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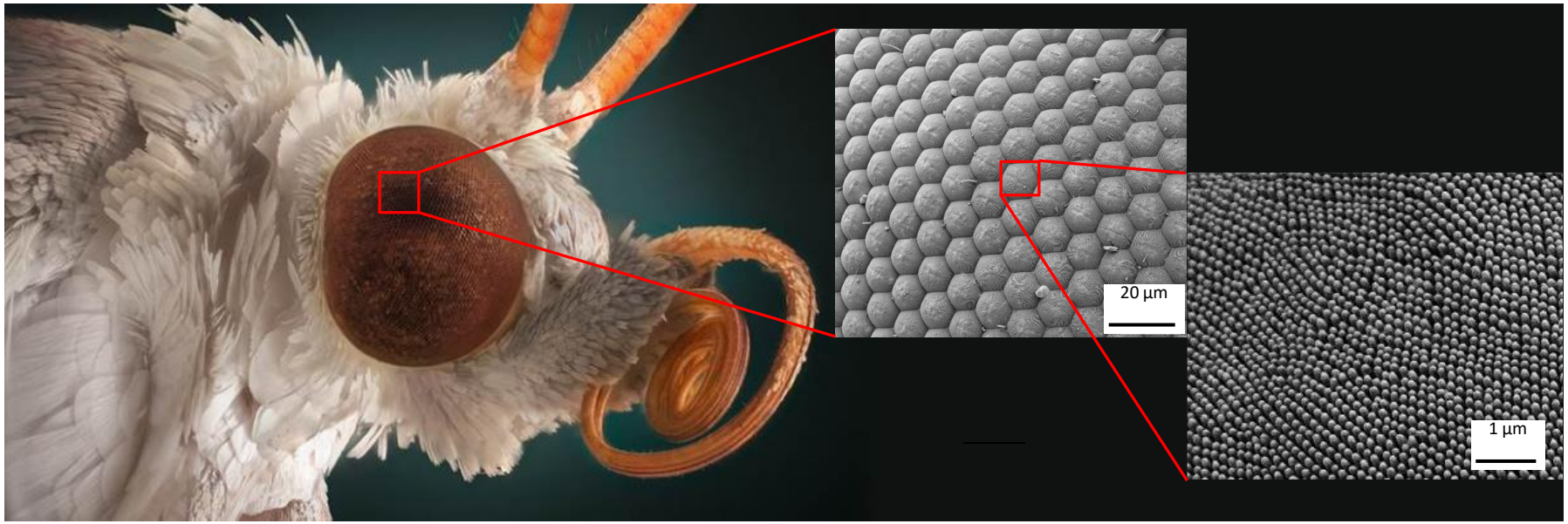
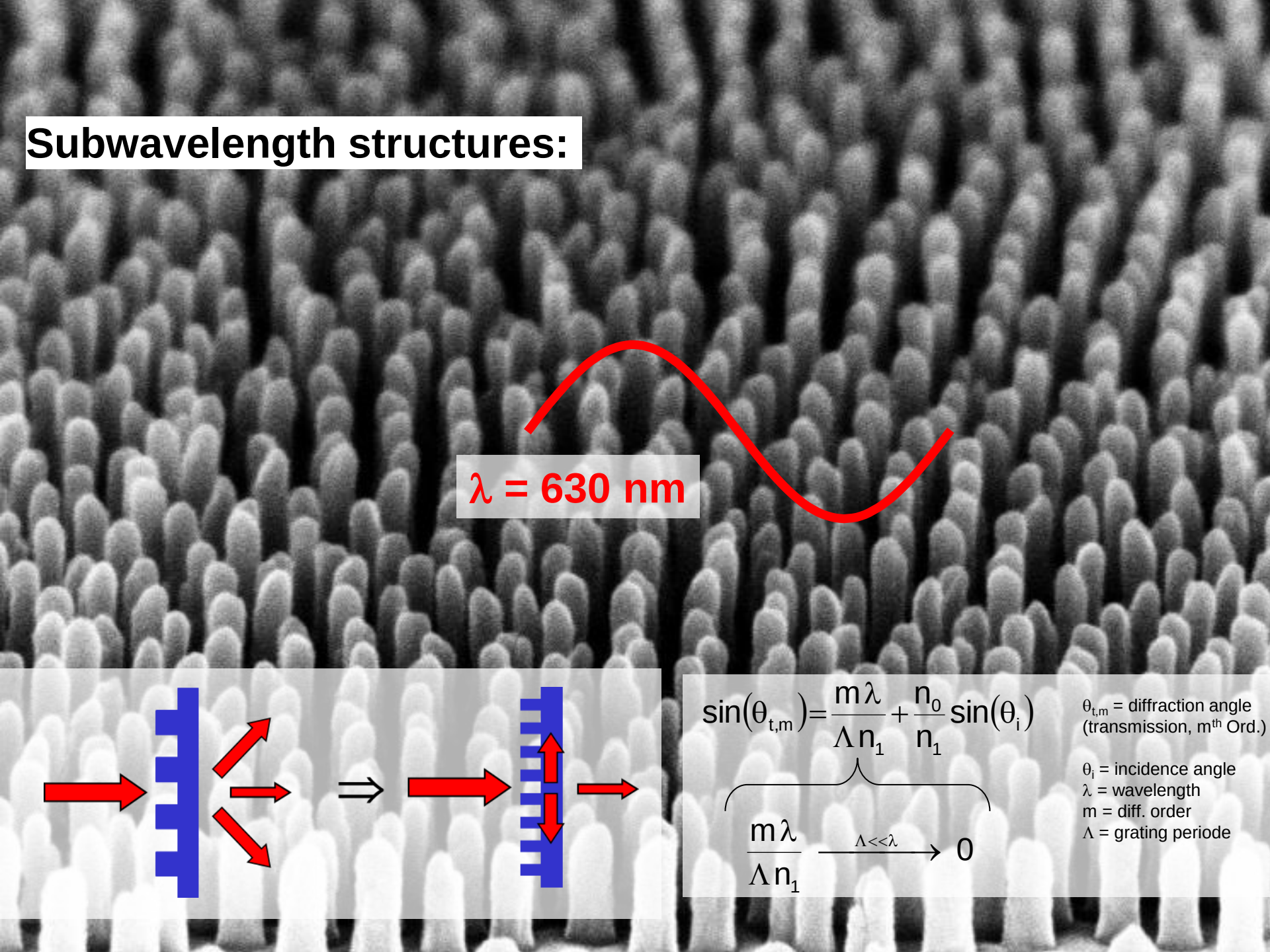
Nature as Blueprint - Anti-reflective Moth-Eye Principle for Tailored Optical Functionality

Robert Brunner

University of Applied Sciences Jena; Germany



Subwavelength structures:



$$\sin(\theta_{t,m}) = \frac{m\lambda}{\Lambda n_1} + \frac{n_0}{n_1}\sin(\theta_i)$$

$$\frac{m\lambda}{\Lambda n_1} \xrightarrow{\Lambda << \lambda} 0$$

$\theta_{t,m}$ = diffraction angle (transmission, m^{th} Ord.)

θ_i = incidence angle
λ = wavelength
m = diff. order
Λ = grating periode

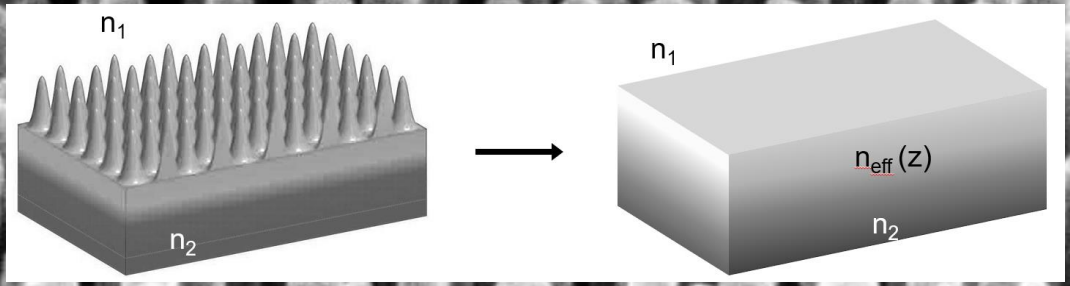
Subwavelength structures:

λ = 630 nm

equivalent to an effective medium with transition in the refractive index n_{eff}

$n_{out} < n_{eff} < n_{in}$

→ Acting as an Anti-Reflection layer ("moth eye" effect):



Global market for AR-coatings:

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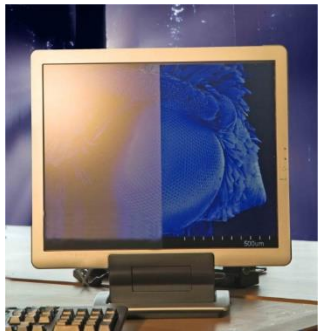
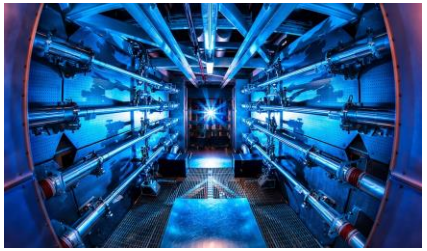


Almost every optical surface has a coating …

AR-coating: (world wide)
appr. 4.5 - 5.4 B$ (2023), to **9.96 - 12.9 B$ by 2033**
CAGR ~9.2% - ~10.8% [1,2]

Important application fields:

- **Consumer displays**
- **automotive,; e.g. in-cabin displays & HUDs.**
- **Eyewear / cameras**
- **Telecom/optics & sensors**
- **High-power lasers**
- **solar!**
- **laser-based inertial fusion!**
- **…**



[1] https://www.grandviewresearch.com/industry-analysis/anti-reflective-coatings-market
[2] https://www.imarcgroup.com/anti-reflective-coatings-market?utm_source=chatgpt.com

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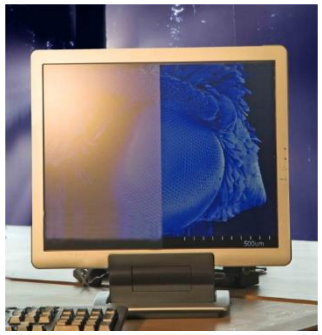

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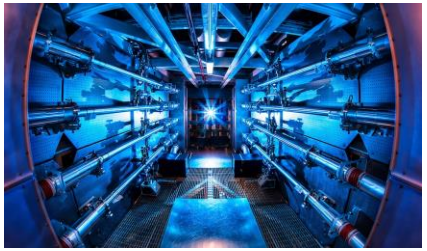

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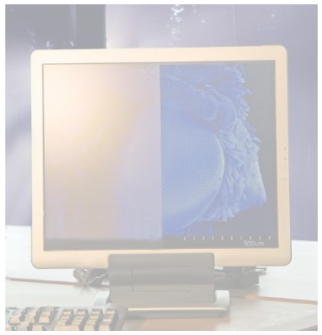

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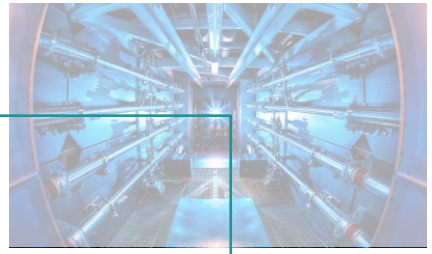

Challenge:

- **Broadband capability**
- **Large angles of incidence**
- **Stability ...**

⇒ **New solutions are necessary!**

Outline:

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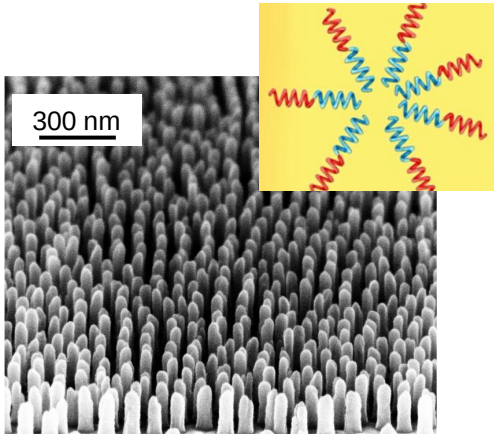
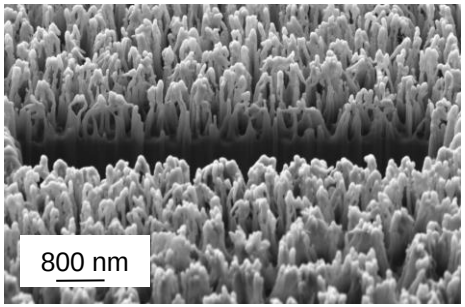


- basic processes / basic specifications
- hybrid antireflective coating
  → continuous graded refractive index (GRIN)
- ‘black’ & ‘white’ fused silica
- (inorganic and organic) hybrid polymers



Anti-reflective (AR) moth-eye structures
Our process

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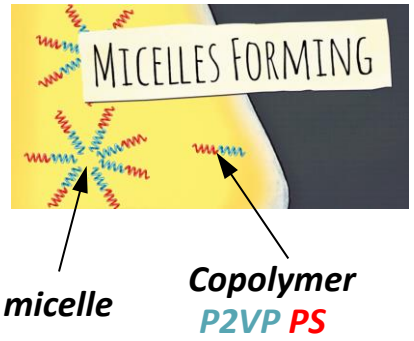
BCML-technique:
Block - Copolymer - Micelle-nano-Lithography



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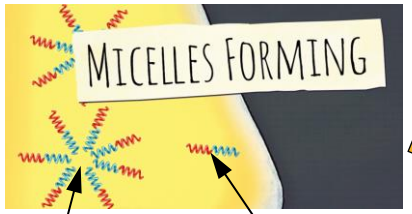
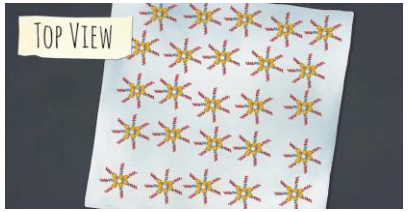
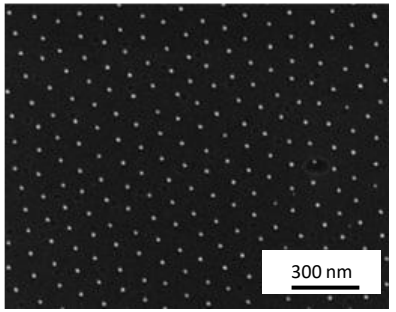


micelle

Copolymer
P2VP PS



self-organised mask



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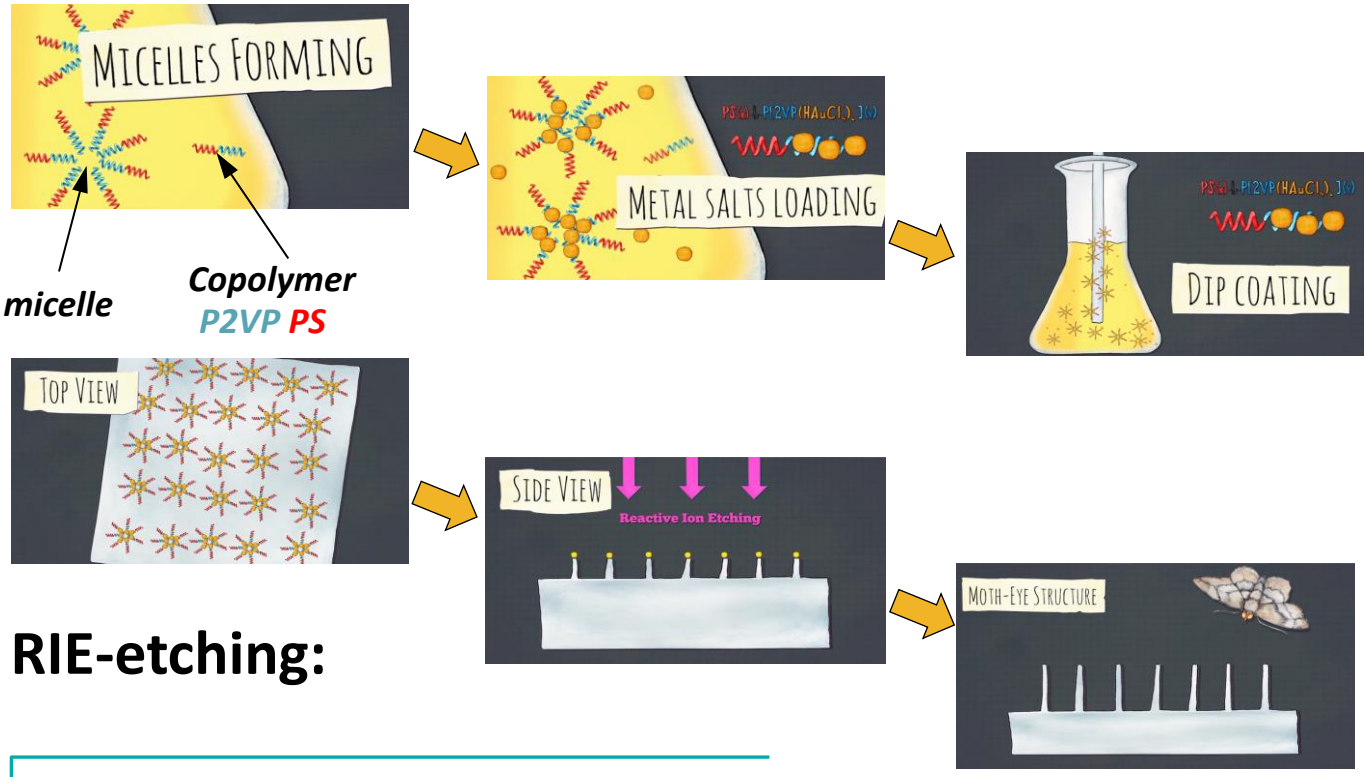
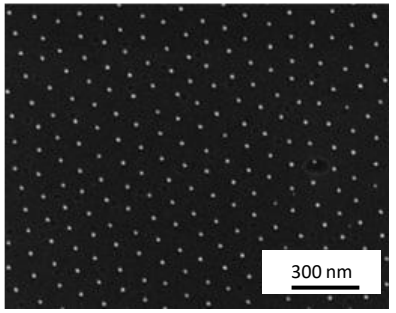
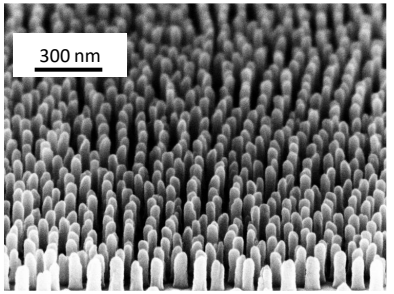


RIE-etching:

self-organised mask



artificial
moth eye structure



⇒ Quasi-periodic structures;
periodicity dependent on length of Copolymer; increasing periodicity with ultrasound

Anti-reflective (AR) moth-eye structures
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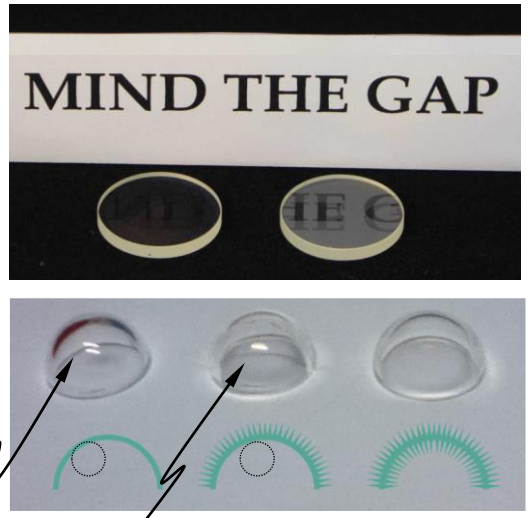
nano. AR structured **normal glass**



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Our process

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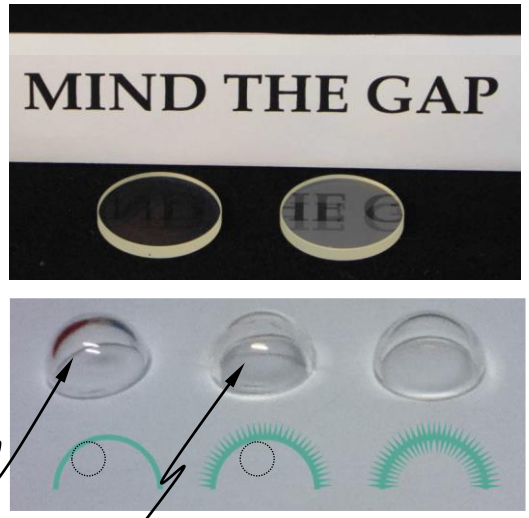
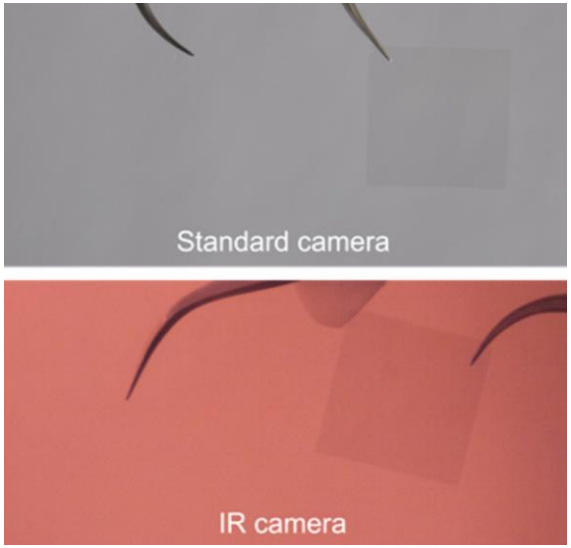


double reflection

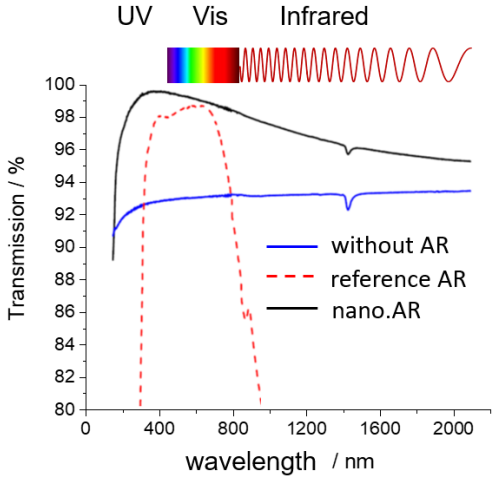
single reflection

… and also for very different wavelengths

nano. AR structured **normal glass**



moth-eye AR structures in comparison to alternative AR-coatings



- **broad spectral range**
- **reduced angle dependency**
- **stability**

Anti-reflective (AR) moth-eye structures
possibilities for variation

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AR coating or high index materials!

Example N-SF10

n = 1.7758 @ 404.7 nm

hybrid antireflective coating: GRIN-AR

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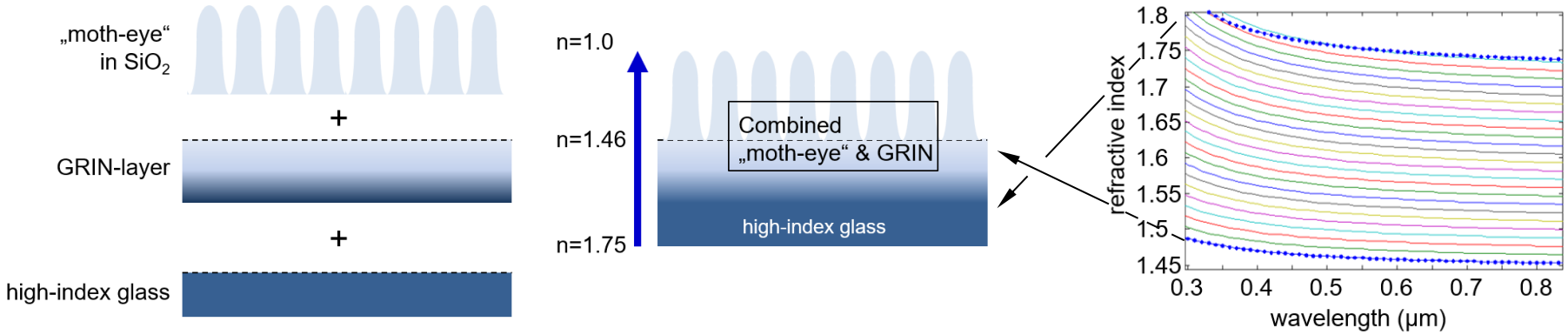

continuous graded refractive index (GRIN)
transition from a high-index substrate down to ambient air.

Anti-reflective (AR) moth-eye structures
AR coating or high index materials!

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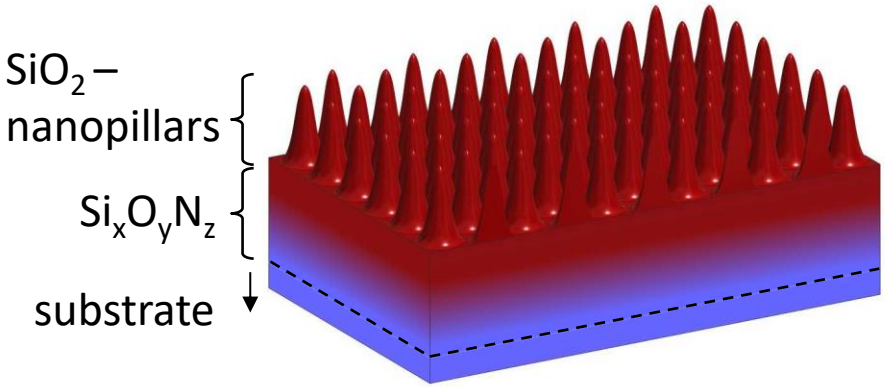

reactive pulse sputtering process (double-ring magnetron system (DRM 400; Fraunhofer FEP)

- GRIN layer: 450 nm thickness (silicon-oxynitride)
- 450 nm homogeneous SiO_2 layer

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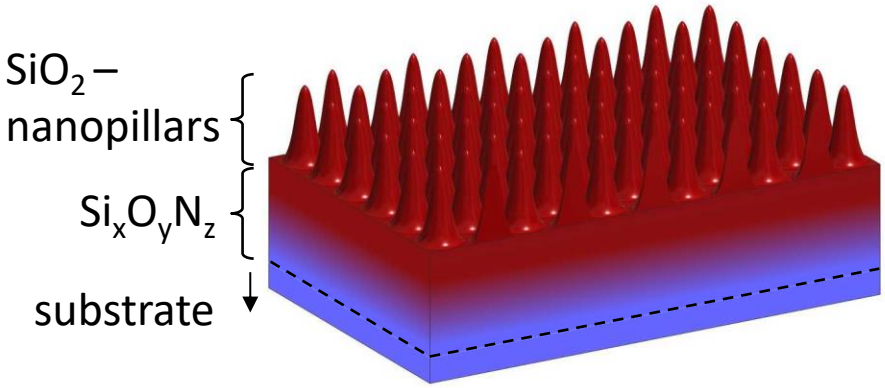

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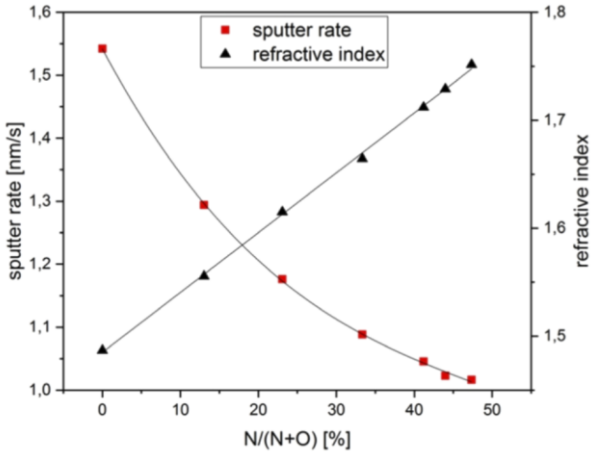
reactive gas composition
$\Rightarrow n(Si_xO_yN_z)$



refractive index of the $Si_xO_yN_z$ layer dependent on reactive gas composition.

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AR coating or high index materials!

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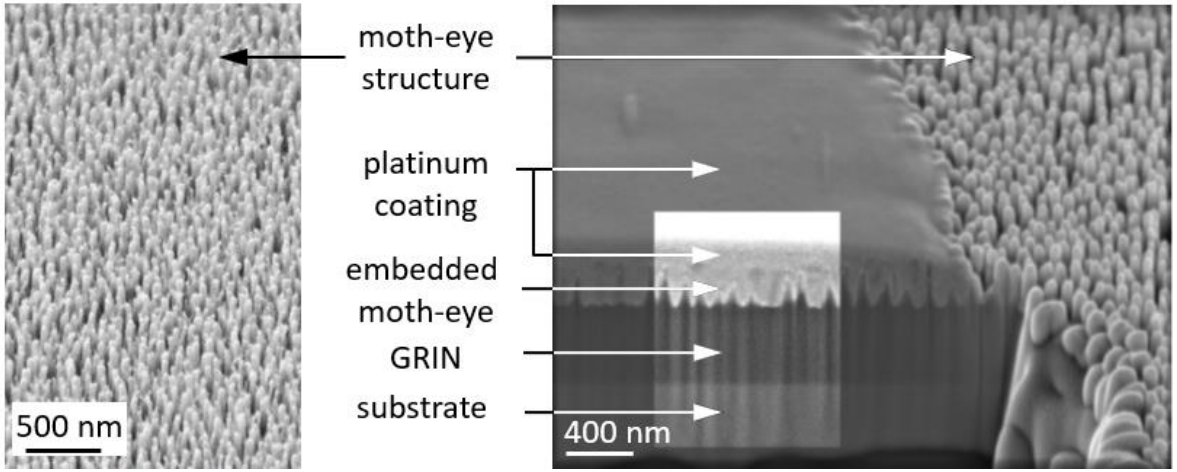
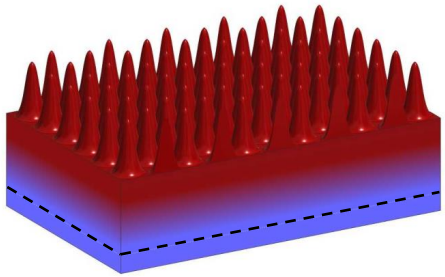
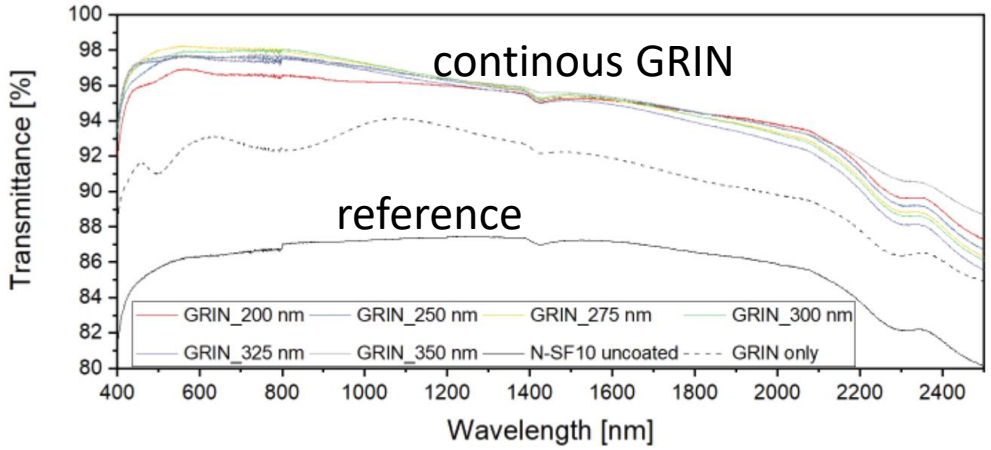




- **up to 14% transmittance gain (in vis)**
- **extremely broad band applicable**



Anti-reflective (AR) moth-eye structures black & white fused silica!

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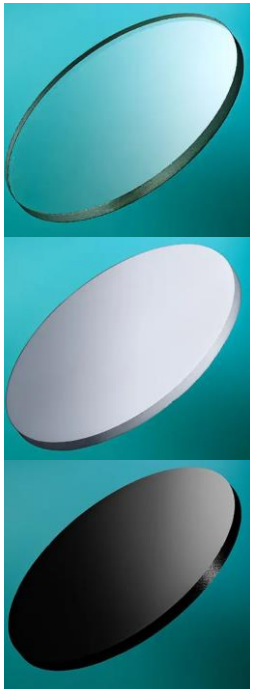
INTELLIGENT QUARTZ SOLUTIONS

Sol-gel derived liquid fused silica suitable for casting

Key properties:

- **Positive optical characteristics of fused silica**
- **Strongly chemical resistance**
- **High radiation and thermal stability,**
  (suitable for space environments)
- **Flexible shaping possibilities**



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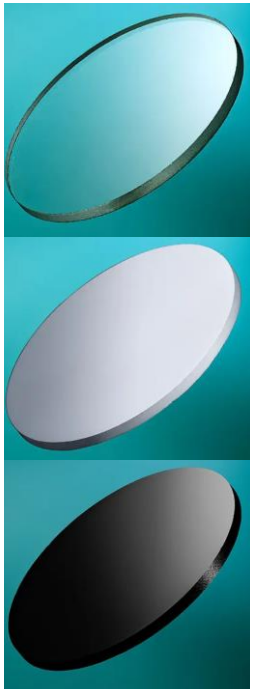

black & white fused silica
⇒ Modification of volume and surface

- **Highly absorbing (‘black’)**
- **& diffuse reflecting material**

(… as a diffuse reflectance target, e.g. as a white standard or for an integrating sphere)

Anti-reflective (AR) moth-eye structures black & white fused silica!

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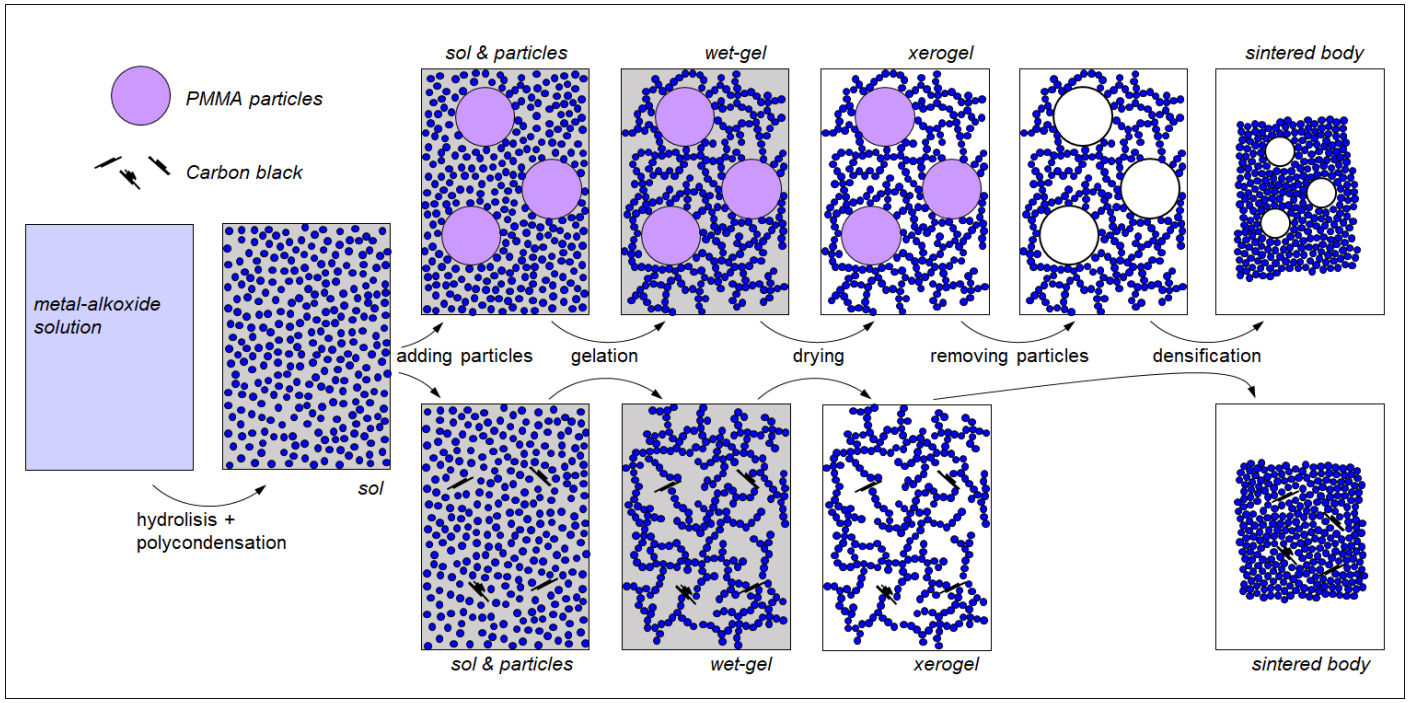
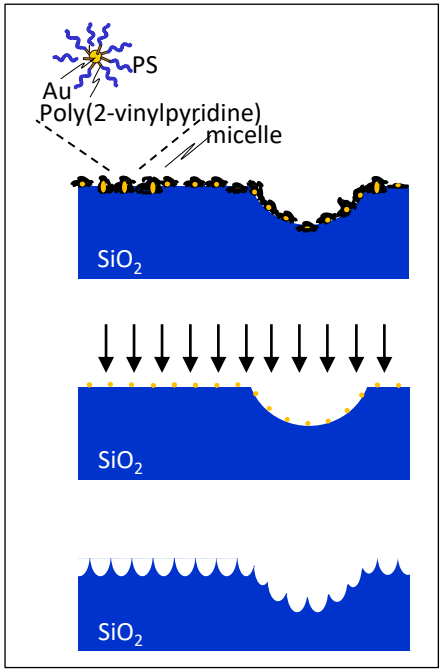
INTELLIGENT QUARTZ SOLUTIONS

Modification of volume and surface

Volume modification:



surface modification:



Integrating

- scattering hollow spheres or
- absorbing black carbon

Anti-reflective (AR) moth-eye structures black & white fused silica!

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INTELLIGENT QUARTZ SOLUTIONS

''moth-eye" structures

without **with**

weak specular reflection

(nearly) no specular reflection

Anti-reflective (AR) moth-eye structures black & white fused silica!

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INTELLIGENT QUARTZ SOLUTIONS

''moth-eye" structures

without **with**

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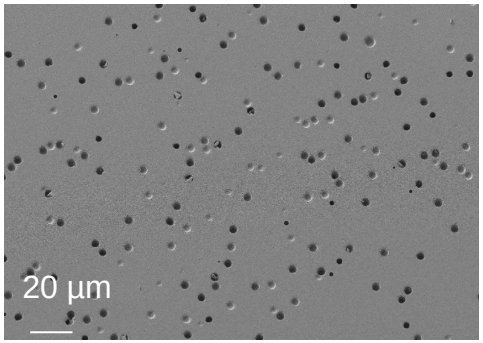
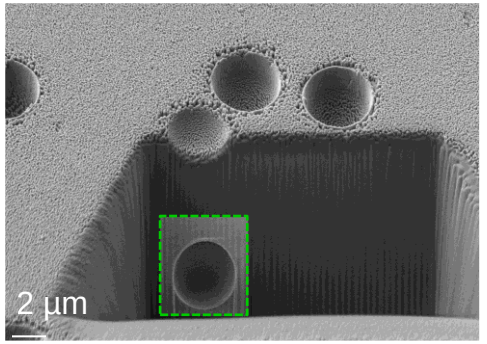
(nearly) no specular reflection

SEM images

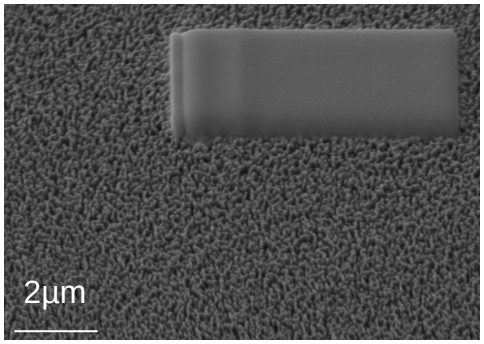
surface **FIB cross section**

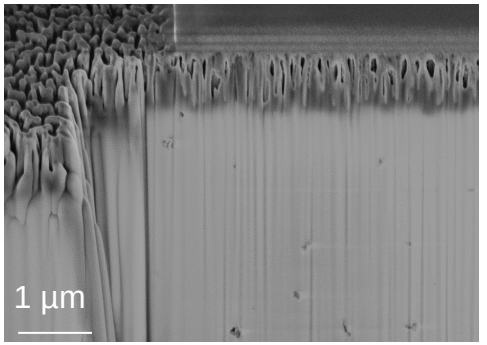
white





black





Anti-reflective (AR) moth-eye structures black & white fused silica!

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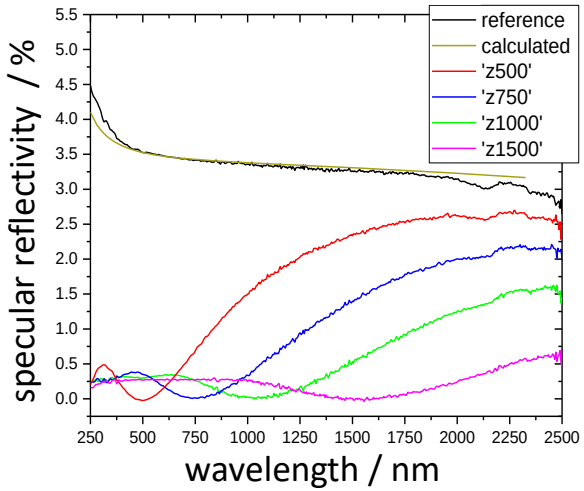
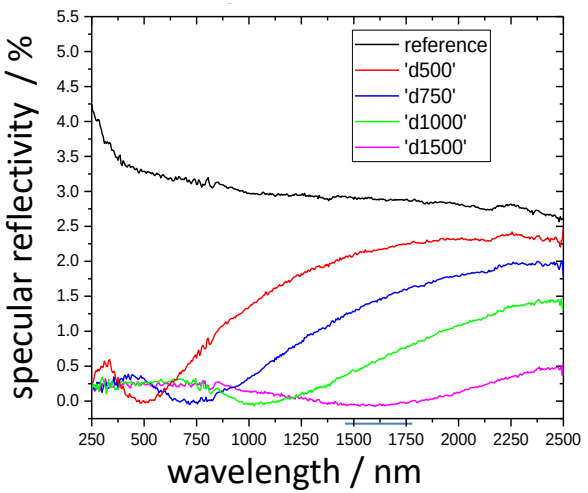
results: (depth variation of ‘moth-eye’-structures)

black

a)

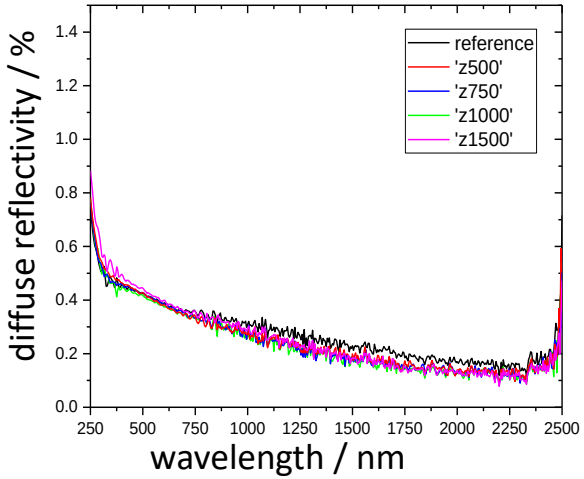


b)

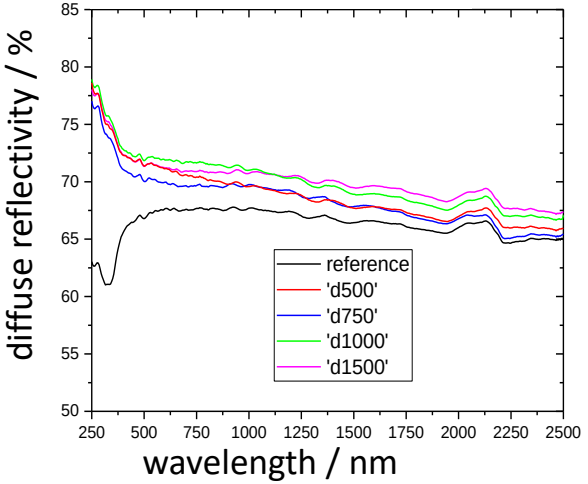


white

c)



d)



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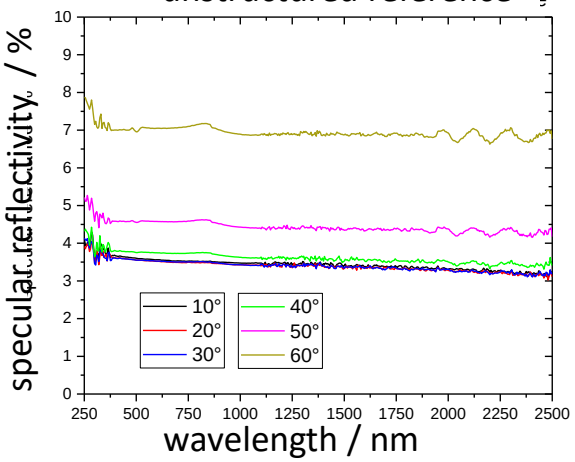
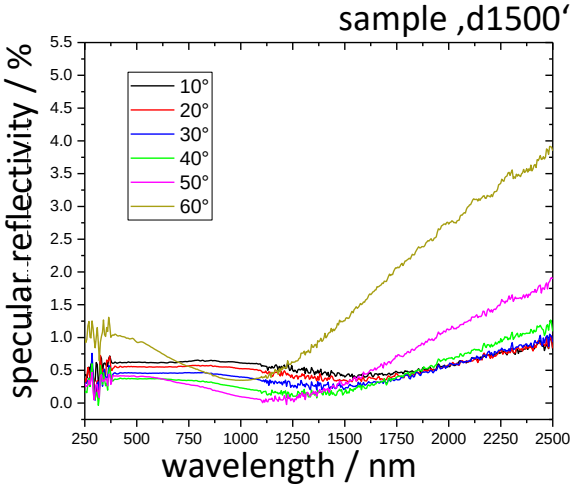
results: (angle dependency)

black

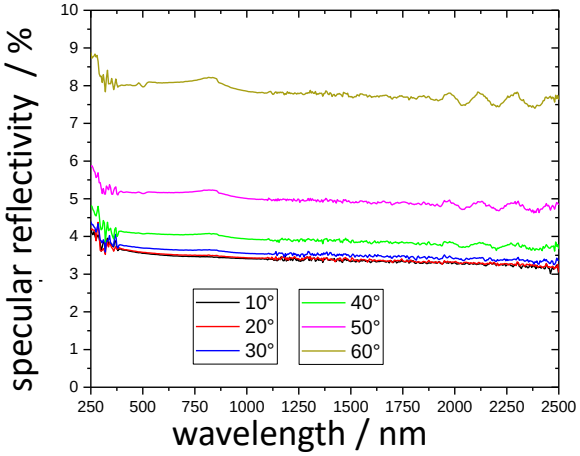
a)



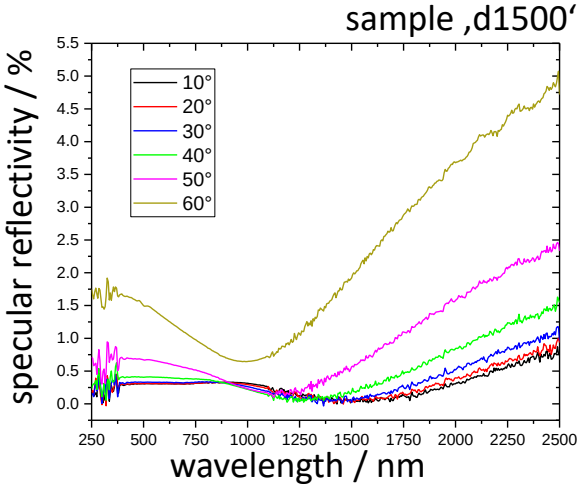
b)



c)



d)



white

Composition of inorganic and organic components

modern camera designs

Key aspects:

- **combine the benefits of inorganic and organic material properties,**
- **can be imprinted (UV embossing) → high volume production**
- **possible applications: car industry; medical endoscopes …**
- **high thermal stability**

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Anti-reflective (AR) moth-eye structures
(inorganic and organic) **hybrid polymers**

Ernst-Abbe-Hochschule Jena
University of Applied Sciences

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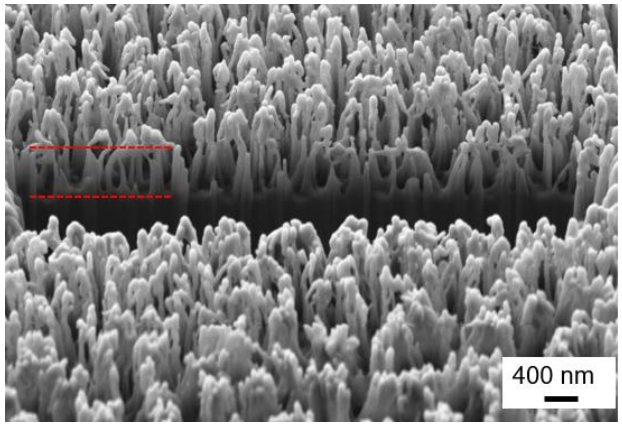

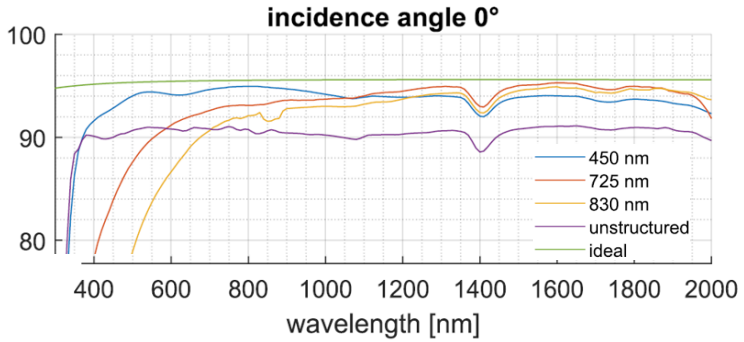

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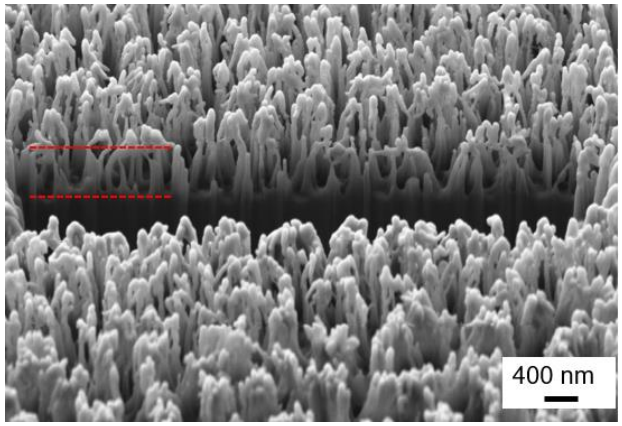

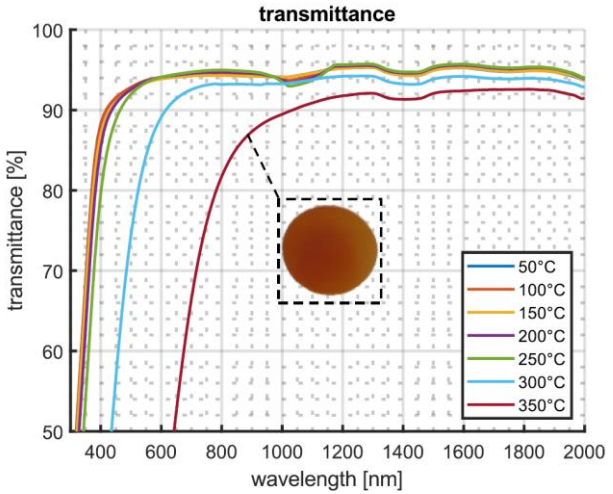

Summary

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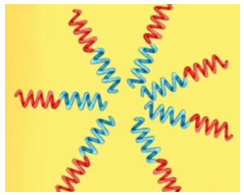
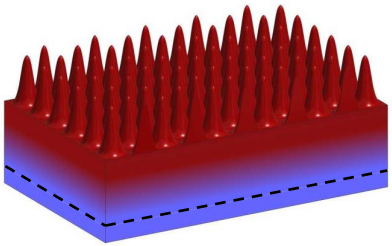
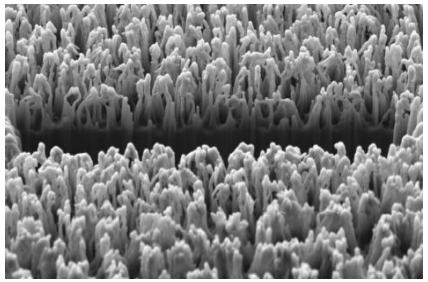
University of Applied Sciences



Block copolymer micellar lithography:

Many opportunities for antireflection applications





Anti-reflective (AR) moth-eye structures

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Many thanks to

M. Abend, H. Ehrlich, T. Helk, S. Klimke, A. Kobylinskiy, M. Kraus, P. Mößnang
U. Müller, S. Resche, L. Schmidt, D. Stumpf, X. Uwurukundo, H. Wagner, L. Werner

Many thanks to the partners

Many thanks for the financial support

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Many thanks for the fi[illegible]pport

Many thanks for the attention!

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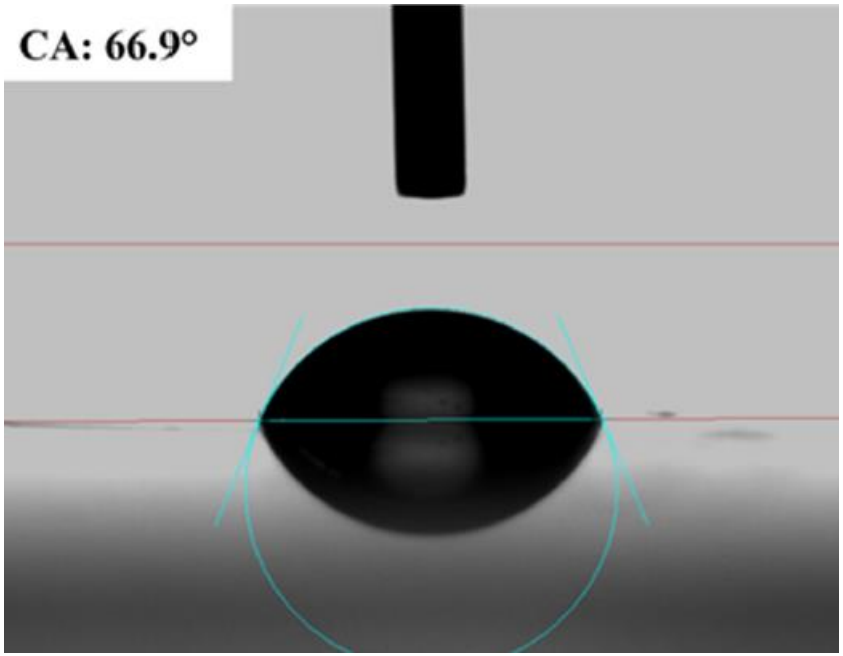
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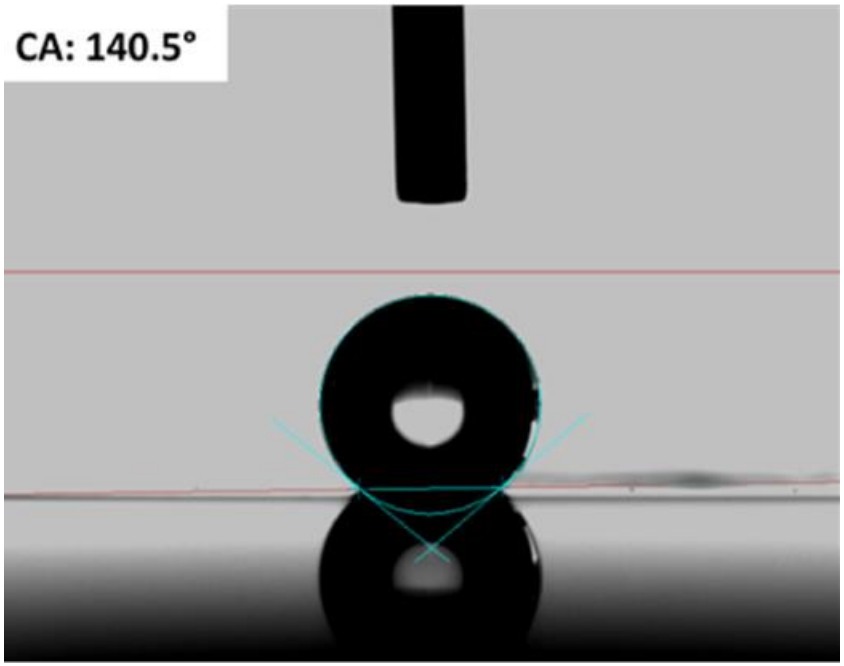
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