Aiming at the mass production by EUVL ~From the beginning to the future prospect~

Deputy Director/Senior Fellow Professor
Institute of Research Promotion and Collaboration
University of Hyogo

Hiroo Kinoshita

Outline

1. Early stage of Development

   Why was the wavelength of 13.5 nm selected?

2. Development of a two aspheric optical system
3. Development of Multilayer film with high reflectivity
4. Progress of light source development;

   Solid, semi-solid, gas, liquid

5. Current status and future high NA optical system
6. Conclusion

First, I’ll explain why I began studying X-ray reduction lithography.
I was involved in research on X-ray proximity lithography (XPL) around 1983.
At that time, the target resolution for XPL was 0.5 μm, which was thought to be difficult to achieve with ultraviolet lithography.
We had already developed apparatus for S&R type proximity X-ray lithography and examined its applicability to the trial production of devices. We were deeply involved in these trials and in improving evaluation procedures.
Our assessment was that the exposure machine and resist performance seemed quite adequate; but we ran into too many problems with the manufacture of proximity masks.
It was around that time that I began to seriously consider X ray reduction lithography as a more viable alternative.

Extended Abstracts (The 47th Autumn Meeting,1986) ;

The Japan Society of Applied Physics

28-ZF-15 Study on X-ray Reduction Projection Lithography

NTT ETL Hiroo Kinoshita, Ryuji Kaneko, et al.

28p−ZF−15 X線縮小投影露光の検討（その１）

ＮＴＴ 電気通信研究所 木下博雄、金子隆司、武井弘次、竹内信行、石原 直

1．まえがき：紫外線露光の限界が見えるにつれ、Ｘ線露光への期待が高まりつつある。一方、半導体製造技術の進歩により優れた金属系多層膜が製作出来るようになり、Ｘ線光学素子[1,2]への適用が検討され始めた。ここでは、Ｘ線露光の新しい展開として、多層膜ミラー光学系によるＸ線縮小投影露光の試みについて報告する。

2．実験の概要：図１に実験装置の概要を示す。光源にはシンクロトロン放射光（高エ研ＢＬ－１Ｃ）を用いた。放射光の波長特性は８度曲げの白金コート石英ミラーを用いていることから、図２に示すような３０Åをピークとした連続スペクトルをもつ。縮小光学系にはSchwarzschild 型の反射鏡を用い、光線追跡により収差を最小とするミラー設計条件を定めた。多層膜は比較的少ない層数で高い反射率と広いバンド幅が得られ、かつ製作が容易な１１０Å付近に分光反射率のピークを設定し、イオンビームスパッタ法[3]でＷ－Ｃ膜を形成した。マスクにはステンシルマスクを、レジストにはＰＭＭＡ、ＦＢＭ－Ｇ等を用いた。

3．実験結果：図３に露光パタン例を示す。マスクに２０ｕｍ幅のワイヤーメッシュを用いた例では、０．２ｍｍ幅の環状露光領域に、パタン幅４μｍのほぼ1/5 に縮小されたレジストパタンが得られた。パタン部の段差は最大でも０．１μｍ程であり、この波長域ではレジストの吸収が大きいため表層での露光が行なわれていることがわかる。露光時間はほぼ２分（ビーム電流１５０ｍＡ、ＰＭＭＡ０．４μｍ）であり、ミラーなしでは１秒以下であることから多層膜ミラーでの反射率は２％程度と推定できる。

4．あとがき：Ｘ線縮小投影露光の１つの試みとして多層膜反射光学系による露光実験を行ない、収差の少ないパタンを得た。今後は装置性能の向上を図り、サブミクロンパタン形成条件の検討を進める。

参考資料 1)E.Spiller 他;SPIE 316 P90 2)松村;IONICS 1985,11 P1
3)武井 他;J.J.A.P 24(10)P1366

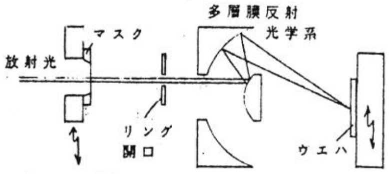


図１ 実験装置の概要

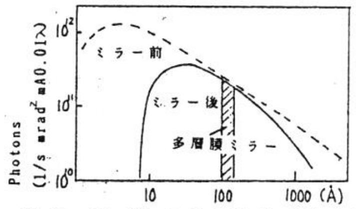


図２ BL-1C の強度分布（推定値）

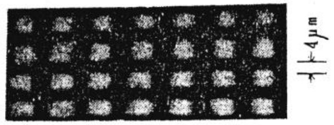
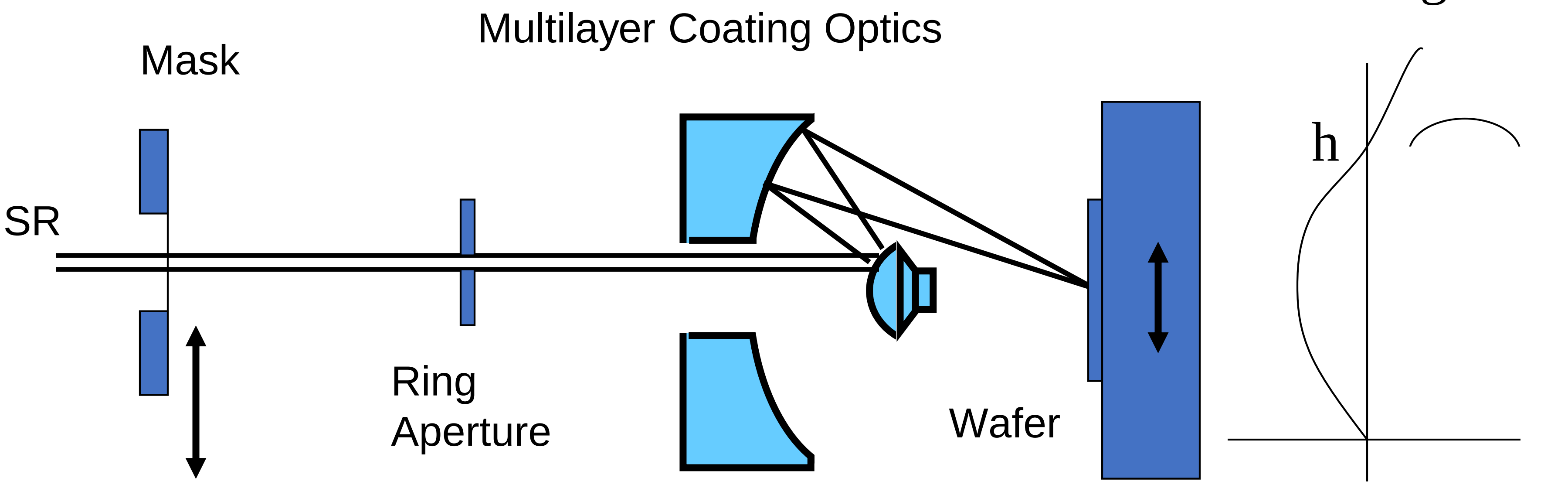


図３ 露光パタン例 PMMA(0.2um)/Si

NTT

λ=11 nm

Ring field



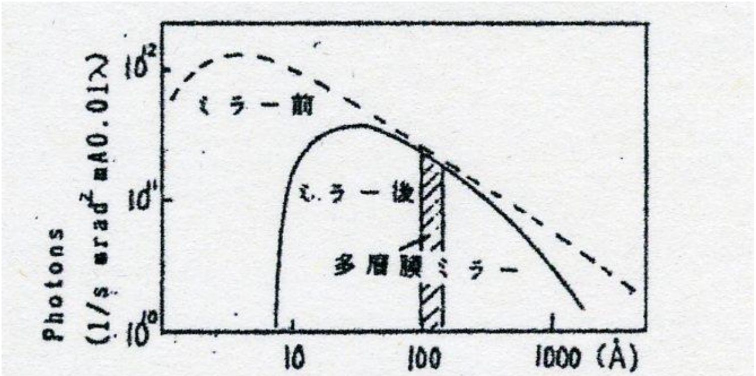


図 2　BL-1C の強度分布（推定値）

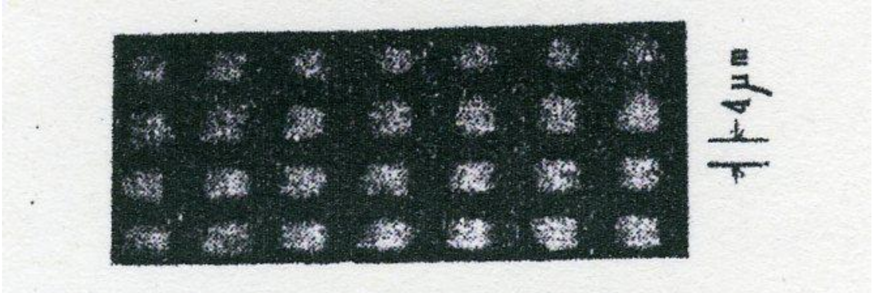


図 3　露光パタン例　PMMA(0.2um)/Si

1986

The response to the announcement was
rather negative.
People seemed unwilling to believe that
we had actually made an image by bending X-rays,
and they tended to regard the whole thing
as a big fish story.

However, my belief remained unshaken that
"theoretically, it is possible to produce an image
using a reduction optical system consisting of a
couple of mirrors coated with multilayer film."

Soft x-ray reduction lithography using multilayer mirrors

H. Kinoshita, K. Kurihara,[a] Y. Ishii, and Y. Torii
NTT LSI Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-01, Japan

(Received 30 May 1989; accepted 11 July 1989)

A soft x-ray lithograpy using multilayer mirrors for demagnifying optics and a reflecting mask has been designed and studied experimentally. In this system, a wavelength of 45–130 Å has been selected based on the optical characteristics, the exposed depth of the resist film, and the reflectivity of the multilayer mirror. To obtain a replication pattern resolution of 0.2 μm, the numerical aperture required is estimated to be greater than 0.0125 or 0.0325 for a wavelength of 50 or 130 Å, respectively. These values show that the multilayer optics using two mirrors can be realized to replicate a 0.2 μm pattern. The experiments were performed on the SR beamline BL-1 of the KEK-PF storage ring. The Schwarzschild demagnifying optics with a ring field were designed and fabricated. Demagnified exposure patterns of less than 0.5 μm have been obtained using a reflecting mask. The feasibility of the soft x-ray reduction method using multilayer mirrors has been confirmed. Furthermore, new telecentric optics are proposed to realize a practical reduction lithography system.

J. Vac. Sci. Technol.B7(6) (1989) 1648

Selection of exposure wavelength

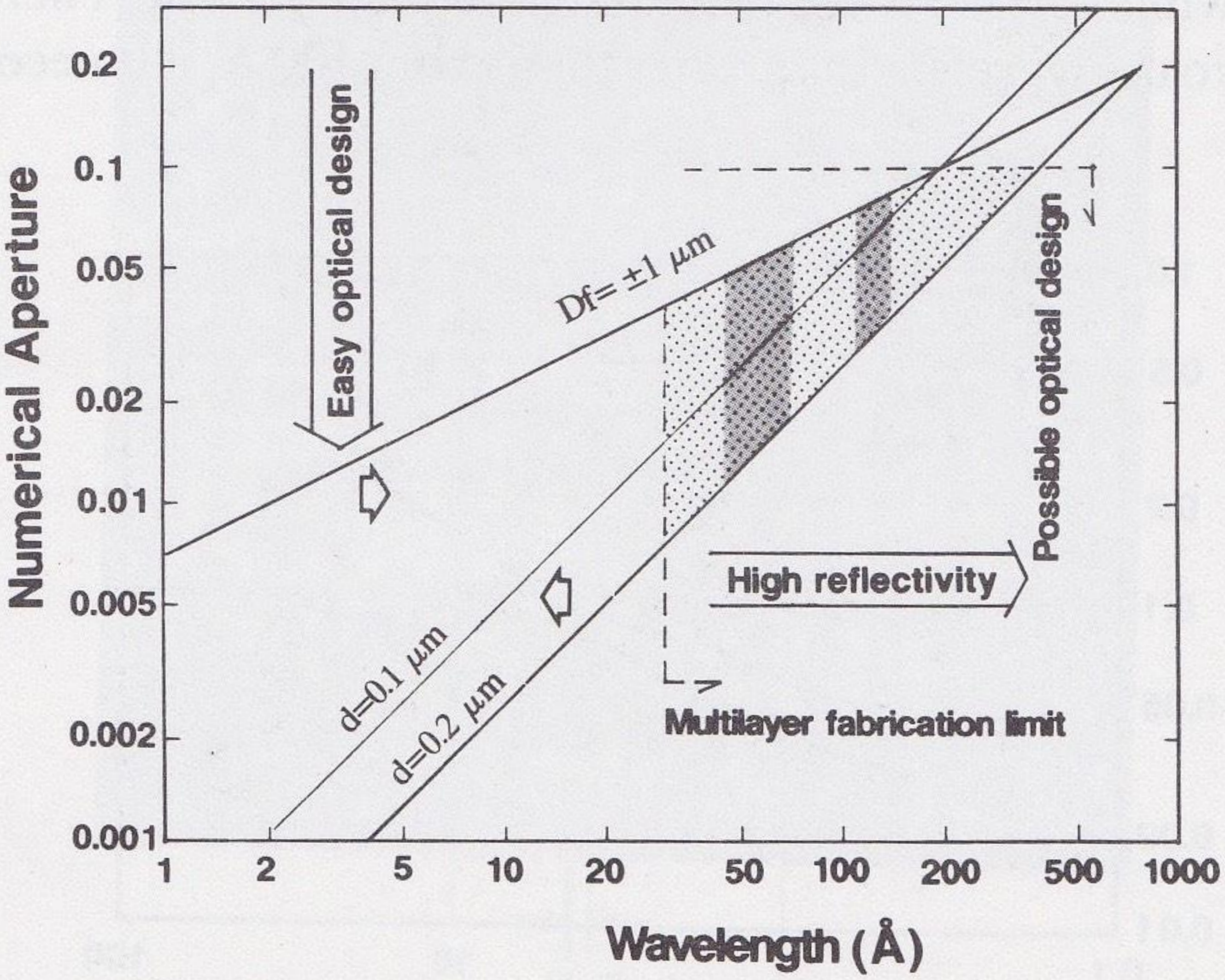


FIG. 1. The optical characteristics dependence on x-ray wavelength.

Optical Condition
$D = \lambda / 2NA$
$Df = \lambda / 2NA^2$

J. Vac. Sci. Technol.B7(6) (1989) 1648

High reflectivity close to theoretical value was achieved in 1985.

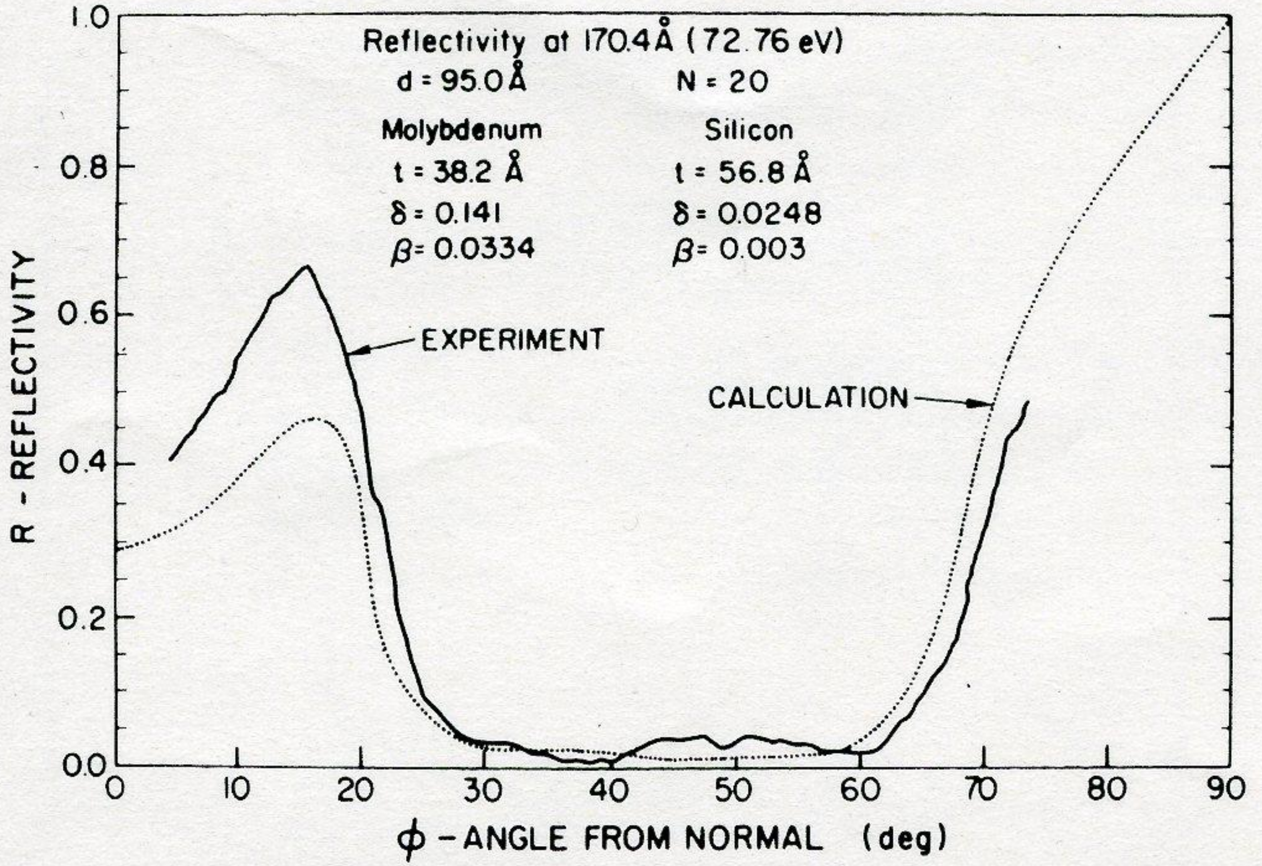
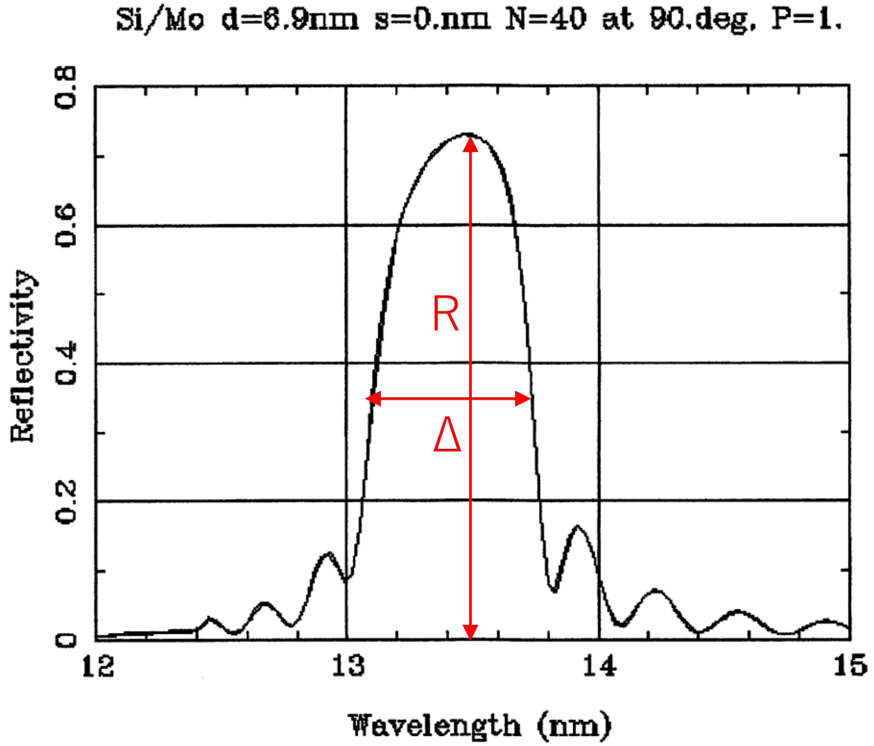
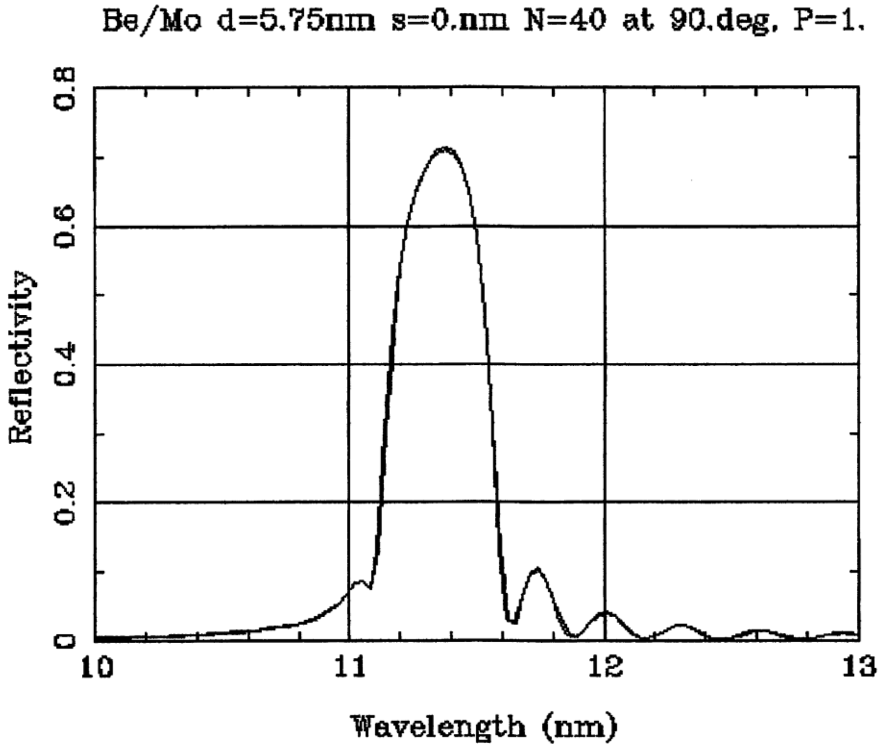


Fig. 3. Experimental continuous scan reflectivity of 170.4-Å light

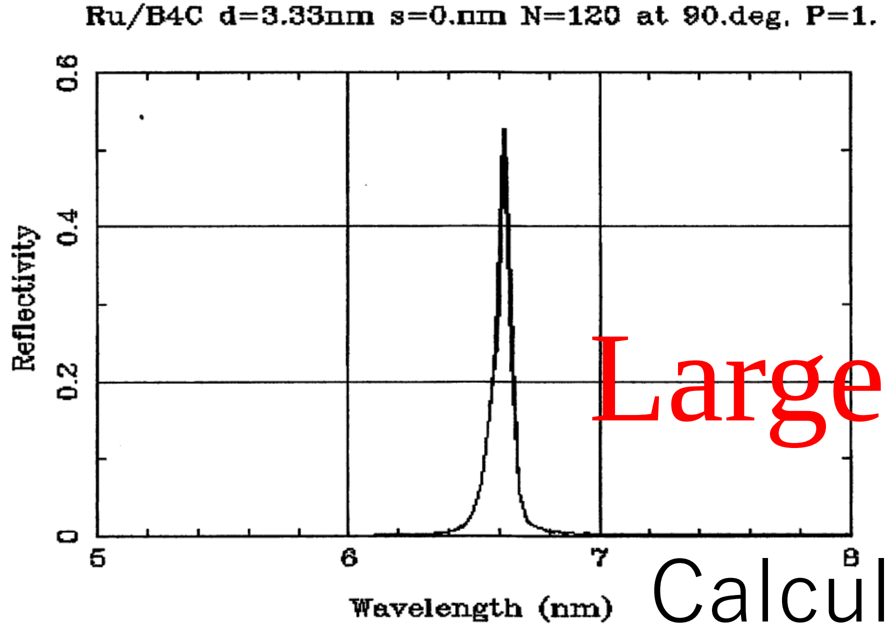
APPLIED OPTICS 24-6 (1985) Troy W. Barbee etal.



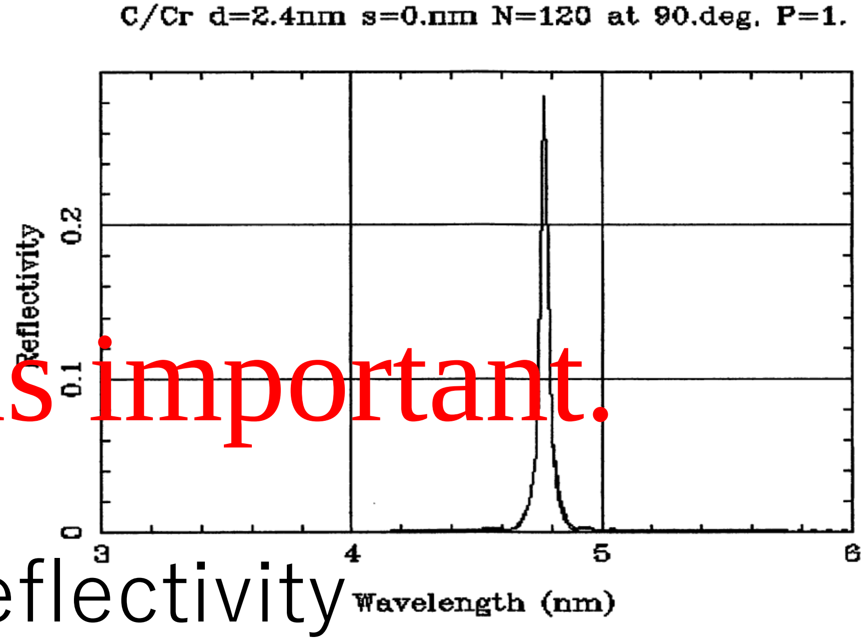
λ = 13.5nm
R=73%
Δ = 0.6nm



λ = 11.4nm
R=72%
Δ = 0.4nm



λ = 6.6nm
R=53%
Δ = 0.04nm



λ = 4.8nm
R=29%
Δ = 0.03nm

Large RxΔ is important.

Calculation Reflectivity

1986

Reflectivity Measurement in the world

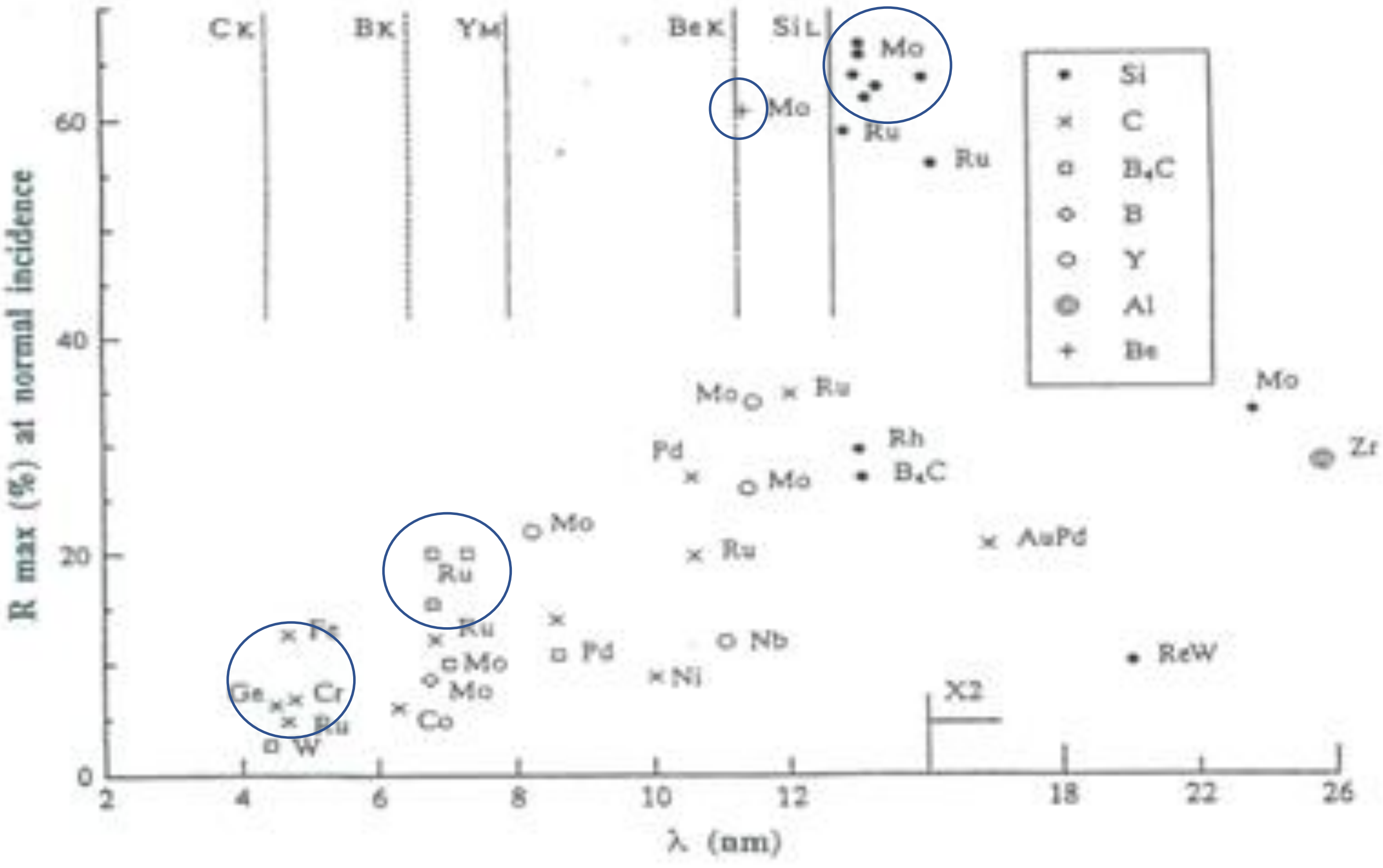
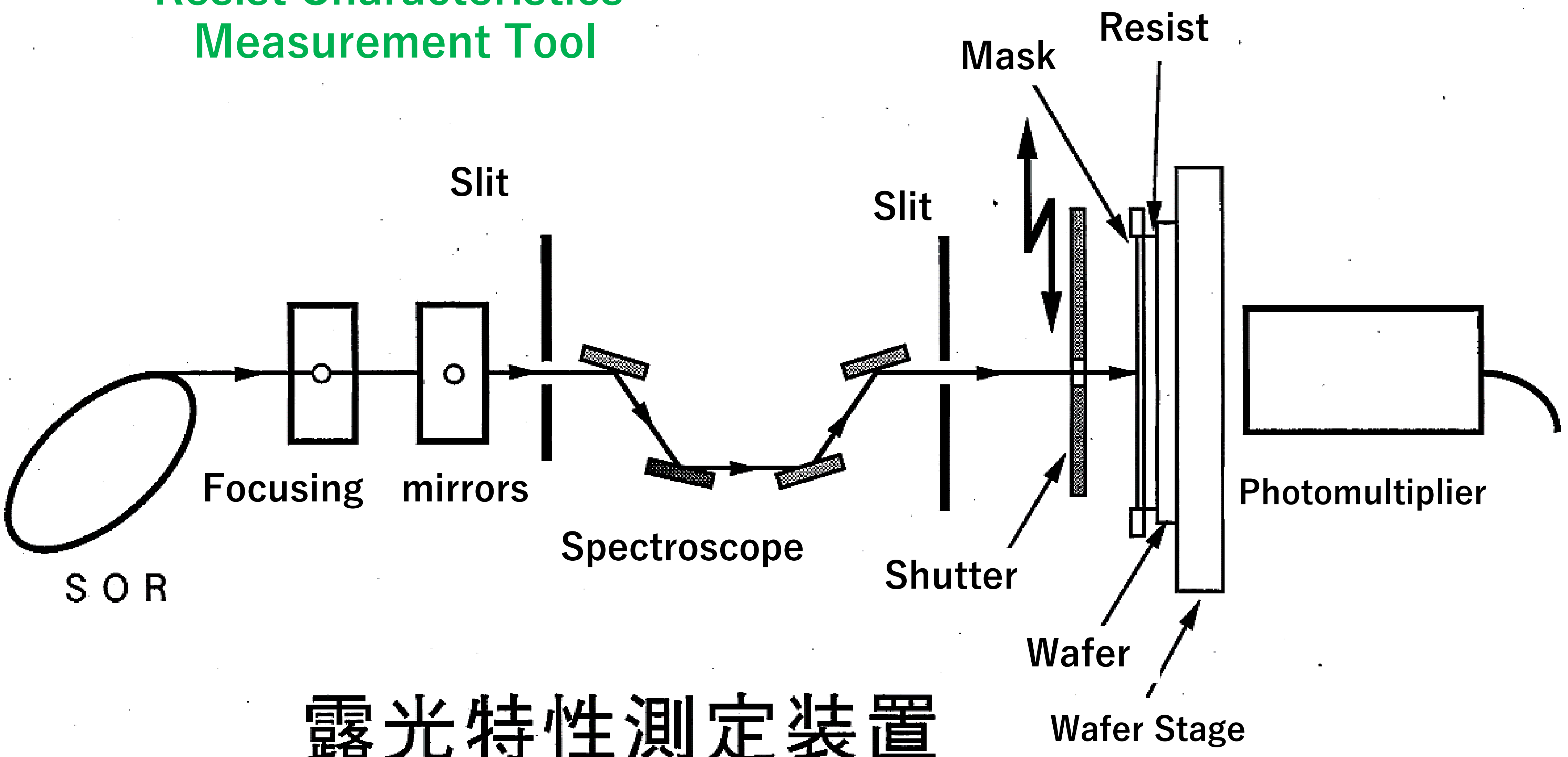


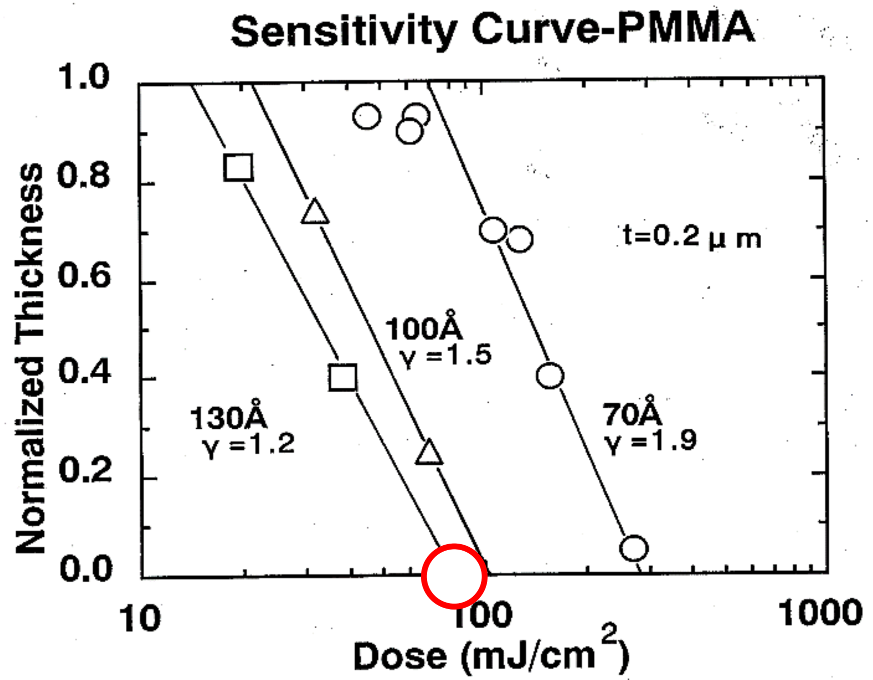
図3 Current trend of the best reflectnaces *vs.* wavelength with various material pairs.

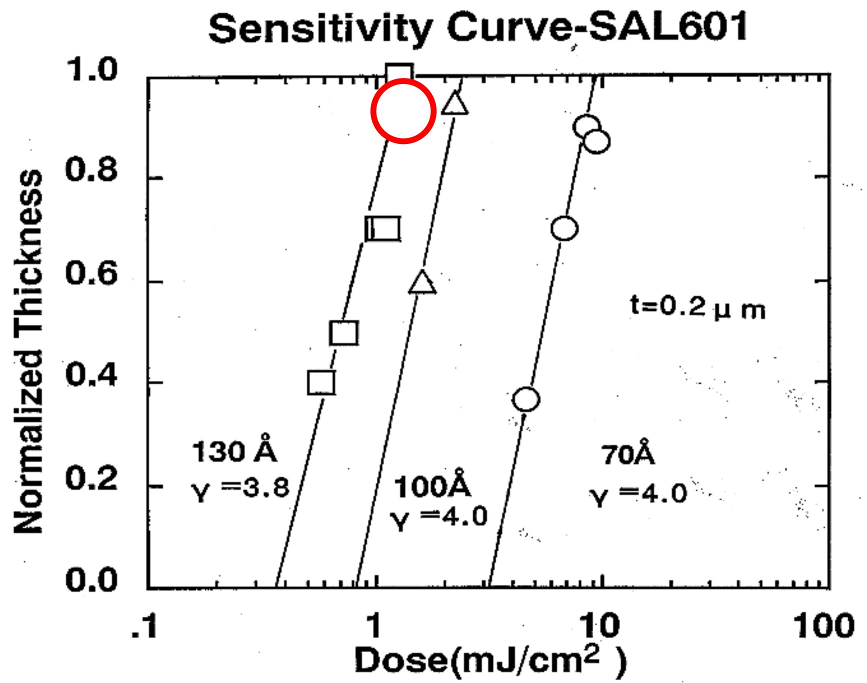
1994

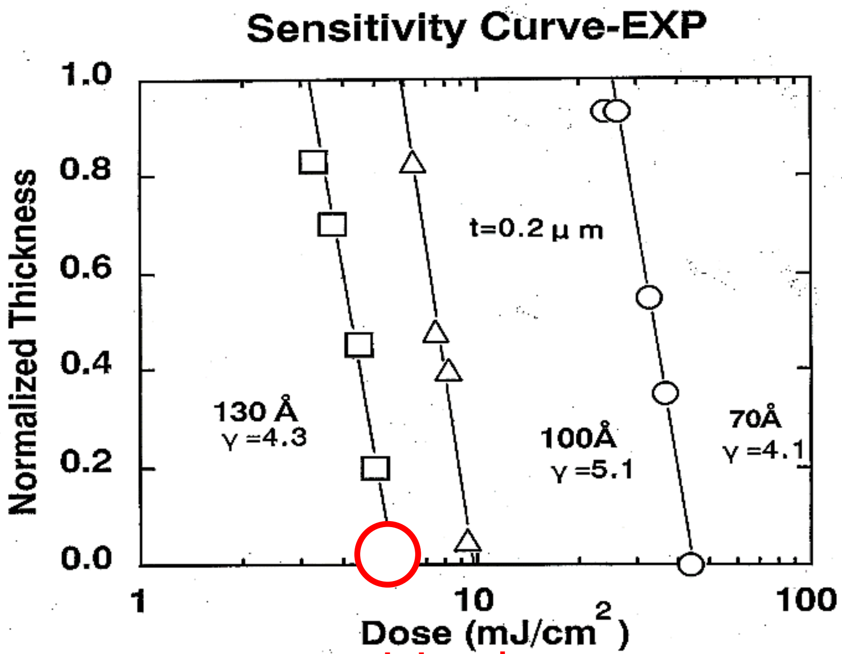
Resist Characteristics Measurement Tool

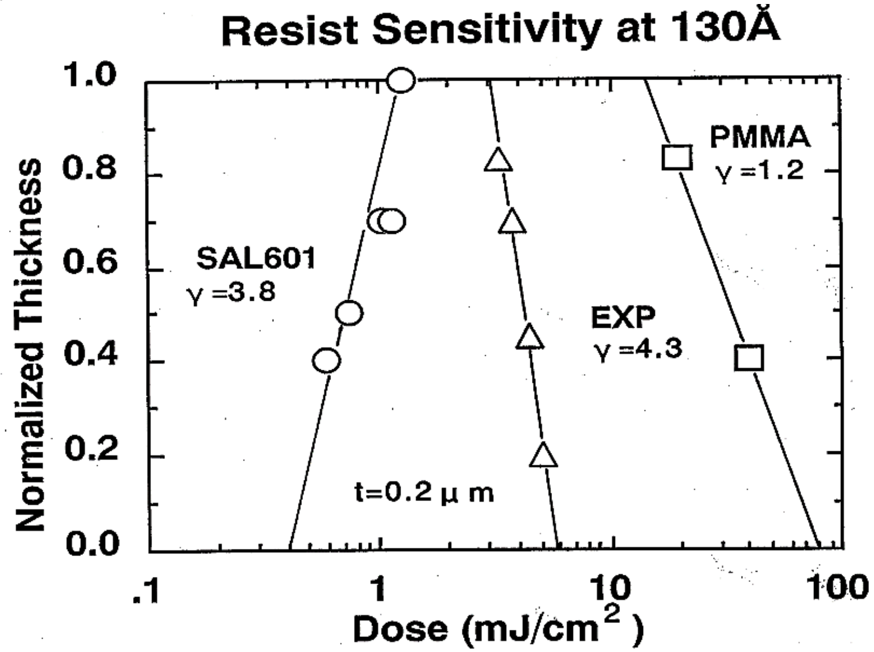


露光特性測定装置





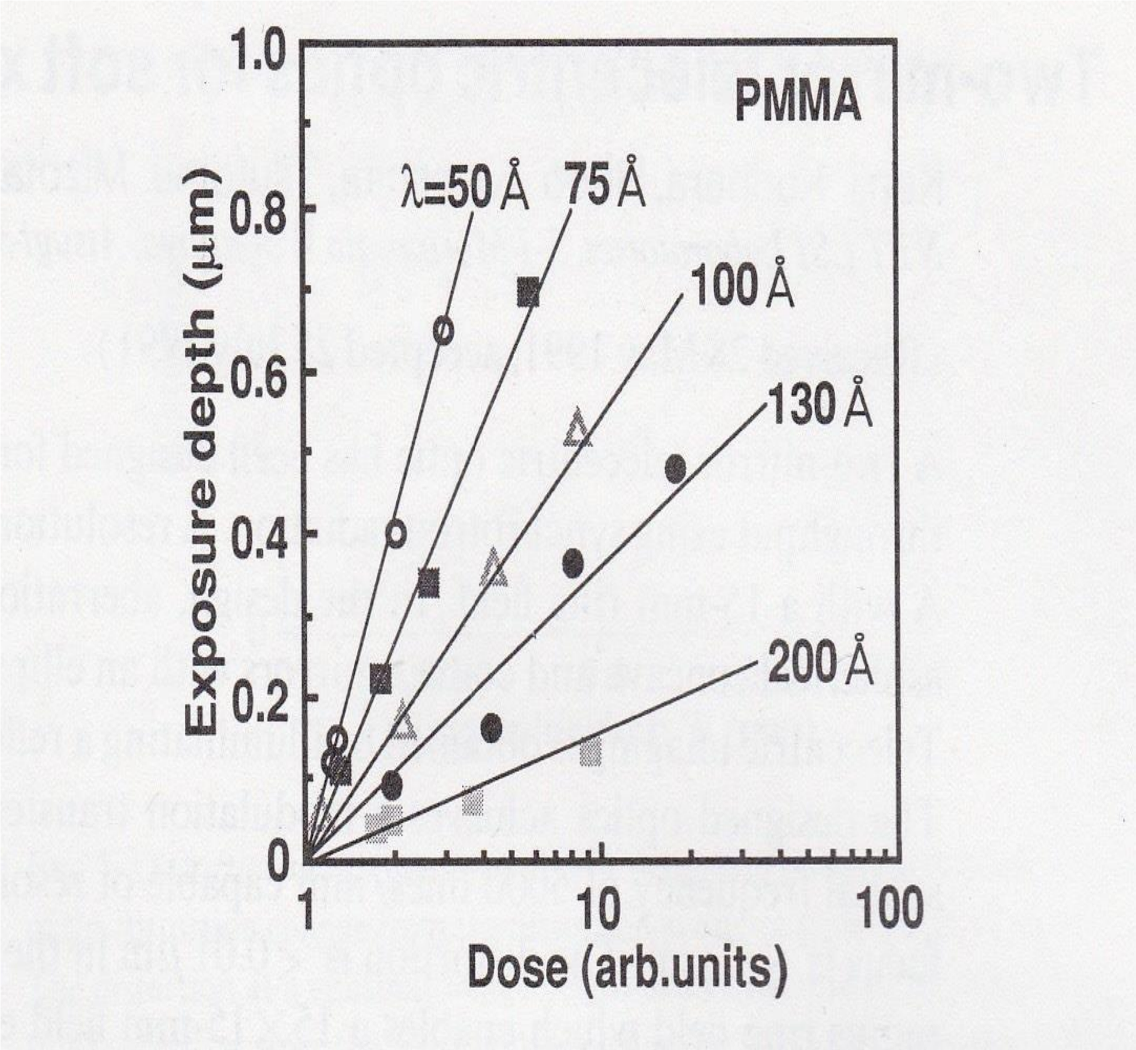


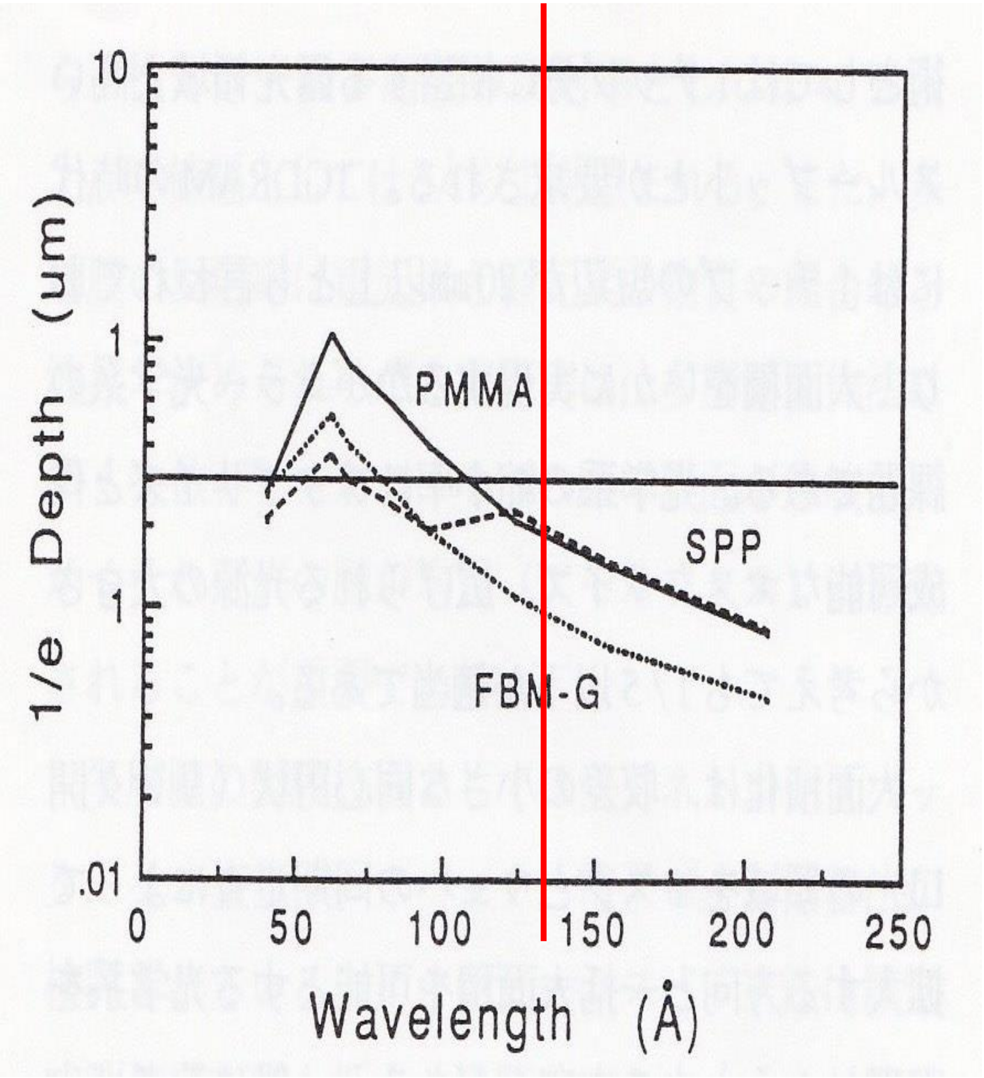


High sensitivity resist was found.

1991 PF Activity Report

Exposure depth of resists





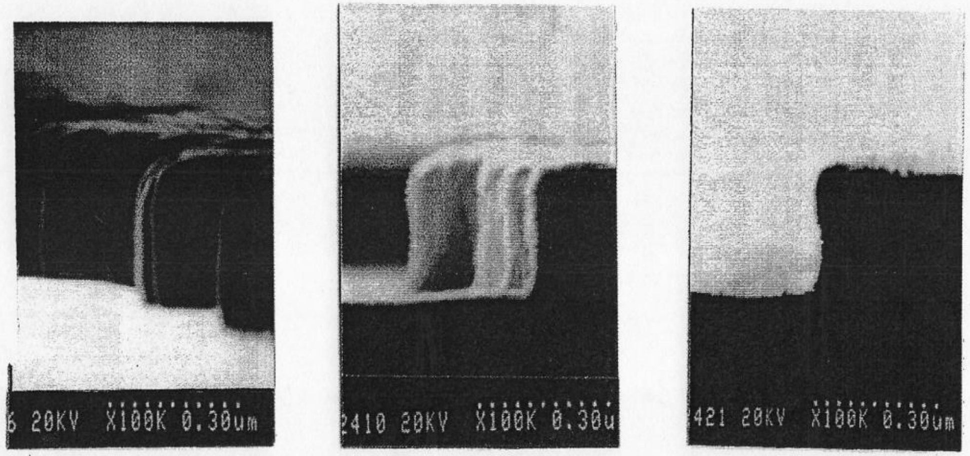
Resist Sensitivity Characteristics

Resist	Wavelength					
	70 Å		100 Å		130 Å	
	$D_{1.0}$	γ	$D_{1.0}$	γ	$D_{1.0}$	γ
SAL601	9.0	4.0	2.2	4.0	1.3	3.8
EXP	31	4.1	9.9	5.1	5.7	4.3
PMMA	290	1.9	101	1.5	83	1.2

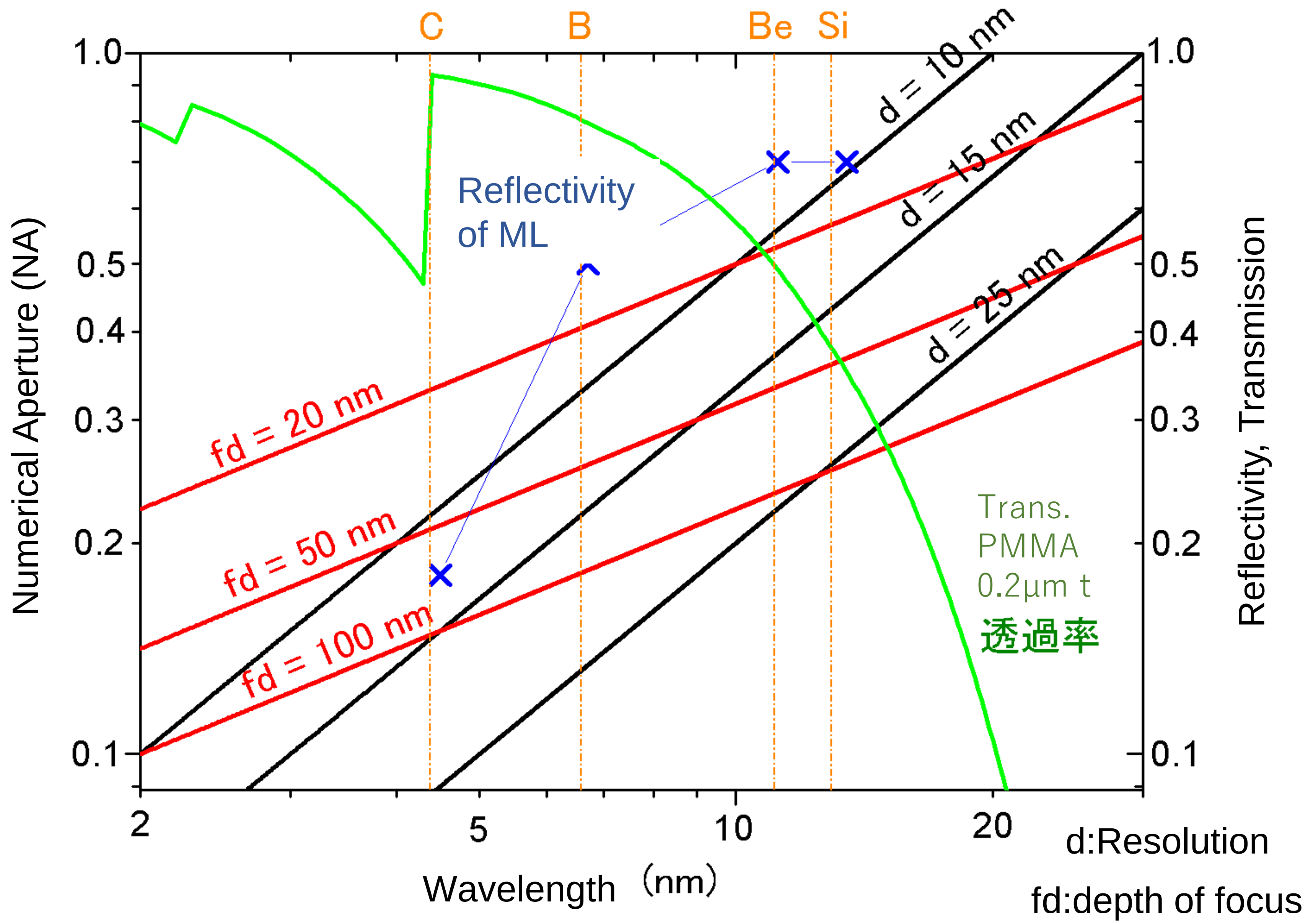
Resist Thickness （t=0.2μm）

D:mJ/cm^2

Pattern Profiles of Chemically Amplified Resist SAL601

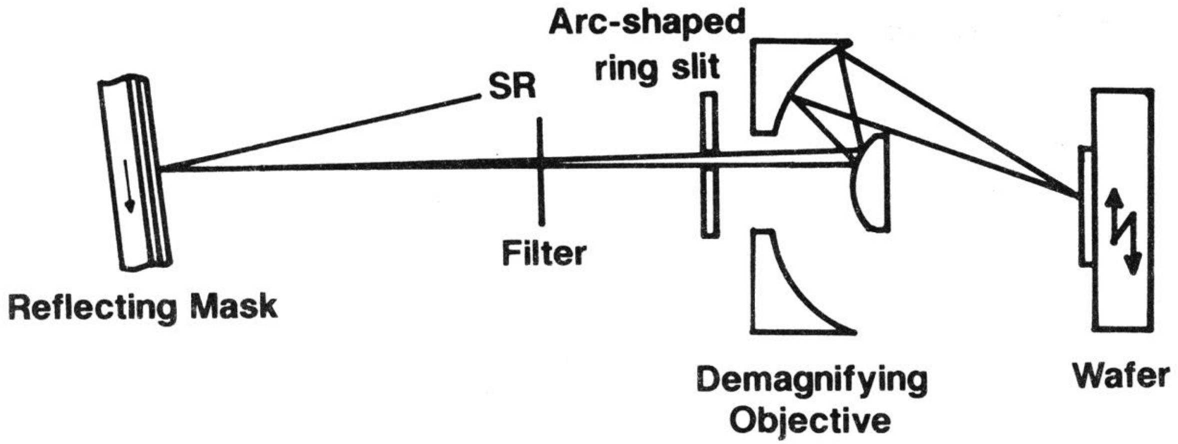


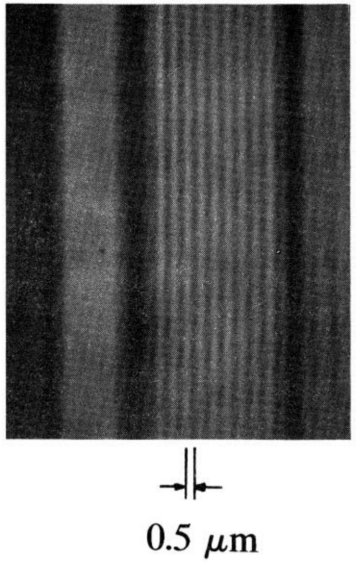
(a) 70 Å (b) 100 Å (c) 130 Å

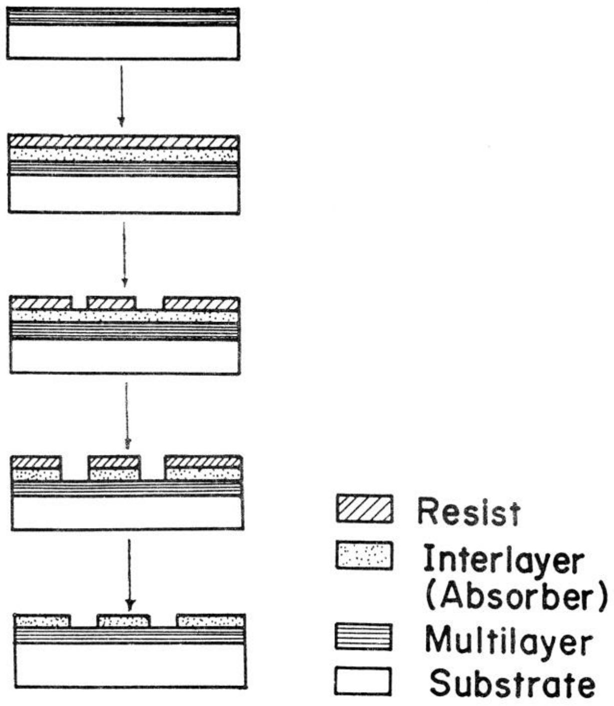


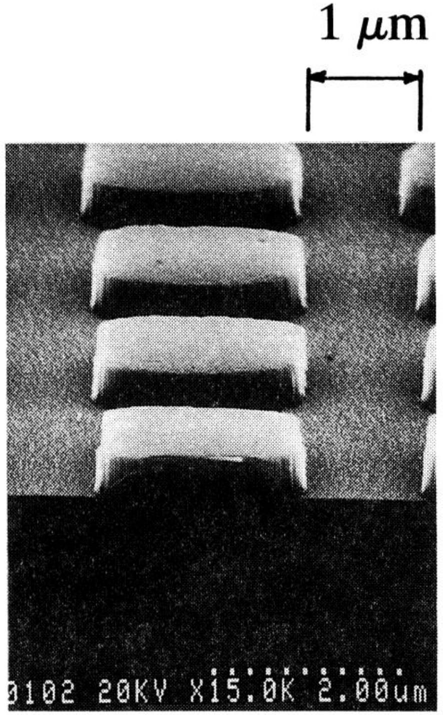
Exposure wavelength of 13.5nm was selected

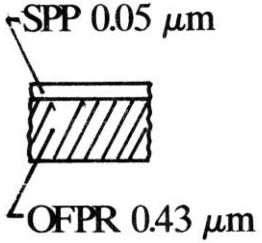
NTT







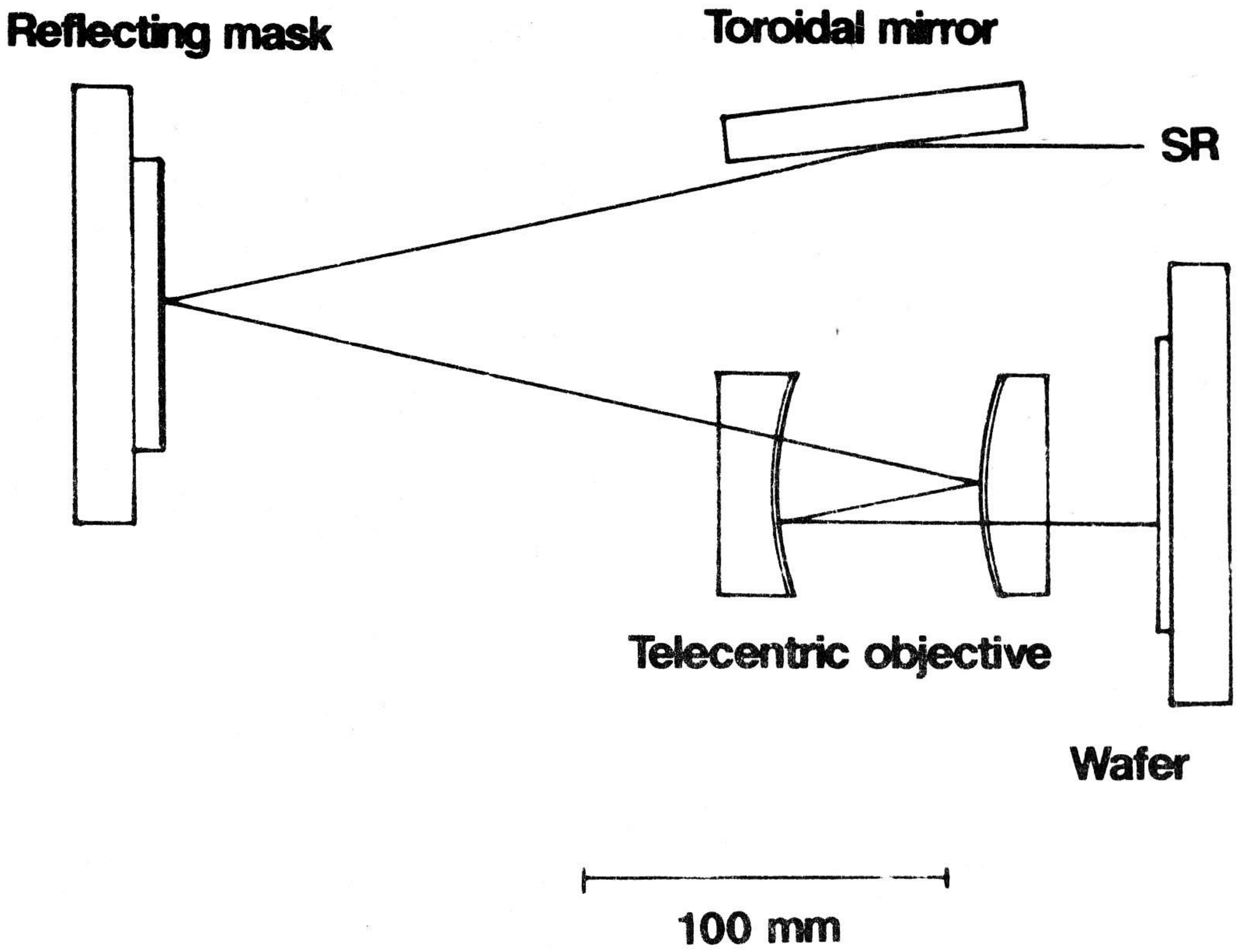




JVST Nov/Dec 1989, H. Kinoshita etal

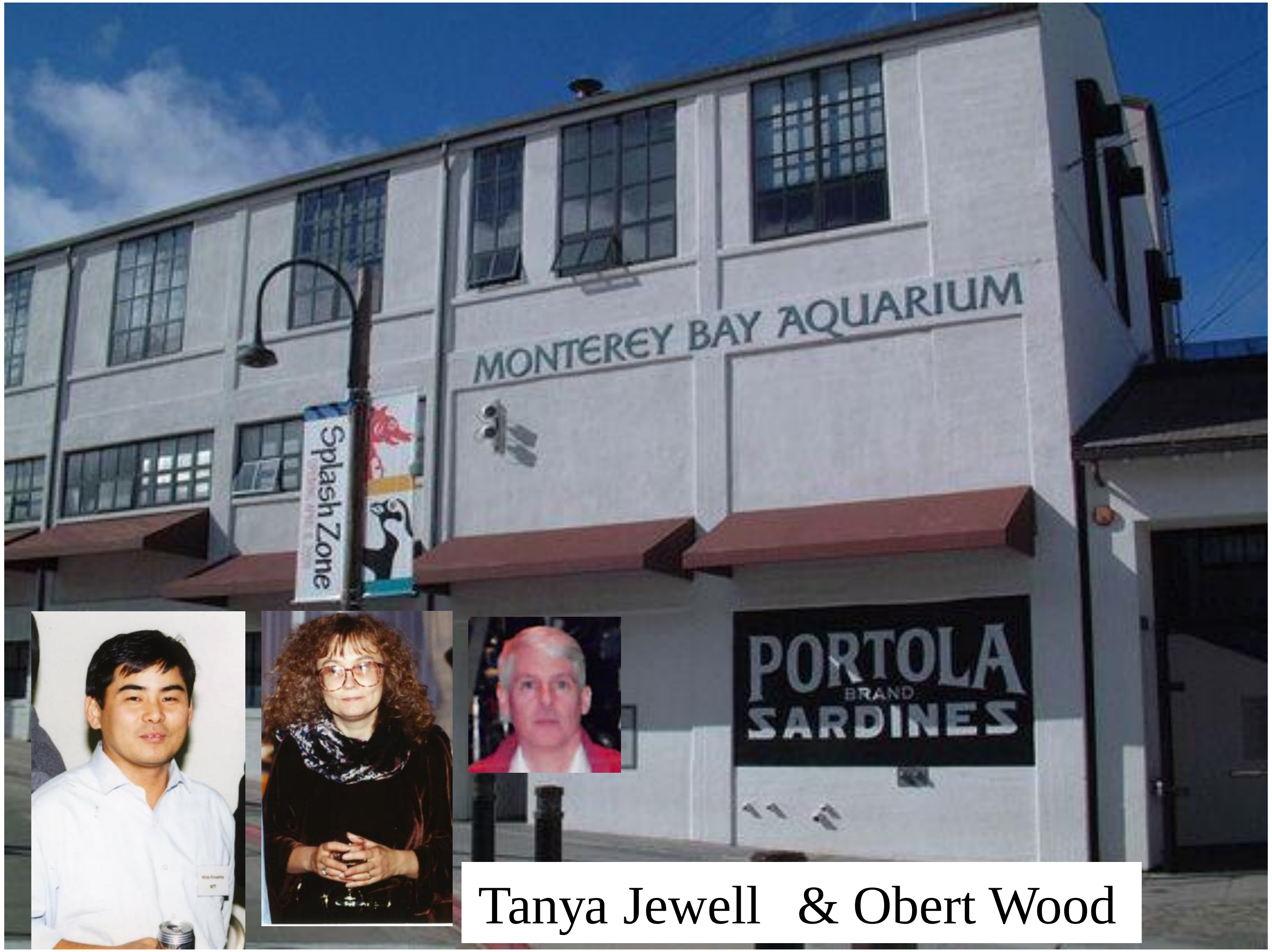
NTT

Telecentric optics design



This concept is the "principle" of EUVL optics.

JVST Nov/Dec 1989, H. Kinoshita etal



Tanya Jewell & Obert Wood

I encountered questions attack from AT&T in Banquet of EIPB'89.

Early stage of development

NTT G 1986～

Proximity Soft X-ray Lithography to EUVL

LLNL G 1988 ～

Application of X-ray optics

AT&T G 1988～

Application of X-ray laser and shortening the wavelength

Three groups with a different career began to run for one purpose.

LLNL

"Soft X-ray projection lithography"

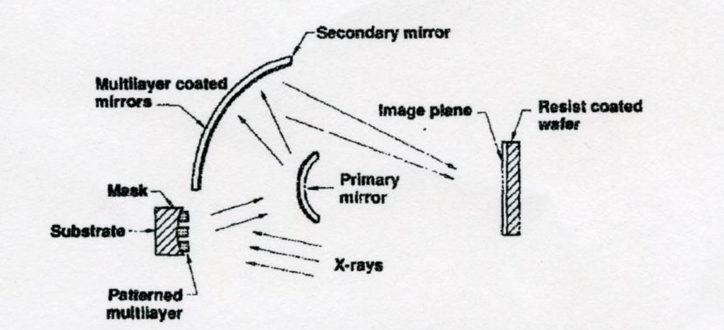


FIG. 1. X-ray reduction camera with corrected field curvature and uniform illumination. The x-ray master pattern (mask) is on a thick, curved substrate.

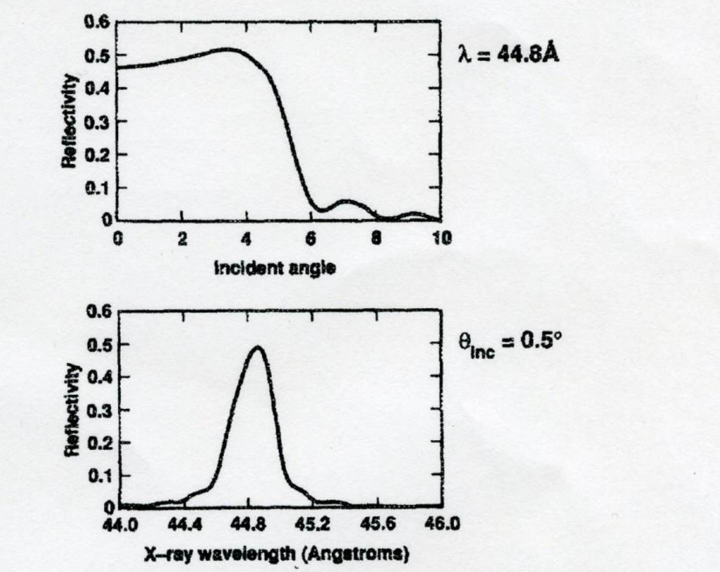


FIG. 2. Theoretical normal incidence performance of a 200 layer pair, carbon–chromium multilayer mirror with a d spacing of 2.25 nm, $N = 200$, $\gamma = 0.35$.

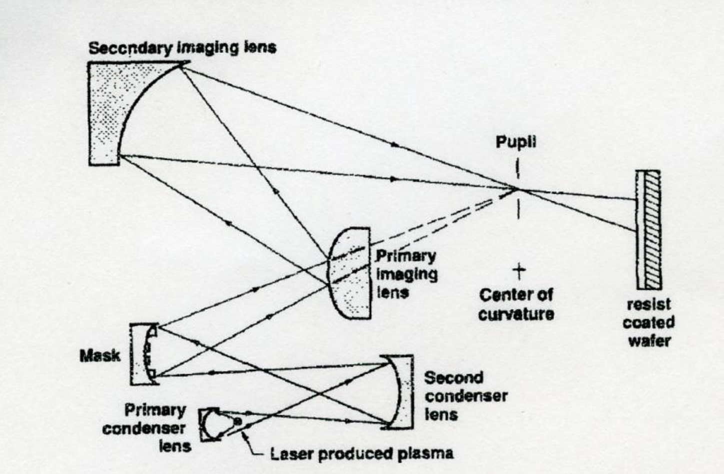


FIG. 3. X-ray reduction camera system configuration with a laser produced plasma source.

JVST Nov/Dec 1988, A. Hawryluk and L. Seppala

LLNL

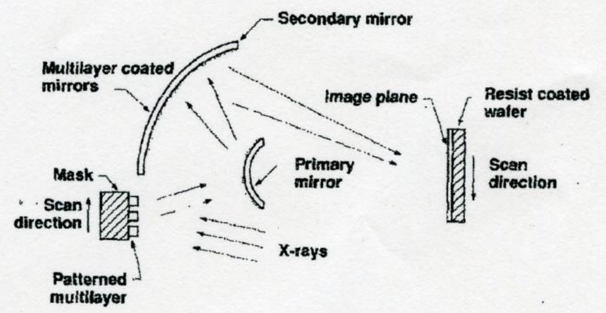


FIG. 1. Illustration of one possible x-ray reduction camera design: off axis scanning system with reflecting mask. In this embodiment, the mask is imaged and scanned onto the wafer (a "step and scan" sequence). An example of a "step and repeat" x-ray reduction camera is shown in Ref. 1.

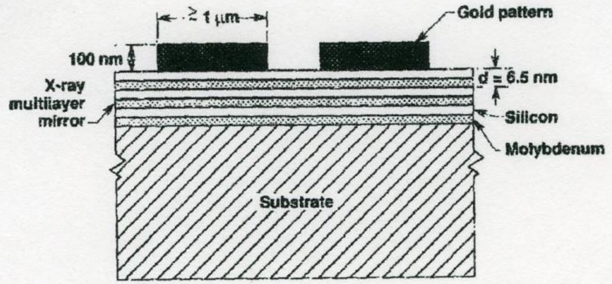


FIG. 2. Cross-sectional view of an XRPL mask. A thin gold absorber pattern with relatively large linewidths is patterned directly onto a soft x-ray multilayer mirror.

4 mirror system, Ring-field

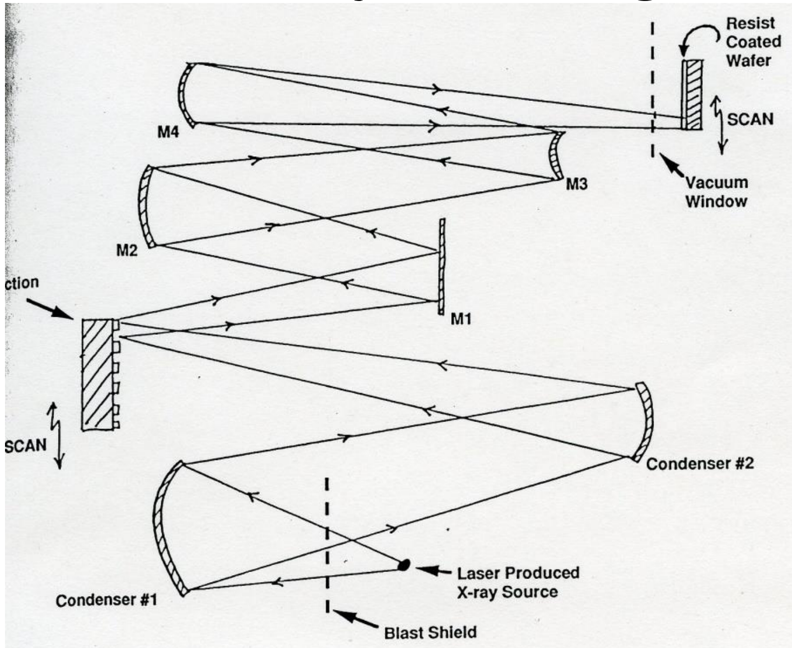


FIG. 4. Schematic representation of a 5× reduction, ring field scanning system employing four imaging mirrors, a reflective mask, two condenser mirrors, and driven by a laser produced "point" source of x rays.

1/5

1990

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

JVST Nov/Dec 1990, N. Ceglio etal.

AT&T

Wavelength 36nm, Ir coated mirror

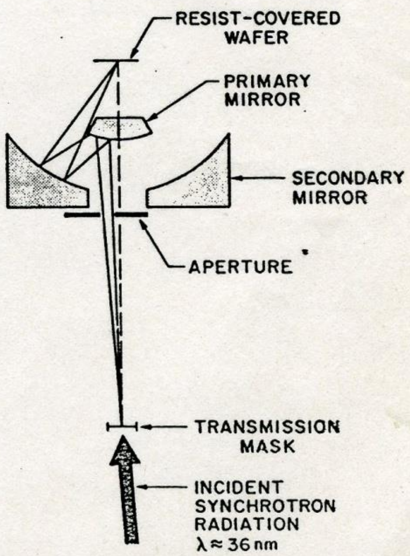


Fig. 1. Schematic diagram showing the basic experimental arrangement. The two mirrors that compose the Schwarzschild objective were mounted in a single housing.

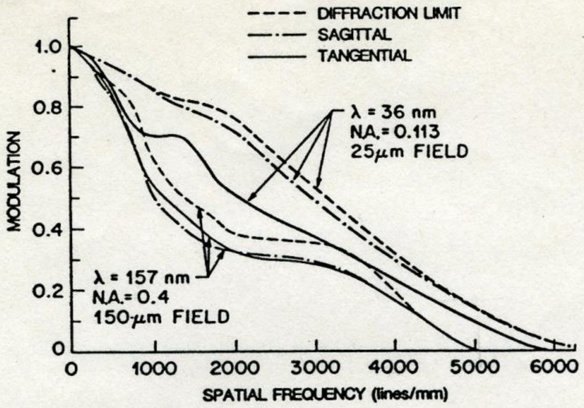
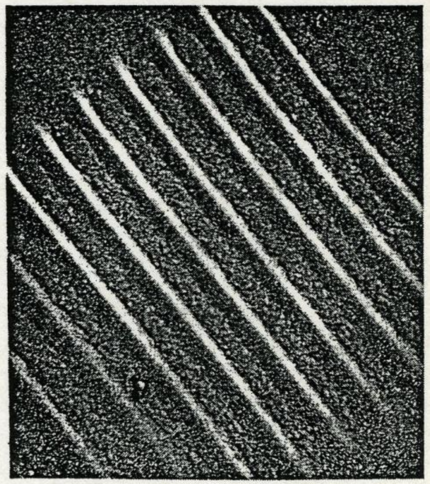


Fig. 2. Calculated MTF curves for the Schwarzschild objective with spatially incoherent illumination for two different situations: on-axis illumination with light at 157 nm and with the full N.A. (0.4), and off-axis illumination at 36 nm with N.A. = 0.113.

(a)



(b)

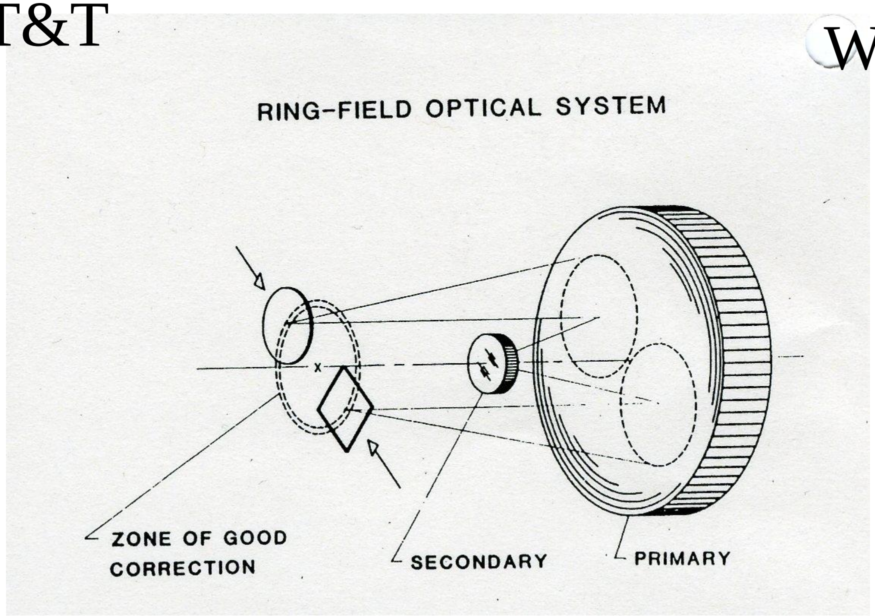
Fig. 3. Scanning electron micrographs of developed images in a 60-nm-thick film of PMMA on silicon: (a) the lines and spaces shown have widths of 1, 0.5, 0.375, 0.25, and 0.2 μm; (b) closeup of the 0.2-μm lines and spaces.

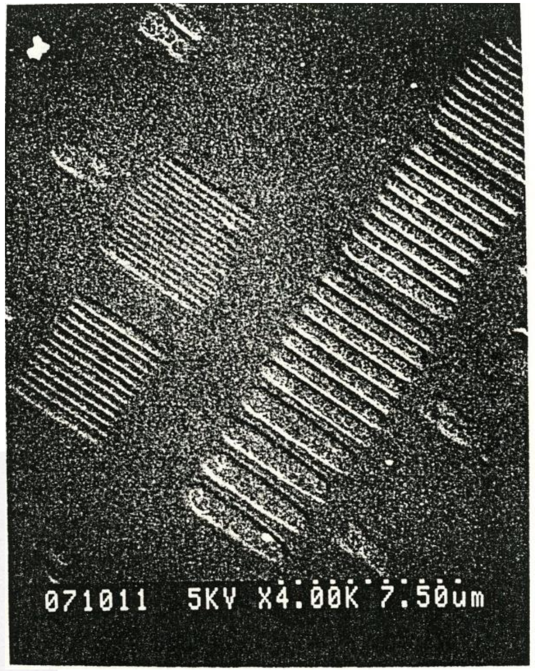
Diffraction limited performance was Obtained using a reflection optics.

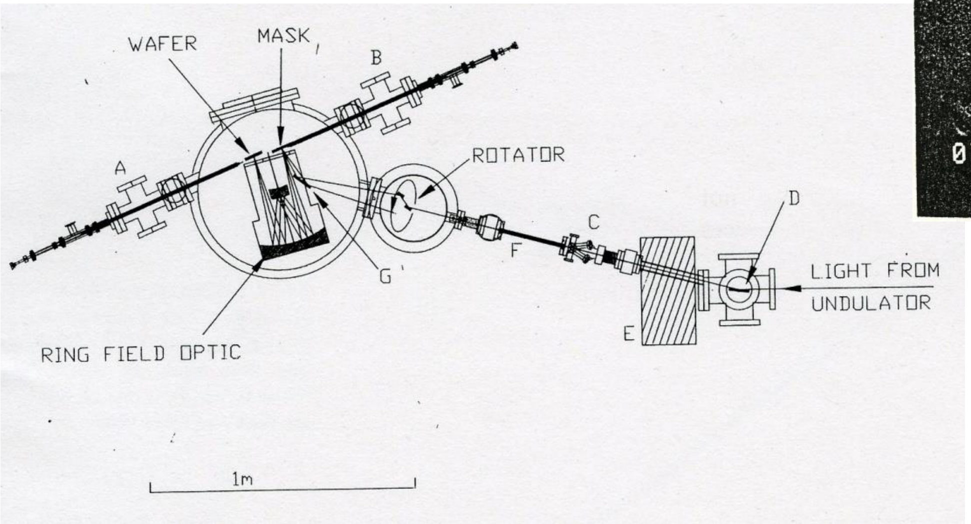
Optics letters May 15, 1990
D. Berreman and J. Bjorkholm etal.

AT&T

Wavelength 42 nm, Ir coated mirror







0.2 um pattern

Diffraction limited performance was obtained.

JVST Nov/Dec 1991, A.MacDowell, J. Bjorkholm, F. Zernike etal.

AT&T

Reduction image at 14 nm using SC optics

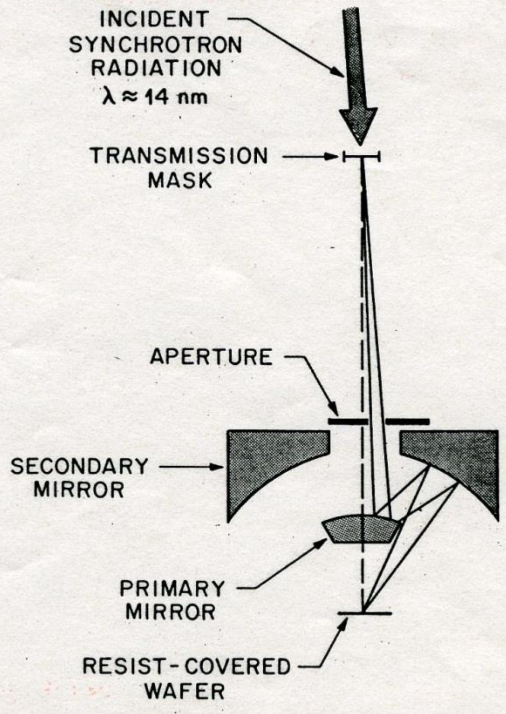
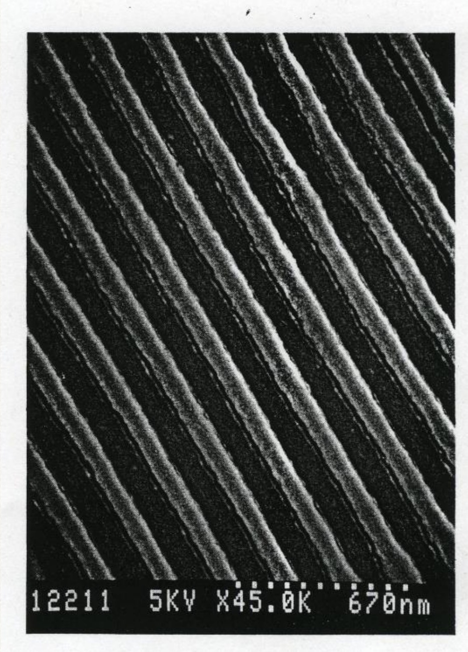
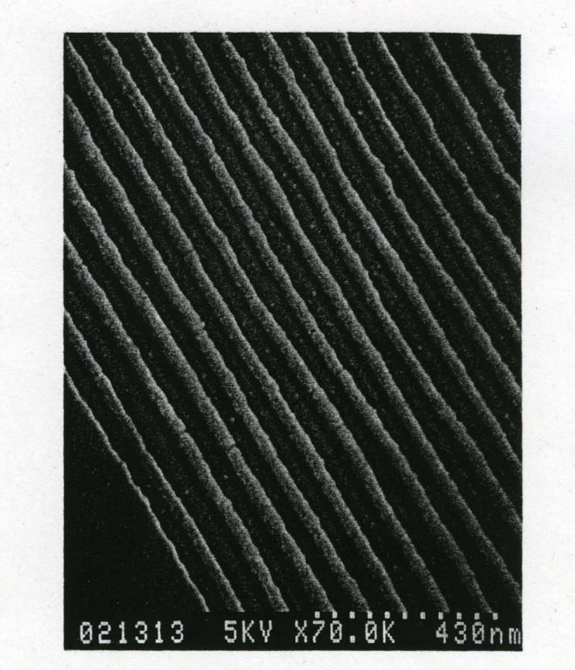


FIG. 1. Schematic diagram of the basic experimental setup. The two mirrors comprising the Schwarzschild objective were coated with Mo/Si multilayers to provide a reflectance of ~40% at 14 nm.



0.1 μm



0.05 μm

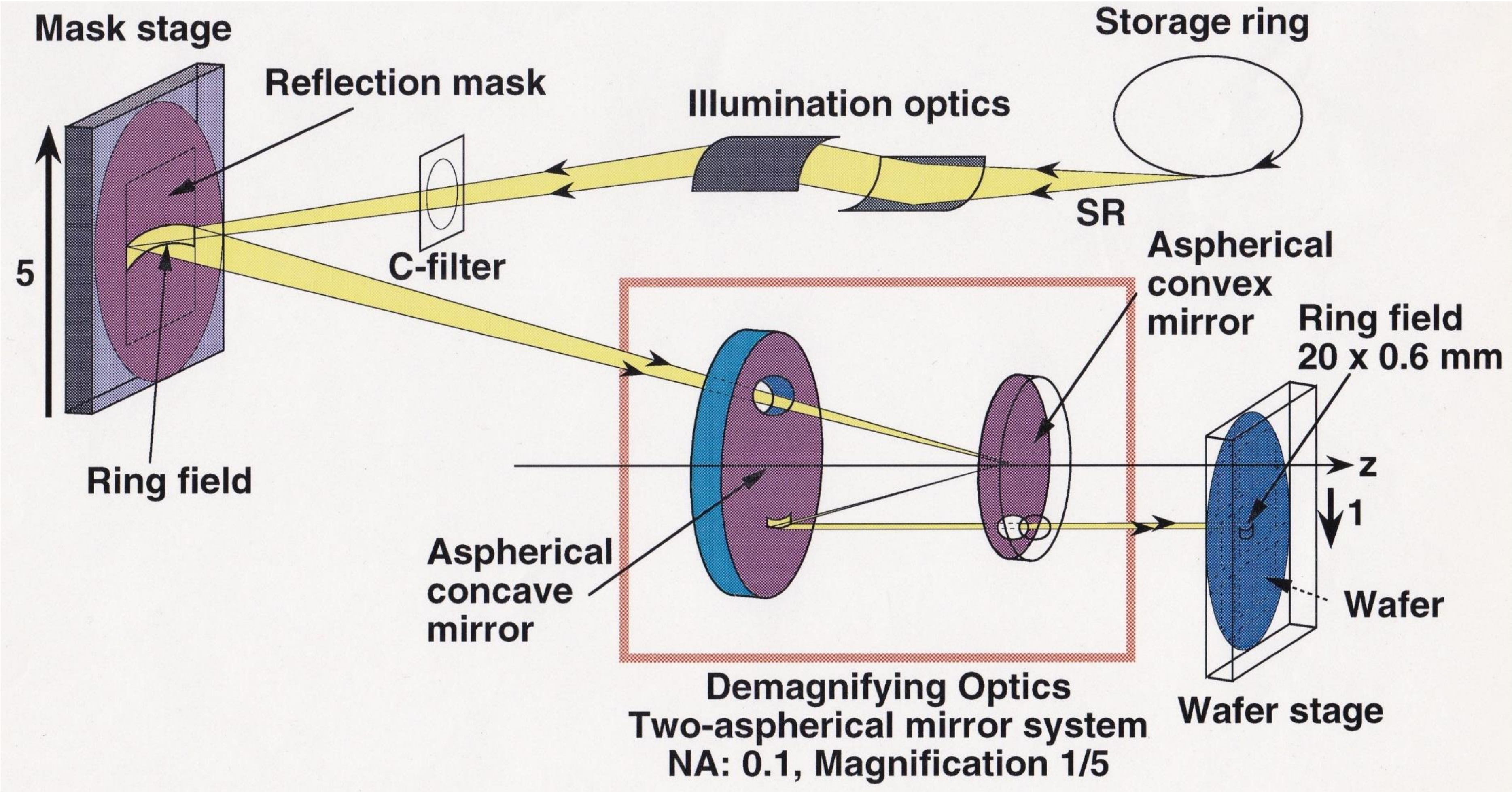
JVST Nov/Dec 1990, J.Bjorkholm, J. Boker, R. Freeman etal.

Although AT&T G specialized in lasers and optical devices, they were also thinking about how to apply laser technology to lithography.
Their main goal was to obtain actual proof of the diffraction-limited performance.

To achieve it, they employed a reflective system consisting of on-axis SC optics without distortion.
That was different from NTT G initial goal of obtaining a large exposure field.

Nevertheless, the evidence they obtained regarding the diffraction-limited performance paved the way to the development of reduction lithography.

From 1989, NTT has developed a two-aspherical mirror system.



NTT

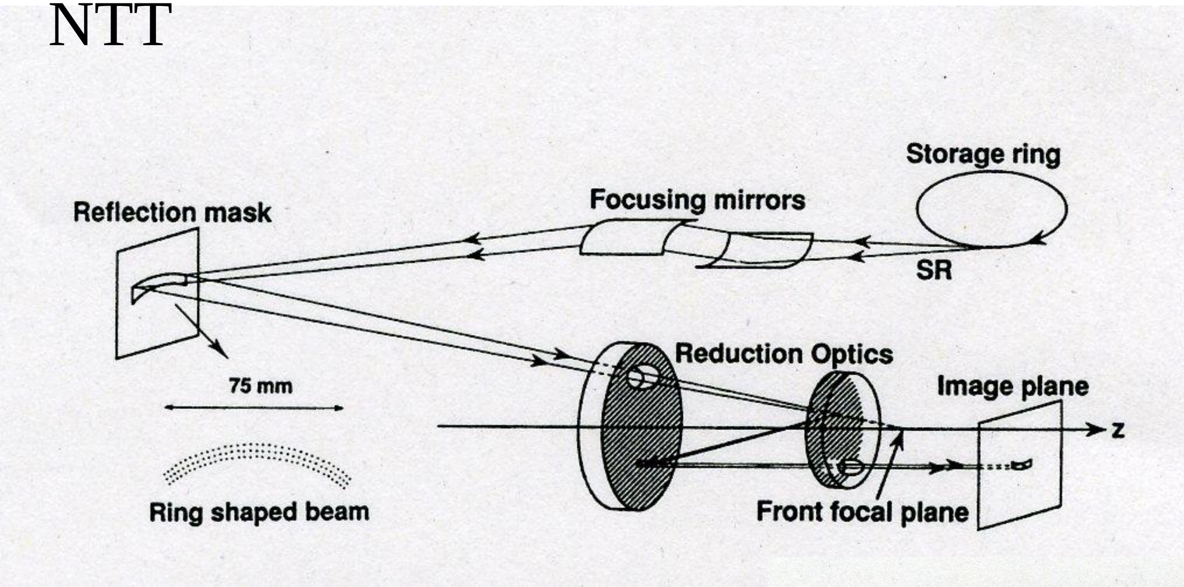
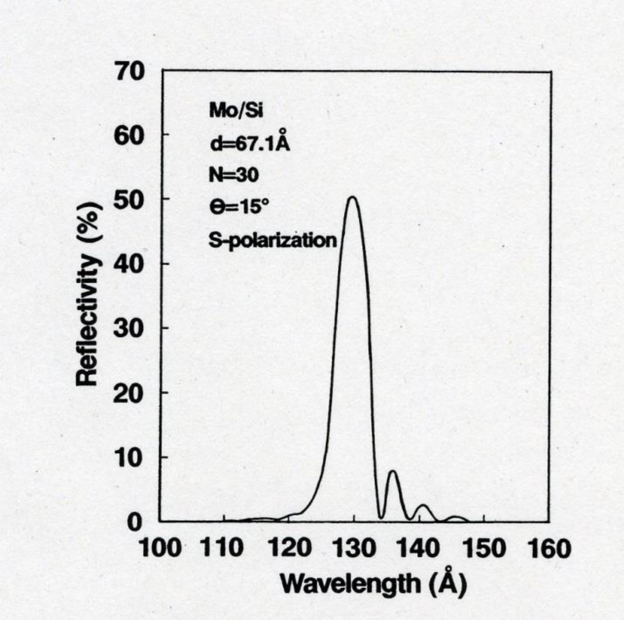
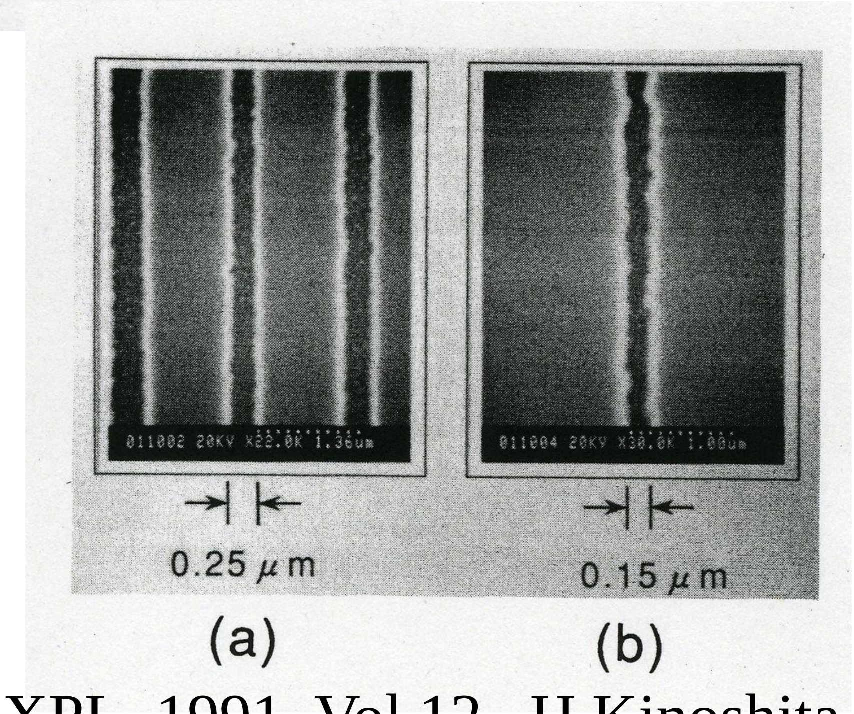


TABLE I. Design goals and conditions.

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

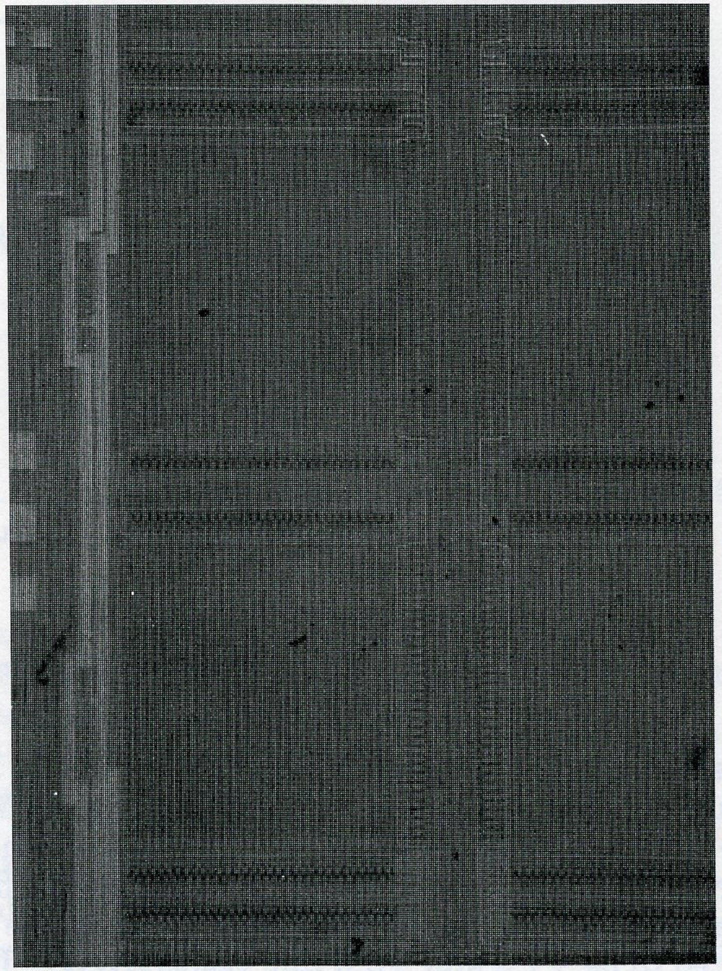




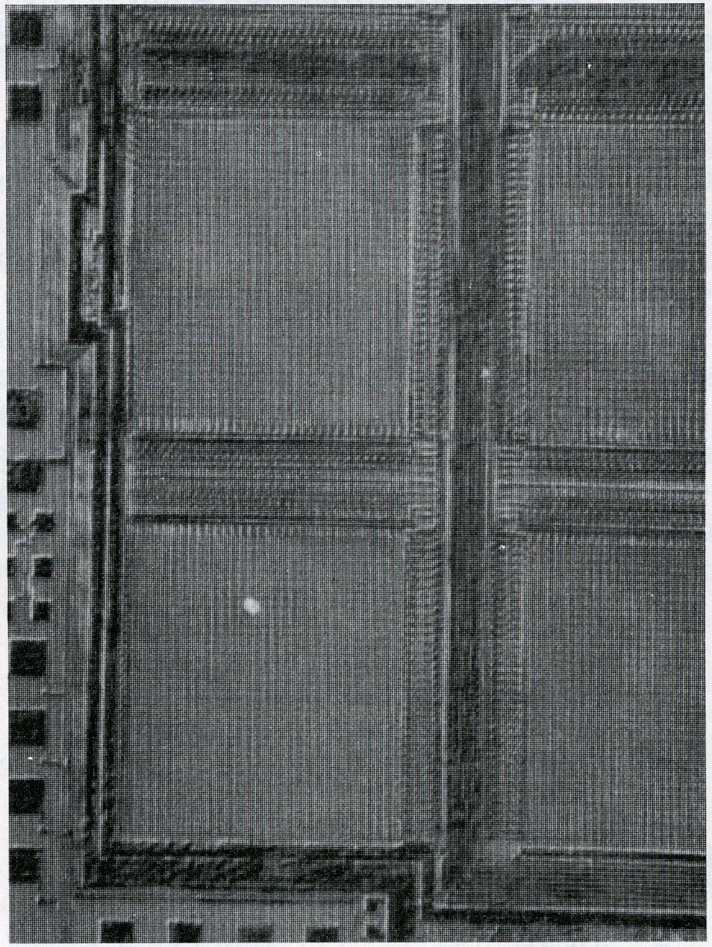
OSA Proceedings on SXPL, 1991, Vol.12 H.Kinoshita

JVST B9(6) (1991) K.Kurihara and H.Kinoshita

NTT



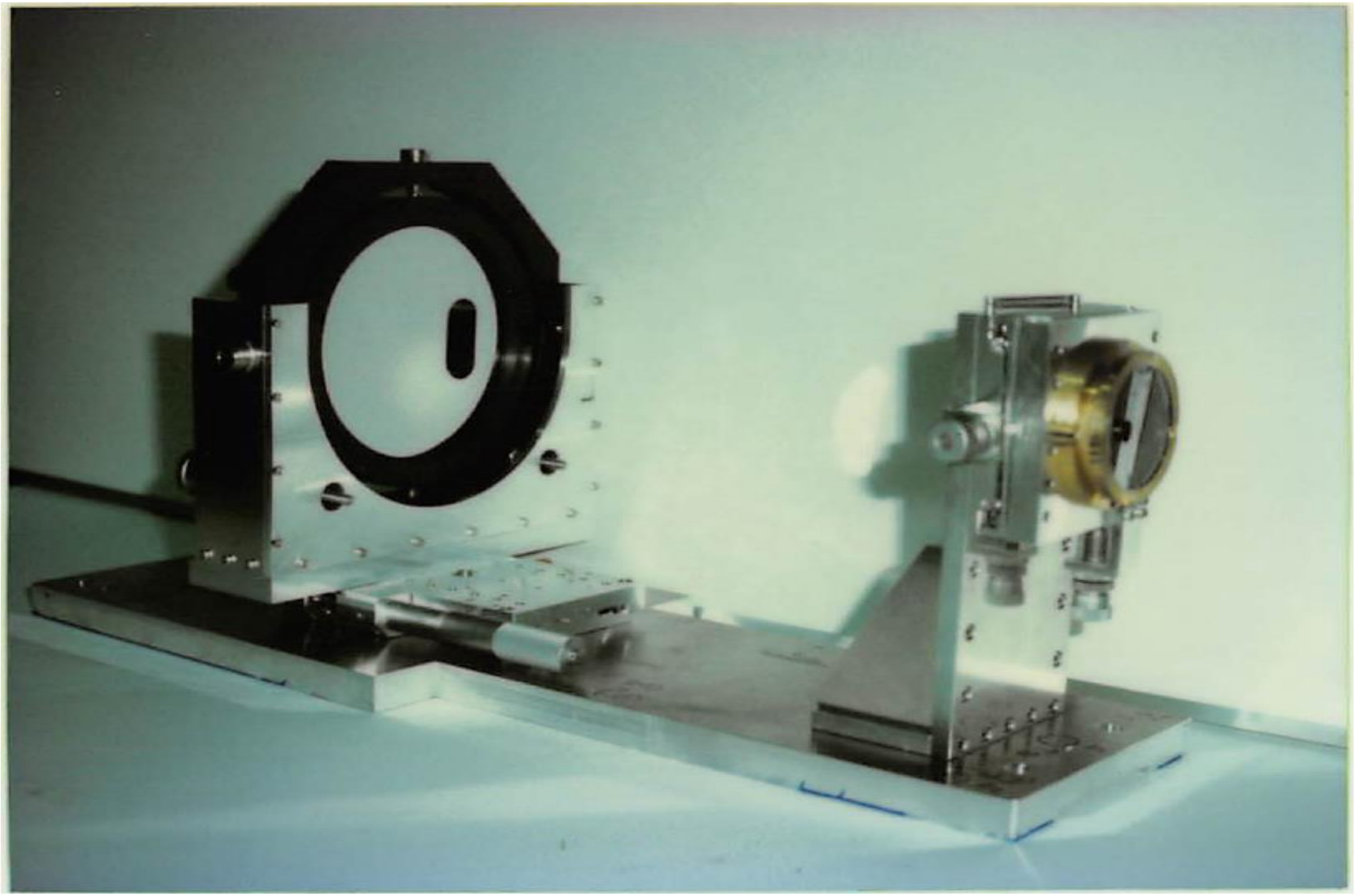
(a) Mask Patterns



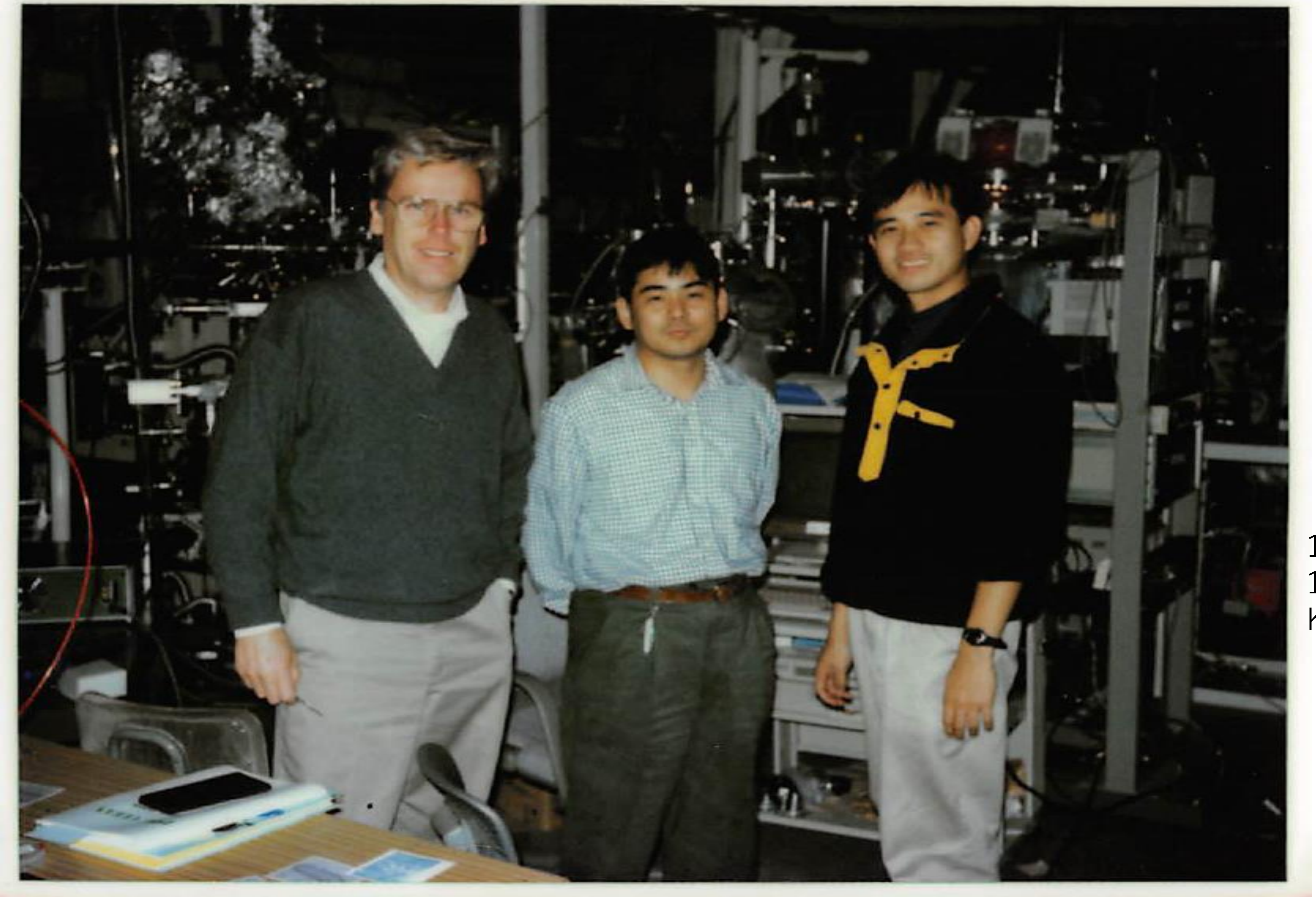
(b) Replicated Patterns

SPIE Vol. 1742 (1992) 583 H. Kinoshita

1992



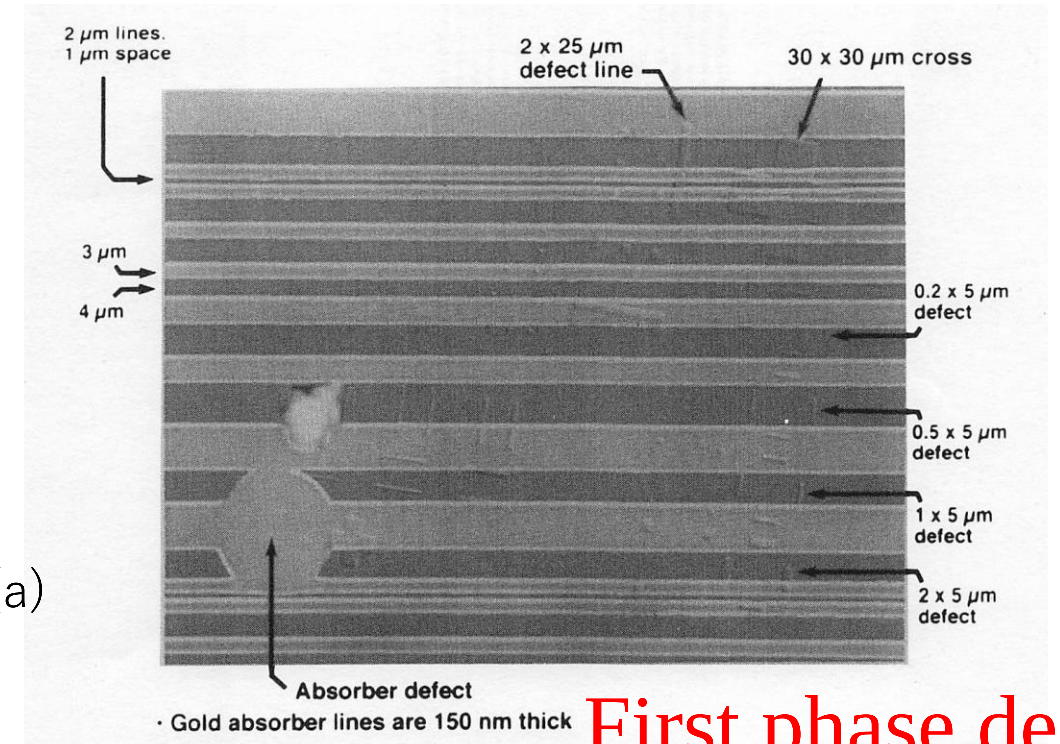
Experimental setup of a two aspherical mirrors system



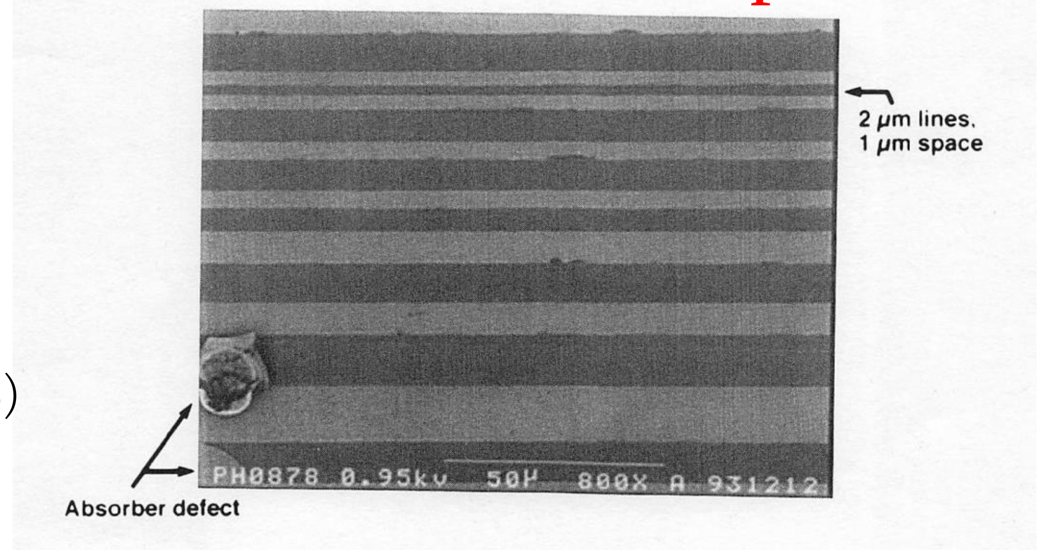
10 Dec. 1993
KEK PF

First phase defect inspection

(a)

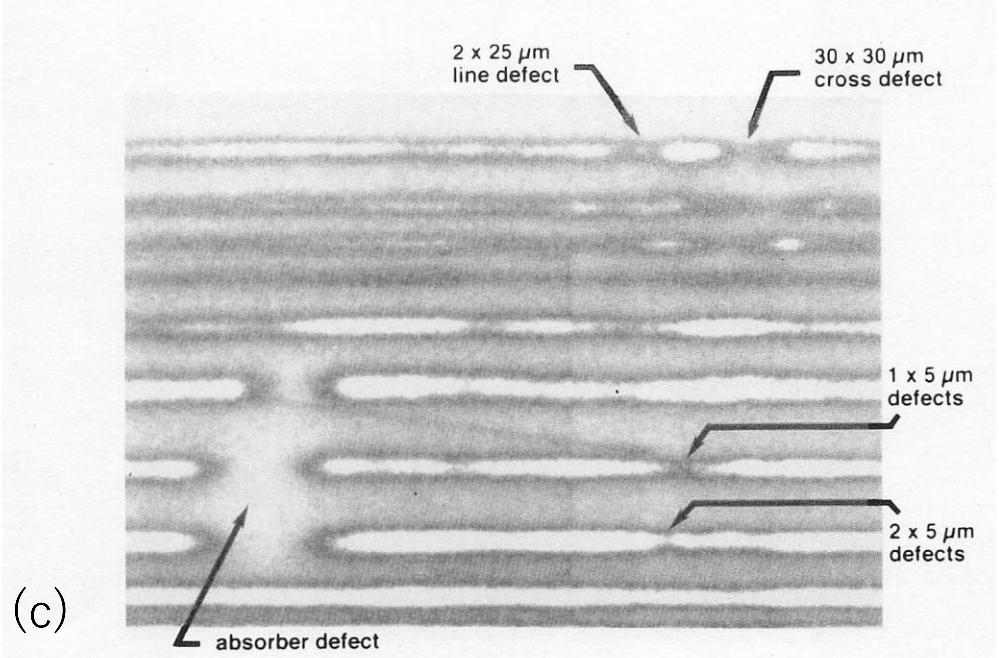


(b)

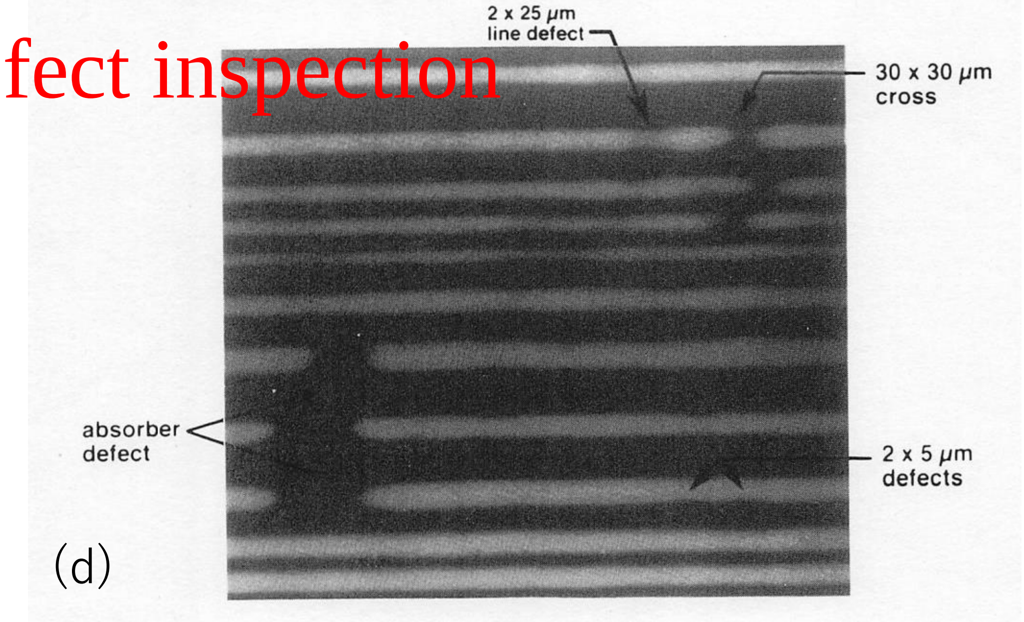


(a) OM image & (b) SEM image

(c)



(d)



Exposure pattern (c) PMMA , (d) SAL601

OSA Proceedings, 1994, Vol.23

Technical Digest on

US-JAPAN Workshop on EUV Lithography

October 27-29, 1993
Hotel Mt. Fuji, Japan

Technical Program Committee

Takeshi Namioka
Universities Space Research Association, USA

David T. Attwood
Lawrence Berkeley Laboratory, USA

David L. Windt
AT&T Bell Laboratories, USA

Hiroo Kinoshita
NTT LSI Laboratories, Japan

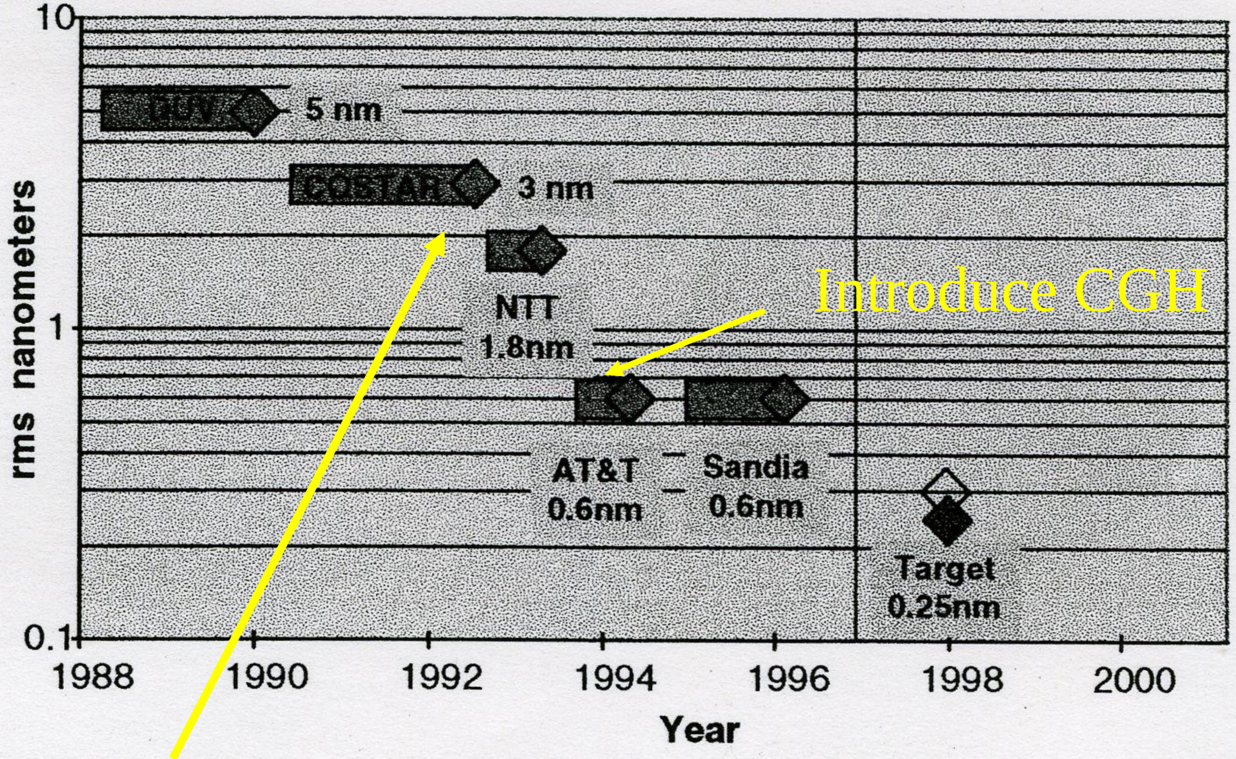
First EUVL Meeting was held in 1993.

US-Japan Workshop on Soft X-ray optics in Mt. Fuji 1996

Fabrication of Aspherical Mirror

tinsley

Figure Improvement Timeline



Fabrication is possible if testing is possible.

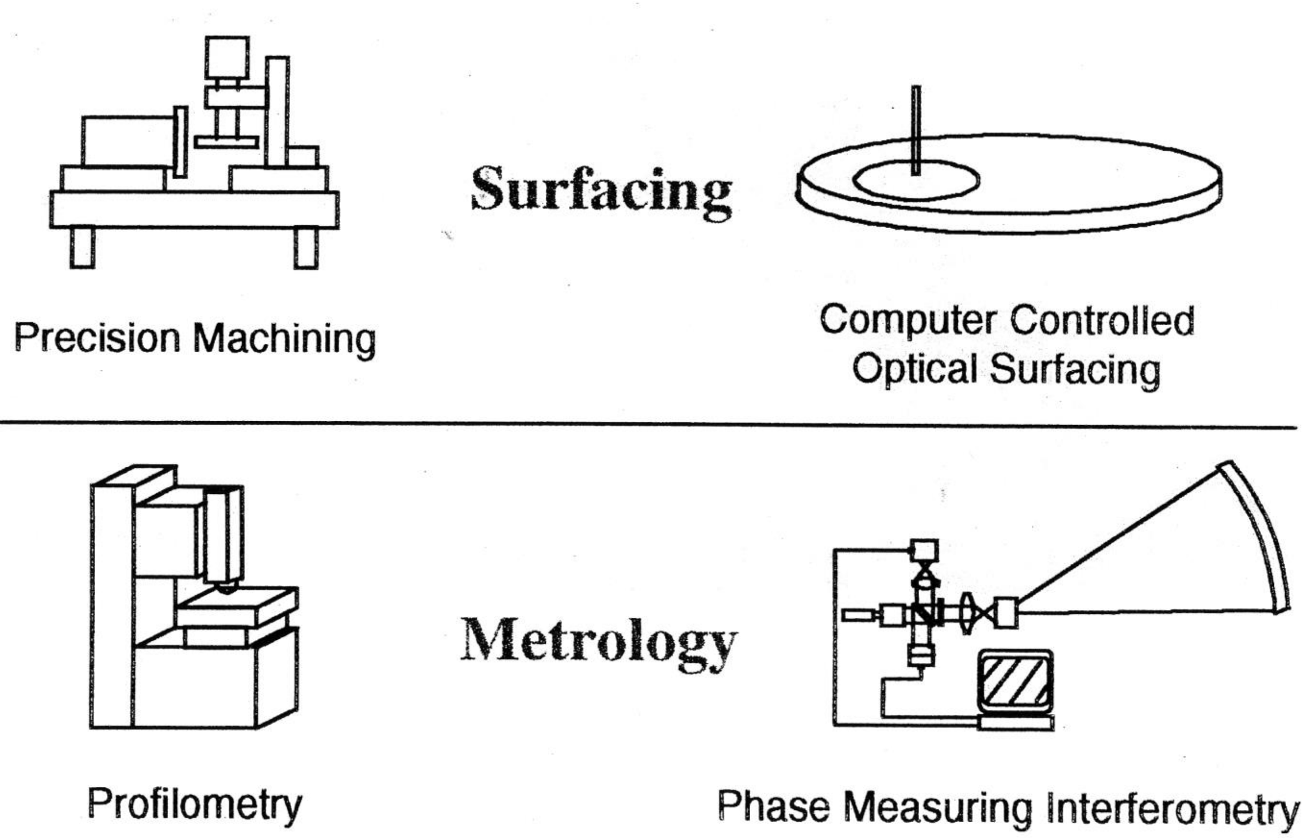
2nd U.S.-Japan Workshop on Soft X-Ray Optics

Figure 11

1996

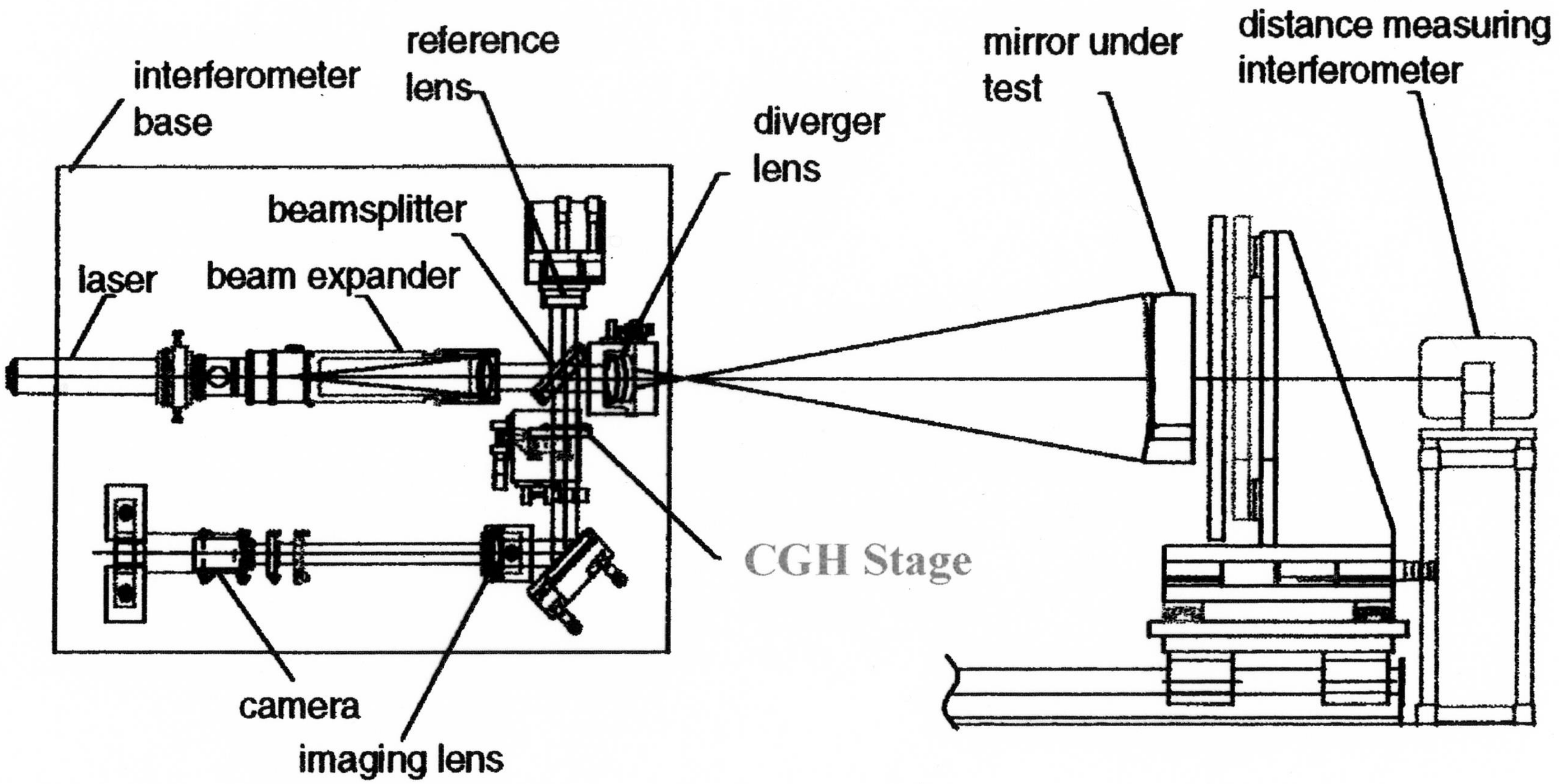
Aspheric Fabrication Process
Four Core Technology

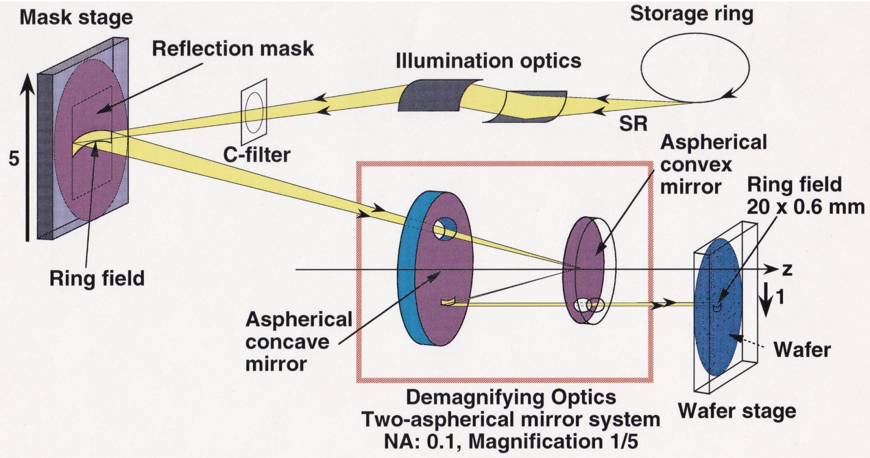
By Tinsley Labo.

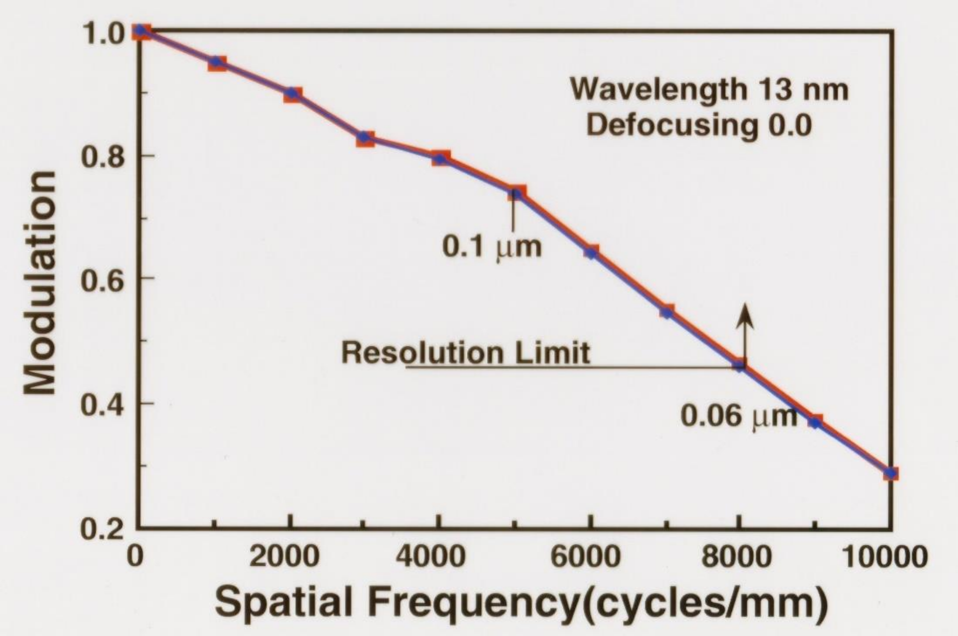


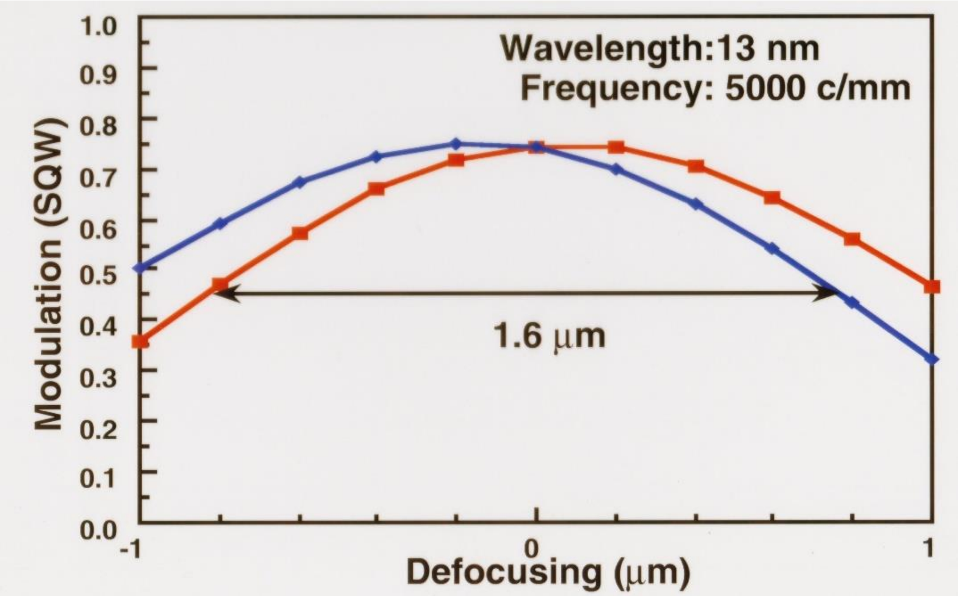
Mr. D. Bajuk

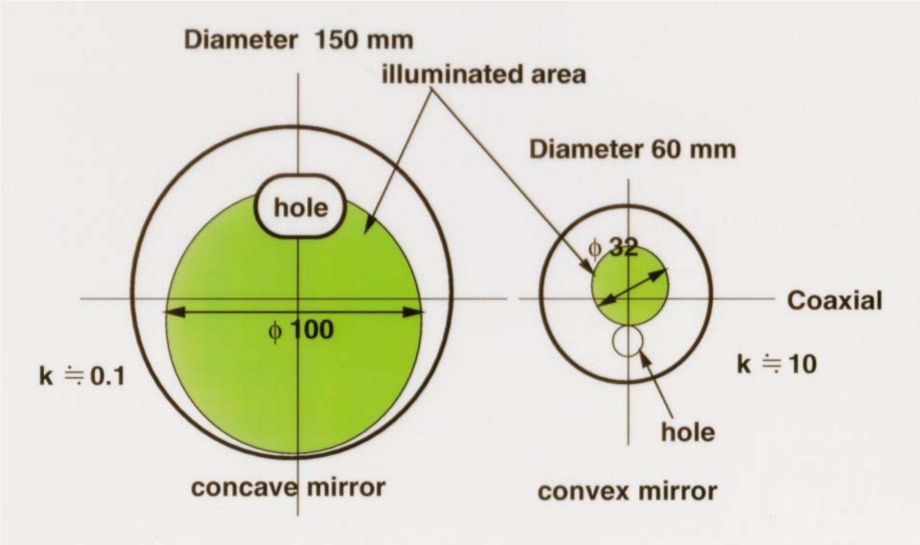
Aspherical Mirror Measurement using CGH



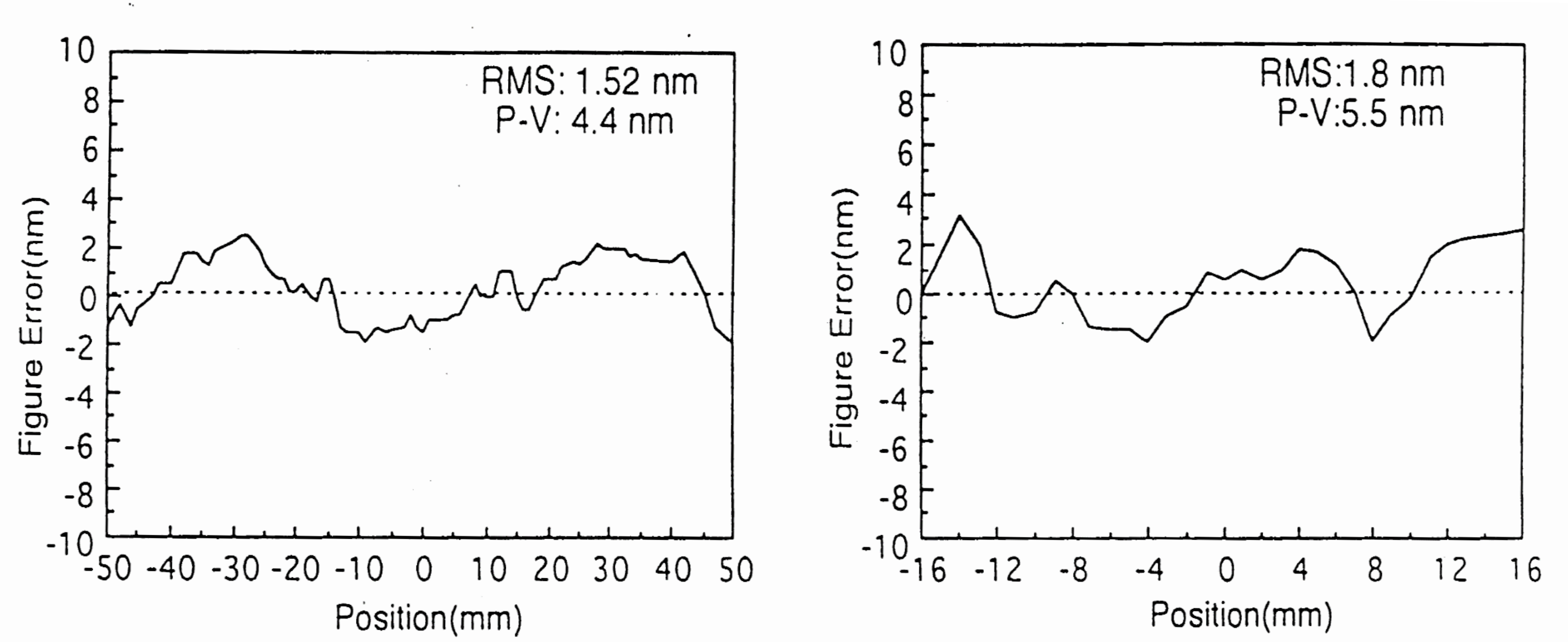

Mask stage
Reflection mask
Illumination optics
Storage ring
SR
C-filter
5
Ring field
Aspherical convex mirror
Ring field 20 x 0.6 mm
z
1
Aspherical concave mirror
Wafer
Demagnifying Optics
Two-aspherical mirror system
NA: 0.1, Magnification 1/5
Wafer stage


Wavelength 13 nm
Defocusing 0.0
0.1 µm
Resolution Limit
0.06 µm
Modulation
Spatial Frequency(cycles/mm)
1.0
0.8
0.6
0.4
0.2
0
2000
4000
6000
8000
10000


Wavelength:13 nm
Frequency: 5000 c/mm
1.6 µm
Modulation (SQW)
Defocusing (µm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-1
0
1

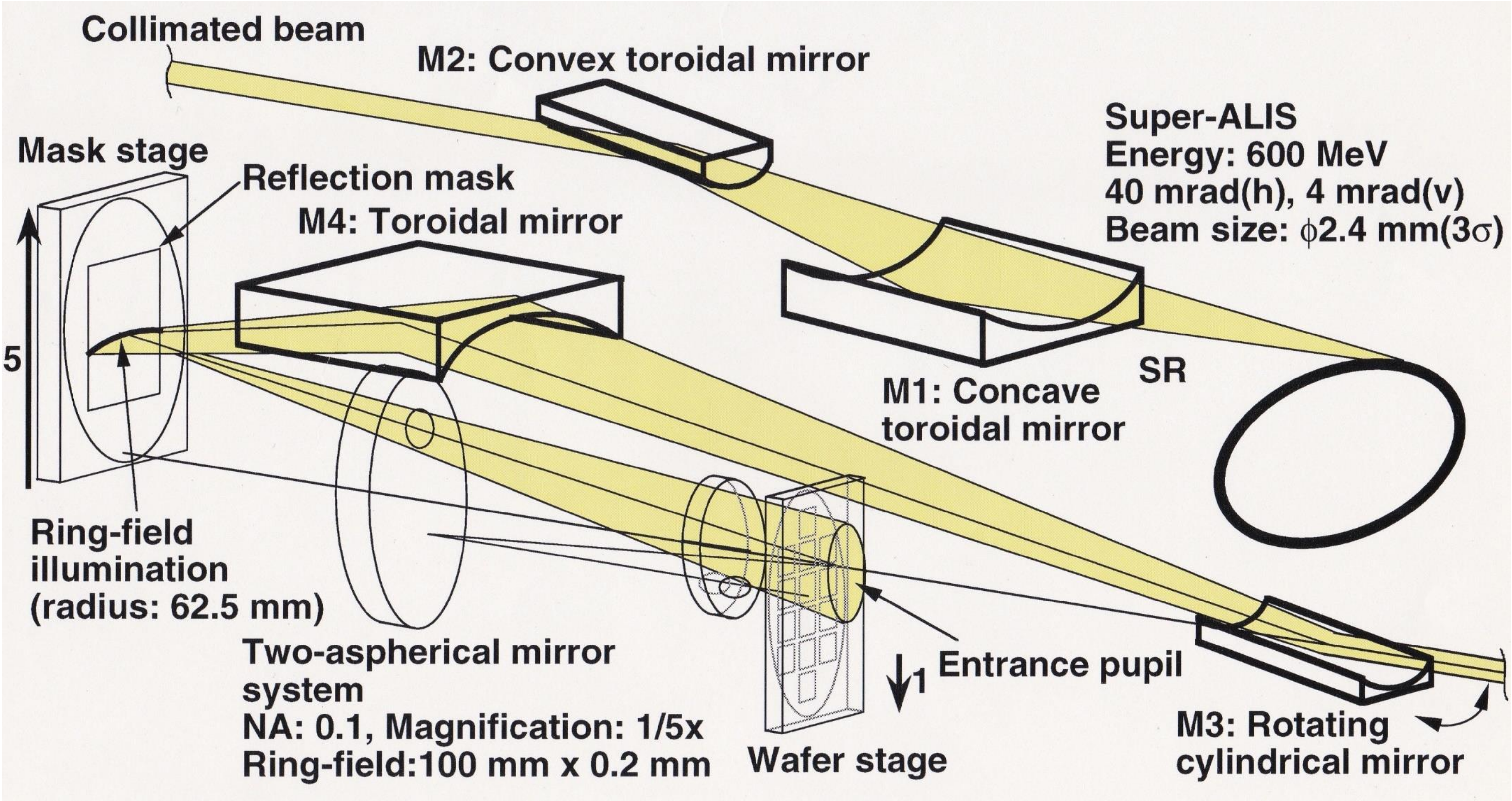


Fabricated by Tinsley



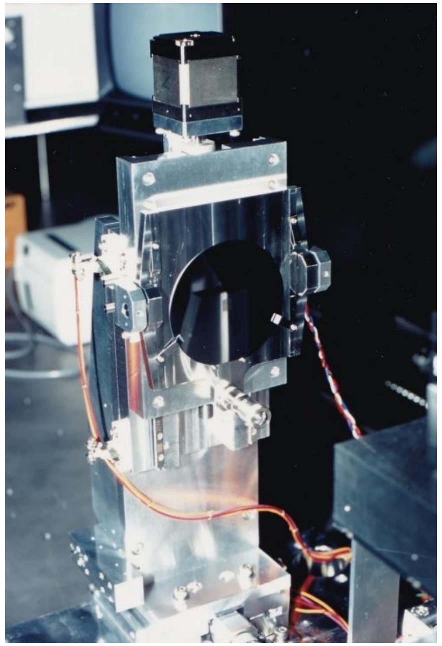
(a) Concave Mirror

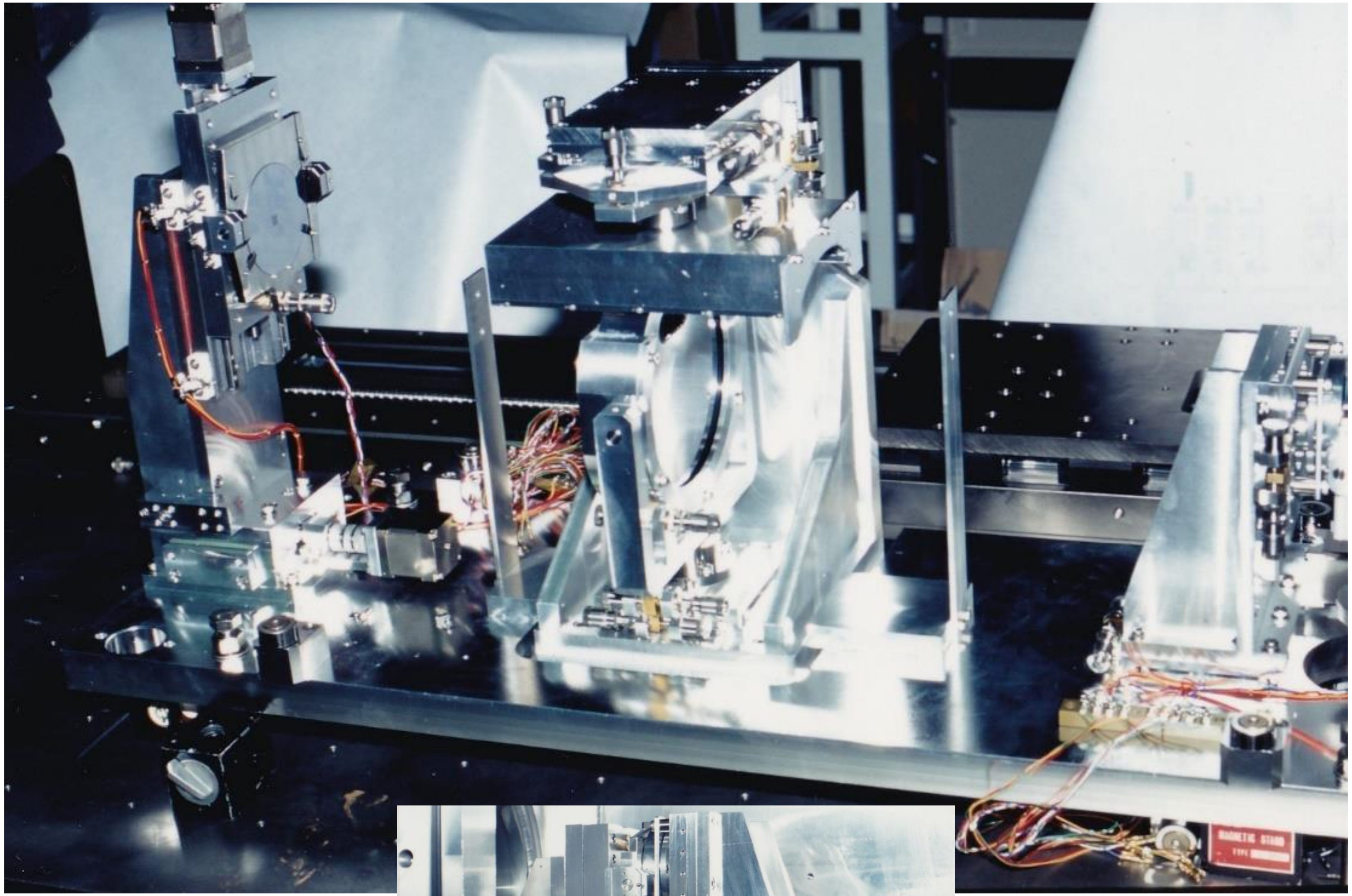
(b)Convex Mirror

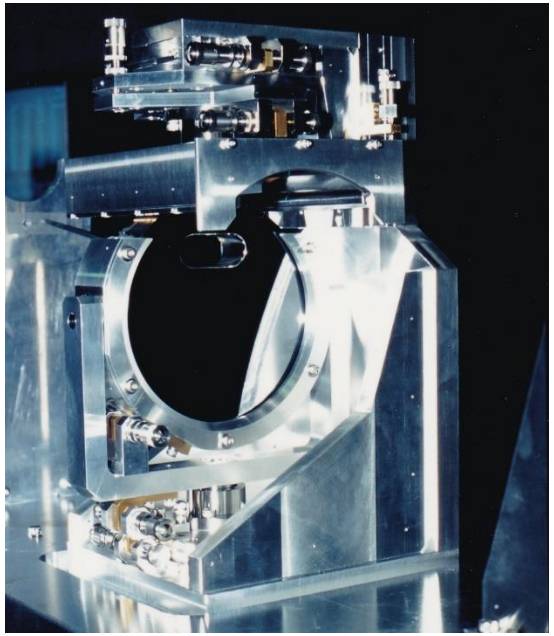


Collimated beam
M2: Convex toroidal mirror
Super-ALIS
Energy: 600 MeV
40 mrad(h), 4 mrad(v)
Beam size: ϕ2.4 mm(3σ)
Mask stage
Reflection mask
M4: Toroidal mirror
5
SR
M1: Concave
toroidal mirror
Ring-field
illumination
(radius: 62.5 mm)
Two-aspherical mirror
system
NA: 0.1, Magnification: 1/5x
Ring-field:100 mm x 0.2 mm
1
Entrance pupil
Wafer stage
M3: Rotating
cylindrical mirror

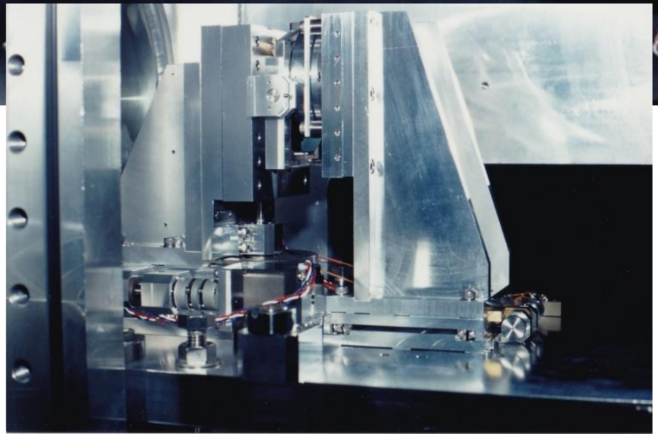
Mask stage





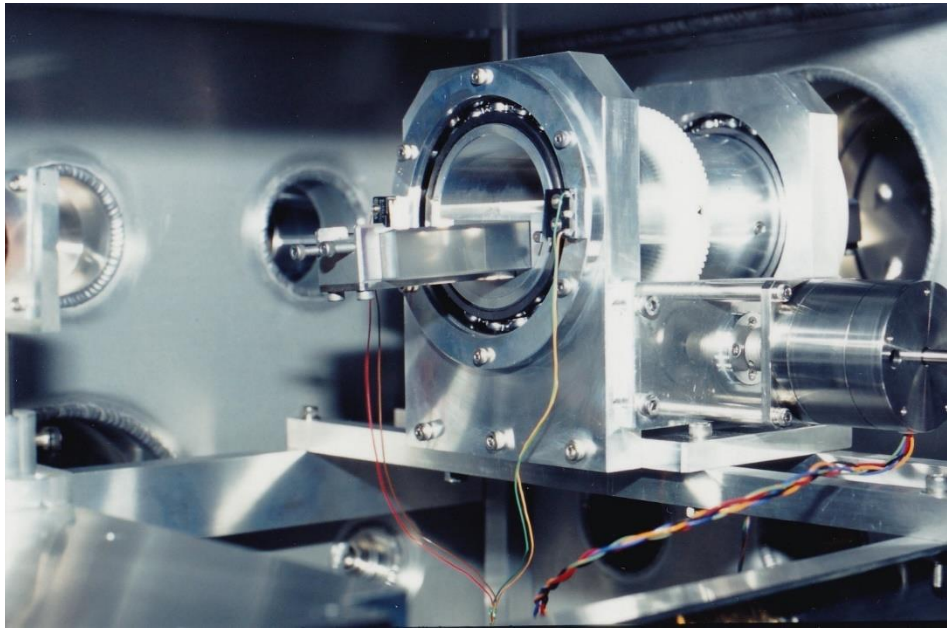


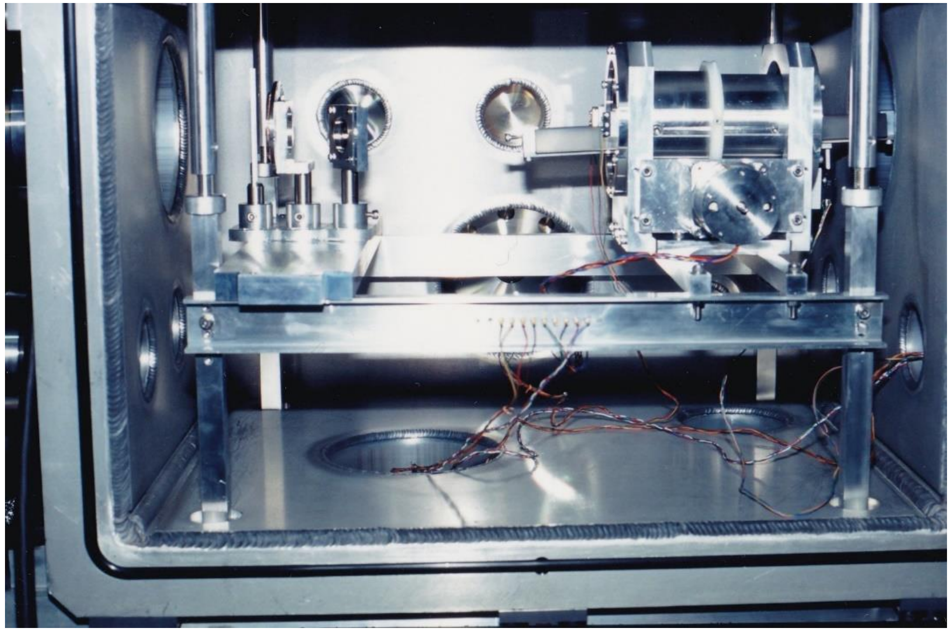
Focusing optics &
Concave mirror

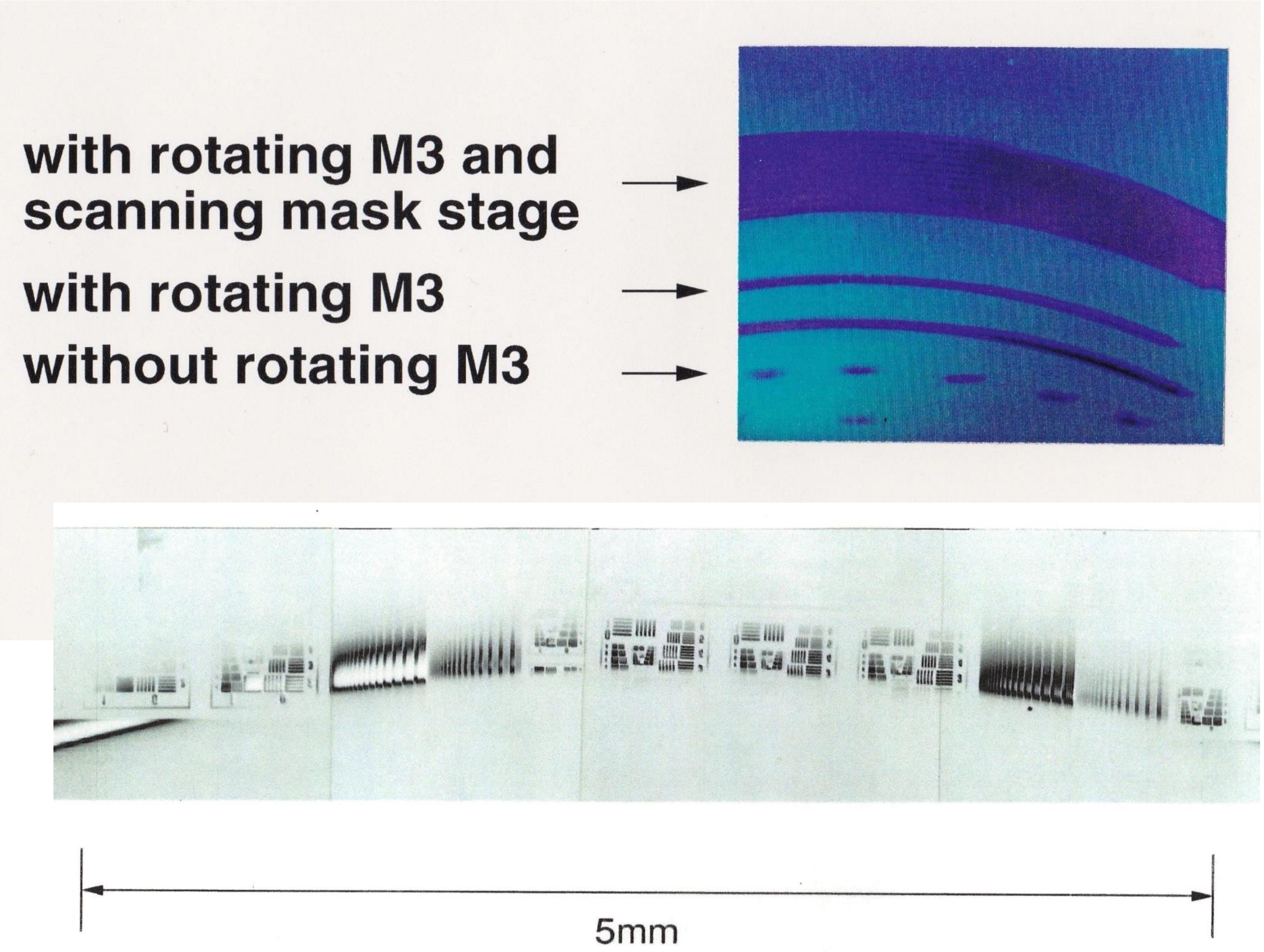


Convex mirror &
Wafer stage

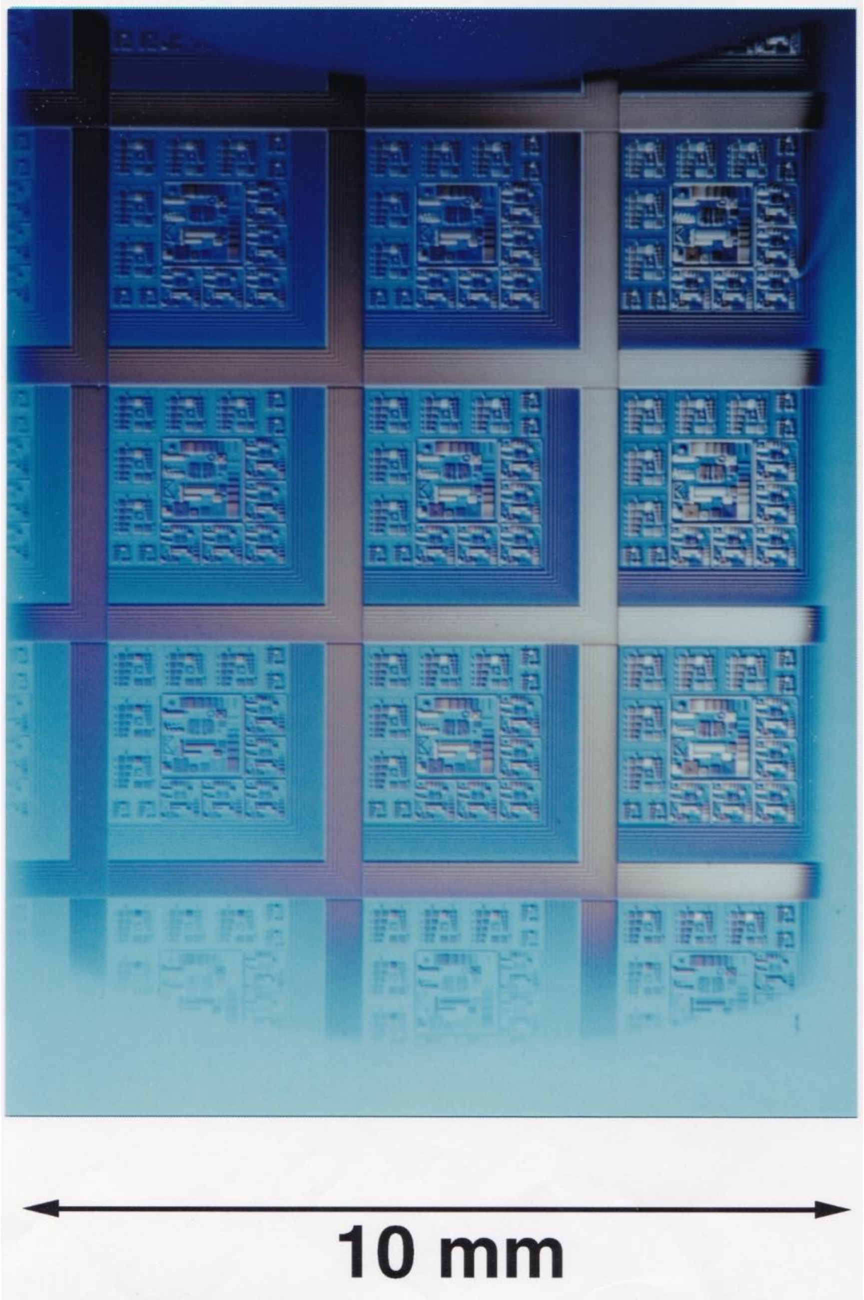
M3 mirror and rotating mechanism

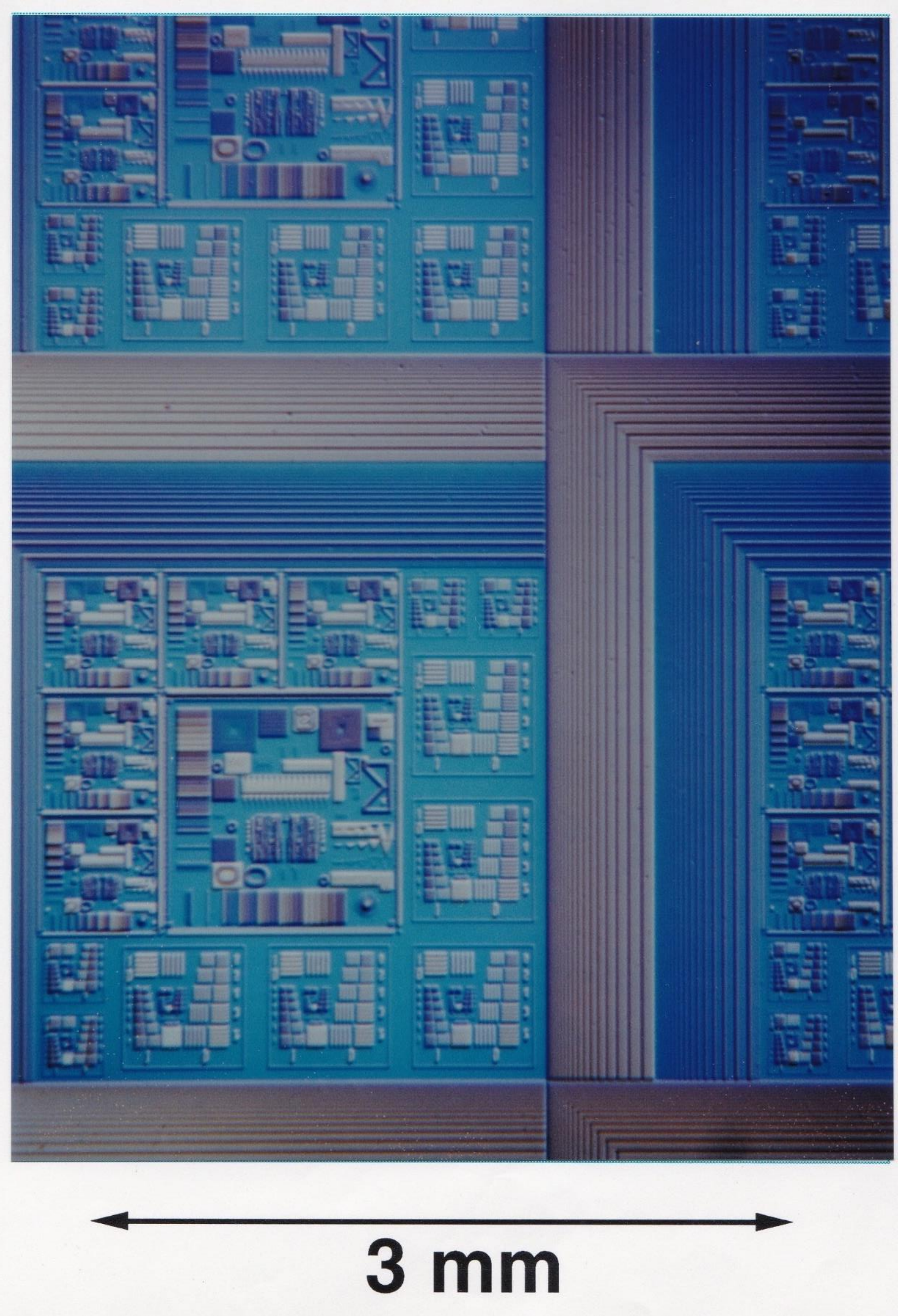





with rotating M3 and
scanning mask stage
with rotating M3
without rotating M3
5mm

1994





1994

Multilayer Fabrication in NTT

- Development of artificial lattice film of metal thin film was promoted as a superconductor at first.
- Dr. Takei etc of Ibaraki ETL developed a W/Cmultilayer film from the early 1980's and the first X-ray reduction experiment was done from 1984.
- In 1985 T. Barbee et al. fabricated a Mo/Si multilayer with a wavelength of 17 nm for astronomical observation and reported values exceeding the theoretical value.
- Since then, we advanced the development of Mo/Si multilayer at Musashino ETL.

Initially, even 45% reflectivity could not fabricated.

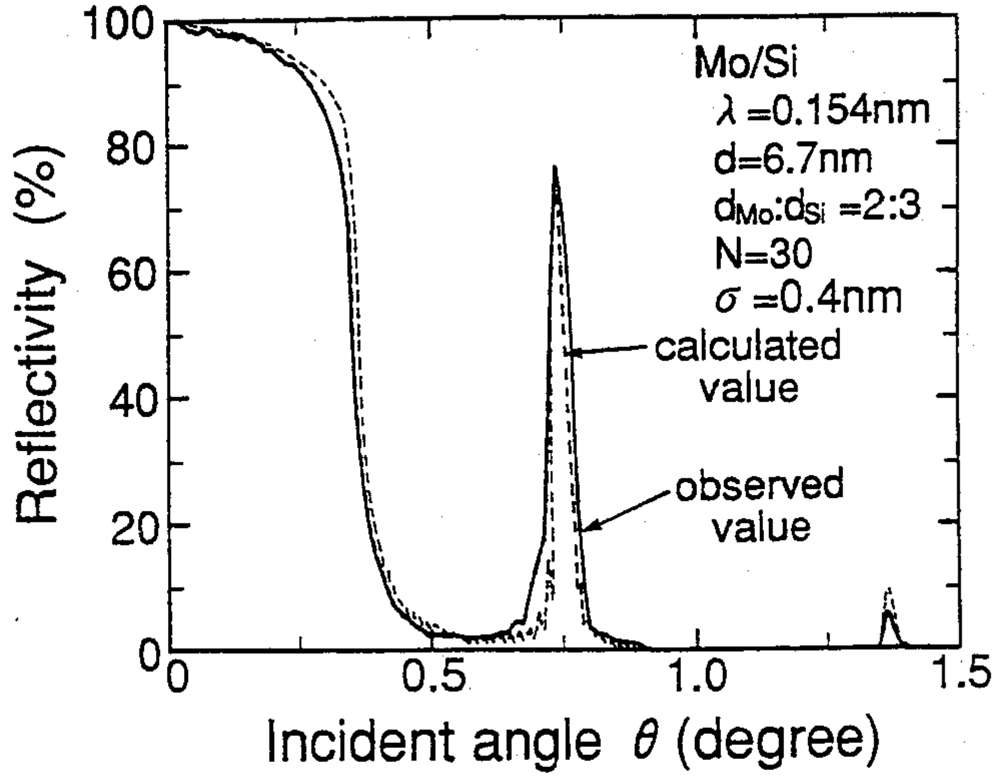
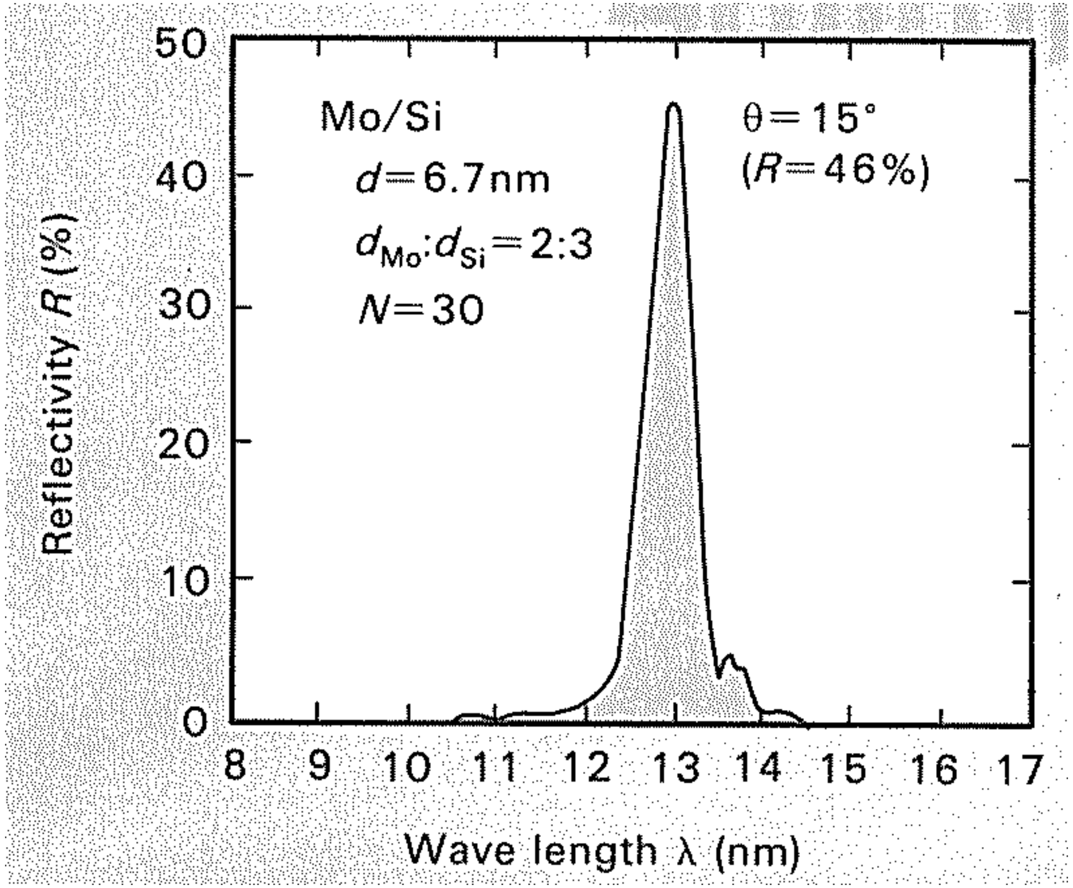


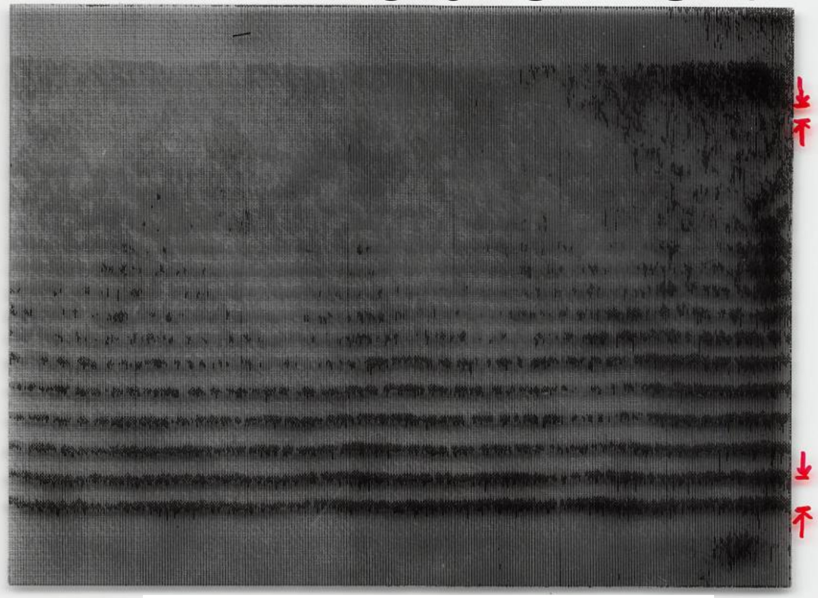
Fig.9. The x-ray reflectivities of the Mo/Si multilayer.



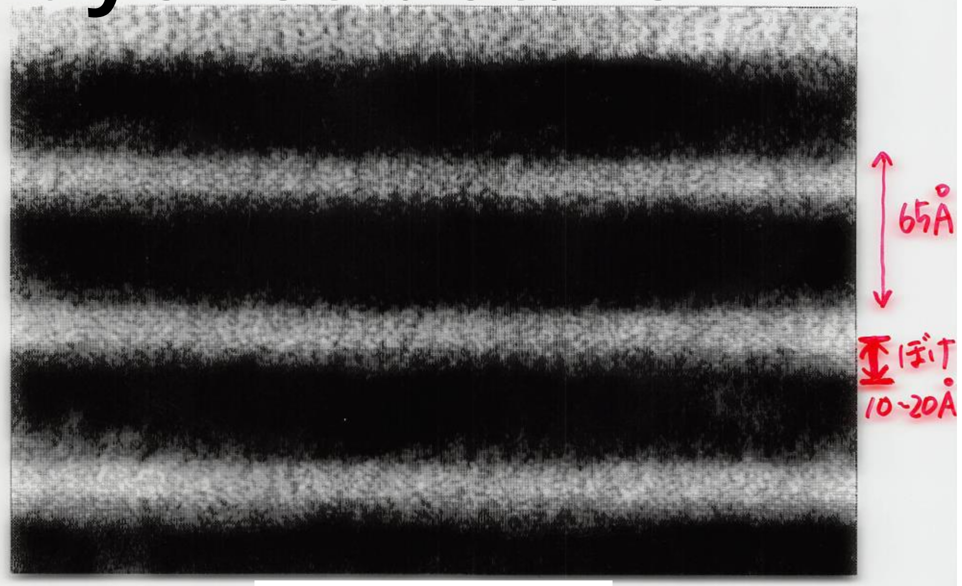
Measured by XRD

Measured by KEK reflectometer

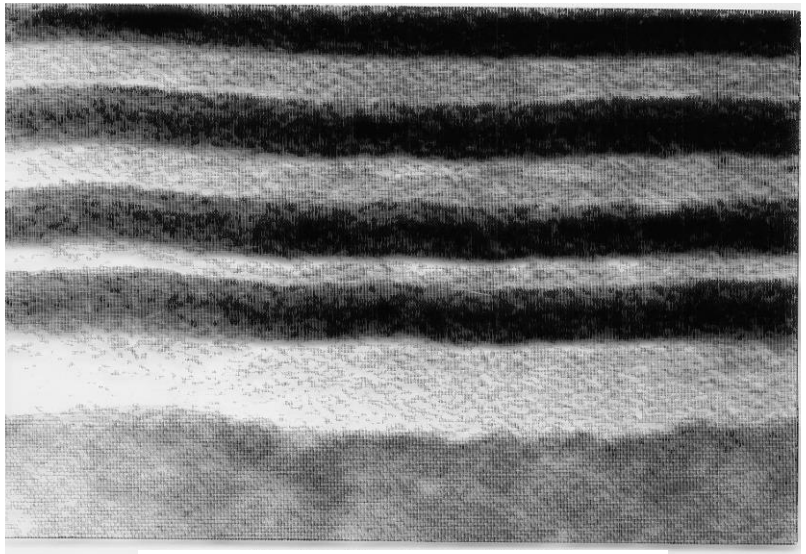
Problems of multilayer structure



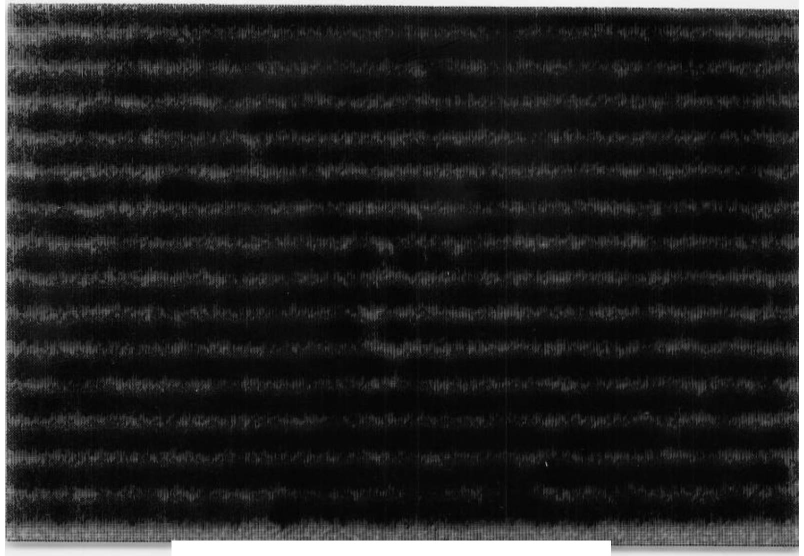
Uneven periods length



Interface blur

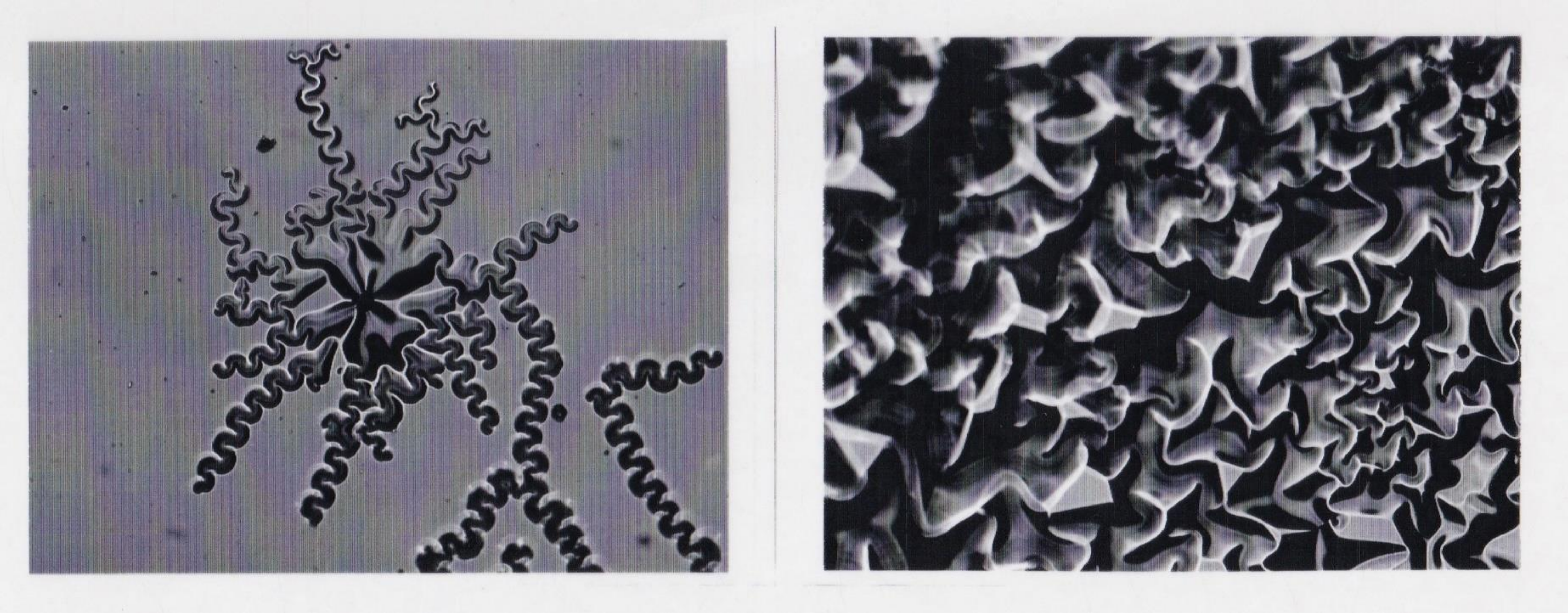


Substrate roughness



Island straucture

In ML fabrication on SC Optics, stress control was difficult and cracks were observed.



Configuration of Magnetron sputter equipment

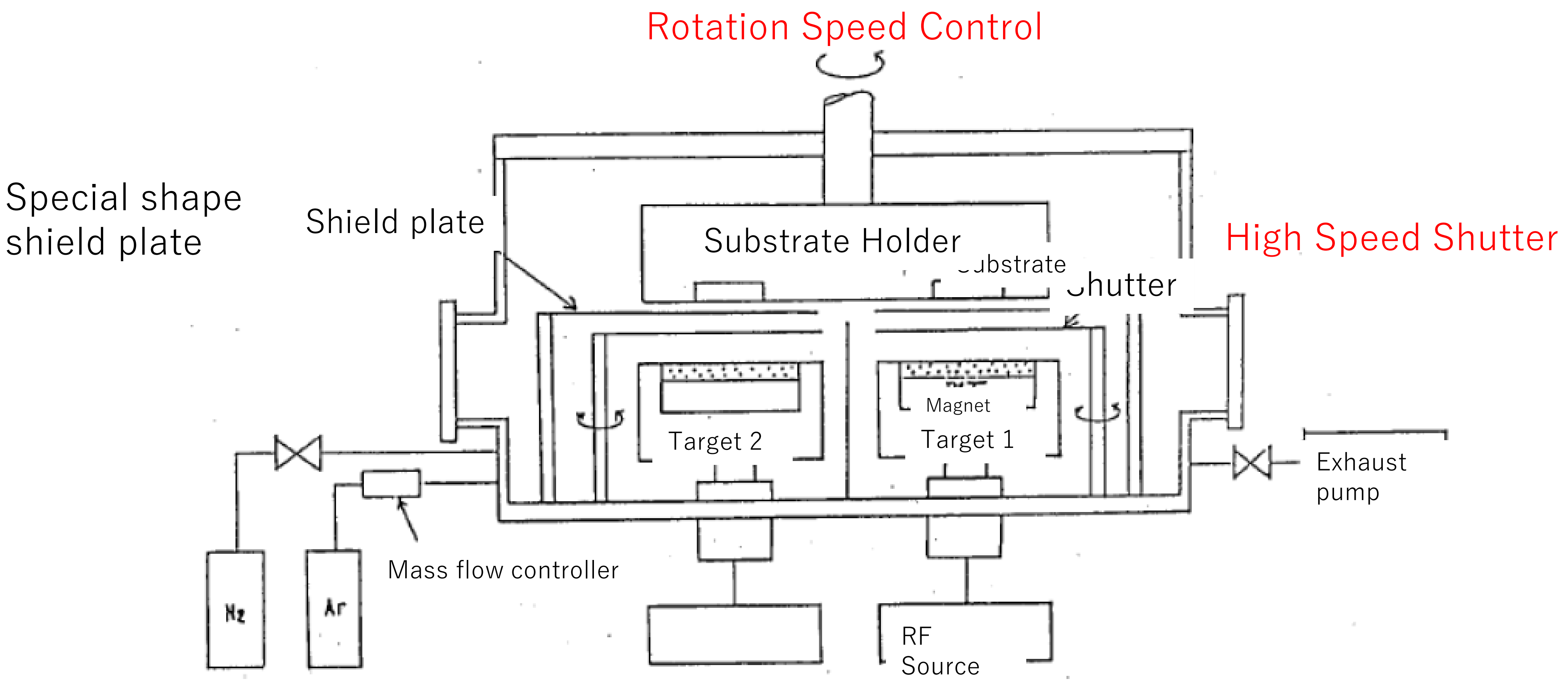
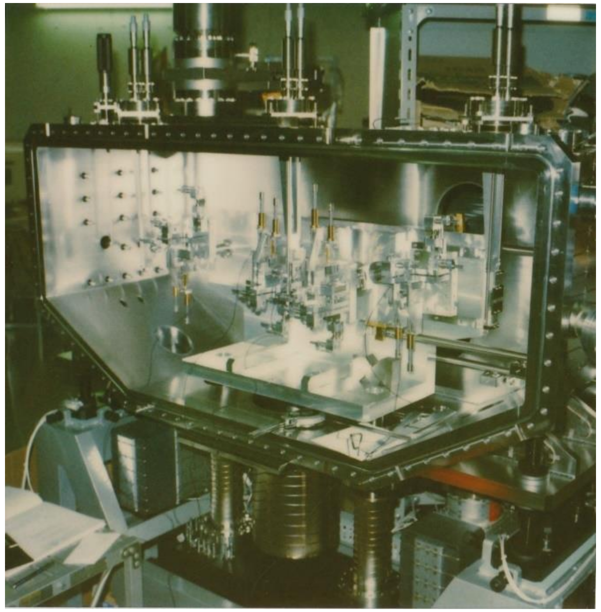
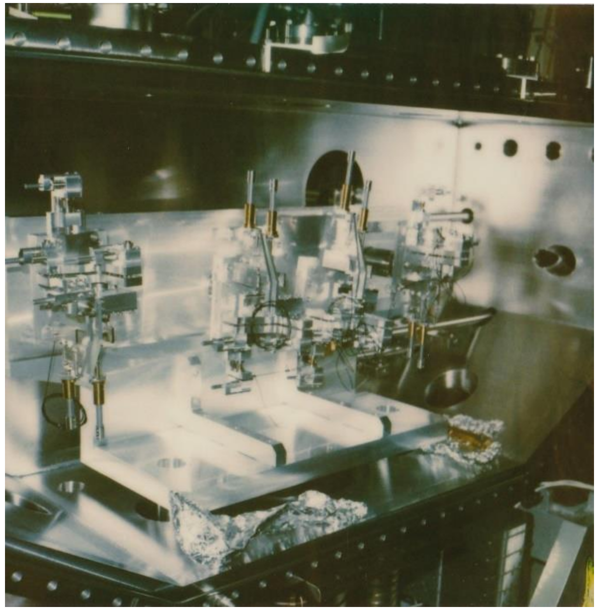
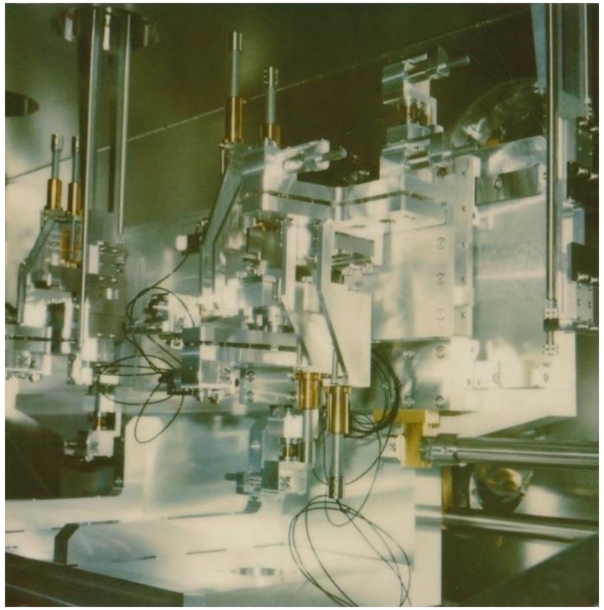
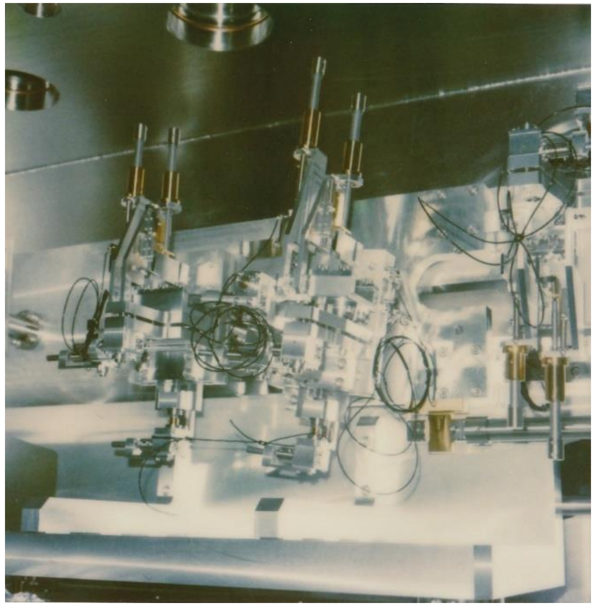
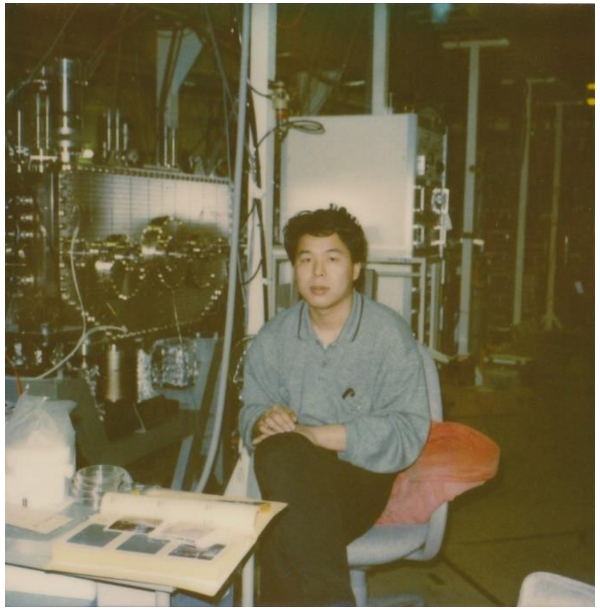
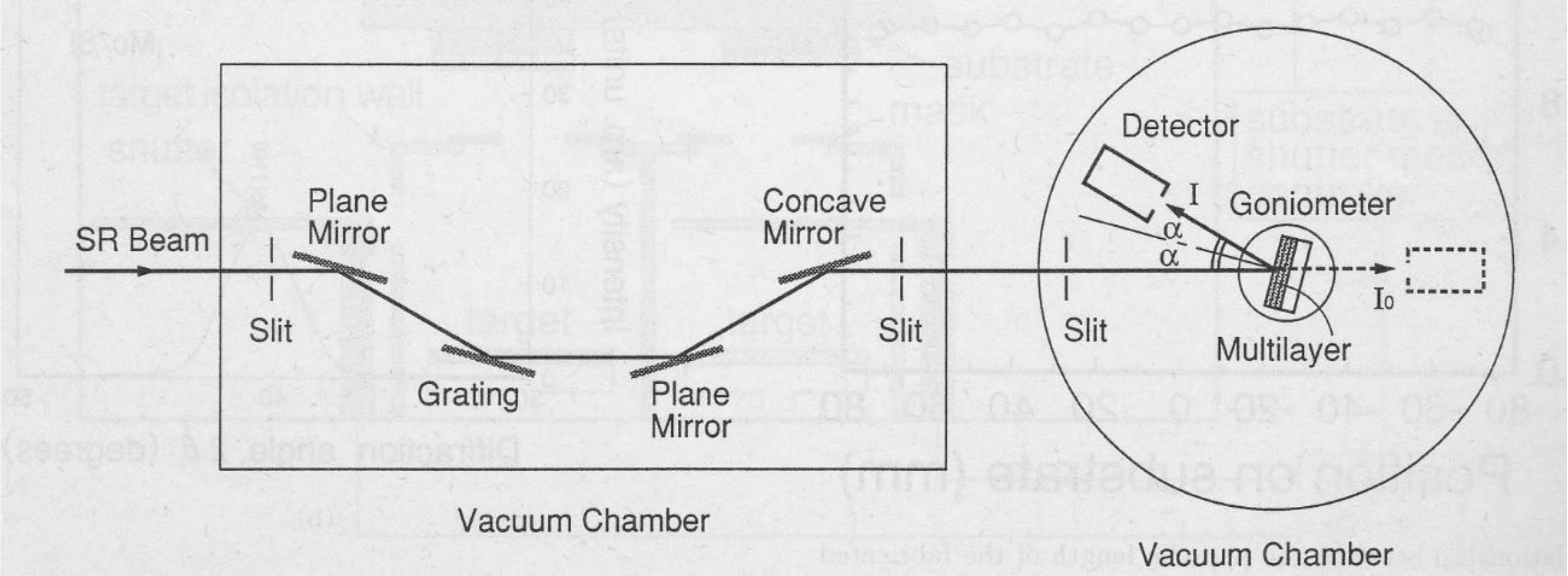
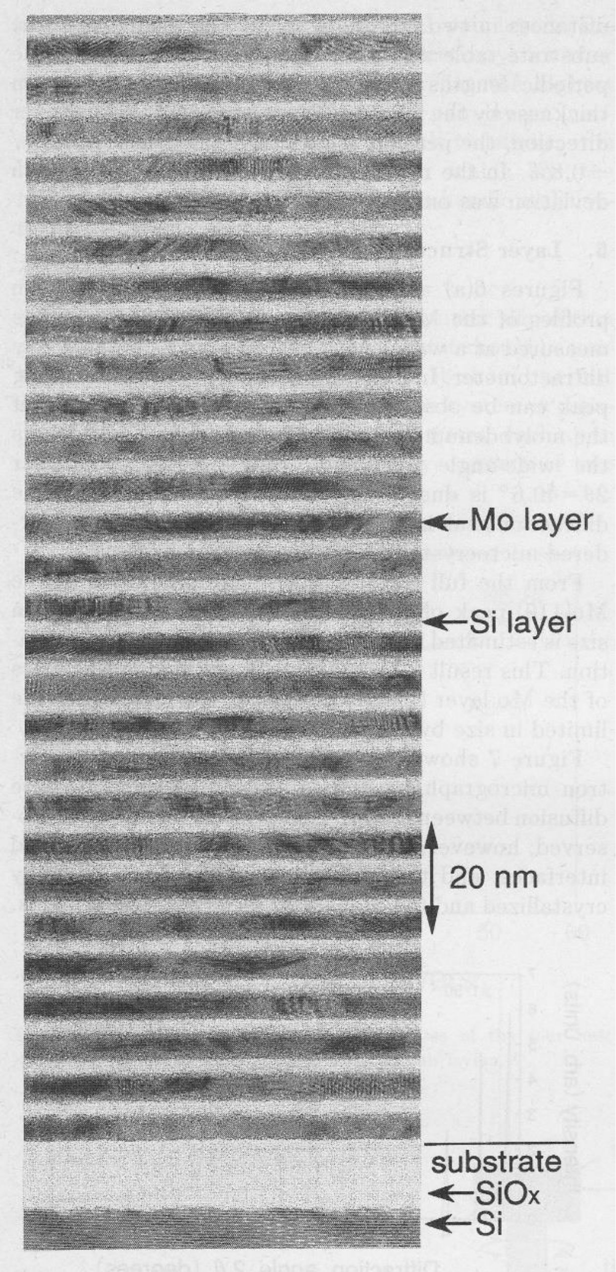
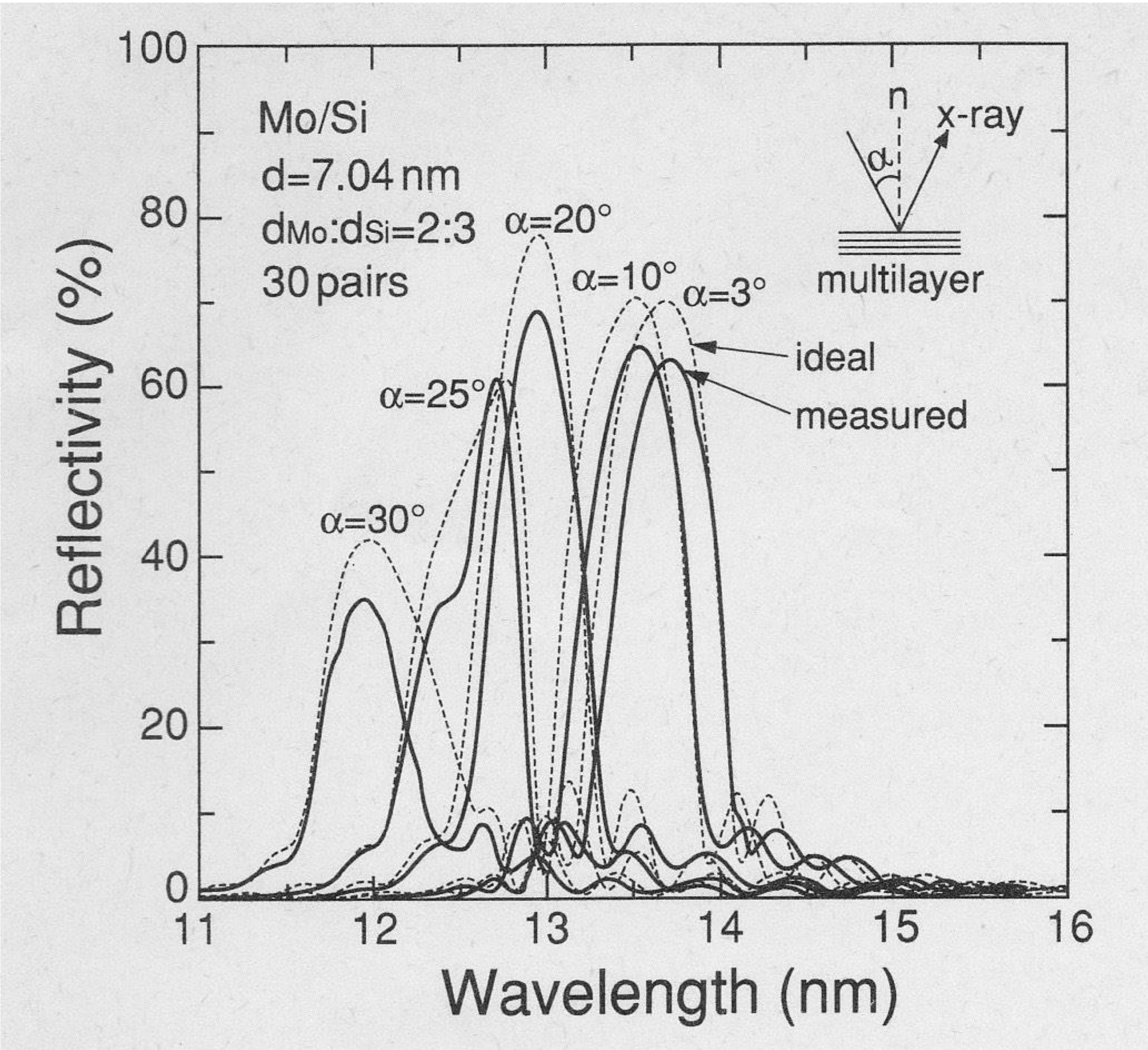


図 2-1-1. rf マグネトロンスパッタリング装置の模式図

A reflectometer was installed in BL-1B of KEK.


Mo layer
Si layer
20 nm
substrate
SiOx
Si


Mo/Si
d=7.04 nm
dMo:dSi=2:3
30 pairs
α=20°
α=10°
α=3°
α=25°
α=30°
n
x-ray
α
multilayer
ideal
measured
Reflectivity (%)
Wavelength (nm)
100
80
60
40
20
0
11
12
13
14
15
16

1995

At first, a laser plasma light source of metal target was developed.

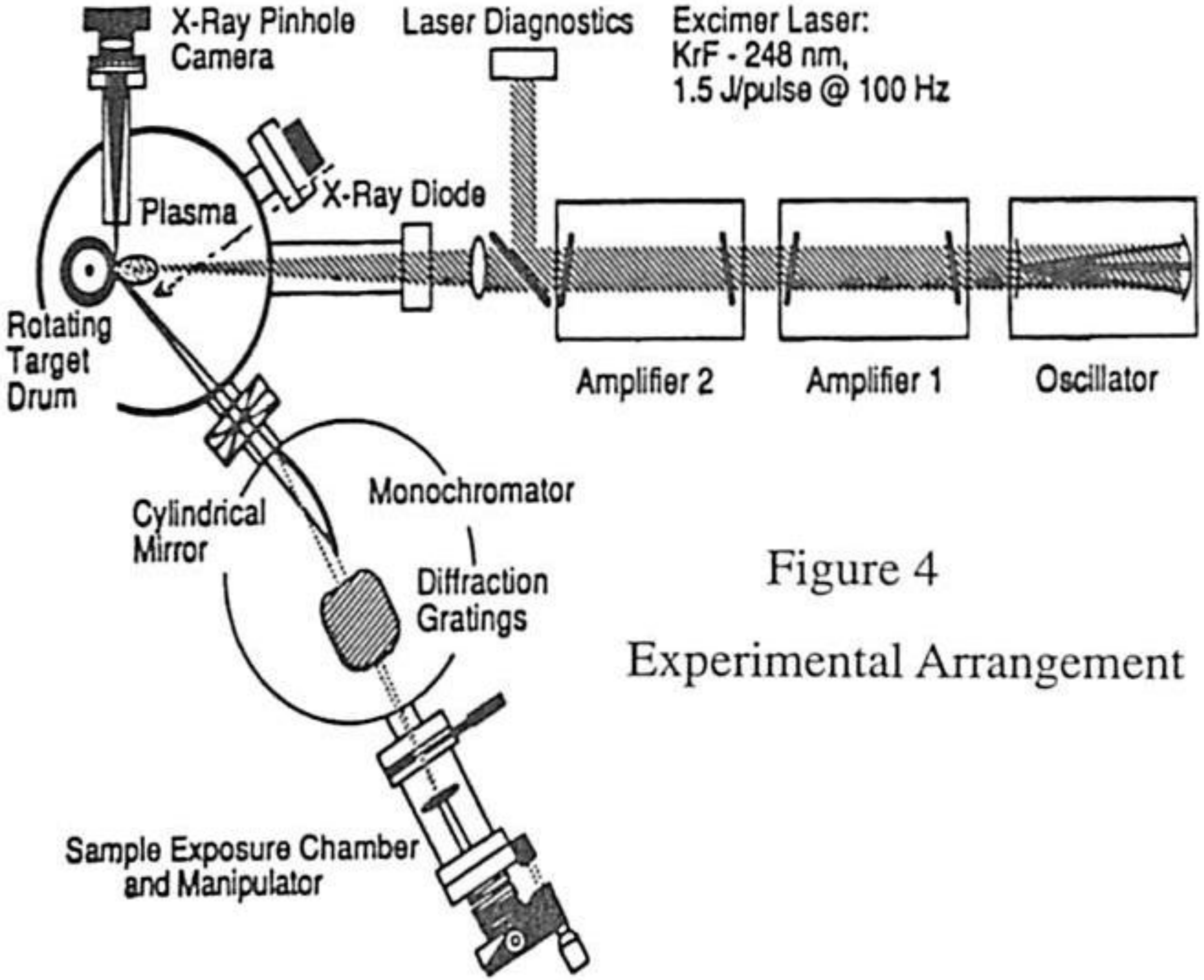


Figure 4

Experimental Arrangement

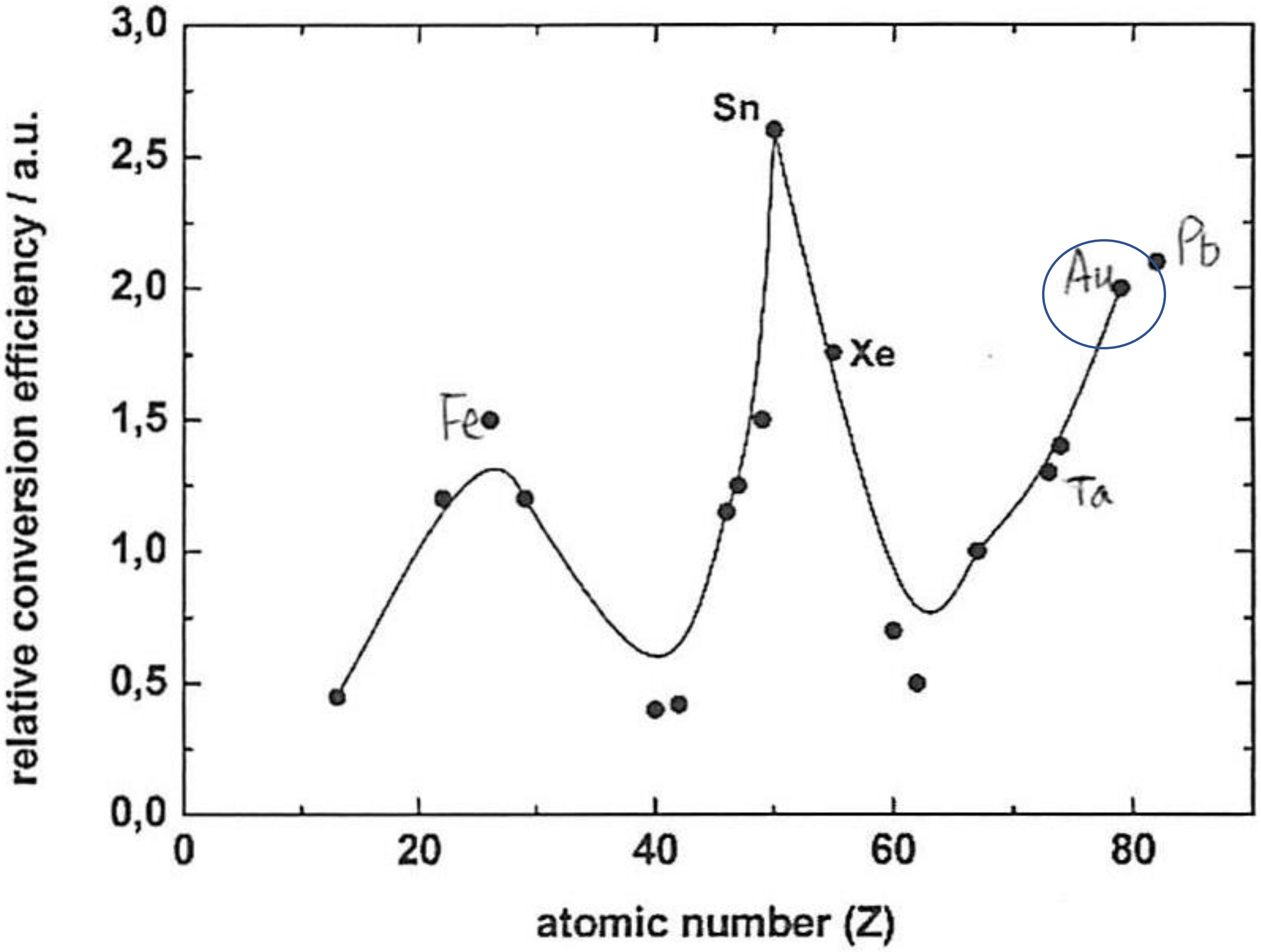


Figure 3.5 Relative CE into 13.5-nm radiation as a function of the atomic number of the emitter. The highly efficient Sn ($Z = 50$) and the frequently used Xe ($Z = 54$) are marked. (Reprinted from Ref. 14.)

$$E_{melt} = [(T_{melt} - T_0)C_p + \Delta H_f]\rho$$

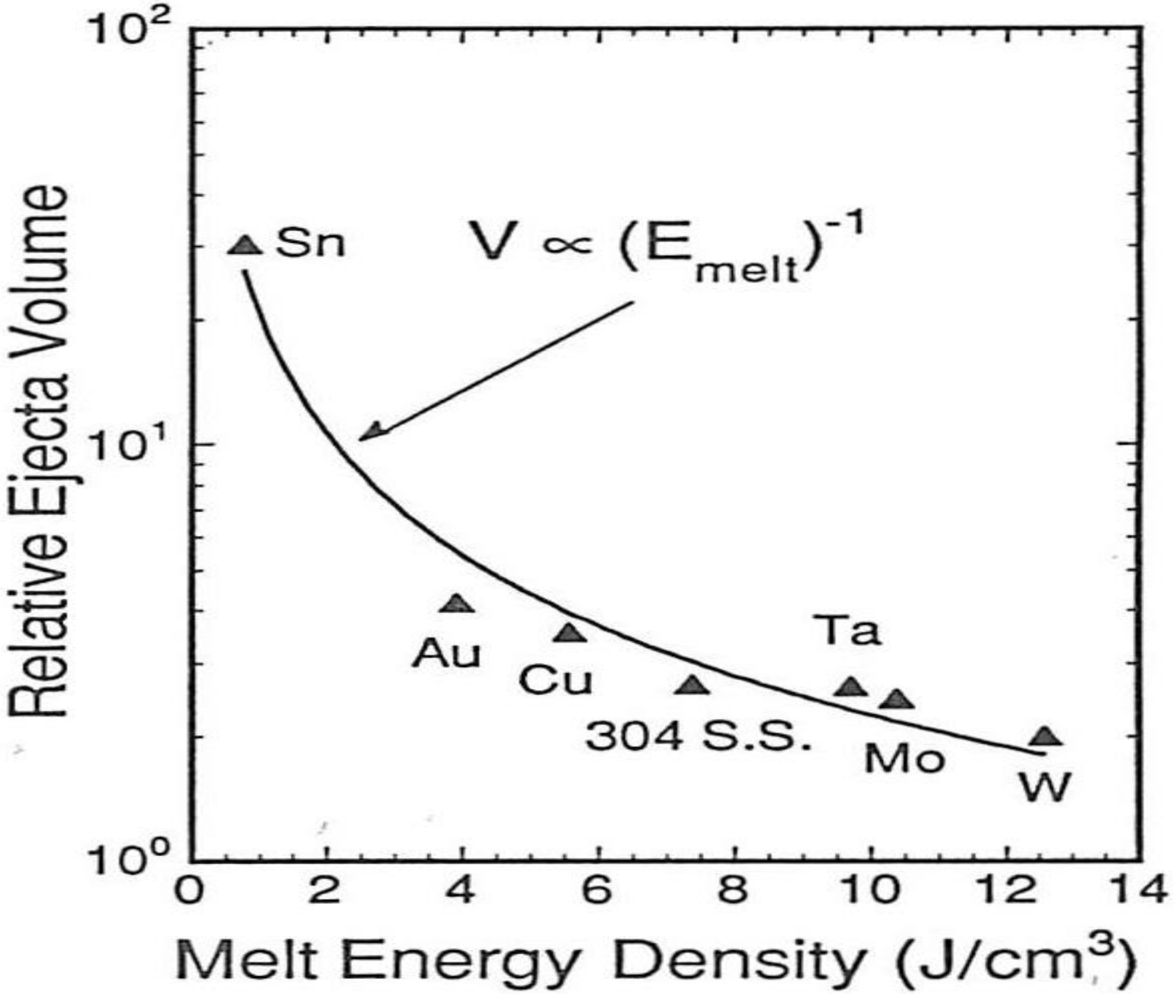
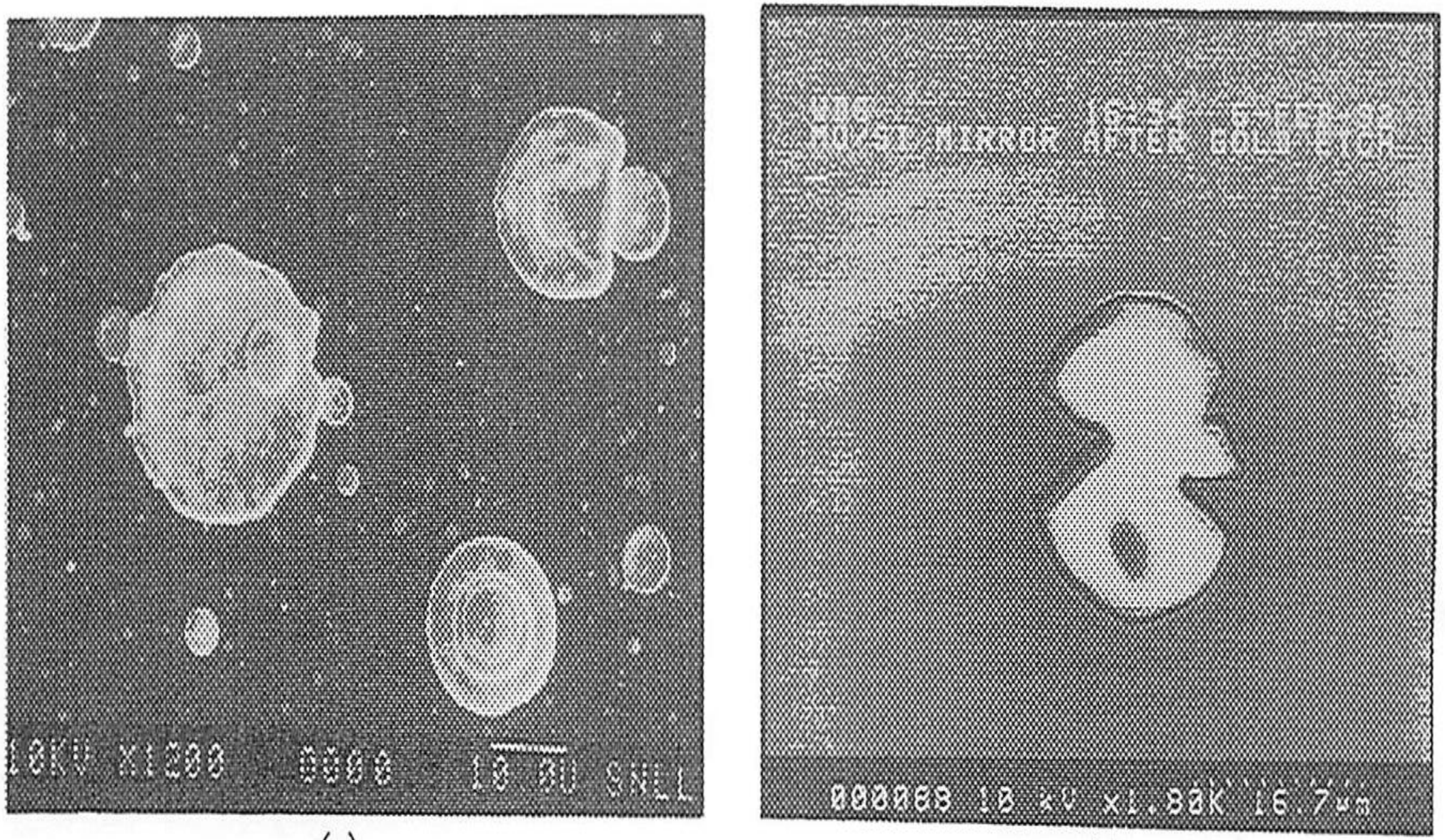


Figure 1. Relative target volume ejected by a 0.8 J, 248 nm laser pulse versus the energy density required to melt the target from a solid at 20°C, plotted for selected target materials.



(a)

(b)

Figure 2. Scanning electron micrographs of a Mo/Si multilayer-coated optic a) after exposure to 630,000 pulses of a laser plasma produced on a solid Au target in the presence of 200 mTorr of He gas, and b) after chemical removal of the Au particulates from the same multilayer coating.

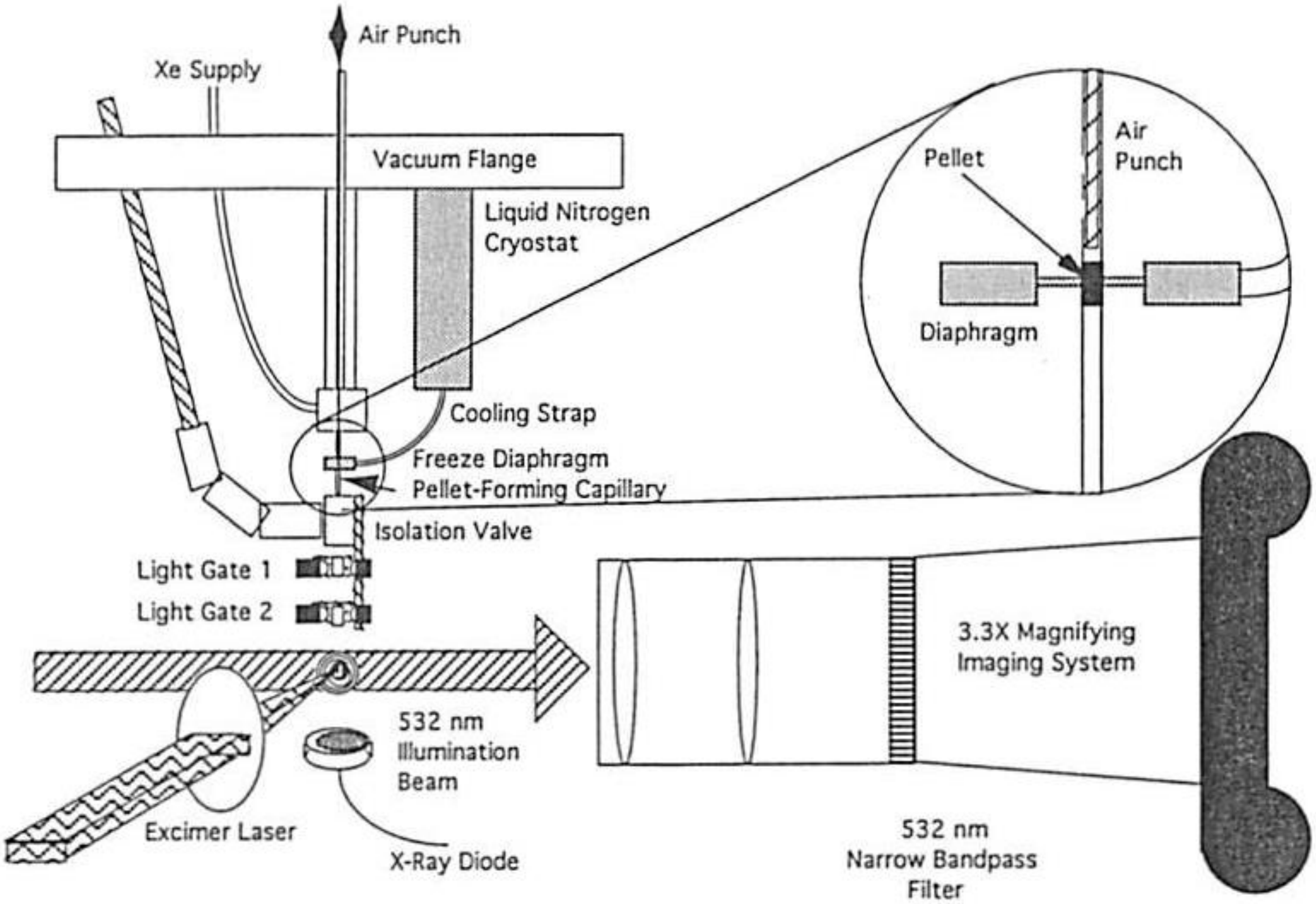
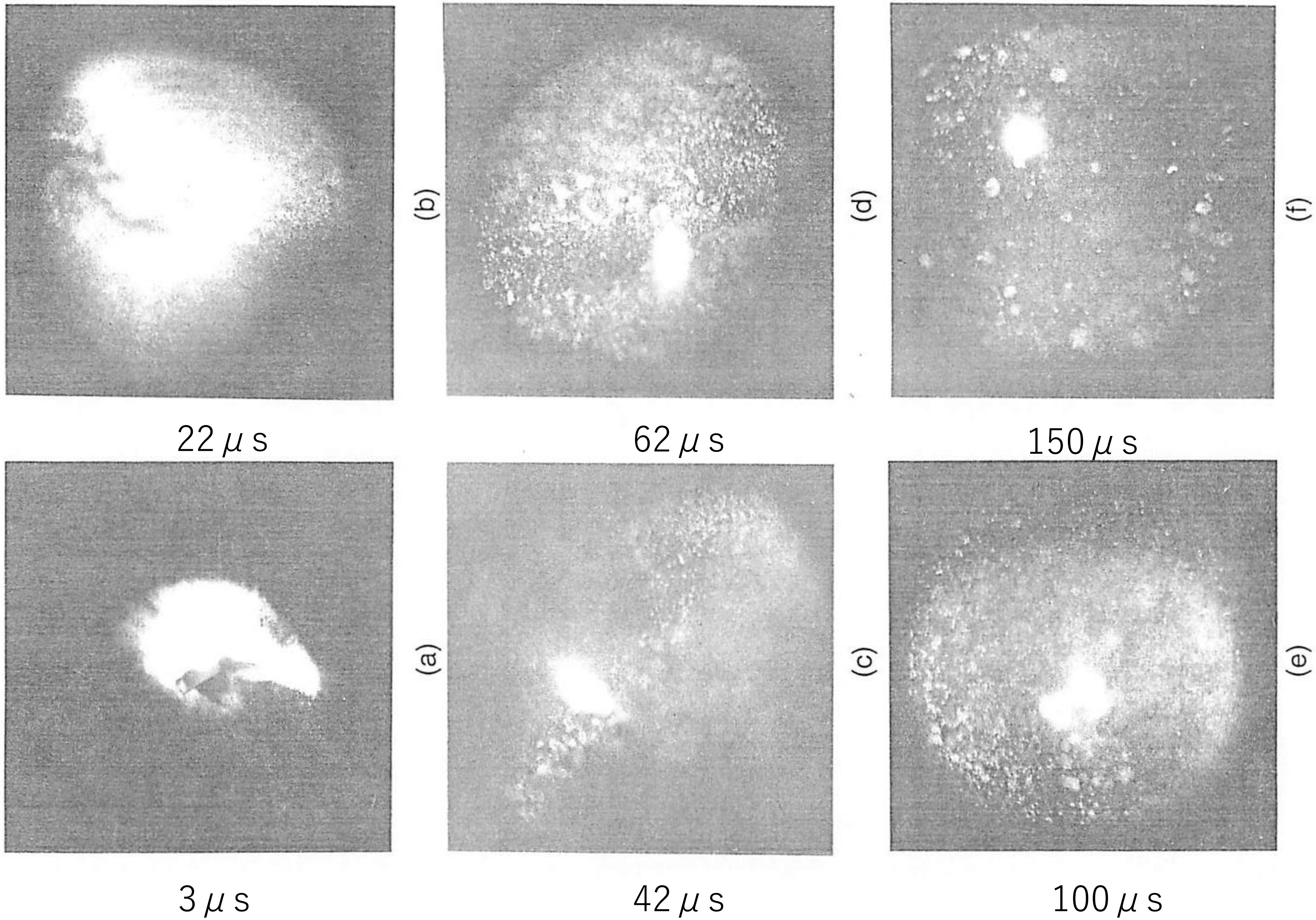
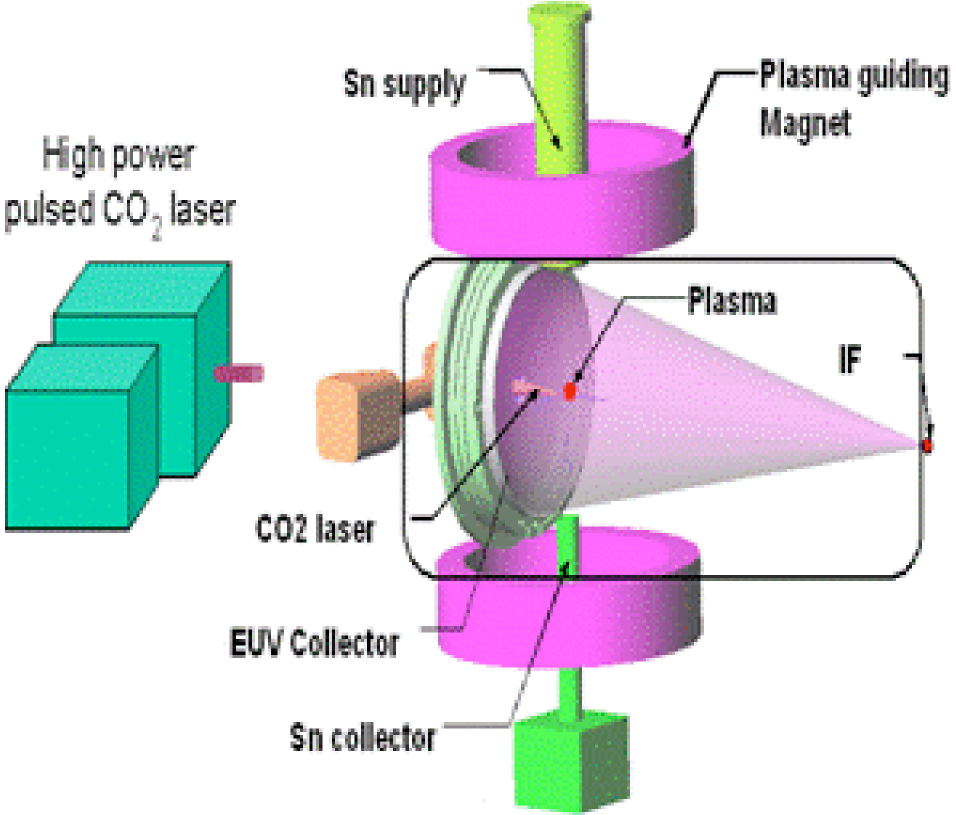


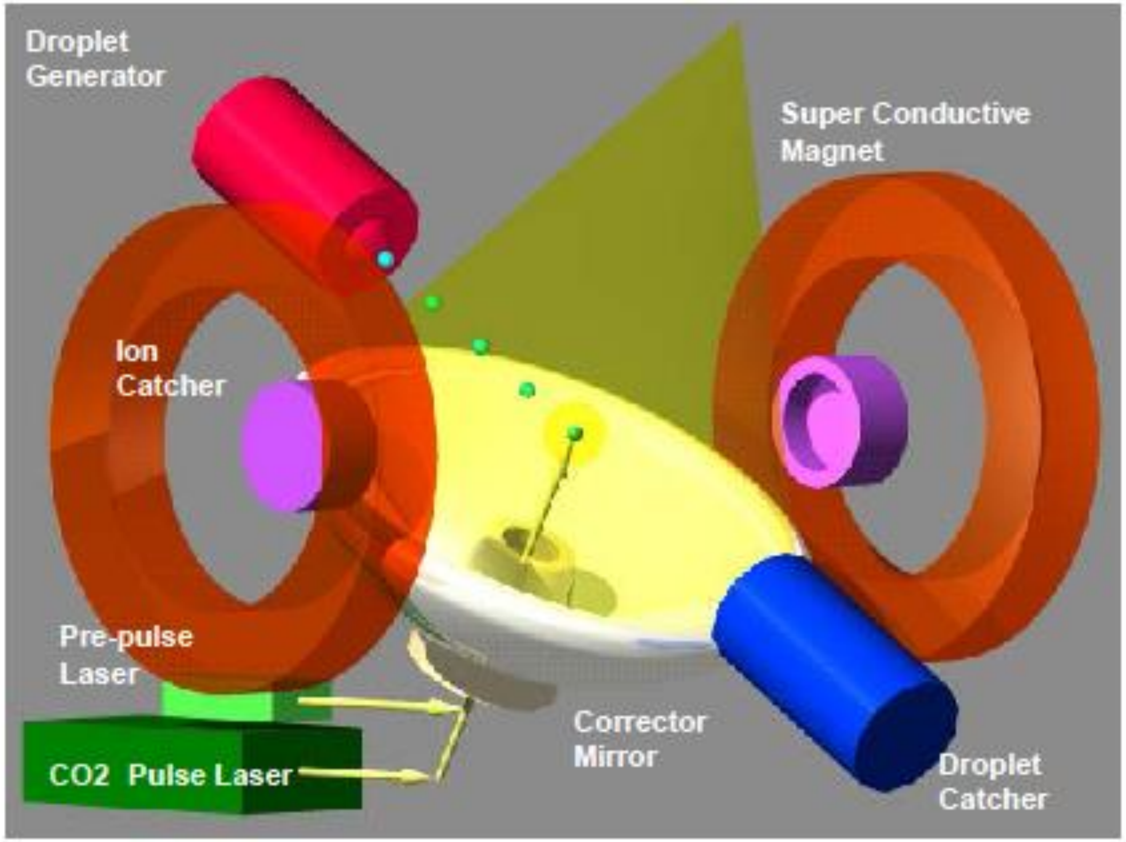
Figure 1. Schematic diagram of Xe pellet injector experiment.



Contamination by Zenon clusters after KrF irradiated.

Gigaphoton's LPP Light Source Concept





Transition of plasma source development

Solid Target:Au
Problem: Debris
Sn large

Semi-solid:
Xe cluster target
Purpose: Debris free,but
Low Efficiency

Since the luminous efficiency of Xe is 1% or less, Mo / Be at 11 nm which is a more suitable wavelength has been proposed.

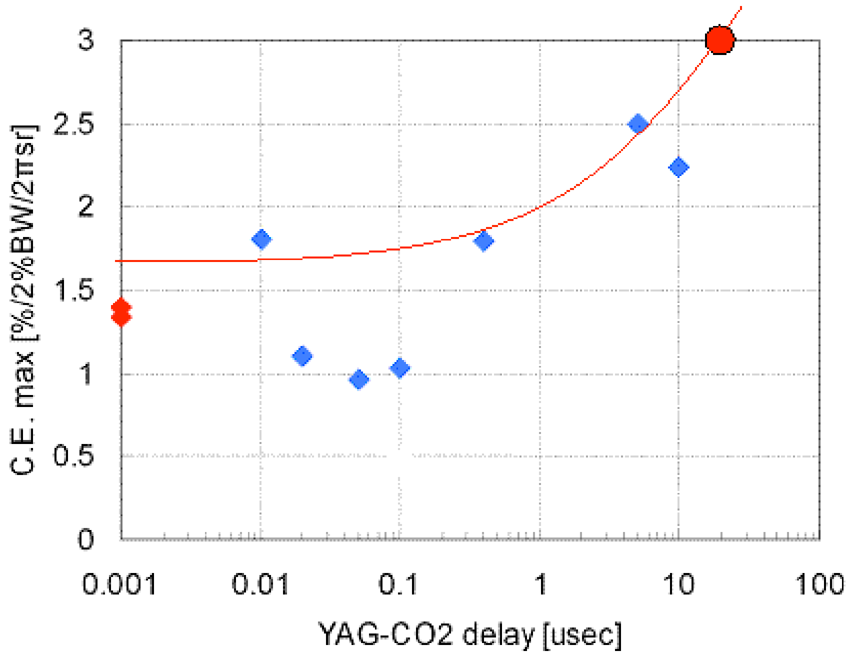
Liquid target of Sn
Proposed;
$\eta > 4\ \%$@13.5 nm

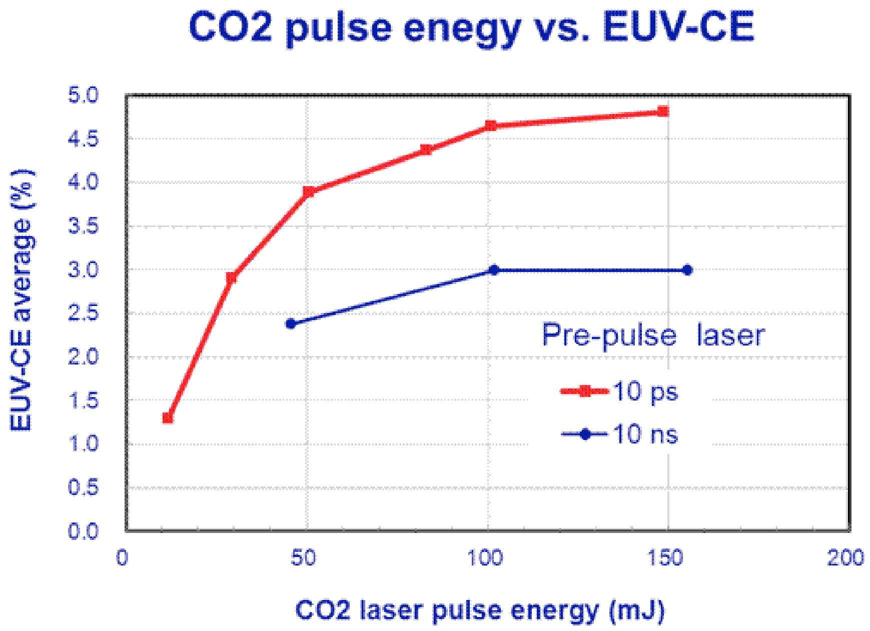
Improve the CE

Liquid target:
Sn Droplet

Pre-pulse method

First, by using YAG laser with a wavelength of 1 μm, Droplet was crushed into fine mist form and further irradiated with CO_2 laser, it was possible to completely evaporate Sn.





The efficiency of ionization was improved by controlling the delay time of the pre-pulse, and as the small Droplet, the high temperature plasma was obtained.

As a result, the conversion efficiency could be improved to 3.3%.

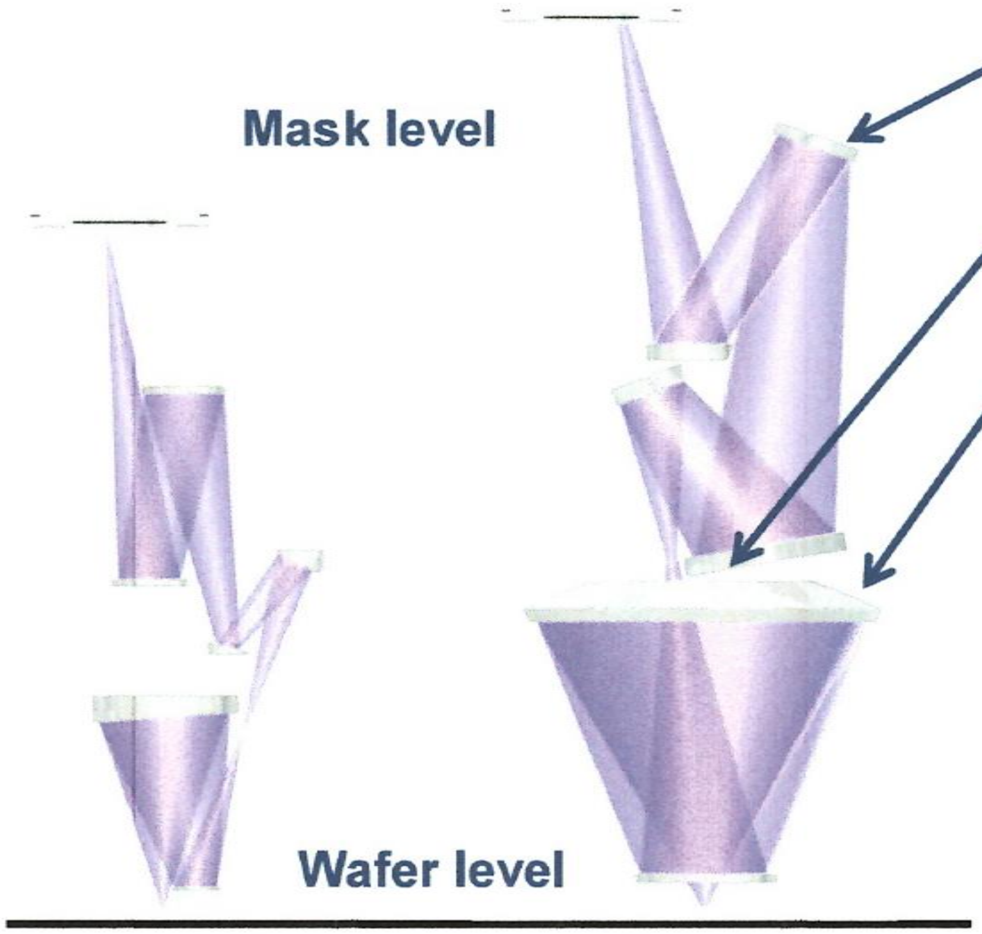
By increasing the pulse width of the pre-pulse laser from 10 ns to10 ps, it improved from 3.3% to 4.7%.

Gigaphoton

Source power of >250W was demonstrated, shipping started in the end of 2017.

High-NA projection optics design available

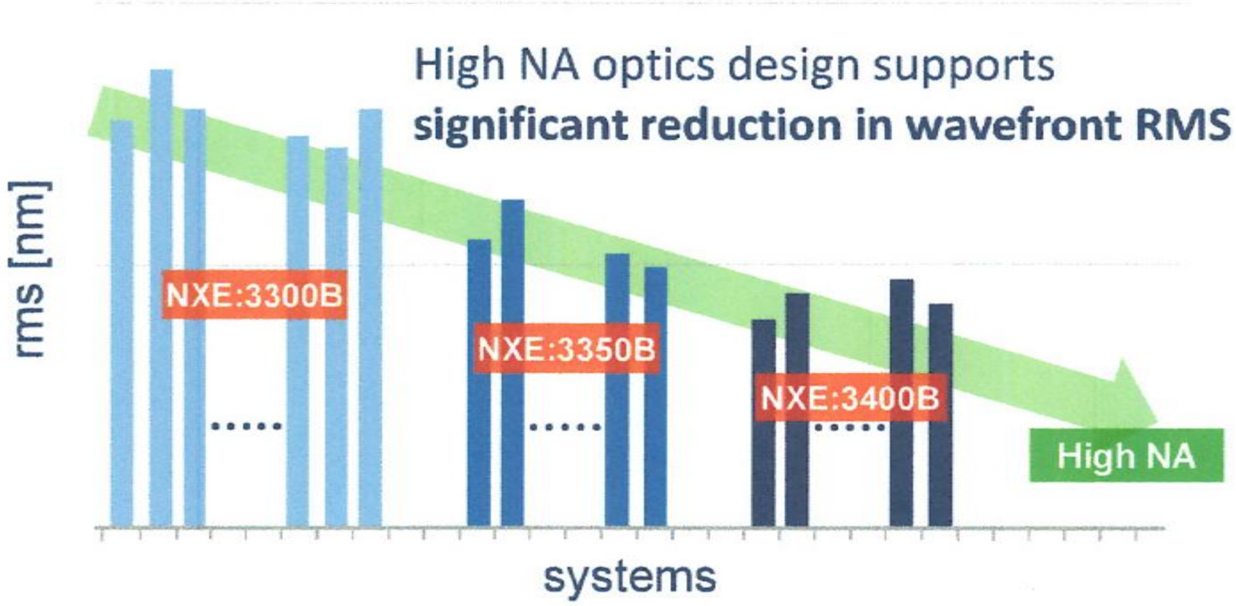
Larger elements with tighter specifications



NA 0.33 NA 0.55

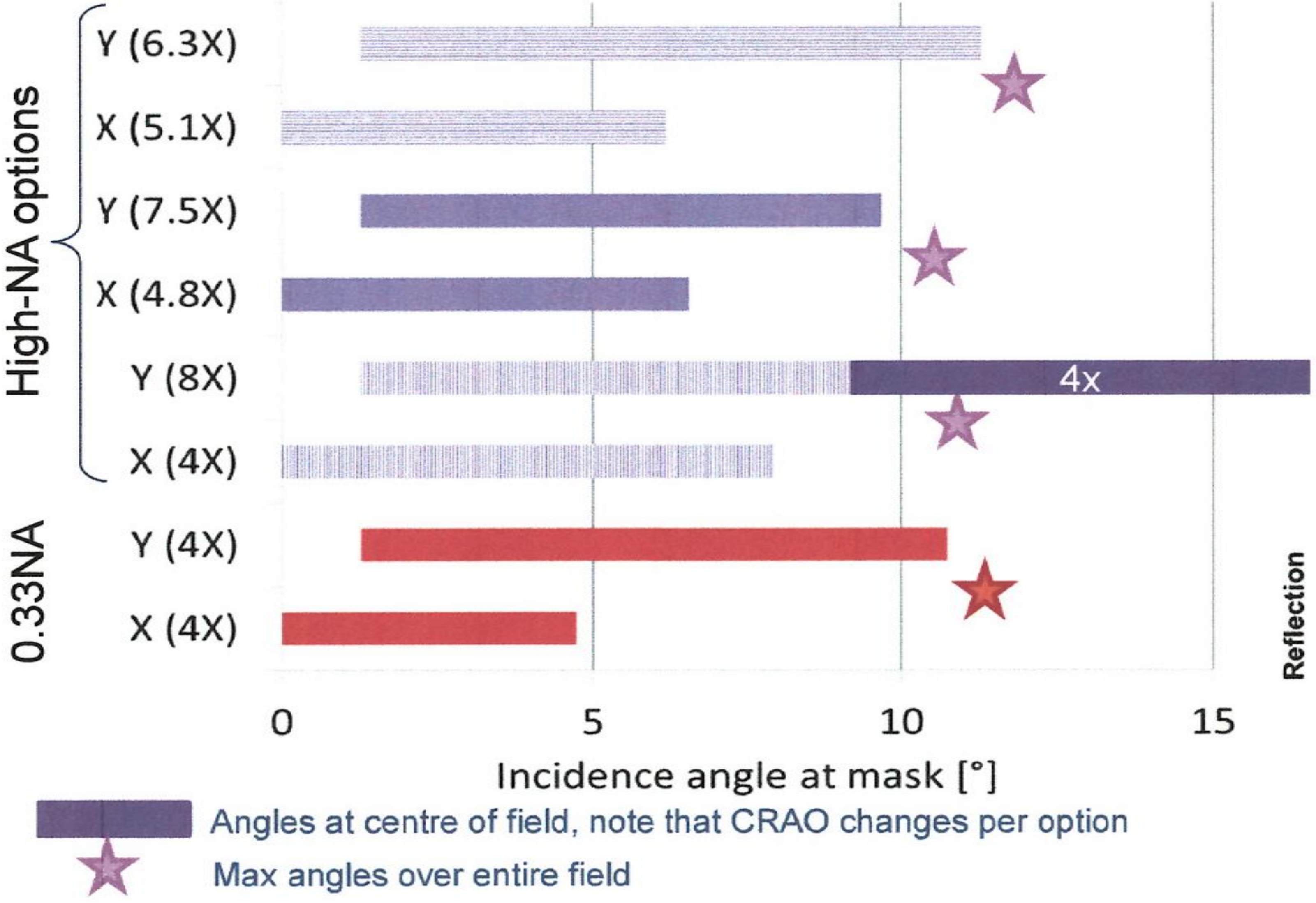
Design examples

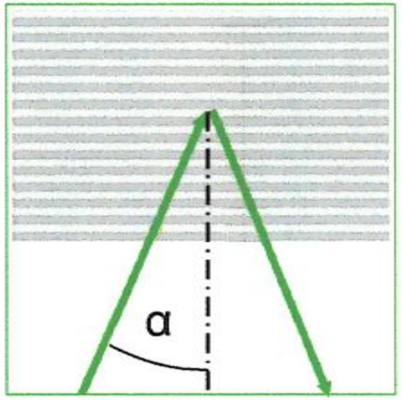
- Extreme aspheres enabling **further improved wavefront / imaging performance**
- Obscuration enables **higher optics Transmission**
- Big last mirror driven by **High-NA**

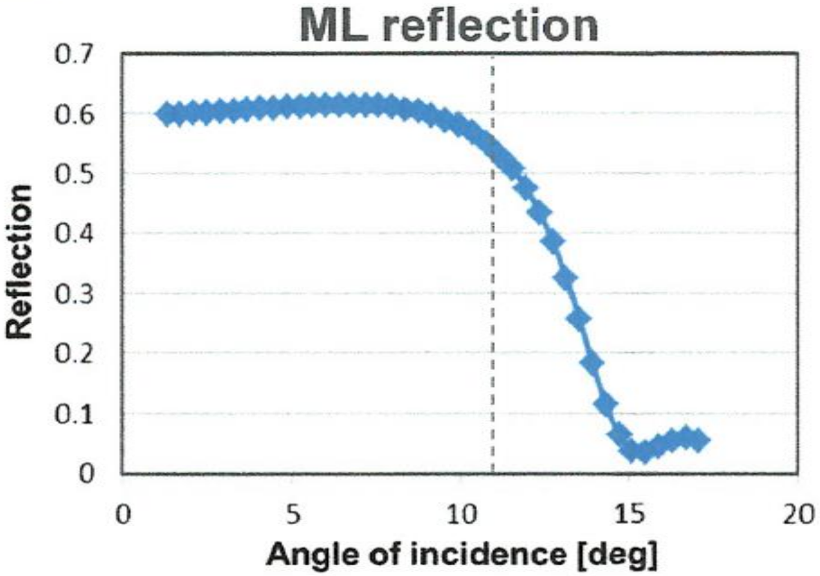


ML Reflection: V- and S-option have lower angles than 0.33NA

The square option has the lowest maximum angle

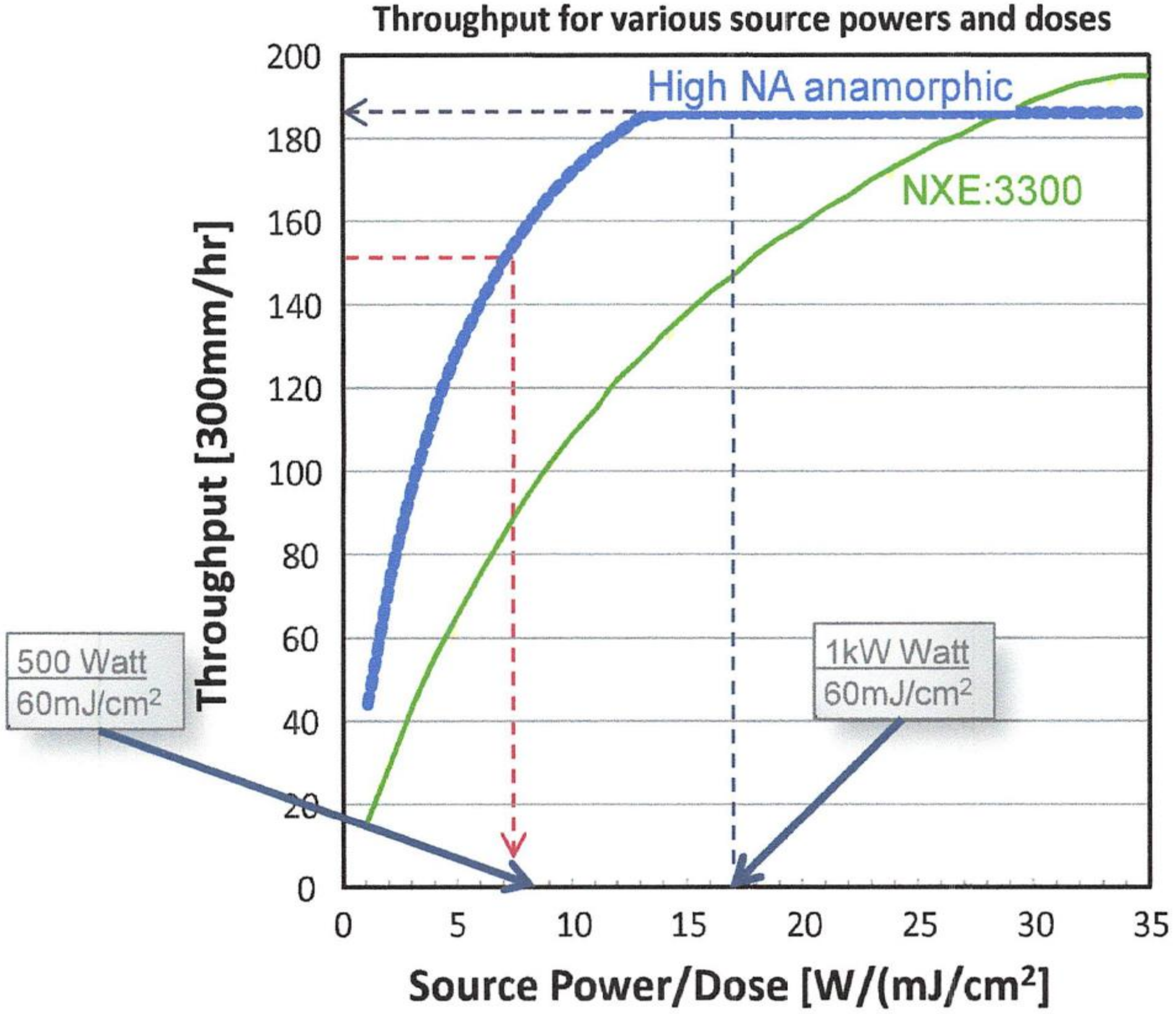


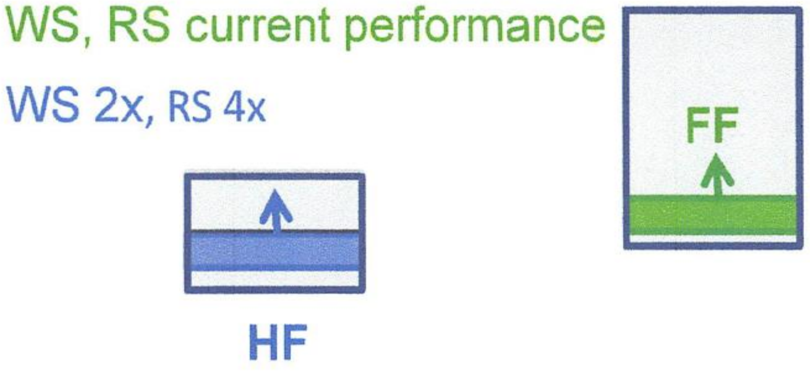




High-NA Field and Mask Size productivity

500W enables throughput of 150wph with anamorphic HF





High-NA Half Field scanner needs 500W for 150wph at 60mJ/cm^2

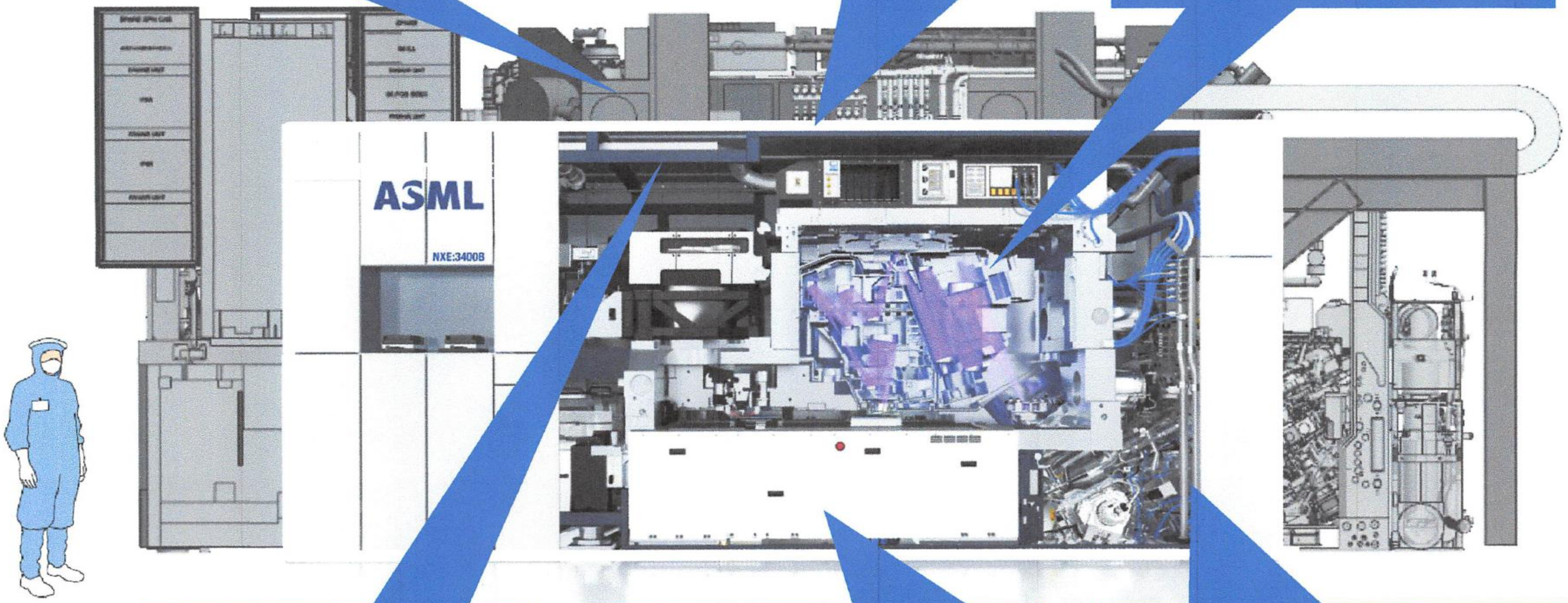
High-NA system architecture available

ASML

Improved metrology
2~3x improvement in overlay/focus

Mask Stage
4x increase in acceleration

Lens & illuminator
- NA 0.55 for sub-10nm resolution
- High transmission



New Frames
Improved thermal and dynamic control with larger optics

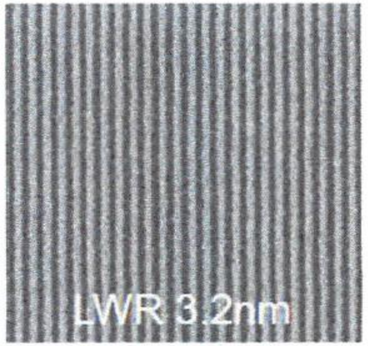
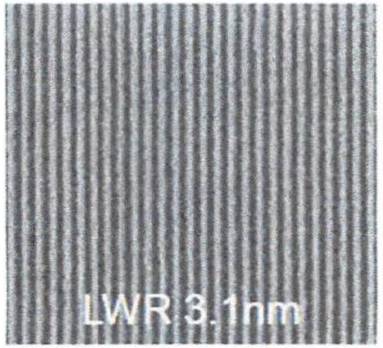
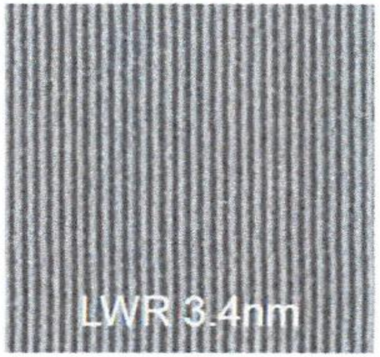
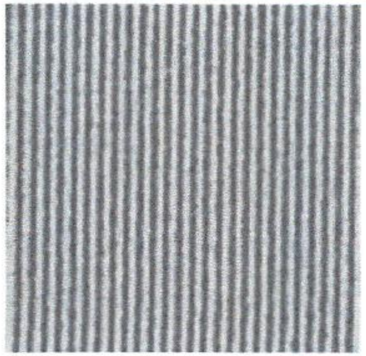
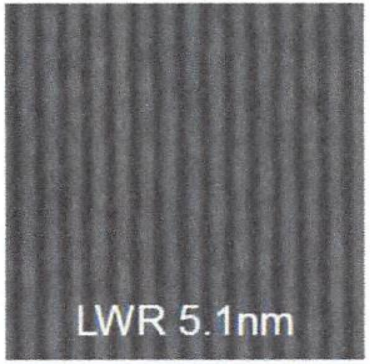
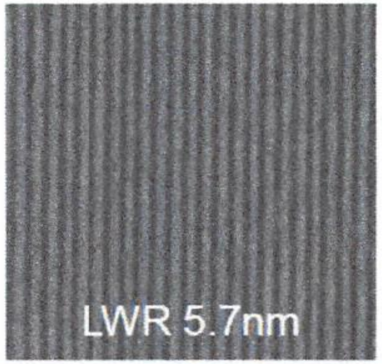
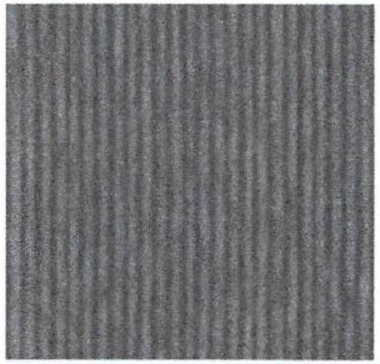
Wafer Stage
2x increase in acceleration

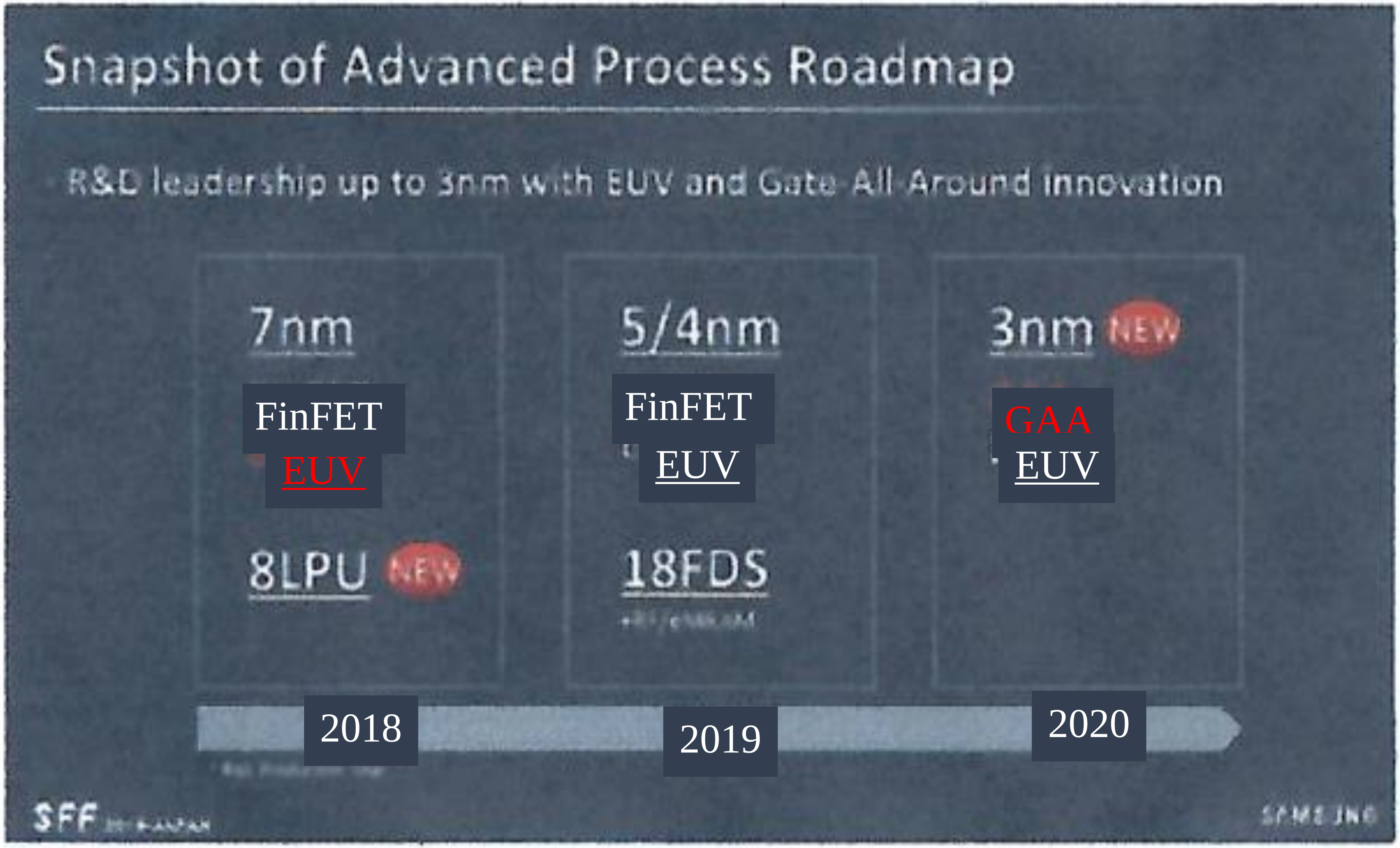
Source
Compatible with 0.33 NA sources, power improvements opportunities over time

Highlights of the Resist Screening Program- 2018

Best performing high resolution EUV resists exposed on EUV-IL

Zuhal Tasdemir et al., Photomask Tech + EUVL, 2018

Resolution [hp]	13nm	12nm	11nm	10nm
Inorganic resist				
Dose (mJ/cm^2)	67	67	77	67
CAR				
Dose (mJ/cm^2)	43	55	57	71



2018 Samsung Foundry Forum

Summary

Research and development on EUVL over 30 years has led to significant breakthrough in processing and measurement technology.

We can now look back at the history with a wonderful feeling of accomplishment.

Although several critical problems still remain with regard to such things as light source, mask inspection and resist, it appears now that solution can be found, since the fabrication of aspherical mirrors and multilayer, which were the biggest headaches, were achieved.

As long as we do not lose the desire that has sprung from with us, technology will steadily advanced from the nano to the pico.