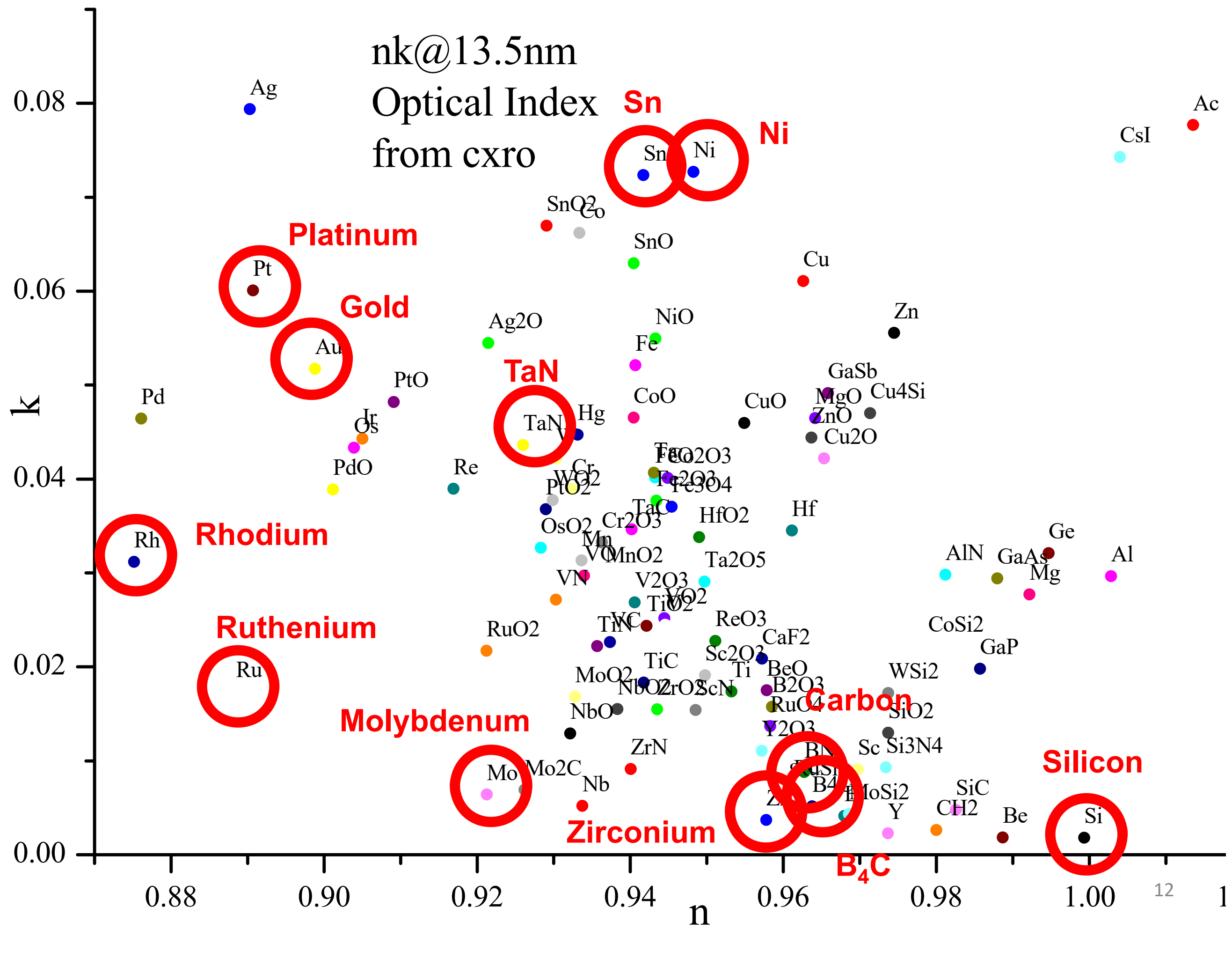


● **強め合いの干渉を利用する反射増加多層膜**

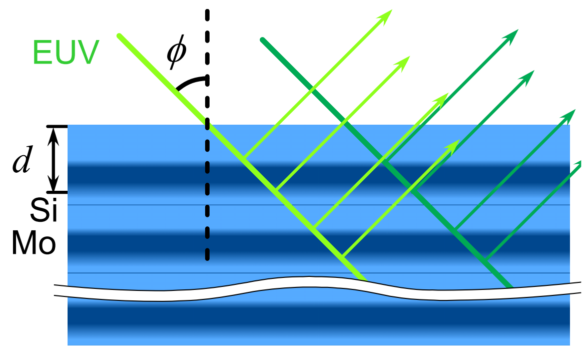
ブラッグ条件 $m\lambda = 2nd\cos\varphi$

m: ブラッグ次数
λ: 波長
n: 屈折率
D: 周期長
ϕ: （直）入射角

自由度の高い直入射光学系を構築可能
（明るく、視野の広い光学系）



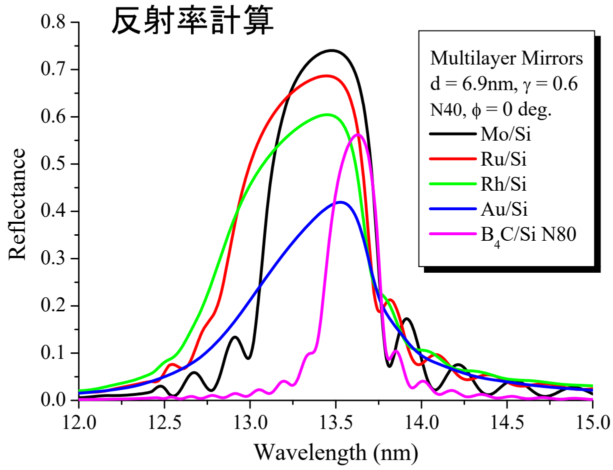
EUVL用多層膜反射鏡



反射増加多層膜
- 二つの物質を交互に積層
- 各界面からのわずかな反射光の強め合い
- 直入射光学素子
- ブッラグ反射と同様に表せる

$$2d\cos\phi = m\lambda \qquad (m=1,2,3,\cdot\cdot)$$

λ: 入射光の波長, ϕ: 入射角, d: 周期長

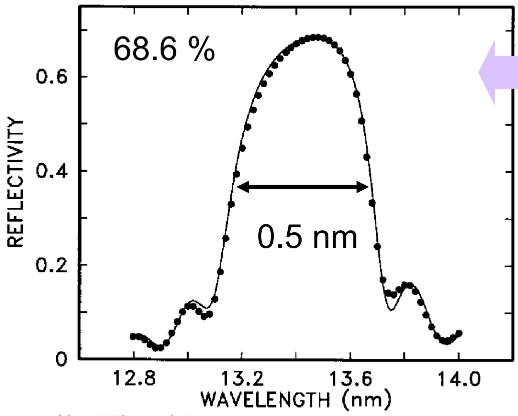


物質対の選択
- 屈折率の差が大きい
  各界面での反射を大きく
- 吸収が小さい
  多くの界面で反射させる

波長	13.5 nm	6.75 nm
物質対	Mo/Si	LaN/B_4C
反射率(実測)	70%	58%
備考	EUVL	BEUV

波長13.5 nm用のMo/Si多層膜(ML)

Extreme Ultraviolet (EUV):
13.5 nm付近、極端紫外線



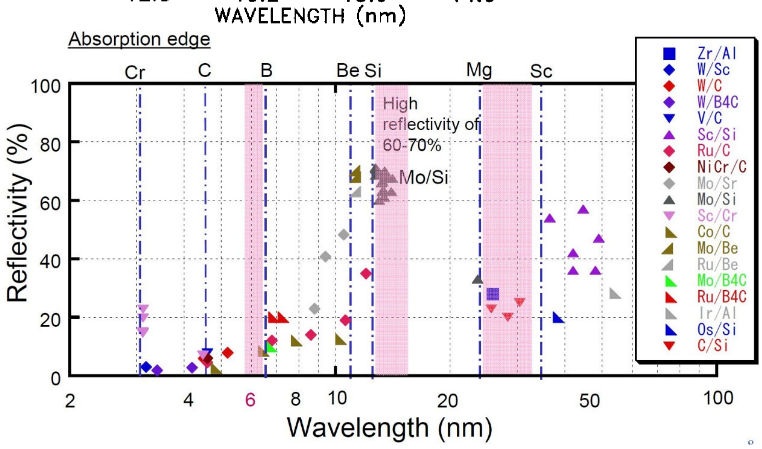
Mo/Si MLの反射スペクトル例

Mo (2.980 nm) /Si (3.974 nm) × 50周期

ピーク反射率 ~ 68.6% (λ = 13.5 nm)

反射バンド幅 $\Delta\lambda$ ~ 0.5 nm (±2%)

EUV領域で70%の高い反射率！



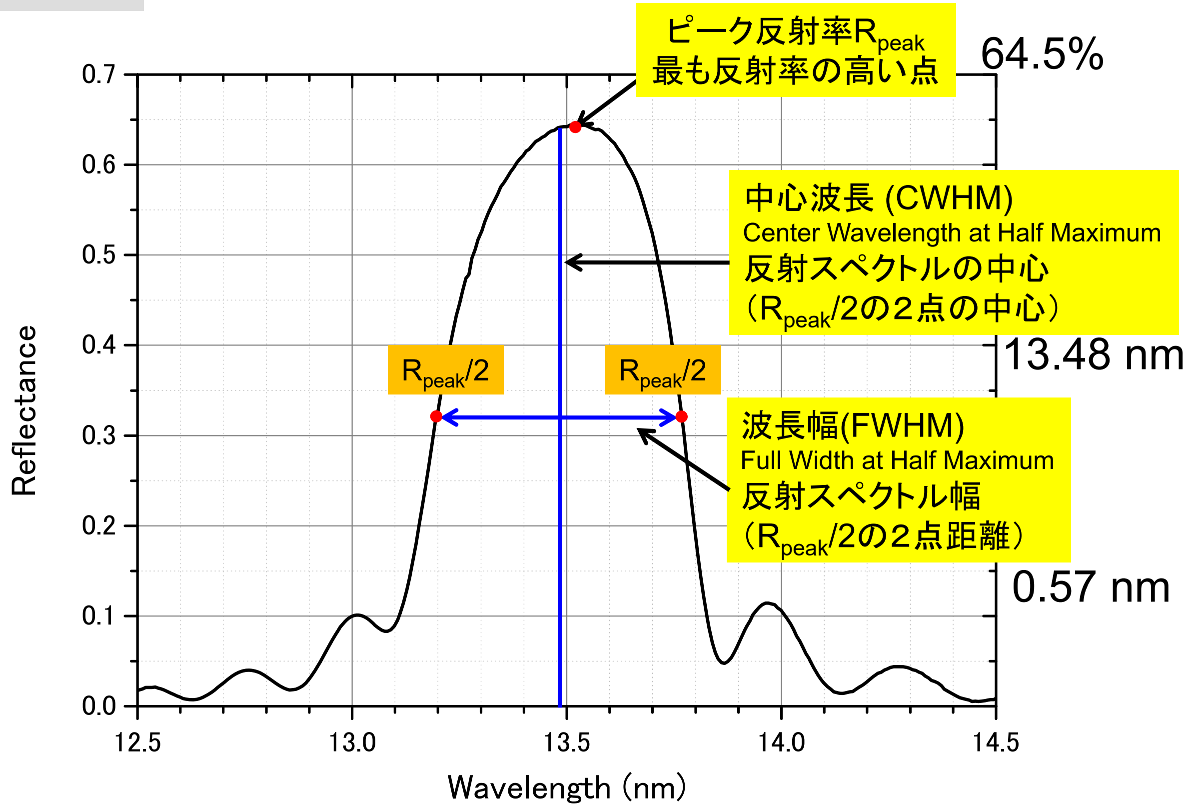
軟X線多層膜の直入射反射率比較（NTT-AT 竹中）

Mo/Si多層膜は高い反射率が得られるため、リソグラフィーへ応用が進む。

他の波長領域の多層膜はせいぜい30%程度しか得られていない。

多層膜の性能が応用を広げる。
性能評価のための反射率計は、軟X線光学における基盤ツールである。

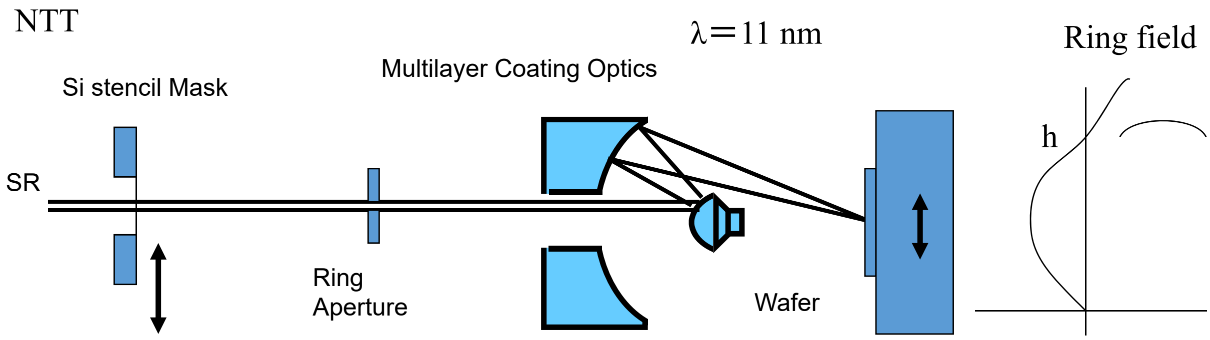
多層膜の反射スペクトル例と性能評価指標



反射率、中心波長、波長幅で性能を評価する。

概要

World 1st Experimental Setup of X-ray Projection Lithography



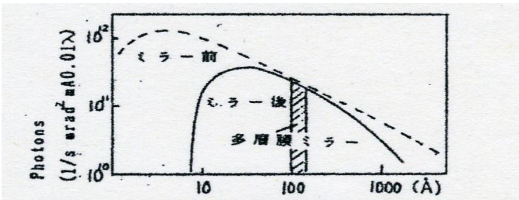


図 2 BL-1C の強度分布（推定値）

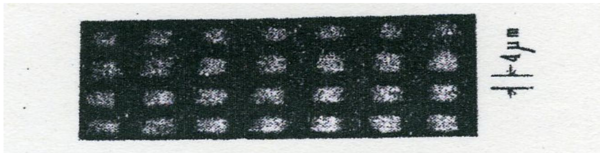


図 3 露光パターン例 PMMA(0.2um)/Si

H. Kinoshita, T. Kaneko, H. Takei, N. Takeuchi, and S. Ishihara, "Study on x-ray reduction projection lithography," presented at the 47th Autumn Meeting of the Japan Society of Applied Physics, Paper No. 28-ZF-15 (1986) 322.

Molybdenum-silicon multilayer mirrors for the extreme ultraviolet

Troy W. Barbee, Jr., Stanley Mrowka, and Michael C. Hettrick

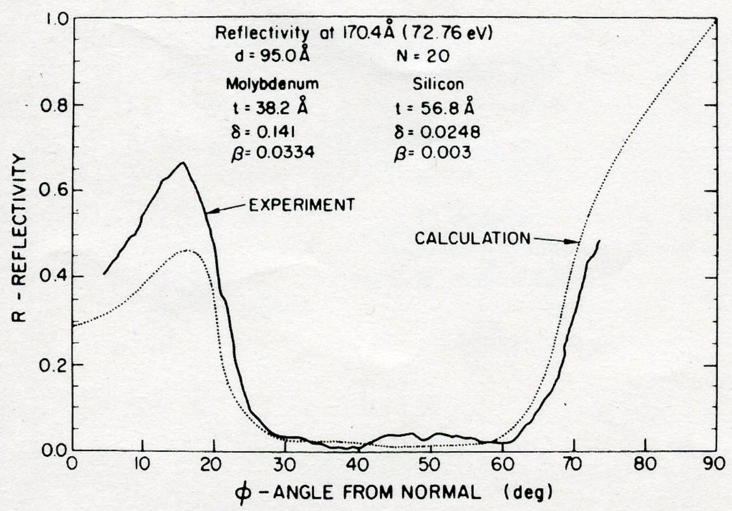
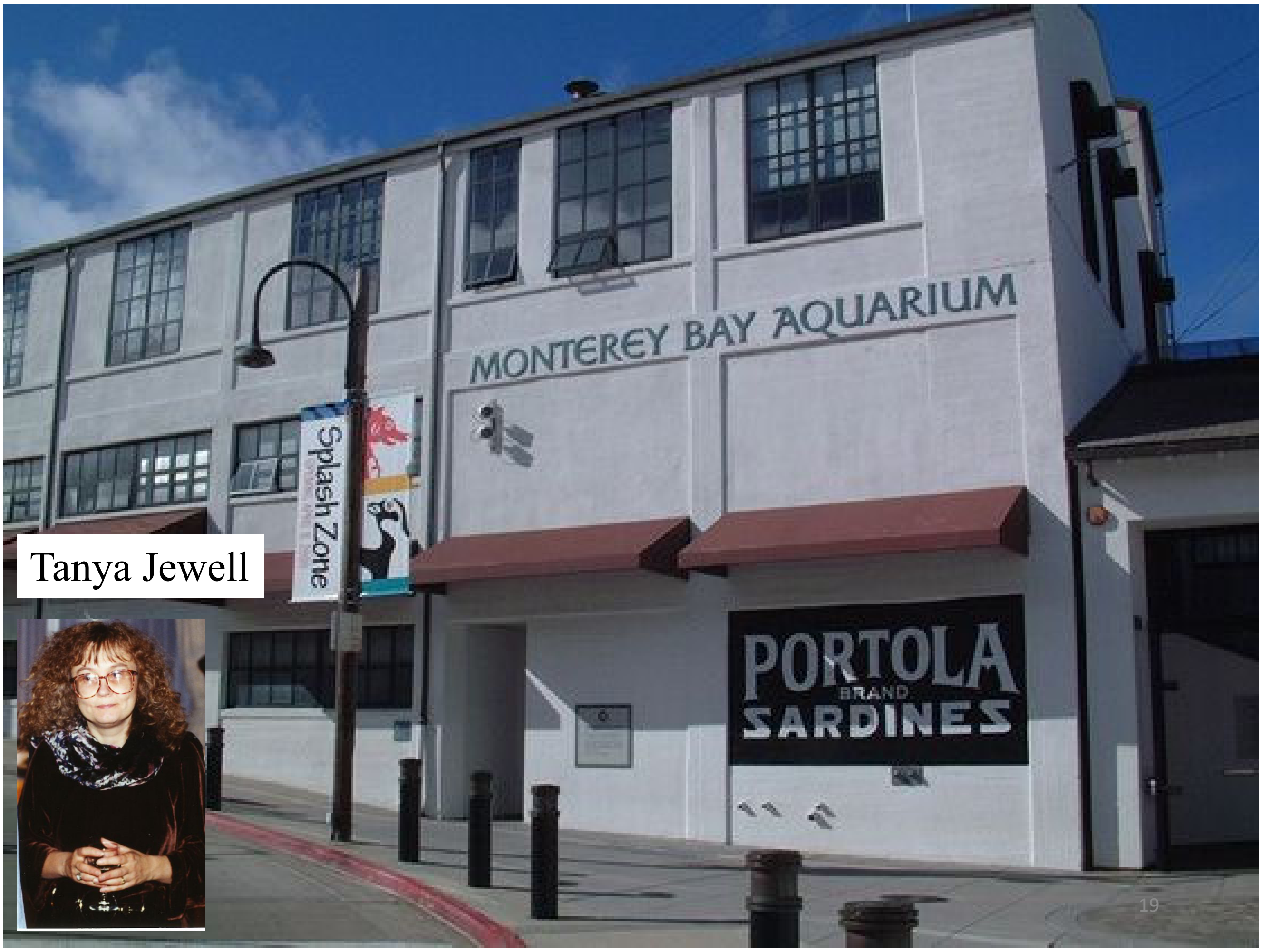
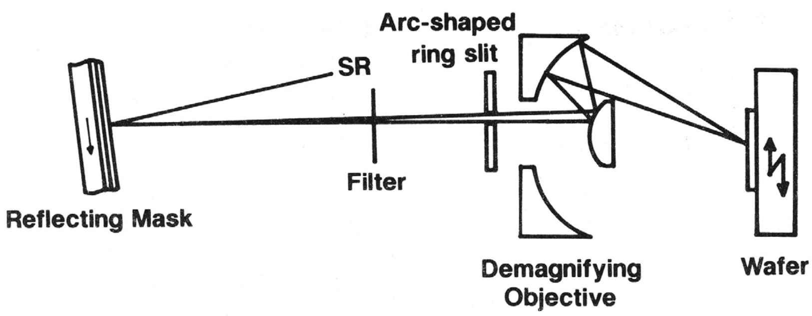
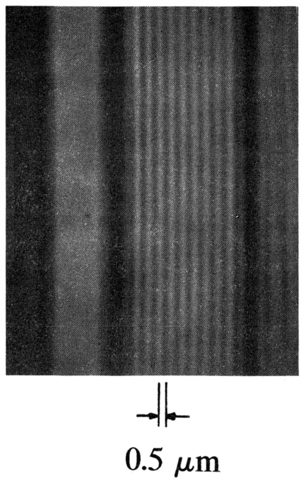


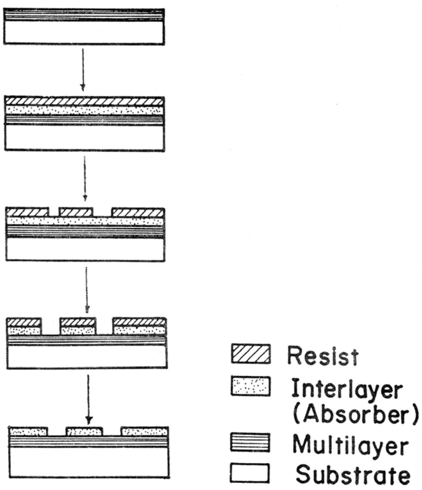
Fig. 3. Experimental continuous scan reflectivity of 170.4-Å light

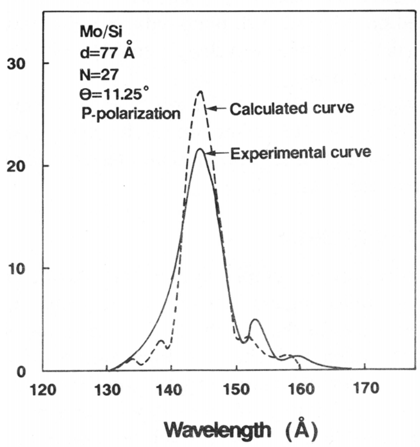
APPLIED OPTICS 24-6 (1985)

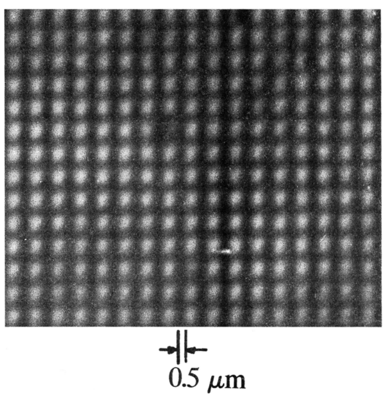












JVST Nov/Dec 1989, H. Kinoshita et. al

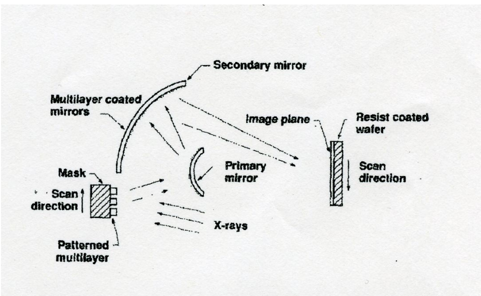


FIG. 1. Illustration of one possible x-ray reduction camera design: off axis scanning system with reflecting mask. In this embodiment, the mask is imaged and scanned onto the wafer (a "step and scan" sequence). An example of a "step and repeat" x-ray reduction camera is shown in Ref. 1.

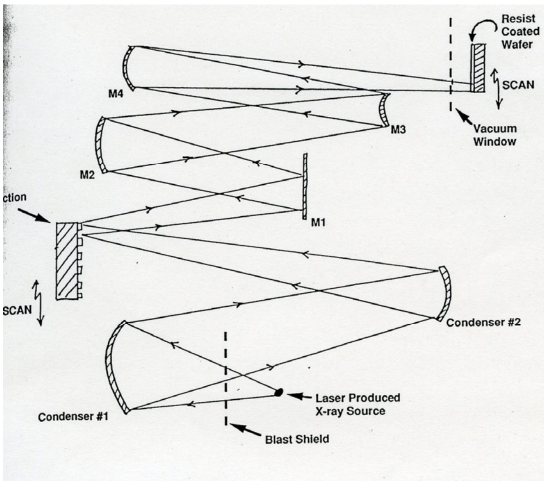


FIG. 4. Schematic representation of a 5× reduction, ring field scanning system employing four imaging mirrors, a reflective mask, two condenser mirrors, and driven by a laser produced "point" source of x rays.

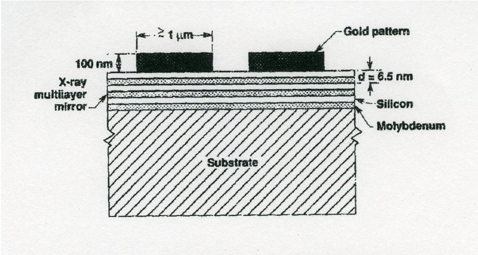


FIG. 2. Cross-sectional view of an XRPL mask. A thin gold absorber pattern with relatively large linewidths is patterned directly onto a soft x-ray multilayer mirror.

JVST Nov/Dec 1989, A. Hawrlyluk and N. Ceglio et. al

Reduction image at 14 nm using SC optics

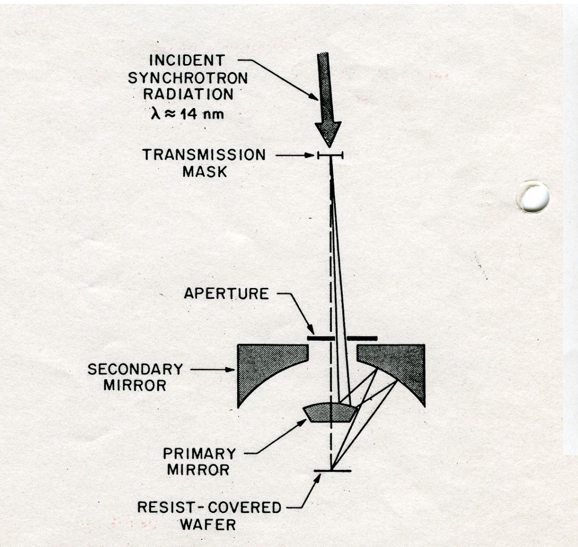


FIG. 1. Schematic diagram of the basic experimental setup. The two mirrors comprising the Schwarzschild objective were coated with Mo/Si multilayers to provide a reflectance of ~40% at 14 nm.

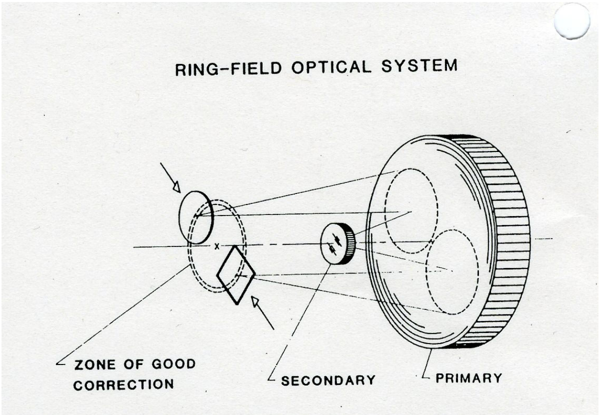
0.1 µm

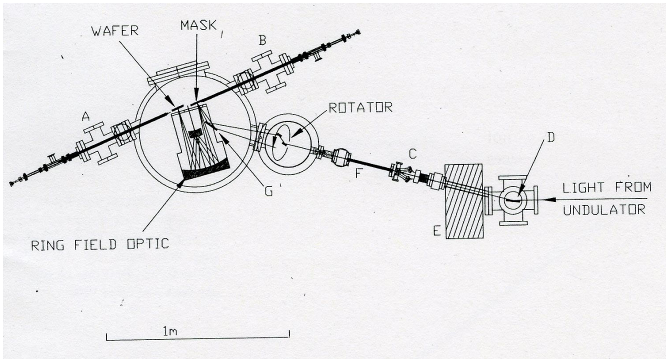
0.05 µm

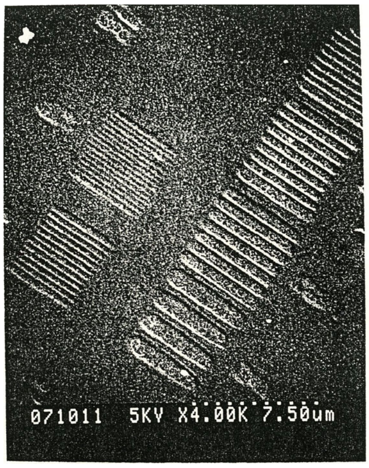


JVST Nov/Dec 1990, J. Bjorkholm, J. Boker et. al

Offner Type Imaging Optics to Enlarged the Exposure Field







0.2 μm pattern

JVST Nov/Dec 1991, A. MacDowell, J. Bjorkholm et. al

Two Aspherical Mirror System in EUV Lithography

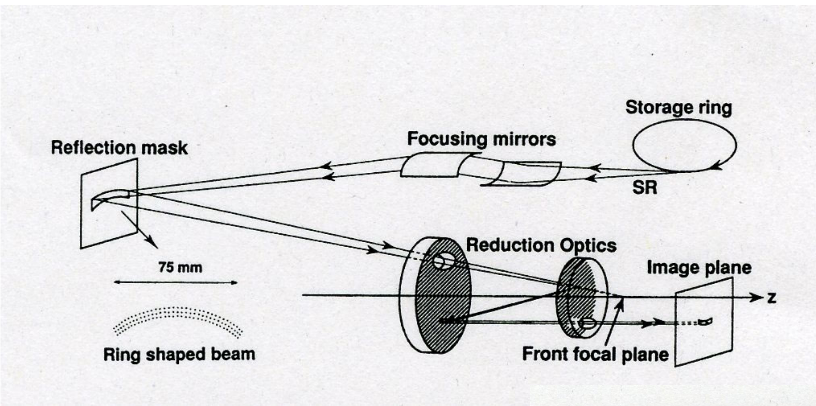
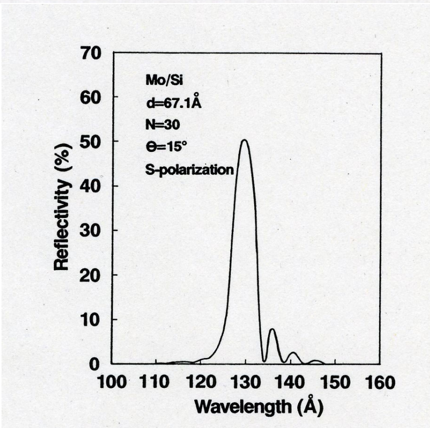
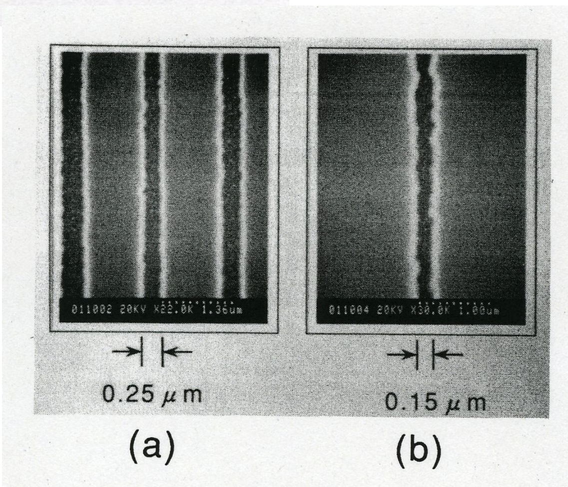


TABLE I. Design goals and conditions.

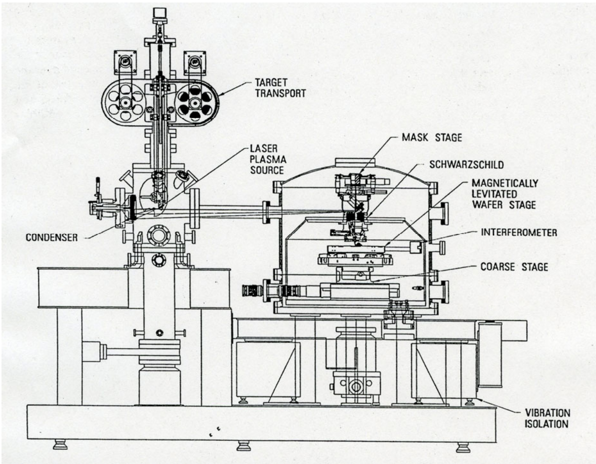
Resolution	0.1 μm
Field size	15×15 mm² (> 10-mm radius ring scan)
Distortion	< 0.01 μm
Depth of focus	± 1 μm
Number of mirrors	2
Wavelength	130 Å
Numerical aperture	0.07
Aberration	⩽0.05 μm
Telecentricity	< 0.6° at ± 1-μm defocus
Magnification	1/5 (mask size: 75×15 mm²)

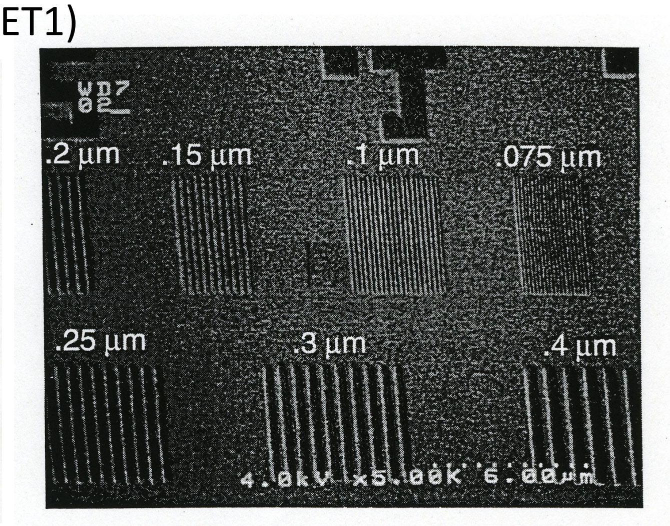




JVST B9(6) (1991) K. Kurihara et. al

EUV LLC Micro Exposure Tool (MET1)





SPIE Vol. 2437, D. Tichenor, G. Kubiak et. al

Fabrication of MOS devices with EUV Lithography

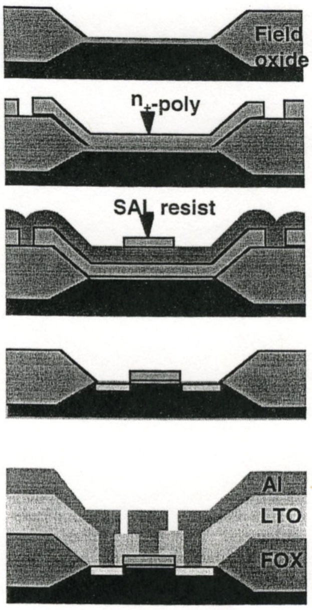


Figure 2. Outline of the NMOS process. After gate oxidation and poly deposition, the EUV alignment marks were etched into the poly layer.

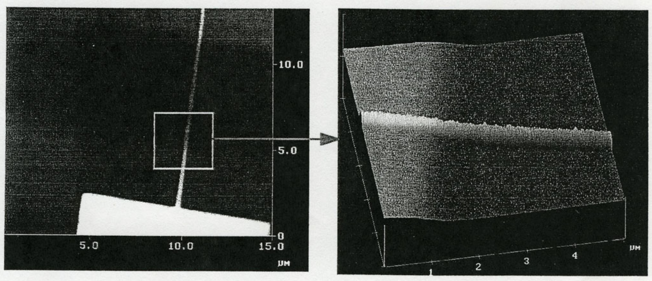


Figure 3. A 0.1 µm gate pattern printed over 500 Å LOCOS topography. Since there is no reflective notching in EUV, adequate linewidth control was achieve with 700 Å thick SAL-601 imaging layer.

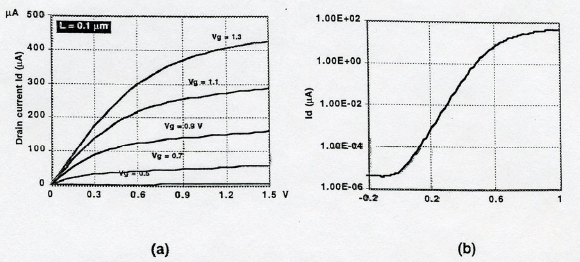


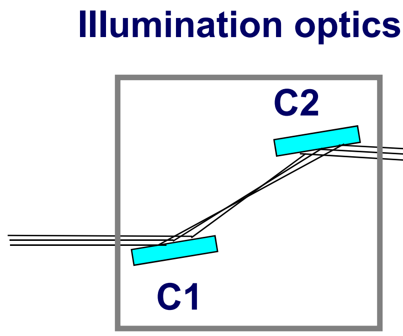
Figure 5. Characteristics of 0.1 µm NMOS transistor with EUVL gate level patterning (3 µm gate width). Threshold voltage V_t is 0.55 V, and I_{dsat} at 1.3 V gate voltage is 400 µA.

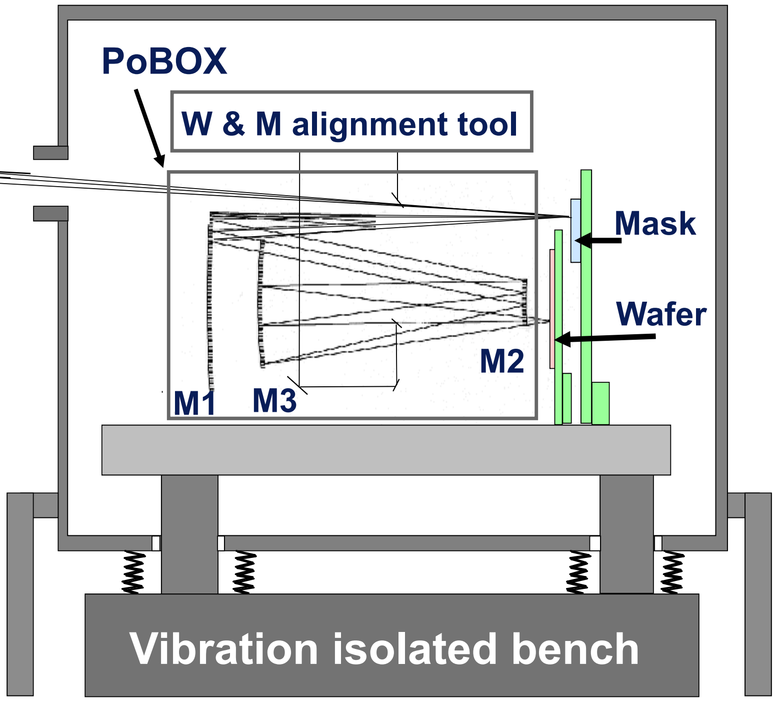
OSA TOPS on EUVL, 1996 K. Nguyen, G. Cardinale et. al

1st US-Japan Workshop on X-ray Projection Lithography @ Hotel Mt. Fuji

2nd US-Japan Workshop on X-ray Projection Lithography @ Hotel Mt. Fuji

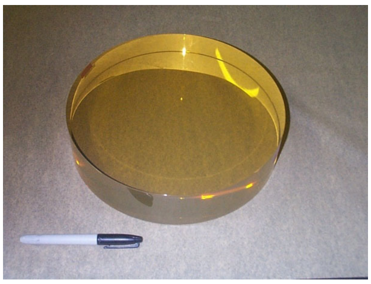
System configuration of ETS-1 (Univ. of Hyogo, Nikon, Hitachi)





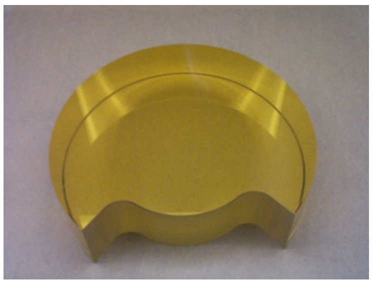
Optics	Three aspherical mirrors
Wavelength	13.5 nm
Numerical aperture	0.1
Demagnification	1/5
Diffraction limit	60 nm
Depth of focus	0.9 μm
Exposure area (in statics)	30 mm (H) × 1 mm (V)
Exposure area (in scanning)	30 mm (H) × 28 mm (V)
Mask	8 inch or 6025ULE
Wafer	8 inch
Exposure environment	In vacuum

Aspherical mirrors for the imaging optics



M1-mirror

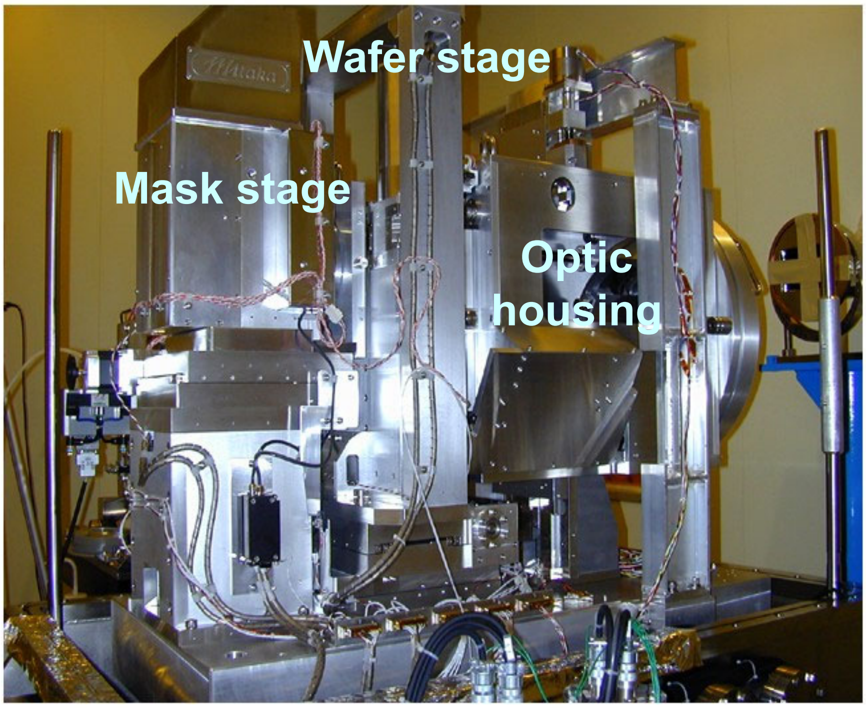
M2-mirror



M3-mirror

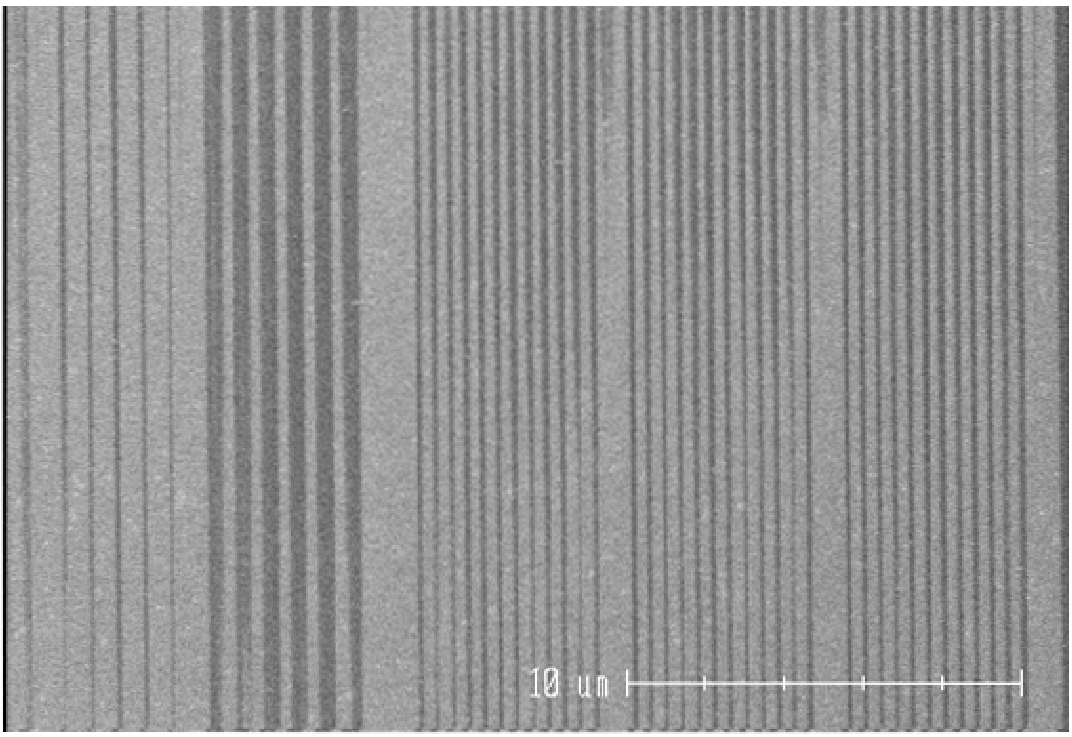
	M1-mirror	M2-mirror	M3-mirror
Diamter	272 mm	116 mm	224 mm
Figure error (rms)	0.58 nm	0.58 nm	0.58 nm
Roughness (rms)	0.28 nm	0.31 nm	0.35 nm

ETS-1 (Univ. of Hyogo and ASET)



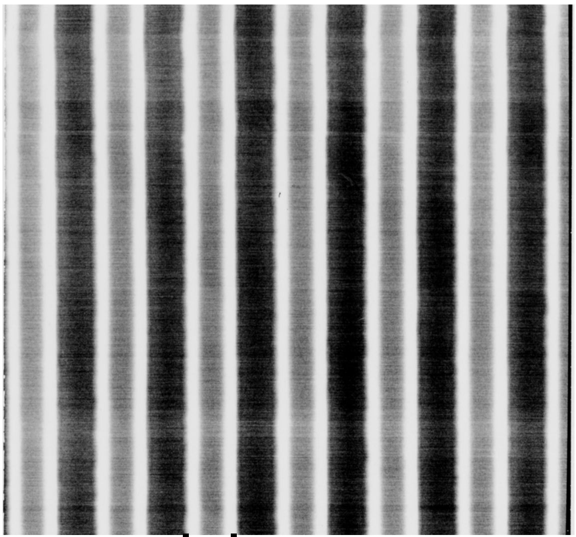
T. Watanabe, K. Mashima, M. Niibe, and H. Kinoshita, "A novel design of three-aspherical-mirror imaging optics for extreme ultra-violet lithography," *Jpn. J. Appl. Phys.,* **36** (1997) 7597-7600.

Replicated patterns (0.1 μm L&S) on ZEP520



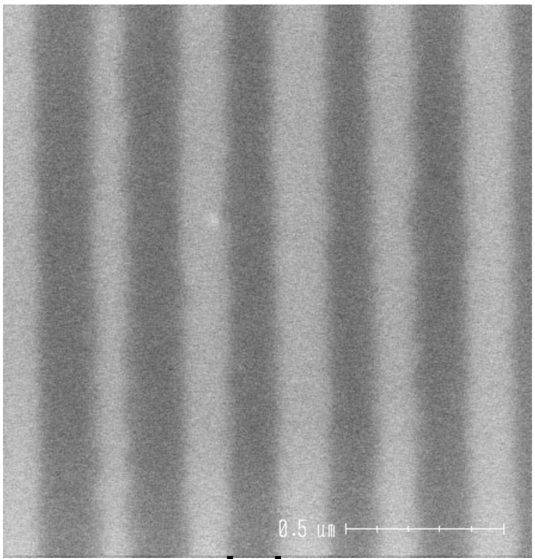
Replication pattern of 100-nm-width line and space

Mask pattern



500 nm

Replicated pattern

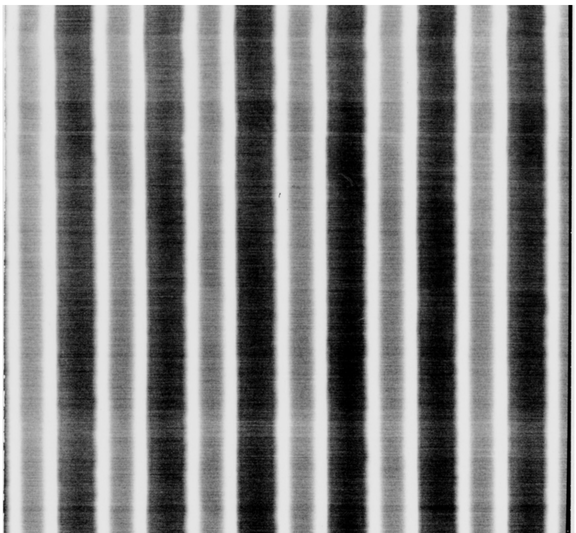


100 nm

resist : ZEP520

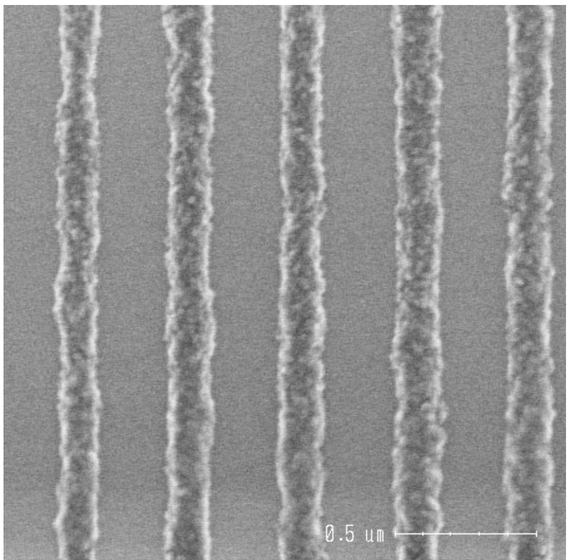
Replication pattern of 100-nm-width line and space

Mask pattern



500 nm

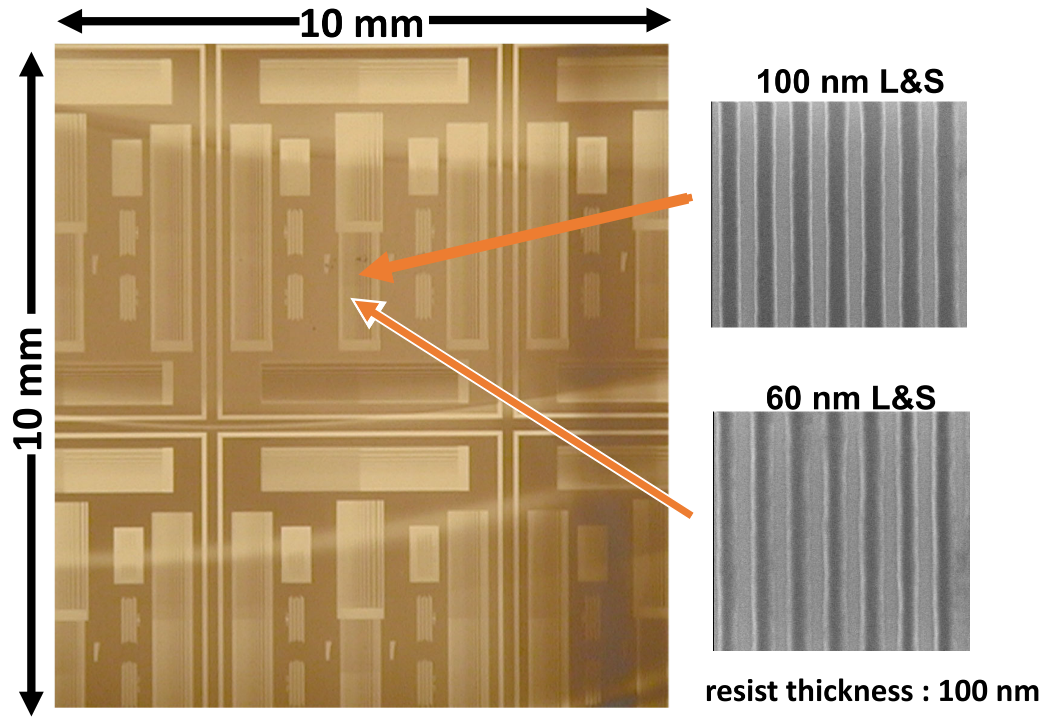
Replicated pattern



100 nm

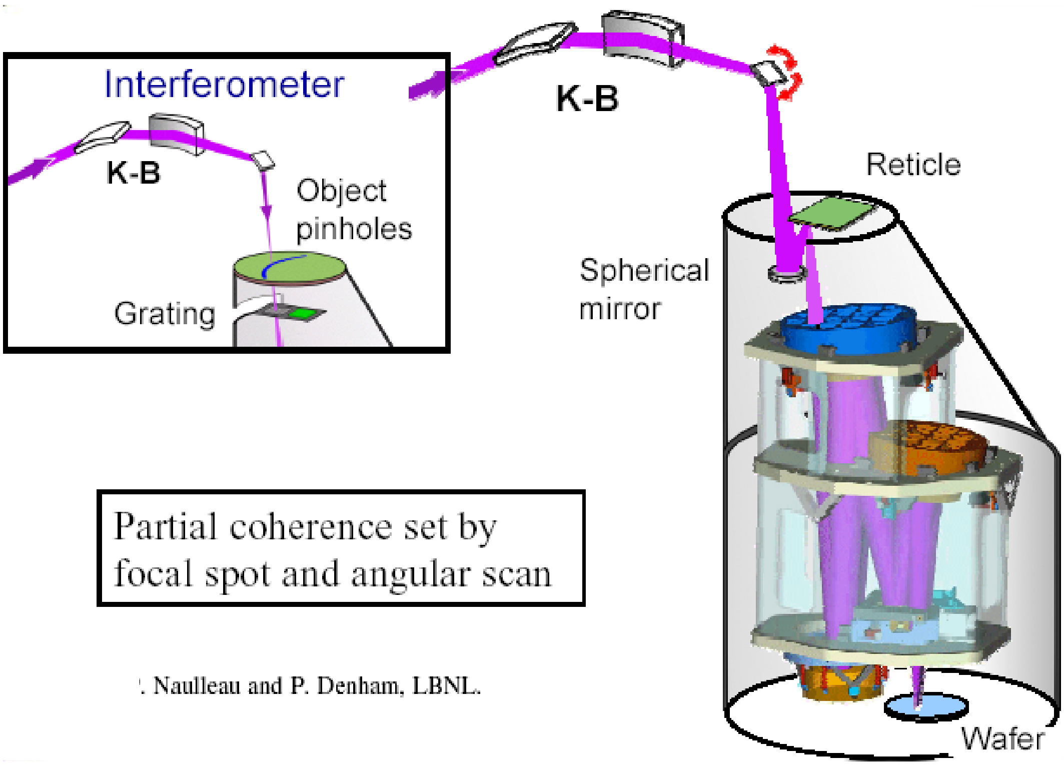
resist : SAL601

Large field exposure pattern



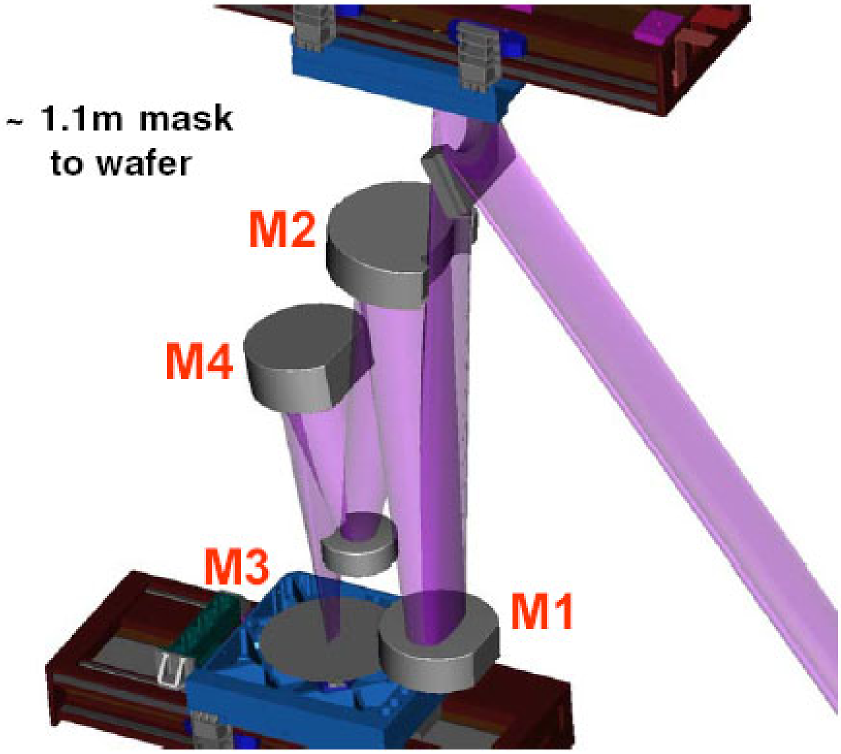
T. Watanabe, H. Kinoshita, K. Hamamoto, M. Hosoya, T. Shoki, H. Hada, H. Komano, and S. Okazaki, "Fine pattern replication using ETS-1 three-aspherical mirror imaging system," *Jpn, J. Appl. Phys.,* **41** (2002) 4105-4110.

Static Exposures with an Active Coherence Controlling Illuminator

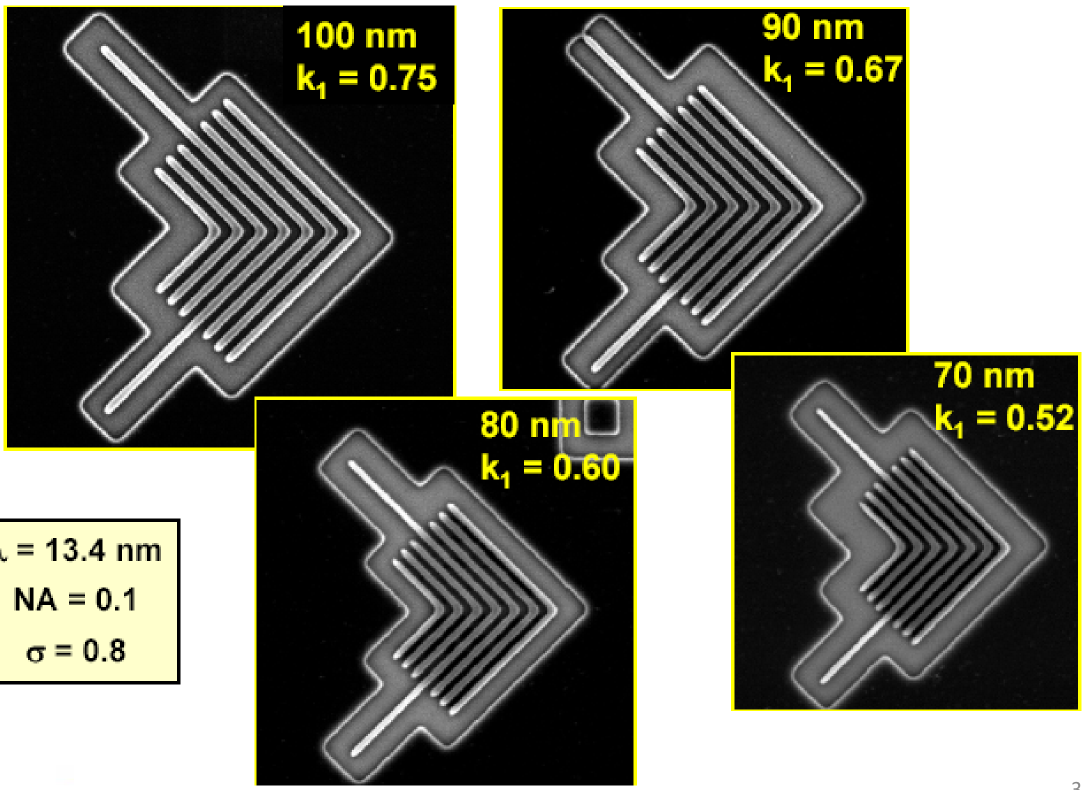


. Naulleau and P. Denham, LBNL.

The 0.1 NA ETS Imaging System Has 4 Mirrors

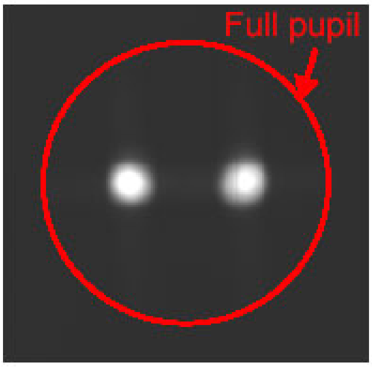


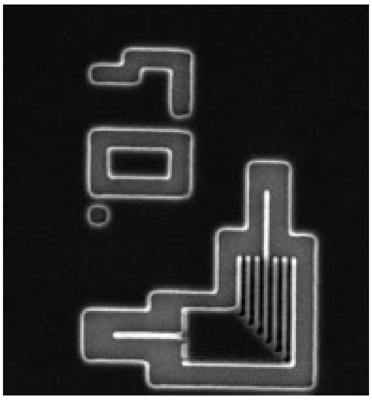
Static Microfield Printing with the ETS Optics at the ALS

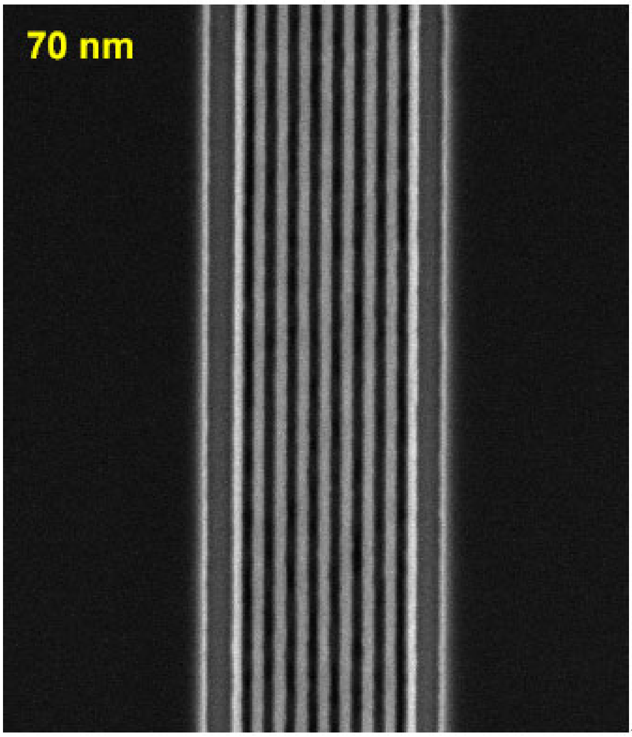


λ = 13.4 nm
NA = 0.1
σ = 0.8

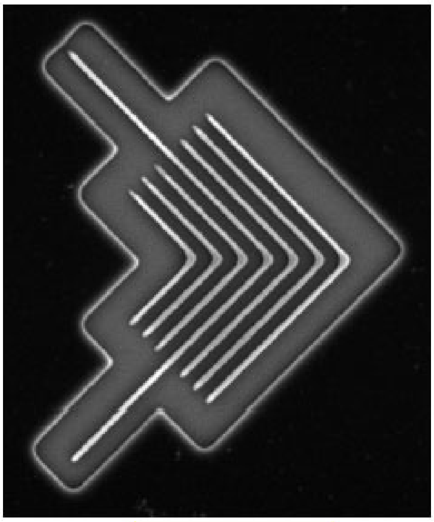
Dipole Illumination Enhances Resolution in One Direction



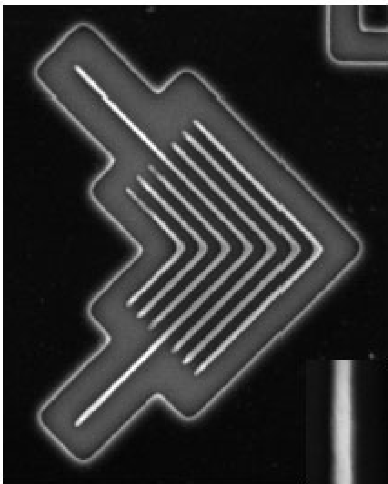




Exposure Process Control Enables Printing of Sub-40-nm Loose Pitch Features



45-nm 3:1



39-nm 3:1

39 nm at 0.1 NA
↓
16 nm at 0.25 NA

概要

1．半導体市場動向と半導体国際ロードマップ

2．EUVリソグラフィの露光波長

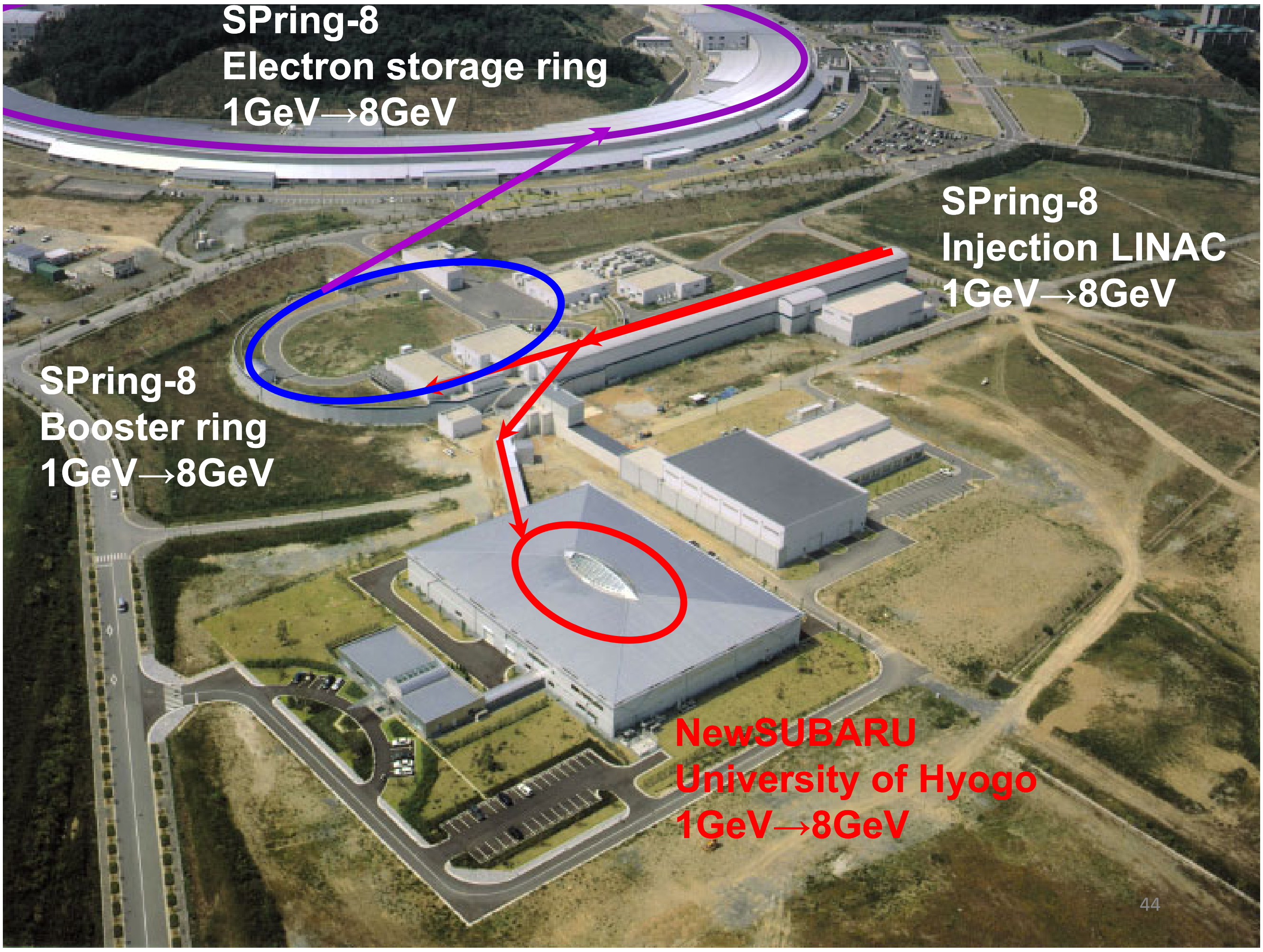
3．EUVリソグラフィの歴史

4．EUVリソグラフィの課題
レジストの線幅バラツキの低減

5．Beyond EUVL

6．まとめ


SPring-8 Experimantal Site
SPring-8
SACLA
Free electron Laser
NewSUBARU


SPring-8
Electron storage ring
1GeV→8GeV
SPring-8
Injection LINAC
1GeV→8GeV
SPring-8
Booster ring
1GeV→8GeV
NewSUBARU
University of Hyogo
1GeV→8GeV

EUV Lithography R&D at University of Hyogo

'95 '98 '01 '02 '07 '08 '11 '14 '16

Resource

Imaging EUV optics
Design and fabrication
Collaboration work with Hitachi・Nikon

World 1st
40 nm patterning

Ready for the mplementation

Mask inspection supported by CREST

World 1st
phase defect inspection

Lensless mask inspection system
supported by CREST
Collaboration work with Riken

World 1st
HHG CSM

Industrial application

National project
ASET EUVL collaboration work
R&D for resist and mask

National project
SELETE, EIDEC
Collaboration work
R&D for mask and resist
SEMATECH mask inspection

EIDEC
µCSM／Outgas testing
EUV interference lithography
For resist tesiong

World 1st PAG bounding polymer resist for EUVL is demonstrated low LER and high sensitivity

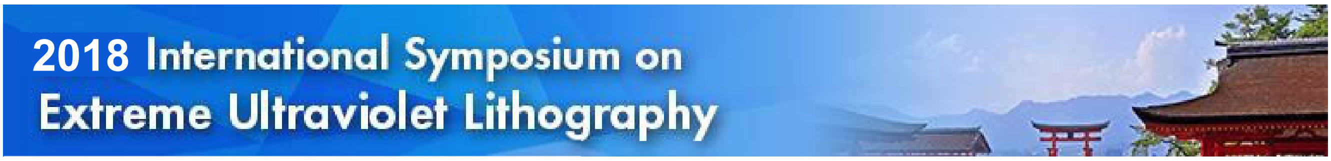
World 1st apply soft x-ray absorption spectroscopy for the EUV resist reaction analysis

ASML started EUV program

αTool 2 sets

βTool 6 sets

EUV preproduction 11台



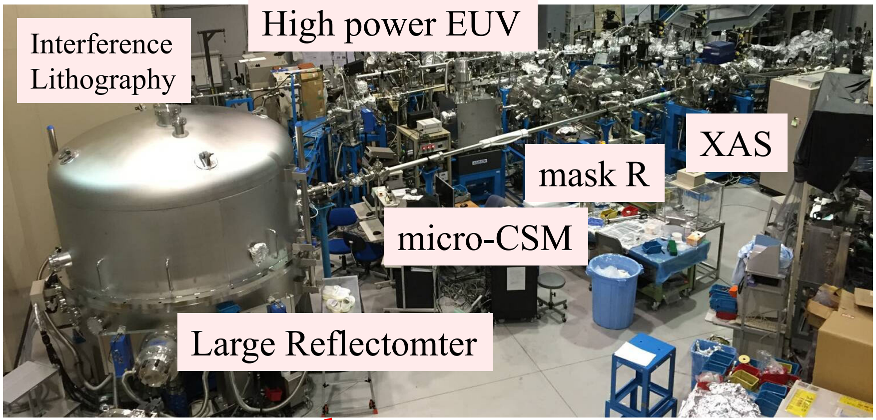
EUV FOCUS AREAS

2015 / 16hp	2016 / 16hp	2017 / 16hp	2018 / 16hp
1. Reliable source operation with > 85% availability – Expectation of 1500 average wafers per day in 2016	1. Reliable source operation with > 85% availability – 1500 wafers per day with consistency in 2017	1. Resist resolution, sensitivity & LER met simultaneously – Sensitivity and LER/LCDU are far from targets. – Stochastic variation needs to be addressed for current and future materials	1. .Resist resolution, sensitivity & LER met simultaneously – Sensitivity and LER/LCDU are far from targets. – Stochastic variation needs to be addressed for current and future materials
2. Resist resolution, sensitivity & LER met simultaneously – Increased focus needed on manufacturing performance (defectivity, pattern collapse,...)	2. Resist resolution, sensitivity & LER met simultaneously – Sensitivity and LER/LCDU are far from targets. – Stochastic variation needs to be addressed for current and future materials	2. Reliable source operation with > 85% availability – 1500 wafers per day with consistency in 2017	2. Reliable source operation with > 85% availability – 1500 wafers per day with consistency in 2018
3. Mask yield & defect inspection/review infrastructure – Sustainability of mask tool supply chain remains critical	3. Keeping mask defect free – Good progress but very far to go for HVM readiness – Need industry focus to bring all the required components together	3. Keeping mask defect free – Good progress but very far to go for HVM readiness – Need industry focus to bring all the required components together	3. Keeping mask defect free – Good progress but very far to go for HVM readiness – Need industry focus to bring all the required components together
4. Keeping mask defect free (by EUV pellicle) - Pellicle demonstration in the field (on 3300) required in 2016	4. Mask yield & defect inspection/review infrastructure – Infrastructure gap for pattern mask inspection remains	4. Mask yield & defect inspection/review infrastructure – Infrastructure gap for pattern mask inspection remains	4. Mask yield & defect inspection/review infrastructure – Infrastructure gap for pattern mask inspection remains

EIDEC imec EUREKA

Center for EUV Lithography

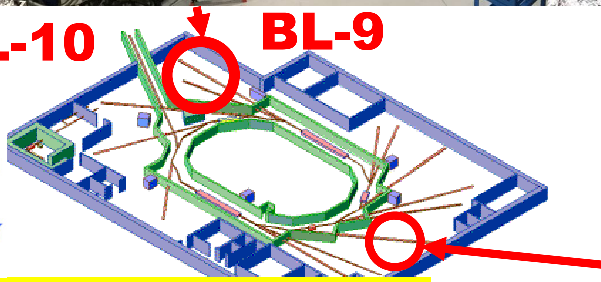
NewSUBARU Synchrotron Radiation Facility



in SPring-8 site

1) Resist
2) Mask
3) Large reflectometer of Collector mirror for EUV light source
4) Pellicle

Microscopes (EUVM)
Resist EUV Sensitivity



EUV & Soft X-ray

Three Beamlines for EUVL

Resist Evaluation Instruments at NewSUBARU Synchrotron Light Facility

Following instruments at three beamlines is for opened usage of the novel EUV resist material evaluation.

1) E_0 sensitivity measurement

2) Outgassing measurement

3) EUV Interference lithography

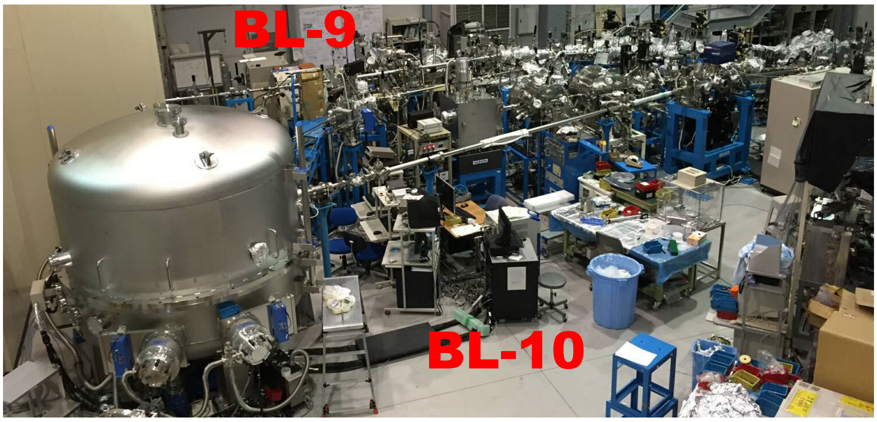
4) Carbon growth in-situ measurement by ellipsometry

5) Resist transmission measurement

6) Resist chemical reaction analysis by Soft X-ray Absorption Spectroscopy

Very few limitations to evaluate novel EUV resist materials using each above tools !!

Beamline for EUVL BL3, BL9, BL10

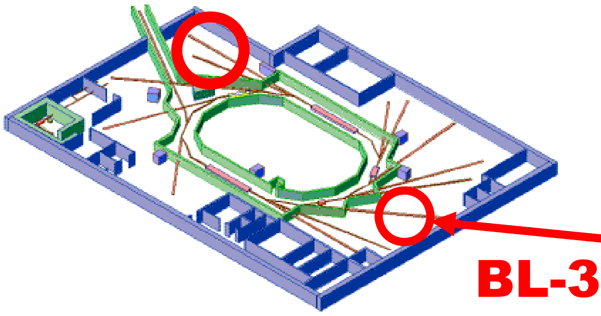


BL09LU beamline

- EUV IL
  LWR and Resolution
- In-situ carbon growth by ellipsometry

BL10 beamline

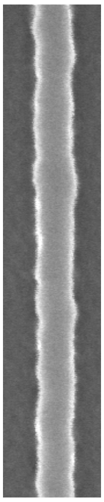
- Resist transmittance
- SXAS for chemical reaction analysis



E_0 sensitivity, Outgassing

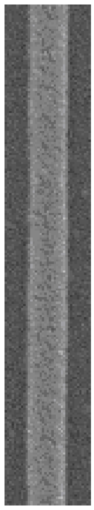
We need smooth resist!!

1) Low LER



High LER

Reduction of
Line edge roughness



Low LER

2) High Sensitivity

3) High Sensitivity

4) Low Outgassing

Origins of LER (Factors of Stochastics)

1） Spatial distribution of functional material in resist
functional groups, photosensitizers (acid generators), additives such as amines, etc.

2） Solvent distribution in prebake process
Spatial distribution of free volume

3） EUV photon shot noise

4） 2ndry electron blur

5） Solvent effect in PEB process
Acid diffusion

6） Development and rinse effects
Spatial distribution of developer penetration and development process yield

7） Out of band (OoB) light effect

Photon statistics - revisited

How Dose fluctuation turns into edge placement

$$\frac{LCDU}{nm} \approx 0.75 \cdot \frac{1}{NILS} \cdot \sqrt{\frac{h\nu / eV}{Dose/(mJ/cm^2)}}$$

NILS = 2.5
$h\nu$ = 92 eV (13.5 nm) → *LCDU = 0.6 nm*
Dose = 20 mJ/cm²

Origins of LER (Factors of Stochastics)

1） Spatial distribution of functional material in resist
functional groups, photosensitizers (acid generators), additives such as amines, etc.

2） Solvent distribution in prebake process
Spatial distribution of free volume

3） EUV photon shot noise

4） 2ndry electron blur

5） Solvent effect in PEB process
Acid diffusion

6） Development and rinse effects
Spatial distribution of developer penetration and development process yield

7） Out of band (OoB) light effect

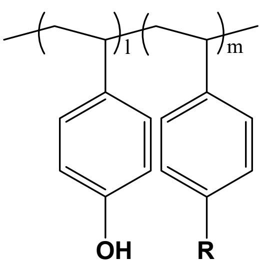
Benefit of PAG Bounded Resist Comparison to the Conventional one

High Sensitivity

- **Optimization of the absorption coefficient of PAG**
- **Acheivement of the uniform chemical reaction density**

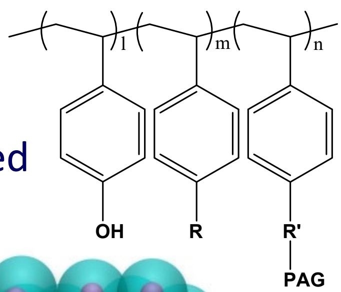
LWR Reduction

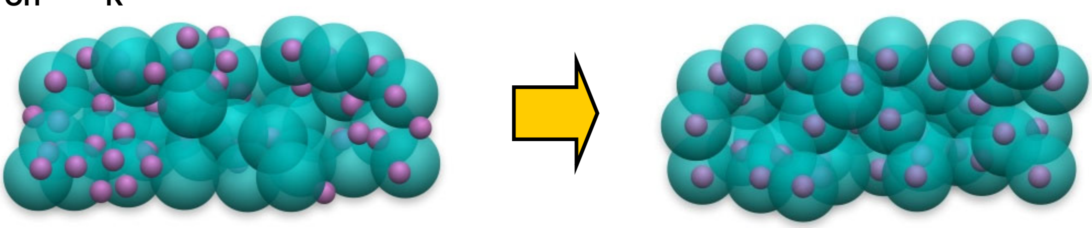
- **Optimization of the molecular size**
- **Small dispersity**
- **Uniform density of PAG**



PAG blended polymer

PAG bounded polymer

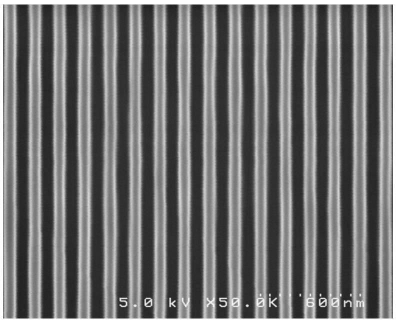




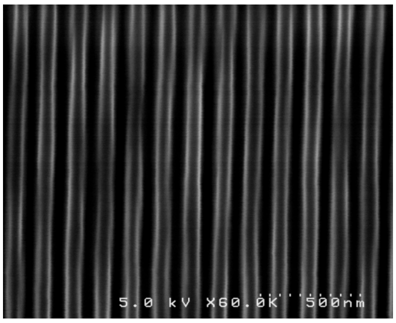
Comparison between PAG Bounded and Blended Resists (EB 30kV)

For the 75 nm L/S resist pattern

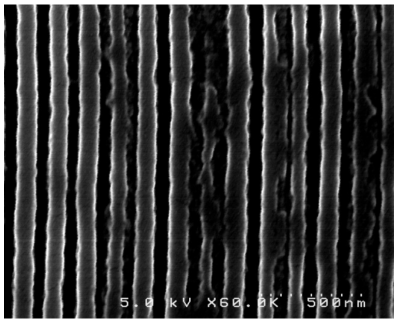
Bounded type



Blend type



Blend type

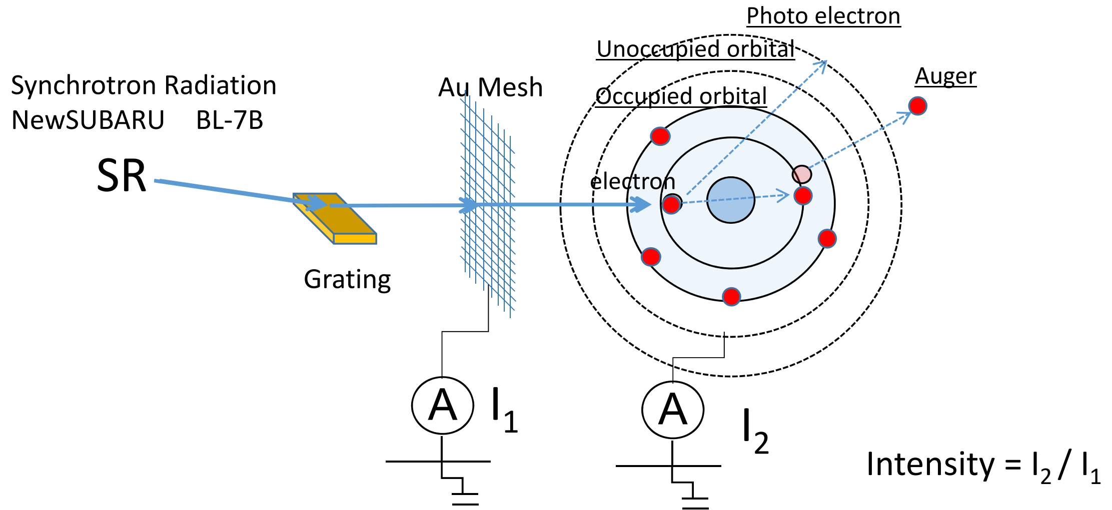


LER = 3.5 nm

LER = 7.5 nm

BAD LER

The soft x-ray absorption spectroscopy

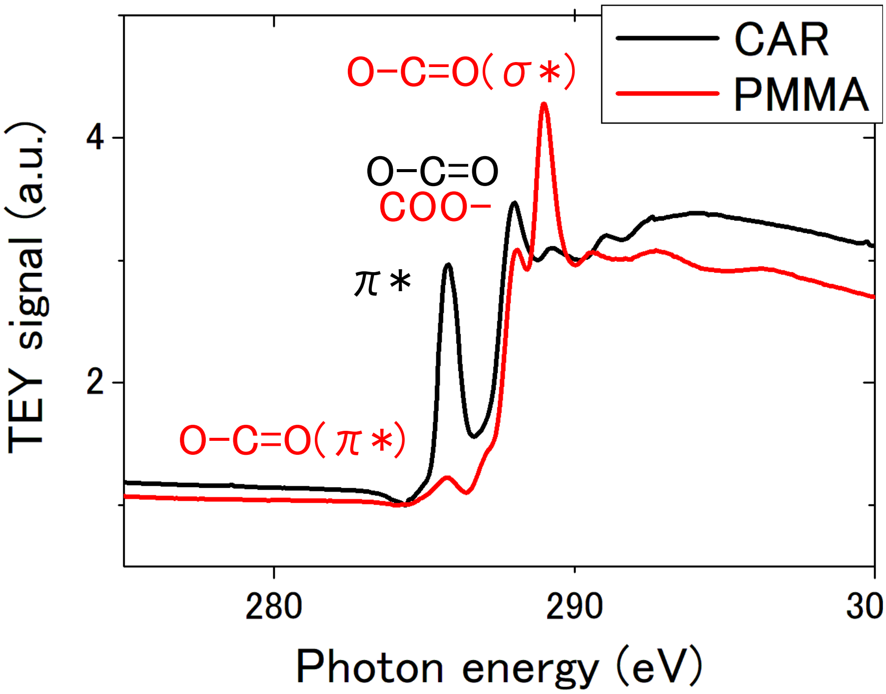


To measure the change of the chemical bonding, the specific energy of the incident energy required for the measurement.

For example,
Carbon 1s core
280~330 eV
Fluorine 1s core
690~730 eV

Powerful tool for evaluating the change of the chemical bonding

SXAS (Soft X-ray Absorption Spectroscopy



How to measure and analize?

・XAS using Cu $K\alpha$ S(8 keV photon) cannot detect the chemical bonding of the elements such as C, N, O, F etc. of resist material.

・SXAS (soft x-ray absorption spectroscopy) is very powerful tool to distinguish the chemical bonding of C, N, O, F etc. in high contrast. (Resonance)

＋

・Soft X-ray Coherent scatterometry method is ver powerful tool to measure the structure of the chemical contents of resist material. (Scattering)

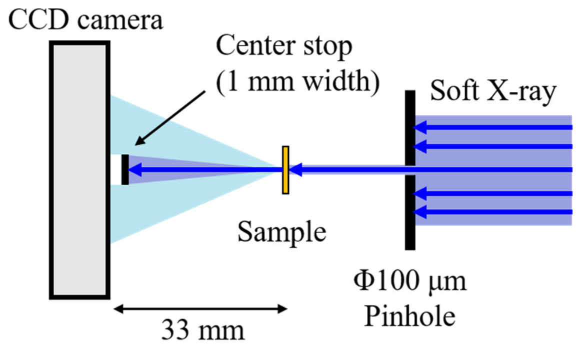
||

・Resonance Soft X-ray Scattering (RSoXS) is very powerful tool to measure the size of the structure of the chemical contents of resist material.

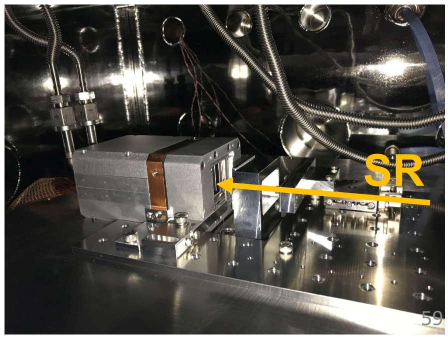
Experimental Setup

◆ RSoXS method

Scattering light from the sample is recorded by the CCD camera in vacuum.



The focal point is located 2.1 m upstream of this system.



【BL-10 beamline】

- Light source : bending magnet
- Monochromator is provided upstream.
- Photon energy range : 60 – 1100 eV
- Energy resolution E/ΔE : 2500

【CCD camera】

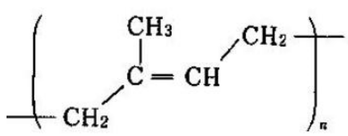
The maximum acceptance angle : 24°
(corresponded to hp 11 nm at 280 eV)

Measured DSA samples (1)

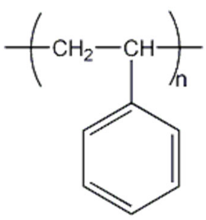
◆ Three polymers in triblock polymer

Triblock polymer consisting of polyisoprene, polystyrene, poly (2-vinylpyridine)

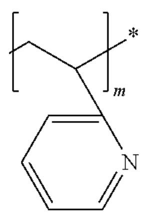
I : polyisoprene



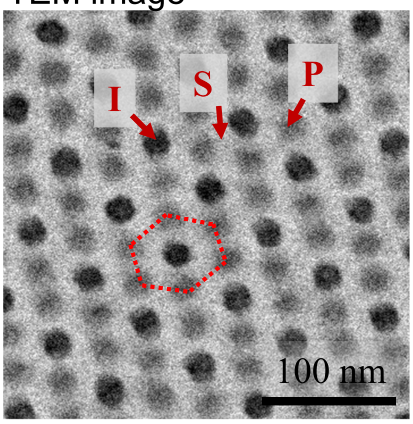
S : polystyrene



P : poly(2-vinylpyridine)

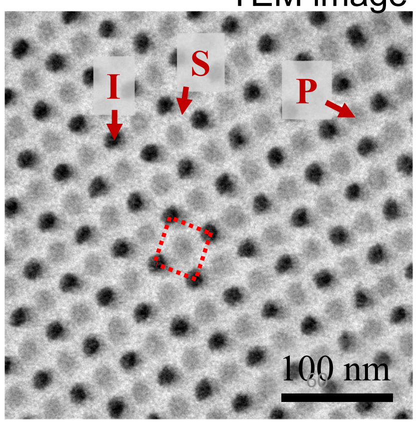


TEM image



Hexagonal Packed Cylinders (ISP:PSP=6:4)

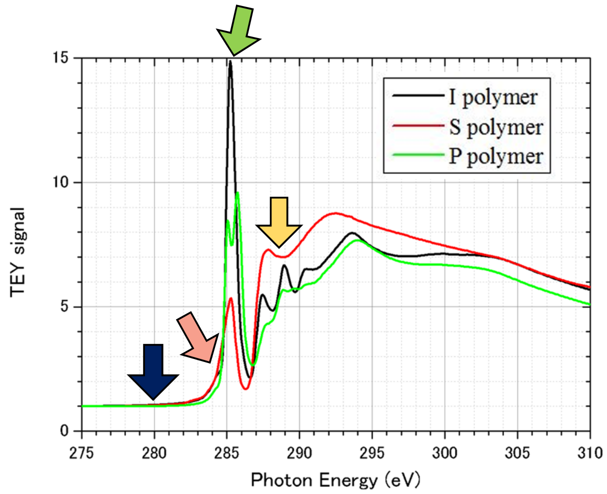
TEM image



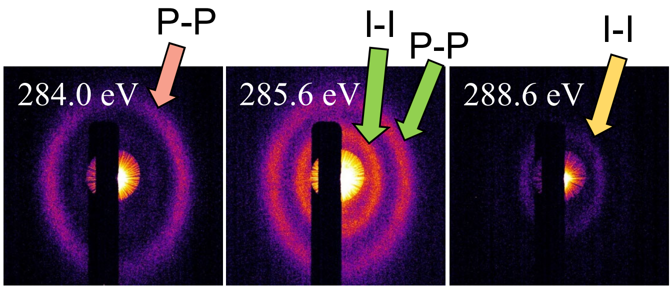
Tetragonal Packed Cylinders (ISP 100%)

Results and Discussion

◆ Hexagonal packed cylinder



XAS results of the three polymers



In the RSoXS measurement, it is possible to distinguish the polymer types by changing the probe photon energy.

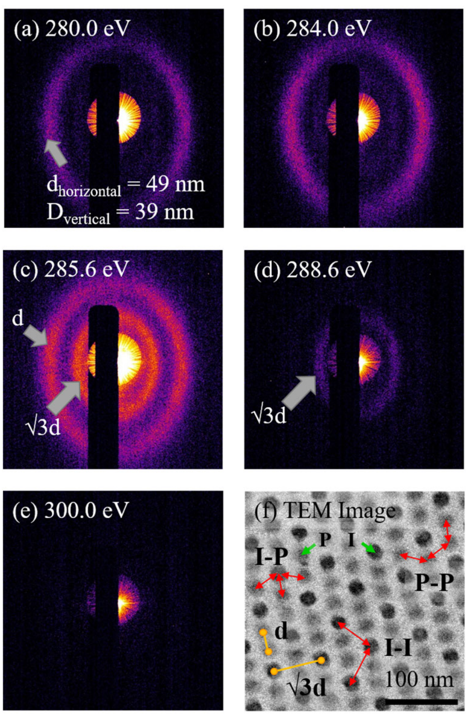
284.0 eV : P polymer had slightly small absorption. → Only P-P scattering

285.6 eV : Three polymers had different absorption. → Both I-I and P-P scatterings

288.6 eV : S polymer and P polymer had approximately same absorption.
→ Only I-I scattering

Results and Discussion

◆ Hexagonal packed cylinder



Scattering measurement results of hexagonal packed ISP triblock polymer

Two scattering signals with the ring-shape were recorded.

<u>Ellipse shape (not circle shape)</u>
→ The sample is streched along the horizontal direction.

<u>Ring-shape</u>
→ The domain size of this polymer is sufficiently smaller than the beam diameter of 100 μm.

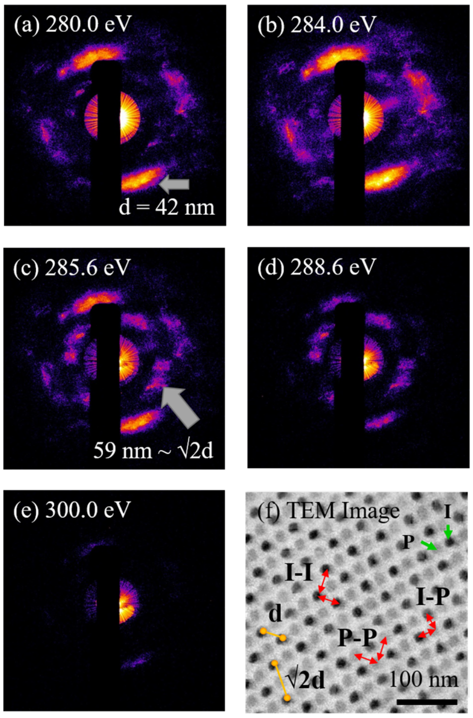
- The outer ring signals
→ were observed at <u>280.0</u>, <u>284.0</u>, <u>285.6</u> eV.
(a) (b) (c)

- The inner ring signals
→ were observed at <u>285.6</u>, <u>288.6</u> eV.
(c) (d)

(c)285.6 eV : π* bonding of benzyl group

Results and Discussion

◆ Tetragonal packed cylinder



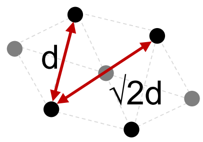
Scattering measurement results of tetragonal packed ISP triblock polymer

Four scattering signals were recorded at each inner and outer region.

Non-ring shape
→ The domain size of this polymer is larger than the illumination size of 100 μm.

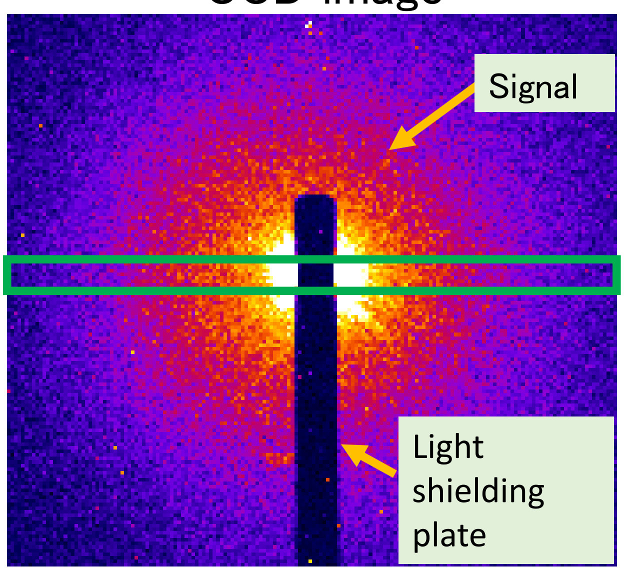
The d-spacing of the scatterings
→ Inner scatterings : 59 nm
Outer scatterings : 42 nm
$\sqrt{2}$ times

Outer scatterings
: The scattering from the I-I and P-P structures



RSoXS method

CCD image



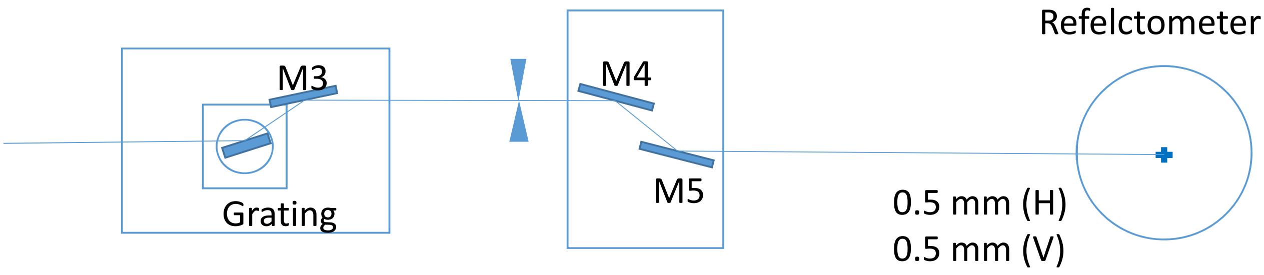
The scattering vector q can be calculated from the scattering intensity distribution obtained by CCD.

Scattering vector

$$q = \frac{4\pi}{\lambda} sin\left(\frac{\theta}{2}\right)$$

λ = wavelength
ϑ = scattering angle

Development of evaluation system of EUV resist by ultraviolet light (BL03)

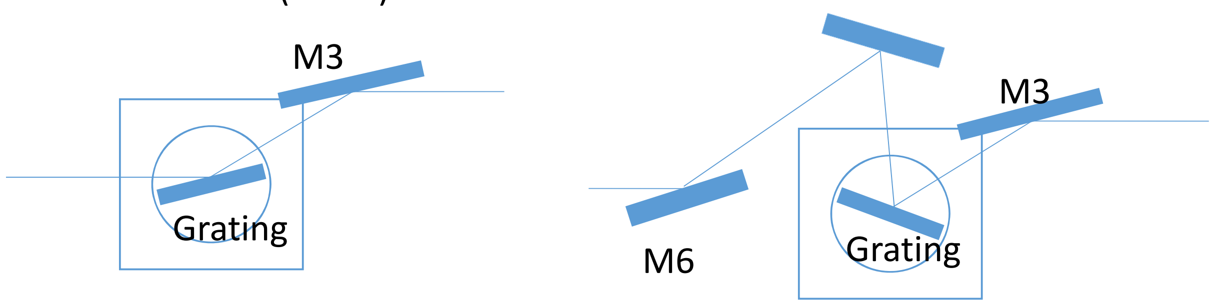


Since beam is almost parallel by the two toroidal mirrors, and a diffraction grating is inserted here. → Since the converging position does not depend on the wavelength, it is suitable for spectroscopic experiments

Development of evaluation system of EUV resist by ultraviolet light (BL03)

λ = 10 nm〜(BL-10)

λ = 80〜300 nm



An oblique incidence optical system is required because of short wavelength

an optical system including a large incident angle is required because of long wavelength

概要

1．半導体市場動向と半導体国際ロードマップ

2．EUVリソグラフィの露光波長

3．EUVリソグラフィの歴史

4．EUVリソグラフィの課題
　　レジストの線幅バラツキの低減

5．**Beyond EUVL**

6．まとめ

List of challenges for Beyond EUVL (λ=13.5 nm → 6.75 nm)

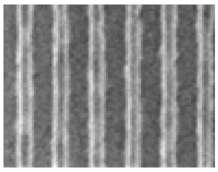
1) Imaging
- Flare level scales $\propto 1/\lambda^2$
- Bandwidth of a single mirror $\Delta\lambda/\lambda$(Mo/Si)=4% ➔ $\Delta\lambda/\lambda$(La/B4C)<1%
- Bandwidth of the optical column $\Delta\lambda/\lambda$(Mo/Si)=2% ➔ $\Delta\lambda/\lambda$(La/B4C)=0.6%

2) Multilayer for masks and optics
- Smaller layer thickness $\propto\lambda$
- Requirements to interlayer diffusion $\propto\lambda$
- Larger number of bi-layers per multilayer to increase the reflectivity.

3) Source
- New fuel is needed in LPP.
- EUV FEL is necessary.

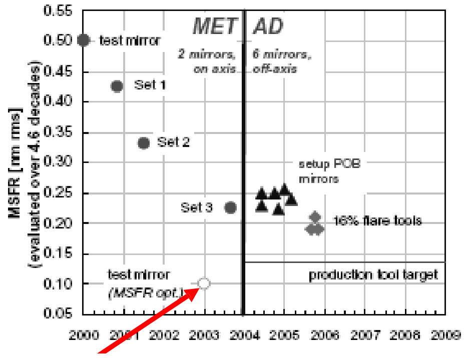
4) Resist
- Resist sensitivity becomes 5-7 times lower
  Quantum efficiency of current EUV resist will decrease due to lower absorption of 6.7nm(186eV) photons vs 13.5nm(92eV) photons
- Potential shot noise increase

Mid-spatial frequency (MSFR) and flare level



- Flare reduces contrast
- MSFR is linked to surface roughness
- Flare scales with wavelength as $1/\lambda^2$ so by 13.5nm➔6.x nm, flare increases 4x at the same MSFR

MSFR, nm	Flare, % 13.5nm	Flare, % 6.7nm
0.2	16	65
0.14	8	32
0.12	6	23
0.1	4	16
0.05	1	4



Achieved for NXE3100

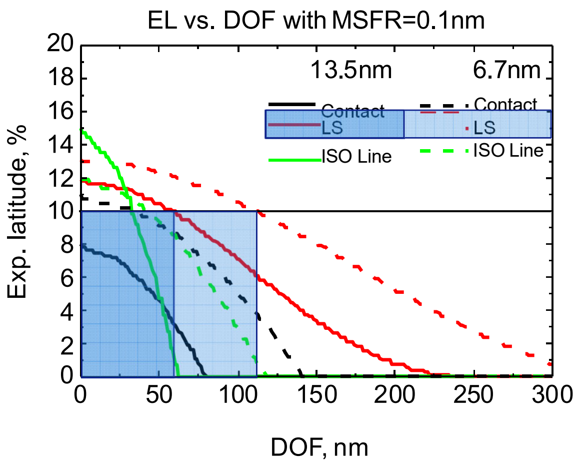
Demonstrated roughness (MSFR optimized)

0.1 nm MSFR can be taken for image simulation

By courtesy of ASML

Exp. latitude vs DOF as calculated for 11nm (conventional illumination σ=0.8)

Comparison 13.5nm@NA0.45 vs 6.7nm@NA0.25



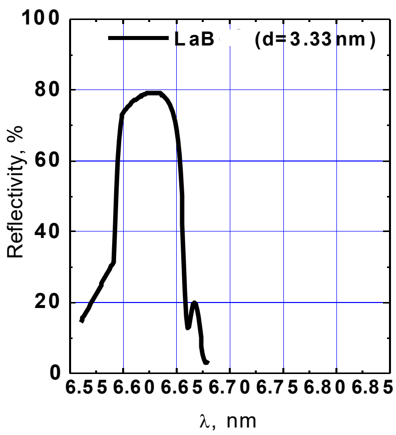
MSFR 0.1nm corresponds:
13.5nm - 4%
6.7nm -16%

Depth of Focus 2x larger with 6.7nm

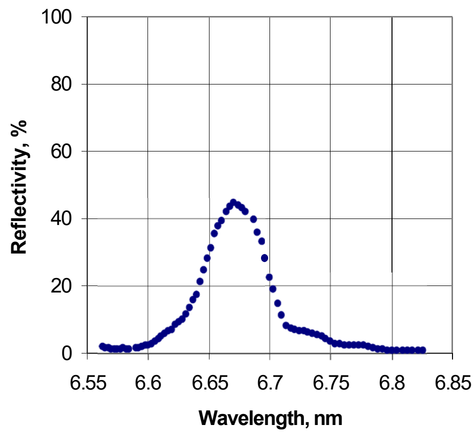
By courtesy of ASML

1st Pilot MLM coating La/B_4C for the range 6.6-7.0 nm

Theoretical



1st experimental MLM



λ=6.63nm, δλ=0.06nm, R=80% λ=6.67nm, R=44.3%, δλ=0.06nm

Reason for low R: interlayer diffusion ➔ Reflectivity can be improved

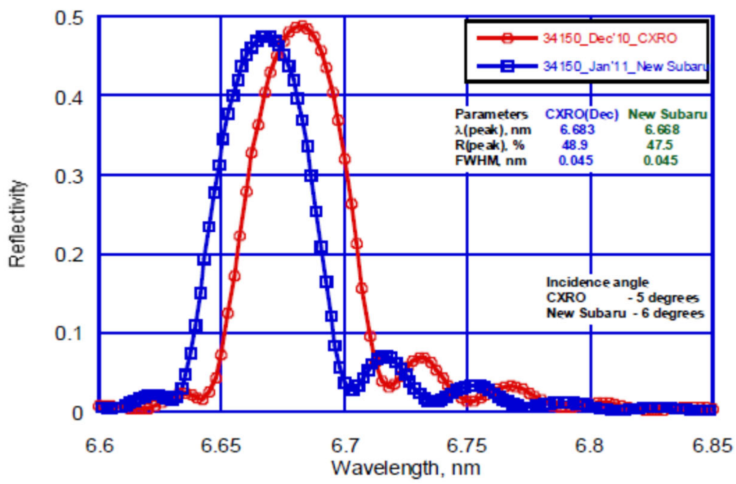
Bandwidth of the optical column (11 mirrors):

ΔλΣ/λ(La/B4C)=0.6% (vs 2% for 13.5 nm)

IPM PhysTeX

Next Generation EUVL Optics for 6.X nm

- Achieved the highest measured reflectivity to date, actively developing multilayers to their theoretical limit ~ 70%

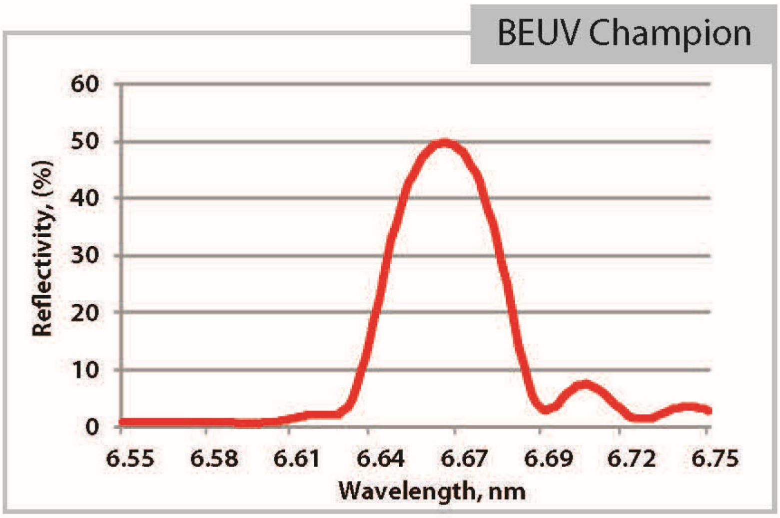


By courtesy of Rigaku

Glancing to Normal Incidence Optics for 6.x nm (BEUV)

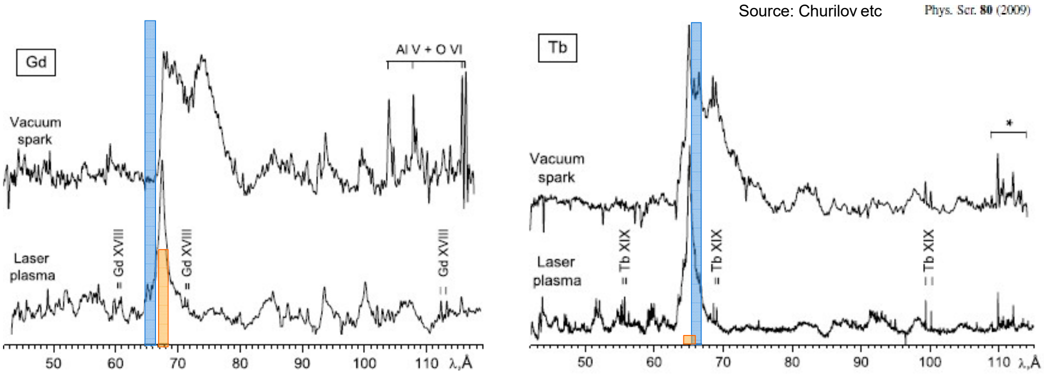
Even as EUVL approaches adoption for high volume manufacturing, the semiconductor industry is investigating next generation tools. Beyond EUV (BEUV) is based on current development of new soft X-ray sources and associated multilayer optics. Today, we offer the highest performance optics available for BEUV.

La/B_4C multilayer on a commercial silicon wafer, measured by New SUBARU at 7 degrees from normal.



By courtesy of Rigaku

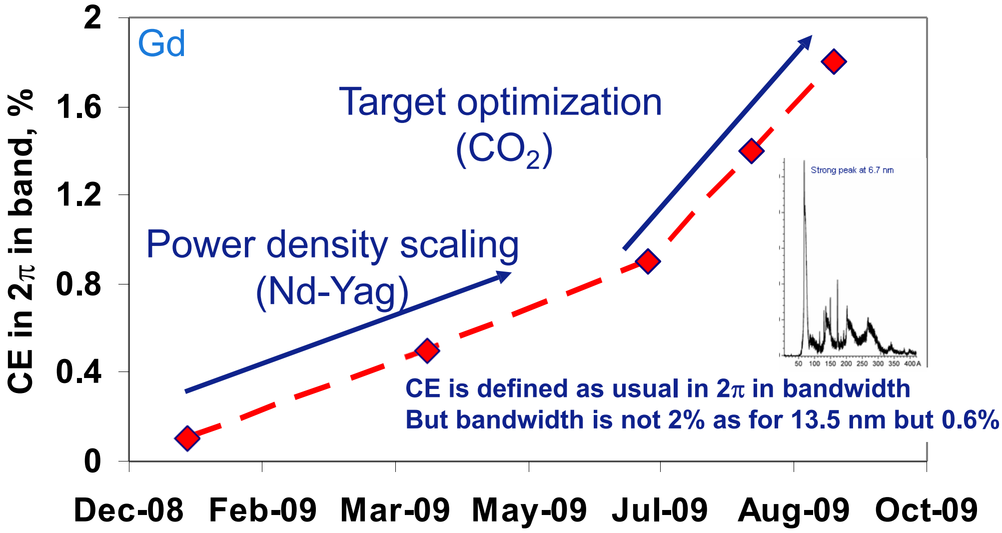
Source: materials and spectra



- Optical throughput optimized for the coating (10 mirrors)
- Optical throughput optimized for the maximum emission spectrum

•Gd and Tb are the main potential materials of choice for 6.x lithography
•Simultaneous optimization of ML band and emission spectral power is required

Investigating Conversion efficiency (CE) for 6.77 nm with LPP

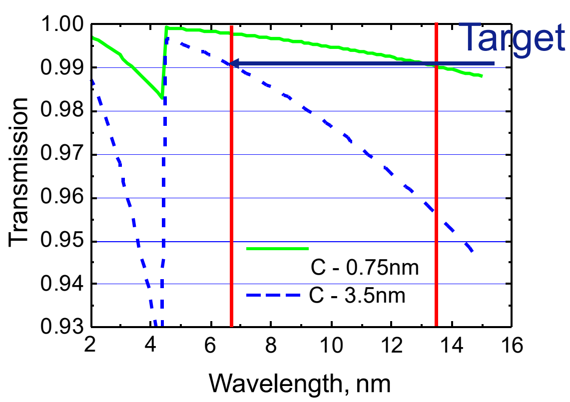


In-band CE for 6.x nm (1.8% vs theoretical 3-5%) is already comparable with that of 13.5 nm Sn

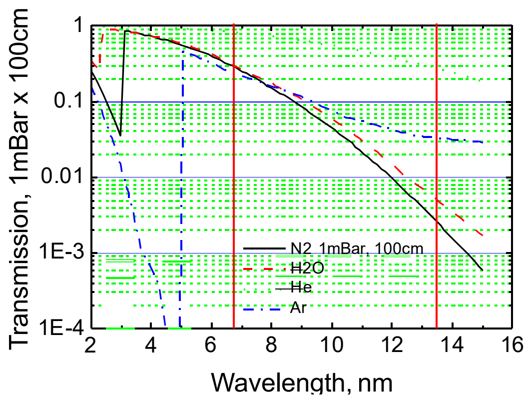
Transmission of C and absorption in gases

6.7 nm vs 13.5 nm

Carbon-contaminated mirror



Gas absorption



No transmission penalty for the same C growth (<10% for optical column) or 5x thicker C on MLMs can be tolerated for the same transmission loss

Less transmission loss (~10%) or Gas absorption is 10-1000x less ➔
-Less strict vacuum specs
-Mitigation schemes will work much better

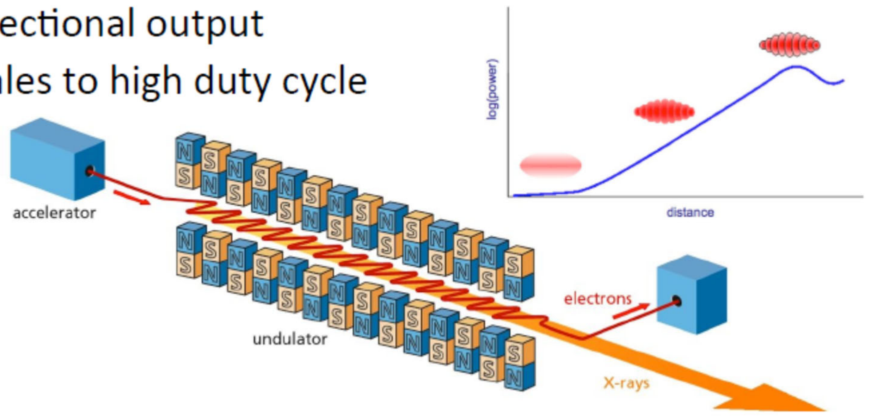
By courtesy of ASML

FEL for EUV Light Source

FEL is a clean light source

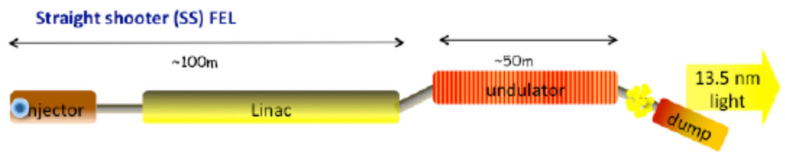
- In Free Electron Laser relativistic electrons travel through the undulator magnet in vacuum and generate X-rays
- No contamination
- Minimal thermal load
- Directional output
- Scales to high duty cycle

high quality e-beam = microbunching and coherent amplification



FEL for EUV Light Source

Short term risk profile comparison



Leveraged on LCLS-II design and development, and X-FEL experience worldwide

Well developed modeling tools

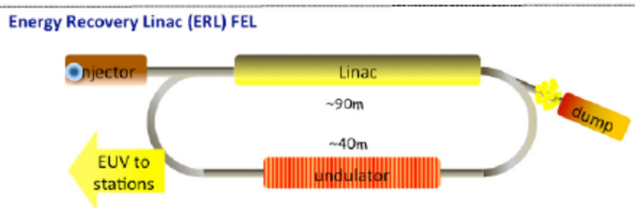
Massive practical experience with single pass X-FEL, large pool of experts and trained personnel

Smaller injected/recirculated current

Untested physics of high efficiency short wavelength FEL

Higher RF and beam dump costs

Modular design, enables future upgrades, also testing can be done in existing facilities



Leveraged on Jlab design and 10 kW IR ERL FEL (2001)

Closed system, has to be developed and tested in its entirety

High injected/recirculated current, machine protection is an issue

Untested physics of short wavelength ERL FEL

Very elegant solution to reducing the RF power and beam dump costs

Very few operating ERL facilities worldwide

Numerical tools require validation

BEUV

1) Lithography for 6.x nm wavelength has a potential to extend EUVL beyond 10 nm node

2) ML coatings
- Potential of for high reflectivity (up to 80%) for LaB_4C
- Currently demonstrated reflectivity is 44% thus better inter-layer diffusion control is required

3) EUV source
- Two types potential source fuels are investigated: Tb and Gd
- Considering resist sensitivity, EUV-FEL is necessary.

4) Optimization of EUV source spectrum with ML optics is required

5) Transmission of gases and contaminants for 6.x is significantly (up to 5x) better than for 13.5 nm

6) 6.x EUVL has a potential for a throughput comparable with 13.5 nm lithography at higher resolution

Thank you for your kind attention!!