Empa
Materials Science and Technology

EPFL

Advanced materials processing with intelligent systems

Dynamics of laser processes

Sergey Shevchik & Patrik Hoffmann

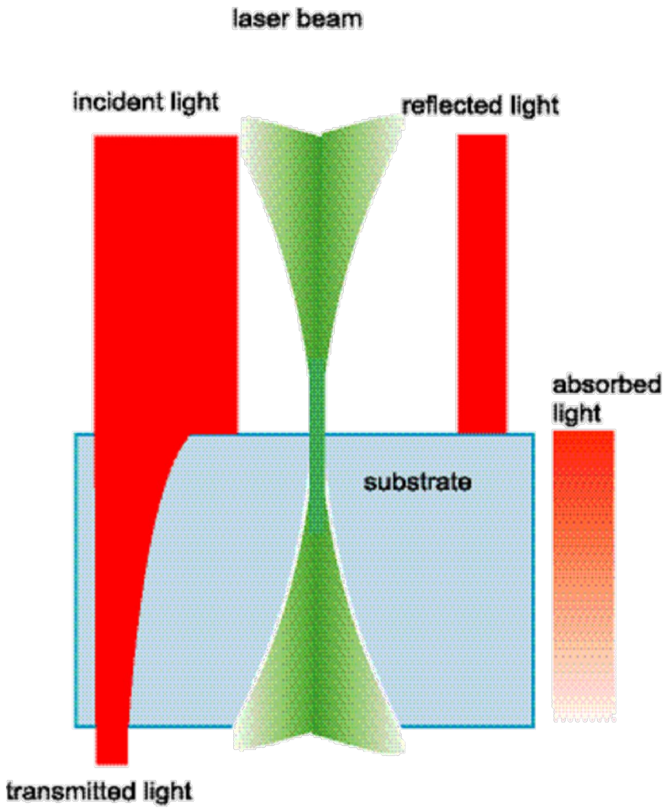
UV- Excimer Laser Ablation

- Model
- Influences
- Examples
- Applications

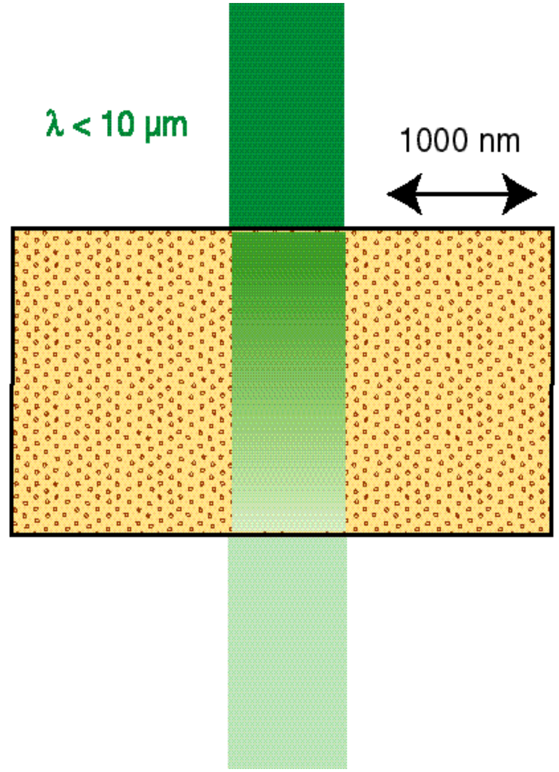
D. Bäuerle; Laser Processing and Chemistry,
3rd Edititon, Springer Berlin, 2000

D. Bäuerle: Laser Processing and Chemistry,
4th Edition, Springer Verlag, Berlin, Heidelberg 2011

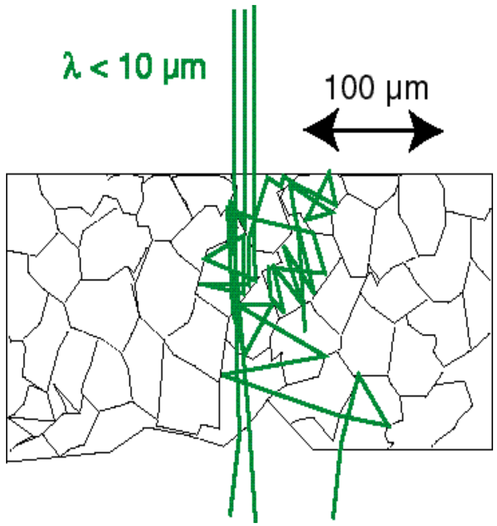
Laser light material interaction



- Flat homogeneous



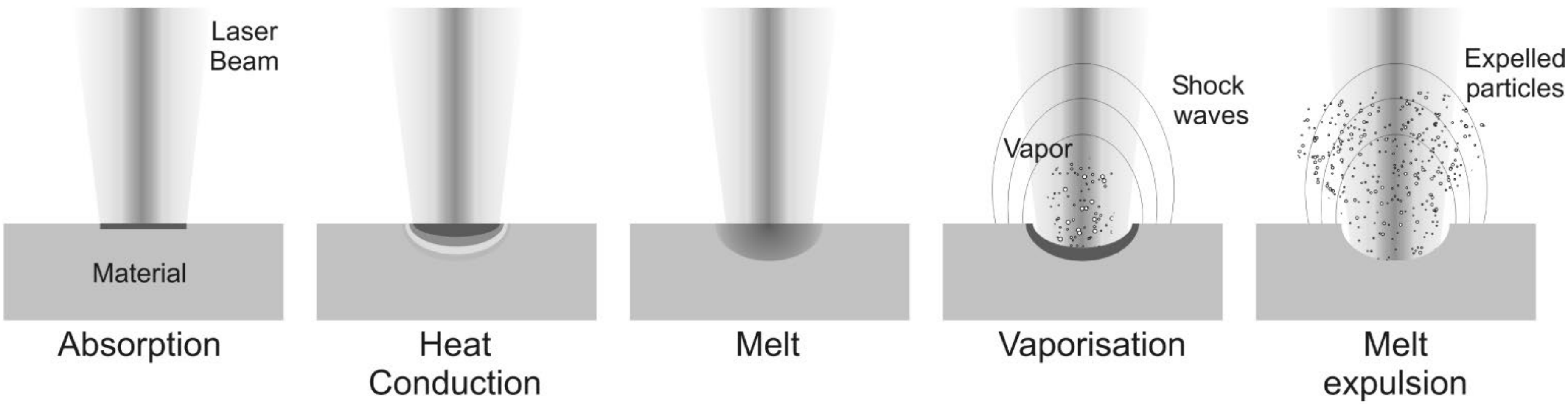
flat composit



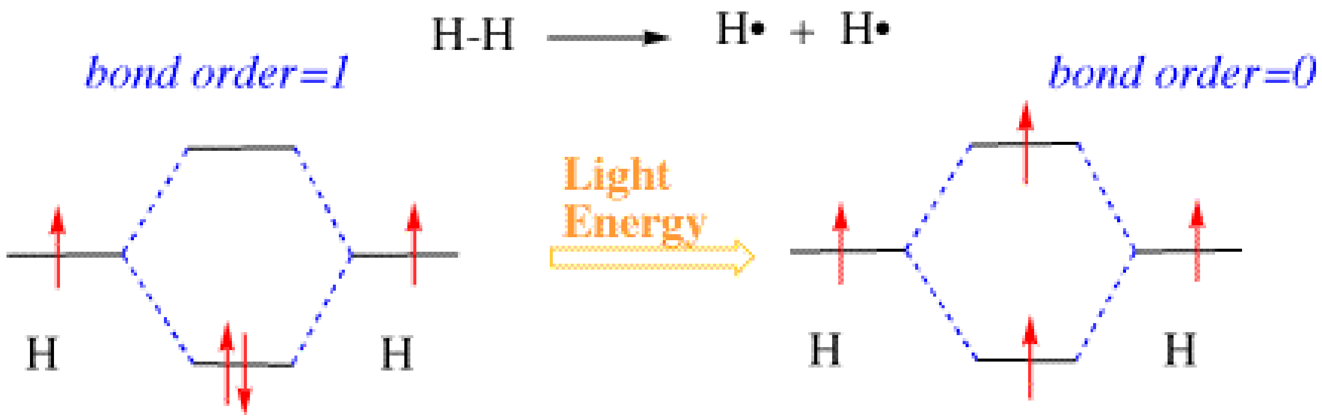
micro- macro- structured

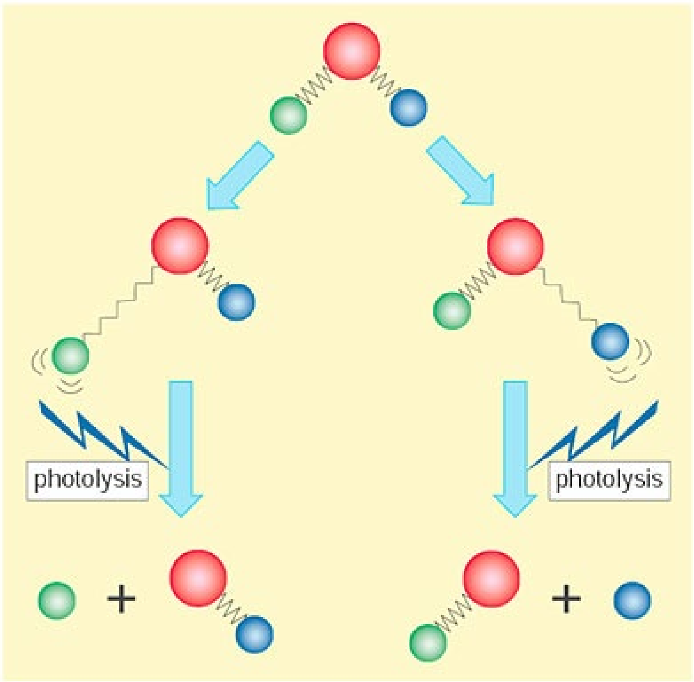
How is rough homogeneus ?

Thermal Influence

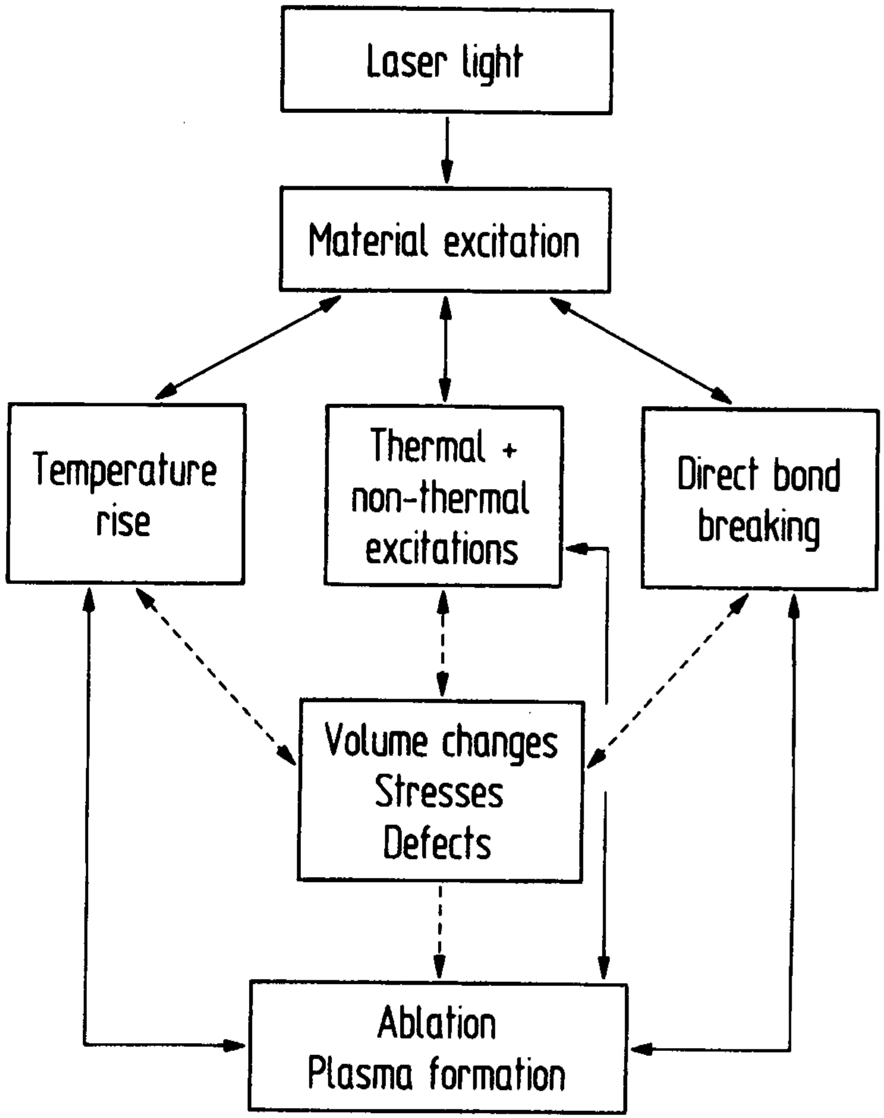


Photolysis – Direct Bond Breaking

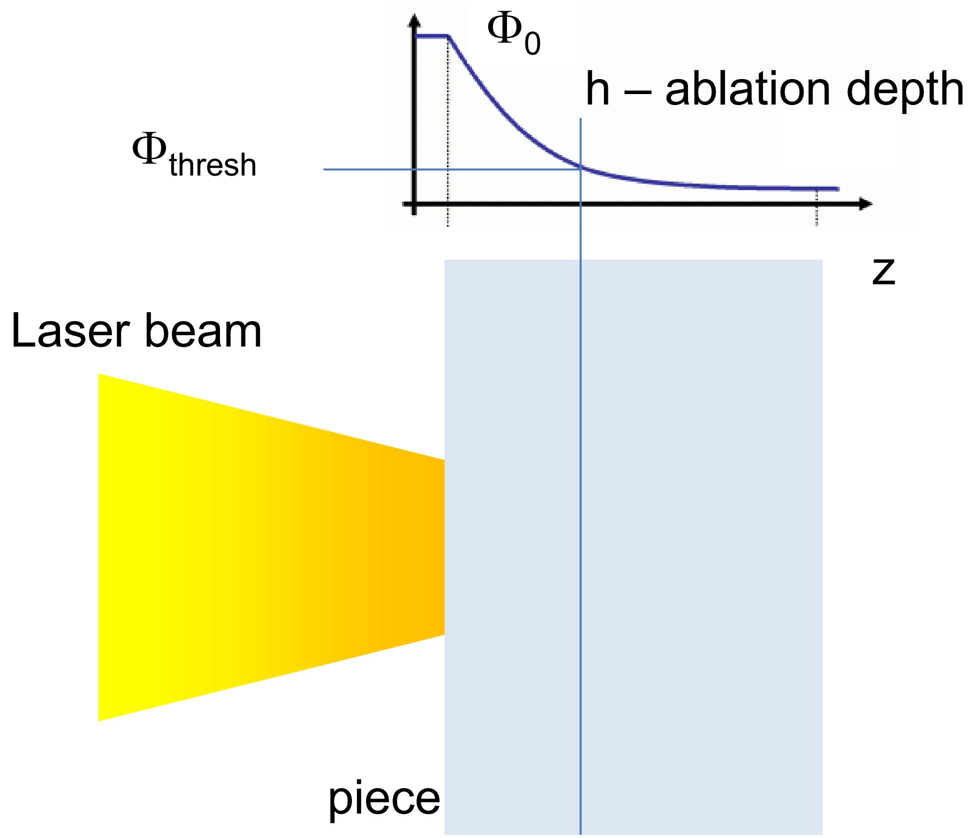




Ablation model



Ablation Depth



Physical Model

$$\Phi(d) = \Phi_{\exp}^{-\alpha_{eff} \cdot d}$$

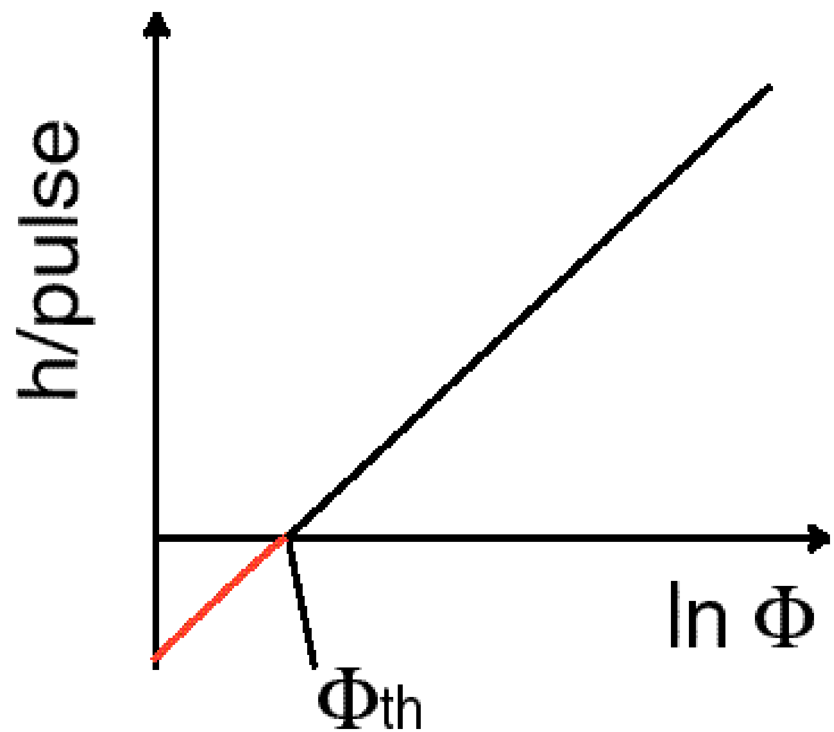
Lambert-Beer's absorption law

$$\Phi_{\Delta h} = \Phi_{thresh} = \Phi_0^{-\alpha_{eff} \cdot \Delta h}$$

threshold fluence is still reached at Δh depth

$$\Delta h(\Phi) = l_{\alpha_{eff}} \ln \Phi - l_{\alpha_{eff}} \ln \Phi_{thresh}.$$

ablation rate vs. fluence dependance



Effective Absorption Coefficient

$$\alpha_{eff} = \alpha_0 + \sigma_D N_D + \alpha_i(N) + \alpha^{NL}$$

α_0 = **linear absorption coefficient**

σ_D = **Dopant cross section**

Limits: no sense at extremely high laser powers, avalanche ionization

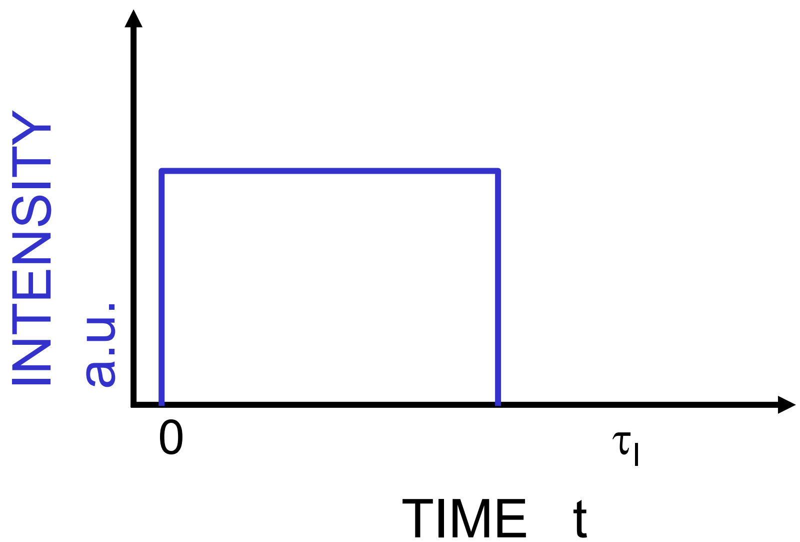
Single Pulse Ablation

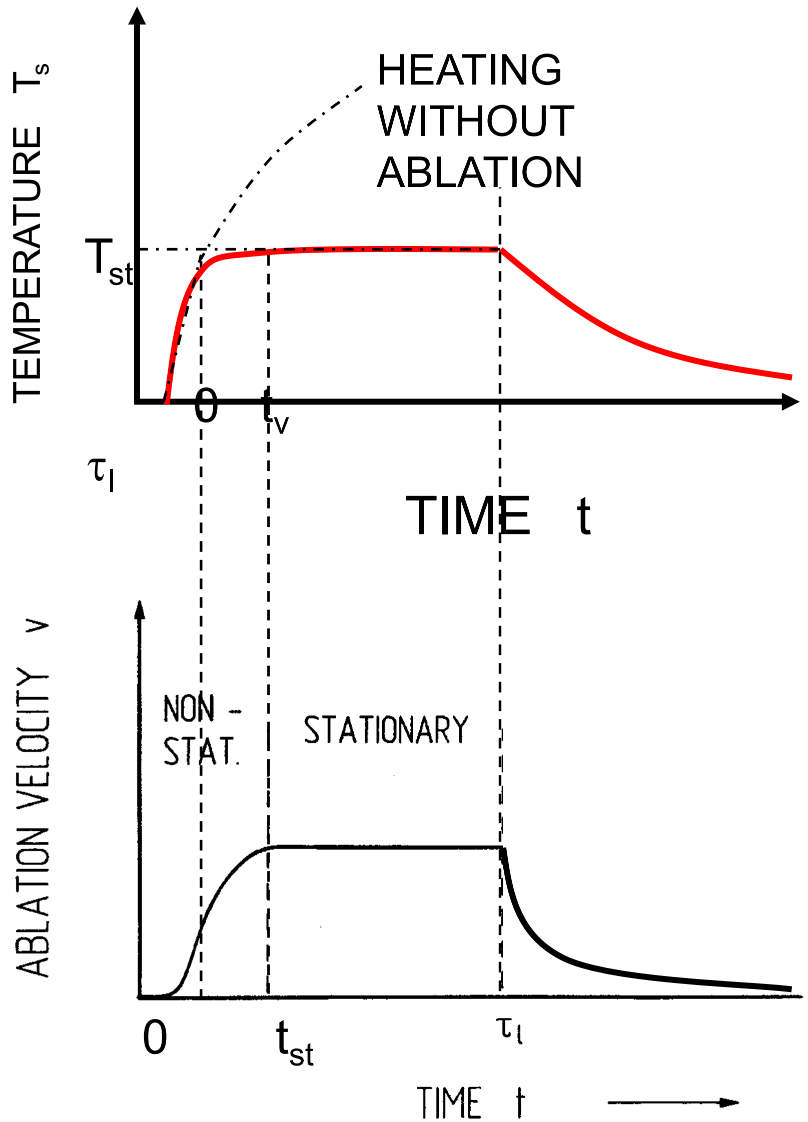
Photothermal ablation

$\tau_T \ll \tau_{des}$ **pure thermal ablation, IR, vis and many UV**

Assumptions:

- **homogeneous irradiation**
- $w \gg l_{th};\ l_\alpha$
- **no stress**
- **no T dependence**





Single pulse ablation

- Influence of pulse duration

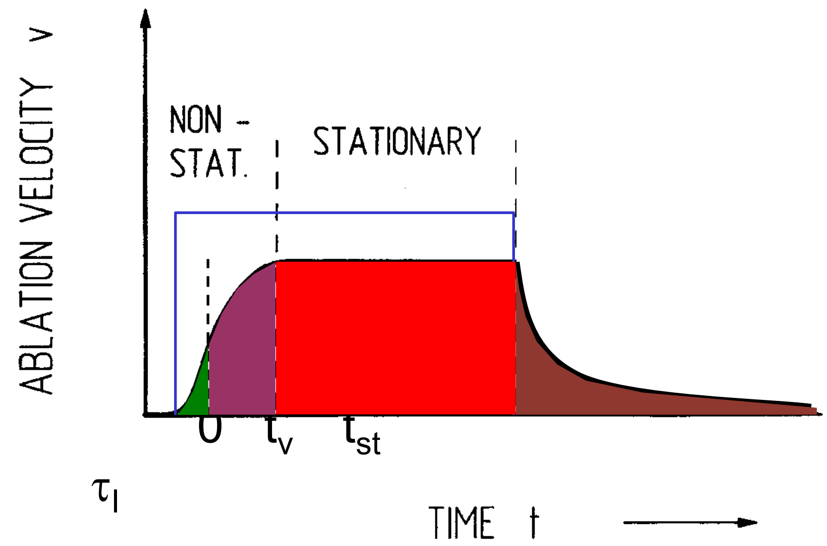
$$\Delta h = \int_0^{\infty} v(t)dt \approx \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4$$

$$\Delta h_1 \equiv \Delta h_1(t \le t_v)$$

$$\Delta h_2 \equiv \Delta h_2(t_v \le t \le t_{st})$$

$$\Delta h_3 \equiv \Delta h_3(t_{st} \le t \le \tau_l)$$

$$\Delta h_4 \equiv \Delta h_4(t \ge \tau_l)$$



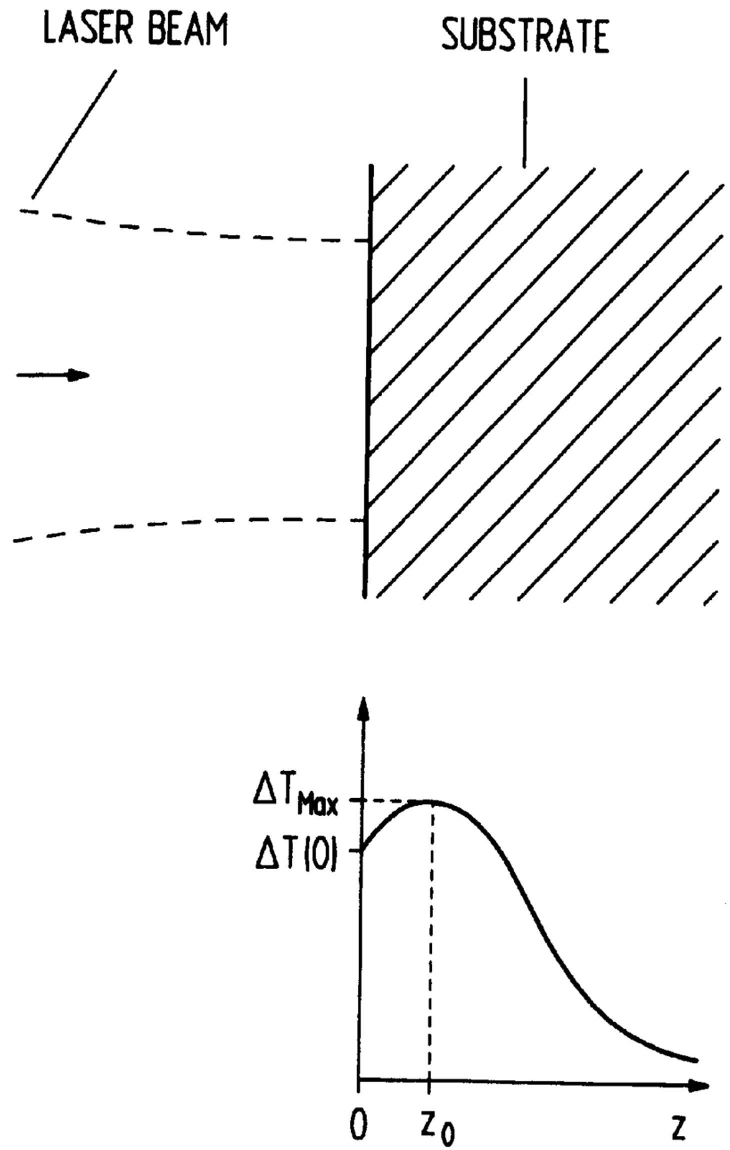
□h_1 to be ignored in all cases

fs, ps ablation □h_4

□s, ms ablation □h_3

ns ablation □$h_{2,}$ □$h_{3,}$ □h_4

Pulsed Laser Ablation



Interaction 193 nm Excimer light with materials

- Optical penetration depth:

$$l_\alpha = \frac{1}{\alpha}$$

- Thermal penetration depth:

$$l_{th} = 2\sqrt{D\tau_l}$$

	l_α	l_{th}
Al	**10 nm**	**2.80 μm**
Mo	**< 30 nm**	**2.04 μm**
SiO_2	**3.3 m**	**270 nm**
PET	**30 nm**	**90 nm**

α: optical absorption coefficient [cm^{-1}]

D: thermal diffusivity [cm^2 /s]

τ_l: pulse duration

Pulsed Laser Ablation (PLA)

- How much material is taken off per laser pulse ?

$$\Delta h \approx \max(l_{th}, l_{\alpha})$$

What are the physical steps ?

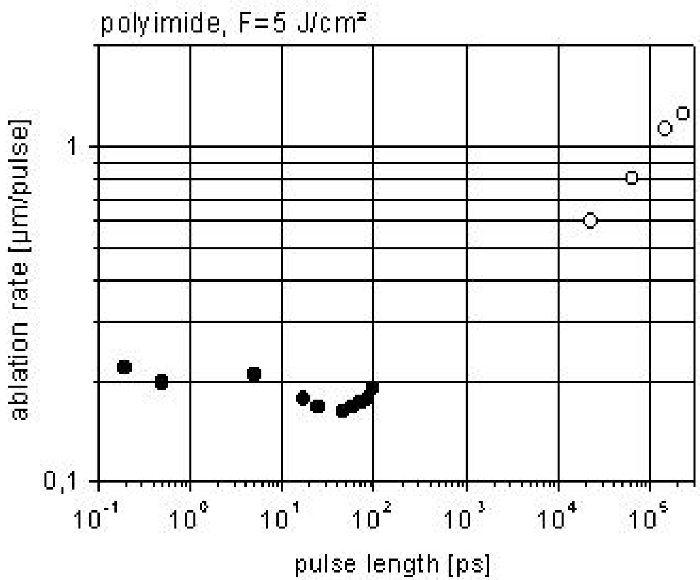
Optical absorption

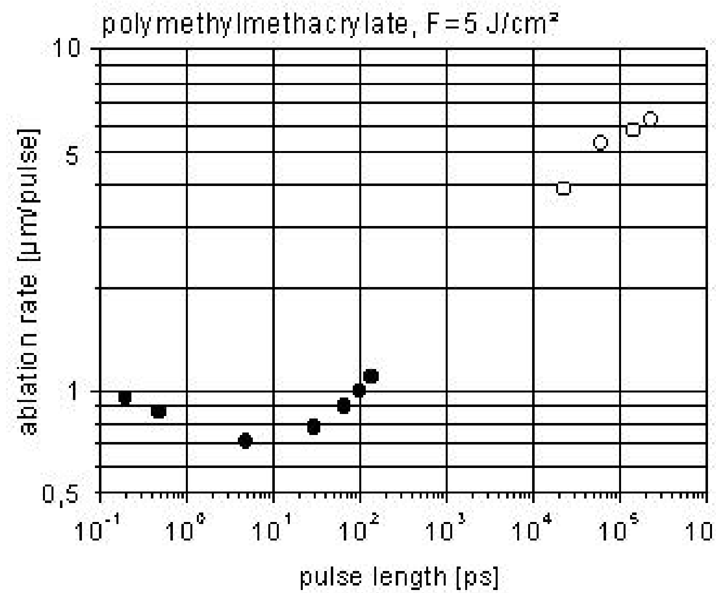
Energy dissipation

Decomposition

Material removal

Ablation rate dependance: Pulse duration





Conclusions

Ablation Process characteristics

threshold value for Laser light fluence ϕ_{th}

$$\phi_{th_{oxides}} = 0.5 - 2 \quad [J/cm^2]$$

$$\phi_{th_{polymers}} = 0.01 - 1 \quad [J/cm^2]$$

ablation depth per pulse : $\Delta h \leq max(l_T, l_\alpha)$

with

the heat penetration depth l_T :

$$l_T \approx 2\sqrt{D\tau_l}$$

including the laser pulse length τ_l

and the thermal diffusivity $D = \kappa/(\rho\, c_p)$

$$D_{metals} = 0.1 - 2 \quad [cm^2/s]$$

$$D_{oxides} = 0.01 - 1 \quad [cm^2/s]$$

$$D_{polymers} = 0.001 - 0.01 \quad [cm^2/s]$$

the light penetration depth l_α :

$$l_\alpha = \alpha^{-1}$$

Is Cold Laser Processing possible ?

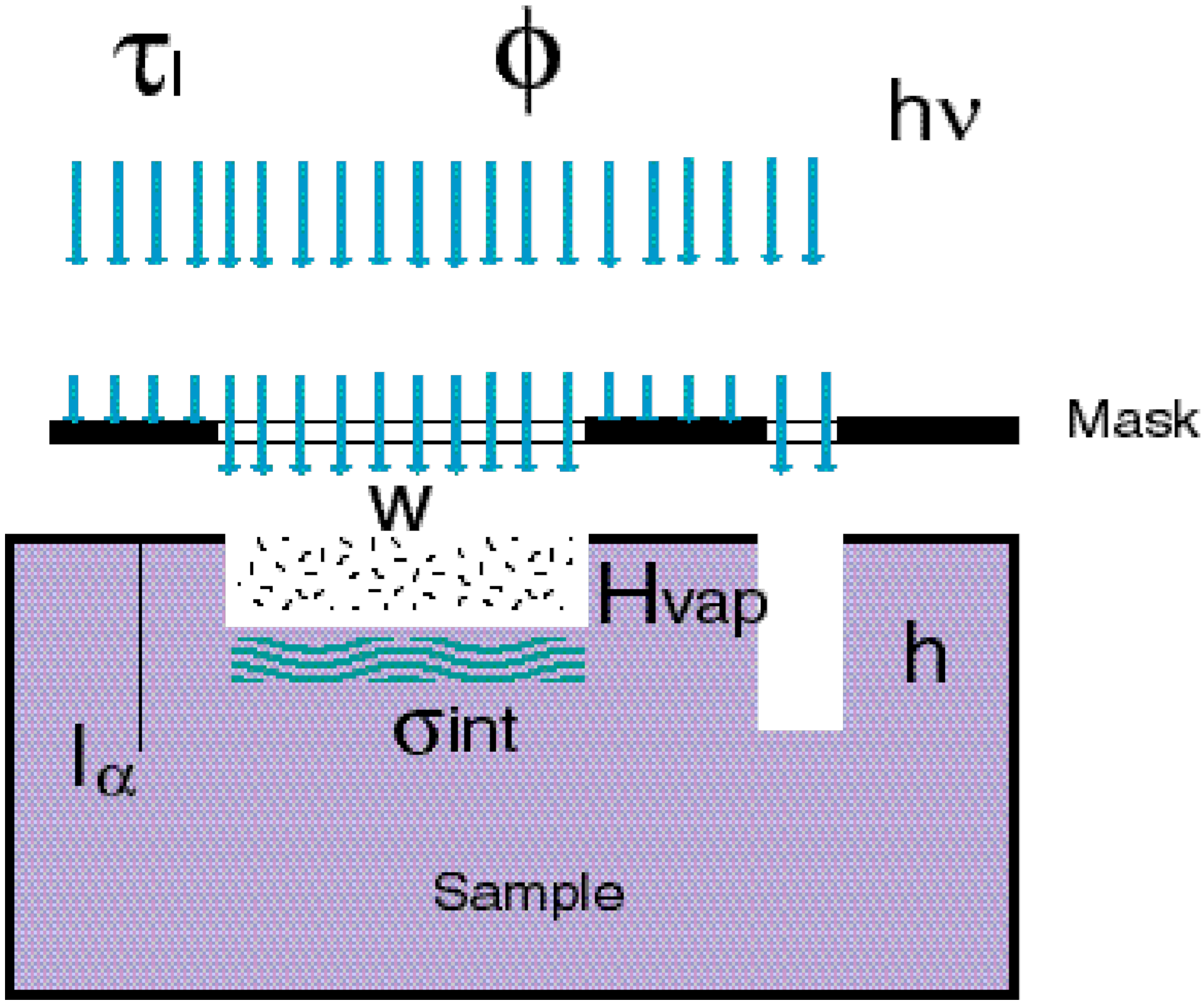
High vacuum molecule photon interactions:
Excitation by absorption – thermal relaxation (10^{-14} – 10^{-6} s) useful for isotope separation, polyatomic molecules, (10^{-13} – 10^{-11} s)

Generally in liquids and solids:

Excitation by absorption – thermal relaxation τ_T
Metals & Semicond. (el-el) 10^{-14}-10^{-13} s ; (el-phon) 10^{-12}-10^{-6} s

Check thermal effects: The heat equation

Ablation – complex phenomenon



Excimer Laser model

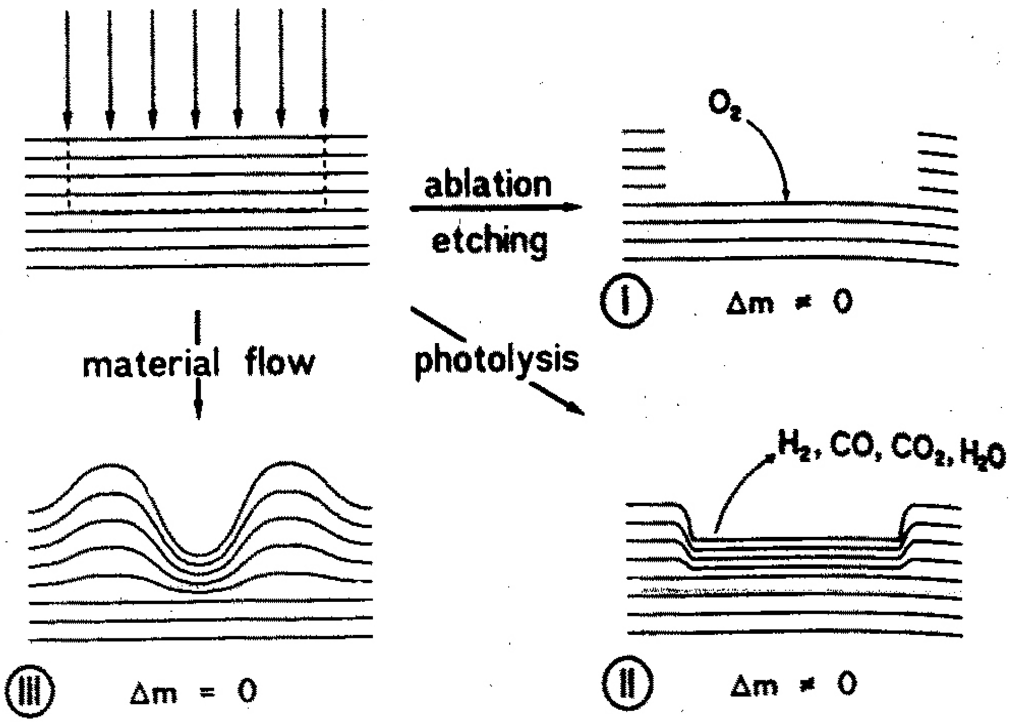
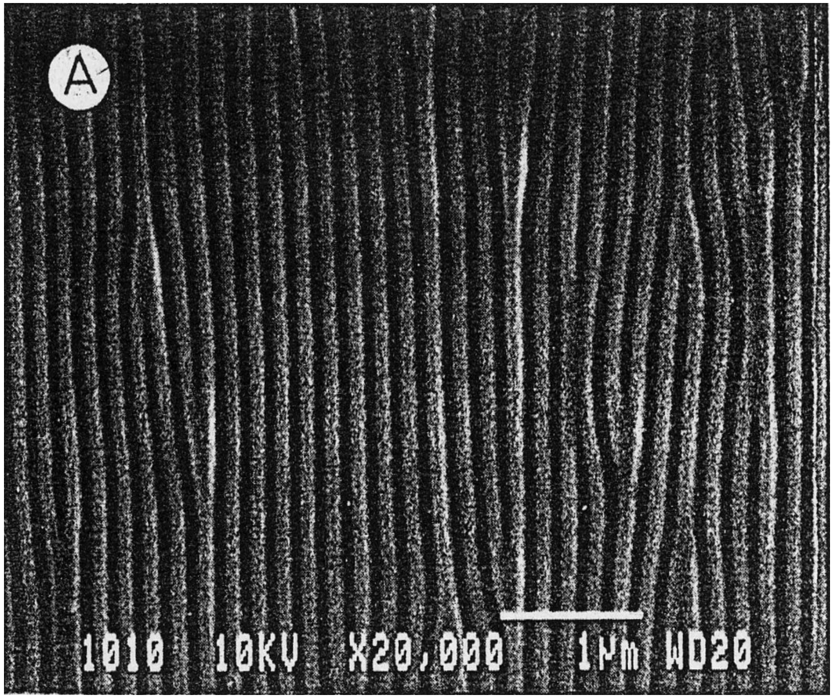


FIG. 13. Three models of photoactivated surface corrugation; (I) ablation or etching; (II) photolysis; (III) is material flow. Processes I and II are accompanied with mass decrease, even in vacuum, whereas III operates at constant mass.



Ceramics Ablation Examples

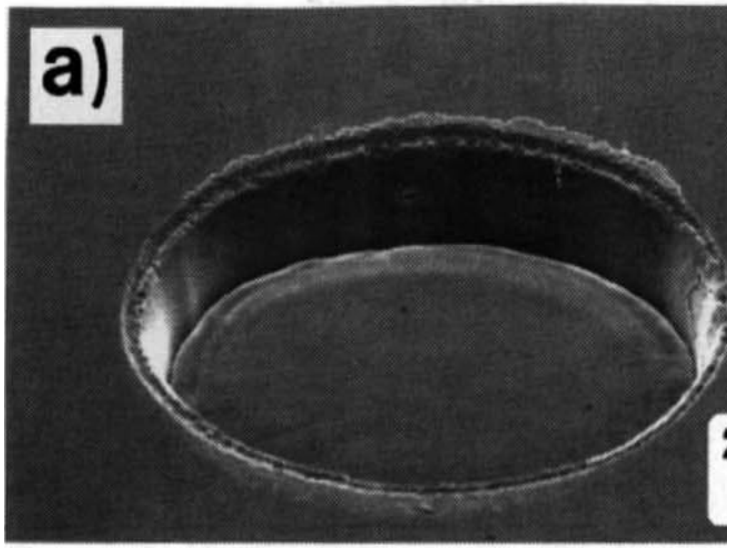
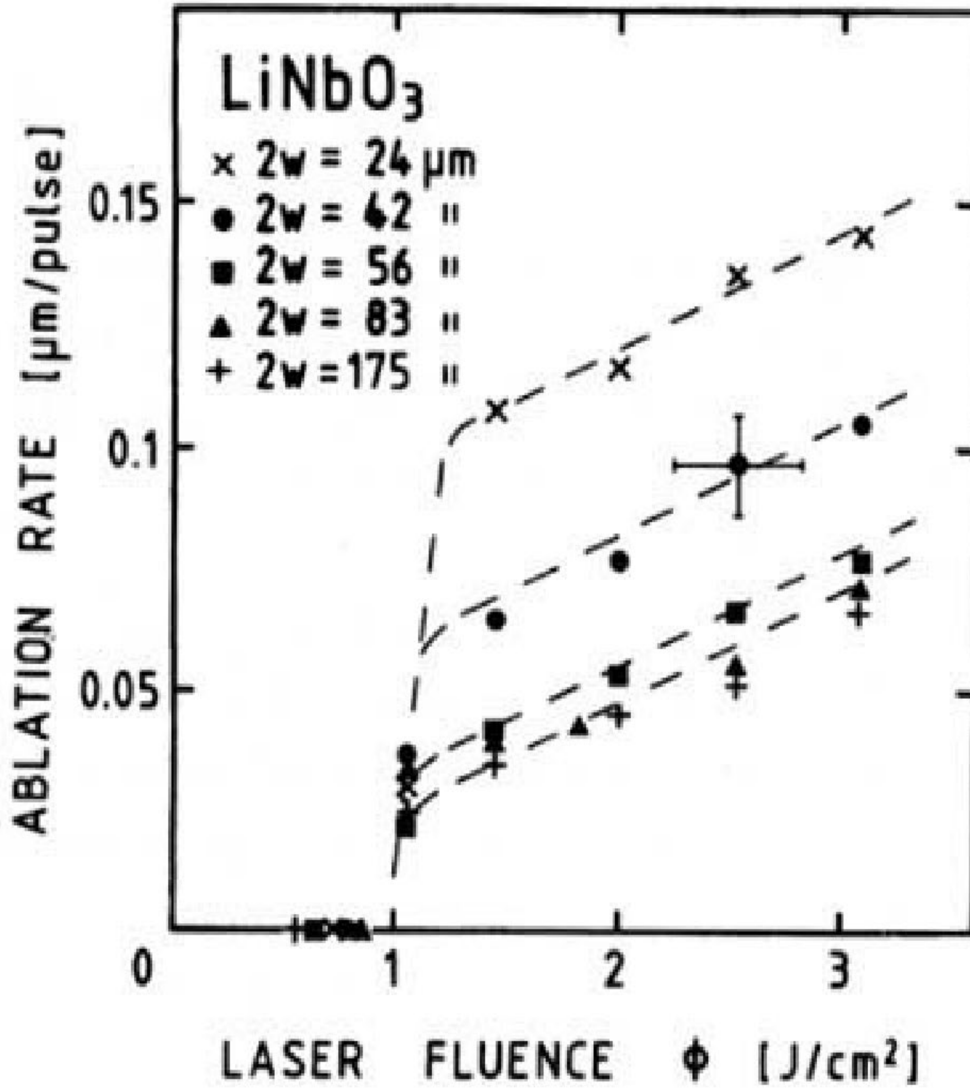
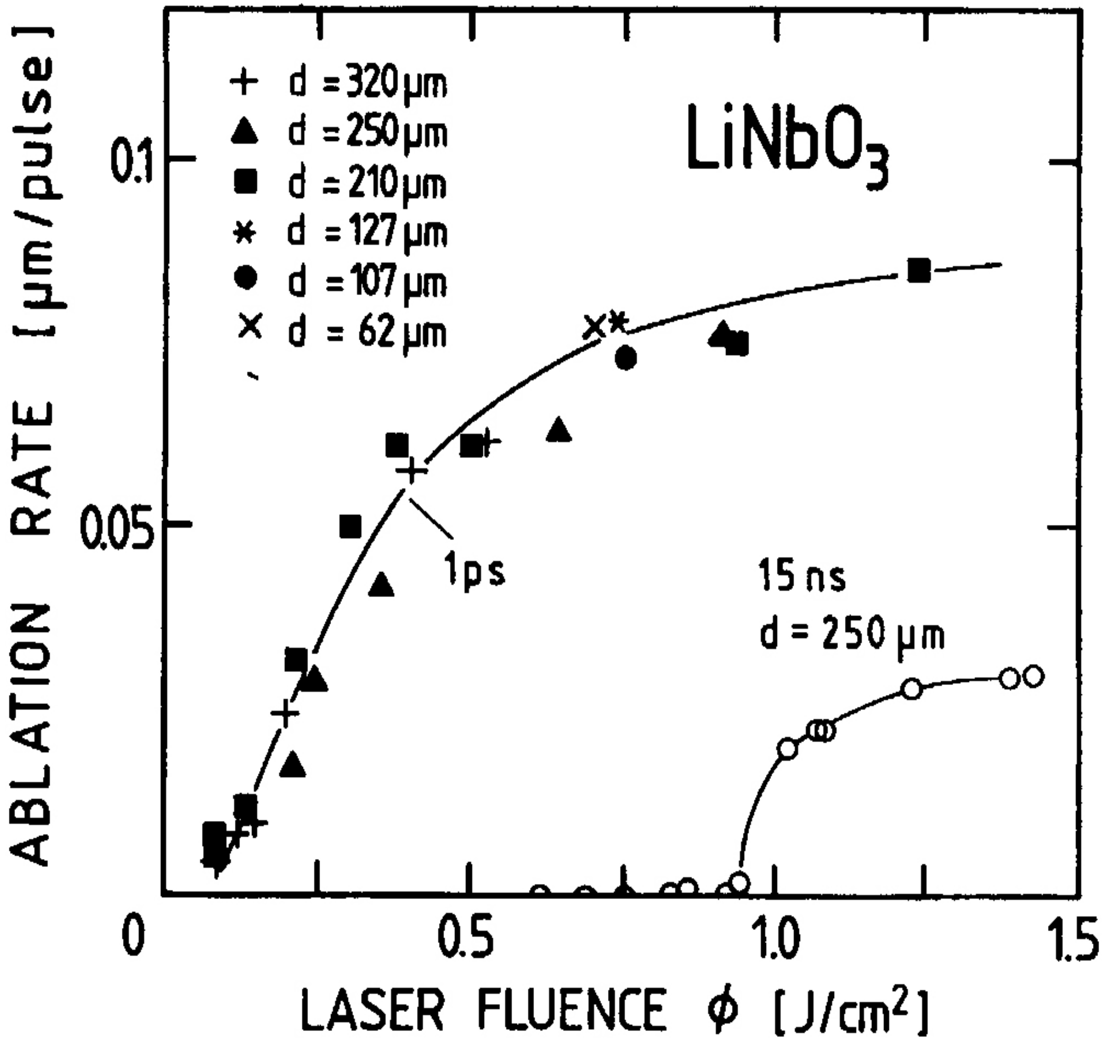
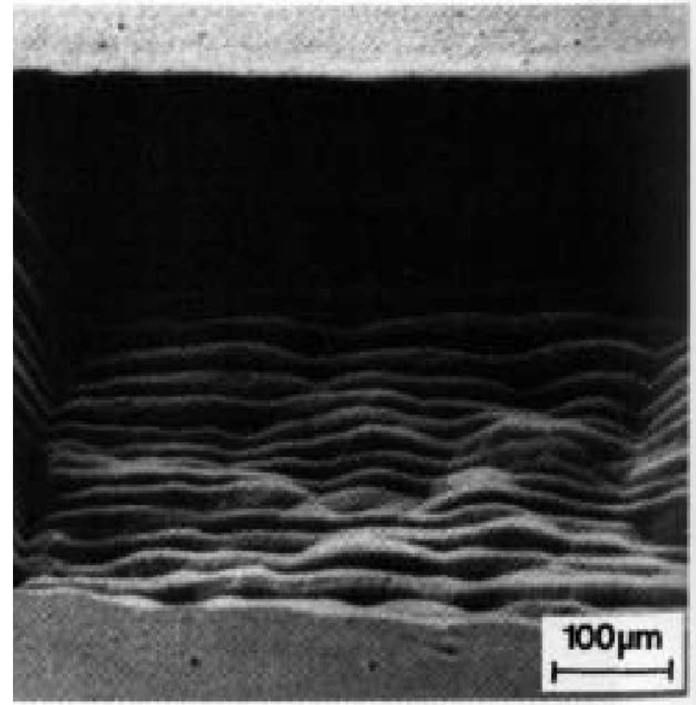


Fig. 12.1.2a,b. Projection patterning by
($\lambda = 308$ nm, $\phi = 2.7$ J/cm^2, $2w = 175$ µr
$YBa_2Cu_3O_7$ film on (100) $SrTiO_3$ sub
[*Heitz* et al. 1990]



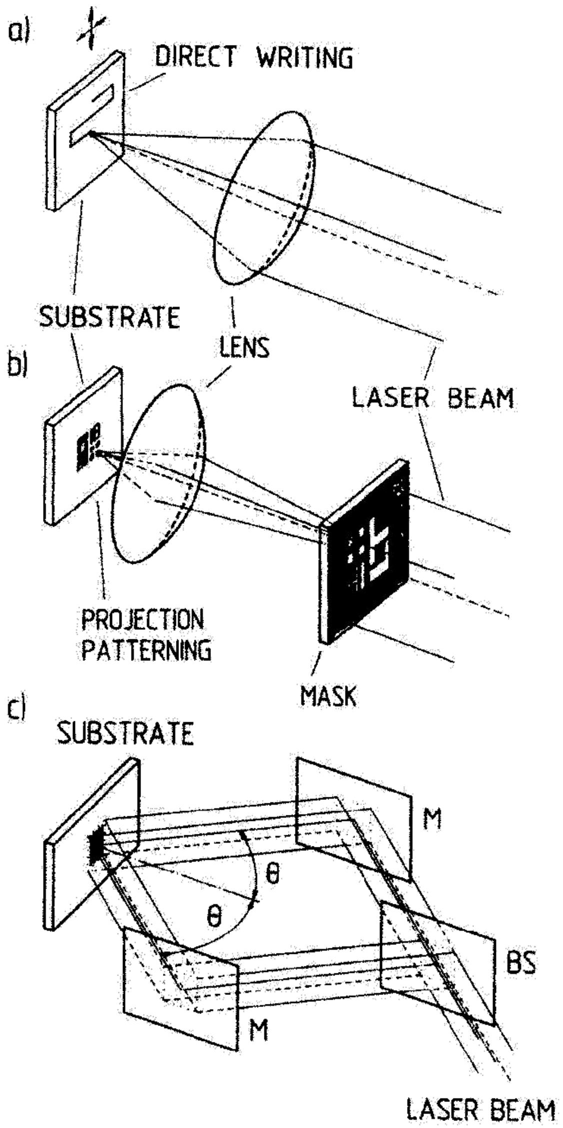
Ablation Influences



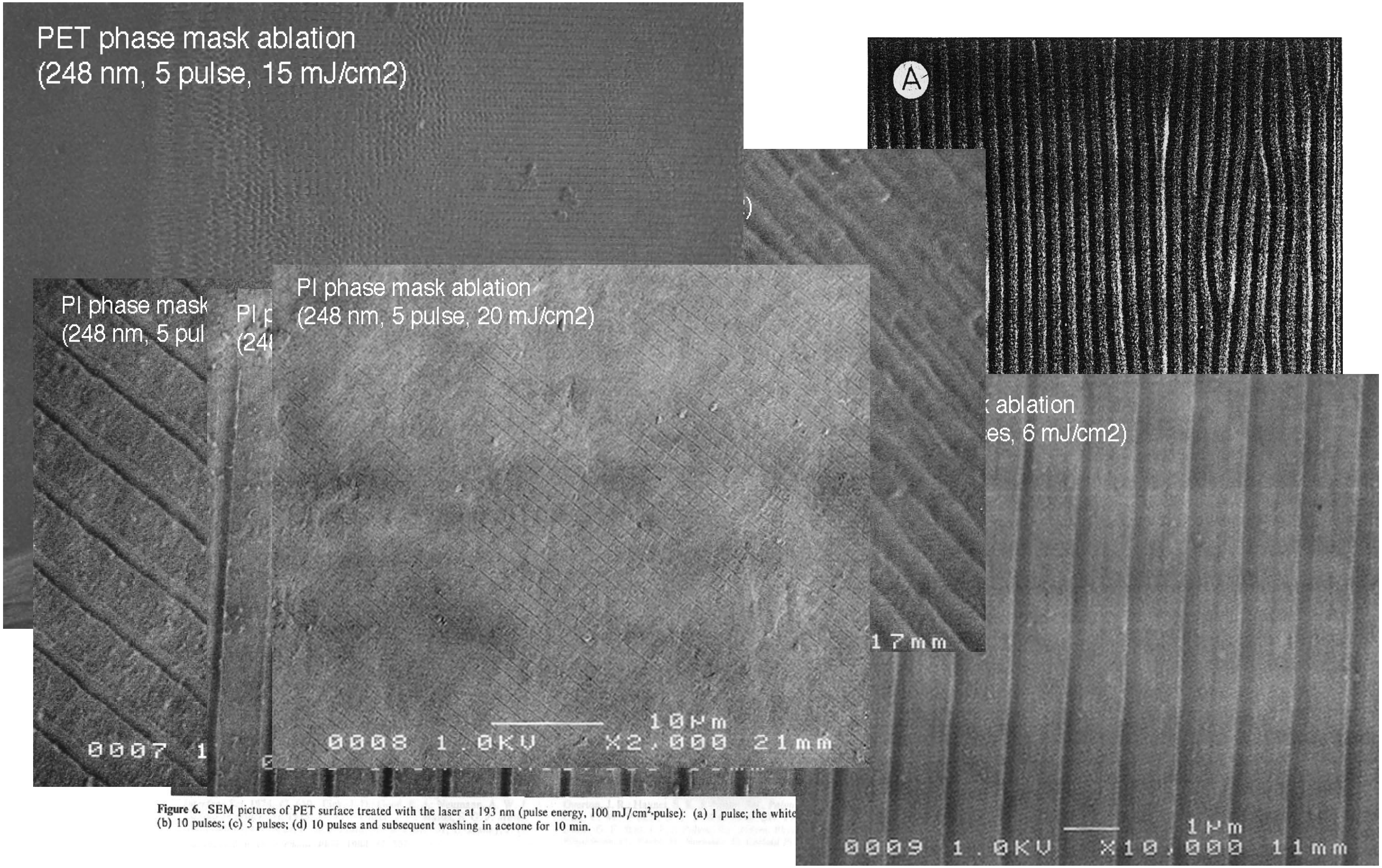


48 nm KrF-laser radiation. (**a**) Irradi-
) = 4.2 J/cm²). An undefined crater is
naterial. (**b**) Irradiation with fs pulses
relatively smooth and no cracks are

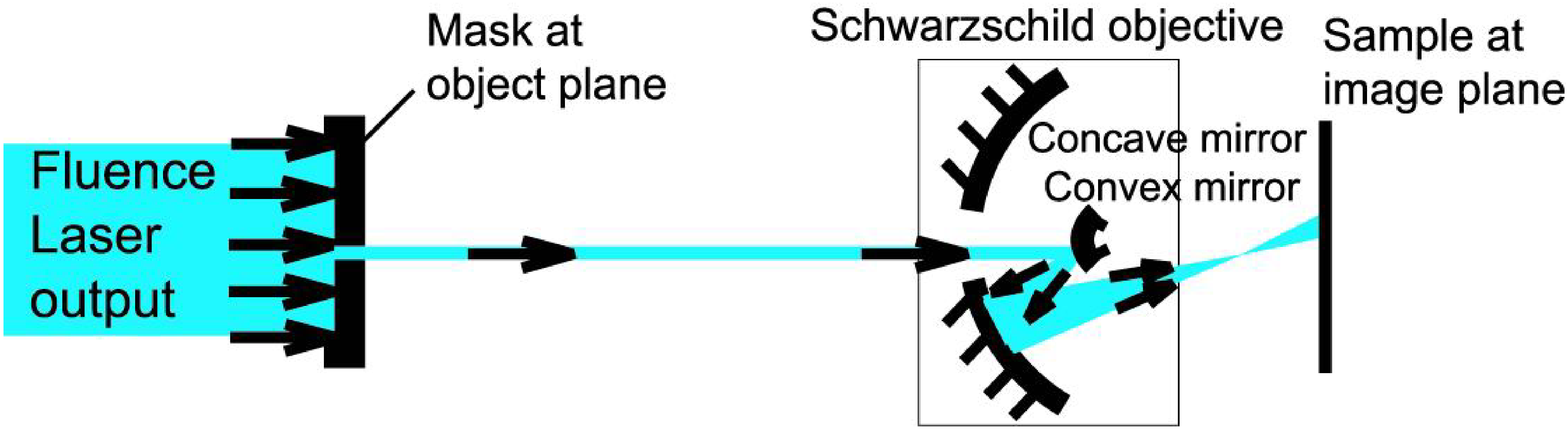
Method Based on Interference



Excimer Laser: Submicrometer structures



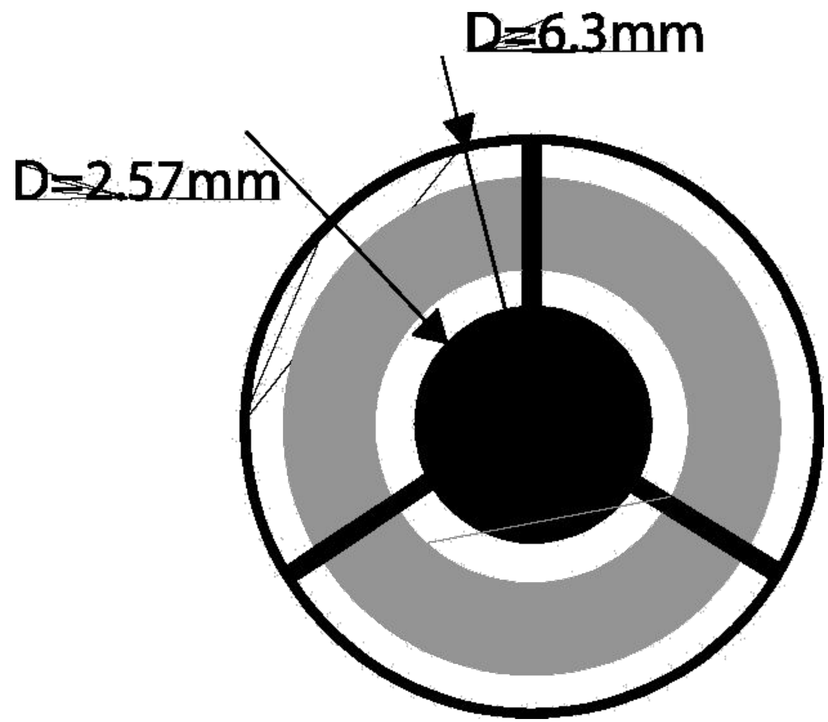
Schwarzschild objective: Set-up



- 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

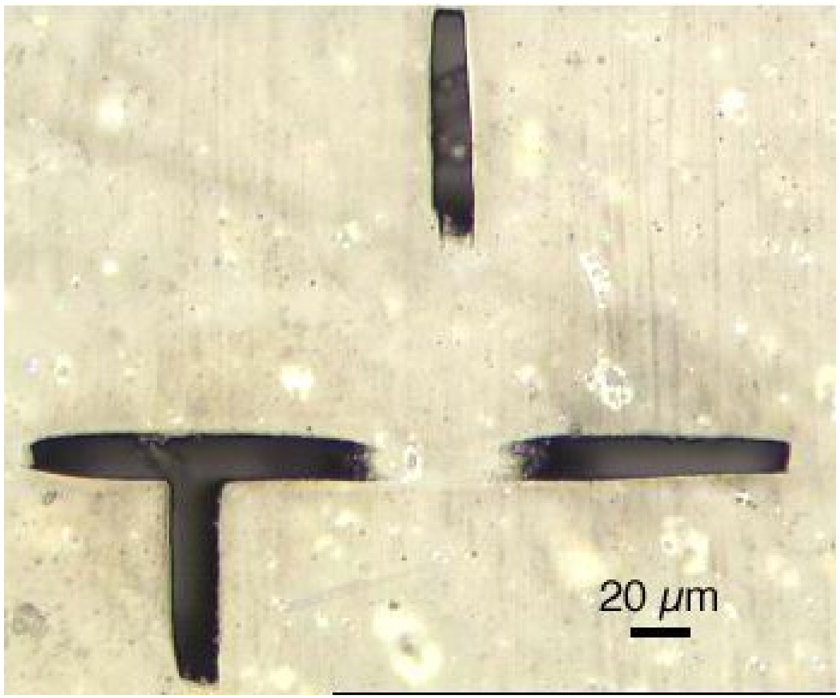
- Magnification 1/25
- Low aberrations, achromatic
- Numerical aperture : NA = 0.4
- Central obscuring : 16.7%
- Mirror : coating for 193 nm
- maximum reflection $R_{max} = 0.5$

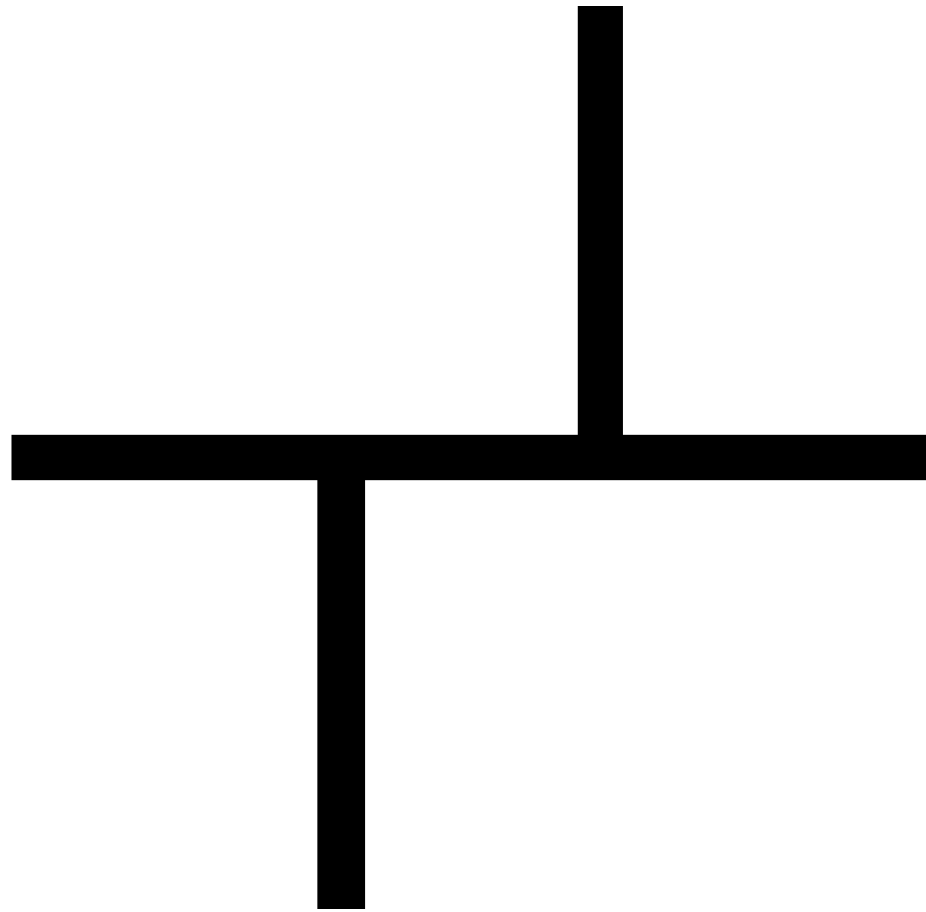


Theoretical optical resolution:

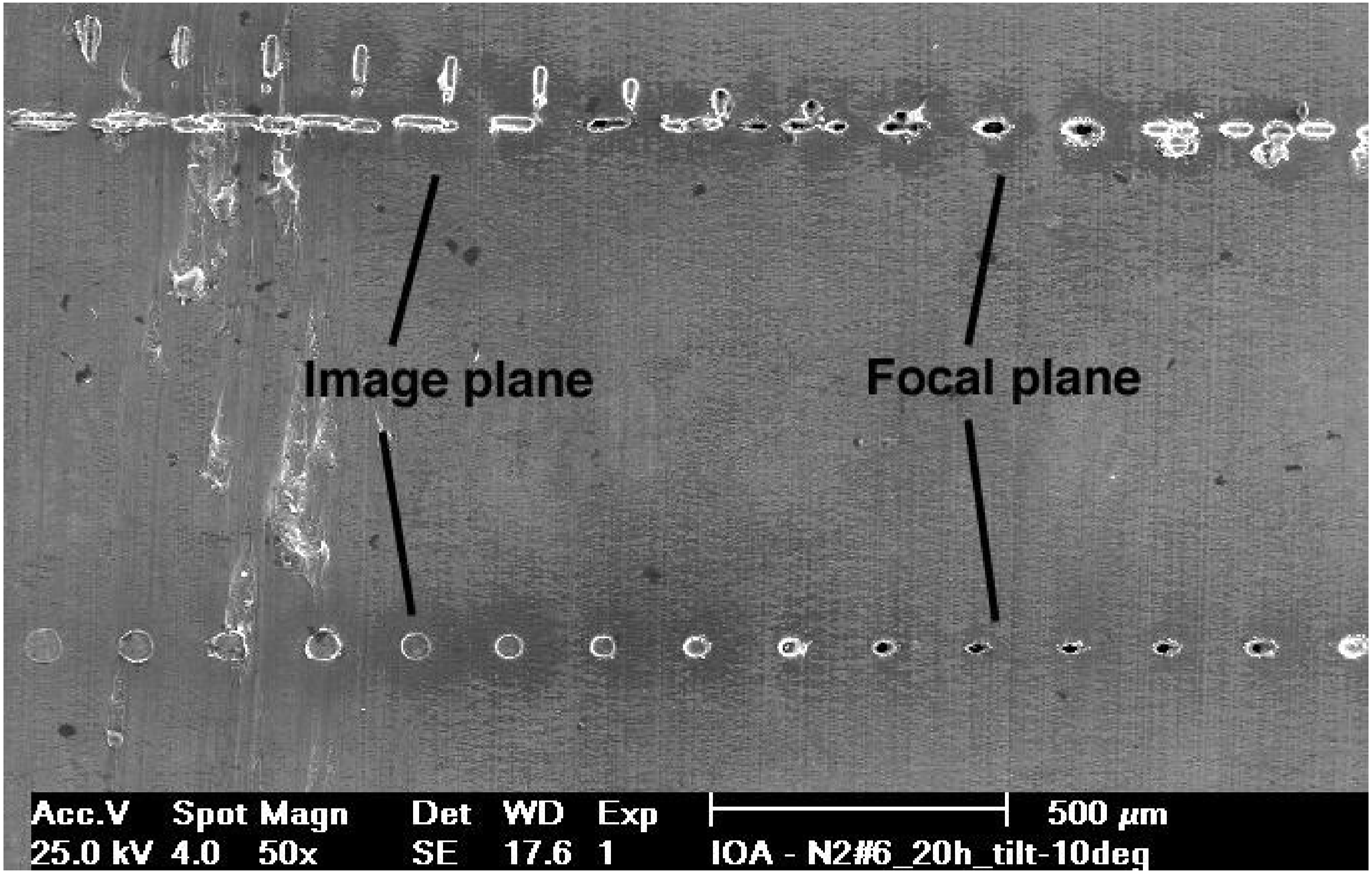
$$r = \frac{\lambda}{2 \cdot NA} = 241\,nm$$

Schwarzschild objective: central obscuring





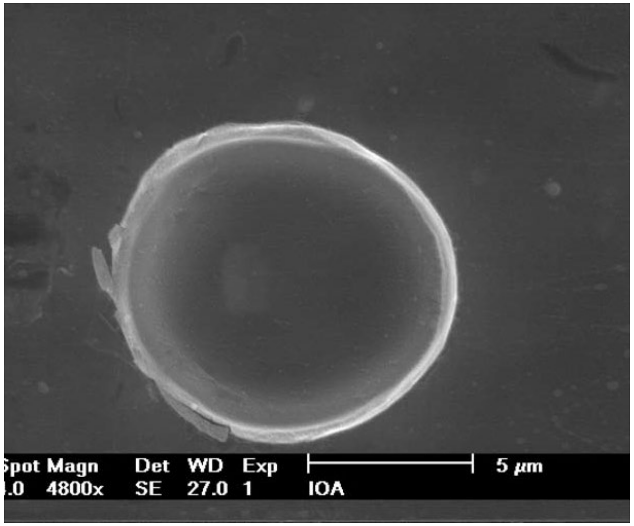
Aluminium: Search for image / focal planes



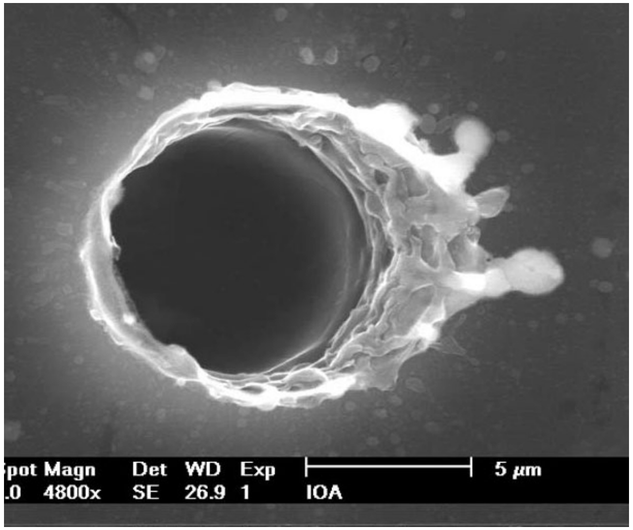
- Distance image-focal planes: 300 µm, F= 50 mJ/cm^2, 5 pulses at 10 Hz

Aluminium: variation of the number of pulses

1 pulse

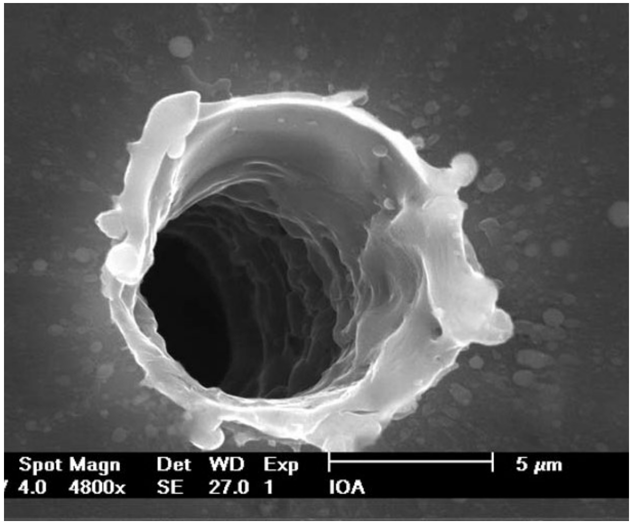


10 pulses



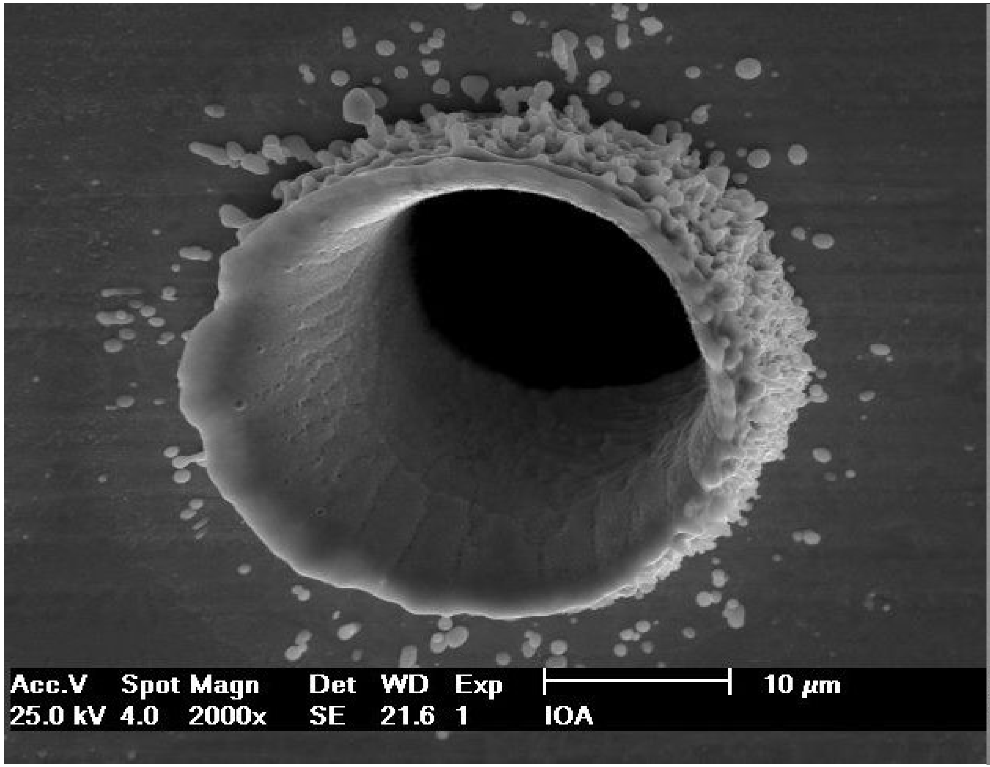
- Thickness : 20 µm, F = 15 mJ/cm^2
- Mask diameter: D = 215 µm

100 pulses

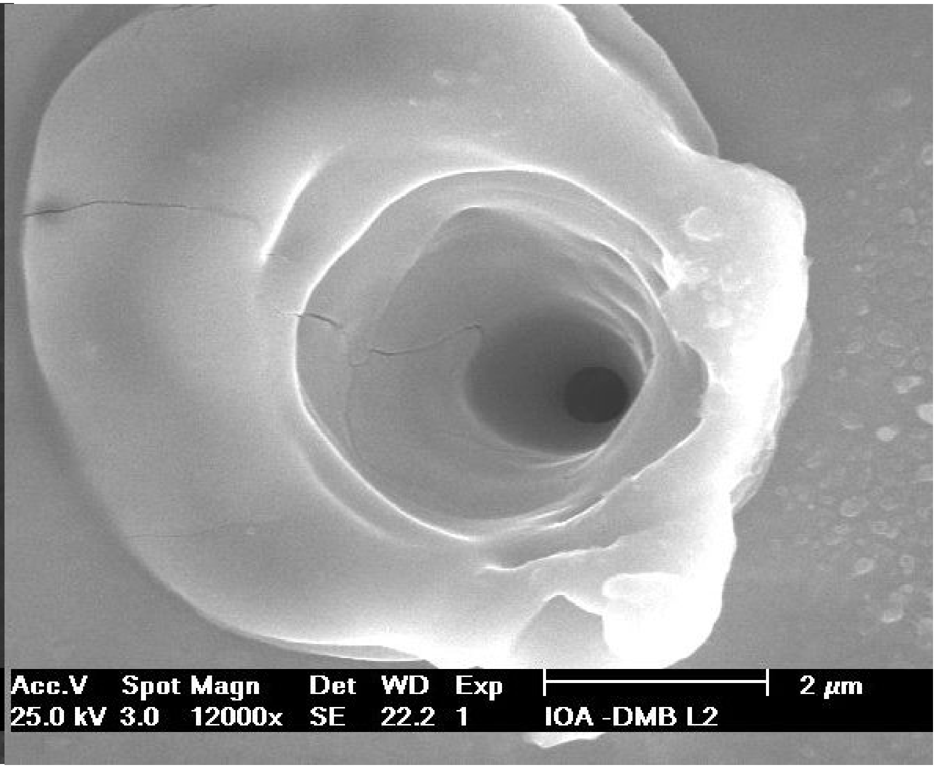


Molybdenum: through-hole

- Thickness of the molybdenum: 12.5µm



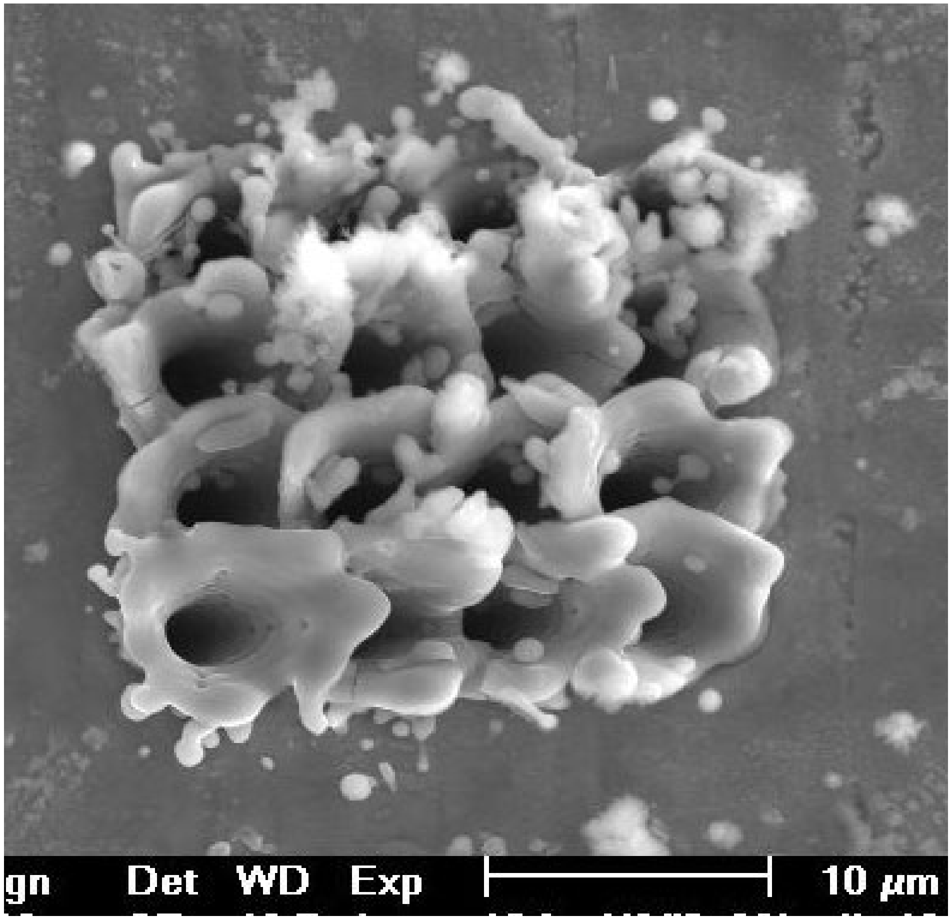
250 mJ/cm², 40 pulses at 10 Hz



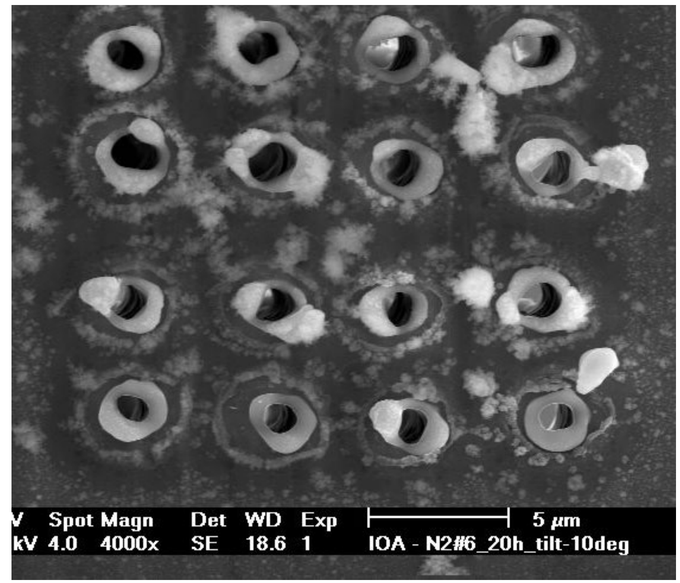
25 mJ/cm², 2000 pulses at 40 Hz

Molybdenum: multiple through holes

Entrance



Exit



F = 25 mJ/cm^2

2000 pulses, 40 Hz

Mask diameter D = 215 µm

Excimer Ablation conical structures

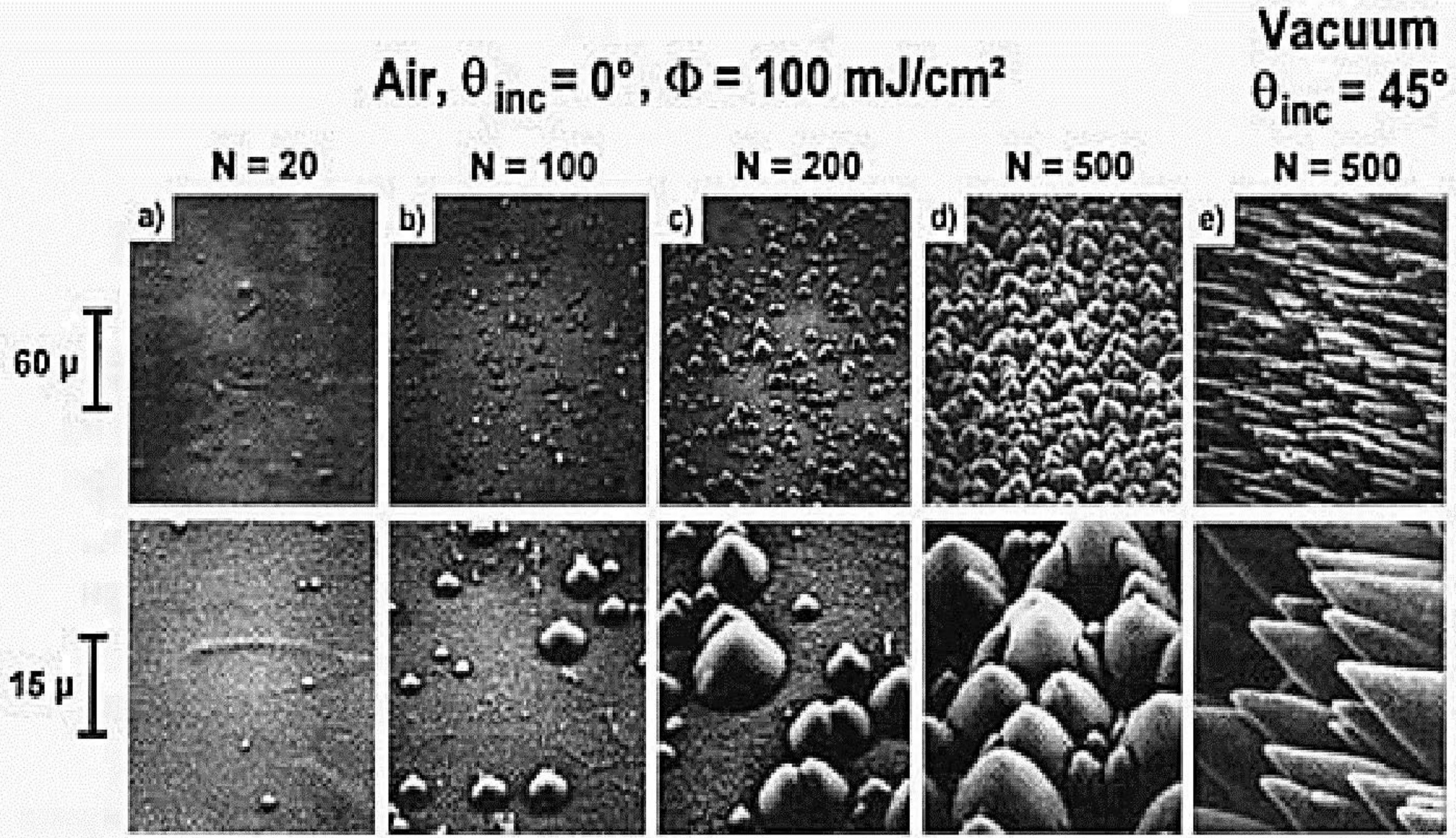


Fig. 28.4.4 a–d. SEM photographs of polyimide ablated in air at $\phi = 100\,mJ/cm^2$ for different numbers of pulses N. The laser beam was normally incident on the sample. (e) Same as (d) but irradiated in vacuum under $\Theta = 45°$ [*Krajnovich* and *Vazquez* 1993]

Excimer Laser glass marking

Static Excimer Ablation Process

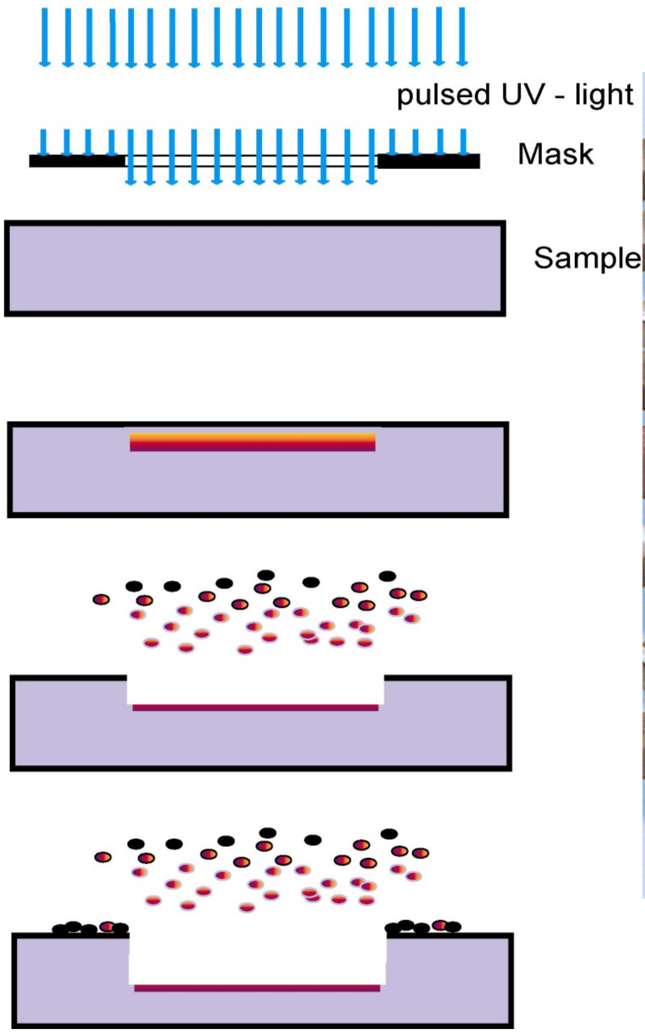


Abb. 4:
Vergrößerung einer mit einem Excimerlaser markierten Glasoberfläche.

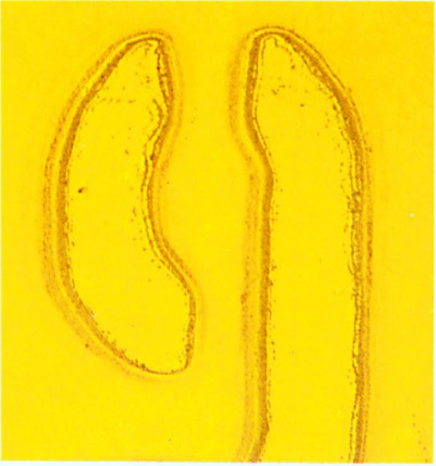
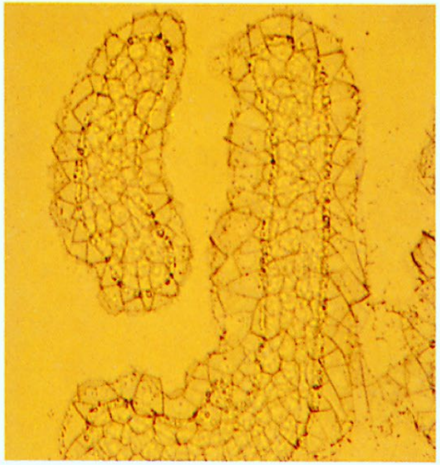
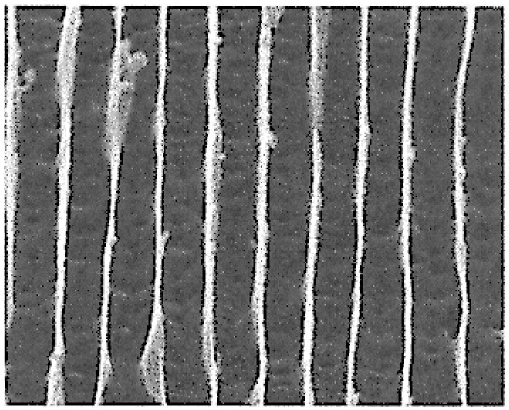


Abb. 5:
Vergrößerung einer mit einem CO_2-Laser markierten Glasoberfläche.

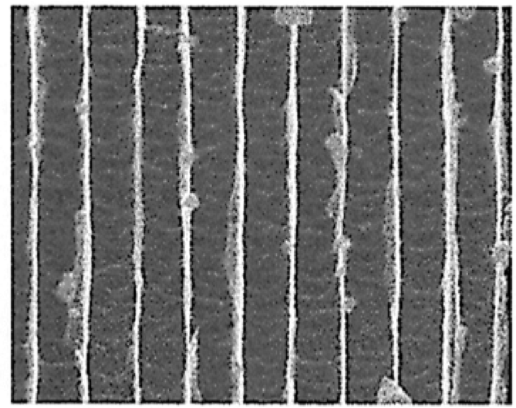


Ablation quality pulse duration

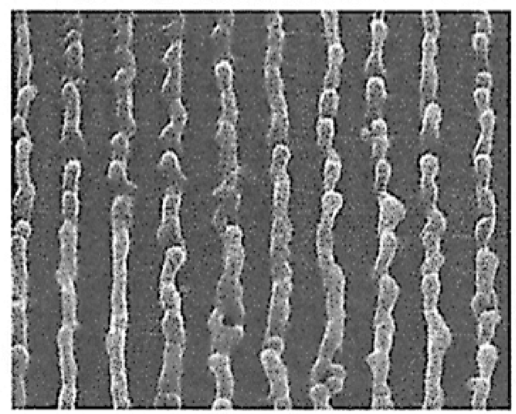
Material: Copper
Laser: 248 nm, 600 mJ/cm², 1 pulse



0.5 ps



5 ps

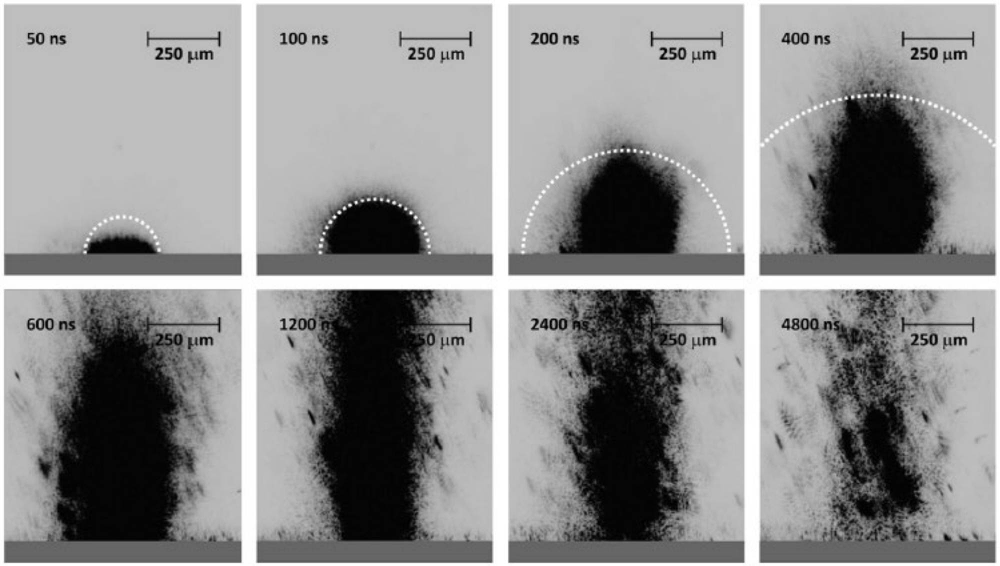


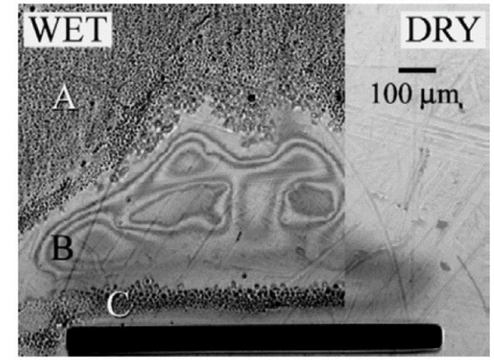
50 ps

1 µm

Laser-Laboratorium Göttingen e.V.

Ultra short pulse ablation





Koch et al.
Tom Lippert PSI
– shadowgraphy
- scatterometry

J. Koch et al. / Spectrochimica Acta Part B 65 (2010) 943–949 945

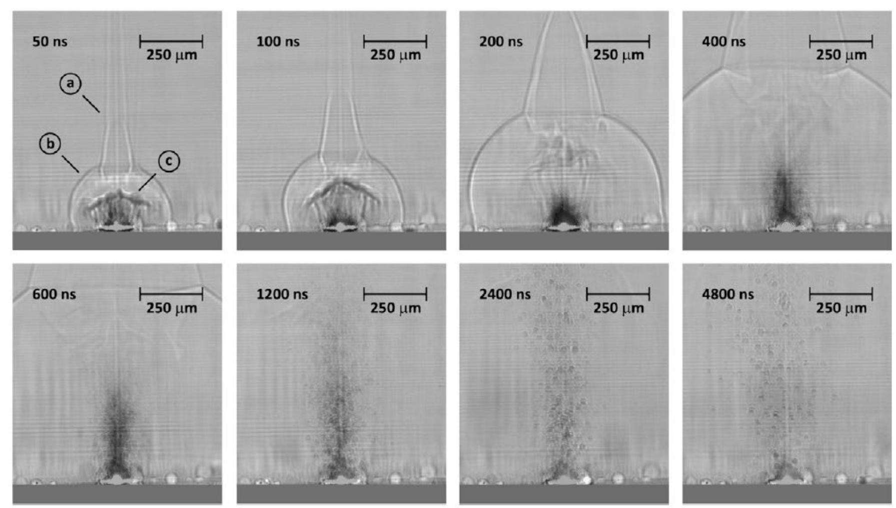


Fig. 1. Shadowgraphs acquired during fs-LA of $Li_2B_4O_7$ in ambient air applying a fluence of 10.8 J/cm^2. Lower cases a, b, and c mark the positions of BSW, CSW-1, and CSW-2, respectively. Shockwave radii were systematically measured between their origin and the intersection of BSW and CSW-1.