Overview of activities of the Department of Scientific Laser Applications and the major results

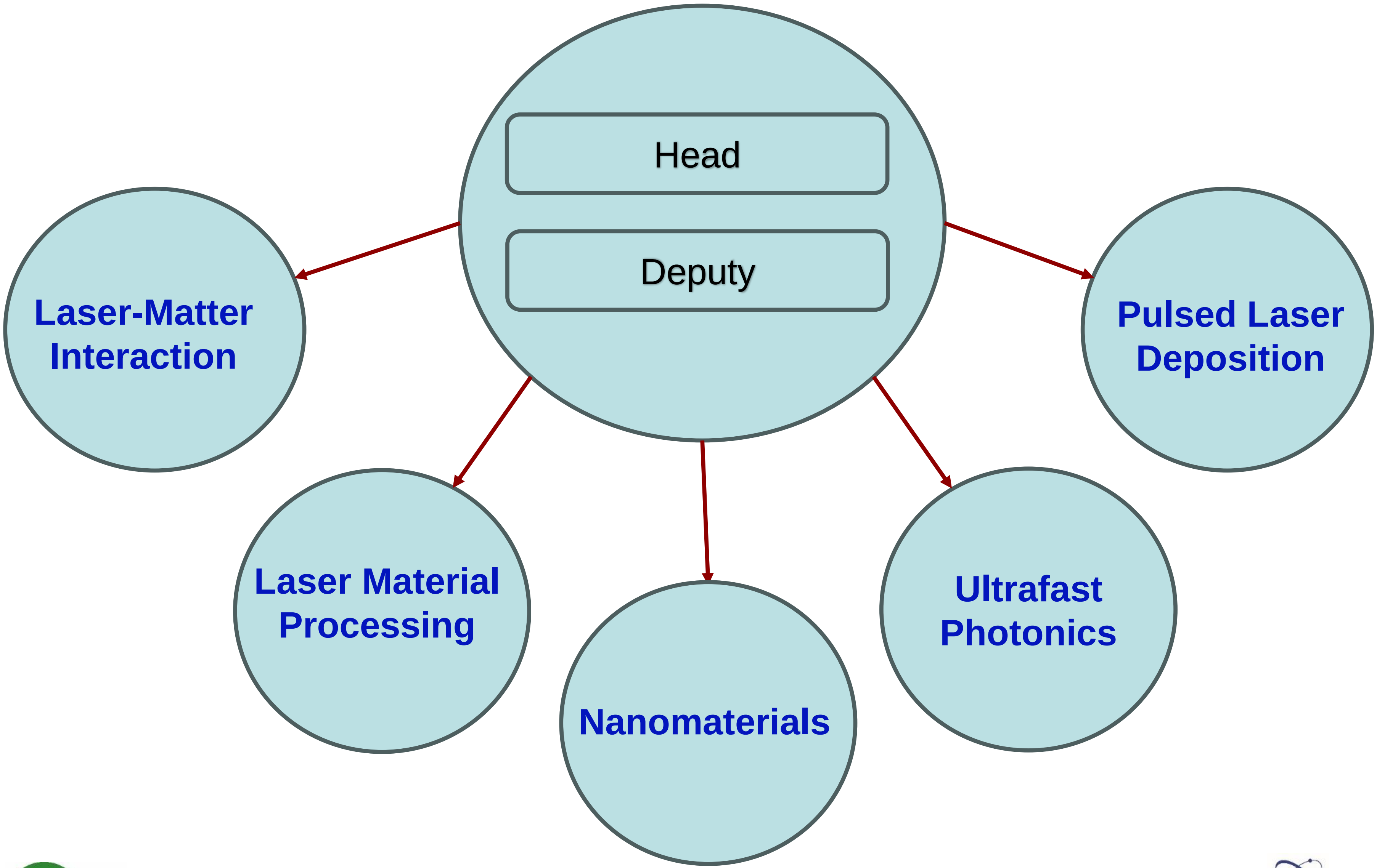
EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 739573 (HiLASE CoE)

SENDISO

SLA organizational scheme



hilase
BIATRI
EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
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FZÚ

SLA experimental lab

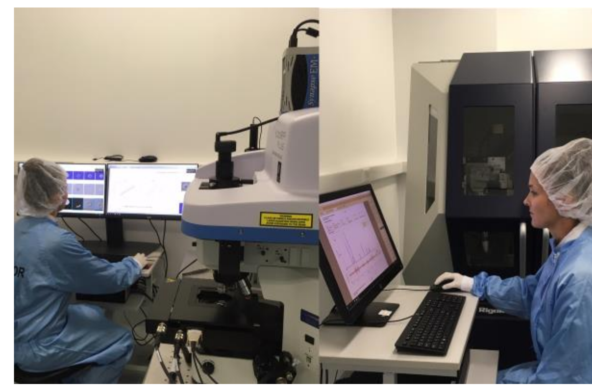
Pharos Laser
from Light Conversion
250 fs, 1030 nm,
200 kHz, 6W
2nd, 3rd and 4th
harmonics

Topas OPA
from Light Conversion
for Astrella laser
50-100 fs, 1.15-15 µm

Astrella Laser
from Coherent
35 fs, 800 nm, 1 kHz, 7W
2nd and 3rd harmonics

Nanosecond Lasers:
Nd:YAG with 2nd and 3rd harmonics
ArF, 193 nm

High-vacuum chamber with
Time-Of-Flight
Mass Spectrometer



LIFT in air and vacuum

Thermal CVD

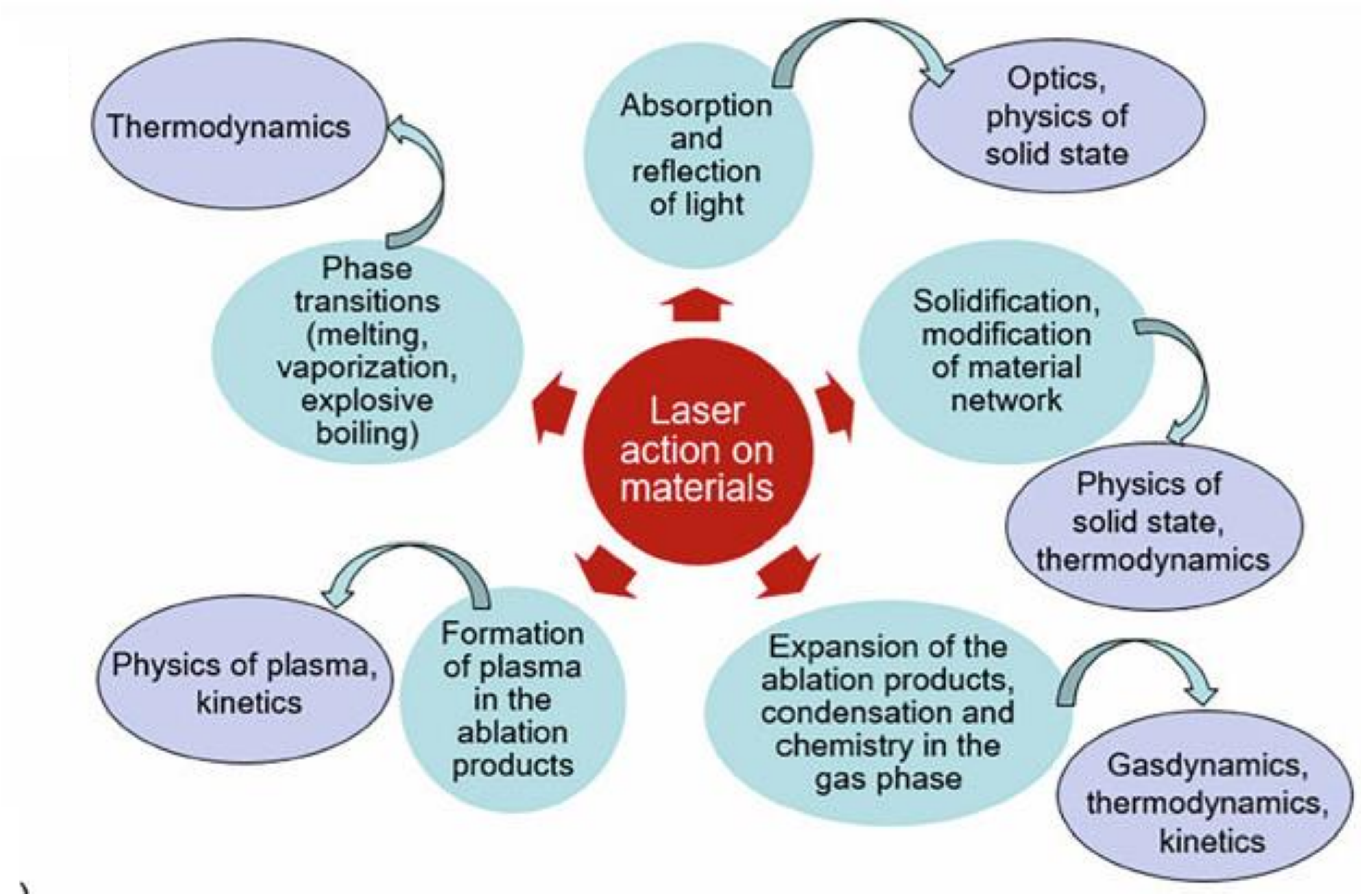
Spectrometers

Hamamatsu Streak camera
1-2 ps time
resolution

ICCD Camera
< 2 ns time resolution

Material characterization lab L4
AFM + Raman;
XRD; SEM

SLA concept: linking experiment with theory



Derrien, T.J.Y., et al. In: Ultrafast Laser Nanostructuring (2023). Springer Series in Optical Sciences, vol. 239 (Springer-Nature, 2023), pp. 3-64. https://doi.org/10.1007/978-3-031-14752-4_1

Our theoretical methods

Modeling predictions of laser-irradiation conditions for material micro/nano processing with **one- and two-temperature modeling** (damage thresholds, optimal irradiation conditions for surface structuring, ablation, and annealing).

Modeling predictions and optimization **of volumetric modification of bandgap materials** for photonics applications

Predictive plasmonic theory (predicting periodicity and regularity of laser-induced periodic surface and interface structures, including dynamic models for semiconductors)

Quantum simulations of material response at high nonequilibrium at ultrashort irradiation timescales including extreme thermodynamic conditions

Nadezhda Bulgakova

Yoann Levy

Thibault Derrien

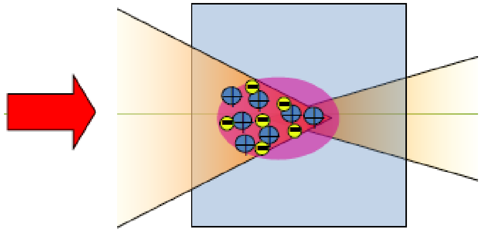
Kryštof Hlinomaz

Jiří Beránek

Kristýna Gazdová

Modeling based on Maxwell's equations

N.M. Bulgakova et al. *JOSA-B* **31,** C8-C14 (2014)
N.M. Bulgakova et al. *JAP*, **118**, 233108 (2015)
V.P. Zhukov et al. *JOSA-B*, **34**, 463-471 (2017)
N.M. Bulgakova et al. *JOSA-B* **36,** 1556-1564 (2019)
M. Zukerstein et al. *Photonics* **10**, 882 (2023).



$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t},$$
$$\nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} + \frac{4\pi}{c}\vec{J},$$

Equation for the electric field accounting free carrier generation:

$$\frac{1}{c}\frac{\partial D}{\partial t} - i\frac{\omega}{c}D = -\frac{4\pi}{c}j + \mathrm{rot}\,H - \frac{8\pi e^2}{mc\omega^2}W_{PI0}\frac{\rho_a}{\rho_0}\left(\frac{|E^2|}{E_*^2}\right)^{\alpha-1}(1+E^2/(4E_*^2))E$$

$$\vec{E} = (\vec{E}_0 e^{-i\omega t} + \vec{E}_0^* e^{i\omega t})/2$$

$$D = E + \sum_m P_m + P_{nl} \qquad P_{nl} = \frac{c}{4\pi}n^2 n_2\left((1-f_r)|E^2| + f_r\int_0^\infty R(\tau)|E^2(t-\tau)|d\tau\right)E$$

coupled with hydrodynamic model for free carriers

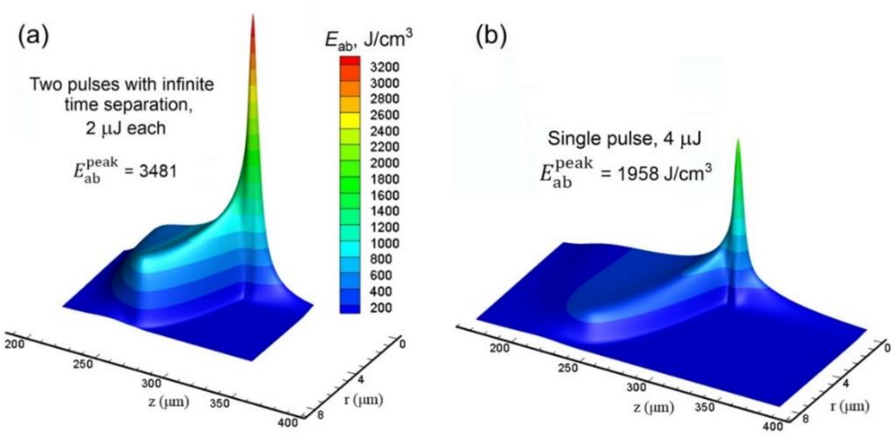
$$j = -\rho e \mathrm{v} \qquad \frac{\partial \rho}{\partial t} = W_{PI} + W_\sigma - \frac{\rho}{\tau_{tr}} \qquad \frac{\partial(\rho \mathrm{v})}{\partial t} - i\omega\rho\mathrm{v} = -\rho\frac{e}{m_e}E - \rho\frac{\mathrm{v}}{\tau_c}$$

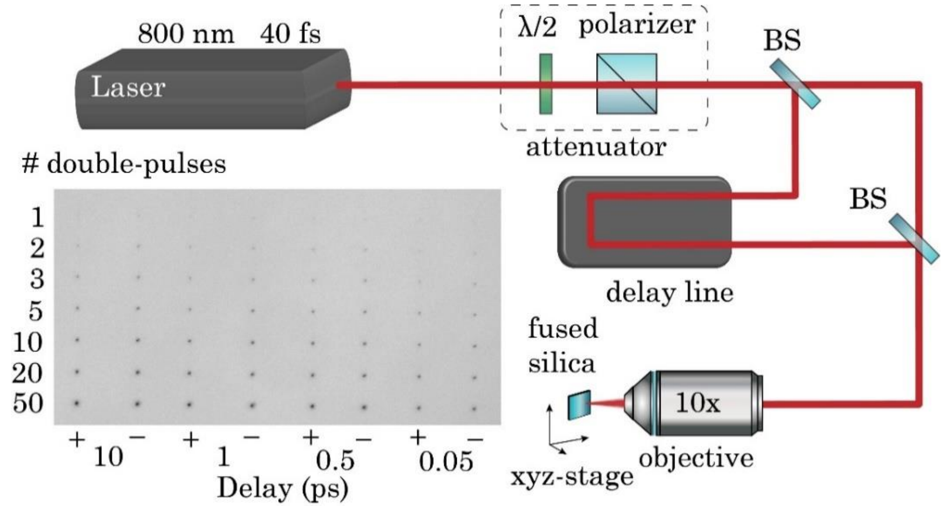
Theory and experiments for volumetric modifications of bandgap materials

Theoretical approach: Multiphysics large scale model based on nonlinear Maxwell's equations supplemented by the equations of electron excitation to the conduction band and their oscillations under the action of the laser wave

Experiments: Ultrashort laser pulses (Astrella, Coherent, 40 fs, 800 nm and harmonics). Application of spatiotemporal pulse shaping techniques (Gaussian, doughnut-shaped, pump-probe)

M. Zukerstein et al. *Photonics* **10**, 882 (2023)
M. Zukerstein et al. *Opt. Express* **32**(7), 12882-12891 (2024)



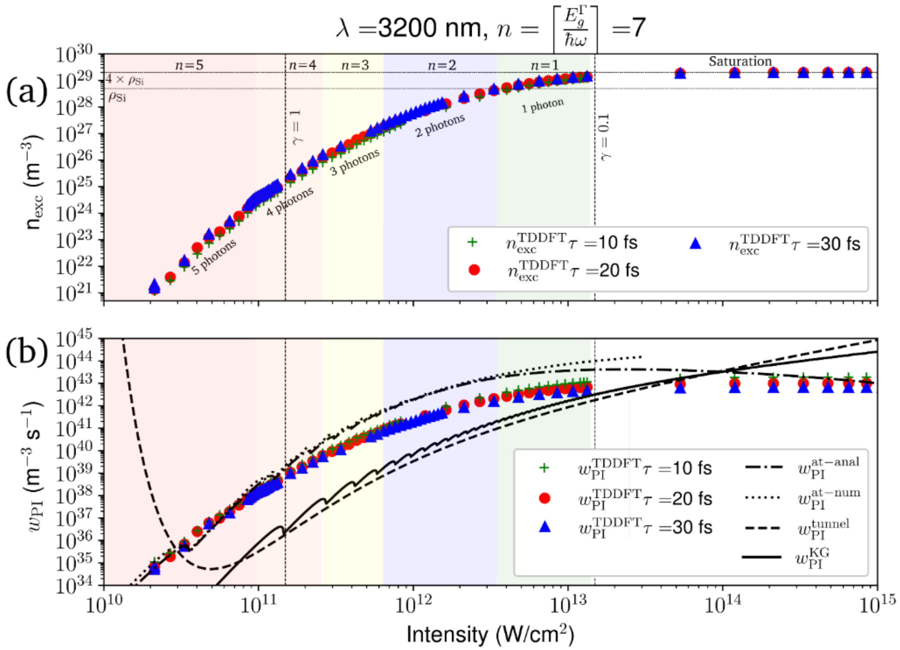


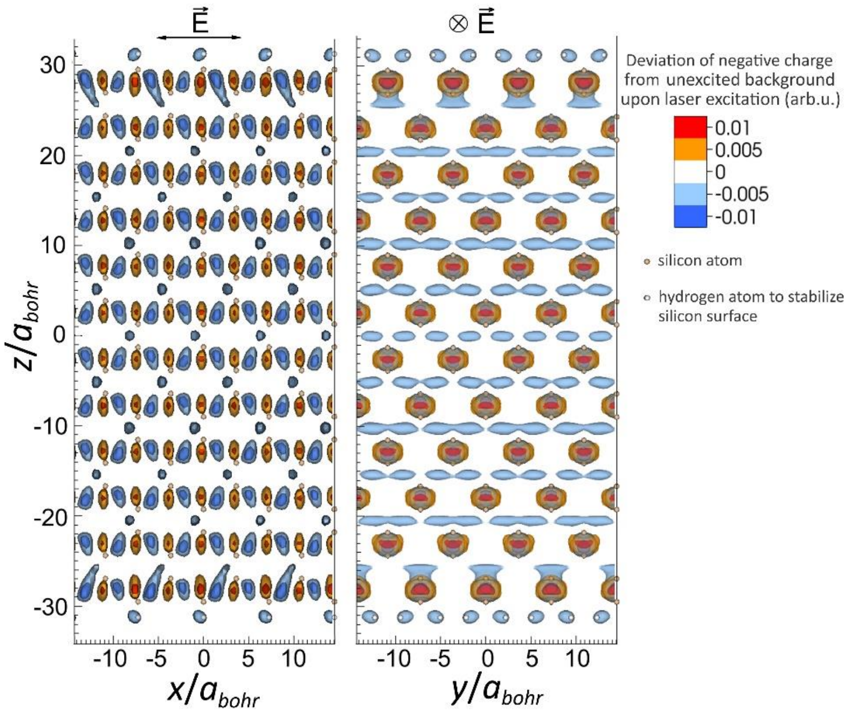
Simulations from first principles

Theoretical approach: Time-dependent density functional theory (TDDFT) simulations. Materials: semiconductors, dielectrics, metals (bulk). Now – extension to 2D materials and bio-molecules.

Deep understanding on photoinduced processes in various materials. Deriving photo-ionization rates beyond the validity of Keldysh theory. Insight into harmonics generation.

Thibault Derrien



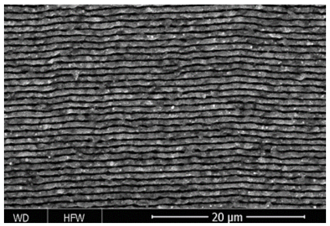


T.J.-Y. Derrien et al. *Phys. Rev. B* **104**, L241201 (2021);
P. Suthár et al. *Commun. Phys*. **5**, 288 (2022); P. Suthar et al. *Commun. Phys*. 7, 104 (2024)

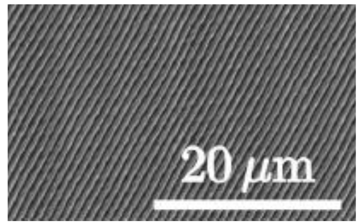
Laser nanostructuring of material surfaces

Ultrashort laser writing of highly-regular periodic nanostructures on material surfaces at high throughput

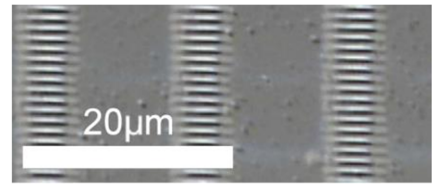
Patent of Czech Republic (June 2018): WO2018010707
European patent (January 2021): EP3481583B1



Silicon

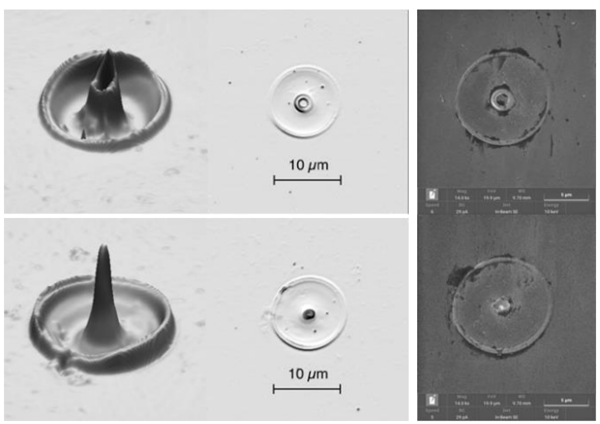


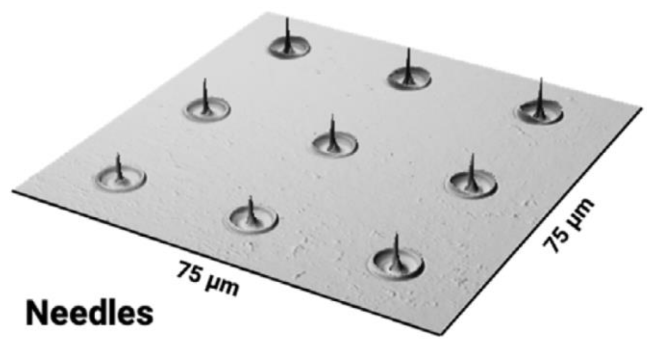
Metals (Mo)



Silicon

J. Gnilitskyi et al. *Sci. Rep.* **6,** 39133 (2017)
J. Sladek et al., *Appl. Surf. Sci*. **605**, 154664 (2022)
J. Sladek et al. *Materials*, **16**, 2883 (2023)





Silicon

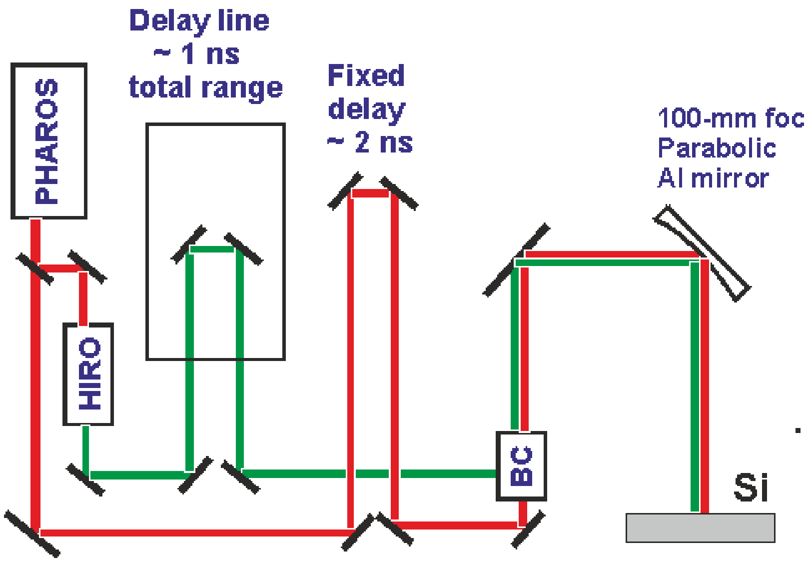
M. Zukerstein et al., *Appl. Surf. Sci*. **592**, 153228 (2022)

Inam Mirza

Yoann Levy

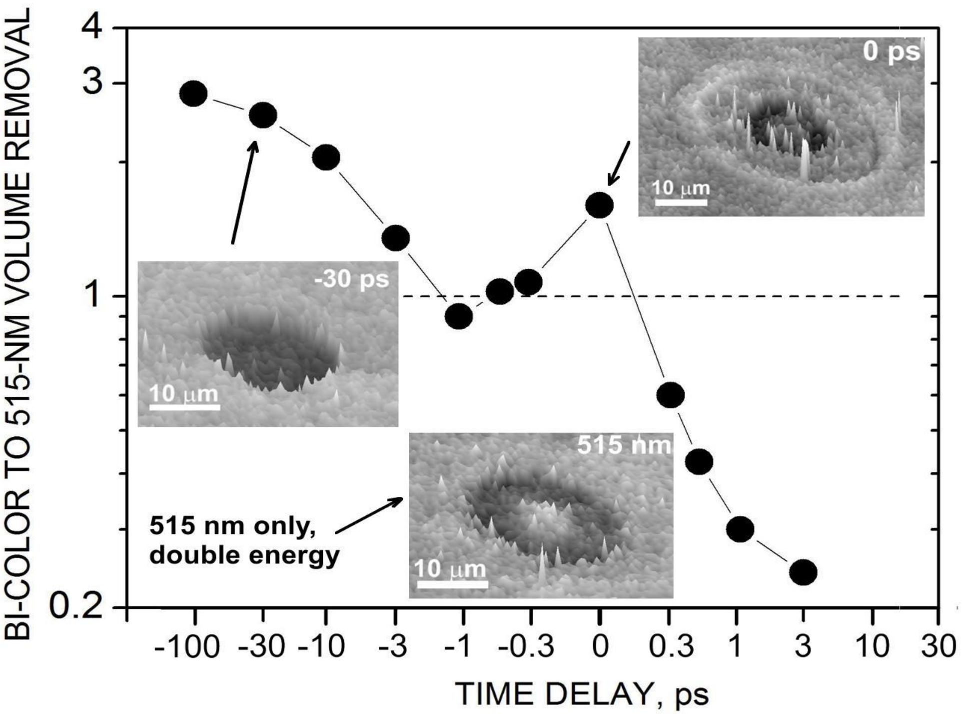
Jan Hrabovsky

Dual wavelength laser processing



Alexander Bulgakov Nadezhda Bulgakova Jan Hrabovsky

Crater volume at femtosecond dual-wavelength (1030 and 515 nm) ablation of Si as a function of delay between the pulses and selected crater images. Negative delays are for the visible pulse coming first.



A.V. Bulgakov et al. *Appl. Surf. Sci.* **643** (2024) 158626

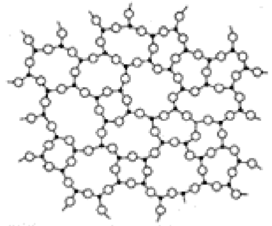
A.V. Bulgakov et al. *Proc. SPIE*, **12939**, 129390F (2024)

V. P. Zhukov & N. M. Bulgakova, Materials **17** (2024) 1763

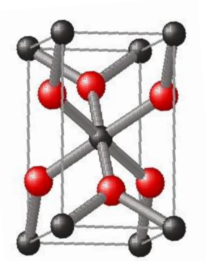
Laser annealing of anodized TiO_2 nanotubes to anatase

Some titania polymorphs

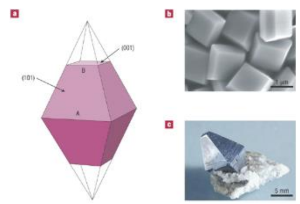
amorphous



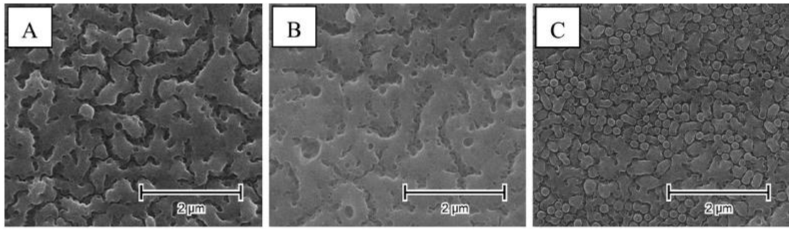
rutile



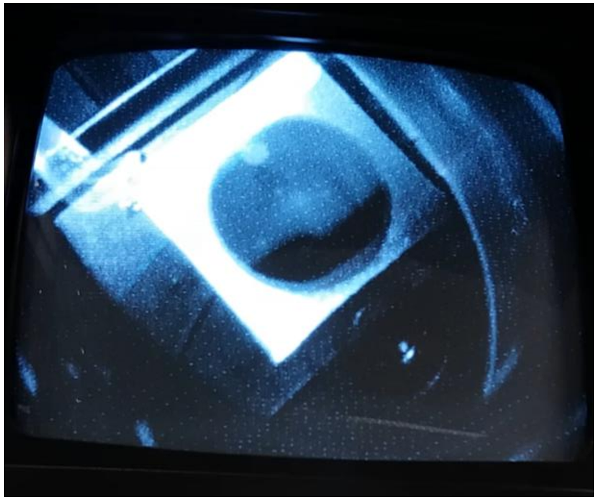
anatase

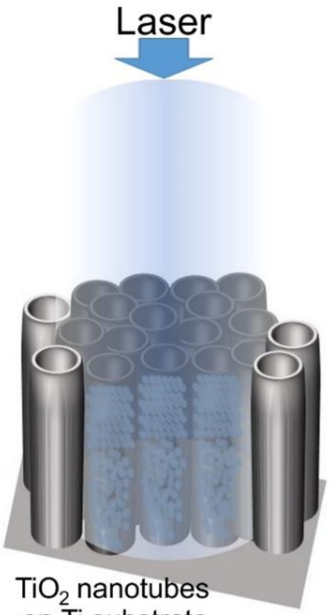


Inam Mirza

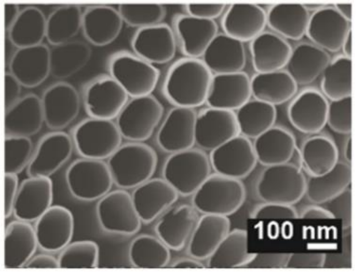


Typical laser annealing: *Appl. Surf. Sci. 508 145143, (2020)*





Laser-annealed sample,
area of 1 cm^2



Magnified top view of laser-annealed
TiO_2 nanotubes with the height of 20 μm

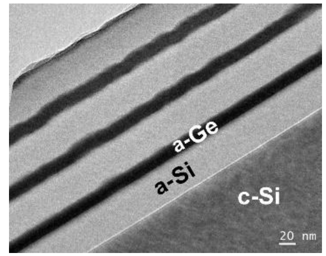
H. Sopha et al., *RSC Adv*. **10**, 22137 (2020)
I. Mirza et al. *Front. Nanotechnol*. **5**, 1271832 (2023)

Selective laser annealing of a-Ge/a-Si nanolayer stacks

without damage and intermixing

V.A. Volodin et al.
Opt. Las. Techn. **161**, 109161 (2023);
A.V. Bulgakov et al.;
Materials **16**, 3572 (2023)
I. Mirza et al. *Front. Nanotechnol.* **5**, 1271832 (2023)

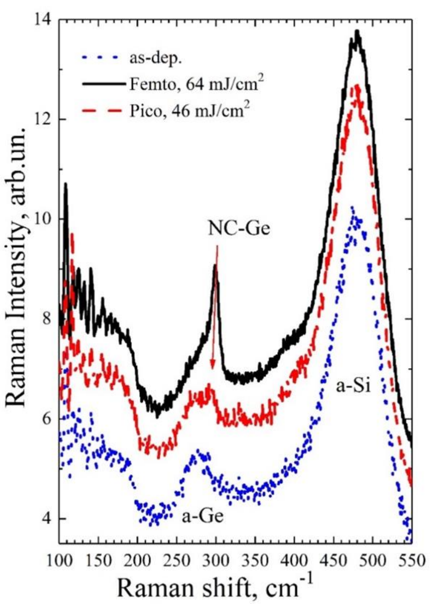
a-Si/a-Ge nanolayers



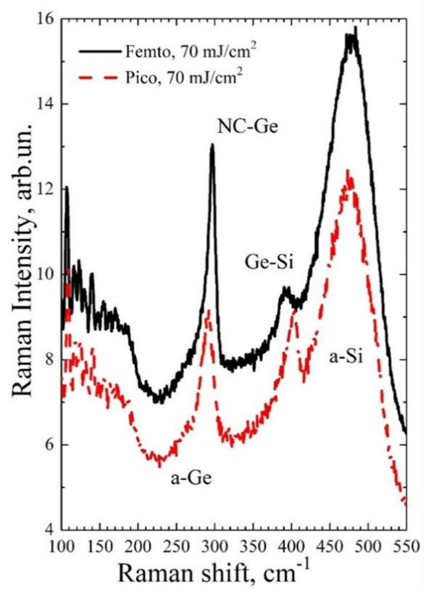
Alexander Bulgakov

Nadezhda Bulgakova

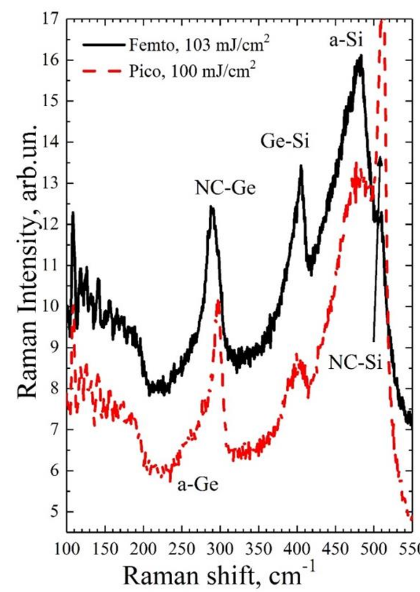
Jiří Beránek



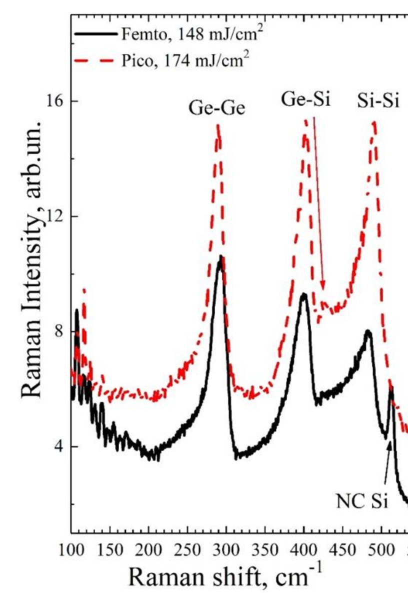
Laser fluence below the melting threshold



Fluence slightly higher than the damage threshold

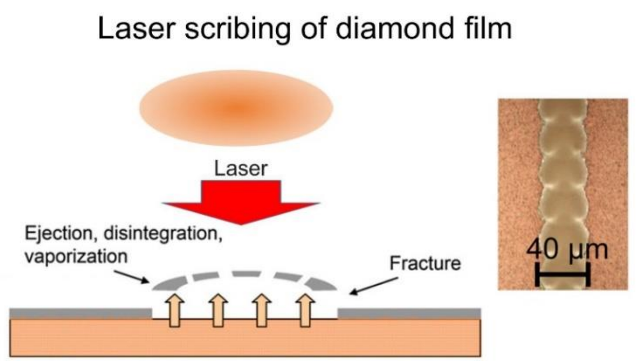


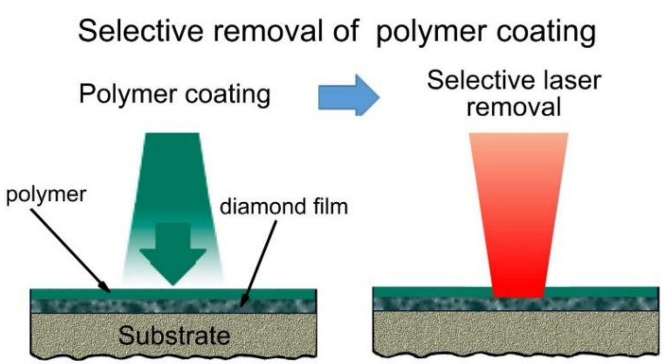
Fluence close to the ablation threshold

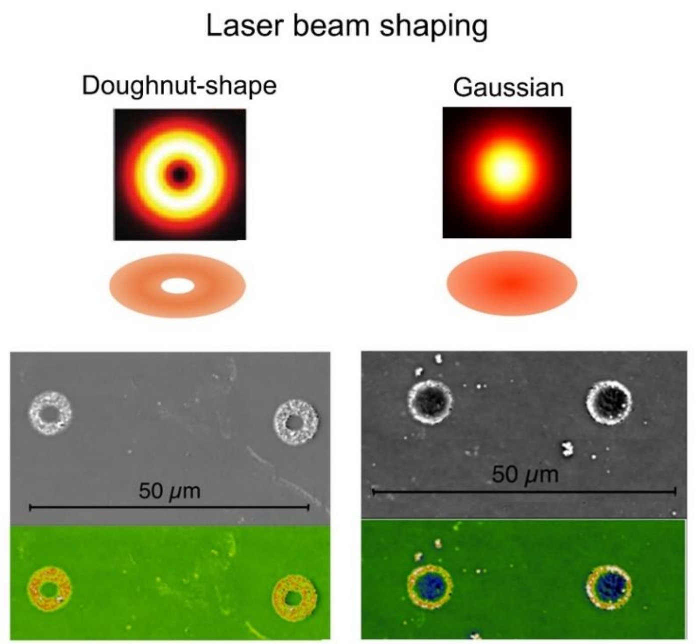


Fluence higher than the ablation threshold

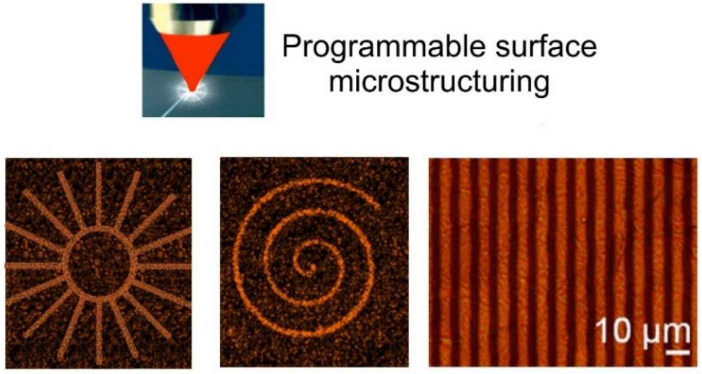
Toward neuron networks on diamond-based chips





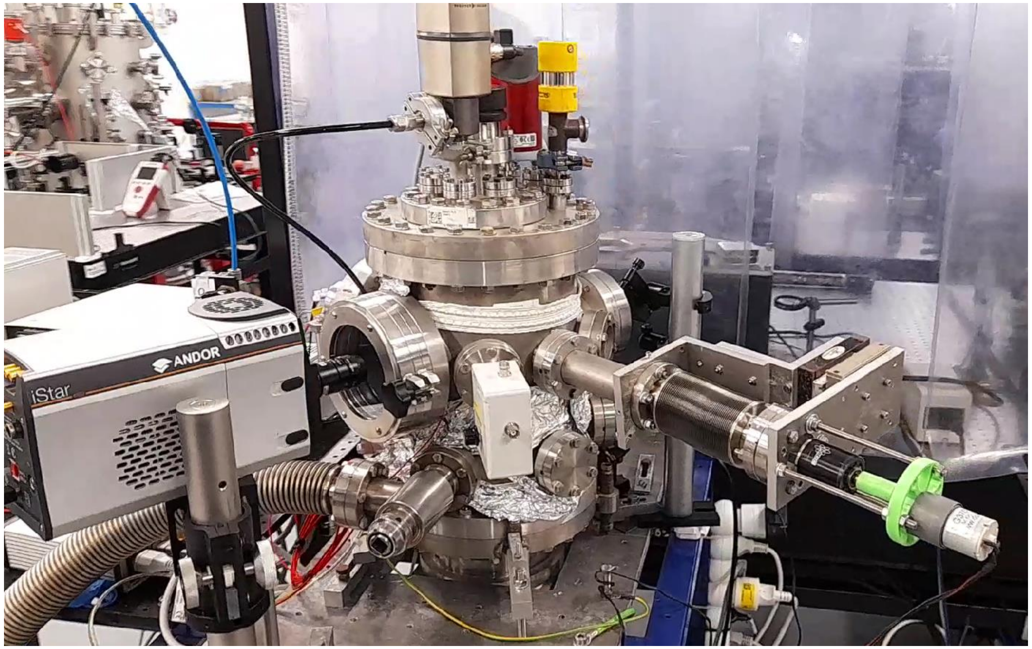


Jan Hrabovsky



J. Hrabovsky at al. *Appl. Surf. Sci*. **639**, 158268 (2023)

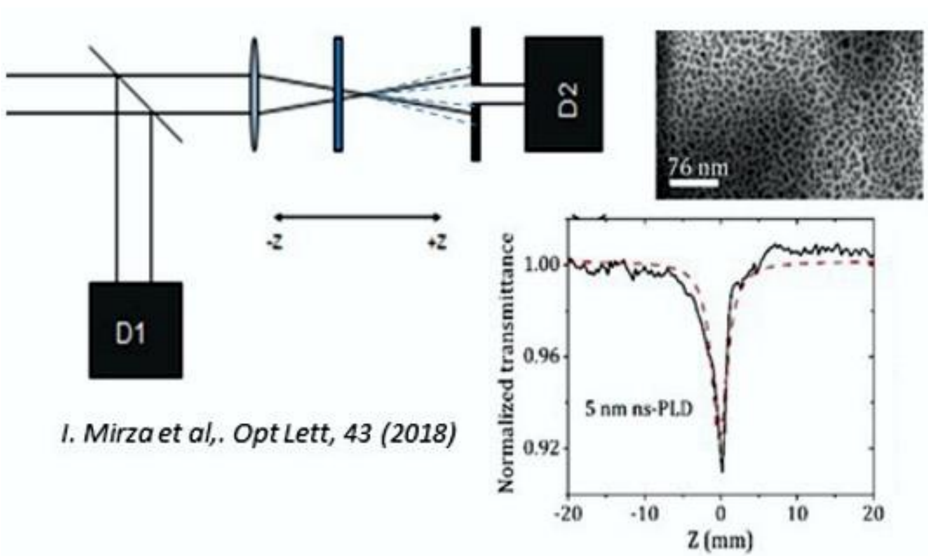
Pulsed laser deposition of various materials



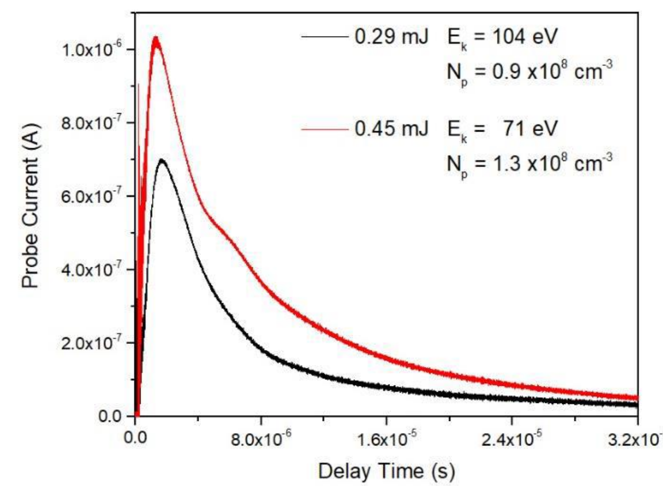
Inam Mirza

Alexander Bulgakov

Thin films of any kind of materials can be deposited in vacuum or in a controllable gas atmosphere, including 2D materials, semiconductors, noble metals (e.g. for SERS application). Various in situ diagnostics, including ToF mass-spectrometry



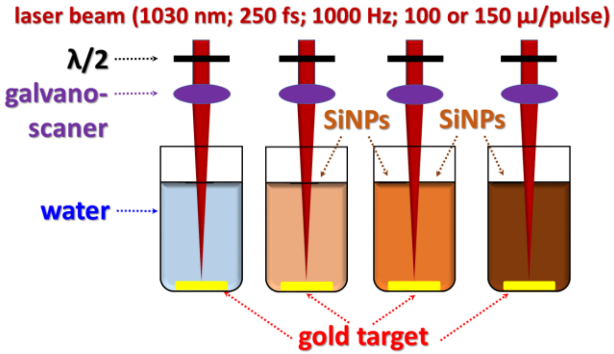
I. Mirza et al,. Opt Lett, 43 (2018)

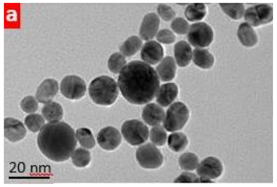


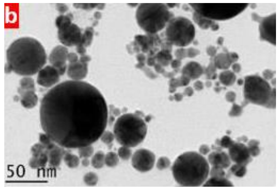
J.G. Quinones-Galvan et al.
MM Science June, 6421-6425 (2023)

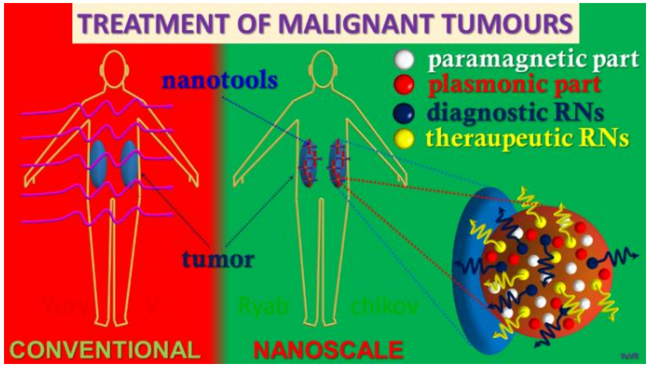
Nanoparticle synthesis

Hybrid (on demand) nanostructures







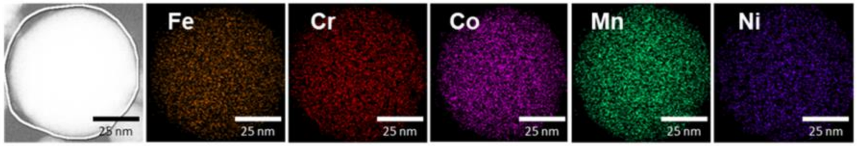


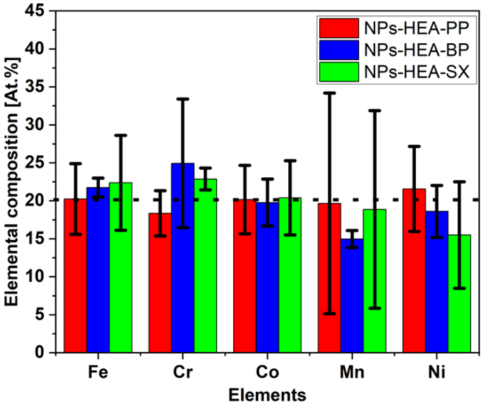
Yuri Ryabchikov

M. Flimelova et al. *Nanomaterials* **13**, 764 (2023)
Yu.V. Ryabchikov, *Crystals* **13**(9), 1381 (2023)
Yu.V. Ryabchikov et al. *Nanomaterials*, **14**(4), 321 (2024)

High-entropy alloy nanoparticles

Elemental powder – pressed (PP)



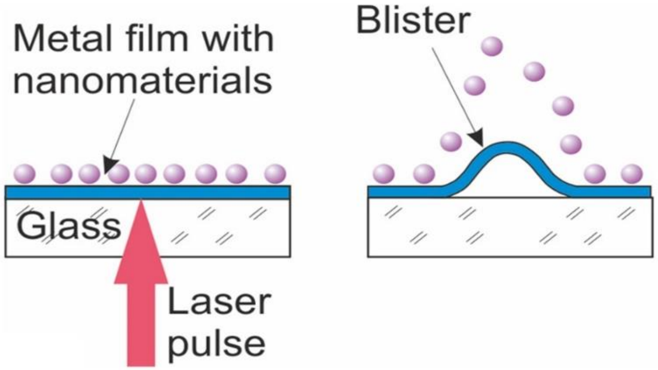


Alexander Bulgakov

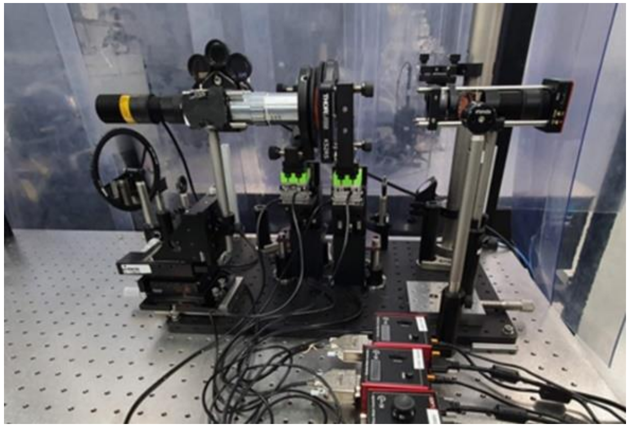
Oleksandr Gatsa

O. Gatsa et al. *Nanomaterials* **14**, 365 (2024)
S. Tahir et al. *ChemNanoMat* **10**, e202400064 (2024)

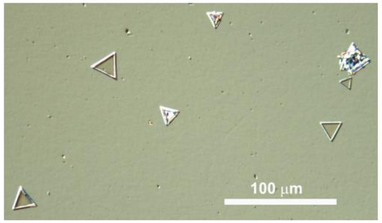
Nanomaterial synthesis, printing and functionalization

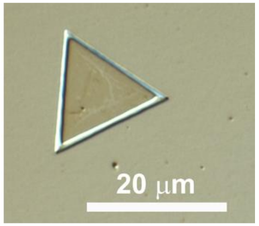


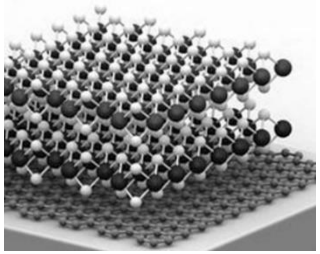
Patents: LU102294 (21. 06. 2022);
US 11801704 B2



Alexander Bulgakov





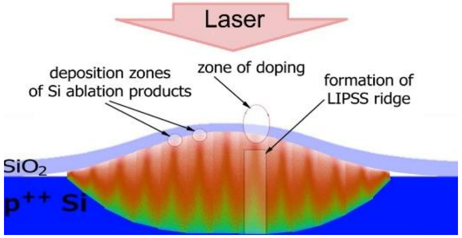


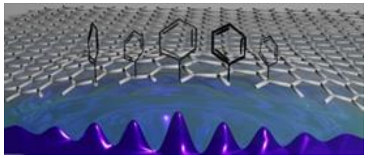
Oleksandr Gatsa

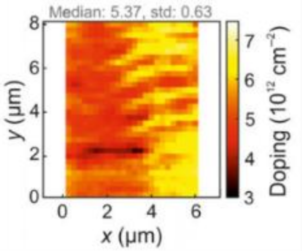
N. Goodfriend et al. *Nanotechnology* **29**, 385301 (2017)

Inam Mirza

Chemical functionalization of 2D materials via laser nanostructuring







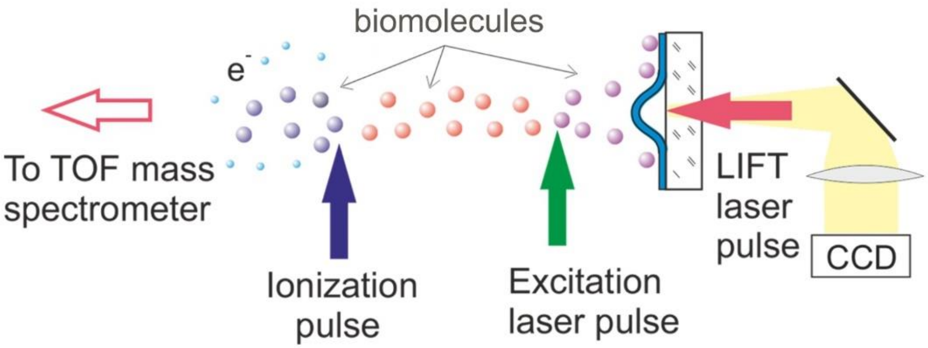
K.A. Drogowska-Horna, *Nano Research* 13, 2332–2339 (2020)

Time-of-flight mass-spectrometry: studying building blocks of nanomaterials at pulsed laser ablation

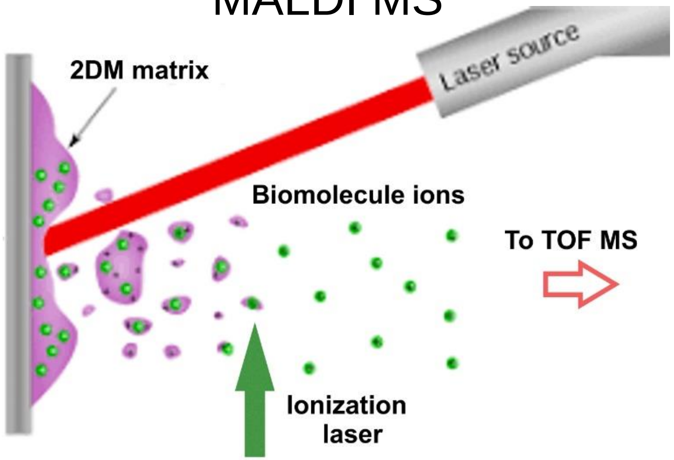
A sophisticated apparatus which include a customized high-resolution high-sensitivity reflectron time-of-flight mass spectrometer connected with a vacuum chamber. A variety of short- and ultrashort-pulse lasers with wavelengths ranging from 193 to 1030 nm and pulse durations ranging from 35 fs to 5 ns can be used.

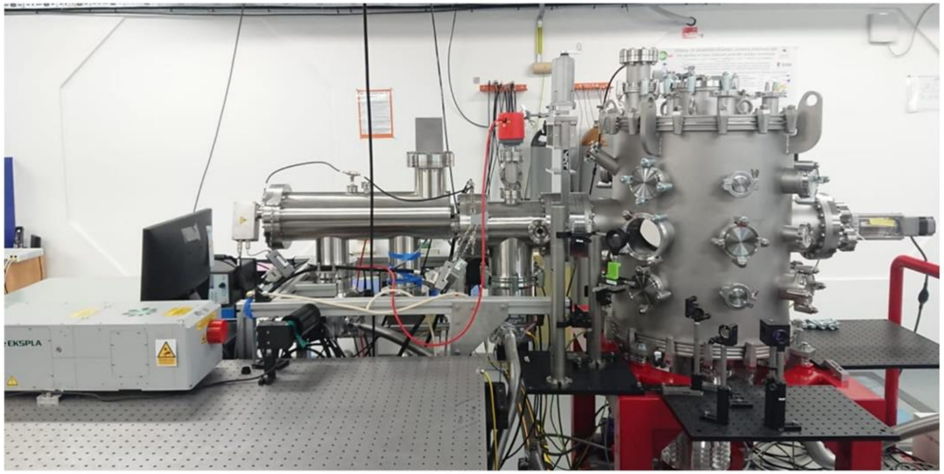

Alexander Bulgakov


Oleksandr Gatsa



MALDI MS





https://www.youtube.com/watch?v=KRhN-oJm1ak&t=1s