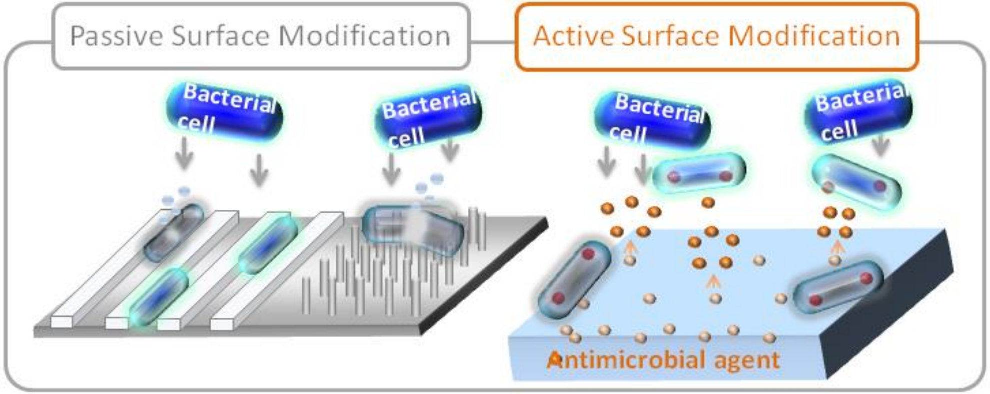
Antimicrobial Surfaces: Physical and Chemical Functionalization

Iban Quintana| EIBAR, May 3^{th} 2017

IK4 TEKNIKER
Research Alliance

Antimicrobial Surfaces

Overview



Passive Approach:

- Anti-biofouling
- Bactericidal

Active Approach:

- Coatings containing silver ions or NPs
- Antibiotics

Surface modification Strategy	Technical complexity	Versatility	Costs	Antibacterial Activity	Resistance induction	Toxicity/ Cytotoxicity
Passive methods	☺	😐	😐	😐	☺	☺
Active methods	😐	😐	☹	☺	😐	☹

Antimicrobial Surfaces: COMPLEXITY

Gram positive and Gram negative: p. aeruginosa (-), e-coli (-), s. aureus (+), s. epidermidis (+), etc.

Real life is more complex:

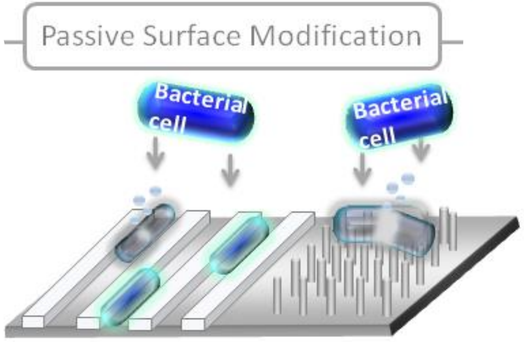
Infected wounds

- Gram positive skin organisms and gram negative gut flora
- *Staphylococci*, MRSA, *Pseudomonas*, *Acinetobacter*, Beta haemolytic *Streptococci*, *Enterococci*, Vancomycin Resistant *Enterococci*, *Corynebacteria*, Bacteroides, Proteus, *E.coli*, etc
- *Mature biofilms*

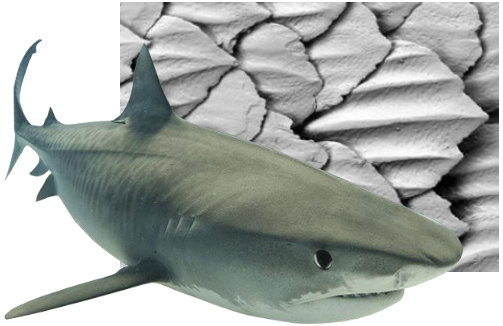
Hip Joint infections

- Predisposing factors
- S. aureus, Streptococci, e.coli, salmonella enterica, P. Aeruginosa, mycobacterias, campylobacter, etc.
- Biofilm formation: antibiotic resistance
- Small colony variants: modification on bacterial cells development

Antimicrobial Surfaces: Passive Approach



Technique	Advantages	Disadvantages	Antibacterial Capacity	Scalability
Chemical Etching (Black Silicon)	Biomimetic	• Material limitation • Time consuming (5 min., 100 mm^2).	P. aeruginasa: 4.3x10^5 S. aureus: 4.5x10^5 B. subtilis: 1.4x10^5	☹
Hydrothermal treatments (Titanium nanowires)	Size control Biomimetic	• Material limitation • Time consuming (1 mm/1 hour at 240°C). • Expensive process	S. aureus, E. faecali, K. pneumoniae: <10% P. aeruginosa, E. coli, B. subtilis: 40%-80%	☹
Pulsed Plasma Polymerization + UV irradiation (photolitography)	Substrate-independent High resolution	• Geometrical restrictions • Photocurable polymers required • Time consuming	E. coli: 13-33% bacterial adhesion reduction after 14 h	😐
Direct laser interference patterning (DLIP)	High quality nano-features in a wide range of materials	• Geometrical restrictions • Depend on laser characteristics • Small areas	S. aureus: up to 60% reduction in adhesion	😐
Ultrashort pulsed laser ablation	Hierarchical structures. Wide variety of materials. Large areas Robust equipment	• Material limitation • Time consuming • Expensive	On titanium. Decreased adhesion of P. aeruginosa ≈90% No effects on S. aureus.	☺
Roll2Roll nanostructuring	Large areas via nanostructuring of the roll – die.	• Uses only flexible materials (films)	E. coli: 32 % reduction in bacterial adhesion, considering PS, PE and PC	☺

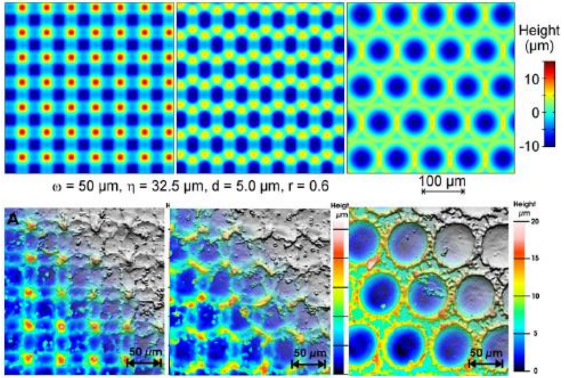


https://softmat.net/2012/05/anti-microbial-materials/

Antimicrobial Surfaces: Passive Approach

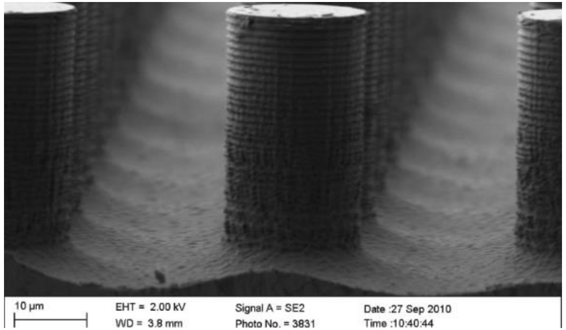
Technologies

Ps pulsed laser ablation: Direct microstructuring



- Wide variety of materials: Metals, ceramics, polymers, glass
- Adapted to 3D-Surfaces
- Reliable process.

Black Silicon + Hot embossing



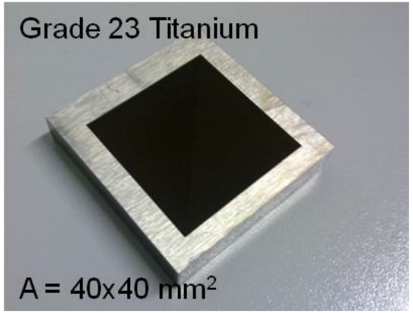
- Replication of Nanostructures on thermoplastics and resins
- Submicro- and nanoscale
- Limited to flat samples

Antimicrobial Surfaces: Passive Approach

Results

Ps pulsed laser ablation: Direct microstructuring

Material: Titanium (ELI 23) (Ti6Al4V)

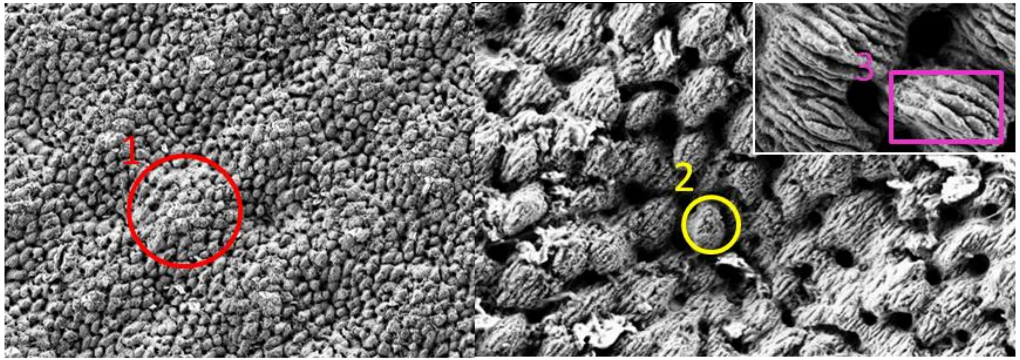


Three-fold scale topography:

1) Major pattern: micro-pyramids

2) Minor pattern: micro-spheres

3) Ripples: nanofeatures

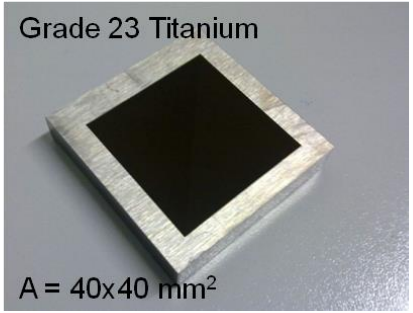


Antimicrobial Surfaces: Passive Approach

Results

Ps pulsed laser ablation: Direct microstructuring

Material: Titanium (ELI 23) (Ti6Al4V)

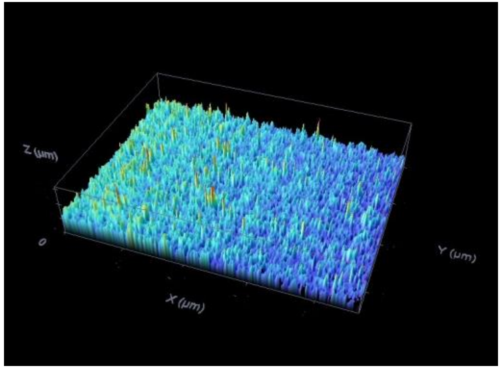


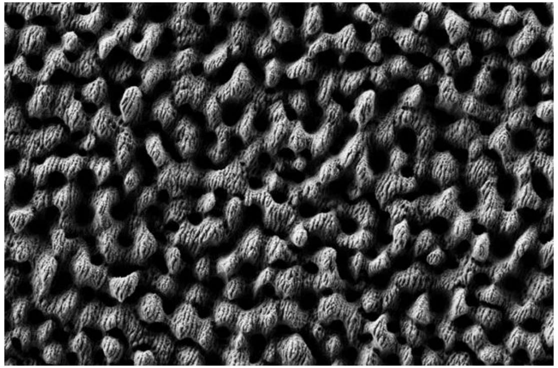
Two-fold scale topography:

~~*1) Major pattern*: micro-pyramids~~

2) Minor pattern: micro-spheres

3) Ripples: nanofeatures





Antimicrobial Surfaces: Passive Approach

Results

Ps pulsed laser ablation: Direct microstructuring

Antibacterial activity:

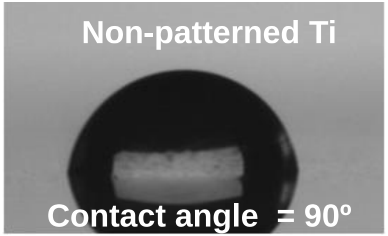
ISO 22196 or **JIS Z 2801:2010**

Percentage of the reduction in bacterial proliferation:

$$R\,(\%) = \frac{Control\left(\frac{Bacterias}{cm^2}\right) - Texturizado\left(\frac{Bacterias}{cm^2}\right)}{Control\left(\frac{Bacterias}{cm^2}\right)} \cdot 100$$

Bacterial assays

Wettability

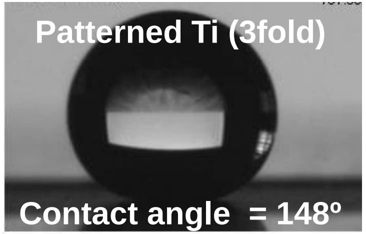


Three-fold topography

S. Aureus: **R = 98%**

S. Epidermidis: **R = 77%**

R > than results published at literature about antibacterial activity of nano/micropatterns (R = 50-90%).

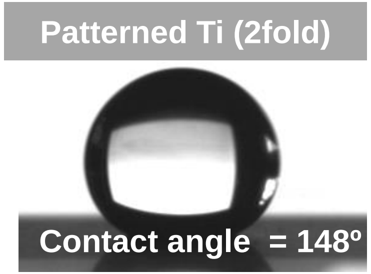


Two-fold topography

S. Aureus: R = 0%

S. Epidermidis: R = 0%

Not antibacterial activity was detected for both bacteria considered.

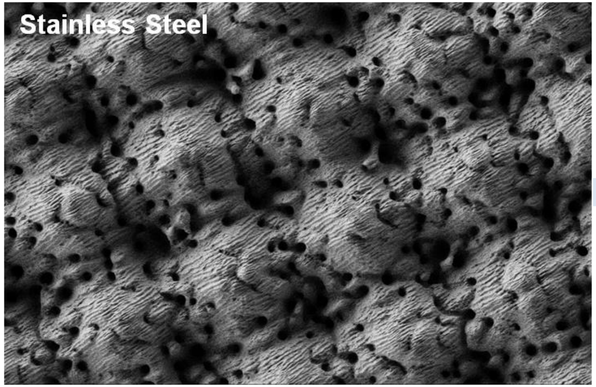


Antimicrobial Surfaces: Passive Approach

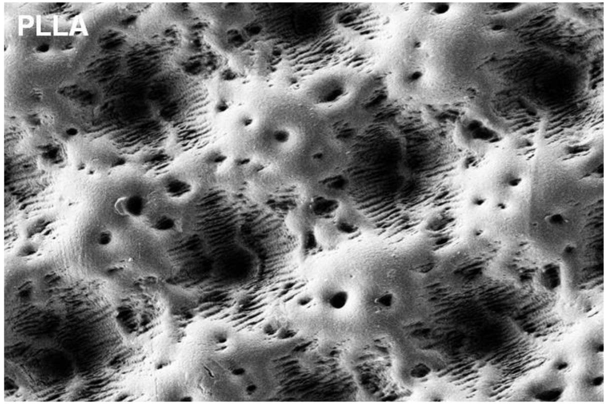
Results

Ps pulsed laser ablation: Direct microstructuring

Other Materials



Hot Embossing



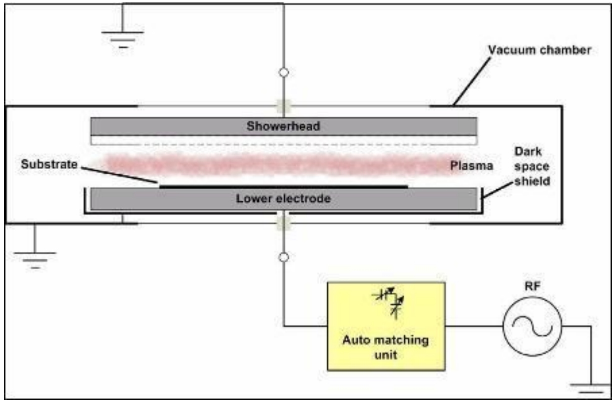
Effective Replication

Bacterial assays in progress

Antimicrobial Surfaces: Passive Approach

Results

Black Silicon: Silicon Etching by RIE

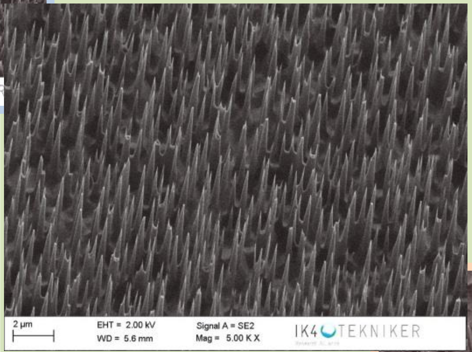


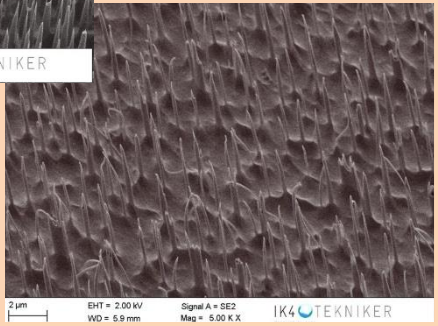
Process Parameters to control:

- SF6/C4F8 ratio
- RF power (W)
- Chamber Pressure (mTorr)
- Etching time (s)

Height ≈ 0.6 µm
Density ≈ 4.5x10^6 pk/mm^2
ϕ = 0.3 µm

Height ≈ 2.2 µm
Density ≈ 1.5x10^6 pk/mm^2
ϕ = 0.3 µm





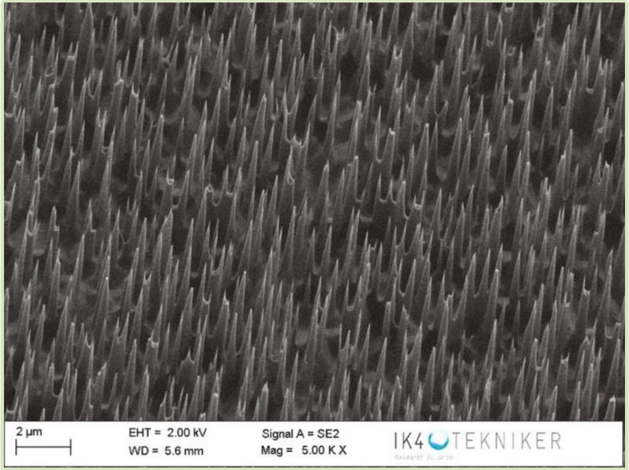
Height ≈ 2.7 µm
Density ≈ 6.5x10^5 pk/mm^2
ϕ = 0.2 µm

Antimicrobial Surfaces: Passive Approach

Results

Black Silicon: Silicon Etching by RIE + HOT EMBOSSING

Height ≈ 2.2 µm
Density ≈ 1.5x10[6] pk/mm[2]
ϕ = 0.3 µm



Antibacterial activity:

Nanostructuring approach

S. Epidermidis: **R(%) = 99.99% (R=4.76)**
P. Aeruginosa: **R(%) = 99.99% (R=5.75)**

Replication in polymers?

HOT EMBOSSING (PC)

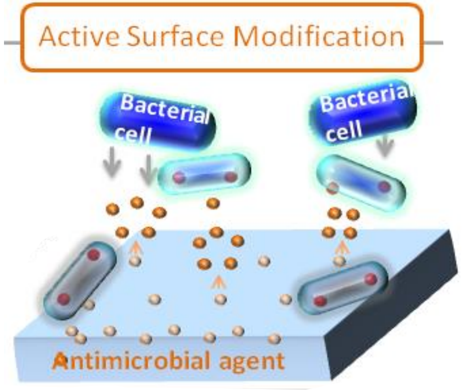
Nanostructuring approach

S. Epidermidis: **R(%) = 3.1% (R=0.02)**

Bacterial colonization on PC is one order of magnitude lower than in Si

Antimicrobial Surfaces: "Active" Approach

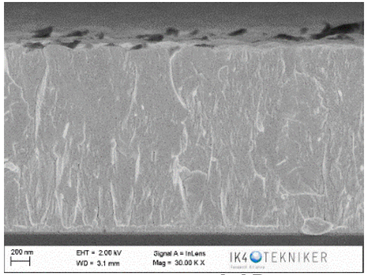
Results



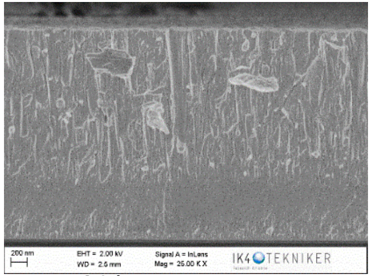
PVD coating: TaN + Metallic Dopant (MD)

- Excellent Tribological properties
- Biocompatible
- Radiopacity

TaN

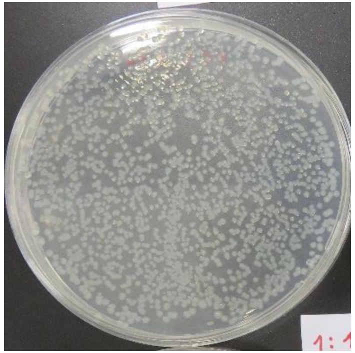


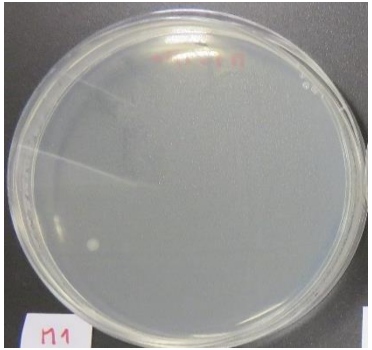
TaN+MD_1



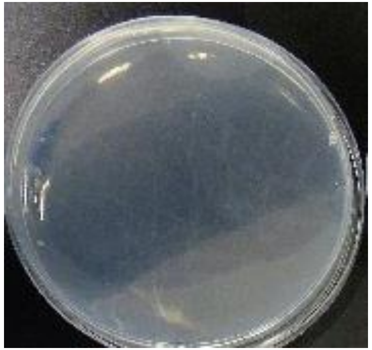
MD content < 50%

Non Cytotoxic





TaN+MD_1



TaN+MD_2

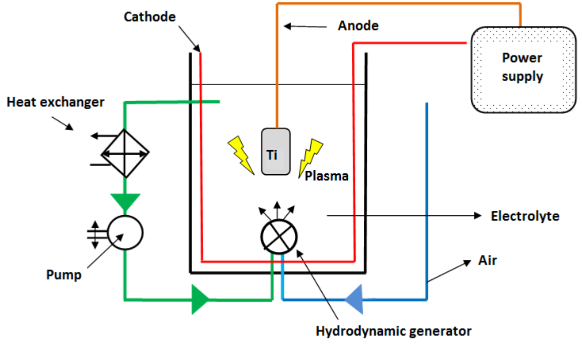
PVD coating approach

E. Coli (TaN+MD_1): R(%) = 99.6% (R=2.4)

E. Coli (TaN+MD_2): R(%) = 99.9% (R=4.8)

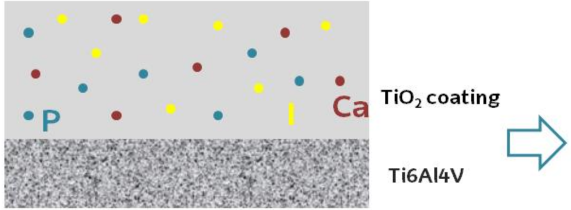
Antimicrobial Surfaces: “Active” Approach

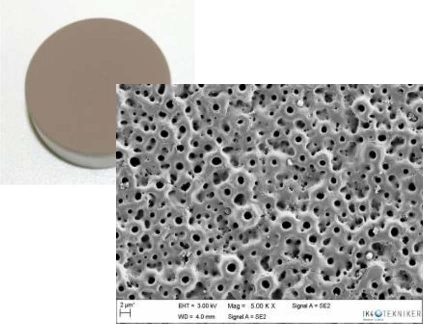
Plasma Electrolytic Oxidation (PEO)



TiO_2, Titanium Oxide

- ✓ Hard coatings
- ✓ Prevent wear
- ✓ Excellent dielectric insulations
- ✓ Prevent galvanic corrosion
- ✓ Superior adhesion strength





Iodine as biocide agent

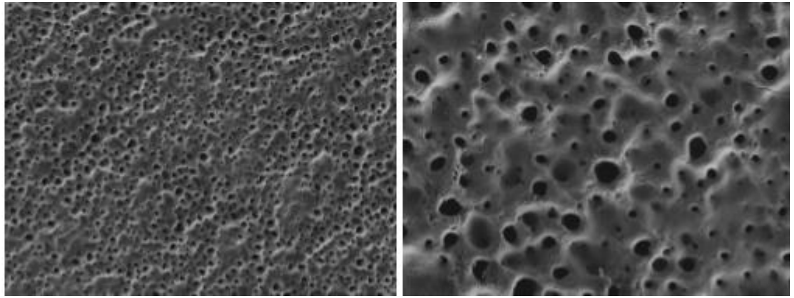
Antimicrobial Surfaces: “Active” Approach

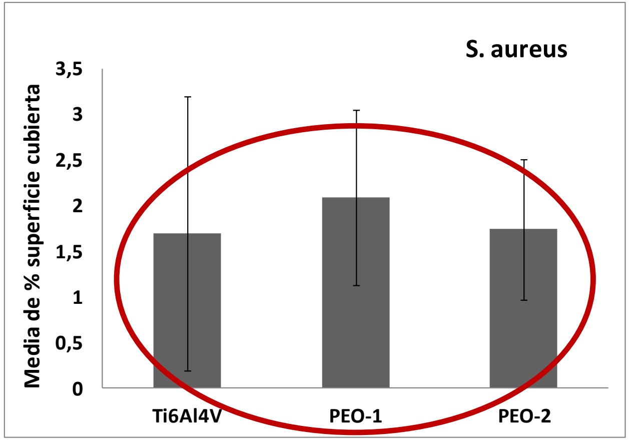
Plasma Electrolytic Oxidation (PEO)

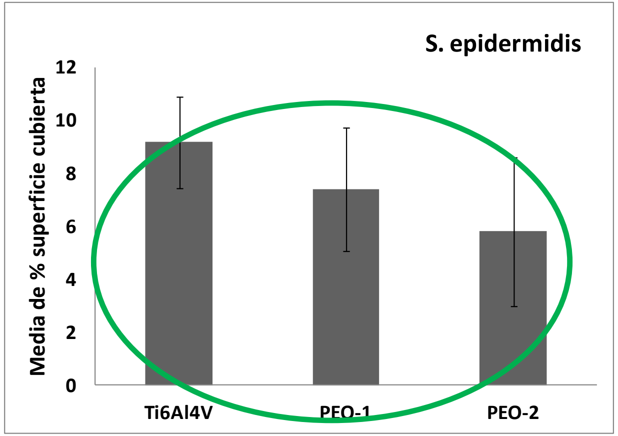
Antibacterial activity: TiO_2 + I

- S. aureus
- S. epidermidis

Collection strains





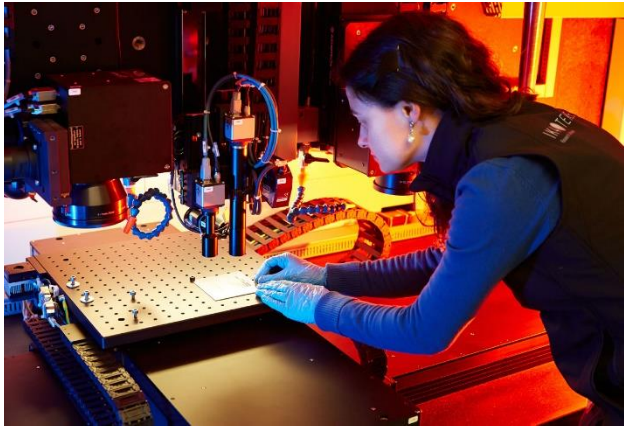


Antimicrobial Surfaces: “Pasive” and “Active” Approaches:

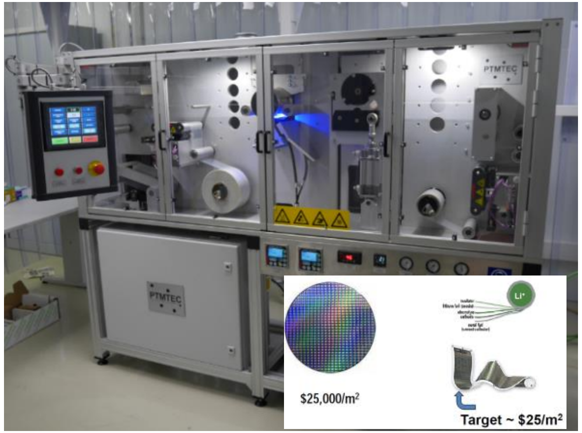
Results

UPSCALING CAPABILITIES AT IK4 - TEKNIKER

Laser microstructuring-cutting of complex surfaces

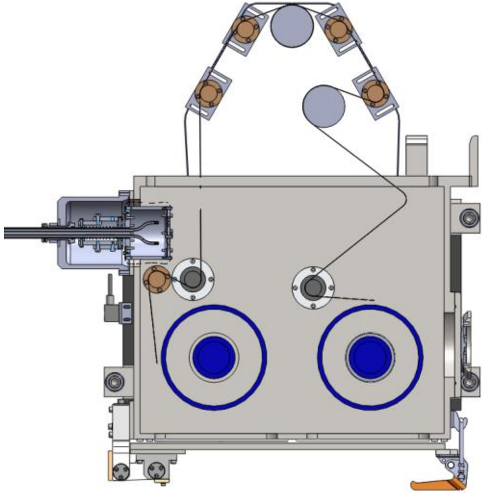


R2R NIL



UV-NIL and Thermal NIL

R2R PVD Process



Web widht: 100 mm

Speed: 10 m/min

Antimicrobial Surfaces

Conclusions

Antibacterial capacity of nano- and microstructuring surfaces depends on the substrate and bacterial type considered: There is no universal solution

Pattern customization has to be determined by considering both substrate and bacterials involved

Laser structuring of Ti substrate leads to good antibacterial capacity for s. aureus and s. epidermidis bacteria

Nanopatterning following the black silicon approach leads to excelent antimicrobial capacity for s. epidermidis and p. aeruginosa, only in silicon

TaN + Metallic Dopant coatings and PEO Surface solutions offer excellent results on tribological properties and antibacterial capacity (e. coli, s. epidermidis) of Ti substrates

All these technologies are applied on complex shape products and large area substrates via up – scaling strategies adopted by IK4-TEKNIKER

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Research Alliance