Laser Micro/Nano Engineering of Materials for Energy and Tissue Engineering Applications

Emmanuel Stratakis

1. Institute of Electronic Structure and Laser, Foundation for Research & Technology Hellas, (IESL-FORTH), P.O. Box 1527, Heraklion 711 10, Greece.

INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

FOUNDATION FOR RESEARCH AND TECHNOLOGY – HELLAS
INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

Ultrafast Laser Micro and Nano Processing Group

Laserlab Europe

LiNaBioFluid

nffa.eu
nanoscience foundries & fine analysis

Ultrafast Lasers for Materials Processing

An emerging exciting field that,

- ✧ **Enables ultimate CONTROL**

  Control of light by matter and control of matter by light

- ✧ **Allows SURFACE AND IN VOLUME photochemical processing based on non-linear effects**

- ✧ **Encourages FUNDAMENTAL STUDIES of laser-materials interactions that influence materials processing at primary timescales.**

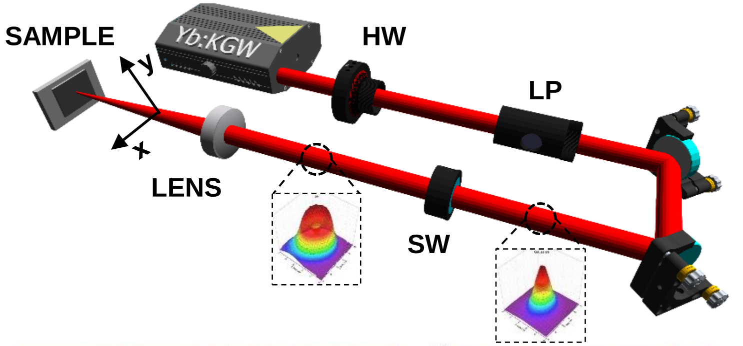
☛ **Ideal tool for micro/nano scale applications**

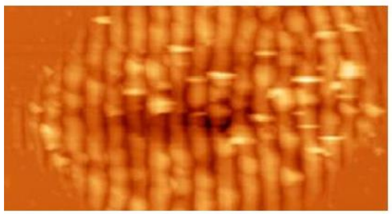
Ultrafast Laser Micro and Nano Processing Group

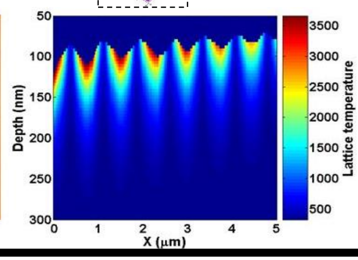
Fundamentals of Ultrafast Laser Processing

in collaboration with G. Tsibidis (IESL)

Phys. Rev. B (2012), (2015) / J. Appl. Phys. (2012) / Opt. Express (2013)/ Appl. Phys A (2014)

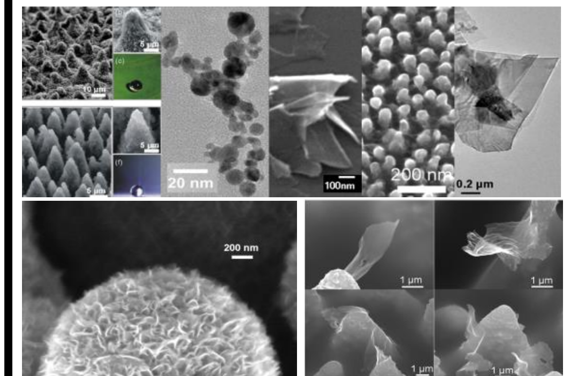


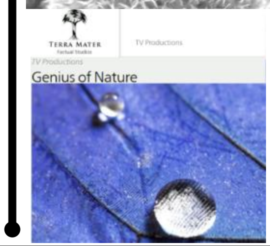




Biomimetic Micro/Nano Materials

Adv. Mater. (2008) / Sci. Adv. Mat (2012)/ Opt. Lett .(2015)



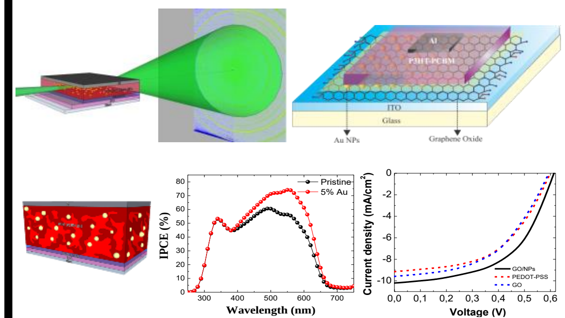


Film Produced by Terra Mater Factual Studios in co-production with BBC

Organic Photovoltaic Applications

in collaboration with E. Kymakis (TEIC)

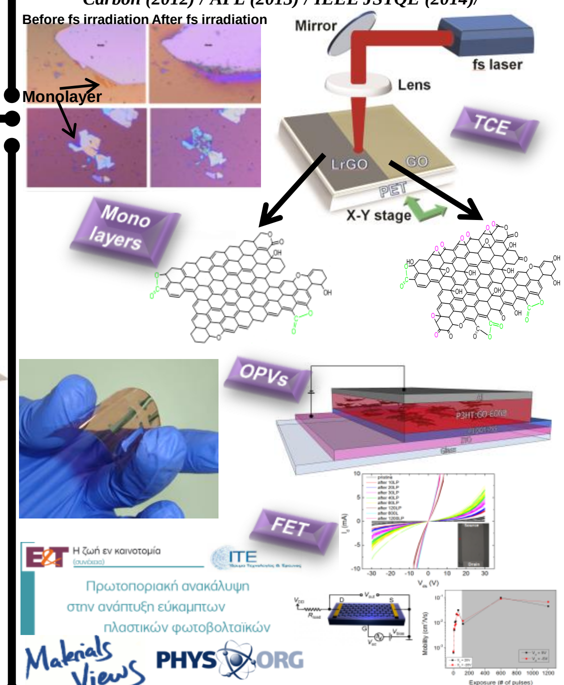
Adv. Ener. Mater. (2016) / Nanoscale (2014)/ RSC Adv. (2013)
Mat. Today (2013) / Adv. Mater. (2013)/ Chem. Comm. (2014)



Laser interaction with 2D materials

in collaboration with E. Kymakis (TEIC), T. D. Anthopoulos (ICL), G. Kioseoglou (IESL)

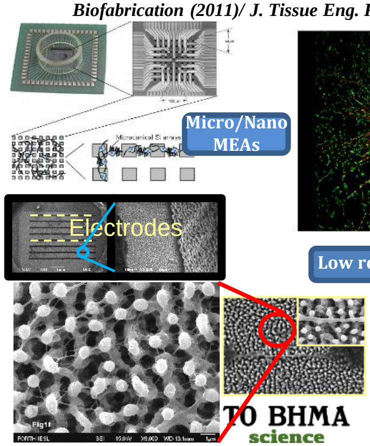
Adv. Func. Mater. (2013)(2015) / Nanoscale (2013)
Carbon (2012) / APL (2013) / IEEE JSTQE (2014)/

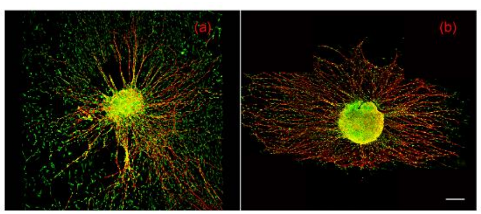


Biological Applications

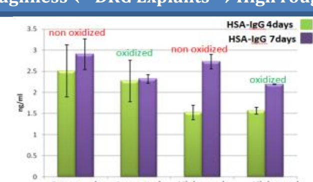
in collaboration A. Ranella (IESL), I. Athanassakis (UoC) and A. Gravanis (IMBB)

Acta Biomaterialia (2010) / Tissue Eng. C (2009)
Biofabrication (2011)/ J. Tissue Eng. Reg. Medicine (2015) / Biomaterials (2015)





Low roughness ← DRG Explants → High roughness

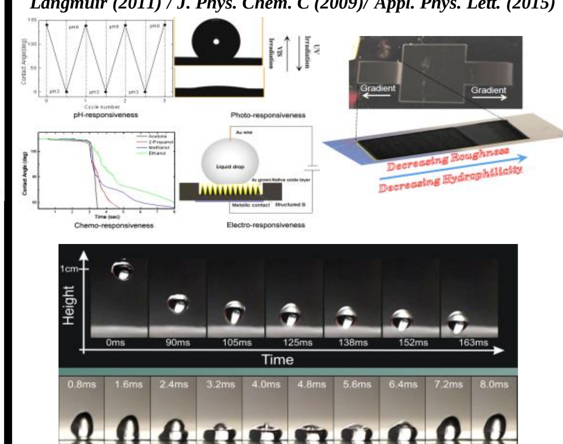


Immune response of Si Scaffolds

Extreme Wetting and Microfluidics

in collaboration with M. Vamvakaki and S. H. Anastasiadis (IESL)

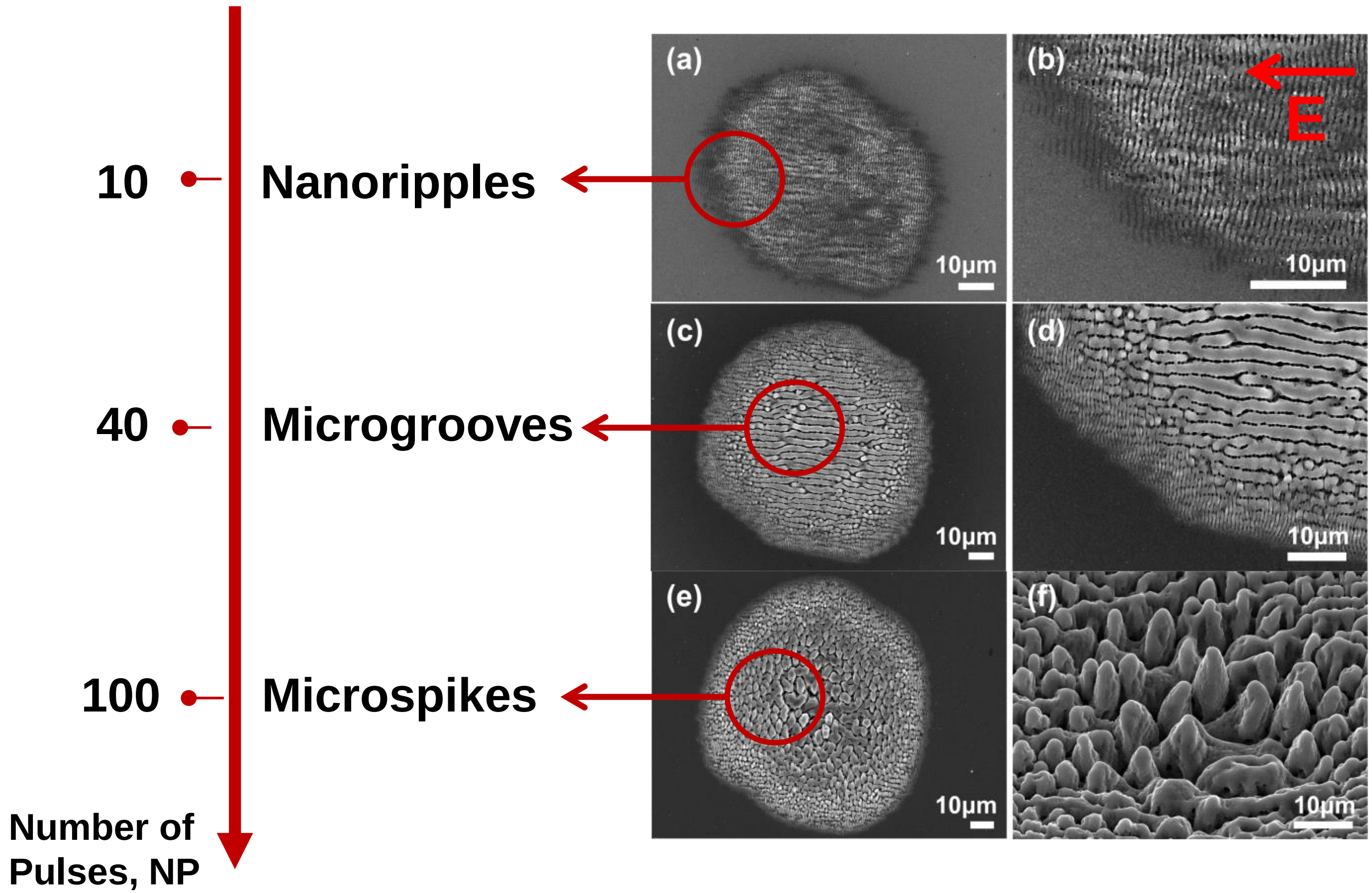
Biomicrofluidics (2010) /Chem. Comm. (2010)
Langmuir (2011) / J. Phys. Chem. C (2009)/ Appl. Phys. Lett. (2015)



Fundamentals of Ultrafast Laser Processing

Theory: George Tsibidis, IESL

Si, 200 fs, 1026 nm, F = 0.3 J/cm^2



Laser induced periodic surface structures (LIPSS) !

Our Model

George Tsibidis

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

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.
- Transition from ripples to grooves to microspikes.
- Description of periodicity dependence on NP.

1. Surface plasmon wave wavelength (Electrodynamics)

$$l_s = l \,/\, \mathrm{Re}\left(\frac{e' + e_d}{e' e_d}\right)^{1/2}$$

2. Carrier-lattice relaxation process and heat transfer

$$C_c \frac{\partial T_c}{\partial t} = \vec{\nabla} \bullet \left((k_e + k_h) \vec{\nabla} T_c \right) - \frac{C_c}{\tau_E}\left(T_c - T_l\right) + S(\vec{r}, t)$$

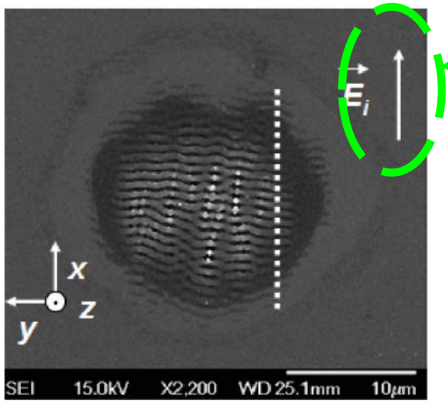
$$C_l \frac{\partial T_l}{\partial t} = \vec{\nabla} \bullet \left(K_l \vec{\nabla} T_l \right) + \frac{C_c}{\tau_E}\left(T_c - T_l\right)$$

3. Molten material dynamics/fluid transport

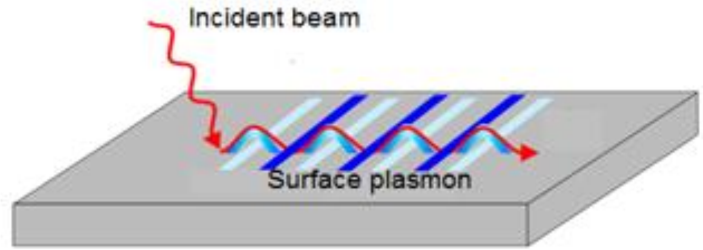
$$\rho_L \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \bullet \vec{\nabla} \vec{u} \right) = \vec{\nabla} \bullet \left(-P\mathbf{1} + \mu\left(\vec{\nabla}\vec{u}\right) + \mu\left(\vec{\nabla}\vec{u}\right)^T \right)$$

Subwavelength Ripples Formation

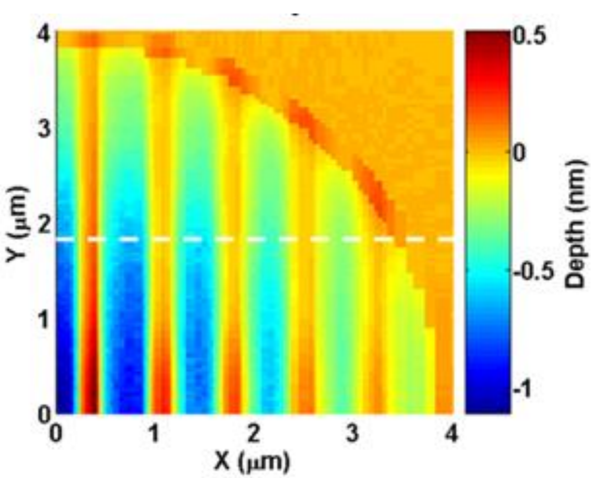
Experiment



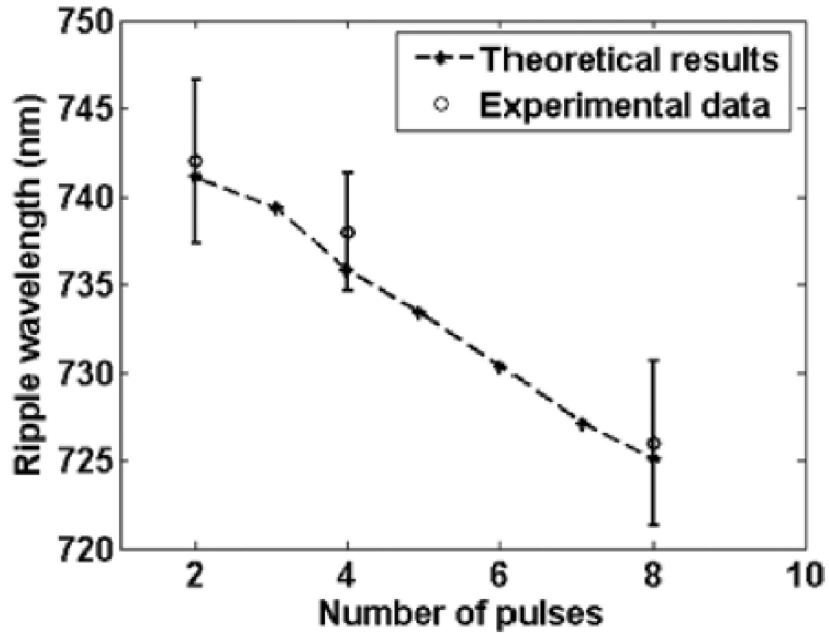
Ripples perpendicular to the polarization



Ripple periodicity:
$\Lambda = \lambda/(\lambda/\lambda_s \pm \sin\varphi)$
φ: incidence angle



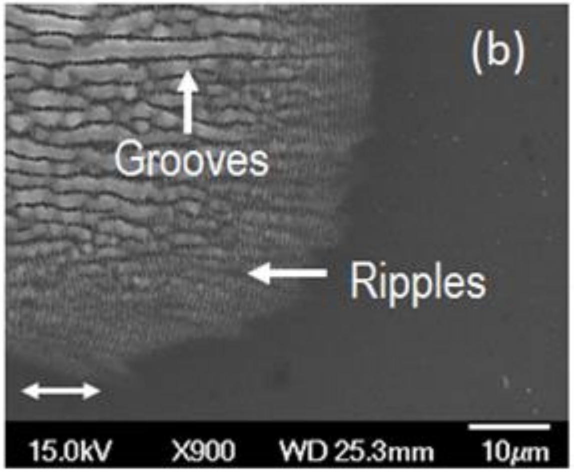
Simulation

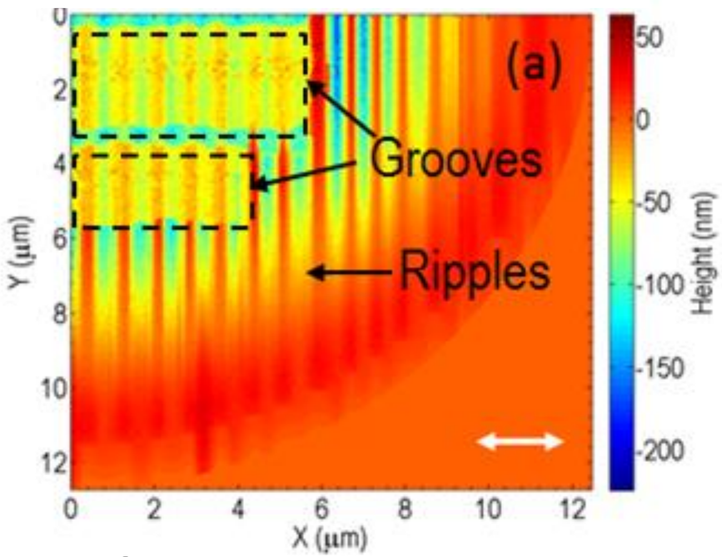


Phys. Rev. B 86, 115316 (2012)

Micro-Grooves Formation

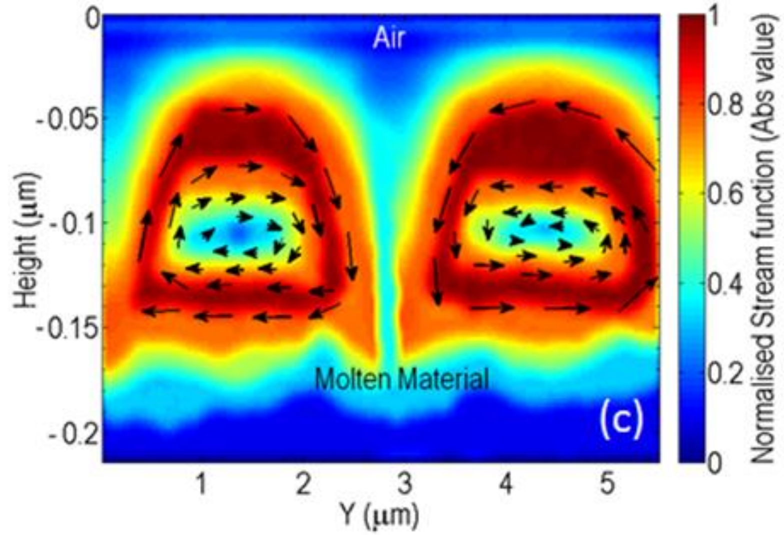
Experiment

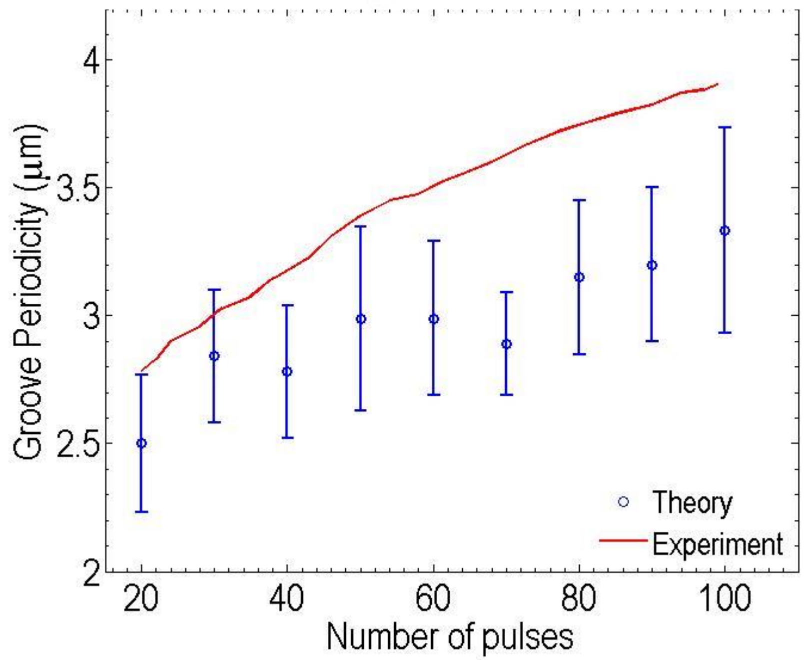




Simulation

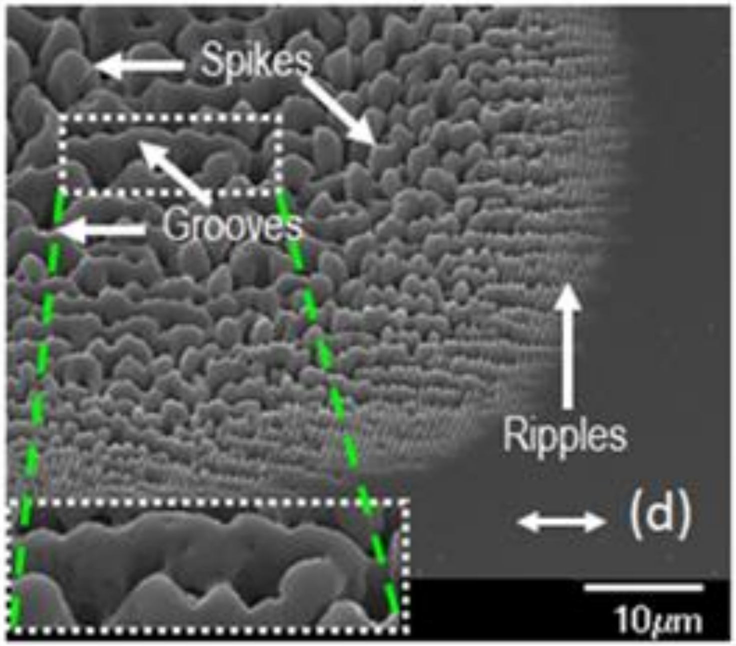
Hydrothermal waves-Convection rolls



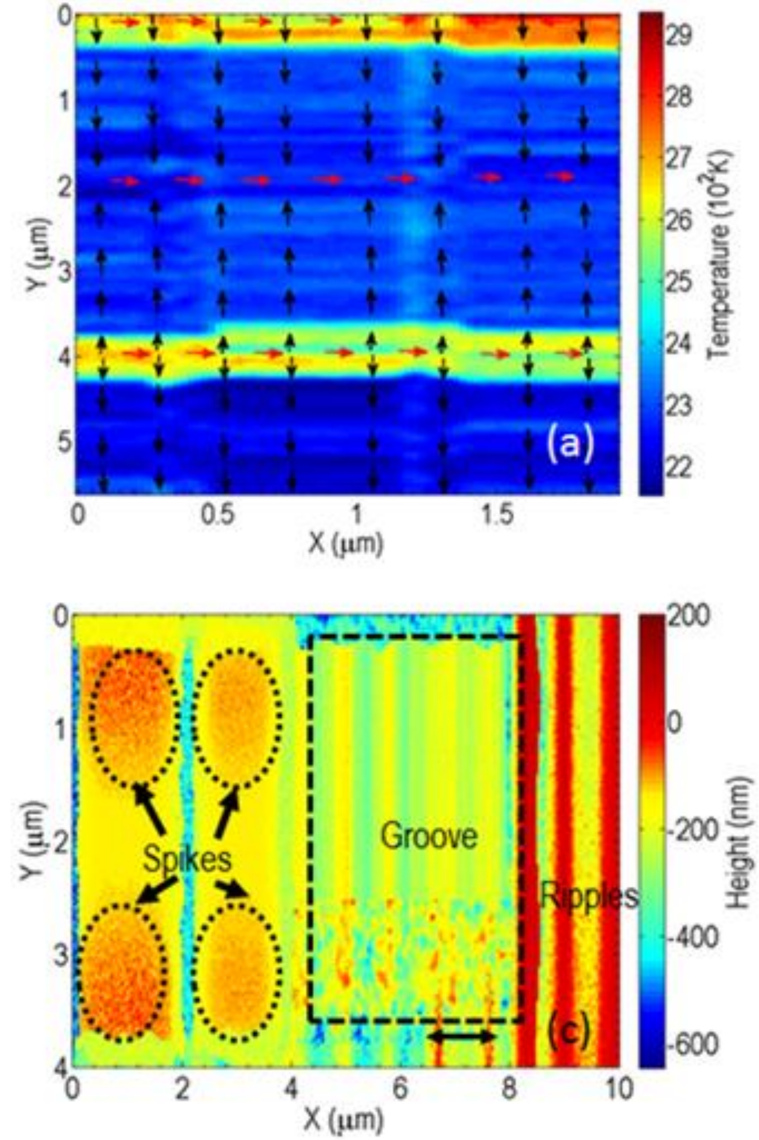


Phys. Rev. B, Rapid Comms, 92 (4), 041405 (2015)

μ-Spikes Formation



Experiment

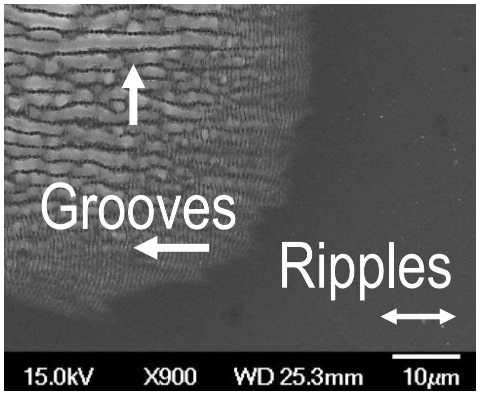


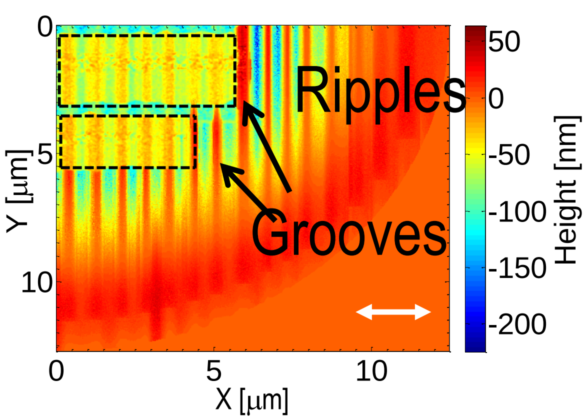
Simulation

Phys. Rev. B, Rapid Comms, 92, 041405 (2015)

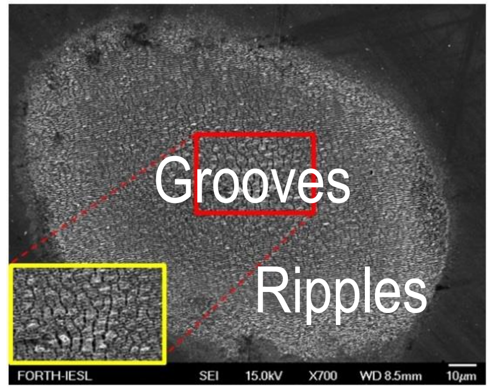
LIPSS formation on solid surfaces

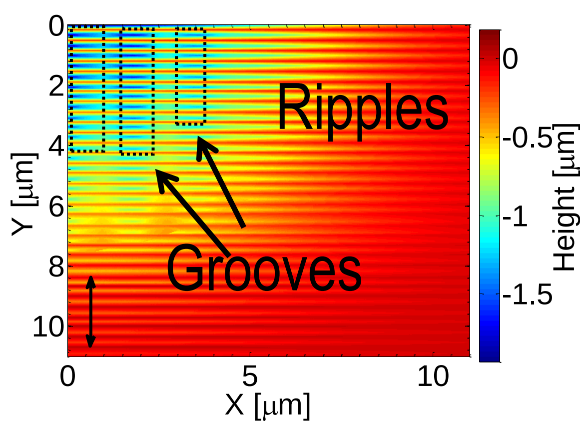
Si



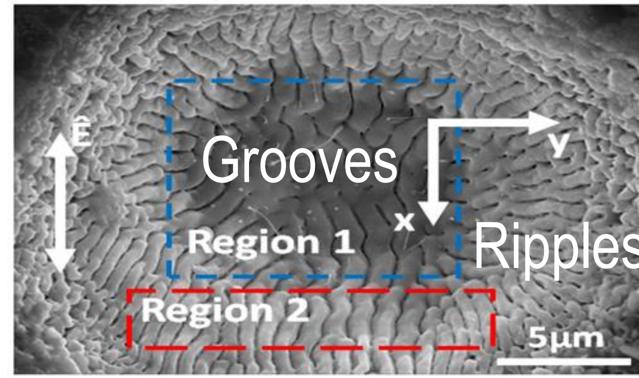


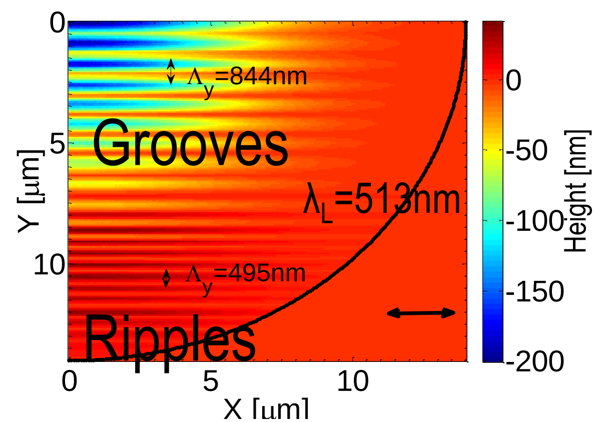
Steel-100Cr_6





SiO_2



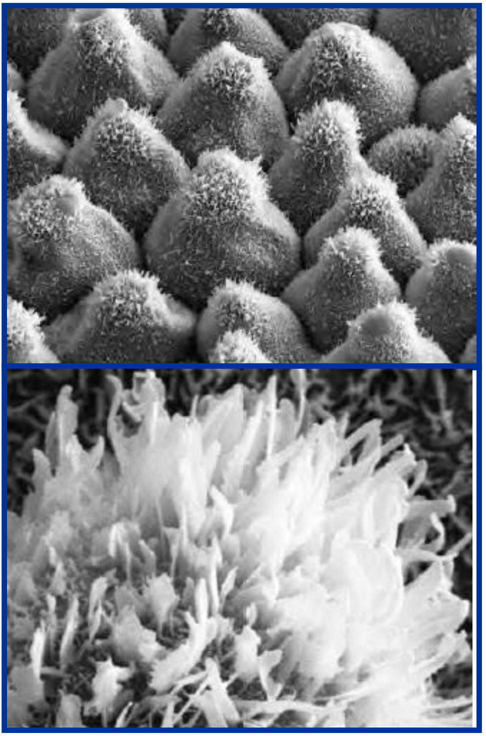


G.D.Tsibidis et al, PRB (2015), 92, 041405
G.D.Tsibidis, et al., PRB (2016), 94, 081305

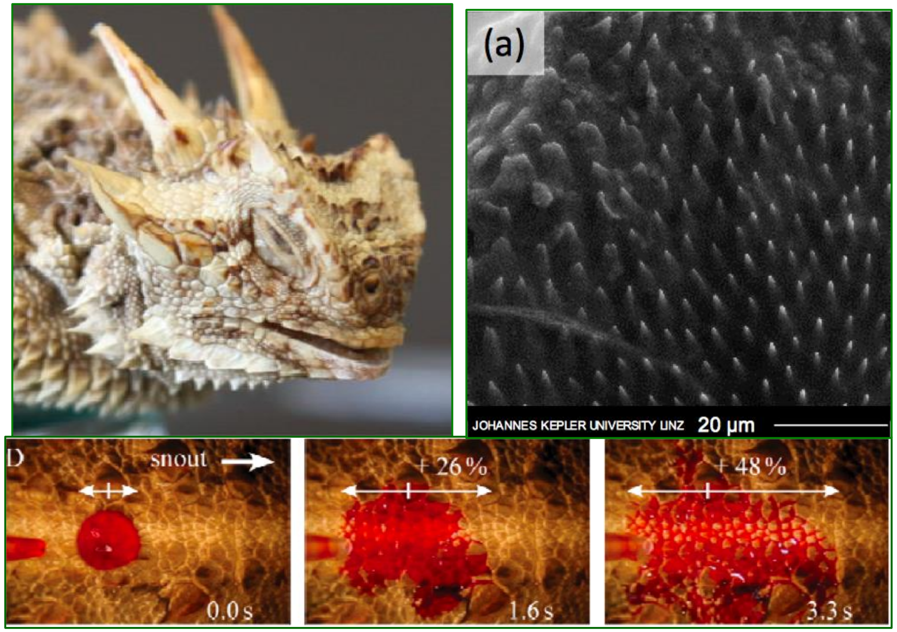
1. Biomimetic Surface Structuring

Biomimetic Surfaces: Inspired by Nature

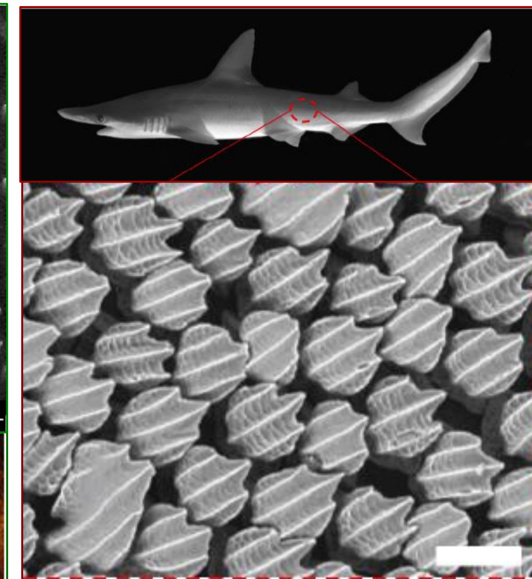
Biomimetics: “Bio” + “Mimesis”



Colocasia Leaf
Superhydrophobicity
Water Repellence
Self Cleaning



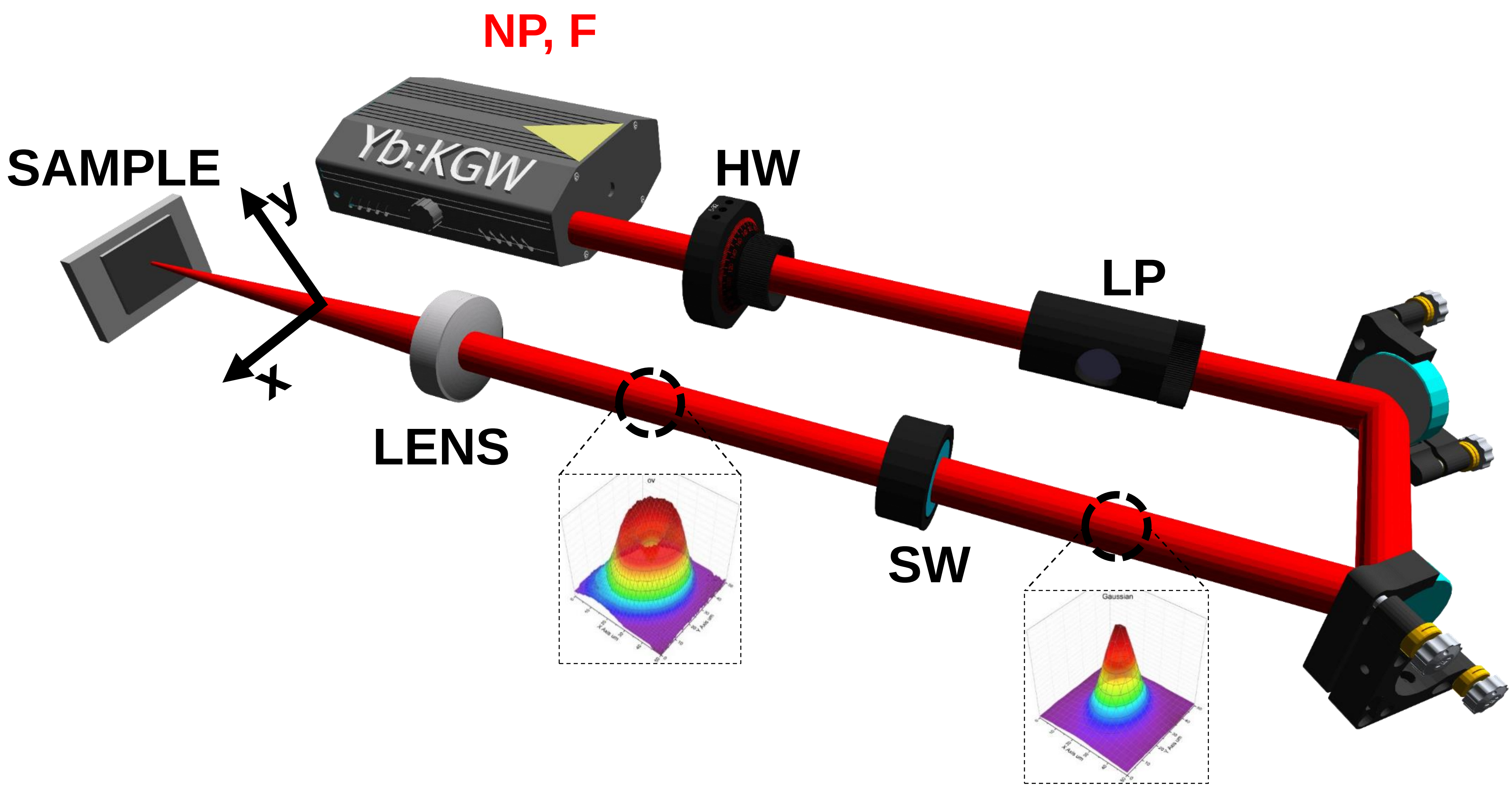
Lizards/Bugs Integument
Directional Fluid Transport



Shark Skin
Low Underwater Friction

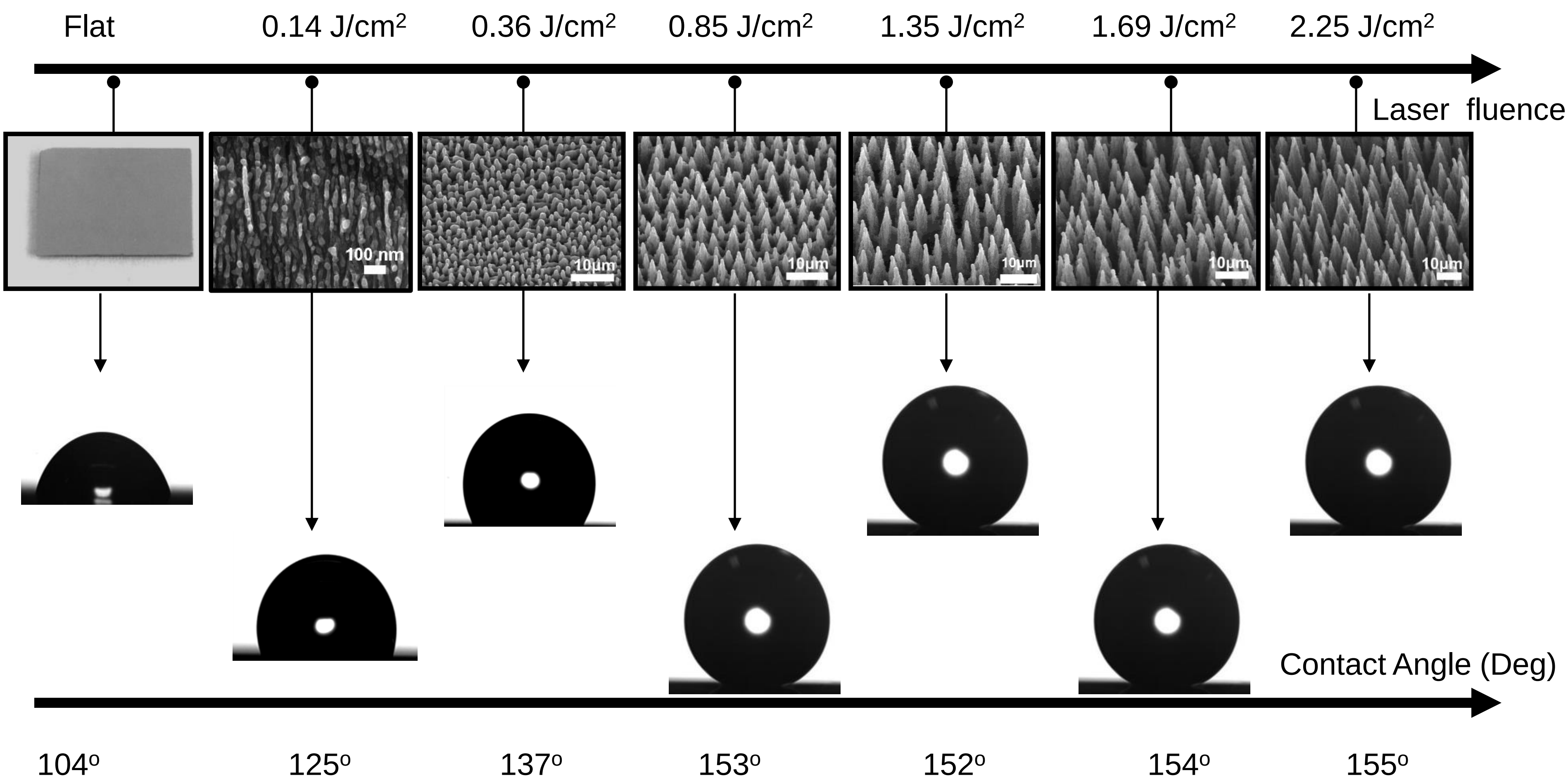
Greta-Oto Scales
Antireflection

Laser Based Fabrication of Biomimetic Surfaces



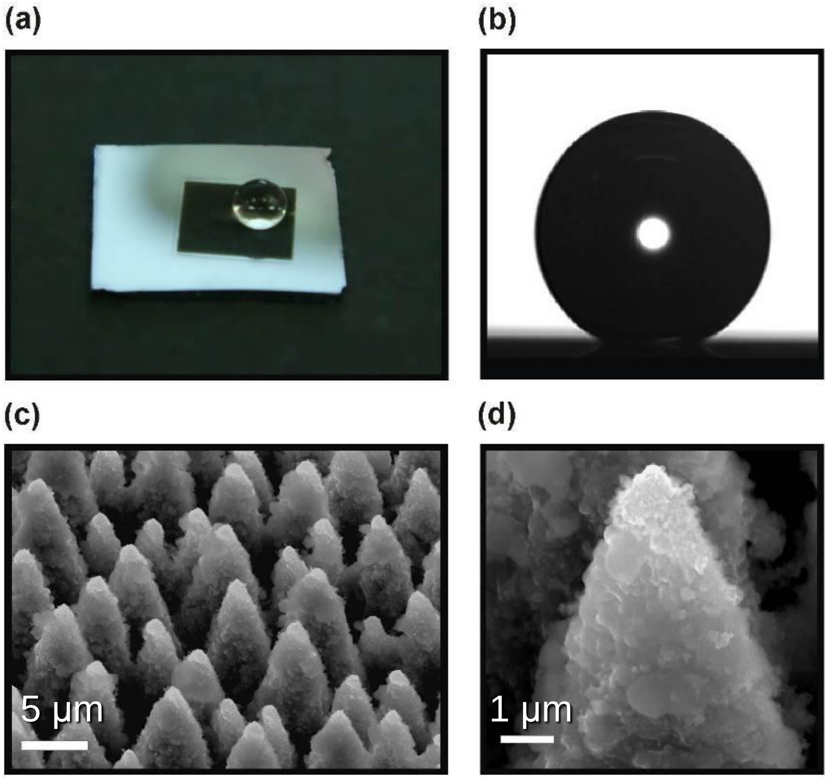
Biomimetic Surfaces for Extreme Wetting Properties

Silicon

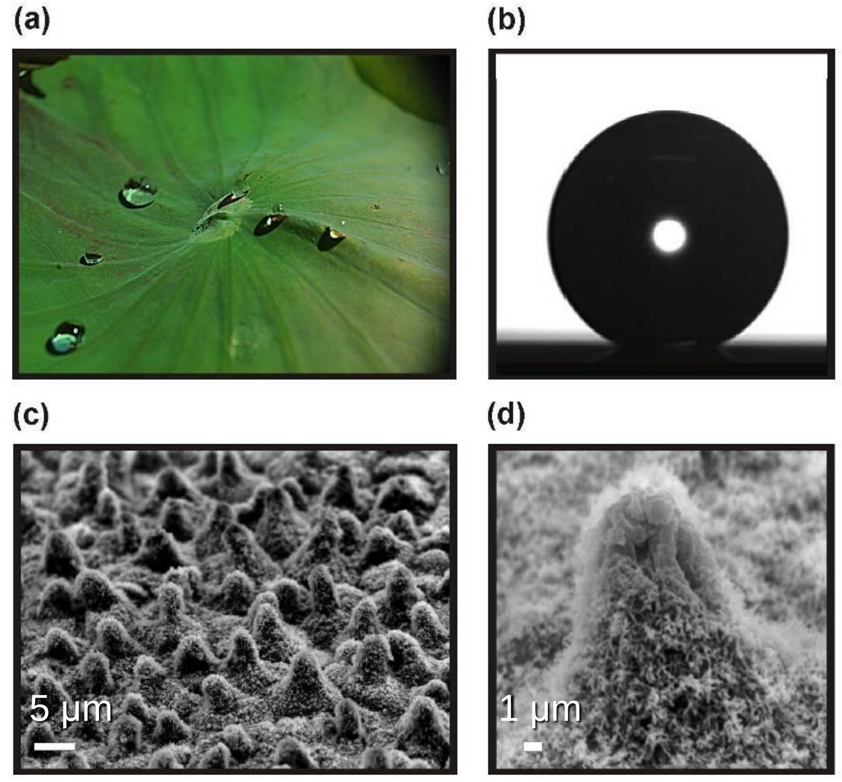


V. Zorba (2008)

Biomimetic Artificial Superhydrophobicity



Artificial Surface

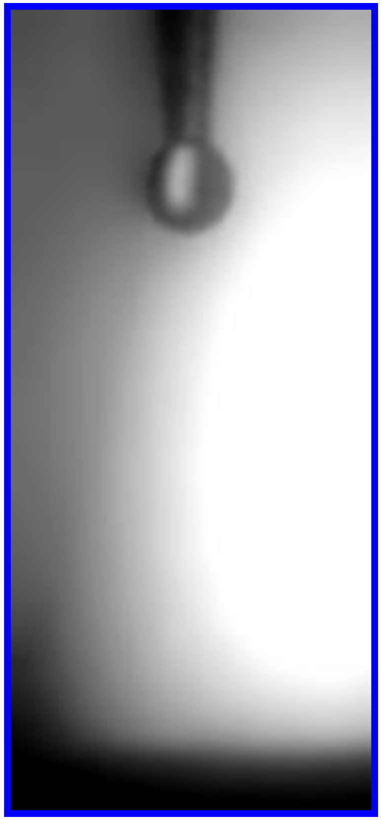


Lotus leaf

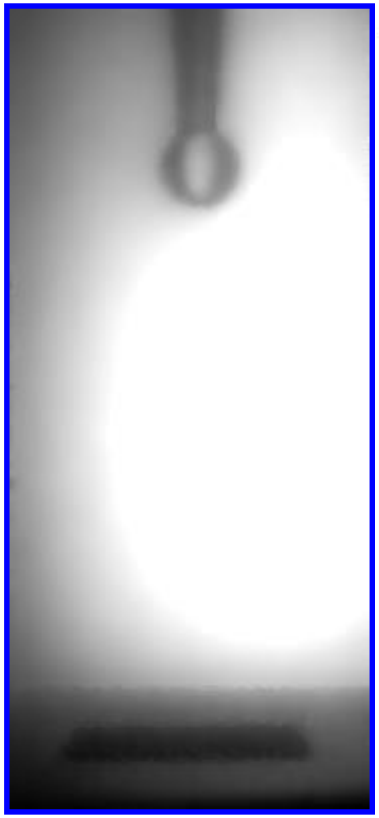
Collaborator: S. H. Anastasiadis

V. Zorba et al., Adv. Mat. 20, 4048 (2008)

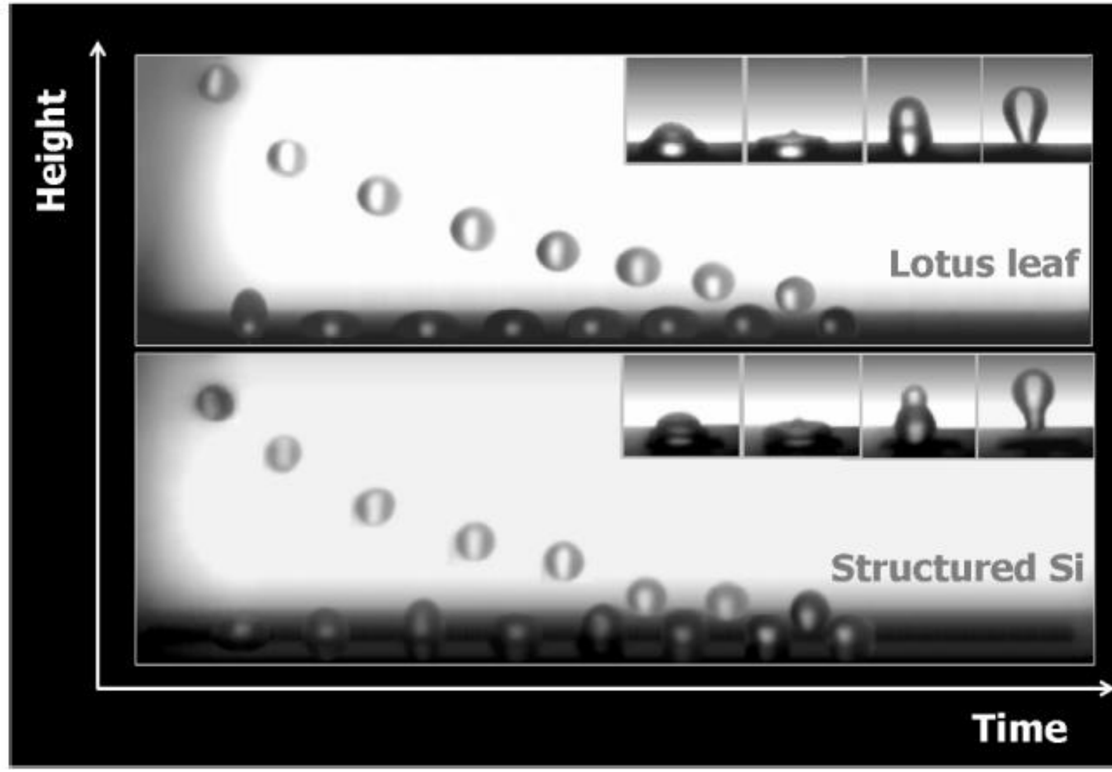
Dynamic Water Repellency



Natural



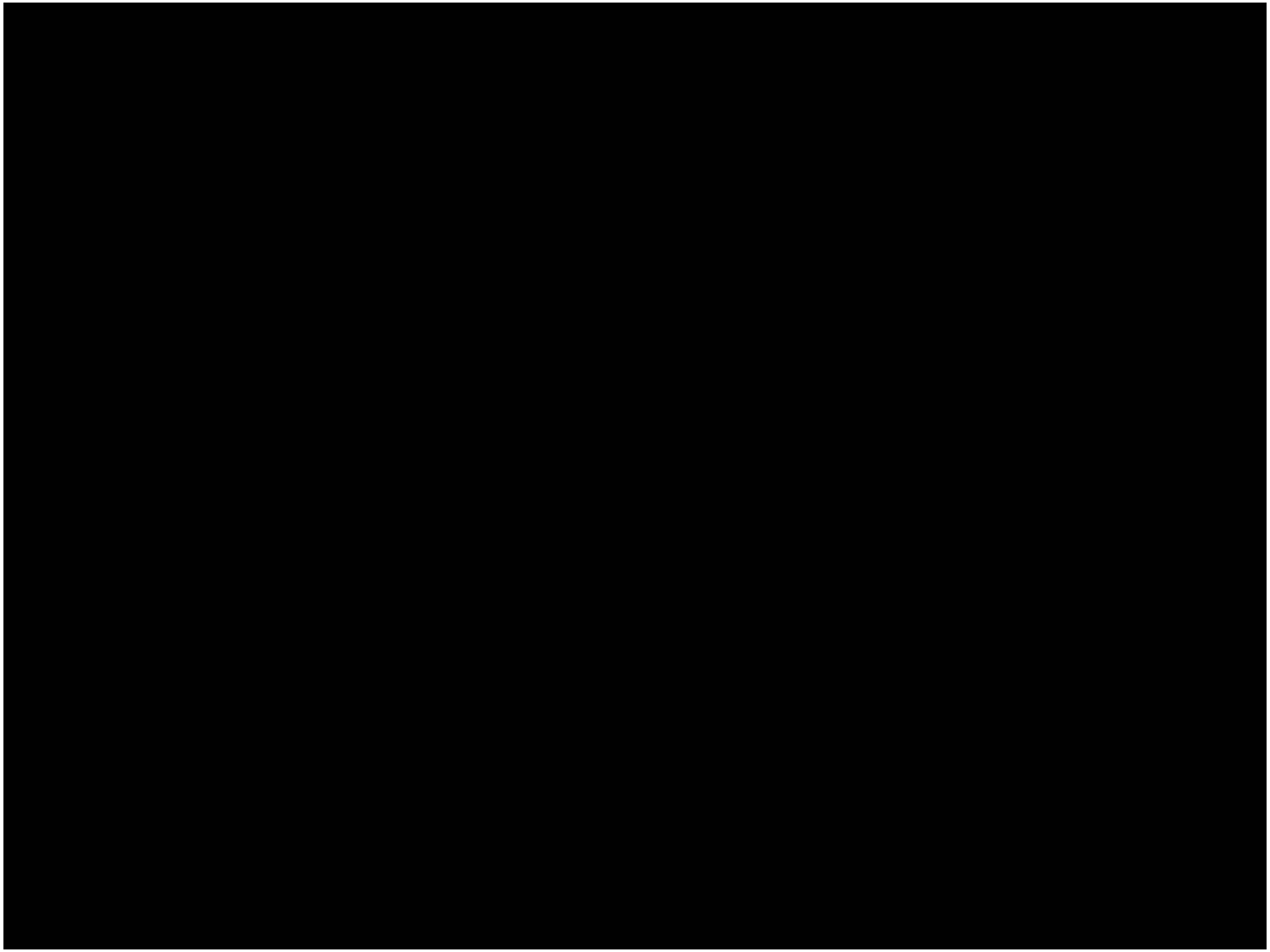
Artificial



Time sequence images of a 2.5 μl water droplet falling on a DMDCS coated laser structured Si surface
Frame rate: 500Hz

Adv. Mat. 20, 4048 (2008)

Water Running Uphill

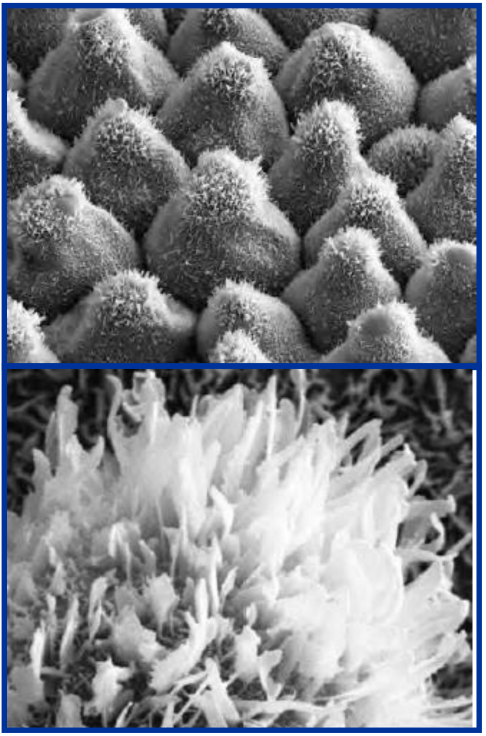


!!! Remarkable Velocity, v~500 mm/sec !!!

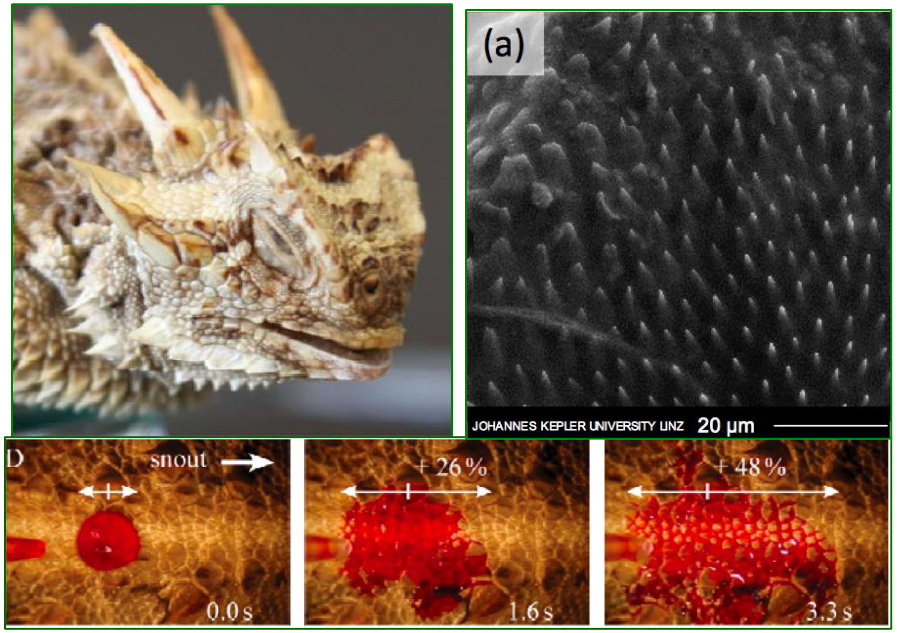
I. Paradisanos et al., Appl. Phys. Lett. 105, 041108 (2014)

Can we further increase the complexity ?

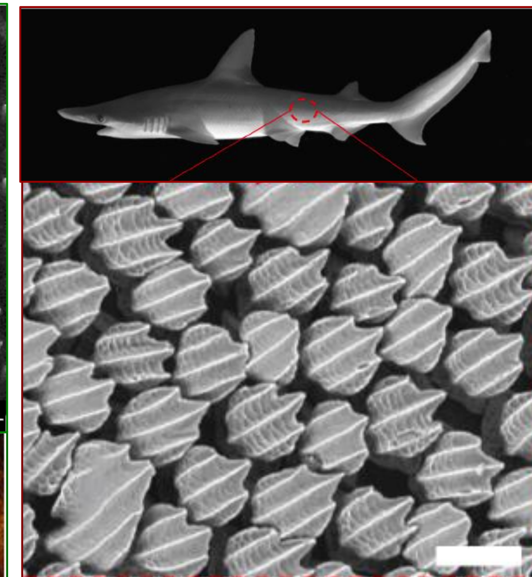
Biomimetics: “Bio” + “Mimesis”



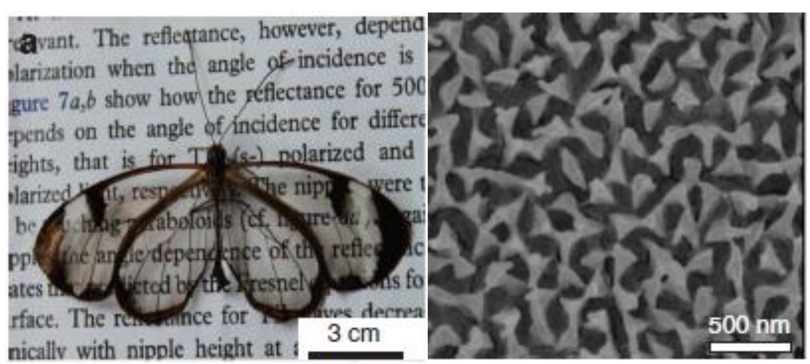
Colocasia Leaf
Superhydrophobicity
Water Repellence
Self Cleaning



Lizards/Bugs Integument
Directional Fluid Transport



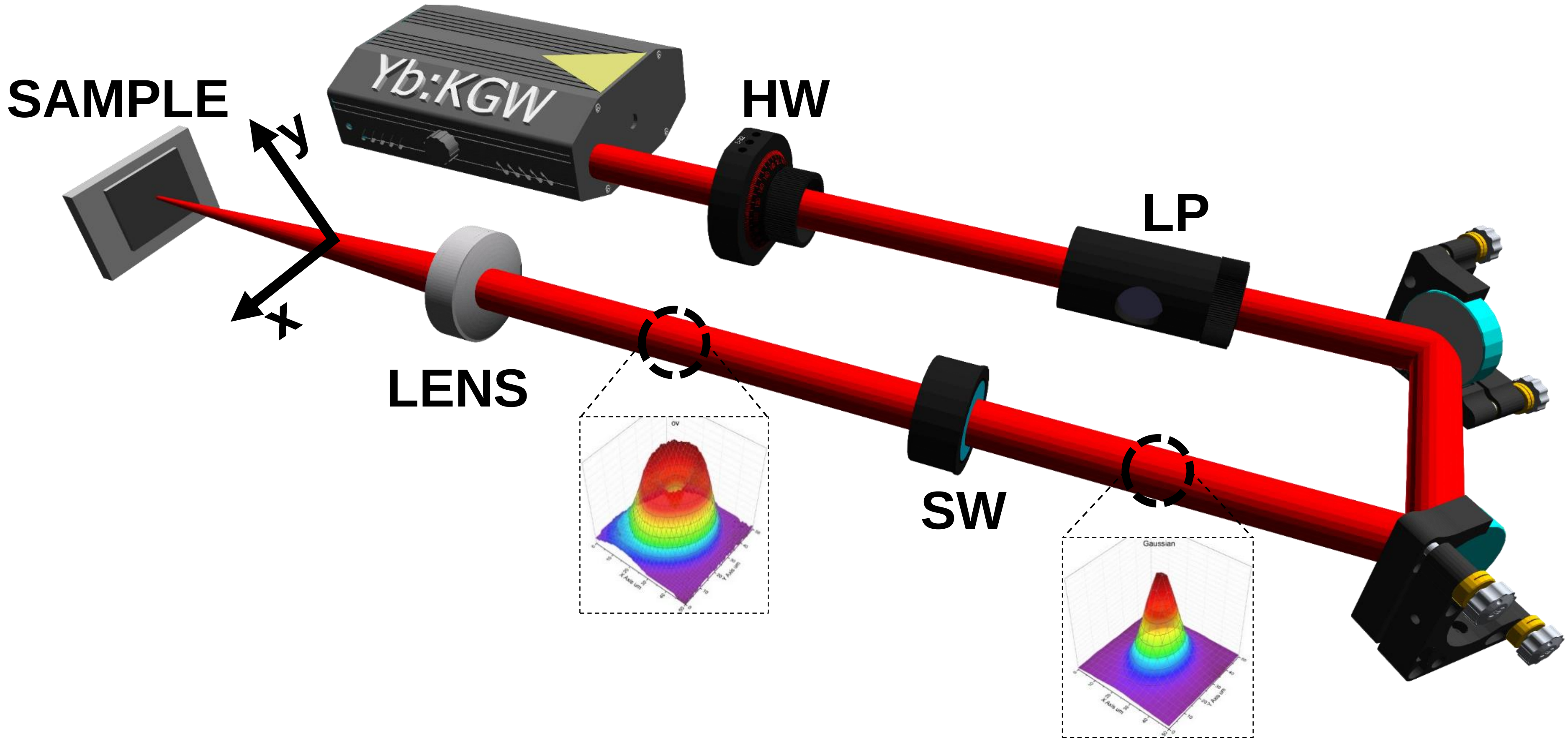
Shark Skin
Low Underwater Friction



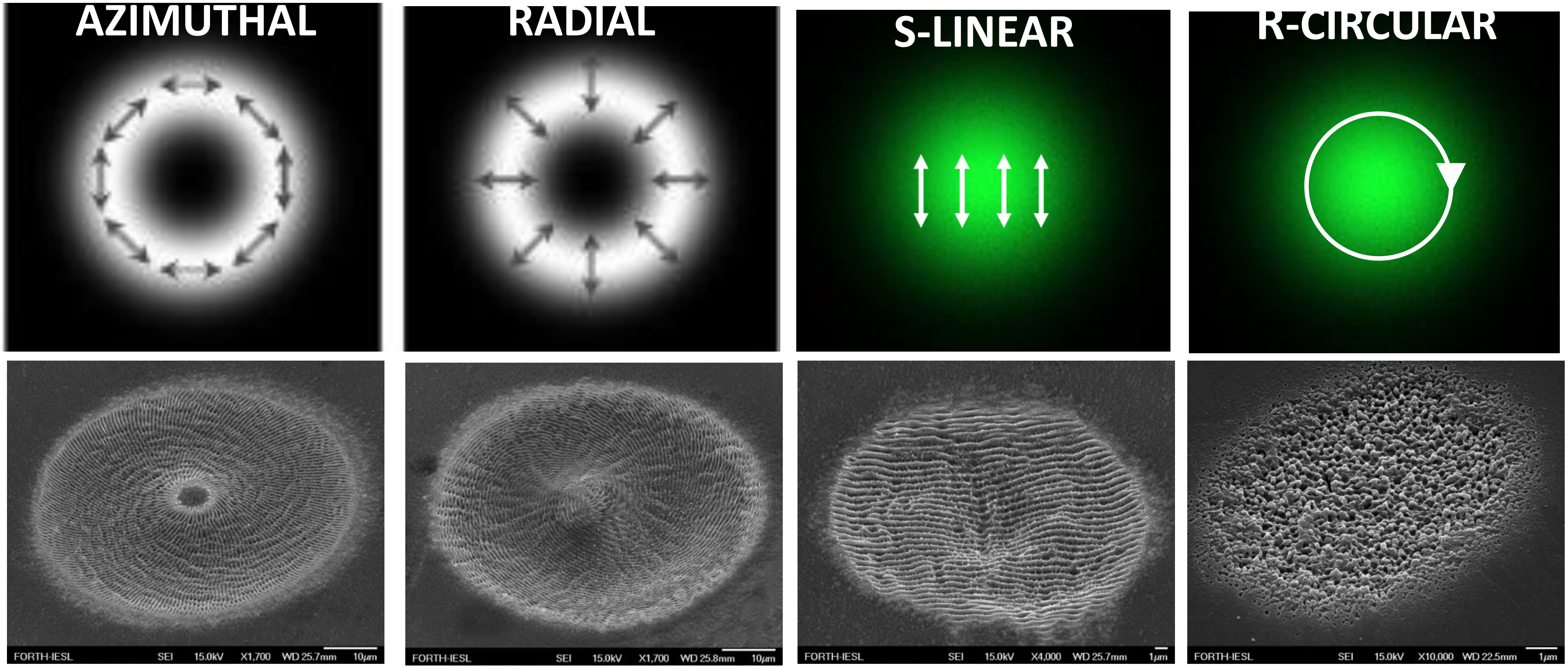
Greta-Oto Scales
Antireflection

Laser Based Fabrication of Biomimetic Surfaces

NP, F, Polarization State

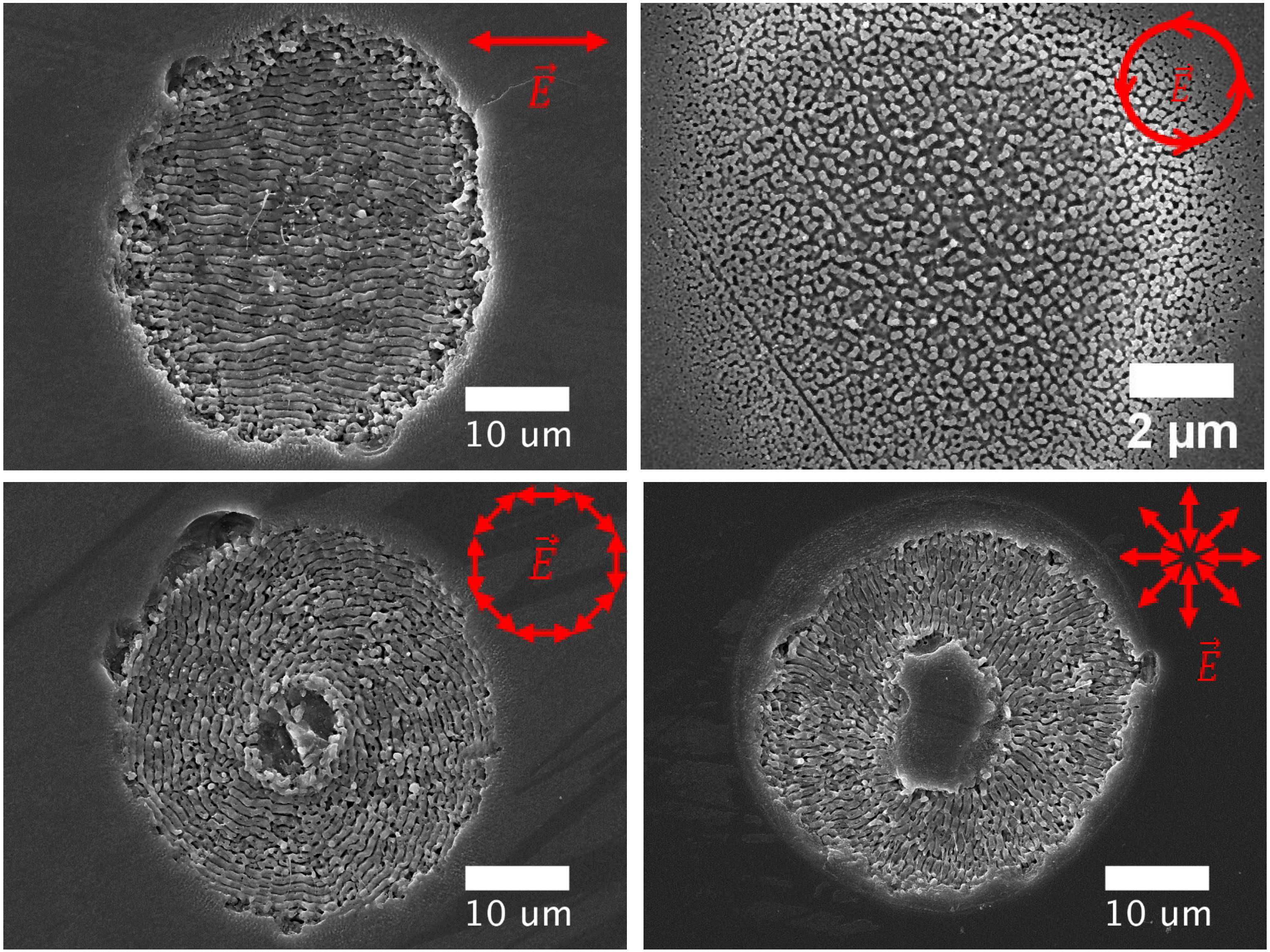


Processing with vectorial polarization beams

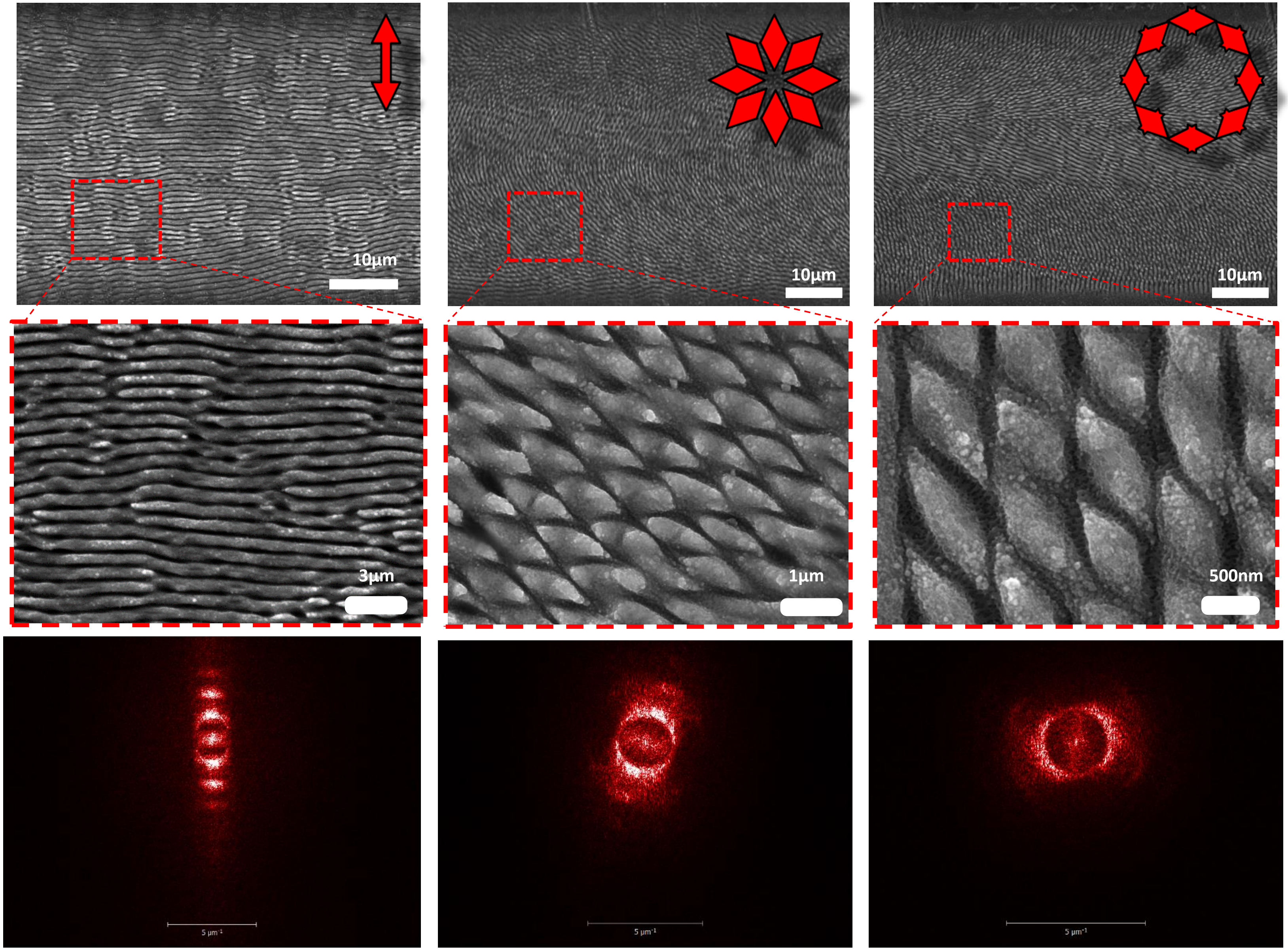


Skoulas et al., Opt. Lett. 40, 5172 (2015)

Transparent Materials: Fused Silica

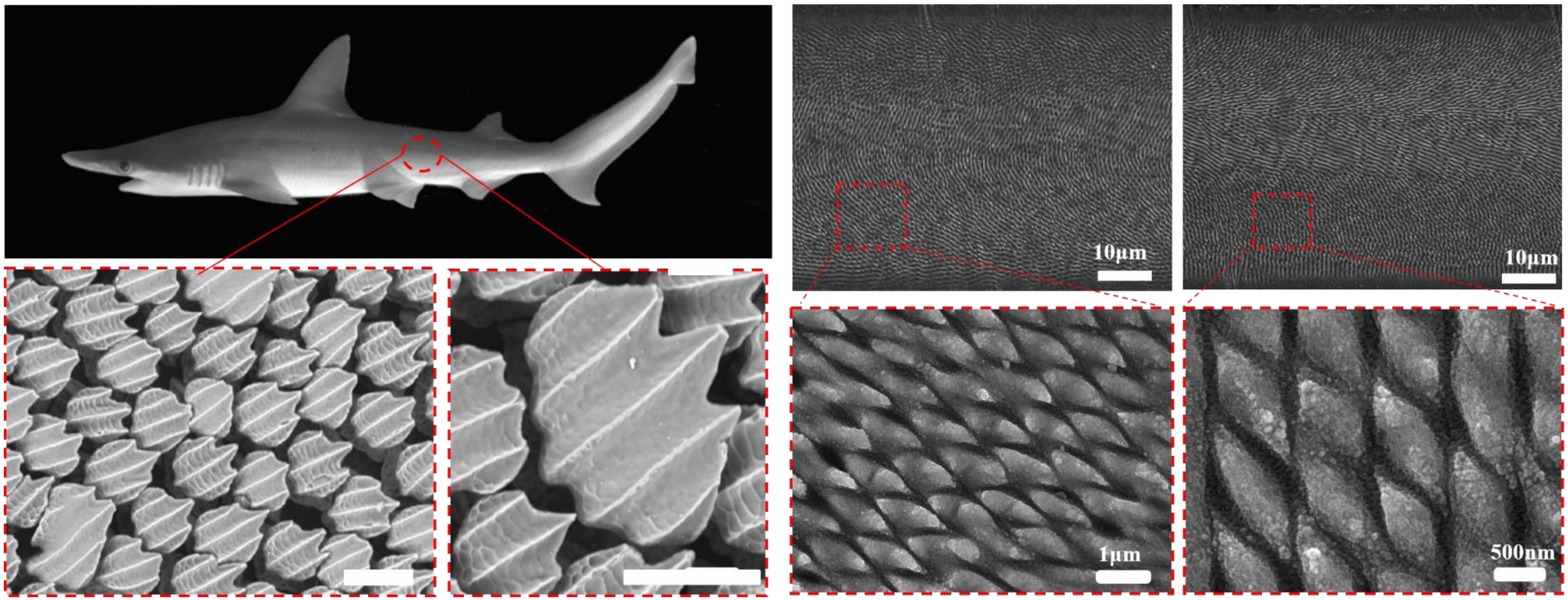


Line scanning with CV vs linear polarization



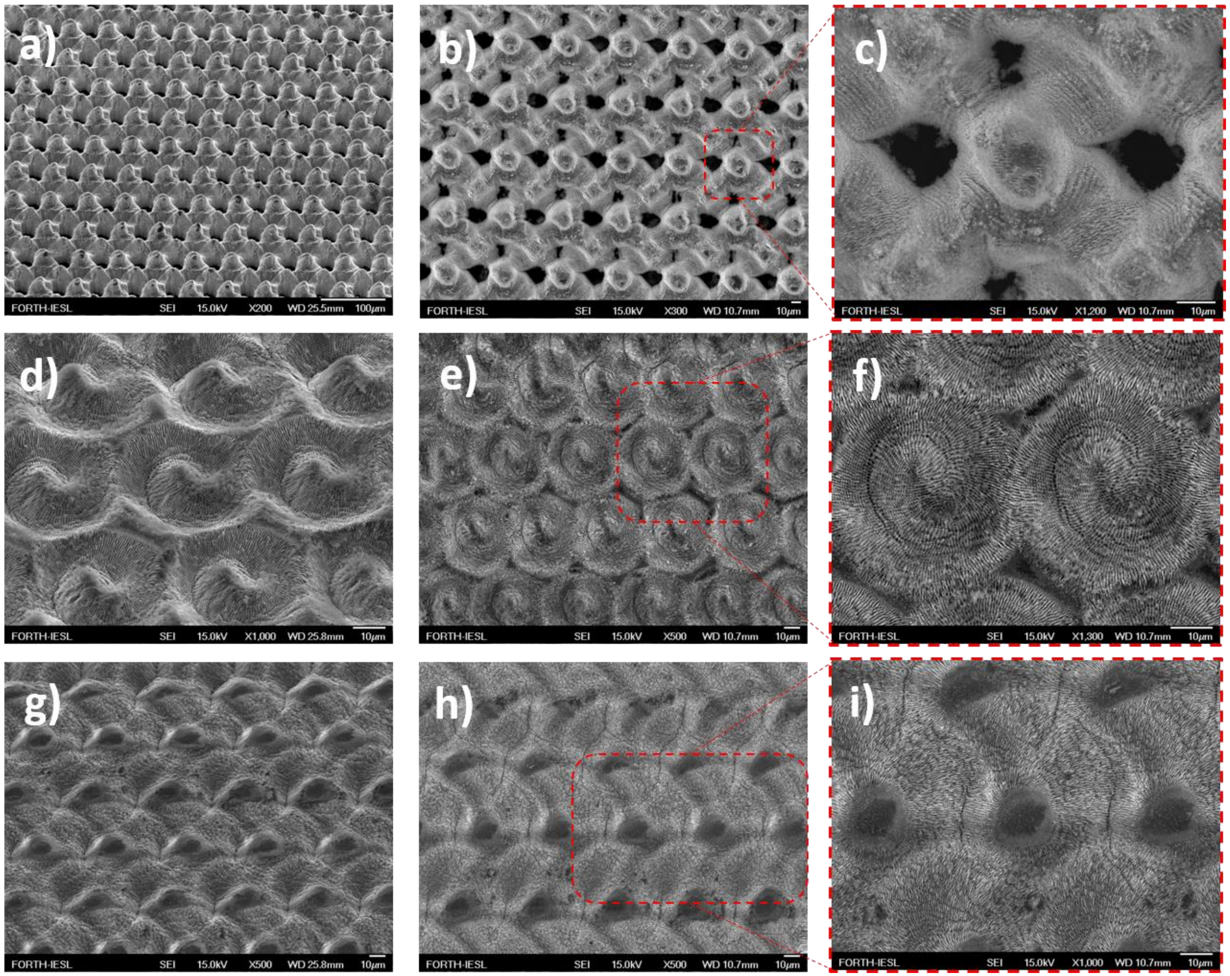
Skoulas et al., Scientific Reports (2017), 7, 45114

Laser processed ‘*shark*-skin’ surface



Skoulas et al., Scientific Reports (2017), 7, 45114

Spot by Spot scanning with CV beams



High roughness hierarchical surface:

- *φ=9.45J/cm²*
- *NP=500*
- *Radial polarization*

Dual periodicity at 60μm and 500nm

Medium roughness hierarchical surface:

- *φ=1.17J/cm²*
- *NP=400*
- *Azimuthal polarization*

Dual periodicity at 50μm and 520nm

Low roughness hierarchical surface:

- *φ=0.42J/cm²*
- *NP=600*
- *Azimuthal polarization*

Dual periodicity at 50μm and 480nm

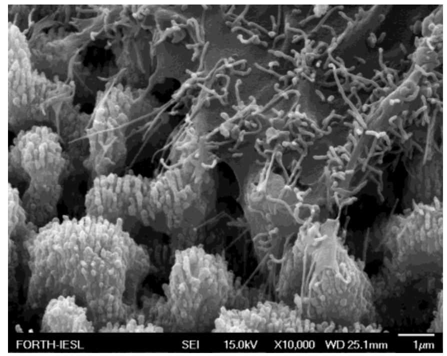
Skoulas et al., Scientific Reports (2017), 7, 45114

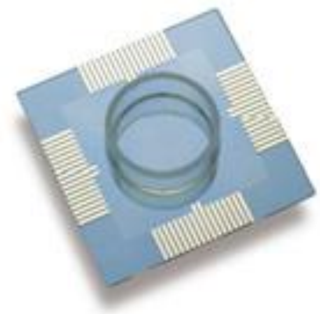
2. Laser structuring of surfaces for neural tissue engineering applications

Neuronal cells on structured surfaces

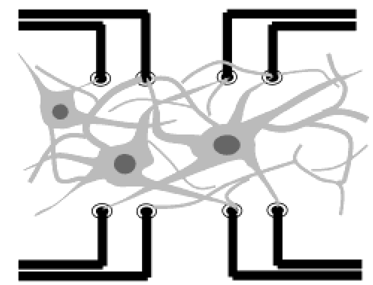
Collaborators: A. Ranella (IESL), A. Gravanis (IMBB), I. Charalampopoulos (UoC) I. Athanassakis (UoC)

I. Cell culture conductive micro/nano platforms (adhesion, orientation, differentiation)

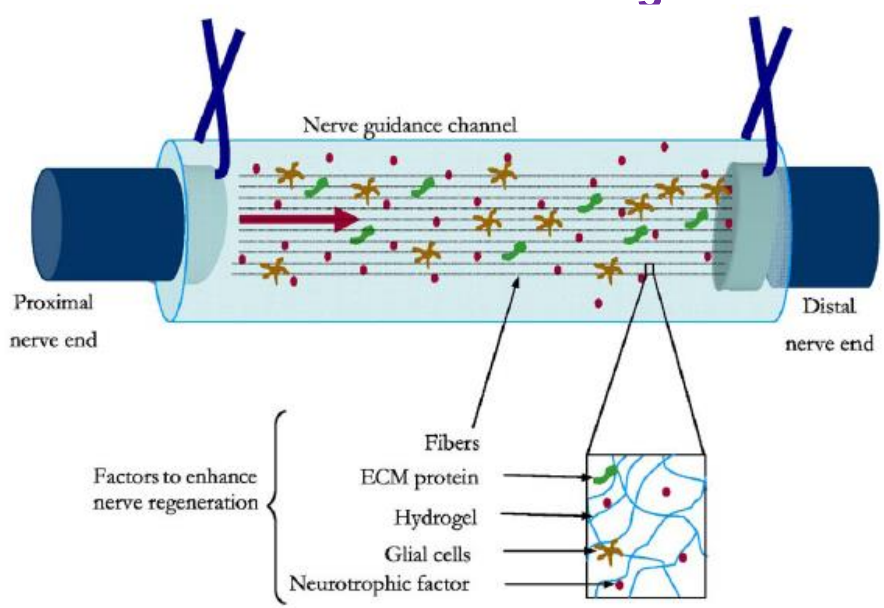




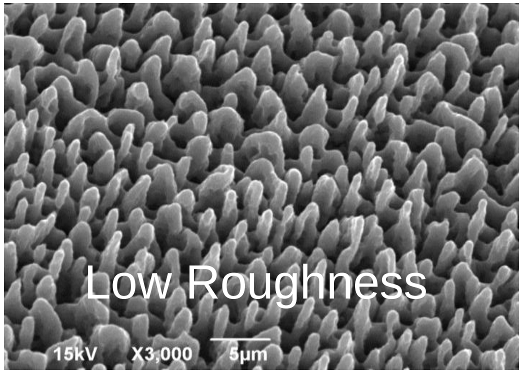
II. Neuronal network interface (Neurochip)

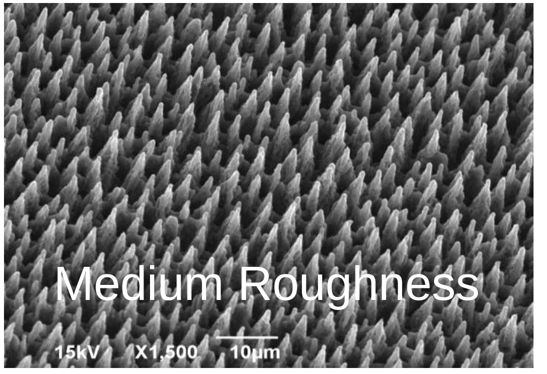


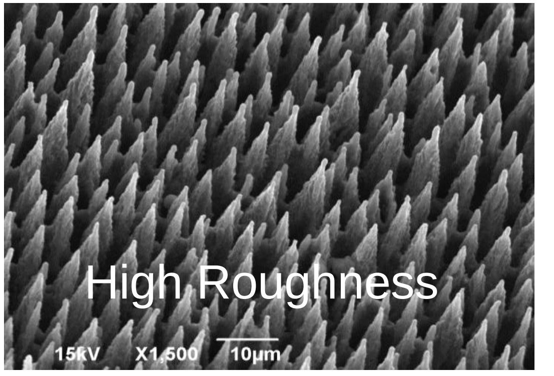
GOAL: Tissue engineering scaffolds for nerve tissue regeneration



Impact on Neuronal Network Morphology

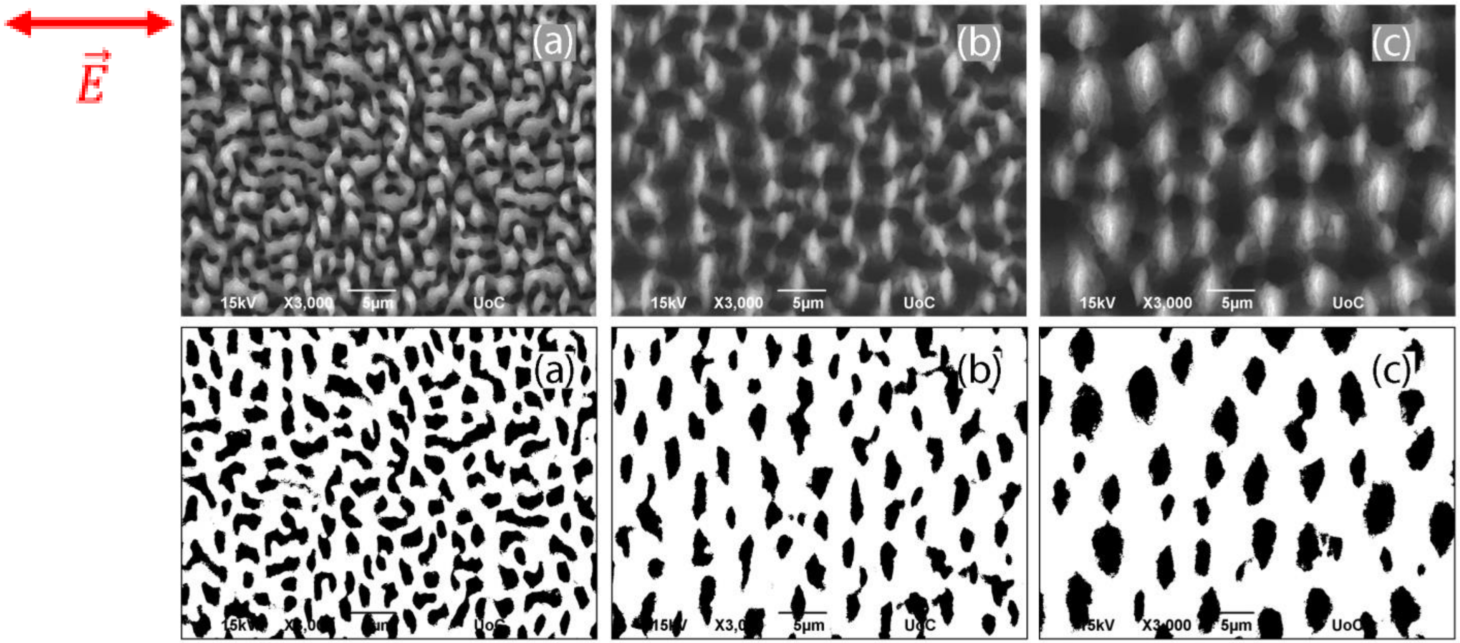


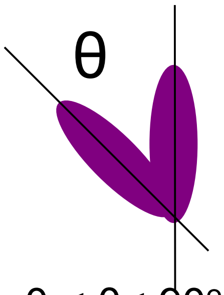




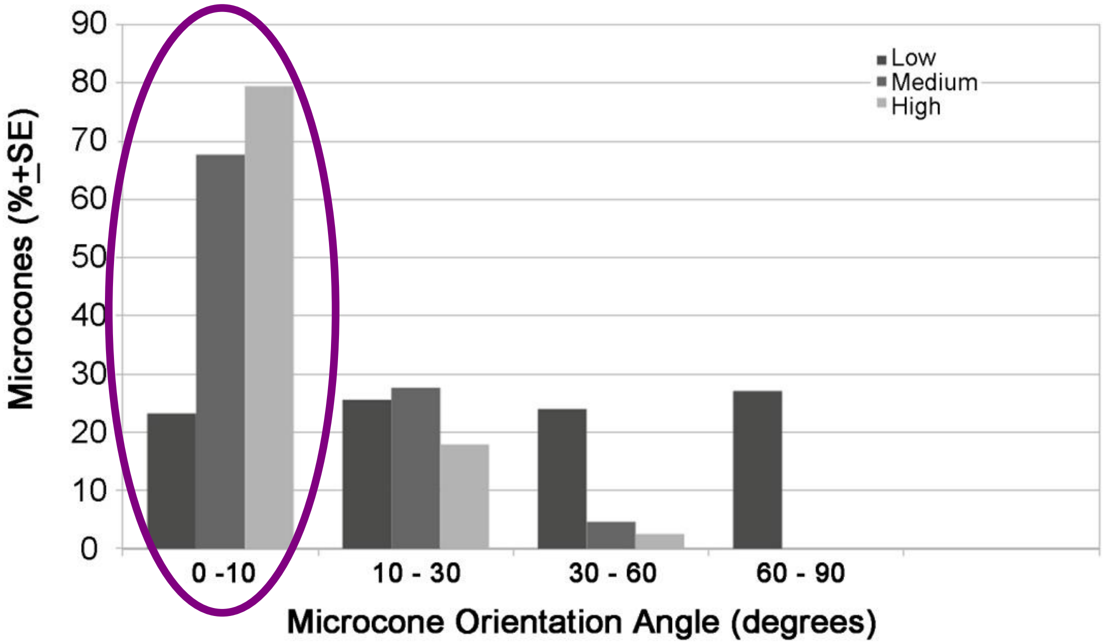
Collaborators: A. Ranella (IESL), A. Gravanis (IMBB), I. Charalampopulos(UoC), I. Athanassakis (UoC)

Directionality depends on laser polarization





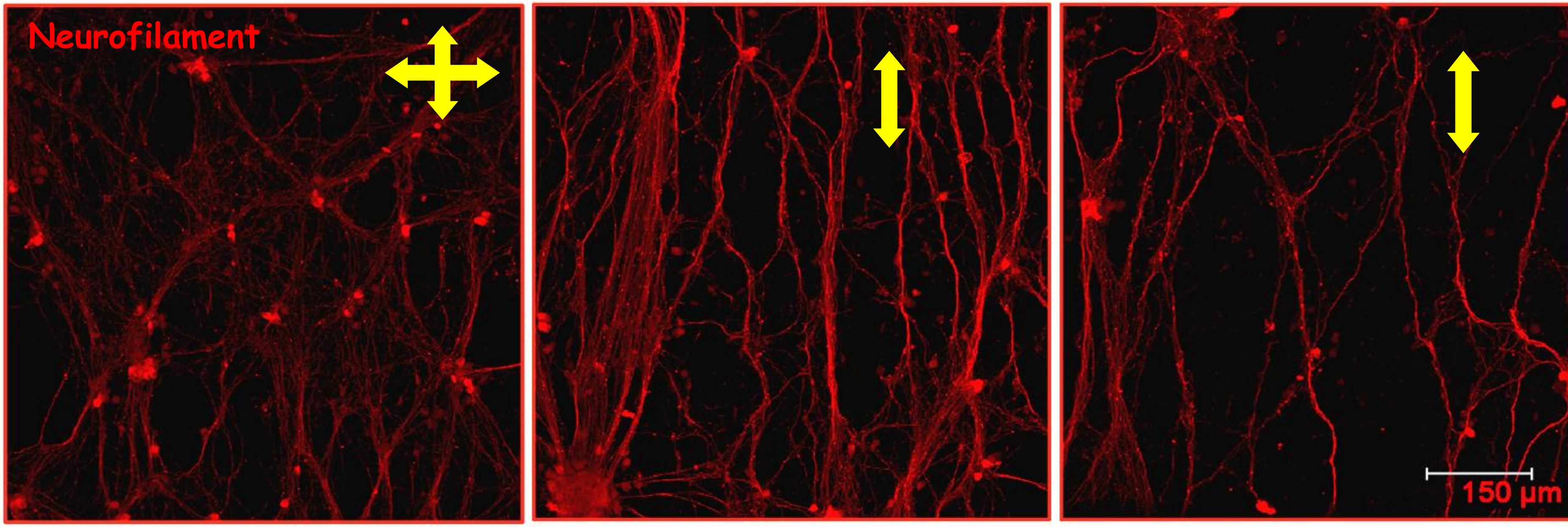
With 0 < θ< 90º



Ellipsoidal cross section

Preferential orientation

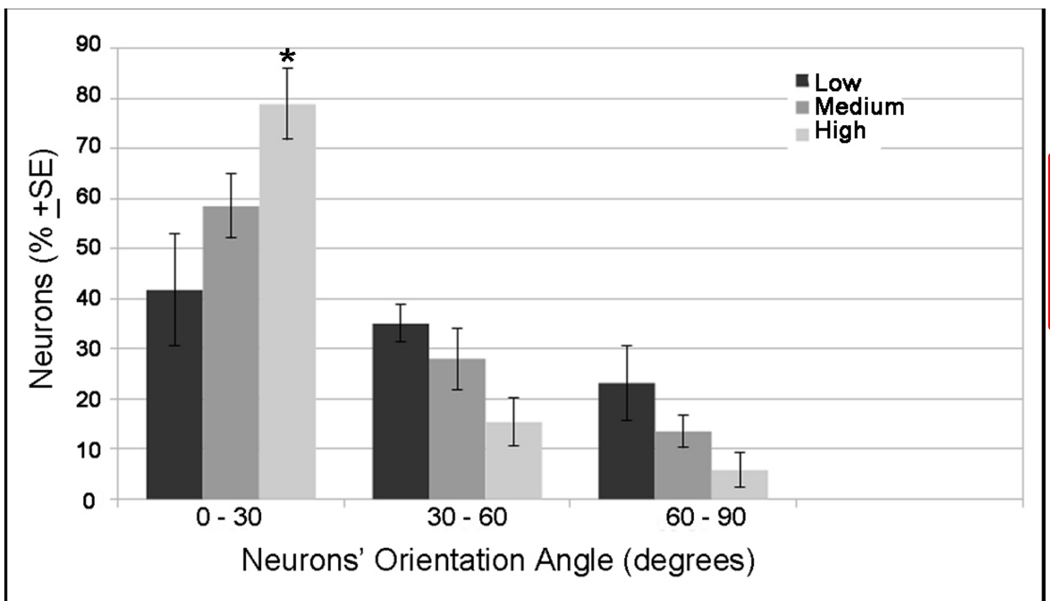
Neuronal Network Morphology



Low Roughness

Mid Roughness

High Roughness



Network morphology induced by the surface topography?

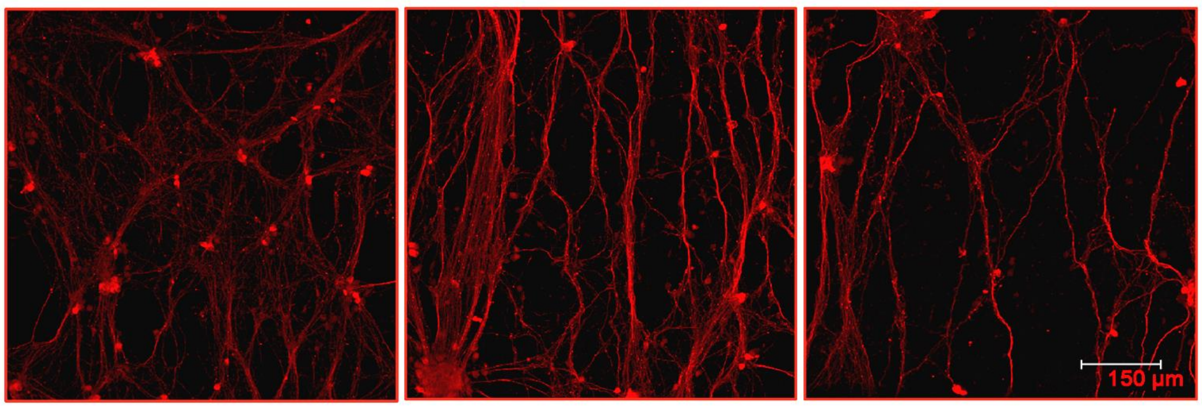
Biomaterials 67, 115 (2015)

SCGs Neurons – μStructures interaction


Contents lists available at ScienceDirect
Biomaterials
journal homepage: www.elsevier.com/locate/biomaterials
ELSEVIER

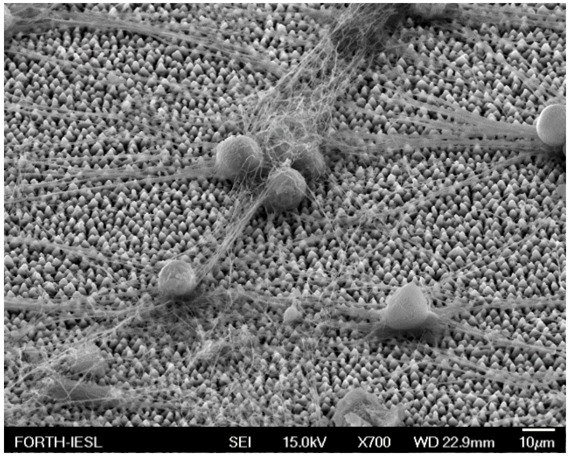
Laser fabricated discontinuous anisotropic microconical substrates as a new model scaffold to control the directionality of neuronal network outgrowth

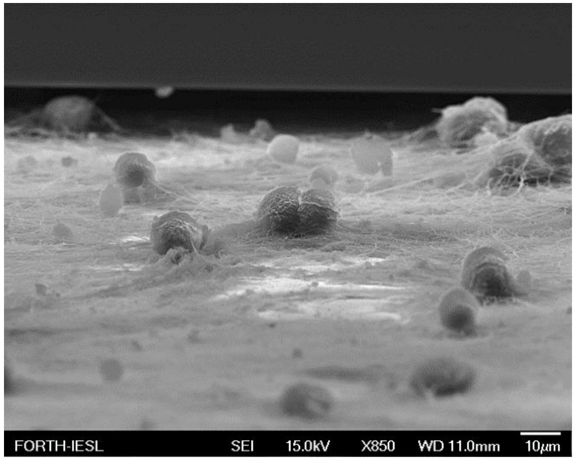
C. Simitzi [a, b, 1], P. Efstathopoulos [c, 1], A. Kourgiantaki [c], A. Ranella [a], I. Charalampopoulos [c], C. Fotakis [a, d], I. Athanassakis [b], E. Stratakis [a, e, *], A. Gravanis [a, c]



Low Roughness **Medium Roughness** **High Roughness**

Biomaterials 67, 115 (2015)



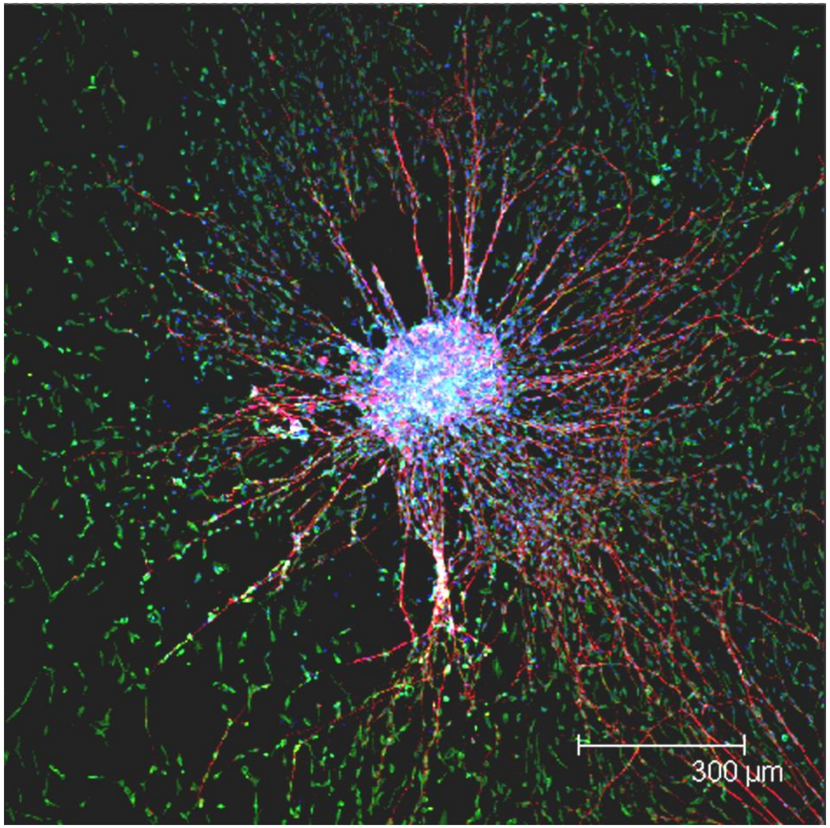


Neurons contact with the upper part and the tips of the spikes, both of which are elliptically-shaped

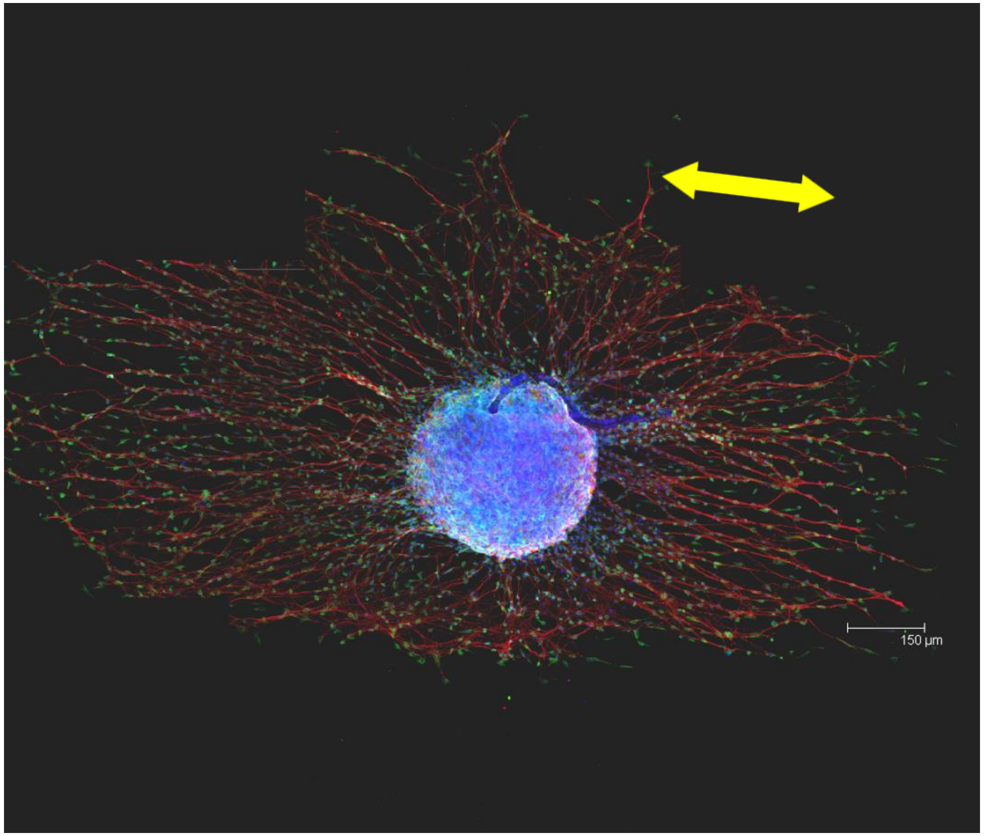
Culture of whole DRG Explants

S100: Schwann Cells
Topro: Nuclei
NF: Neurons

E13.5
Mouse



Low Roughness
Isotropic Cell Outgrowth

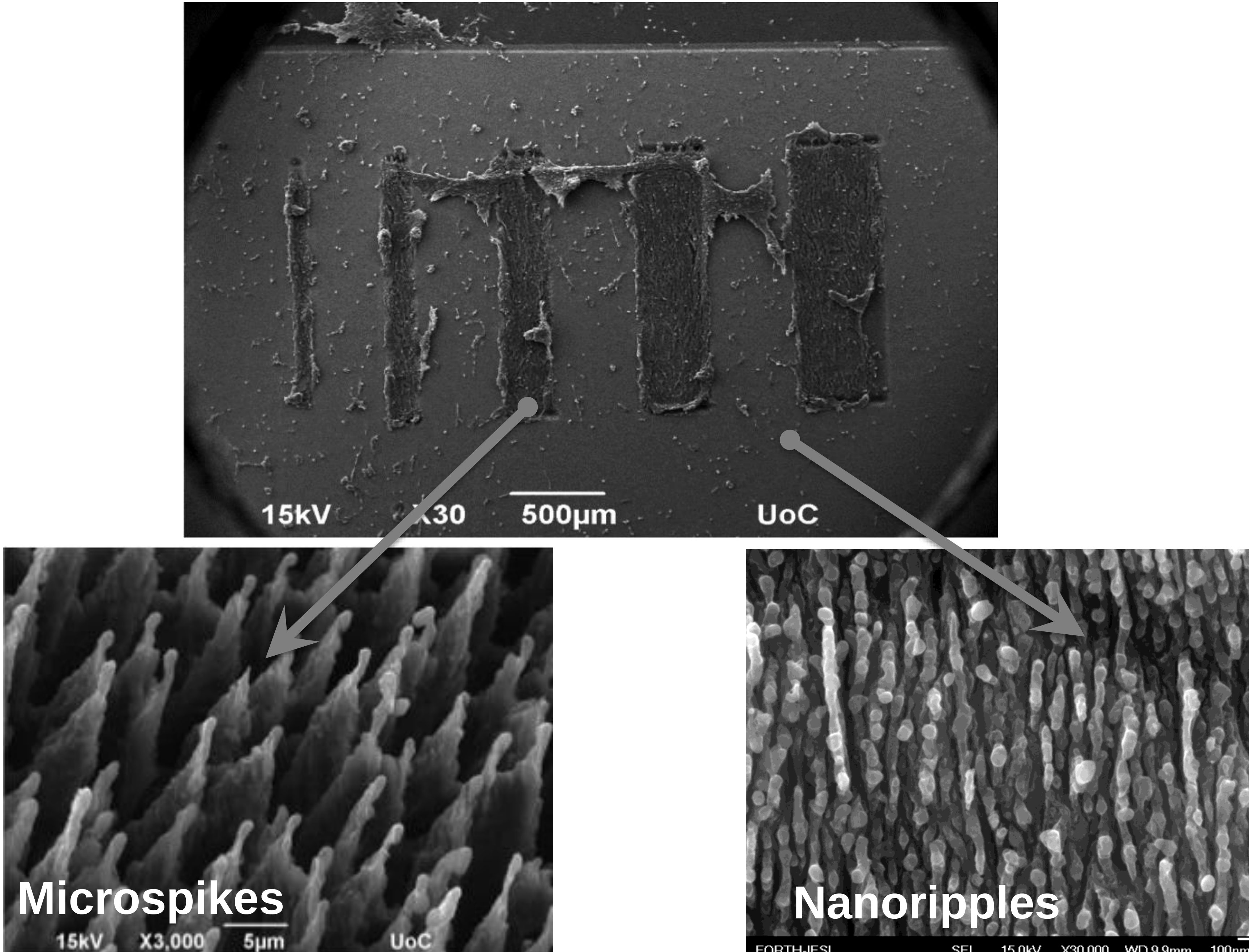


High Roughness
Anisotropic Cell Outgrowth

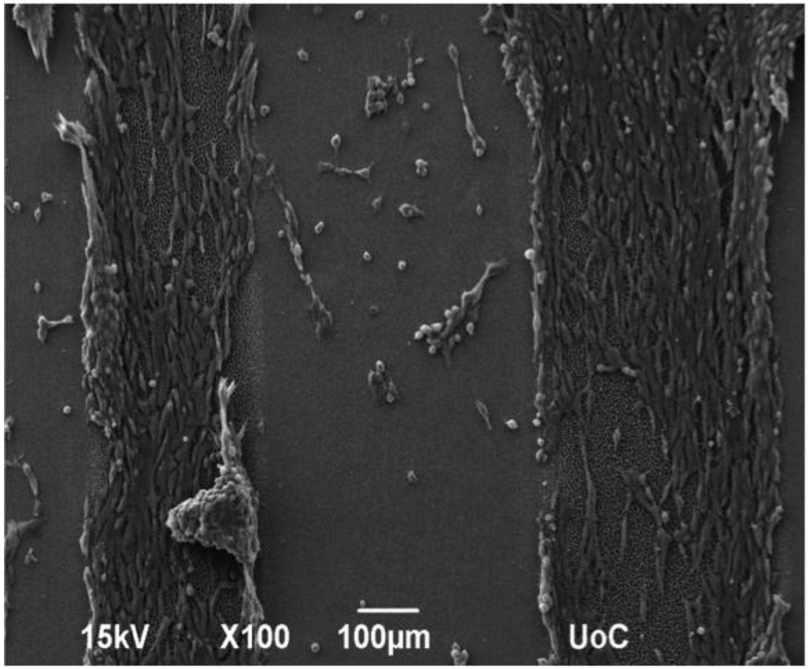
Ch. Simitzi

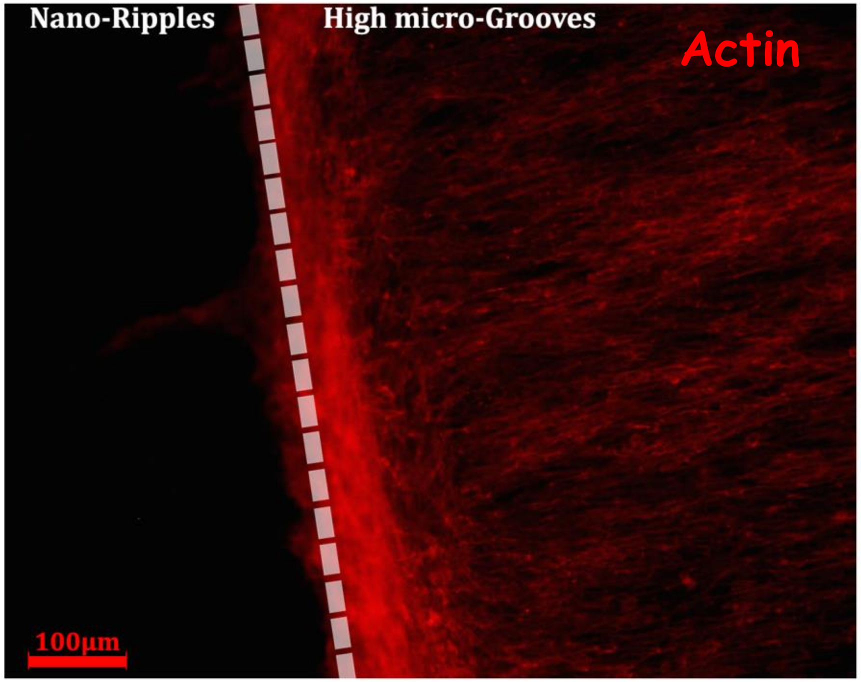
Biomaterials 67, 115 (2015)

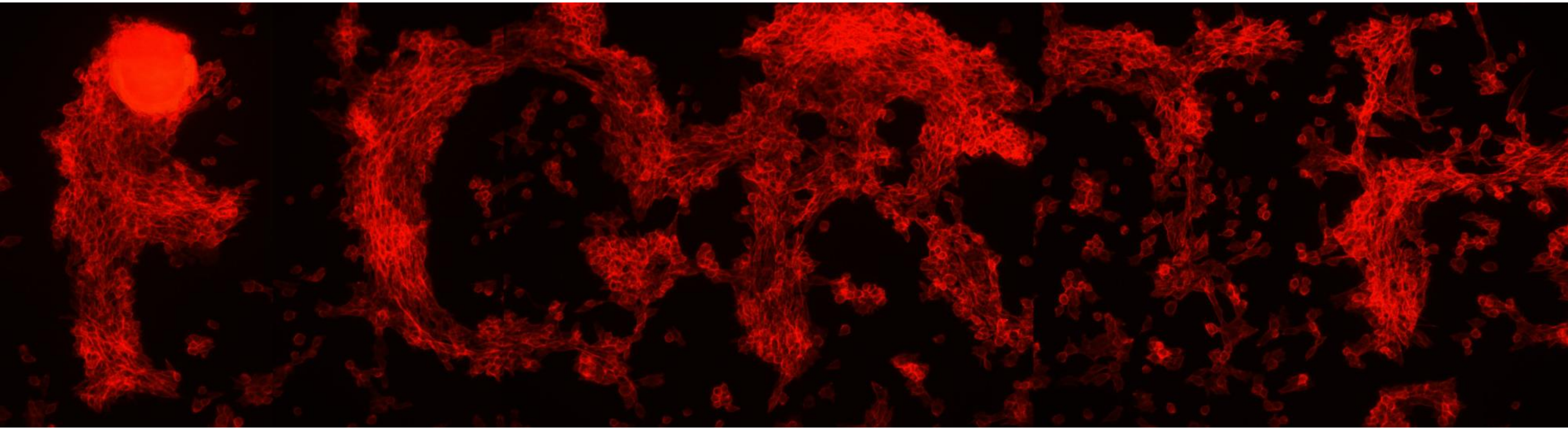
Patterning of Neurons



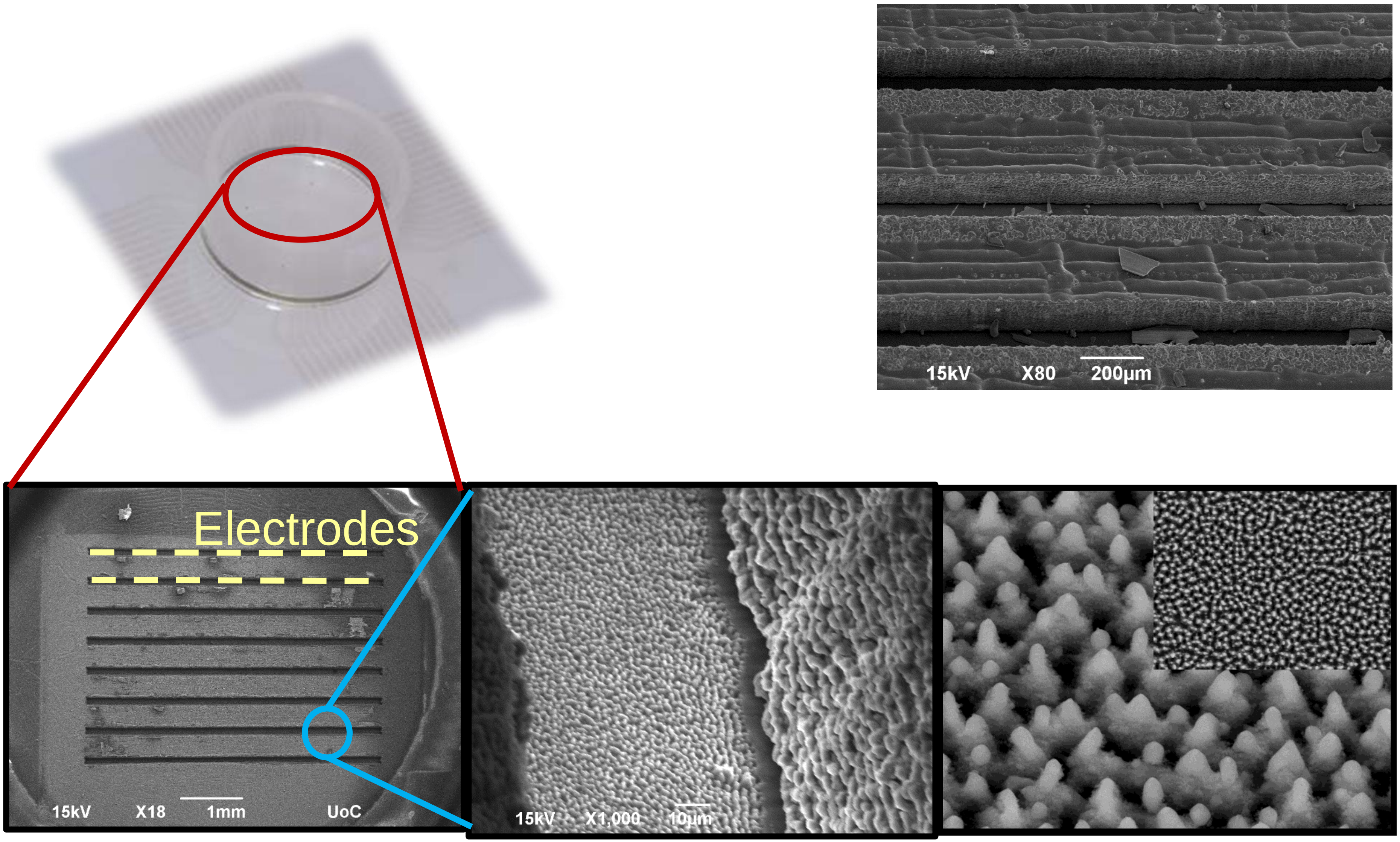
Patterning of Neurons







μ-spike Si Multielectrode Arrays (MEAs)



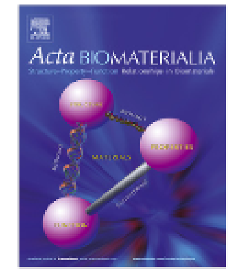
REVIEW

Contents lists available at ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat

ELSEVIER



Review article

Controlling the morphology and outgrowth of nerve and neuroglial cells: The effect of surface topography

CrossMark

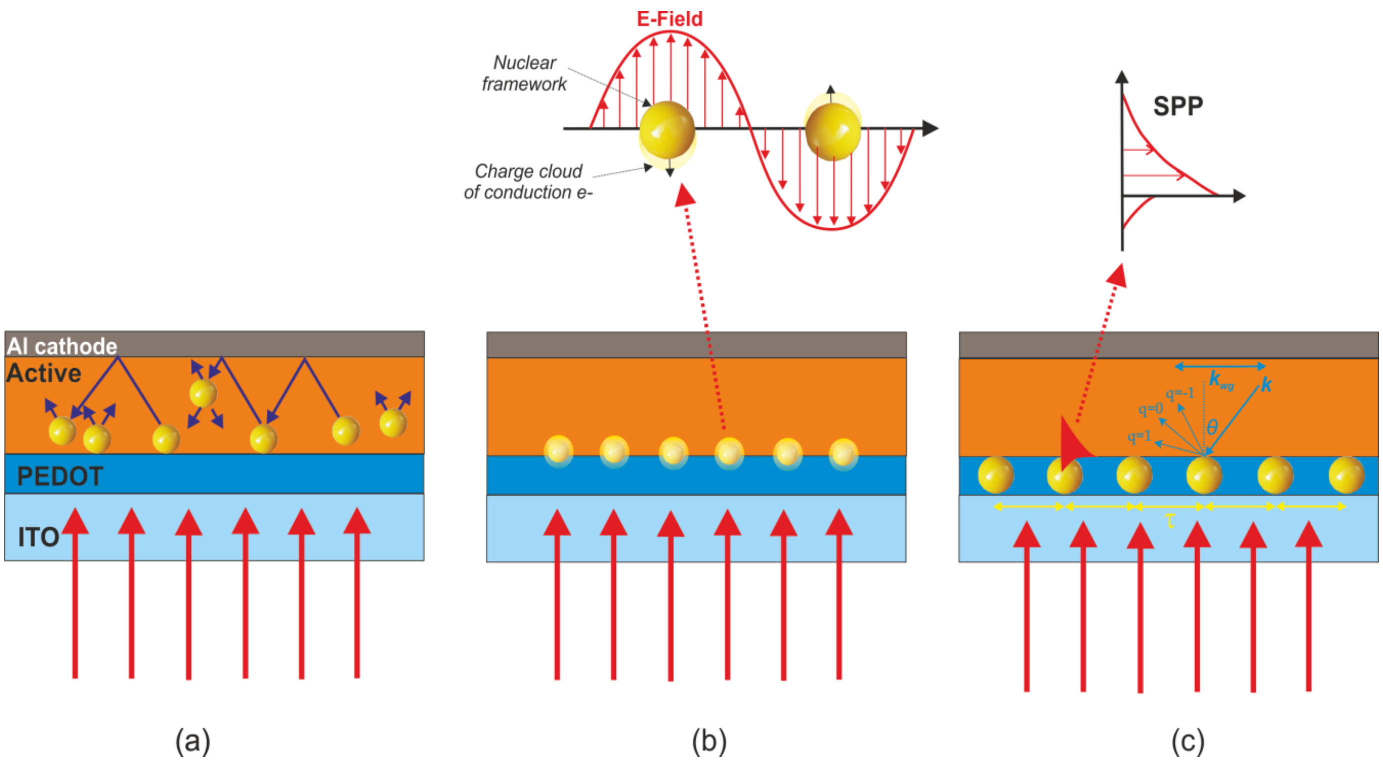
C. Simitzi, A. Ranella, E. Stratakis *

3. Nanomaterials’ Synthesis and Functionalization for New Generation Photovoltaics

Collaborator: Emmanuel Kymakis, TEIC

Light Harvesting in Organic Solar cells (OSCs)

Increasing OSCs Efficiency



Multiple Scattering

> 30nm

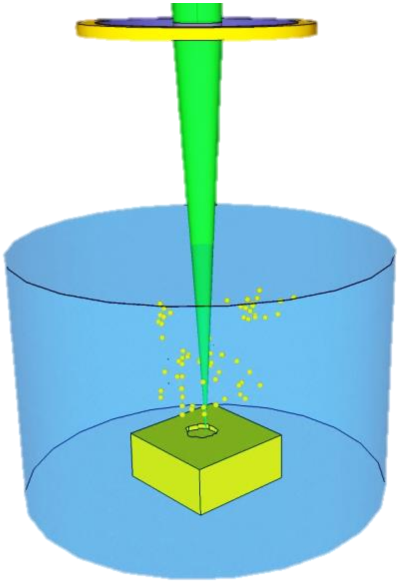
Surface Plasmon Excitation (LSPR)

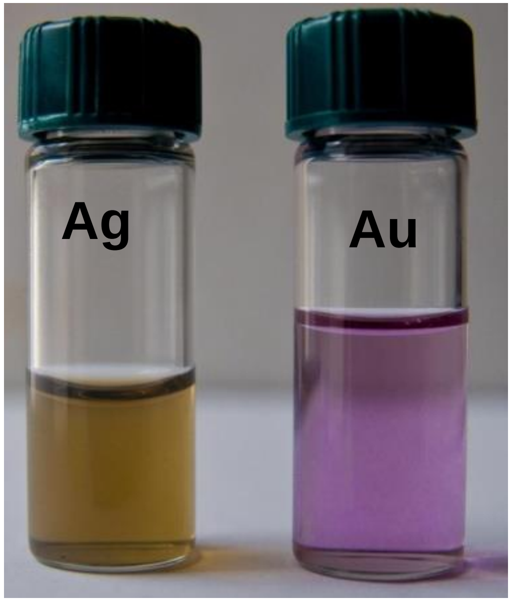
> 5 – 20nm

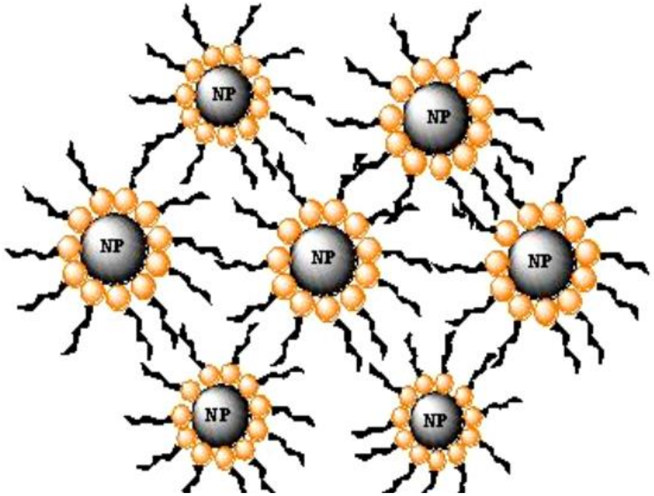
SP Polariton Excitation

Collaborator: Emmanuel Kymakis, TEIC

Laser Synthesized NPs for Plasmonic OSCs







Chemically synthesized NPs

Key Advantages

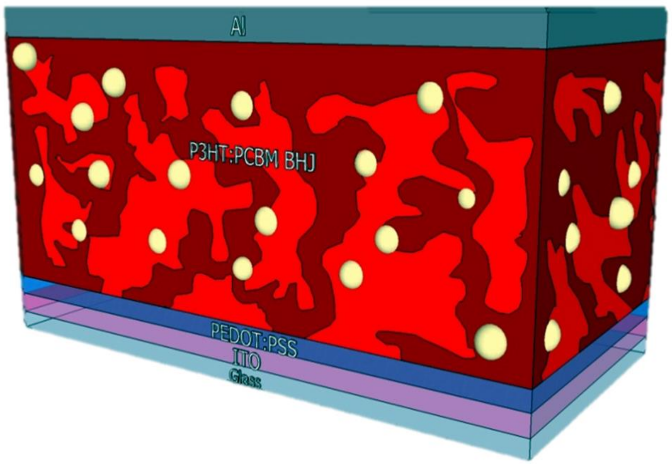
✧ *Free of surfactants & passivation layers – no capping layers*

✧ *Ablating using ultrashort laser pulses could minimize the formation of surface oxide*

Optics Express (2009) 17, 12650

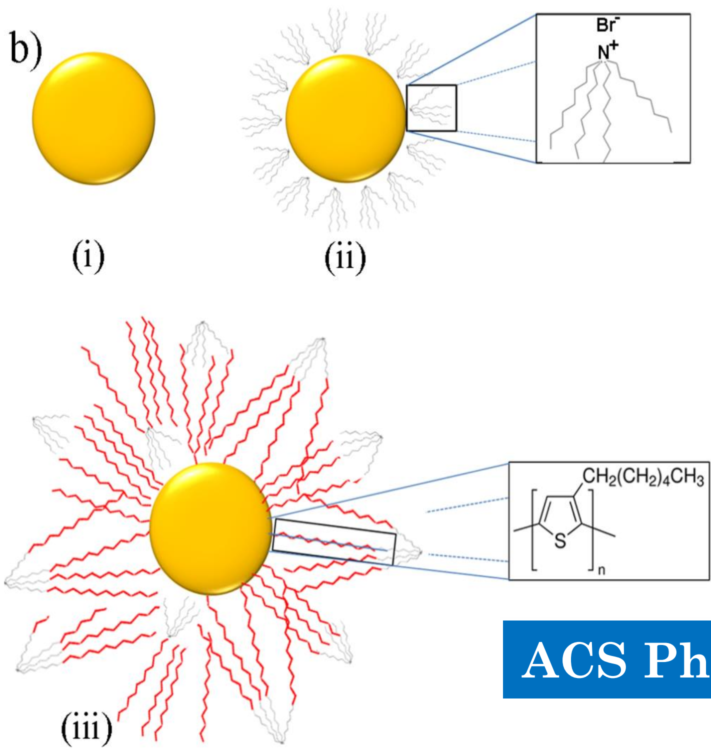
NPs' Ligand Effect on OSCs Performance

a)

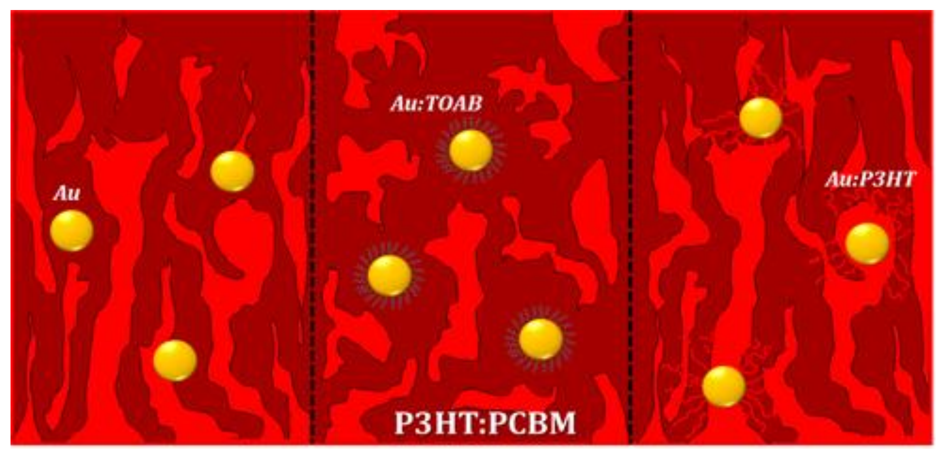


	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	PCE (%)
P3HT:ICBA	10.48±0.18	0.84±0.01	65.78±0.23	5.79±0.20
P3HT:ICBA + Au	11.56±0.24	0.84±0.01	68.83±0.31	6.68±0.25
P3HT:ICBA + Au:TOAB	10.25±0.19	0.79±0.02	56.93±0.25	4.61±0.23
P3HT:ICBA + Au:P3HT	12.06±0.27	0.83±0.01	71.51±0.34	7.16±0.28

b)



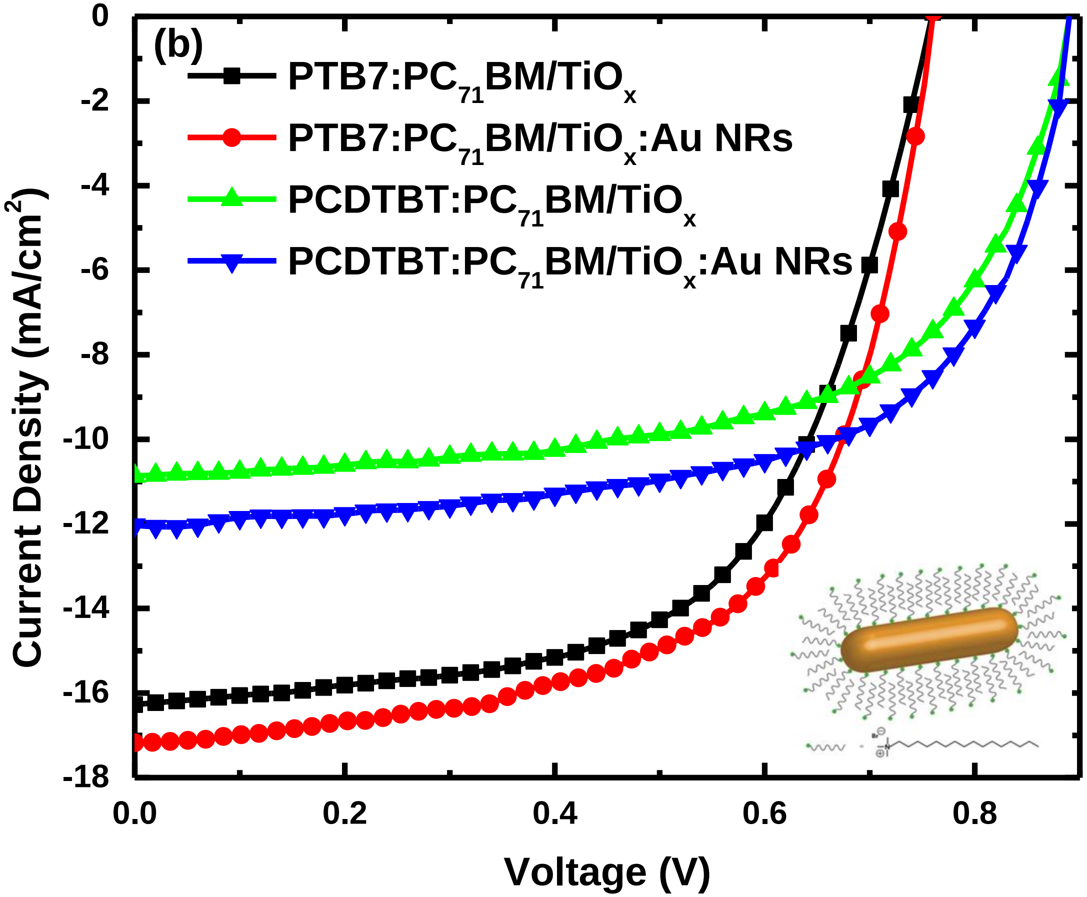
PCE enhancement → *NPs metallic core is in direct contact with the active layer polymer donor*

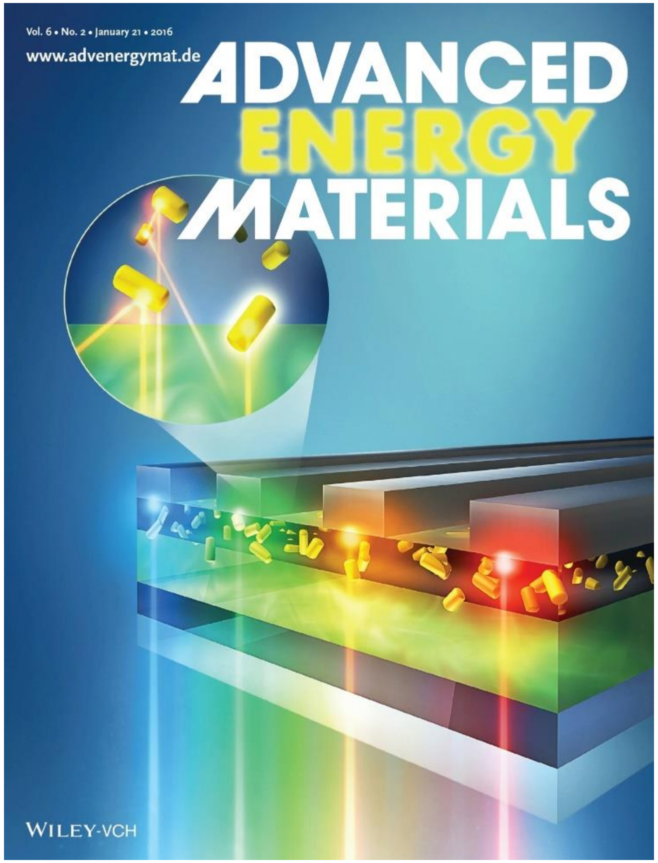


ACS Photonics, 2 , 714–723 (2015)

Collaborator: Antonios Kanaras, UoS, UK

Au NRs as Back Reflectors





Device	Jsc (mA/cm²)	Calculated Jsc (EQE)	Voc (V)	FF(%)	PCE (%)	Rs (Ω cm)	Rsh (Ω cm)
PTB7:PC71BM/TiOx	16.27±0.22	15.75±0.38	0.760±0.03	60.1±0.5	7.43±0.19	10.15	472
PTB7:PC71BM/TiOx: AuNRs	**17.17±0.29**	**16.71±0.41**	**0.760±0.02**	**61.4±0.6**	**8.01±0.24**	**5.71**	**609**

Adv. Energy Mater., 6, 1501640 (2016)

NPs-based Plasmonic OSCs: Diagnostics

Adv. Mater. 25, 4760 (2013)

www.MaterialsViews.com

ADVANCED MATERIALS
www.advmat.de

COMMUNICATION

Spatially-Resolved In-Situ Structural Study of Organic Electronic Devices with Nanoscale Resolution: The Plasmonic Photovoltaic Case Study

B. Paci, D. Bailo, V. Rossi Albertini, J. Wright, C. Ferrero, G. D. Spyropoulos, E. Stratakis,* and E. Kymakis*

Beamline ID11
ESRF The European Synchrotron

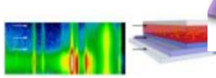
Organic photovoltaic device local structure revealed by combined X-ray diffraction and fluorescence

25-09-2013

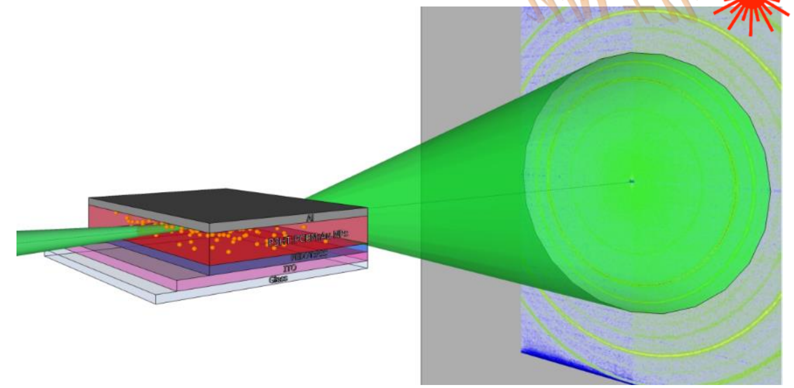
The detailed structure of post-fabricated multilayered organic electronic devices has been revealed by an in situ spatially-resolved study, using vertical scanning X-ray diffraction combined with fluorescence spectroscopy. The mechanisms leading to the structural properties of the different organic layers and interfaces could be interpreted. This experimental investigation prepares the way for in situ diagnosis of nanolayered structures.

ESRF spotlight

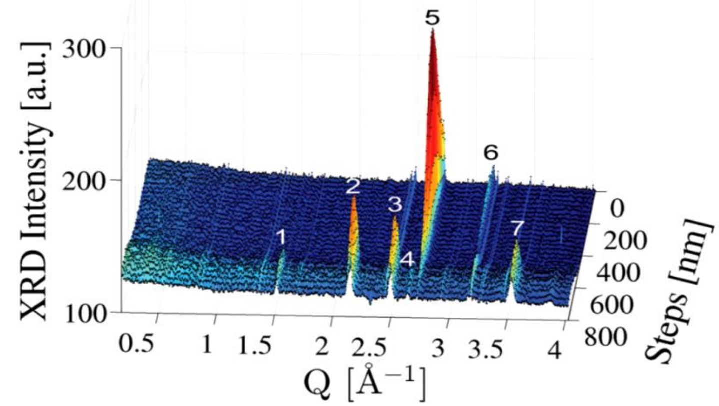
Polymer-based materials are ubiquitous in almost every aspect of modern society. Their interest arises from their simple chemical processing and the low-cost fabrication of thin films via vacuum evaporation or solution casting technologies. Polymer-based organic photovoltaic devices



In situ spatially-resolved X-ray study of an integrated organic photovoltaic device at beamline ID11



Cross-sectional X-ray diffraction + fluorescence imaging of plasmonic OPVs



Energy dispersion X-ray pattern

Adv. Func. Mater. 21, 3573 (2011)

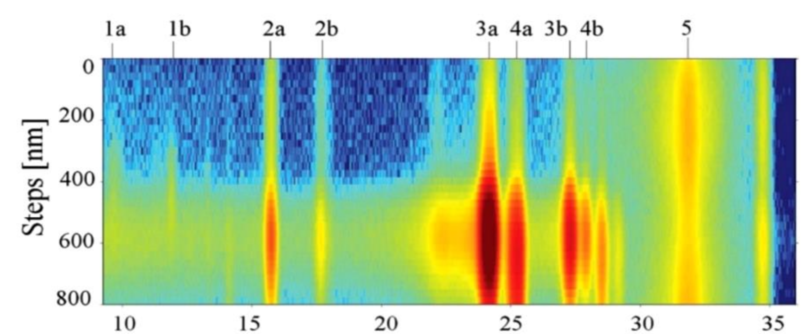
www.MaterialsViews.com

ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

FULL PAPER

Enhanced Structural Stability and Performance Durability of Bulk Heterojunction Photovoltaic Devices Incorporating Metallic Nanoparticles

Barbara Paci, George D. Spyropoulos, Amanda Generosi, Daniele Bailo, Valerio Rossi Albertini, Emmanuel Stratakis, and Emmanuel Kymakis*



Collaborator: Barbara Paci, CNR, IT

Fluorescence pattern

Materials Today • Volume 16, Number 4 • April 2013 RESEARCH

Nanoparticle-based plasmonic organic photovoltaic devices

ELSEVIER

RESEARCH: Review

Emmanuel Stratakis[1,*] and Emmanuel Kymakis[2,*]

ELSEVIER

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

journal homepage: www.elsevier.com/locate/jcis

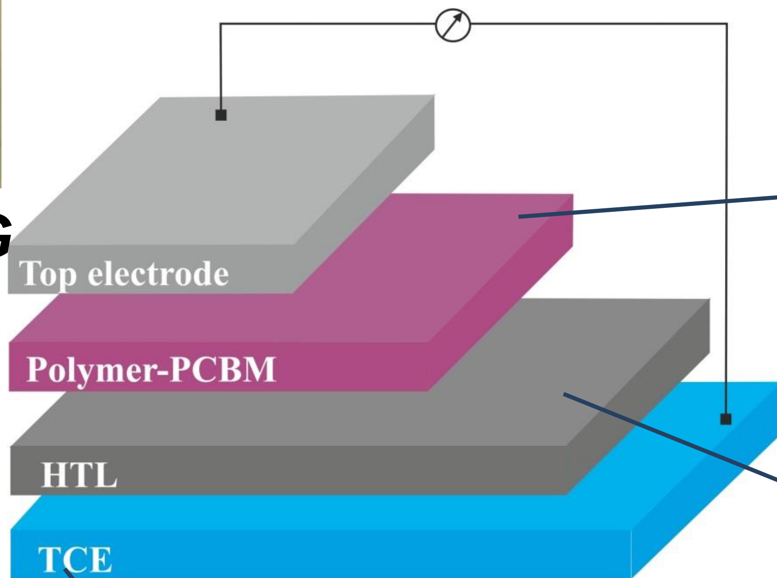
Laser generated nanoparticles based photovoltaics

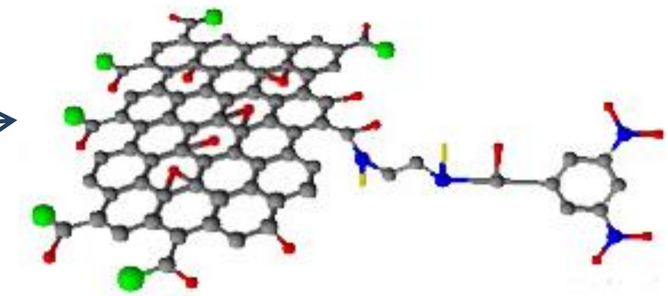
CrossMark

C. Petridis [a,b], K. Savva [c,d], E. Kymakis [b,e], E. Stratakis [c,*]

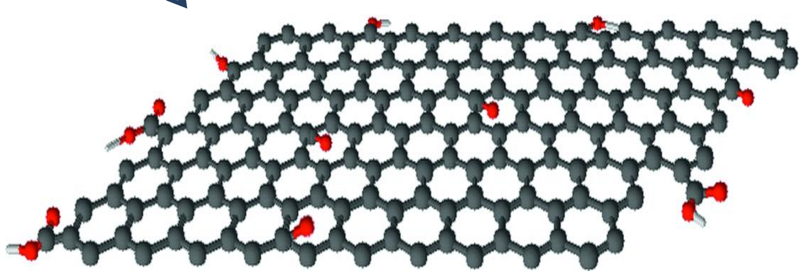
Solution processed Graphene (SPG)-based OSCs

SPG

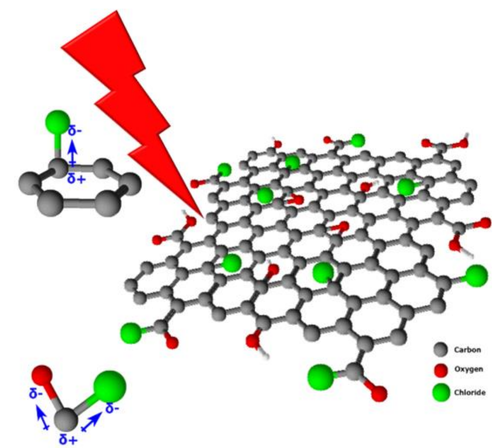




Laser Functionalized SPG



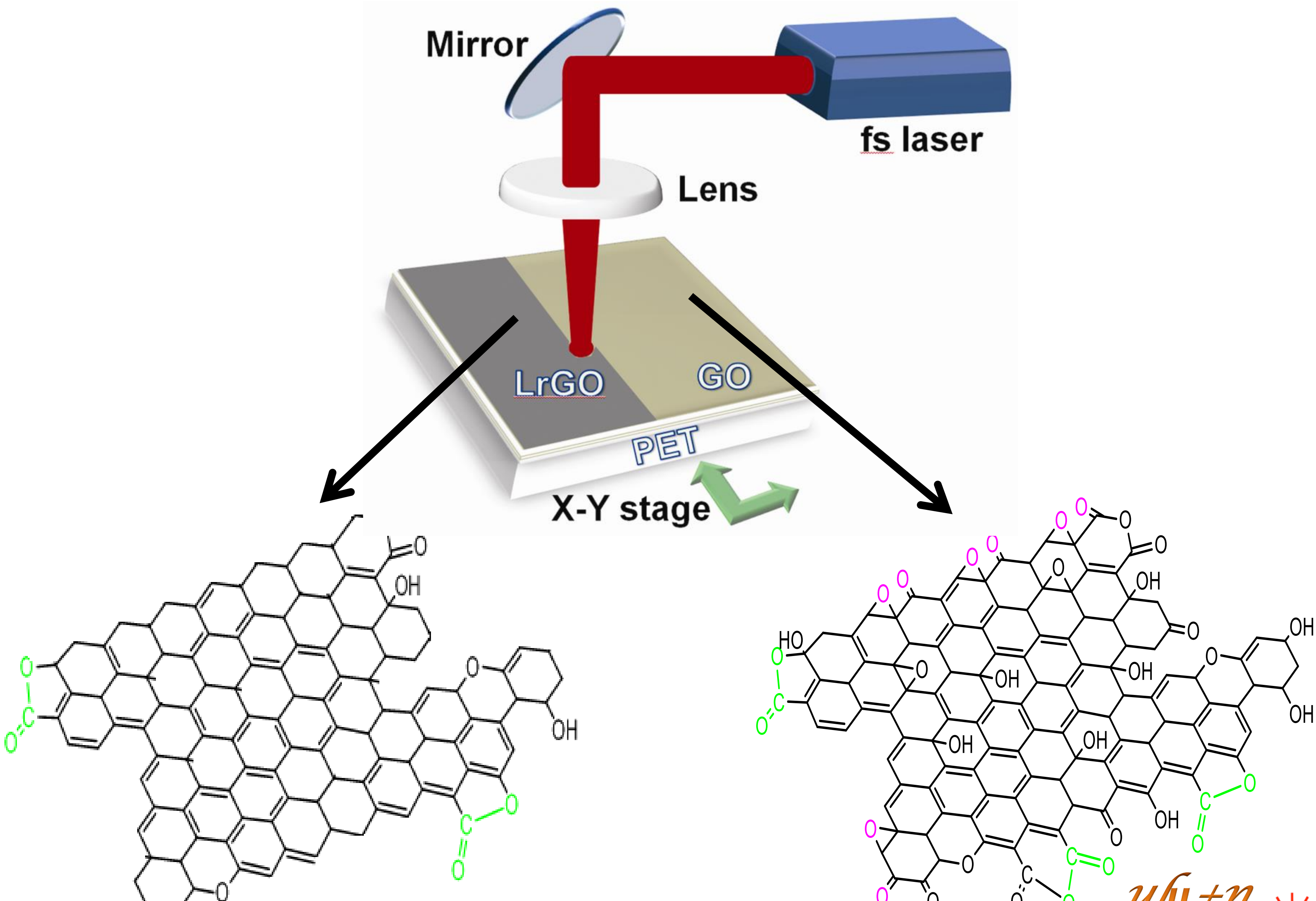
Laser Reduced SPG



Laser Doped SPG with tunable WF

With Emmanuel Kymakis, TEIC

Laser in-situ reduction of SPG on flexible substrates



Adv. Funct. Mater. (2013), 23, 2742

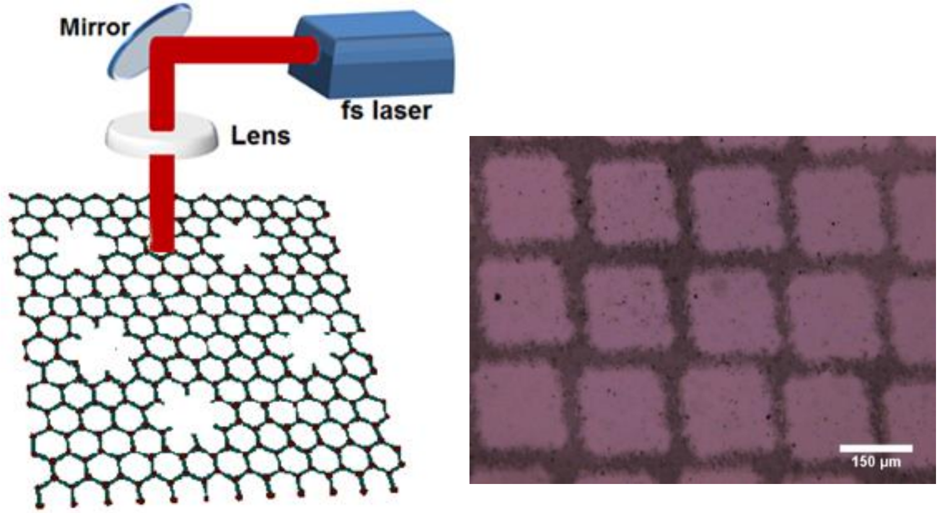
Laser Fabricated LrSPG Micromesh Flexible TCEs

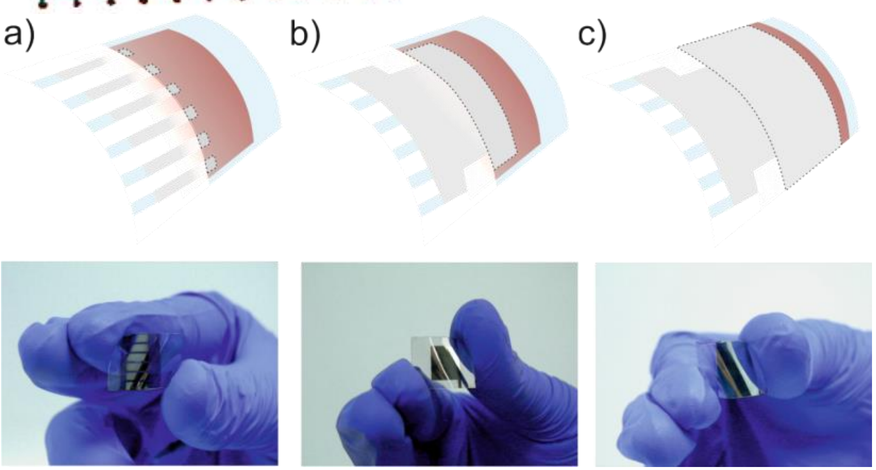
www.afm-journal.de

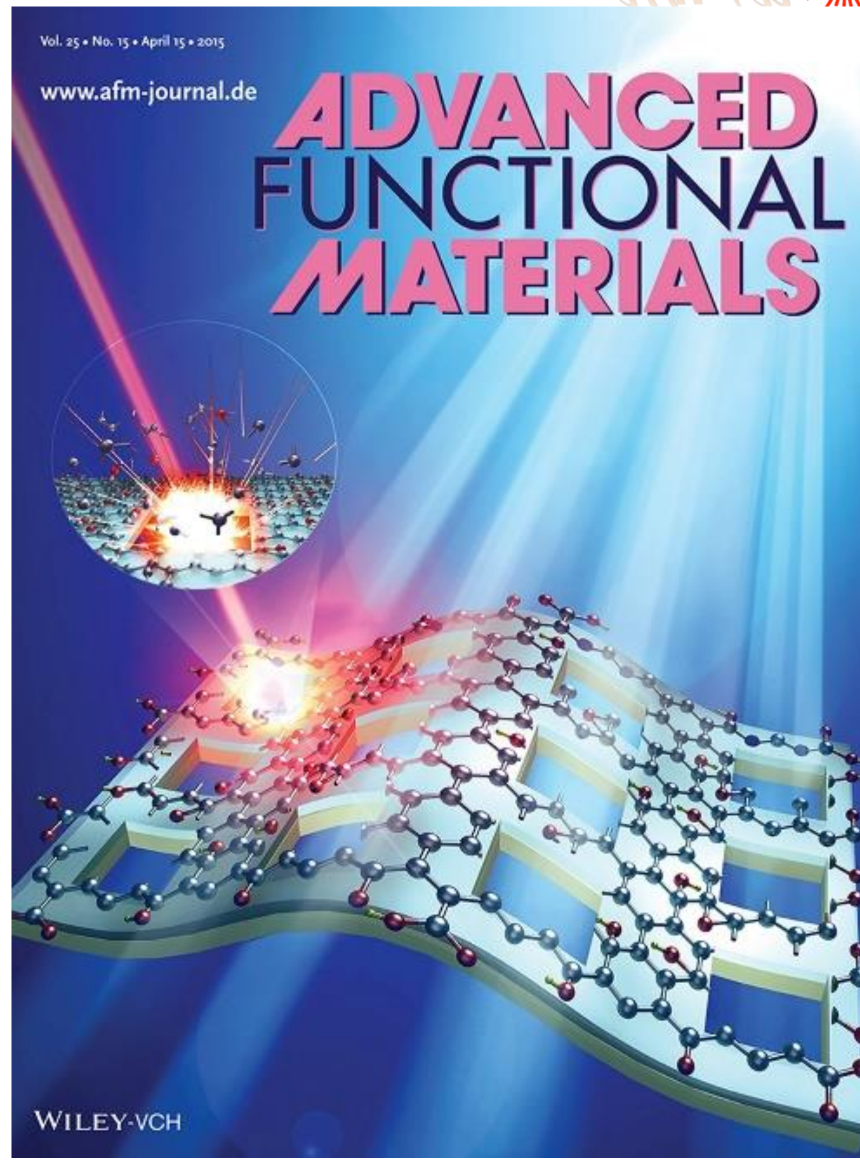
ADVANCED FUNCTIONAL MATERIALS

Reduced Graphene Oxide Micromesh Electrodes for Area, Flexible Organic Photovoltaic Devices

By *Dimitrios Konios, Constantinos Petridis, George Kakavelakis, Maria Sygletou, Kyriaki Savva, Emmanuel Stratakis,* and Emmanuel Kymakis**







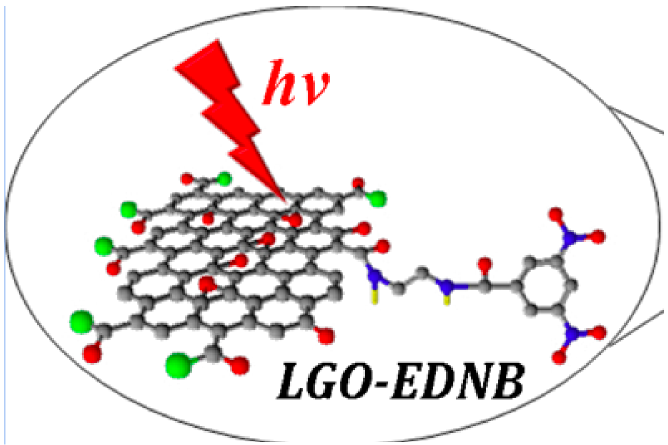
Adv. Func. Mat. (2015) 25, 2206

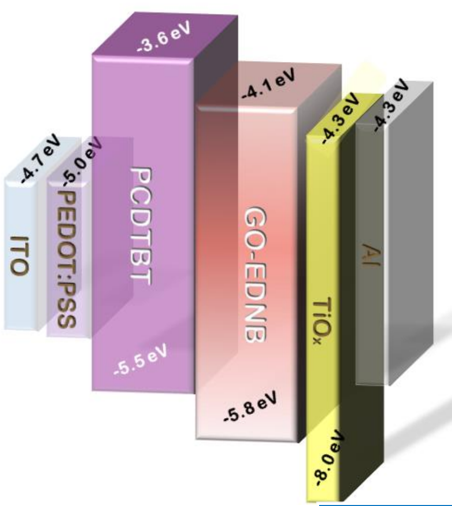
Photochemical Synthesis of Graphene-based Acceptors

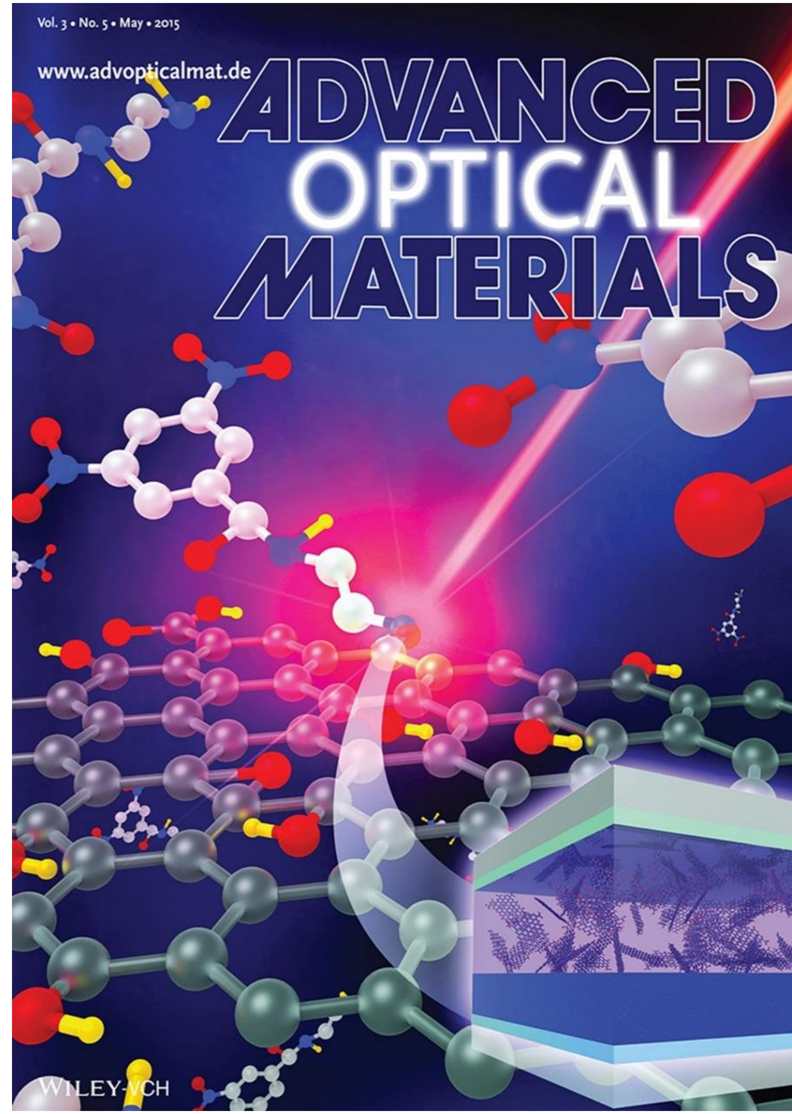
Materials Views
www.MaterialsViews.com
ADVANCED OPTICAL MATERIALS
www.advopticalmat.de

Photochemical Synthesis of Solution-Processable Graphene Derivatives with Tunable Bandgaps for Organic Solar Cells

Minas M. Stylianakis, Maria Sygletou, Kyriaki Savva, George Kakavelakis, Emmanuel Kymakis, and Emmanuel Stratakis**







Adv. Opt. Mat. (2015), 3, 658

REVIEW

Adv. Mater. 2017, 1700335DOI: 10.1002/adma.201700335

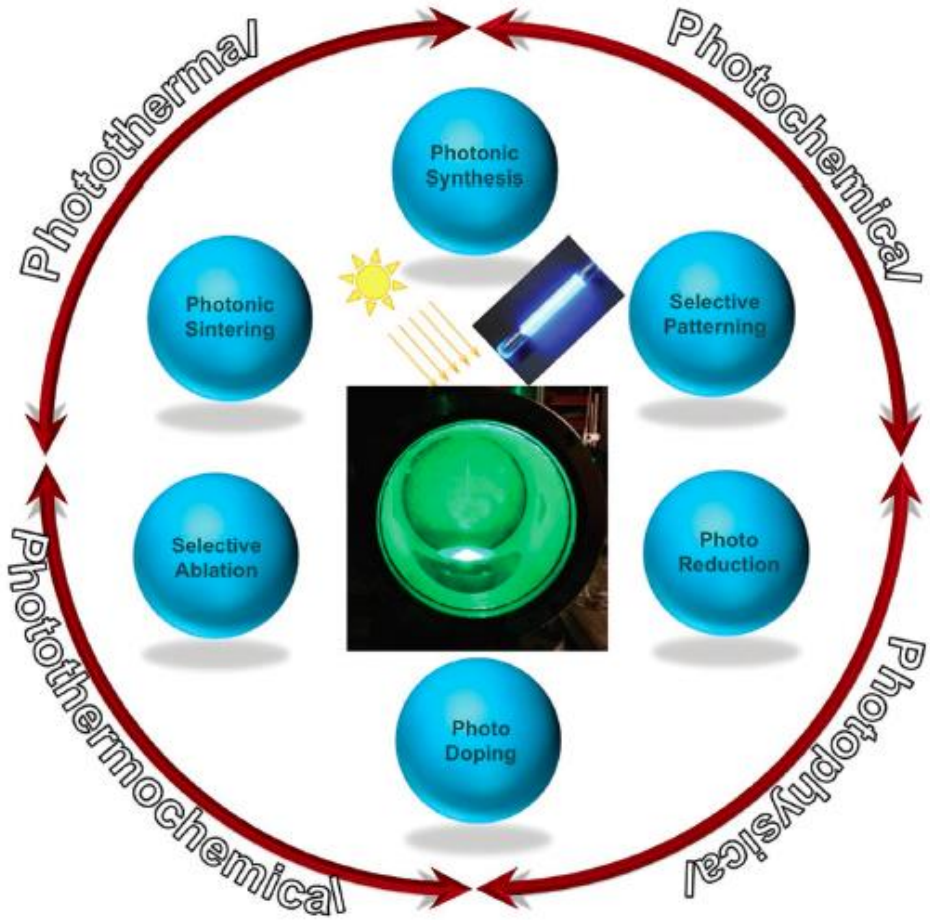
Photonics

ADVANCED MATERIALS

www.advmat.de

Advanced Photonic Processes for Photovoltaic and Energy Storage Systems

*Maria Sygletou, Constantinos Petridis, Emmanuel Kymakis, and Emmanuel Stratakis**

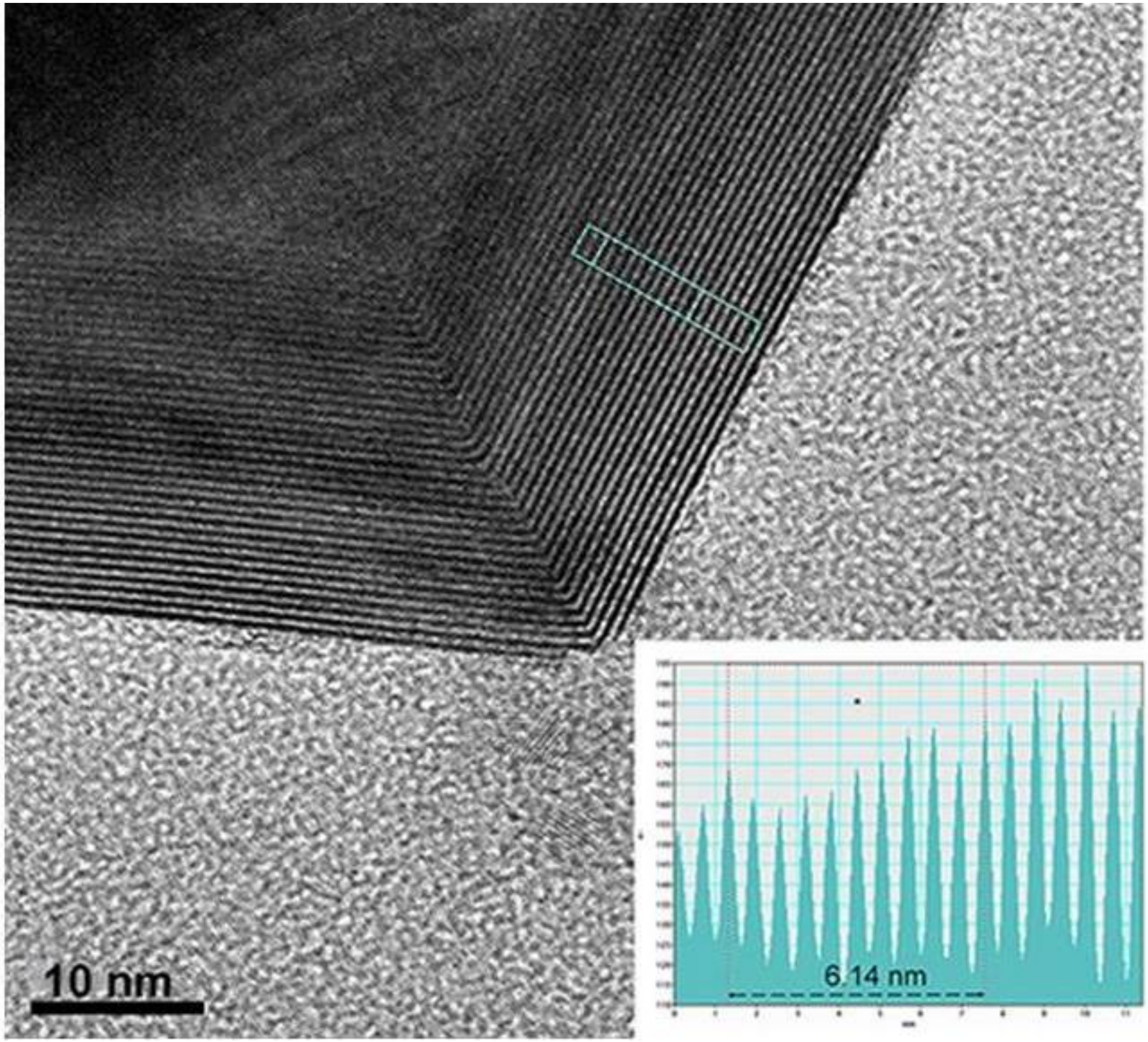


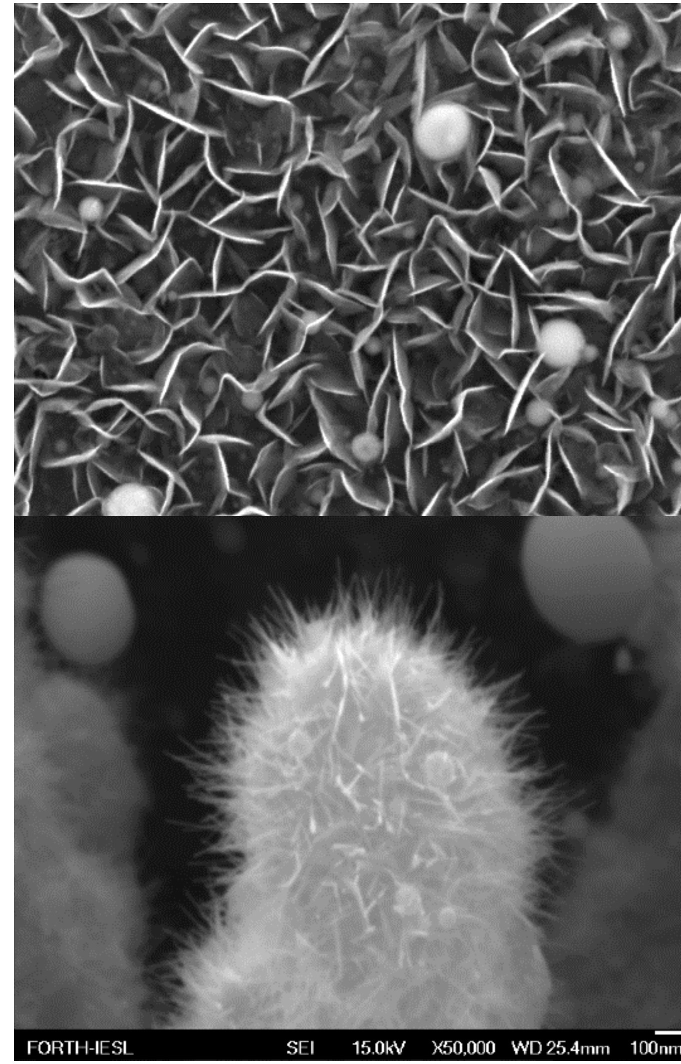
Laser Synthesis and Diagnostics of 2D Materials

ulμ+n

FORTH
INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

Laser Synthesis of 2D WS_2 Nanostructures





ACS Omega (2017), 2, 2387

in collaboration with R. Tenne(WIS)

Spatial non-uniformity in exfoliated WS_2 monolayers

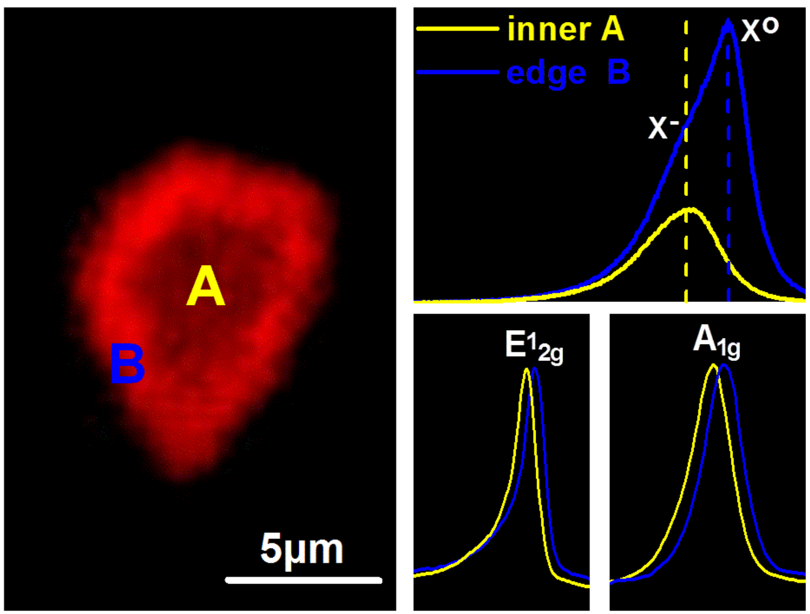
Nanoscale

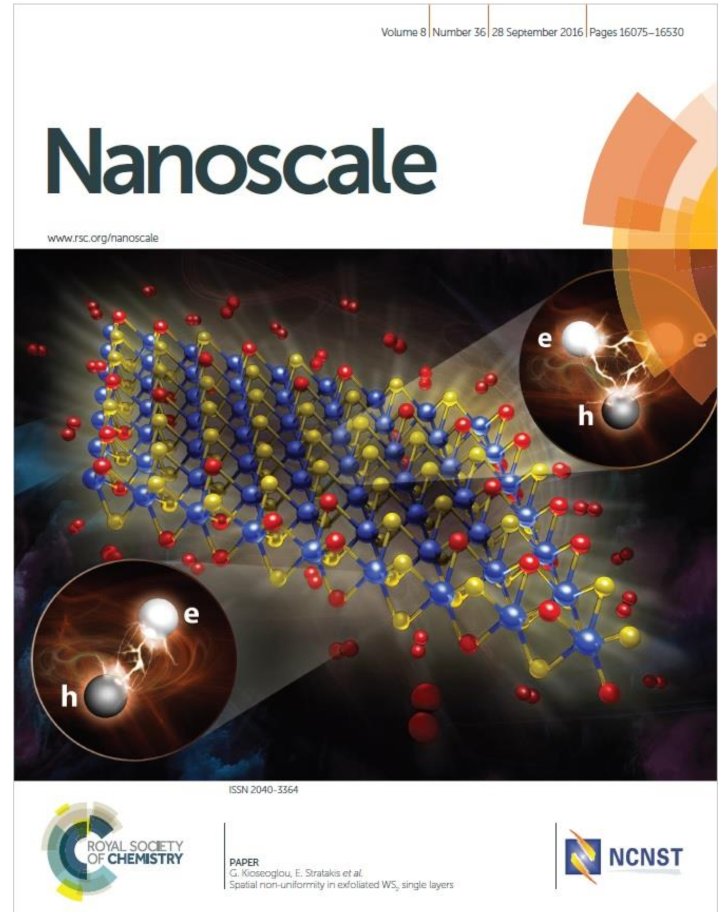
PAPER

Cite this: *Nanoscale*, 2016, **8**, 16197

Spatial non-uniformity in exfoliated WS_2 single layers†

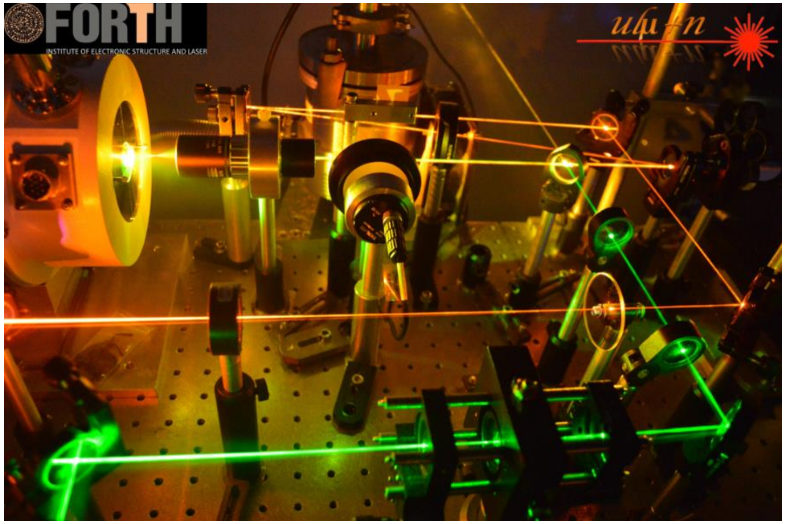
I. Paradisanos,[a,b] N. Pliatsikas,[c] P. Patsalas,[c] C. Fotakis,[a,b] E. Kymakis,[a,d] G. Kioseoglou*[a,e] and E. Stratakis*[a,e]

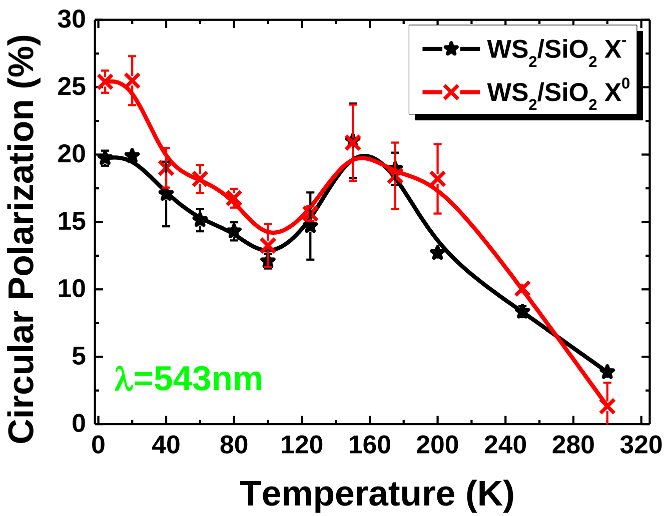




in collaboration with P. Patsalas (AUTH)

Exciton properties in 2D monolayers

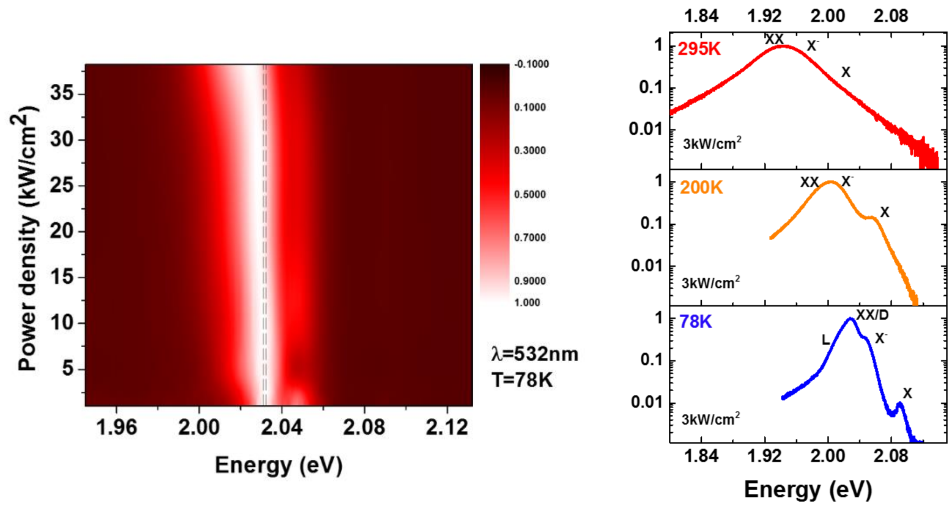




APPLIED PHYSICS LETTERS **110**, 193102 (2017)

Room temperature observation of biexcitons in exfoliated WS_2 monolayers

I. Paradisanos,[1,2] S. Germanis,[1] N. T. Pelekanos,[1,3] C. Fotakis,[1,2] E. Kymakis,[1,4] G. Kioseoglou,[1,3,a)] and E. Stratakis[1,3,a)]
[1]*Institute of Electronic Structure and Laser, Foundation for Research and Technology - Hellas, Heraklion 71110, Crete, Greece*
[2]*Department of Physics, University of Crete, Heraklion 71003, Crete, Greece*
[3]*Department of Materials Science and Technology, University of Crete, Heraklion 71003, Crete, Greece*
[4]*Center of Materials Technology and Photonics and Electrical Engineering Department, Technological Educational Institute (TEI) of Crete, Heraklion 71004, Crete, Greece*



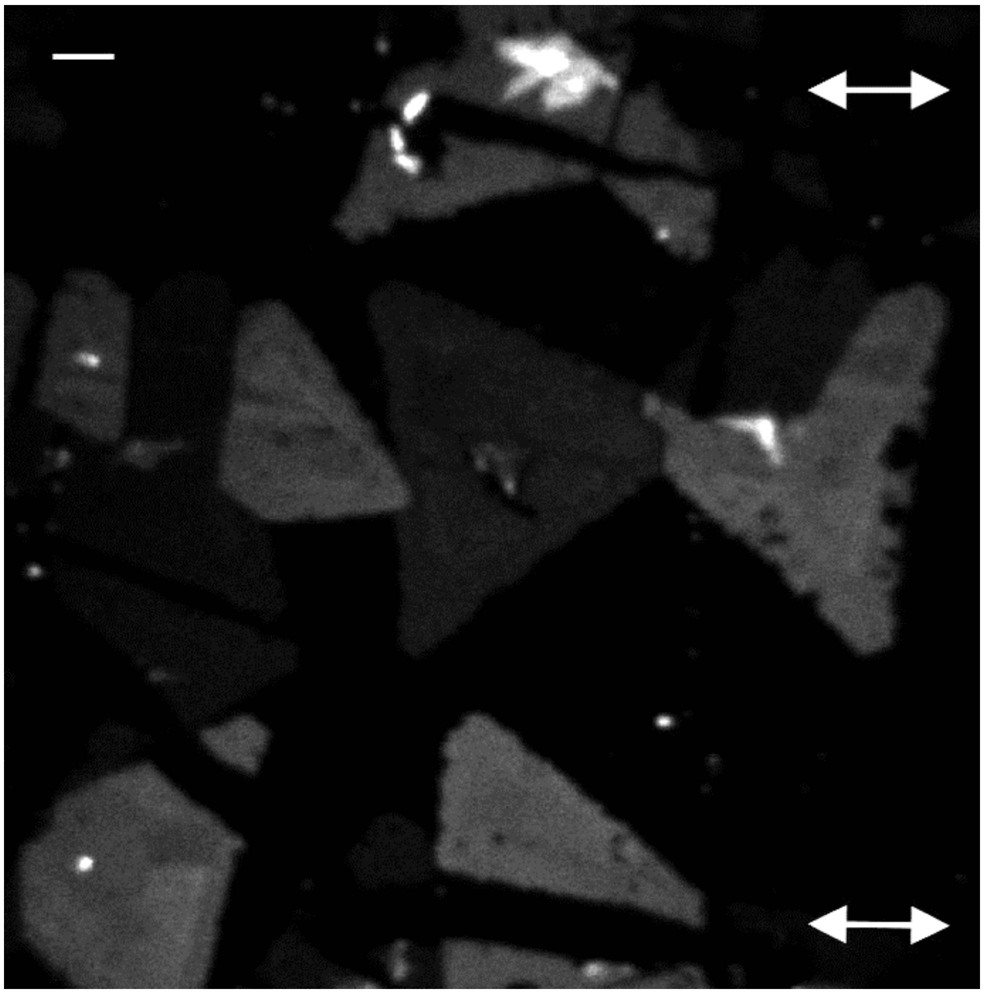
✓ **Temperature Dependent Spin-Valley Polarization (4K-300K)**

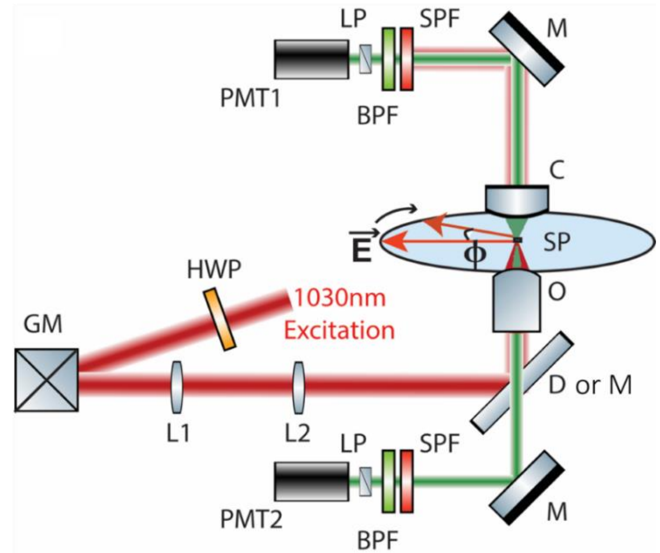
With George Kioseoglou (IESL)

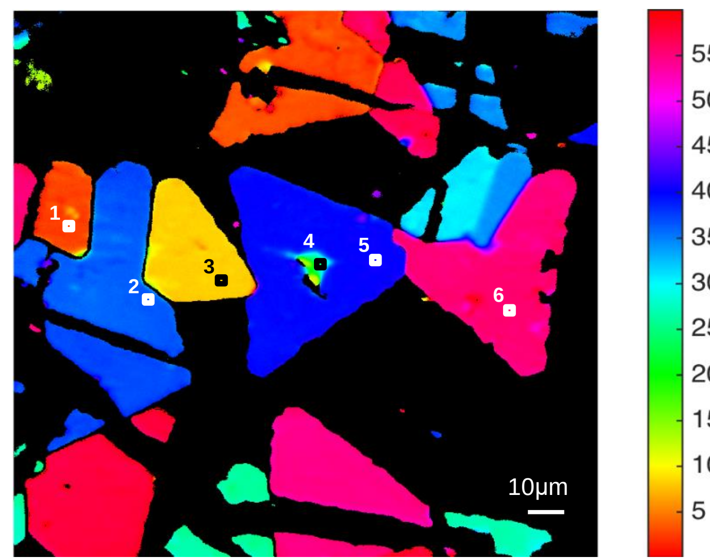
Ultrahigh-Resolution Microscopy of 2D crystals

Light | Science & Applications

S. Psilodimitrakopoulos, L. Mouchliadis, I. Paradisanos
A. Lemonis, G. Kioseoglou and E. Stratakis, in print (201







With George Kioseoglou (IESL)

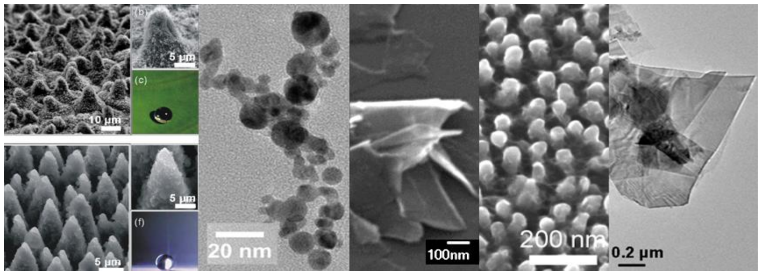
Funding

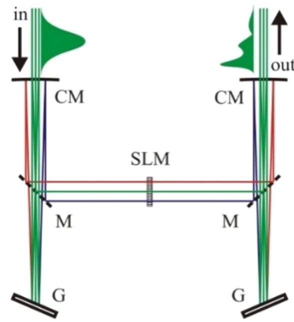
✧ **NFFA-EUROPE**	H2020 – INFRASTRUCTURES (2015-2019)
✧ **LASERLAB-EUROPE**	H2020 – INFRASTRUCTURES (2015-2019)
✧ **LiNaBioFluid**	H2020 – FET OPEN (2015-2018)
✧ **NANoREG 2**	H2020 – FET OPEN (2015-2018)
✧ **MouldTex**	H2020 – FOF-06-2017 (2017-2021)

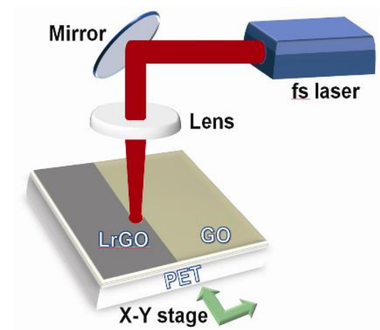
The ULMNP Team

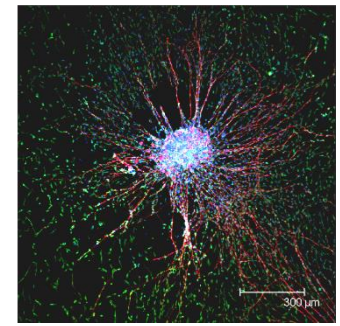
INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

Contact









Ultrafast Laser Micro/Nano Processing Group

http://www.iesl.forth.gr/ULMNP

Emmanuel Stratakis: stratak@iesl.forth.gr