Patterning of solids with the employment of ultrashort laser pulses

George D. Tsibidis

IESL-FORTH

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Traditional light sources *vs* Laser

- Each color of light has a different wavelength.
- Our eyes see this mixture of wavelengths as white light.

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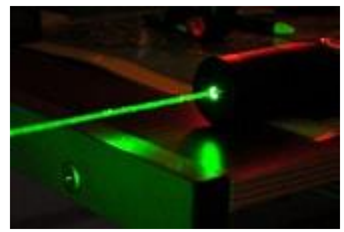
- A laser is different.



- Lasers do not occur in nature.
- Lasers produce a narrow beam of light in which all of the light waves have very similar wavelengths. This is why laser beams are very narrow, very bright, and can be focused into a very tiny spot.
- Laser beams can travel very long distances. They can also concentrate a lot of energy on a very small area

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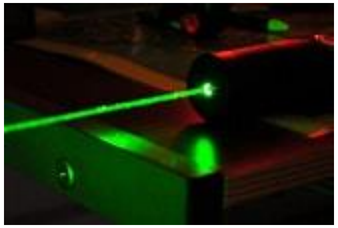

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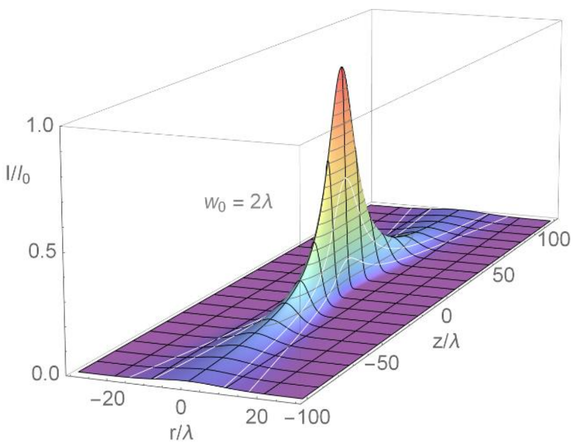
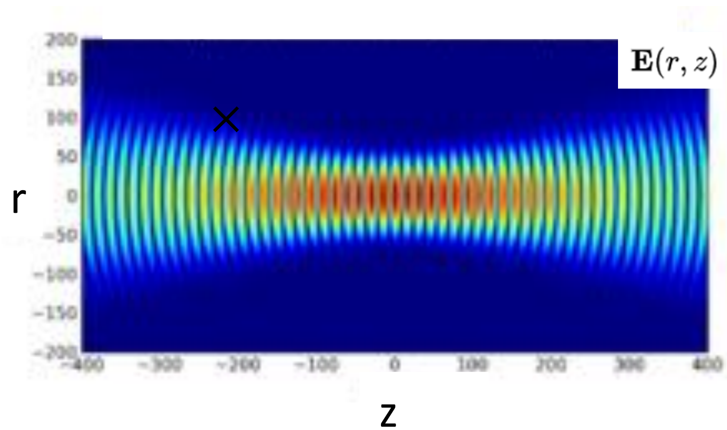
Lasers can be used for changing the morphology of the irradiated solid

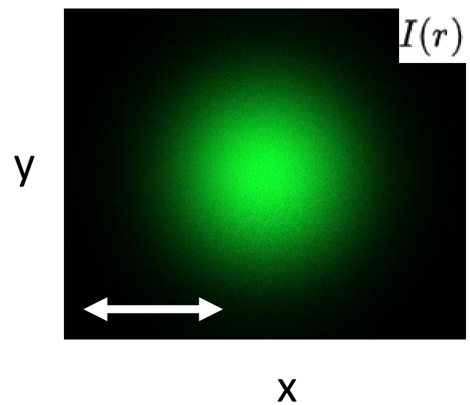
Characteristics of lasers

- Most laser beams have a Gaussian beam profile

$$\mathbf{E}(r,z) = E_0\,\hat{\mathbf{x}}\,\frac{w_0}{w(z)}\exp\left(\frac{-r^2}{w(z)^2}\right)\exp\left(-i\left(kz\right)\right) \qquad I(r,z) = I_0\left(\frac{w_0}{w(z)}\right)^2\exp\left(\frac{-2r^2}{w(z)^2}\right)$$







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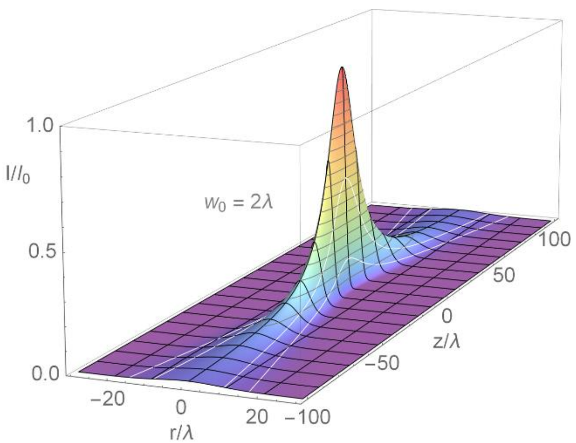
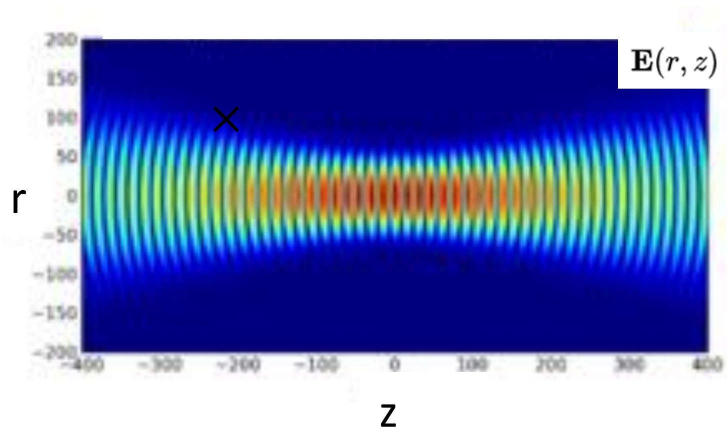
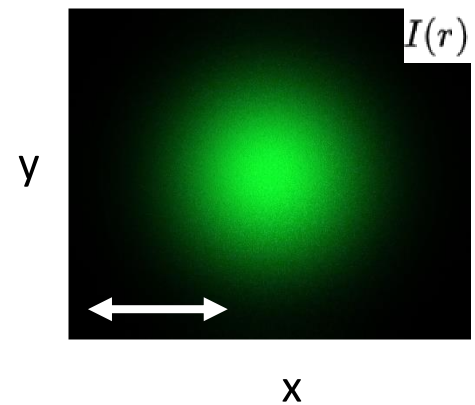
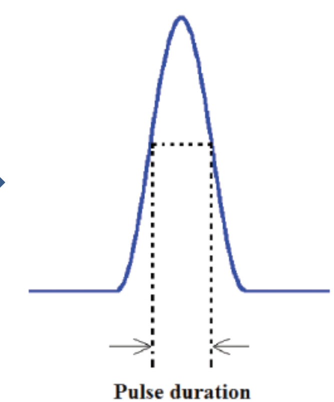




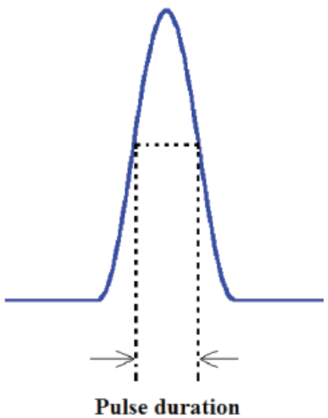


- Use of laser pulses of certain duration (for example, by modulating a continuous-wave light source)

$$I(r,z) \times \exp\left(-4\log(2)\left(\frac{t}{\tau_p}\right)^2\right)$$



Fs *vs* longer laser pulses



τ_p:pulse duration

Femto-second=10^{-15} sec
Pico- second=10^{-12} sec
Nano- second=10^{-9} sec

Chichkov *et* al, *Appl.Phys.A*. **63**, 109 (1996)

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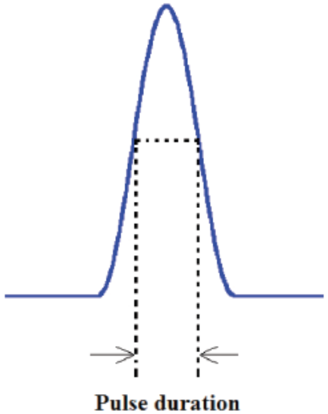

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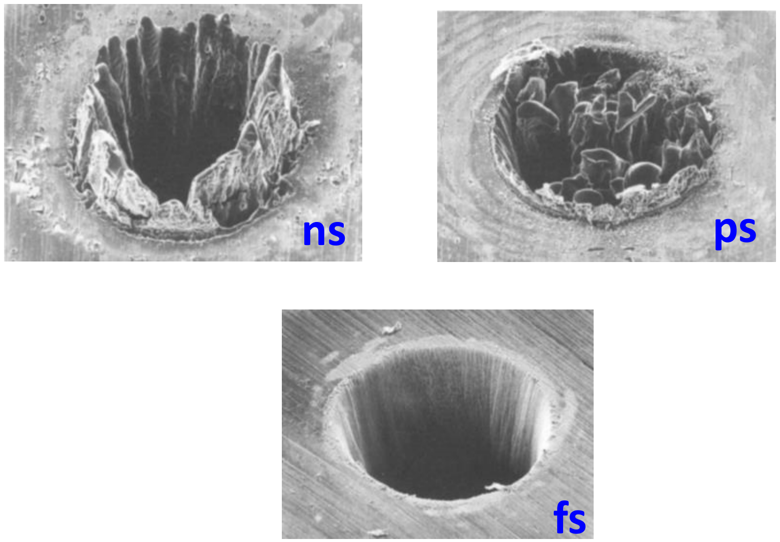
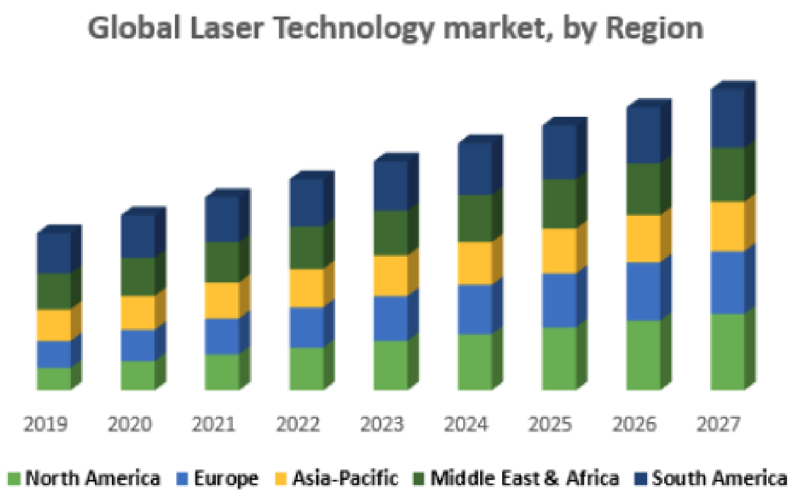
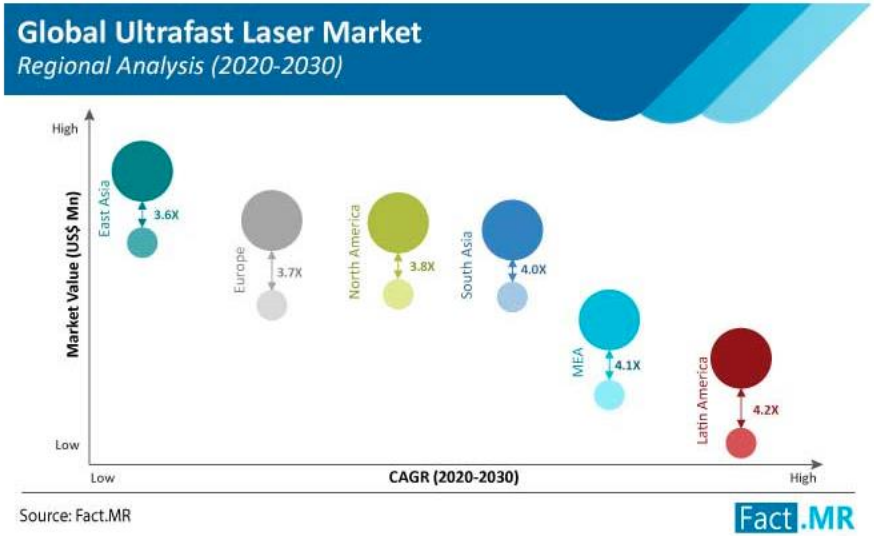


Chichkov *et* al, *Appl.Phys.A*. **63**, 109 (1996)

Impact of Laser Technology on Industrial Applications





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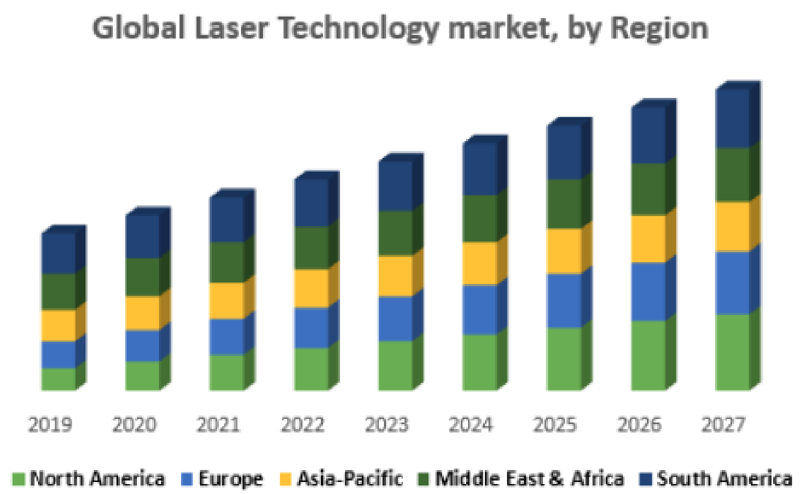
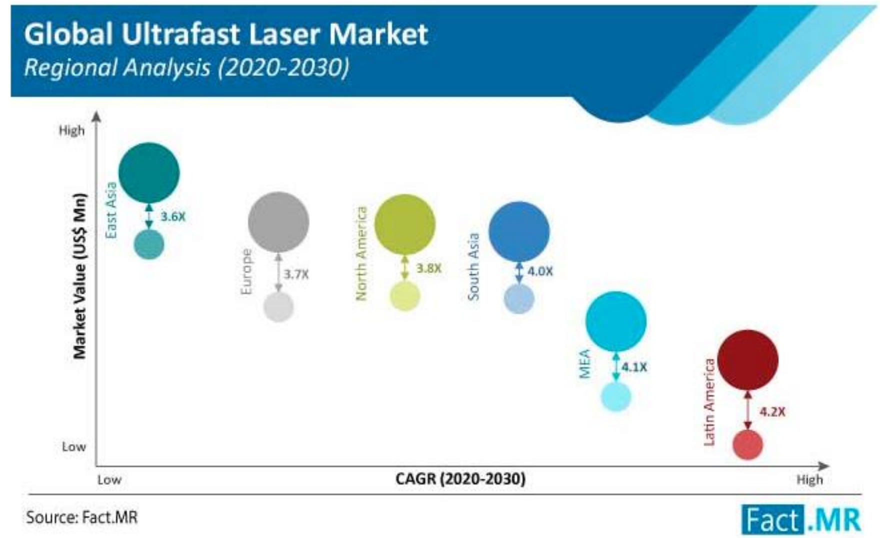
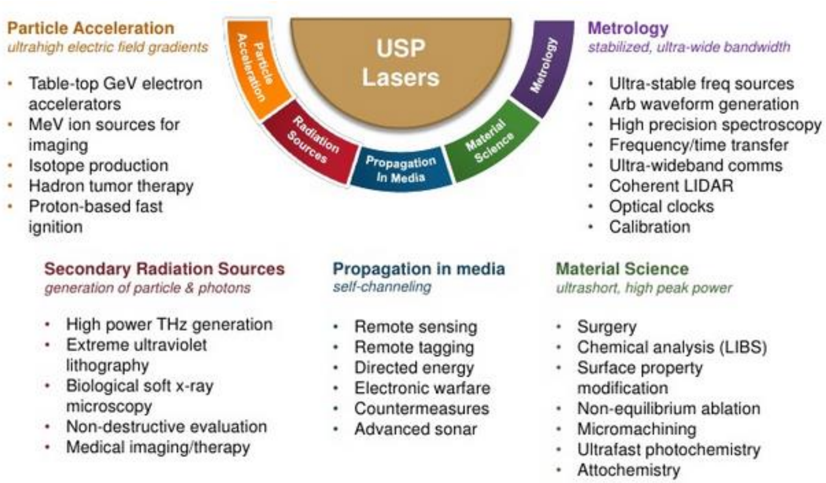
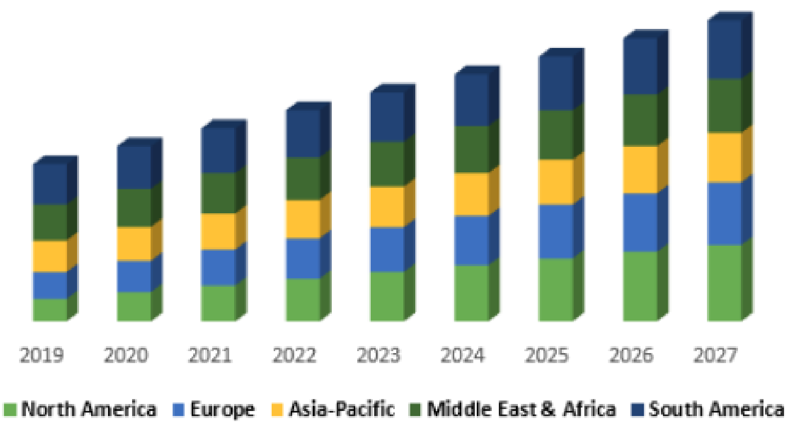


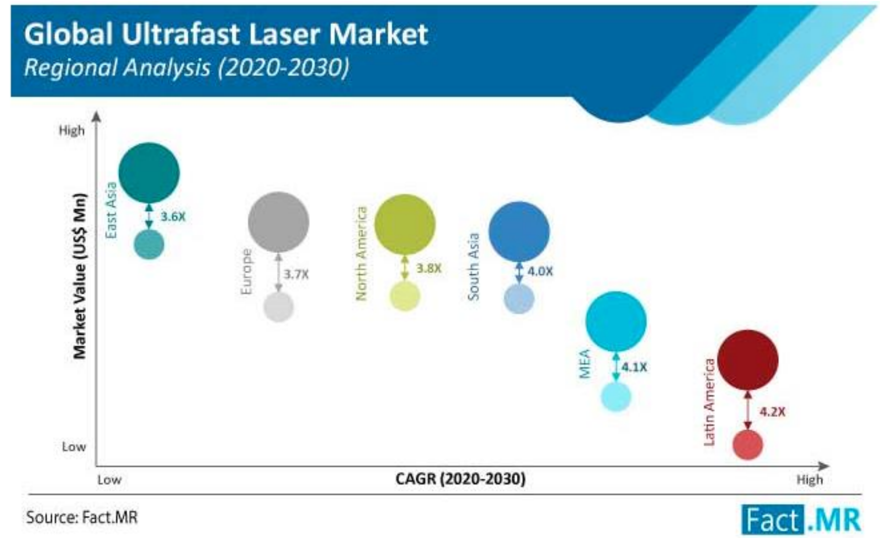




Impact of Laser Technology on Industrial Applications

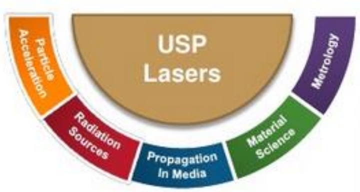
Global Laser Technology market, by Region





Particle Acceleration
ultrahigh electric field gradients

- Table-top GeV electron accelerators
- MeV ion sources for imaging
- Isotope production
- Hadron tumor therapy
- Proton-based fast ignition



Metrology
stabilized, ultra-wide bandwidth

- Ultra-stable freq sources
- Arb waveform generation
- High precision spectroscopy
- Frequency/time transfer
- Ultra-wideband comms
- Coherent LIDAR
- Optical clocks
- Calibration

Secondary Radiation Sources
generation of particle & photons

- High power THz generation
- Extreme ultraviolet lithography
- Biological soft x-ray microscopy
- Non-destructive evaluation
- Medical imaging/therapy

Propagation in media
self-channeling

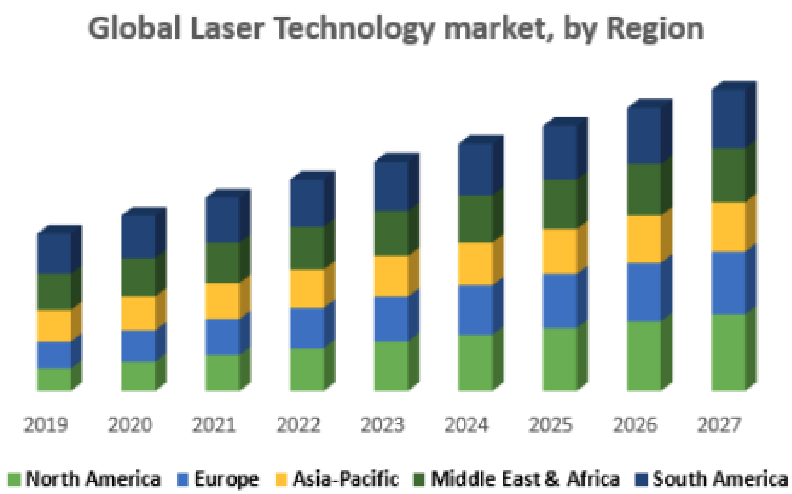
- Remote sensing
- Remote tagging
- Directed energy
- Electronic warfare
- Countermeasures
- Advanced sonar

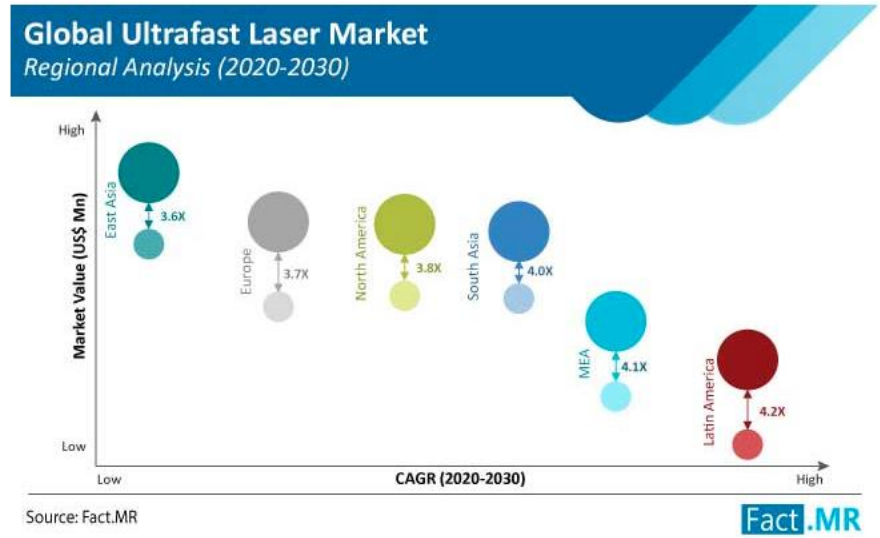
Material Science
ultrashort, high peak power

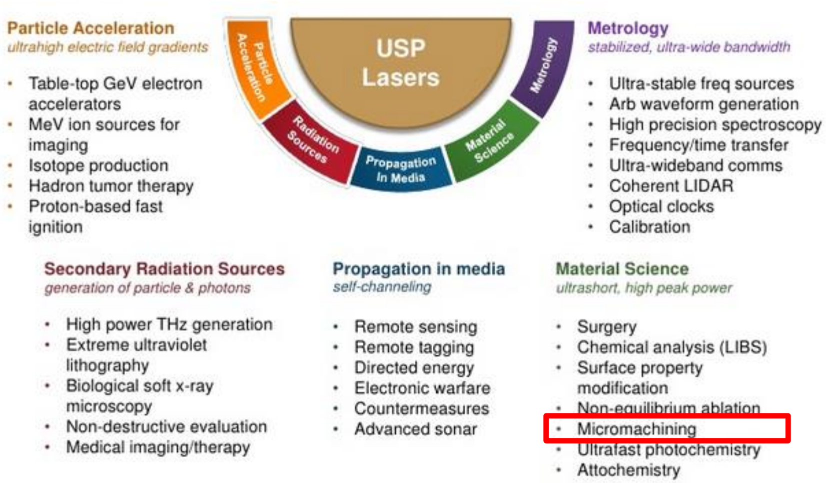
- Surgery
- Chemical analysis (LIBS)
- Surface property modification
- Non-equilibrium ablation
- Micromachining
- Ultrafast photochemistry
- Attochemistry

*The Nobel Prize in Physics 2018 was awarded……to Gerard Mourou and Donna Strickland 'for their method of generating high-intensity **ultrashort optical pulses**''*

Impact of Laser Technology on Industrial Applications



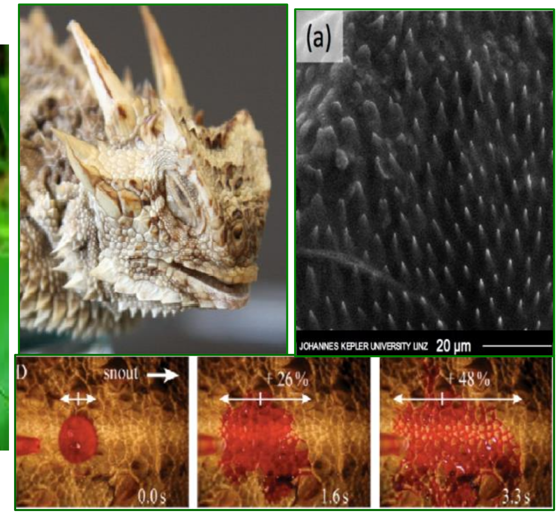




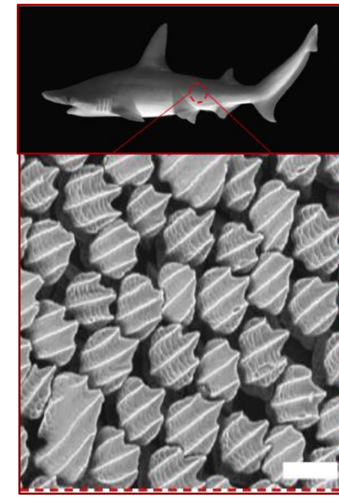
*The Nobel Prize in Physics 2018 was awarded……to Gerard Mourou and Donna Strickland 'for their method of generating high-intensity **ultrashort optical pulses**''*

Sky is the limit but…the inspiration comes mostly from the ground

Leaf
Wetting properties

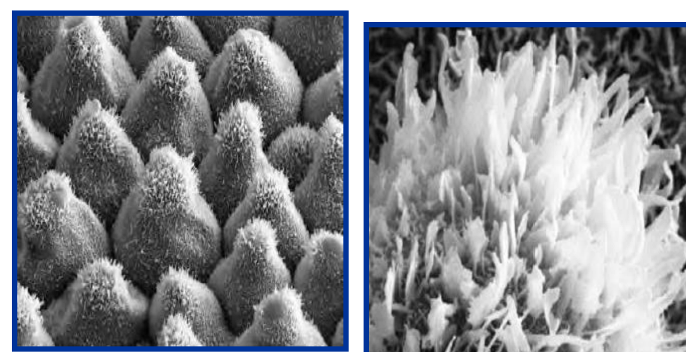


***Lizards/Bugs* Integument**
Directional Fluid Transport



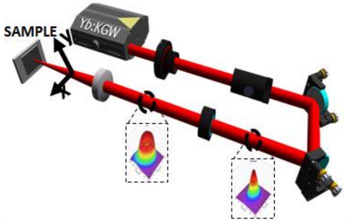
***Shark* Skin**
Low Underwater Friction

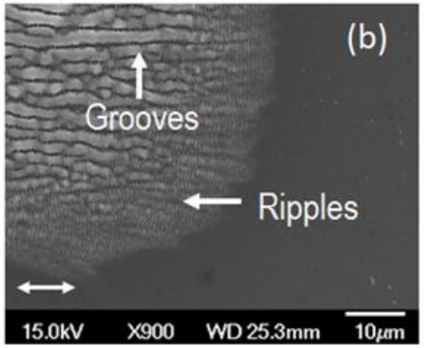
***Greta-Oto* Scales**
Antireflection



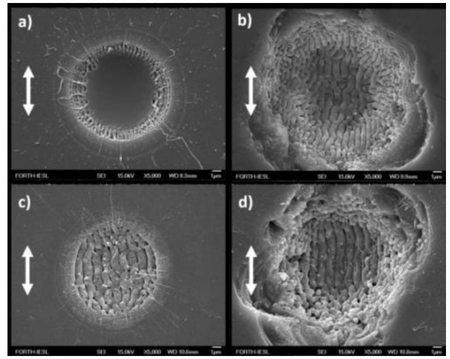
***Colocasia* Leaf** Superhydrophobicity
Water Repellence Self Cleaning

Surface modification after irradiation with ultrashort-pulsed lasers

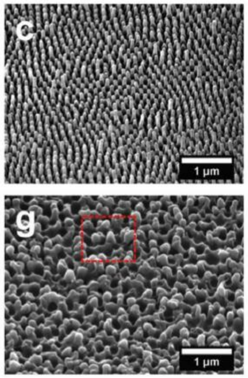


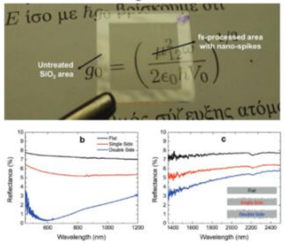


Si



SiO_2



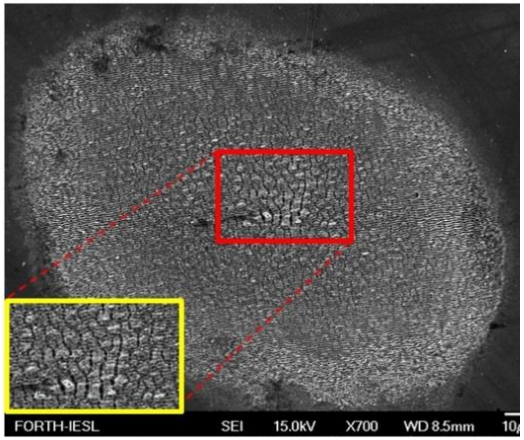


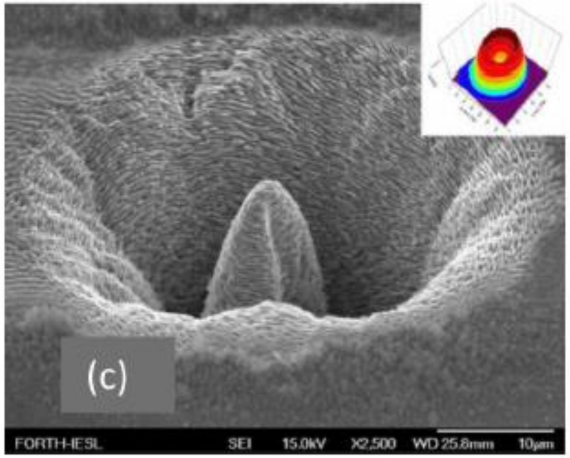
Antireflective properties

Phys.Rev.B **92**, 041405 (2015)
Phys.Rev.B **86**, 115316 (2012)

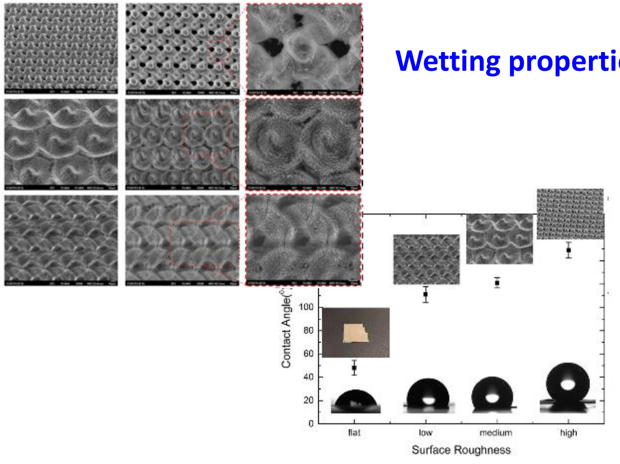
Phys.Rev.B **94**, 081305, (2016)

Adv. Mater. 1901123 (2019)





Wetting properties



100Cr6

Applied Physics A **124**:27 (2018)

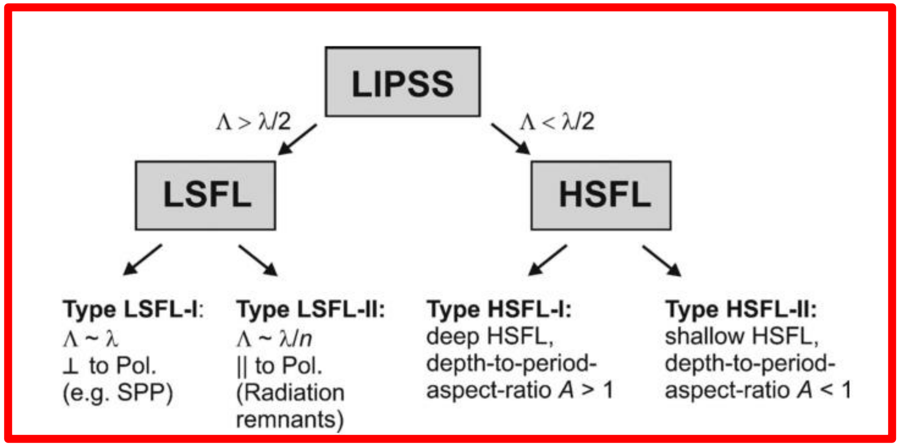
Ni (vector polarisation)

Optics Letters **40**, 5172 (2015)
J.App.Phys. **121**, 163106 (2017)

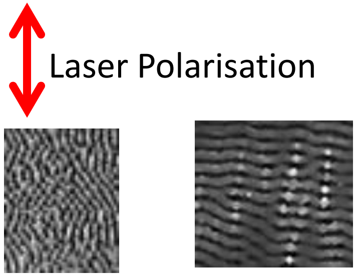
Ni (vector polarisation/scanning)

Scientific Reports **7**, 45114 (2017)

Laser-fabricated biomimetic surfaces



Bonse at al., *IEEE J.Sel.Topics in Quant. Electr.* 23, 3, (2017)



HSFL **LSFL**

Stratakis E. et al, *Mat. Science & Eng. R* **141**, 100562 (2020)

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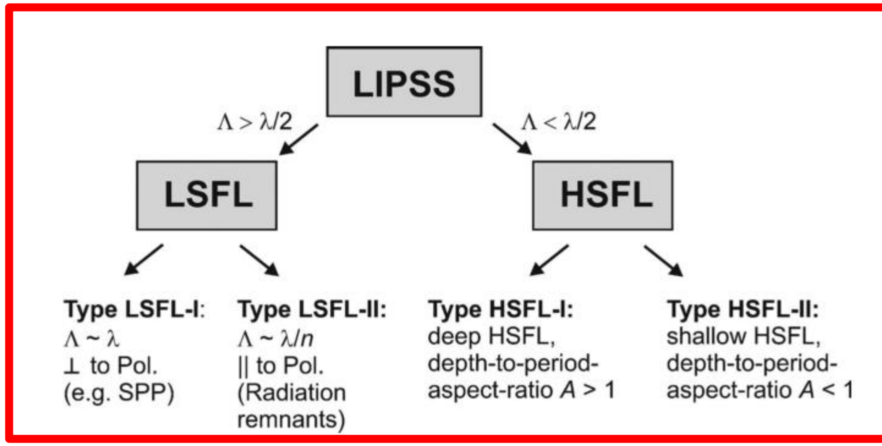

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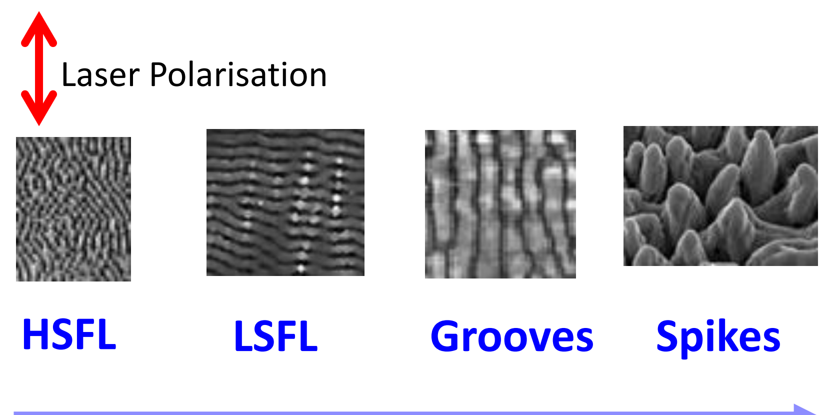

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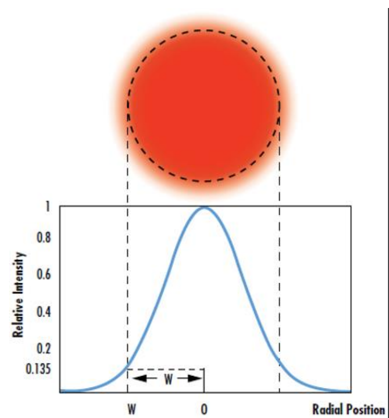
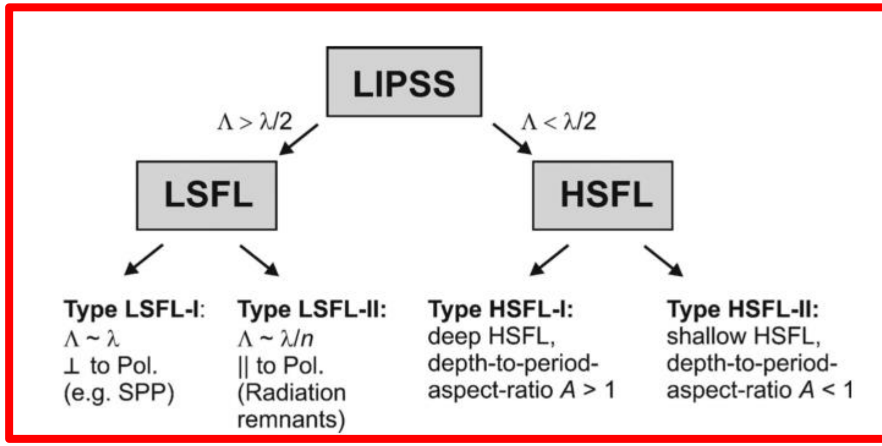


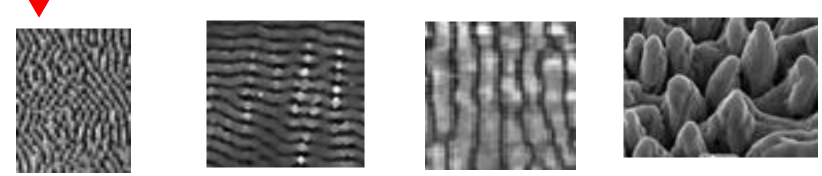
Self-organisation: the surface is irradiated using a homogeneous spatial beam profile in a spot or scanning geometry but the resulting surface topography features characteristic (quasi-)periodic surface morphologies.

Stratakis E. et al, *Mat. Science & Eng. R* **141**, 100562 (2020)



Bonse at al., *IEEE J.Sel.Topics in Quant. Electr.* 23, 3, (2017)

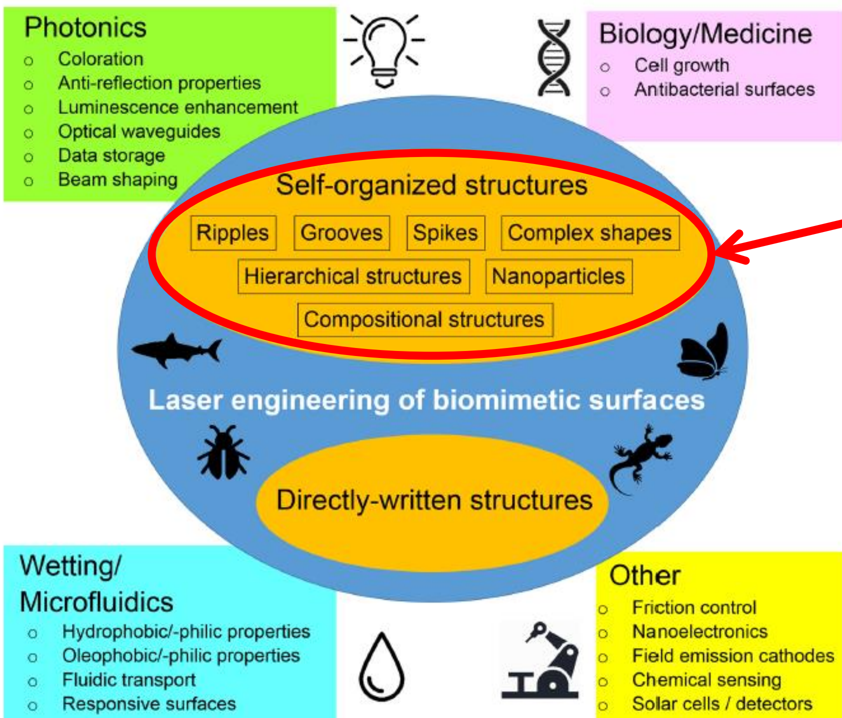
Laser Polarisation

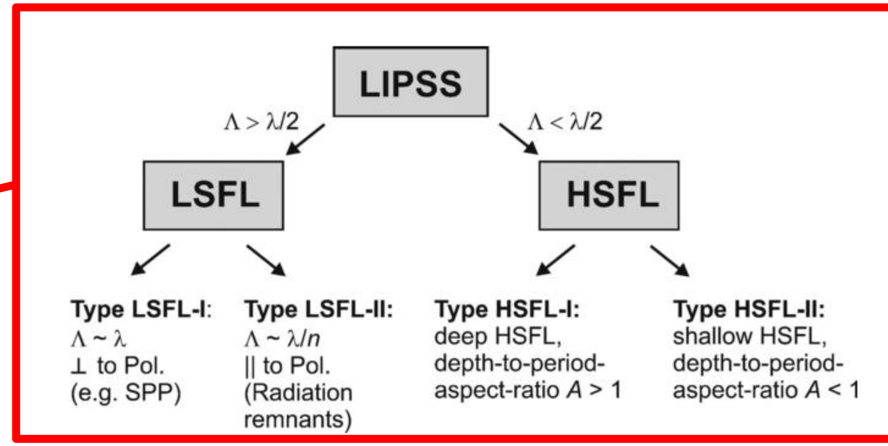


HSFL **LSFL** **Grooves** **Spikes**

Number of pulses and Fluence

Applications of laser-fabricated self-organized biomimetic surfaces





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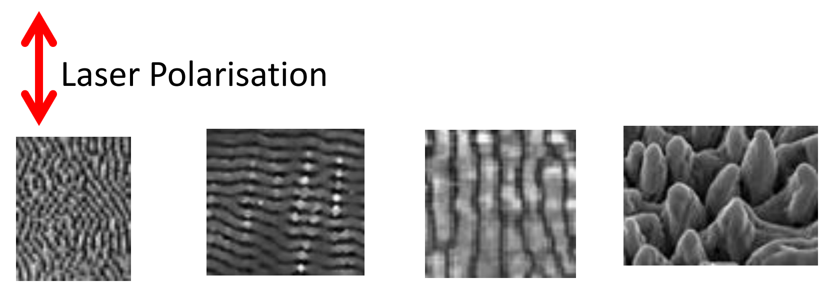

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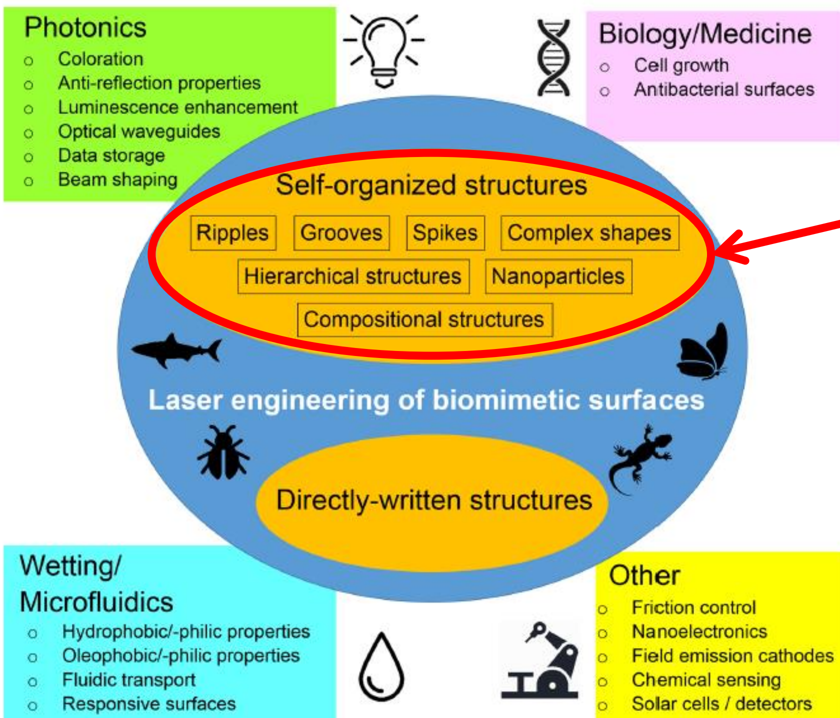

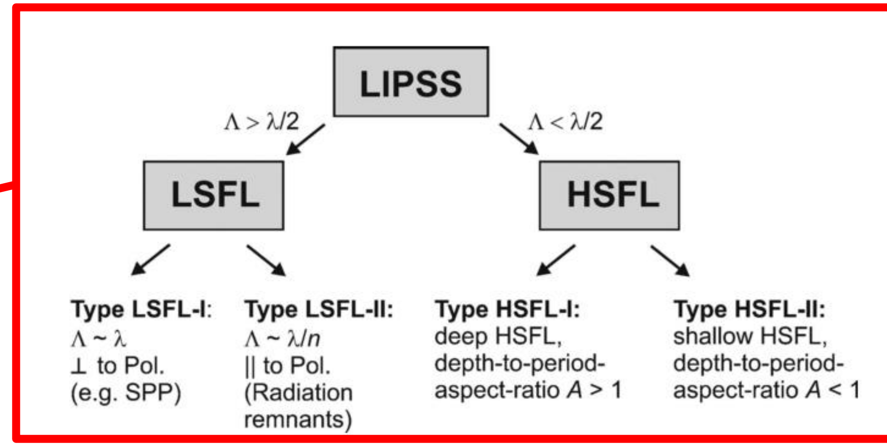

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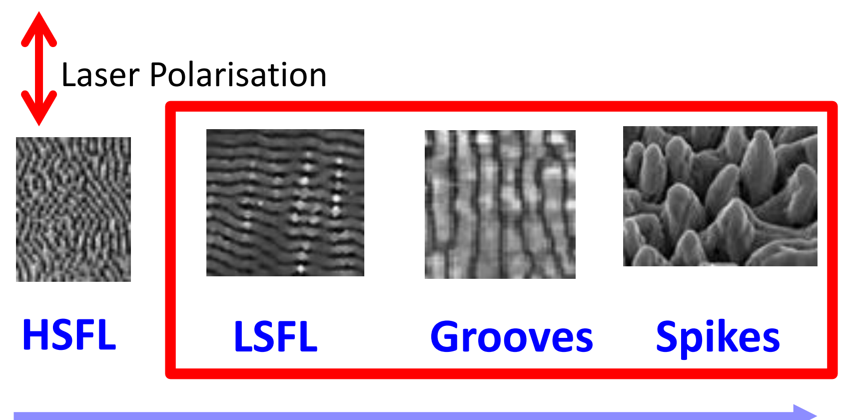

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Stratakis E. et al, *Mat. Science & Eng. R* **141**, 100562 (2020)

Control of surface pattern features with **ultrashort** pulsed lasers

Applications

?

Capability to modify properties of the target

Control of surface pattern features with **ultrashort** pulsed lasers

Applications

?

Laser-Matter Interaction fundamentals

Capability to modify properties of the target

Critical parameters that influence surface morphology

- Fluence
- Number of pulses (energy dose)
- Laser wavelength
- Laser polarisation
- Angle of Incidence
- Crystal orientation
- Pulse duration
- Material
- Thickness of material
- Temporal separation between pulses
- Shape of beam (i.e. Gaussian, etc.)

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Outline of the talk

- Multiscale physical processes following irradiation of solids with ultrashort pulses
  - *Semiconductors*

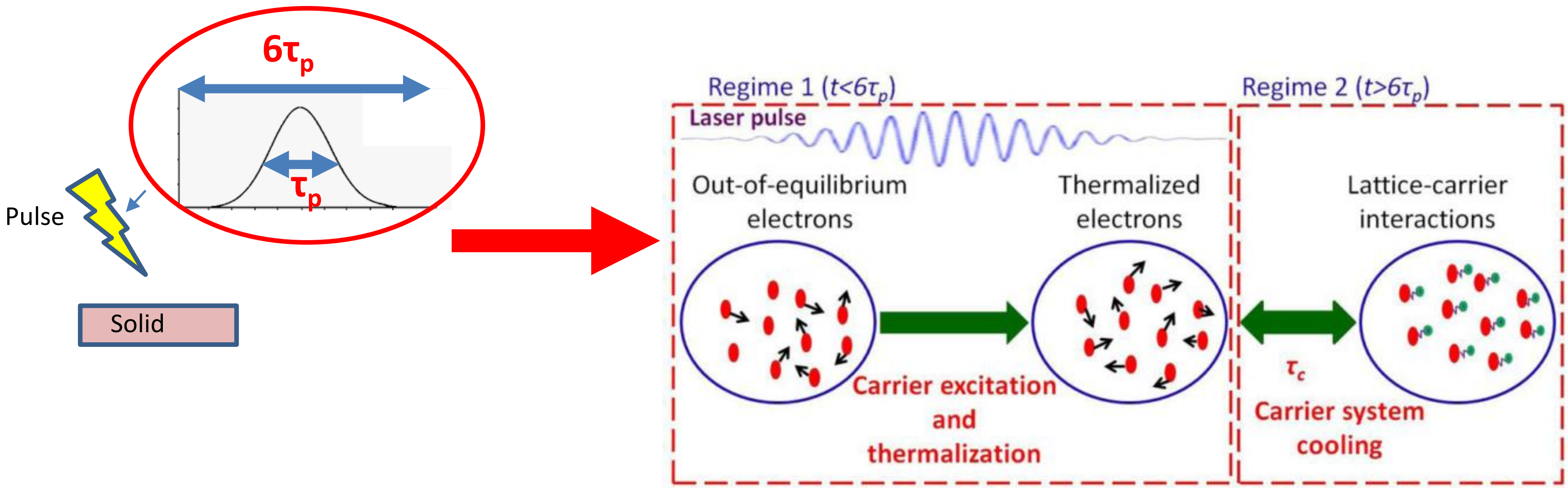
- Do we need additional processes to explain surface modification?
  - *Hydrodynamical effects*
  - *Elastic effects*

- Surface patterning through spatially varying intensity profiles
  - *Direct Laser Interfering Pattern techniques*

- Challenges

- Concluding Remarks

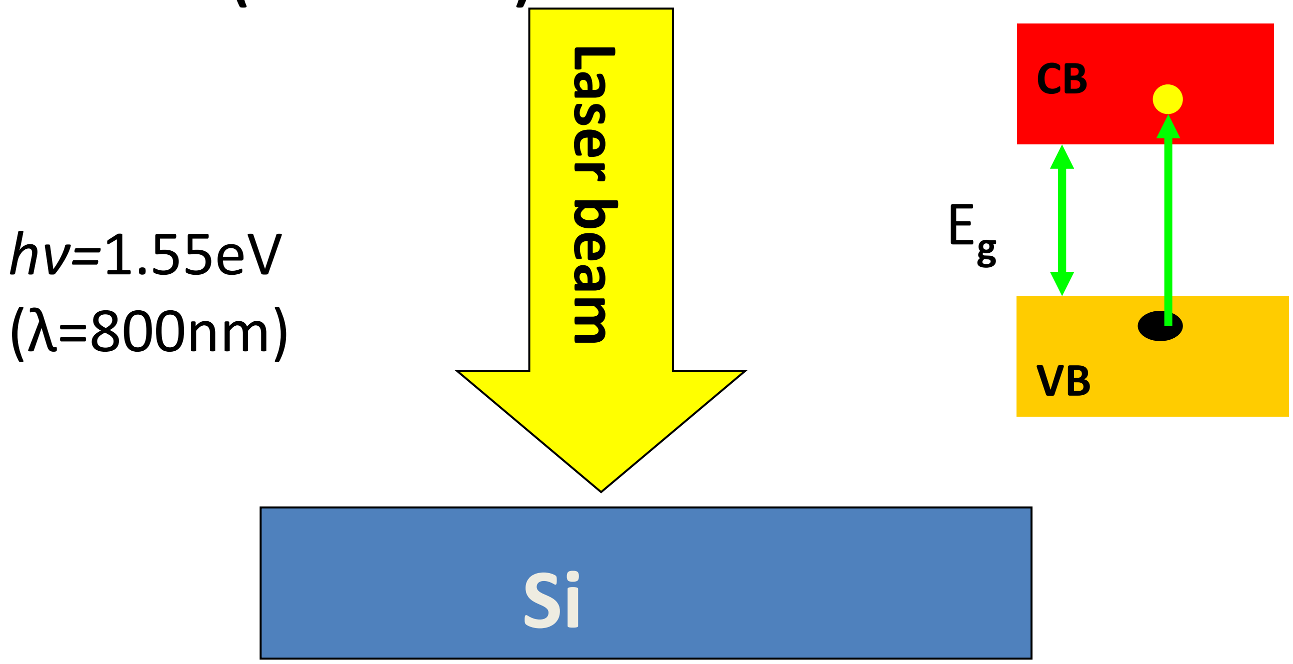
Irradiation of solids with fs pulses



Tsibidis et al, *Phy.Rev.B* **101**, 075207 (2020)

Effect of laser irradiation of semiconductors

- E_g**(300K)~1.12eV (for Silicon)**



Ultrafast electron and lattice dynamics

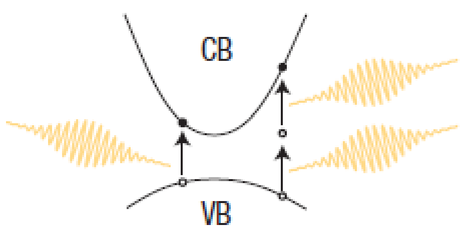
The laser-matter interaction involves four regimes

Ultrafast electron and lattice dynamics

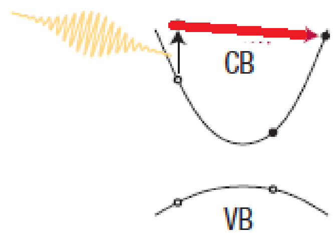
The laser-matter interaction involves four regimes

1. Carrier excitation

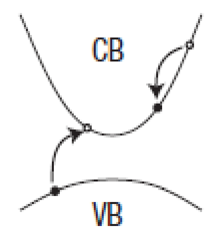
Single and two-photon absorption

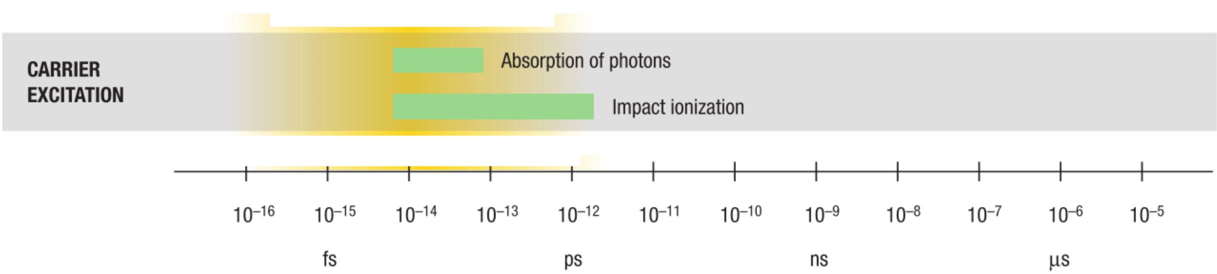


Free carrier absorption



Impact Ionisation





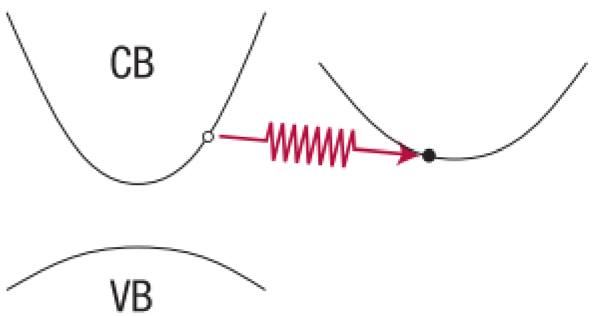
Sundaram SK and Mazur. E., *Nature Materials*, *B* **86**, 1,217(2002)

Ultrafast electron and lattice dynamics

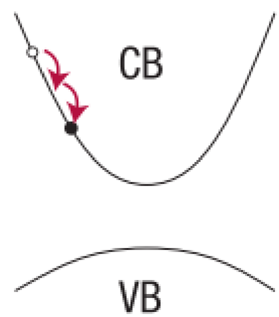
The laser-matter interaction involves four regimes

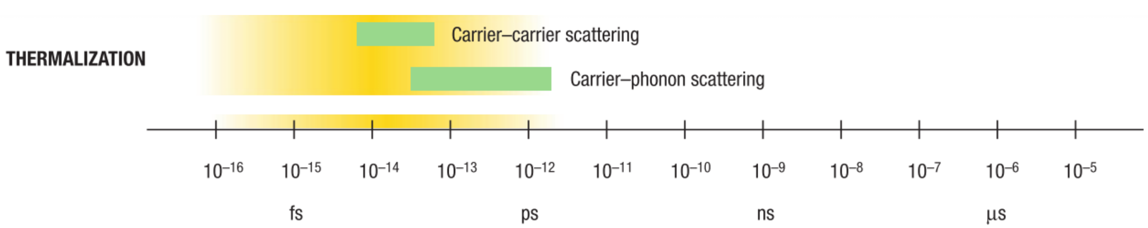
2. Thermalisation

Electron-phonon scattering



Electron-electron scattering





- *e-e* and *e-ph* scattering occur concurrently during the first few hundreds fs
- *e-ph* thermalization ends after a few ps

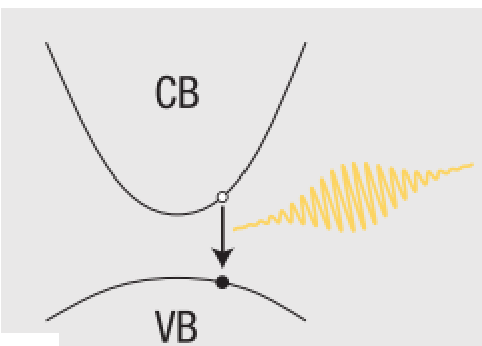
Sundaram SK and Mazur. E., *Nature Materials*, *B* **86**, 1,217(2002)

Ultrafast electron and lattice dynamics

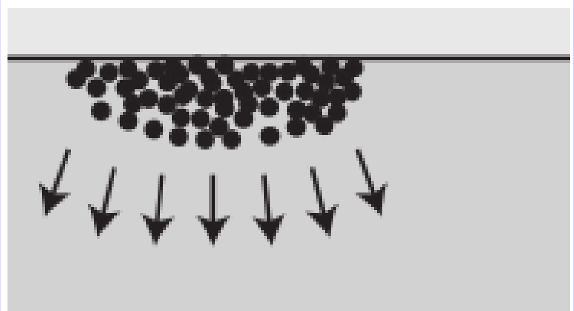
The laser-matter interaction involves four regimes

3. Carrier removal

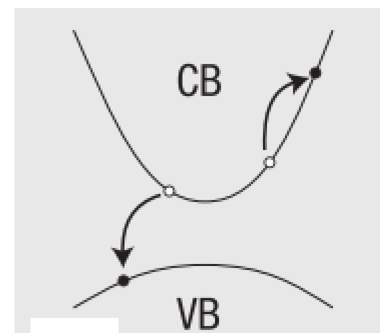
Carrier recombination

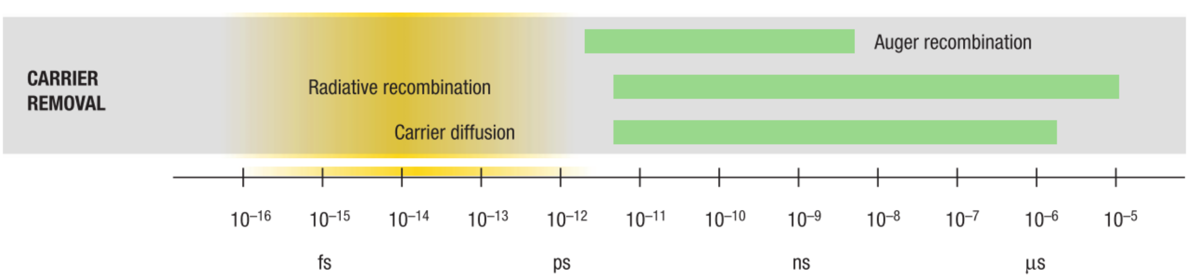


Carrier diffusion



Auger recombination





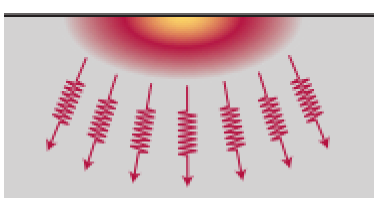
Sundaram SK and Mazur. E., *Nature Materials*, *B* **86**, 1,217(2002)

Ultrafast electron and lattice dynamics

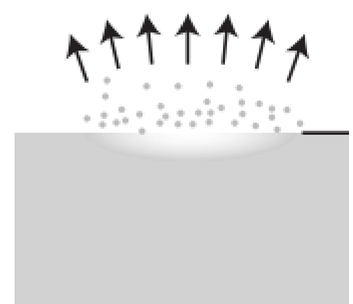
The laser-matter interaction involves four regimes

4. Thermal and structural effects

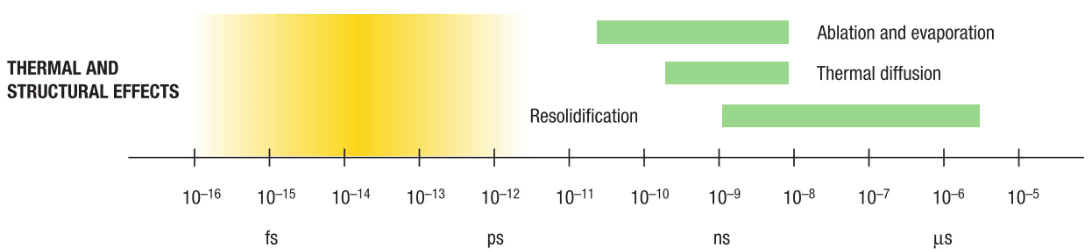
Thermal diffusion



Ablation/Evaporation



Resolidification



Sundaram SK and Mazur. E., *Nature Materials*, *B* **86**, 1,217(2002)

Theoretical Model (Semiconductors)

$$I(x,y,z=0,t)=\frac{2\sqrt{\ln 2}E_p(1-R(z=0,t))}{\sqrt{\pi}\tau_p}e^{-\left(\frac{2(x^2+y^2)}{R_0^2}\right)}e^{-4\ln 2\left(\frac{t-t_0}{\tau_p}\right)^2}$$

Laser Intensity on the surface

$$\frac{\partial I(\vec{r},t)}{\partial z}=-\alpha_{FCA}I(\vec{r},t)-\beta_{TPA}I^2(\vec{r},t)-\alpha_{SPA}I(\vec{r},t)$$

Free carrier absorption

Two photon absorption

One photon absorption

Spatial change (along z-axis) of laser Intensity

$$S(\vec{r},t)=\alpha_{FCA}I(\vec{r},t)+\alpha_{SPA}I(\vec{r},t)+\beta_{TPA}I^2(\vec{r},t)-\vec{\nabla}\cdot\vec{W}$$

$$-\frac{\partial N_e}{\partial t}\left(E_g+3k_BT_e\right)-N_e\left(\frac{\partial E_g}{\partial T_L}\frac{\partial T_L}{\partial t}+\frac{\partial E_g}{\partial N_e}\frac{\partial N_e}{\partial t}\right)$$

$$\vec{W}=\left(E_g+4k_BT_e\right)\vec{J}-(k_e+k_h)\vec{\nabla}T_e$$

$$\vec{J}=-D\left(\vec{\nabla}N_e+\frac{N_e}{2k_BT_e}\vec{\nabla}E_g+\frac{N_e}{2T_e}\vec{\nabla}T_e\right)$$

Source Term (due to free carrier absorption, single and multiphoton-absorption, carrier density change, Band gap energy change)

Electron diffusion

Electron phonon coupling

$$C_c\frac{\partial T_c}{\partial t}=\vec{\nabla}\cdot\left(K_e\vec{\nabla}T_c\right)-\frac{C_c}{\tau_e}(T_c-T_L)+S(\vec{r},t)$$

$$C_L\frac{\partial T_L}{\partial t}=\vec{\nabla}\cdot\left(K_L\vec{\nabla}T_L\right)+\frac{C_c}{\tau_e}(T_c-T_L)$$

Two Temperature Model

Auger recombination

$$\frac{\partial N_e}{\partial t}=\frac{\beta_{TPA}}{2\hbar\omega_L}I^2(\vec{r},t)+\frac{\alpha_{SPA}}{\hbar\omega_L}I(\vec{r},t)-\gamma N_e^{\ 3}+\theta N_e-\vec{\nabla}\cdot\vec{J}$$

Impact ionisation

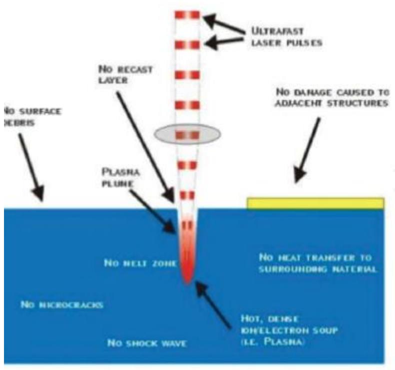
Change of carrier density

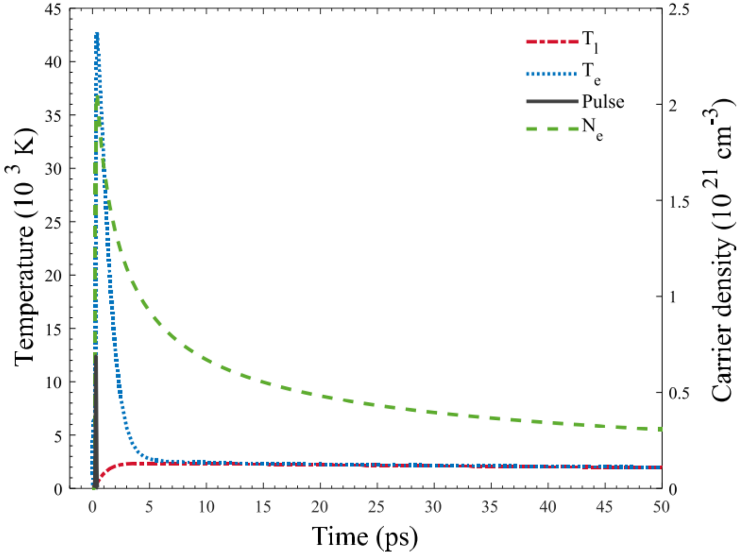
Van Driel HM., *Phys. Rev. B* ***35***, 8166 (1987)

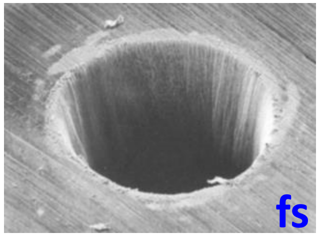
Tsibidis GD et al., *Phys. Rev. B* 86, 115316 (2012)

Fs *vs* longer laser pulses

Short pulse (τ_p< ps)





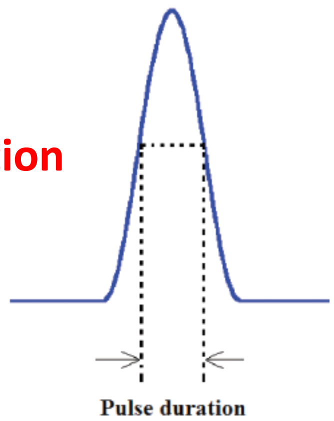


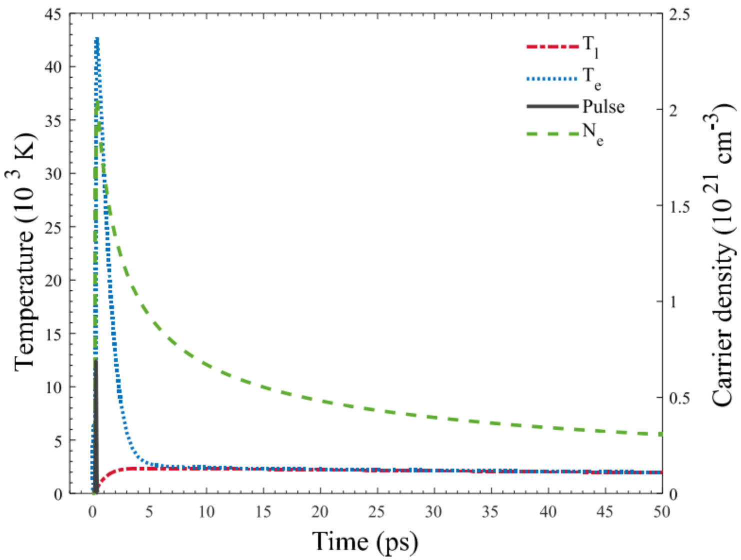
Chichkov *et* al, *Appl.Phys.A*. **63**, 109 (1996)

Tsibidis GD et al., *Phys. Rev. B* 86, 115316 (2012)

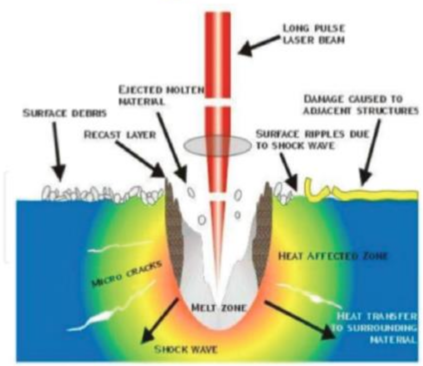
Fs *vs* longer laser pulses

τ_p**:pulse duration**

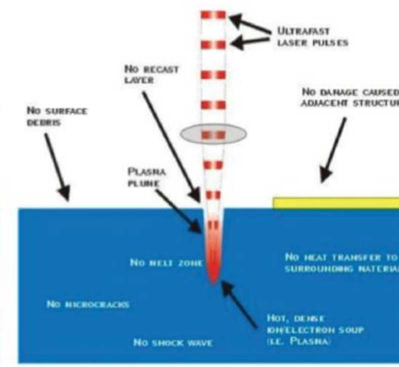


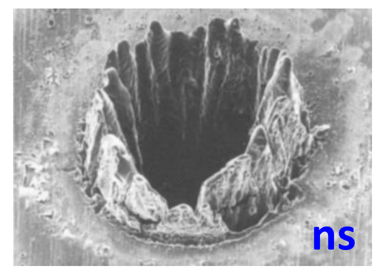


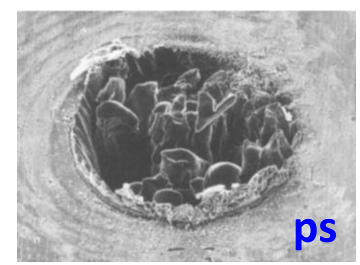
Long pulse **(τ_p ~ns)**

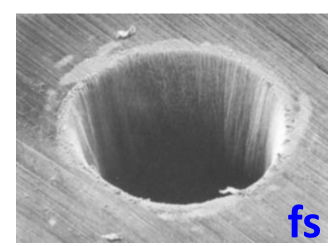


Short pulse **(τ_p< ps)**





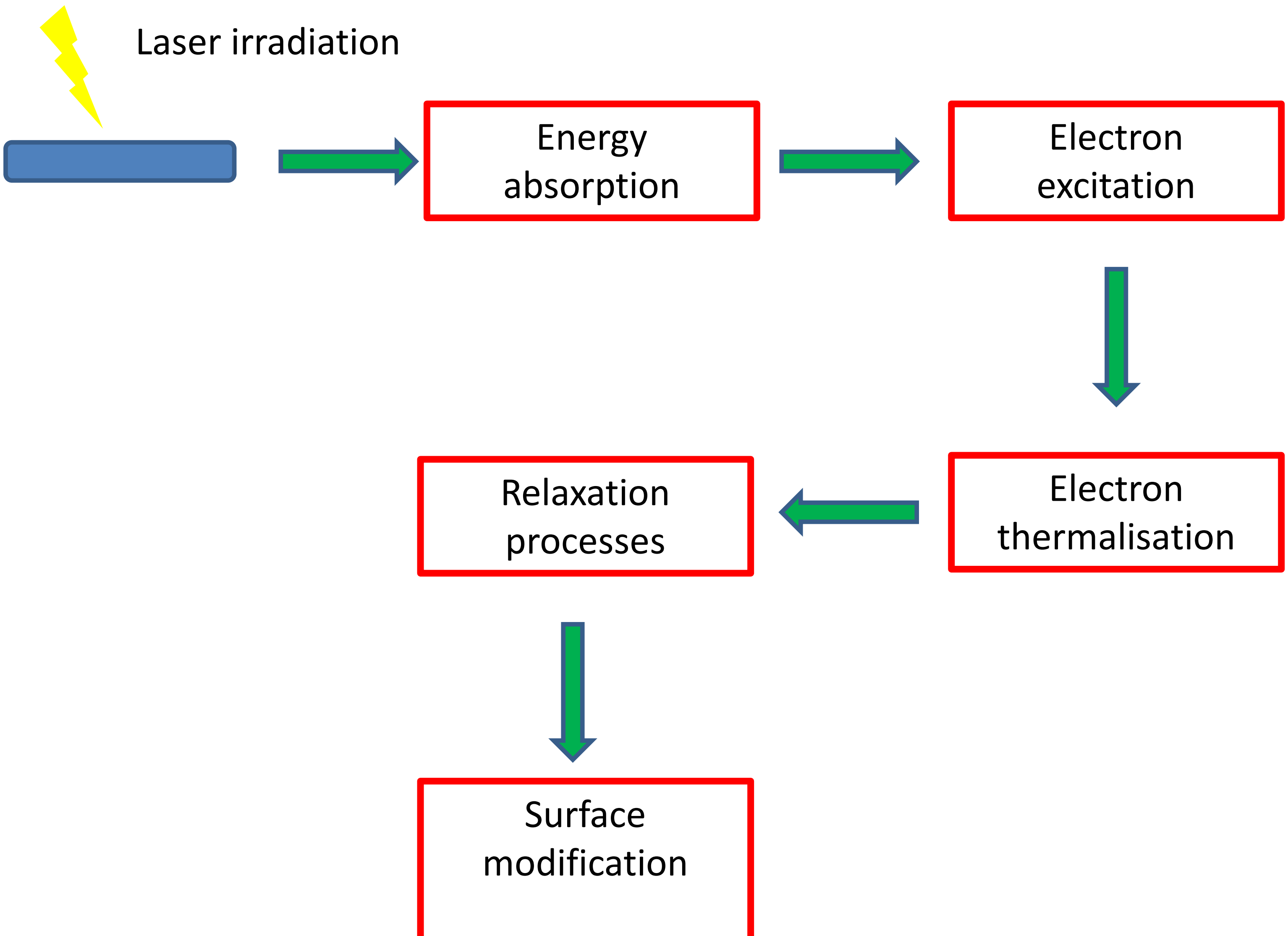




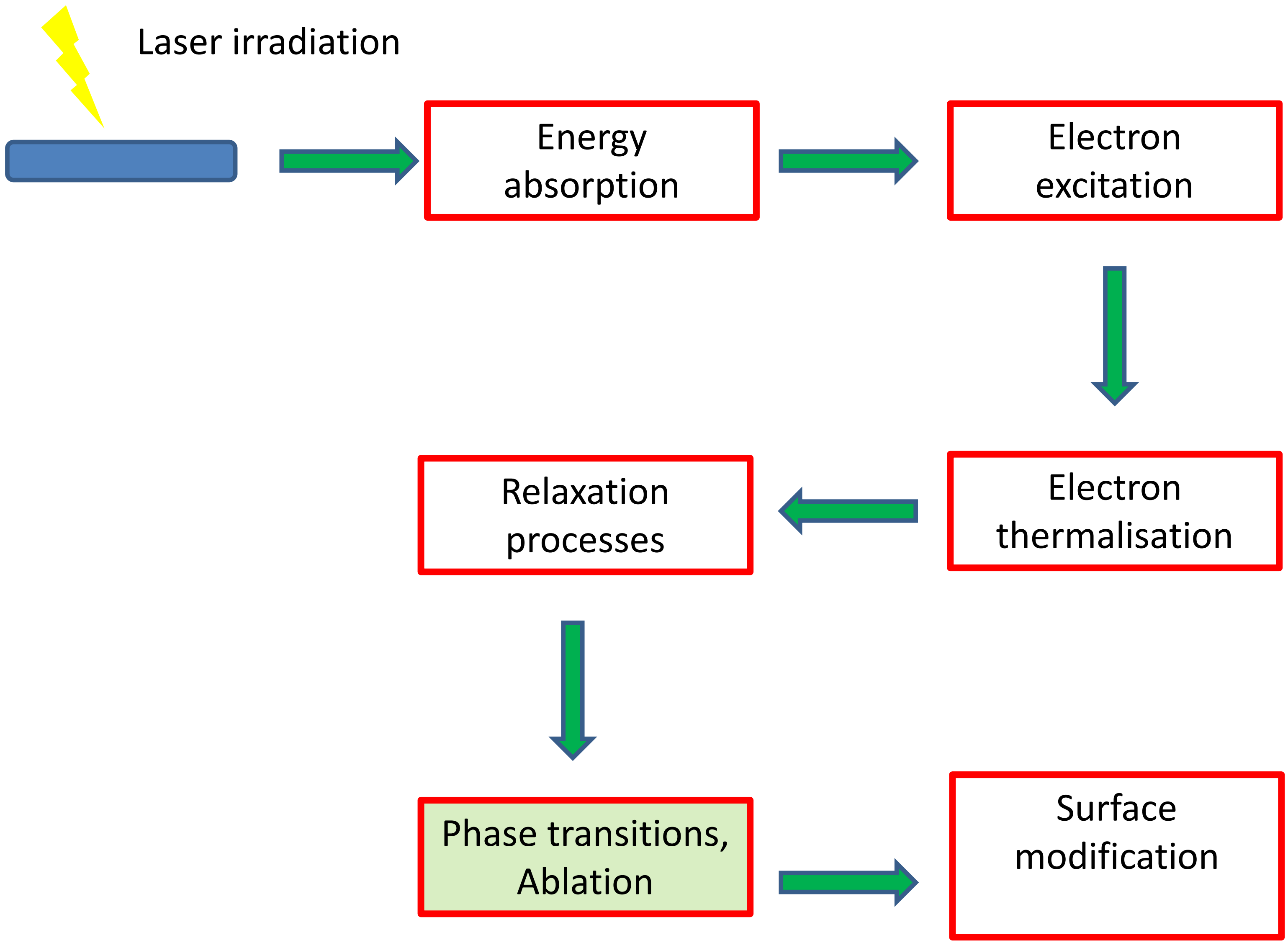
Chichkov *et* al, *Appl.Phys.A*. **63**, 109 (1996)

Tsibidis GD et al., *Phys. Rev. B* 86, 115316 (2012)

Missing link from the multiscale physics model



Missing link from the multiscale physics model



Blending relaxation processes with Fluid dynamics

Molten material dynamics/fluid transport (Hydrodynamics) for incompressible fluid (i.e. $\vec{\nabla}\cdot\vec{u}=0$)

$$\rho_0\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\vec{\nabla}\vec{u}\right)=\vec{\nabla}\cdot\left(-P+\mu(\vec{\nabla}\vec{u})+\mu(\vec{\nabla}\vec{u})^T\right)$$

: Navier Stokes equations

P: Total pressure: surface tension +Recoil Pressure

$\vec{u}$: velocity of fluid

μ: viscosity

ρ_0: density

$$P_r=0.54P_0 exp\left(L_v\frac{T_L^{(S)}-T_{boiling}}{R_G T_L^{(S)}T_{boiling}}\right)$$

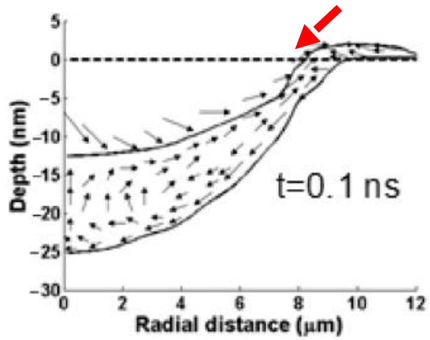
Surface tension variance leads to the development of clockwise flow which eventually causes surface depression in regions of higher pressure

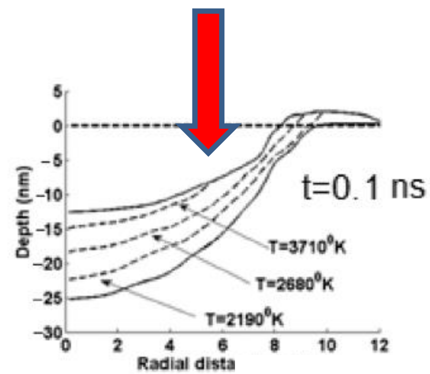
Boundary conditions

(Thermocapillary conditions)

$$\frac{\partial u}{\partial z}=-\sigma/\mu\frac{\partial T_L}{\partial x}$$

$$\frac{\partial v}{\partial z}=-\sigma/\mu\frac{\partial T_L}{\partial y}$$





T_L: Lattice temperature

σ: surface tension

Shallow water equation

$$\frac{\partial H(\vec{r},t)}{\partial t}+\vec{\nabla}\cdot\left(H(\vec{r},t)\vec{u}\right)=0$$

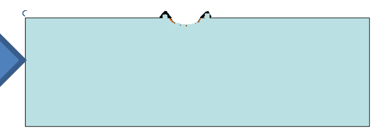
Tsibidis GD et al., *Phys. Rev. B* **86**, 115316 (2012)

Surface patterning and electrodynamical effects (what is the role?)

N=1

Flat surface → Energy absorption → Electron excitation+relaxation process+heat transfer

→ Phase transition+ melting → Resolidification →



Tsibidis GD et al., *Phys. Rev. B* **86**, 115316 (2012)

Surface patterning and electrodynamical effects

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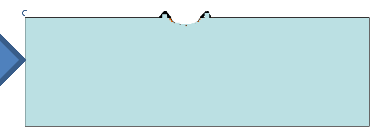
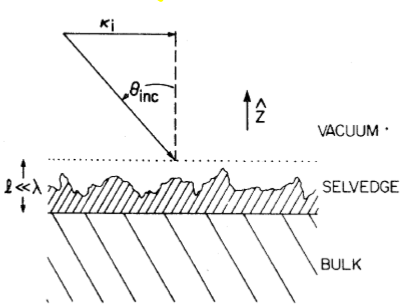
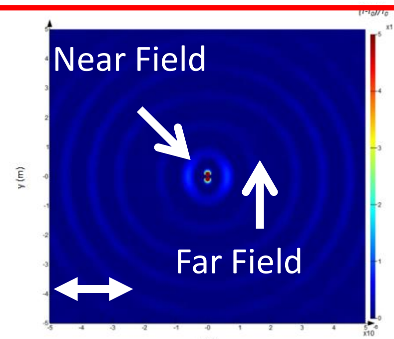
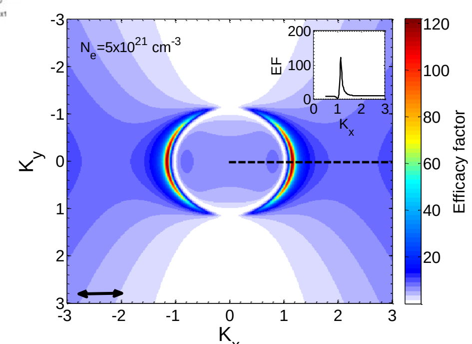


N=2





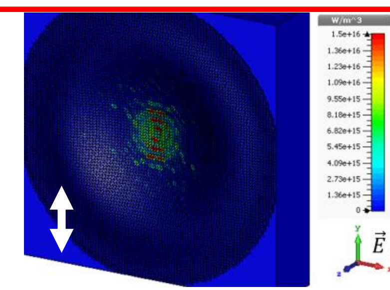
Simulations (off a hole) in metals



Simulations (off a corrugated surface)

Sipe JE et al., *Phys Rev B* **27**, 1141 (1983)

SPP excitation?



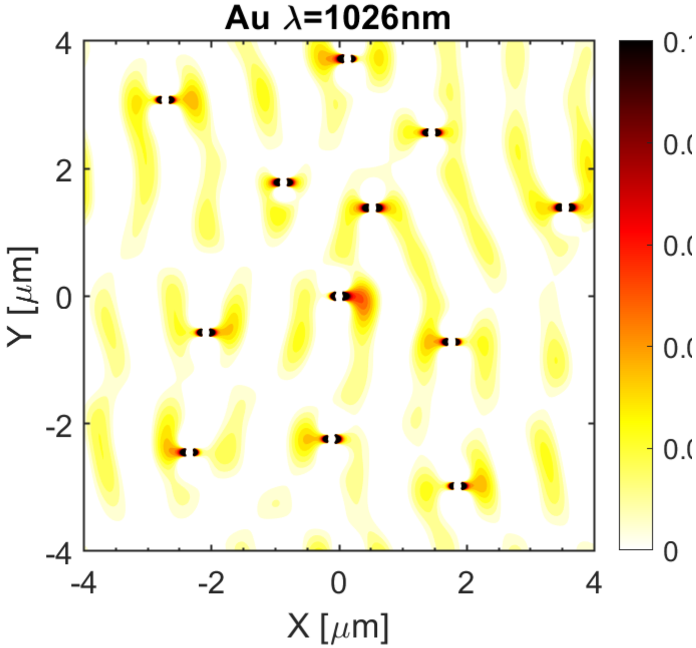
Simulations (from a crater)

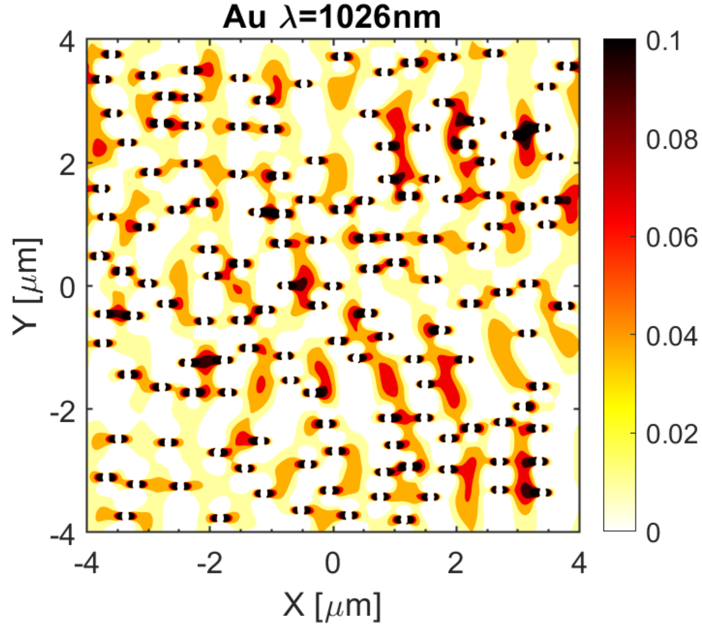
(In collaboration with M.Kafesaki's Group)

Tsibidis GD and Stratakis E., *Scientific Reports* **10**, 8675 (2020)

Tsibidis GD and Stratakis E., *J.Appl.Phys.*, **97**, 013538 (2005)

EM effects

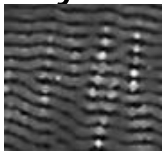




Data procuded from P.Lingos

Our Model for ‘Ripples’ formation

Introduction of Periodic Energy Deposition (due to interference of the incident beam with SPP) into Hydrodynamics



LSFL

Si, 200 fs, λ=800 nm, F = 0.3 J/cm²

Modules of the model

- Electrodynamics: SP excitation + interference with incident beam.
- Heat transfer: carrier-lattice thermalisation and heat conduction.
- Hydrodynamics: Marangoni related effects.
- Resolidification.

Advantages of the model

- Multiscale – description.
- Coupling of EM with hydrodynamical phenomena.
-
-

1. Surface plasmon wave excitation (Electrodynamics)

2. Carrier-lattice relaxation process and heat transfer

$$C_c\frac{\partial T_c}{\partial t} = \vec{\nabla}\cdot((k_e+k_h)\vec{\nabla}T_c) - \frac{C_c}{\tau_e}(T_c - T_l) + S(\vec{r},t),$$

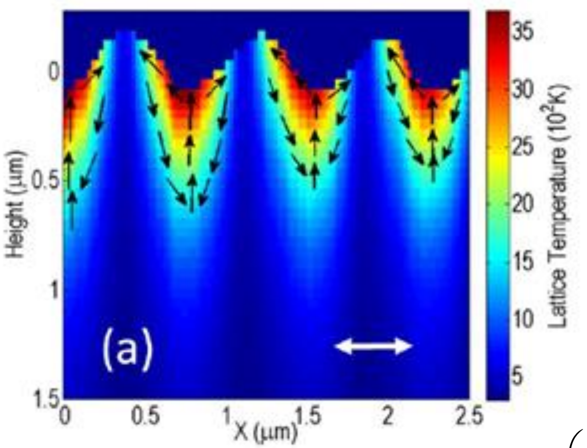
$$C_l\frac{\partial T_l}{\partial t} = \vec{\nabla}\cdot(K_l\vec{\nabla}T_l) + \frac{C_c}{\tau_e}(T_c - T_l),$$

$$\frac{\partial N}{\partial t} = \frac{\alpha}{h\nu}\Omega I(\vec{r},t) + \frac{\beta}{2h\nu}\Omega^2 I^2(\vec{r},t) - \gamma N^3 + \theta N - \vec{\nabla}\cdot\vec{J}$$

$$\Omega = \frac{1-R(T_l)}{\cos\varphi}.$$

3. Molten material dynamics/fluid transport (Hydrodynamics)

$$\rho_L^{(m)}\left(\frac{\partial\vec{u}}{\partial t} + \vec{u}\cdot\vec{\nabla}\vec{u}\right) = \vec{\nabla}\cdot\left(-P\mathbf{1} + \mu\left(\vec{\nabla}\vec{u}\right) + \mu\left(\vec{\nabla}\vec{u}\right)^T\right)$$



Simulation

Tsibidis GD et al., *Phys. Rev. B* **86**, 115316 (2012)

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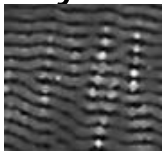

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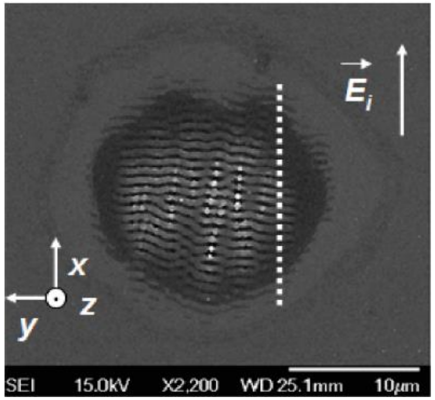

1. Surface plasmon wave excitation (Electrodynamics)

Corrugation dependent SP wavelength

2. Carrier-lattice relaxation process and heat transfer

$$C_c\frac{\partial T_c}{\partial t} = \vec{\nabla}\cdot((k_e+k_h)\vec{\nabla}T_c) - \frac{C_c}{\tau_e}(T_c - T_l) + S(\vec{r},t),$$

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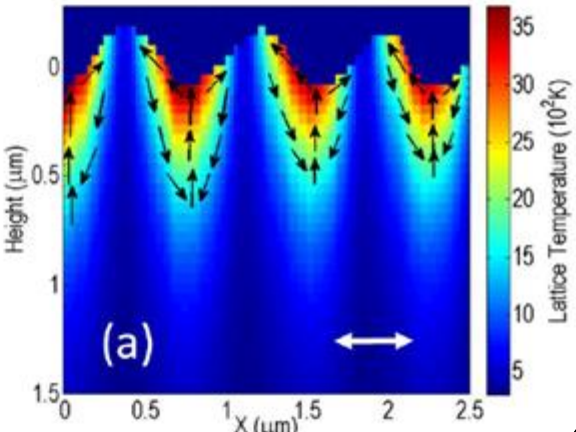
Advantages of the model

- Multiscale – description.
- Coupling of EM with hydrodynamical phenomena.



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Simulation

Tsibidis GD et al., *Phys. Rev. B* **86**, 115316 (2012)

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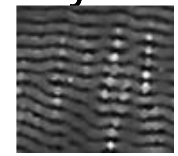

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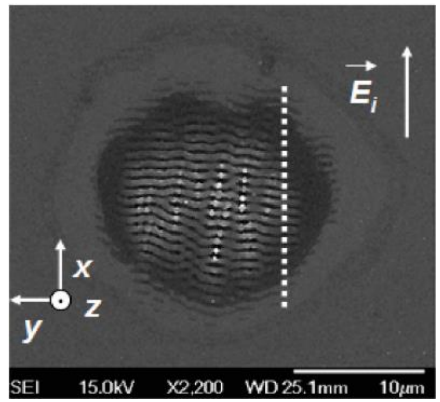

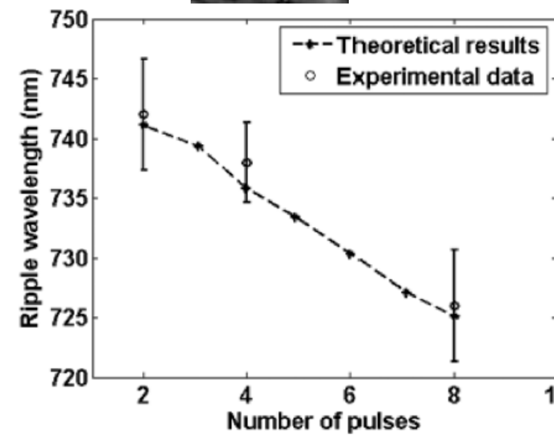

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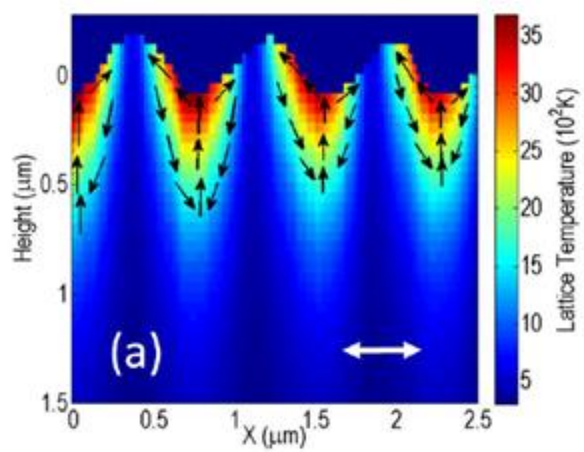
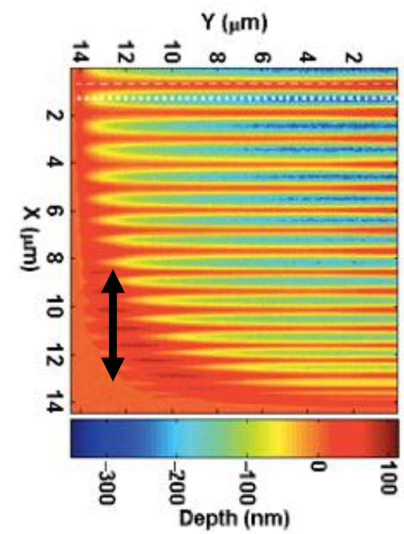




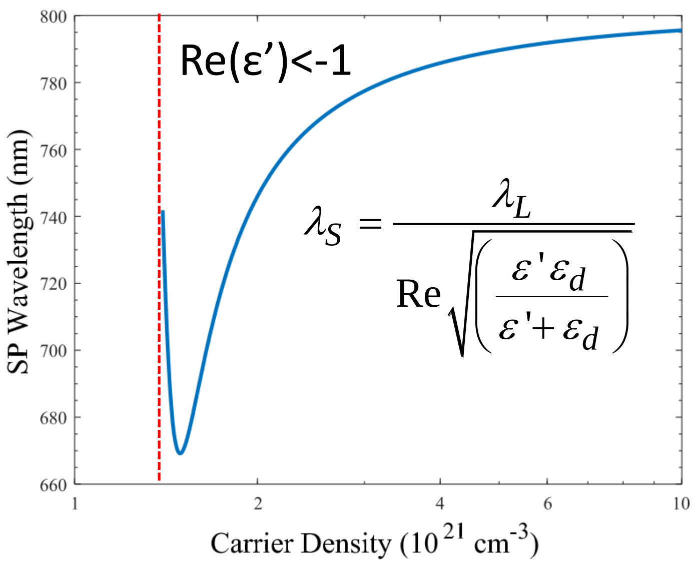
Simulation

Tsibidis GD et al., *Phys. Rev. B* **86**, 115316 (2012)

Surface plasmon excitation?

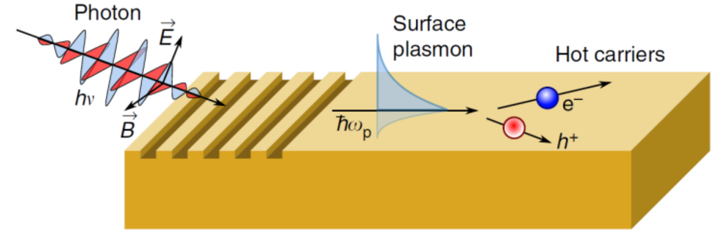
For approximately flat surface

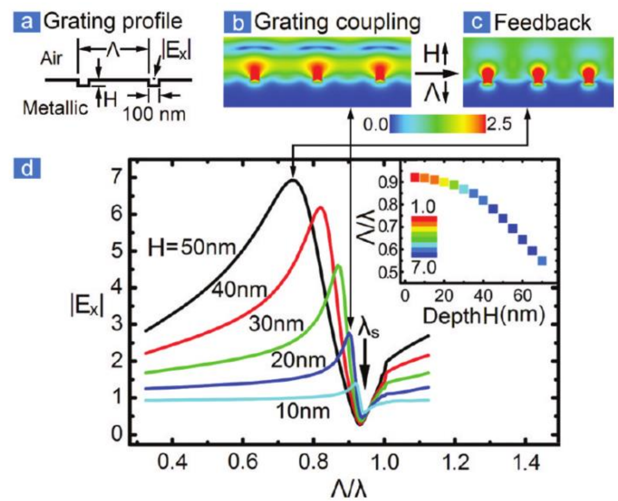
$$\varepsilon' = \varepsilon_{un} - \frac{e_c{}^2 N_c}{m_r m_e \varepsilon_0 \omega_L{}^2} \frac{1}{\left(1+i\frac{1}{\omega_L \tau_c}\right)}$$



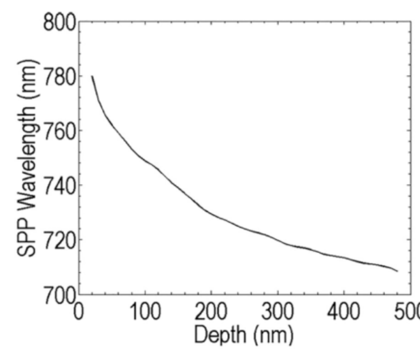
Tsibidis GD et al., *Phys. Rev. B* **86**, 115316 (2012)
Tsibidis GD et al., *Appl. Phys. A* **114**, 57 (2014)
Margiolakis et al, *Phys. Rev. B* **98,** 224103 (2018)

For corrugated (periodic topography)





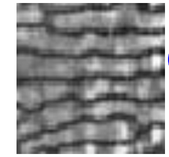
Huang et al., *ACS Nano*, **3** (12) 4062 (2019)



Tsibidis GD et al., *J. App.Phys.* **121**, 163106 (2017)

Our Model for 'Ripples-Groove' formation

Introduction of Periodic Energy Deposition (due to interference of the incident beam with SPP) into Hydrodynamics



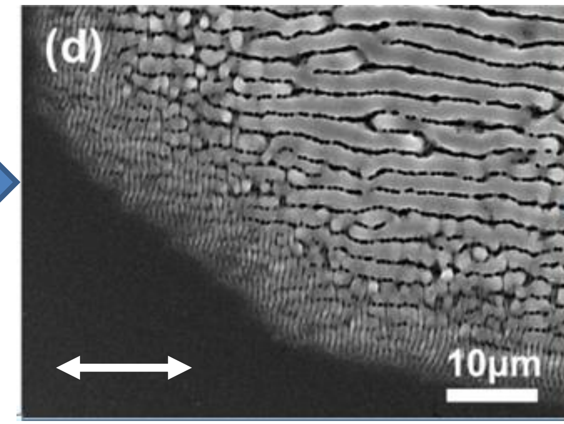
Grooves

Si, 200 fs, λ=800 nm, F = 0.3 J/cm^2

Modules of the model

- Electrodynamics: SP excitation + interference with incident beam.
- Heat transfer: carrier-lattice thermalisation and heat conduction.
- Hydrodynamics: Marangoni related effects.
- Resolidification.

At moderately higher fluences or larger number of pulses



Advantages of the model

- Multiscale – description.
- Coupling of EM with hydrodynamical phenomena.

Our Model for 'Ripples-Groove' formation

Introduction of Periodic Energy Deposition (due to interference of the incident beam with SPP) into Hydrodynamics

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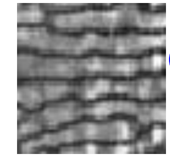
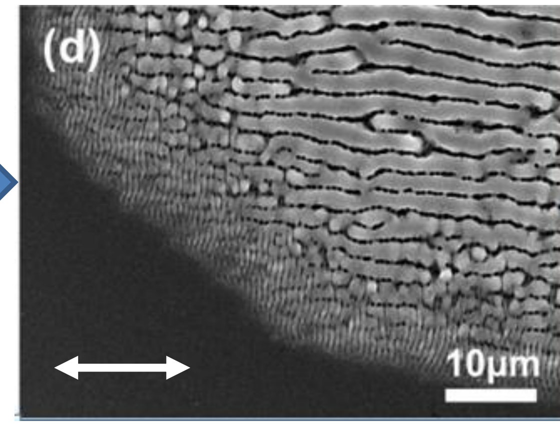


Grooves



At moderately higher fluences or larger number of pulses

Modules of the model

- Electrodynamics: SP excitation + interference with incident beam.
- Heat transfer: carrier-lattice thermalisation and heat conduction.
- Hydrodynamics: Marangoni related effects.
- Resolidification.

Advantages of the model

- Multiscale – description.
- Coupling of EM with hydrodynamical phenomena.

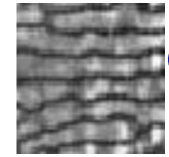
Lava movement

Cloud movement

Mega Ripples on Mars

Our Model for 'Ripples-Groove' formation

Introduction of Periodic Energy Deposition (due to interference of the incident beam with SPP) into Hydrodynamics



Grooves

Si, 200 fs, λ=800 nm, F = 0.3 J/cm²

Modules of the model

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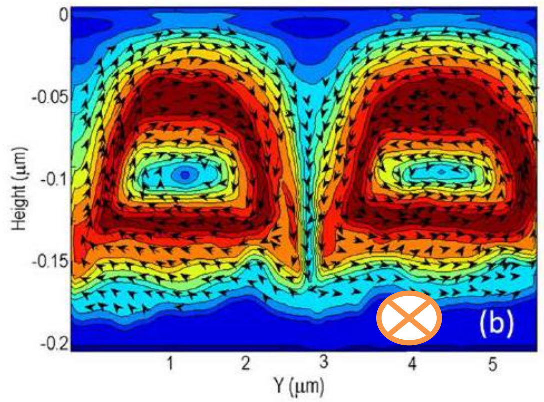
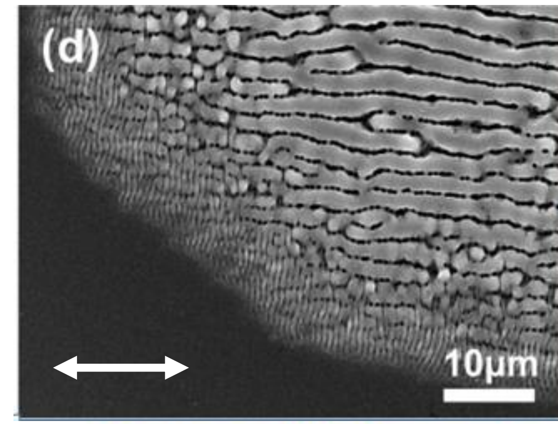
- ✧ Heat transfer: carrier-lattice thermalisation and heat conduction.
- ✧ Hydrodynamics: Marangoni related effects.
- ✧ Resolidification.

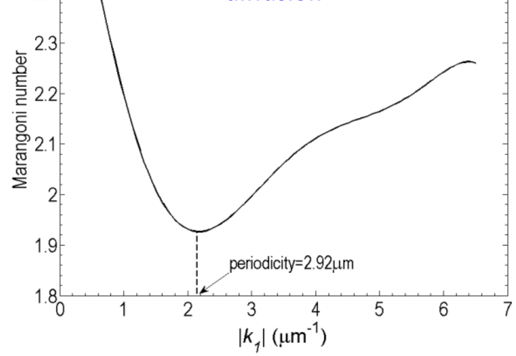


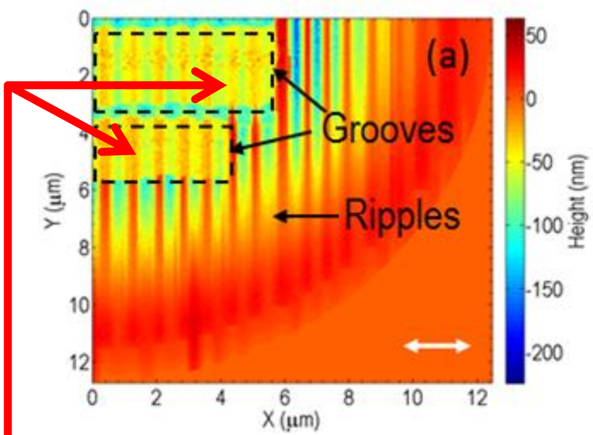


Advantages of the model

- ✧ Multiscale – description.
- ✧ Coupling of EM with hydrodynamical phenomena.
- ✧ Transition from ripples to grooves.
- ✧

Marangoni number=transport due to Marangoni/transport due to diffusion





Simulation

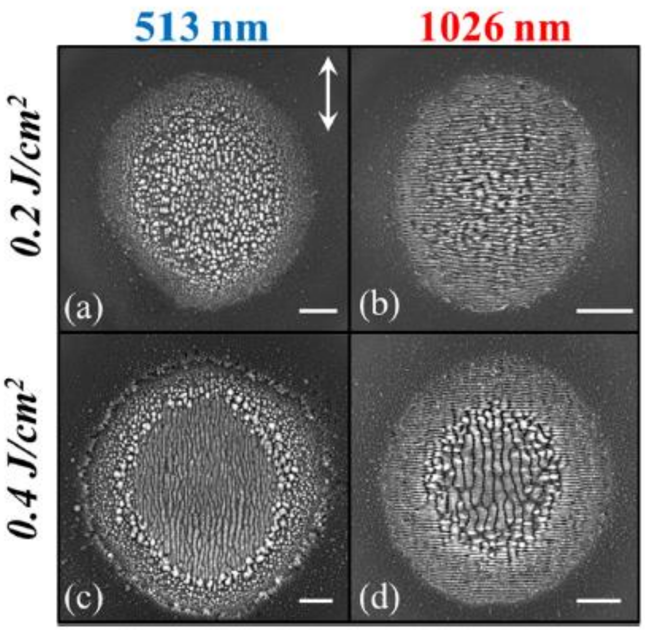
Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **92**, 041405 (2015)

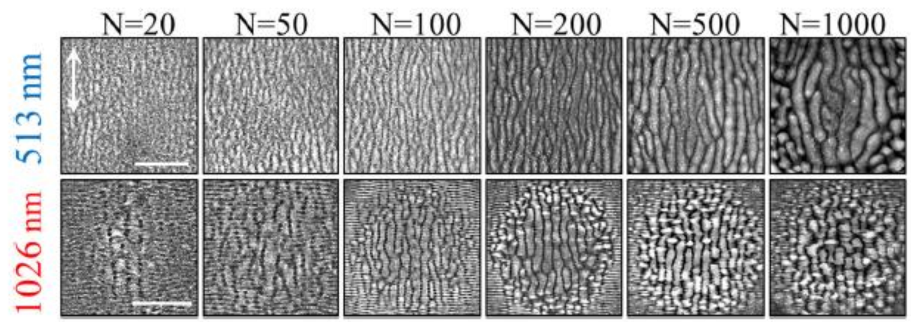
Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **94**, 081305 (2016)

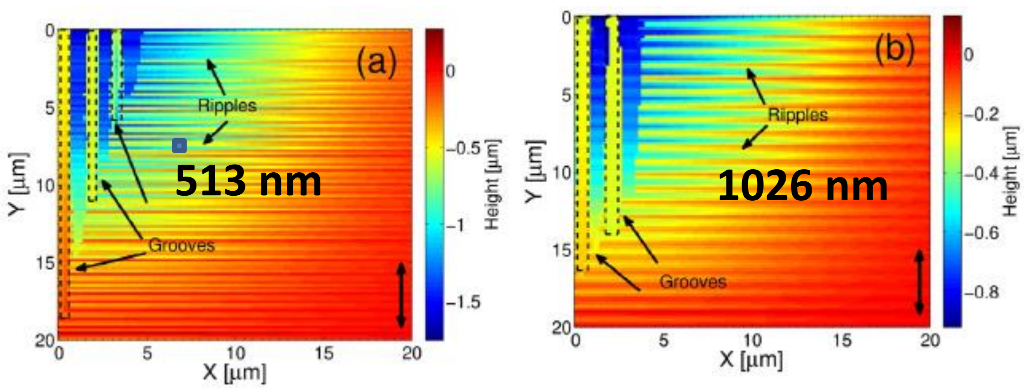
Surface patterns for excitation at different wavelengths

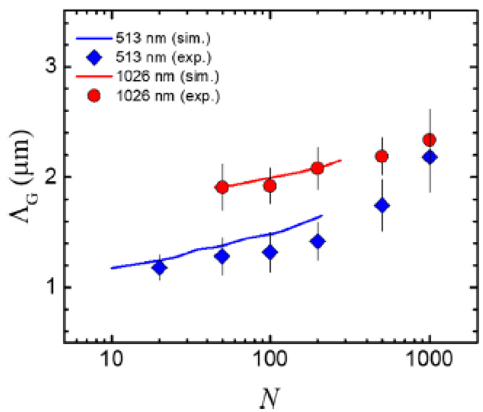
Si τ_p=170 fs

513 nm→2.4 eV 1026 nm→1.2 eV





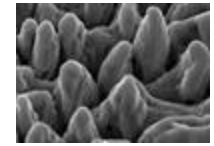




Applied Surface Science **528** 146607 (2020)

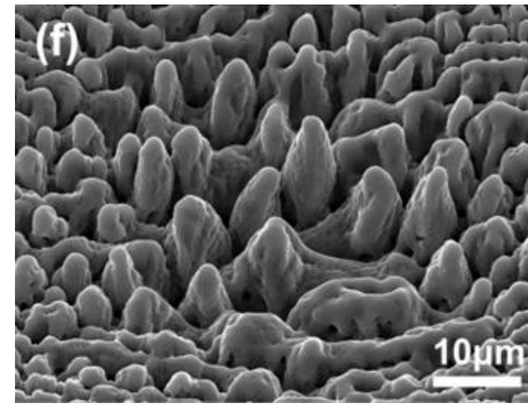
Our Model for 'Ripples-Groove-Spike' formation

Introduction of Periodic Energy Deposition (due to interference of the incident beam with SPP) into Hydrodynamics



Spikes

Si, 200 fs, λ=800 nm, F = 0.3 J/cm²



At even higher fluences or even larger number of pulses

Modules of the model

- Electrodynamics: SP excitation + interference with incident beam.
- Heat transfer: carrier-lattice thermalisation and heat conduction.
- Hydrodynamics: Marangoni related effects.
- Resolidification.

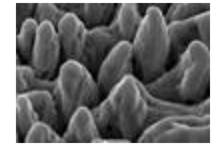
Advantages of the model

- Multiscale – description.
- Coupling of EM with hydrodynamical phenomena.
- .
-

Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **92**, 041405 (2015)
Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **94**, 081305 (2016)

Our Model for 'Ripples-Groove-Spike' formation

Introduction of Periodic Energy Deposition (due to interference of the incident beam with SPP) into Hydrodynamics



Spikes

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- Electrodynamics: SP excitation + interference with incident beam.
- Heat transfer: carrier-lattice thermalisation and heat conduction.
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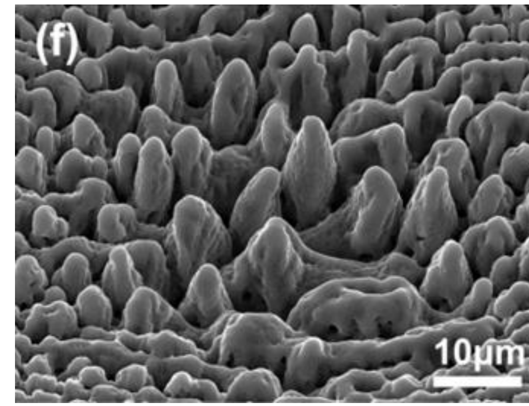
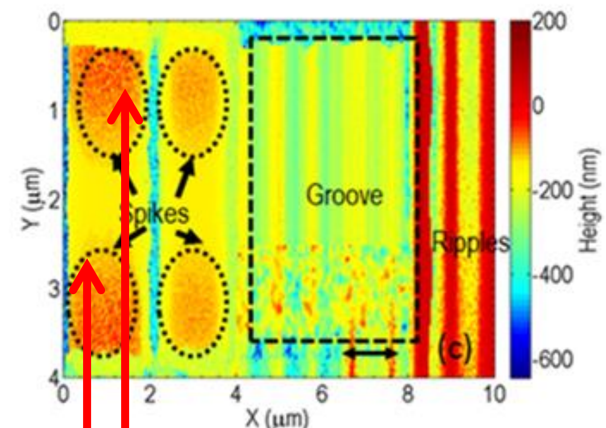


Advantages of the model

- Multiscale – description.
- Coupling of EM with hydrodynamical phenomena.
- Transition from ripples to grooves and spikes.
-



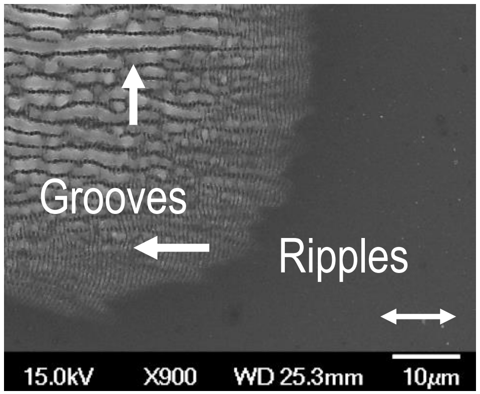
Simulation

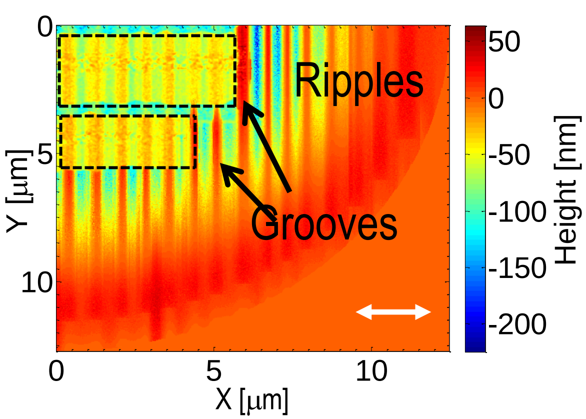
Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **92**, 041405 (2015)

Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **94**, 081305 (2016)

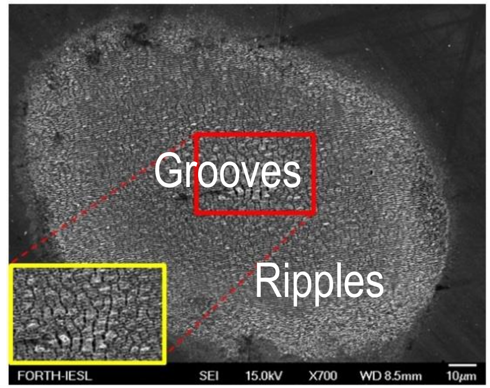
LIPSS formation on solid surfaces

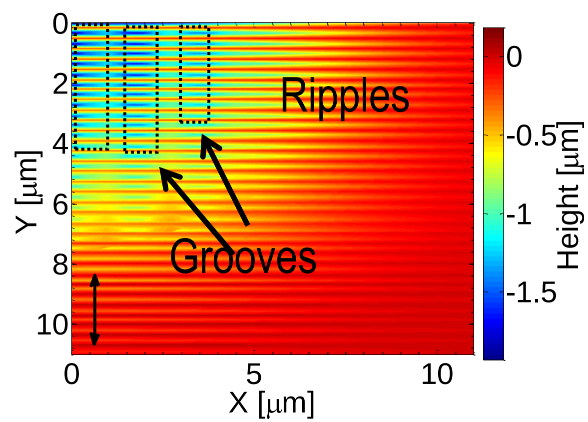
Si



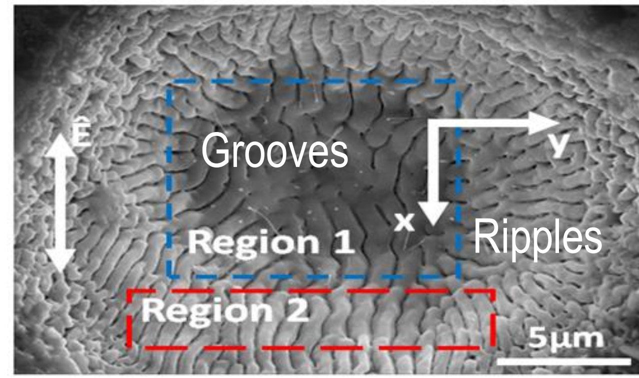


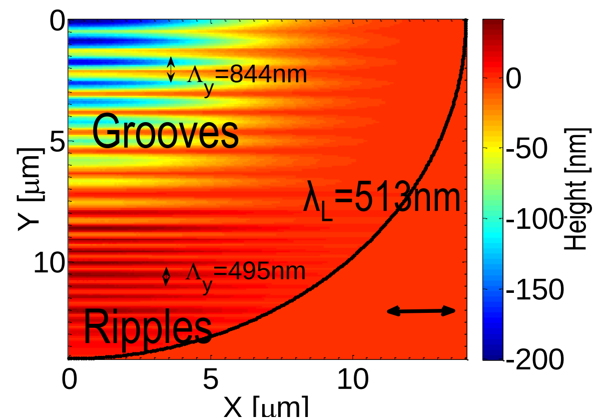
Steel-100Cr6





SiO2





Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **92**, 041405 (2015)

Tsibidis GD et al., *Phys. Rev. B (Rapid Comms)* **94**, 081305 (2016)

Tsibidis GD et al., *Applied Physics A* **124**, 27 (2018)

Energy Balance + Hydrodynamics + Elasticity

$$C_e \frac{\partial T_e}{\partial t} = \vec{\nabla}\cdot(\kappa_e \vec{\nabla} T_e) - g(T_e - T_L) + S(\vec{r}, t)$$

$$C_L \frac{\partial T_L}{\partial t} = g(T_e - T_L) - (3\lambda_{\mathrm{Ni}} + 2\mu)\alpha' T_L \sum_{i=1}^{3} \dot{\varepsilon}_{ii}$$

Energy balance

$$C_L \left(\frac{\partial T_L}{\partial t} + \vec{\nabla}\cdot(\vec{u} T_L) \right) - L_m \delta(T_L - T_{\mathrm{melt}}) \frac{\partial T_L}{\partial t} = \vec{\nabla}\cdot(\kappa_L \vec{\nabla} T_L)$$

$$\rho_L^{(m)} \left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\vec{\nabla}\vec{u} \right) = \vec{\nabla}\cdot\left(-P + \mu^{(m)}(\vec{\nabla}\vec{u}) + \mu^{(m)}(\vec{\nabla}\vec{u})^T\right)$$

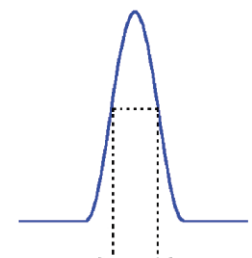
Fluid dynamics

$$\rho_L^{(s)} \frac{\partial^2 V_i}{\partial t^2} = \sum_{j=1}^{3} \frac{\partial \sigma_{ji}}{\partial x^j}, \qquad i, j = 1, 2, 3$$

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \lambda_{\mathrm{Ni}} \sum_{k=1}^{3} \varepsilon_{kk}\delta_{ij} - \delta_{ij}(3\lambda_{\mathrm{Ni}} + 2\mu)\alpha'(T_L - 300)$$

$$\varepsilon_{ij} = 1/2 \left(\frac{\partial V_i}{\partial x^j} + \frac{\partial V_j}{\partial x^i} \right),$$

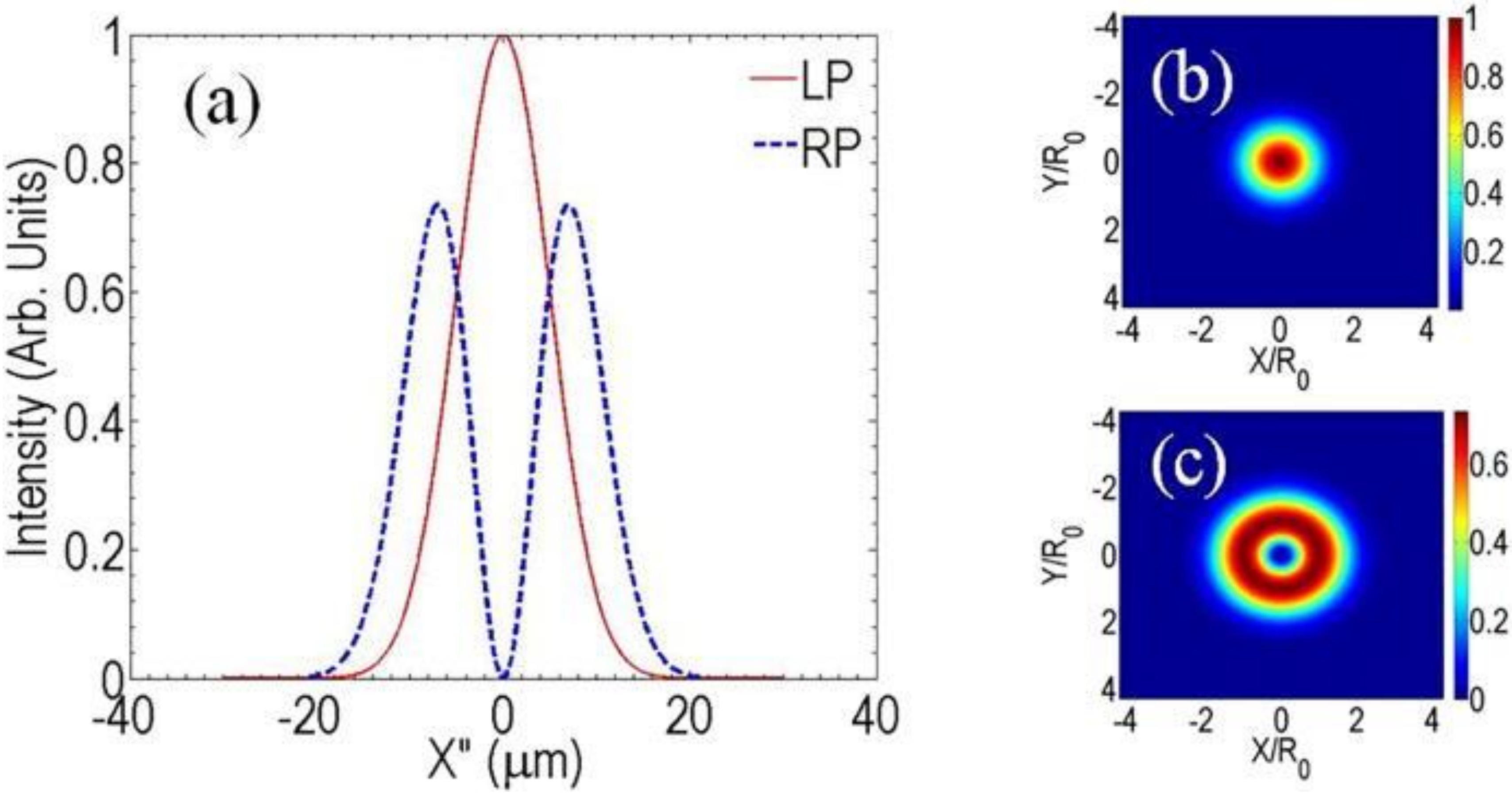
Elasticity



Tsibidis GD et al *Optics Letters* **40**, 5172 (2015)

Tsibidis GD et al *J.Appl.Phys*. **111**, 053502 (2012)

Thermal response in RP and Surface modification



Tsibidis GD et al *Optics Letters* **40**, 5172 (2015)
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Tsibidis GD et al *J.Appl.Phys*. **121**, 163106 (2017)

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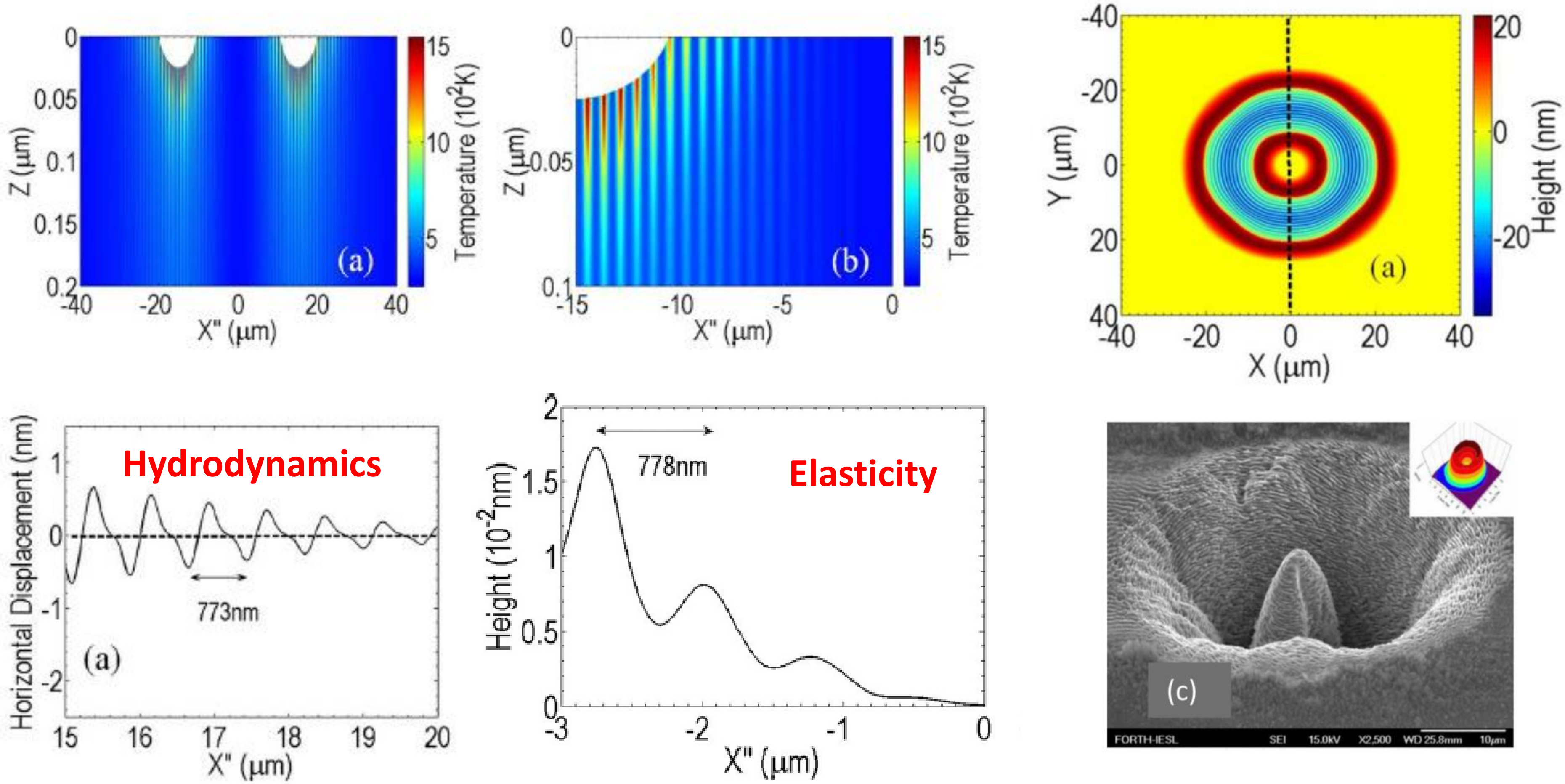
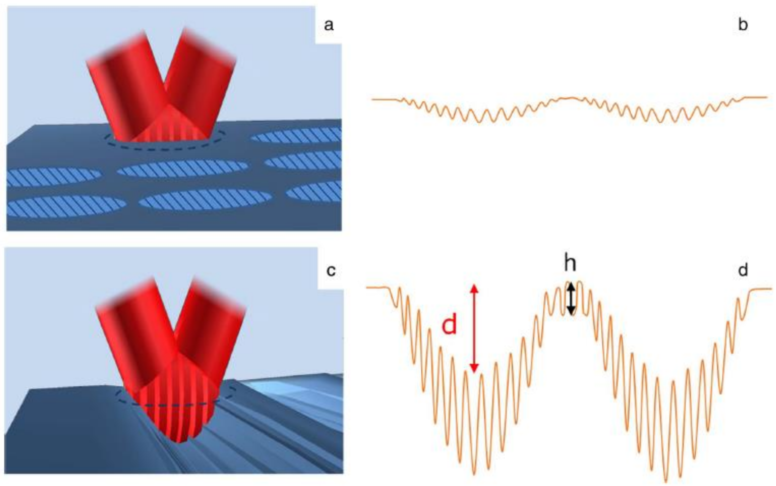
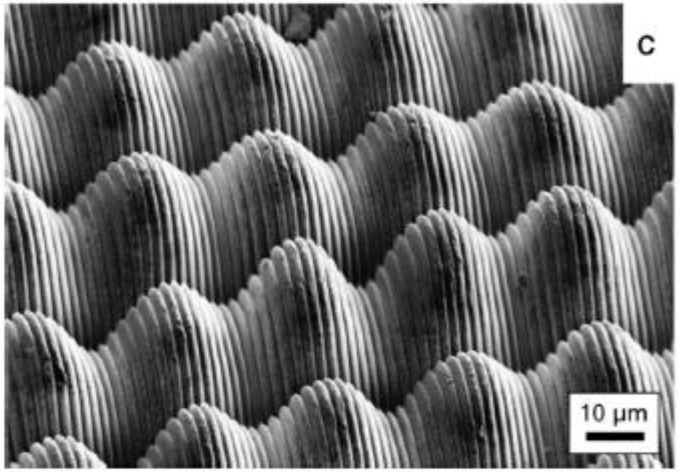


Tsibidis GD et al *Optics Letters* **40**, 5172 (2015)
Tsibidis GD et al *J.Appl.Phys*. **111**, 053502 (2012)
Tsibidis GD et al *J.Appl.Phys*. **121**, 163106 (2017)

Direct laser Interference patterning (DLIP)

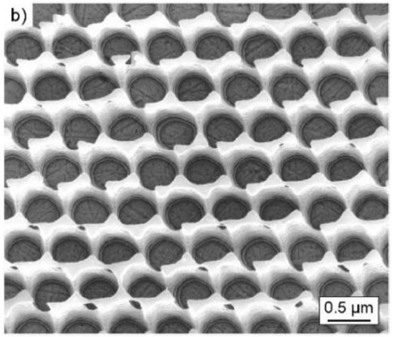
Wettability polycarbonate

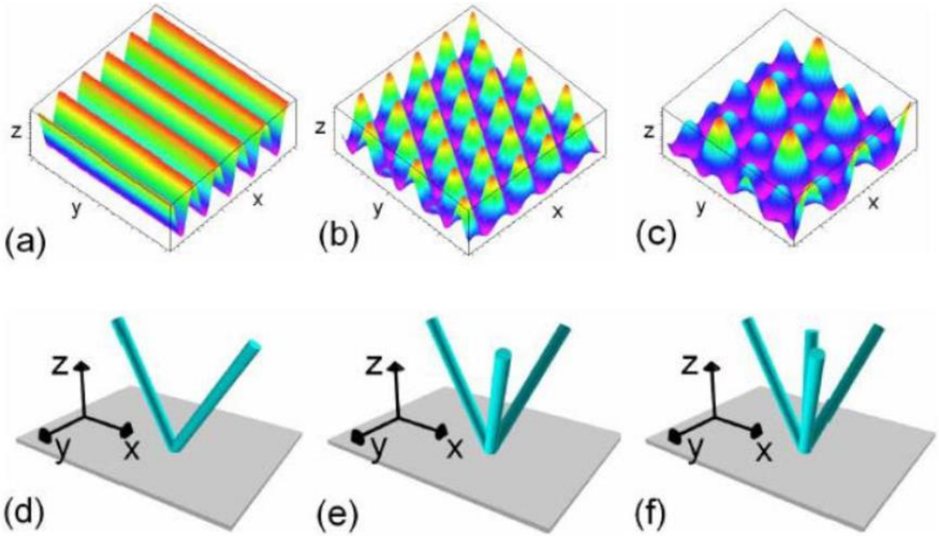




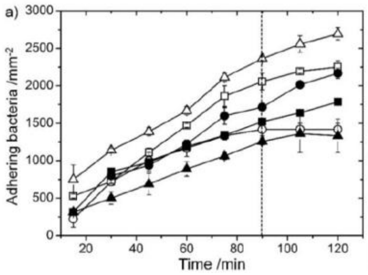
Alamri et al, *European Polymer Journal*, **99**, 27 (2018)

Stainless steel



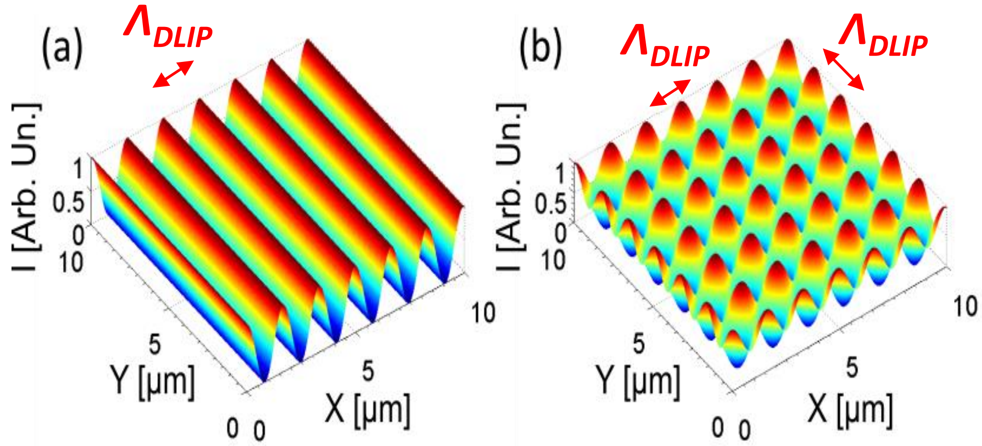


Antibacterial



Rosenkranz et al, *Lubricants* **4**, 2 (2016)

Resulting interference pattern



$$\vec{E}_{total}(z_s) = \sum_{n=1}^{N} \vec{E}_{n0}\, e^{-i(\omega t - \vec{k}\cdot\vec{r})} = \sum_{n=1}^{N} \vec{E}_{n0}\, e^{-i(\omega t - 2\pi/\lambda_L sin(\theta_n/2)[xcos(\beta_n)+ysin(\beta_n)]}$$

$$I_1 \sim e^{-2\left(\frac{x^2+y^2}{R_0^2}\right)}$$

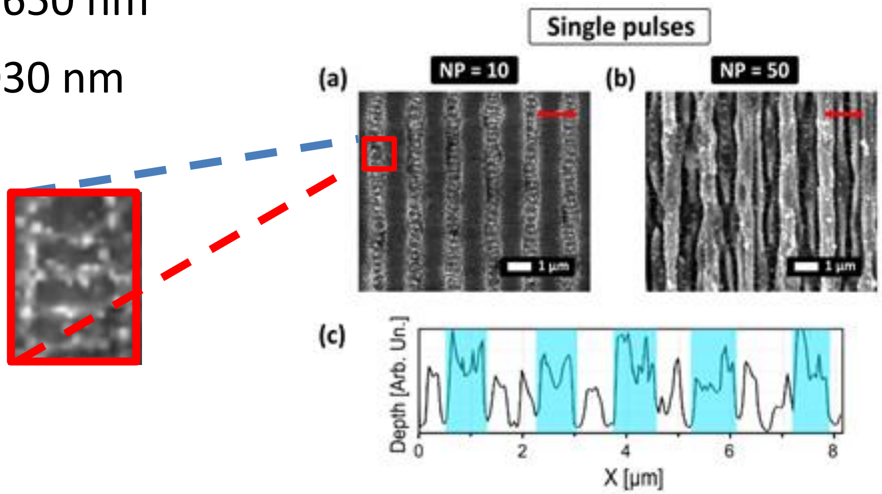
$$I_0^{(2)} = I_1[1 + cos(2kxsin\theta)]$$

$$I_0^{(4)} = I_1\left\{\left[1 + \frac{1}{2}cos(2kxsin\theta) + \frac{1}{2}cos(2kysin\theta) + 2cos(kxsin\theta)cos(kysin\theta)\right]\right\}$$

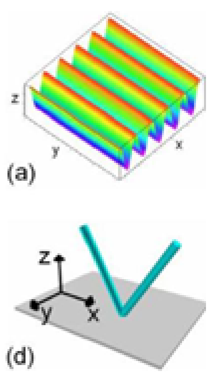
Fraggelakis F *et al, Physical Review B* **103**, 054105 (2021)

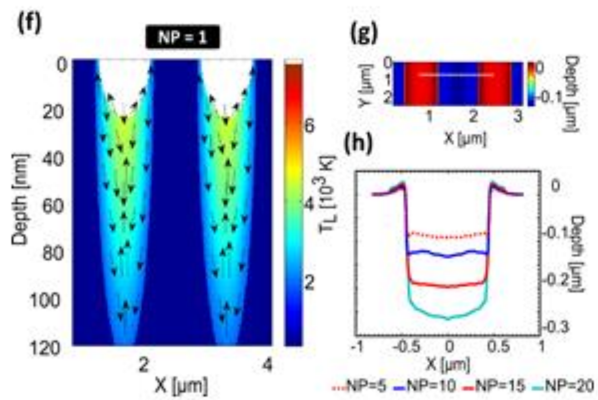
Λ_{DLIP} ~1650 nm

λ_L ~1030 nm



2 DLIP

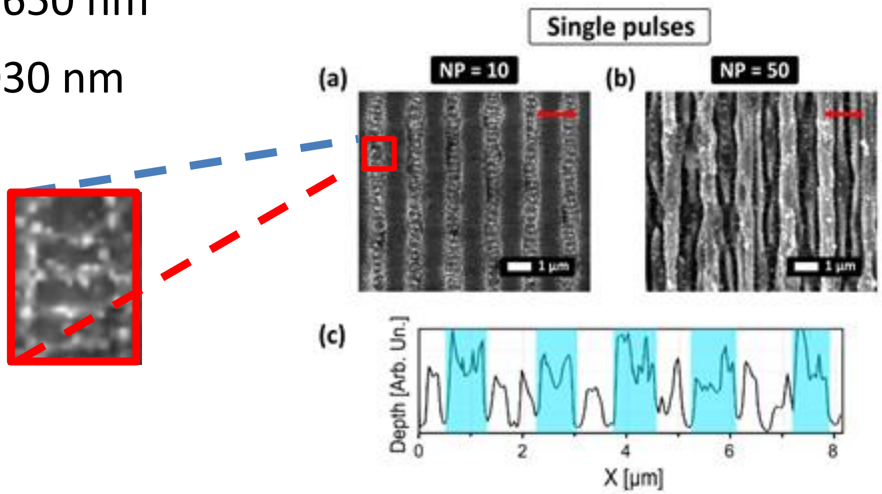


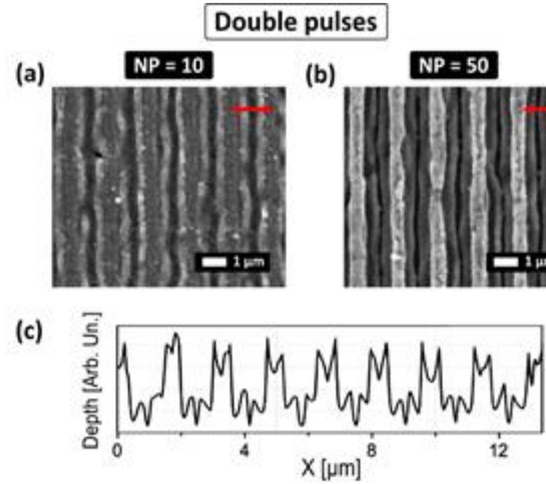


Fraggelakis F *et al*, *Physical Review B* **103**, 054105 (2021) **(Experiments performed from F.Fraggelakis)**

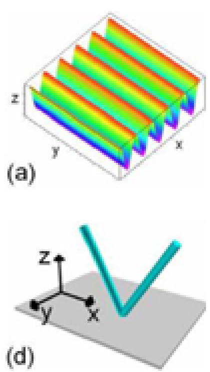
Λ_{DLIP} ~1650 nm

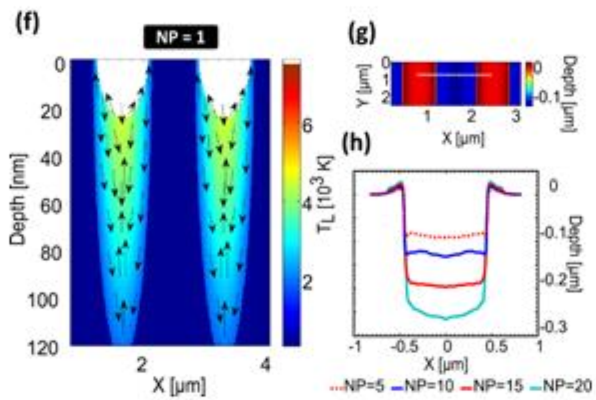
λ_L ~1030 nm

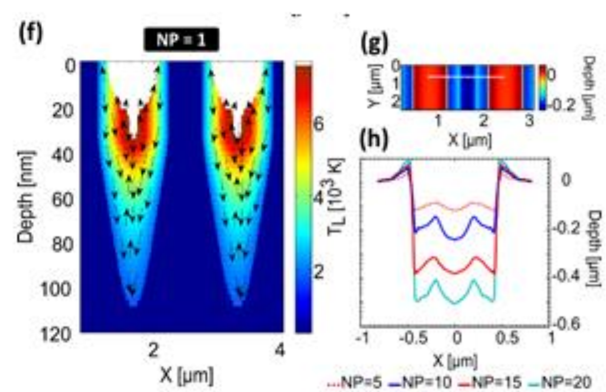


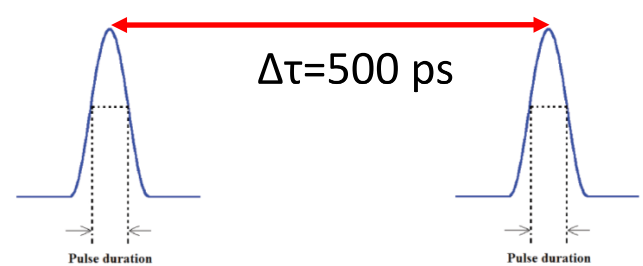


2 DLIP





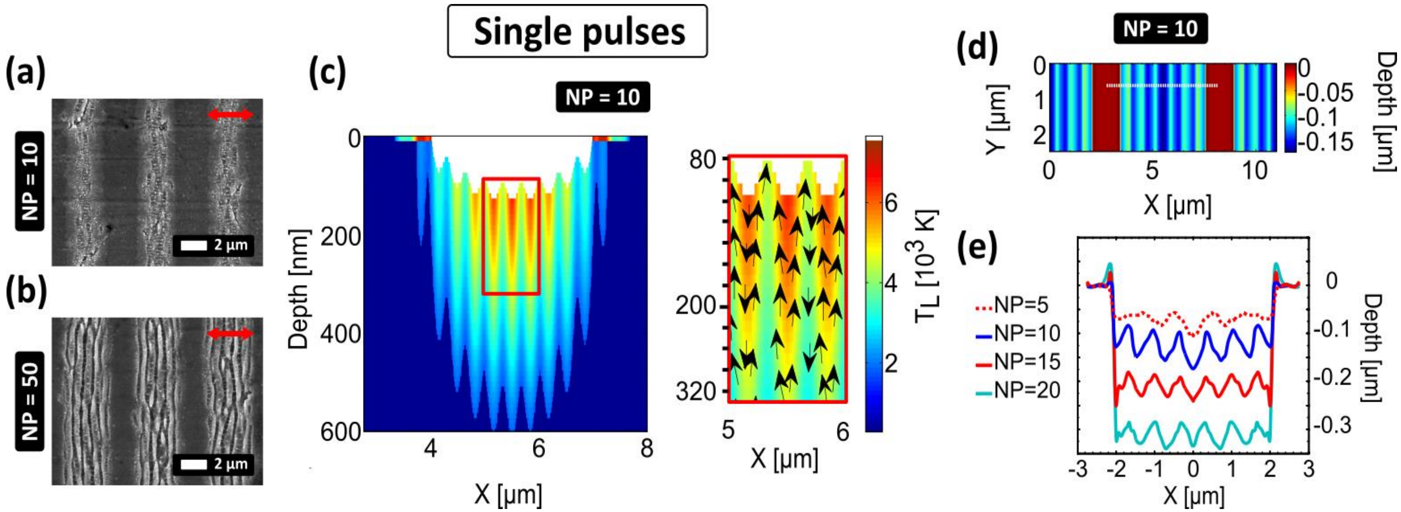


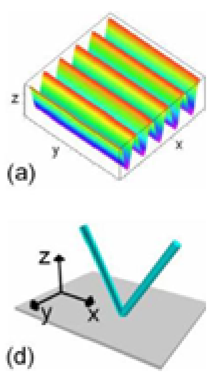


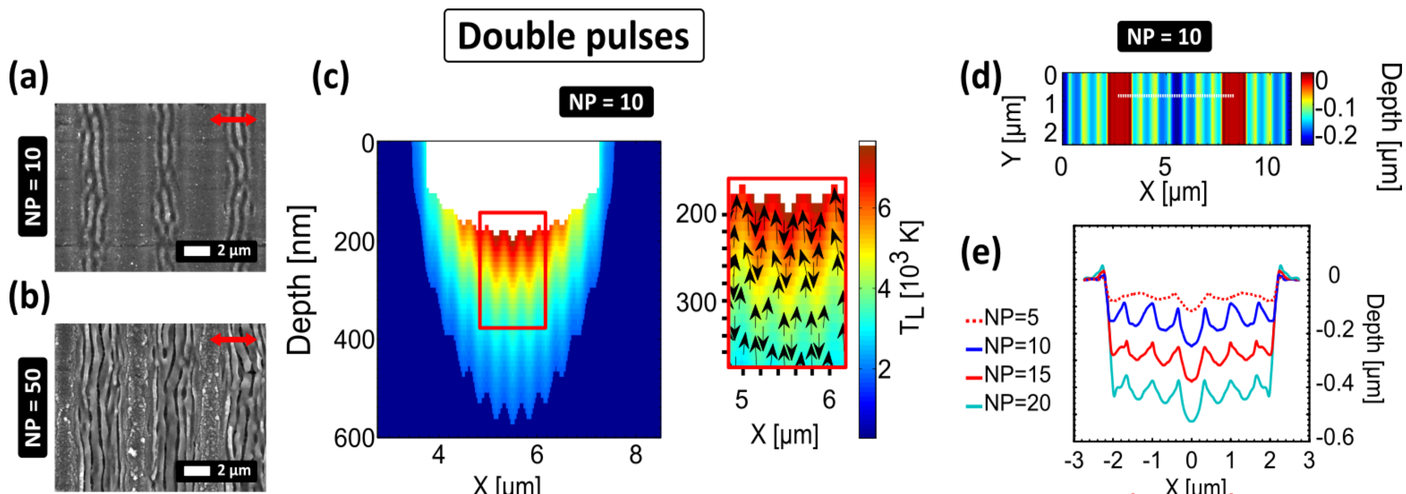
Fraggelakis F *et al*, *Physical Review B* **103**, 054105 (2021) **(Experiments performed from F.Fraggelakis)**

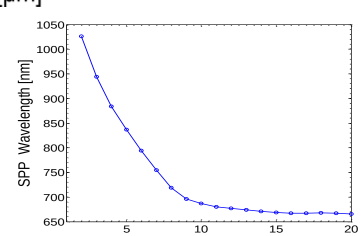
Λ_{DLIP} ~5500 nm

2 DLIP







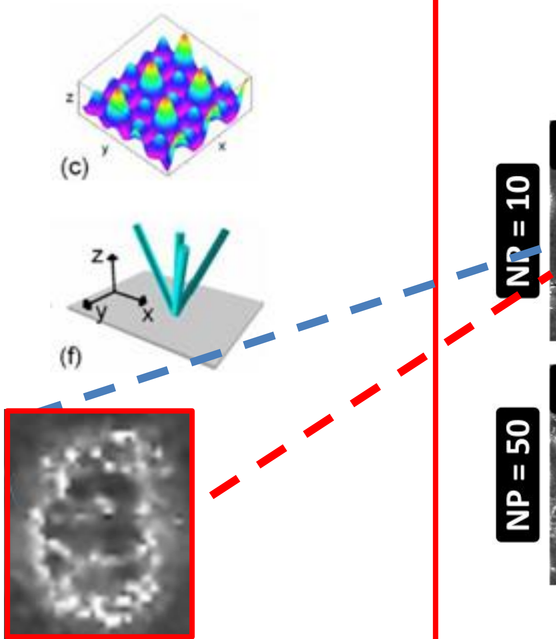


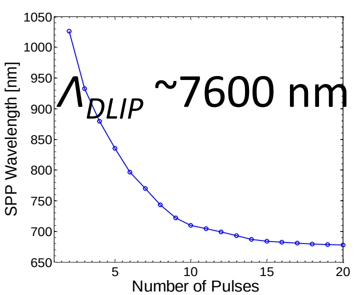
SP wavelength varies with NP

(Experiments performed from F.Fraggelakis)

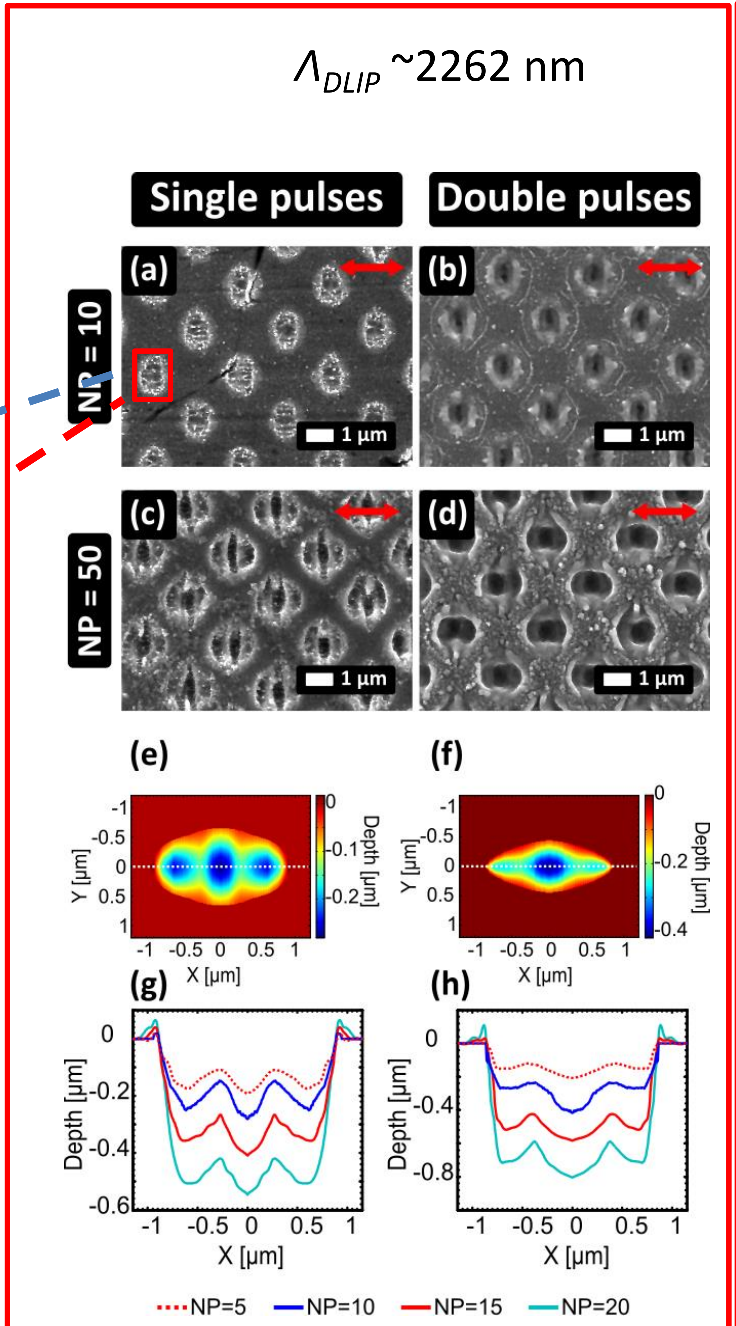
Fraggelakis F *et al*, *Physical Review B* **103**, 054105 (2021)

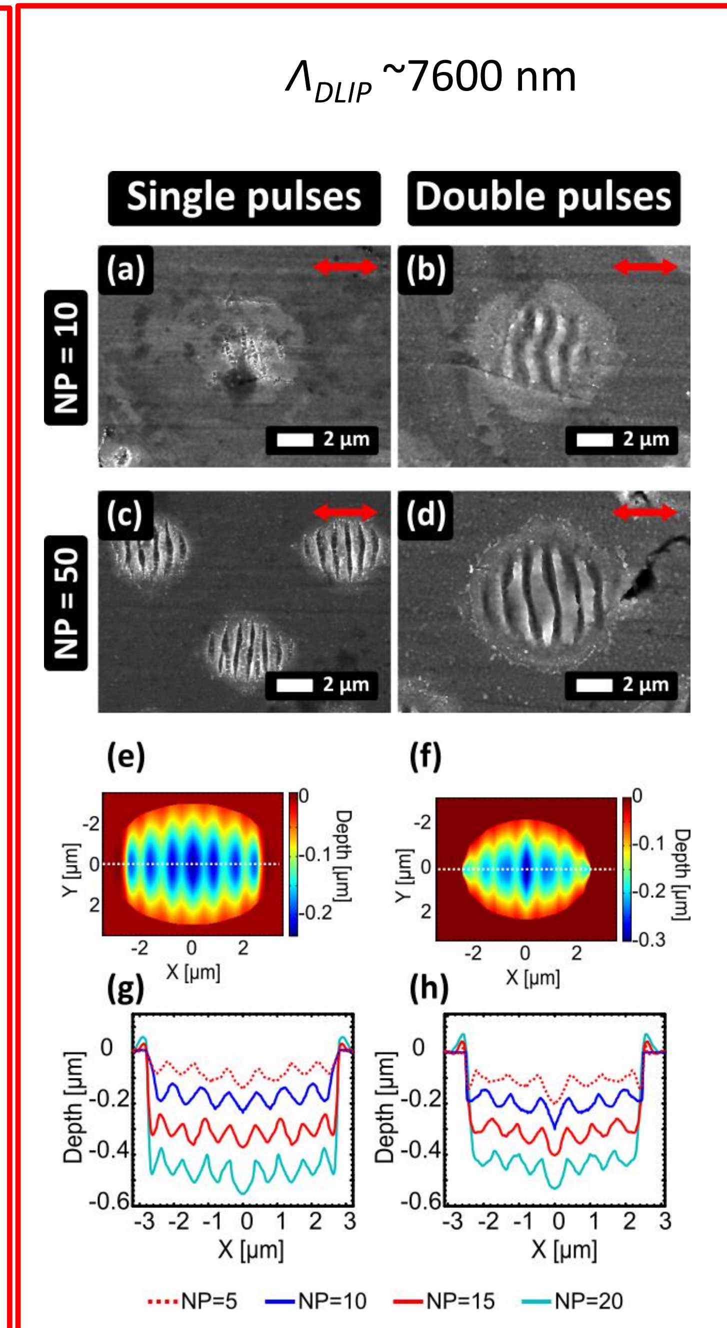
4 DLIP





SP wavelength varies with NP

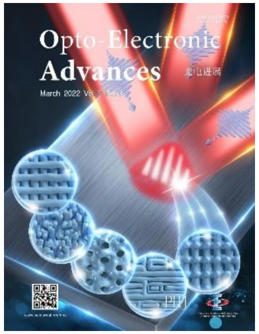


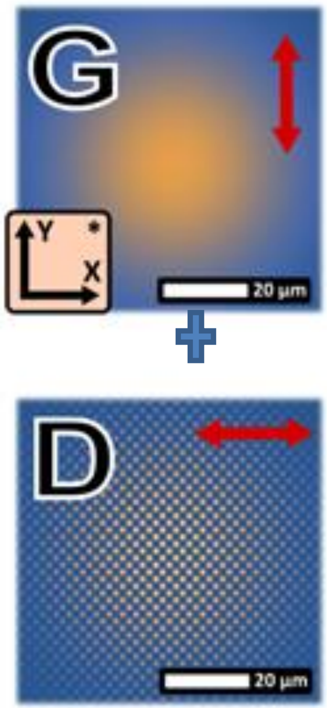


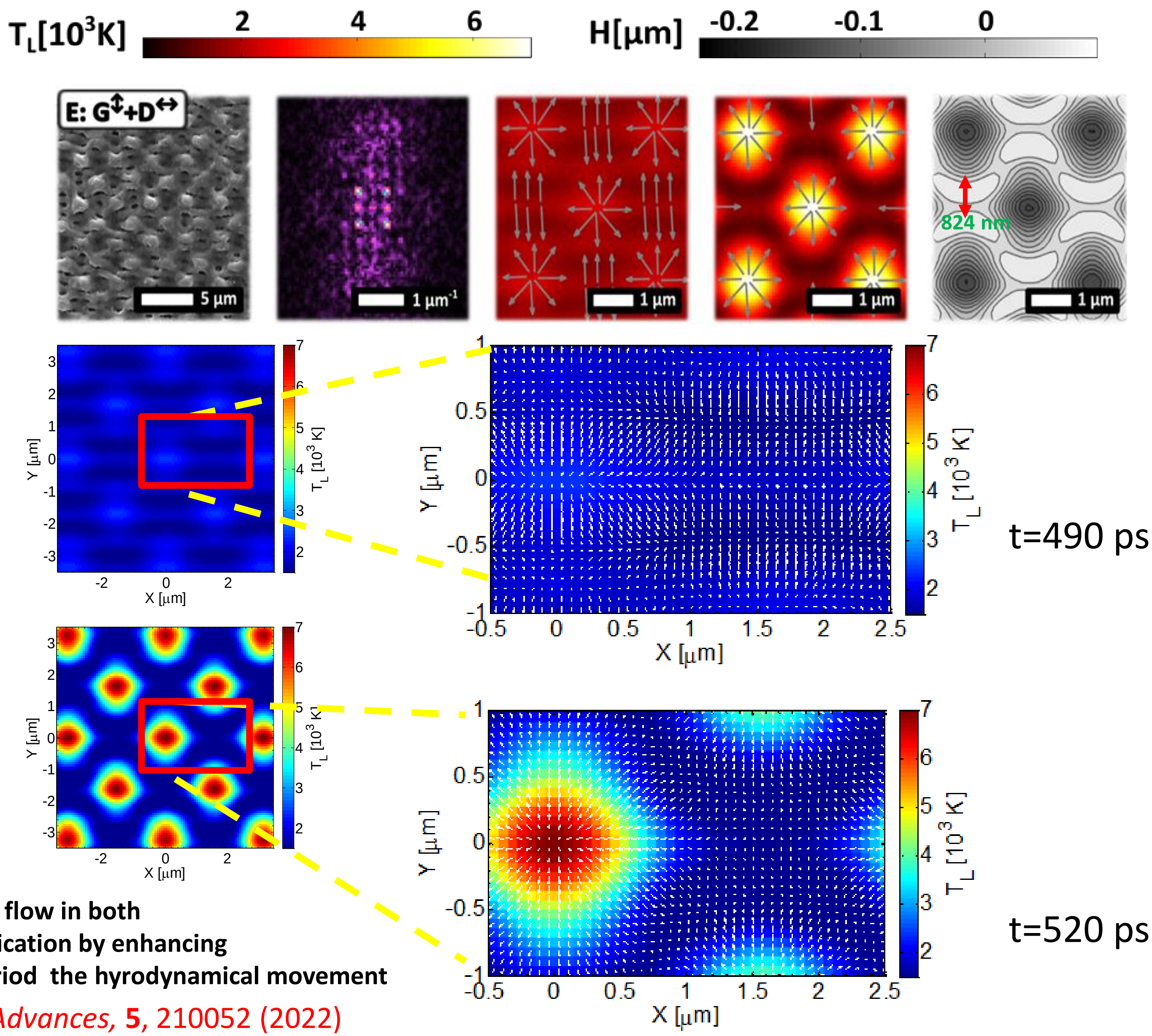
Fraggelakis F *et al*, *Physical Review B* **103**, 054105 (2021)

(Experiments performed from F.Fraggelakis)

Order of irradiation schemes leads to different patterns



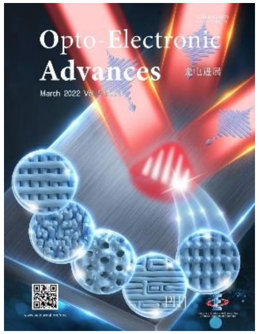


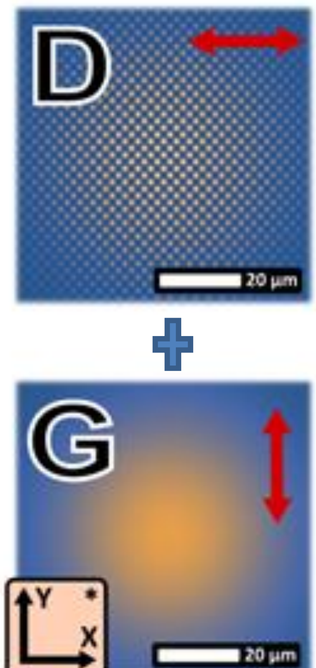


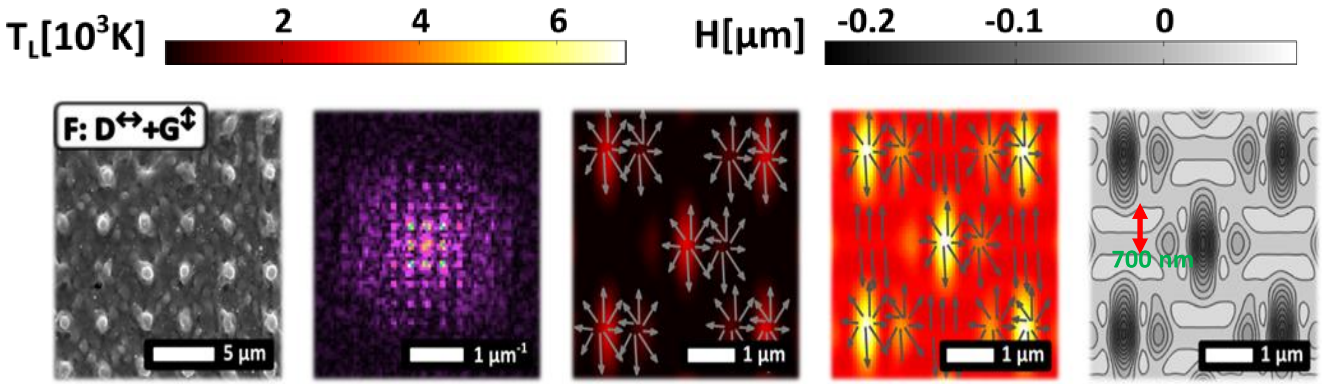
- **Gaussian beams→LIPSS (horizontal)**
- **The second pulse (D) drives the melt flow in both directions the x-y-axes before solidification by enhancing locally and in places of the LIPSS period the hyrodynamical movement**

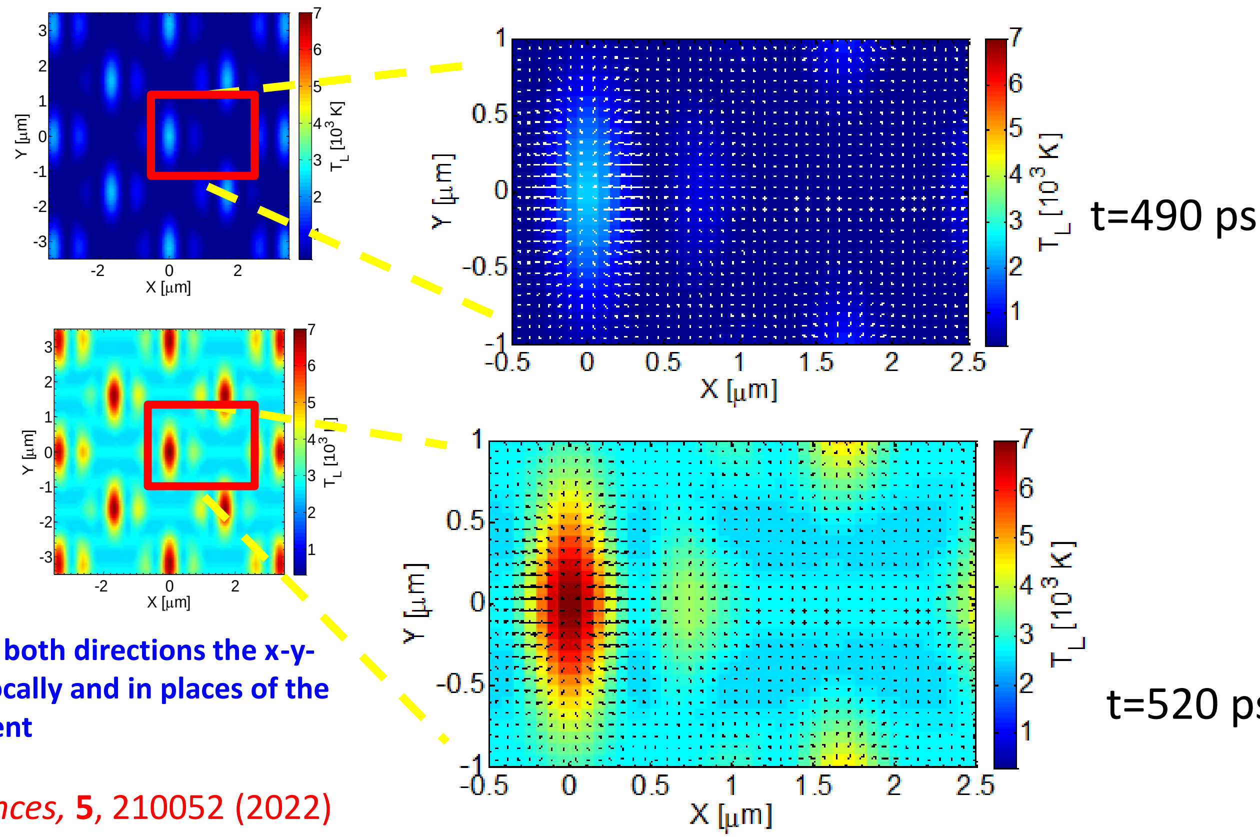
Fraggelakis *et al, Opto-Electronic Advances,* **5**, 210052 (2022)

Order of irradiation schemes leads to different patterns







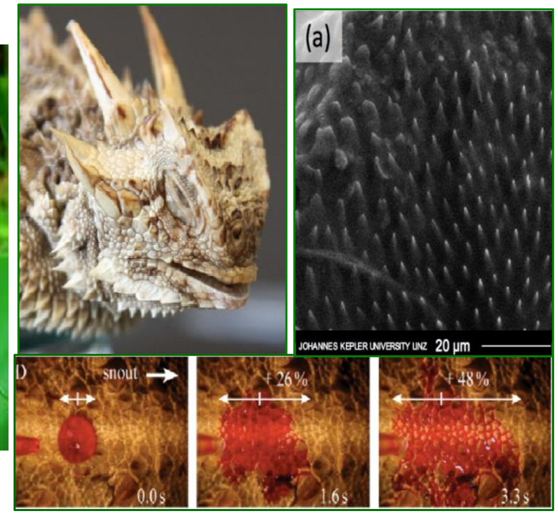


- **The first pulse (D) drives the melt flow in both directions the x-y-axes before solidification by enhancing locally and in places of the LIPSS period the hyrodynamical movement**
- **The Gaussian beams→LIPSS (horizontal)**

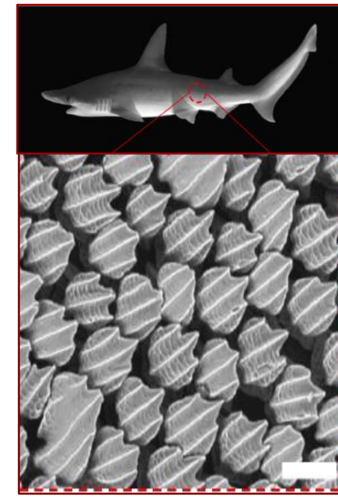
Fraggelakis *et al, Opto-Electronic Advances,* **5**, 210052 (2022)

Sky is the limit but…the inspiration comes mostly from the ground

Leaf
Wetting properties

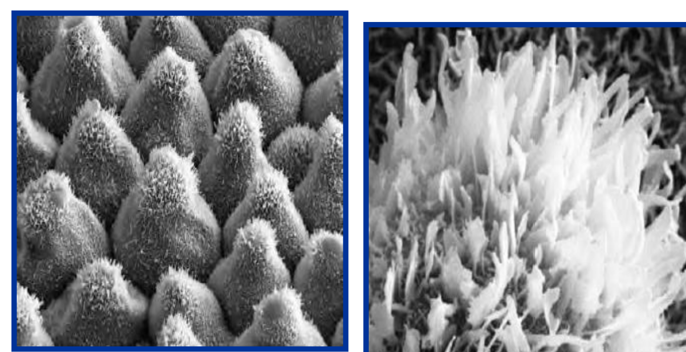


Lizards/Bugs Integument
Directional Fluid Transport



Shark Skin
Low Underwater Friction

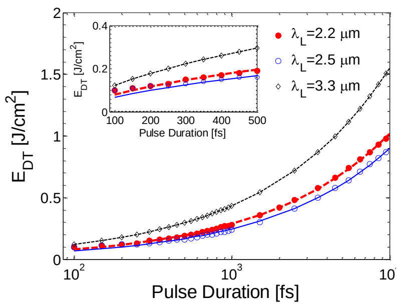
Greta-Oto Scales
Antireflection

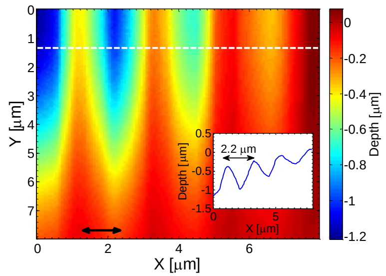


Colocasia Leaf Superhydrophobicity
Water Repellence Self Cleaning

Extension of the multiscale physics model

Mid-IR (Carrier dynamics+surface modification)



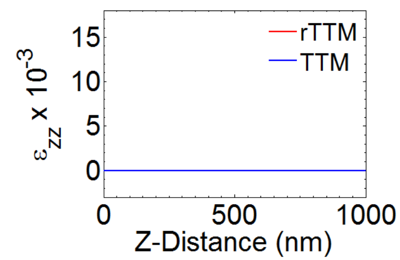


Si
SiO_2

Scientific Reports **10**, 8675 (2020)
Phys. Rev. B **99**, 195201 (2019)

(remote experiment at ELI-ALPS)

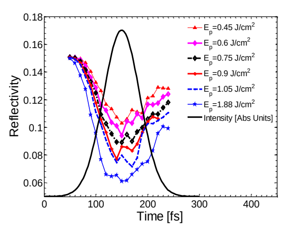
Strain Propagation



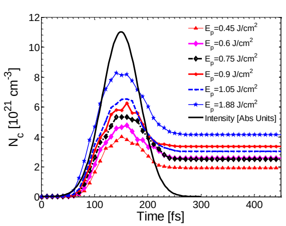
Metals
Si
SiO_2

Journal of Applied Physics **123**, 085903 (2018)
Optics Letters **40**, 5172 (2015)

Very short pulses<50 fs



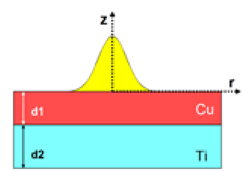
SiC
Metals

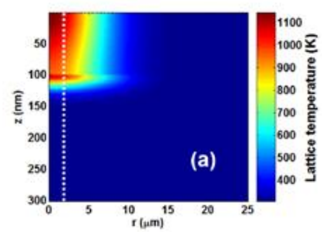


Phys.Rev B **101**, 075207 (2020)

Multi-layered materials

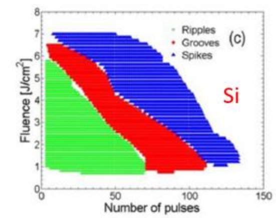
Metals/SiO_2
Metals





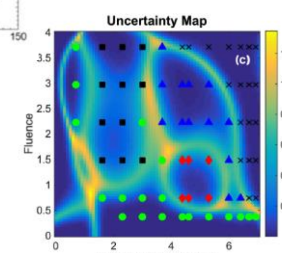
App.Phys.Lett., **104**, 051603 (2014)

Machine learning approaches



(with Y.Pantazis)

Metals
Si



J. Appl. Phys. **128**, 183102 (2020)

New directions: XUV, Thin films, Topography changes due to the use of more complex polarization schemes

Conclusions-Challenges-Prospects

- Knowledge of fundamental knowledge is very important towards controlling and modulating surface patterning
- Differences in surface patterns demonstrate the significant role of a number of parameters and certainly polarization, material, hydrodynamics are among the most dominant
- LIPSS at larger photon energies (XUV?) or very small pulse durations
- LIPSS and fluid dynamics on thin films or multilayered materials

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→ Basic Science ↔ Multiscale Modelling ↔ Applications

Acknowledgements

Collaborators [at IESL-FORTH (ULMNP Group)]

- Stratakis E. (Head of ULMNP Group)
- Fraggelakis F.
- P.Lingos
- Mouchliadis L.
- Maragkaki S.
- Vlahou M.
- Velli M.C.
- Skoulas E.
- Mimidis A

International Collaborators

- Kanaev A. (CNRS and Univ. de Paris)
- Museur L. (CNRS and Univ. de Paris)
- Amoruso S. (Univ. di Napoli, Italy)
- Bonse J. (BAM, Germany)
- Uteza O. (CNRS and Univ. of Marseille)
- A.Kabashin (CNRS and Univ. of Marseille)
- ELI-ALPS (Exp. And Th. Groups)

Other local Collaborators (past and present)

- Pantazis Y. (IACM-FORTH)
- Loukakos P. (IESL-FORTH)
- Pissadakis S. (IESL-FORTH)
- Tsilipakos O. (IESL-FORTH)
- Kafesaki M. Group (UoC and IESL-FORTH)
- Fotakis C. (IESL-FORTH)

Funding Projects

(Horizon 2020, FET, Bilateral, ΕΣΠΑ)

Thank you for your attention