微細加工用レジスト

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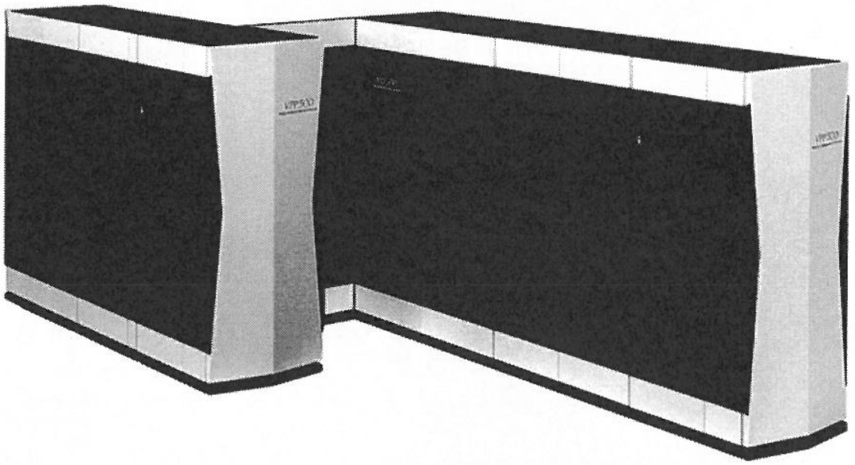
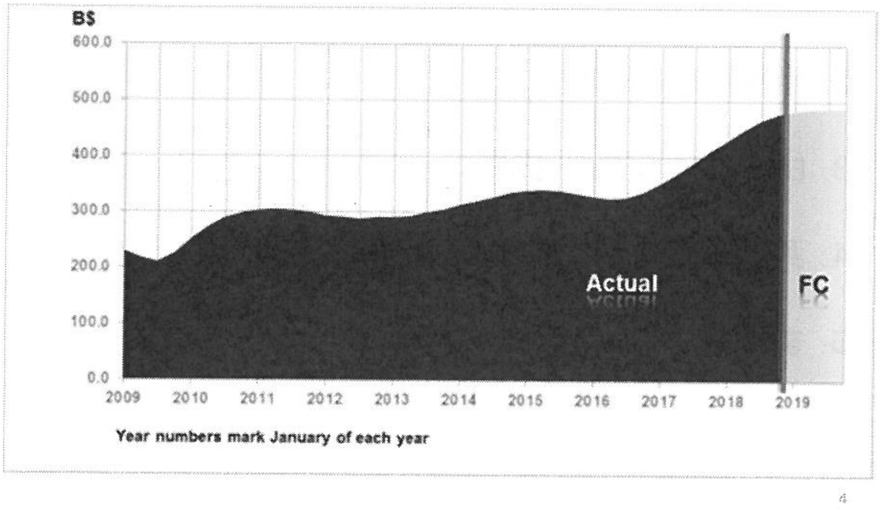
概要

1. はじめに
   半導体の市場、微細加工の必要性
2. 半導体用レジスト
3. EUVリソグラフィー技術
4. 兵庫県立大学のEUVレジスト研究開発
5. まとめ

1990年代後半のスーパーコンピュータ （foot print = 6 m × 6m）
＝ iPhone SEと同等の処理能力



WSTS（WORLD SEMICONDUCTOR TRADE STATISTICS
Participating company: Total 45 companies
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.



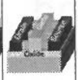
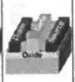
WSTS Forecast Summary

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

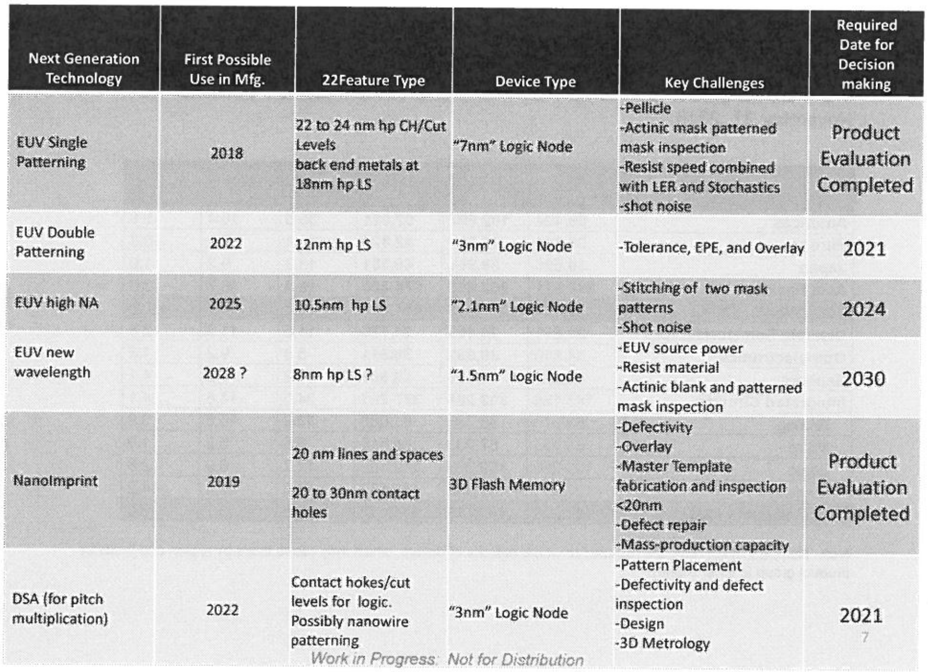
Note: Numbers in the table are rounded to whole millions of dollars, which may cause totals by region and totals by product group to differ slightly.

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							
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

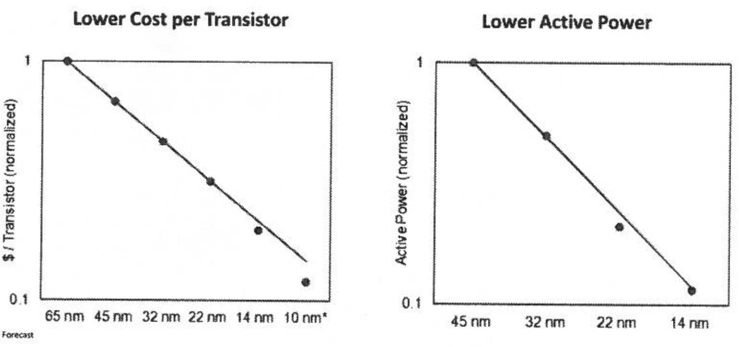


Next Generation Technology	First Possible Use in Mfg.	22Feature Type	Device Type	Key Challenges	Required Date for Decision making
EUV Single Patterning	2018	22 to 24 nm hp CH/Cut Levels back end metals at 18nm hp LS	"7nm" Logic Node	-Pellicle -Actinic mask patterned mask inspection -Resist speed combined 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

Moore's Law: Economics and Power

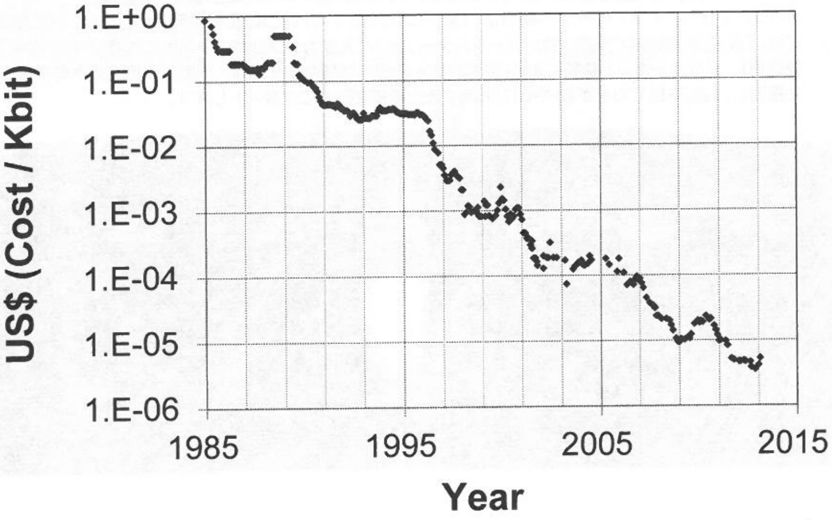
Cost and Power



Reference: Intel, Bill Holt, ISSCC 2016

Embedded Systems and Innovation Technologies for IoT Applications, Ali Keshavarzi. IEDM 2016.

Memory Cost



微細加工の必要性とその効果

半導体国際ロードマップに従い、微細加工技術の開発が進めれてきた。

微細加工技術により以下の効果がある。

1）集積度向上

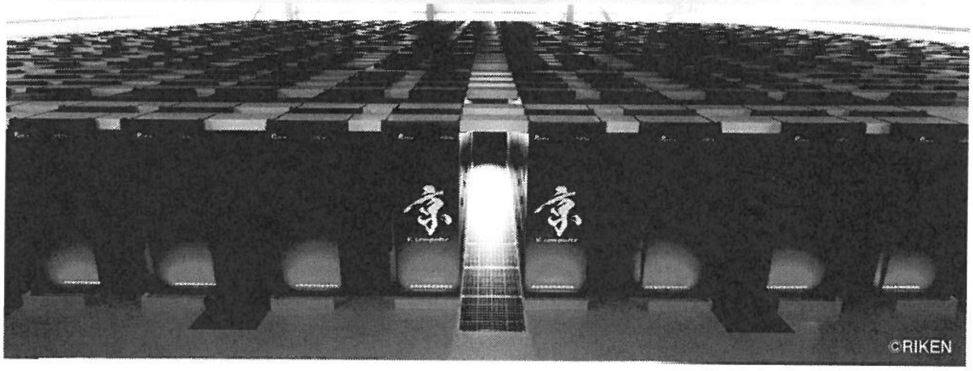
2）処理速度の向上

3）低消費電力の実現

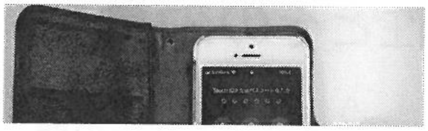
スーパーコンピュータ（スパコン）

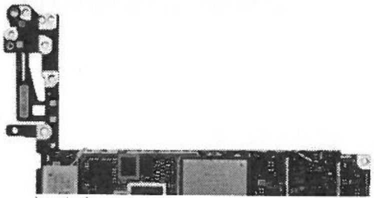
～「京」直結の端末を備えた個室で快適な作業を～

HPCIアクセスポイント神戸(AP神戸)は、「京」をはじめとするHPCIの産業利用拠点です。２室の作業用個室には、「京」と高速回線で接続されたワークステーション（入出力やプリポスト処理に最適）と利用端末（ジョブ管理用）、インターネット接続による「京」以外のHPCIの利用端末を完備。手厚い利用支援や高セキュリティも提供し、「京」をはじめとするHPCIを利用する企業様を強力にサポートします。

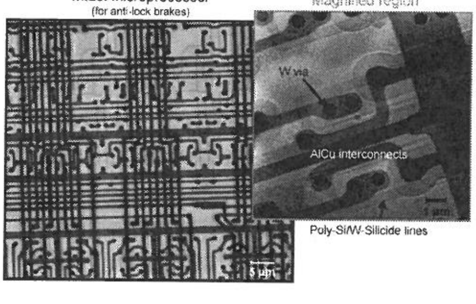


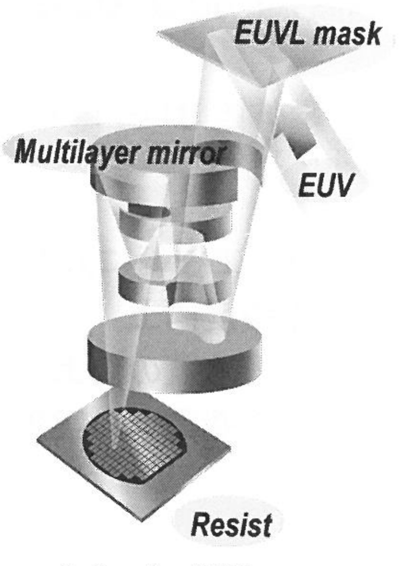
EUVリソグラフィー技術　いよいよ量産開始！！





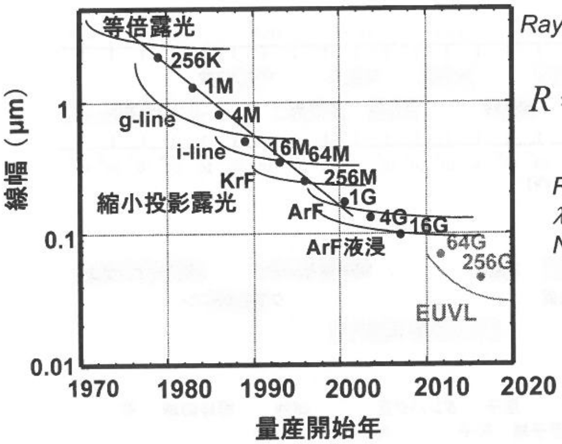
Intact microprocessor
(for anti-lock brakes)





Configuration of EUVL

リソグラフィ技術のトレンド



Rayleigh equation

$$R = k_1 \frac{\lambda}{NA}$$

R : 解像度

λ : 波長

NA : 開口数

縮小投影露光方法に於ける解像度、焦点深度

$$R = k_1 \frac{\lambda}{NA}$$

$$DOF = k_2 \frac{n\lambda}{NA^2}$$

R: 解像度

DOF: 焦点深度

NA: 開口数

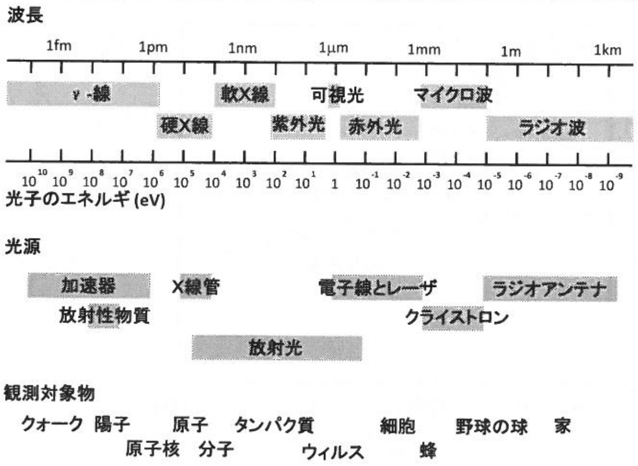
k1: プロセス系数

k2: プロセス系数

n: 媒質の屈折率

λ: 露光波長

光の種類、波長、エネルギ、光源、観測可能な物質について



波長

1fm　1pm　1nm　1μm　1mm　1m　1km

γ-線　軟X線　可視光　マイクロ波

硬X線　紫外光　赤外光　ラジオ波

10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}

光子のエネルギ (eV)

光源

加速器　X線管　電子線とレーザ　ラジオアンテナ

放射性物質　クライストロン

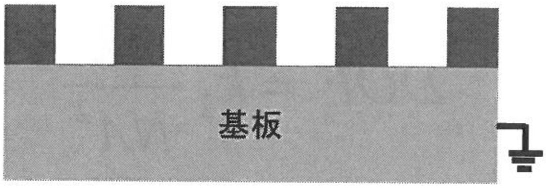
放射光

観測対象物

クォーク　陽子　原子　タンパク質　細胞　野球の球　家

原子核　分子　ウィルス　蜂

リソグラフィとドライエッチングによるSiO_2のパタン形成



ULSI（Ultra Large Scaled Integrated Circuit）

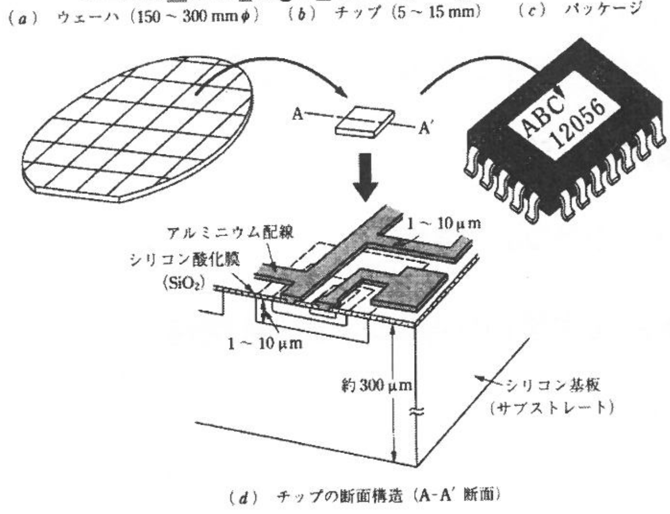


図 3.1 モノリシック IC

半導体リソグラフィの3原則

1） バルク基板マスクが使用できること

2） 縮小投影光学系を使用できること

3） 複数世代に渡って使用できる技術であること

概要

1. はじめに
 半導体の市場、微細加工の必要性

2. 半導体用レジスト

3. EUVリソグラフィー技術

4. 兵庫県立大学のEUVレジスト研究開発

5. まとめ

感光性樹脂の研究の歴史

1820年代 Niepceがヘリオグラフィーを考案
ポリオレフィンの光架橋マスク

重クロム酸塩感光性材料（現在でも使用）

銀塩感光性材料（現在でも銀塩写真に使用）

1940年 プリント配線板の開発 英国Eisler

1948年 トランジスタの発明 Shockley

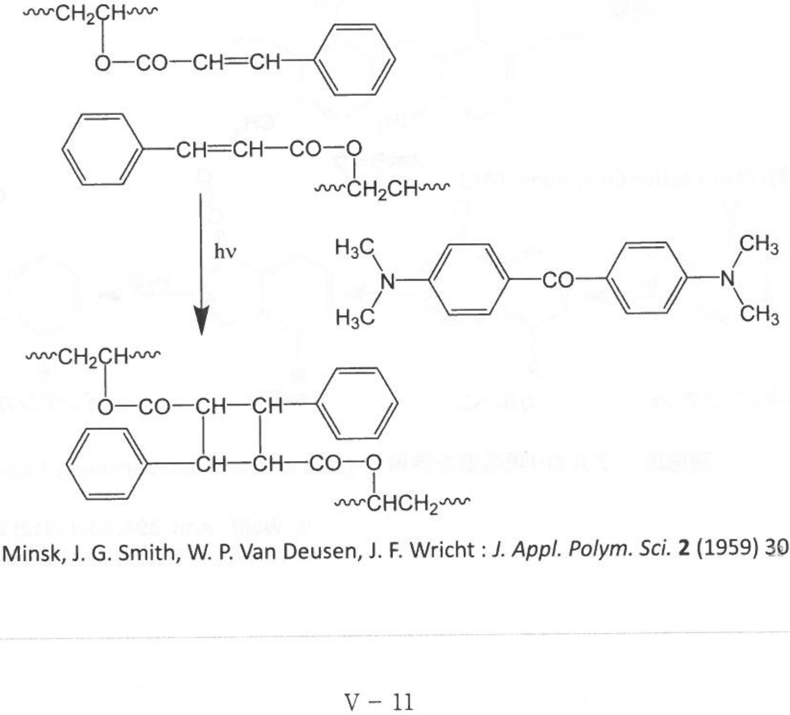
1950年代初期 感光性樹脂凸版の開発 Dupon, Timelife

レジスト材料に要求される性能

- 安全な溶媒に溶ける
- 欠陥のない均一な膜を生成する。
- 種々の基板の接着する。
- 合成が容易である。
- 保管保全性が良い。
- 人体、環境に害を及ぼさない。
- 熱安定性が高い。
- 露光波長に対して適度な吸収がある。
- 良好なドライエッチング耐性を有する。
- 高いコントラストを有する。
- 高い解像度を有する。
- 広いプロセス余裕度を有する。
- 低価格である。

レジスト材料発展の歴史

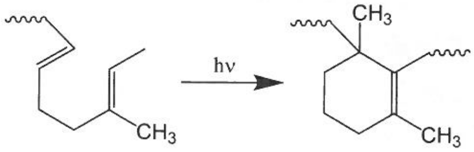
Kodak Photo Resist (KPR)

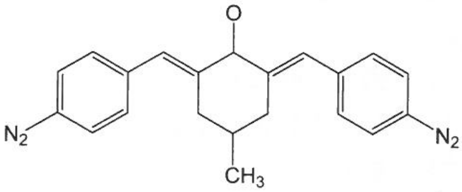


L. M. Minsk, J. G. Smith, W. P. Van Deusen, J. F. Wricht : *J. Appl. Polym. Sci.* **2** (1959) 302.

レジスト材料発展の歴史

Kodak Thin Film Resist (KTFR)



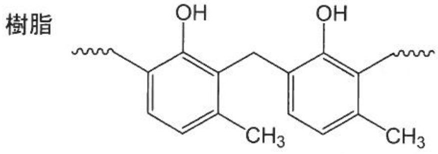


ビスアジド感光剤

E. Kodak : USP. 2852379 (1958) ; 2940853 (1960)

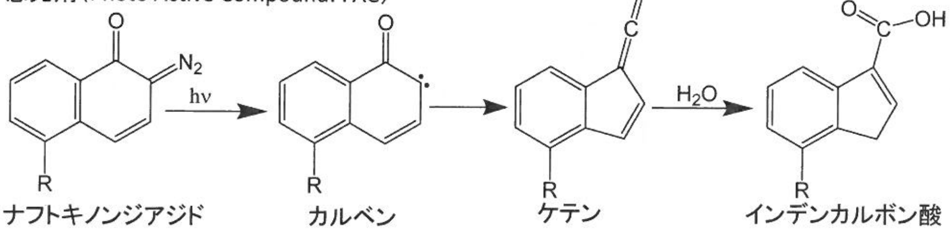
レジスト材料発展の歴史

ナフトキノンジアジド（Diazonaphthoquinone (DNQ)）



ノボラック

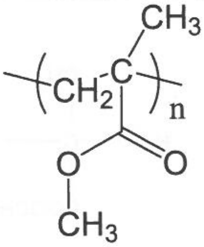
感光剤（Photo Active Compound: PAC）



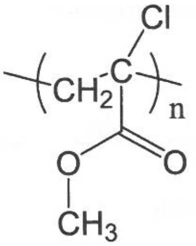
現像液: アルカリ現像液を使用 (2.38 wt% tetra ammonium hydroxide)

L. Wolff : Ann. **394**, 65, (1912) 25.
F. Arrndt, B. Eister : Ber. **68** (1935) 200.

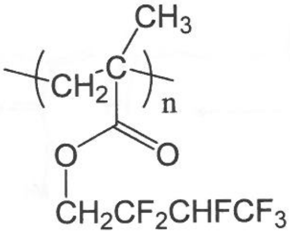
主鎖切断型レジストの例



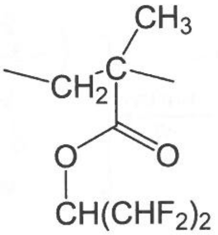
PMMA



EBR-9

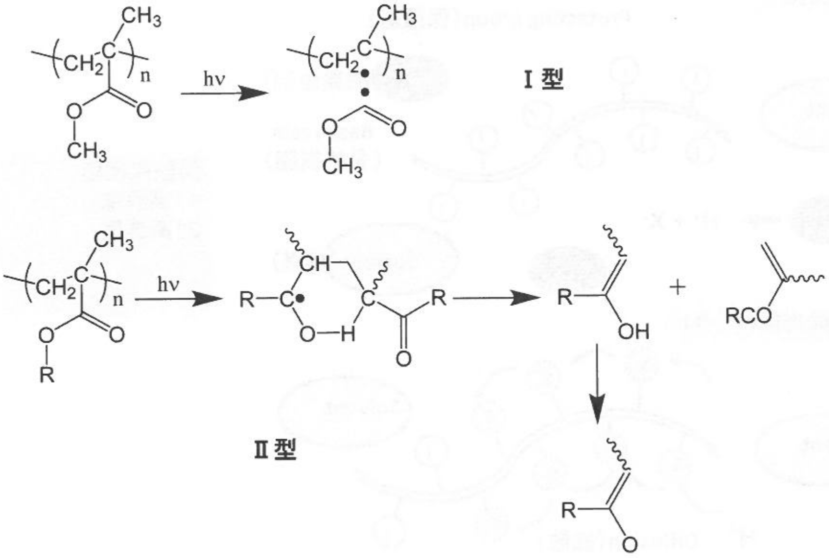


FBM



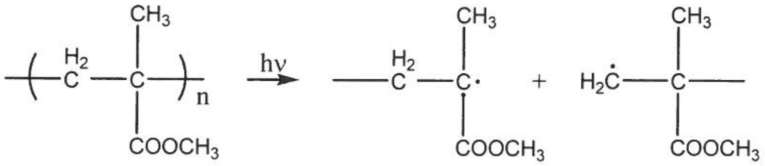
FPM

主鎖切断型レジストの例



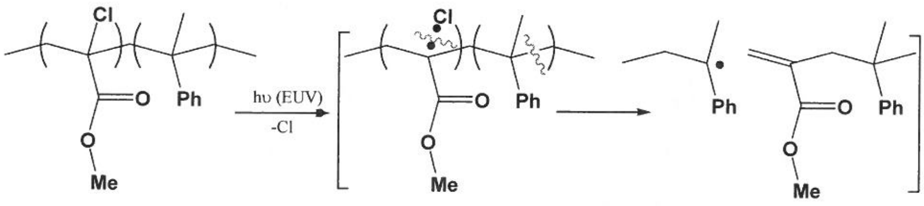
主鎖切断型レジストの例

PMMA（poly (methyl methacrylate)）

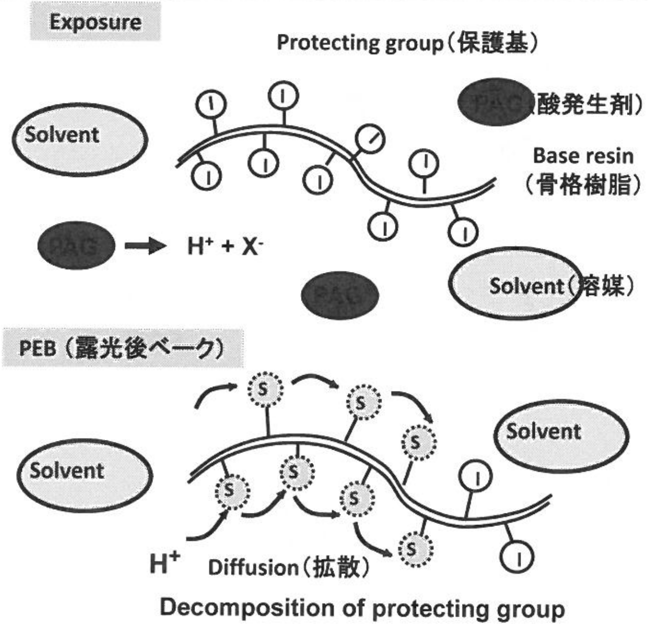


$$-\!\left(CH_2-C(CH_3)(COOCH_3)\right)_n- \xrightarrow{h\nu} -CH_2-\dot{C}(CH_3)(COOCH_3) + H_2\dot{C}-C(CH_3)(COOCH_3)-$$

ZEP520A



Chemically amplified resist (positive-tone)
化学増幅系レジスト（ポジ型）



Exposure

Protecting group（保護基）

PAG（酸発生剤）

Solvent

Base resin（骨格樹脂）

PAG → $H^+ + X^-$

Solvent（溶媒）

PEB（露光後ベーク）

Solvent

Solvent

H^+ Diffusion（拡散）

Decomposition of protecting group

酸触媒反応
1）高解像
2）高感度

レジスト材料の歴史
ー EUV用レジスト材料は？ ー

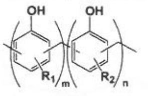
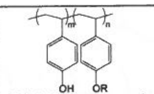
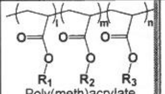
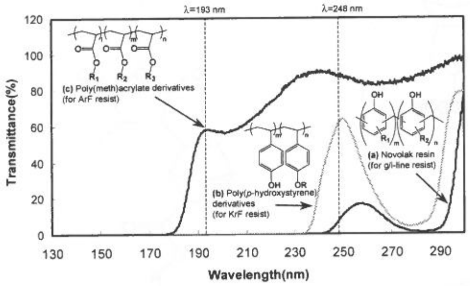
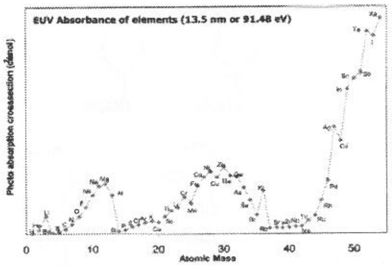
Light source	g-line/ i-line	KrF	ArF	EUV	EB
Wave length	365 nm	248 nm	193 nm	13.5 nm	—
Base polymer	 Novolak resin	 Poly(*p*-hydroxystyrene) derivatives	 Poly(meth)acrylate derivatives	??	Similar to KrF resist

Figure. Examples of resist base polymer compatible with various exposure light sources.

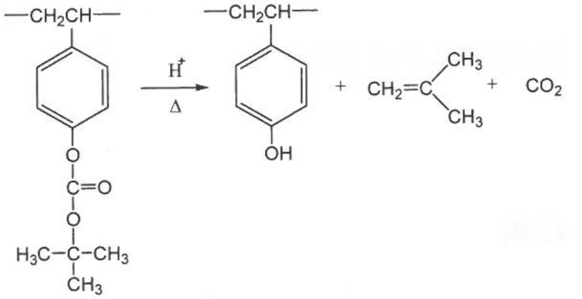




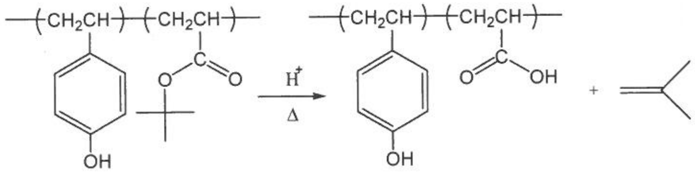
C. K. Ober et.al, EUV Symposium 2004.

化学増幅系レジストの例

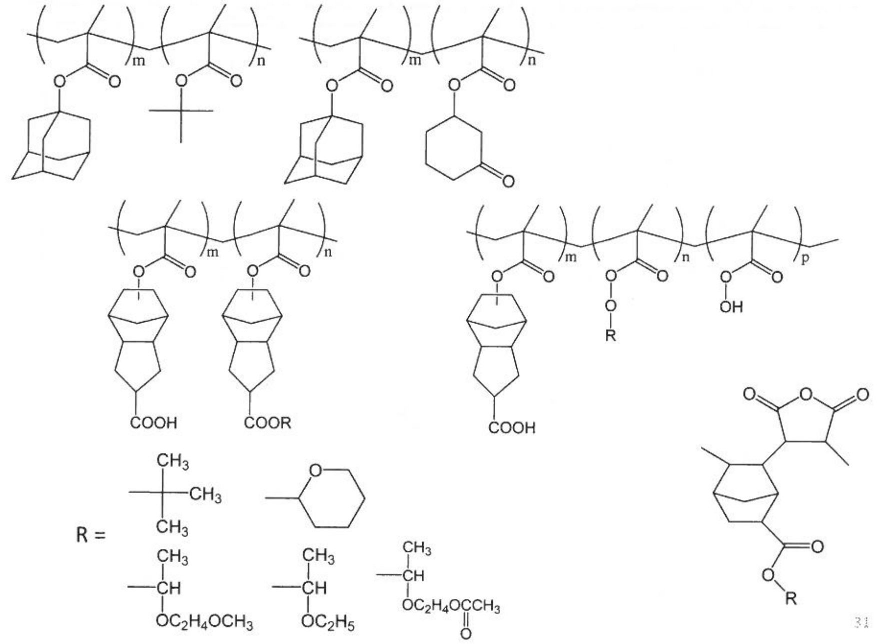
Polyhydroxystyrene t-butoxycarbonyl group



ESCAP (環境安定化学増幅系レジスト)



ArF用レジスト材料



概要

1. はじめに
   半導体の市場、微細加工の必要性

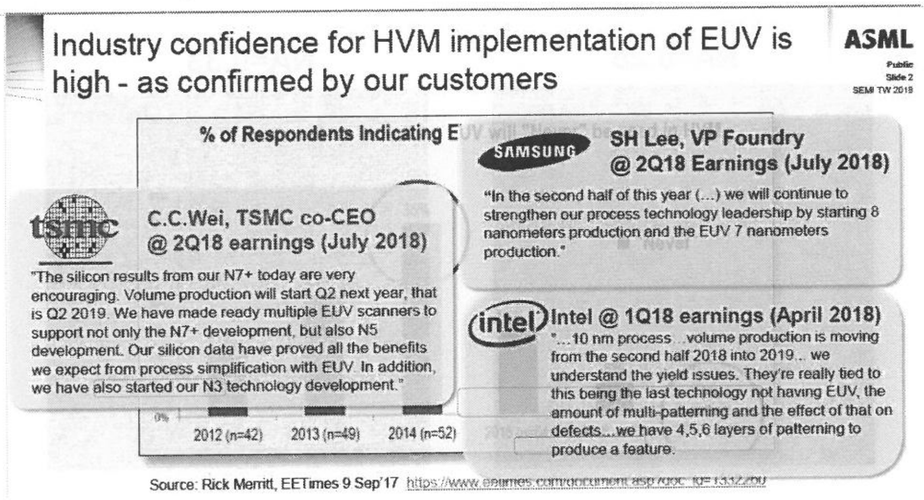
2. 半導体用レジスト

3. EUVリソグラフィー技術

4. 兵庫県立大学のEUVレジスト研究開発

5. まとめ

EUV is ready to go…



Industry confidence for HVM implementation of EUV is high - as confirmed by our customers

ASML
Public
Slide 2
SEMI TW 2018

C.C.Wei, TSMC co-CEO @ 2Q18 earnings (July 2018)

"The silicon results from our N7+ today are very encouraging. Volume production will start Q2 next year, that is Q2 2019. We have made ready multiple EUV scanners to support not only the N7+ development, but also N5 development. Our silicon data have proved all the benefits we expect from process simplification with EUV. In addition, we have also started our N3 technology development."

SH Lee, VP Foundry @ 2Q18 Earnings (July 2018)

"In the second half of this year (...) we will continue to strengthen our process technology leadership by starting 8 nanometers production and the EUV 7 nanometers production."

Intel @ 1Q18 earnings (April 2018)

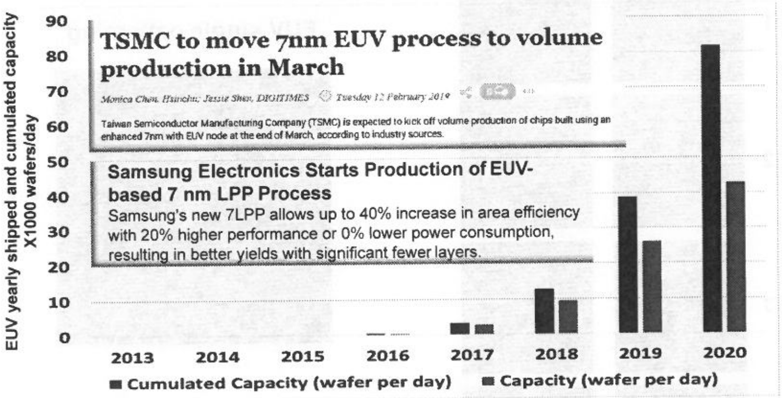
"...10 nm process...volume production is moving from the second half 2018 into 2019... we understand the yield issues. They're really tied to this being the last technology not having EUV, the amount of multi-patterning and the effect of that on defects...we have 4,5,6 layers of patterning to produce a feature.

Source: Rick Merritt, EETimes 9 Sep'17 https://www.eetimes.com/document.asp?doc_id=1332260

November 16 2018

With 40 systems now in the field and increasing year on year productivity, EUV capacity is increasing rapidly

Public
Slide 3
SPIE 2019



TSMC to move 7nm EUV process to volume production in March

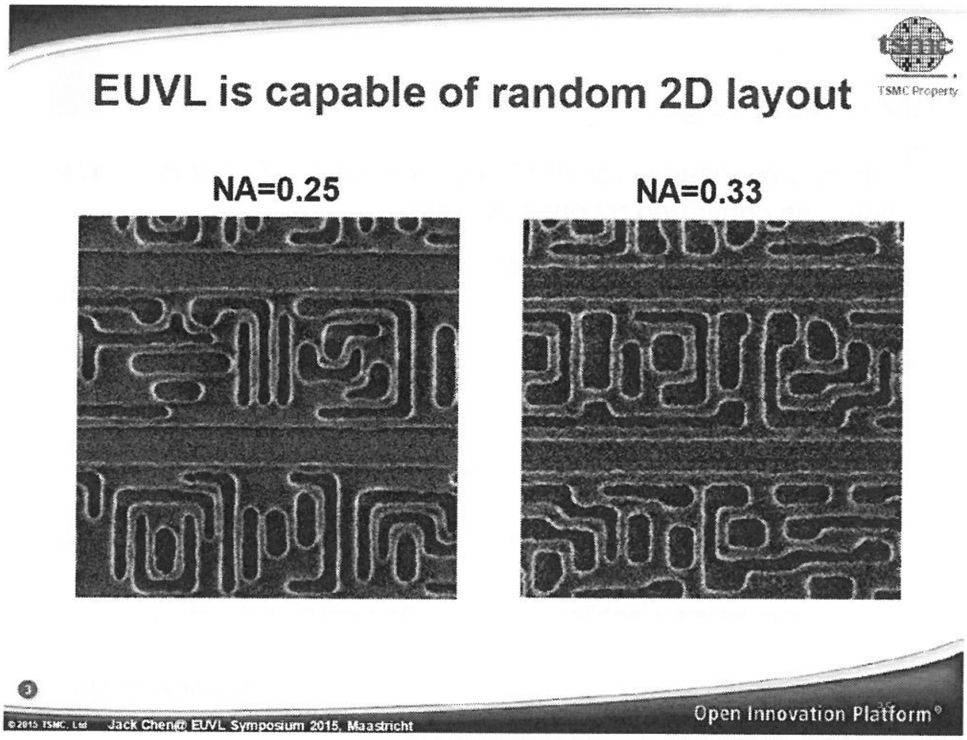
Monica Chen, Hsinchu; Jessie Shen, DIGITIMES Tuesday 12 February 2019

Taiwan Semiconductor Manufacturing Company (TSMC) is expected to kick off volume production of chips built using an enhanced 7nm with EUV node at the end of March, according to industry sources.

Samsung Electronics Starts Production of EUV-based 7 nm LPP Process

Samsung's new 7LPP allows up to 40% increase in area efficiency with 20% higher performance or 0% lower power consumption, resulting in better yields with significant fewer layers.

Source: 'TSMC to move 7 nm EUV process to hvm in March', Digitimes 12 Feb 2019 / 'Samsung starts production of EUV-based 7 nm LPP process', Samsung press room, 18 Oct 2018



EUVL is capable of random 2D layout

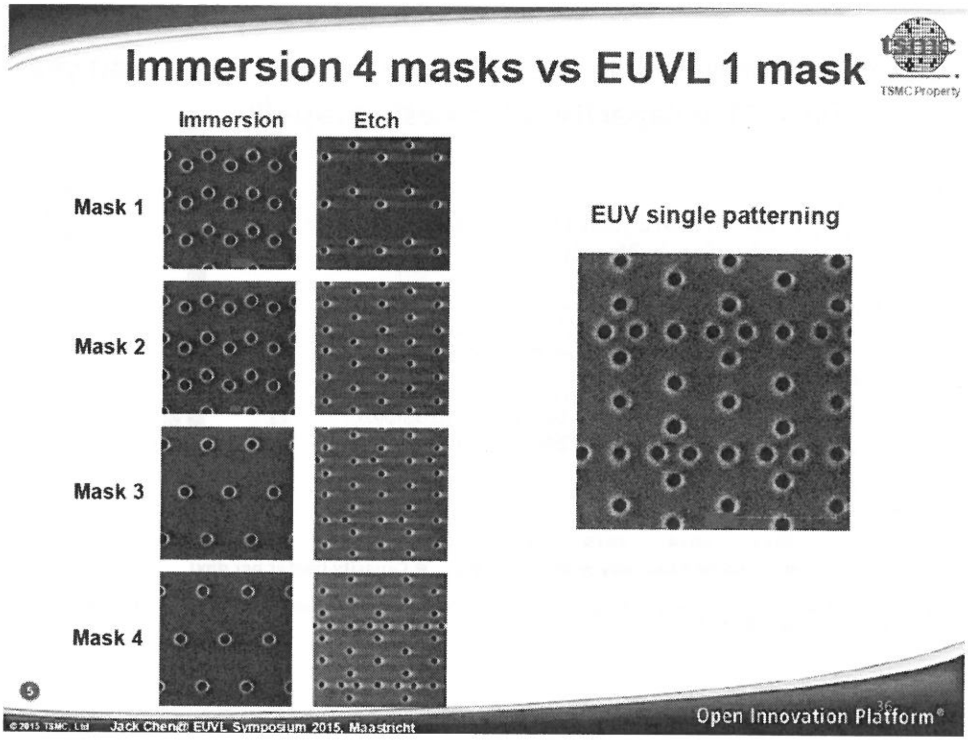
TSMC Property

NA=0.25 **NA=0.33**

③

©2015 TSMC, Ltd Jack Chen@ EUVL Symposium 2015, Maastricht

Open Innovation Platform®



Immersion 4 masks vs EUVL 1 mask

TSMC Property

Immersion Etch

Mask 1

Mask 2

Mask 3

Mask 4

EUV single patterning

⑤

©2015 TSMC, Ltd Jack Chen@ EUVL Symposium 2015, Maastricht

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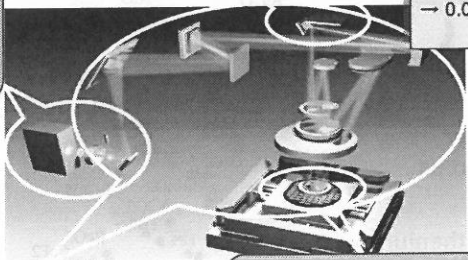
Technical issues of EUV Lithography



Mask with no defects
Mask Inspection, repair, a handling, and contamination control

0.1 /cm2 @56nm
→ 0.01 /cm2 @40nm (Pilot Line)
→ 0.003 /cm2 @25nm (HVM)

High power EUV light source with good stability

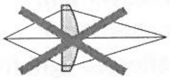
55 W @IF
80 W @IF 2013
125 W @IF 2014
250 W @IF 2015

EUV imaging optics
ASML ADT 32 nm node NA 0.25
ASML NXE-3100 25 nm node
ASML NXE-3300B 22 nm node NA 0.33

EUV resist
High sensitivity, low line width roughness (LWR), low outgassing

20 mJ/cm2, LWR 5 nm
→ 10 mJ/cm2, LWR 2 nm

Background: Comparison of soft x-ray optics



- Refractive optics can not be used in principle.

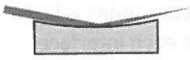
Refractive index ≈1

- Zone plate using diffraction

Suitable for pencil beam radiation
Field of view is as narrow as several mm
Low diffraction efficiency is low.
It is suitable for light collection.

- Grazing incidence optical system using total reflection

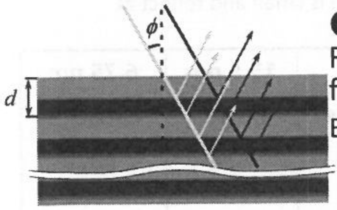
It is difficult to achieve both a large numerical aperture and low aberration.



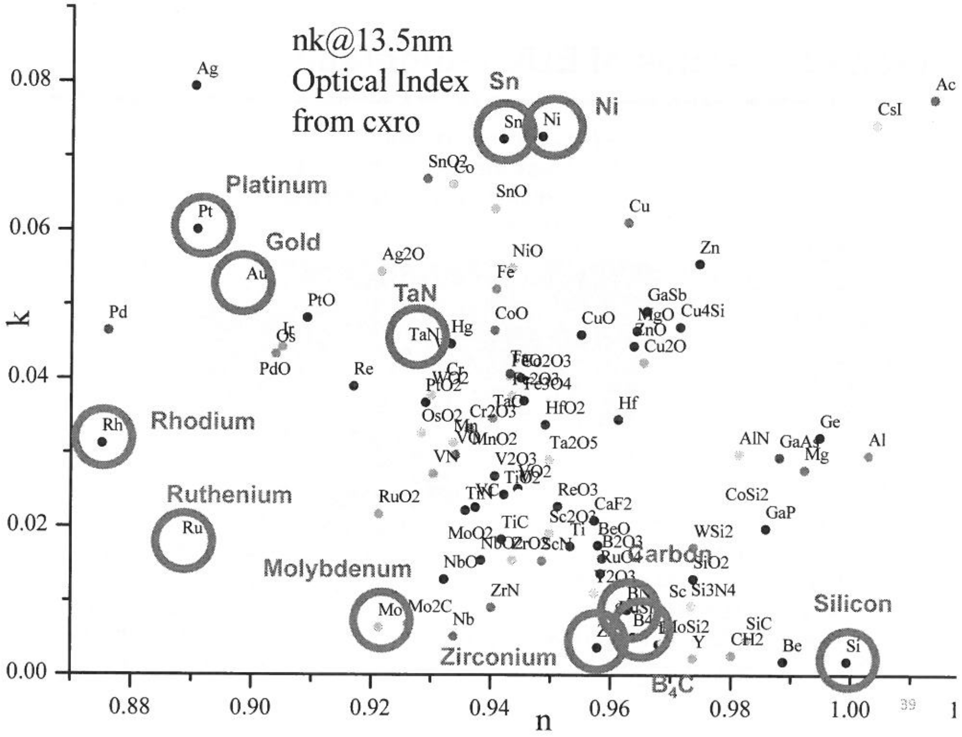
- Use constructive interference

Reflection increasing multilayer film
Bragg condition $m\lambda = 2nd\cos\varphi$

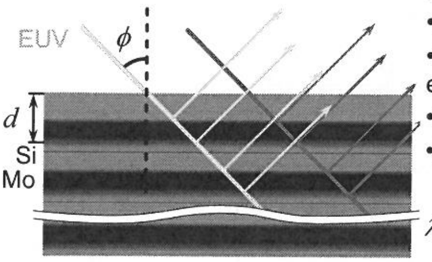
m: Bragg order
λ: Wavelength
n: Refractive index
d: Cycle length
ϕ: Normal incidence angle



Possible to construct reflective optics with high degree of freedom and bright and wide-field optical



Multilayer film reflector for EUVL

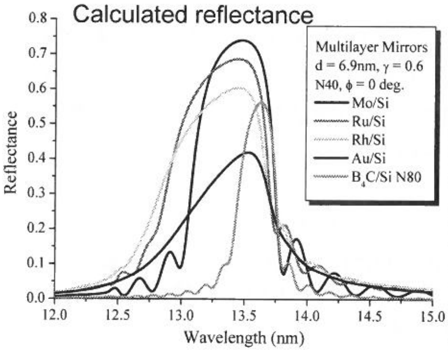


Reflection increasing multilayer film

- Stacking two substances alternately
- Enhancement of slight reflected light from each interface
- Normal incidence optical element
- Expressing by Bragg equation

$$2d\cos\phi = m\lambda \quad (m=1,2,3,..)$$

λ: wavelength, ϕ: incident angle, d: cycle length

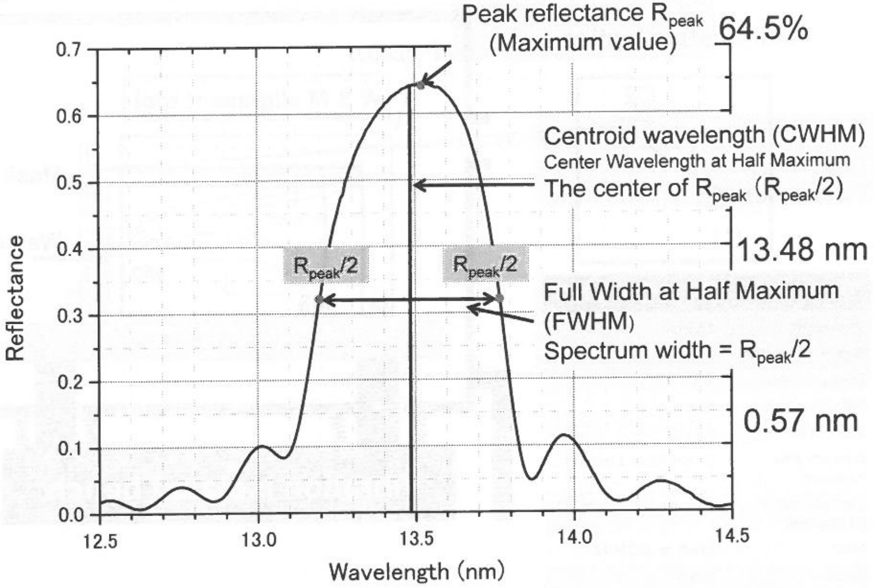


Selection of substance pairs

- The difference in refractive index is large Increase the reflection at each interface
- The absorption is small and reflect at many interfaces

Wavelength	13.5 nm	6.75 nm
Pair materials	Mo/Si	LaN/B_4C
Reflectance (measured)	70%	58%
Remarks	EUVL	BEUV

Reflection spectrum of multilayer film and its performance evaluation index



Definitions of Reflectance, centroid wavelength, and wavelength width

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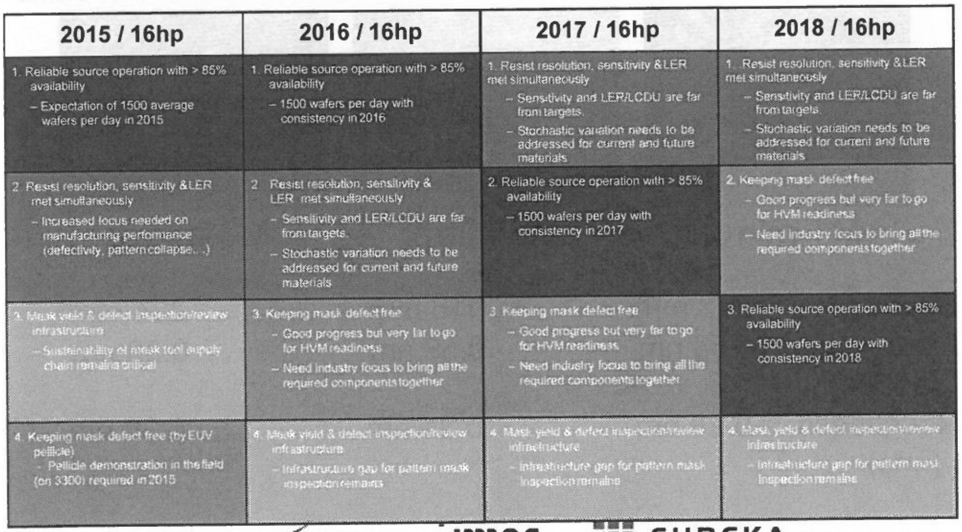
2018 International Symposium on Extreme Ultraviolet Lithography

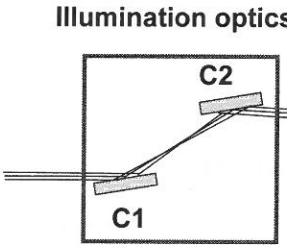
EUV FOCUS AREAS

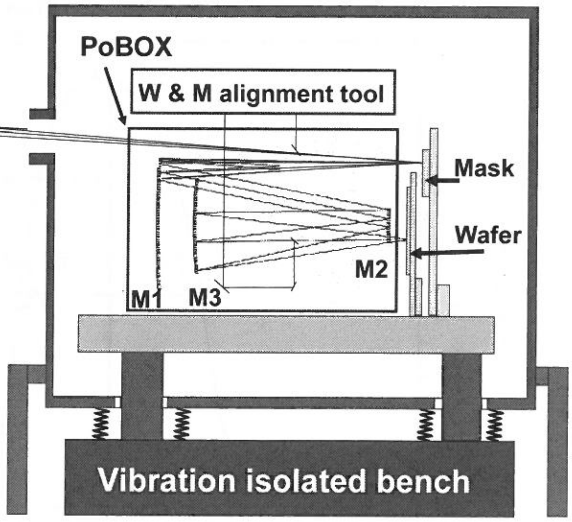


2015 / 16hp	2016 / 16hp	2017 / 16hp	2018 / 16hp
1. Reliable source operation with > 85% availability – Expectation of 1500 average wafers per day in 2015	1. Reliable source operation with > 85% availability – 1500 wafers per day with consistency in 2016	1. Resist resolution, sensitivity &LER met simultaneously – 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. 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. 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. Reliable source operation with > 85% availability – 1500 wafers per day with consistency in 2018
4. Keeping mask defect free (by EUV pellicle) - Pellicle demonstration in the field (on 3300) required in 2015	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

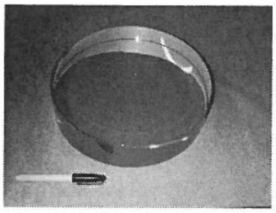
System configuration of ETS-1 (Univ. of Hyogo, Nikon, Hitachi)



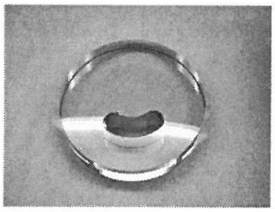


Optics	Three aspherical mirrors
Wavelength	13.5 nm
Numerical aperture	0.1
Demagnification	1/5
Diffraction limit	60 nm
Depth of focus	0.9 μm
Exposure area (in statics)	30 mm (H) × 1 mm (V)
Exposure area (in scanning)	30 mm (H) × 28 mm (V)
Mask	8 inch or 6025ULE
Wafer	8 inch
Exposure environment	In vacuum

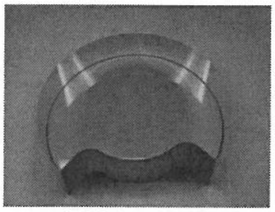
Aspherical mirrors for the imaging optics



M1-mirror



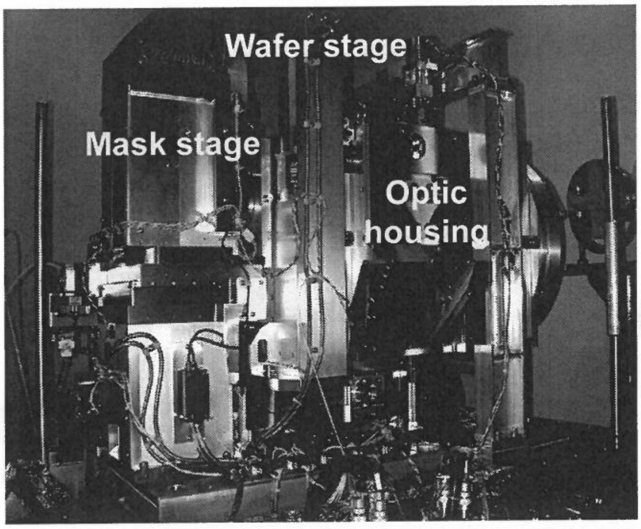
M2-mirror



M3-mirror

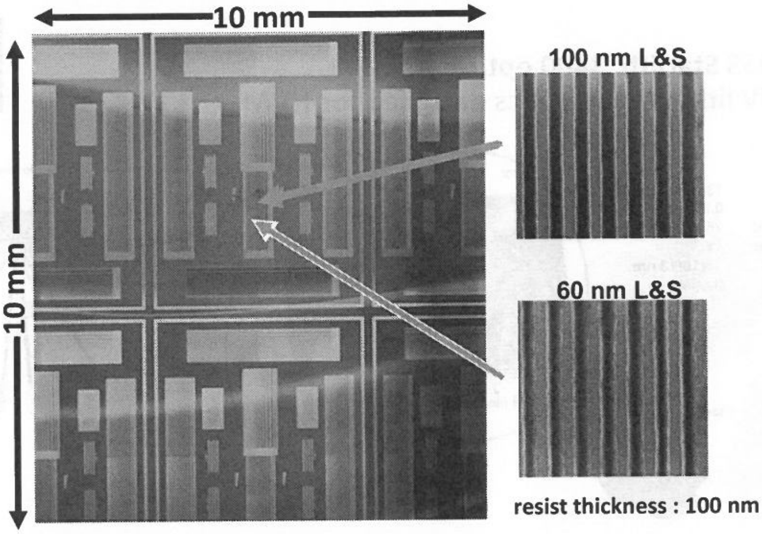
	M1-mirror	M2-mirror	M3-mirror
Diamter	272 mm	116 mm	224 mm
Figure error (rms)	0.58 nm	0.58 nm	0.58 nm
Roughness (rms)	0.28 nm	0.31 nm	0.35 nm

ETS-1 (Univ. of Hyogo and ASET)



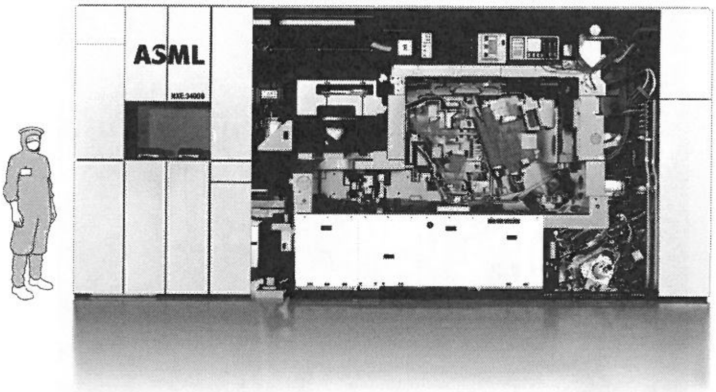
T. Watanabe, K. Mashima, M. Niibe, and H. Kinoshita, "A novel design of three-aspherical-mirror imaging optics for extreme ultra-violet lithography," *Jpn. J. Appl. Phys.*, **36** (1997) 7597-7600.

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.

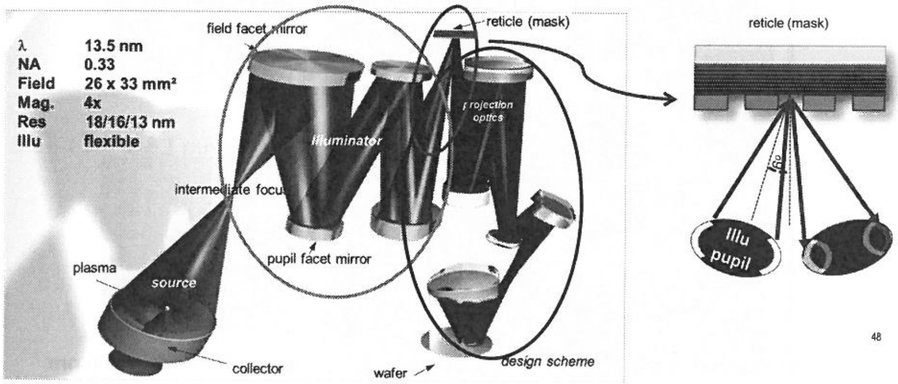
… for the ASML NXE: 3400B



Source: Jan Van Schoot et al., EUVL Symposium, Monterrey 2017

November 16 2018

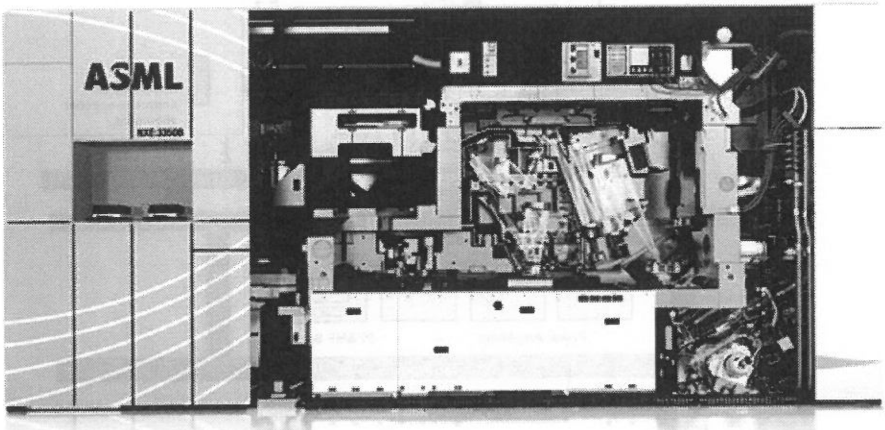
ZEISS Starlith® 3400 optical train: EUV lithography optics designed for HVM



λ	13.5 nm
NA	0.33
Field	26 x 33 mm²
Mag.	4x
Res	18/16/13 nm
Illu	flexible

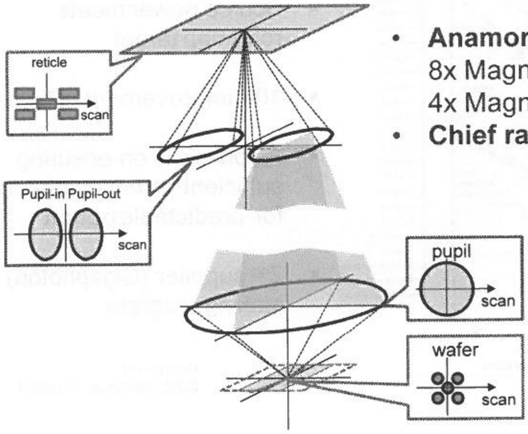
November 16 2018

- ASML社の最先端EUVスキャナー「NXE:3400B」21台受注
- 2017年中に出荷を開始　250 W @IF 125 wafers/hr
- 旧型の「NXE:3300B」と「NXE:3350B」を14台出荷済みしこの大半をアップグレード予定



High-NA >0.5NA 4x/8x anamorphic magnification Chief Ray Angle at Mask can be maintained

Public
Slide 12
October 2016



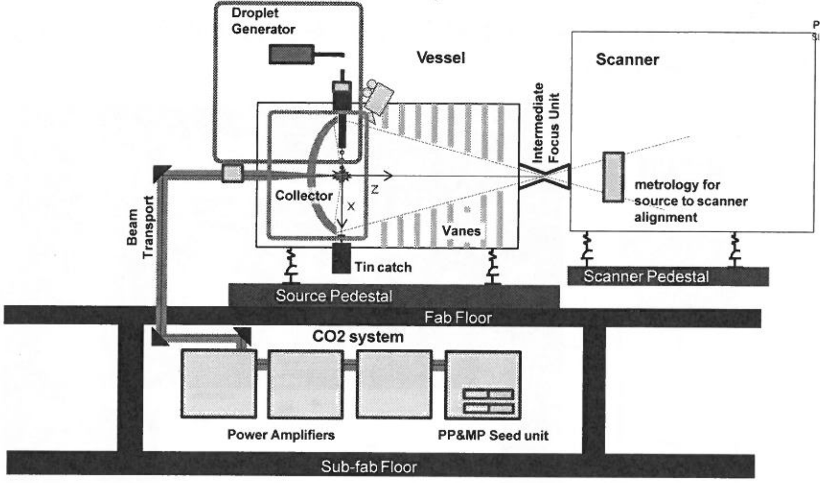
- **Anamorphic optics → half field:**
  8x Magnification in scan
  4x Magnification in other direction
- **Chief ray angle ok → Imaging ok**

The pattern at the mask will be 2x larger →
Scanner prints half fields

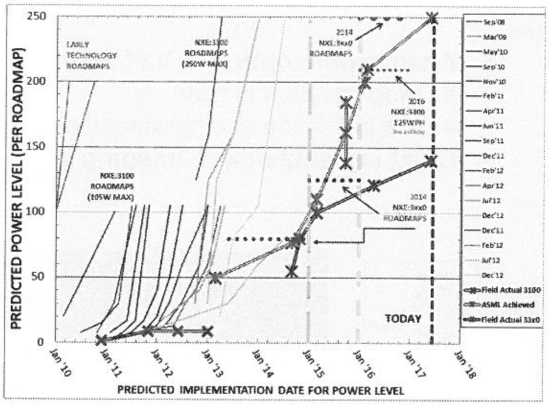
EUV Source - Principle of operation

ASML

Public
Slide 17

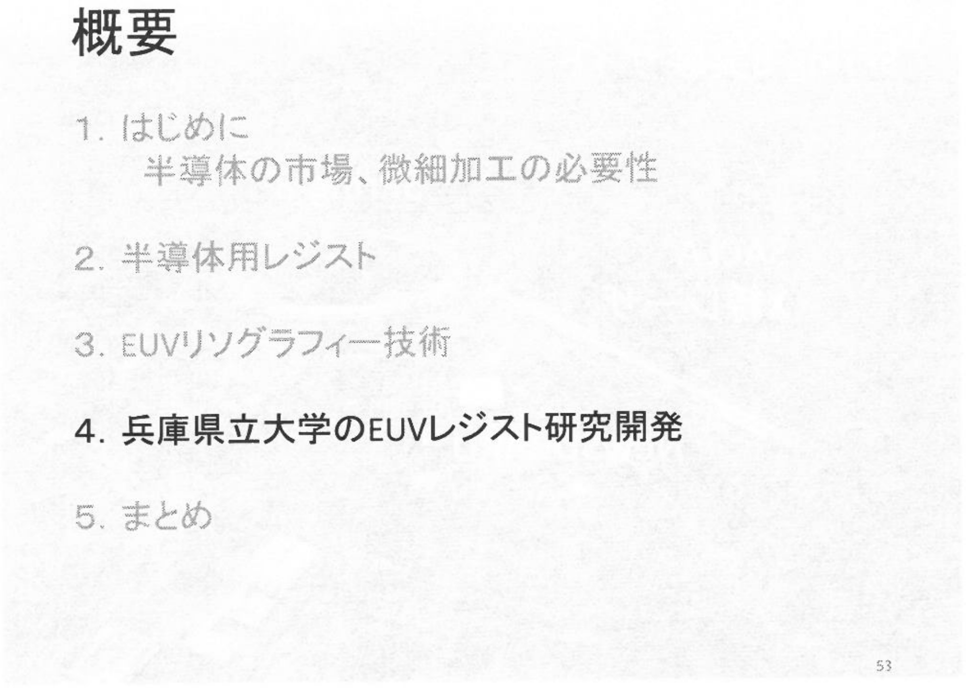


Source Power Improvements



- Source power meets roadmap target
- 10X improvement in 5 years
- Emphasis is on ensuring sufficient power overhead for predictable output
- 2nd supplier (Gigaphoton) is making progress

Britt Turkot
EUVL Workshop , June 2017



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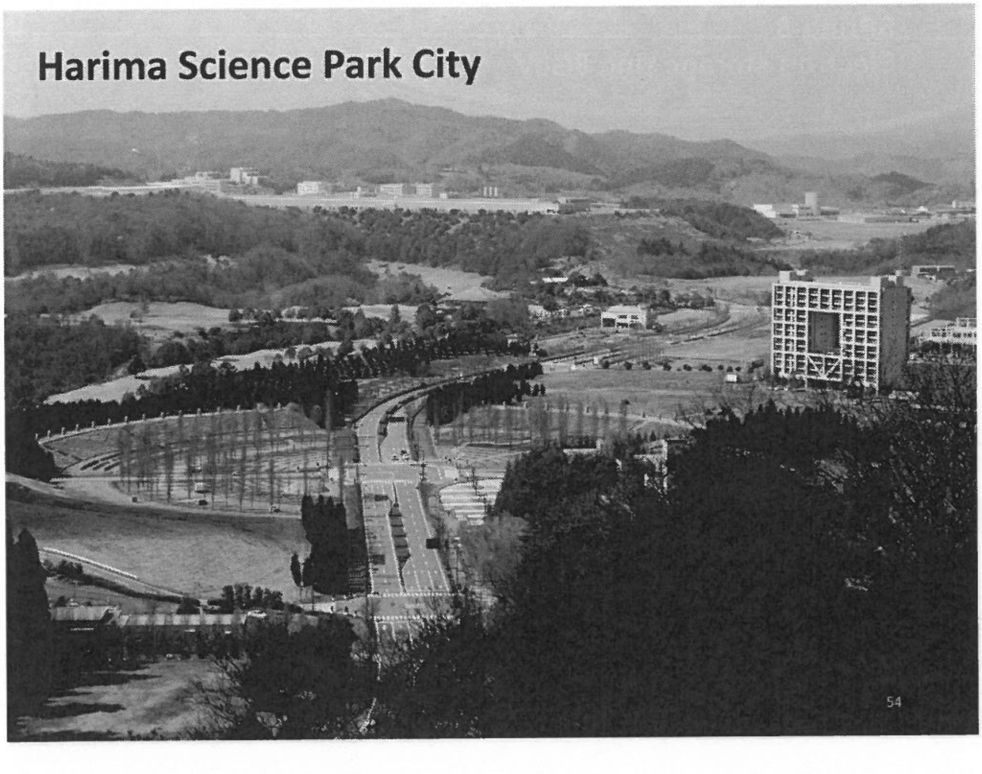
5. まとめ



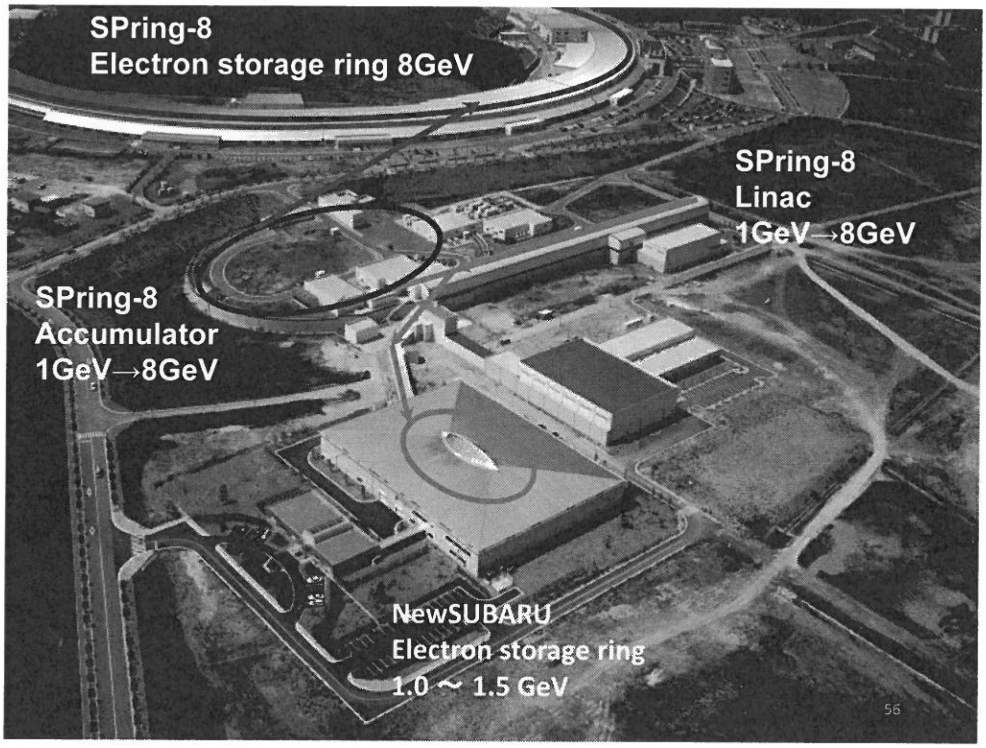
Harima Science Park City

SPring-8実験サイト

SPring-8

SACLA
X線レーザ

NewSUBARU



SPring-8
Electron storage ring 8GeV

SPring-8
Linac
1GeV→8GeV

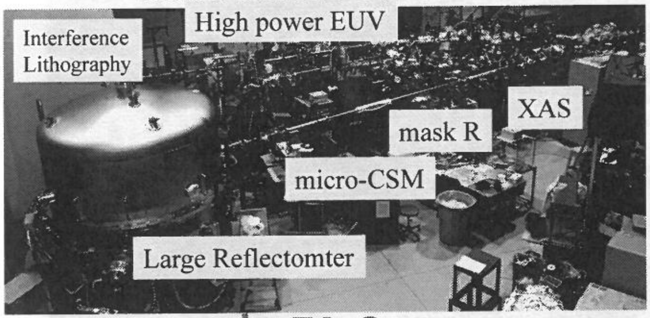
SPring-8
Accumulator
1GeV→8GeV

NewSUBARU
Electron storage ring
1.0 ~ 1.5 GeV

Center for EUV Lithography

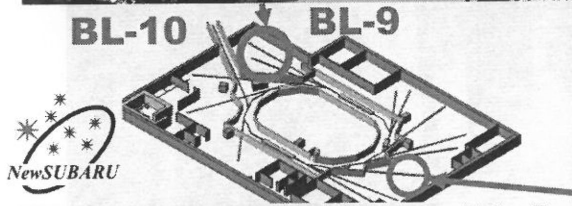
NewSUBARU Synchrotron Radiation Facility

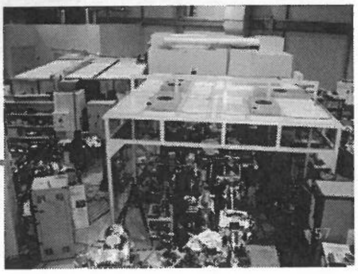
in SPring-8 site



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

Microscopes (EUVM)
Resist EUV Sensitivity



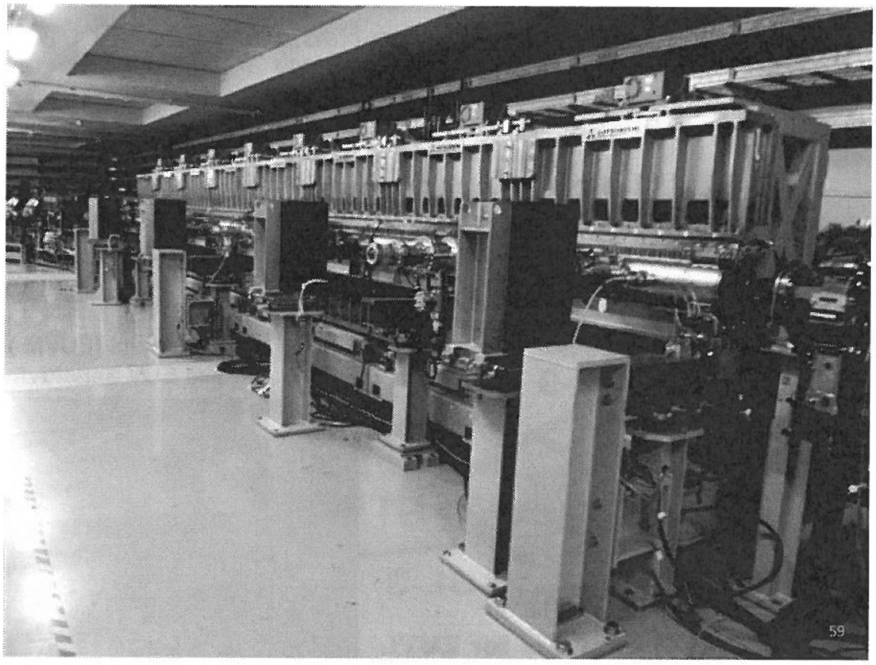


EUV & Soft X-ray

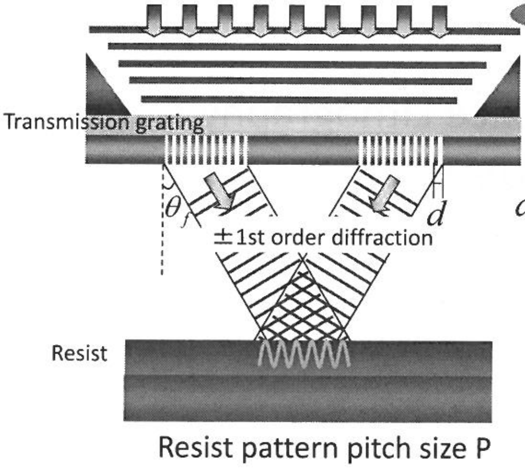
Three Beamlines for EUVL

EUV Interference Lithography
(EUV-IL)

11-m Long Undulator (LU)



Principle of interference lithography



$$m\lambda = d(\sin\theta_f - \sin\theta_i)$$

m : diffraction order

λ : wavelength

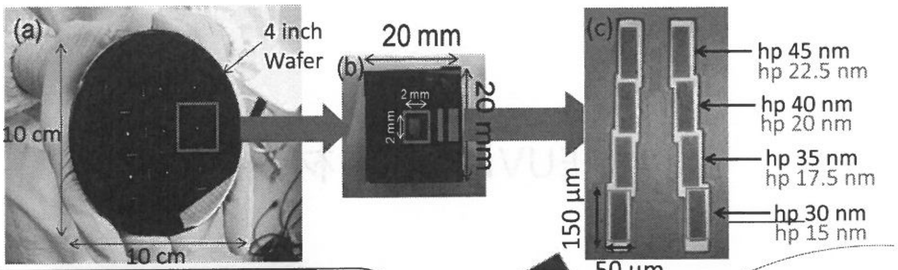
d : pitch size of grating pattern

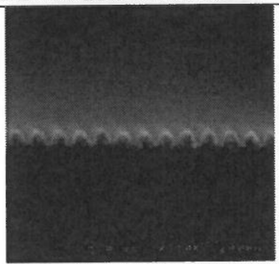
θ_i : incident angle

θ_f : diffraction angle

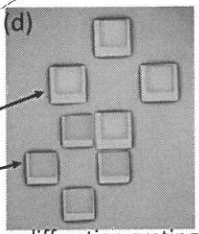
$$P = \frac{\lambda}{2\sin\theta_f} = \frac{d}{2}$$

Two window transmission diffraction grating



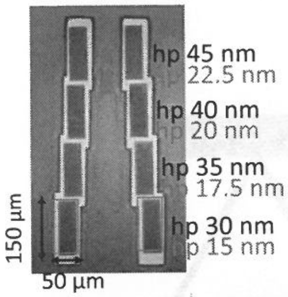


The SEM image of hp 30 nm pattern of TaN
hp 15 nm

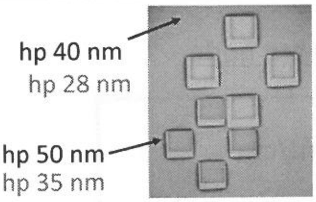


Four window diffraction grating

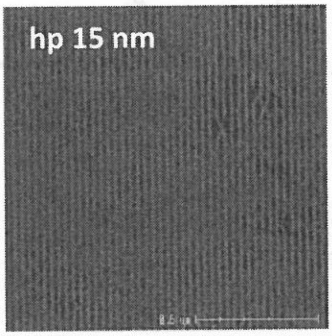
Resist replication results

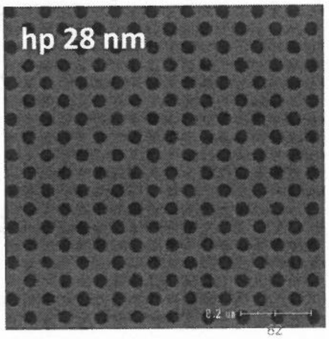


Two window transmission grating



Four window transmission grating





EUVレジスト材料

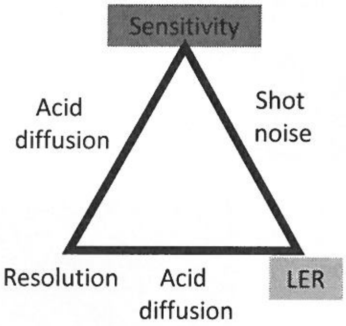
Issue of EUV Resist Development

Specification of 10 nm node

Sensitivity ≦ 10 mJ/cm^2

LWR ≦ 0.8 nm (3σ)

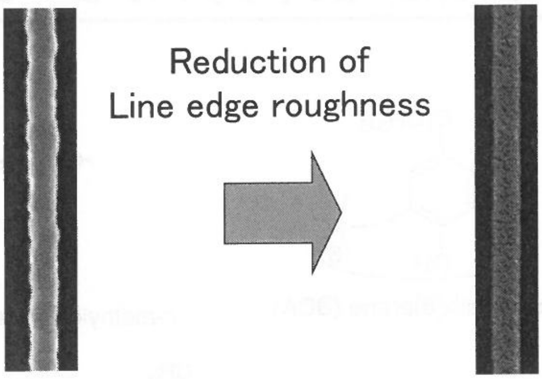
Low Outgassing ≦ 5 × 10^{13} molecules/cm^2/s



Development of LER reduction and high sensitive resist is most significant issue.

We need smooth resist!!

1) Low LER


Reduction of Line edge roughness

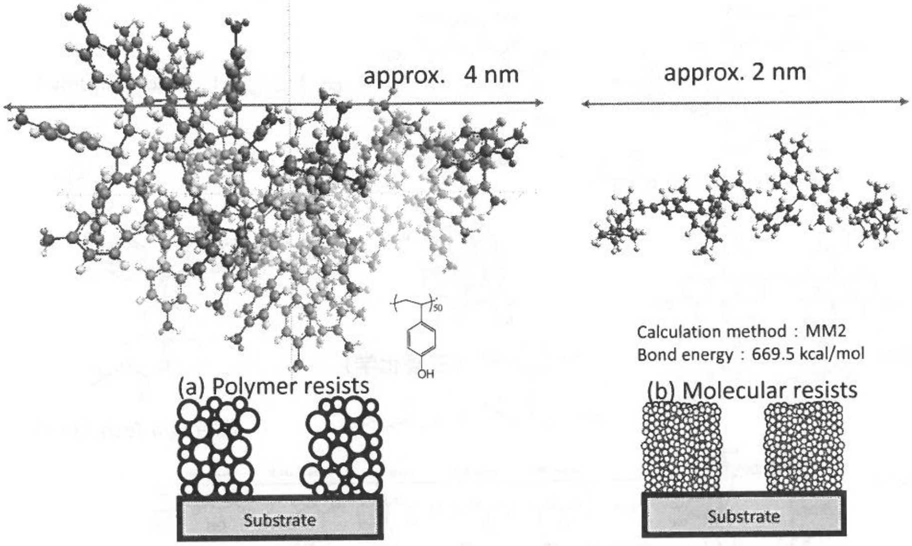
High LER 10 nm (3σ)

Low LER 2 nm (3σ)

2) High Sensitivity

3) Low Outgassing

Molecular size comparison



Calculation method : MM2
Bond energy : 669.5 kcal/mol

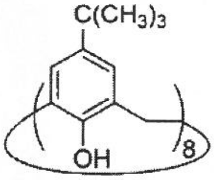
(a) Polymer resists

(b) Molecular resists

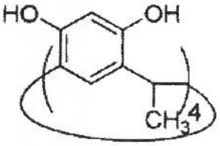
Figure. Schematic illustrations of cross sectional resist pattern based on (a) the conventional polymeric material and (b) the low molecular base matrix.

T. Kadota, et.al., Proc. SPIE, 4345 (2001) 891.

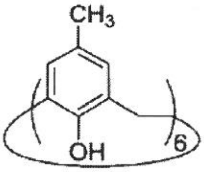
Calixarene （カリックスアレーン）



t-butylcalix[8]arene (BCA)

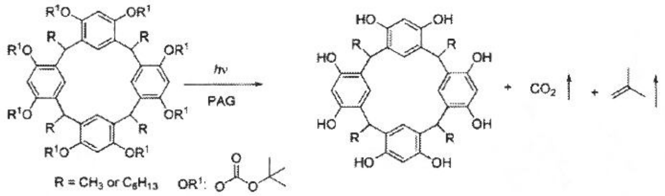


c-methylcalixresorcin[4]arene (CRA)

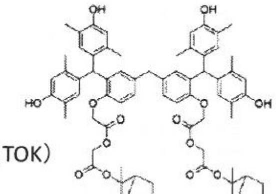


p-methylcalix[6]arene (MCA)

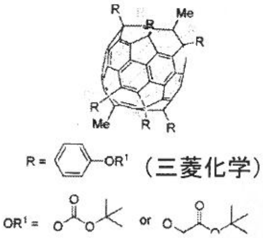
Calixarene系レジスト



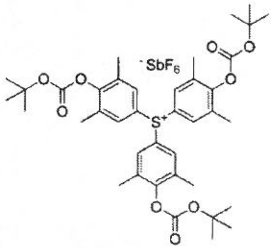
(Cornell Univ.)



(TOK)



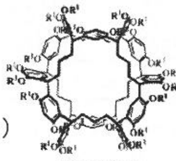
（三菱化学）



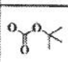
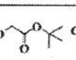
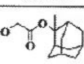
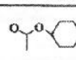
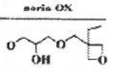
(Georgia Tech. Univ)

Noria

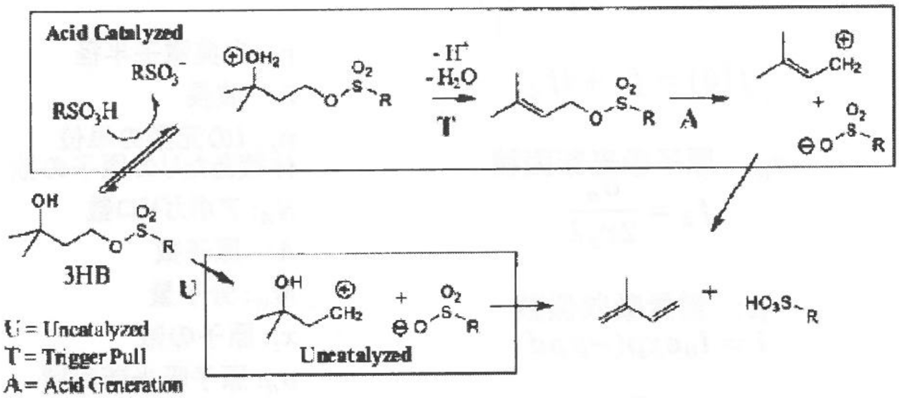
（神奈川大）



noria derivative

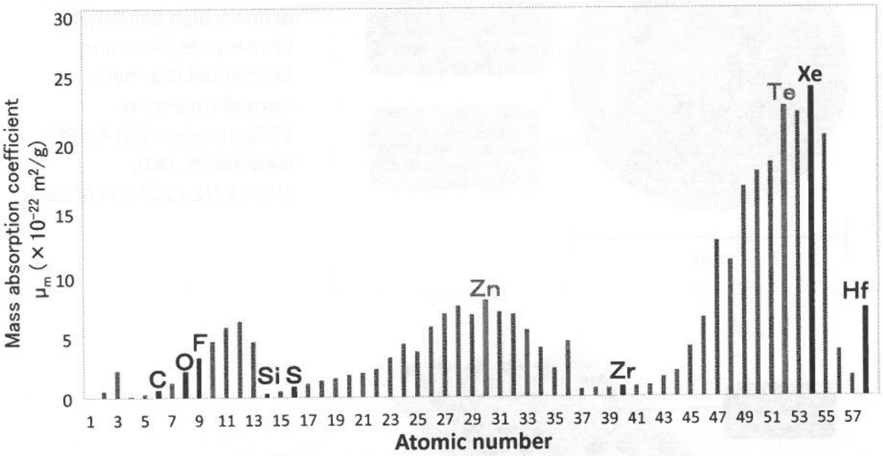
	noria BOC	noria BAe	noria AD	noria CHVE	noria OX
OR1					
exposure	EB	EB	EUV	EUV	EUV
type	positive	positive	positive	positive	negative
resolution	70 nm	50 nm	22 ~ 26 nm	35 nm	45 nm

酸増感剤（Acid Amplifier (AA)）の検討



Ref. R. Brainard, S. Kruger, C. Higgins, S. Revuru, S. Gibbons, D. Freedman, W. Yueh, and T. Younkin: J. Photopolym. Sci. Technol. **22**(2009) pp.43-50.

Achievement of high sensitivity EUV resist



Mass absorption coefficient for EUV light

Since the EUV absorption of EUV resist increased, the secondary electron yield can increase.

原子散乱因子と質量吸収係数

$$n = 1 - \delta - i\beta = 1 - \frac{r_e}{2\pi}\lambda^2 \sum_i n_i f_i(0)$$

$$f(0) = f_1 + i f_2$$

σ_a: 原子吸光断面積

$$f_2 = \frac{\sigma_a}{2 r_e \lambda}$$

μ: 質量吸収係数

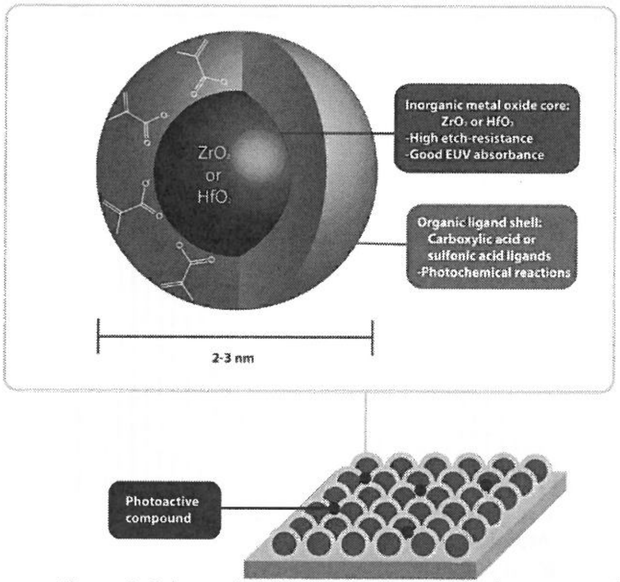
$$I = I_0 exp(-\mu\rho d)$$

$$\mu = \frac{N_A}{A}\sigma_a$$

$$\mu = \frac{N_A}{M_w}\sum_i x_i \sigma_{ia}$$

r_e: 古典電子半径
λ: 波長
n_i: iの元素の単位体積あたりの原子の数
N_A: アボガドロ数
A: 原子数
M_w: 分子量
x_i: 原子の数
σ_a: 原子吸光断面積
μ: 質量吸収係数
μd: 線吸収係数

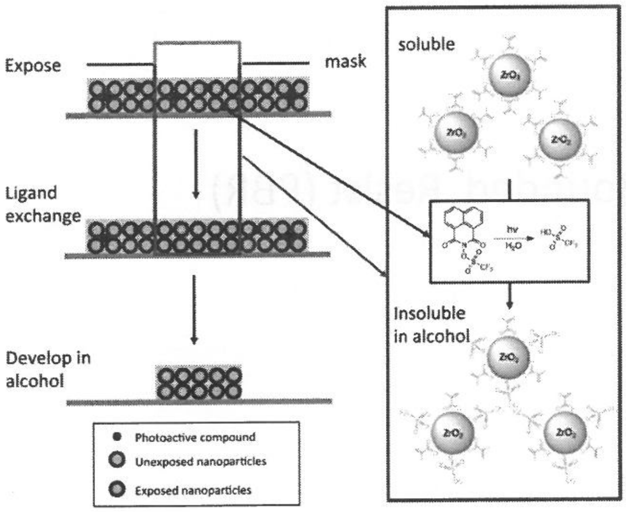
Nano Particle Resist for EUVL



SPIE News Room
New oxide nanoparticle extreme-UV photoresists achieve high sensitivity
Christopher Ober and Emmanuel Giannelis
Cornell University
15 September 2014, SPIE Newsroom. DOI: 10.1117/2.1201409.005552

Figure 1. Schematic of the extreme-UV (EUV) nanoparticle photoresist with its core metal oxide and the organic ligand surrounding the core. ZrO_2: Zirconium dioxide. HfO_2: Hafnium oxide.

Nano Particle Resist for EUVL



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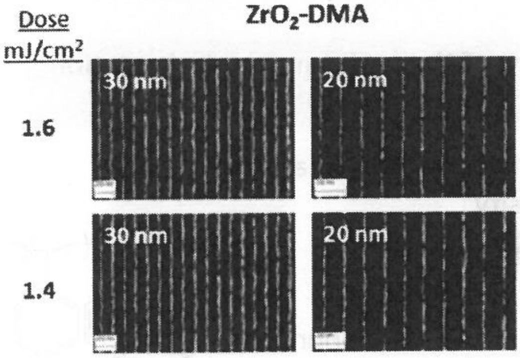
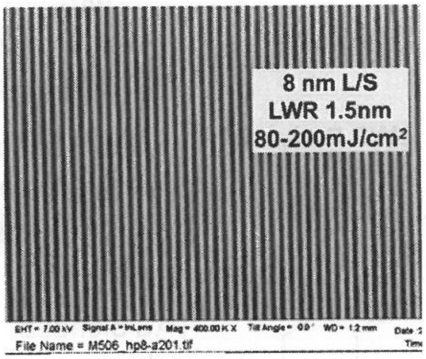
New oxide nanoparticle extreme-UV photoresists achieve high sensitivity
Christopher Ober and
Emmanuel Giannelis
Cornell University
15 September 2014, SPIE Newsroom. DOI: 10.1117/2.1201409.005552

Figure 2. Schematic of the ligand-displacement patterning mechanism for negative-tone pattern formation. hv: Energy. H_2O: Water.

Possibility of Metal Resist for EUVL





S. Chakrabarty, C. K. Ober, Cornell University

PAUL SCHERRER INSTITUT PSI

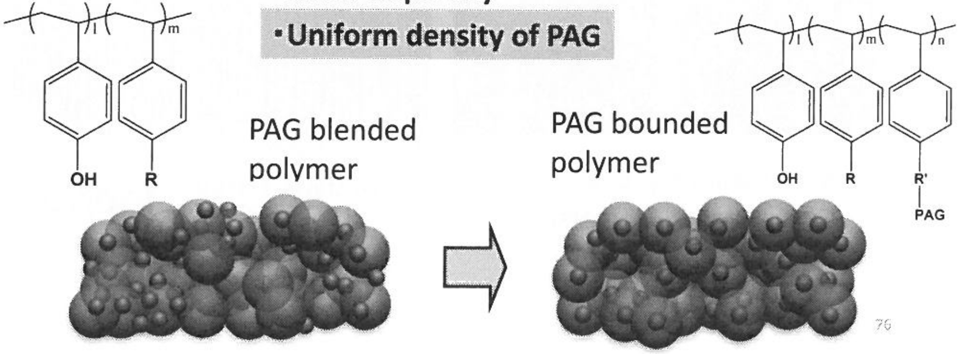
Inpria

PAG Bounded Resist (PBR)

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

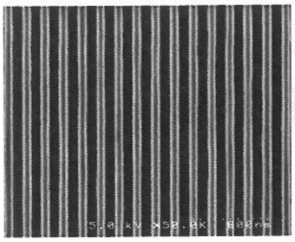
LWR Reduction
- Optimization of the molecular size
- Small dispersity
- Uniform density of PAG



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

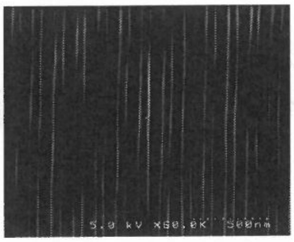
For the 75 nm L/S resist pattern

Bounded type



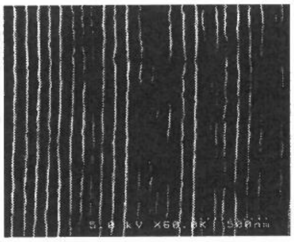
LER = 3.5 nm

Blend type



LER = 7.5 nm

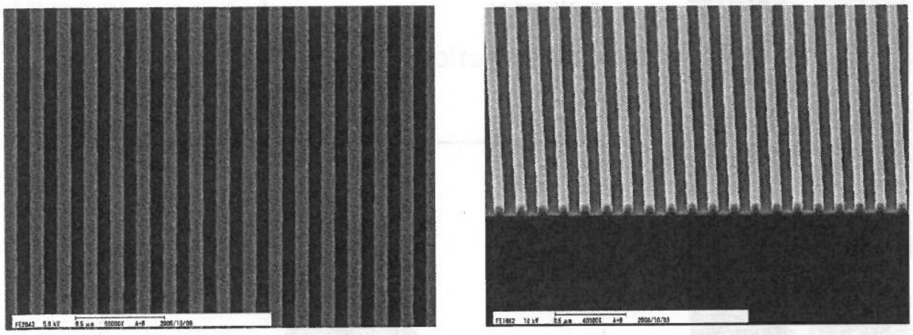
Blend type



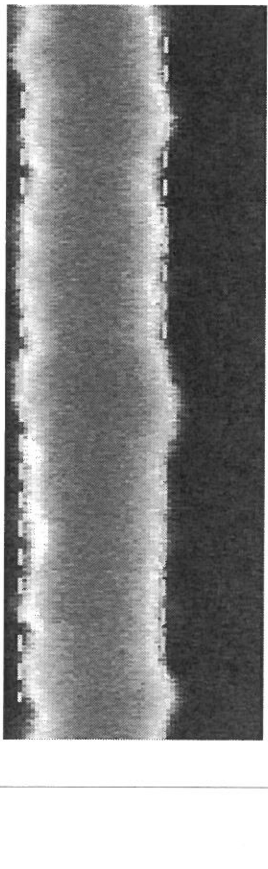
BAD LER

Exposure characteristics (1/2) (E=50 kV) Resist D

75 nm L/S pattern (80 nm^t)



軟X線領域の放射光を用いた EUVレジストの分析評価技術



線幅バラツキの評価

$$Z\text{-}factor = (Resolution^3) \times (LER^2) \times (Sensitivity)$$

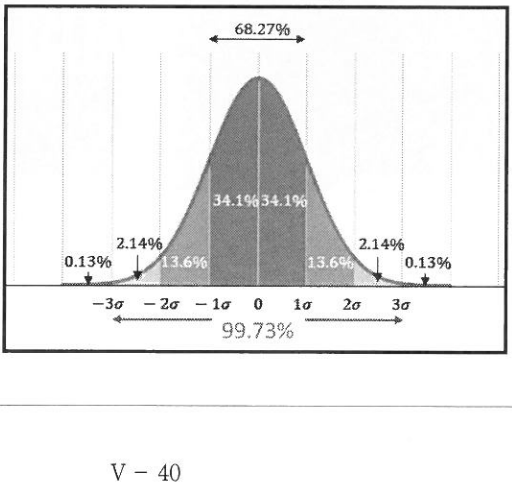
LER: Line edge roughness $LER = 3\sigma$

LWR: Line width rougness $LWR = \sqrt{2} \times LER$

1σ: 標準偏差

Standard deviation

$$\sigma = \sqrt{\frac{1}{n}\sum_{n=1}^{n}(x_i - \bar{x})^2}$$



線幅バラツキの要因

1)レジスト中の基材の空間分布
  機能性官能基、感光剤(酸発生剤)、アミン等の添加物等
2)Prebake時の溶媒分布
  自由空間の分布
3)露光時のショットノイズ
4)Post Exposure Bake時の効果
  酸拡散等
5)現像効果
  現像液の浸透の空間分布、現像過程の空間分布
6)リンス効果
  ・リンス液の浸透の空間分布
  ・リンス過程の空間分布
7)Out of band(OoB)光による影響

Analysis of the spatial distribution of functional material in resist functional groups, photosensitizers (acid generators), additives such as amines, and so on

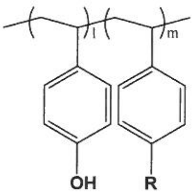
Benefit of PAG Bounded Resist Comparison to the Conventional one

High Sensitivity

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

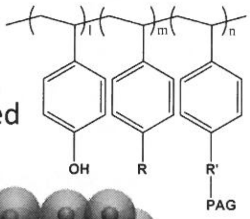
LWR Reduction

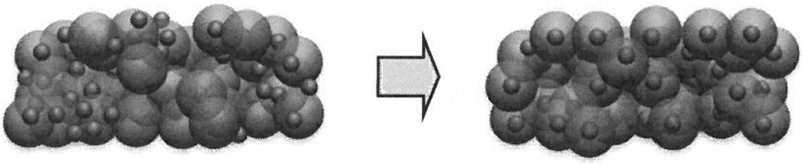
- Optimization of the molecular size
- Small dispersity
- Uniform density of PAG



PAG blended polymer

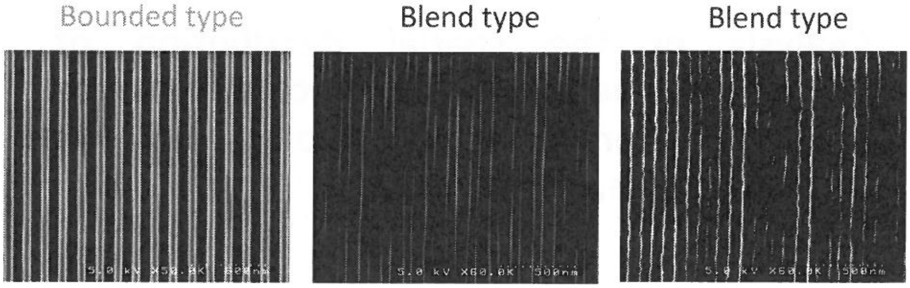
PAG bounded polymer





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

For the 75 nm L/S resist pattern

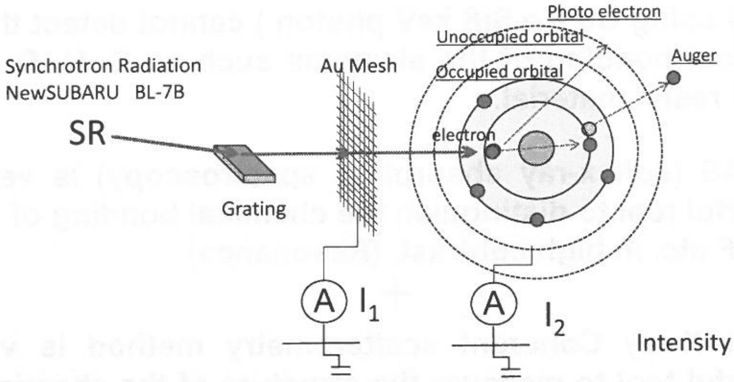


Bounded type — LER = 3.5 nm

Blend type — LER = 7.5 nm

Blend type — BAD LER

The soft x-ray absorption spectroscopy



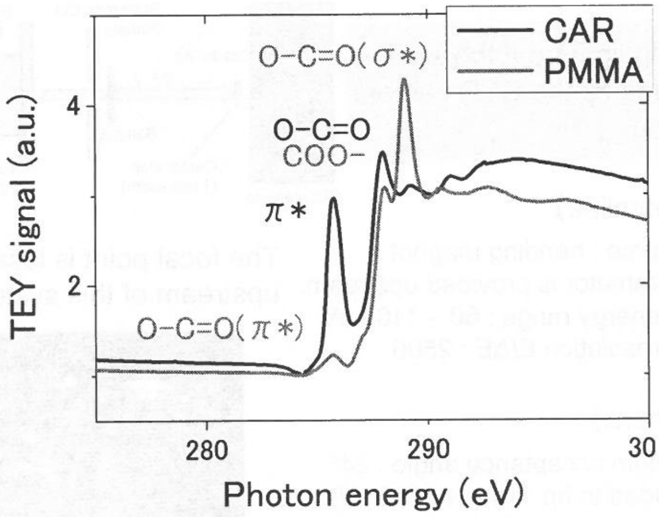
Intensity = I_2 / I_1

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 *Kα* 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)

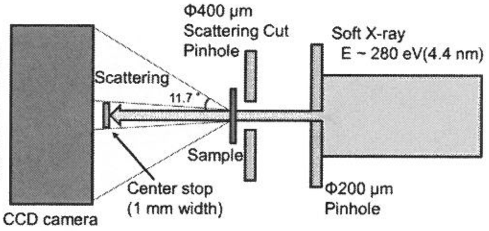
||

- 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.



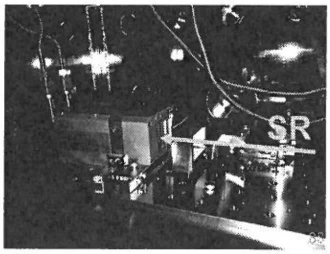
【BL-10 beamline】

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

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

【CCD camera】

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

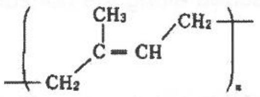


Measured DSA samples (1)

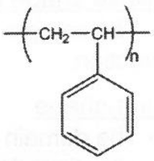
◆ Three polymers in triblock polymer

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

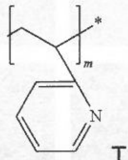
I : polyisoprene



S : polystyrene

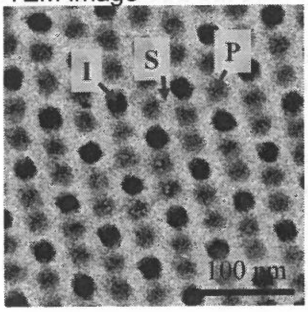


P : poly(2-vinylpyridine)



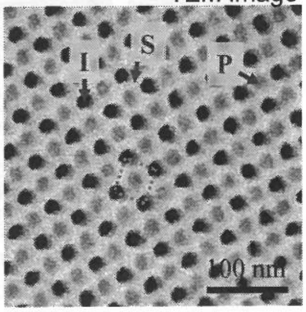
Hexagonal Packed Cylinders (ISP:PSP=6:4)

TEM image



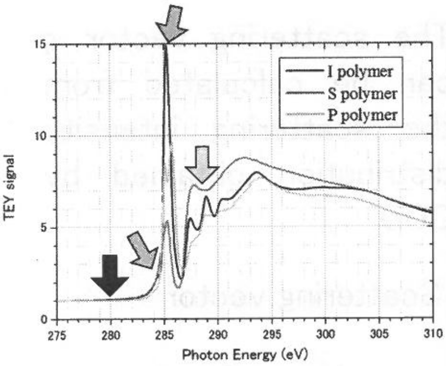
Tetragonal Packed Cylinders (ISP 100%)

TEM image

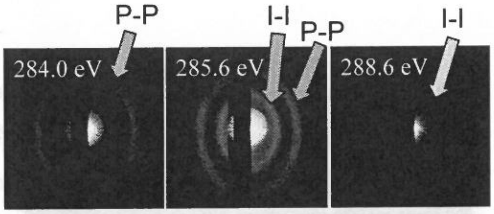


Results and Discussion

◆ 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.

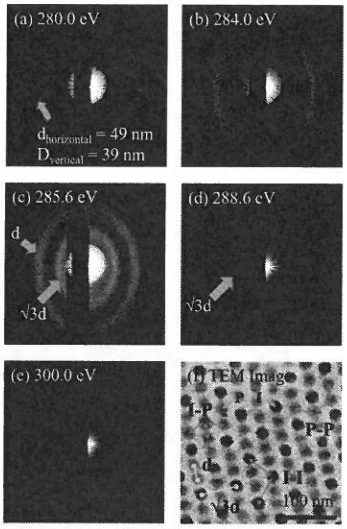
284.0 eV : P polymer had slightly small absorption. → Only P-P scattering

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.

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

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

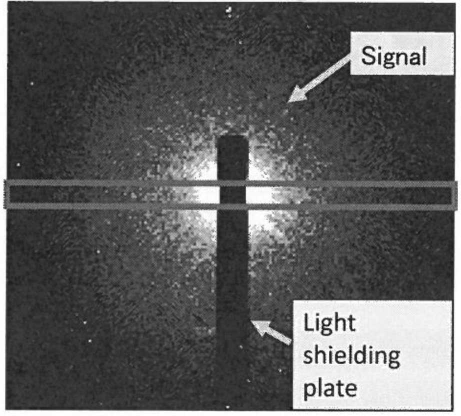
- The outer ring signals
→ were observed at 280.0, 284.0, 285.6 eV.
(a) (b) (c)

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

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

RSoXS method

CCD image



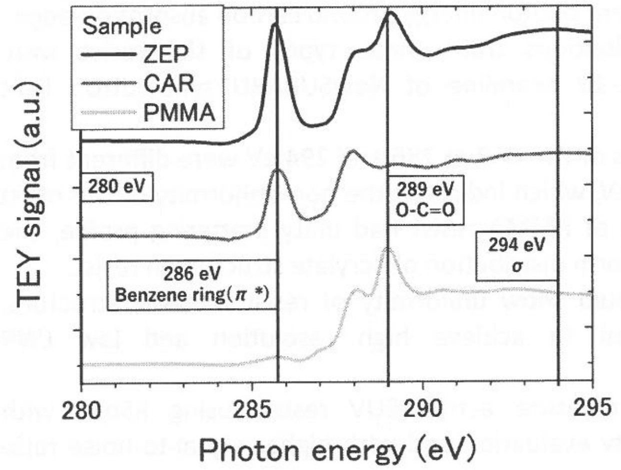
The scattering vector q can be calculated from the scattering intensity distribution obtained by CCD.

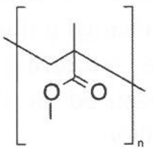
Scattering vector

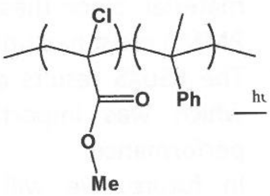
$$q = \frac{4\pi}{\lambda} sin(\frac{\theta}{2})$$

λ = wavelength
ϑ = scattering angle

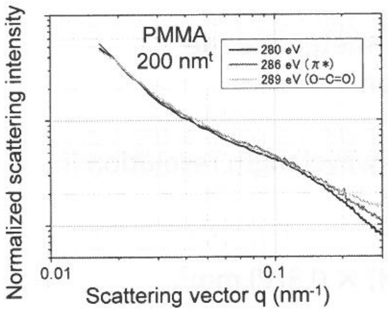
Carbon K-edge absorption spectra of PMMA, CAR, and ZEP520A

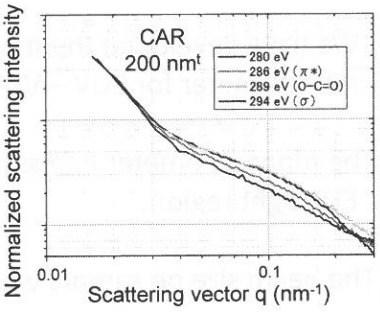


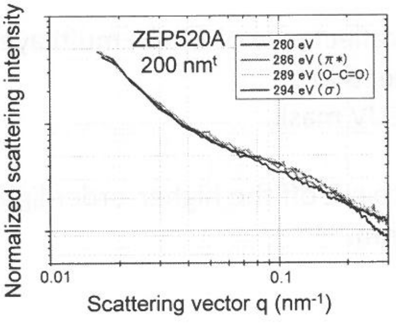




Scattering vector spectra of PMMA, CAR, and ZEP520A







Results

1) RSoXS method to evaluate uniformity of resist material distribution was developed, which can modulate absorption contrast of functional group by changing the incident photon energy around carbon absorption edge.
2) The scattering distributions from three types of the resist were measured at the BL-10 beamline of NewSUBARU synchrotron light facility.
3) The scattering profiles of the CAR at 286 and 294 eV were different from that of 280 and 289 eV, which indicated the non-uniformity of the resist material. Since these of PMMA resist had unity scattering profile, the PMMA resist had uniform distribution of acrylate structure in resist.
4) The RSoXS results could show uniformity of resist material structure, which was important to achieve high resolution and low LWR performance.
5) In future, we will measure actual EUV resists using RSoXS with quantitative uniformity evaluation and with higher signal-to-noise ratio condition.

Result

1) We have developed the monochrometer and the reflectometer for EUV – VUV region.

2) The monochrometer had sufficient wavelength resolution in the EUV light region.

3) The beam size on sample was 0.6(H) × 0.3(V) mm^2.

4) We mwasured reflectance of Mo/Si multilayer, absorber(TaN), and glass substrate, that
was composed EUV mask.

5) Future issue is to cut off the higher-order light in wavelength region of 20~100 nm.

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

Challenges for Beyond EUVL in shortening wavelength) (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.

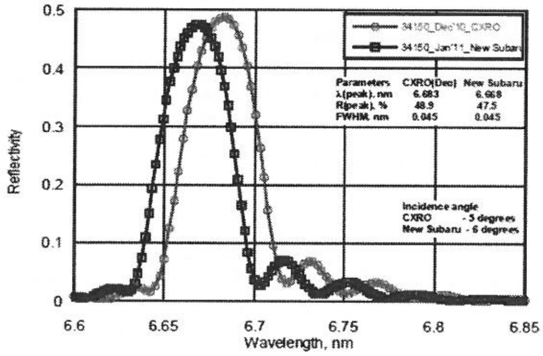
4) Resist

- ☐ 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 increases

Next Generation EUVL Optics for 6.X nm

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



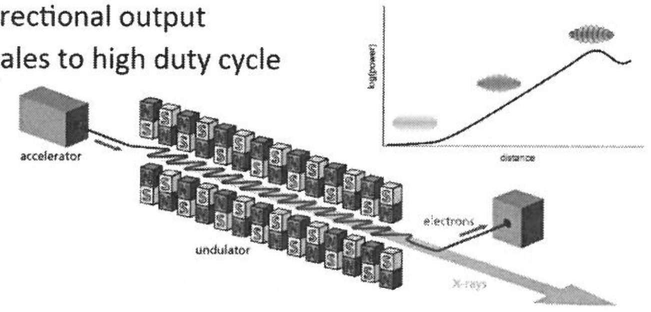
By courtesy of Rigaku

FEL for EUV Light Source

FEL is a clean light source

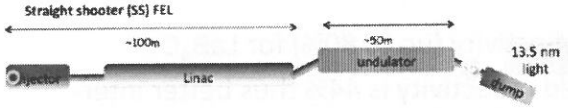
- In Free Electron Laser relativistic electrons travel through the undulator magnet in vacuum and generate X-rays
- No contamination
- Minimal thermal load
- Directional output
- Scales to high duty cycle

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

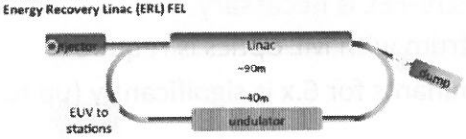
Massive practical experience with single pass X-FEL, large pool of experts and trained personnel

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

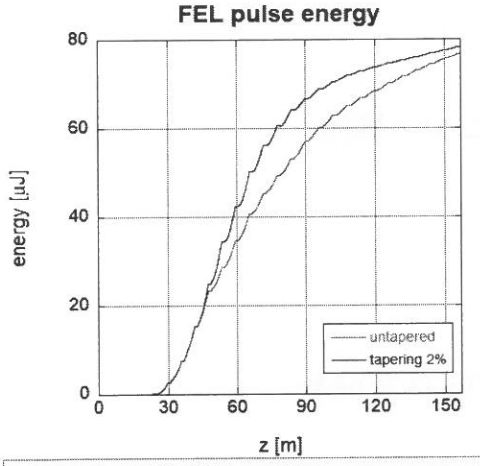
Untested physics of short wavelength ERL FEL

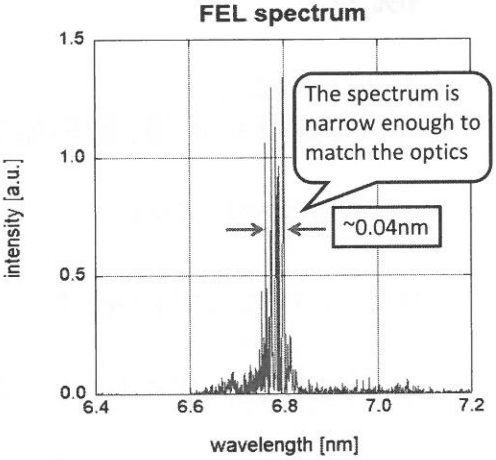
Very elegant solution to reducing the RF power and beam dump costs

Very few operating ERL facilities worldwide

Numerical tools require validation

Recent study about the power and spectrum at BEUV





The spectrum is narrow enough to match the optics

~0.04nm

FEL power with 2% tapering:
12.7/25.4 kW @ 9.75/19.5 mA (162.5/325 MHz)

$\Delta\lambda/\lambda = 6 \times 10^{-3}$

Accelerator Parameters: E_{acc} = 1131 MeV ($800 \times \sqrt{2}$),
The other conditions are almost same to these of EUV-FEL

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

概要

1. はじめに
   半導体の市場、微細加工の必要性

2. 半導体用レジスト

3. EUVリソグラフィー技術

4. 兵庫県立大学のEUVレジスト研究開発

5. まとめ

まとめ

1）半導体の市場状況および半導体微細加工の必要性を学んだ。

2）半導体微細加工技術は、3次元実装技術と併せて、高集積、高速動作、低消費電力を実現するために今後も必要な技術である。

3）量産用のリソグラフィ技術は、低コストでなければならない。このためには、開発段階からコスト削減を意識した開発をせねばならない。

4）レジストの歴史と各種リソグラフィ用レジストプロセスおよびレジスト材料について学ぶことができた。また、先端のリソグラフィについて、学ぶことができた。

5）極端紫外線リソグラフィー技術開発の現状と今後について多くを学ぶことができた。

6）Sub 10 nmを視野に入れ、今後のリソグラフィの展望について議論を深めることができた。

SPIE. PHOTOMASK TECHNOLOGY + EUV LITHOGRAPHY

Monterey Conference Center and Monterey Marriott
Monterey, California, United States
15 - 19 September 2019

Make your plans to join us in September 2019

Online program details available
This key technical meeting is for mask makers, EUVL, emerging technologies, and the future of mask business. SPIE Photomask Technology and the International Conference on Extreme Ultraviolet Lithography are co-located conferences.

Review the 2019 program details: Browse papers, see keynote speakers, view special events.

Hotel discounts
cut-off 16 August

Registration increases
after 30 August

Manuscripts Due
21 August 2019

The 37th International Conference of Photopolymer Science and Technology (ICPST-37)

Materials & Processes for Advanced Lithography, Nanotechnology and Phototechnology

International Conference Hall, Makuhari Messe, Chiba, Japan

May 18 - 21, 2020

http://www.spst-photopolymer.org

Photomask Japan 2020

April 19-21, 2020

The 27th Symposium on Photomask and Next Generation Lithography Mask Technology

PMJ2020 will be held on

April 19(Sun.)-21(Tue.), 2020.

Special Events on 19th (Sun.), Regular Symposium on 20th (Mon.) & 21st (Tue.)

What's New!

- 1st Announcement is available!

https://www.photomask-japan.org/

ご清聴有難うございました。
Thank you for your kind attention!!