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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SCHOOL ON THE USE OF SYNCHROTRON RADIATION IN SCIENCE AND TECHNOLOGY:
"John Fuggle Memorial"

3 November - 5 December 1997

Miramare - Trieste, Italy

X-ray Microfibracation with Synchrotron Radiation

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X-ray microfabrication with synchrotron radiation

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Table of content

Glossary of terms

- **Micromachining**: the ability to fabricate microstructures and microsystems
- **LIGA**: German acronym for a three-step process to make microstructures by synchrotron deep X-ray lithography, electroplating and molding
- **Deep X-ray lithography**: lithography with 2-3 A wavelength region
- **MEMS**: Micro-electro-Mechanical Systems, generic term for microsystems in Europe, micromachines in Japan.
- **HAR-MEMS**: High-Aspect-Ratio MEMS
- **Aspect ratio**: ratio of depth/thickness to width of smallest dimension

BOOKS / PROCEEDINGS:

"Introduction to Microlithography", Second Edition, Edited by Thompson, L. F.; Willson, C. G.; Bowden, M. J.; Chapters 2 and 3, American Chemical Society, 1994.

"The Physics of Submicron Lithography", Valiev, K. A.; Plenum Press, 1992.

"Handbook on Synchrotron Radiation", Volume 1B, Edited by Ernst-Eckhard Koch, North Holland Publishing Company, Chapter 13, *"Synchrotron radiation X-ray lithography"*, Grobman, W. D.; pp. 1131-1165, 1983.

"Handbook of Microlithography, Micromachining, and Microfabrication", SPIE Press Monograph PM 39, 1997, Volume 1: Microlithography, Edited by Rai-Choudhury, P.; Chapter 3, *"X-ray Lithography"*, Cerrina, F.; pp. 251-320, 1997.

"Journal of Vacuum Science and Technology", Nov-Dec Issue, *"The International Conference on Electron, Ion and Photon Beams, Technology and Nanofabrication"*.

"Japanese Journal of Applied Physics", *"Microprocess Conference Proceedings"*.

"Proceedings of Micro- and Nano-Engineering", published by Elsevier.

"SPIE Symposia on X-ray, Electron and Ion Lithography", published by SPIE.

"Proceedings of the Ninth Annual International Workshop on Micro Electro Mechanical Systems", February 11-15, 1996, San Diego, California, USA, published by IEEE.

"Semiconductor Lithography: Principles, Practices, and Materials", Moreau, W. M.; Plenum Press, July 1991.

"Fundamentals of Microfabrication", Madou, M.; CRC Press, Boca Raton, New York, 1997, Chapter 6, "LIGA" pp. 275-319.

"Mikrosystemtechnik fur Ingenieure", Menz, M.; Bley, P.; VCH, 1993.

Other sources of information:
- Liga news (http://www.uni-mainz.de/IMM/Lnews/Lnews_3/cont3.html)

CONFERENCES:

"SPIE's 22nd Annual International Symposium on ***Microlithography****"*, 9-14 March 1997, Santa Clara Convention Center and Westin Hotel, Santa Clara, California, USA.

"Microprocess and Nanotechnology '98", 1998 International Microprocesses and Nanotechnology Conference, July 13-16, 1998, Hotel Hyundai, Kyoungju, Korea.

"Micro- and Nano- Engineering '98", 22-24 September 1998, Leuven, Belgium.

"The 42nd International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication, EIPBN '98", May 26-29, 1998, The Westin Hotel, Chicago, Illinois, USA.

"HARMST '97", June 20-21, 1997, Madison, Wisconsin, USA.

"Eleventh IEEE International Workshop on Micro Electro Mechanical Systems", January 25-29, 1998, Heidelberg, Germany.

"The 1997 International Conference on Solid-State Sensors and Actuators (Transducers '97)", May 26-29, 1998, Hyatt Regency Hotel, Chicago, USA.

"Tenth IEEE International Workshop on Micro Electro Mechanical Systems", January 26-30, 1997, Hotel Nagoya Castle, Japan.

"SPIE's 1997 Symposium on Micromachining and Microfabrication", September 29-30, 1997, Austin Marriott at the Capitol, Austin, Texas, USA.

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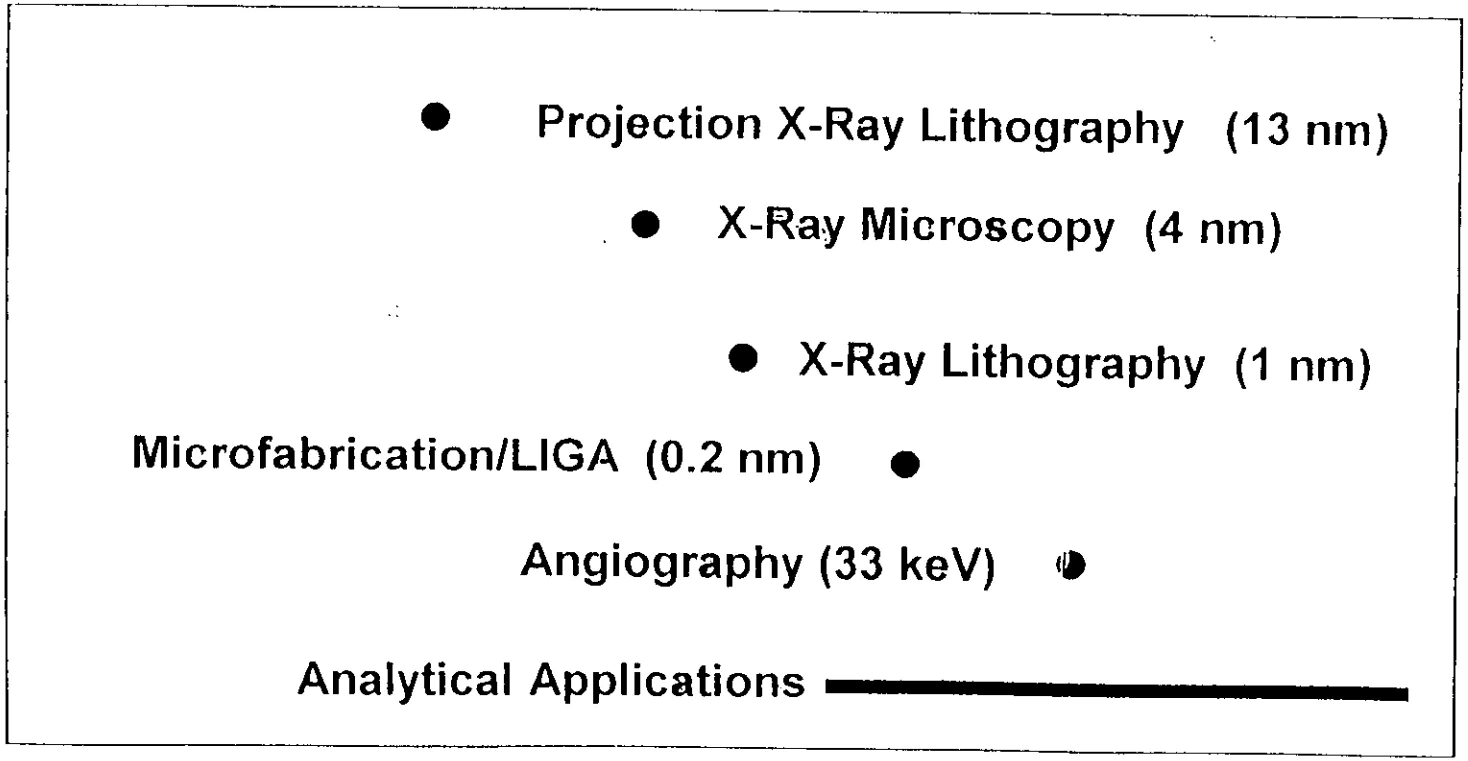
Introduction

Applications of Synchrotron Radiation

	1	10	100	1k	10k	100k	eV
IR	VIS/UV	VUV	soft X-Rays	X-Rays	hard X-Rays		
	1k	100	10	1	0.1	0.01	nm



- Projection X-Ray Lithography (13 nm)
- X-Ray Microscopy (4 nm)
- X-Ray Lithography (1 nm)
- Microfabrication/LIGA (0.2 nm)
- Angiography (33 keV)

Analytical Applications

MICROFABRICATION AND SYNCHROTRON RADIATION

- **Synchrotron radiation for microfabricating devices**
    - **Lithography**
        - X-ray lithography by proximity printing (7-10 A)
        - EUV projection lithography (130 A)
        - Deep X-ray lithography (1-3 A)
    - **Radiation-assisted processes**
        - Deposition
        - Ablation/etching
- **Microfabricated devices for synchrotron radiation**
    - **X-ray optics**
        - Gratings, zone plates, Bragg-Fresnel optics
        - Multilayer mirrors
    - **Detectors**
        - Channel plates, CCD

MICROFABRICATION TECHNOLOGIES

- Resolution
    - Microfabrication
    - Nanofabrication
- Aspect ratio
    - 2-D technology
        - Micro-electronics planar technology
            - Microstructure thickness <a few µm , aspect ratio <10
    - 3-D technology
        - Bulk micro-structuring
            - Hundreds of µm - 1 cm, aspect ratio: 10 - few 100
- Tolerances
- Materials

MICROFABRICATION PROCESS

- Lithographic step
  - + define the pattern on surface
- Pattern transfer
  - + transfer pattern from surface to underlying layers/bulk
    - => substractive process
      - – dry etching
        - x physical process: ion beam etching
        - x chemically assited process: e.g. reactive ion etching
      - – wet etching
        - x isotropic/anisotropic: orientation dependent etching of crystal
    - => additive process
      - – e.g. electroplating, lift-off
    - => material modification
      - – ion implantation

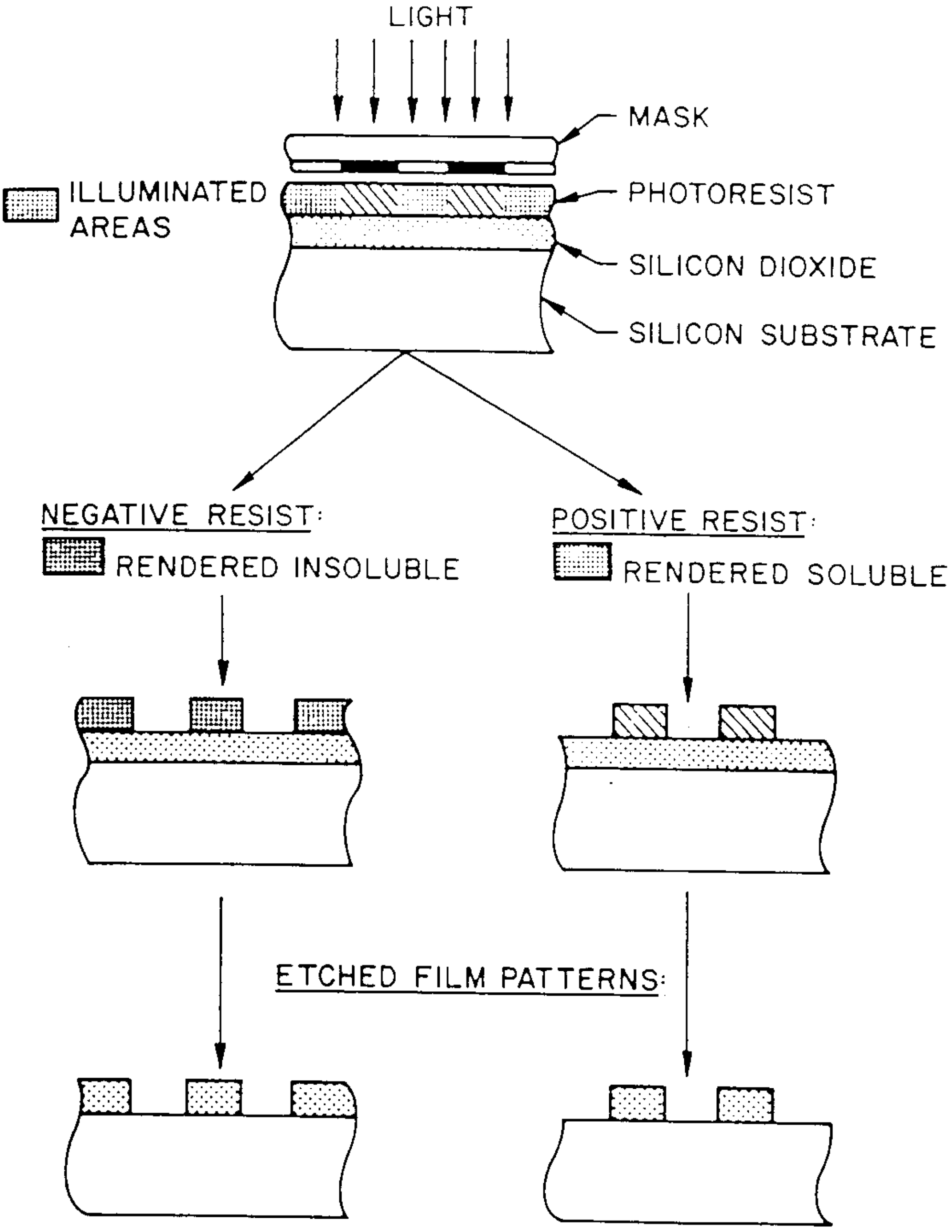


Figure 1. Schematic of contact or proximity printing using positive and negative resists.

(Thompson and Bowden)

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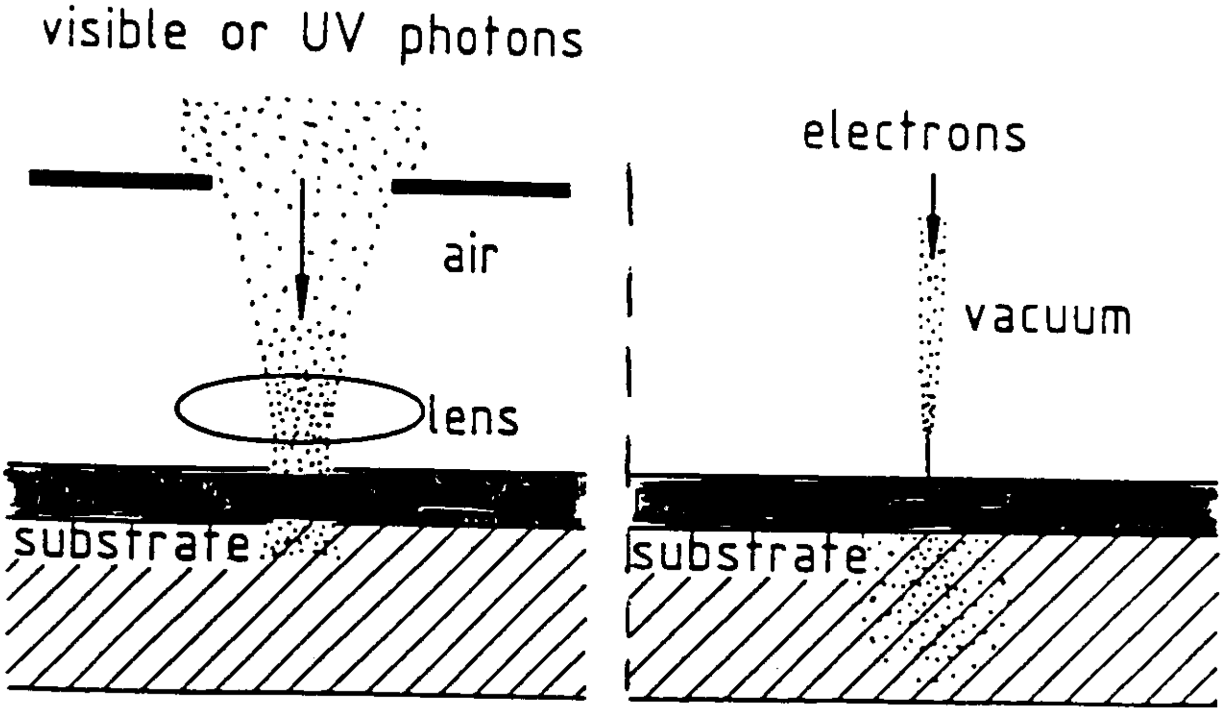
Lithographic process

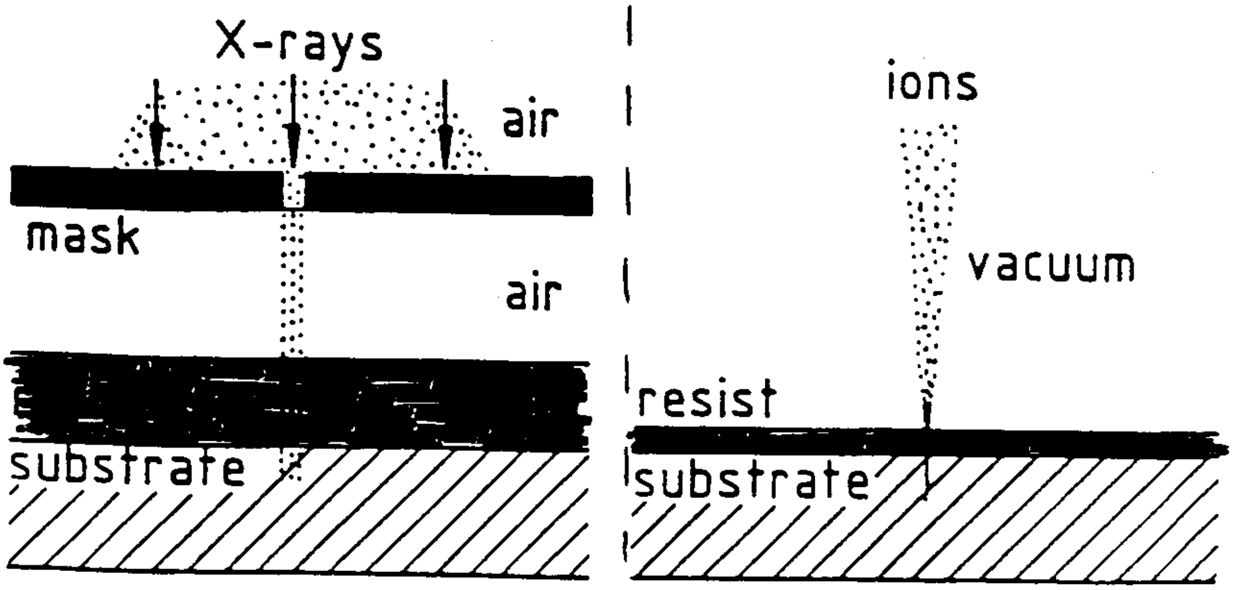
- Resist: recording medium

- Lithographic tool: pattern definition
  - \+ parallel exposure
    - => replication with mask (1:1, demagnification)
      - optical lithography
      - X–ray lithography
      - projection electron beam lithography
      - projection ion beamlithography
  - \+ serial exposure
    - => direct write without mask: focused beam
      - electron beam lithography
      - focused ion beam lithography



(a) photolithography

(b) electron-beam lithography



(c) X-ray lithography

(d) ion-beam lithography

MAIN TYPES OF LITHOGRAPHIC MEANS

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(after Murray - Brodie)

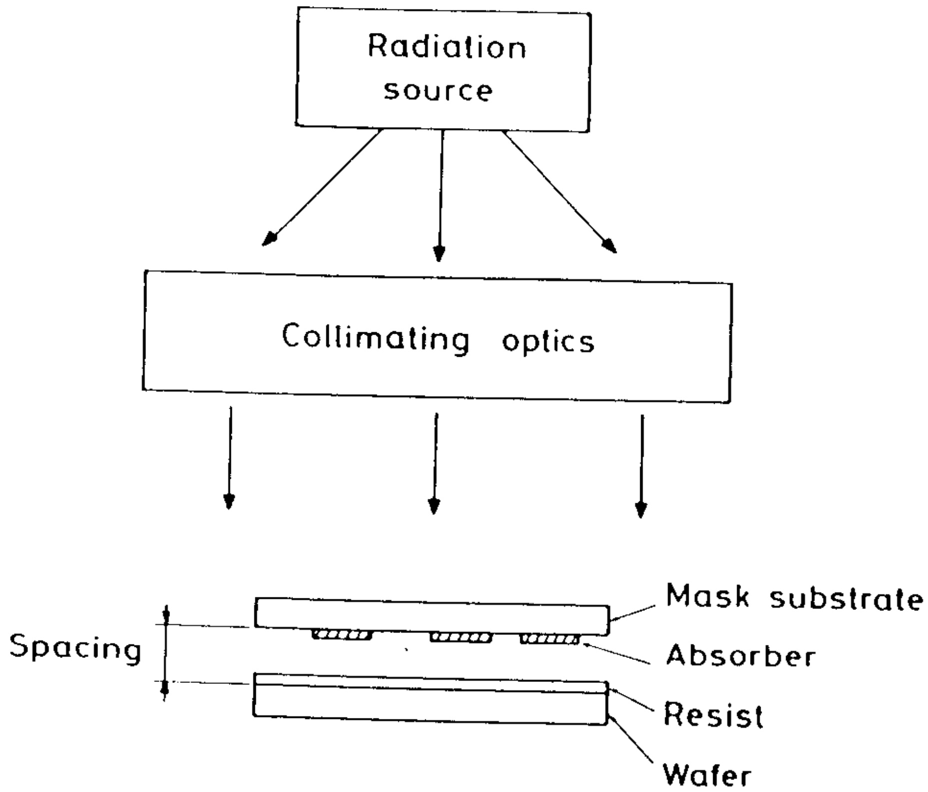


FIG. 6.4 Shadow casting system configuration.

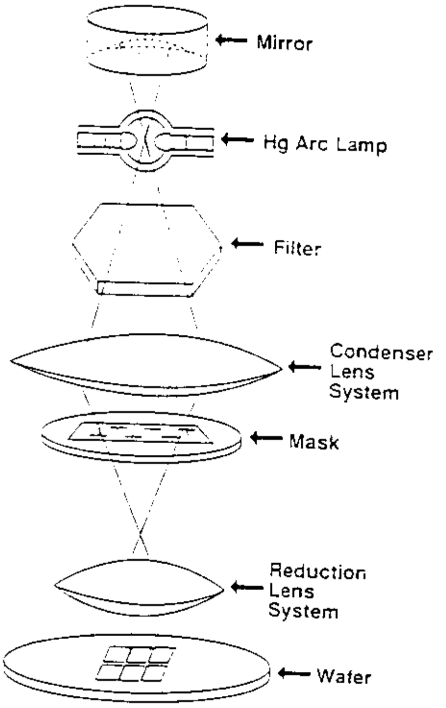
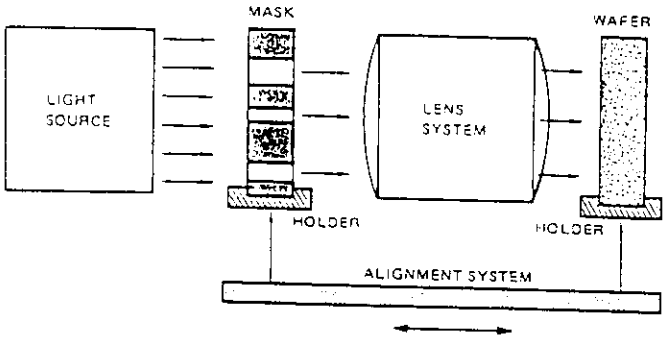
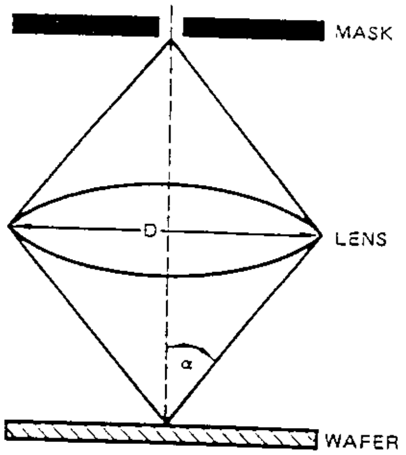


Figure 8. Schematic of a reduction step-and-repeat system with refractive optics.





PARAMETER	SPECIFICATION
FOCAL LENGTH	f
APERTURE DIAMETER	D
F NUMBER	$f/D = F$
NUMERICAL APERTURE	$N.A. = n \sin \alpha = \frac{D}{2f}$
RESOLUTION	$1.22\,\lambda F = \Delta x$
DEPTH OF FIELD	$\pm 2\lambda F^2 = \pm \Delta a$

Rayleigh Equations For Projection Printing

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

$$\Delta Z = k_2 \frac{\lambda}{NA^2}$$

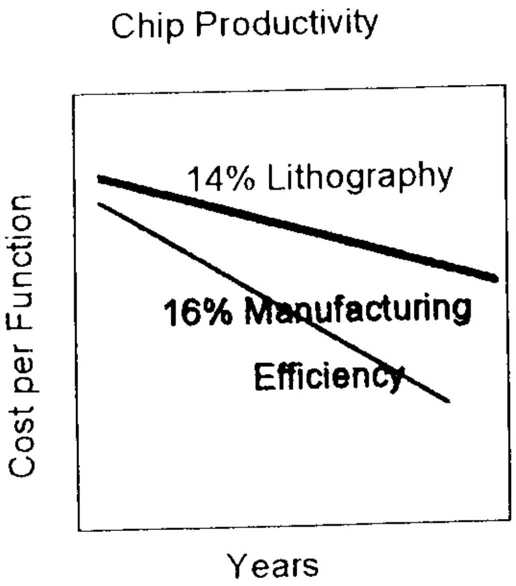
Dimensionless Parameters For Projection Printing

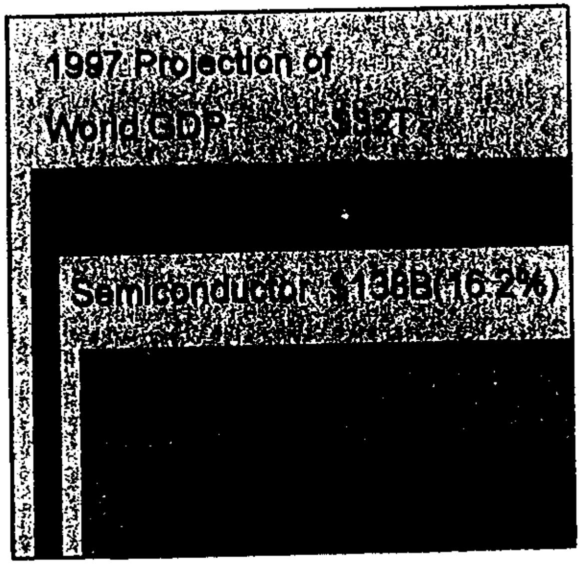
$$Resolution \equiv W_o = W \frac{NA}{\lambda} = k_1$$

$$DOF \equiv \Delta Z_o = \Delta Z \frac{NA^2}{\lambda} = k_2$$

(KM I 9)

Lithography is Key Driver

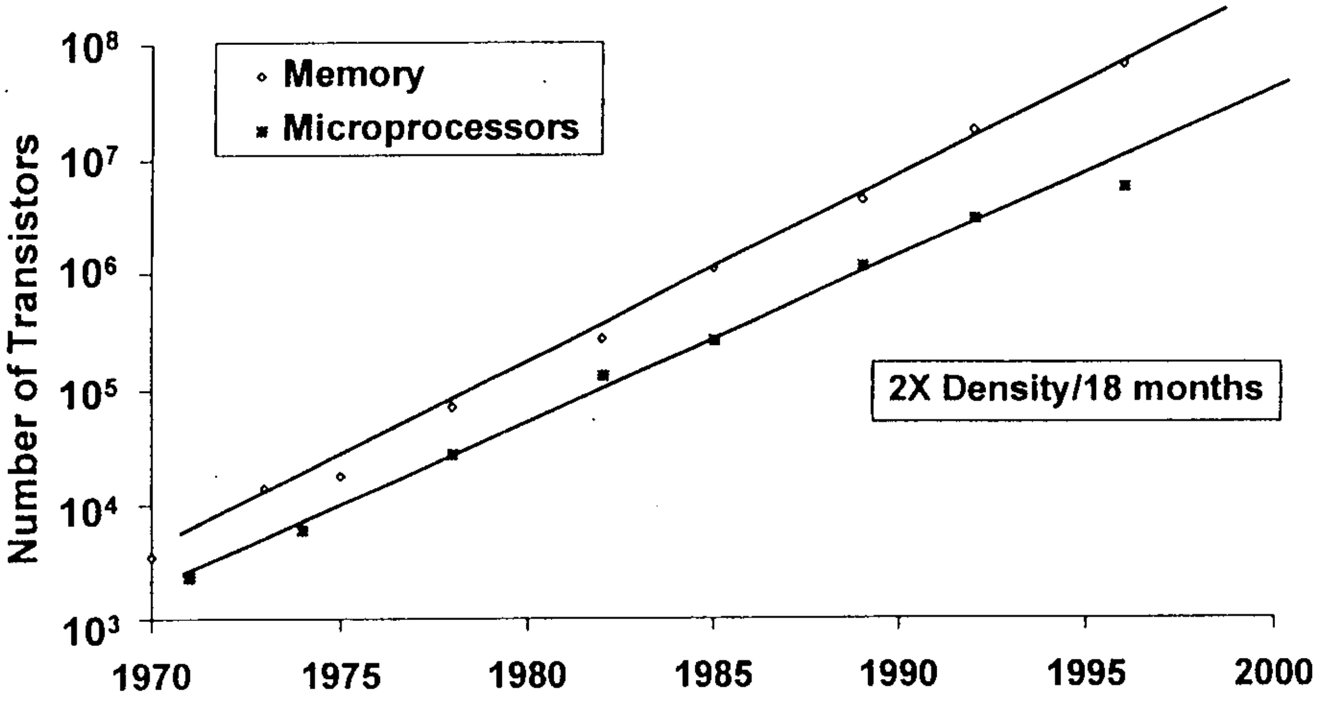




1997 Projection of
World GDP $32T

Semiconductor $136B(16.2%)

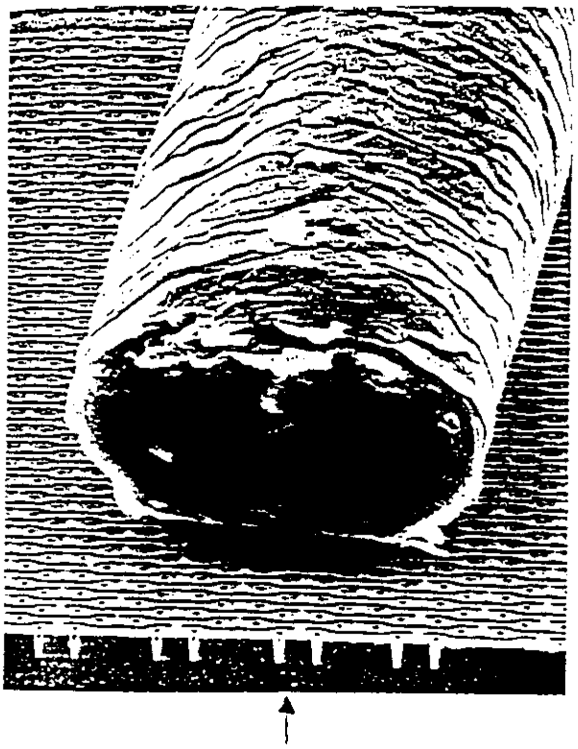
Moore's Law

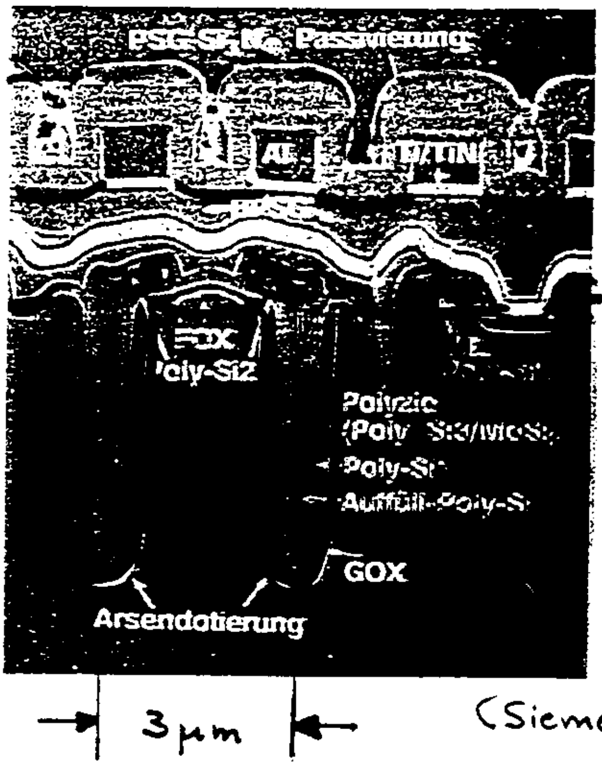


2X Density/18 months

Source: Intel

4 Mbit DRAM





(Siemens)

~ 400 Processing Steps

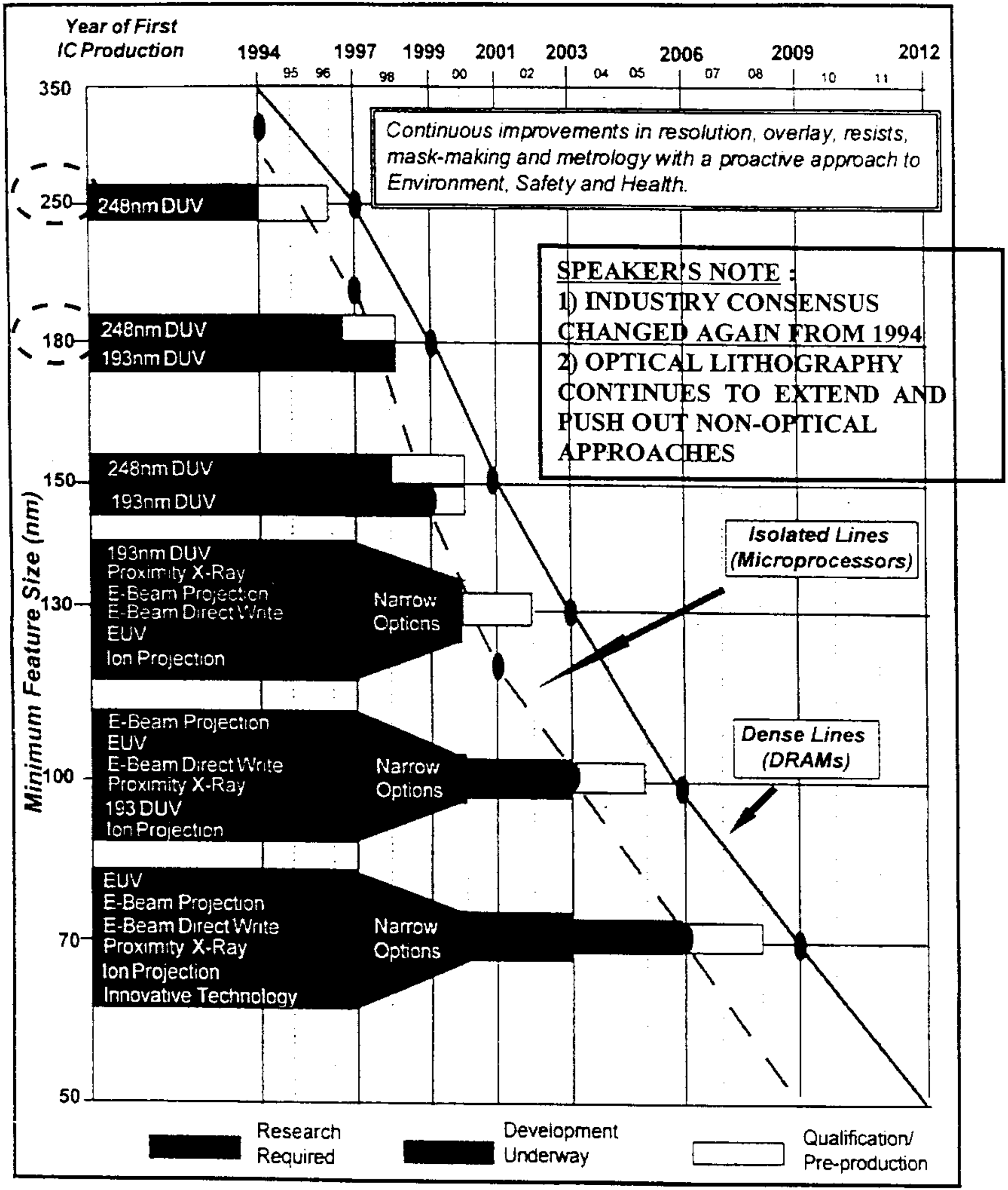
Stores 400 pages of text on 91 mm^2

No. of elements : 8.9 million , No. of transistors : 4.7 m

Smallest features: 0.8 µm

Critical defects : 0.2 µm

From recent DRAFTof SIA's National Technology Roadmap to be revised in 1997



SPEAKER'S NOTE :
1) INDUSTRY CONSENSUS CHANGED AGAIN FROM 1994
2) OPTICAL LITHOGRAPHY CONTINUES TO EXTEND AND PUSH OUT NON-OPTICAL APPROACHES

Figure 13 Critical Level Exposure Technology Potential Solutions Roadmap
"Work in Progress"

Eighth Draft 1997 Roadmap 6/12/97 *The National Technology Roadmap for Semiconductors*

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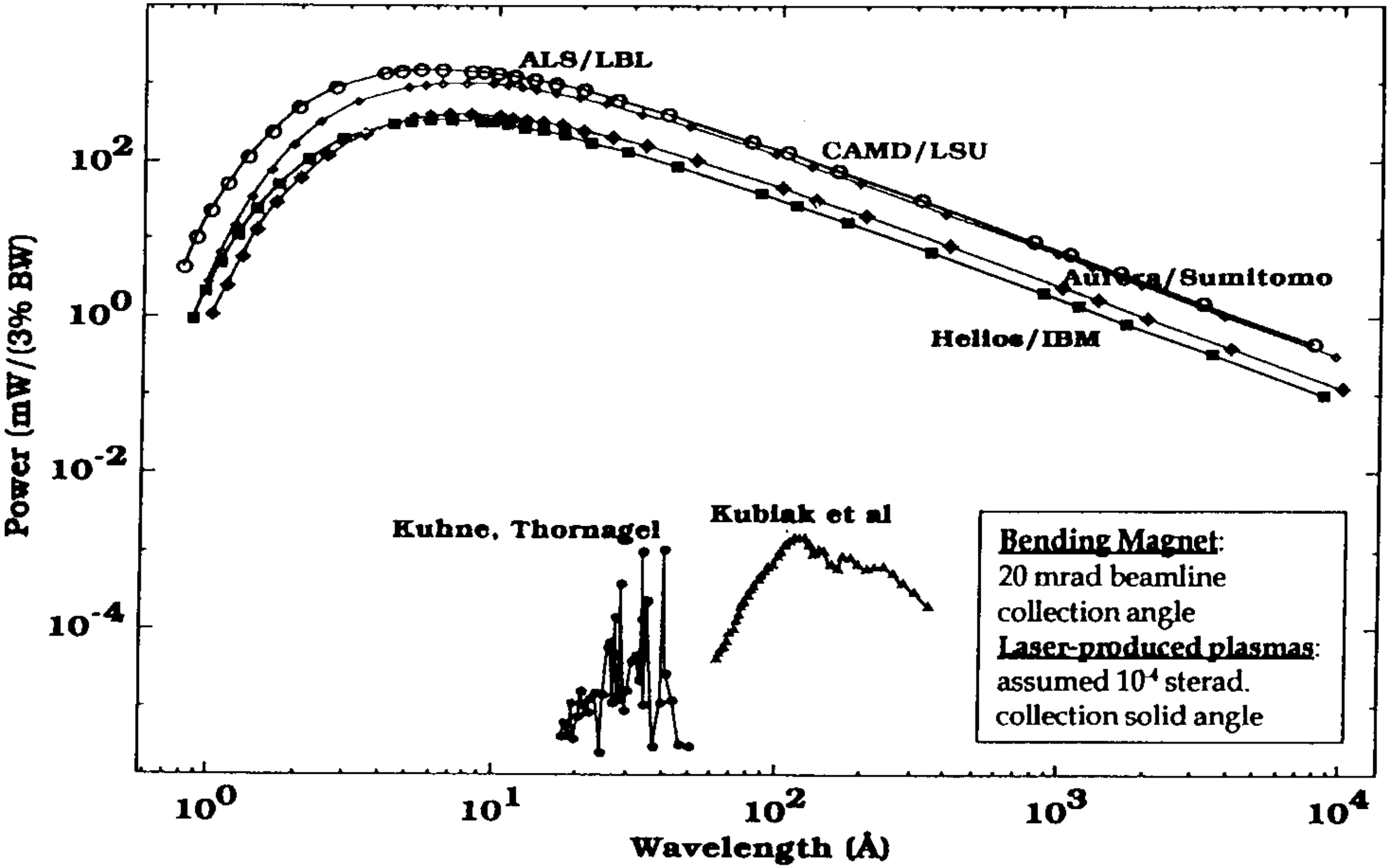
Post-Optical Challenges

Option	Main Challenges
1X X-Ray Lithography	• Mask : Defects, Distortion, Life • Magnification correction • Reduction of gap
EUV Lithography	• Source intensity • Optics reflectivity and flare management • Mask fabrication (defect management) • Surface imaging resists
Electron Projection Lithography	• Development of large field electron optics • Butting errors due to stitching • Throughput • Mask fabrication
Ion Projection Lithography	• Stencil mask fabrication • Butting errors due to dual mask requirement • Electrostatic lens fabrication
Electron Beam Direct Write	• Butting errors due to stitching • Data handling • Very low throughput

Presently, bending magnet radiation from a synchrotron has higher deliverable power to a wafer than does a laser-produced plasma



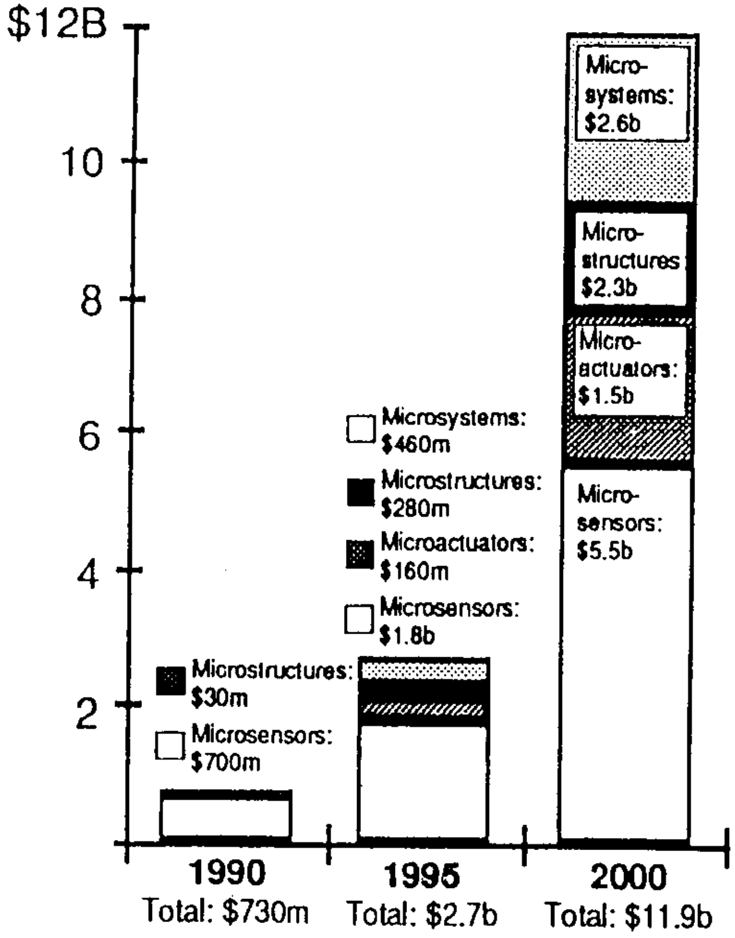
Bending Magnet:
20 mrad beamline collection angle
Laser-produced plasmas:
assumed 10^{-4} sterad. collection solid angle

storage rings

Comparison -1-

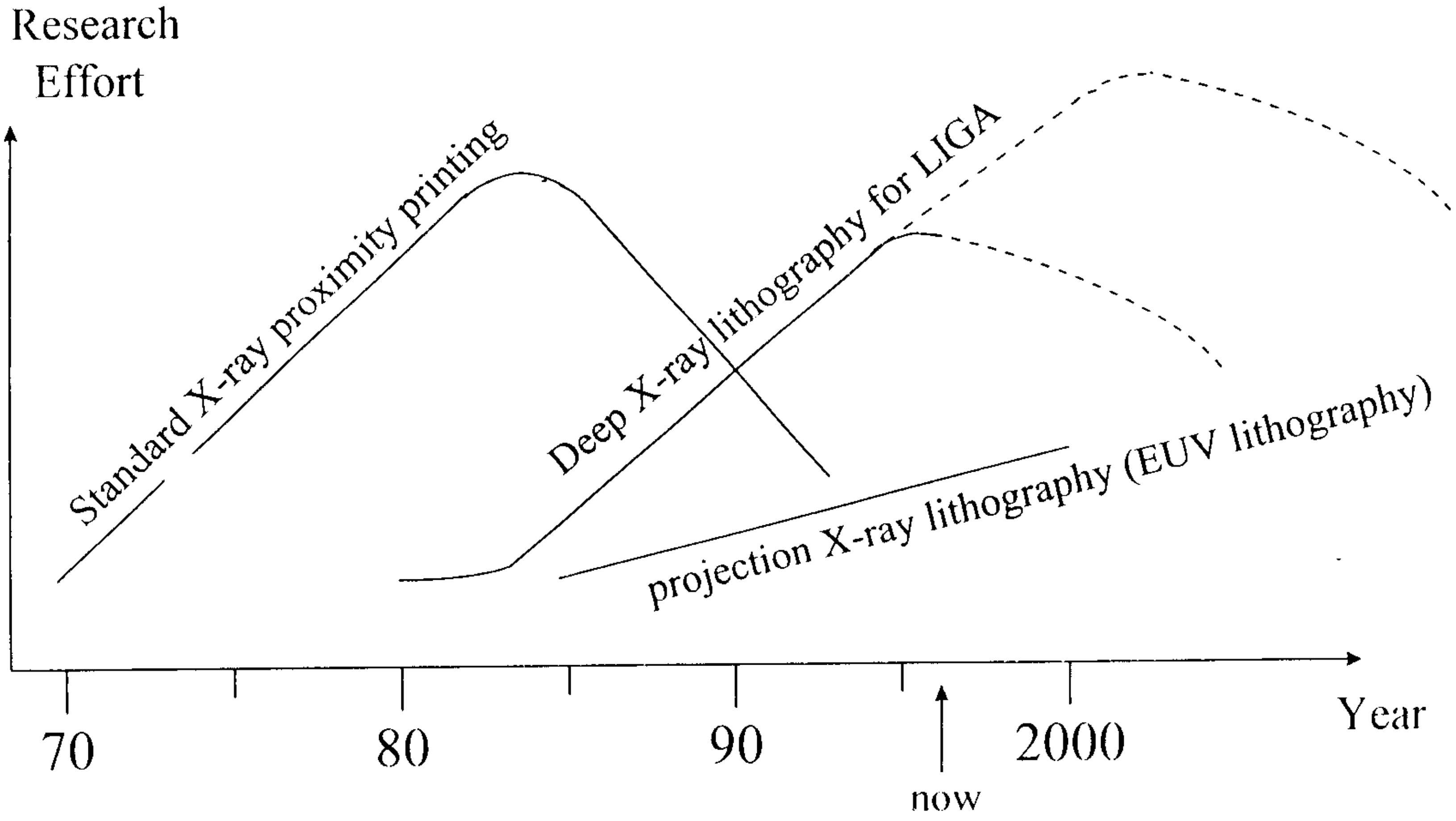
	Small	**Large**
Size - Diameter (m)	1-20	50-500
Cost/Construction ($million)	15-25	50-500
Cost/Operation ($million/year)	3-10	25-100
Staff:	30-80	Several 100
Cost per Beamline ($million)	0.8	8
Distance to Source (m)	3-10	15-50
Emittance	medium/high	low
Flexibilty of Operation	high	low
Mission/Owner	regional/ind.	national facilities

FIGURE 1
World Market for Micromechanical Components



Source: sgt Sensor Gruppe

X-Ray Lithographies



X-RAYS: ASPECTS LINKED TO THE WAVELENGTH

- **little difference in atomic absorption coefficient**

  no material really transparent or opaque to X-rays

- **index of refraction n ~1**

  reflective demagnifying optics

  multiply the interfaces for constructive interference at normal incidence

=> X-ray proximity printing: no demagnifying optics (1X)

=> EUV projection lithography: reduction optics with multilayer mirror system (4X)

X-ray lithography

Mass production forULSI and components

- **Asia: Memory, components**
  - **Japan**
    - **ASET/NTT**: 15,000 wafers with XRL
    - **Mitsubishi:** 1Gb DRAM with 0.14 μm feature and 4 X-ray levels
      - Plans for manufacturing 256 Mb devices
  - **Korea**
- USA
  - **IBM: Memory, Logic:**
    - 256 Mb DRAM, 64 Mb SRAM 0.18 μm technology (0.13 μm test sites)
    - X-ray masks with 2 chip, 0.18 μm Gbit DRAM (46 mmx23 mm field)
  - **Motorola: Memory, Logic**
    - X ray-masks: 100/month (450 masks in 1996)
  - **CXrL:** Sematech Center for Excellence in XRL (Univ. of Wisconsin)

Nanolithography: USA (MIT, Naval Research. Lab), France (CNRS-L2M), ...

CAMD, CKM-Nov. 97

Absorption of X-rays

- **Beer's law-type dependence**

$$I = I_0 \exp(-\mu_m \rho l)$$

I_0 and I: intensities before and after passage through the absorbing layer

density (ρ),

thickness (l),

mass absorption coefficient (μ_m)

$$\mu_m = A_i \mu_{mi} / A_i$$

A_i and atomic weights and μ_{mi} mass absorption coefficients

- **Elemental absorption μ_{mi} is given by**

$$\mu_{mi} = C\lambda^n$$

C and n dependent on element and type of absorption event (K, L, M,...)

n = 3 for PMMA and polymers with light elements

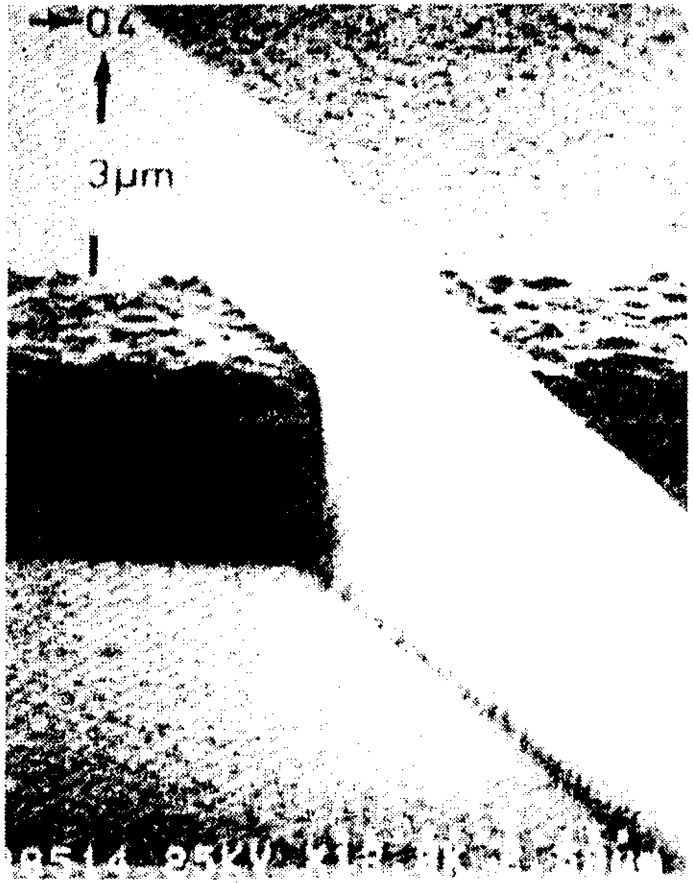
- **Mass absorption of polymers, μ_{mp}**

maximized by incorporation of high weight absorbing elements (Z > 25)

Advantages of synchrotron radiation X-ray lithography

- High resolution (0.25 µm in manufacture)
- Single level resist
- Throughput
- Linewidth control
- Uniformity
- Transparency of defects
- Large depth of focus
- Large field size
- No reflection from substrate
- Small proximity effect

Advantage of XRL: High resolution on high-step coverage



X-ray Resists

- X-ray sensitivity < 100 mJ/cm^2
- Technological stability (etching)
- Resolution < 0.1 µm

Single Layer Resists

- PMMA (chain scission): 0.01 µm but 1000 mJ/cm^2
  poor etching stability
- Novolak-resists: well proven technology
  sensitivity to be improved
  → Novolak/diazotype
  => 500 mJ/cm^2
  → Chemical Amplification
  => < 100 mJ/cm^2

XRL

Technology Status: Resist Exposures

- **Work to date done with commercially available resists chosen by customers**
  - Allows customers to continue process development (e.g., etch) with same resists used with DUV exposures
  - Apex-E sensitivity ~ 60-160 mJ/cm²
  - UVIIHS/UV-4 sensitivity ~ 140 - 240 mJ/cm²
- **Resolution demonstrated to < 100 nm in thick resist**
  - 100 nm line/space patterns (at 15 μm gap)
  - 70 nm isolated lines (smallest on mask to date)
  - Extendibility optimization discussed in poster by Hector et al.
- **Excellent exposure latitude and control demonstrated**
- **Resist sensitivity primary issue**

Membrane Materials

1) X-ray transparency (>50%) : light element, thin film
2) Stable with radiation and time
3) Optically transparent, no scattering : alignment
4) Stiff (elim. distortion)
5) Strong (sustain-handling)

Absorber Materials

Requirements:

1) high attenuation (>10db) (10:1 contrast)

2) stable with radiation and time

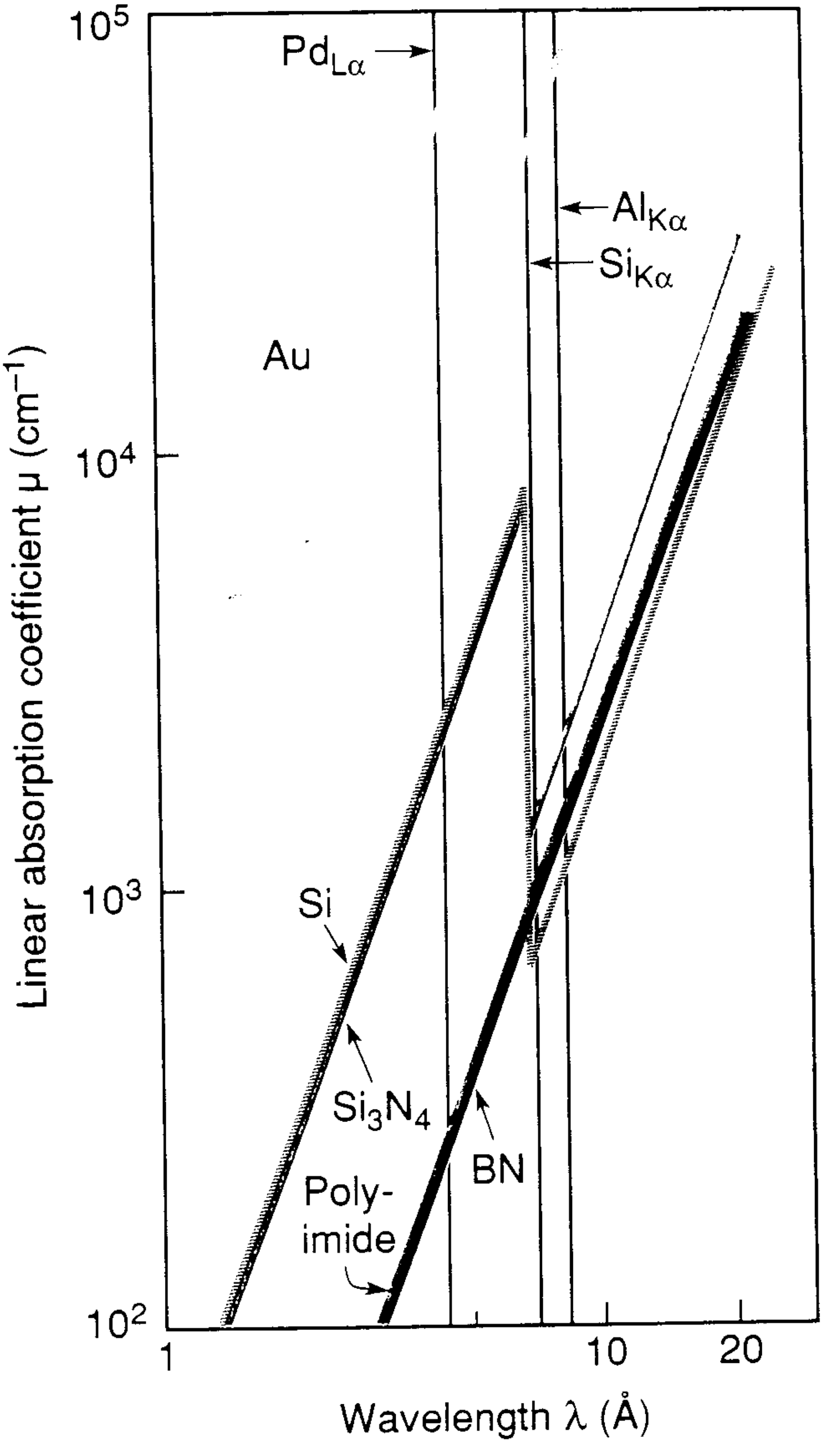
3) negligible distortion (stress $< 10^8$ dynes/cm^2)

4) ease of patterning

5) repairable

6) low defect density

Linear Absorption Coefficients of X-ray Mask Materials



Source: B. Fay, Micronix

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Membrane Materials

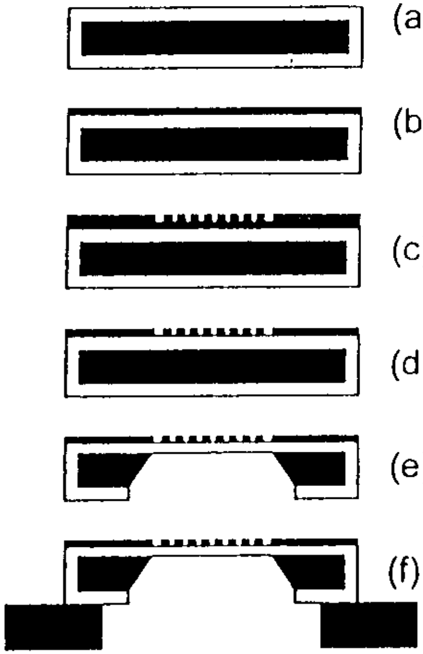
- Si: Single x-tal well developed, red hard, stacking faults => scattering, some brittleness
- SiNx: Amorphous, well developed, rad hard if O_2-free, resistant to breakage
- SiC: Poly and amorphous, rad hard, some resistance to breakage
- diamond: Poly, research topic, highest stiffness

Absorber Materials

Gold:	questionable stability (grain growth)
	low stress
	electroplating only
	defects repairable
Tungsten:	refractory and stable
	stress control => special care
	dry etchable
	repairable
Tantalum:	refractory and stable
	stress control => special care
	dry etchable
	repairable
Alloys:	easier stress control
	greater thickness to achieve 10db

X-ray mask fabrication process flows

(1) wafer processing



(a) SiN or SiC film deposition

(b) absorber film deposition

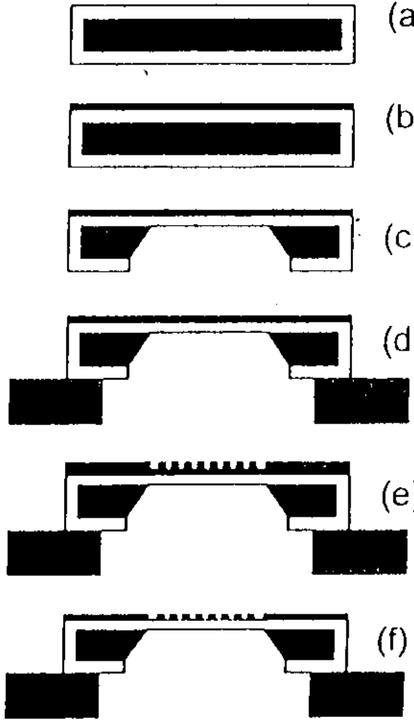
(c) e-beam writing

(d) absorber etching

(e) back-etching

(f) frame bonding

(2) membrane processing



(a) SiN or SiC film deposition

(b) absorber film deposition

(c) back-etching

(d) frame bonding

(e) e-beam writing

(f) absorber etching

Some issues in XRL mask fabrication

HOYA x-ray mask blank

Advantages

SiC membrane
- high Young's modulus
- high SR durability
- smooth surface

Ta4B absorber
- amorphous structure
- high SR durability
- excellent stress stability

CrN etching mask and etching stop layers
- high etching selectivity to Ta4B
- low stress

Fig.1. Structure and advantages of HOYA x-ray mask blank

HOYA

Table1. Substrate specification for SiC membranes

Parameter	Unit	Target	HOYA Spec. (Now)
Optical Properties			
Transmission	aveg λ=780 nm	>60%	peak<82%, valley>40%
Life Damage	Δ transmission	<2%	~0%
Mechanical Properties			
Thickness nominal	μm	2.00±0.1	2.00±0.1
Thickness uniformity	μm,3σ	<0.1	<0.1
Surface roughness	Å Ra	<10	<10
Nominal Stress	MPa	+80~+180	+50~+250
Stress Uniformity	MPa	<±5 (in 70 mmϕ)	<±10 (in 40 mmϕ)
Biaxial modulus	GPa	>400	>400
Burst strength	atmospheres	>0.35	>0.35
X-ray Properties			
Life damage	distortion 3σ(nm)	<15	<20 (measurement error)
Other Properties			
Defect Density	defects/cm²	<1 for >0.5μm size <5 for >0.2μm size	<3 for >0.5μm size <5 for >0.3μm size

HOYA

Stress contol of Ta4B film

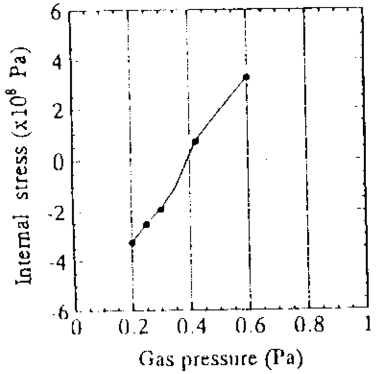


Fig 2. Internal stress of Ta4B films as a function of Xe gas pressure

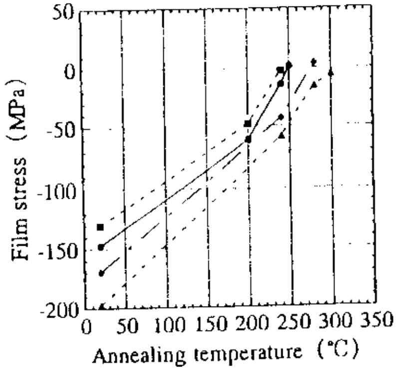


Fig.3. Stress change of four Ta4B films with different compresive stresses before and after annealing process.

HOYA

Stress stability of Ta4B film

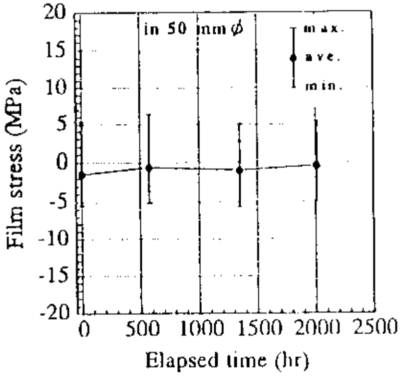


Fig.4. Long-term stress stability of Ta4B film.

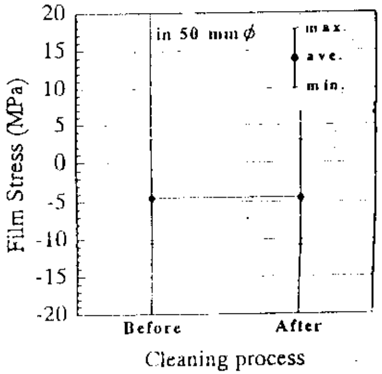


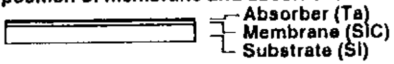
Fig.5. Stress of Ta4B film before and after the treatment in $H_2SO_4+H_2O_2$ for 1 hr at 100°C.

HOYA

Some issues in XRL mask fabrication

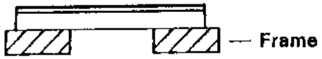
Mask structure and fabrication process

(1) Deposition of membrane and absorber films on substrate



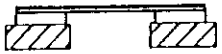
- Ta stress : 4 MPa (controlled by annealing)

(2) Adhesion to the frame



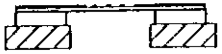
- Adhesion : 200 ℃, Epoxy film

(3) Underlying Si etching

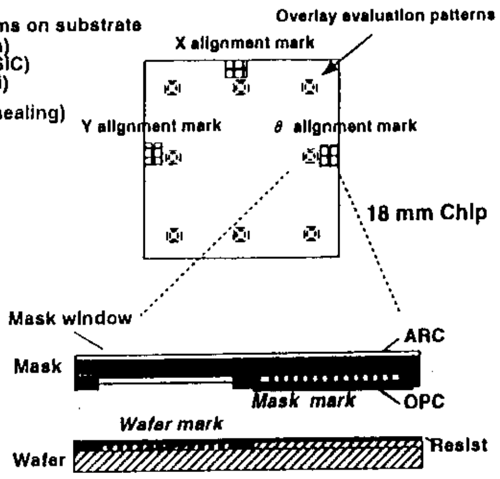


- Etchant : HF/HNO$_3$

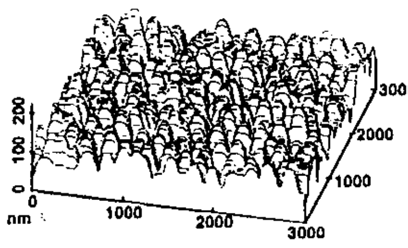
(4) Patterning



- E-beam exposure
- Ta etching : RIE

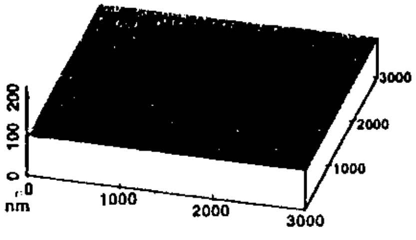


Improvement of SiC surfaces



As deposited

Ra (geometrical average): 15 nm



After polishing

Ra: 0.2 nm

Thickness uniformity (3σ): 20 nm

Requirement for anti-reflection coating and opaque coating

1. Mask window optical reflectance

   < 0.5%

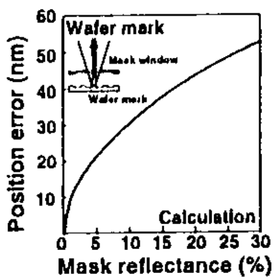
   ⟶ n = 1.62 ± 0.05
   (n_{SiC} = 2.64)

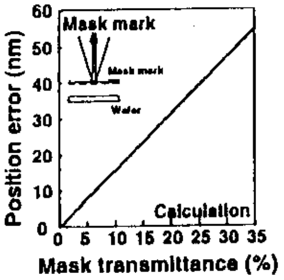
2. Mask mark optical transmittance

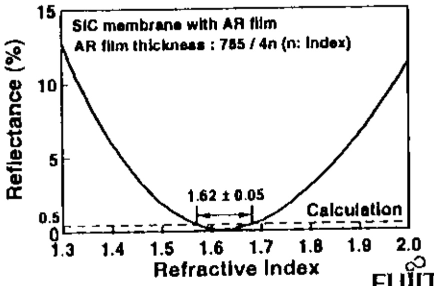
   < 5%

3. Durability to chemicals ($H_2SO_4+H_2O_2$)

4. Low stress



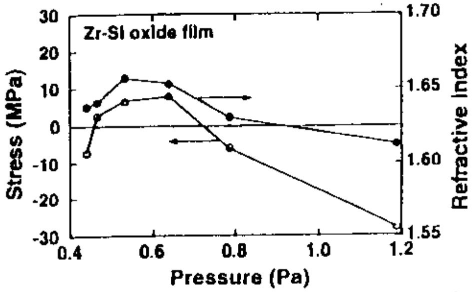


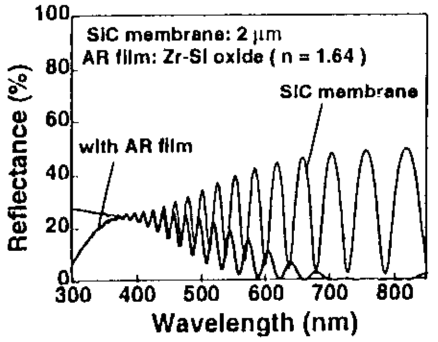


Characteristics of anti-reflection film

Acid : $H_2SO_4 + H_2O_2$

AR film material	Durability to acid	Refractive Index	Coating method
SiO$_2$	Good	1.46	sputtering
Al$_2$O$_3$	Poor	1.63	evaporation
ITO	Poor	2.00	sputtering
Zr-Si oxide	Good	1.64	sputtering





X-ray Mask - Current Status

Generation Technology	0.18 μm	0.13 μm	0.10 μm	0.07 μm
Minimum Feature Size	0.14 μm *0.18 μm routine*	0.10 μm *Today=0.13μm*	0.07 μm *PO demo 0.1 μm*	0.05 μm *Gaussian spot*
Image Placement *Today = 50's*	22 nm *Demo = 30's (repeatability)*	14 nm	10 nm	8 nm
CD Uniformity	15 nm *Today = 16 nm*	10 nm *Demo = 10 nm*	8 nm	5 nm
Defect Size	36 nm *Today = 90nm*	26 nm	20 nm	14 nm
Data Volume *Today = 4 GB*	8 GB	32 GB	128 GB	512 GB

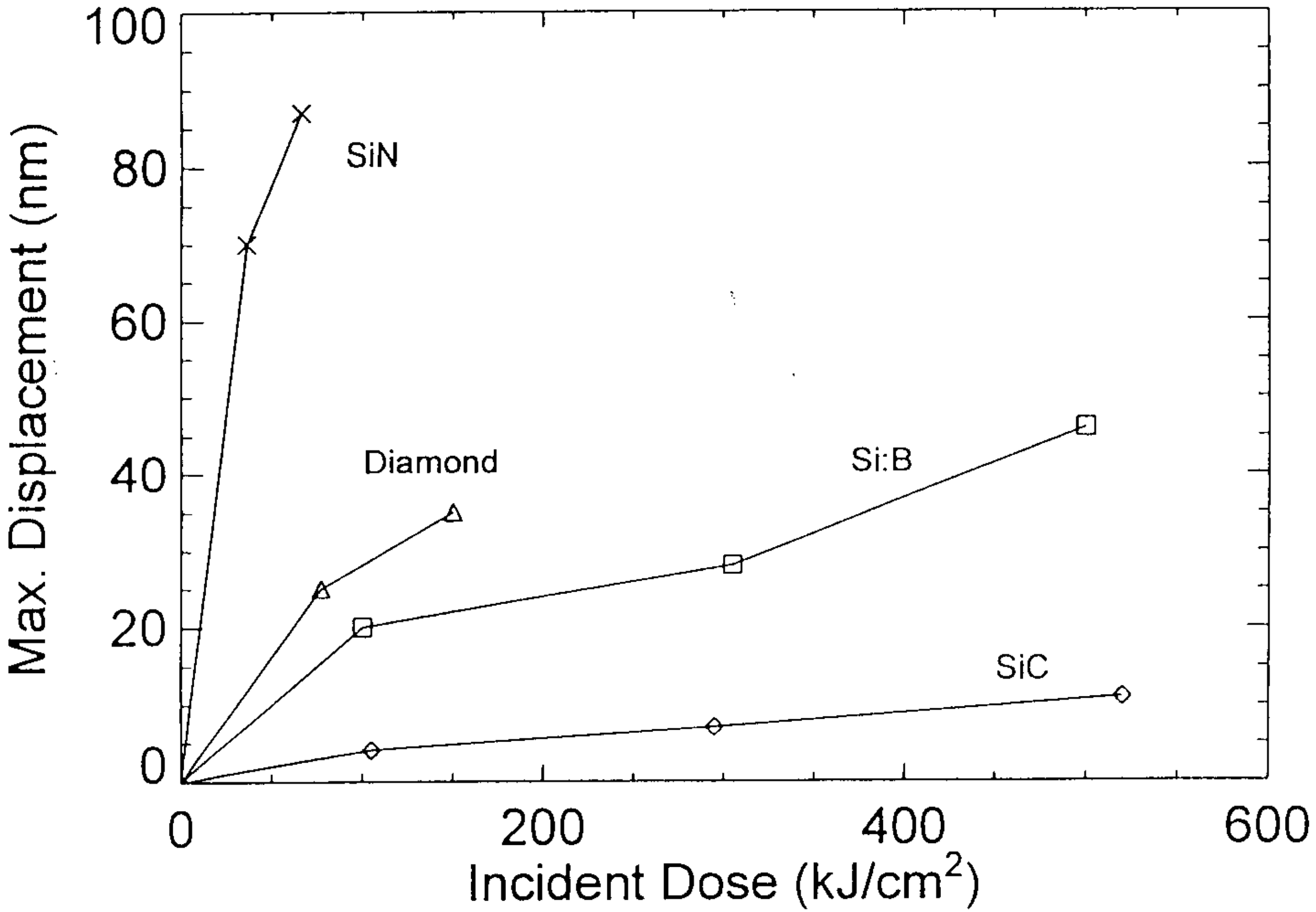
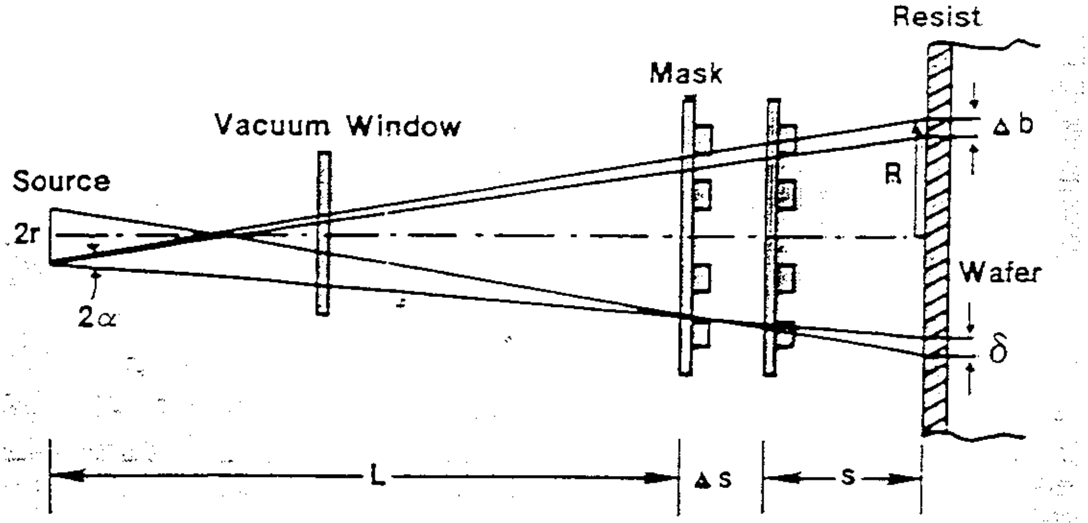


Figure 1. Radiation Stability of SiC membranes is well suited for use in x-ray masks for high volume production.



Geometrical Distortions:

Run-Out: $\Delta b = \Delta s \left(\frac{R + r}{L}\right)$ **Blurring:** $\delta = s \frac{2r}{L}$

Fundamental Parameters of X-Ray Sources for Application in Lithography

Performance		Storage Ring	X-Ray Tube	Plasma Focus	Laser Plasma
Divergence	α	5 mrad	~ 50 mrad	~ 50 mrad	~ 50 mrad
			(4 × 4 cm² print field)		
Distance Source/Mask	L	4 m	0.4 m	0.4 m	0.4 m
Source Diameter	2r	0.5 mm	3 mm	0.2mm	0.1 mm
Proximity Gap	S		50 μm		
Max. Variation of Proximity Gap	ΔS		5 μm		
Run Out	Δb	~ 250 nm	~ 250 nm	~ 250 nm	~ 250 nm
Blurring	δ	< 10 nm	~ 400 nm	≤ 35 nm	~ 15 nm
Spectrum		broadband 0.4–2 nm	line 0.44–1.3 nm	line 0.7–1.5 nm	line 0.9–1.7 nm
Total Power on mask (mW/cm²)		> 100	> 1	≥ 10	≥ 1

A. Heuberger IMT, Berlin

CKM 2.17

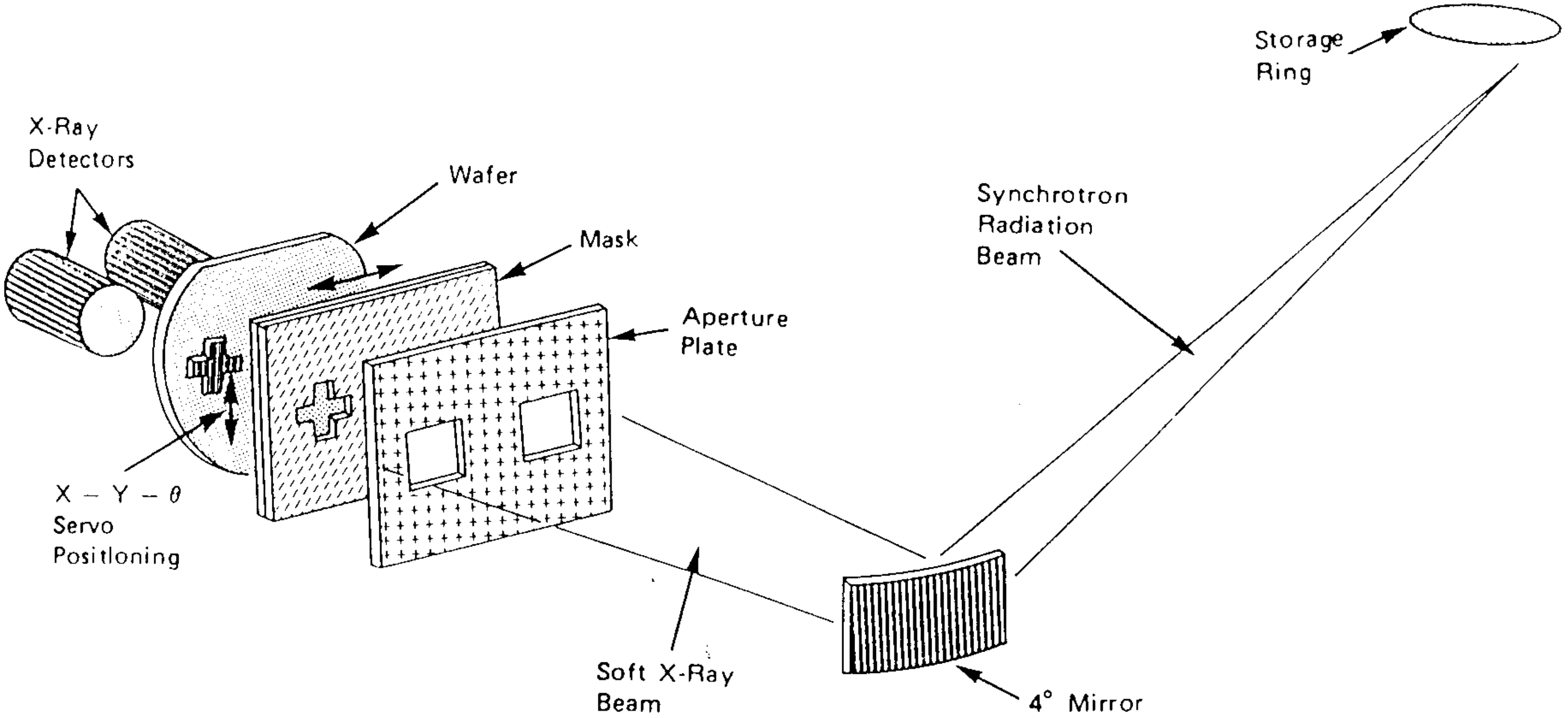
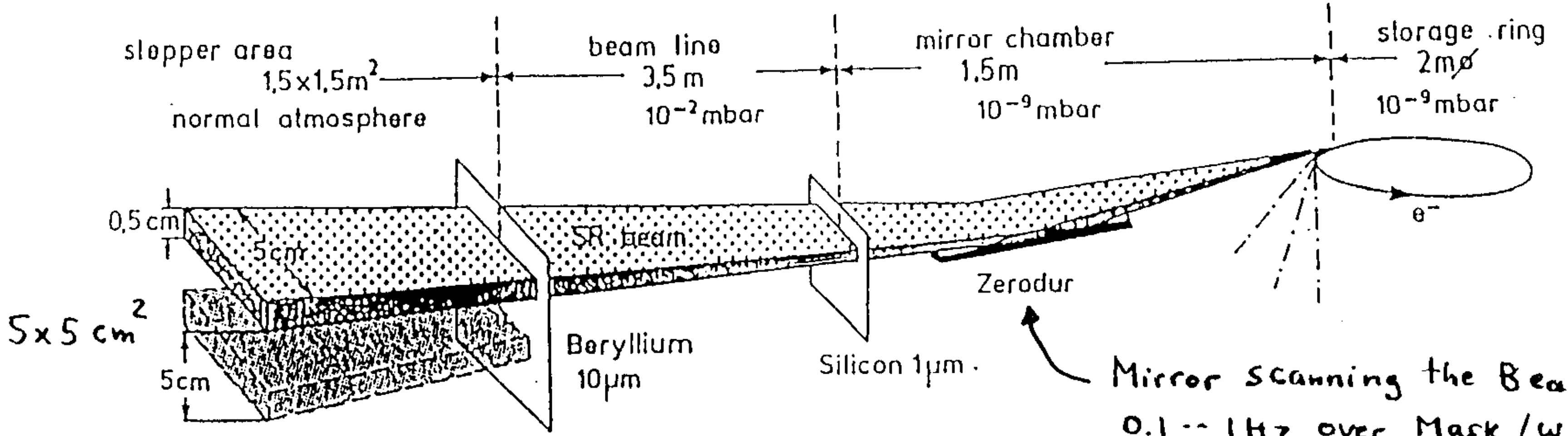


FIGURE 3-1-9. Synchrotron source for soft X-ray lithography. From J. McCoy, *Circuit Manuf.* Nov. 1977, p. 42, copyright and courtesy of Morgan–Grampian Publ. Co.

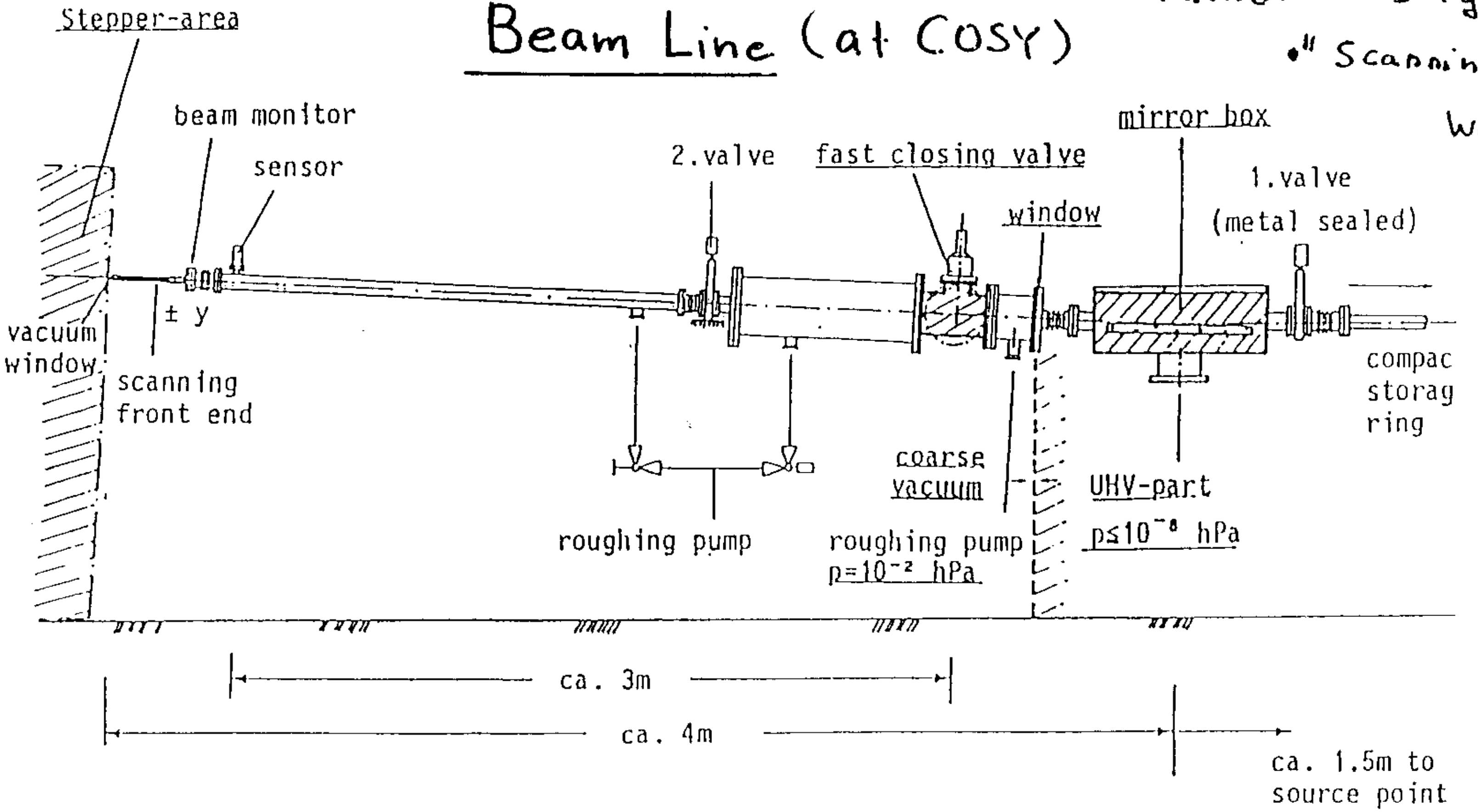


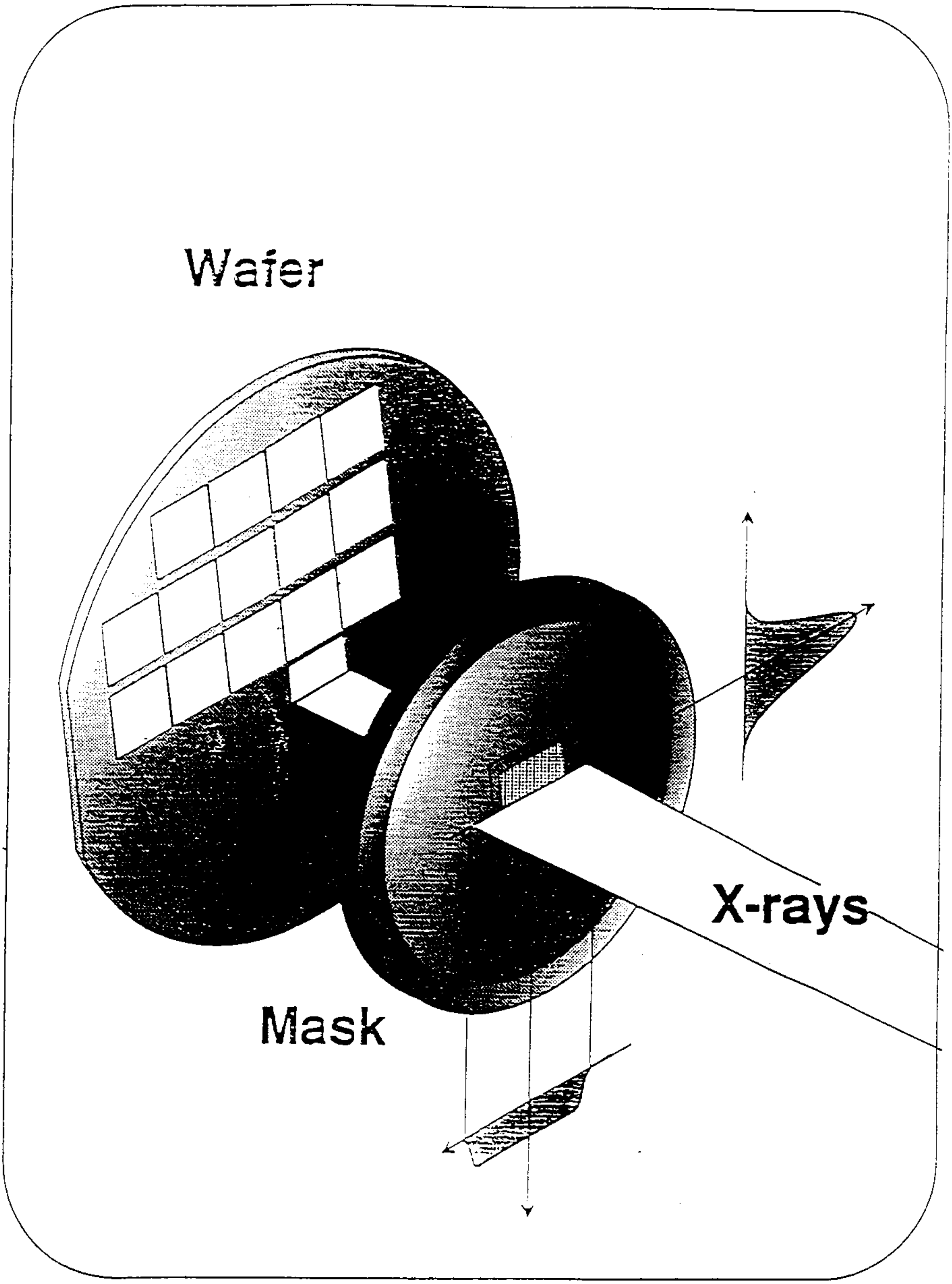
Mirror scanning the Beam with 0.1 -- 1Hz over Mask / Wafer.

Alternative: • "Wobbling of e⁻ Bea

• "Scanning of mask / Wafer Set-up"

Beam Line (at COSY)

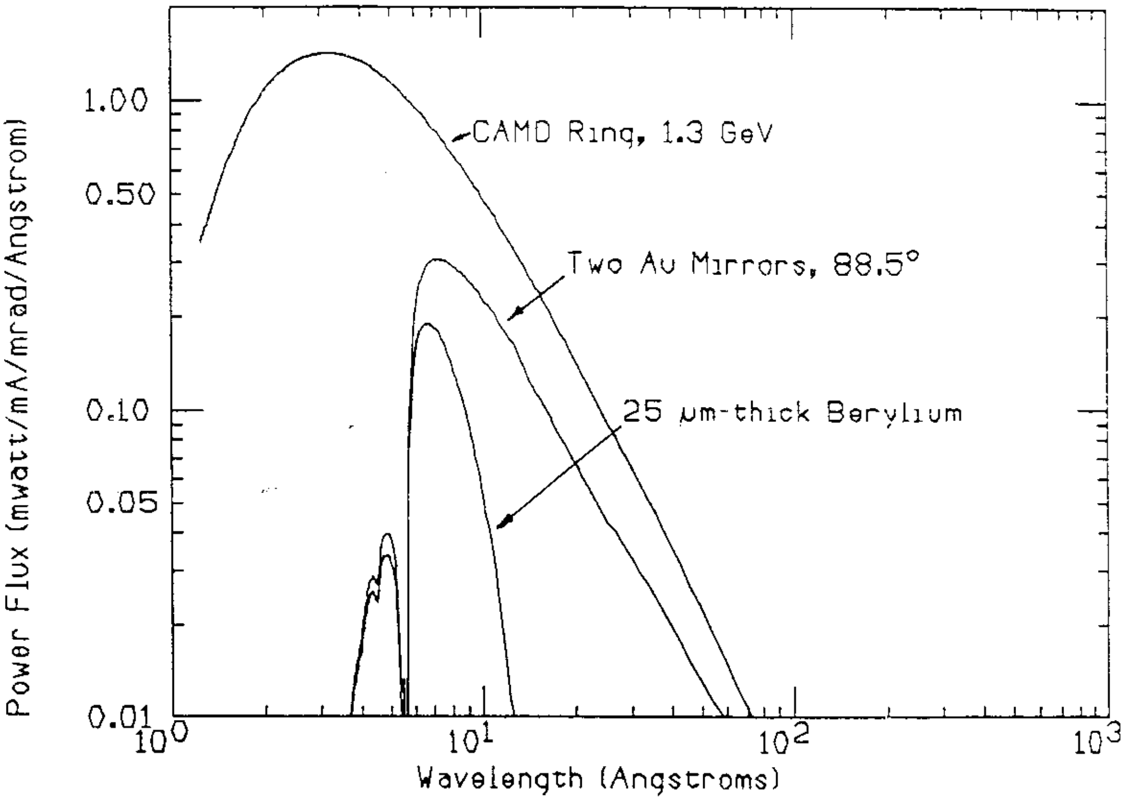




XRL

скп 9.20

XRL Beam Line Power



Integrated Power	mwatt/mA/mrad
Source	13.7
After 2 Au mirrors, 88.5° Incidence angles	4.07
After Berylium Window, 25 microns thick	0.68

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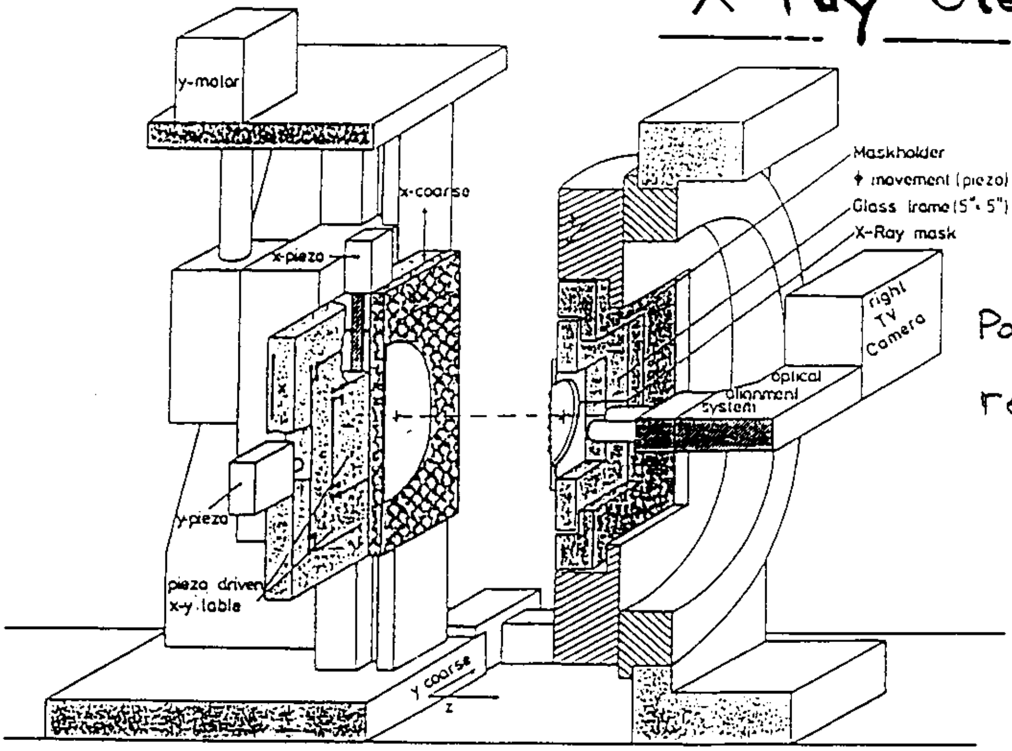
X-ray Stepper



Pattern recognition

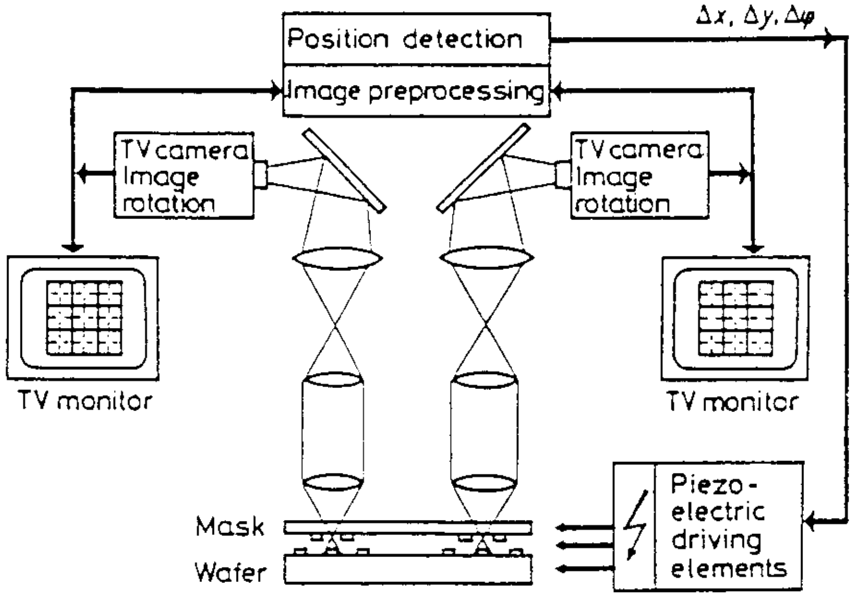
Max. waferdiameter	175 mm
Max. masksize	Ø 100 mm - 90x90 mm
Prealignment-accuracy	± 20 µm
Auto-alignment accuracy	± 0.02 µm
Stepper stage X,Y movement	175 mm
Stepper stage accuracy	1 µm
Stepper stage max. speed	150 mm/s
Piezostage smallest imcrement	0.01 µm
Proximity gap range	var. typ 50 µm
Separation accuracy	0.3 µm
Dimensions L, W, H (without X-ray source)	1330, 800, 1220 mm

CKM 2.22

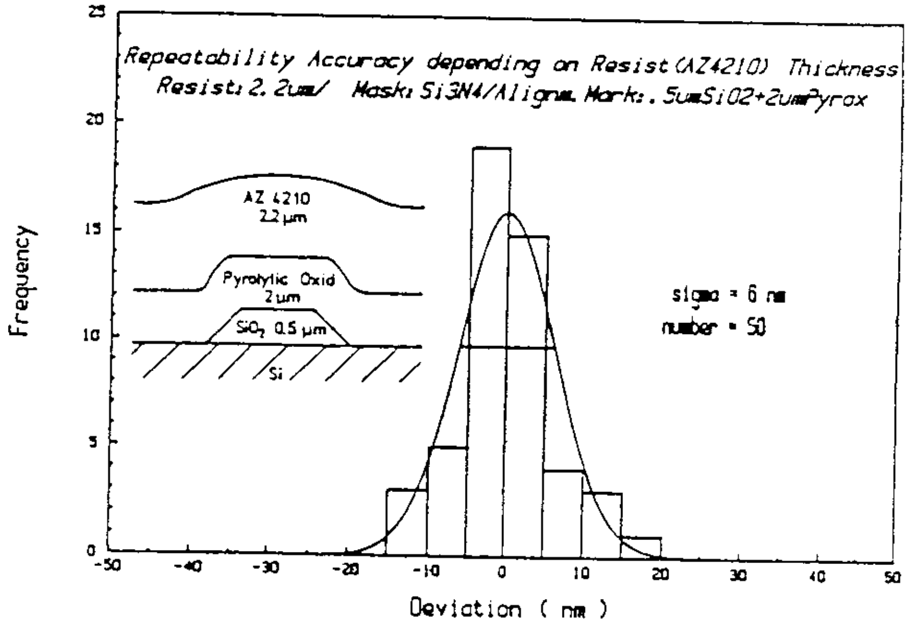
Alignement + Overlay:

Error Budget for 256 Mbit: ~ 0.1 μm (for 0.25 μm)

Througput: 20 - 50 Wafers / hour.



Automatic alignment system for X-ray lithography



Repeatability of light optical pattern recognition for a typical layer sequence

CKM 2.93

(Suss)

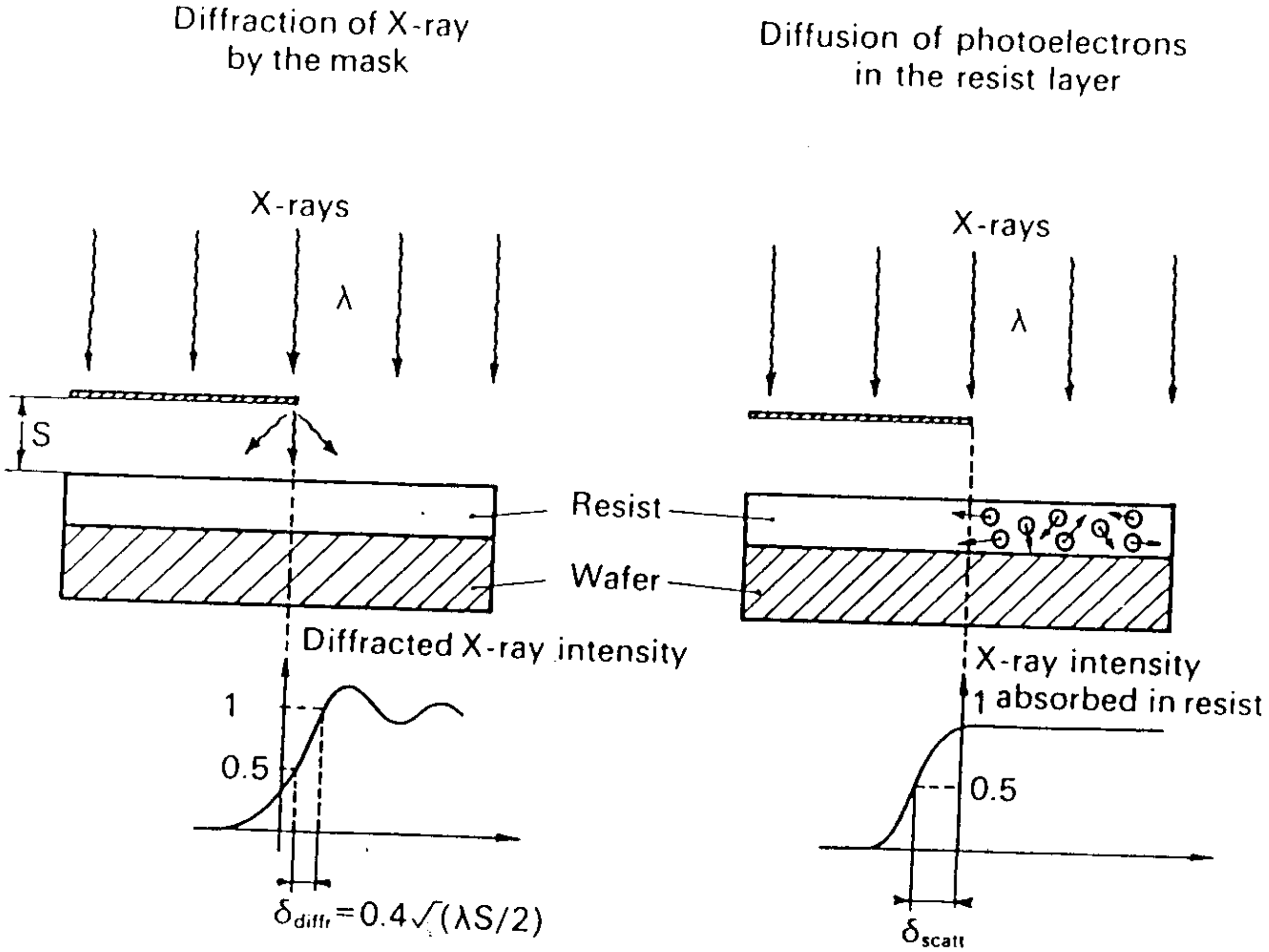


Fig.2. Effects of diffraction and of diffusion in X-ray lithography.

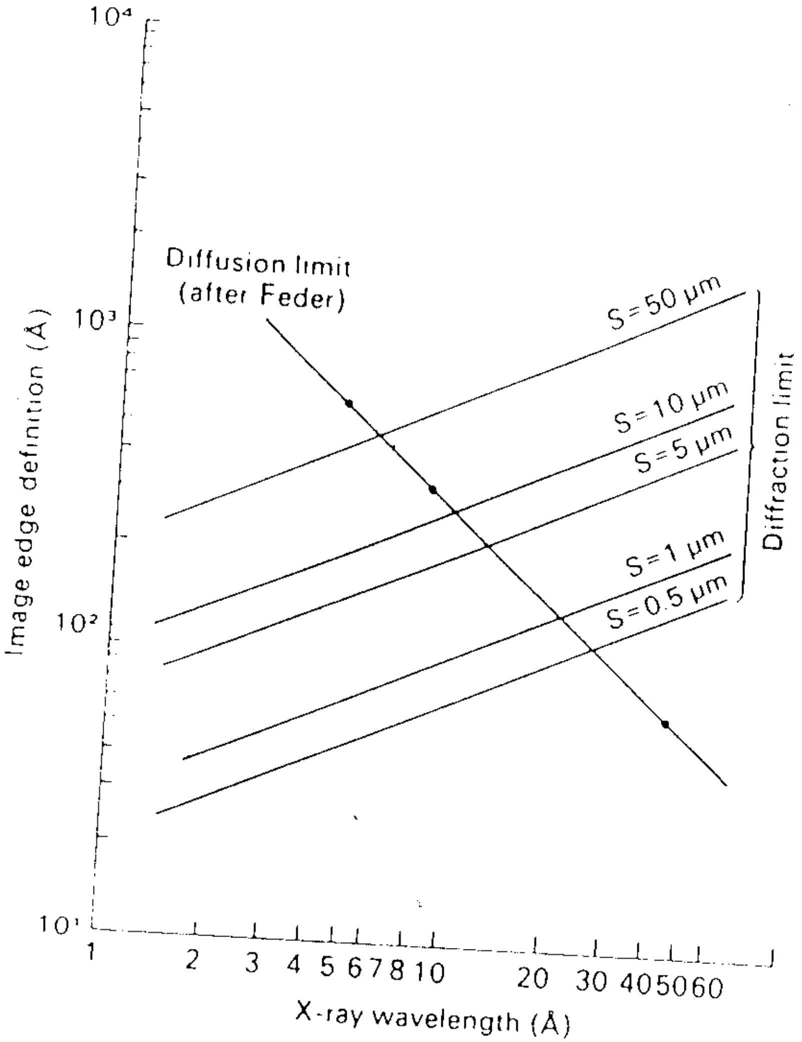
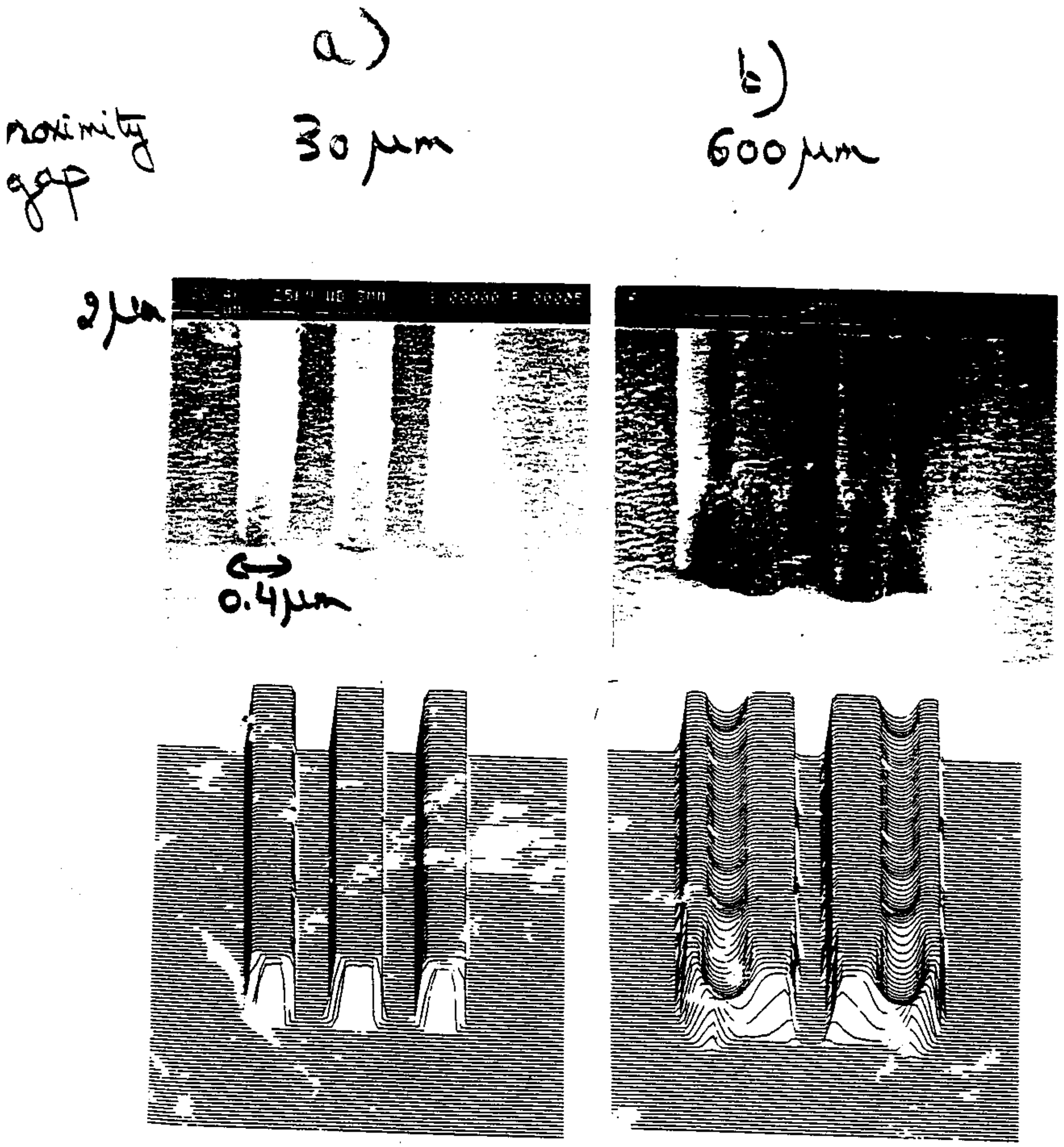


Fig.5. Effect of diffusion and of diffraction on the image edge definition. Several diffraction limit curves are plotted corresponding to different values of the gap spacing S.

(Fay)



Effect of proximity gap variation in X-ray lithography: a) proximity gap [illegible] um. b) proximity gap 600 um. Top: SEMs of structures obtai[illegible] [illegible] um thick RAY-PF resist, bottom: calculated resist profiles as ob[illegible]ed from AMAS

Fresnel diffraction

(Fraunhoffer)

CKП 2.26

EIPB'97 A4 41st Int. Conf. on Electron, Ion and Photon Beam Technol. and Nanofabrication.

30 nm x-ray nanolithography using standard mask technologies on monochromatized synchrotron radiation

G. Simon, A.M. Haghiri-Gosnet, J. Bourneix, D. Decanini, Y. Chen, F. Rousseaux and H. Launois

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Submitted to 41st International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication, May 27-30, 1997

Substrate Photoelectrons in X-ray Nanolithography

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January 14, 1997

Micro and Nano Engineering 97 (MNE'97)

ABSORBER EDGE EFFECT IN PROXIMITY X-RAY LITHOGRAPHY

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Preferred Session: X-ray Lithography, Resists
Preferred Presentation mode: ORAL or POSTER

CKM 2.97

MATURITY OF LITHOGRAPHY TECHNOLOGIES

Lithography Technology	**193**	**XRL**	**SCALPEL**	**EUV**
# Steppers	1 (production field size) 7 (1–2 mm field size)	>23 (50 mm × 50 mm field size)	1 (for proof of lithography)	Engineering test stand planned for 1999
Commercial Suppliers	SVGL, ISI	Canon, NTT/Nikon, SAL, SVGL	Lucent/ISI	??
Lens Material	Development	Not needed	Electromagnetic in development	Electromagnetic in development
Reduction	4x	1x	4x	4x
Source	Development	Compact storage ring available (>98% uptime) Point source in development	Development	Development
Mask Material	Not yet defined	Membrane Technology SiC/Tantalum	Membrane technology SiN/Tungsten	Molybdenum/ silicon multilayer development
Product Masks	None reported	Demonstration masks available from quasi-commercial mask facility	None	None
Commercial Resist	Close to commercialization	Same as 248-nm DUV (APEX, SAL 601, UV-4)	Same as 248-nm DUV (ARCH, UVII HS)	Research (TSI required)
Products Produced	None reported	Partial list: 64 MB DRAMs, 0.2 µm SRAMs, 0.1 µm CMOS devices, 1 Gb and 4 Gb cells	None	None
Summary of Overall Maturity	**Manufacturing insertion issues identified**	**Manufacturing insertion issues identified**	**Discovery Phase**	**Discovery Phase**

THE X-RAY MASK ADVANTAGE

Making 1:1 x-ray masks isn't exactly easy. Achieving the required tolerances for placement accuracy, CD control, and defects is a challenge. Other potential post-optical technologies have a perceived advantage because they will use 4:1 masks, or no masks at all. Those technologies may have a mask advantage, but they don't have a lithography advantage! They are just deferring the challenge to the wafer exposure process where manufacturing personnel have to achieve the tolerances over and over again.

Some potential post-optical lithography methods, such as SCALPEL, will use 4:1 masks which will require stitching. The mask will be easier to make but, by stitching, the burden of meeting the placement tolerances will be shifted to the wafer exposure process on product wafers.

Other systems like e-beam direct write (EBDW) lithography tools will bypass the need for masks by writing patterns directly on product wafers. EBDW has to meet product tolerances at final size on substrates of various conditions/materials/topographies in the fab.

X-ray lithography requires mask tolerances that are equivalent to the final tolerances on product wafers. Itís not easy to make x-ray masks, but the difficulties are manageable. Once the mask is made, transferring the image to product wafers, hundreds or thousands of times, is relatively easy.

X-ray lithography does the hard part just once!

ckn 2 .28

LIGA and LIGA-like processes

- **Precursor work**
  - + **X-ray lithography & electroplating (LIG)**

    Bubble devices (IBM, 1975); 20 μm thick

    Extension of "through-mask plating" (Romankiw, 1969)

    optical lithography and electroplating

- **Original LIGA process from Karlsruhe**

  Separation nozzle for uranium isotopes (Becker, Ehrfeld, et al. 1982)

  - **LI** (Lithographie): Synchrotron X-ray lithography
  - **G** (Galvanoplastie): Electroforming
  - **A** (Abformung): Molding

  outside semiconductor industry

- **LIGA-type processes**
  - + **SLIGA** (Guckel)
    - **S**: Surface micromachining with sacrificial layer releasing
    - **LI**: Lithography
    - **A**: Assembly

    compatibility with semiconductor industry

  - + **Poor man's LIGA**

    Optical lithography in thick resist

  - + **Precision machining with ultra-deep X-ray lithography** (Siddons, Johnson, Guckel)

TURNING POINT FOR LIGA

- **80-90:**
  - 1 group in Karlsruhe (inventor)
  - 1 group in Wisconsin
- **now: many more groups**
  - **Europe**
    - Germany

      Karlsruhe and Mainz: approx. 150 people/each insitute

      Commercial company: Microparts (Dortmund)

      ALIGA
    - Other Europe: France, England, Russia, Sweden: approx. 10-20
  - **US:** approx. 50 people
    - + Wisconsin, CAMD, Brookhaven, ALS [West-Coast (CXRO, JPL, Sandia)], Argonne, Hi-MEMS (MCNC, CAMD, WI, etc)
    - + Commercial company: MEMStek (Vancouver, WA)
    - + LIGA-MUMPS (MCNC)
  - **Asia:** Japan,Taiwan, China

LIGA = SERIES OF STEPS

- **Lithographic step:** ***Resist template formation***

  - Synchrotron radiation deep X-ray lithography

  - Photolithography

    "through the mask technology," "poor man's LIGA"

- **Replication steps:** ***Copies of primary template***

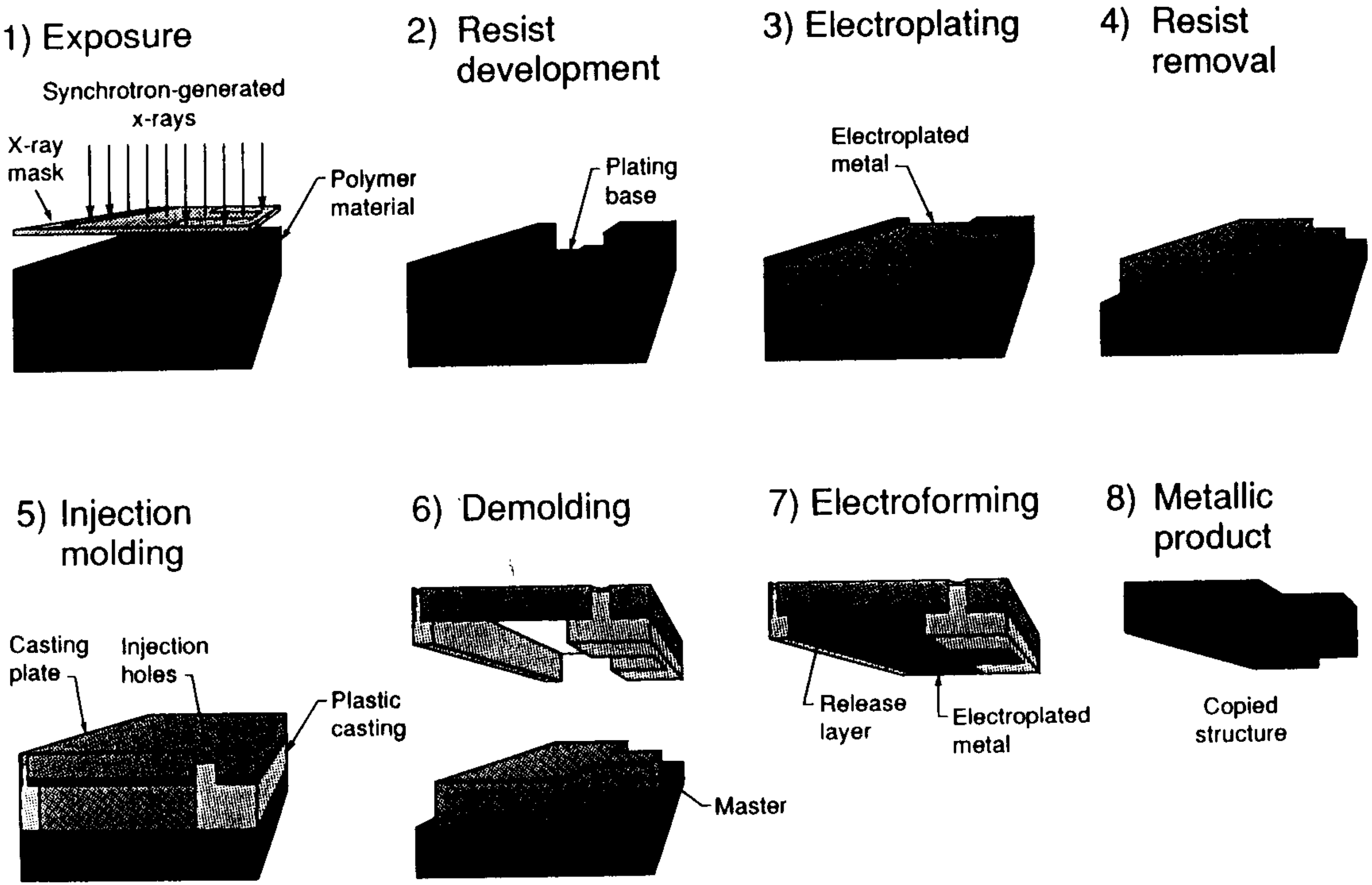
  - Electroplating: metal, alloys

  - Molding:

    hot embossing: plastics

    injection molding: plastics, ceramics, etc.

The LIGA Process


1) Exposure

2) Resist development

3) Electroplating

4) Resist removal

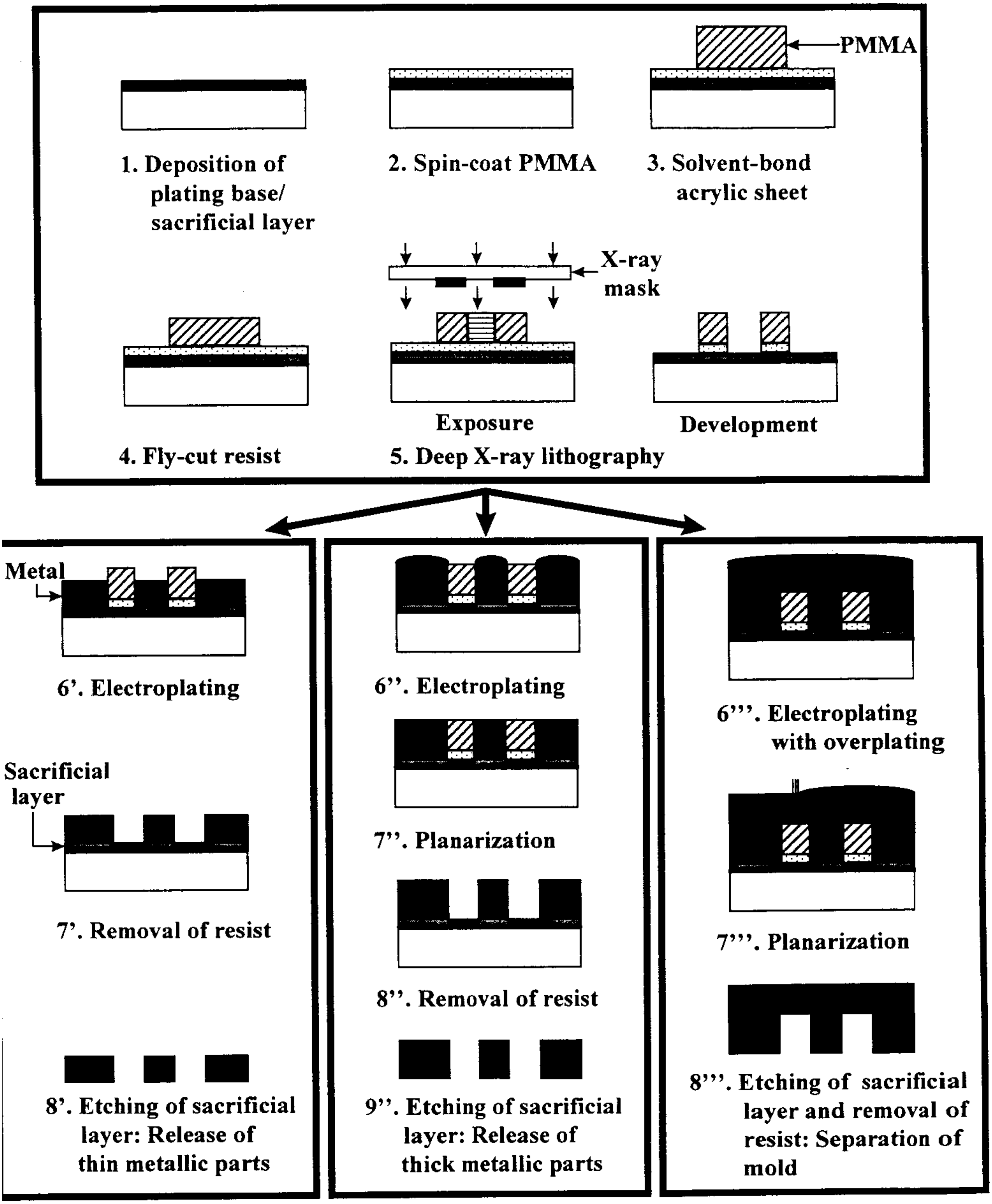
5) Injection molding

6) Demolding

7) Electroforming

8) Metallic product

Fabrication of metallic parts and molds by (S)LIGA



1. Deposition of plating base/ sacrificial layer

2. Spin-coat PMMA

3. Solvent-bond acrylic sheet

4. Fly-cut resist

Exposure

Development

5. Deep X-ray lithography

6’. Electroplating

7’. Removal of resist

8’. Etching of sacrificial layer: Release of thin metallic parts

6’’. Electroplating

7’’. Planarization

8’’. Removal of resist

9’’. Etching of sacrificial layer: Release of thick metallic parts

6’’’. Electroplating with overplating

7’’’. Planarization

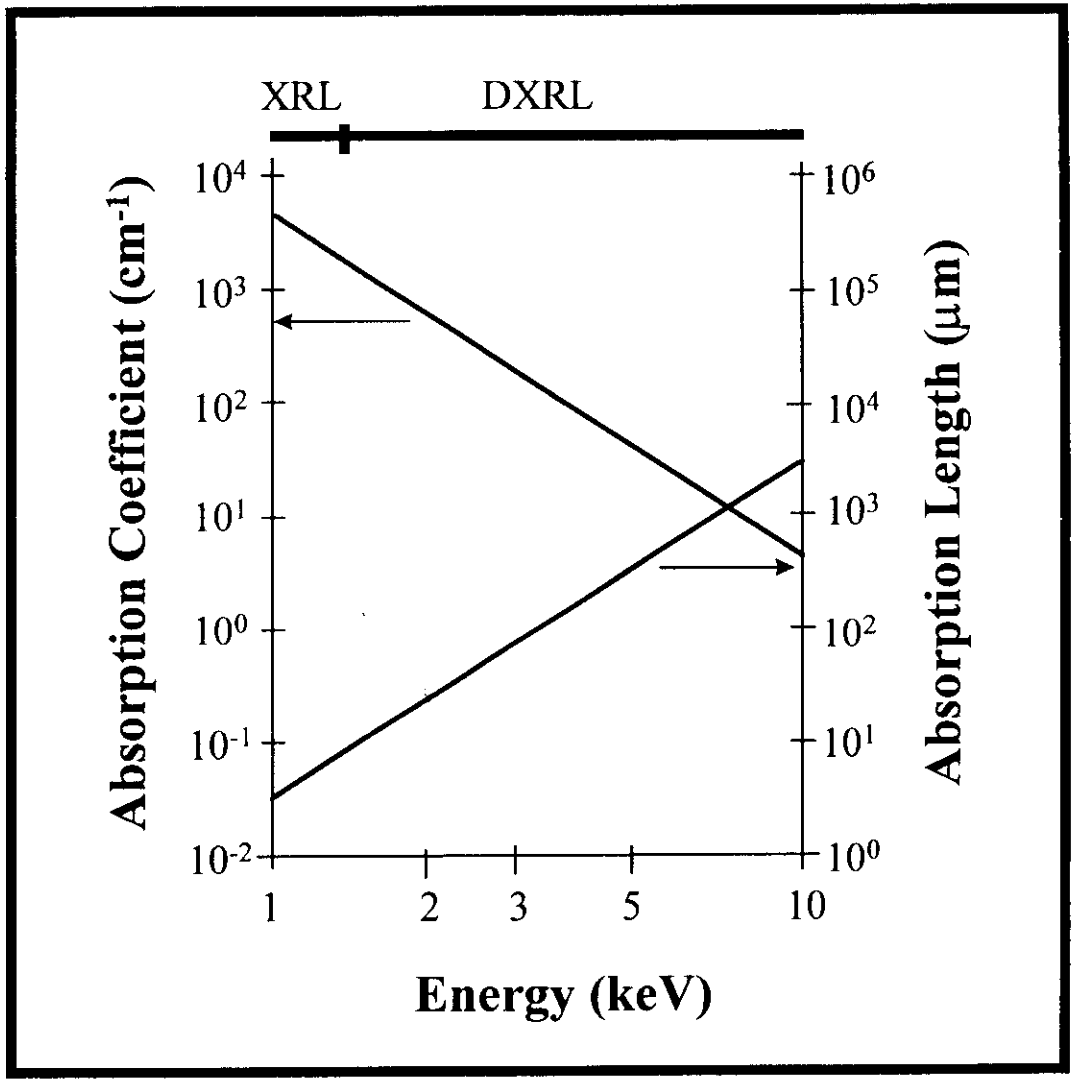
8’’’. Etching of sacrificial layer and removal of resist: Separation of mold

CKH 3.5

EXPOSURE STRATEGY FOR DEEP X-RAY LITHOGRAPHY

- 1: 1 replication process
- Source
    - short wavelength (2-10 keV)
        - penetration depth in resist
    - collimated X-ray
        - pattern transfer quality
    - high flux
        - throughput
- Scanner
- Alignment system for multiple levels

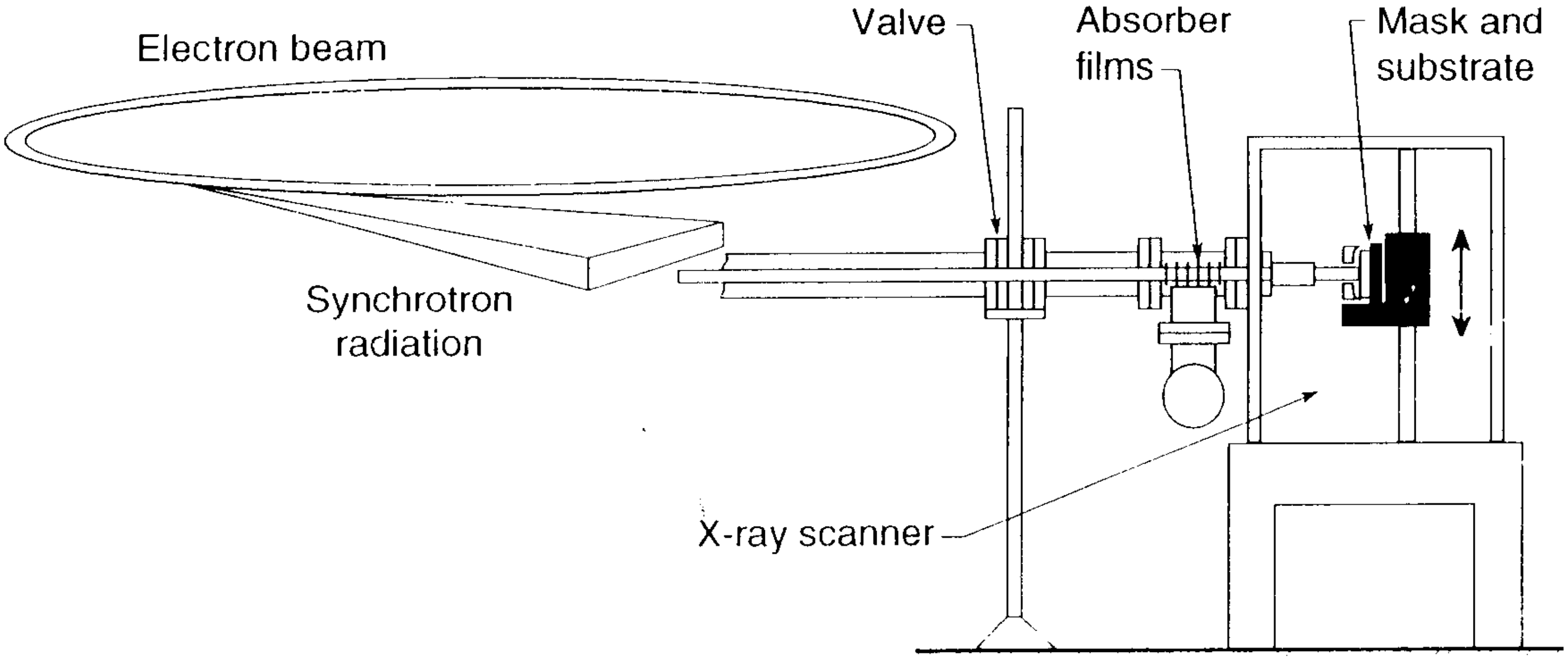
Absorption of PMMA



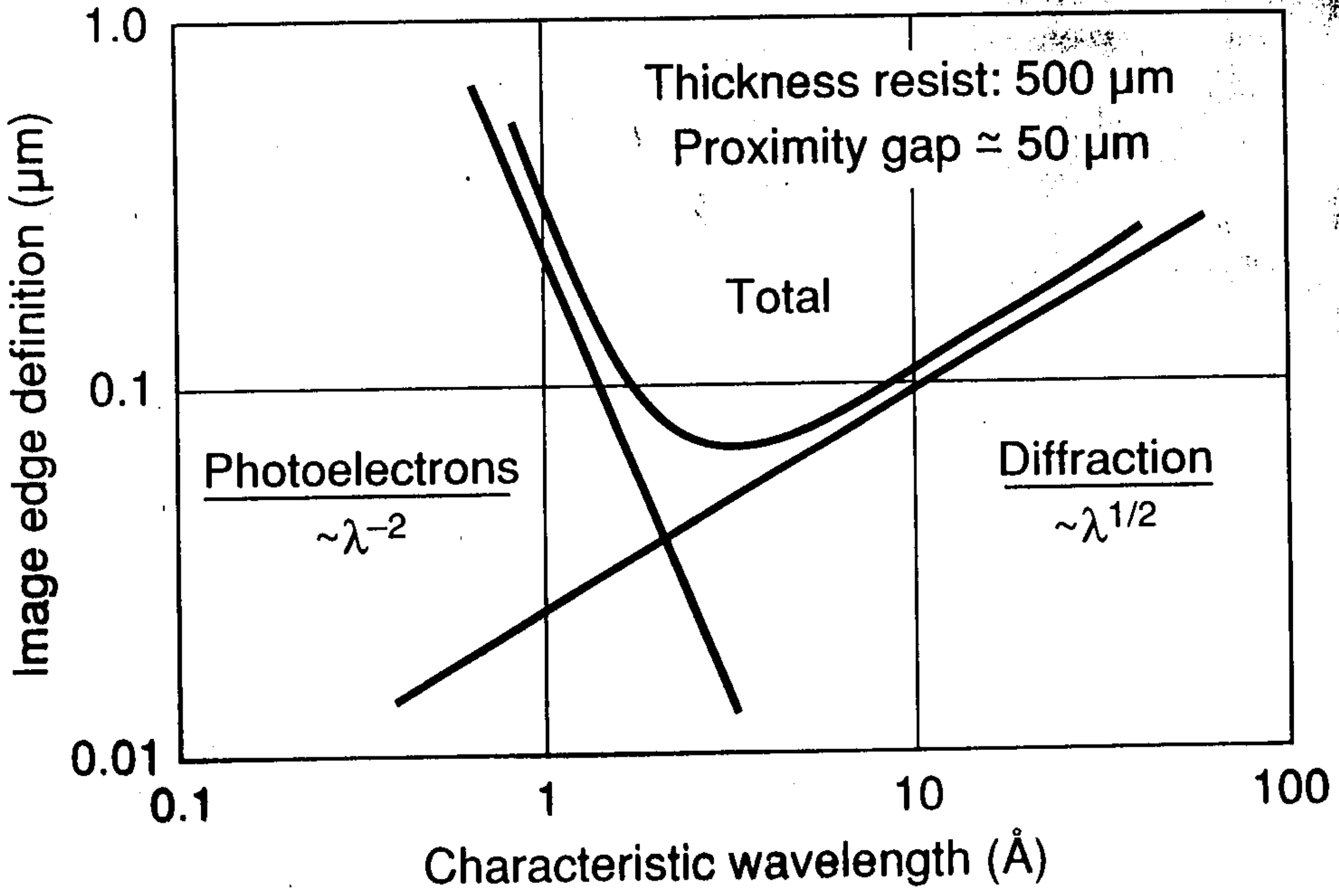
Advantages of synchrotron deep X-ray lithography

- Single thick resist process
- Large structural heights (100 µm to mm)
- Minimum feature size in micron range
- Quality and accuracy of pattern transfer
    - smooth walls with low surface roughness (30-50 nm)
    - straight and planar walls
    - highly parallel walls
    - submicron accuracy over total height of device
- Large depth of focus
- High throughput

Deep Etch Lithography End Station

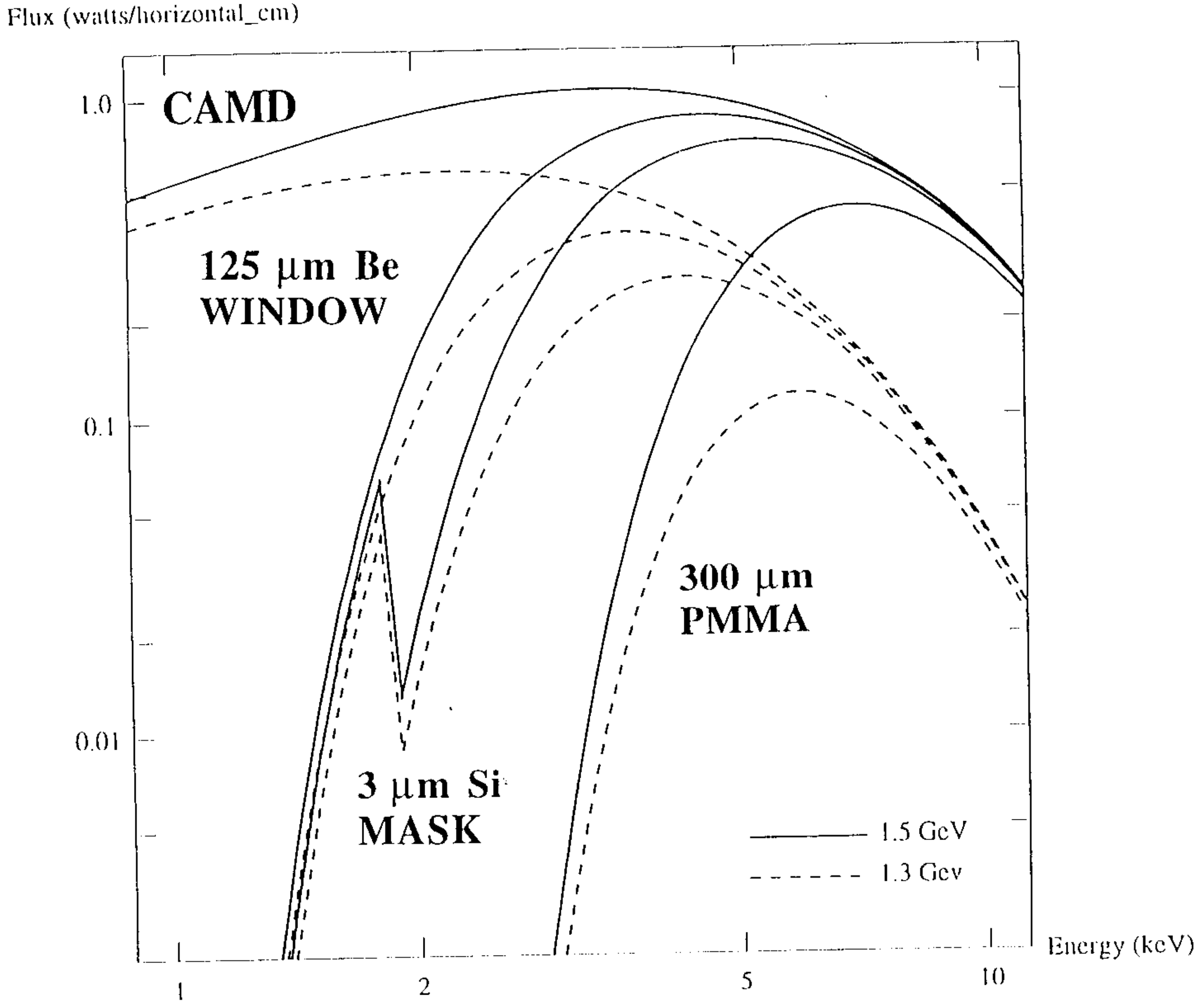


Optimum Wavelength for Deep X-ray Lithography



Source: Ehrfeld et al. 1991

Transmitted Intensity during PMMA exposures for LIGA (7B-XRLM3)



LIGA mask fabrication

Mask type

>> Stencil mask

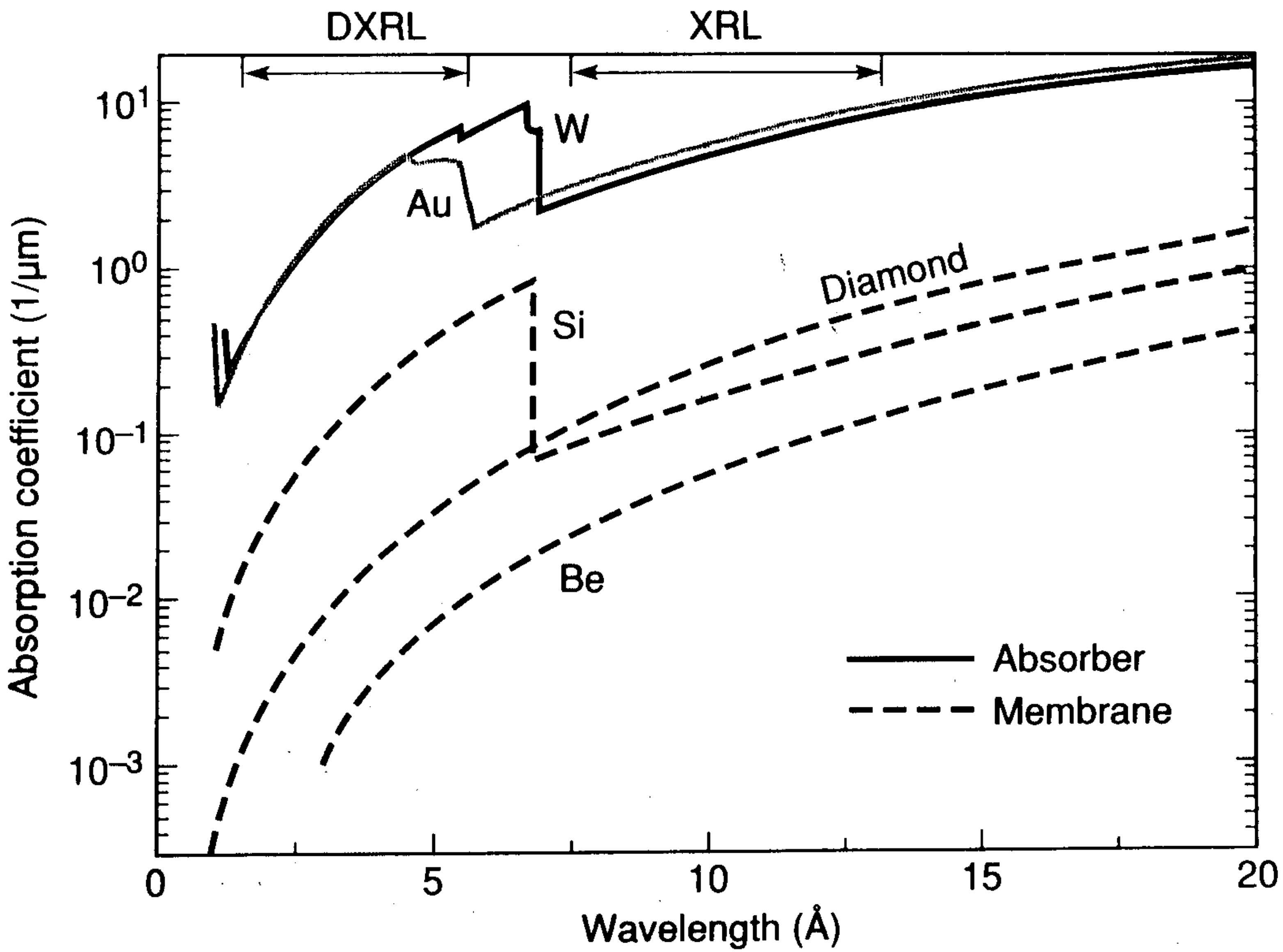
chemically etched, plated, laser-etched, miromachined

>> Mask blank with absorbing structures

- transparent substrate/membrane
- absorbing patterns

>> Conformal mask

Mask Materials for Deep X-ray Lithography



MASK FOR DEEP ETCH LITHOGRAPHY

- High contrast at short wavelength ≥500
- Dimensionally stable
- Flat

Mask substrate

- X-ray transparent
    - light material
    - thin membrane
- Good mechanical properties
    - high Young's modulus
- Radiation resistant
- Optically transparent

Absorber pattern

- X-ray absorbing structures
    - heavy material
    - absorber thickness: 5-15 μm
    - minimum lateral width: 1 μm
    - vertical walls
- Low stress

PROPERTIES OF MEMBRANE MATERIALS

	Young Modulus (10^5 MPa)	Thermal Expansion Coefficient (10^{-6} °C^{-1})	Density (g/cm^3)	Thermal Conductivity (W/cm.°C)	Refractive Index
Si	1.1–1.9	2.6–3.7	2.33	1.5	3.5–3.9
SiN	1.6–3.8	2.1–2.7	3.1–3.4		2.2
SiC	3.8–4.6	4.6	3.2–4.7	2.0	2.48
BN	0.9–1.33	1.0	2.3	0.7	2
Diamond	10–15	0.8–3.5	3.5	13–20	2.41
Be	3.0	12.3	1.42		
Ti	1.2	9	4.5		
Kapton	0.025	18	1.4		
Au	0.8	14.3	19.3	2.97	
W	4.0	4.3	19.3	1.78	
Ta	1.9	6.5	16.6		
Pt		9	21.5		
Re	4.5	6.7	20		
Cu		9.3	8.9		

COMPARISON OF MEMBRANE MATERIALS FOR DEEP ETCH LITHOGRAPHY MASKS

	Be	Diamond	Si	Ti	Kapton
X-ray transparency	+ +	+	–	–	+
Young's modulus	+	+ +	o	o	– –
Optical transparency	– –	+ +	o	o	++
Surface quality	+	–	+ +	+	–
Chemical stability	o	+ +	+ +	o	+
Dimensional stability	++	++	++	++	– –
Non toxicity	– –	+ +	+ +	+ +	++
Price	+	– –	–	–	++

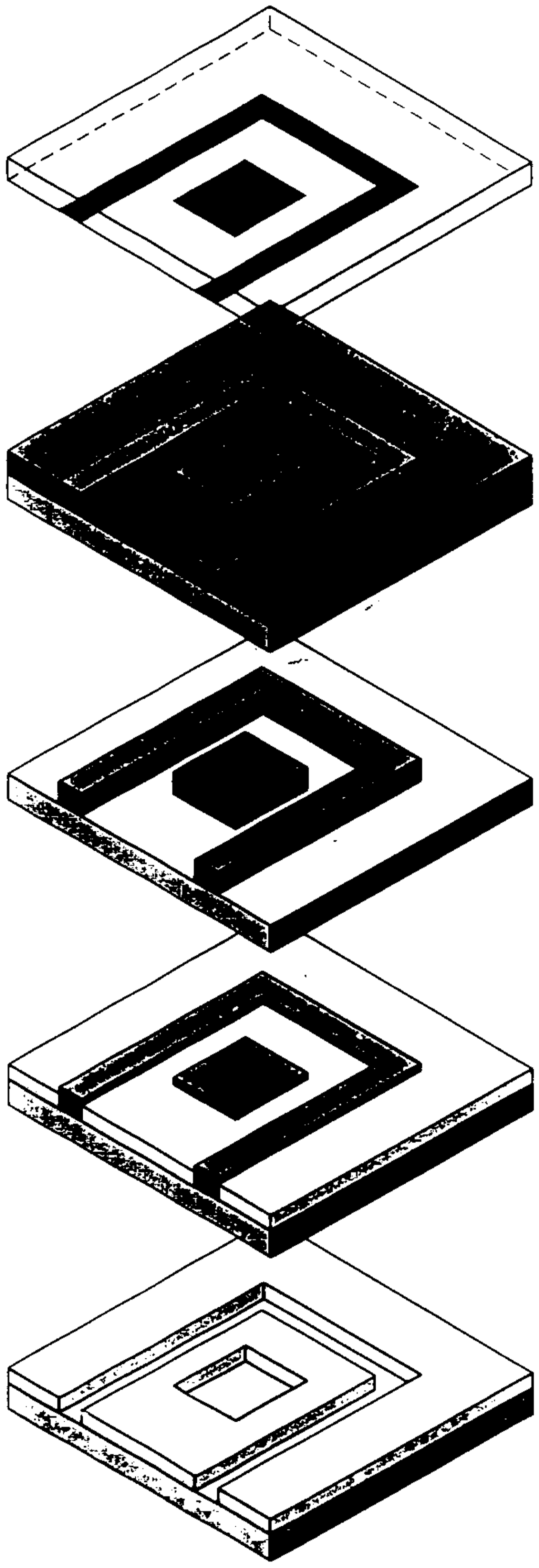
+ +: excellent, +: good, o: reasonable, –: bad, – –: very bad

COMPARISON OF ABSORBER MATERIALS FOR DEEP ETCH LITHOGRAPHY MASKS

		Au	W	Ta
X-ray absorption coefficient		+ +	+ +	+
Stress		+	o	o
Thermal expansion matching to	Be	+ +	–	–
	Diamond	– –	+ +	+
	Si	–	+	+
	Ti	+	– –	–
Microstructure formation	RIE	– –	+ +	+ +
	Electroplating	+ +	– –	– –

+ +: excellent, +: good, o: reasonable, –: bad, – –: very bad

X-Ray Mask Fabrication



Optical mask

Expose photoresist
(10-30 μm)

Develop away
exposed photoresist

Electroplate gold
in photoresist holes
(5-25 μm)

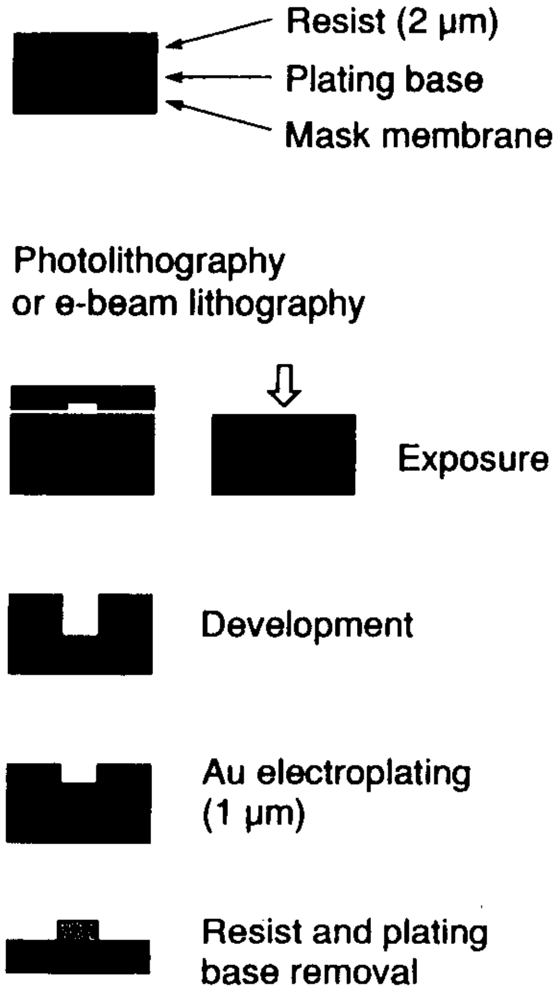
Remove photoresist

CKH 2.18

Mask Fabrication for Deep Etch Lithography

2 Step Fabrication Process with X-ray Mask Copying

Intermediate XRL Mask



Resist (2 µm)
Plating base
Mask membrane

Photolithography
or e-beam lithography

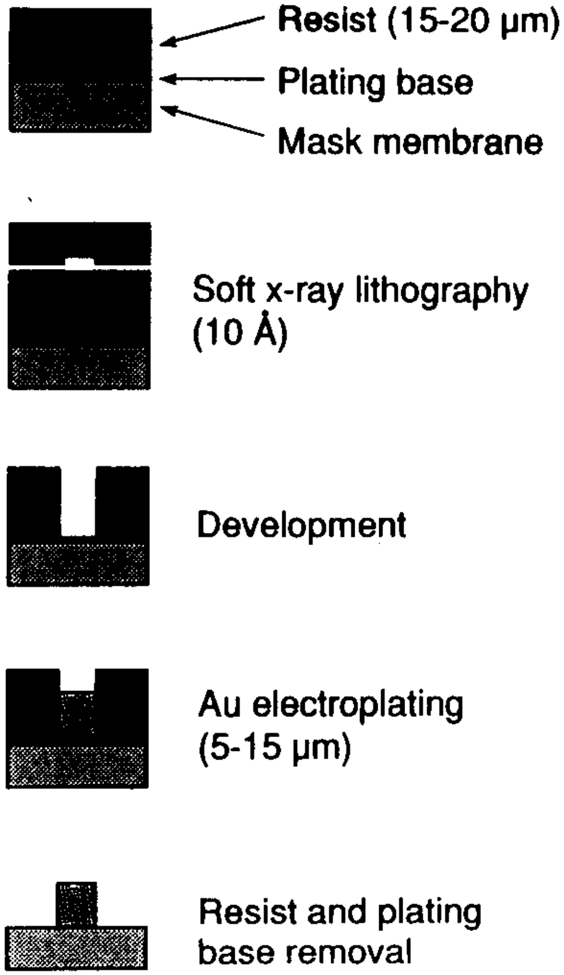
Exposure

Development

Au electroplating
(1 µm)

Resist and plating
base removal

Deep Etch Lithography Mask



Resist (15-20 µm)
Plating base
Mask membrane

Soft x-ray lithography
(10 Å)

Development

Au electroplating
(5-15 µm)

Resist and plating
base removal

MATERIALS FOR LIGA

- **Substrates**
  - **Silicon wafers**
    - compatibility with IC process
    - integration with Si micromachining and electronics
      - plating bases for electroplating
      - sacrificial layers for release of parts
  - **Thick metallic substrates**
    - mechanical stability for molding processes
      - conductive for electroplating
- **Eventual adhesion promotion**
  - **Substrate treatment for roughening**
  - **Adhesion promoters/primers**

MATERIALS FOR LIGA

- **Resist: mainly high molecular weight PMMA**
  - **- Free-standing acrylic sheets**
  - **- Acrylic sheet solvent-bonded to substrate**
  - **- Cast resist**

PMMA in MAA syrup + catalyst (Karlsruhe, Mainz)

In-situ polymerization at RT

Thermal treatment

- **Development: mainly "GG" developer**
  - **Specially tailored developer** ("GG": Ghia & Glashauser)

highly selective

minimization of stress corrosion

2 baths: (percentage in volume)

- (1): Glycolic ether (2- 2-butoxyethoxyethanol) 60 %, (azine) morpholine: 20 %,

- primary amin (2-aminoethanol) 5%, water: 15%

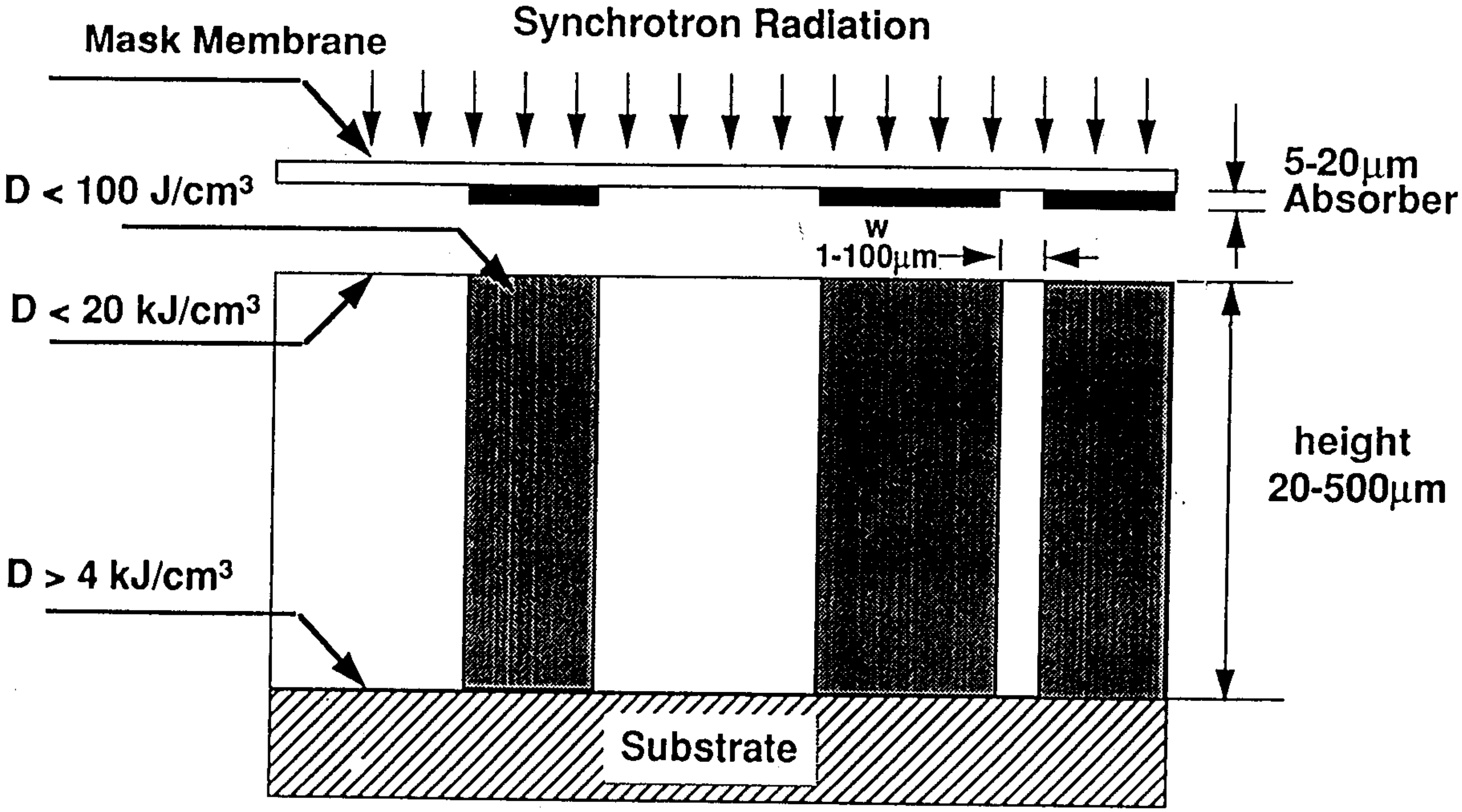
(2): 2- 2-butoxyethoxy)ethanol: 80 %, water: 20%

rinse: DI water

PMMA Characteristics

- Very high resolving power
- Low adherence on some substrate
- Low sensitivity
- Medium mechanical properties
- Good optical transmission properties in visible and IR
    - waveguides
    - optical components

High Aspect Ratio Resist Pattern



Aspect ratio= h/w= 20-500

Proximity Printing X-ray Lithography Comparison - 1

Lithography Type	XRL	DXRL
Technology	Microelectronics	High Aspect Ratio MEMS
Process	Planar Patterning	3D - Microstructures
Production Method	Direct Exposure	Moulds for Replication or Direct Exposure
Applications	DRAM, Processor (Optoelectronics) (Nanolithography)	Sensors, Actuators, Optics,...
Typical Wavelength (nm)	0.8 - 1.4	0.2 - 0.4
Typical Resolution (μm)	High ≤ 0.25	Medium ≥ 1
Typical Thickness (μm)/Resist	1/Various	$\leq 10^3$/PMMA
Aspect Ratio	Low ≤ 10	High ≤ 100

Proximity Printing X-ray Lithography Comparison - 2

Lithography Type	XRL	DXRL
X - Ray Source	Synchrotron or Point Source	Synchrotron
Synchr. Energy (GeV)	0.6 -1.2	1.0 - 2.0
Wavelength Shifter		≥ 0.8
Beamline	Collimating Mirrors	Filters, no/plane mirrors
Stepper/Scanner	Complex Stepper Atm. He Internal Alignment	Scanner Low pressure or Atm.He External Alignment
Mask	Membrane (SiC, Si) Refractory Metal, Au e-beam	Membrane (Si, Ti, Be..) Au optical or e-beam
Resist	various types	PMMA
Typical Exposure Time/Field	1 sec	1 hour
Typical Field Size (mm^2)	300	≤ 10,000
Substrates	Si wafers	Si Wafers, Metal Plates, Ceramics, none

Proximity Printing X-ray Lithography Comparison - 3

Lithography Type	XRL	DXRL
Status X-Ray Source	“++” (SR) expensive ($15-20m) “-” (Point Source) Collimator required	“++” very expensive (≥ $20m)
Status Beamlines	“++”	“++”
Status Stepper/Scanner	“(+)” Throughput	“+”
Status Mask	“(-)” Defect-Free, Complex	“+” 2 Mask Providers

Proximity Printing X-ray Lithography Comparison - 4

Lithography Type	**XRL**	**DXRL**
Status Metrology	“(+)”	“-” **Fidelity of Pattern Transfer**
Status Manuf. Infrastr.	“(-)” **no Commitment** **Mitsubishi (?)**	“(+)” **HI-MEMS Alliance** **MicroParts** **MEMStek**
Status Production Plans	**after 2000**	**1998/99**

“++”	**excellent**
“+”	**very good**
“(+)”	**good**
“(-)”	**improvements required**
“-”	**major improvements required**
“—”	**insufficient**

LIGA PROCESSING CONSIDERATIONS (2)

- What people need to know about a process:
  - Minimum line width (w). Dependent on:
    - Resist thickness
    - Microstructure length
    - Fill density
  - Orthogonality of pattern
  - Sidewall run-out (Δw/resist thickness)
  - Surface smoothness
  - Adhesion of resist to substrate
  - Mechanical integrity of resist
  - Insensitivity to following processes (thermal, etc.)

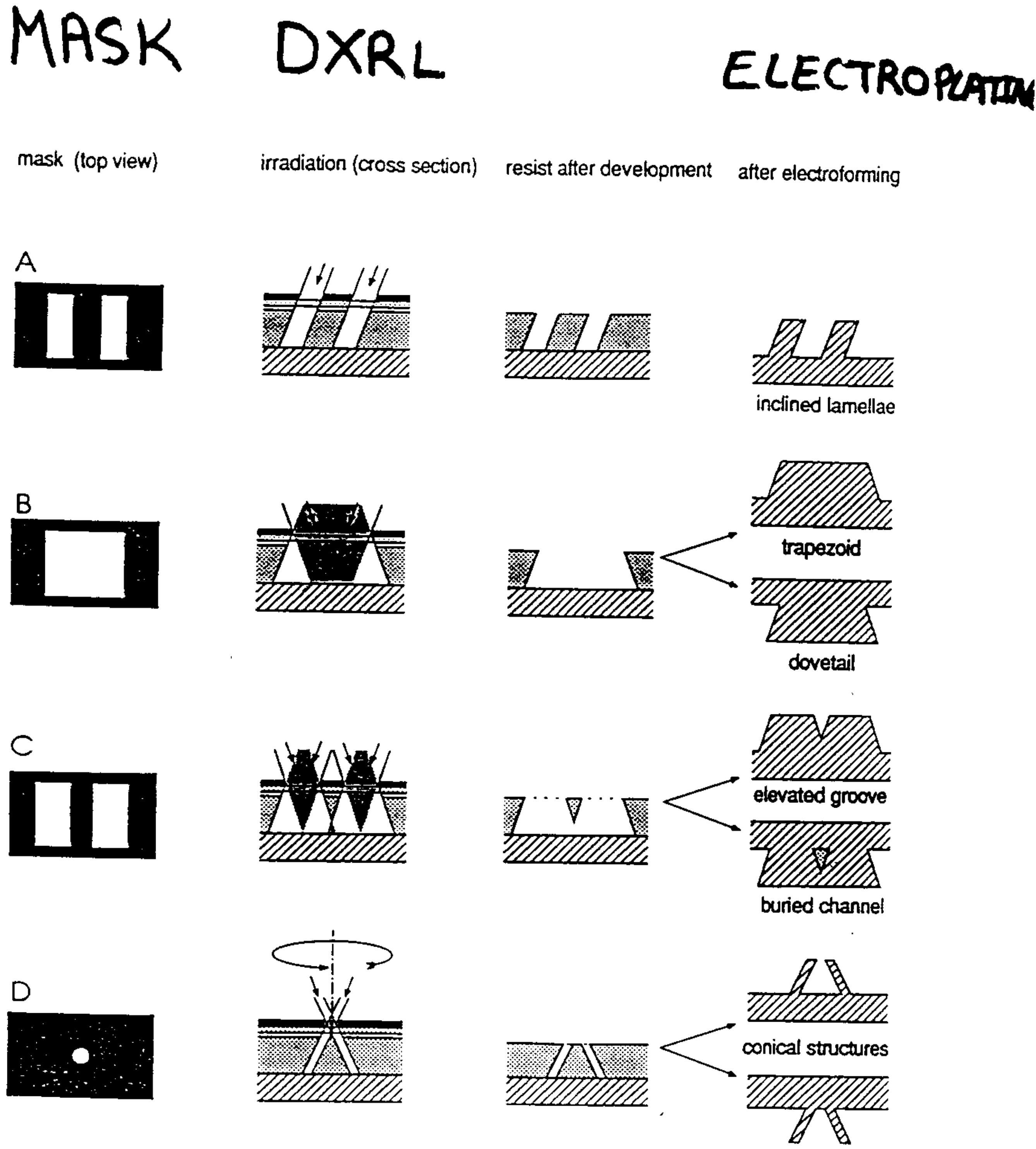
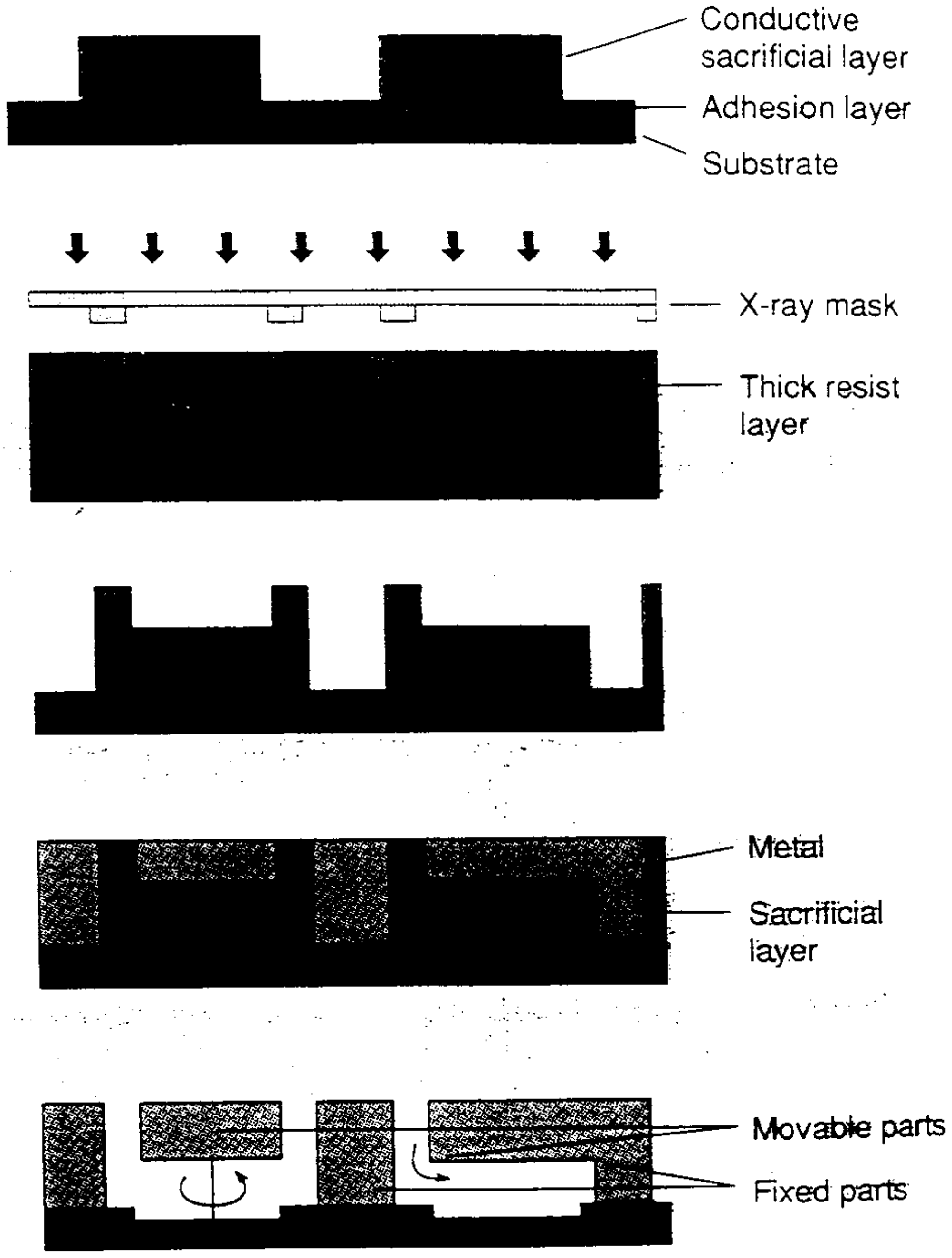


Fig. 2: Special 3D structures obtainable by tilting and rotating the mask-sample set during irradiation: Unidirectionally inclined structures after a single exposure (A), trapezoid structures after two exposures from different directions (B,C), and conical structures after a 2π wobbling movement during exposure (D).

Ckn 3.29

[Hoser et al. (1992)]

Movable, Flexible and Free Microstructures: SLIGA



Sacrificial layer preparation

DXRL resist exposure

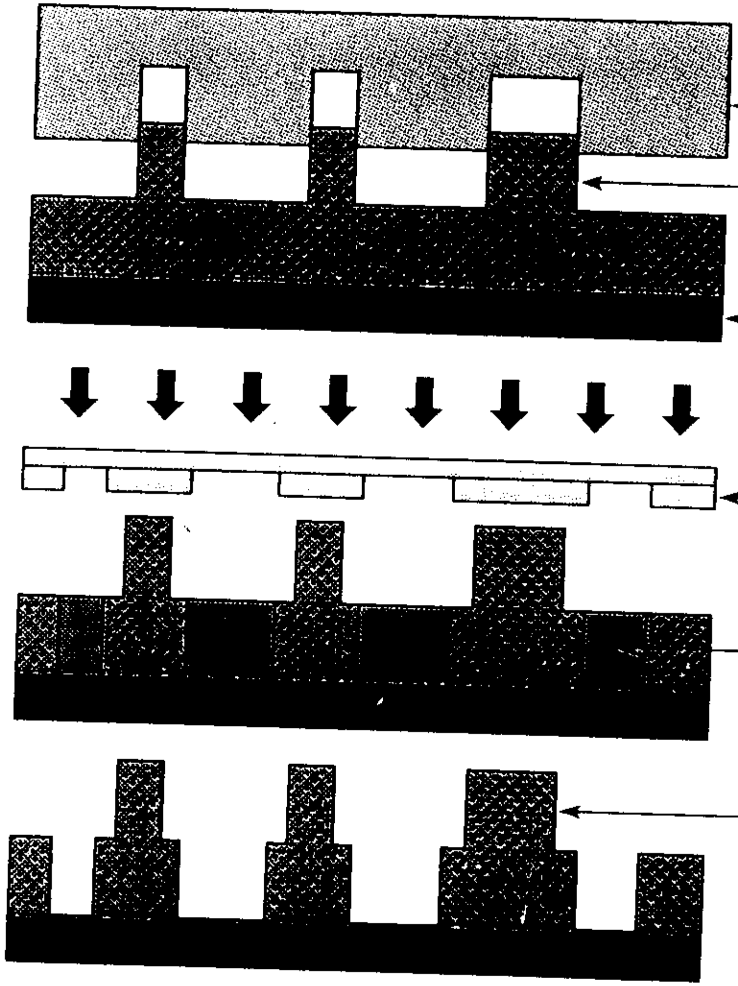
Resist development

Electroforming

Stripping of resist and of sacrificial layer

СКП 3.30

Multiple Level Microstructure Using LIGA



1) Relief Printing

LIGA-mold insert

Molded resist

Substrate

2) Deep Etch Lithography

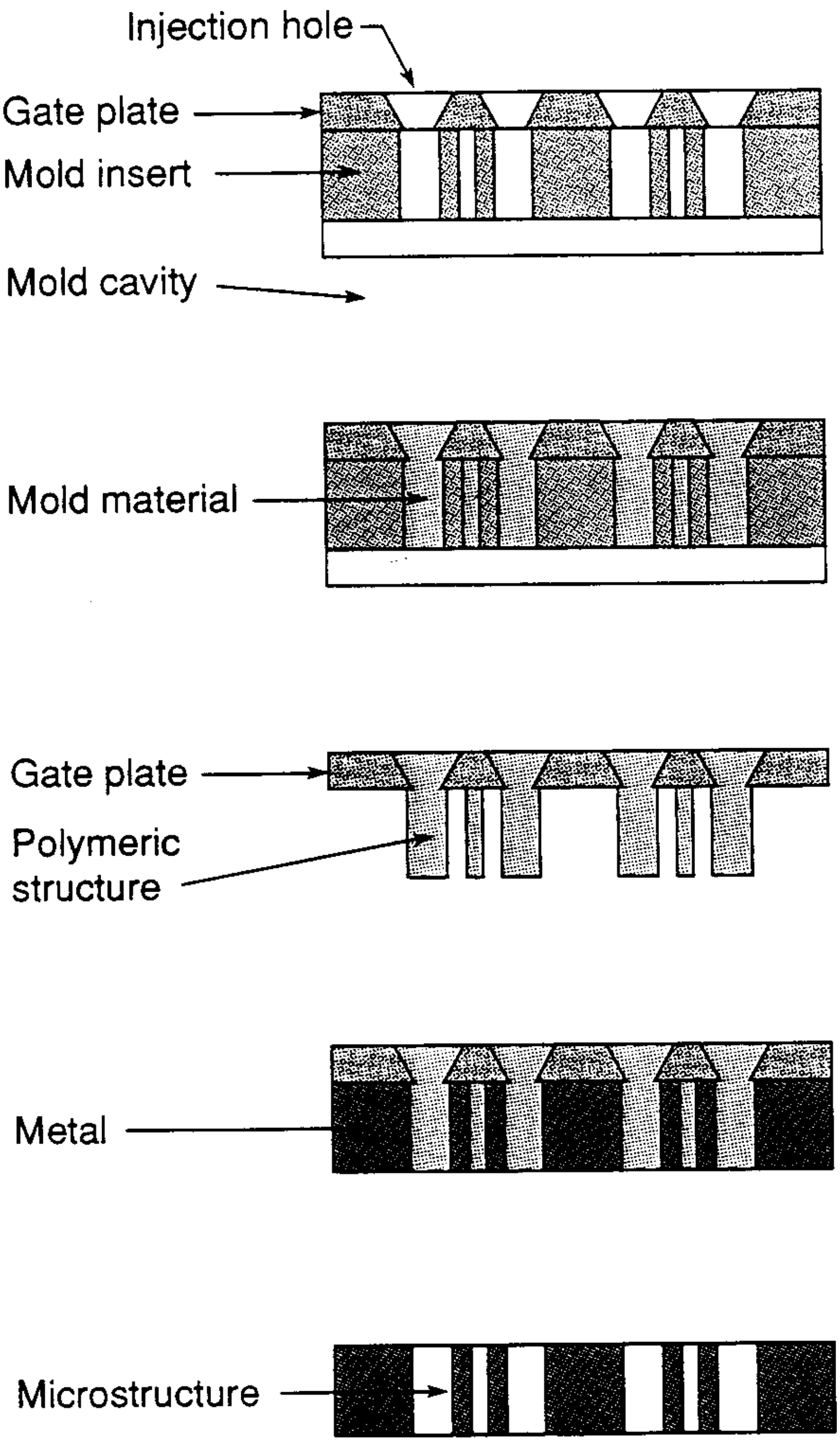
X-ray mask

Irradiated resist

3) Development

Microstructure with two level heights

Molding Process



Mold fabrication

Mold filling

Removal from the mold

Electroforming

Finishing

(KfK)

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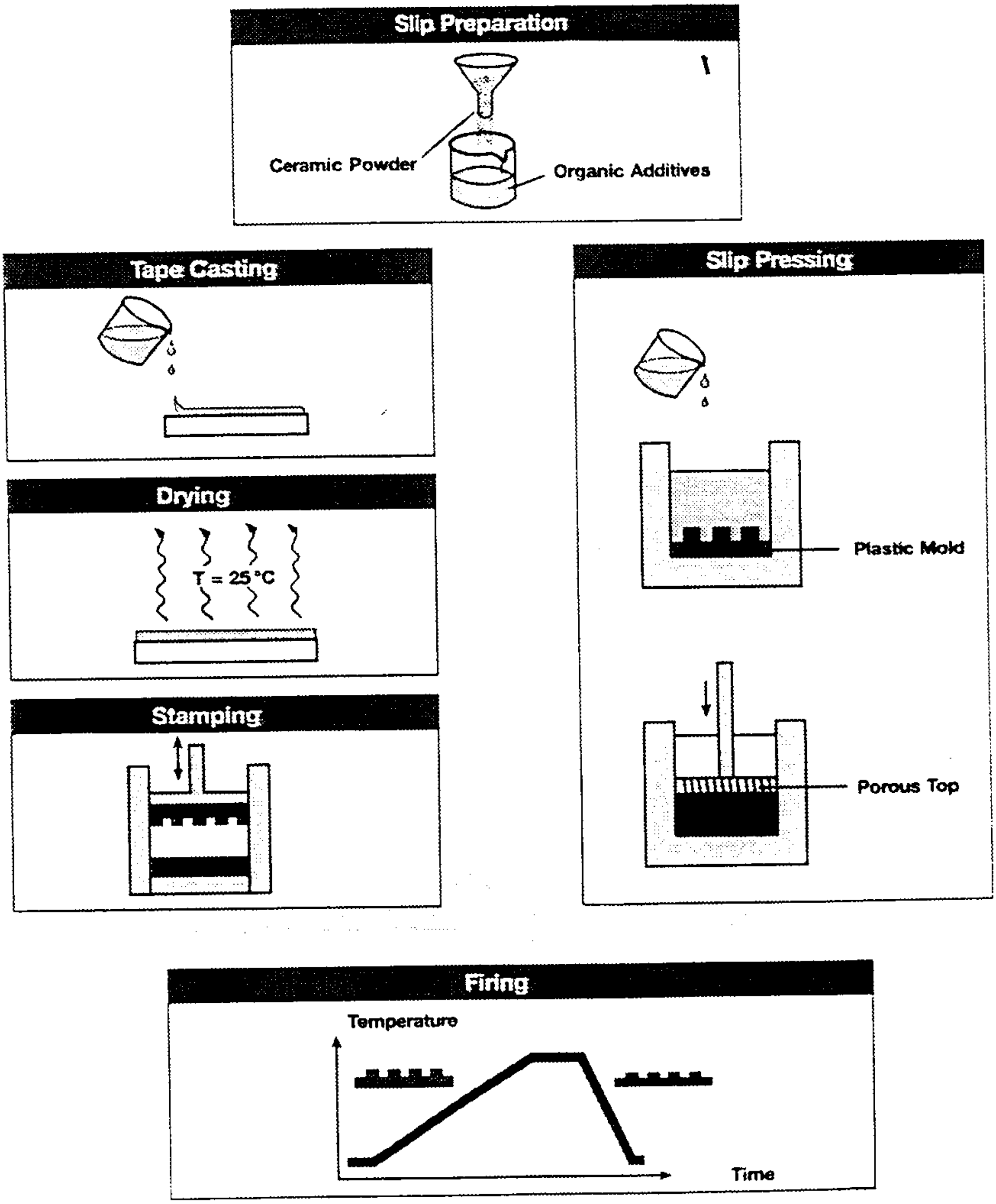
Fabrication of Ceramic Microstructures

Tape Casting and Stamping **Slip Pressing**



(KfK)

CKM 3.33

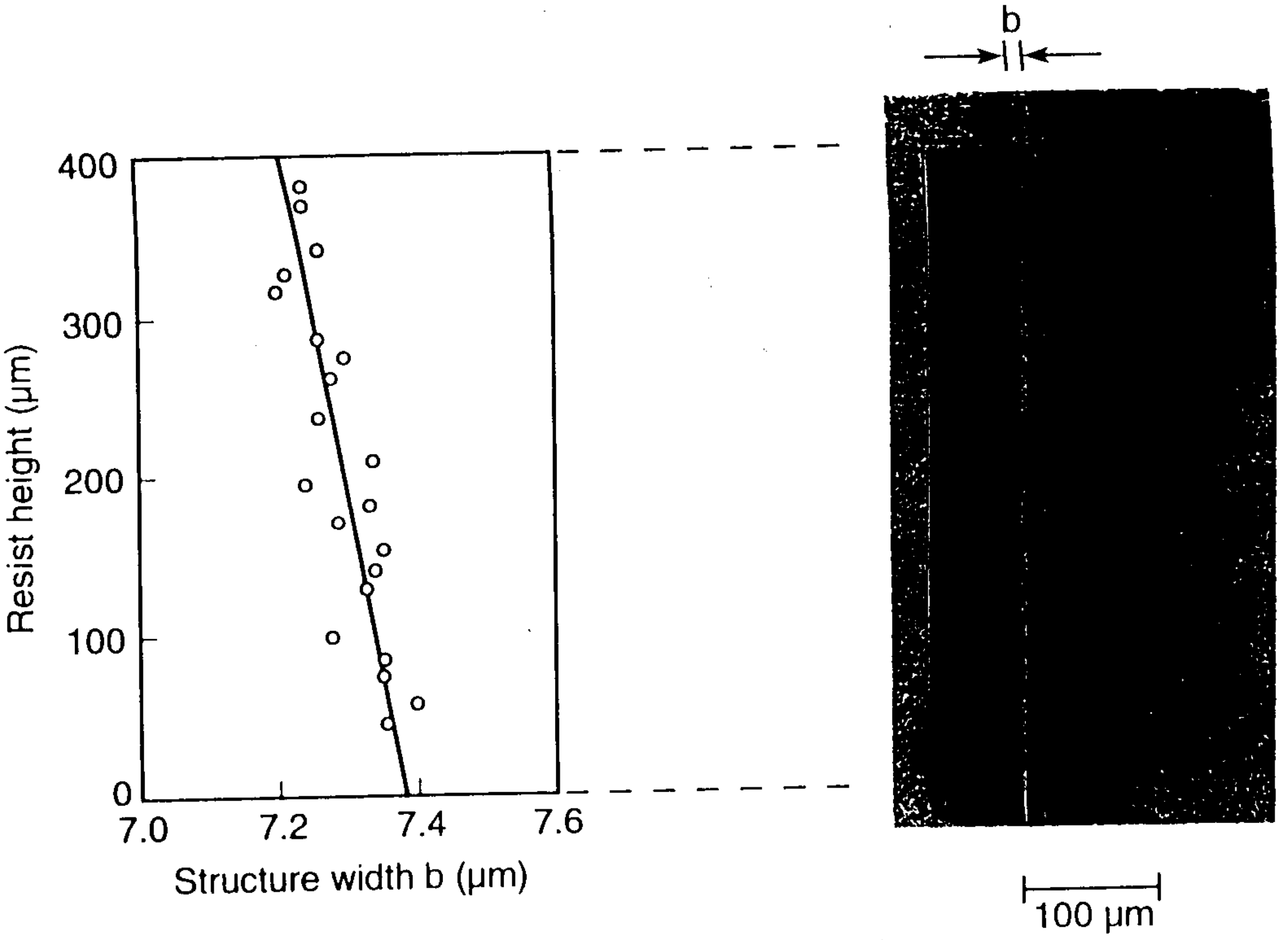
LIGA CHARACTERISTICS (1)

- **High aspect ratio**
  - Structural height: several 100 µm to cm
  - Minimum lateral dimension in micron range
- **Excellent replication quality**
  - High precision micro-parts with submicron tolerances
  - Accurate mold inserts
- **Large variety of materials**
  - Metals, alloys, plastics, ceramics, glass, composites
- **Large variety of shapes**
  - No restriction on 2-D patterning
  - Sloped and different height structures
- **Large variety of substrates**
- **Multiple levels with alignment possible**

LIGA CHARACTERISTICS (2)

- **Integration/compatibility with other processes**
  - Conventional and non conventional micromachining
    - + Mix and Match with other lithographic techniques
    - + Integration with silicon micromachining
      - Surface micromachining: Sacrificial layer technique
        - Released parts
        - Free/flexible structures
      - Bulk micromachining
        - Membrane
  - Electronics
  - Molding
  - Assembly
- **Batch process for mass fabrication**

Structural Accuracy of Deep X-ray Lithography



Source: KfK, Karlsruhe, Germany

LIGA PROCESSING CONSIDERATIONS (2)

- What people need to know about a process:
  - Minimum line width (w). Dependent on:
    - Resist thickness
    - Microstructure length
    - Fill density
  - Orthogonality of pattern
  - Sidewall run-out (Δw/resist thickness)
  - Surface smoothness
  - Adhesion of resist to substrate
  - Mechanical integrity of resist
  - Insensitivity to following processes (thermal, etc.)

LIGA in an Industrial Environment

- **At your worksite**
  - Device design
  - Process simulation
  - Substrate preparation
  - Resist coating
  - Resist development
  - Characterization
- **At the synchrotron**
  - X-ray exposure
- **At your worksite**
  - Electroforming
  - Planarization
  - Injection molding
- **Mass production at your worksite**

  Far from synchrotron source

  Small and medium size companies

EVALUATION OF LIGA PROCESS SEQUENCES

Level of difficulty (scale 1 to 5)	Processing step
2	Resist preparation
2	Mask making
1	X-ray exposure
1	Development
3	Electroforming
4	Replication

3-D MICROFABRICATION TECHNOLOGIES

- Silicon micromachining

limited pattern design geometry (orientation dependent etching)

- Basic LIGA process and variants: "LIGA-like processes"

high aspect ratio

high accuracy

variety of materials through replication processes

- Photoforming

truly 3-D

limited resolution

- Deep reactive ion etching

limited depth, vertical walls

no alignment of one level to the next

Competing emerging technologies

LIGA for a long time (10 years) was the only way to get arbitrary shapes with significant thickness. Now, with low heights (< 200 μm), it is vulnerable to competition from:

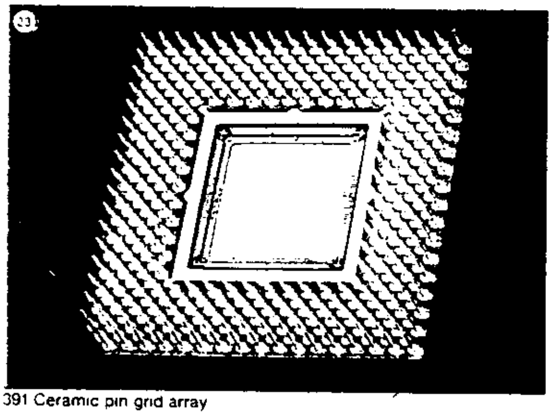
- **Stamping**
  - Batch process, very cost-effective but limited sumicron tolerance
- **Optical lithography with thick resist**
  - Batch process. Sloped walls, limited height (exception SU8)
- **Deep reactive ion etching**
  - Cooling of substrate, limited height
- **Micro-Electro-Discharge Machining**
  - Issues with pattern complexity and tolerance
- **Precision milling**
  - Serial process, limited resolution
- **Bulk silicon micromachining**
  - Batch process, but shapes limited by crystallographic axes
- **Stereo-lithography**
  - Serial process, limited resolution

Fields of application of LIGA

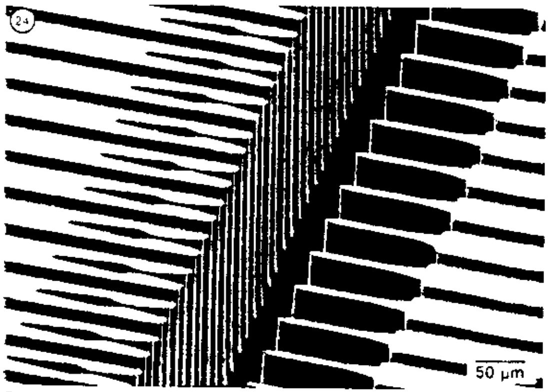
- Broad market
    - HAR-MEMS
        - + larger actuation force
          motor with higher torque
        - + stiffer structures
    - Micro-parts with very higher tolerance
        - + where assembly is needed
        - + gear boxes
    - Wide variety of materials through replication processes

LIGA Products

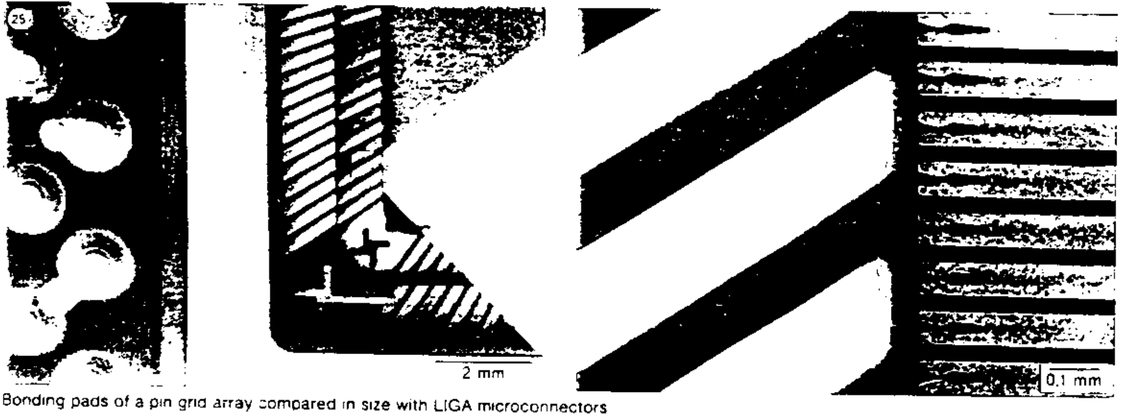
- Microsensors
- Microactuators and robotics
- Electronics
- Microoptics, fiber optics and integrated optics
- Fluid technology
- Bio-engineering and medical technology
- Packaging



391 Ceramic pin grid array

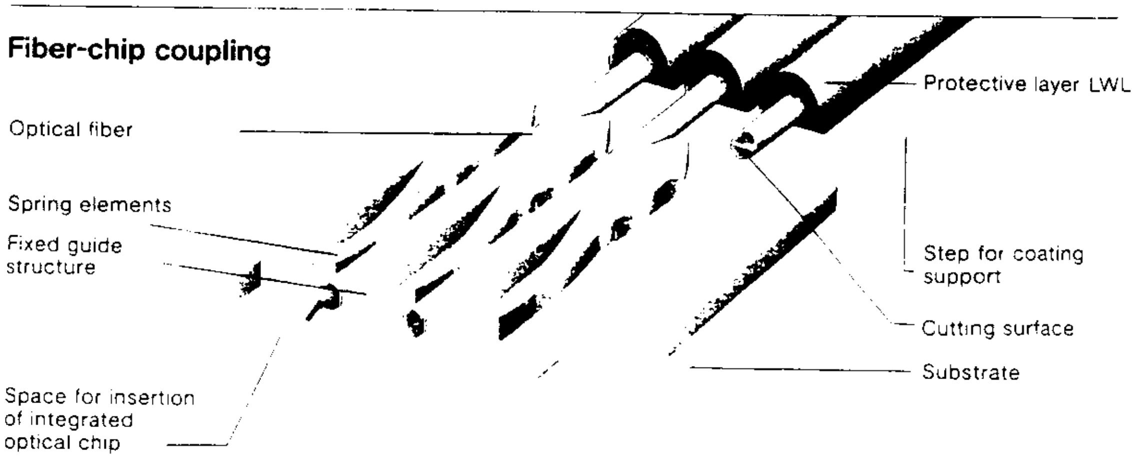


Detachable microconnector



Bonding pads of a pin grid array compared in size with LIGA microconnectors

Fiber-chip coupling



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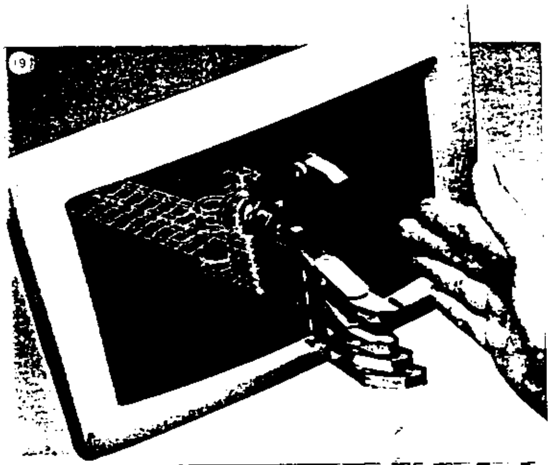
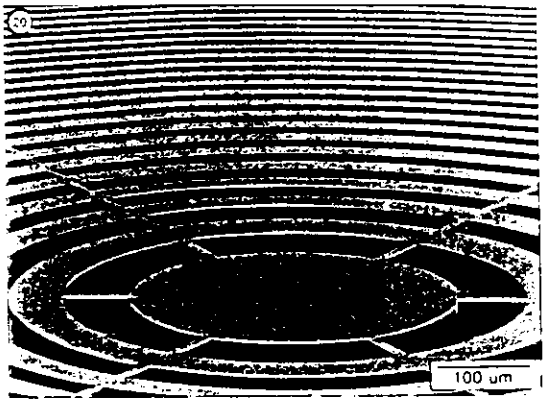
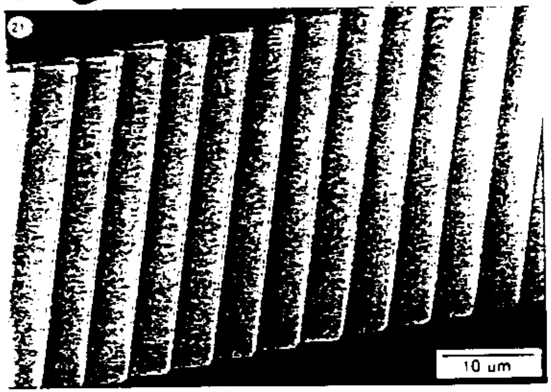
MicroParts





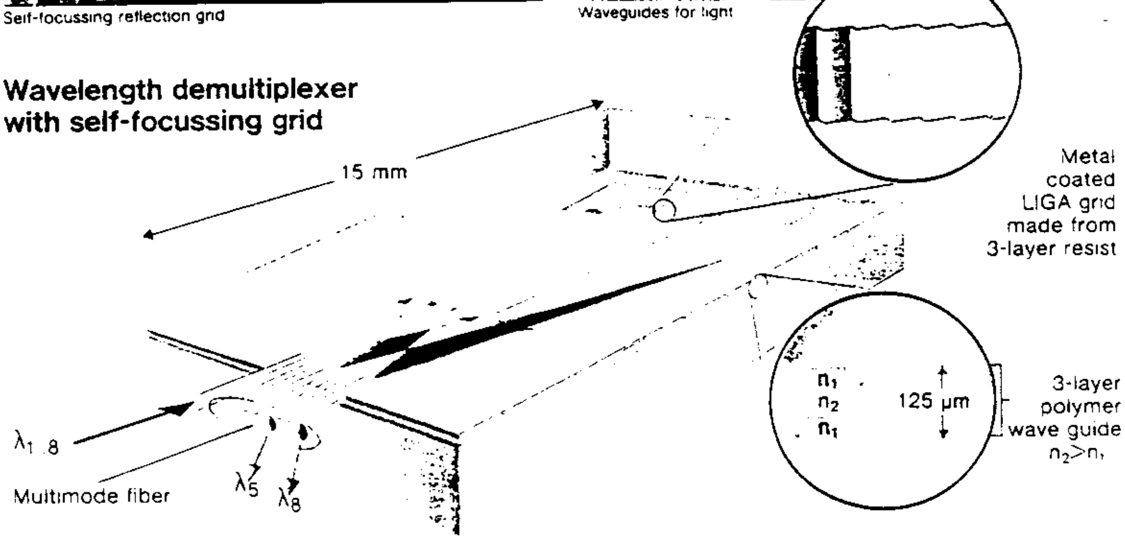
Fresnel zone plate



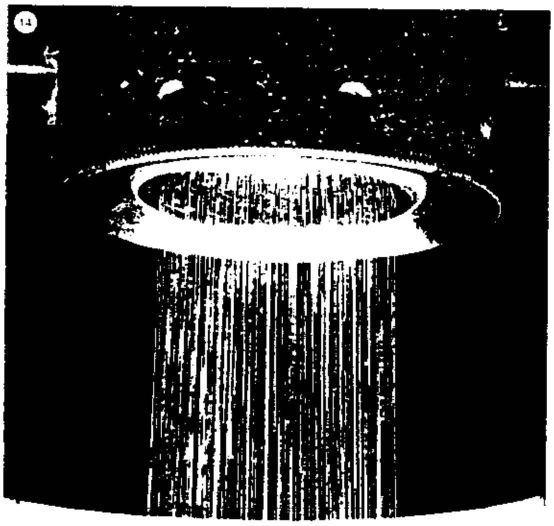
Self-focussing reflection grid

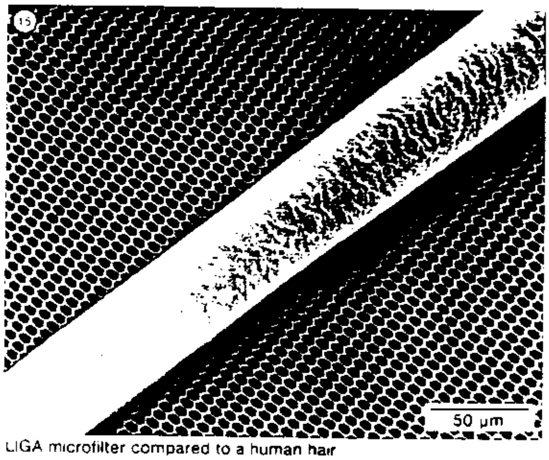
Waveguides for light

Wavelength demultiplexer with self-focussing grid



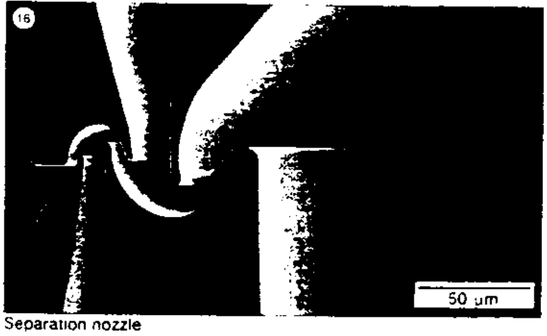
MicroParts



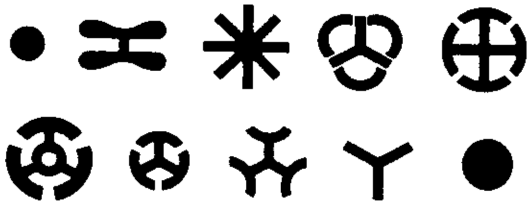


LIGA microfilter compared to a human hair

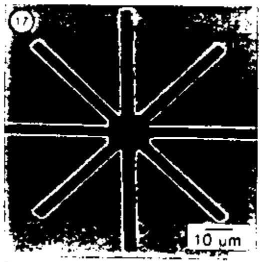
● Uniform pore size	→ Sharp separation boundary
● Extremely high porosity	→ High filtration flow
● Designable pore shape	→ Optimized filtration characteristics
● constant channel cross-section	→ Ideal surface filter
● Integrated supporting structures	→ High strength
● Wide range of materials	→ Suitable for corrosive media → Suitable for high temperatures



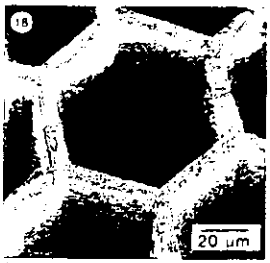
Separation nozzle



Examples for spinneret nozzle profiles



Spinneret nozzle



Ceramic honeycomb

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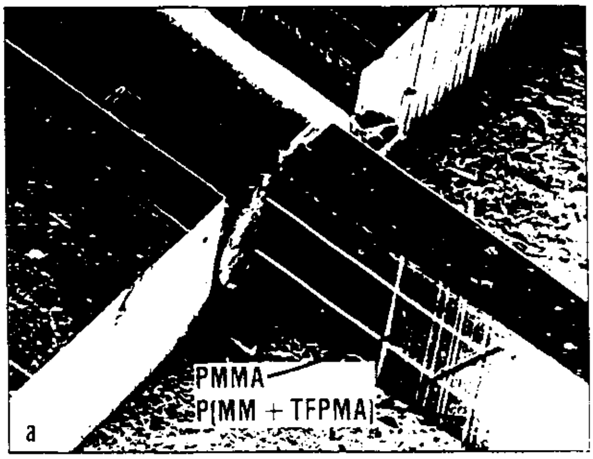
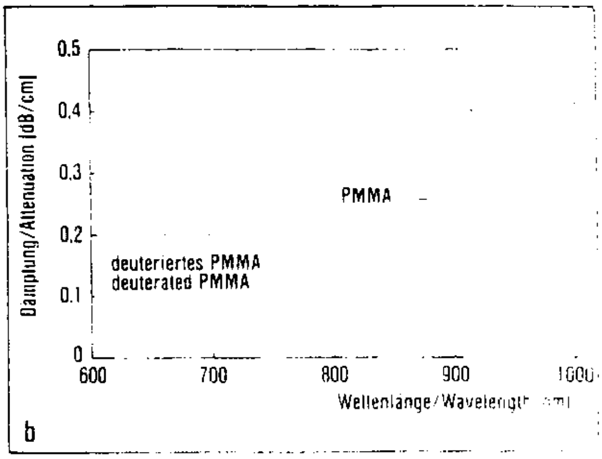


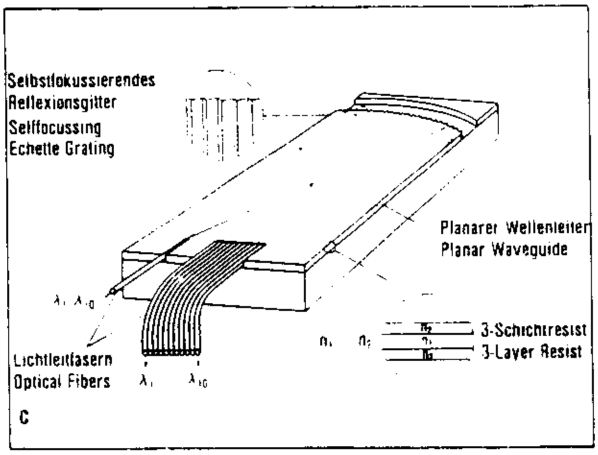
Mit Röntgentiefenlithographie strukturierter Streifenwellenleiter (3-Schichtresistsystem)

Planar waveguide fabricated by deep-etch X-ray lithography (3-layer resist system)



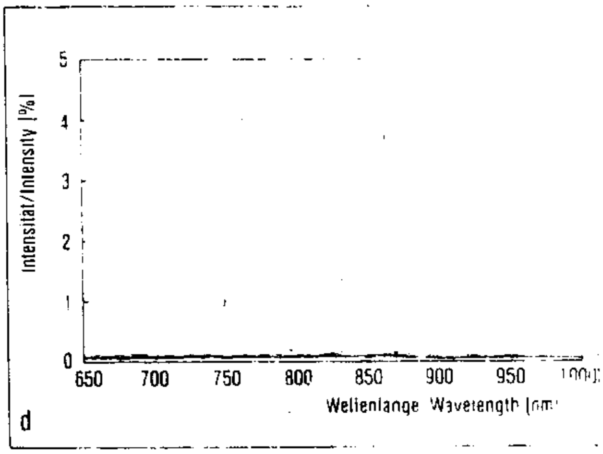
Lichtdämpfung von Streifenwellenleitern in Abhängigkeit von der Wellenlänge

Attenuation of planar waveguides as a function of the wavelength



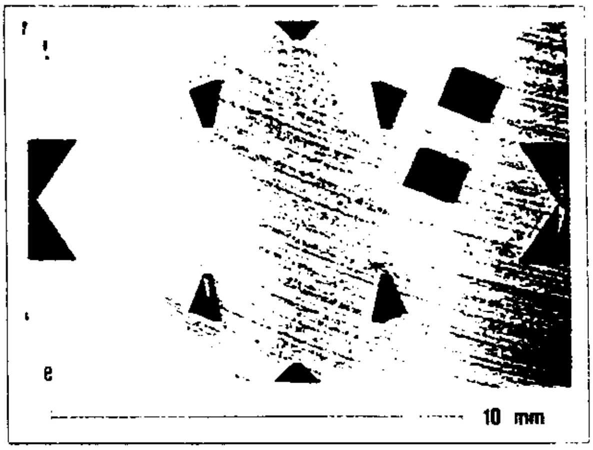
Prinzip eines planaren Gitterspektrographen

General layout of a planar grating spectrograph



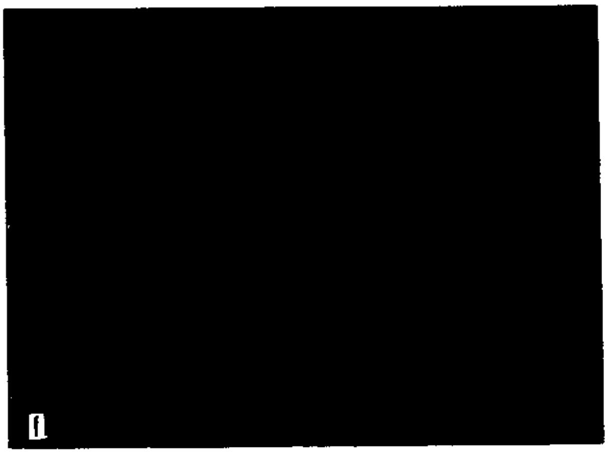
Gemessene Intensität in den 10 Kanälen des planaren Gitterspektrographen

Intensities measured in the 10 channels of the planar grating spectrograph



Durch Röntgentiefenlithographie hergestellte Mikroprismen

Microprisms fabricated by deep-etch X-ray lithography

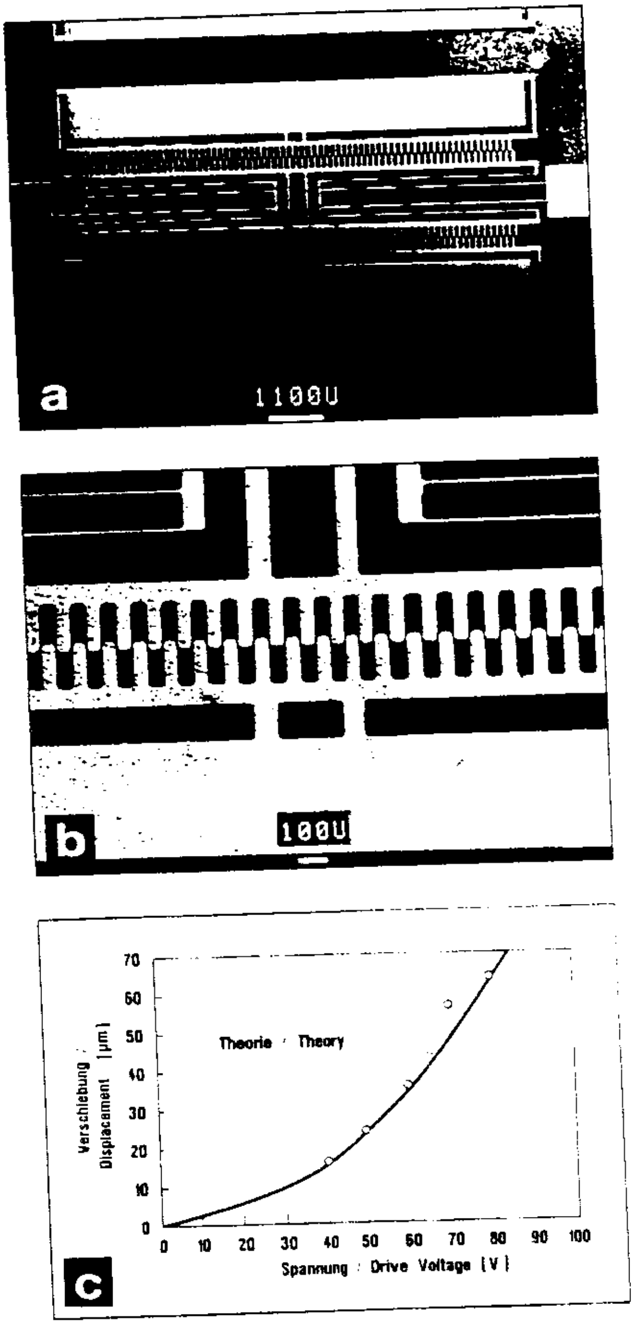


Strahlenverlauf durch die mikrooptische Bank

Light path through this microoptical beam system

CKП 3.46

KfK

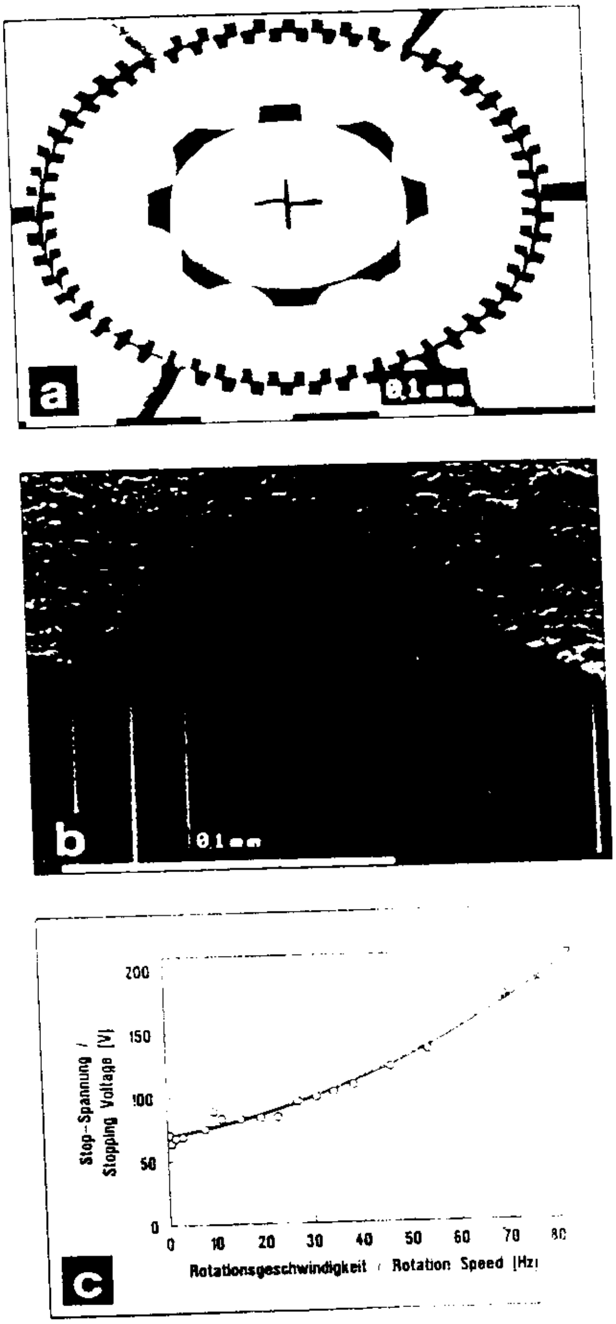


Elektrostatischer Linearantrieb

Gesamtansicht (a) und Detail der Kammstruktur aus Nickel (b) sowie gemessene Verschiebung als Funktion der angelegten Spannung (c). Höhe 70 µm, Breite der Kammstrukturen 50 µm. Spaltbreite der Kondensatoren 5 µm.

Electrostatic linear actuator

Full view (a), detail of the comb elements made of nickel (b), and measured displacement as a function of the applied voltage. Height 70 µm, width of the comb elements 50 µm, width of the capacitor gaps 5 µm



Elektrostatischer Motor

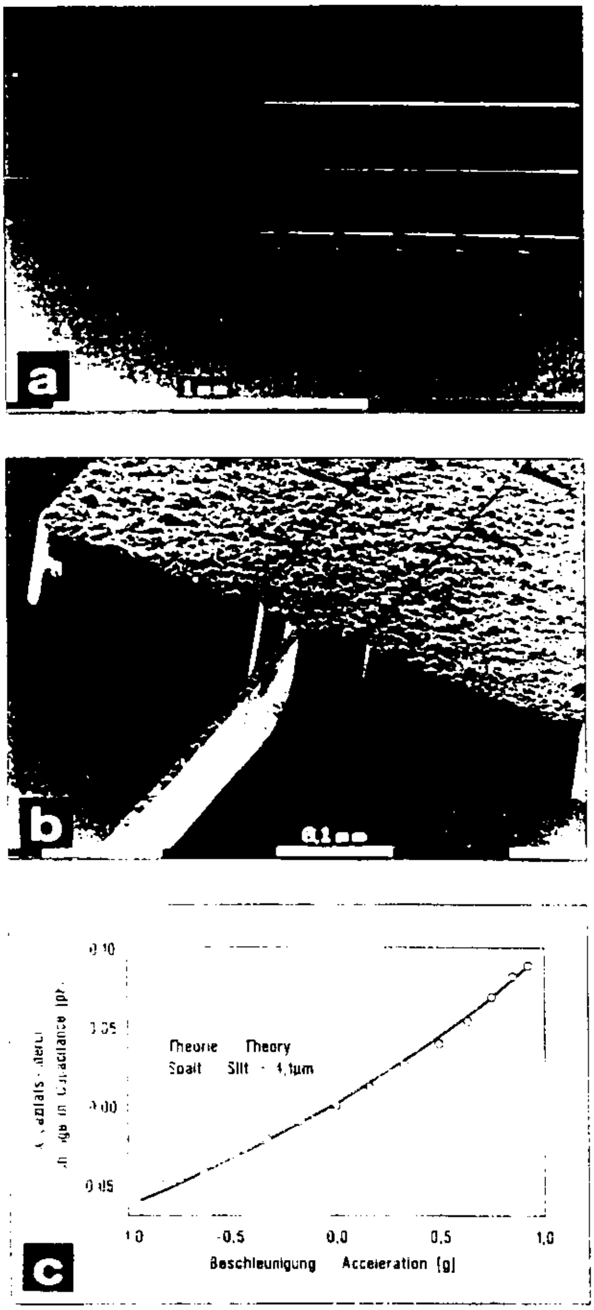
Aufsicht auf einen elektrostatischen Schrittmotor mit gewelltem Lager (a), Detail der gezahnten Kondensatoren (b) und gemessene Minimalspannung, die den Motor mit einer vorgegebenen Geschwindigkeit am Laufen hält (c). Höhe 100 µm. Durchmesser des Rotors 535 µm, engster Spalt zwischen Rotor und Achse 4,5 µm

Electrostatic motor

View of the top of an electrostatic stepping motor with corrugated bearing (a), detail of toothed capacitor (b), and the measured minimum voltage required to keep the motor rotating at a given speed (c). Height 100 µm, diameter of the rotor 535 µm, minimum gap between rotor and stator 4,5 µm

KBK

[illegible]

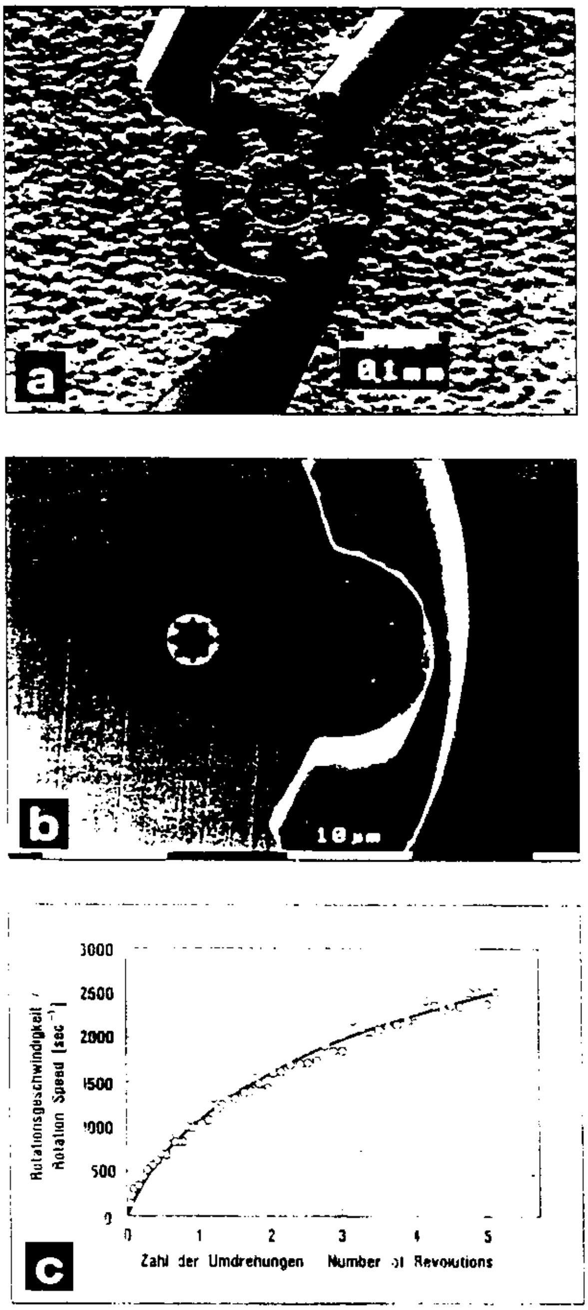


Beschleunigungssensor

PMMA Form nach der Röntgentiefenlithographie (a) Detail der Nickel-Struktur (b) und gemessene Signaländerung beim Drehen des Sensors im Schwerefeld der Erde (c) Höhe 100 µm. Breite der Biegezunge 10 µm, Spaltbreite 4 µm

Acceleration Sensor

PMMA template made by X-ray lithography (a), detail of the nickel structure (b), and change in capacitance measured by tilting the sensor in the earth's gravitational field Height 100 µm. width of the cantilever 10 µm width of the slit 4 µm



Mikroturbine

Nickelstruktur mit integrierter optischer Faser zur Drehzahlmessung (a), Detailaufnahme eines Lagers aus Kupfer mit Wellenstruktur (b) und gemessene Rotationsgeschwindigkeit während eines Anlaufvorgangs in einem Gasstrom (c)

Microturbine

Nickel microstructure with integrated optical fiber to measure rotation speed (a), detail of a corrugated bearing (b), and measured rotation speed in a gas stream during start up phase (c)

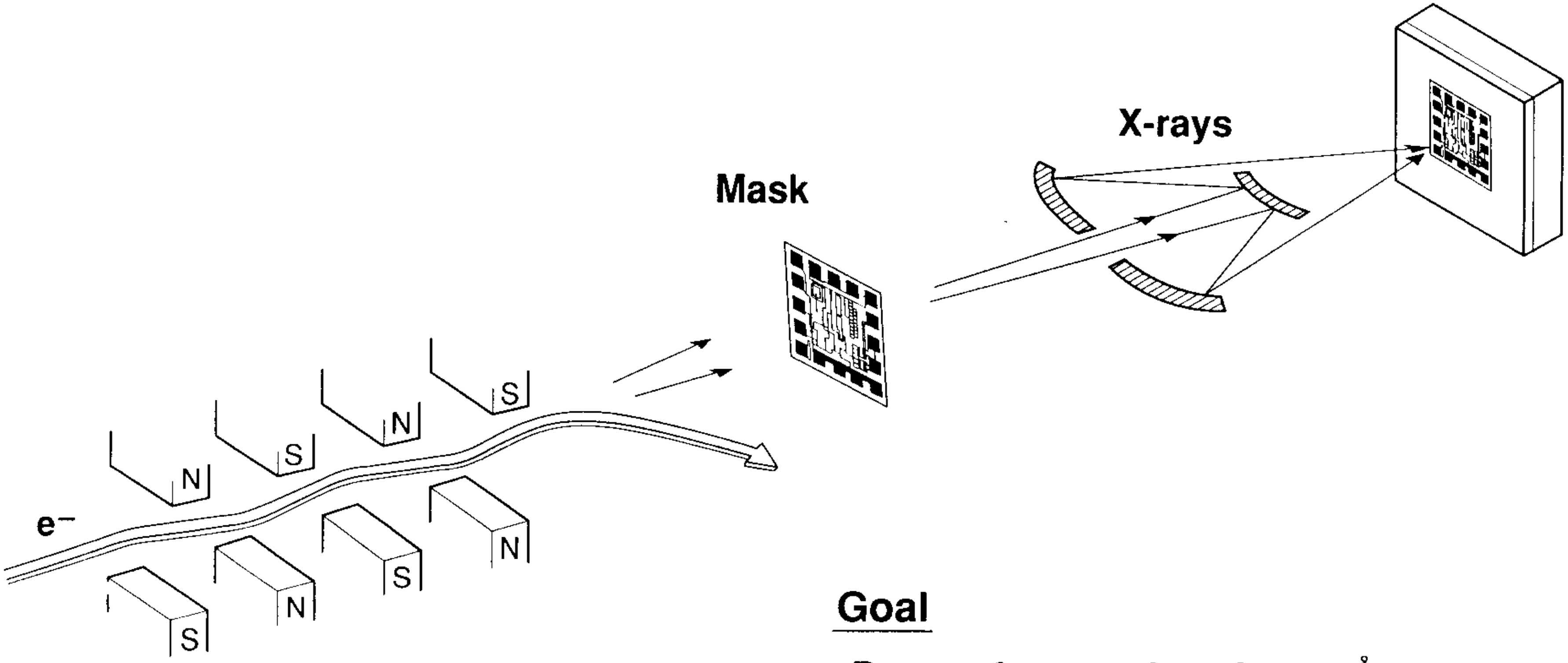
KfK

CKП3 49

EUV·

~~Reduction X-ray~~ Lithography Using Reflective Optics

(CXRO/LBL and CXRL/U.Wisc.)

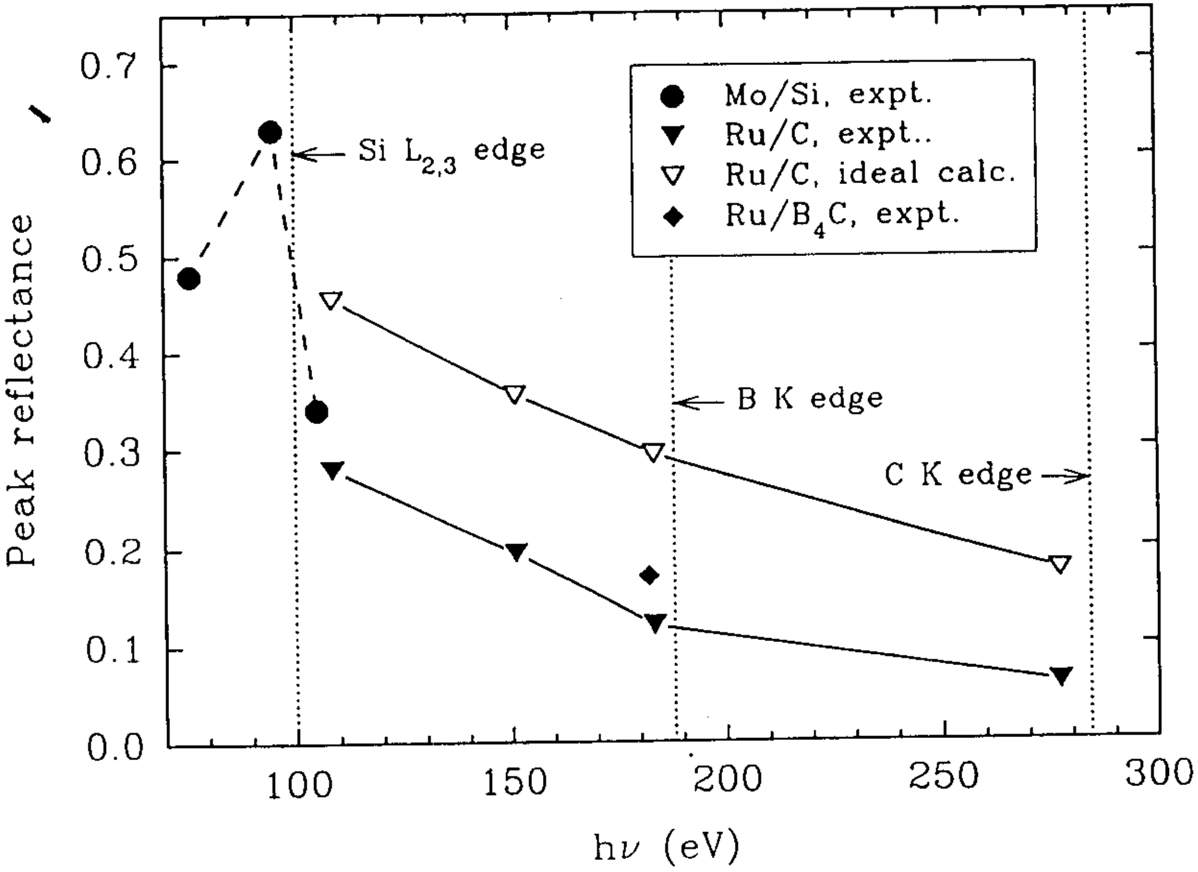


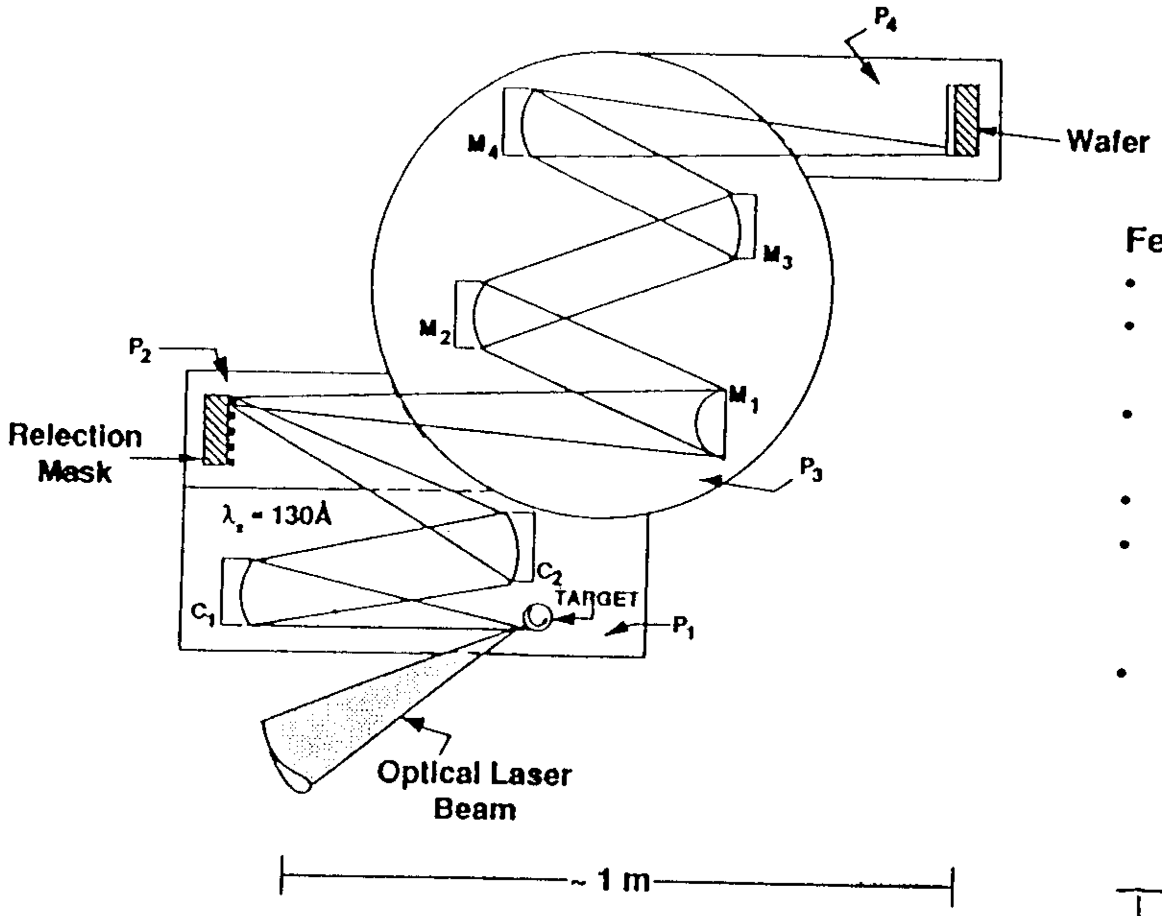
Goal

- Pattern feature size of 1000 Å

XBL 898-6588A

Summary of normal-incidence reflectance: measured performance becomes farther from ideal as λ decreases.





C_1, C_2: condenser optics
M_1, M_2, M_3, M_4: imaging optics
P_1, P_2, P_3, P_4: four different vacuum environments

Features:

- Step and scan exposure
- X-ray source: laser produced plasma
- 4 component, precision imaging system
- X-ray reflection mask
- 7 reflecting surfaces and 3 vacuum windows between x-ray source and wafer
- 5x reduction

Problems:

$T = R^7$ $\overset{\nabla}{\circ}$

Surface Fig. Accuracy ~5-8 Å $\overset{\nabla}{\circ}$