Empa
Materials Science and Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Laser Processing of Materials

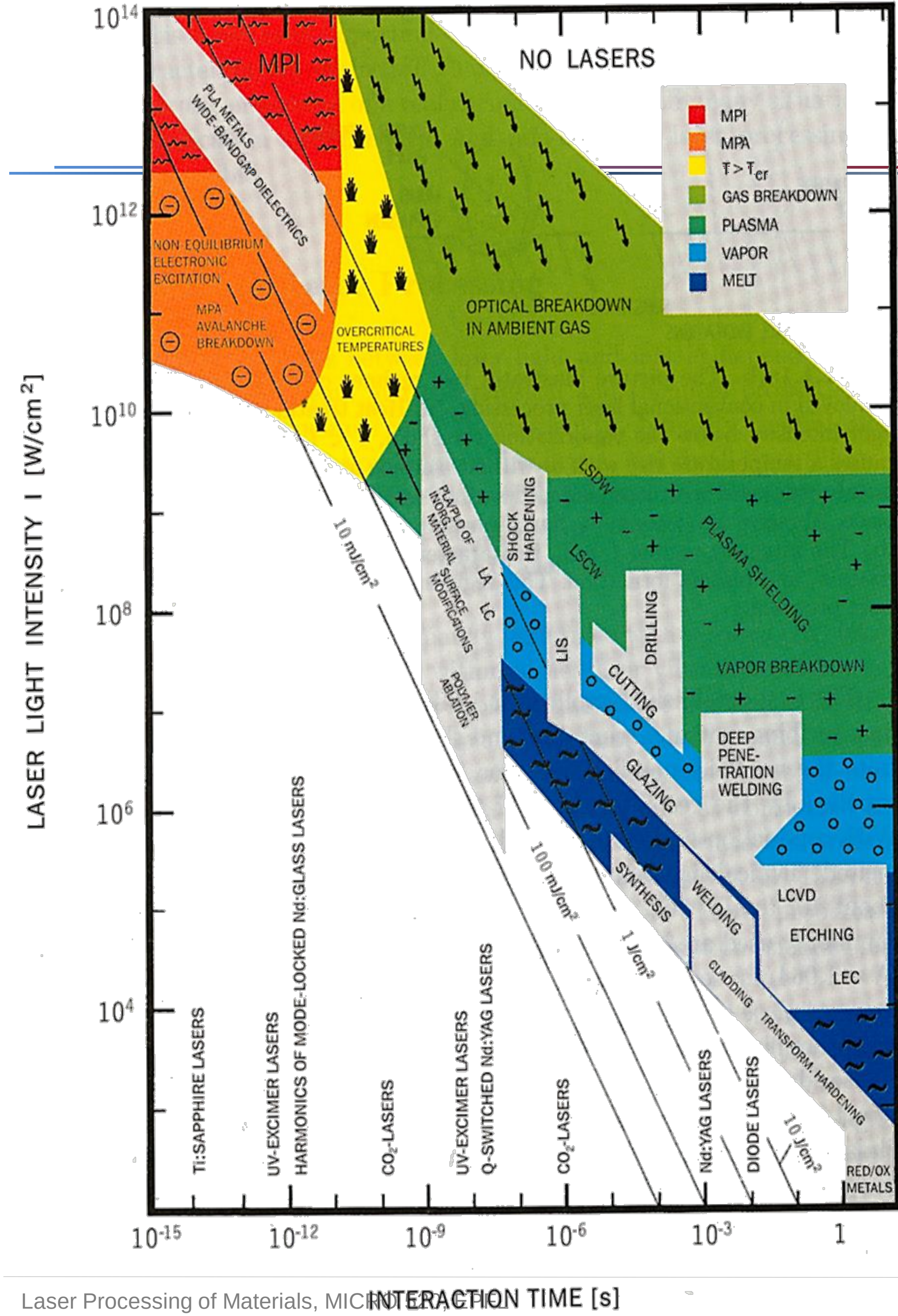
Applications: Ablation

Patrik Hoffmann

UV- Excimer Laser Ablation

- Excimer lasers
- Excimer installations in Thun
- Examples

D. Bäuerle; Laser Processing and Chemistry,
3rd Edititon, Springer Berlin, 2000

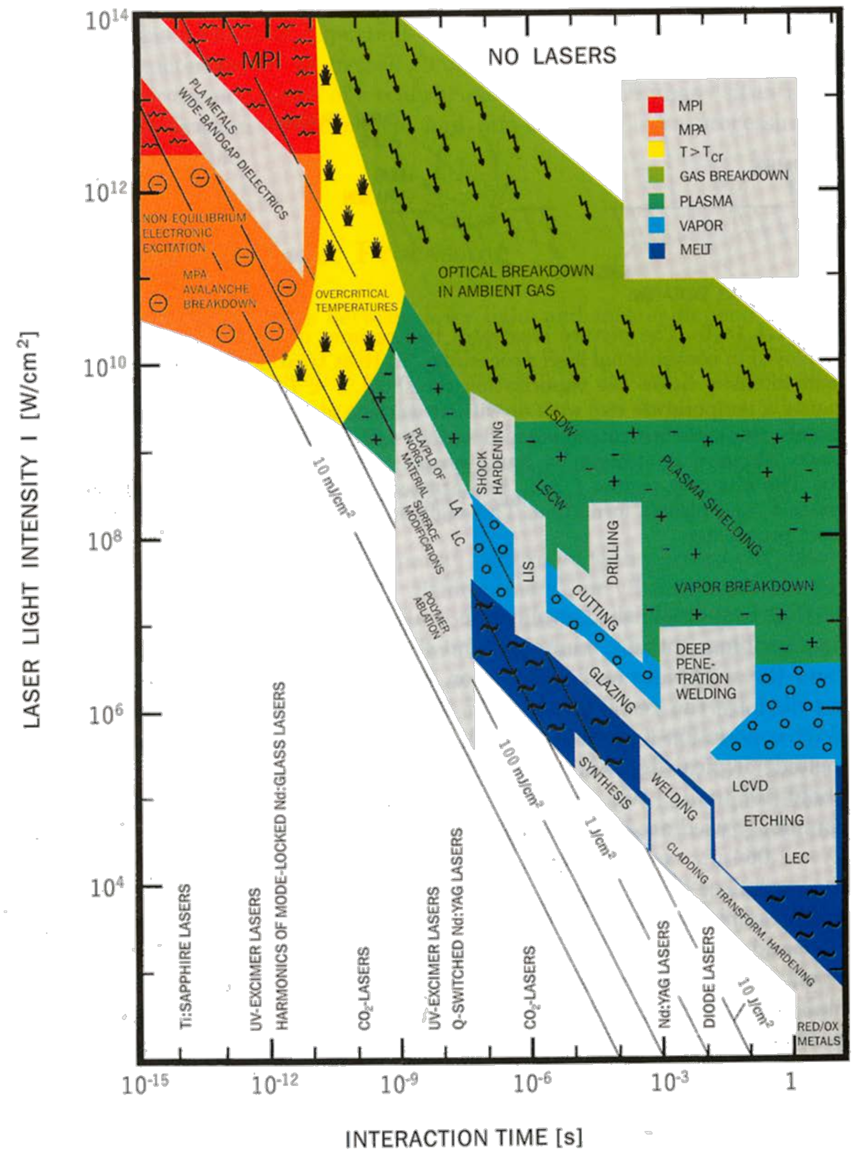


D. Bäuerle;
Laser Processing and Chemistry, 3rd ed.
Springer, Berlin, 2000

What kind of laser do you propose for bending / welding?

Application of lasers in materials processing:
Intensity-Time Diagram

- PLA/PLD – pulsed laser ablation/ deposition
- LA – laser annealing
- LC – laser cleaning
- LIS – laser induced isotope separation/IR – laser photochemistry
- MPA/MPI – multiphoton absorption ionization
- LSDW/LSCW – laser supported detonation/combustion waves
- LCVD – laser induced chemical vapour deposition
- LEC – laser induced electrochemical plating/etching
- RED/OX – long pulse or cw CO_2-laser induced reduction/oxidation



D. Bäuerle; Laser Processing and Chemistry, 3rd ed. Springer, Berlin, 2000

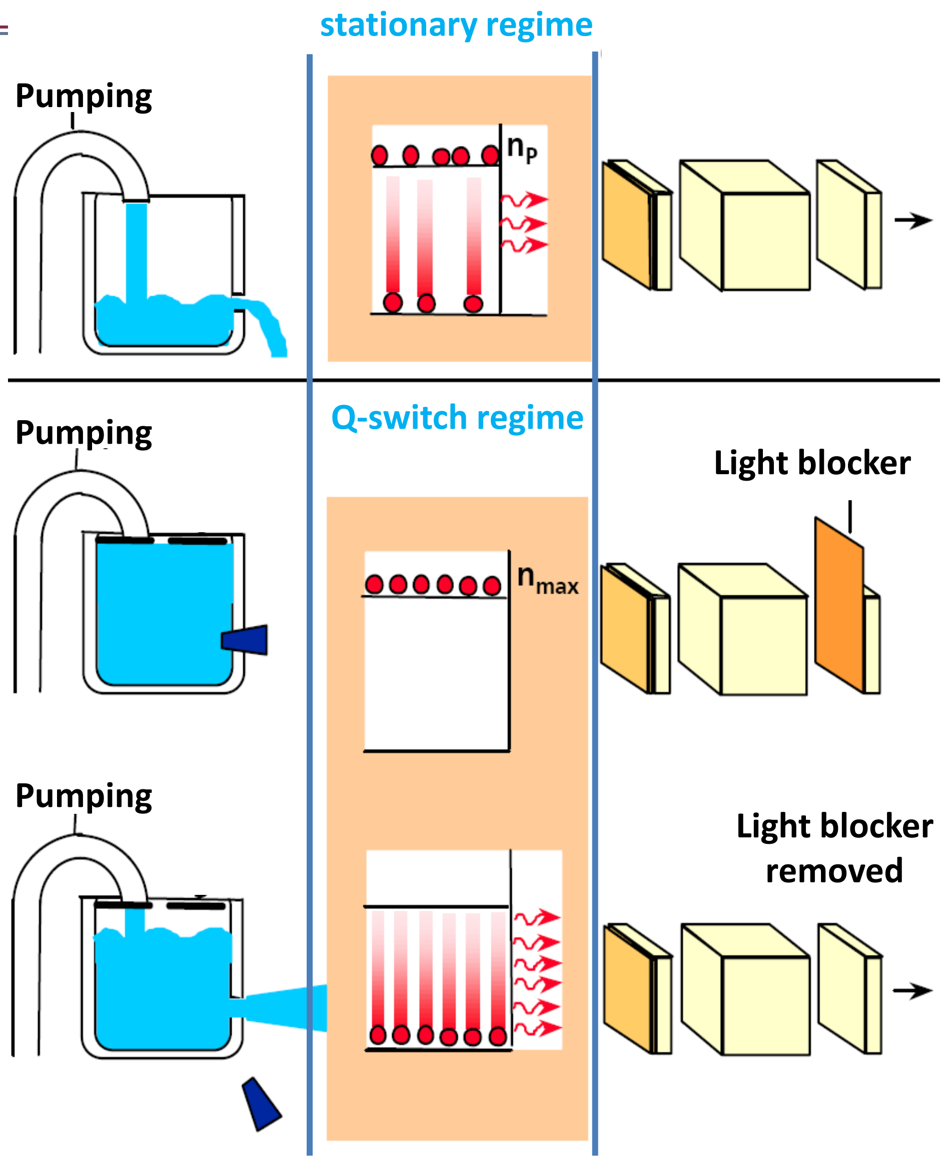
Laser Types: Pulsed & CW

Type of laser	Pulse length determined by	Typical pulse length	Characteristic pulse peak power
Continuous wave (cw)	-	∞	Ws – kWs
Free running laser	Pump pulse length (flash lamp)	100 µs – 1ms	kWs
Q-switched laser	Time constants of active material and modulating element	1 ns – 100 ns	MWs
Mode-locked laser	Number of coupled modes, pulse compression	10 fs – 10 ps	GWs

Q-switch mode

Idea of Q-switch regime – accumulate energy and release in a short time

Q → stands for quality of resonator, quality is switched in time



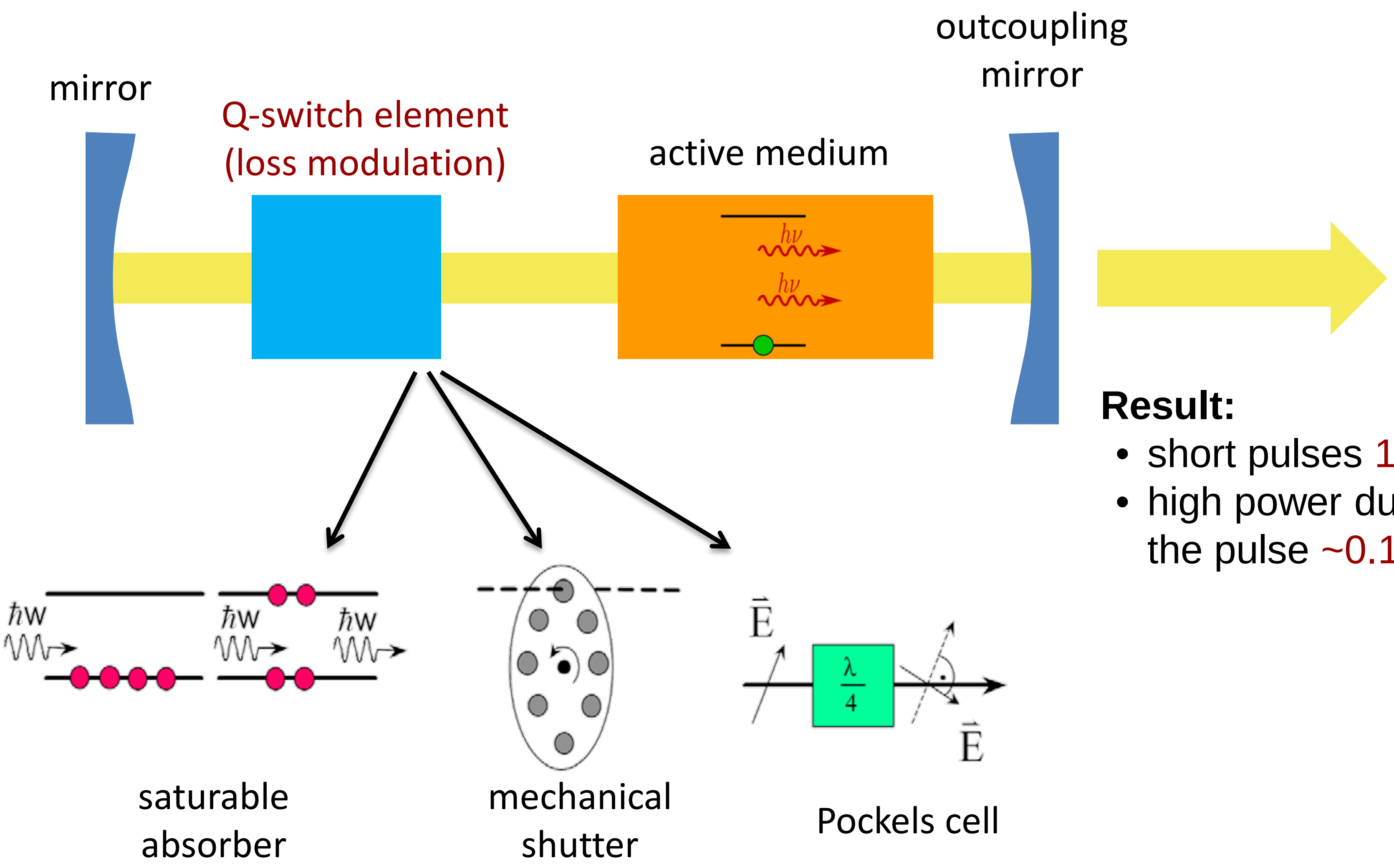
Resonator state A – resonator is closed/blocked

- stimulated emission is not possible
- energy is accumulated

Resonator state B – resonator opens abruptly

- inversion is high → amplification coefficient is very high
- all accumulated energy is emitted in a short burst/pulse

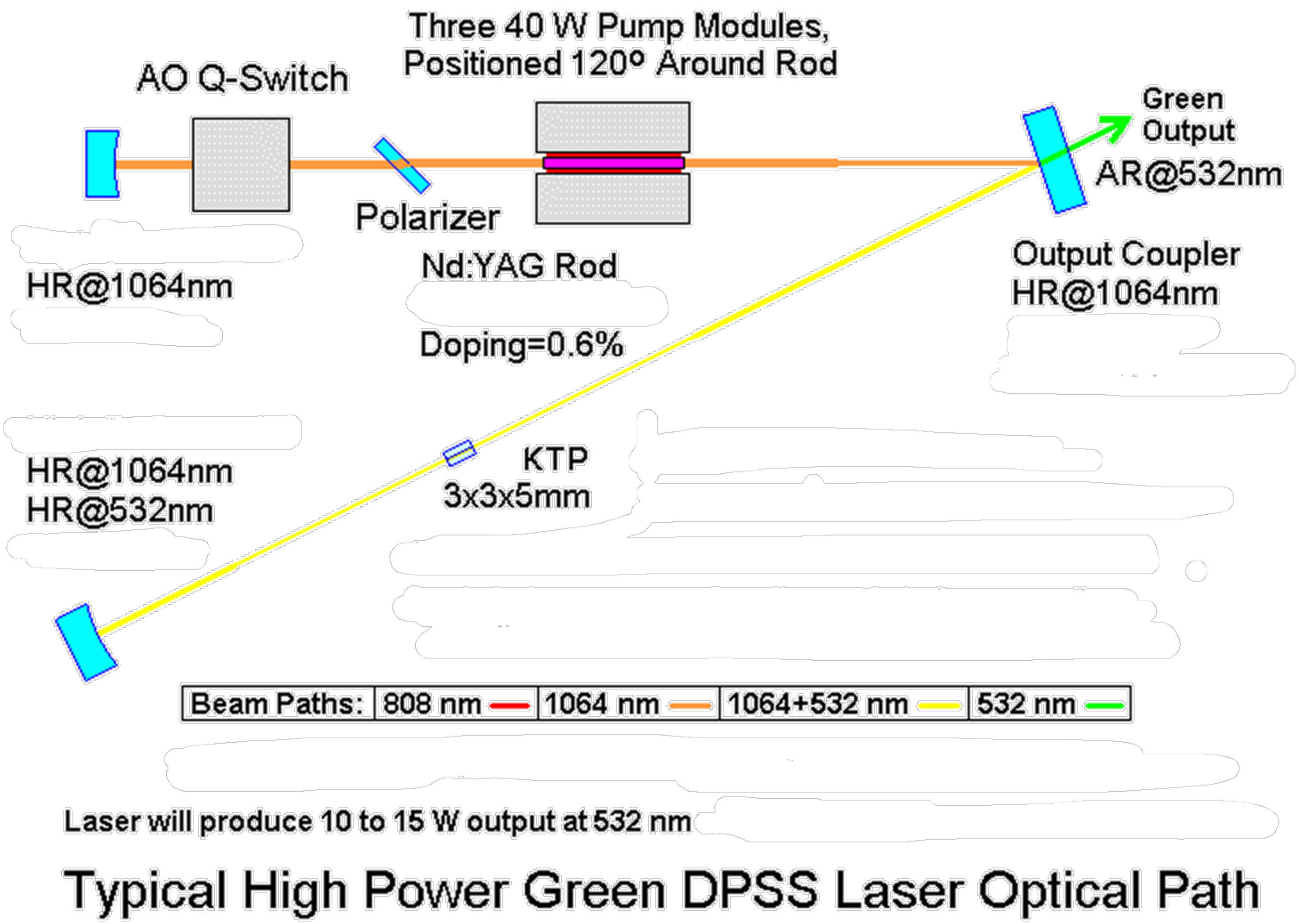
Q-switching the Resonator



Result:

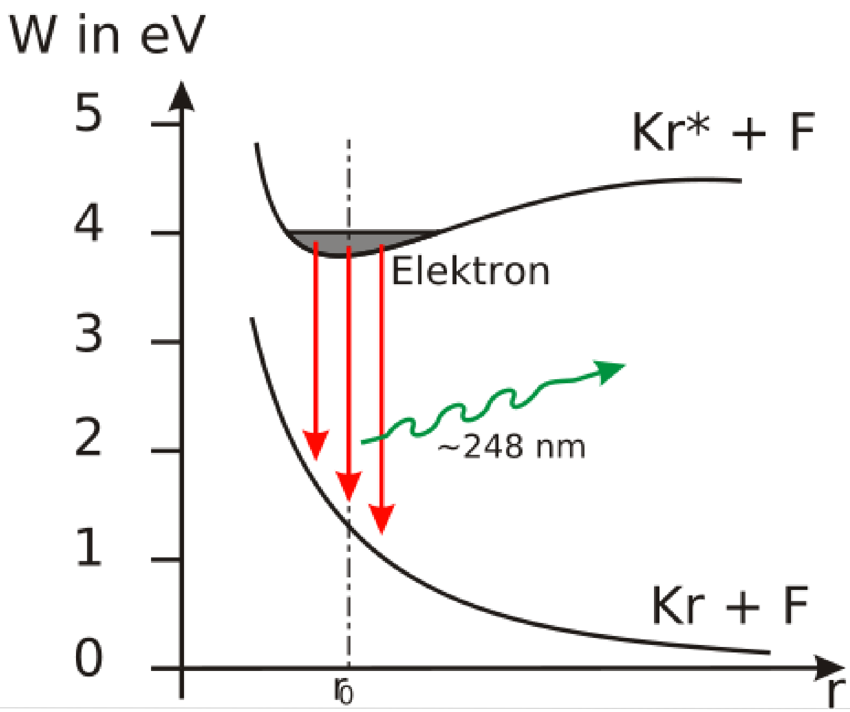
- short pulses 1-100 ns
- high power during the pulse ~0.1-100 MW

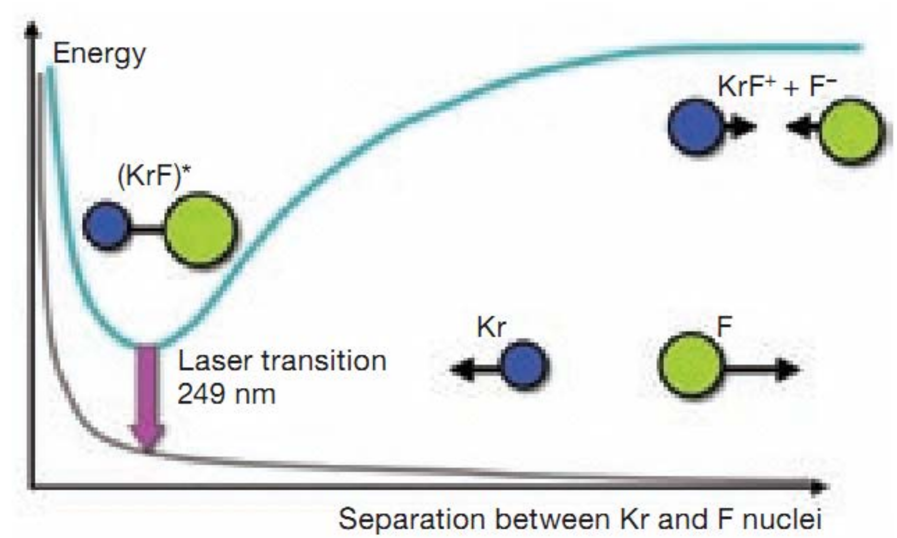
Q-swiched Solid State Lasers



What is an Excimer laser?

- Gas laser using a combination of a noble and a reactive gas
- Under pressure and electrical stimulation a pseudo molecule called Excimer (= excited dimer) is created
- By spontaneous or stimulated emission it dissociates back into two unbound atoms (laser with one energy level!)





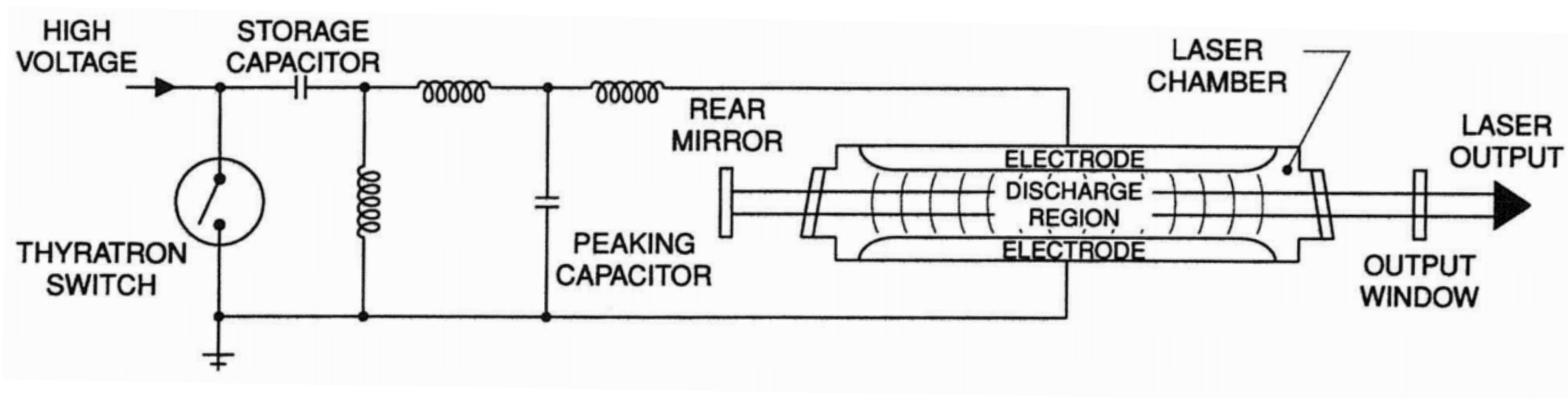
Wavelength of Excimer Lasers

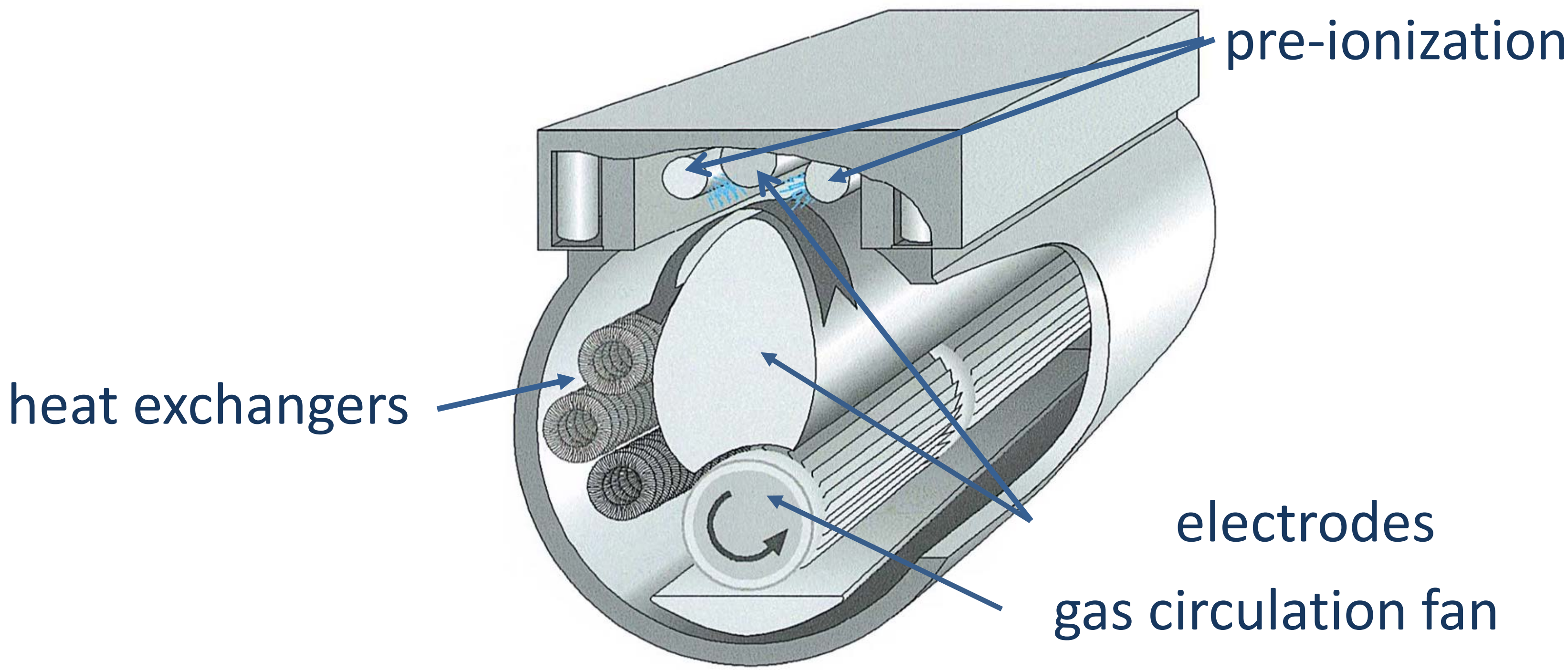
- The wavelength of an excimer laser depends on the molecules used (can not be tuned)
- emission is in the ultraviolet range

Excimer	Wavelength
F_2 (fluorine)	157 nm
ArF (argon fluoride)	193 nm
KrF (krypton fluoride)	248 nm
XeBr (xenon bromide)	282 nm
XeCl (xenon chloride)	308 nm
XeF (xenon fluoride)	351 nm

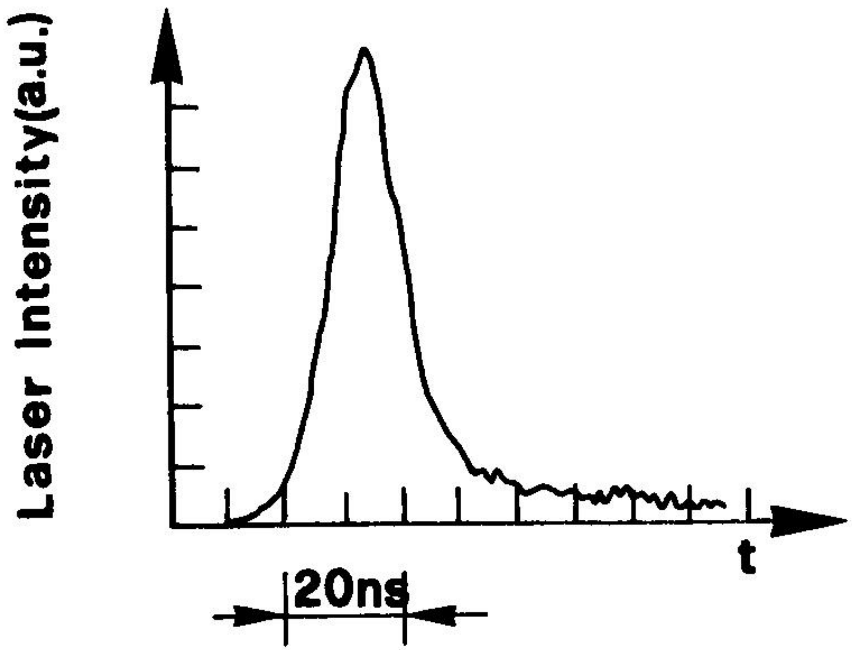
Most important technologically are **ArF (193 nm)** and **KrF (248 nm)**

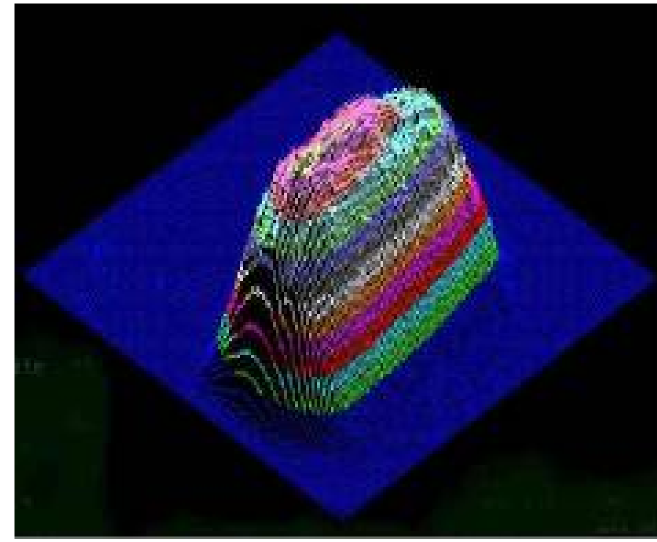
Schematic Set-up

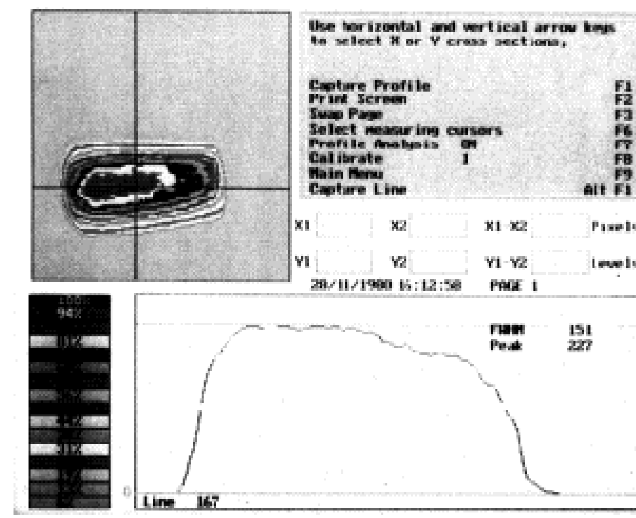




Temporal and Spatial Profile of the Beam







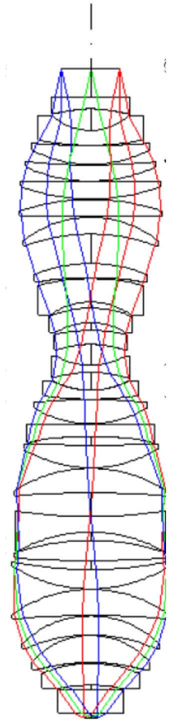
- ~20 ns is a characteristic pulse length of ArF and KrF lasers
- determined by the excimer molecule properties - can not be easily tuned

Excimer laser technical specs

- Average power: 1 W – 1000 W
- Peak power: up to 50 MW
- Pulse frequency: 1 Hz – 6 kHz
- Pulse duration: 5ns – 200ns

Microelectronic production

State-of-the-art microstepper with laser and lens



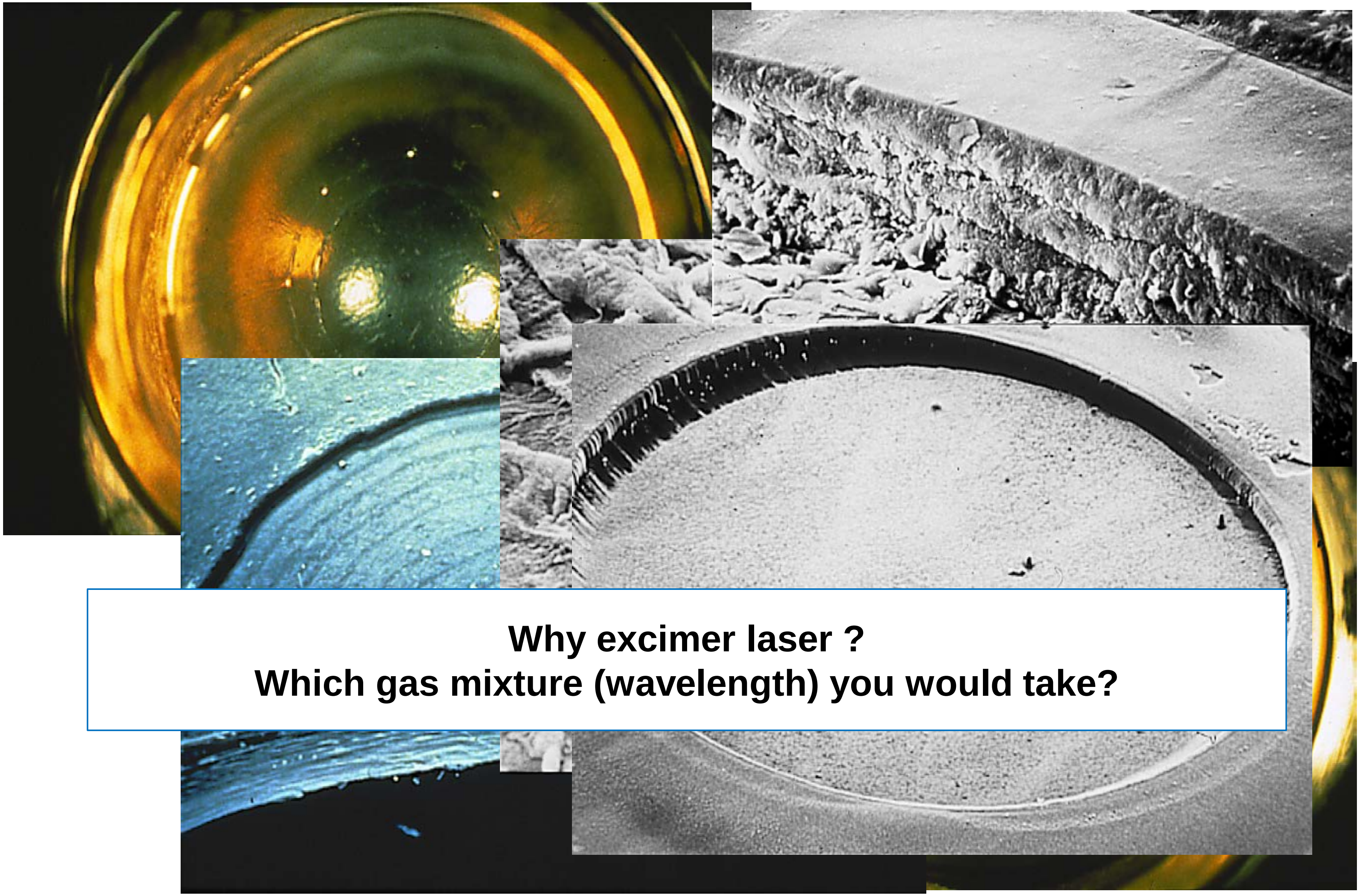
Wavelength 193 nm

Lens		Field Size	Overlay	Throughput
NA	Resolution	X & Y	16-point Alignment	300 mm Wafers 30 mJ/cm2 (125 shots)
Variable 0.85-1.35	38 nm	26 X 33 mm	2.5 nm*	175 wph

* Single machine overlay including chuck dedication

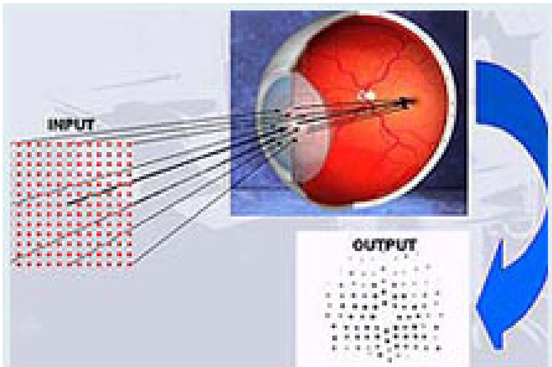
NA =0.85 y_{imax} = 13.8mm, λ =193nm (ArF) J

Excimer Laser: Keratectomy

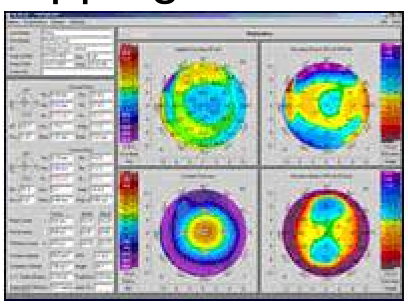


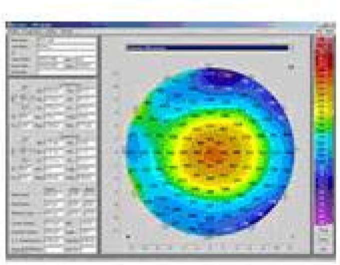
Why excimer laser ?
Which gas mixture (wavelength) you would take?

LASIK (laser in situ keratomileusis)

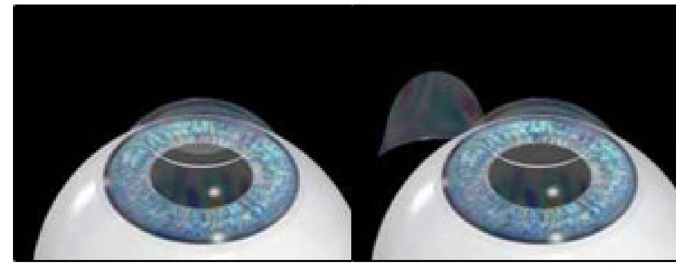


Mapping of cornea by measuring wavefront error



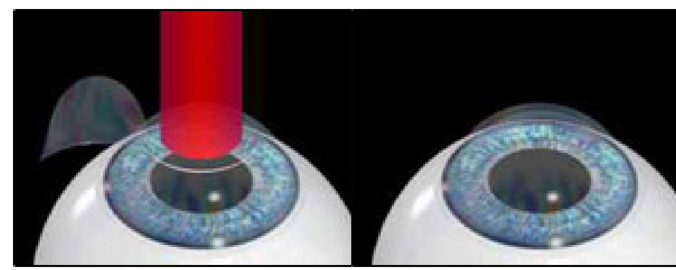


ArF laser @ 193 nm



Step 1: Corneal flap is created with a microkeratome.

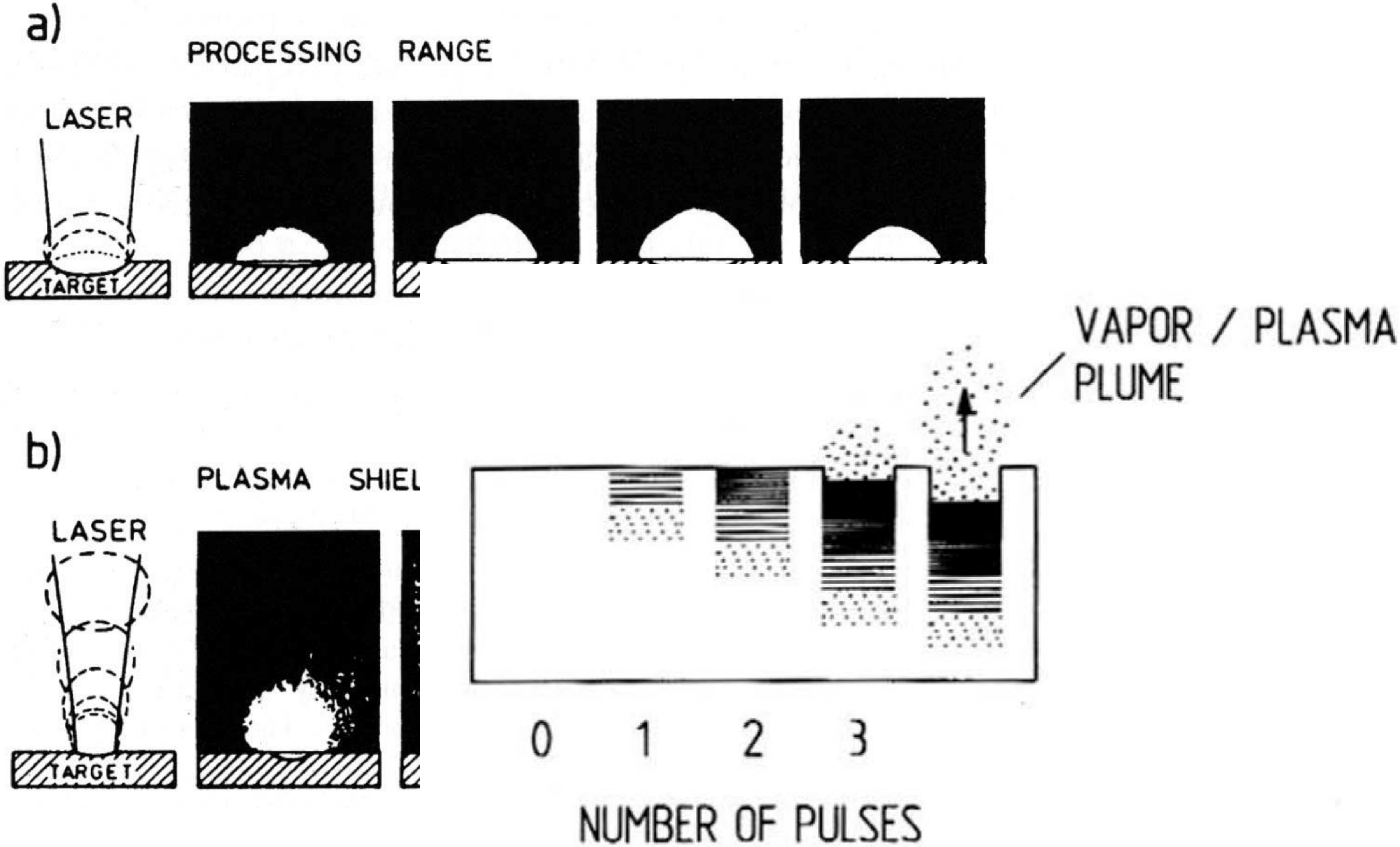
Step 2: The corneal flap is folded back.



Step 3: Excimer laser beam reshapes the cornea.

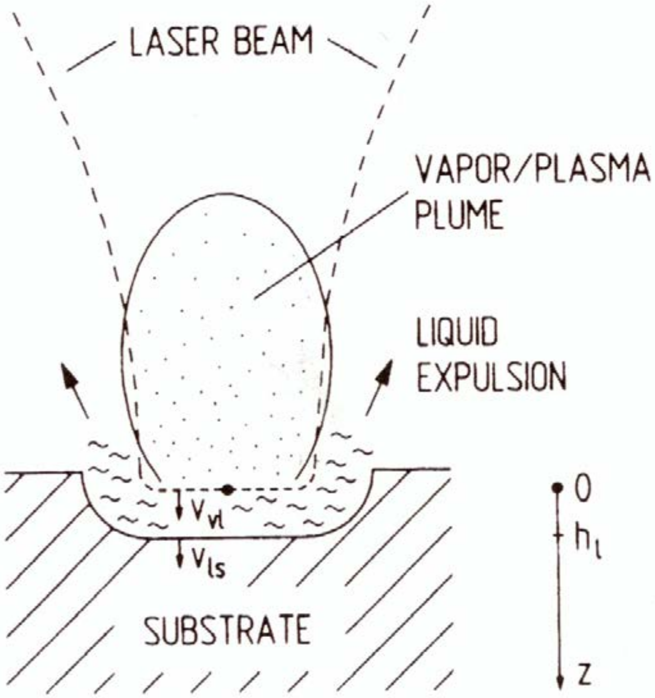
Step 4: The corneal flap is folded back in place.

Pulsed Laser Ablation - Schematics



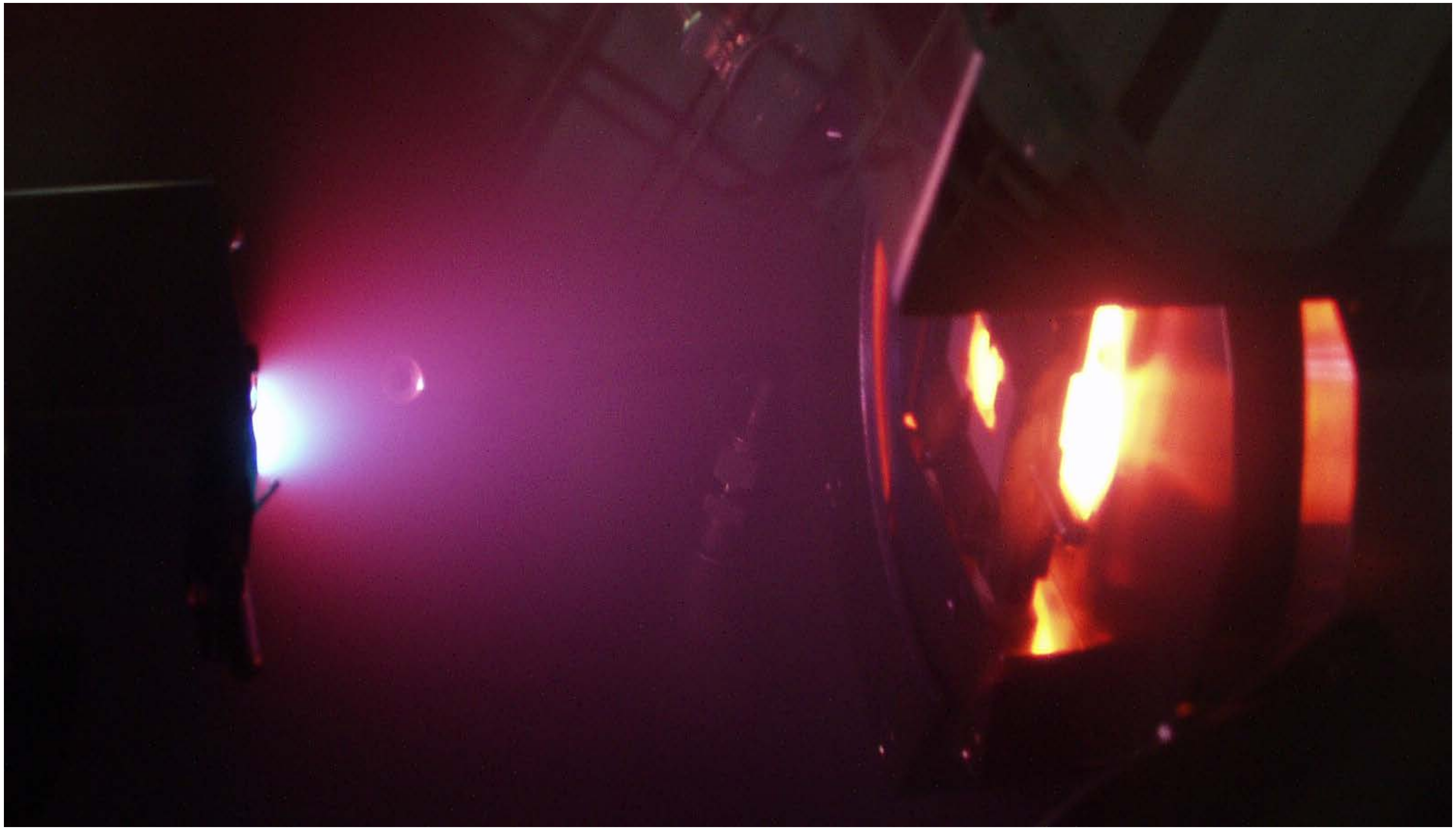
Interaction of Excimer light pulse with material

Excimer ArF, 193 nm, 1000 mJ/cm^2, 20 ns, image projection

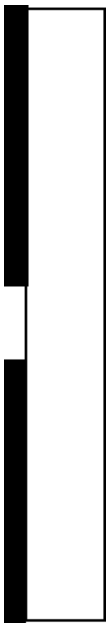


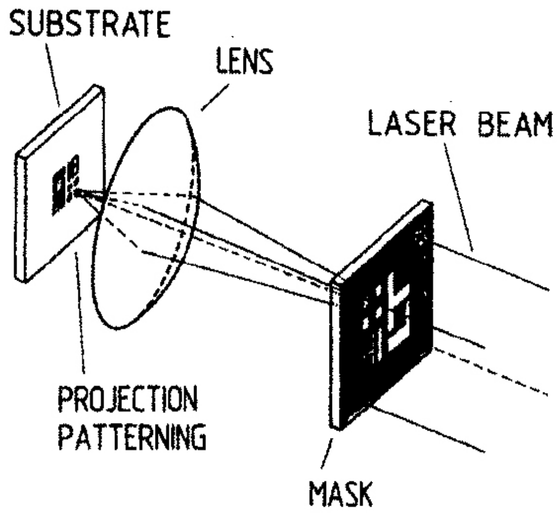
- UV light is absorbed
- Melting takes place
- Plasma appears and ablation products are ejected

Laser Ablation Plume in Vacuum



Mask material





Industrially applied for 193 nm lithography:

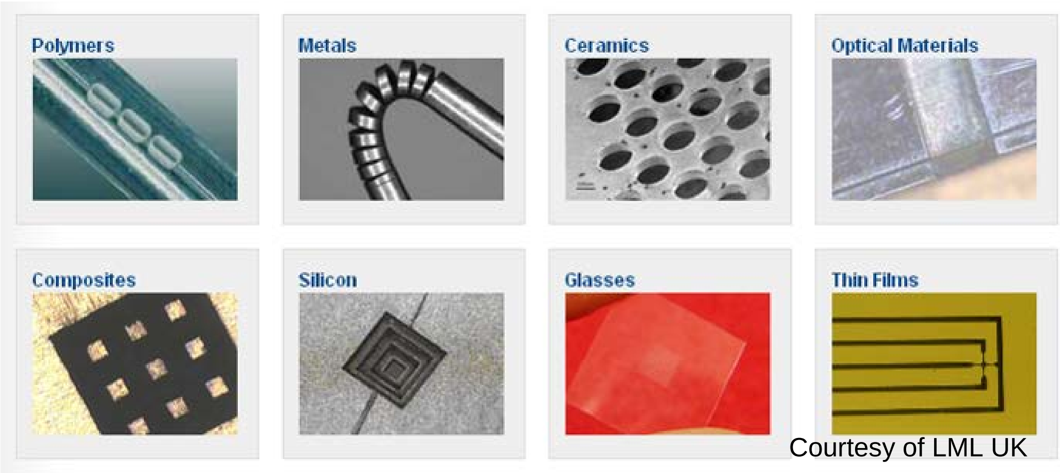
- 75 nm Cr layer on fused silica
- with AR Cr_2O_3

Materials for excimer laser ablation masks

Material	Mo – Molybdenum sheets	Cr on SiO_2	Dielectric multilayer coating
Reflectivity [%]	58	65	>99
Damage Threshold [J/cm^2]	0.5	0.3	>2

Wide range of materials can be ablated

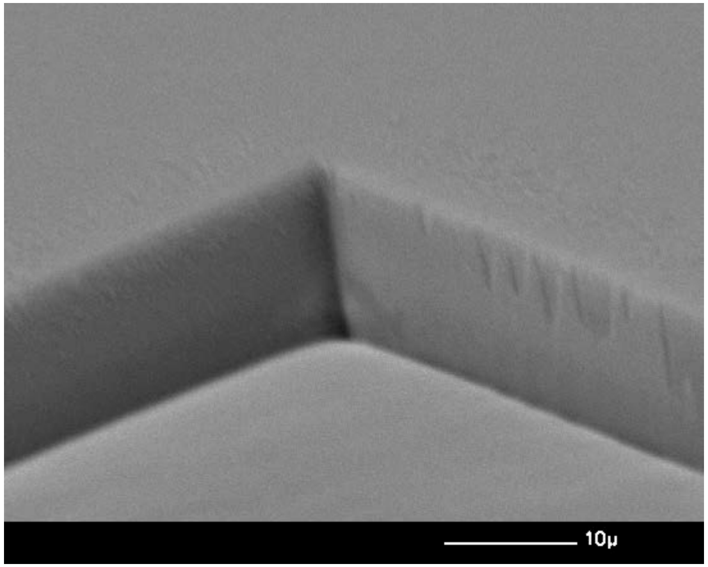
- Polymers
- Metals
- Glasses
- Silicon
- Optical materials
- Composites
- Ceramics
- Thin films



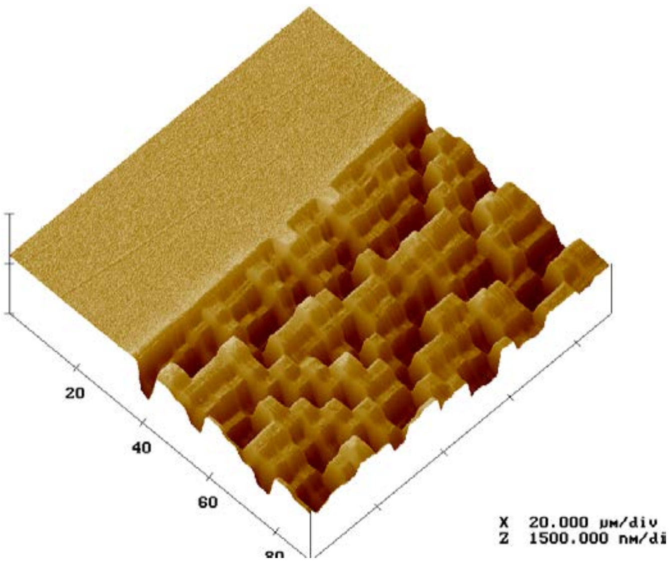
Courtesy of LML UK

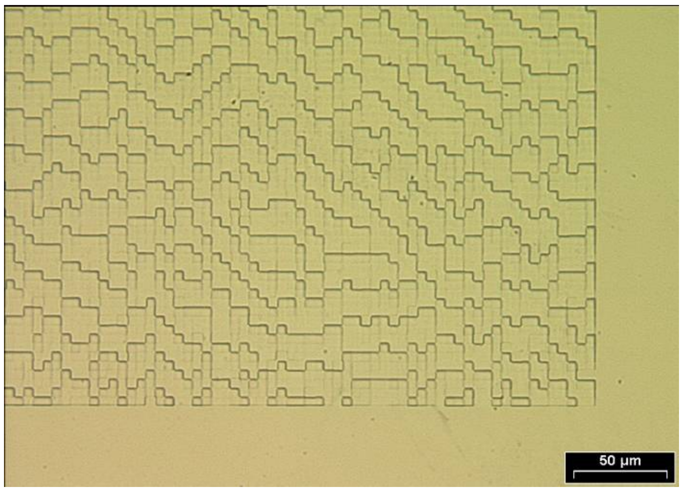
Laser machining of polymers

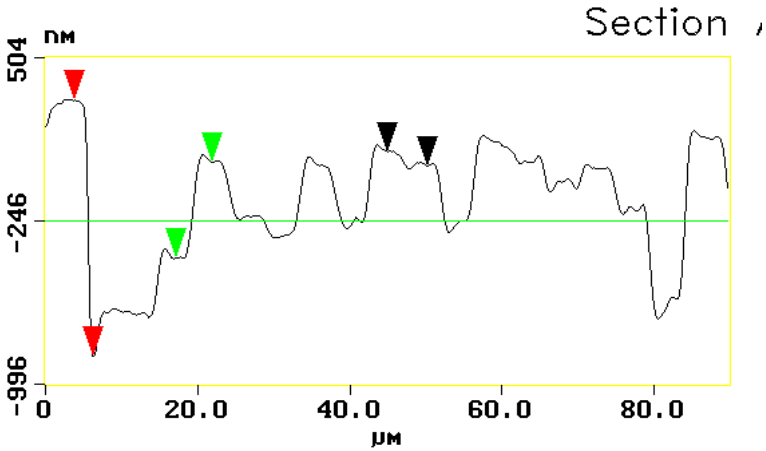
- Low ablation threshold (< 100 mJ/cm^2)
- Low surface roughness
- High edge definition
- …



DOE-halftone ablation

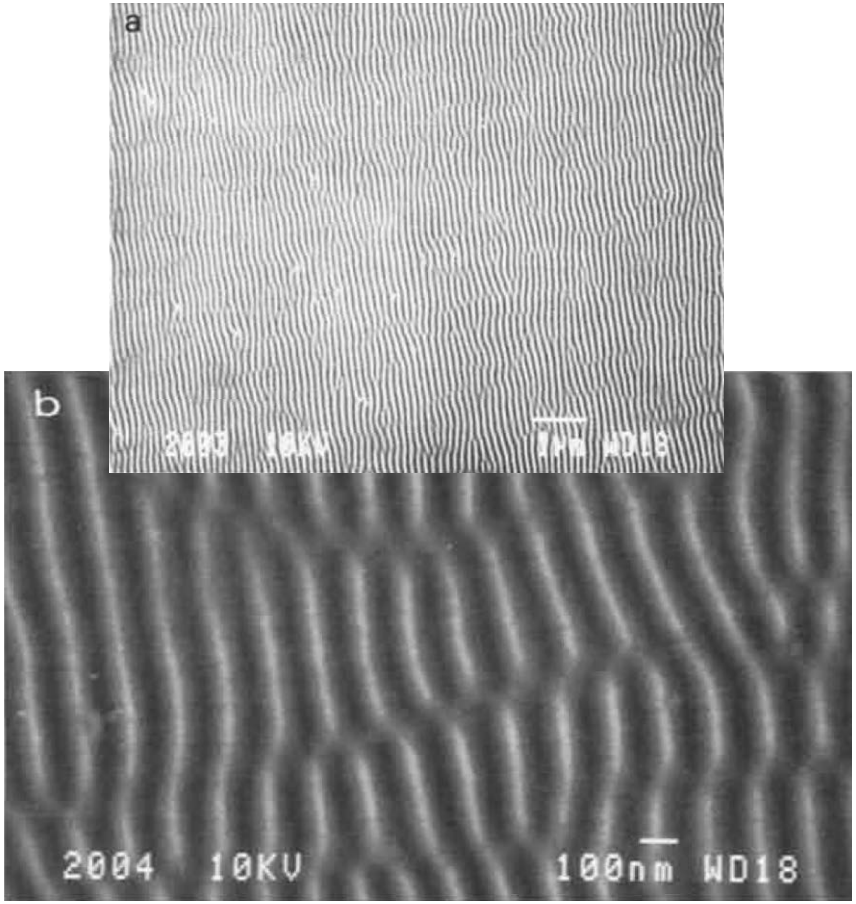






Surface distance	3.012 µm
Horiz distance(L)	2.461 µm
Vert distance	1.176 µm
Angle	25.533 deg
Surface distance	4.805 µm
Horiz distance	4.746 µm
Vert distance	438.31 nm
Angle	5.276 deg
Surface distance	5.276 µm
Horiz distance	5.273 µm
Vert distance	62.632 nm
Angle	0.680 deg
Spectral period	
Spectral freq	
Spectral RMS amp	

Submicron structures



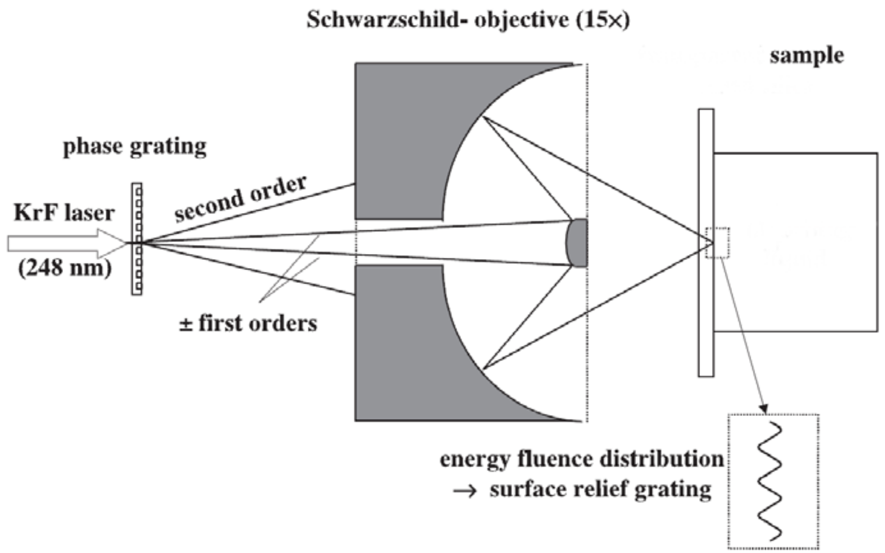
PET thin film on a silicium wafer. The film was irradiated with 1000 pulses of 193 nm at a fluence of 3mJ/cm^2.

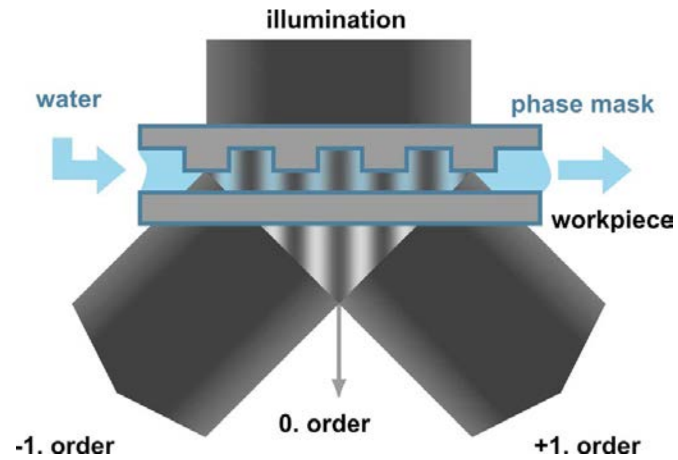
- Sub exposure wavelength periodicity in polymers by polarized excimer laser radiation.
- Important parameters are:
  - Polymer
  - Wavelength
  - Angle of incidence

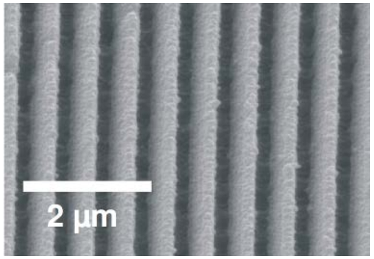
M. Bolle and S. Lazare, Applied Surface Science (1993)

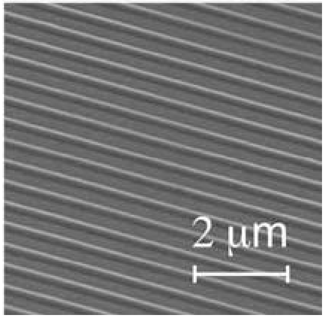
Submicron structures (cont)

- Phase mask setup for submicron structures









Experimental set-up for the generation of sub-micron gratings by laser-ablation

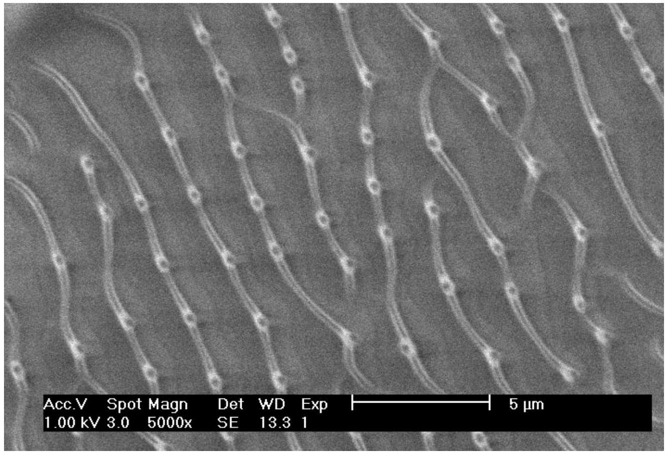
K. Zimmer et al, Appl. Phys. A 74, 453–456 (2002)

Principle of the proximity phase mask setup with water immersion

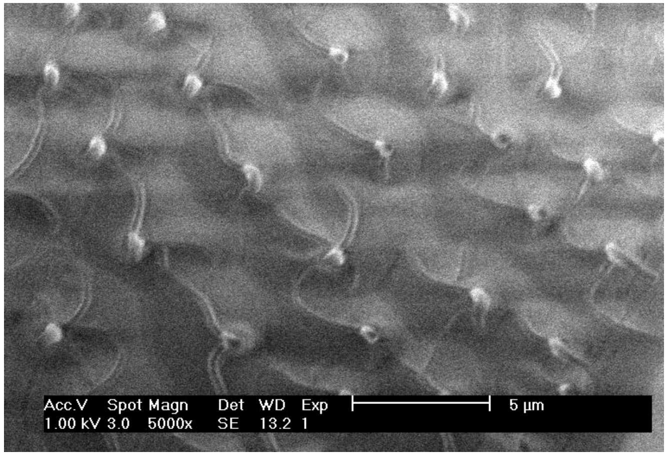
B. Borchers et all, Appl. Phys. 107, 2010

Submicron structures (cont)

PET exposed at 193nm



75 mJ/cm^2

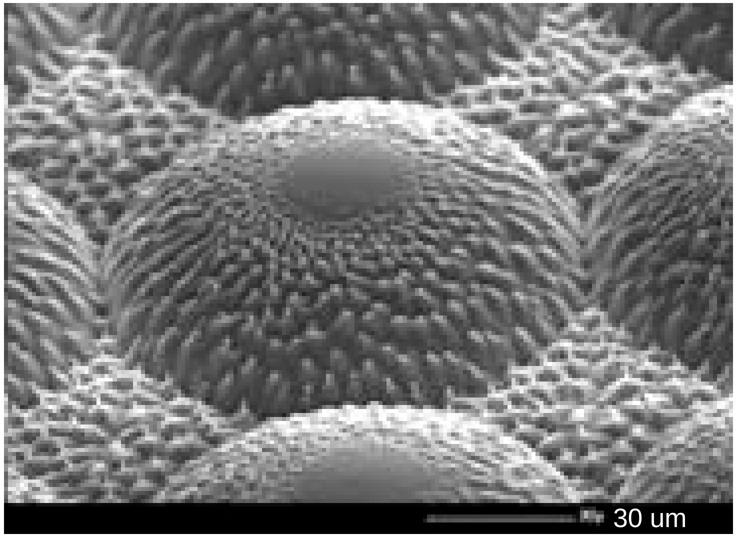


120 mJ/cm^2

Sub micron features through material stress release

Important parameters are:

- Stretch direction of polymer
- Wavelength
- Angle of incidence
- Energy density



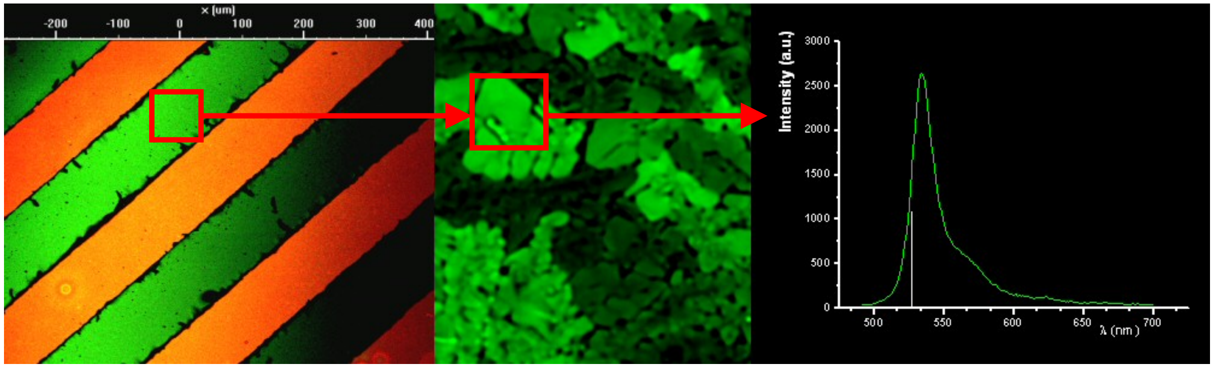
PET exposed at 248 nm

400 mJ/cm^2

Courtesy Epfl

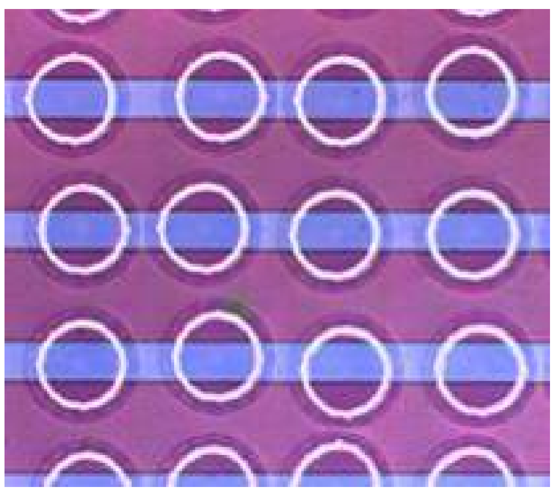
Thin film ablation

Al cathode

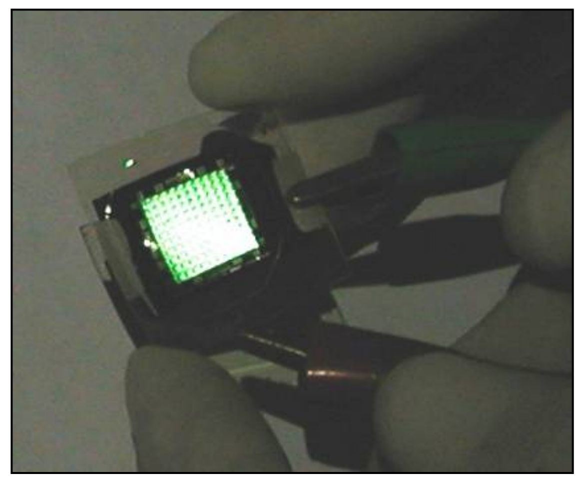


Thin metal ablation without damaging organics underneath. Metal strips (orange) ablated from OLED (green) material with high magnification picture and intensity profile of emitted light.

ITO anode

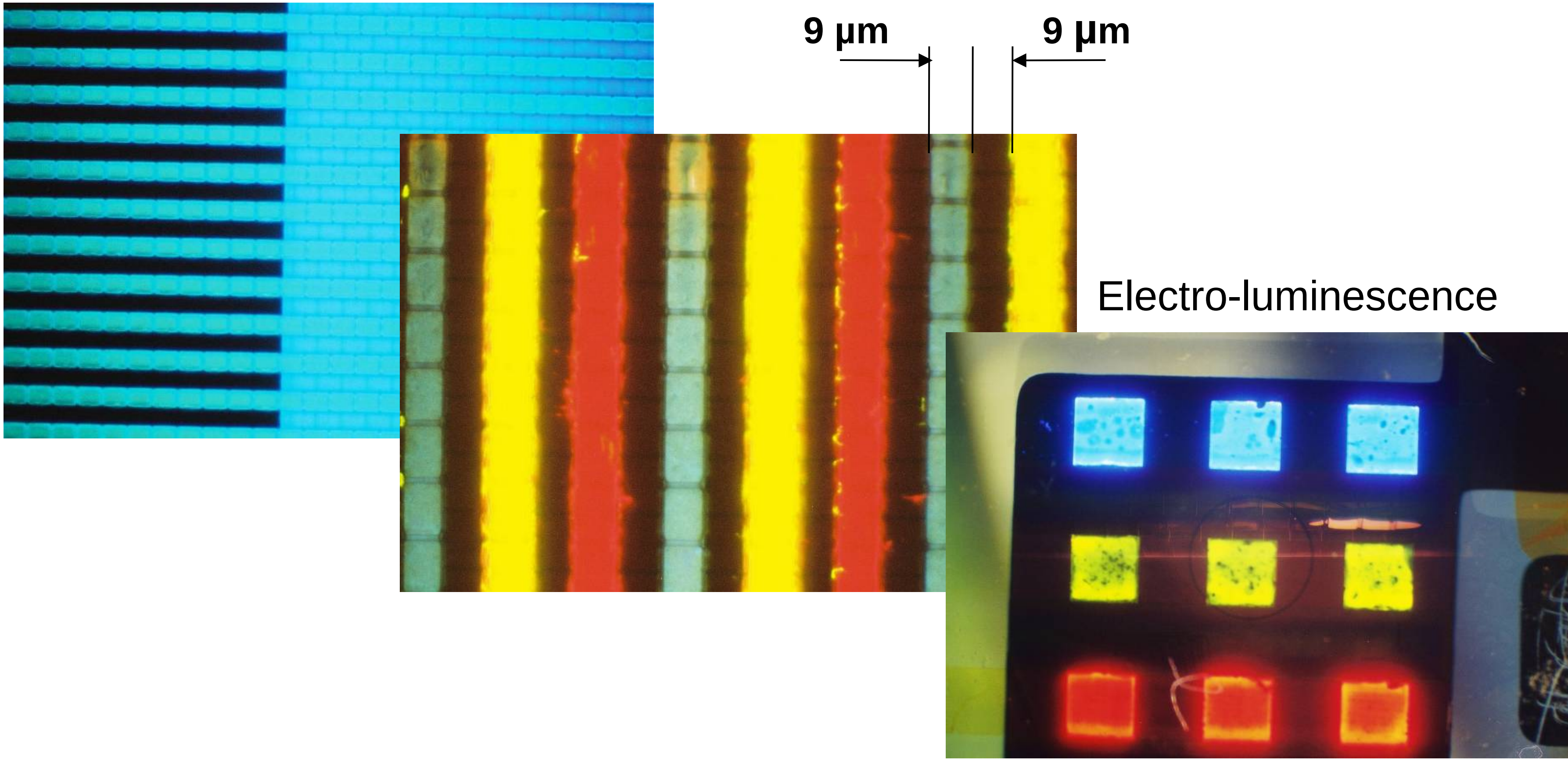


Laser scribed ITO and the UV-embossed lens array aligned to the ITO lines.



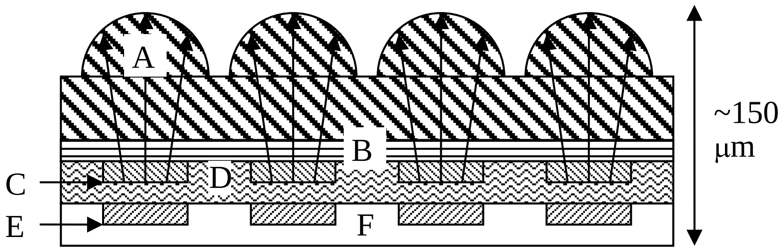
Flexible organic illuminator demonstrator.

Laser assisted multicolour OLED printing



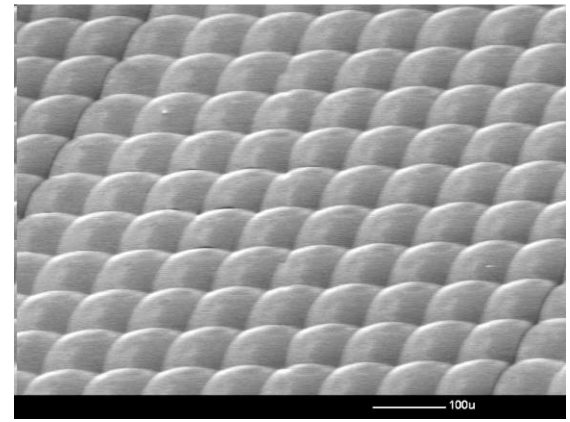
- Well defined pixels (< 10 µm), for high resolution micro-display
- Long molecules multicolour application (spin coated)

Rapid prototyping



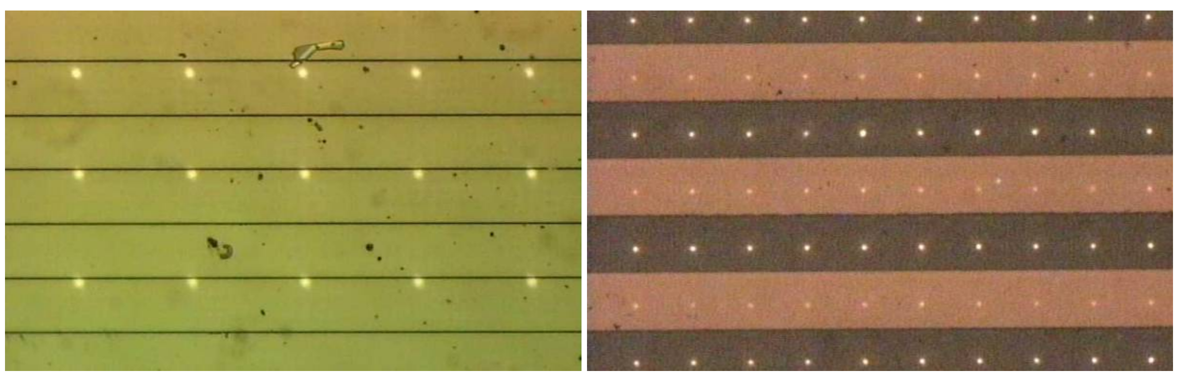
Device structure of flexibel OLED illuminator or display: A) micro optics, B) barrier layer, C) ITO andode, D) OLED material, E) Al cathode, F) Encabsulation

A



Micro lenses directly laser ablated into PET

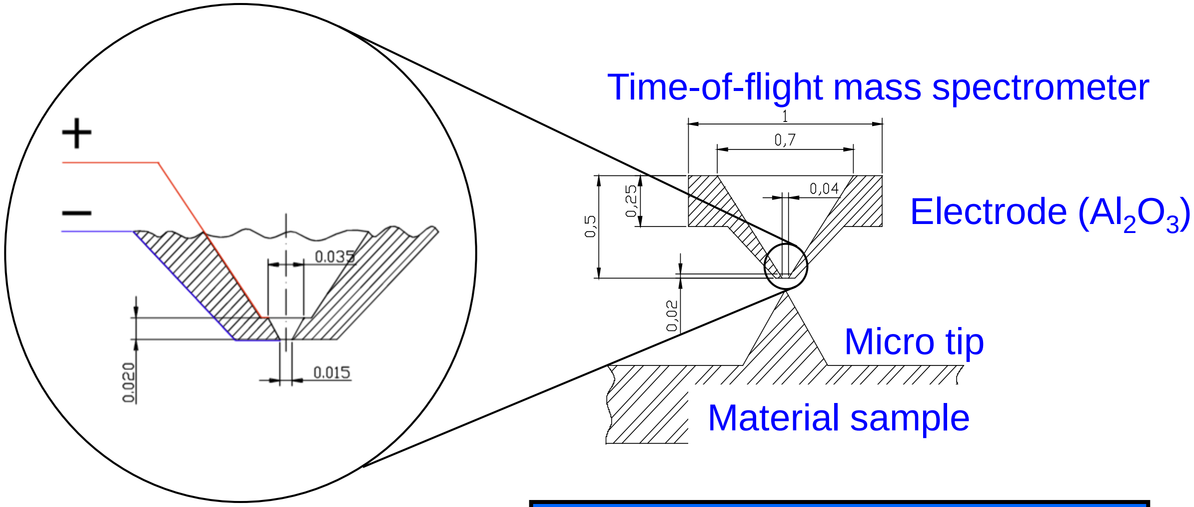
C



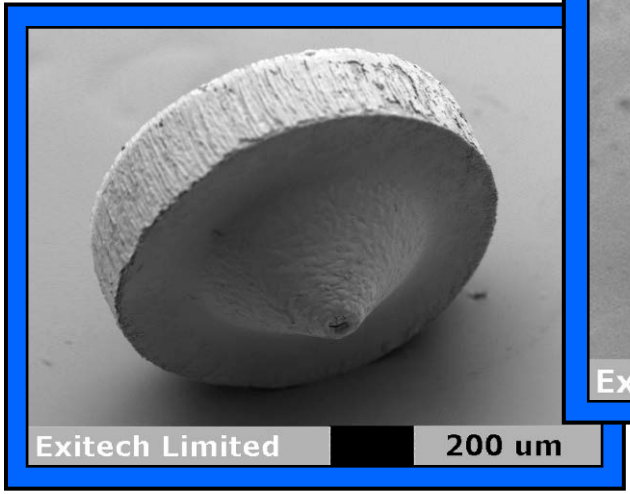
ITO ablation of 10 µm (left) and 100 µm lines nicely aligned to lenses on the backside.

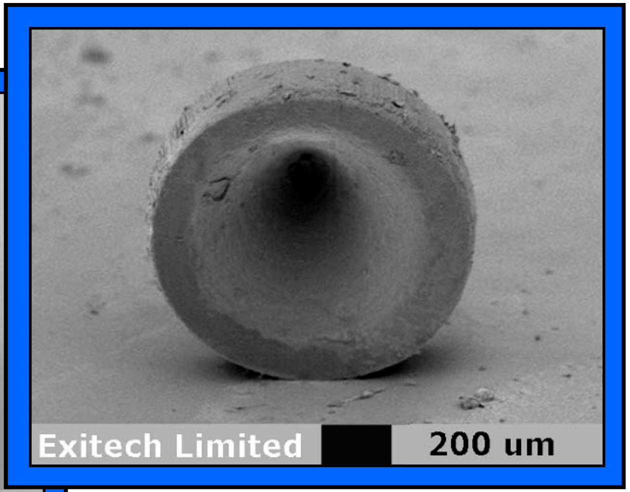
Laser machining of ceramics

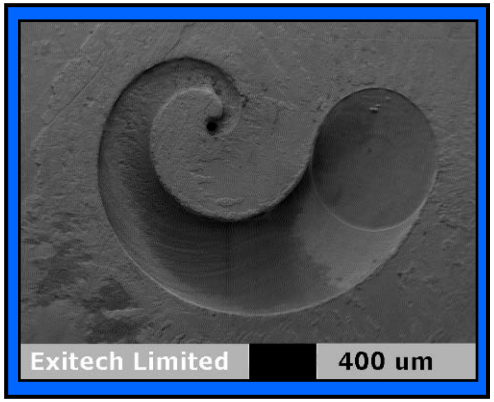
- *Schematic of one part of Scanning Atom Probe Instrument (SAP)*



248nm (KrF)
10 J/cm^2

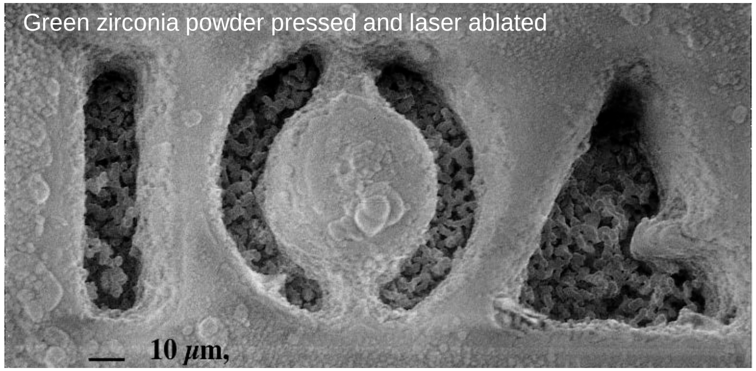


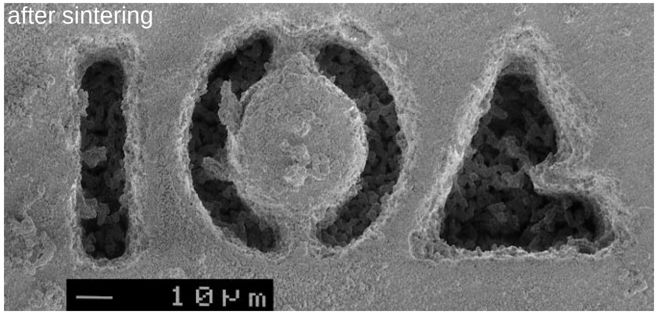




Microstructures in „green“ ceramics

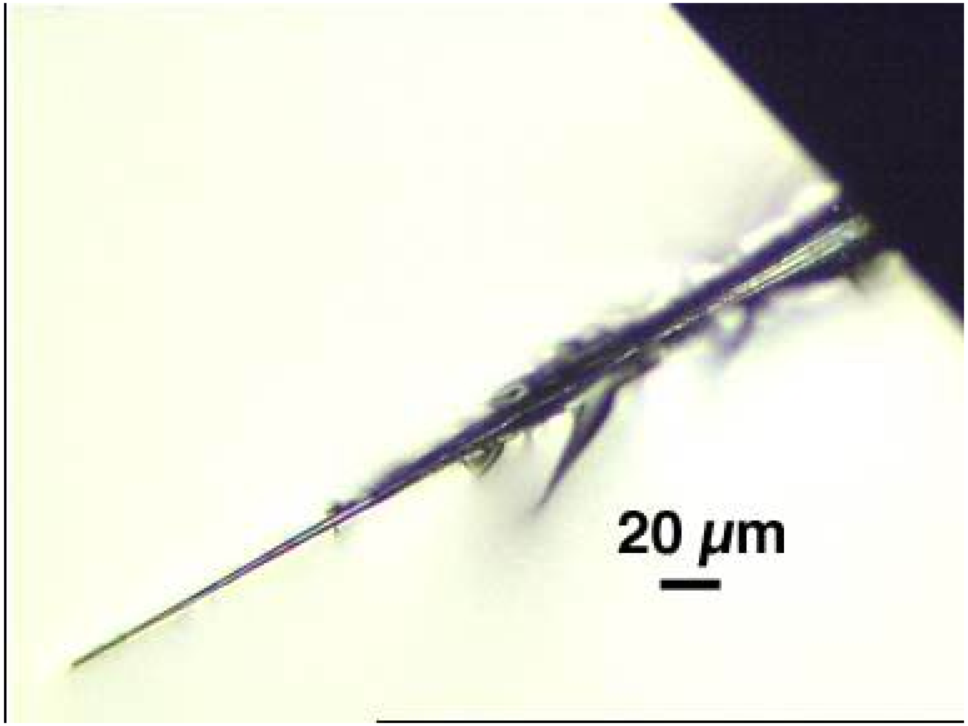
- 1/50 of energy density needed to machine
- Potential for highly efficient micro structuring of ceramics

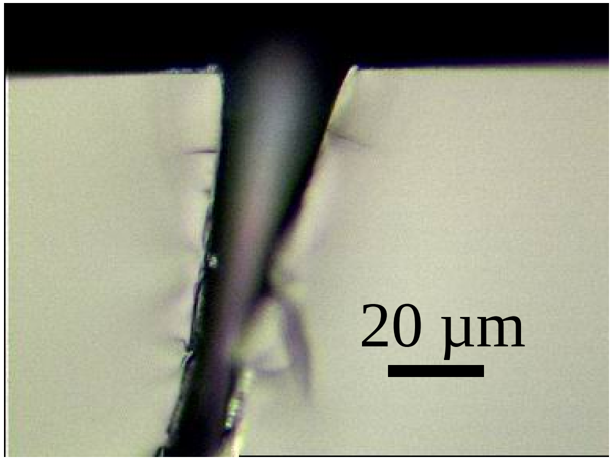




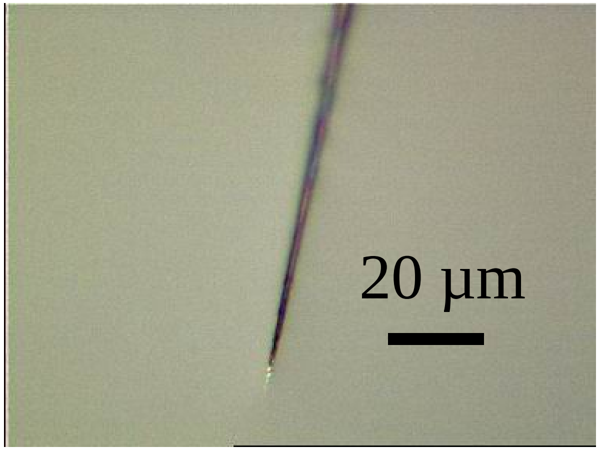
Courtesy of EPFL

Glass





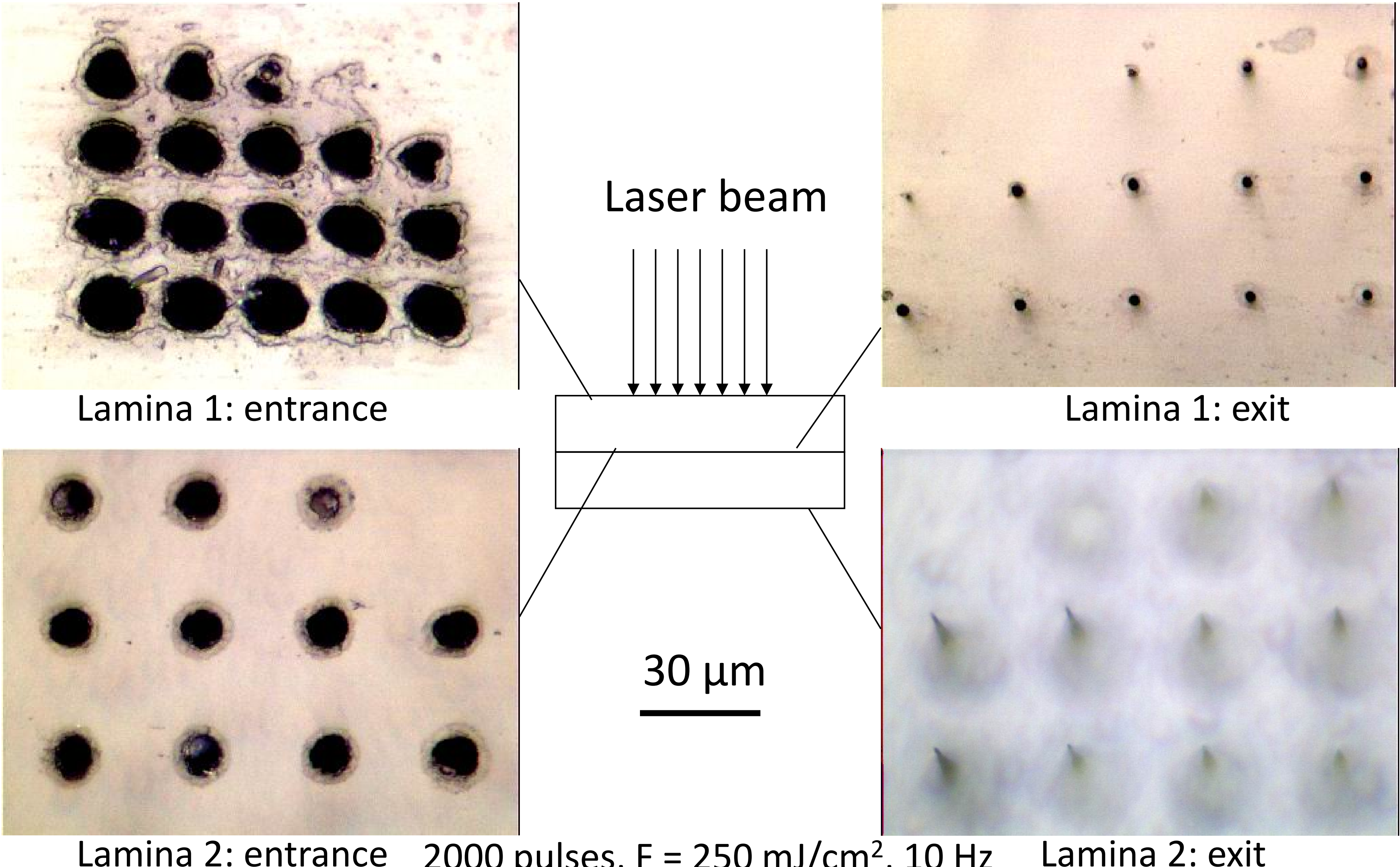
entrance



end

- Mask diameter: D= 500 μm
- F = 100 mJ/cm^2, 5000 pulses, 40 Hz

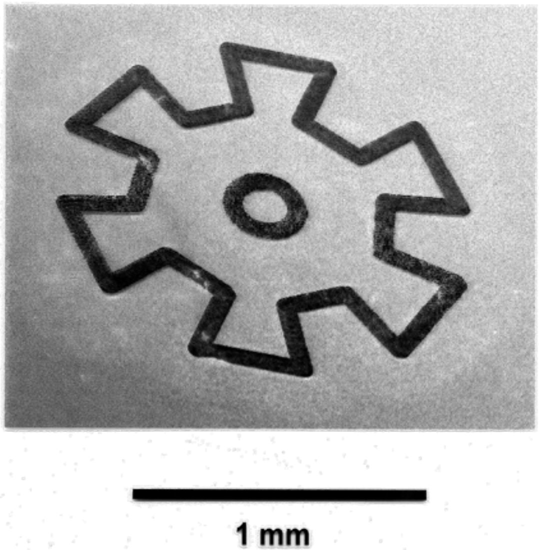
Glass

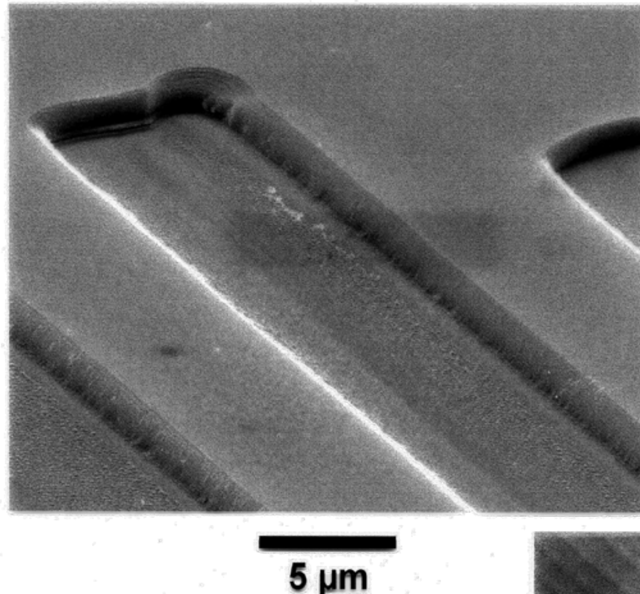


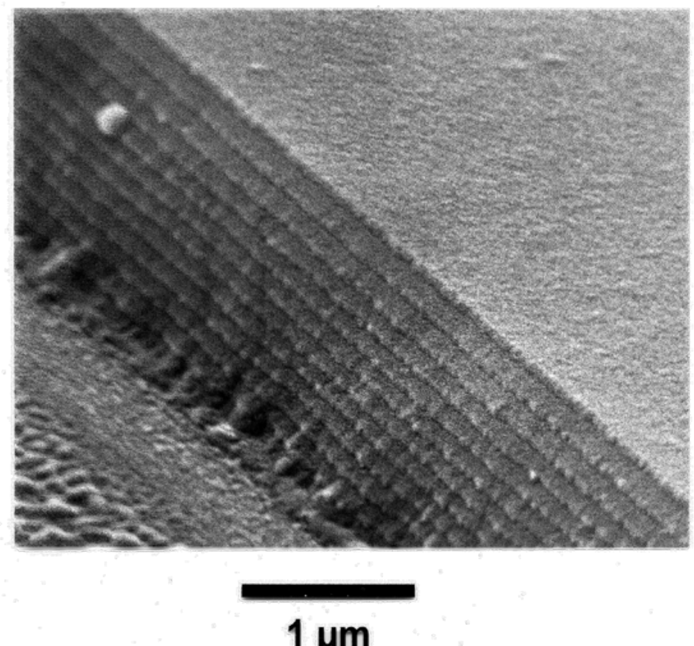
2000 pulses, F = 250 mJ/cm^2, 10 Hz

Ablation of the Mask

HR 308 nm Mask





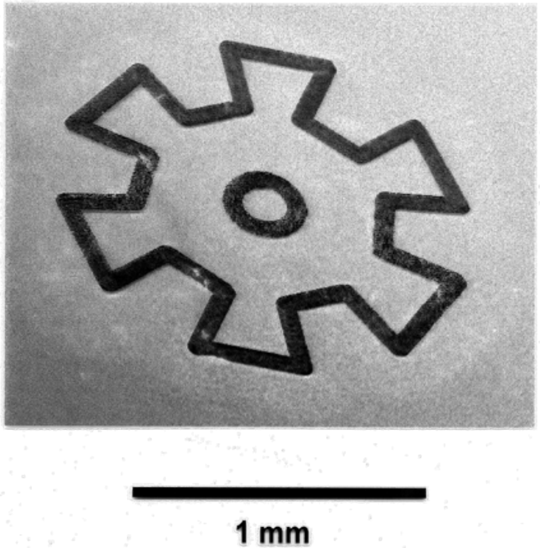


Material: HfO_2/SiO_2 on fused silica
Laser 193 nm, 170 mJ/cm^2, 1 pulse

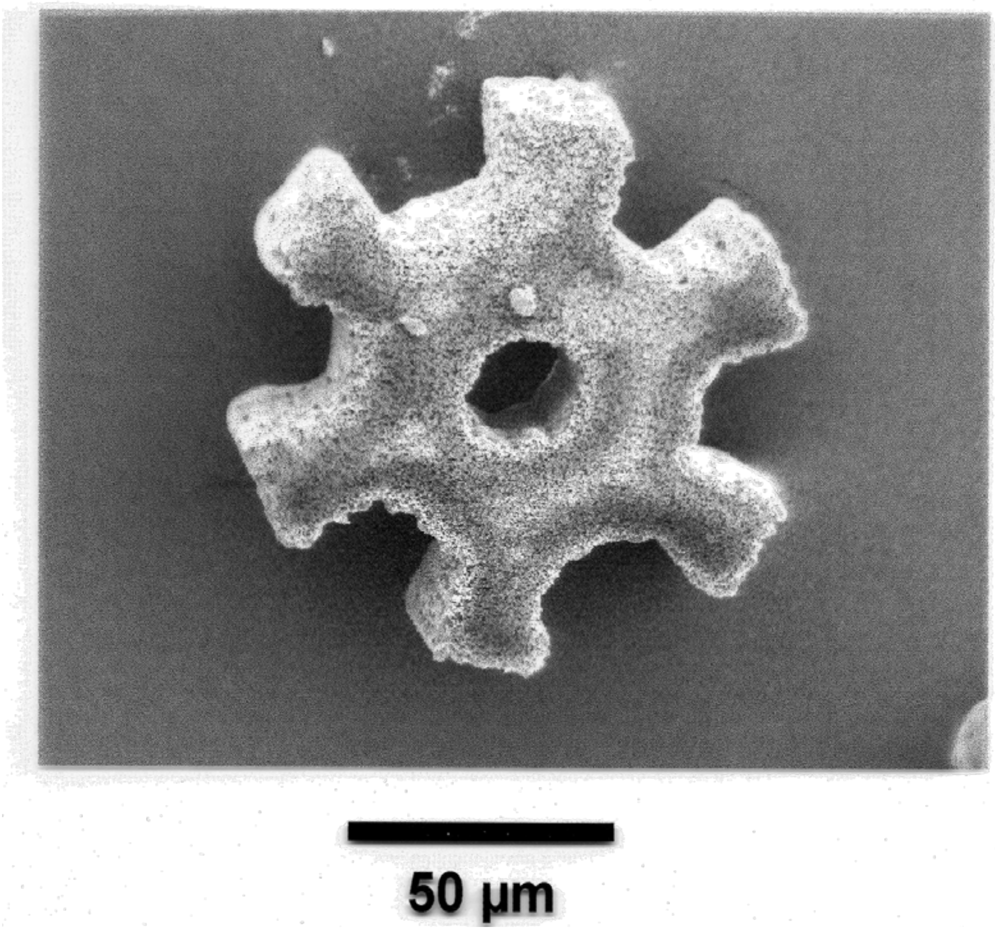
Laser-
Laboratorium
Göttingen e.V.

Ablation through the Mask

HR 308 nm Mask



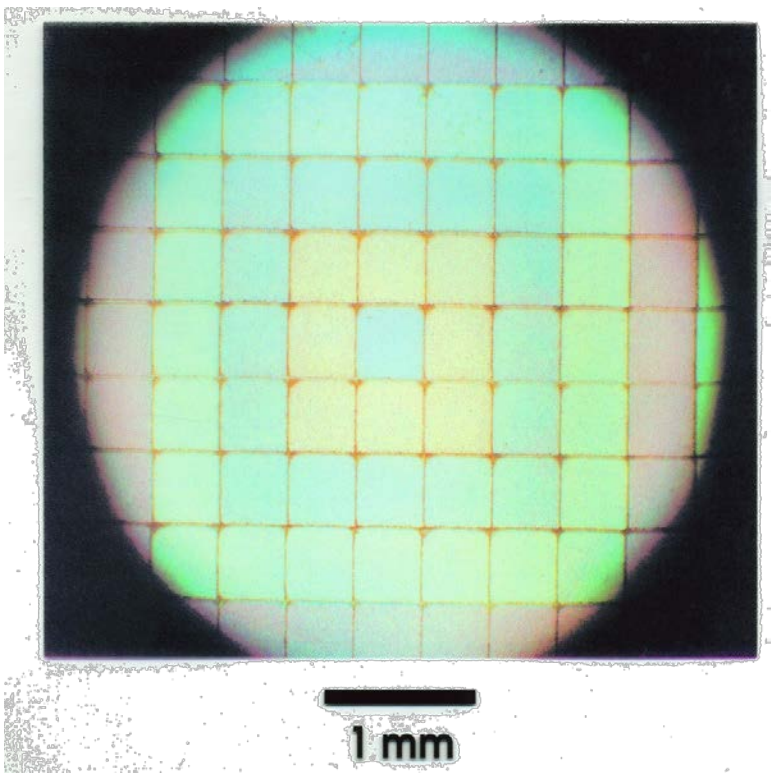
Material: Al_2O_3 - ceramics
Laser 308 nm, 10 J/cm^2, 2000 pulses

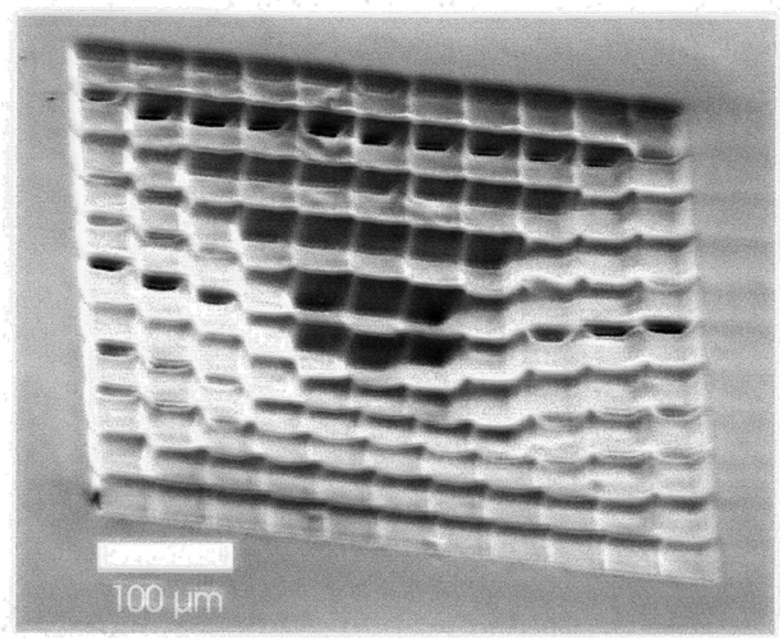


Ablation through the Graded Mask

Graded Mask
Material: HfO_2/SiO_2 on fused silica

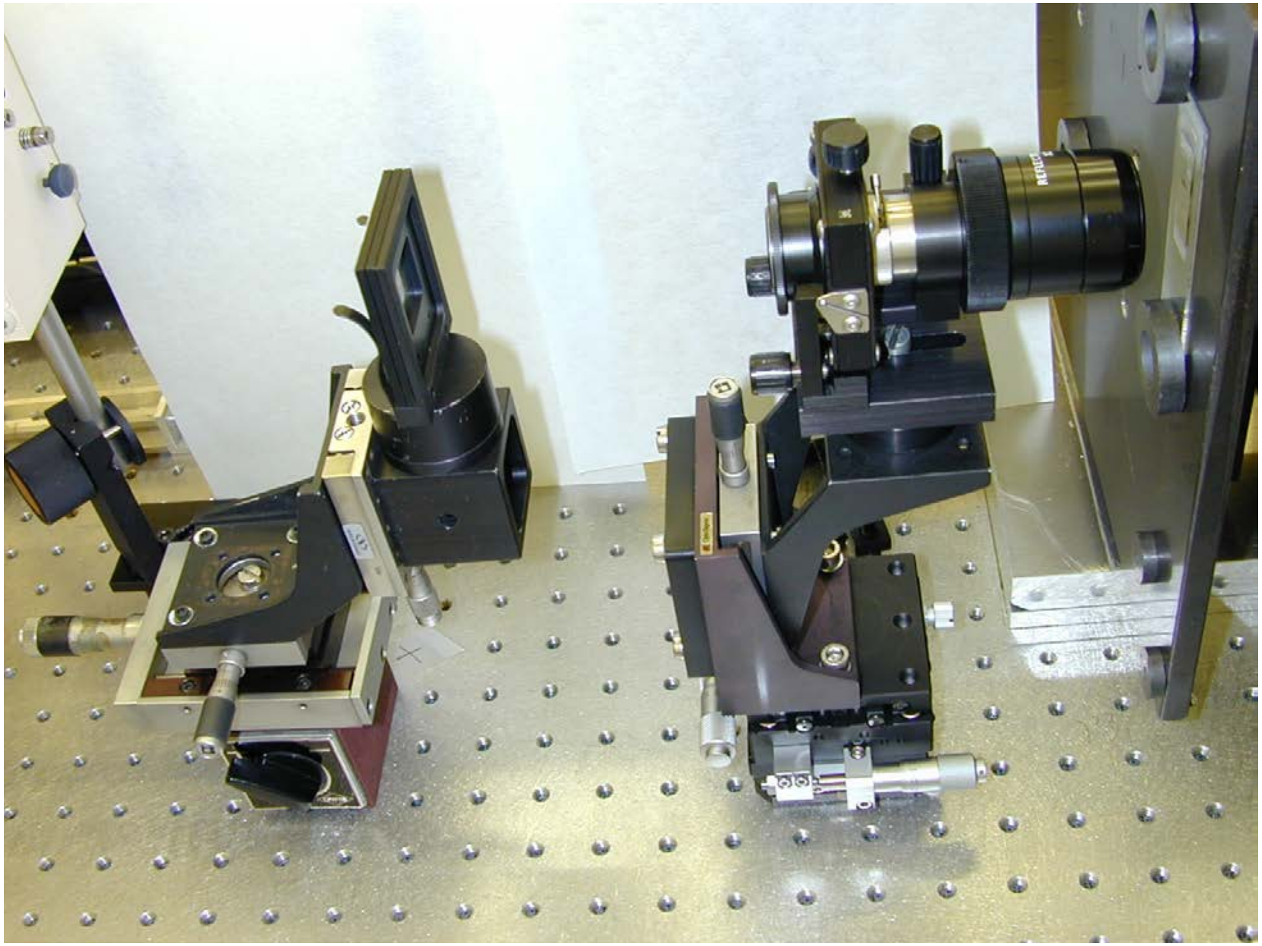
Material: Polycarbonate
Laser 248 nm, 960 mJ/cm^2 (average), 100 pulse





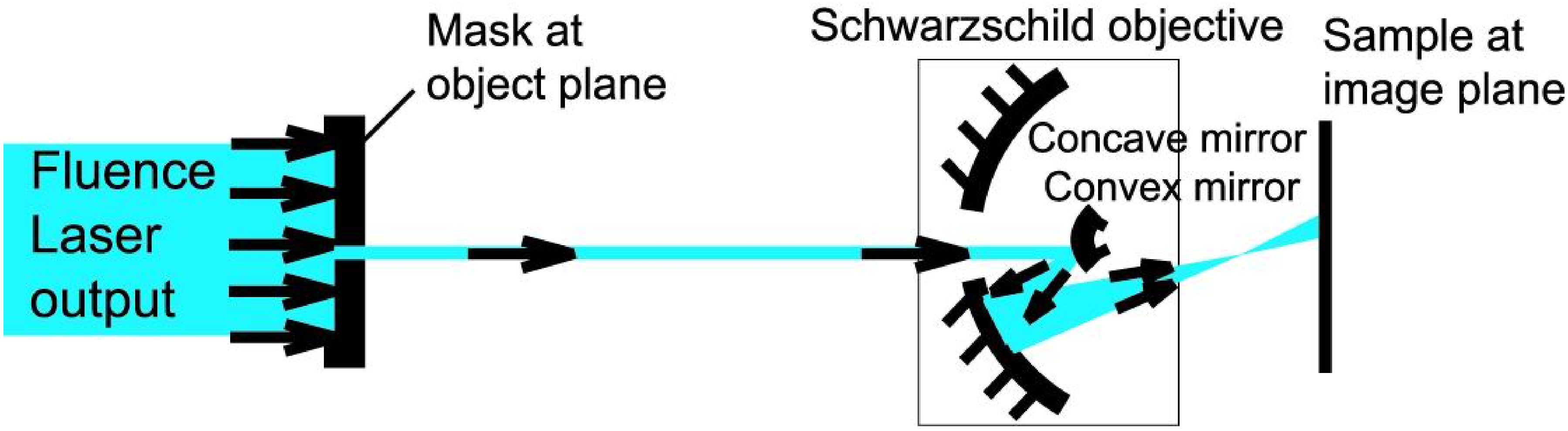
Laser-
Laboratorium
Göttingen e.V.

Schwartzschild – optics for Excimer laser



- X. Schwab with T. Bret
- Group of Dr. P. Hoffmann

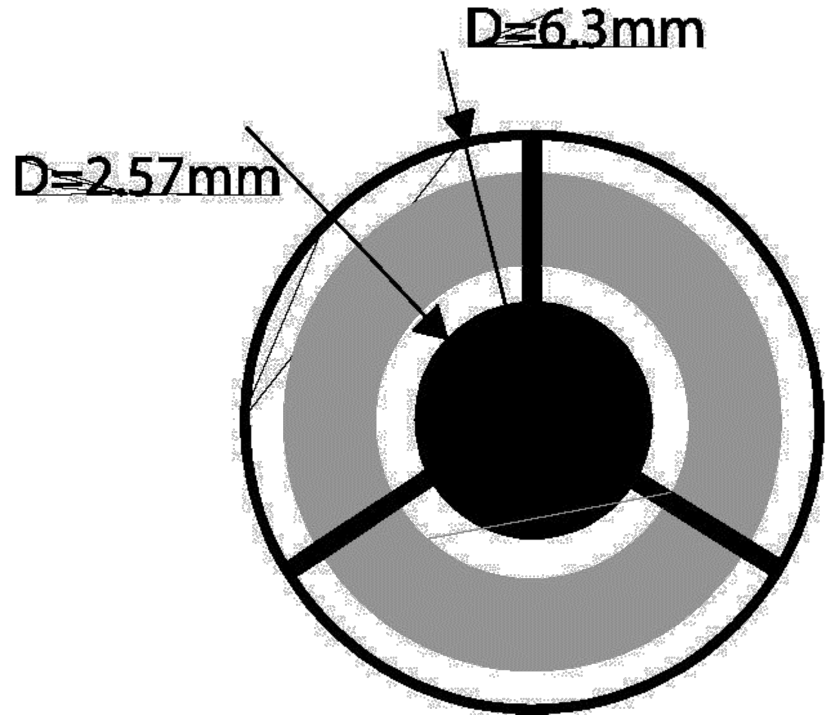
Schwarzschild objective: Set-up



- ArF Excimer Laser pulsed at 20ns
- Fluence Laser output : 25-250 mJ/cm^2
- Image magnification: 1/25
- Fluence gain : 45 x Fluence at Laser output

Schwarzschild objective

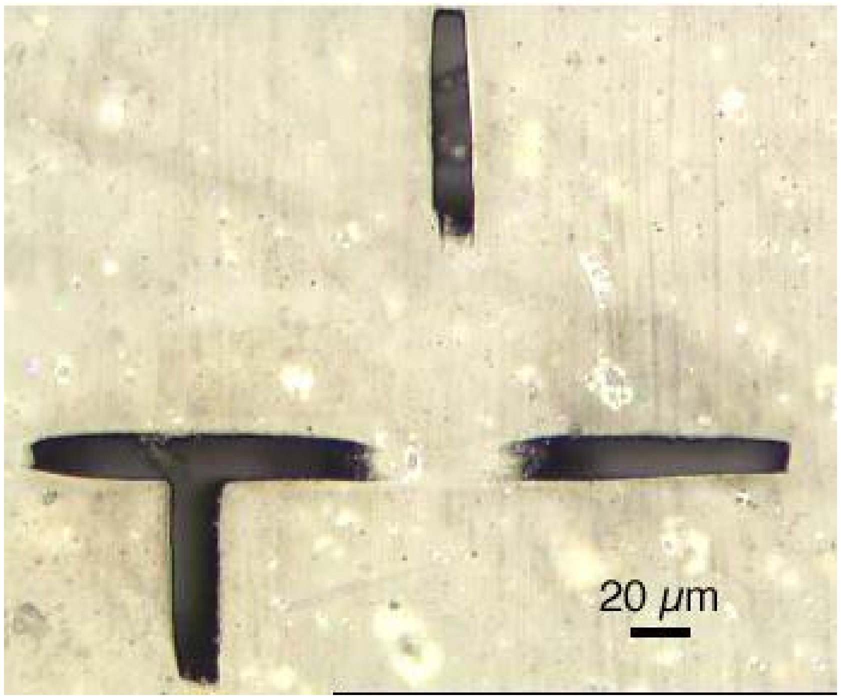
- Magnification 1/25
- Low aberrations, achromatic
- Numerical aperture : NA = 0.4
- Central obscuring : 16.7%
- Mirror : coating for 193 nm
- maximum reflection $R_{max} = 0.5$

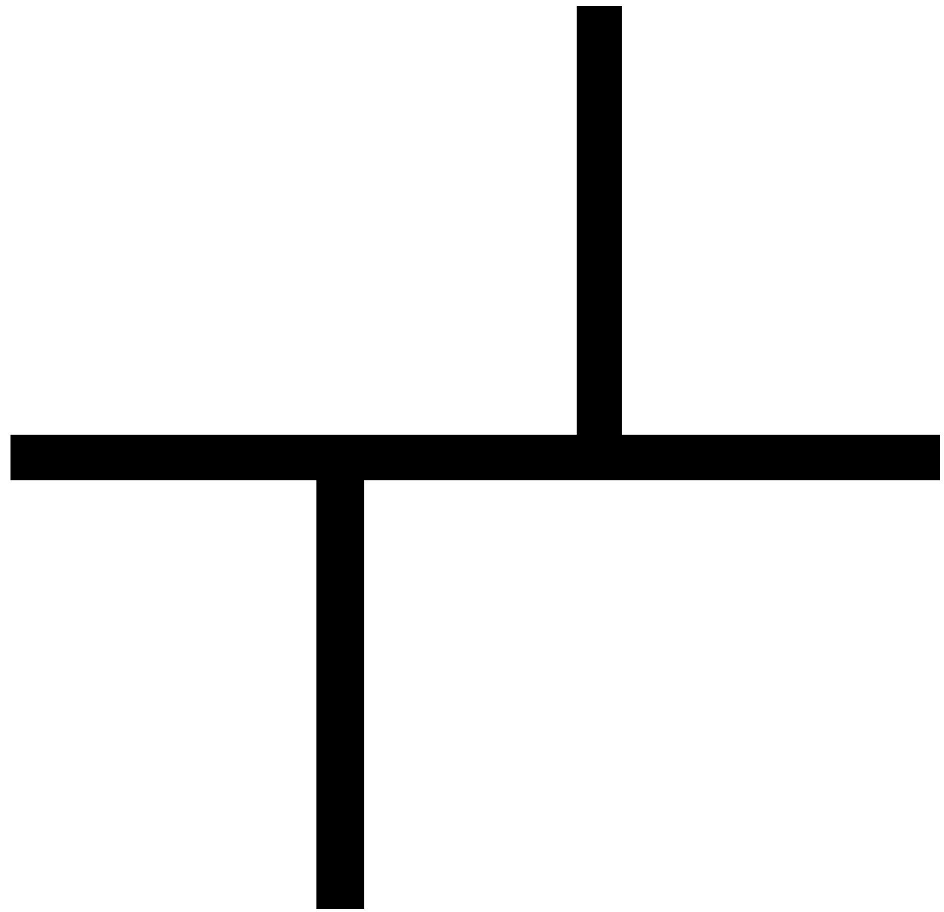


Theoretical optical resolution:

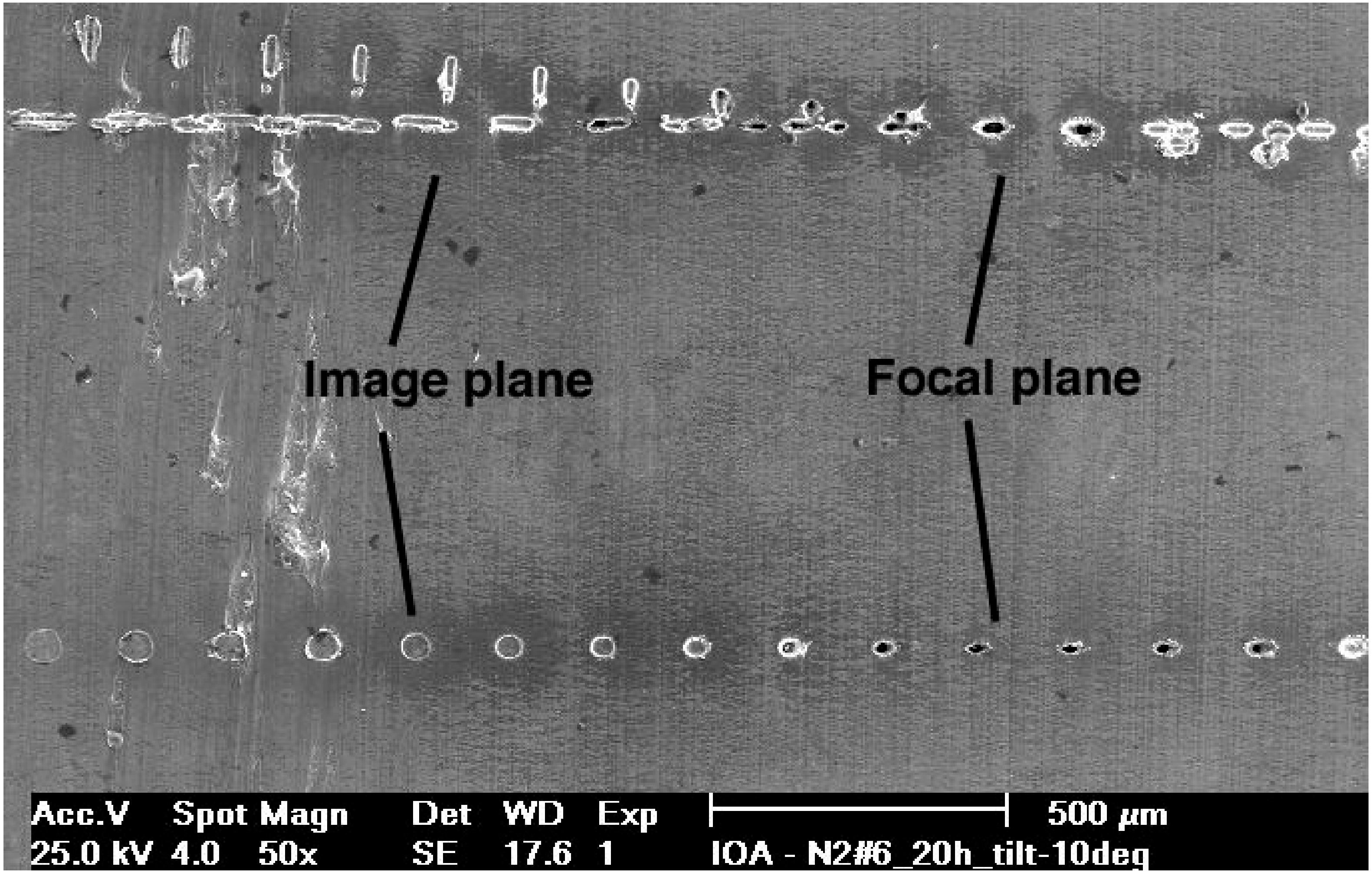
$$r = \frac{\lambda}{2 \cdot NA} = 241\, nm$$

Schwarzschild objective: central obscuring





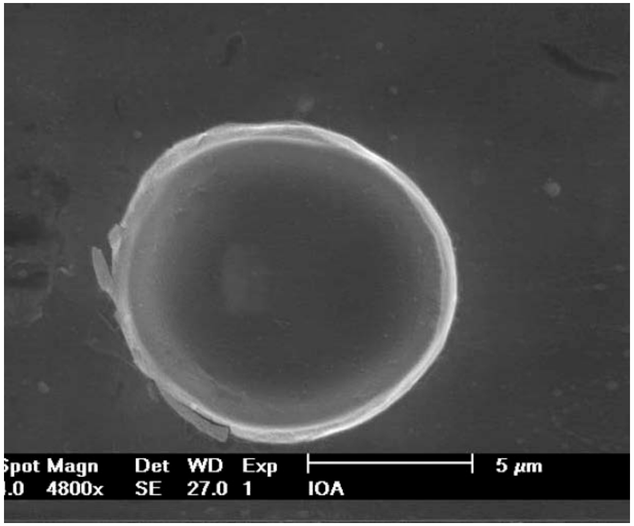
Aluminium: Search for image / focal planes



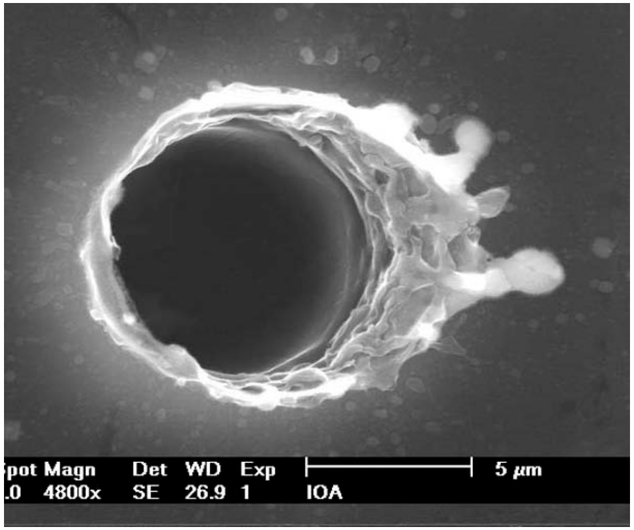
- Distance image-focal planes: 300 µm, F= 50 mJ/cm^2, 5 pulses at 10 Hz

Aluminium: variation of the number of pulses

1 pulse

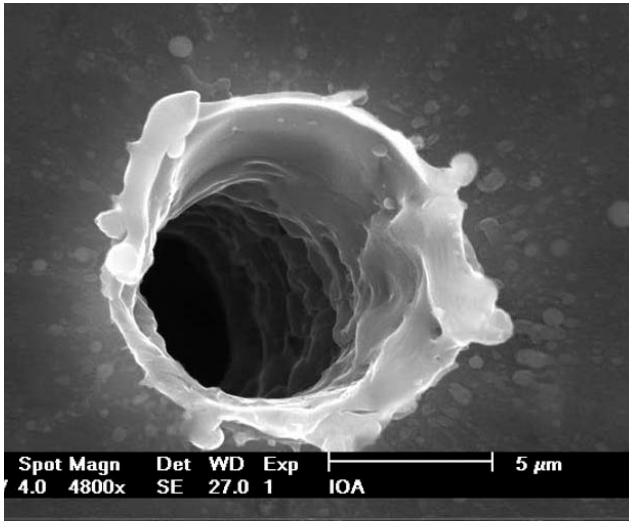


10 pulses



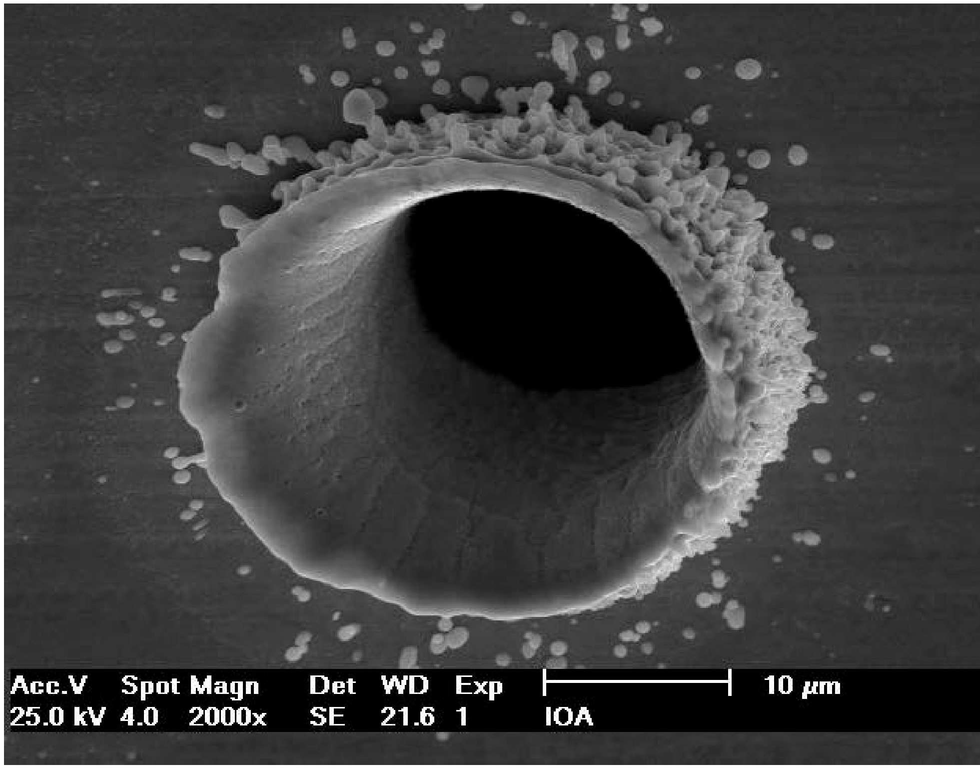
- Thickness : 20 µm, F = 15 mJ/cm^2
- Mask diameter: D = 215 µm

100 pulses

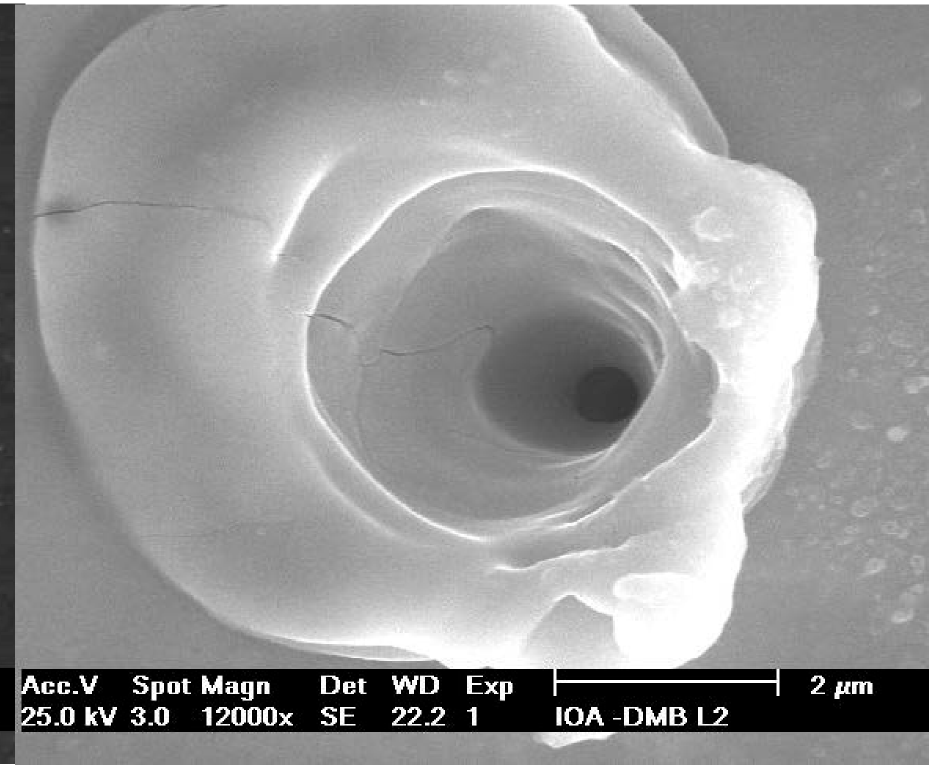


Molybdenum: through-hole

- Thickness of the molybdenum: 12.5µm



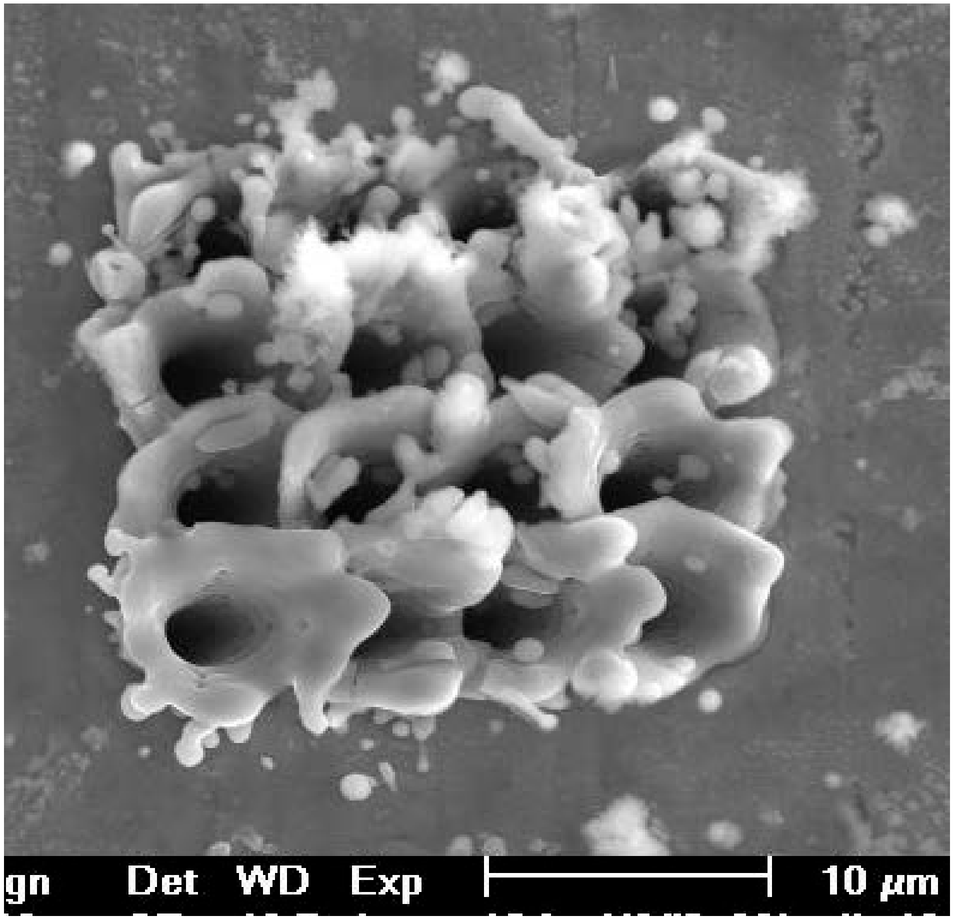
250 mJ/cm², 40 pulses at 10 Hz



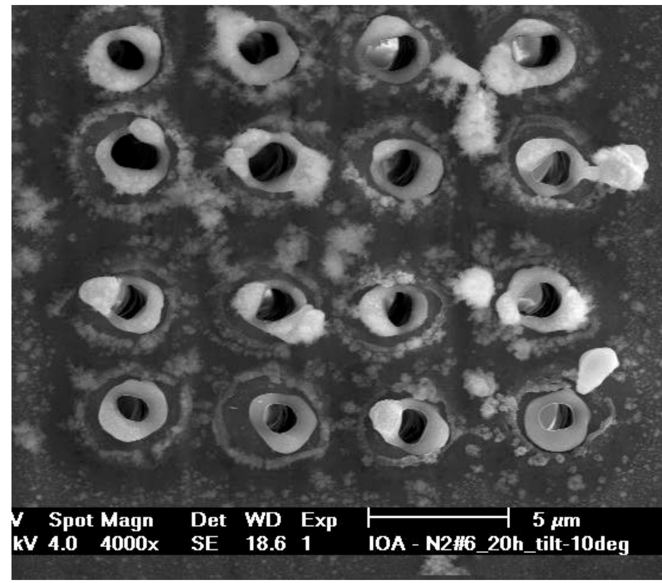
25 mJ/cm², 2000 pulses at 40 Hz

Molybdenum: multiple through holes

Entrance



Exit

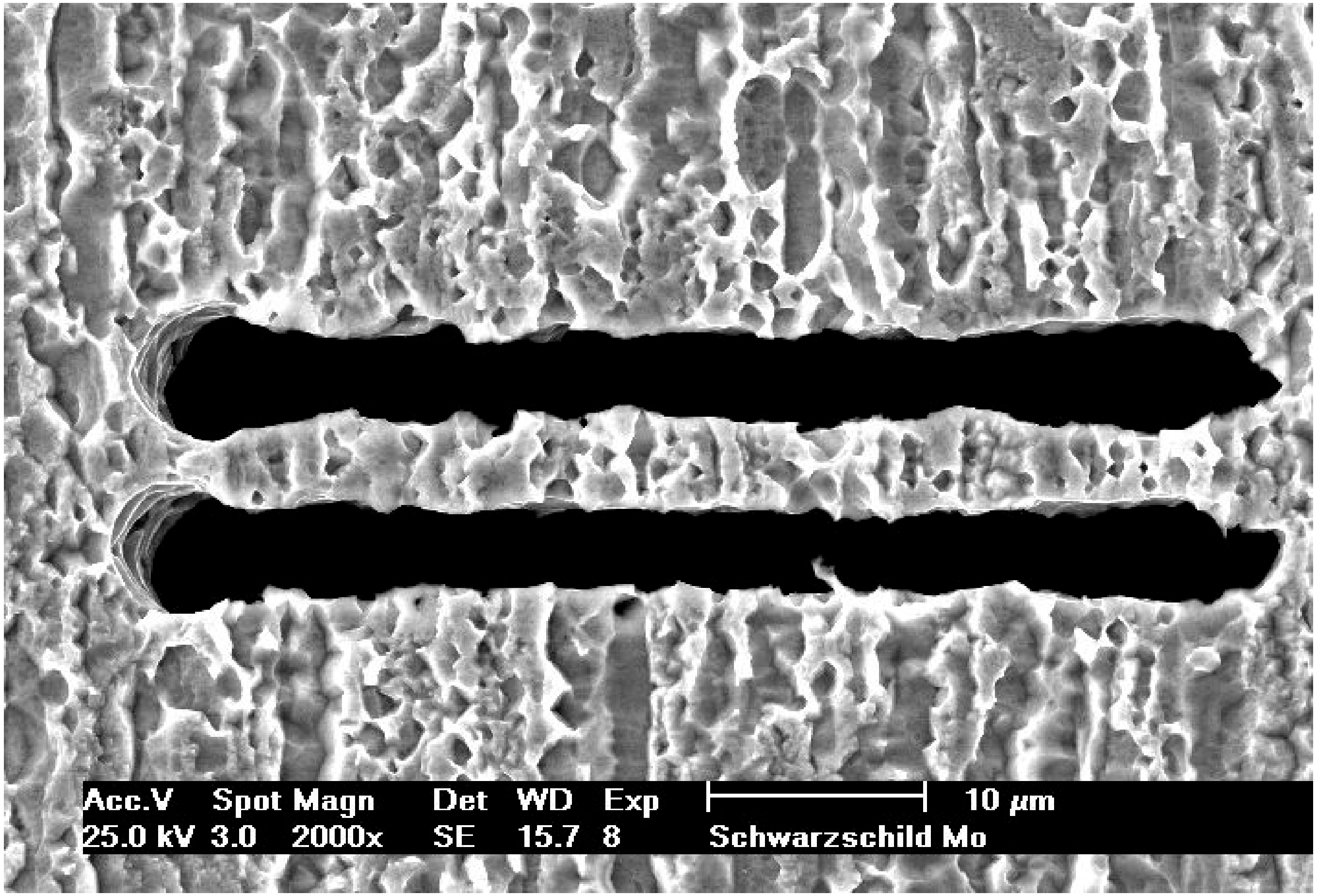


F = 25 mJ/cm^2
2000 pulses, 40 Hz
Mask diameter D = 215 µm

Molybdenum: Micro line

Mask diameter: D = 500 µm
F = 100 mJ/cm^2, 40 Hz
Table speed: v = 2 µm/sec

- Chemical etching: 20% H_2SO_4, 80% HNO_3



Ablation comparison

- **Metals:**
  melting, ejection of material and deposit on the side of the hole.
- **SiO_2, polymers:**
  limited thermal penetration -> Less deposit.