Deep Lithography for Microfabrication

Part 1: Deep X-ray Lithography (DXRL)

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  - METALFOTO LTDA.
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  - Post doctorate: Julio Fernandes

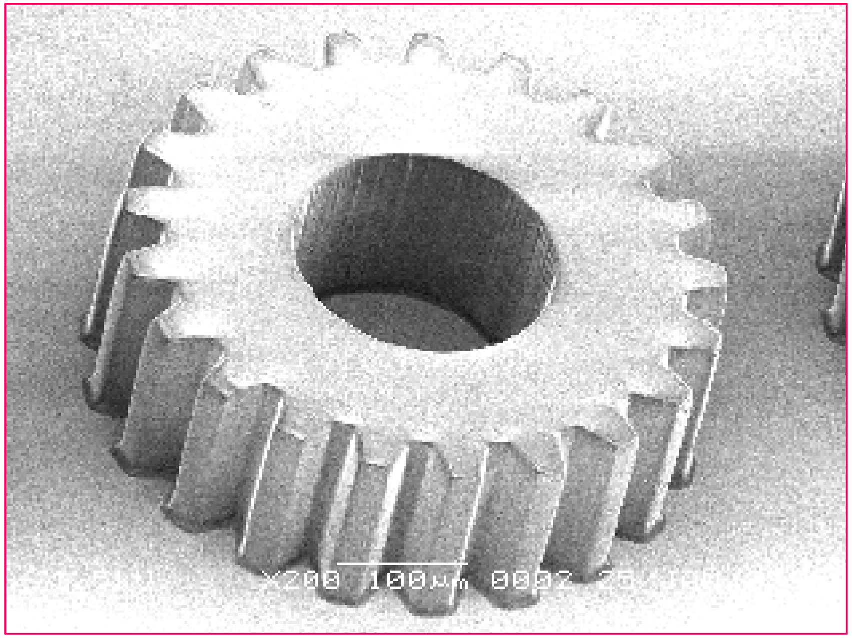
Presentation Outline

- Introduction
- History
- X-ray sources
- Resists
- Masks
- Irradiation
- Development
- DXRL on SU-8

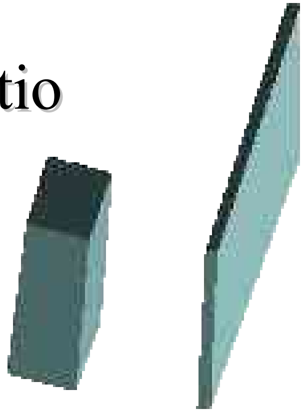
Introduction

- Challenges:
  - To startup a LIGA microfabrication laboratory at the Brazilian Syncrotron Facility – LNLS.
  - To create a LIGA prototyping service like LIGA-MUMPS at LNLS.

Deep X-ray Lithography



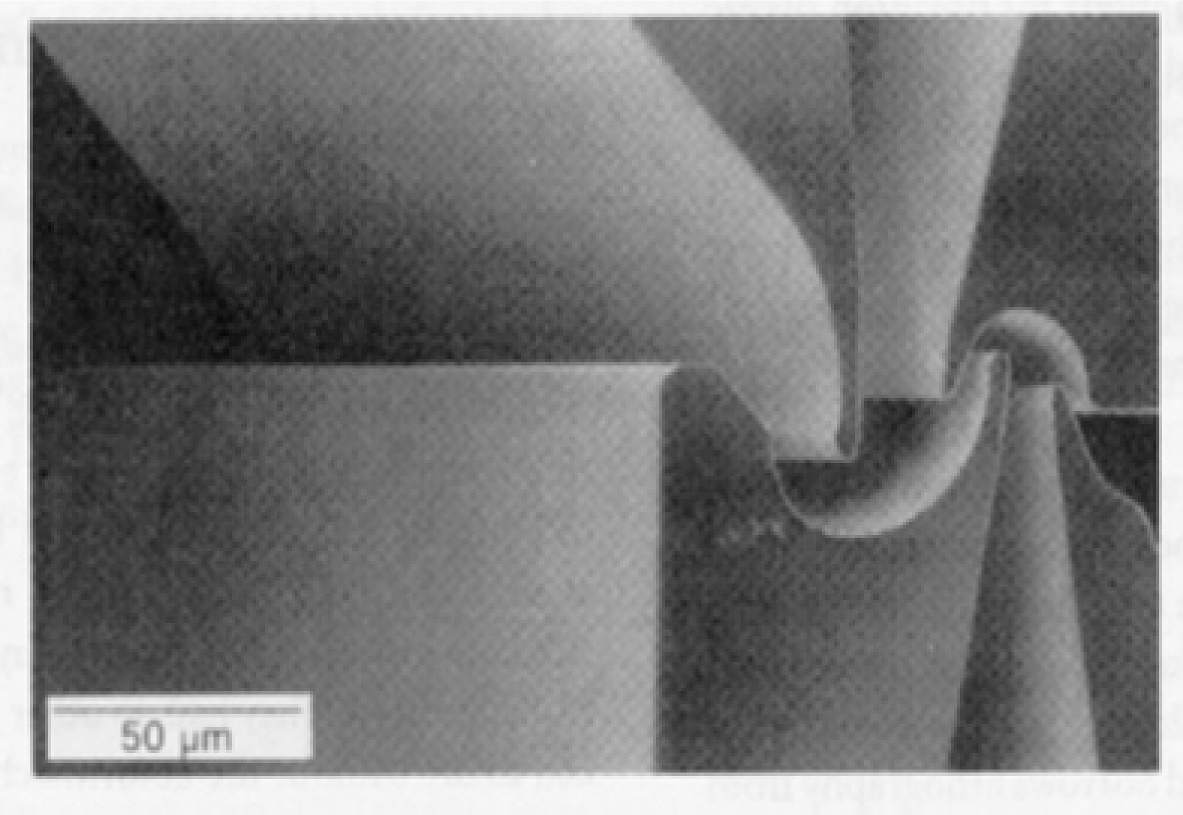
- Main direct application of synchrotron radiation on technology.
- Thick films
- Highly 3D.
- High-aspect-ratio



History

- 1982 – Ehrfeld – KfK (Karlshure Nuclear Research Center – Germany)
  - LIGA process: Lithographie Galvanoformung Abformtechnik (Lithography, Electroforming and Molding)
  - Replaced molding for DXRL on mass production.

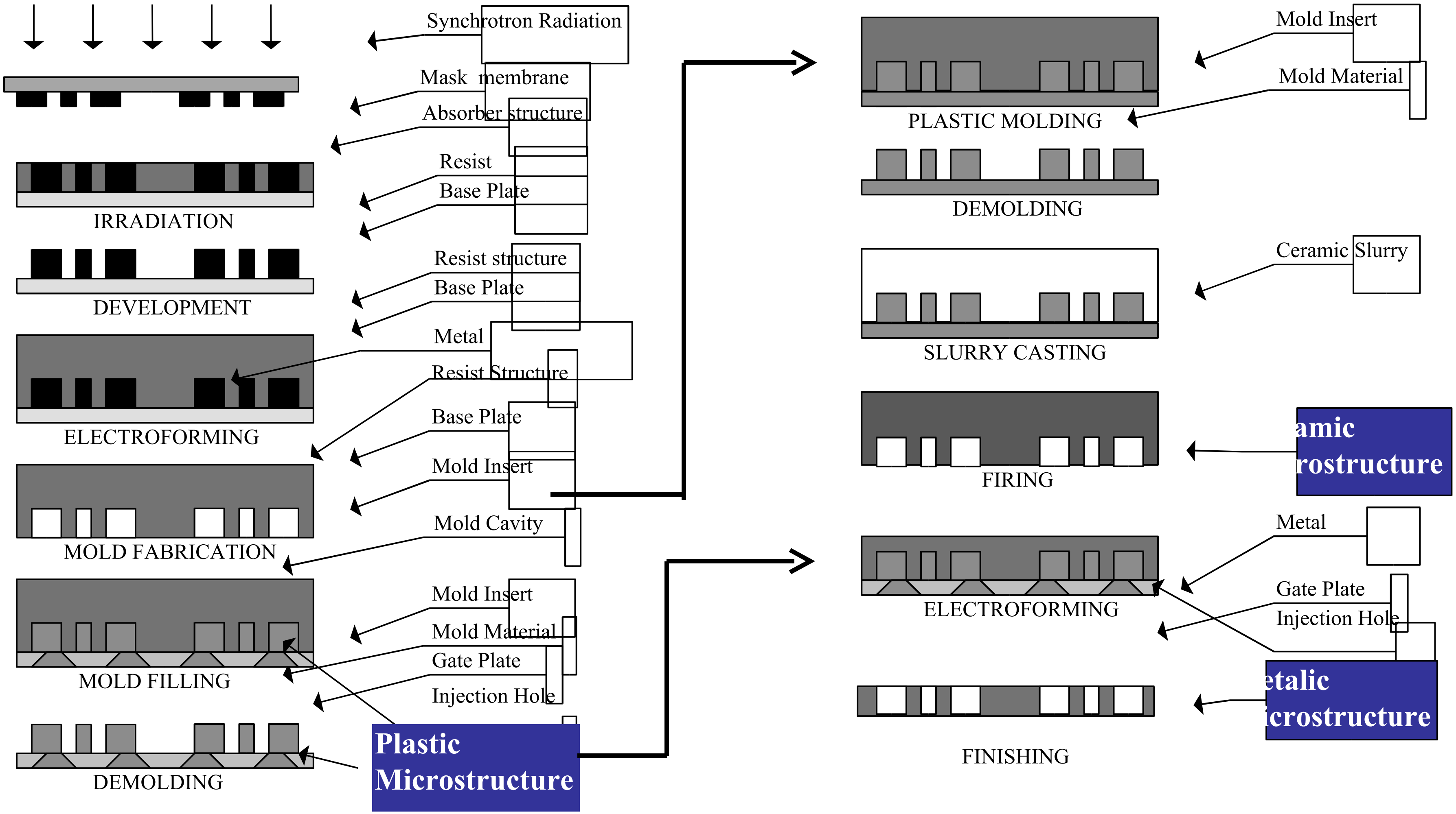
1st LIGA device



- Uranium isotope separation nozzles.

From: Madou, Marc J.; **Fundamentals of Microfabrication**, CRC Press, 1997

LIGA Process Flowchart



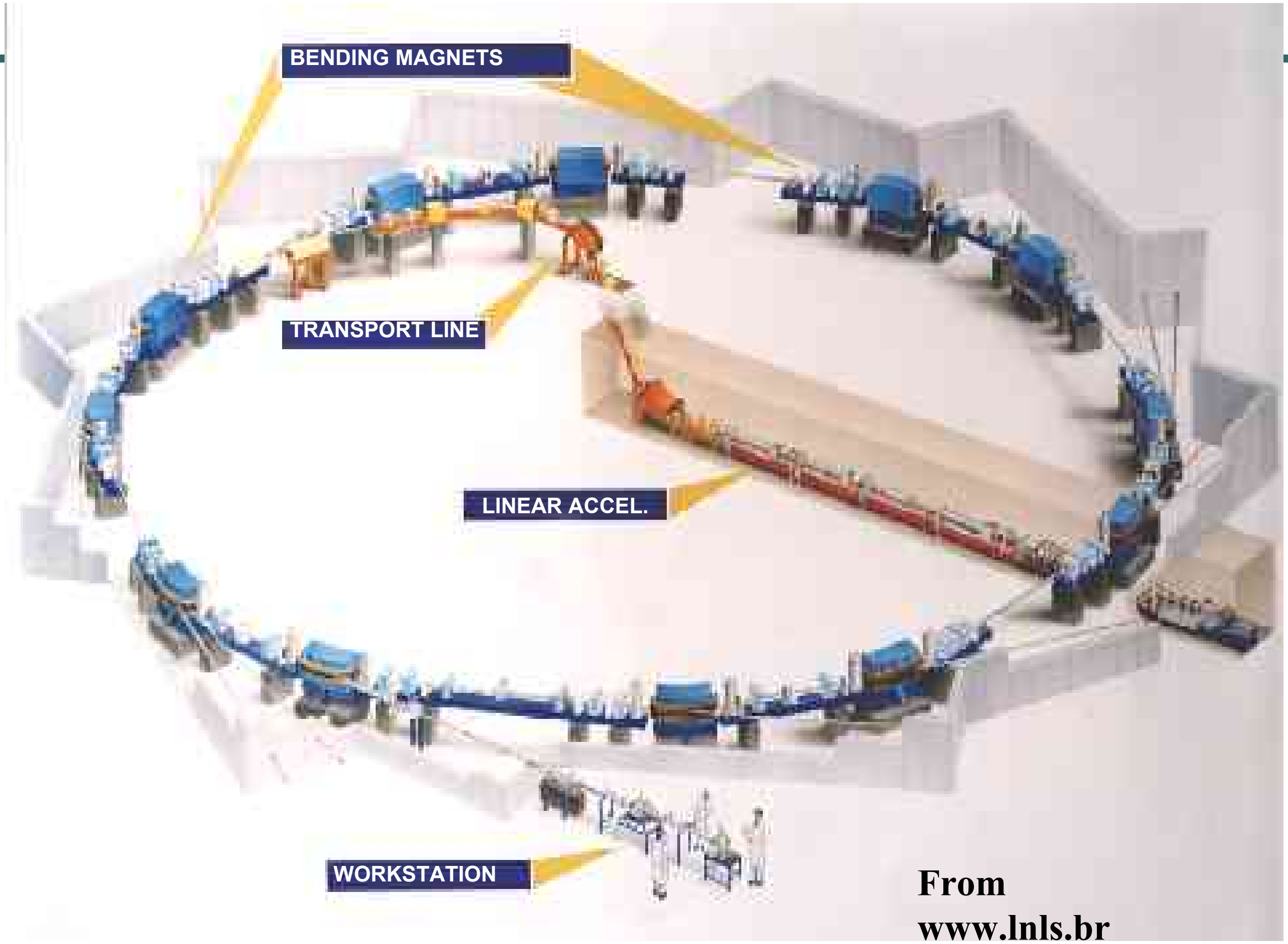
Adapted from: W. Ehrfeld and H. Lehr, “Deep X-ray lithography for the production of three-dimensional microstructures from metals, polymers and ceramics”,*Radiat. Phys. Chem*., Vol. 45, No. 3, pp. 349-365, 1995

X-ray Source for DXRL

- Synchrotrons are the prefered source
  - Wavelenght: 2 – 10Å
  - Highly colimated photons beam
  - High photon flux

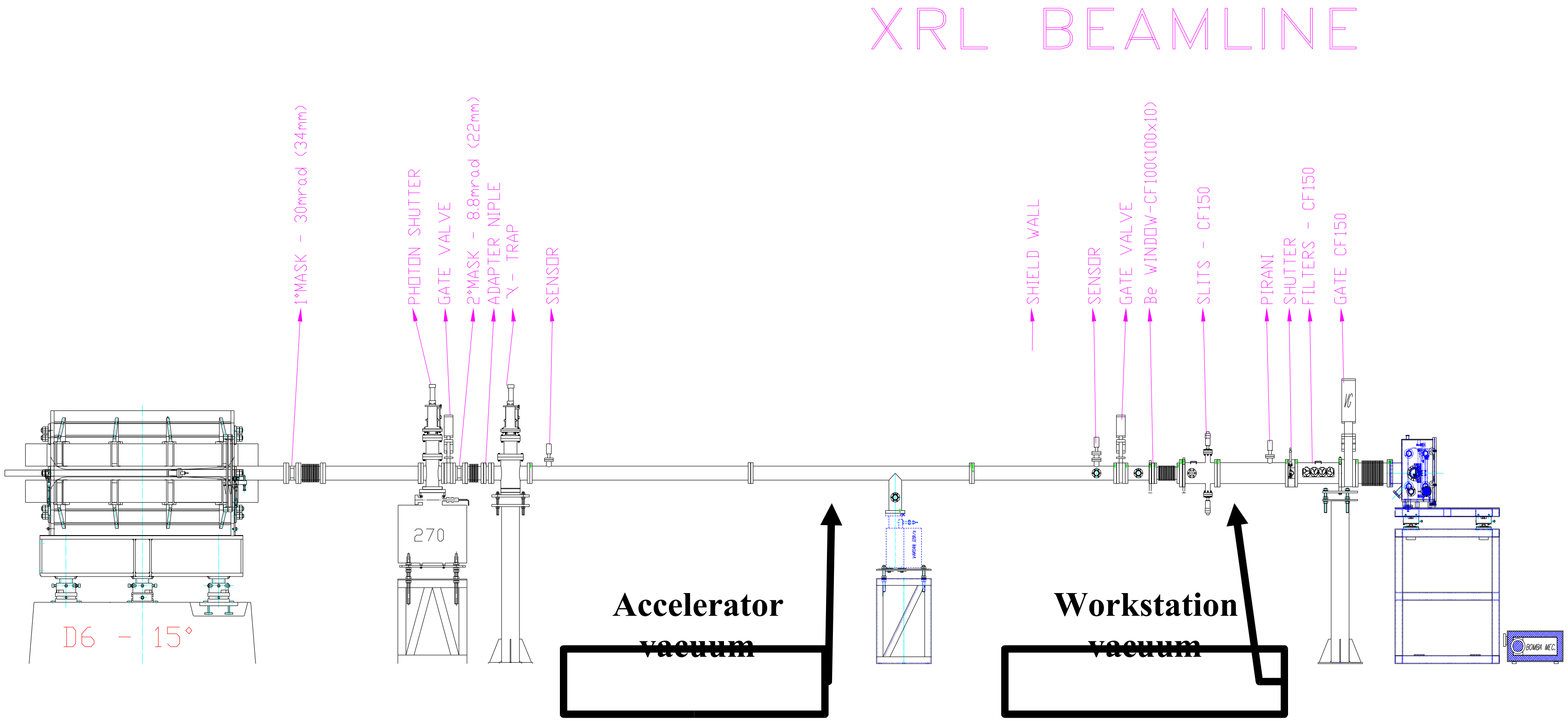
A Synchrotron X-ray Source

The Brazilian Synchrotron Facility (LNLS)



From www.lnls.br

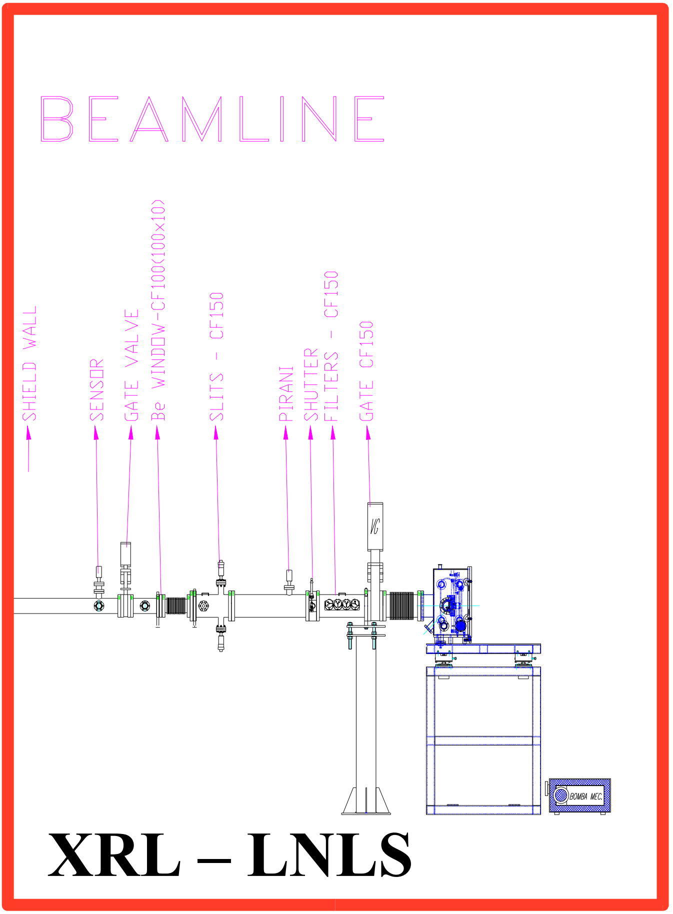
Specifying the XRL beamline



The XRL beamline at the Brazilian Synchrotron Facility – LNLS

1.37GeV @ 100mA; 100 mm X 3 mm beam; 10 m from source to exposure plane

The XRL Beamline - I



XRL – LNLS

Exposure Chamber

Filter Bank

XRL – LNLS

The XRL Exposure Chamber

- CCTV
- Computer control
- Chemicals resistant vacuum system
- Able to radiation induced etching
- Able to fluidic cooling of the sample holder
- Under laminar flow filter

Radiation Shield

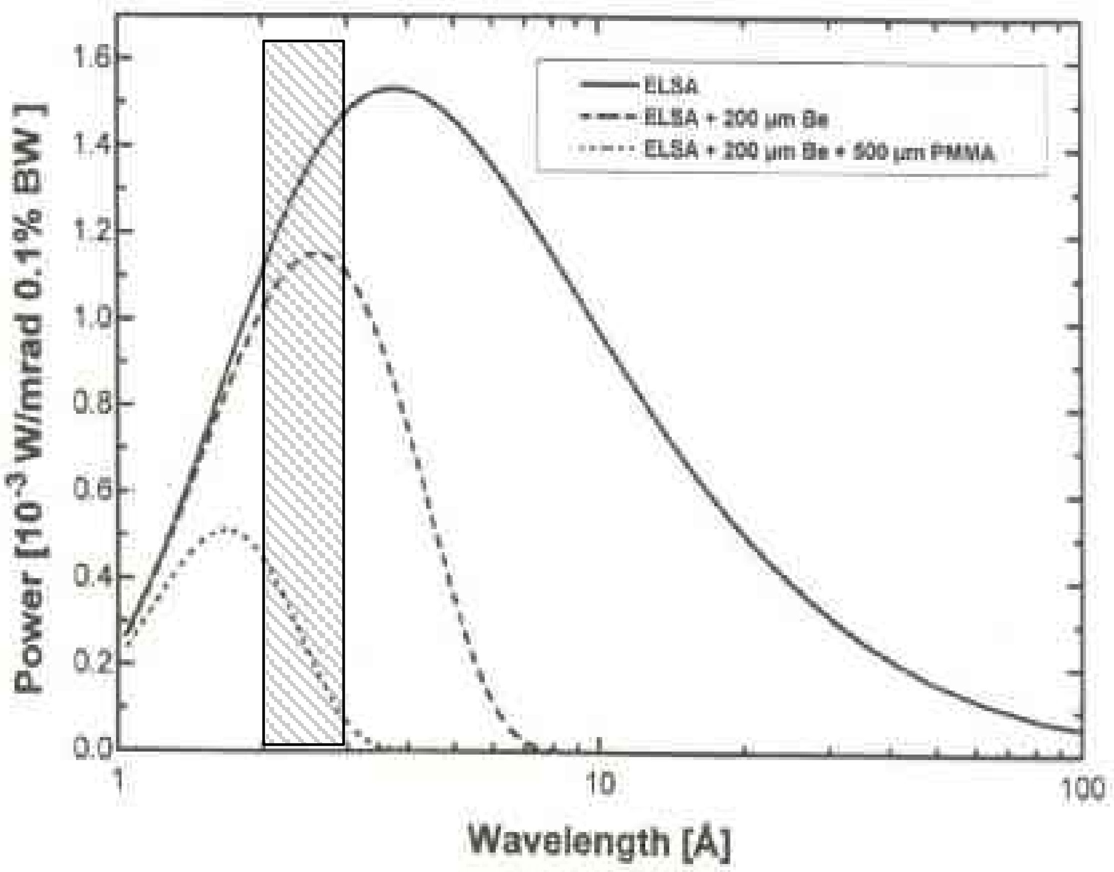
Scanner

Mask/Sample holder

The Synchrotron Radiation

- A continuum spectrum from infrared to hard X-rays.
- The band between 2 to 10 Å is the most interesting to DXRL.
- The radiation MUST be filtered to be used for DXRL.

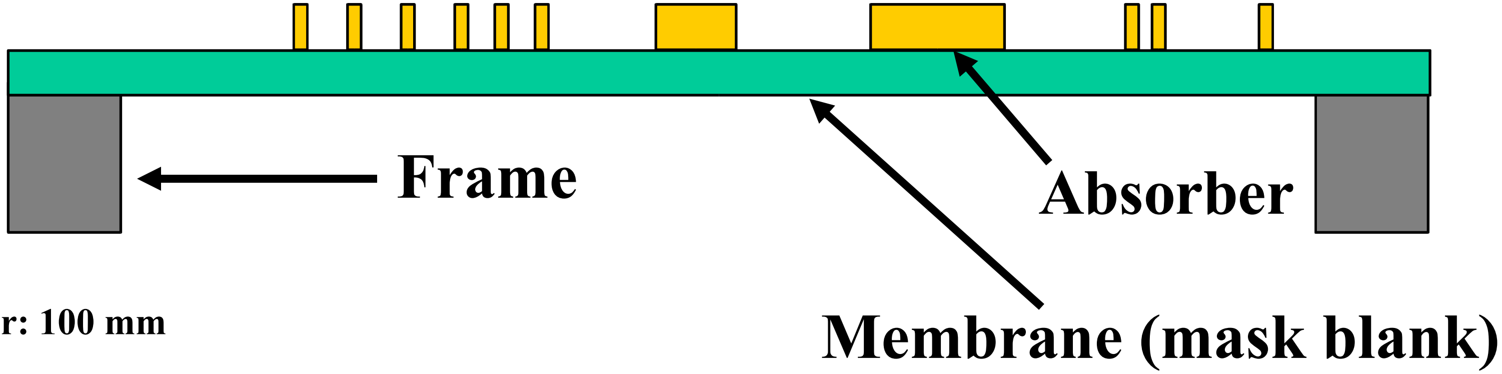
Typical Power Spectrum



- Power spectrum from the synchrotron light source ELSA (upper curve), filtered by an absorber with total thickness of 200 µm Be (middle curve) and additional 500 µm PMMA (lower curve).

From: W. Ehrfeld and H. Lehr, “Deep X-ray lithography for the production of three-dimensional microstructures from metals, polymers and ceramics”,*Radiat. Phys. Chem.*, Vol. 45, No. 3, pp. 349-365, 1995

Standard X-ray Mask



Diameter: 100 mm

Absorber: 3-15 um thick Au film (blocks X-ray)

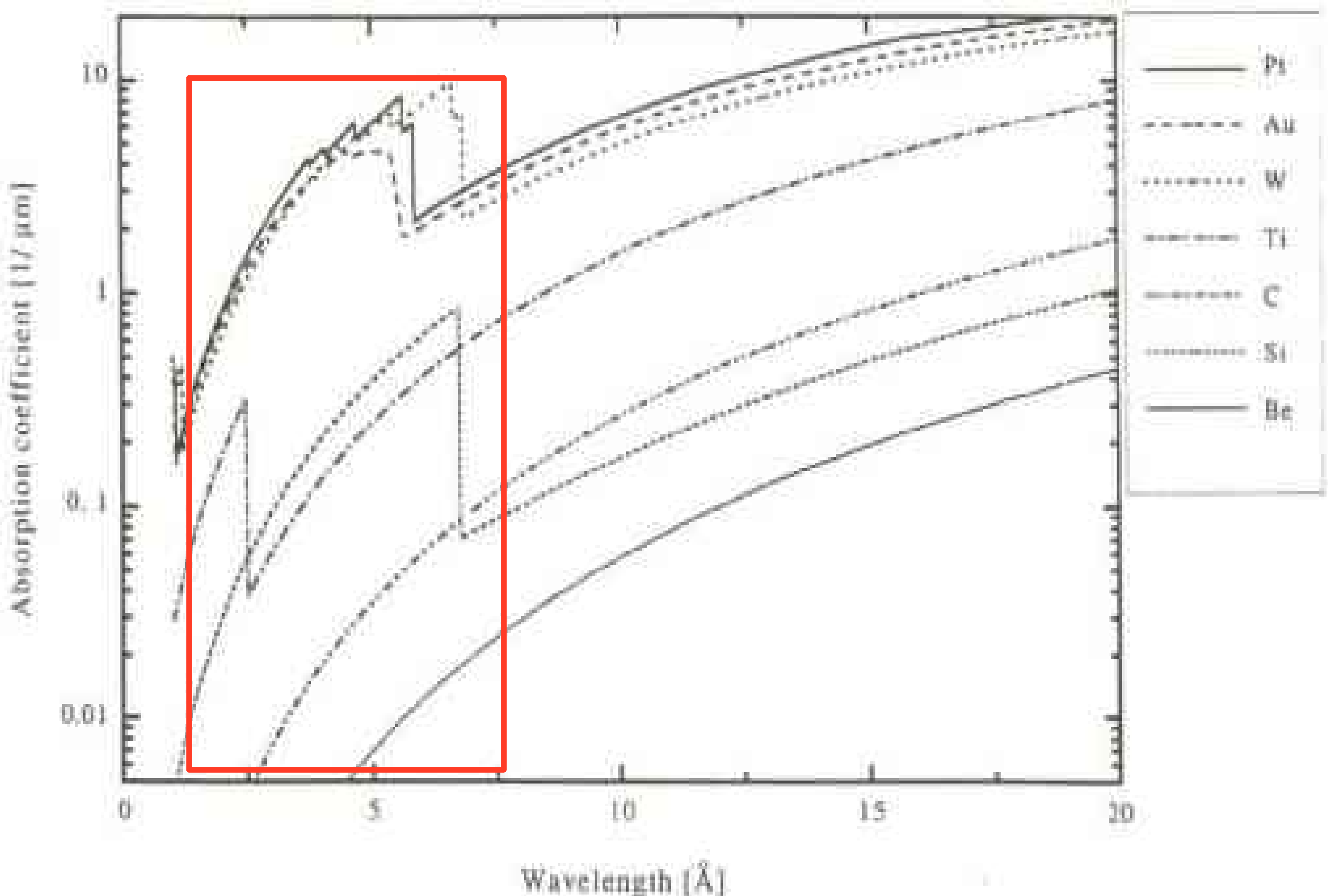
Mask blank: thin membranes transparent to X-ray
Si, SiN_x, SiC, Diamond, BN, Be, Ti

Cost: 5,000.00 to 15,000.00 (US$)

Imported: long delivery time

Fragile: risky handling

Mask Blanks and Absorbers



Absorption coefficients as function of wavelenght for elements with small atomic charge (*botiom*) and high atomic charge (*top*).

From: W. Ehrfeld and H. Lehr, "Deep X-ray lithography for the production of three-dimensional microstructures from metals, polymers and ceramics",*Radiat. Phys. Chem.*, Vol. 45, No. 3, pp. 349-365, 1995

- **The blanks must be highly transparent and resistant to radiation.**
- **The absorbers must be good absorbers and resistant to radiation.**
- **Both must be very stable.**

Mask Blanks for DXRL

Material	X-ray Transparency	Nontoxicity	Dimensional stability	Remark
Si	**0**	**++**	**0**	**Single crystal Si, well developed , radiation hard, stacking faults cause scattering, material is brittle.**
SiN_x	**0**	**++**	**0**	**Amorphous, well eveloped, radiation hard if free of oxygen, resistant to breakage.**
SiC	**+**	**++**	**++**	**Poly and amorphous, radiation resistant, some resistance to breakage,**
Diamond	**+**	**++**	**++**	**Poly, research only, highest stiffness**
BN	**+**	**++**	**0**	**Not radiation resistant, i.e., not applicable to LIGA**
Be	**++**	**-**	**++**	**Research, specially suited for LIGA; even at 100 µm the transparency is good, 30 µm typical; difficult to electroplate; toxic material**
Ti	**-**	**++**	**0**	**Research, used for LIGA, not very transparent, films must be more than 2 to 3 µm thick**

++, Excellent; +, good; 0, reasonable; -, bad; - - very bad / not existing.

Adapted from: Madou, Marc J.;**Fundamentals of Microfabrication**, CRC Press, pp. 281, 1997

Mask Absorbers for DXRL

Material	Au	W	Ta	Pt
X-ray absorption coefficient	+ +	+ +	+	+ +
Stress control	+	0	0	-
Stress stability	-	+	+	+
Thermal expansion matching to				
Be	+ +	-	-	+
Diamond	- -	+ +	+	-
Ti	+	- -	- -	+ +
Electroplating	+ +	- -	- -	-
Reactive Ion Etching	- -	+ +	+ +	- -

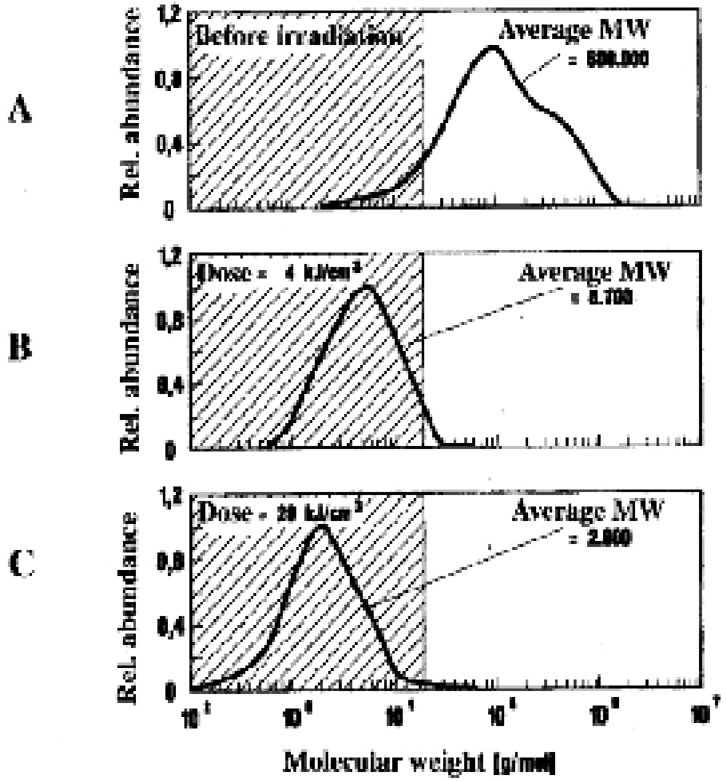
+ +, Excellent; +, good; 0, reasonable; -, bad; - - very bad / not existing.

From: W. Ehrfeld and H. Lehr, "Deep X-ray lithography for the production of three-dimensional microstructures from metals, polymers and ceramics",*Radiat. Phys. Chem.*, Vol. 45, No. 3, pp. 349-365, 1995

Resist for DXRL

- ❑ PMMA (polymethylmetacrylate) is the most used.
  - The best quality resist.
  - High resolution: fraction of microm.
  - High quality sidewalls: < 30 nm rms roughness.
  - Low sensitivity (2 kJ/cm^3 minimum dose).
  - Long exposure times.
  - Up to 100µm thick ⇒ 1-3 keV energy.
  - From 100µm to 500µm thick ⇒ 3 - 7 keV energy.

Irradiation of PMMA



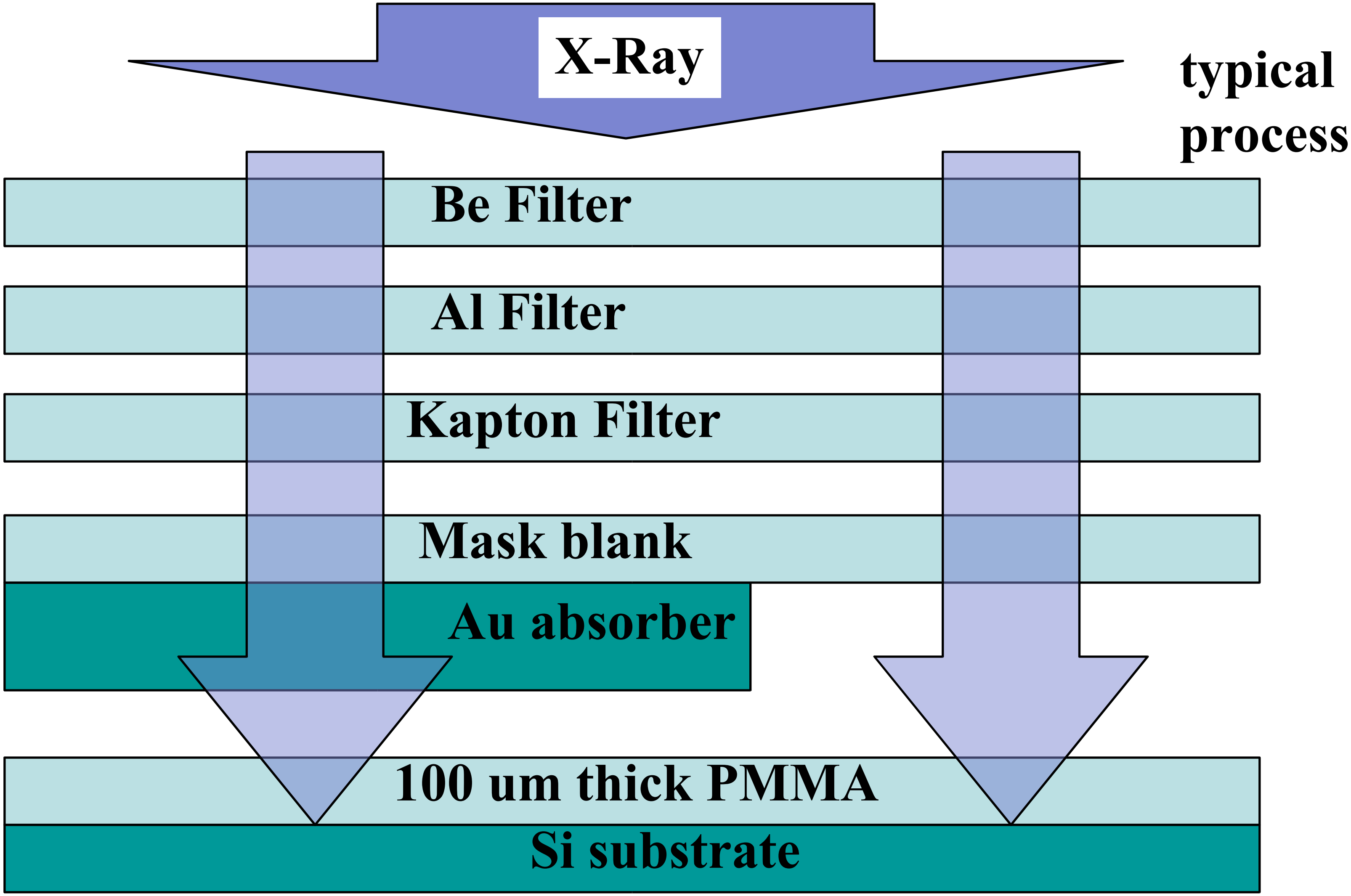
- Surface dose (D_S) <= 20 kJ/cm³
- Bottom dose >= 4 kJ/cm³ (usual value)
- Minimum dose for **development** (D_D): 2 kJ/cm³
- Maximum dose for **non-development** (D_{TH}): 100 J/cm³
- Contrast ratio of the mask (D_D / D_{TH}) > 200:1
- Typical exposure time for a 100 µm thick film: ONE HOUR

From: Madou, Marc J.; **Fundamentals of Microfabrication** CRC Press, 1997

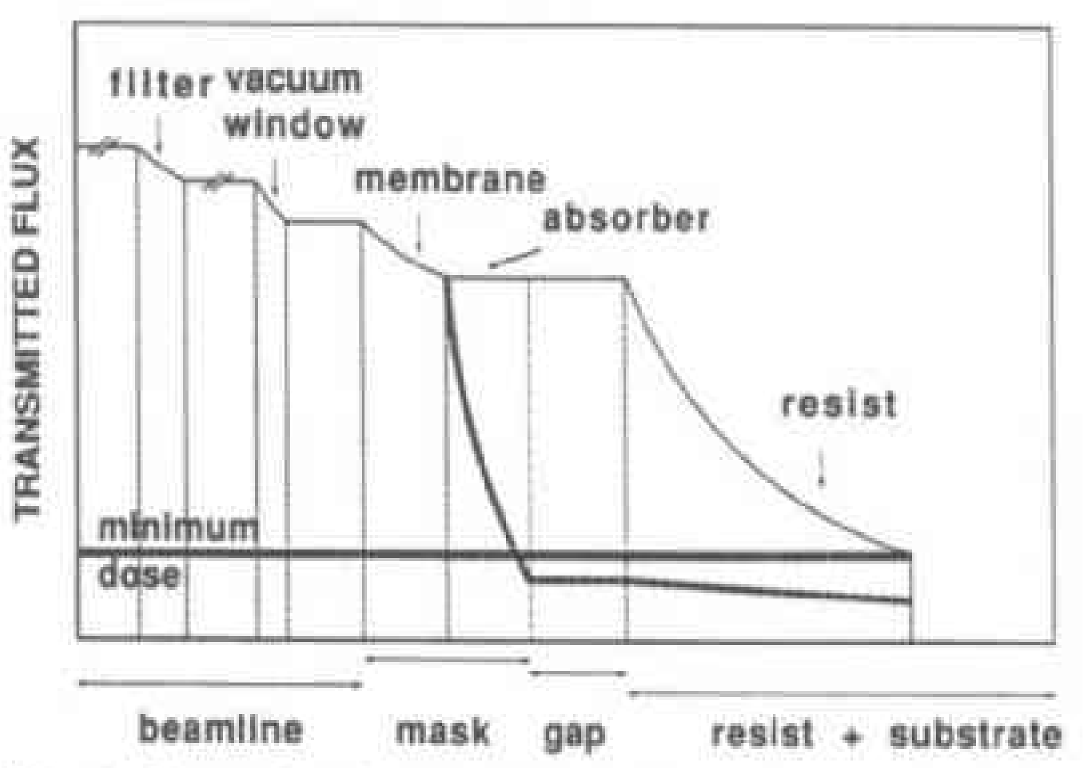
PMMA Film Preparation

- Up to 100 µm thick films: spinning
- More than 100 µm thick films:
  - Bonding and lapping.
  - Casting *in situ*.

The Irradiation Process 1



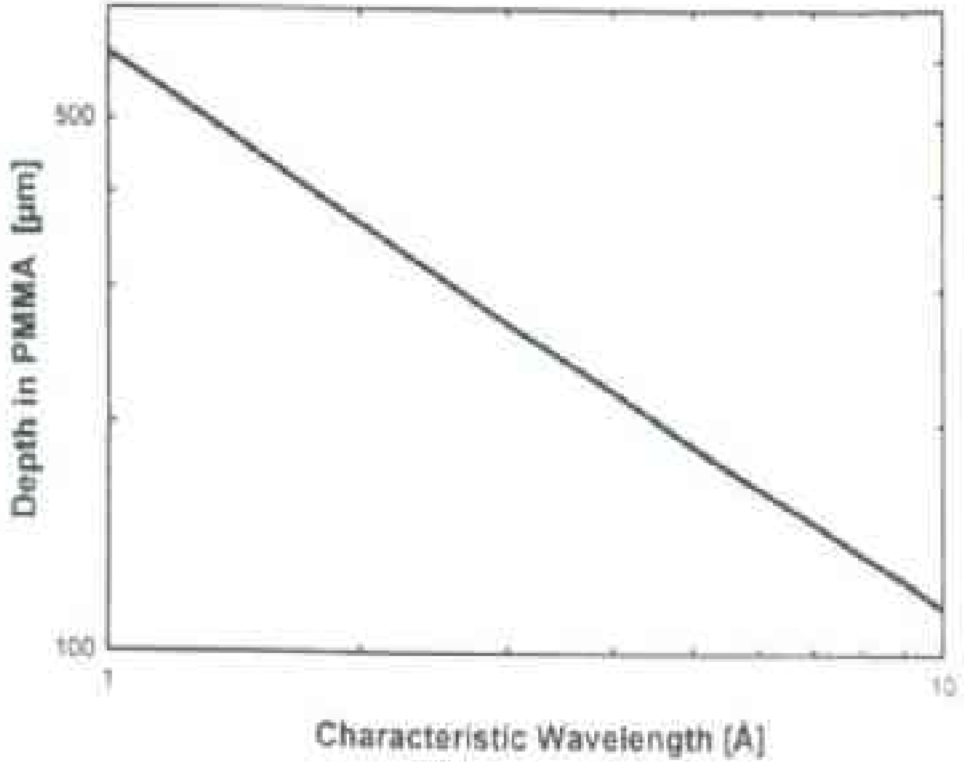
The Irradiation Process 2



From: W. Ehrfeld and H. Lehr, “Deep X-ray lithography for the production of three-dimensional microstructures from metals, polymers and ceramics”, *Radiat. Phys. Chem.*, Vol. 45, No. 3, pp. 349-365, 1995

- The transmission of the synchrotron radiation between the light source and the bottom of the resist must be tuned by filtering to fit the resist needs.
- High energy photons are transmitted better.
- He atmosphere is used.
- Air is ionized by X-ray: chem. species aggressive to chamber, mask and sample.

The Irradiation Process 3



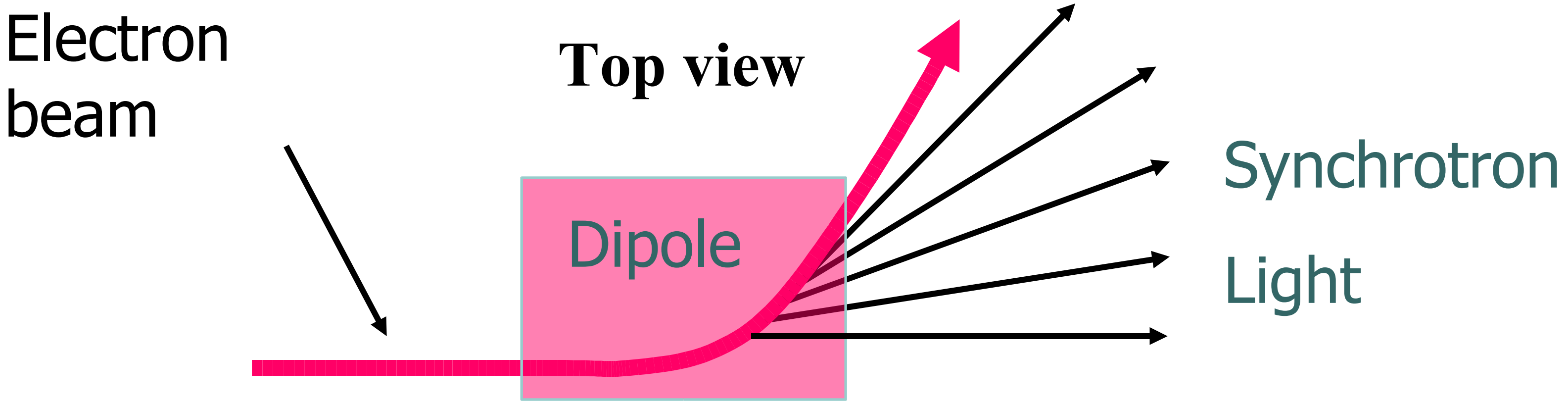
From: W. Ehrfeld and H. Lehr, “Deep X-ray lithography for the production of three-dimensional microstructures from metals, polymers and ceramics”, *Radiat. Phys. Chem.*, Vol. 45, No. 3, pp. 349-365, 1995

- Maximum depth in PMMA as function of wavelenght with requirement Ds / D_D = 5, for a 200 µm thick Be absorber.

Lateral Accuracy

- Factors that determine the lateral accuracy of the shadow printing:
  - Divergence of the light beam
  - Fresnel diffraction at the mask
  - Photoelectrons at the resist

Divergence of the Light Beam



Electron beam

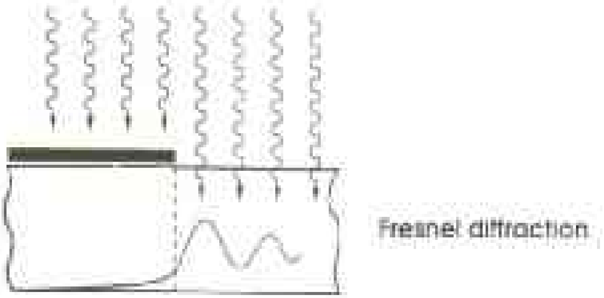
Top view

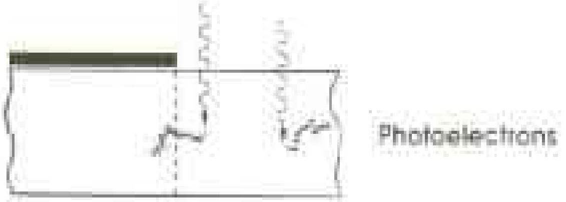
Dipole

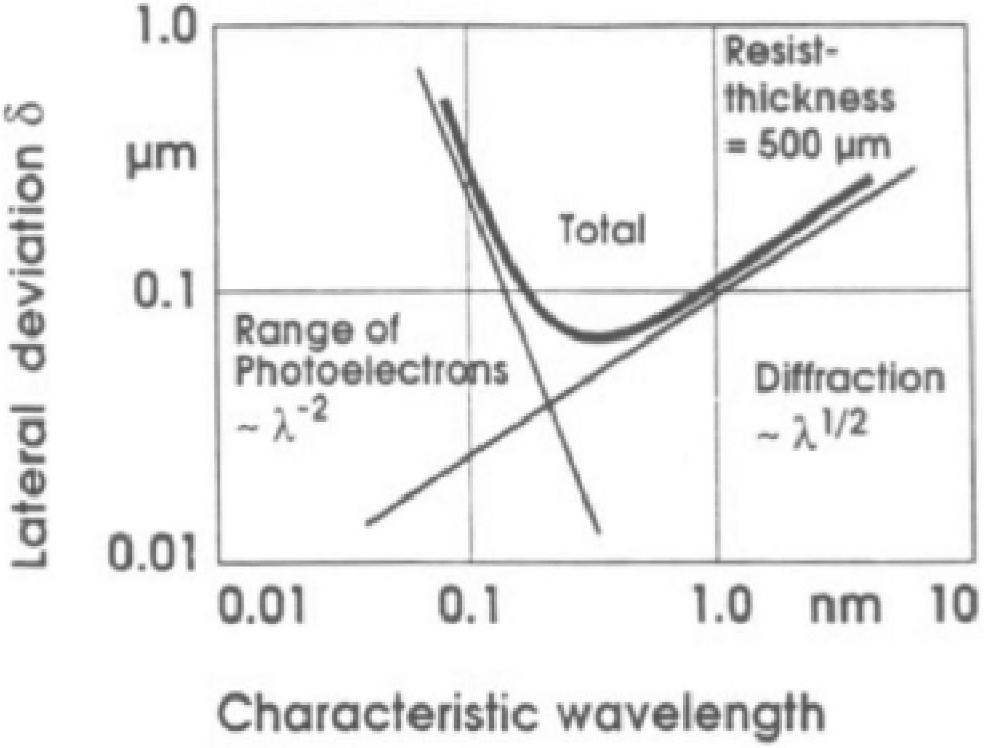
Synchrotron Light

- Horizontal divergence is limited by a slit (typ: 5-10 mrad)
- Vertical divergence is determined by the natural divergence of the light cone plus a divergence caused by the oscillation of the electrons around their equilibrium orbit. A typical value is 0.3 mrad.
- XRL: 10 mrad H x 0.3 mrad V ⇖ 100 mm H x 3 mm V at 10 m

Fresnel Diffraction and Photoelectrons







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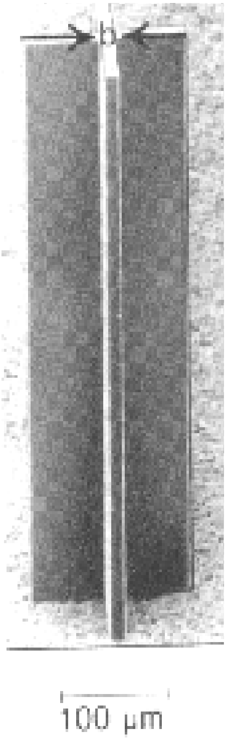
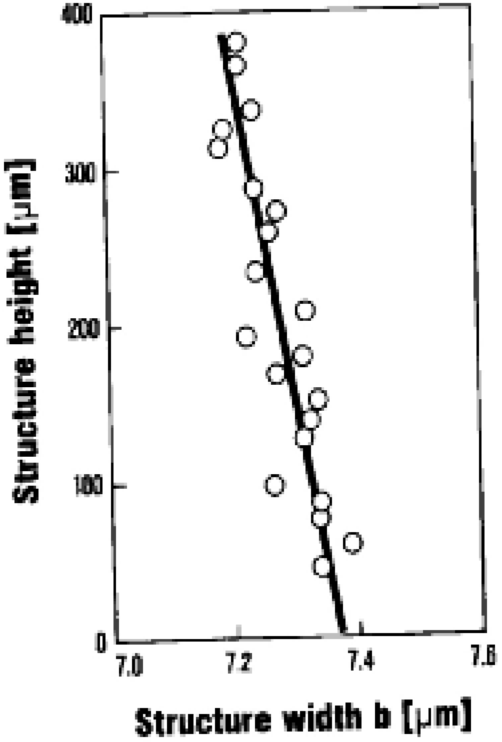
Lateral Tolerance





0.2 µm over 400 µm tall structure.

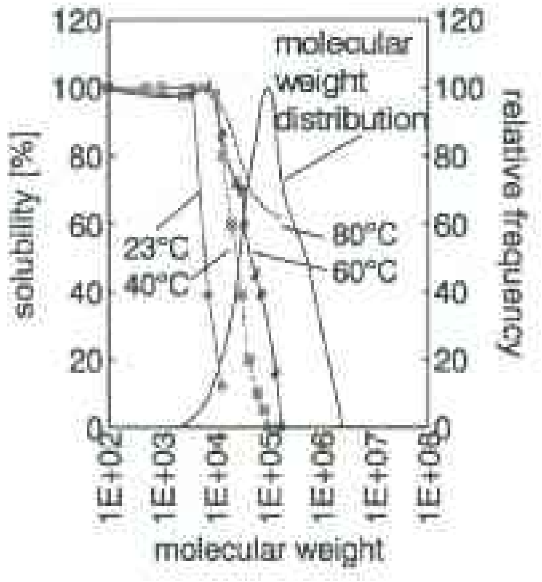
From: Madou, Marc J.; **Fundamentals of Microfabrication**, CRC Press, 1997

Development of PMMA

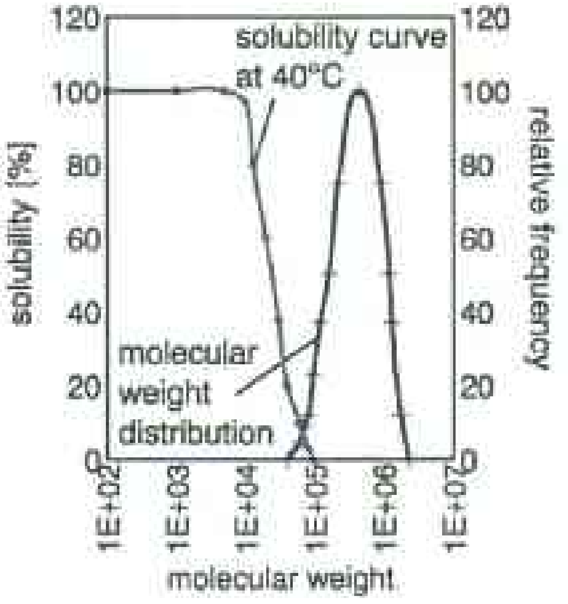
- GG developer:
  - 60 vol% di(ethilene glycol) butyl ether
  - 20 vol% morpholyne
  - 5 vol % ethanolamine
  - 10 vol% deionized water
- Temperature: 35°C
- Megasonic assistance may be needed.

Development Characteristics of PMMA

Commercial PMMA

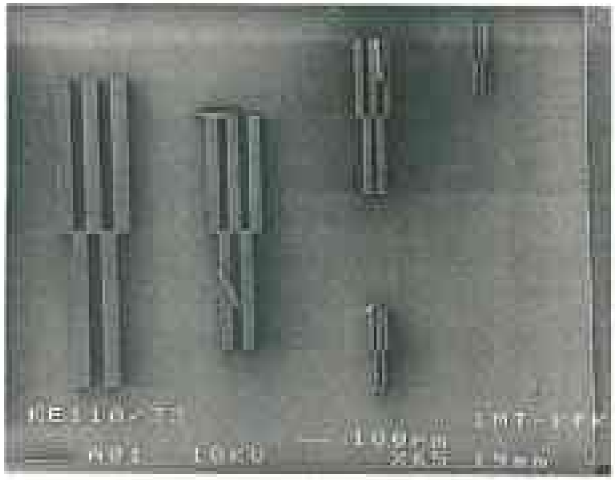


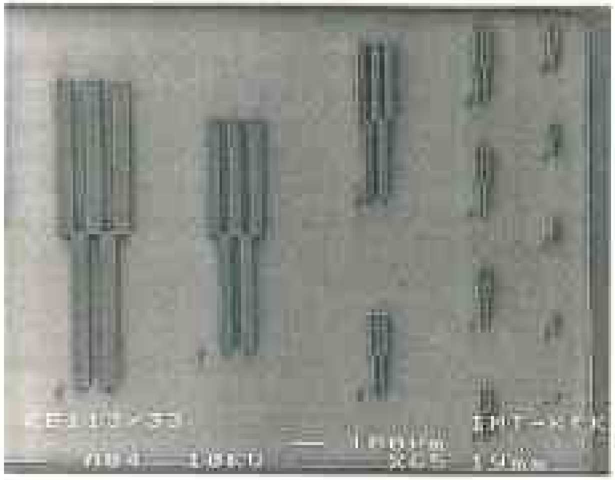
Optimized PMMA



From: A El-Kholi, P. Bley, J. Gottert and J. Mohr, **"Examination of the solubility and the molecular weight distribution of PMMA in view of an optimized resist system in deep etch X-ray lithography"**, *Microelectronic Engineering* 21 (1993) 271-274

Secondary Effects of the Radiation-1

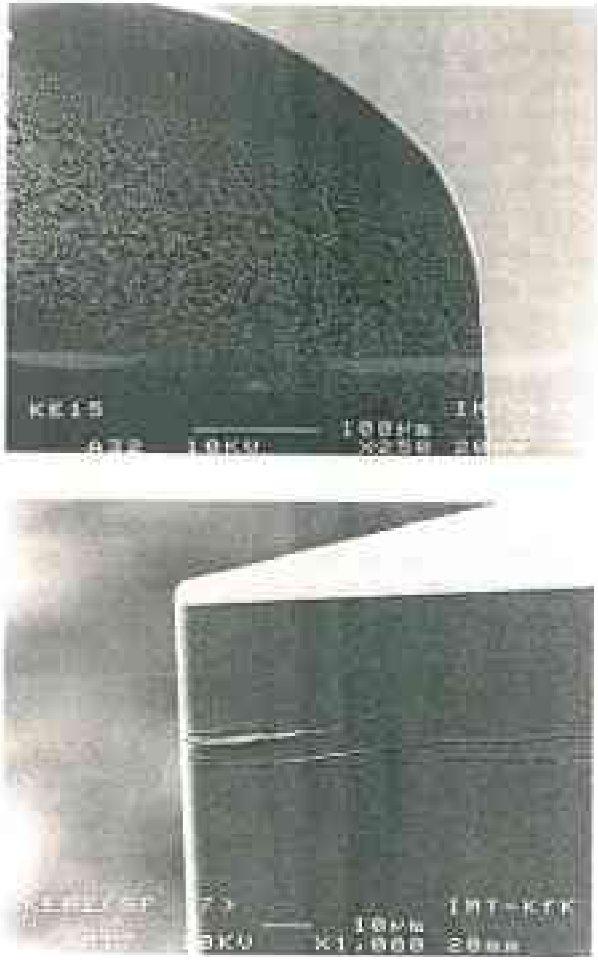




- Secondary radiation from the substrate
  - Reduces the adhesion resist-substrate.
  - Top: higher energy
  - Bottom: lower energy

From: F. J. Pantenburg and J. Mohr,**"Influence of secondary effects on the structure quality in deep X-ray lithography"**, *Nuclear Instruments and Methods in Physics Research B*97 (1995) 551-556.

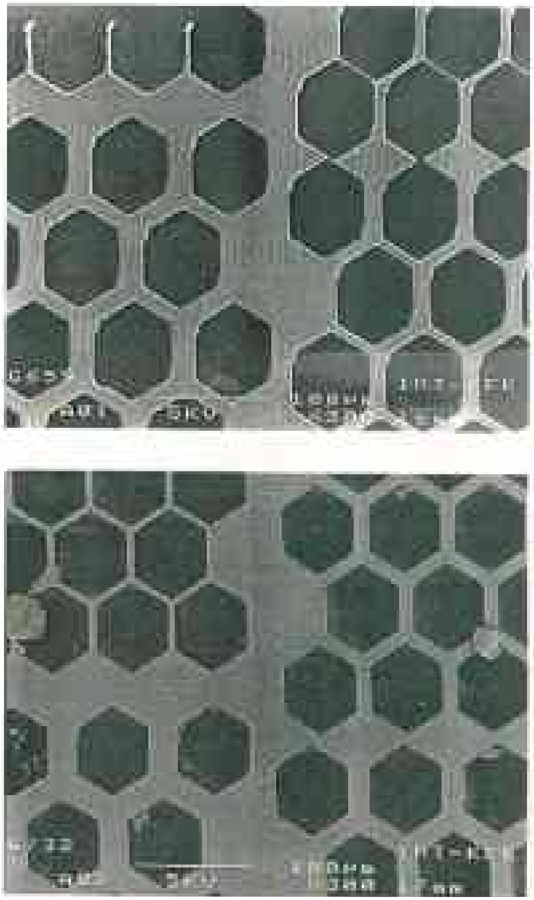
Secondary Effects of the Radiation-2



- Secondary radiation from the mask membrane
  - Absorbed X-rays produce fluorescence radiation: higher doses at the upper edges of the structures. Produces beveled edges.
  - Top: absorber in front of the mask.
  - Bottom: absorber in between mask and resist.

From: F. J. Pantenburg and J. Mohr,**"Influence of secondary effects on the structure quality in deep X-ray lithography"**, *Nuclear Instruments and Methods in Physics Research B*97 (1995) 551-556.

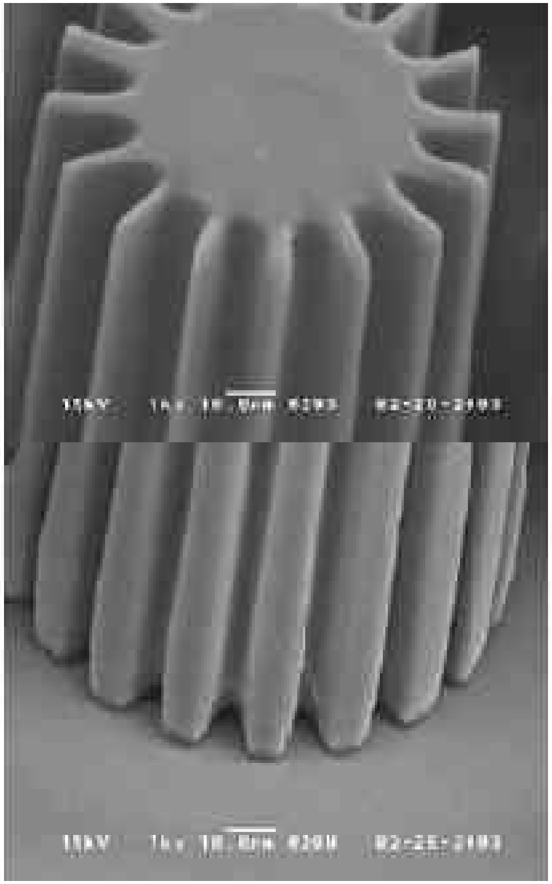
Secondary Effects of the Radiation-3

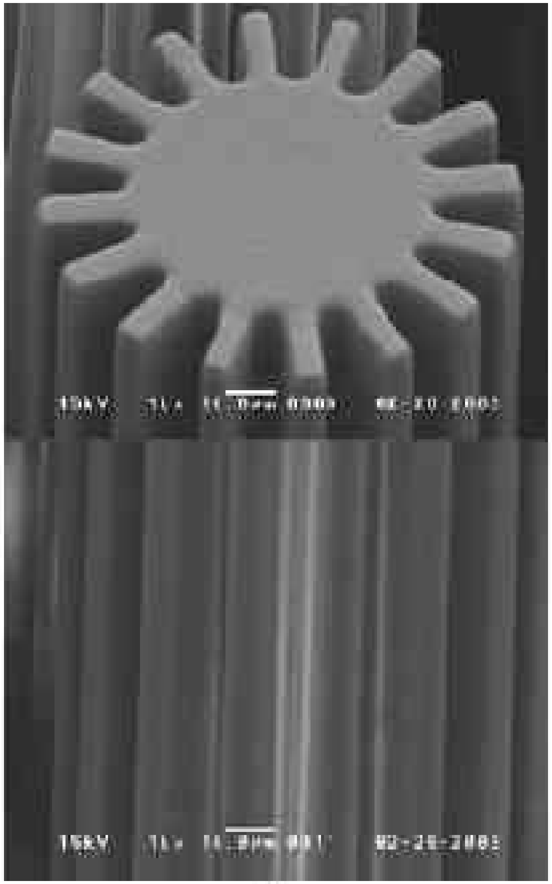


- Heat load on mask: produces distortion due to the expansion of the mask and resist.
- Top: X-ray power of 1W/cm^2.
- Bottom: X-ray power of 0.1W/cm^2.

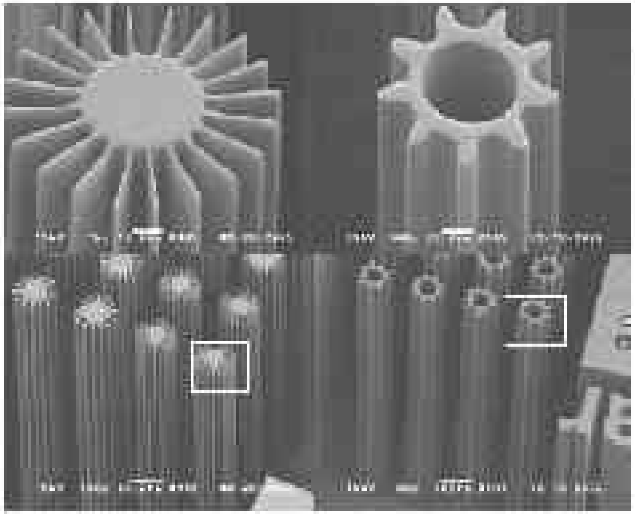
From: F. J. Pantenburg and J. Mohr, **“Influence of secondary effects on the structure quality in deep X-ray lithography”**, *Nuclear Instruments and Methods in Physics Research B*97 (1995) 551-556.

A process with Reduced Secondary Effects





- 1 mm tall structures
- Left: exposure without wavelenght shift.
- Center and right: exposure with wavelenght shift.



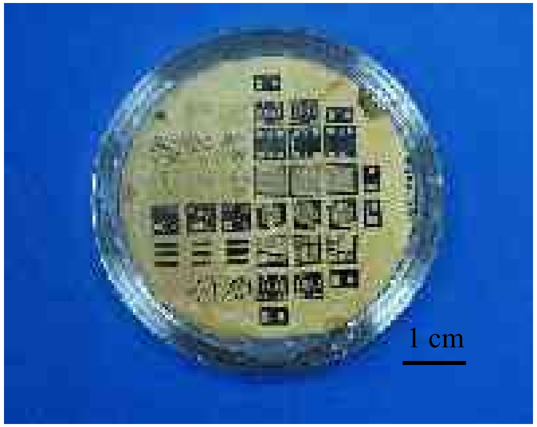
From: Jin Tae Kim, Sang-Pil Han and Myung Yung Jeong,**“A modified DXRL process for fabricating a polymer microstructure”**, *J. Micromech. Microeng*, 14 (2004) 256-262

DXRL on SU8 Photoresist

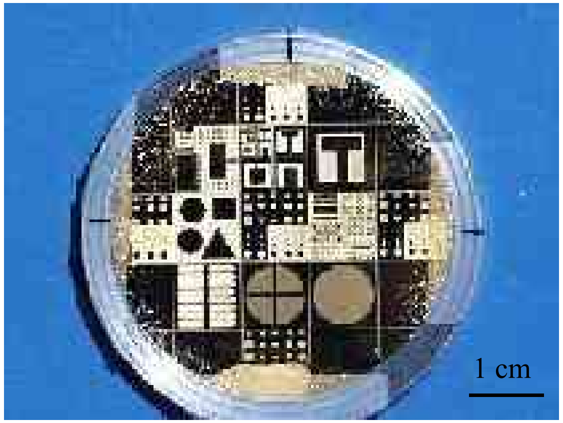
- Negative tone
- Short exposure times: from hours to seconds
- Kapton or Si (thick) membrane mask
- Thin gold absorber (< 2μm thick)
- Electroless plating (low stress, high uniformity)
- Deep UV lithography on SU8
- Prototyping service: The MUSA Project (deep UV lithography and electroforming)

The X-ray mask for SU8

- Kapton or Si membrane
- Up to 50 µm thick Si membrane

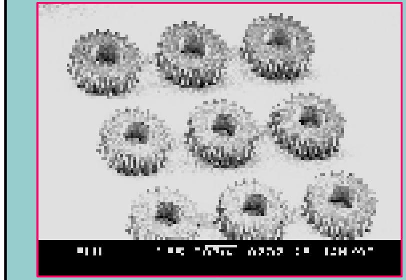


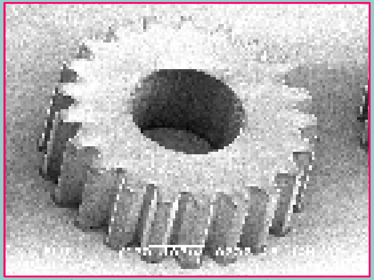
MUSA 1999

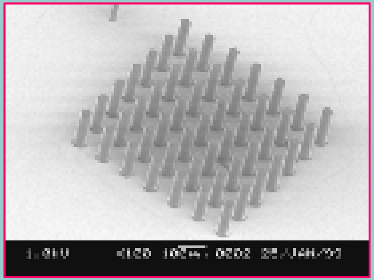


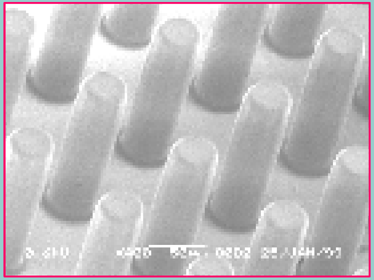
MUSA 2000

X-ray Lithography on 125µm thick SU-8 resist


GEARS


(DETAIL)


STICKS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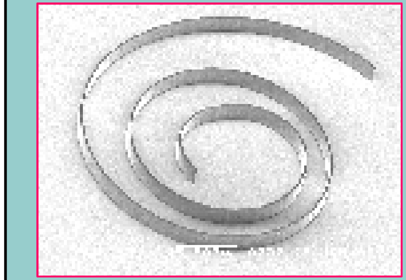
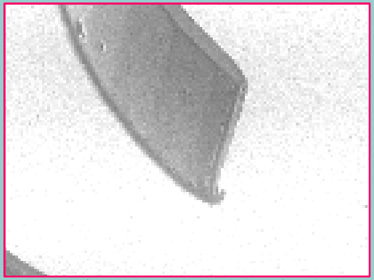

SPIRAL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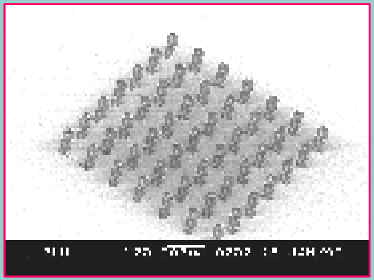
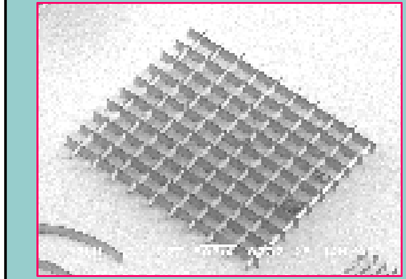
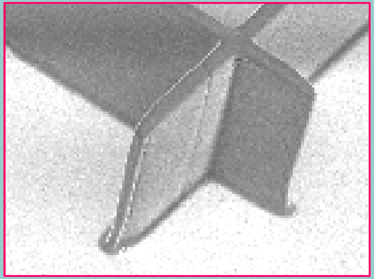

SPINERETTE MOLD


(DETAIL)


MESH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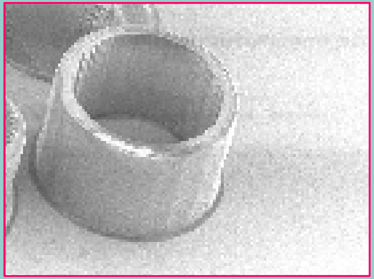
TUBE

Photos JSM-5900LV
LME/LNLS

Final Remarks

- A complete cicle of DXRL was developed: light source; exposure station; mask and lithography on SU8.
- While the DXRL process was developed, the UV Deep Lithography process developed for mask fabrication was offered to the community for 3 years thru The MUSA Project (1999-2001).
- The number of users of LIGA technique in Brazil grew from one (myself) to more than 30 in three years thanks to The MUSA Projetc.
- The hands-on processing lab created in LNLS at that time is still active.
- Since 2002 I am a full time teacher at the Mech. Fac. of the Campinas State University – Campinas – SP - BRAZIL
- The challenge now is on:
  - **Teaching MEMS to people.**
  - **Low cost MEMS to medical diagnosis.**
- My next seminar: Tutorial on UV deep lithography.
- THANKS FOR ATTENTION.
- QUESTIONS?