Laserinduziertes Mikroplasma in reaktiven Gasen
- Ein Tool zum präzisen Ätzen von Materialien -

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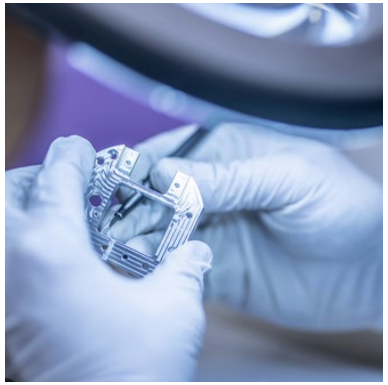
Outline

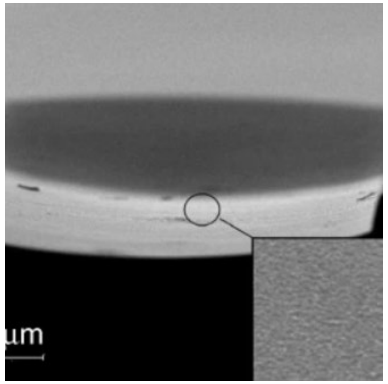


Requirements of UPSM

- lasers for UPSM
- status of different approaches for UPSM with lasers

Towards UPSM with laser radiation

- Laser-induced plasmas (LIP) an optically pumped plasma in gas
- Impact of selected parameters
- Surface characteristics



Summary/conclusions/future

- summarizing conclusions
- future developments

Ultraprecise surface machining (UPSM)

Integrity of Surface: “Inherent or enhanced condition of a surface produced by machining processes or other surface generation operations.”
application requirements ←→ determining/measurement ←→ machining process

Process demands
- atomic level material removal
- digital surface machining
- near-surface limited interaction process
- fast convergence of the machining
- specificity of the machining process
  - high material selectivity
  - homogeneous nonselective process
- surface binding energy management

ultra precise surface machining

Surface requirements
- Atomic level smoothness
- Angstrom depth precision
- low/no surface defects
- across all scales; also small areas

Tool requirements
- capabilities to fulfil basic requirements of UPSM
- variable tool in size/shape/strength
- no momentum transfer to the surface
- low contamination / inert tool

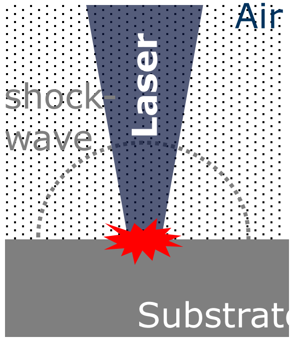
I. S. Jawahir et al., CIRP Annals 60(2011)603

Specific approaches for laser-based surface machining with view to UPSM

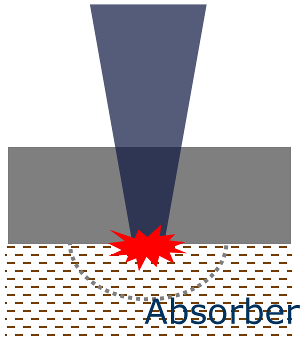
- Laser beam technology provides excellent preconditions for ultra precise surface machining (UPSM) as the tool
  - is not in mechanical contact with the surface
  - well controllable in space and time
  - enables in-process measurement and process control
  - …

- but the machining mechanism determines the surface quality.

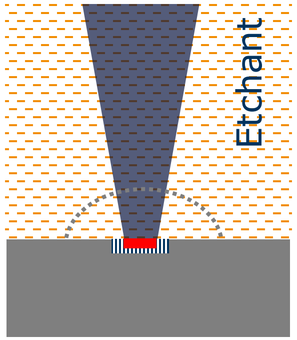
physical **chemical**



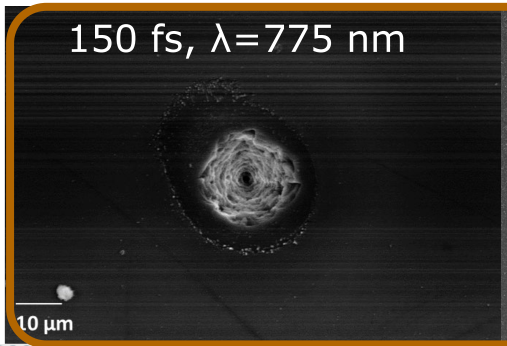
Ablation

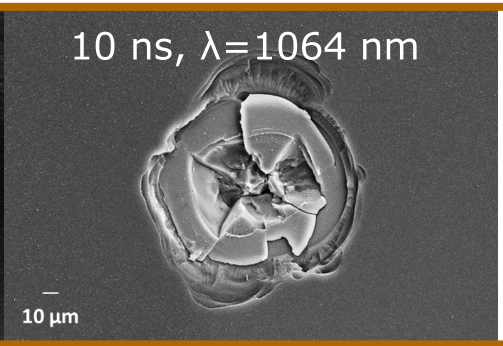


Heating,
Decomposition
Ablation



Etching,
Heating


150 fs, λ=775 nm

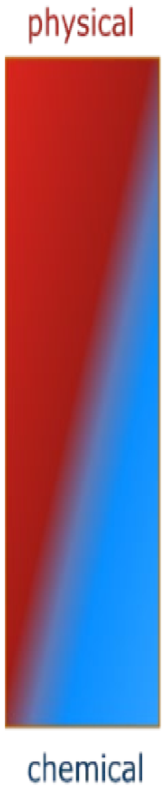

10 ns, λ=1064 nm

Laser ablation

Laser-induced backside etching

Laser-enhanced chemical etching

Fundamental/experimental limit of precision for different laser–based techniques



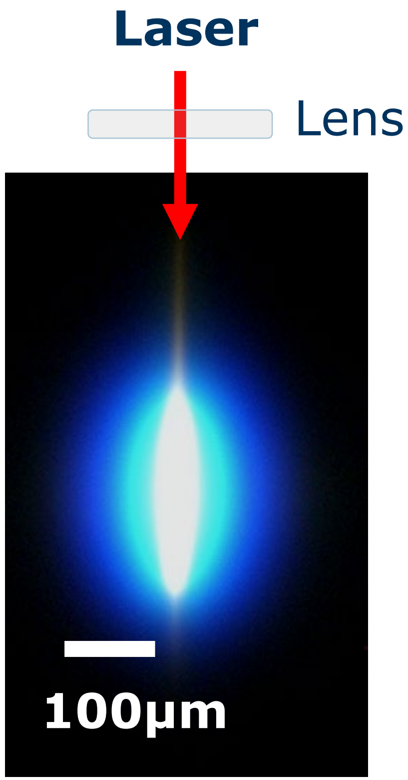
Process	Laser	Material removal rate in average	Material
PW laser ablation	Pulse	>150 nm	
USPL ablation	Pulse	50 to 150 nm	SiO2
LIBWE	Pulse	10 to 20 nm	SiO2
LESAL	Pulse	1 to 2 nm	SiO2
LIBDE	Pulse	80nm	SiO2
LIPhotoE etching	cw, min	1 to 2µm	SiO2
laser-induced plasma dry etching	Pulse	0.02nm to 0.05nm	SiO2

Characteristics of laser beams: λ, t_p, f, P_L, E_p, $2\omega_0$, v_s …

Introduction to LIP

- **Electric field discharge**: Focused lasers can produce high electric fields of the order of 10^5 V/cm.

→ Focusing laser pulses with high intensity results in an optical breakdown



Typical optical breakdown threshold in air:

- USP laser peak power density: $>10^{14}$ W/cm^2
- SP laser peak power density: $>10^{12}$ W/cm^2

Electrical	and	optical breakdown (USP)
$\sim 3\ 10^6$ V/m		$>10^7$ V/m

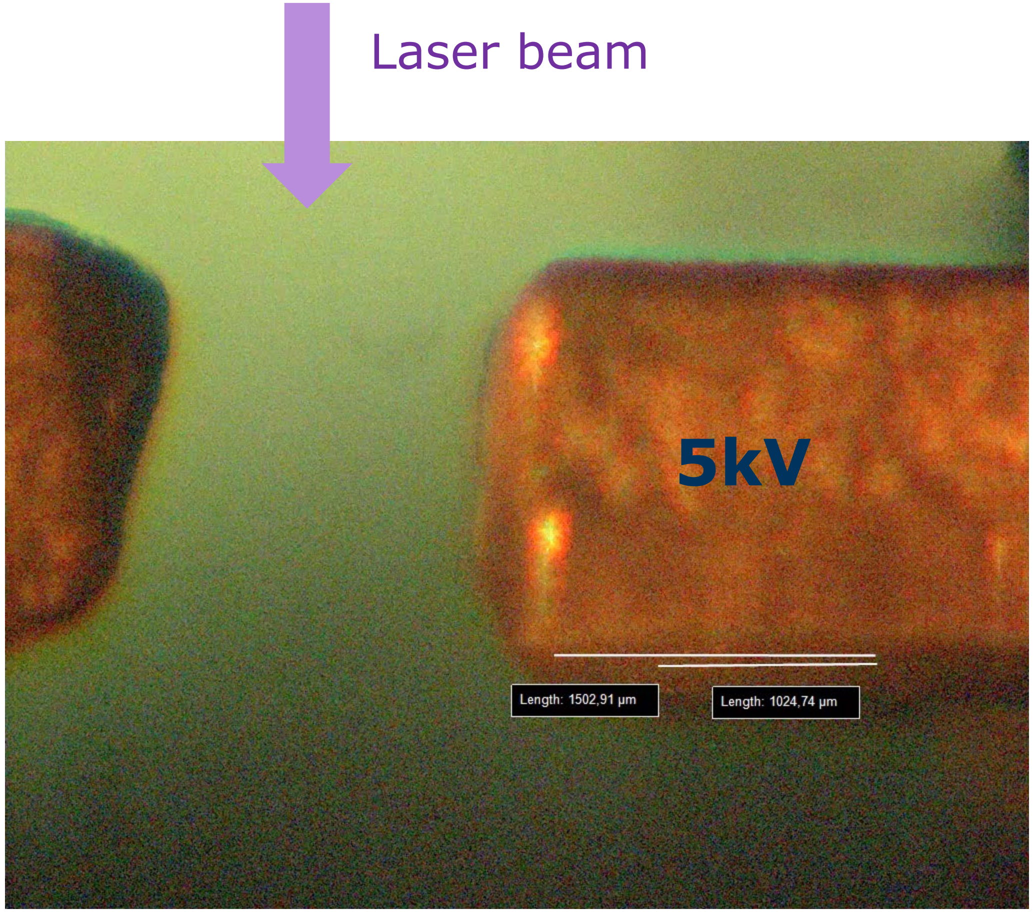
➔ different mechanism of break down?

Parameters:
tp = 150 10^{-15}s
Ep = 0,5mJ

Electron generation and ionisation

Examples of laser-induced plasmas

- Laser ablation
- Pulsed laser deposition (PLD)
- Laser shock peening (LSP)
- Laser-induced breakdown spectroscopy
- Laser plasma for inducing/guiding elecrical discharge

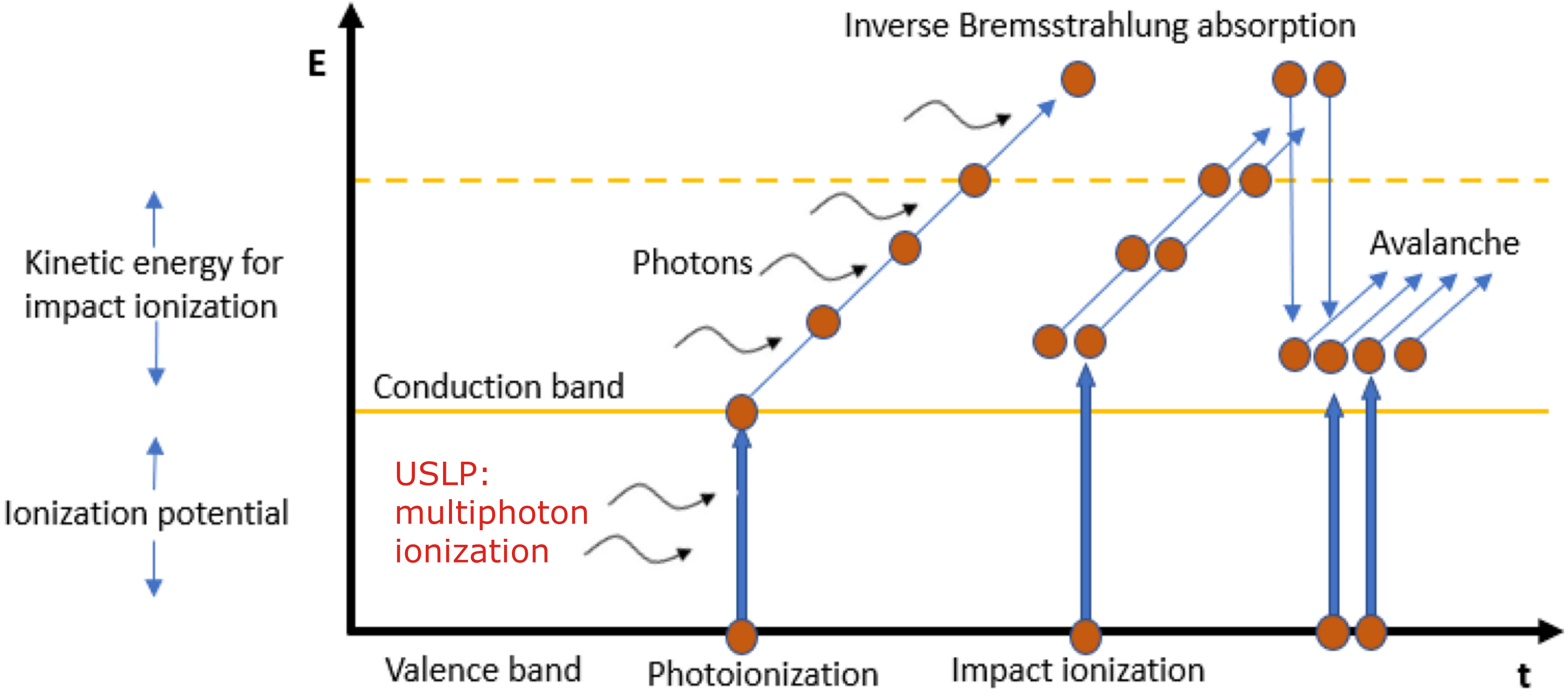


Laser-induced plasma etching (LIPE)

Electron generation and ionisation

Various processes

thermal
energetic photons
high electric fields
particles impact
charge transfer
energetic rays
…



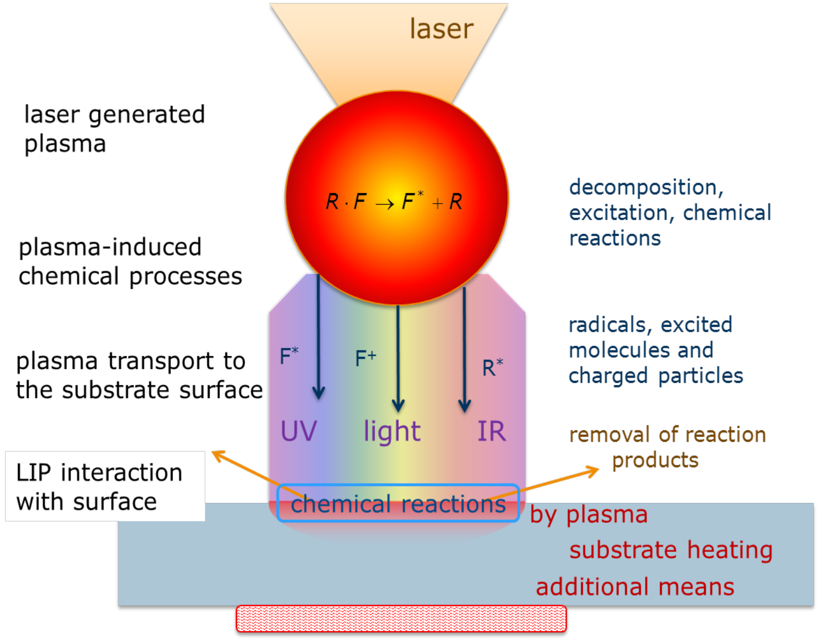
tp~10^{-13}s

pulse length	$<10^{-13}$s	10^{-11}s	10^{-9}s
frequency	>10THz	100GHz	1GHz

Schema of the expected process of surface processing with LIP

Laser Induced Plasma etching (LIPE)

- Ignition of a plasma in a gas by laser induced optical break down with USP laser



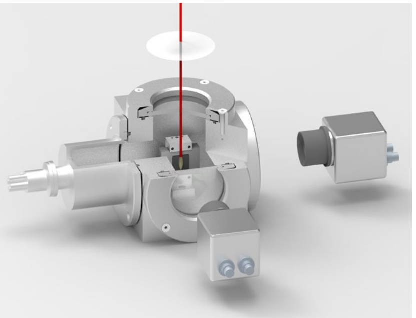
Characteristic laser induced plasma in gas:

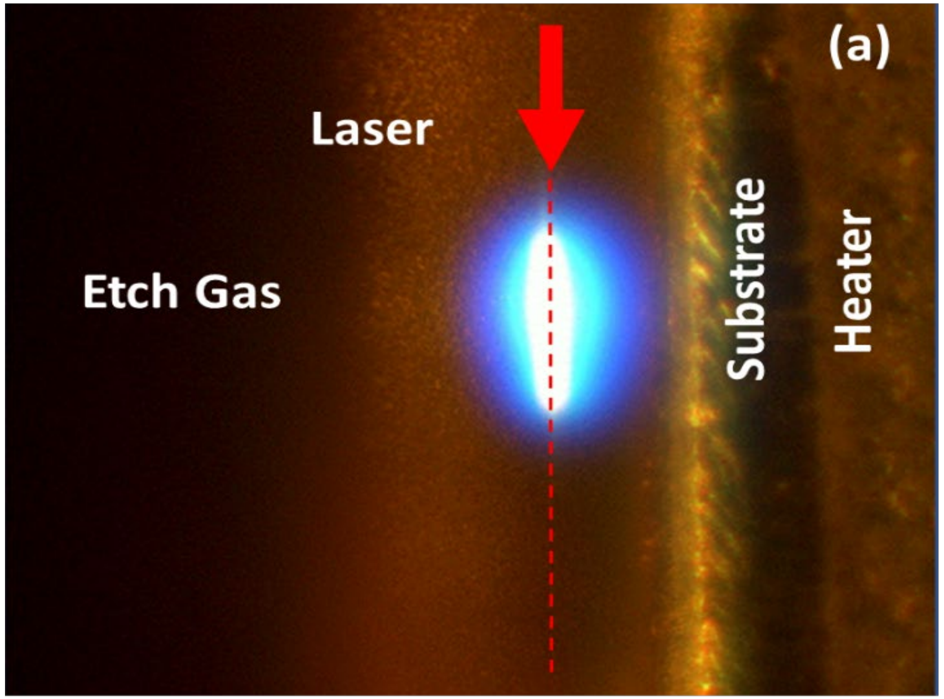
- Small size plasma
- Contact free →“Contamination free“
- Atmospheric pressure plasma
- Generated and manipulated with optical methods

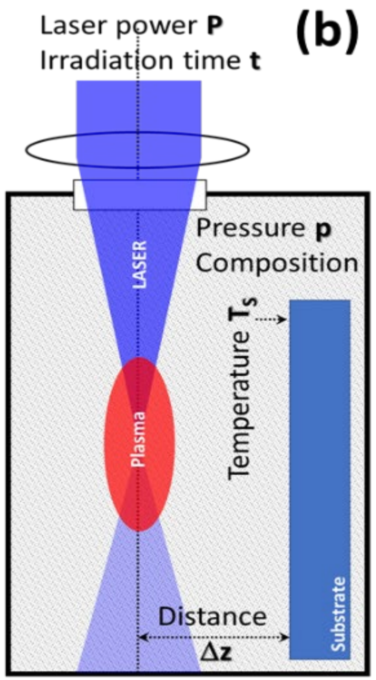
→ Generating reactive species by decomposition/excitation of the gas

Laser-induced plasma etching

- Glancing angle of incidence in order to avoid direct irradiation the substrate







- Gas: CF_4/O_2; Pressure absolute: 0.3 bar to 2 bar; Temperature: RT to 500 °C
- Material: Fused Silica; Silicon

Experimental Setup

Using ultrashort laser pulses for ignition of the plasma

- Pulse duration = 150 fs
- Rep. Rate = 1 kHz
- E_{max} = 800 µJ
- Wavelength = 775 nm

- Low pulse energy (but high $\hat{P}$)
- Low thermal/mechanical effects e.g., shockwaves

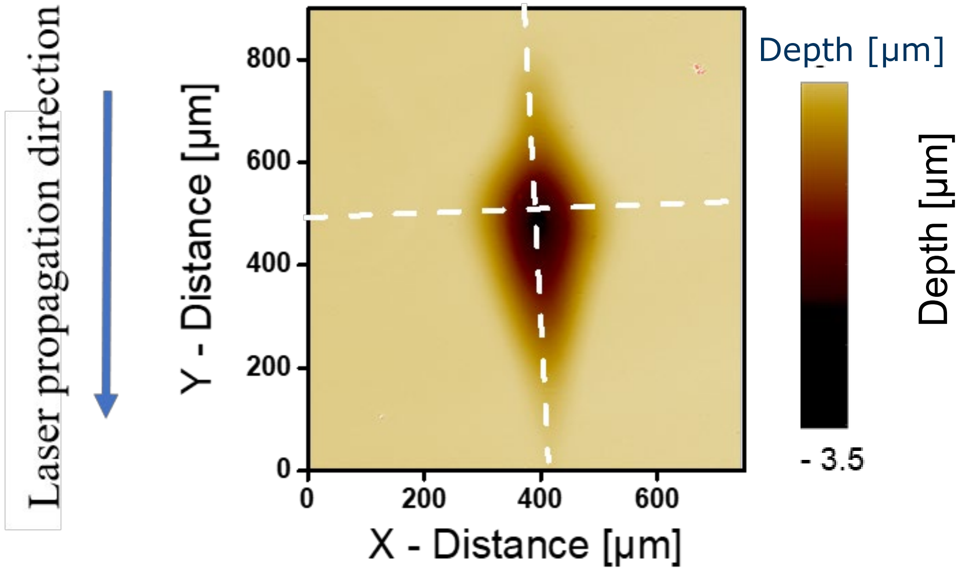
- High pulse repetition rate (MHz)
- Small plasma size (spot size)

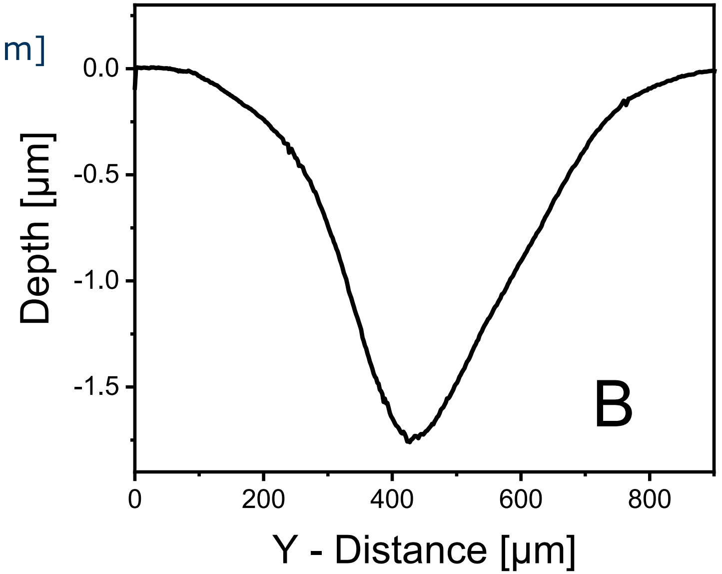
Etching gas

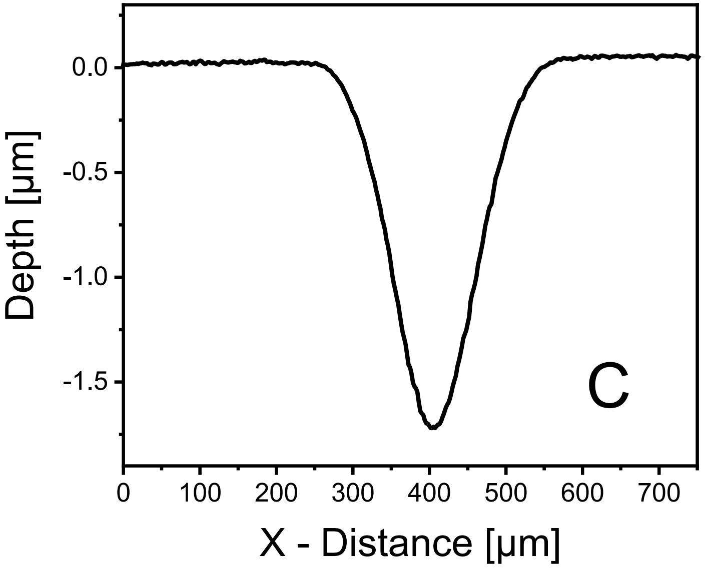
- **CF_4**
- O_2
- CF_4/O_2
- Air
- SF_6

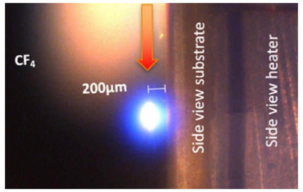
Results

- Etching of SiO_2 with laser-induced plasma ignited in a CF_4 gas mixture





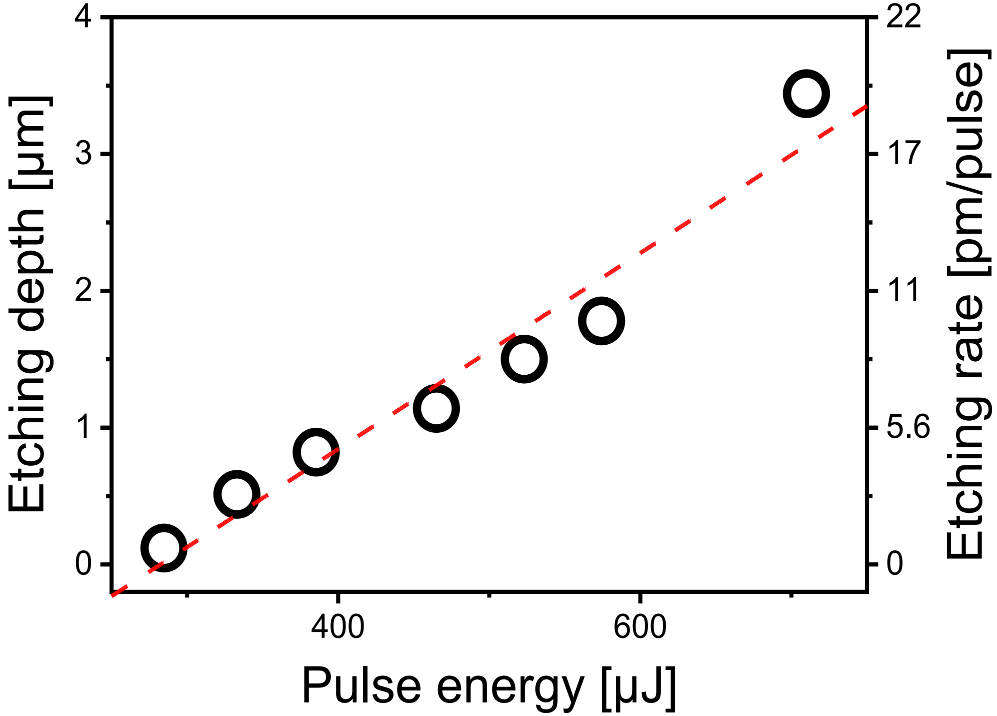




Material: SiO_2; Gas: CF_4; Absolute pressure: 0.85 bar; Temperature: 450°C; Etching time: 3 min

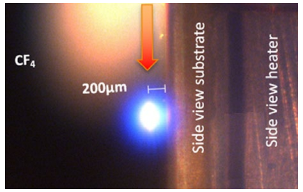
Results

Dependency of etching depth on laser pulse energy



Etching rate
in the pm range!

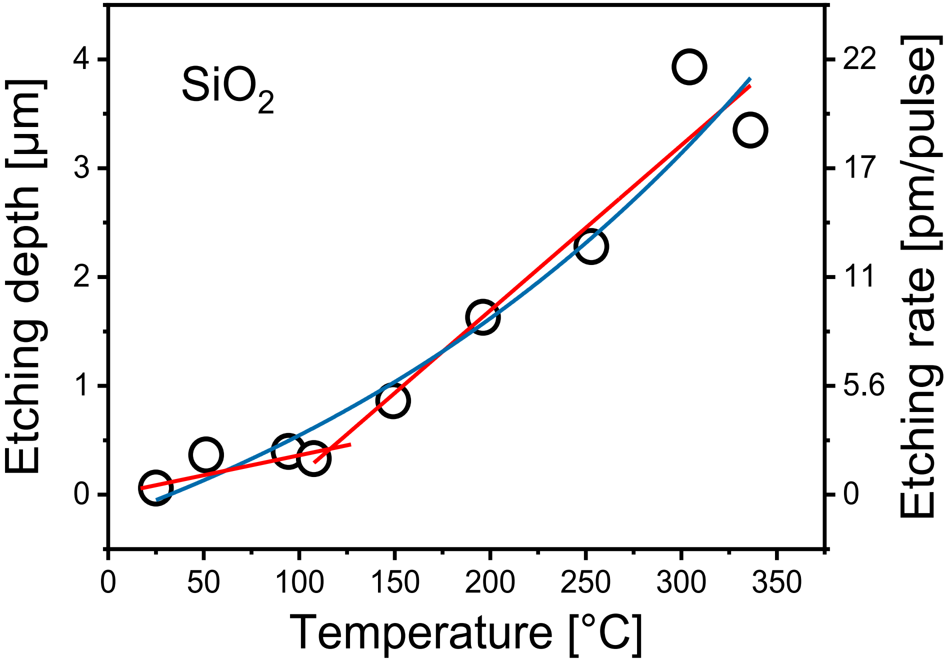
Material: SiO$_2$; Gas: CF$_4$; Absolute pressure: 0.85 bar; Temperature: 450 °C; Etching time: 3 min; Distance: 100 µm



- Linear increase of etching depth with increasing laser pulse energy
- Threshold for etching at ~ 250 µJ

Results

Dependency of etching depth on the substrate temperature



Material: SiO$_2$, Gas: CF$_4$; Absolute Pressure: 0.85 bar;
Etching time: 3 min, Distance: 100 µm

Arrhenius equation

$$K = A \exp\left(-\frac{E_a}{R\,T}\right)$$

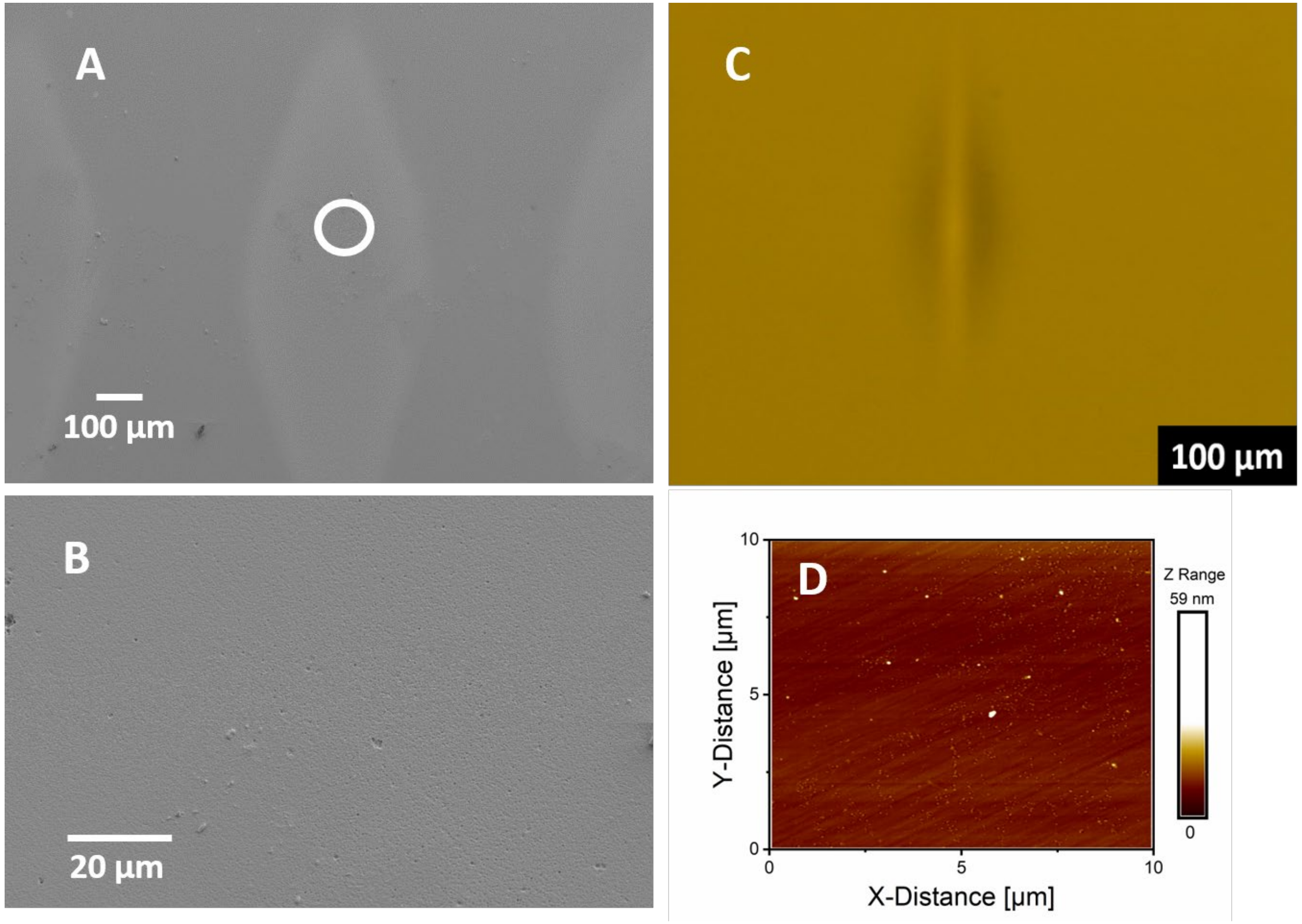
E_a Activation energy
T Temperature
K Reaction rate

→ E_a *of* 4.3 kcal/mol

- For the simplest case of heterogeneous chemical reactions at the substrate the reaction rate K is usually described by the Arrhenius equation

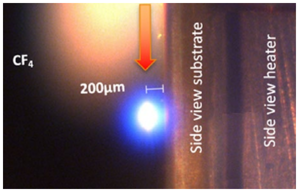
Results

Surface roughness of laser-plasma etched surface



Surface roughness
1-2 nm RMS!

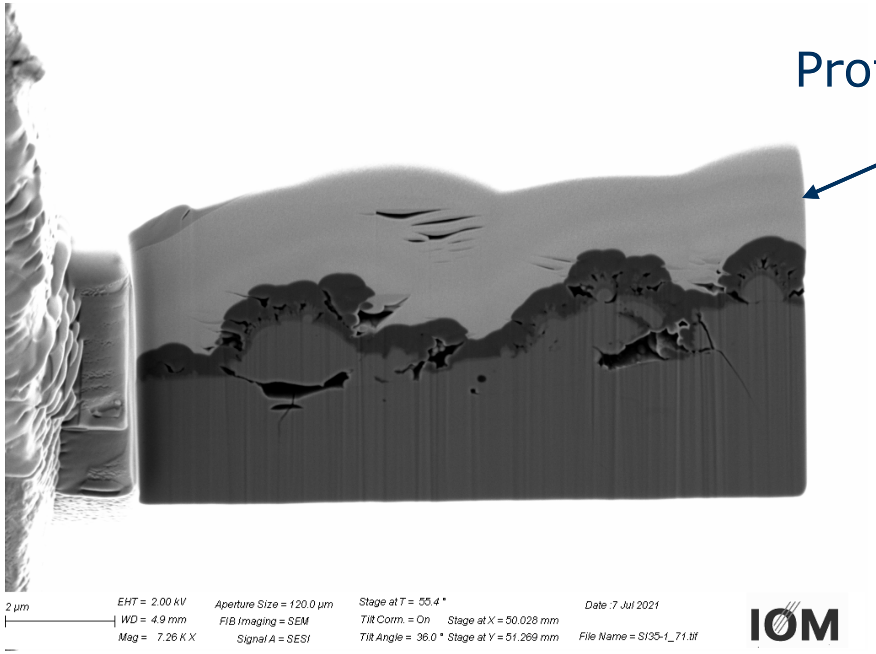
SEM, AFM and optical images of LIP-etched area SiO_2



Surface fidelity

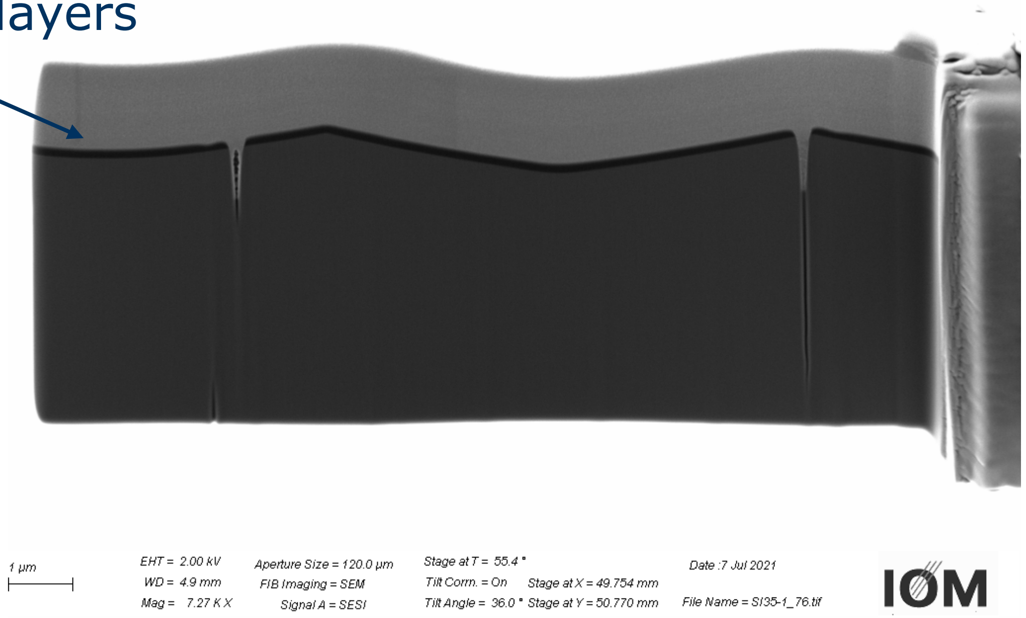
- Cross-section of laser ablated and LIP etched silicon surface

Laser ablation



Protection layers

LIP etching

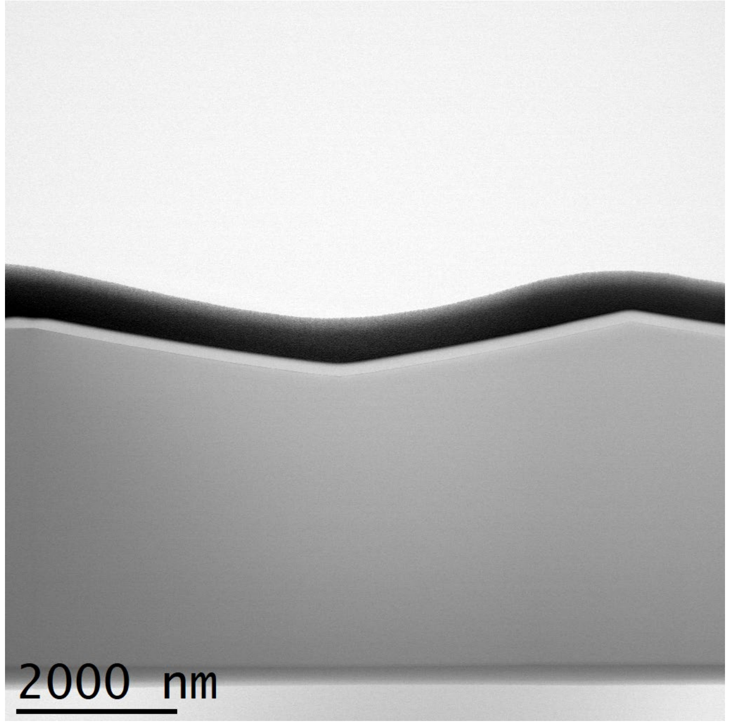


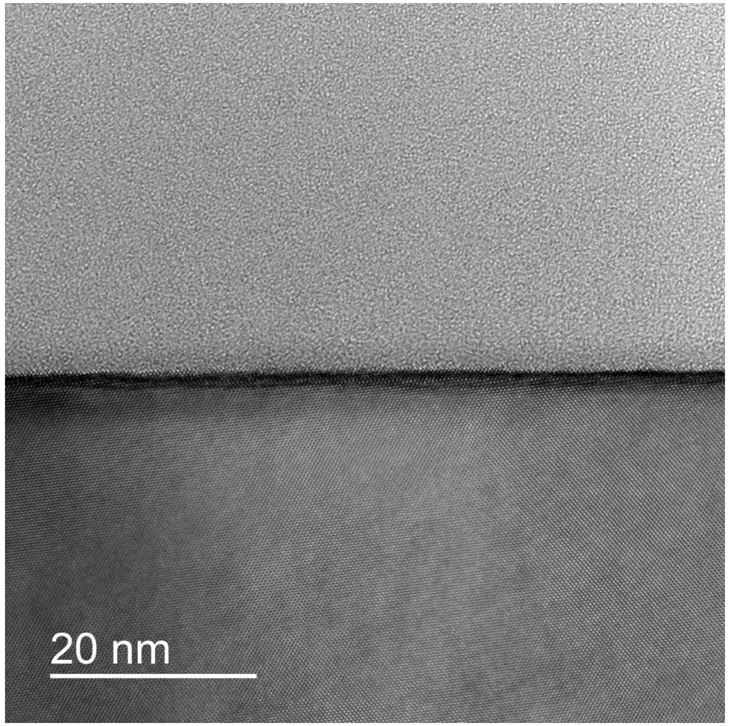
Strong (sub) surface damage is visible in the SEM.
TEM confirm:
melting, cracks, stress, and amorphization

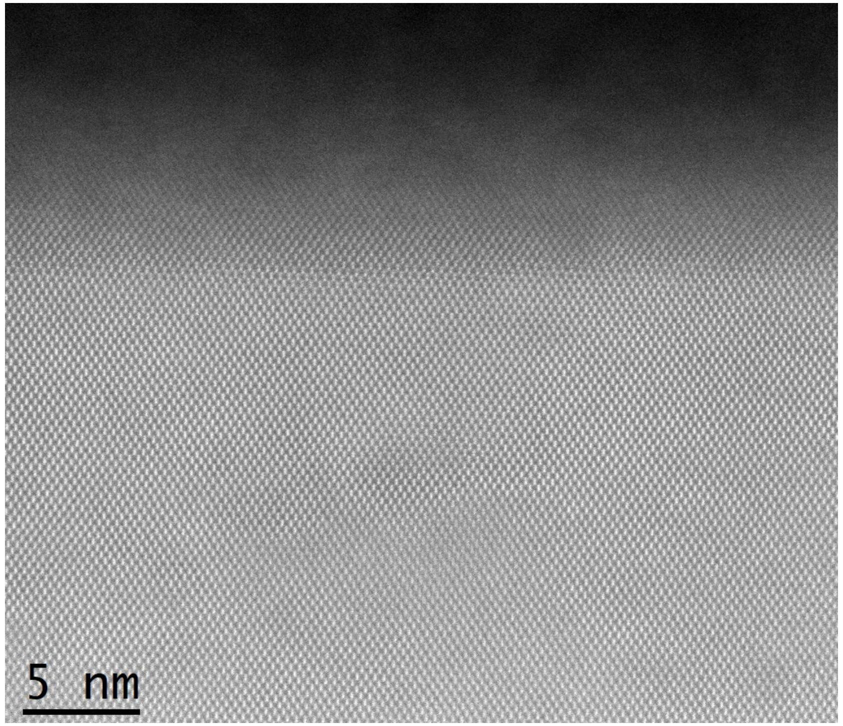
?

Results

- TEM image of LIP etched crystalline silicon.



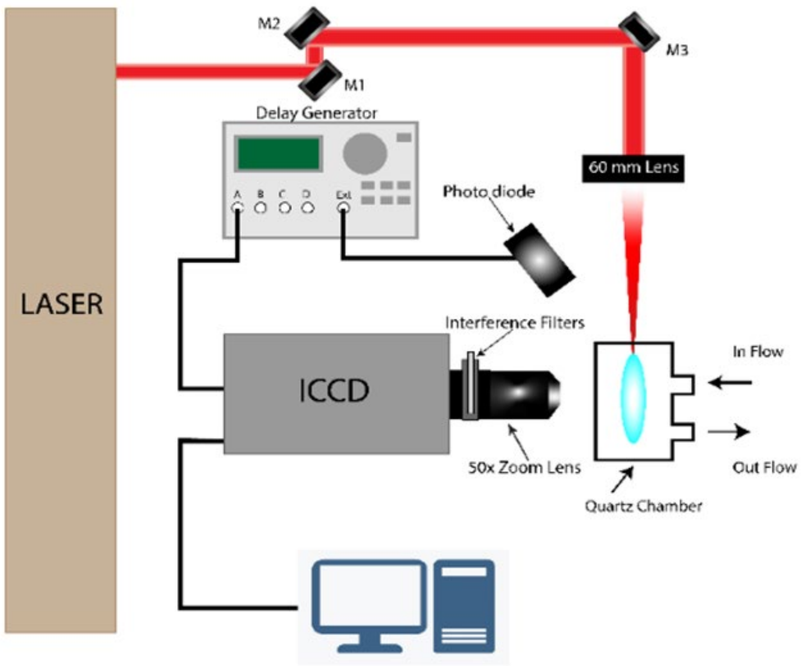


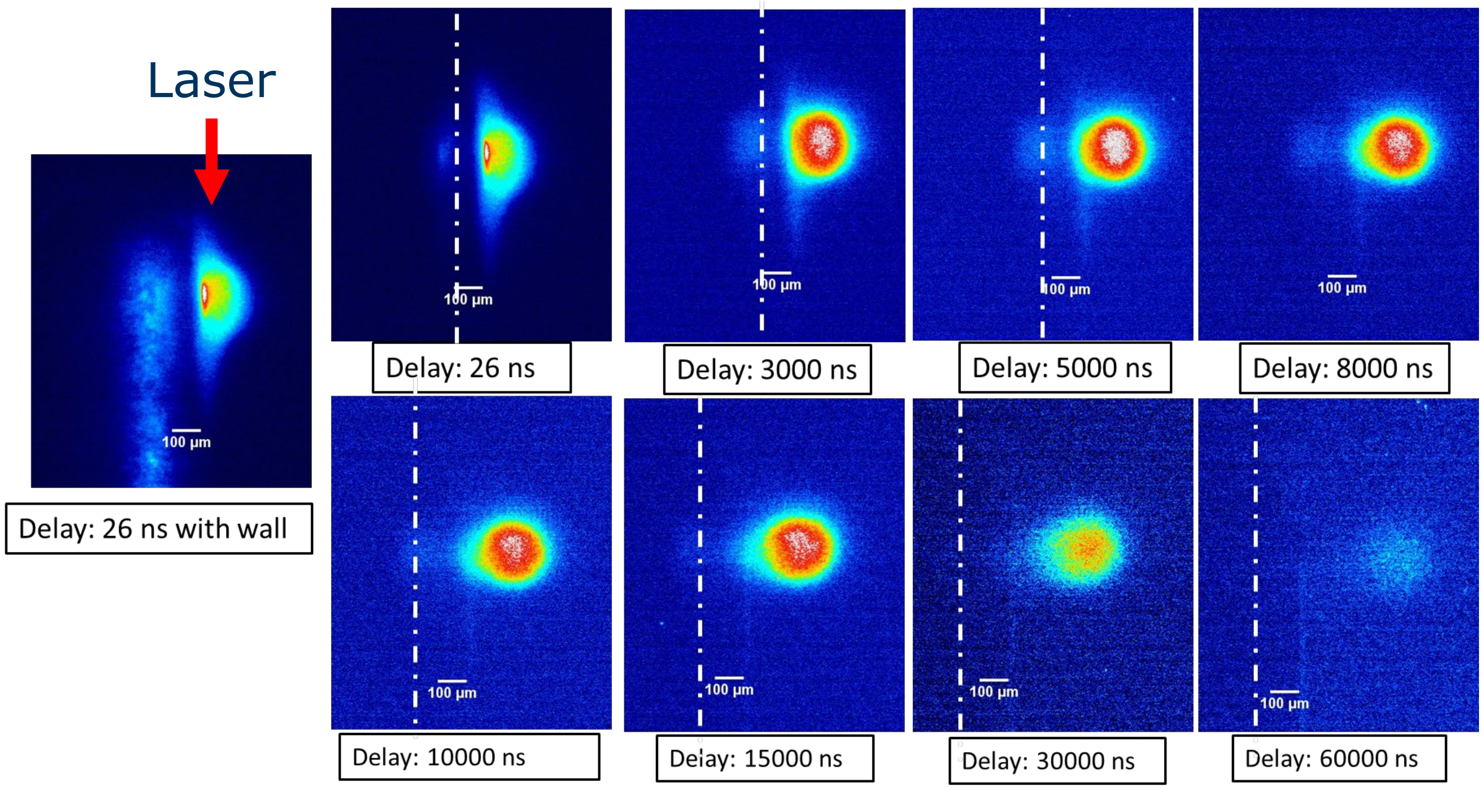


→ Almost no (sub-)surface damage!

Results

- Example of optical diagnostics of LIP

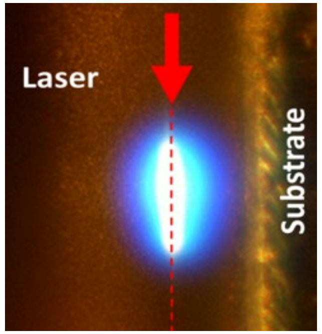


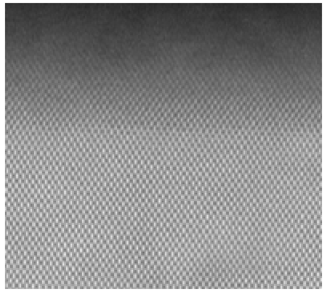


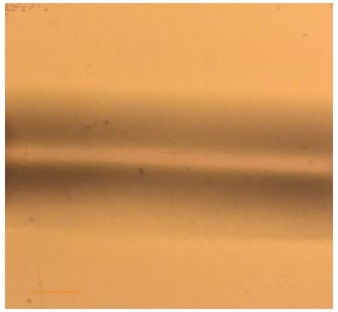
Delay: 26 ns with wall
Delay: 26 ns
Delay: 3000 ns
Delay: 5000 ns
Delay: 8000 ns
Delay: 10000 ns
Delay: 15000 ns
Delay: 30000 ns
Delay: 60000 ns

Emission of a laser-induced plasma near a substrate surface

Summary/conclusion







Laser-induced plasma as a new tool for UPSM.

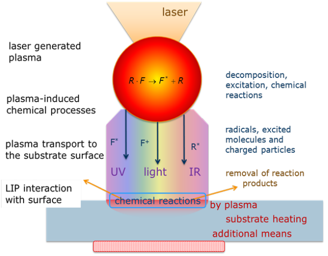
- atmospheric pressure process conditions
- sub-mm size dimensions of the tool
- Extreme low etching rates ➔ pm-range
- smooth etching enabled ➔ nm rms
- almost no (sub)surface damage
- strong impact of the material to the etching (masking …)

Understanding of LIPE mechanism

- LIPE mechanism
- governing processes
- physical-chemical model and the mathematical formulation simulation of the LIPE ➔ good to have collaboration

Development of applicative cases for

- UPSM for optics, precision mechanics, etc.
- localized plasma-based processing



Improvements of the mechanism

Thank you for your attention!

Questions?

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Further reading

[1] M. Ehrhardt, K. Zimmer, P. Lorenz et al., Germany Patent No. B23K 26/362 (04.09.2019 2019).
[2] M. Ehrhardt, P. Lorenz, B. Han et al., Applied Physics a-Materials Science & Processing 126 (2020) 9.
[3] R. Heinke, M. Ehrhardt, P. Lorenz et al., Applied Surface Science Advances 6 (2021) 100169.
[4] A. M. Hossain, M. Ehrhardt, M. Rudolph et al., J. Phys. D 55 (2021) 125204.
[5] M. Ehrhardt, P. Lorenz, K. Zimmer, in Ultrafast Laser Nanostructuring, in The Pursuit of Extreme Scales, edited by Razvan Stoian and Jörn Bonse (Springer Cham, 2022).
[6] R. Heinke, M. Ehrhardt, J. Bauer et al., Appl. Surf. Sci. 597 (2022) 153712.
[7] L. Streisel, M. Ehrhardt, P. Lorenz et al., in JLMN-Journal of Laser Micro/Nanoengineering, (2022), Vol. 1.
[8] K. Zimmer, M. Ehrhardt, P. Lorenz et al., Ceram. Int. 48 (2022) 90.
[9] A. M. Hossain, M. Ehrhardt, M. Rudolph et al., ACS Photonics (2023).

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