STRJ WORKSHOP 2014
March 7, 2014, Shinagawa KOKUYO HALL

EUVリソグラフィ:
その進展とさらなる微細化への取り組み

EUV Lithography: Progress and Further Extendibility

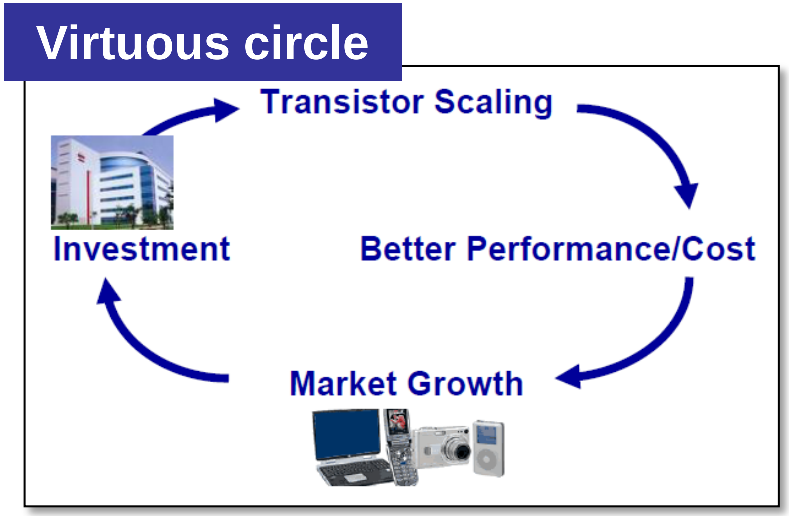
（株）EUVL基盤開発センター
森　一朗

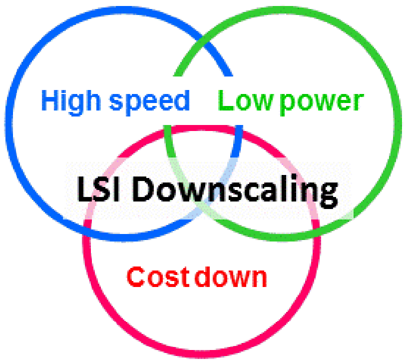
EUVL Infrastructure Development Center, Inc.

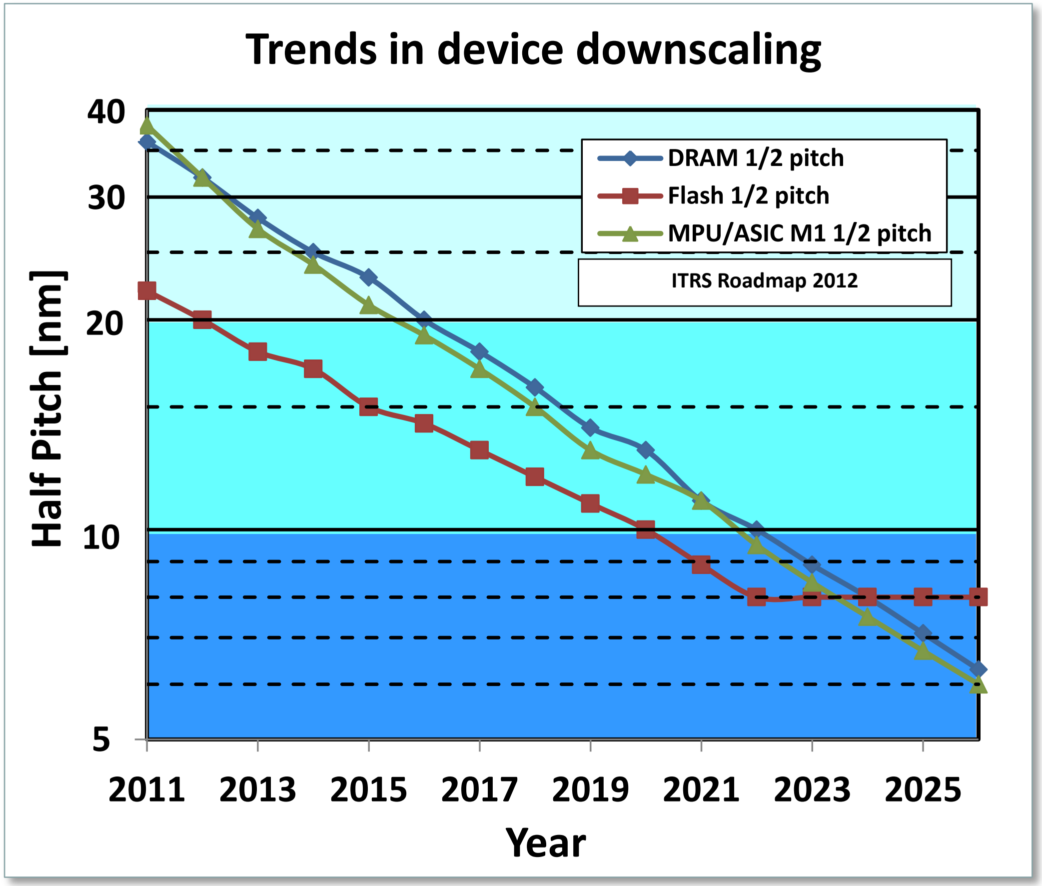
Outline of Presentation

- Introduction
  - Device trends & Lithography prospect
- EIDEC project
  - Basic concept & Scheme
- Actinic blank inspection
- Patterned mask inspection
- EUV resist materials and process
- EUV resist outgassing control
- Summary

A fundamental enabler of device downscaling

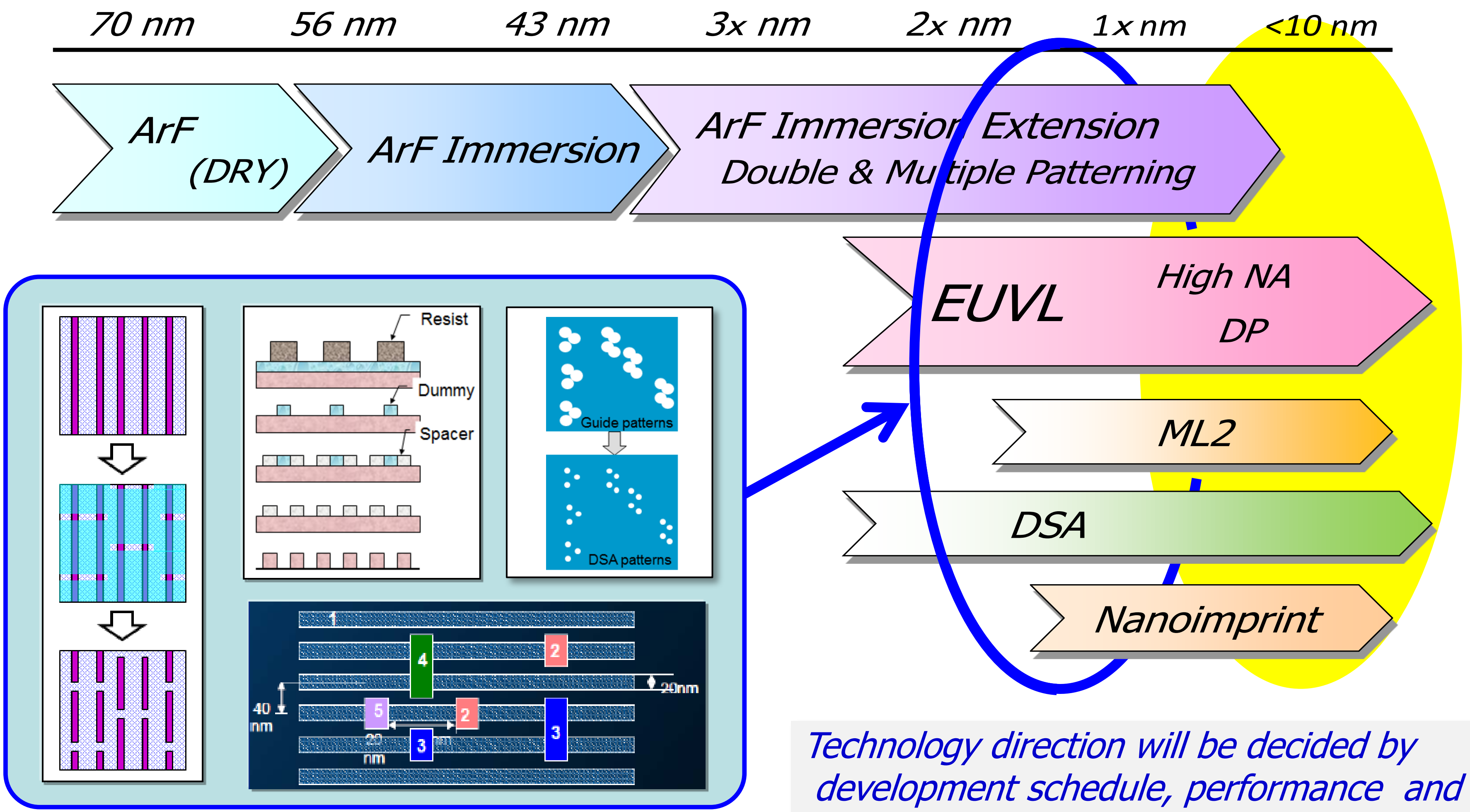






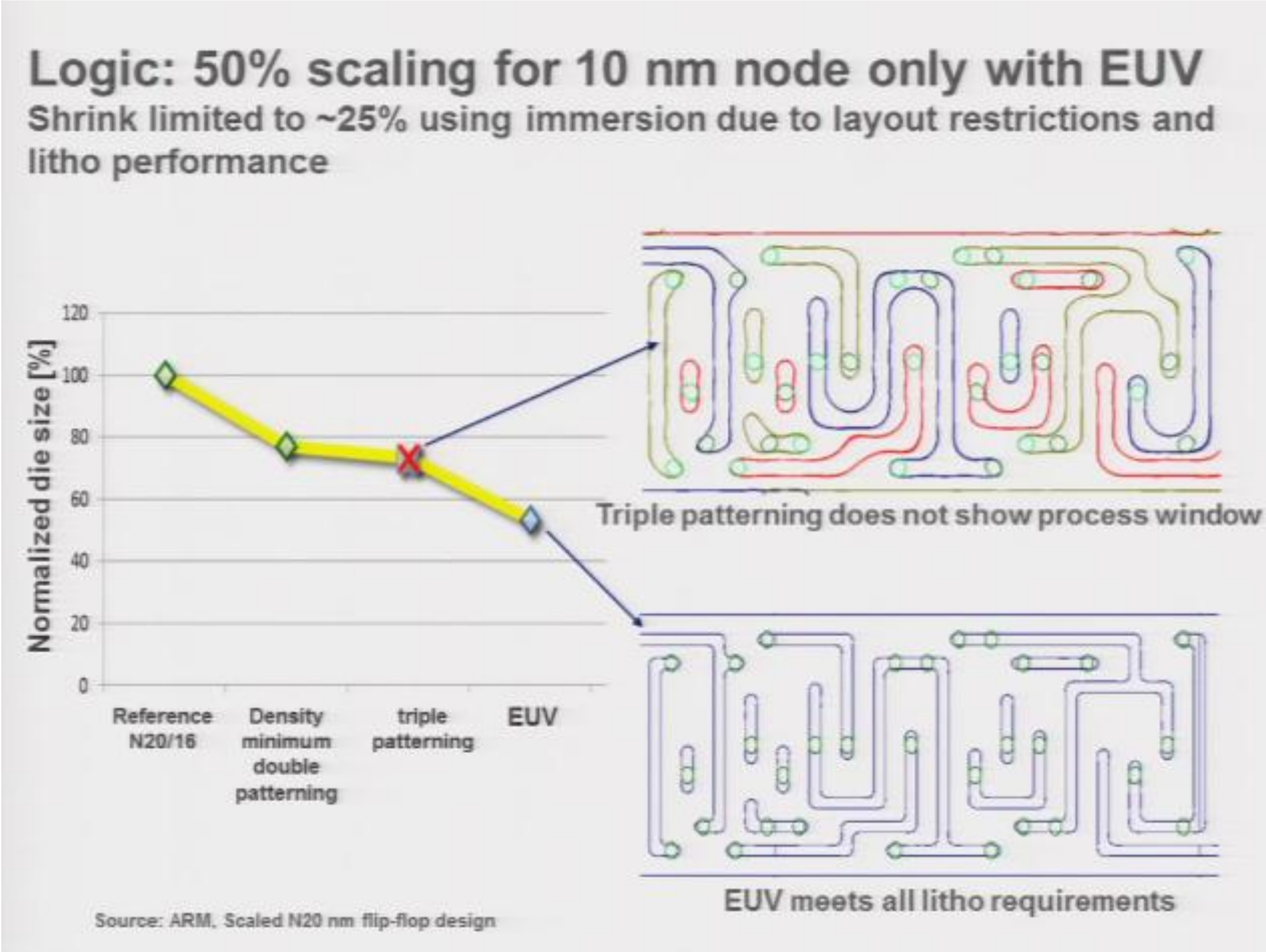
Miniaturization of semiconductor devices supports the growth of semiconductor industry and lithography remains a fundamental enabler of this downscaling.

Lithography Prospect



Technology direction will be decided by development schedule, performance and economics.

EUVL will be the main stream technology from cost and extendibility viewpoints.



Martin van den Brink, “Continuing to Shrink: Next-Generation Lithography- Progress and Prospects,” ISSCC 2013 Plenary Session, Feb., 2013
http://isscc.org/media/2013/plenary/Martin_van_den_Brink/StandardPlayer.html?plugin=Silverlight

2013 International Symposium on Extreme Ultraviolet Lithography

Toyama, Japan ● 6 - 10 October, 2013

2009-2013 EUV Focus Areas

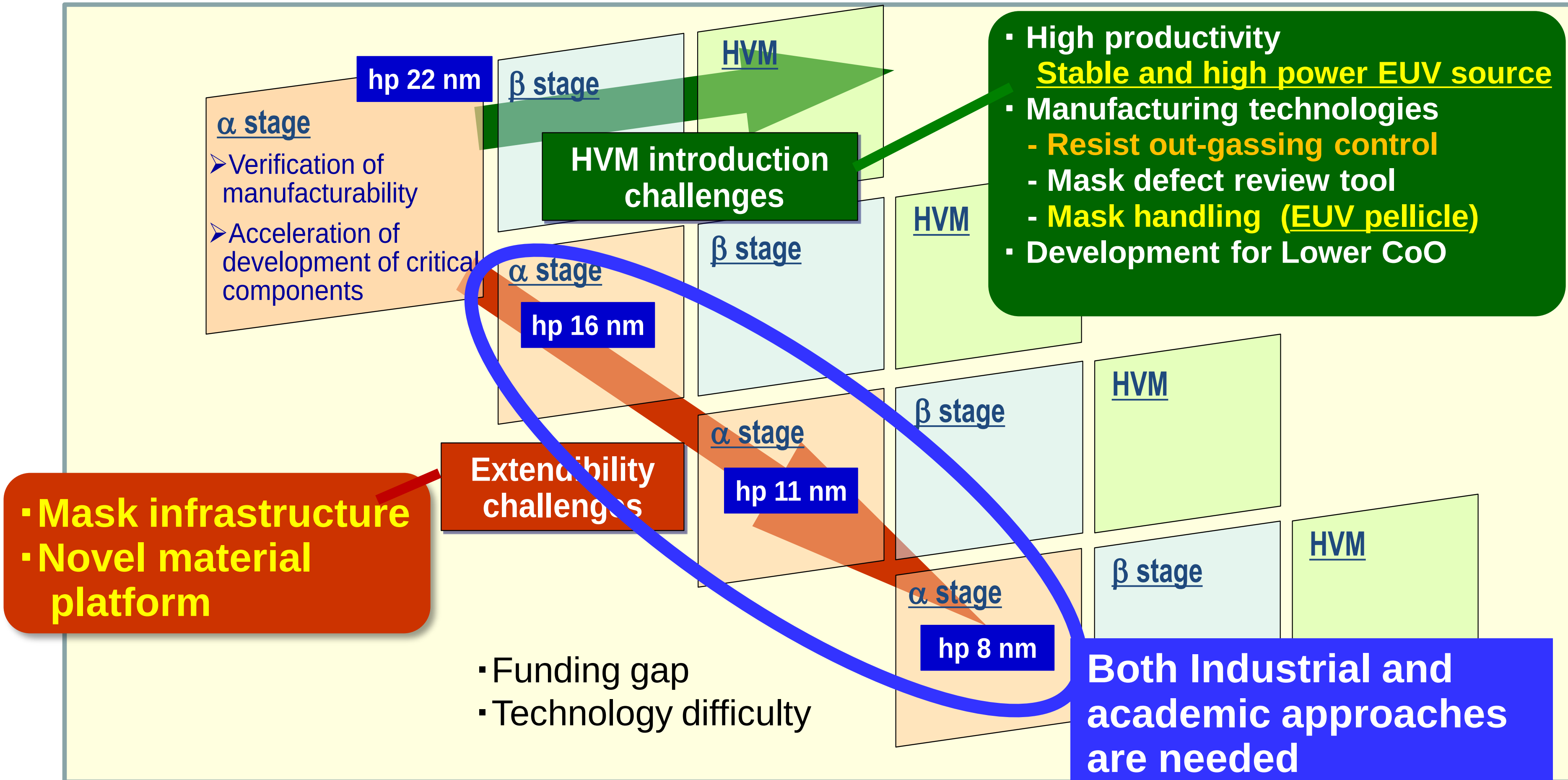
22nm HP Insertion

2009 / 22hp	2010 / 22hp	2011 / 22hp	2012 / 22hp	2013 / 22hp
1. Mask yield & defect inspection/review infrastructure	1. Mask yield & defect inspection/review infrastructure	1. Long-term reliable source operation with 200 W at IF*	1. Long-term reliable source operation with a. 200 W at IF in 2014 b. 500 W-1,000 W in 2016	1. Long-term reliable source operation with a. 125 W at IF in 2014 b. 250 W in 2015
2. Long-term reliable source operation with 200 W at IF	1. Long-term reliable source operation with 200 W at IF	2. Mask yield & defect inspection/review infrastructure	2. Mask yield & defect inspection/review infrastructure	2. Mask yield & defect inspection/review infrastructure
3. Resist resolution, sensitivity & LER met simultaneously	2. Resist resolution, sensitivity & LER met simultaneously	3. Resist resolution, sensitivity & LER met simultaneously	3. Resist resolution, sensitivity & LER met simultaneously	3. Keeping mask defect free - Availability of pellicle mtg HVM req't - Minimize defect adders during use
• EUVL manufacturing integration	• EUVL manufacturing integration	• EUVL manufacturing integration	• EUVL manufacturing integration	4. Resist resolution, sensitivity & LER met simultaneously

2013 EUVL Symposium 10

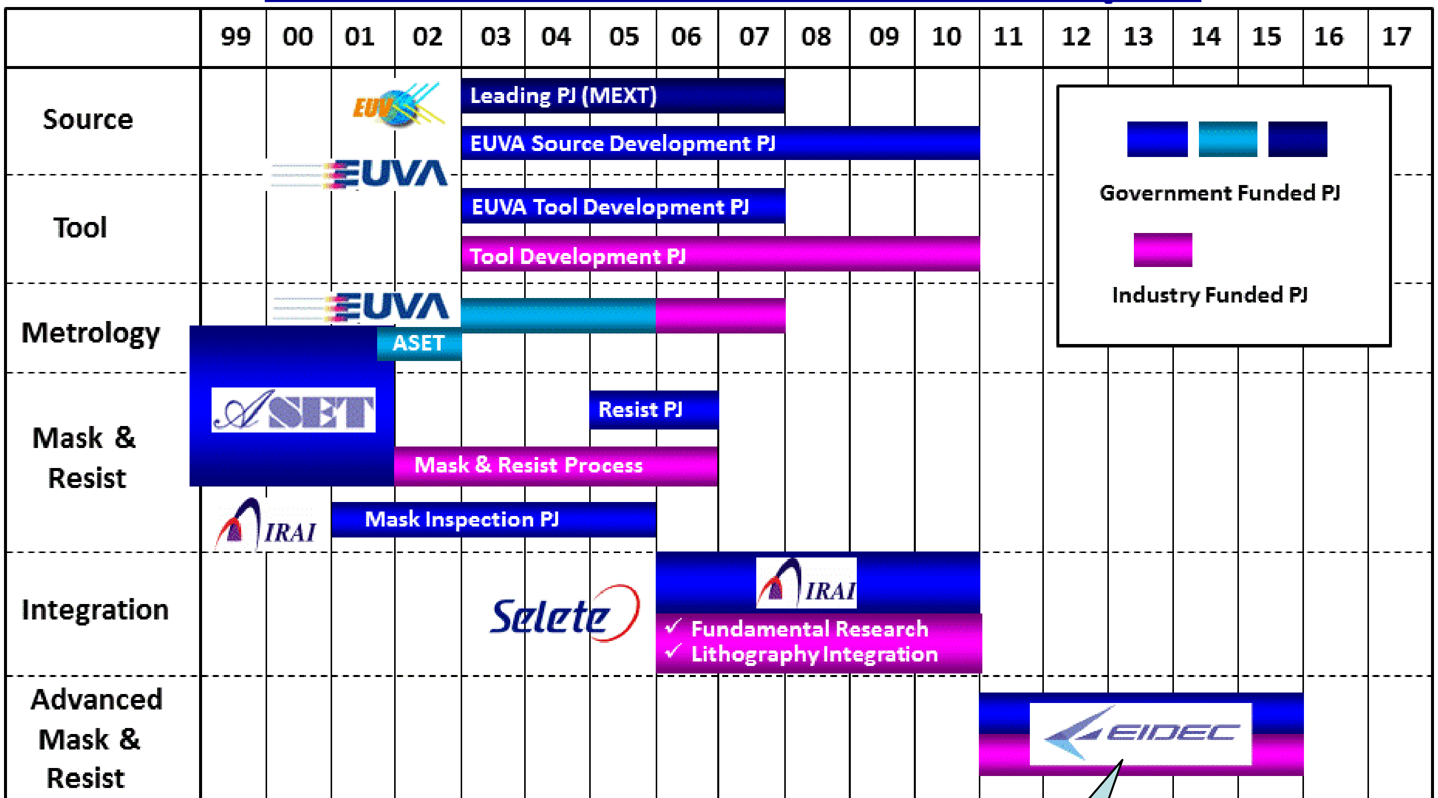
Challenges in EUVL for HVM Introduction and Extendibility

- We still face several challenges in preparing for HVM.
- Extendibility of EUVL for future technology generations also needs to be focused because it will take a large amount of time and cost to develop **novel material platform** and build up **mask infrastructure**.



EIDEC project

Consortia-driven EUV R&D in Japan



- **Succeed to MIRAI-Selete accomplishments**
- **Globally open consortium**
- **Mask and resist dedicated development programs**
- **Strategic partnership for mask infrastructure**

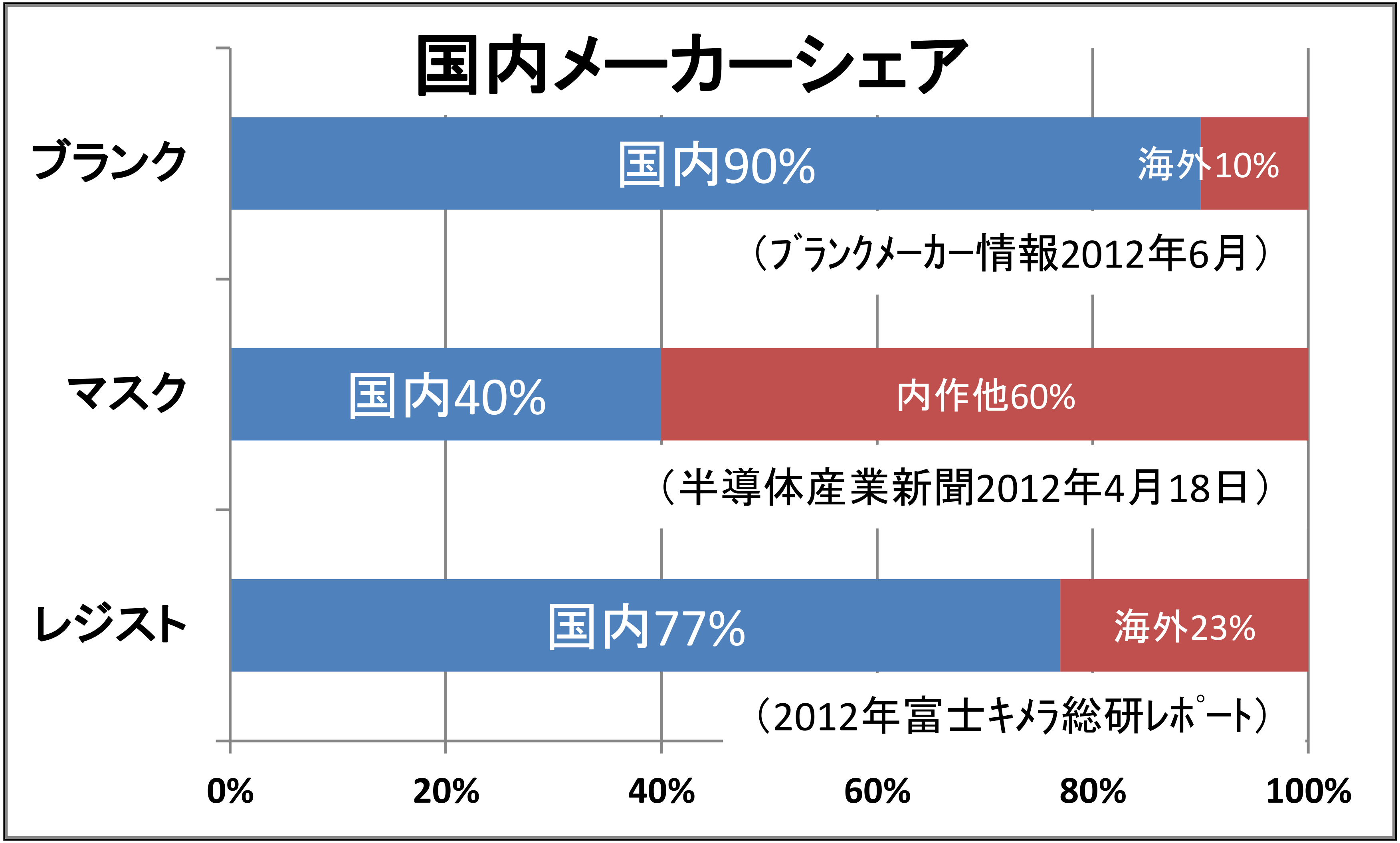
◆Stockholders
- AGC
- DNP
- FUJIFILM
- HOYA
- JSR
- Nikon
- Nissan Chemical
- Renesas Electronics
- Shin-Etsu Chemical
- TEL
- TOK
- TOPPAN
- TOSHIBA

◆JDP (Overseas)
- Intel
- Samsung
- SanDisk
- SK hynix
- TSMC
- AZ

◆JD Partners
- EBARA
- Lasertec

◆JD Research Institutes
- AIST
- Osaka University
- University of Hyogo
- Tohoku University
- Kyoto University
- Tokyo Institute of Technology

半導体マスク･レジスト関連日本企業の健闘



Development programs

Blank Inspection technology

- MIRAI tool utilization
- Actinic BI tool technology
- Lithographic impact
- Defect characterization

Lasertec
ABI tool development

Tohoku University

University of Hyogo

Patterned mask Inspection technology

- PMI tool technology with EB projection optics
- Defect characterization
- Lithographic impact

Osaka University

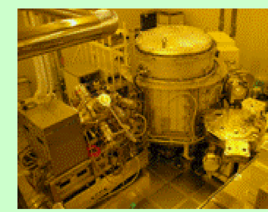
EBARA
PMI tool development

EUV Resist out-gassing Control

- Criteria of resist out-gassing
- Quantitative analysis
- EB based method
- Correlation between EB & EUV

EUV Resist Material research

- SFET utilization
- Fundamental research
- New resist platform
- Alternative resist process



DSA research

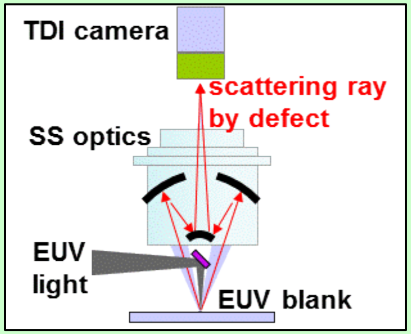
- Material evaluation for high χ parameter
- Process (Guide patterning, Anneal, Pattern transfer, Integration)
- 3-dimentional nanostructure analysis
- Simulation

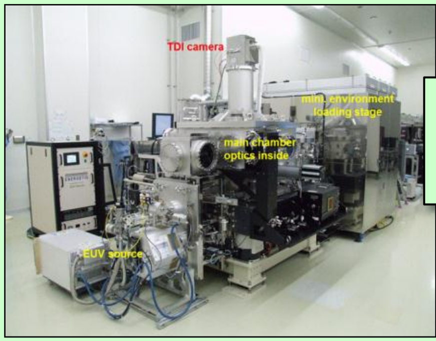
Kyoto University

Tokyo Institute of Technology

AIST

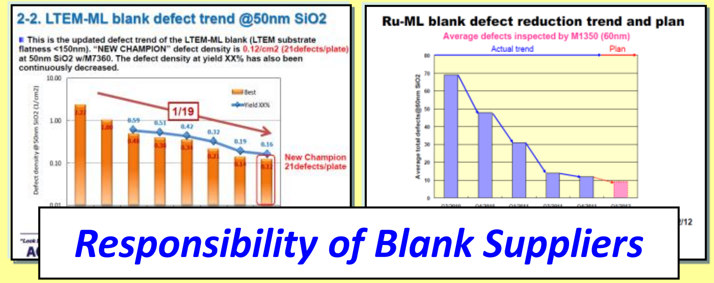
Approach for "Effective" Phase Defect-free Blank



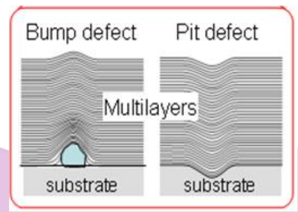


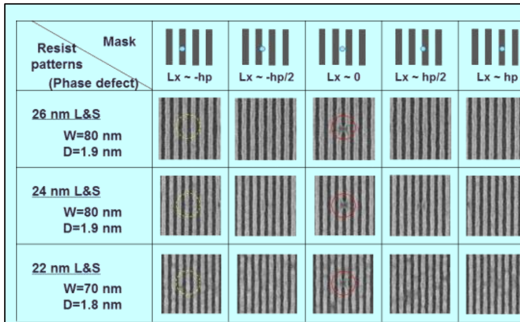
ABI-Tool

Defect Inspection



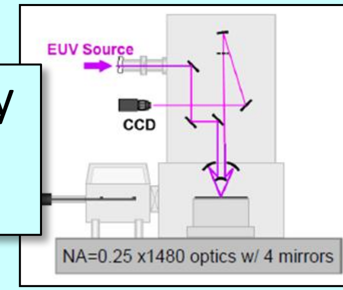
Defect Reduction





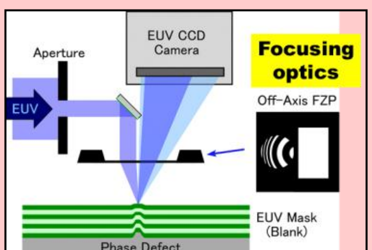
CD impact (Scanner & simulation)

CD Printability
(Real Defect Traceability)

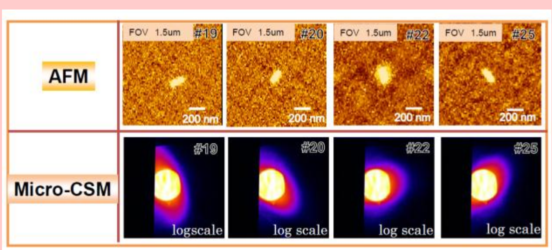


EUV microscope
(Tohoku University)

Defect Characterization

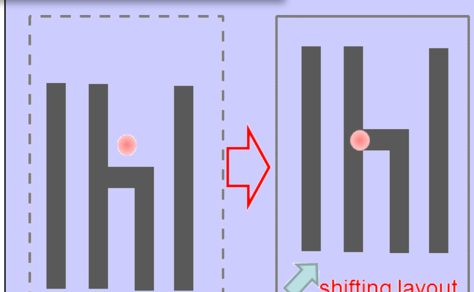


m-CSM
(University of Hyogo)



Diffraction patterns to various figures

Defect Mitigation



Mitigation process

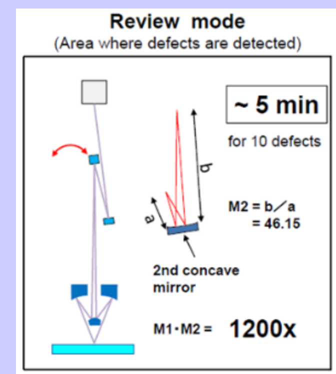
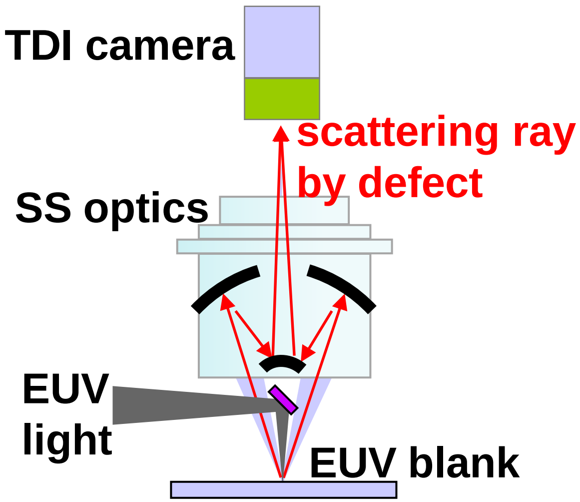
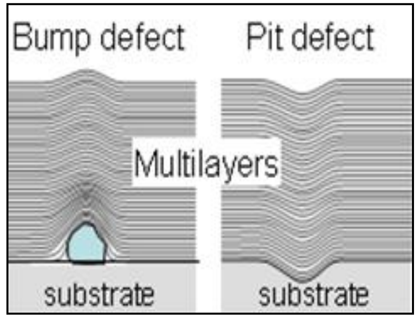


Image acquisition by review optics

ABI consistent development strategy





HVM by EIDEC(2011-2015)
ABI for hp16nm HVM
w/ Lasertec

-Development target-
1nmH/50nmW detection
in 45 min. scan

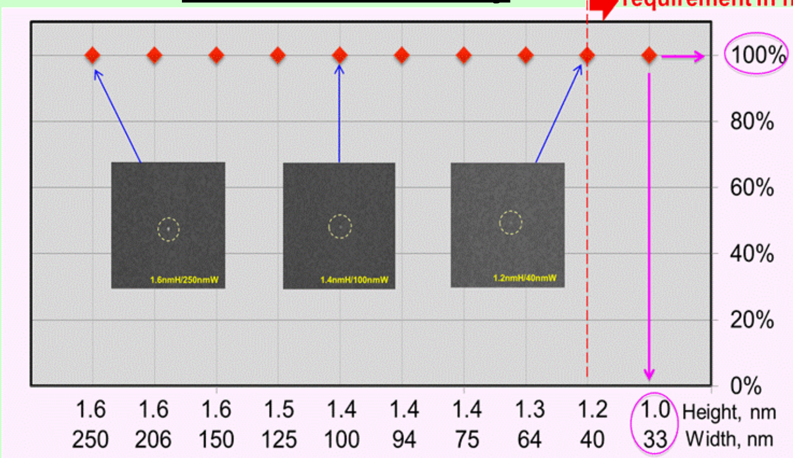
Proto by MIRAI-Selete(2006-2010)
full mask area ABI inspection

POC by MIRAI I,II (2001-2005)
feasibility of ABI,
dark field ABI by AIST & ASET

Blank Inspection & related technology update

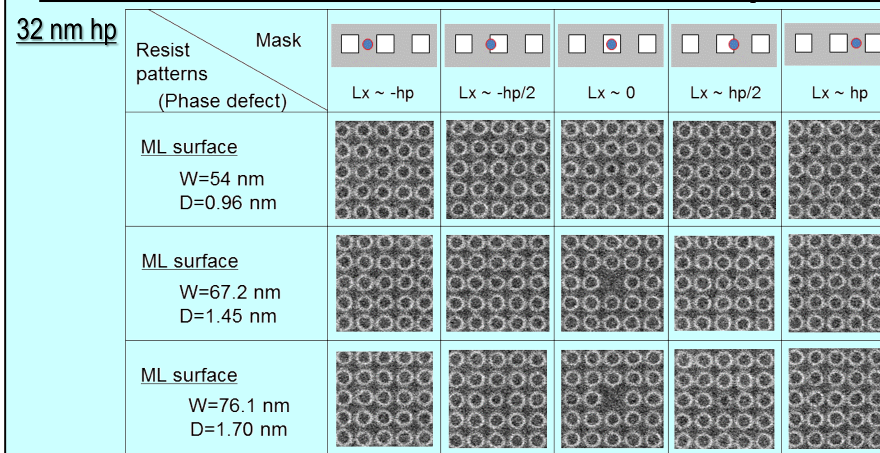
STRJ

ABI detectability



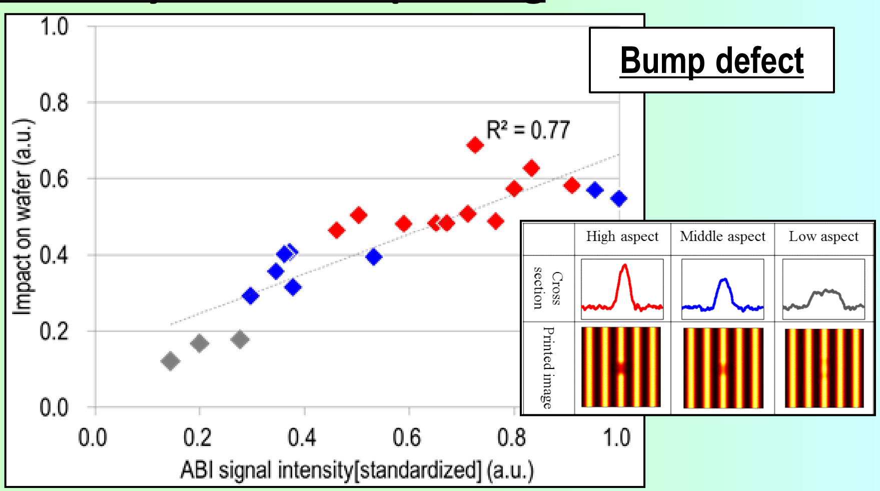
Capture Rate for programmed bump defects by defect size, nm, (based on 10 inspections)

Phase defect effect on contact hole pattern



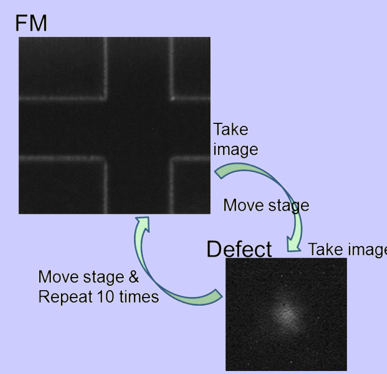
Y. Kim et al., "Analysis of phase defect effect on contact hole pattern using a programmed phase defect in EUVL mask," 9048-97, SPIE 2014

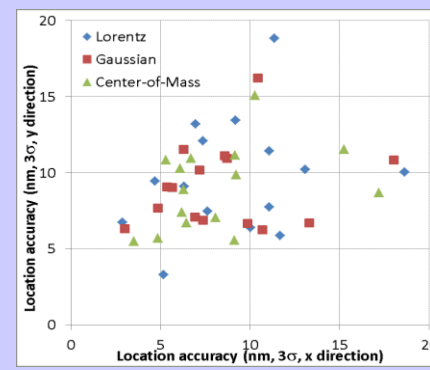
Impact of phase defect shape on ABI signal intensity and wafer printing



N. Takagi et al., "Experimental verification of effect of phase defect shape on ABI signal intensity," 9048-73, SPIE 2014

Defect location accuracy of Lasertec-ABI



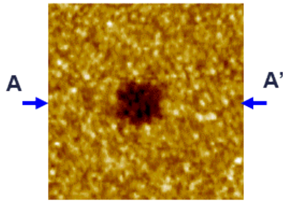


➤ **Worst case: 17.17 nm 3s**

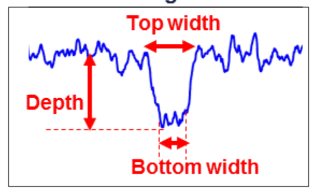
T. Murachi et al., "Improvement of defect mitigation with EUV Actinic Blank Inspection Prototype for 16 nm hp," 9048-71, SPIE 2014

Phase defect printability prediction

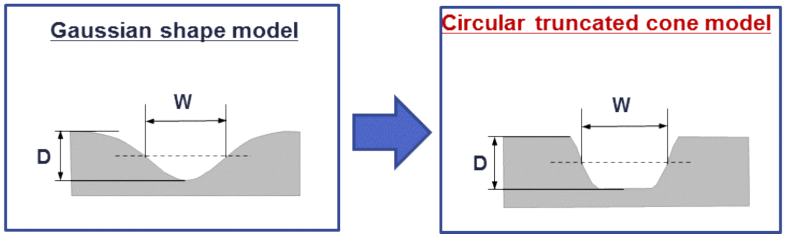
AFM measurement of pit phase defect

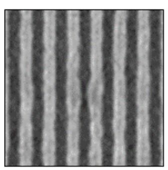
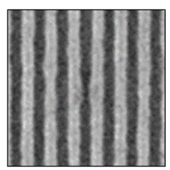
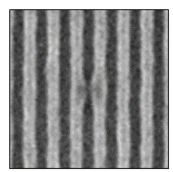
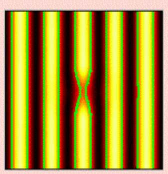
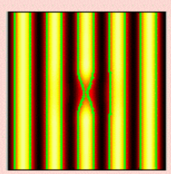
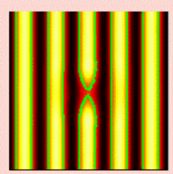
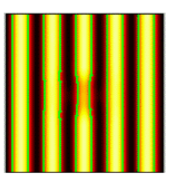
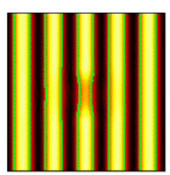
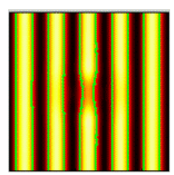


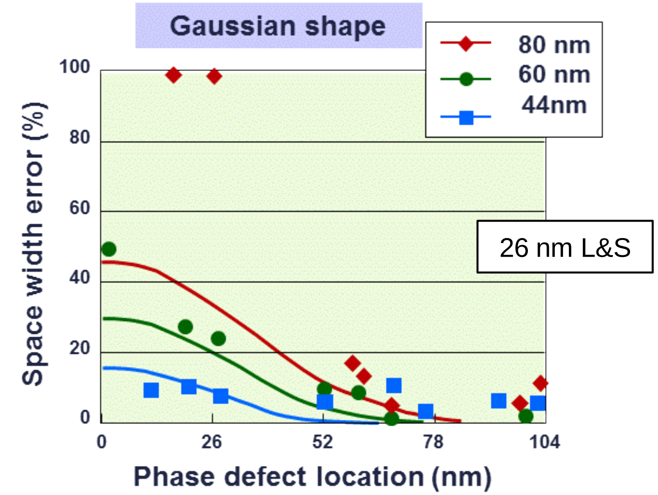
Profile along line A-A'

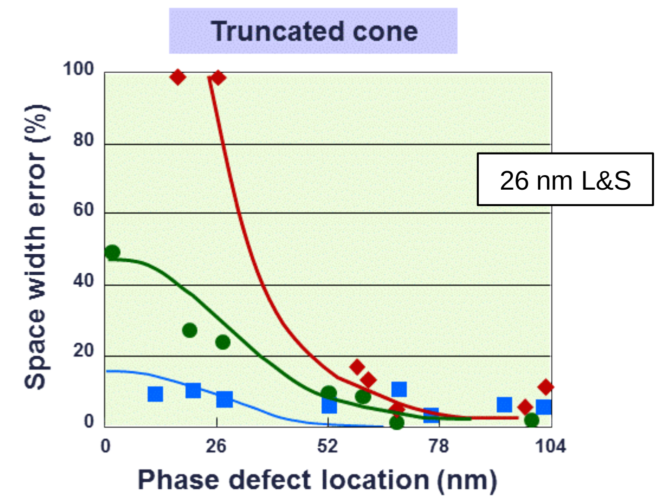


Pit phase defect model



Defocus [nm]	-30	0	30
Printed 24 nm L&S, Pit phase defect @mask (W=80 nm, D=1.9 nm) NA=0.25, Dipole			
Simulated images - Truncated cone model			
Simulated images - Gaussian shape model			

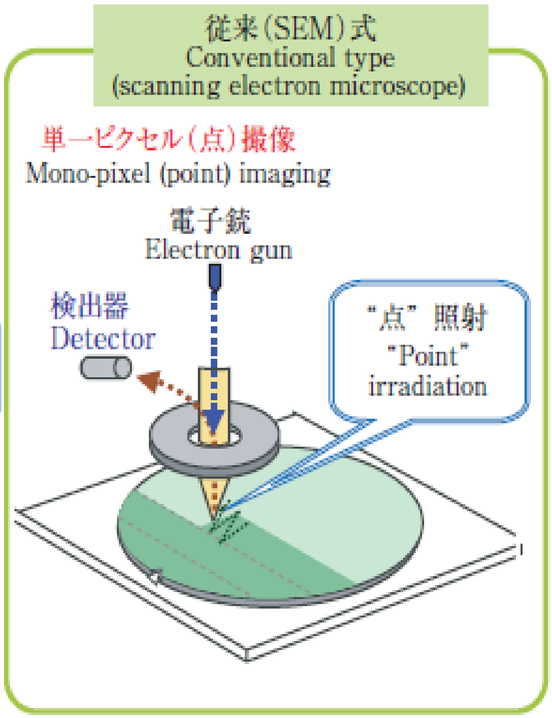




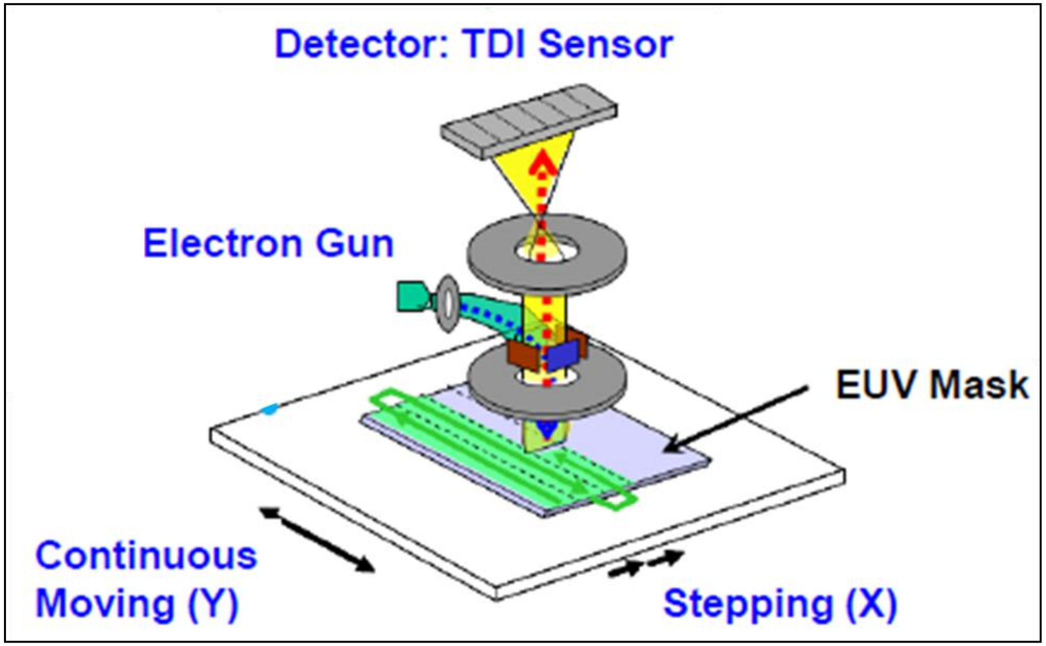
CD error prediction accuracy improvement using the truncated cone shape defect model

T. Terasawa et al., "Accuracy verification of phase defect printability prediction with various defect shape models," *2013 International Symposium on Extreme Ultraviolet Lithography, Toyama, Oct., 2013*

Patterned Mask Inspection



電子ビーム写像投影方式



同符号電荷の反発力で電子線が広がる
Repulsion force of charge expands electron beam (EB)

像ぼけ（Coulomb blur）となる

電流の最大値の制限

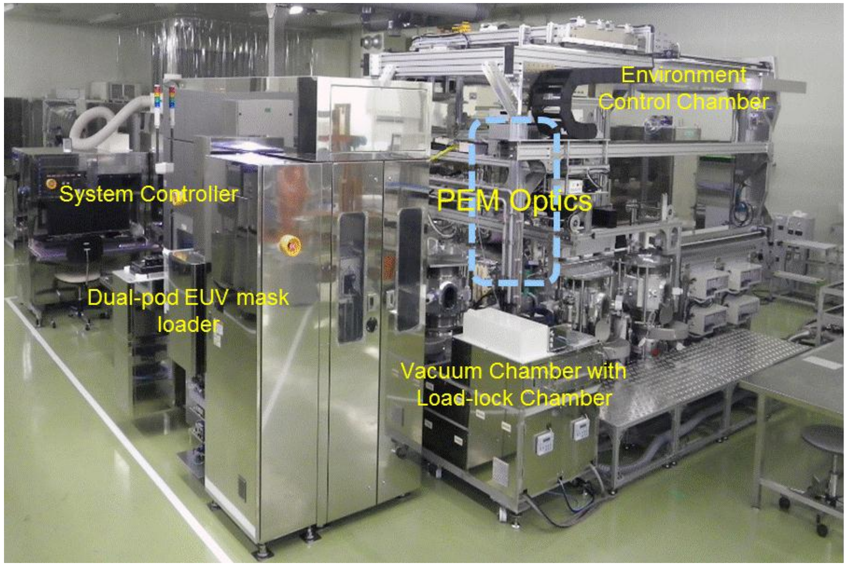
<u>写像投影方式の利点</u>

★ スループットの短縮
面照明で TDIセンサによる面画像取得が可能となるため、試料面で同一の電流密度の場合、SEM方式に比べて高速の検査が可能
（SEM方式では、空間電荷効果により 電流値に上限あり）

★ 強度情報をもった三次元画像
⇒ 光学検査装置の画像と同質 ⇒ 光学検査装置技術が応用できる
（SEM方式は、二次元画像（図形輪郭の線画像））

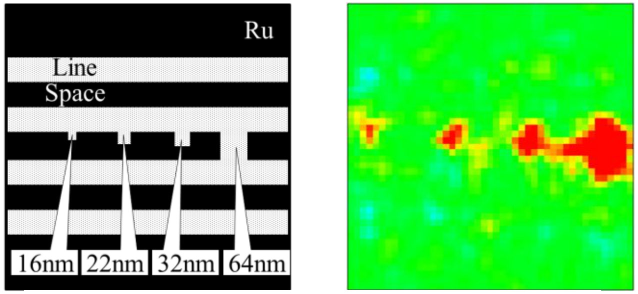
Patterned Mask Inspection

Overview of the system

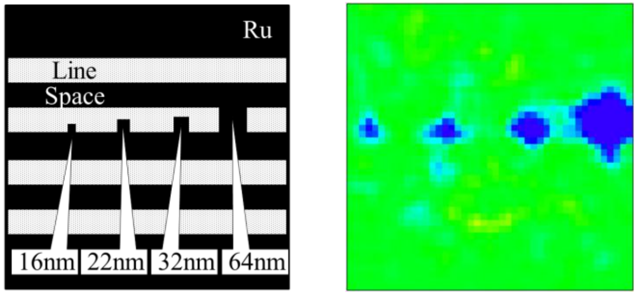


Calculated die-to-die-image

64 nm dense lines (hp 16 nm @mask)

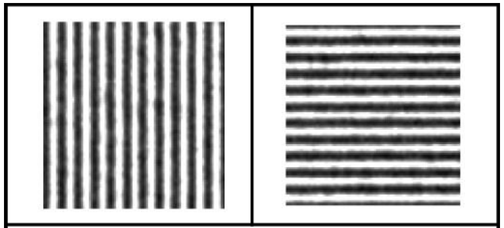


Extrusion defects

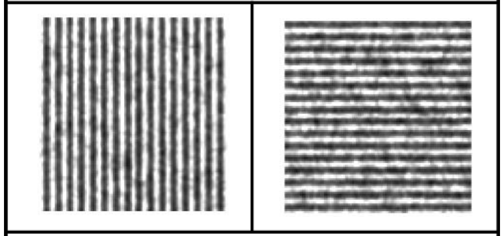


Intrusion defects

Captured images



(a) 64nm dense line



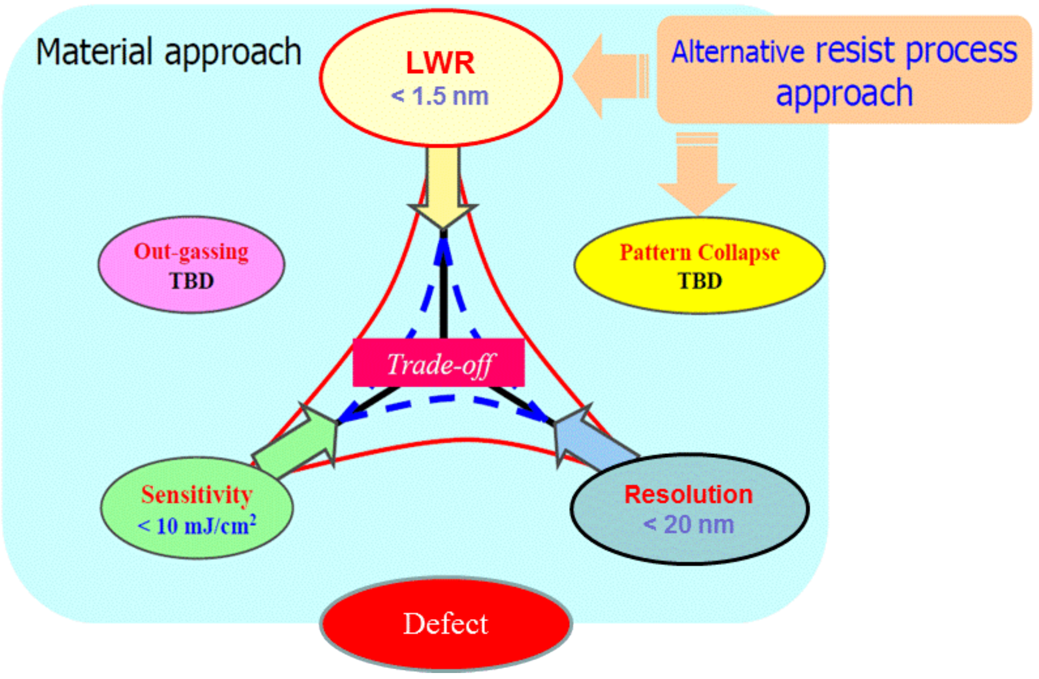
(b) 44nm dense line

- ✓ Performance verification of novel projection electron microscope (PEM) inspection system is in progress
- ✓ Resolved images of 64 nm dense lines (hp 16 nm) and 44 nm lines (hp 11 nm) were acquired
- ✓ Capturing the defects of 16 nm in size was verified by computer simulation

Challenges for EUV resist materials

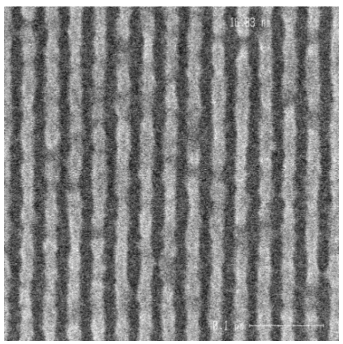
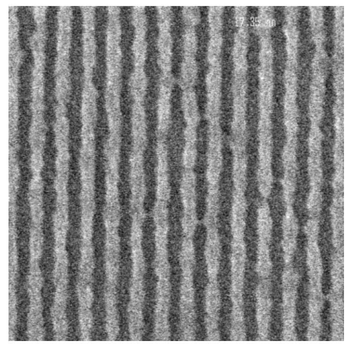
- ✓ Improve resist meeting resolution, line edge roughness (LER) and sensitivity (RLS trade-off)
- ✓ Realize novel resist platform for 11 nm and sub 10 nm patterning
- ✓ Make it clear where resist sensitivity limitation is
  - Can resist community reduce burden of EUV source community?

➢ **For all challenges, to understand mechanism occurring in resist pattern formation is needed.**



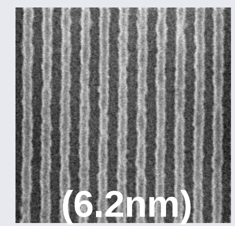
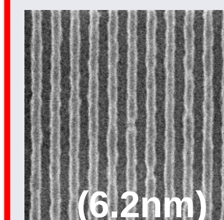
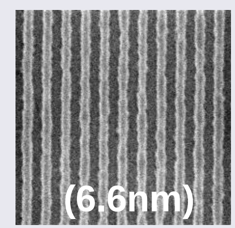
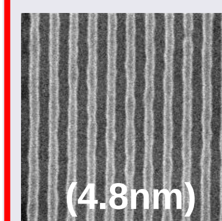
Present status of resist development in EIDEC

Ultimate resolution by SFET

	Positive-tone	Negative-tone
Resolution	16 nm	17 nm
Top-Down SEM Image (Mag. 300k)		

SFET Illumination : X-dipole
Resist Thickness : 35nm

Surfactant rinse solution with post rinse bake

	DIW	Surfactant Rinse
Resolution (nm)	26	**24**
Sensitivity (mJ/cm2)	20.0	19.4
30nm L/S after Rinse (LWR)	 (6.2nm)	 (6.2nm)
30nm L/S after Post Rinse Bake (LWR)	 (6.6nm)	 (4.8nm)

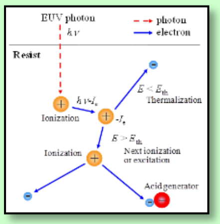
- The ultimate resolutions of hp 16 nm & hp 17 nm have achieved by chemical amplified positive and negative resists respectively.
- Combining surfactant rinse solution with post rinse bake shows further improvement of LWR by smoothing effect.

Fundamental approaches in EIDEC to understand mechanism occurring in resist pattern formation

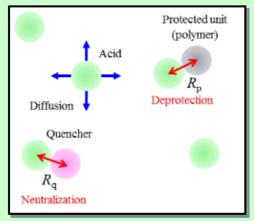
✓ Draw up guideline for resist material design and process development

Simulation for Stochastic effect

During exposure

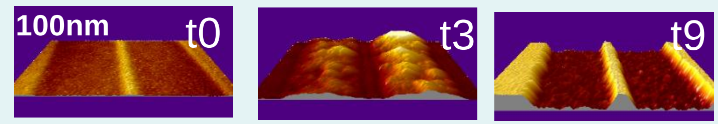


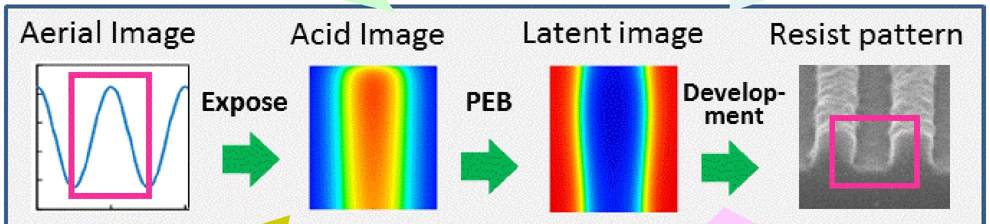
During PEB



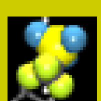
In collaboration with Prof. T. Kozawa

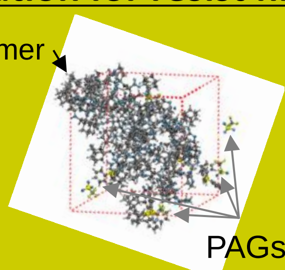
In-situ dissolution monitor (HS-AFM)

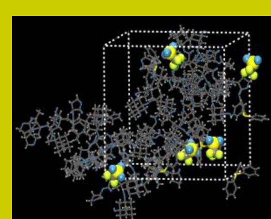




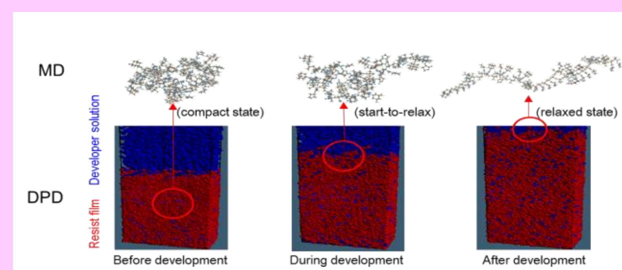
MD simulation for resist film Inhomogeneity





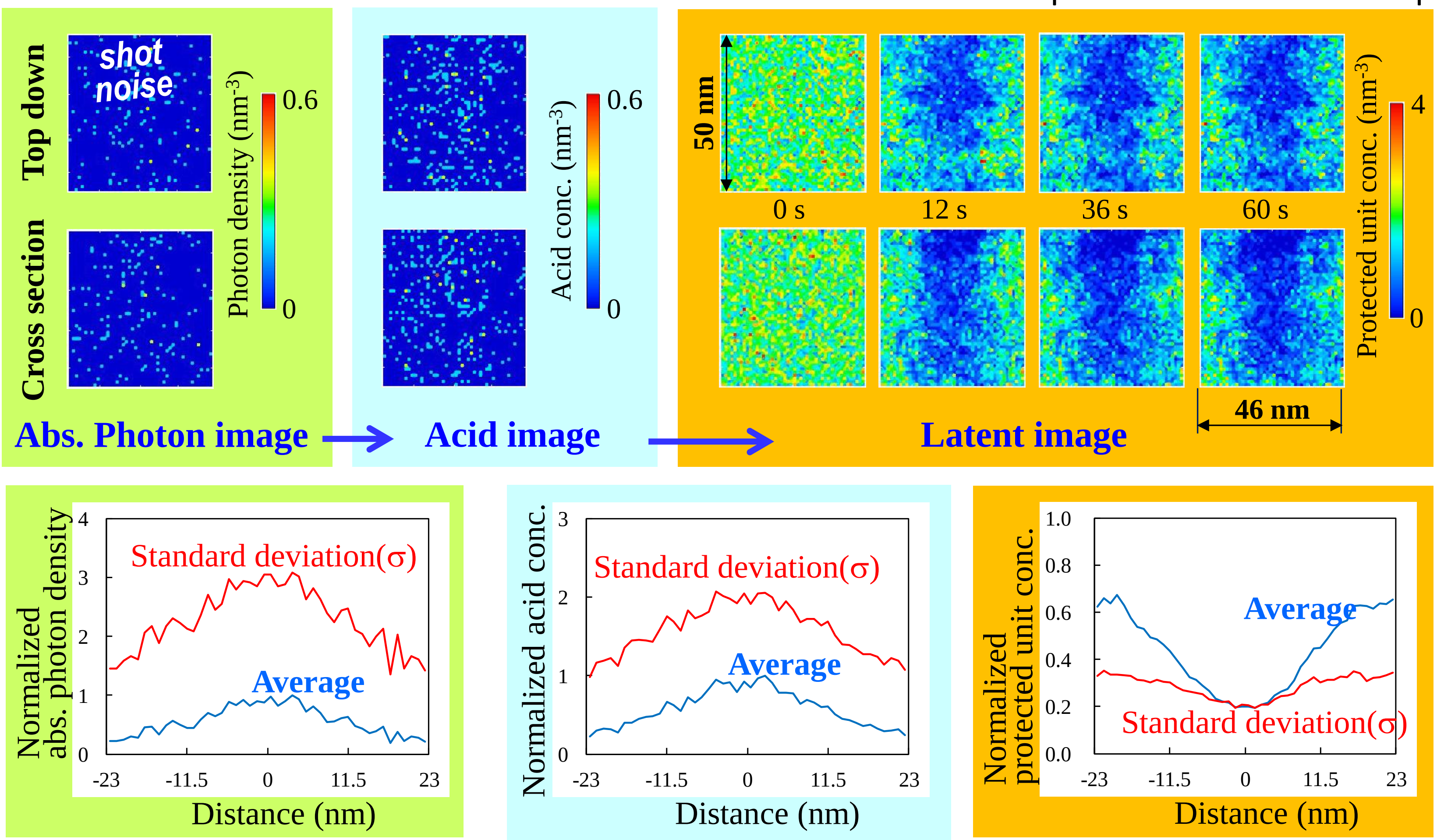


Combination of MD & DPD for resist dissolution



Stochastic effect simulation

23 nm LS pattern at 16 mJ cm^{-2} exposure

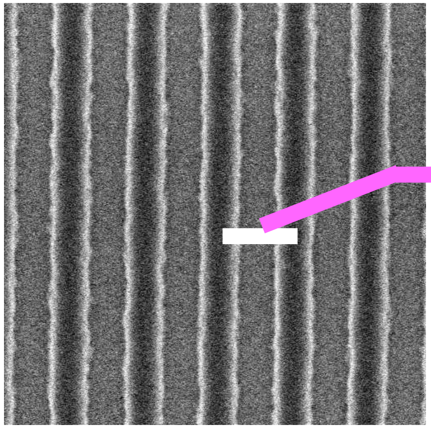


- ✓ The standard deviation (s) of absorbed photons is significantly larger than the average value.
- ✓ The ratio of s to the average value was decreased after acid generation because a single EUV photon produce approximately 2 acid molecules.
- ✓ The ratio of s to the average was further decreased after the acid catalytic reaction.

Ref.: T. Kozawa et al., “ Analysis of Stochastic Effect in Line-and-Space Patterns Fabricated by Extreme Ultraviolet Lithography”, 2012 EUVL symposium

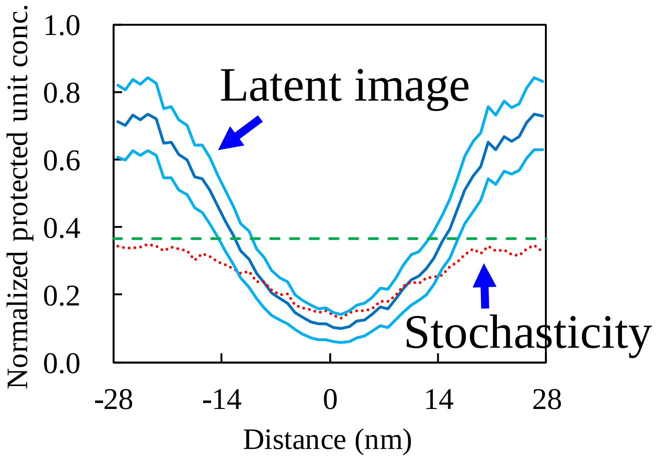
Concept of resist characterization

Conventional characterization



Reconstruction of chemical image

Advanced characterization



SEM image

Resolution
Line edge roughness
Sensitivity
Exposure latitude
Information

Inadequate for material design of 16 and 11 nm node

\+

Latent image & stochasticity

Absorption coefficient
Quantum efficiency
Effective reaction radius
Dissolution point
Dissolution efficiency
Information

Extraction of chemical information from SEM images is essential to efficient resist development.

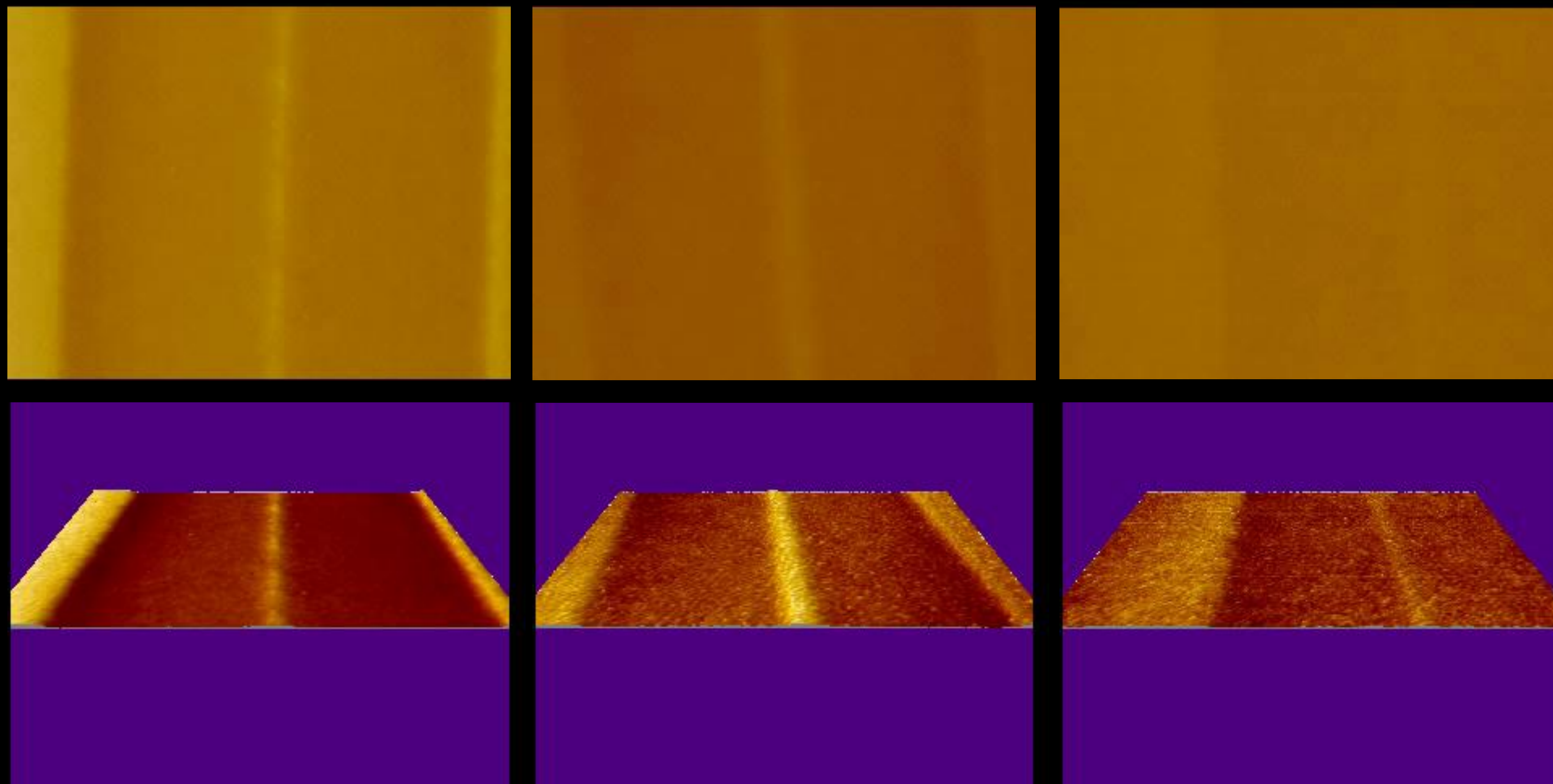
Ref.: T. Kozawa et al., "Stochastic Effects in Resist Processes of Extreme Ultraviolet Lithography", 2013 EUVL symposium

Early results: Dissolution characteristics of various EUV resist types

Pattern size: 32nm l/L
Developer: 1/20 diluted TMAH

2D

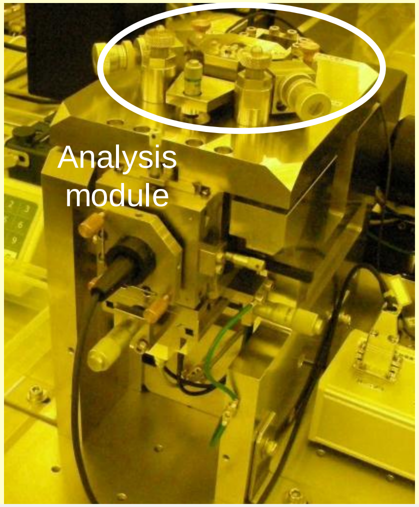
3D



PHS	Acryl	Fullerene
Grain-like	Swelling	Finer grains

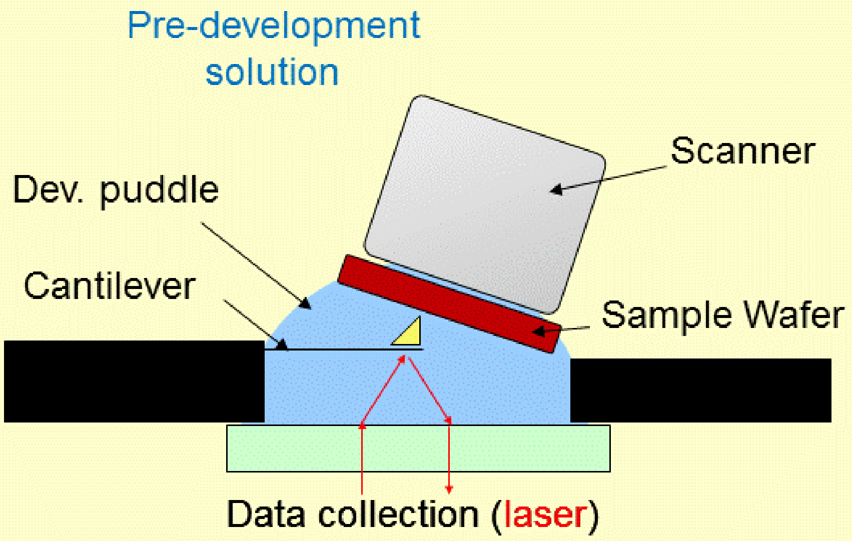
Ref: T. Itani and J.J. Santillan: J. Photopolym. Sci. Technol., 23, (2010) 639.

In situ analysis of pattern formation during development



Nano Explorer NEX (HS-AFM) by RIBM (*)

Scan area	XY : 1000 x 750nm
Scan Speed	0.5 (Max: ~12) frames/s
Cantilever *(radius of curvature)*	<10nm



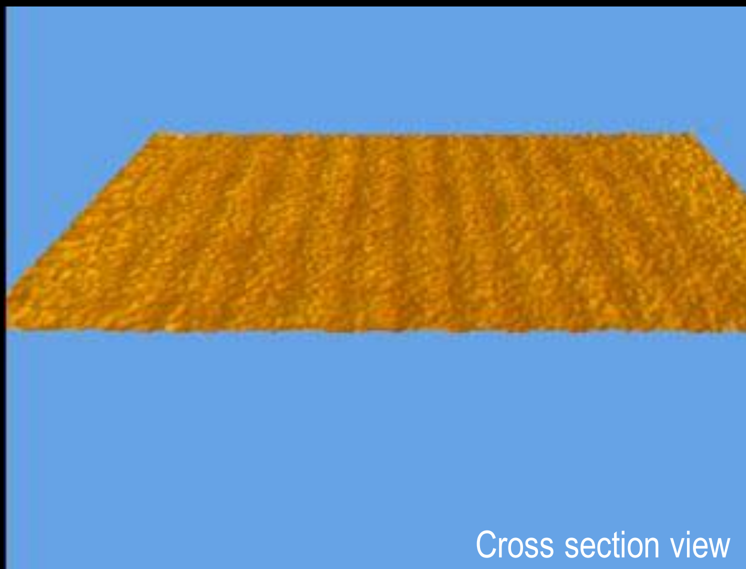
(*) RIBM: Research Institute of Biomolecule Metrology

Real-time analysis of resist pattern formation during dissolution realized.

Pattern formation at organic solvent vs. typical alkali developer

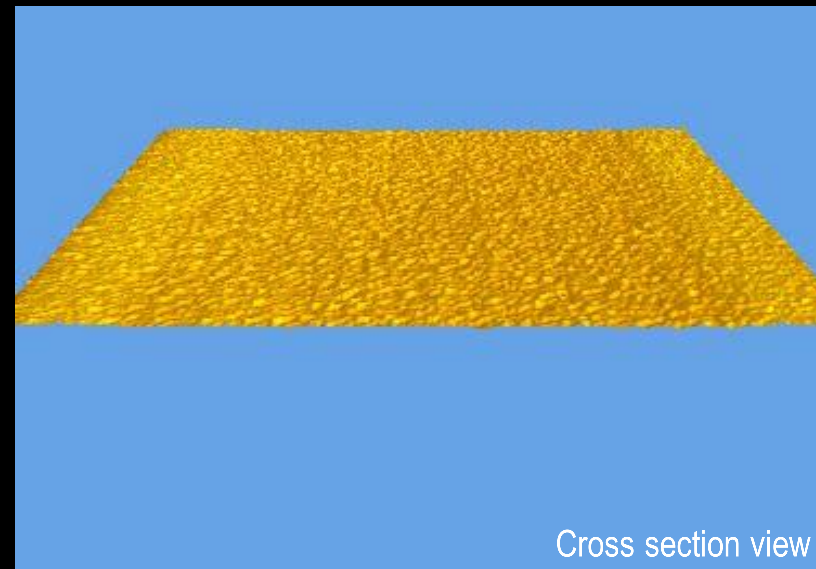
at 32 nm hp L/S pattern

Dissolution **in organic solvent**



NTD: Dev. Solution: nBA

Dissolution in **alkali solution**



PTD: Dev. Solution: TMAH 2.38%

◆ NTD: Smooth line edge roughness & Smooth top roughness

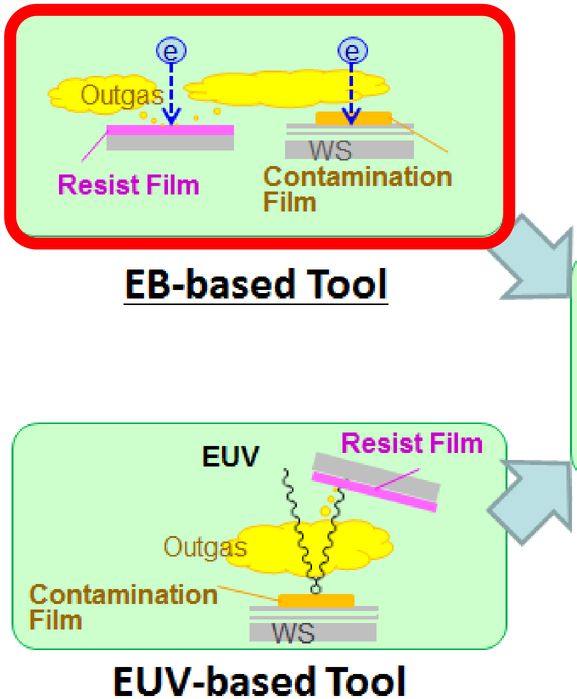
- PTD: Dissolution is affected by the image quality exposed on the resist film (from the exposure tool) and effectiveness / uniformity of the resulting chemical reactions from exposure.
- NTD: Dissolution is mostly affected only by the dissolvability of the resist film in the applied solvent.

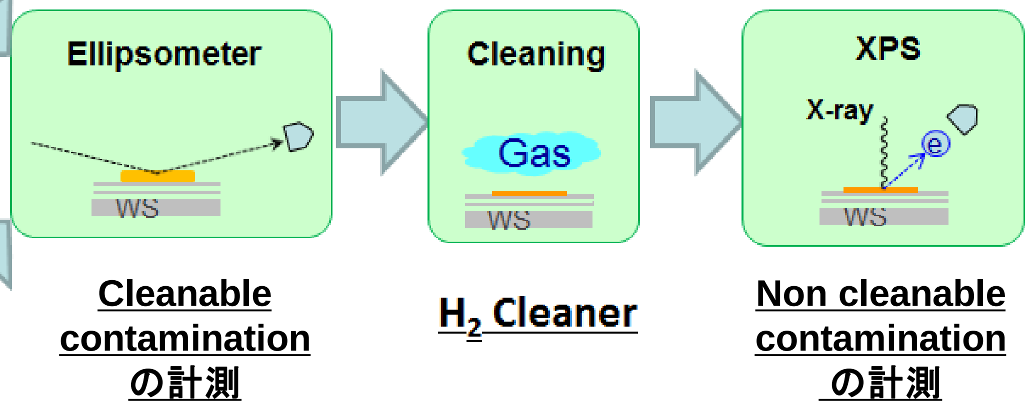
EUVレジストアウトガス計測制御技術開発

STRJ

レジストアウトガスの許容値に対する基本的な考え方（ASML社）

◆ 露光装置内のコンタミネーション現象を模擬した評価手法を提案
◆ 評価における許容値設定
　・露光装置寿命期間内の反射率低下を一定の割合に抑える
　・レジストアウトガスの寄与率を全要因の分析結果から配分

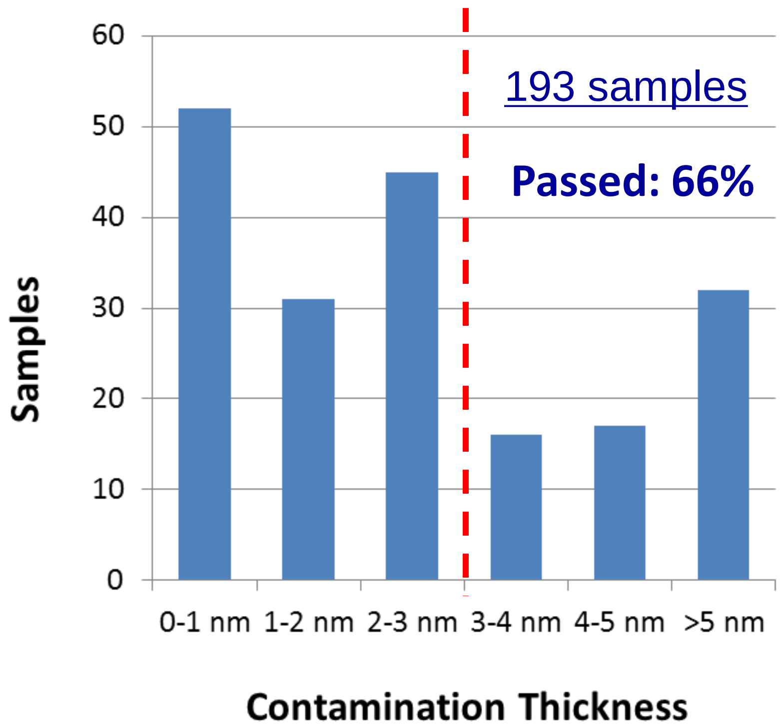




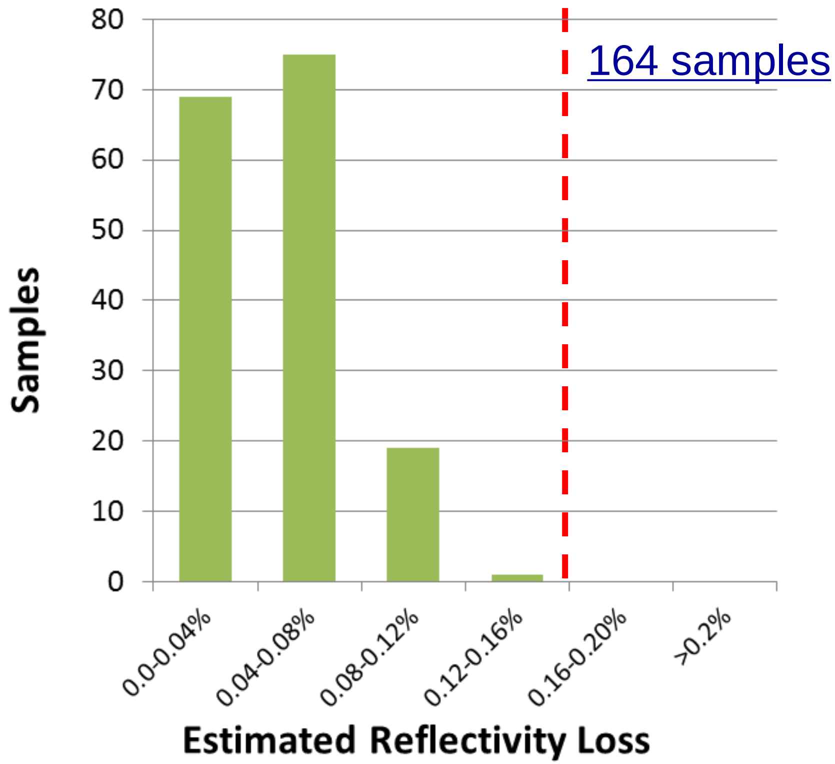
Cleanable contamination	Non cleanable contamination
許容値（コンタミ膜厚）： 3 nm 以下	許容値（ ミラー反射率低下）： 0.16% 以下
生産性を考慮したメンテナンス時間内に実施されるミラー洗浄で除去可能なコンタミ膜厚に対して、レジストアウトガス の寄与率を勘案して設定。	30,000時間露光した場合の光学系全体の反射率低下を10%以下に抑えるように、レジストアウトガスの寄与率を勘案して設定。

Cumulative Number of Commercial Samples

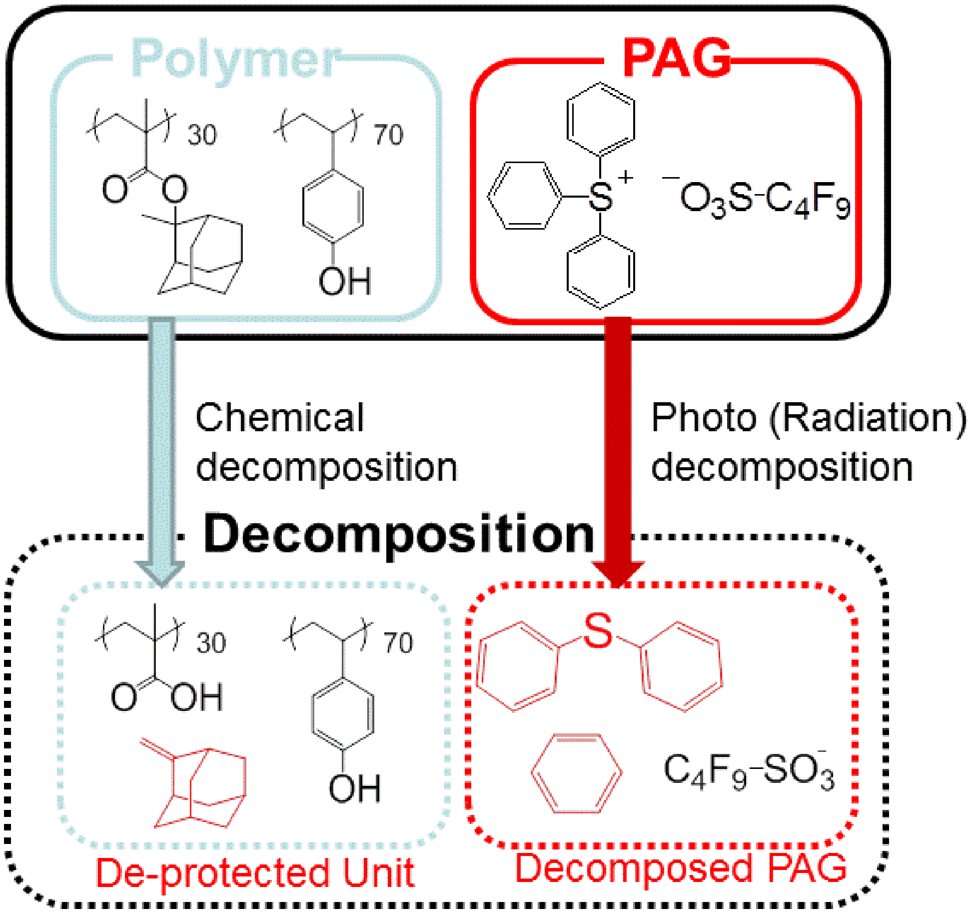
Cleanable

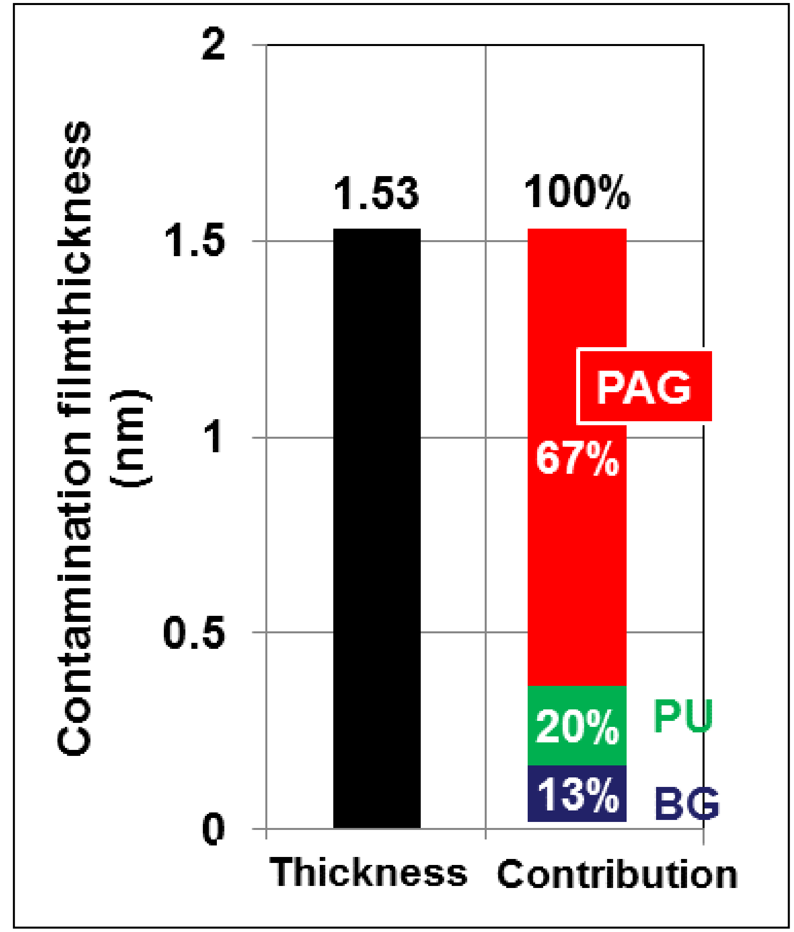


Non-Cleanable



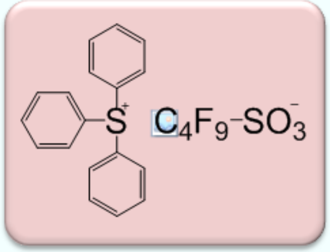
Model Resist Outgassing mechanism (Cleanable): Contribution of each component





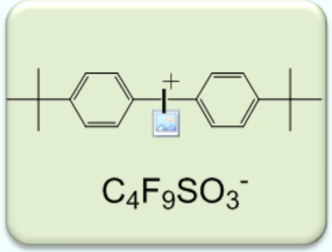
- ～70% of the Contamination Thickness is by PAG component

Model Resist Outgassing mechanism (Non-Cleanable): Influences to permanent reflectivity loss



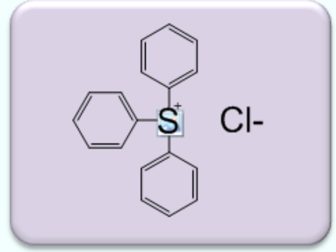
Sulfur

30wt% of polymer



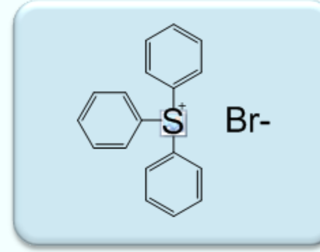
Iodine

equal mol% to TPS-Nf (Sulfur)



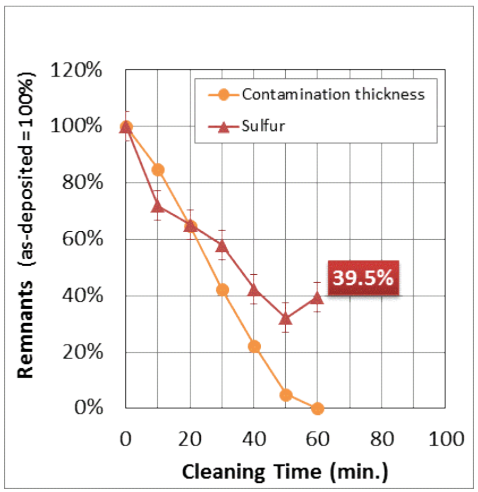
Chlorine

equal mol% to TPS-Nf (Sulfur)

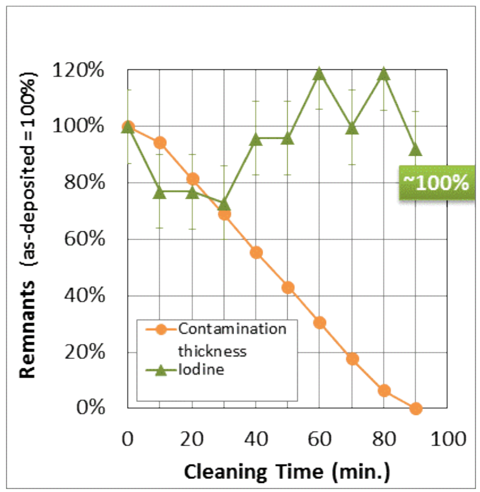


Bromine

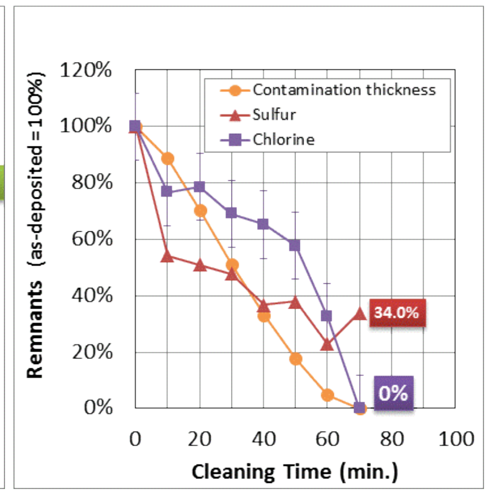
equal mol% to TPS-Nf (Sulfur)



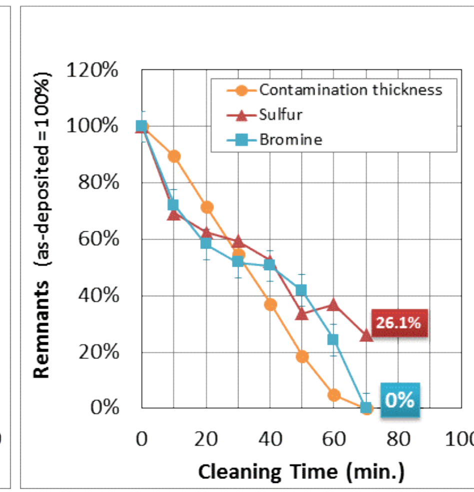
Surfur Cleanability = 60.5%



Iodine Cleanability = 0%



Chlorine Cleanability = 100%



Bromine Cleanability = 100%

- Iodine is most critical element for permanent reflectivity loss.
- Sulfur should also be carefully managed if used in high amount.

Summary

- Lithography remains an enabler of miniaturization of semiconductor devices.
- EUV lithography will be the main stream technology from the viewpoint of cost and extendibility.
- The source no doubt needs to increase in power dramatically with sufficient stability.
- EIDEC project was launched on the basis of the globally open concept.
- The phase defect sensitivity specification of the ABI tool for hp 16 nm generation has been confirmed.
- Performance verification of the novel PMI with projection electron microscope (PEM) is in progress
- There is incremental improvement in resist meeting resolution and sensitivity for HVM insertion. Progress in LER/LWR will be still needed.
- Mechanism occurring in resist pattern formation such as stochastic effect and dissolution behavior is becoming understandable
- EB-based resist outgassing evaluation method is being verified.
- Industrial and academic concurrent-approach will drive EUVL extendibility.

Acknowledgments

- Many thanks to:
  - Prof. T. Kozawa, Osaka university
  - Prof. H. Kinoshita & Prof. T. Watanabe, University of Hyogo
  - Committee members of EIDEC stock holders and JDP partners for their supports

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