Laser Induced Forward Transfer of High Viscosity Fluids. Application To Solar Cell Metallization and Bio-Printing

M. Morales, D. Munoz-Martin, S. Lauzurica, A. Márquez, Y. Chen, D. Canteli, C. Molpeceres

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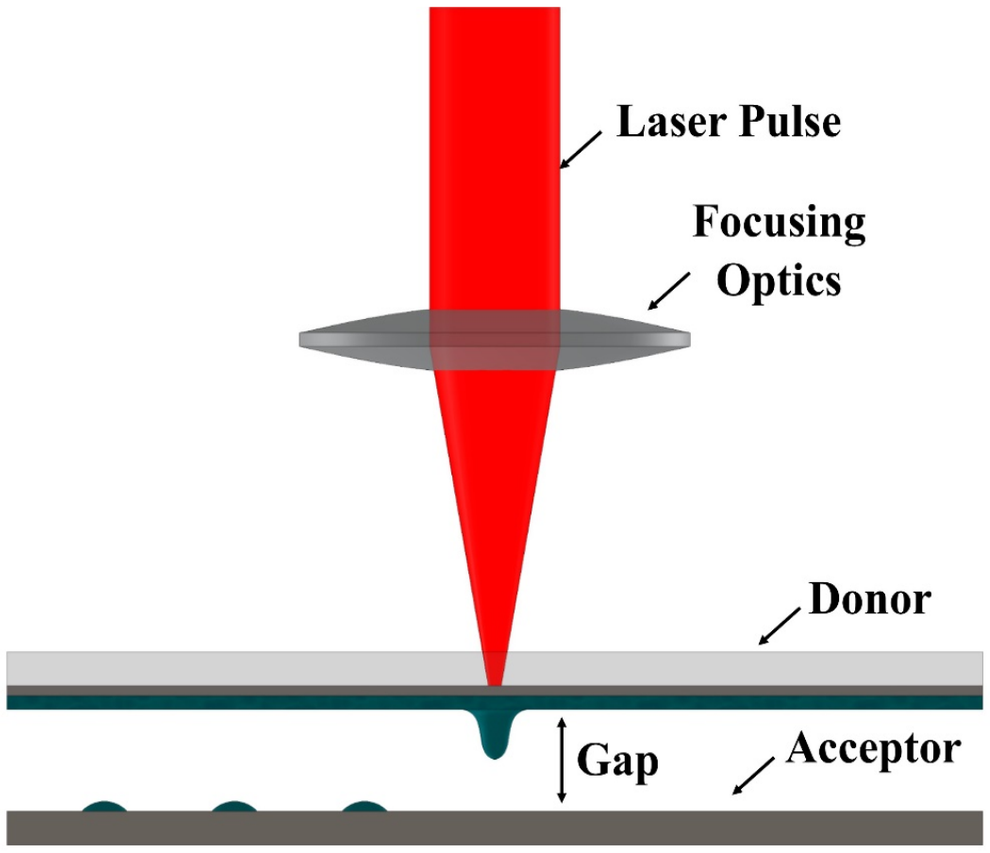
Outlook

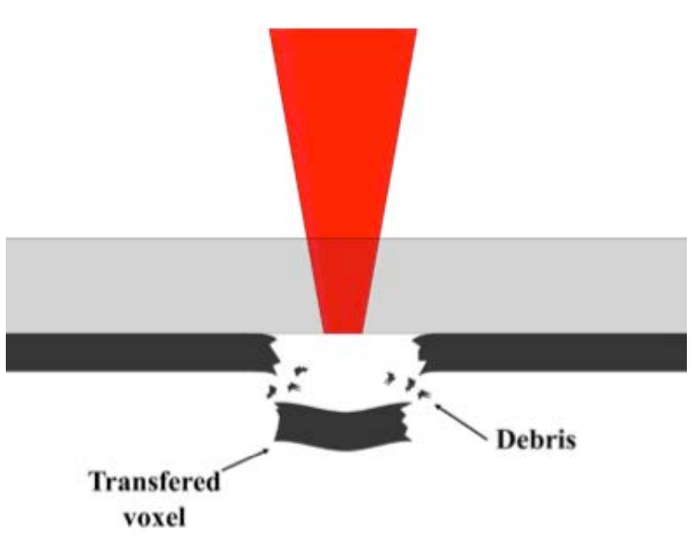
1. Introduction to Laser Induced Forward Transfer (LIFT)
2. Application to PV industry: solar cell metallization
3. Application to bio-printing
4. Understanding the printing process: numerical simulation
5. Summary & Acknowledgements

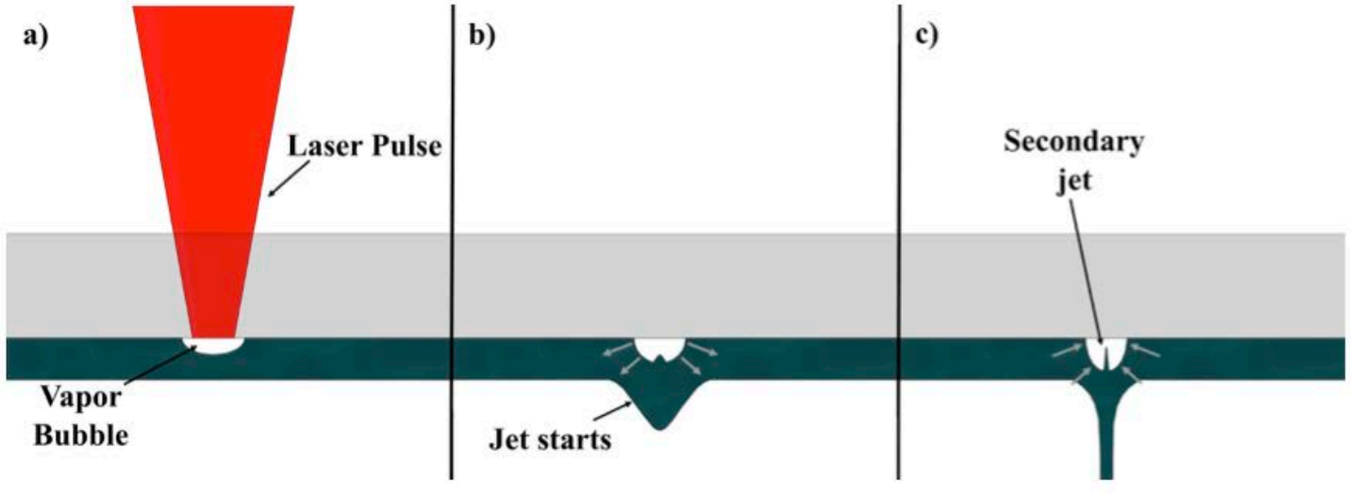
Laser Induced Forward Transfer



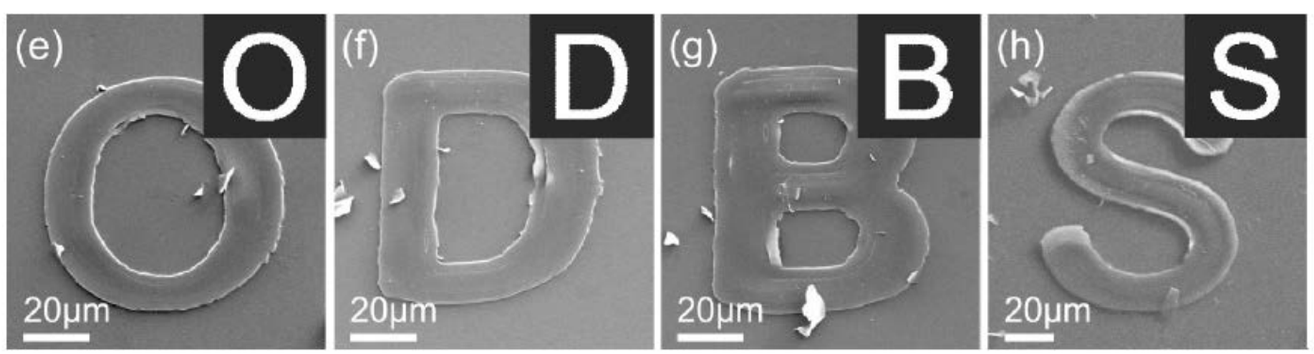
Some materials deposited using LIFT:

- Metals
- Oxides
- Nanopowders
- Organic polymers
- Biomaterials & living cells
- Conductive inks
- Ag nanoparticles pastes





Laser Induced Forward Transfer



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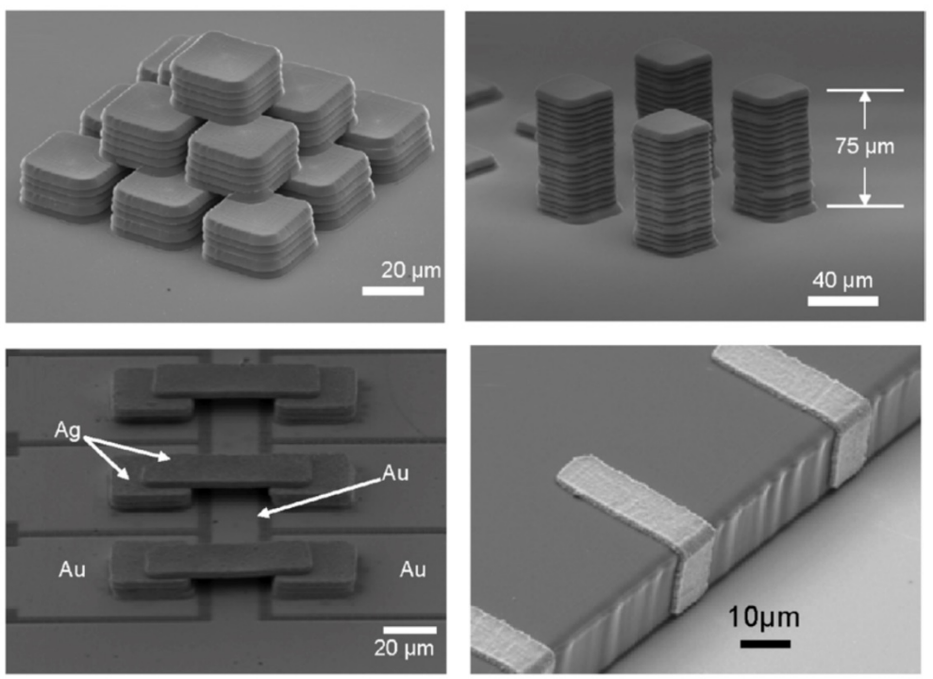

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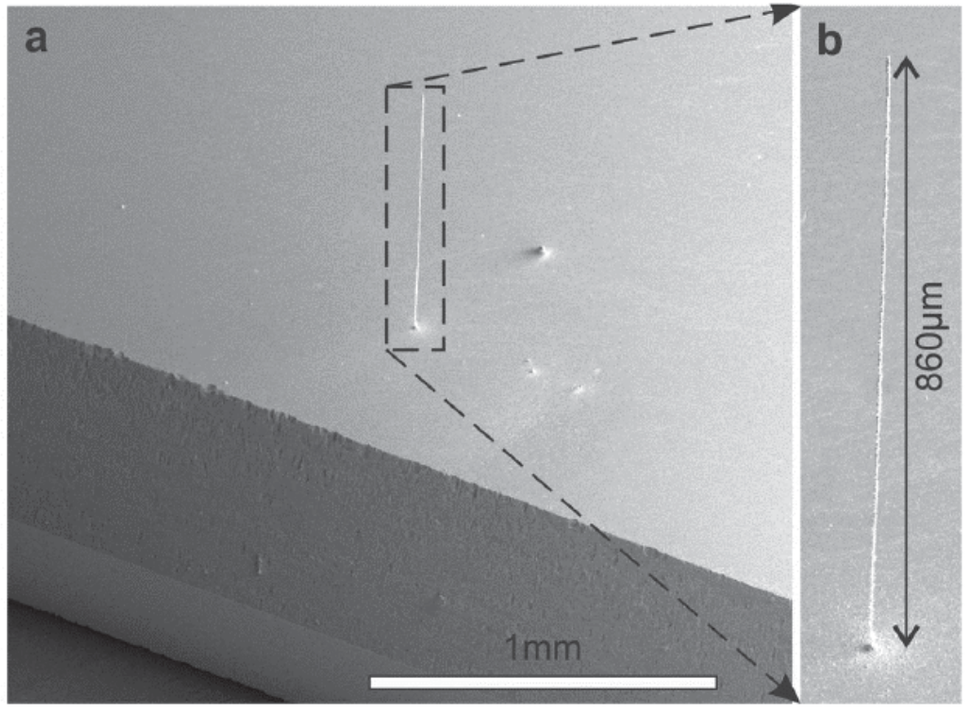

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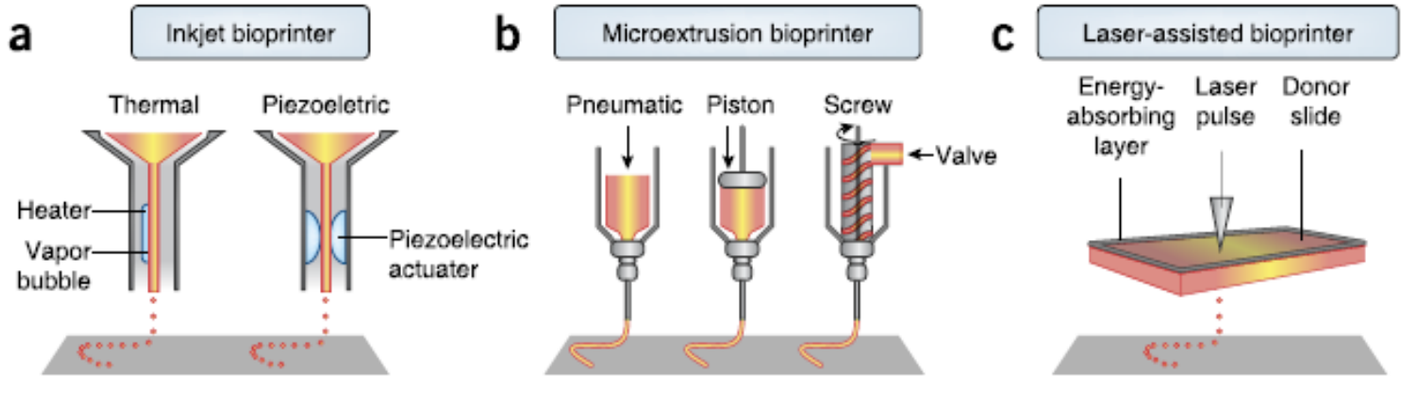
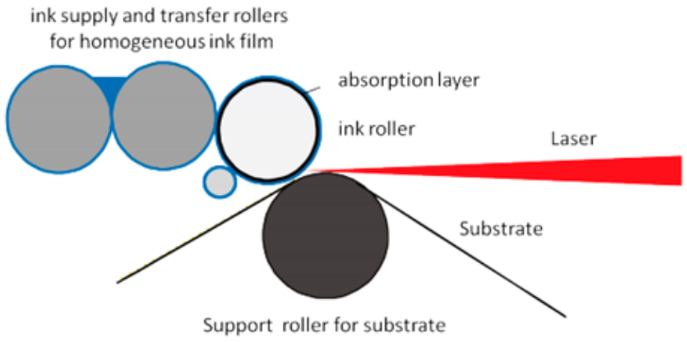


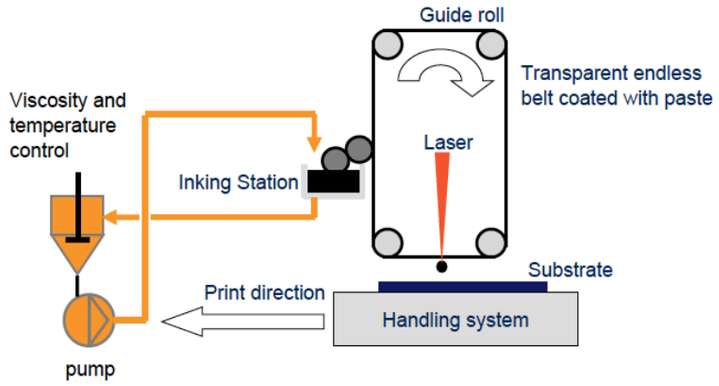
Murphy & Atala, Nat. Biotechnol. 32 (2014) 773-785

Laser Induced Forward Transfer

Lasersonic® LIFT Process



Hennig et al, J. Laser Micro Nanoeng. 7 (2012) 299–305



BASF
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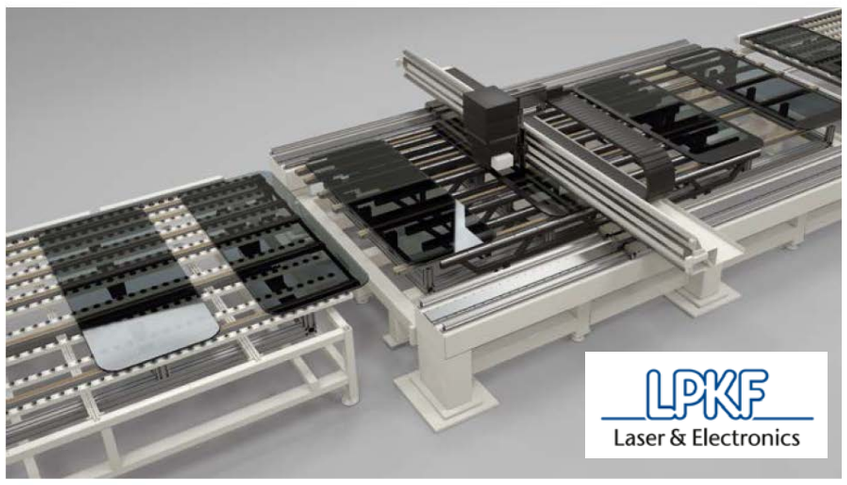

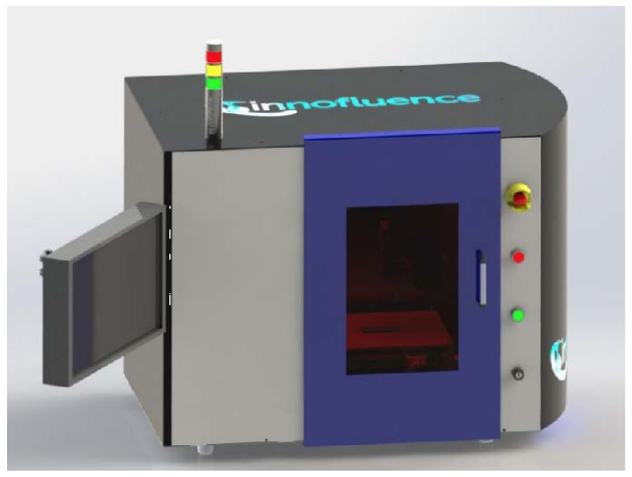

innofluence

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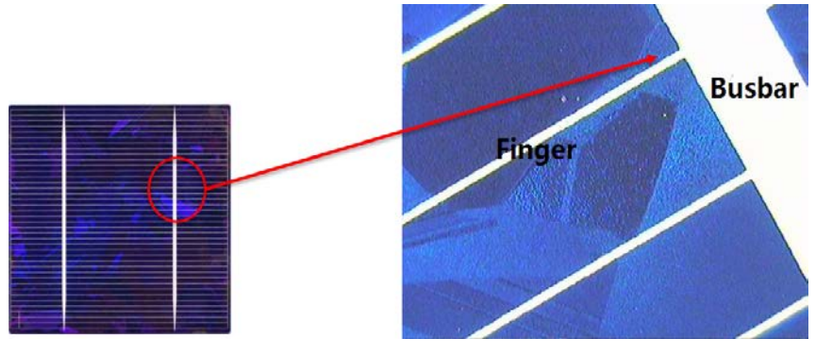
LIFT for solar cell metallization

Front-side metallization: key process for enhancing efficiency in a cost effective way. It comprises different steps:

1. Pre-metallization processes
2. Metallization
3. Curing, sintering and firing

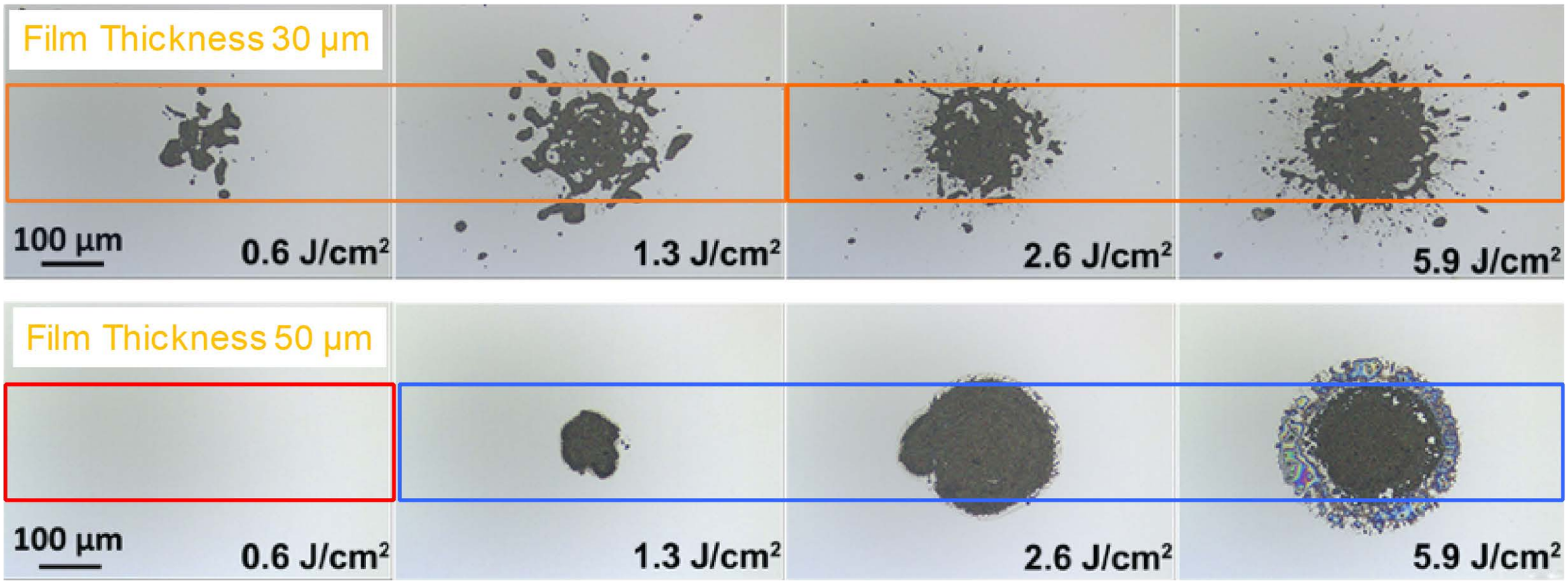


- ns- & ps- pulsed lasers emitting at 532 nm
- Beam scanned using motorized axis, galvo and polygon scanners.
- Basic LIFT configuration (no intermediate absorbing layer or assisting liquid matrix). Gap distance: in de order of tens of µm.

- DuPont PV17F & PV19B commercial screen printing Ag pastes.
- Non-newtonian, pseudoplastic, thixotropic fluids
- µ up to 250 ± 30 Pa·s
- Ag particles size: 1-5 µm
- Donor film thickness < 100 µm

LIFT for solar cell metallization

LIFT Voxel Printing



No transfer

Cluster transfer

Explosive transfer

Concrete-dot transfer

D. Munoz-Martin et al. Applied Surface Science 366 (2016) 389–396

LIFT for solar cell metallization

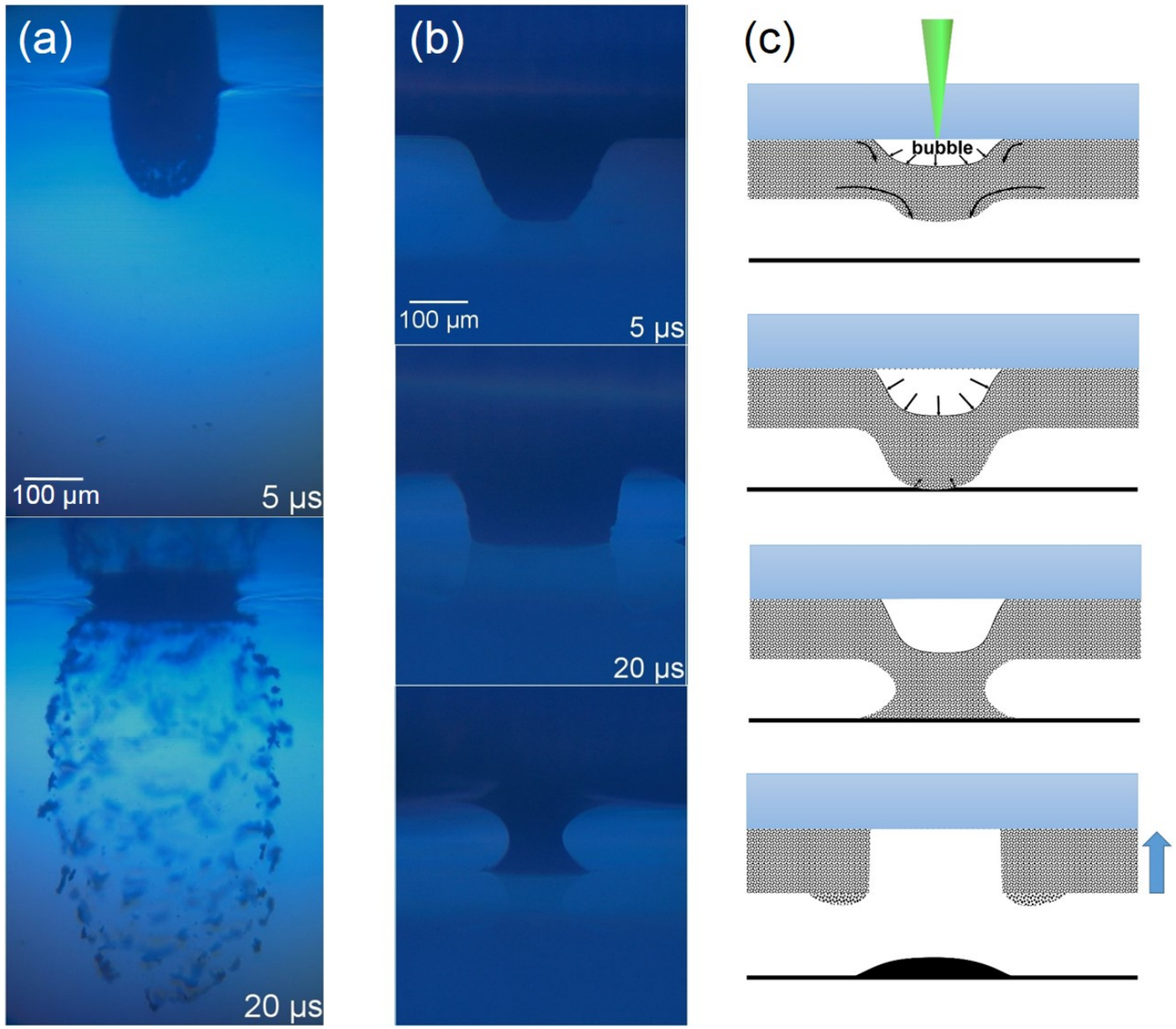
High viscosity paste transfer mechanisms

- Morphology of the transferred voxel depends on laser fluence (*F*), donor film thickness (*h*) and gap distance (*d*)

- Voxels transferred using large F consist of non-continuous clusters of paste (cluster-dot transfer)

- F just larger than the transfer threshold allows printing single dots of paste with large aspect ratio (concrete-dot transfer)

- **Effect of the substrate:** formation of a continuous pillar between donor and acceptor

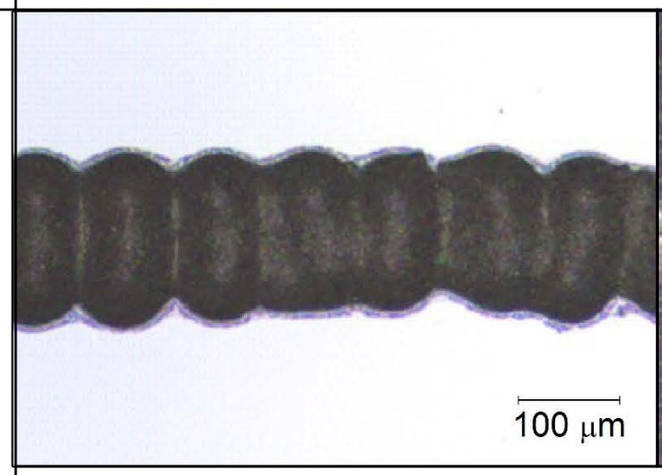


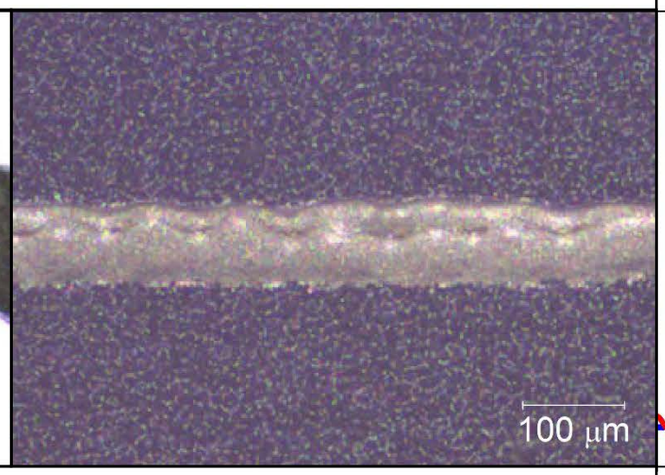
D. Munoz-Martin et al. Applied Surface Science 366, 389–396 (2016)

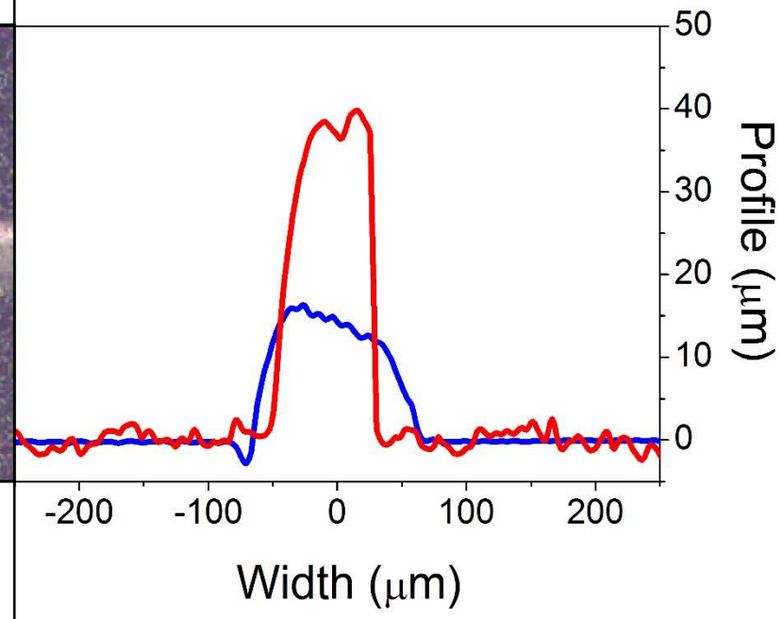
LIFT for solar cell metallization

Printing of lines

Substrate	polished c-Si	textured c-Si
Laser	ns-laser	







E_p = 13 µJ
ω_0 = 15 µm
Rep Rate = 20 kHz
v = 1800 mm/s
h = 50 µm
d = 50 µm

LIFT for solar cell metallization

Printing of lines

Substrate	polished c-Si	textured c-Si
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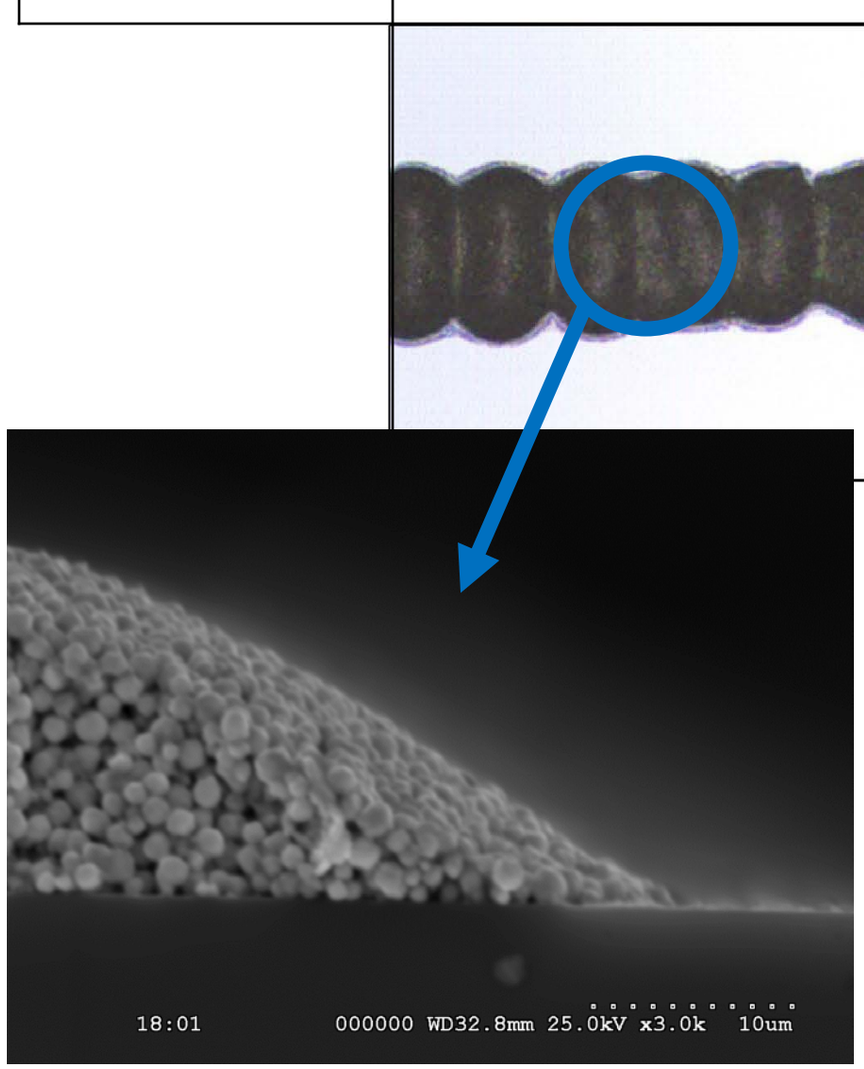
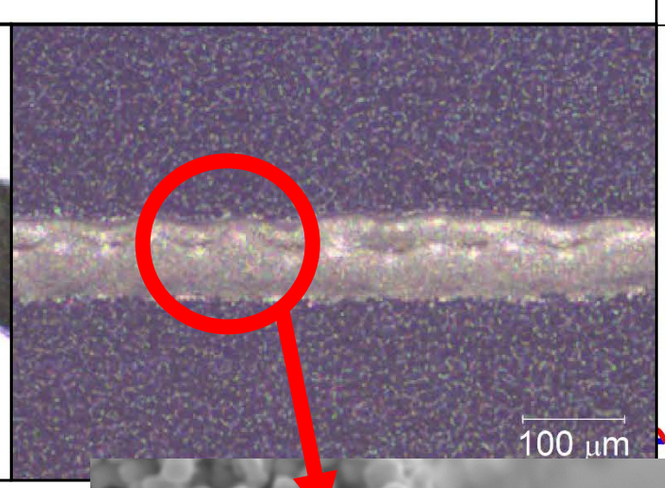
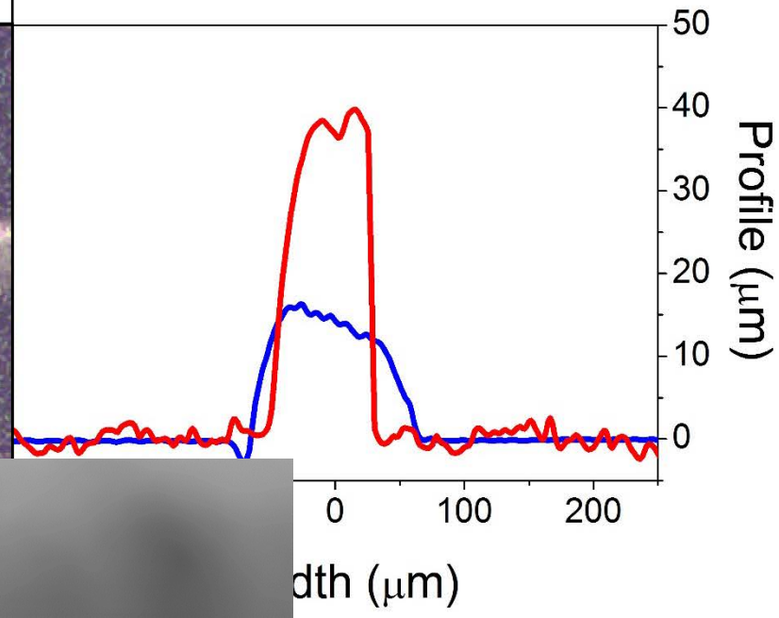


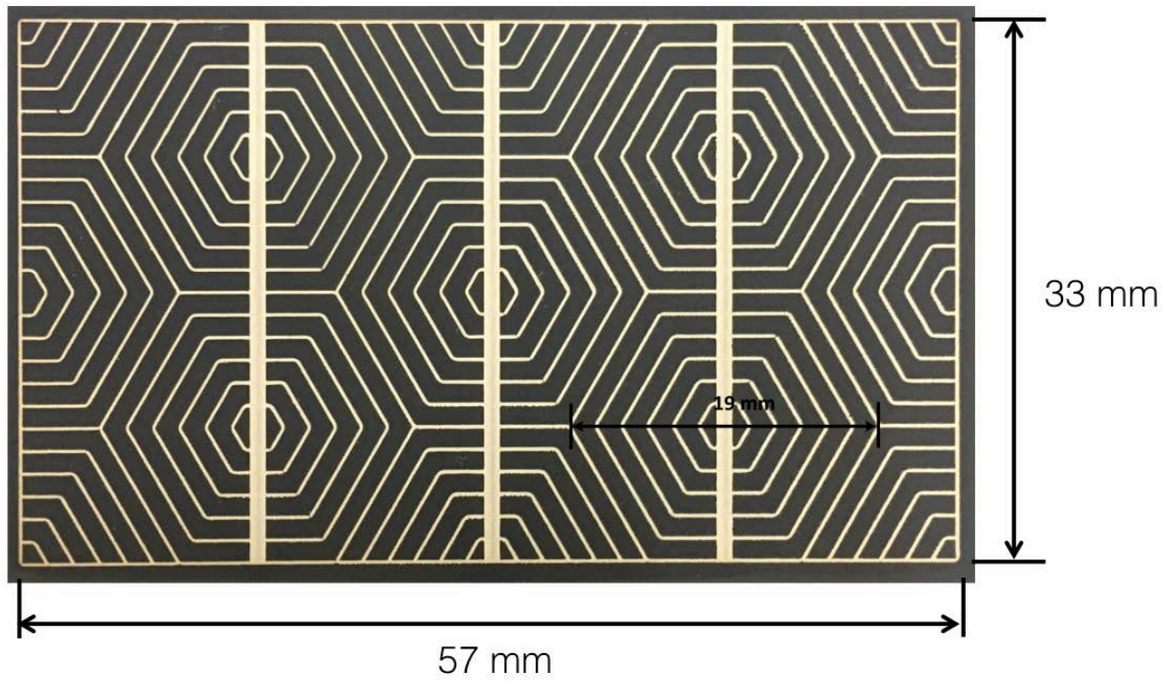




LIFT for solar cell metallization

Printing of lines: design flexibility

- Optical scanners allows fast processing and flexible design to print large areas.
- Very versatile, allowing any freeform design for the solar cells personalization.
- Application in Building integrated PV.



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LIFT for solar cell metallization

Proof of concept: full metallization of a CIGS solar cell on steel flex substrate

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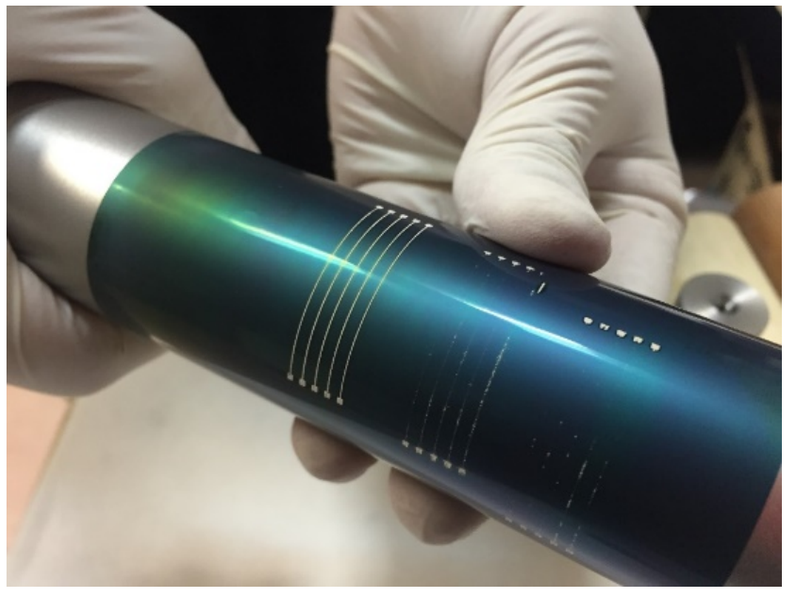
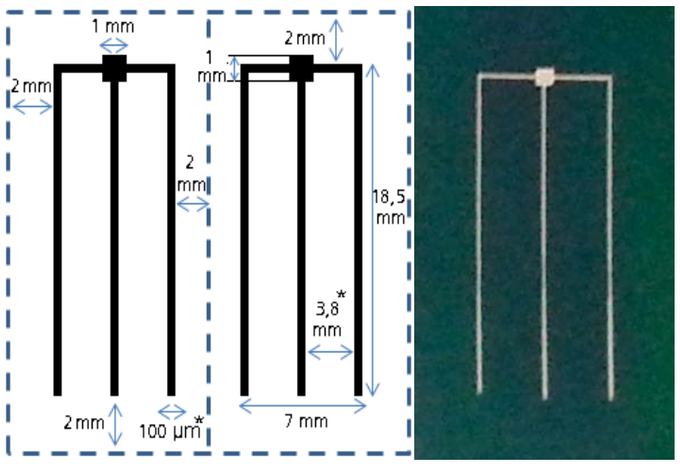
COOPERATION

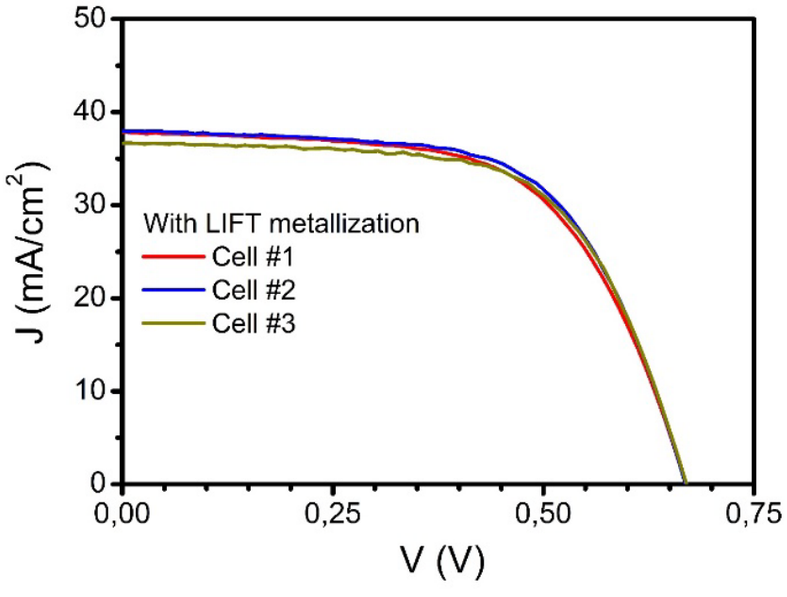
ABENGOA SOLAR



Good adherence after bending with radius down to 12 mm

Resistivity	40 μΩ·cm
Specific contact resistance	50 mΩ·cm^2





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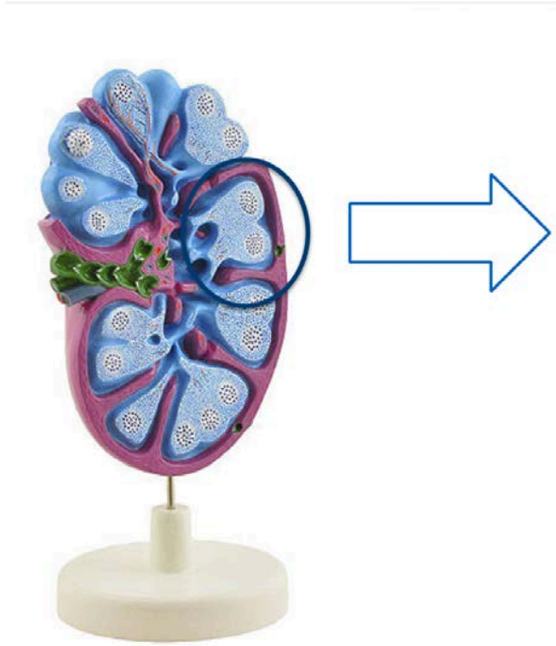
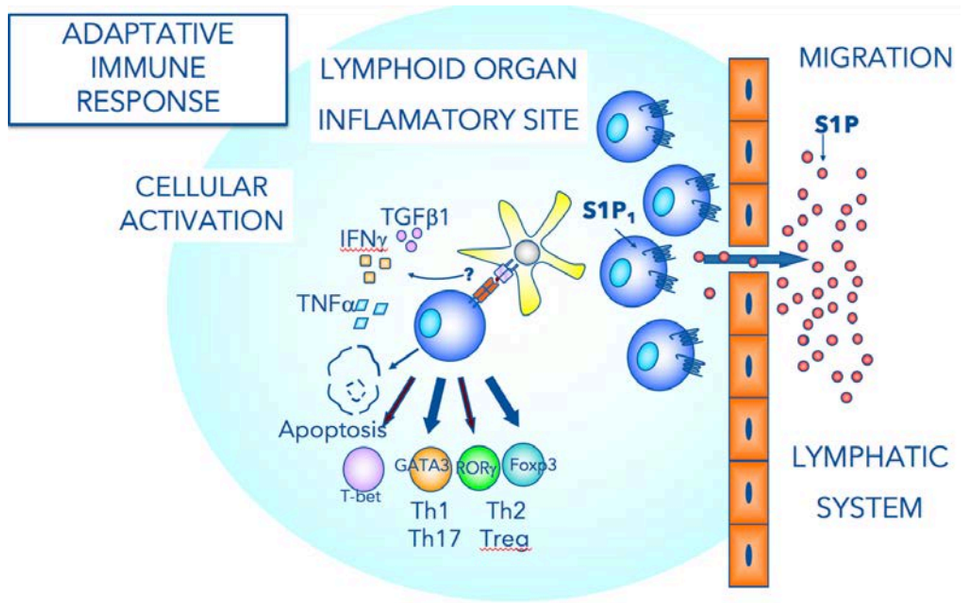
LIFT for bio-printing





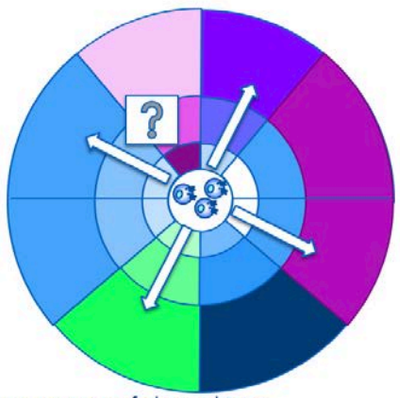
1. PRINTING different size of droplets with different cell concentration in order to control the number of cells inside them.

2. PRINTING different type of cells as close as possible.

3. Cell Activation, the interaction between different cell types is measured by cytokine reporters .

4. Study of cellular migration by means of different chemokine gradients

Different concentration gradients of chemokines



Different types of chemokines

LASER ENGINEERING

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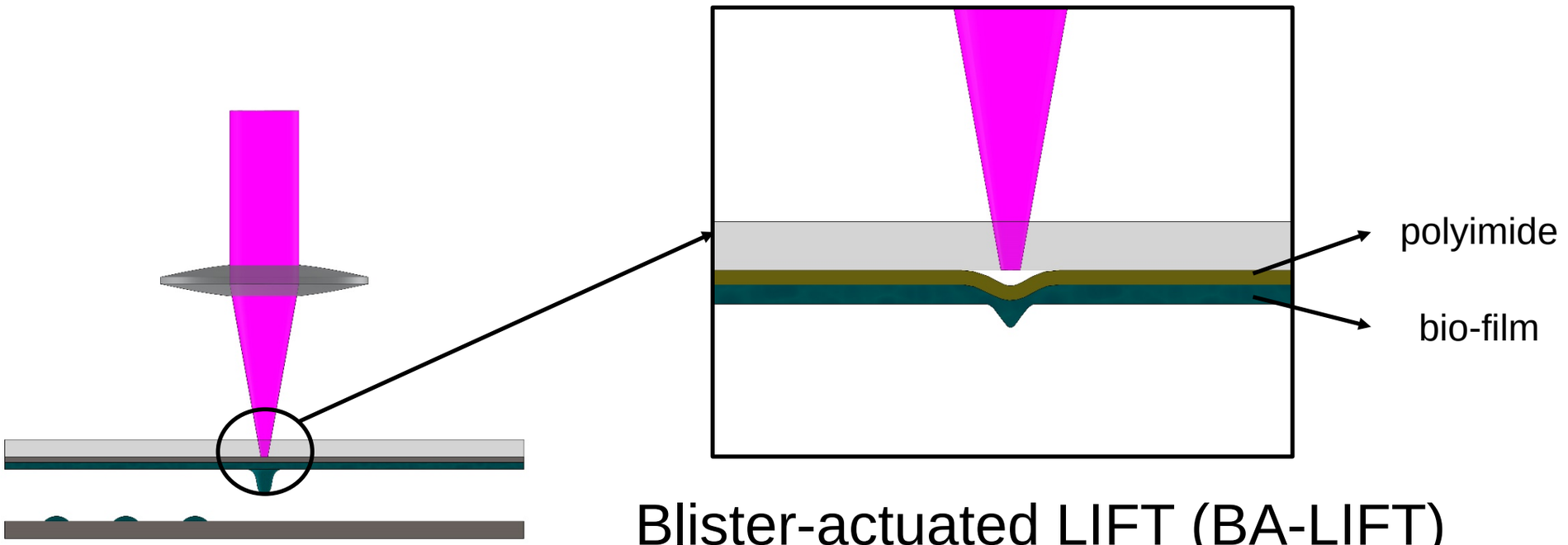
LIFT for bio-printing



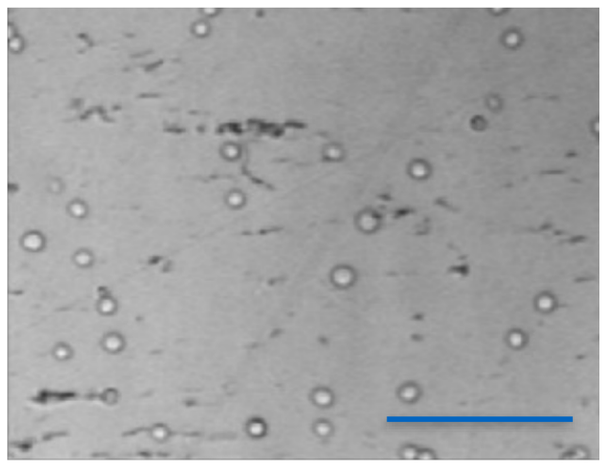
Blister-actuated LIFT (BA-LIFT)

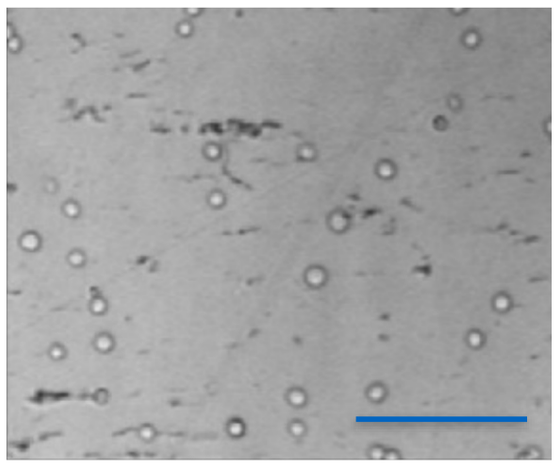
- ns- pulsed lasers emitting at 355 nm
- Beam scanned using a galvo scanner.
- BA-LIFT
- Donor film thickness: ~30 μm.
- Gap distance: ~500 μm.

LIFT for bio-printing

Two different cell types were used:

Dendritic cells (antigen presenting cells)





T lymphocytes from both human (jurkat cell line) and mouse (RMA/S cell line)

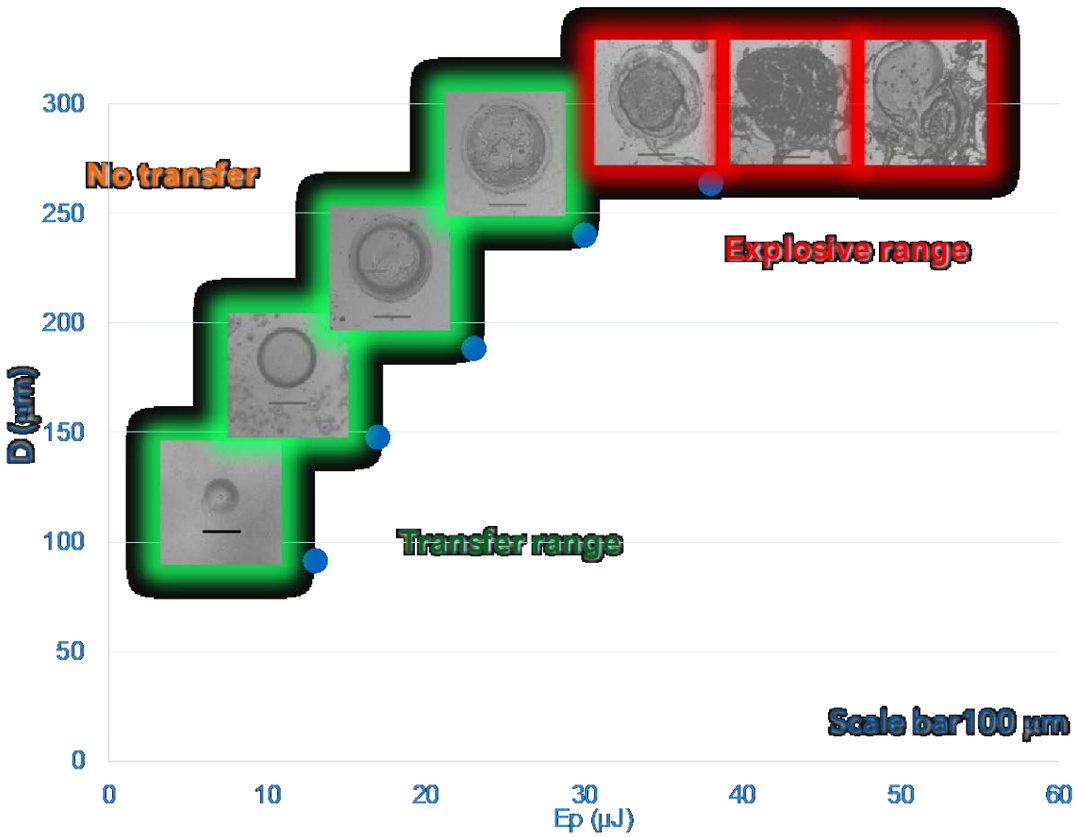
Cells need to be in a **matrix** that:

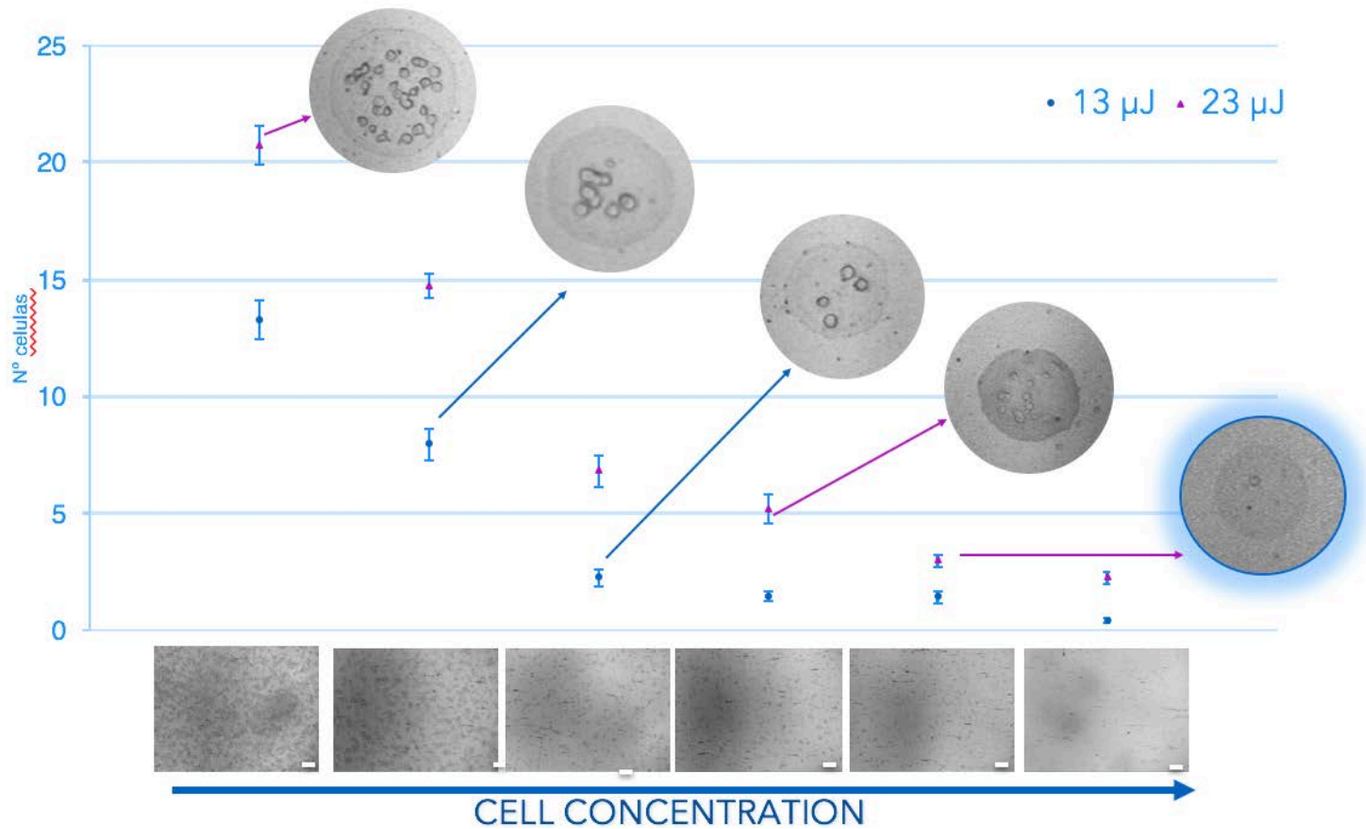
- allows keeping cells alive
- acts as a carrier during the cell printing process
- allows the formation of 3D structures once printed

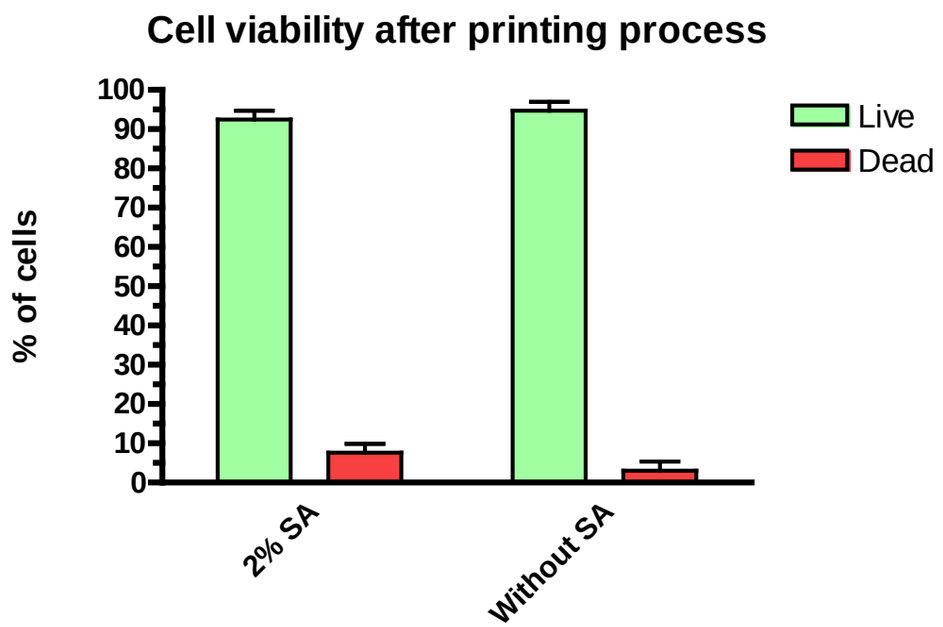
Different media can be used (sodium alginate solution in water and hydrogels)

Non Newtonian fluids with viscosities strongly dependent on the concentration and the temperature ($\mu \sim 10^{-3}$ – 1 Pa·s)

LIFT for bio-printing

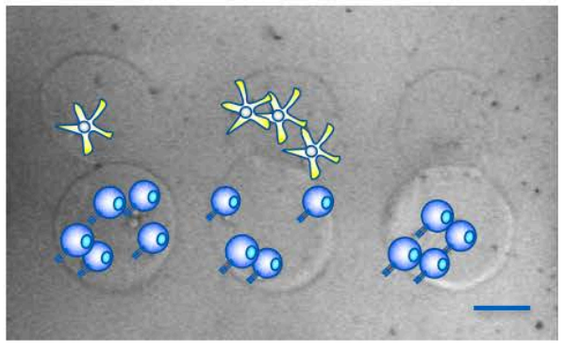




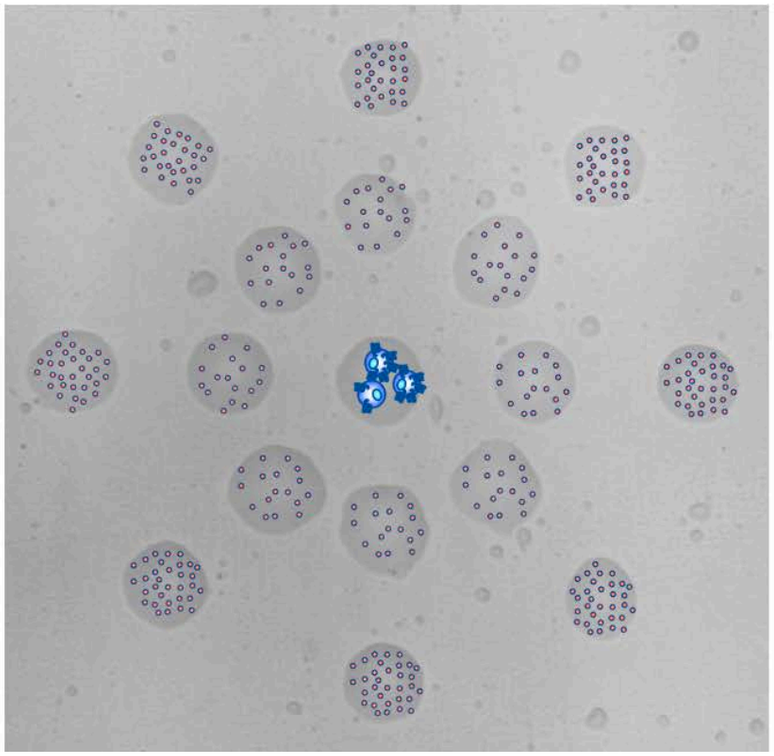


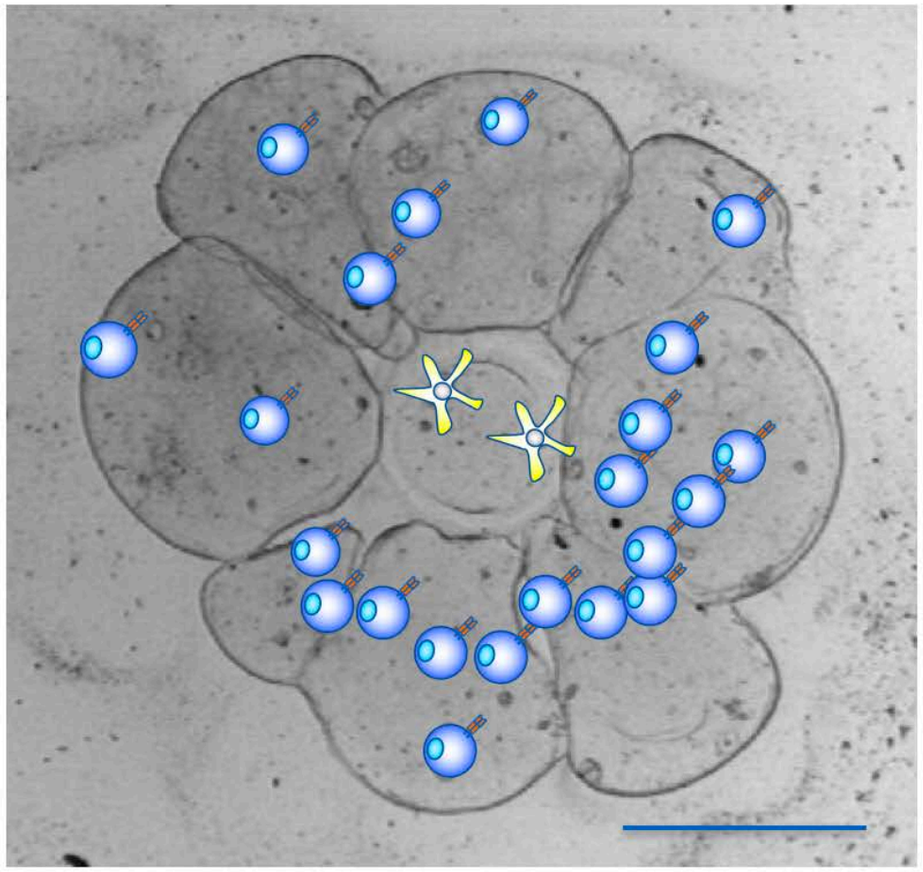
LIFT for bio printing

Two different cell type printed in different configuration



Different S1P chemokine concentration





Scale bar 100 μm

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Numerical simulation

Numerical simulation of the expansión of low and high viscosity fluids using BA-LIFT

COMSOL MULTIPHYSICS®

Navier-Stokes equations

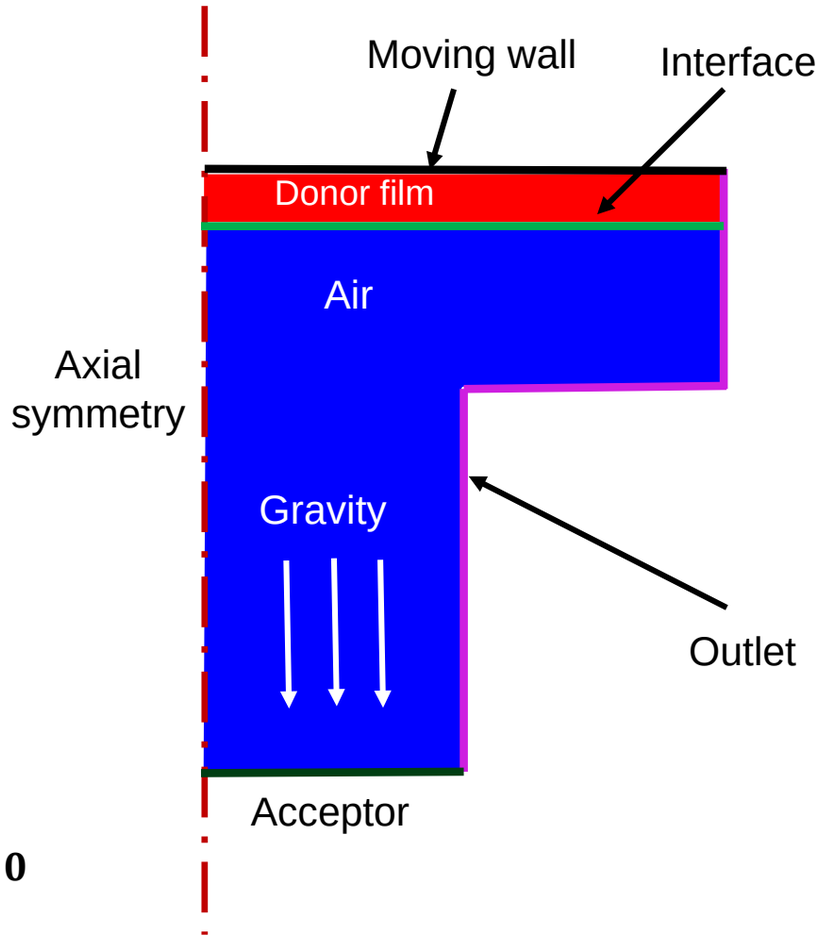
$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right) - \nabla\cdot\left(\mu(\nabla\vec{u} + \nabla\vec{u}^T)\right) + \nabla p = \overrightarrow{F_{ST}}$$

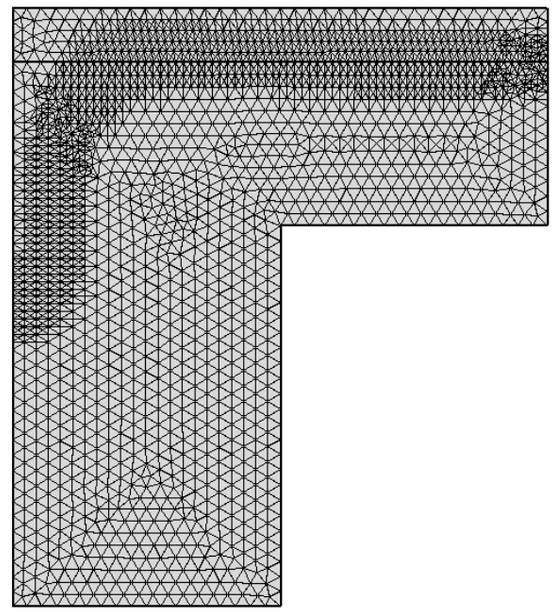
$$(\nabla\cdot\vec{u}) = 0$$

Two phase flow – level set interface

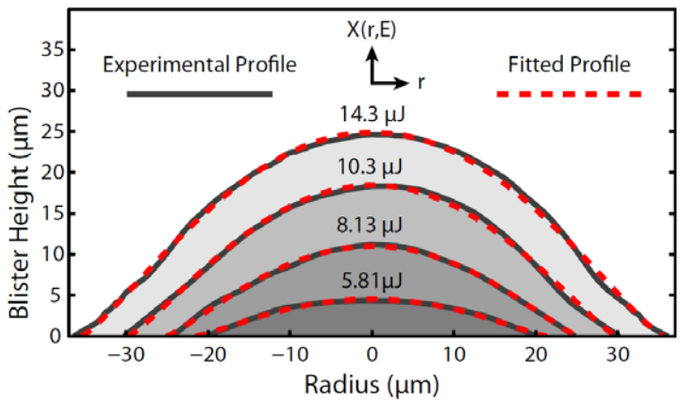
$$\phi = \begin{cases} \phi = 0\ air \\ 0 < \phi < 1\ interface \\ \phi = 1\ film \end{cases}$$

$$\frac{\partial\phi}{\partial t} + \nabla\cdot(\phi\vec{u}) + \gamma\left[\left(\nabla\cdot\left(\phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right)\right) - \varepsilon\nabla\cdot\nabla\phi\right] = 0$$





Adaptive Mesh Refinement



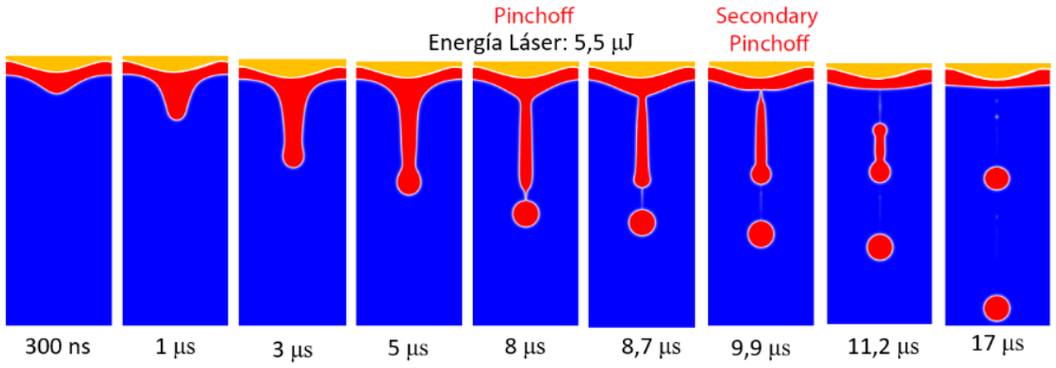
Blister Movement

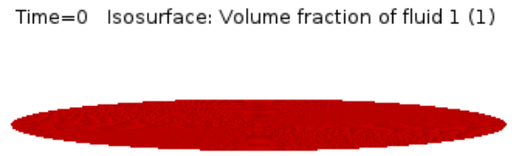
Brown, PhD Thesis (2011)

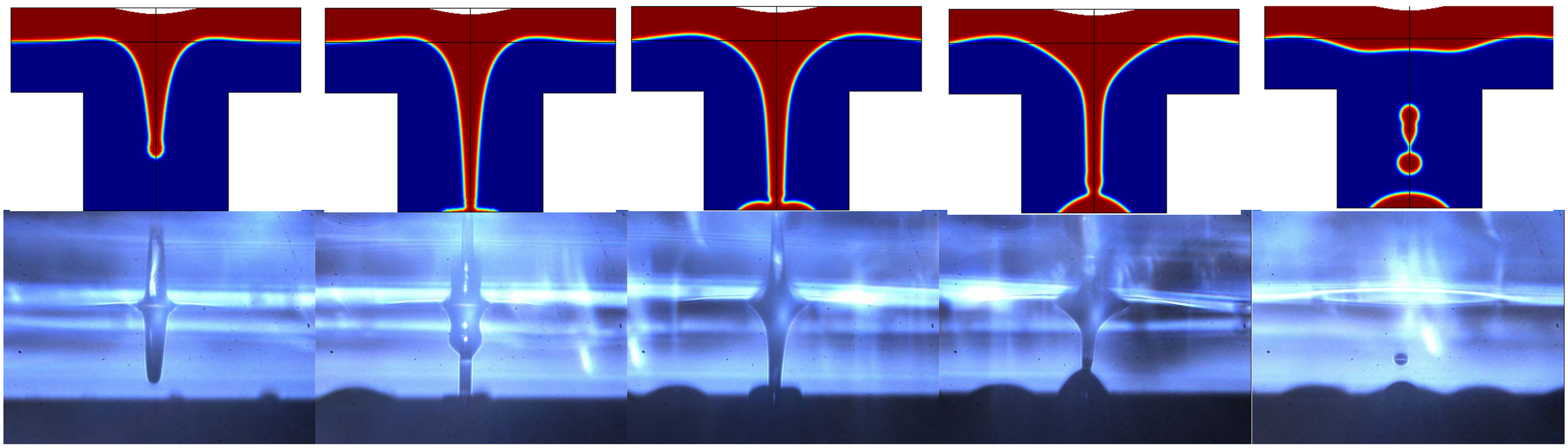
PRINCETON UNIVERSITY

Numerical simulation

Low viscosity: ~mPa·s

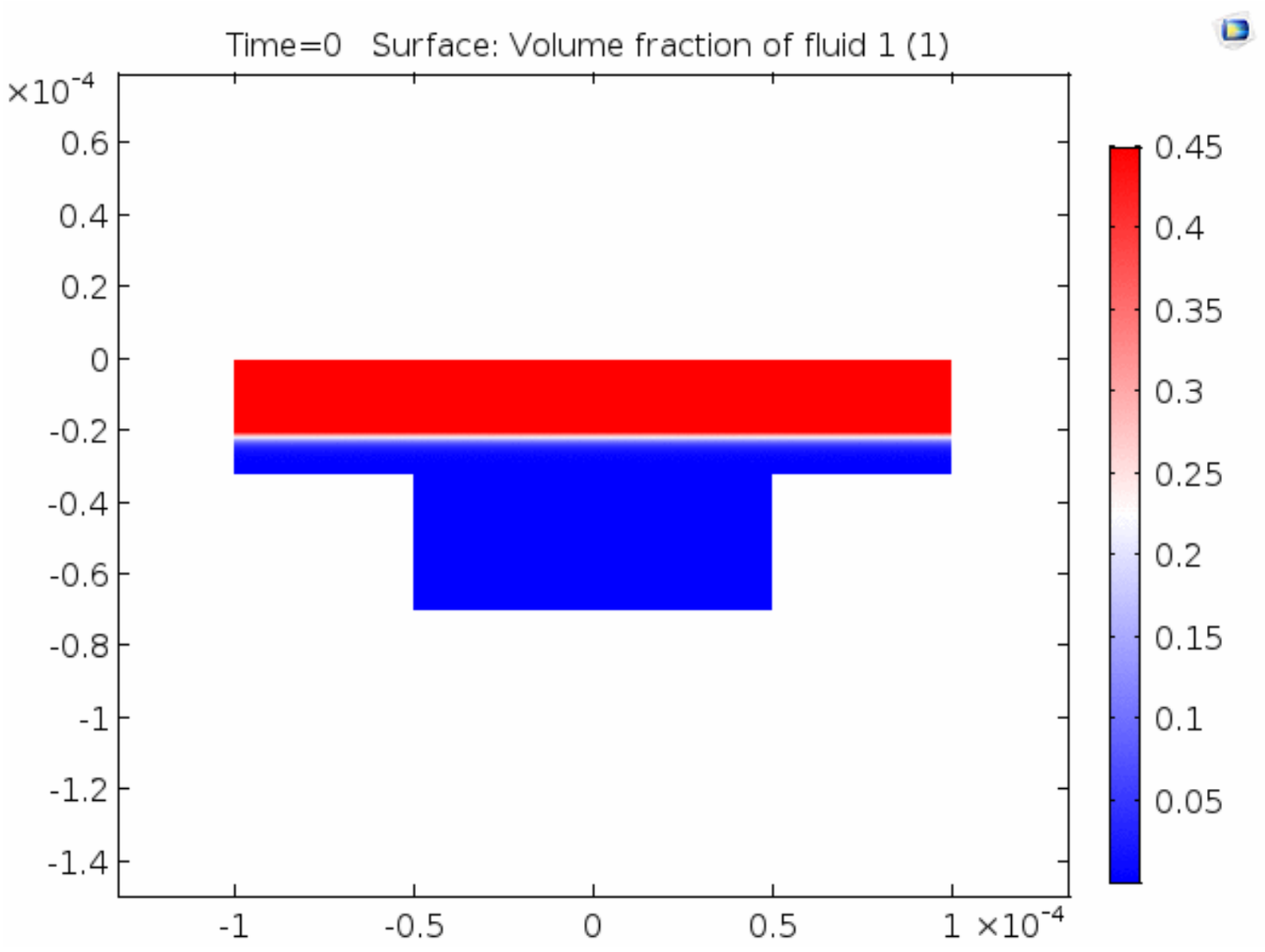






Numerical simulation

High viscosity: ~Pa·s



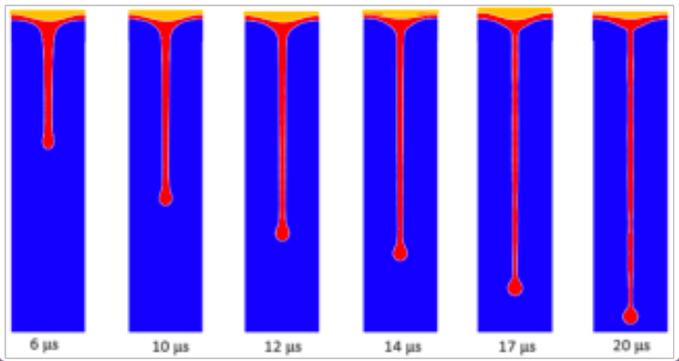
Numerical simulation

Dimensionless Parameters

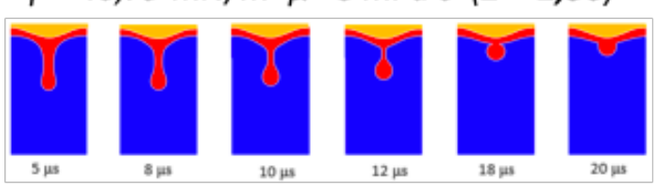
$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho d v}{\mu} \qquad \mathrm{We} = \frac{\text{inertial forces}}{\text{cohesion forces}} = \frac{\rho d v^2}{\gamma}$$

$$\mathrm{Oh} = \frac{\text{viscous forces}}{\sqrt{\text{inertia forces} \cdot \text{cohesion forces}}} = \frac{\mu}{\sqrt{\rho \gamma d}} \qquad Z = \frac{1}{\mathrm{Oh}}$$

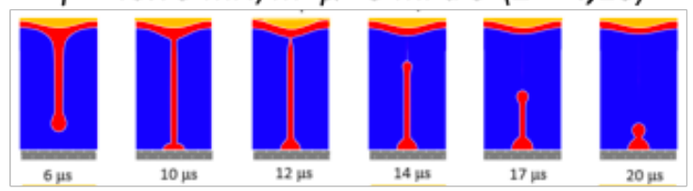
γ = 10.40 mN/m μ= 5 mPa·s ***(Z = 2,94)***



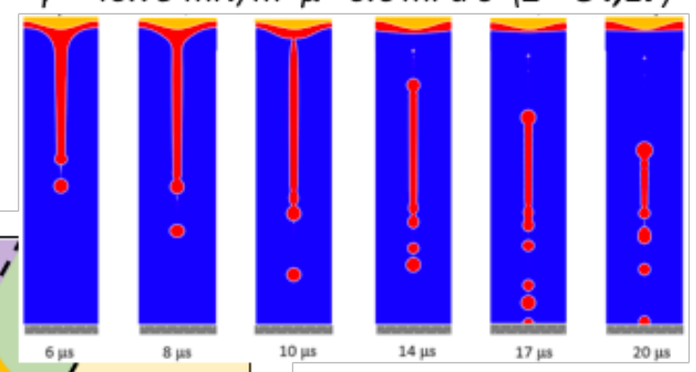
γ = 40,79 mN/m μ= 8 mPa·s ***(Z = 2,56)***

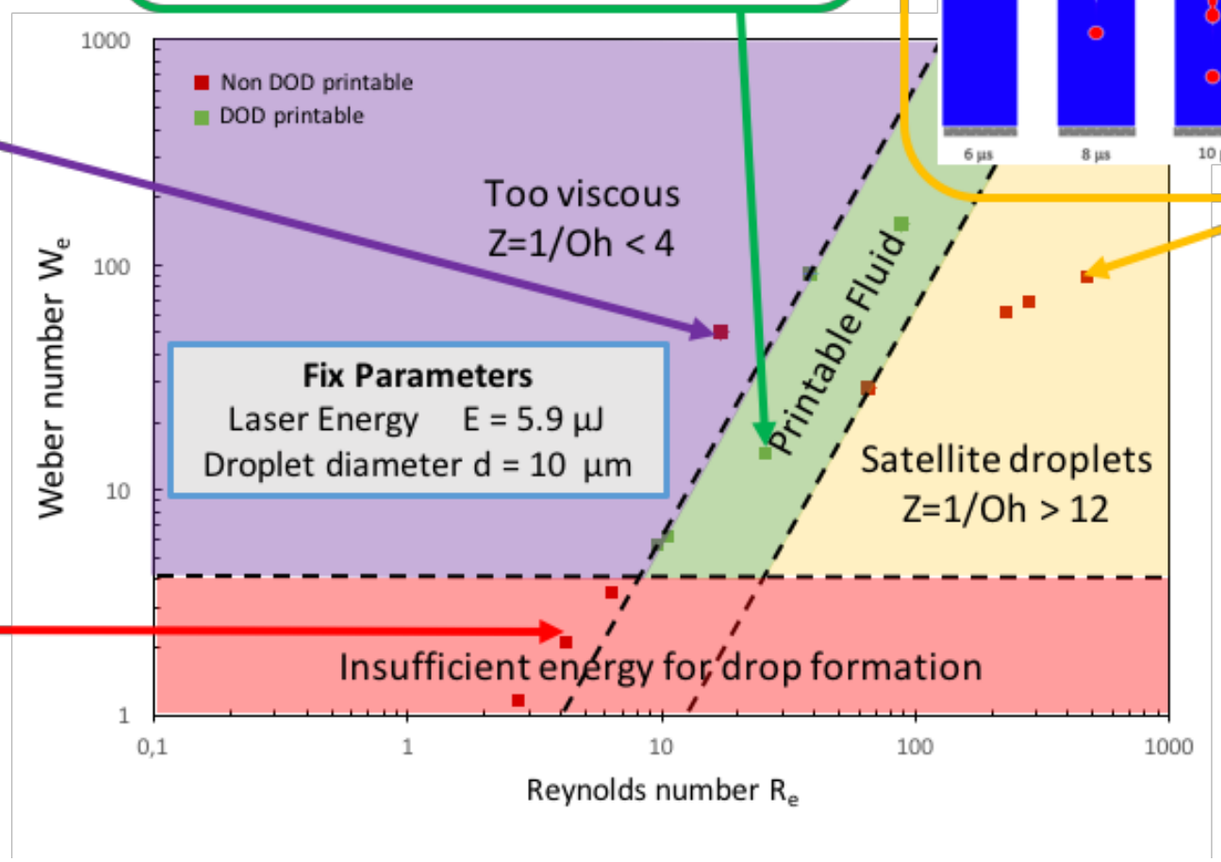


γ = 40.79 mN/m μ= 5 mPa·s ***(Z = 4,10)***



γ = 40.79 mN/m μ= 0.6 mPa·s ***(Z = 34,17)***





Summary

1) LIFT is laser direct writing technique very promising for printing high viscosity fluids, since it allows printing fully personalized, customized designs.

2) Two different applications of LIFT have been shown:

   - Using LIFT is possible to print the front metallization pattern of solar cells in a single step from standard silver pastes. The lines obtained have large aspect ratios, low electrical resistance, and show good mechanical adherence. Lab CIGS cells are functional.

   - LIFT is a tool for bio- researchers, since it allows printing living cells with controlled 2D and 3D geometries, for example, for studying the immune response.

3) Numerical models are been developed for understanding the transfer mechanisms and predict the best parametric window for printability.

Acknowledgments

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appolo

Hub of Application Laboratories for Equipment Assessment in Laser Based Manufacturing

Supported by the European Commission

COOPERATION

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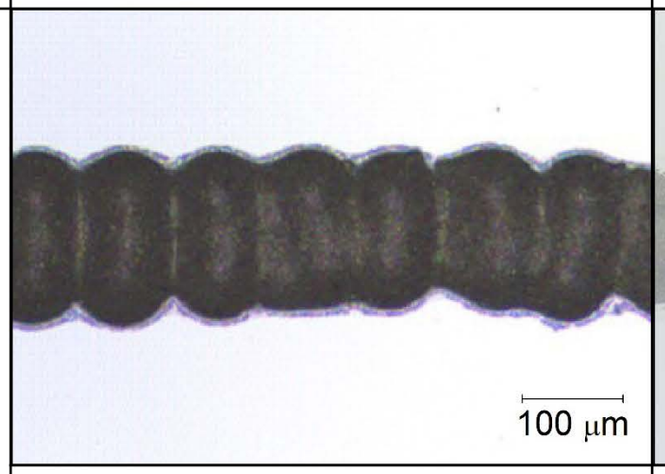
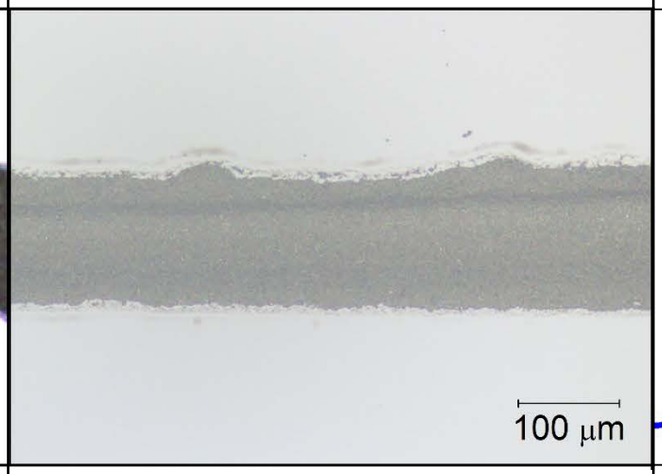
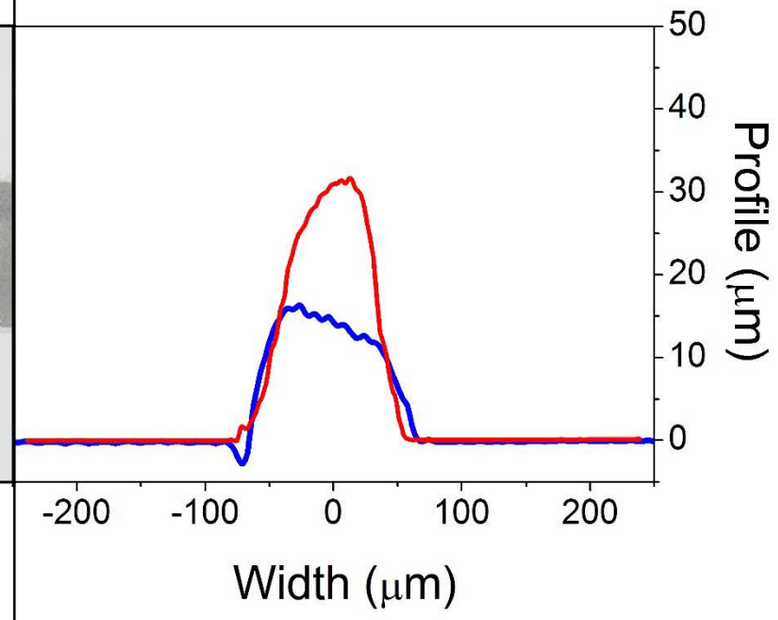
תודה
Dankie
Gracias
Спасибо
شكراً
Merci
Takk
Köszönjük
Terima kasih
Grazie
Dziękujemy
Dėkojame
Ďakujeme
Vielen Dank
Paldies
Kiitos
Täname teid
谢谢
Thank You
Tak
感謝您
Obrigado
Teşekkür Ederiz
감사합니다
Σας ευχαριστούμε
ขอบคุณ
Bedankt
Děkujeme vám
ありがとうございます
Tack

LIFT for solar cell metallization

Printing of lines

Substrate	polished c-Si	
Laser	ns-laser	ps-laser
		
	E_p = 13 µJ ω_0 = 15 µm Rep Rate = 20 kHz v = 1800 mm/s h = 50 µm d = 50 µm	E_p = 11 µJ ω_0 = 5 µm Rep Rate = 0.6 kHz v = 60 mm/s h = 40 µm d = 50 µm

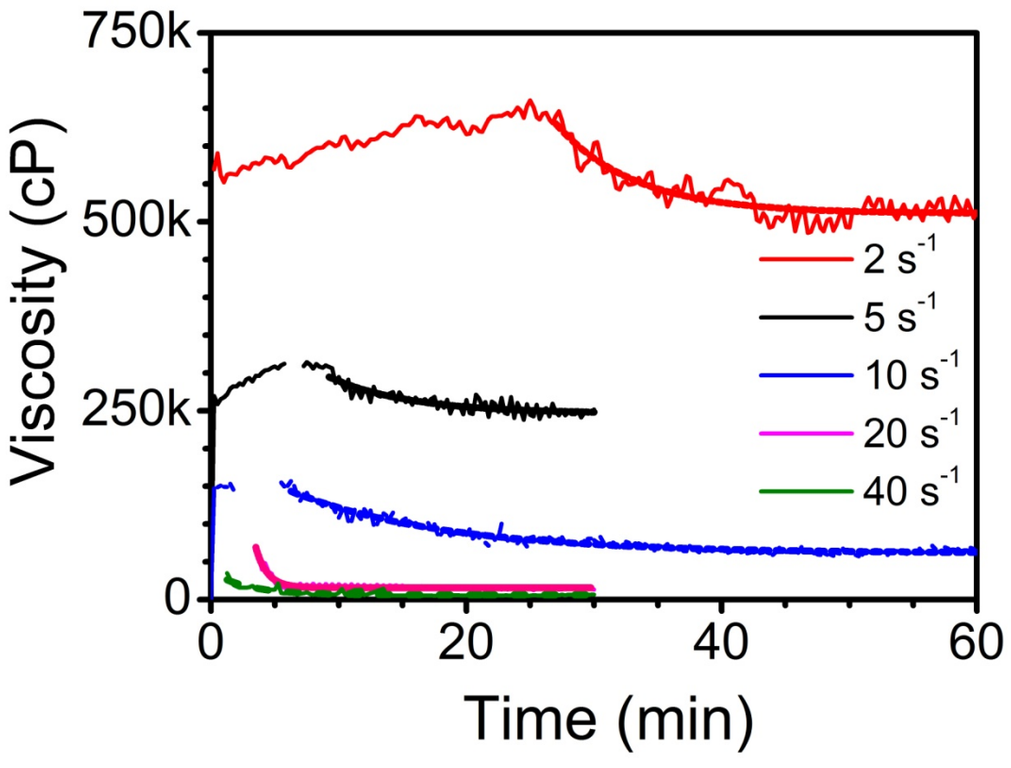


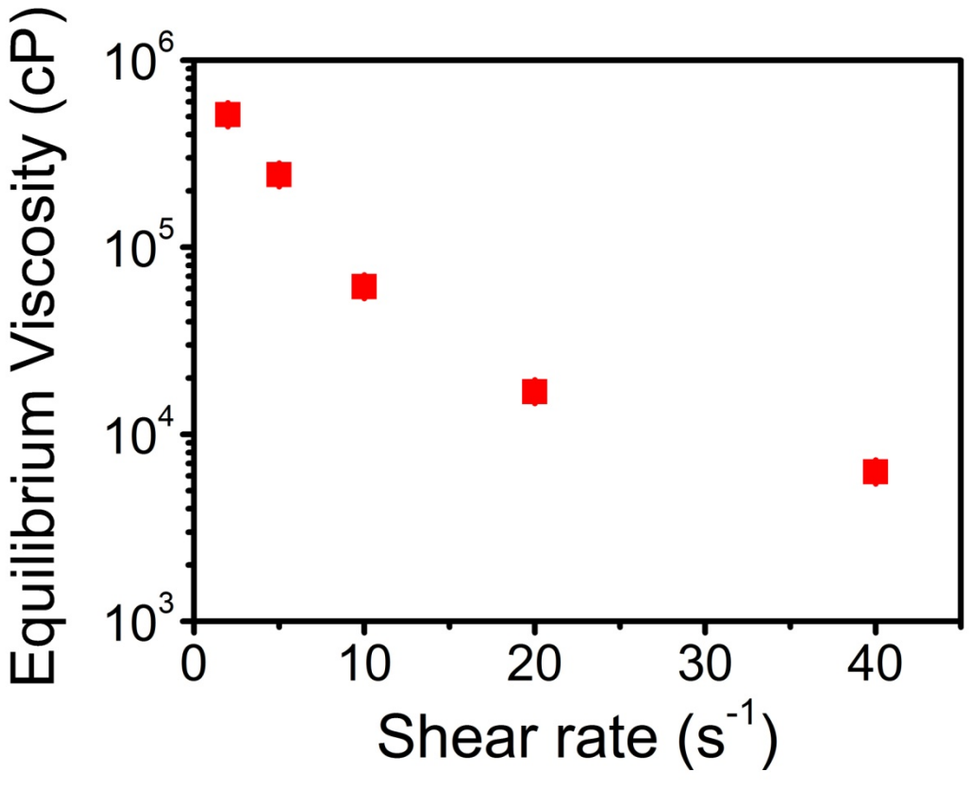
Metallization using LIFT

DuPont PV17F

Viscosity (Brookfield HBT, 10 rpm SC4-14/6R utility cap and spindle, 25ºC)	280 - 400 Pa·s
Solid Content at 750 ºC	89.5 - 91.0 %
Resistivity	< 5 mΩ/sq/µm
Silver grain	1-5 µm
Organic carrier	N,N'-Ethane-1,2-diylbis(decanamide) 12-Hydroxy-N-[2-[1-oxydecyl)amino]ethyl]octadecanamide N,N'-Ethane-1,2- diylbis(12-hydroxyoctadecanamide)
Thinner	9450

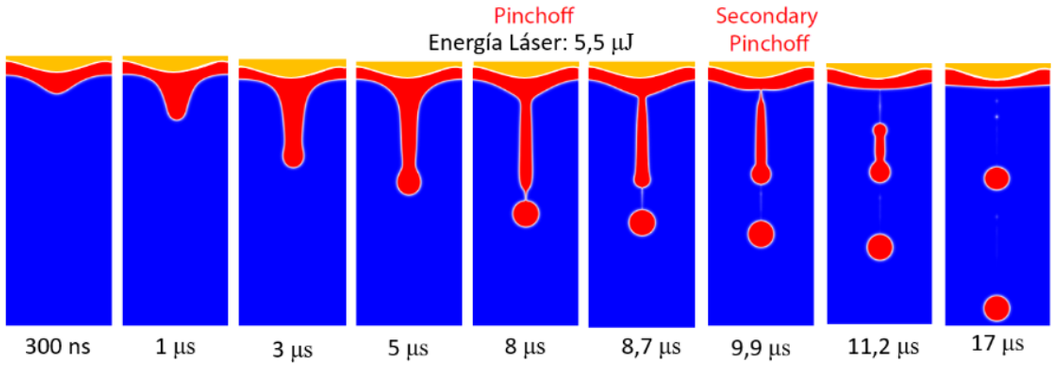
Non-newtonian, high-viscosity fluids

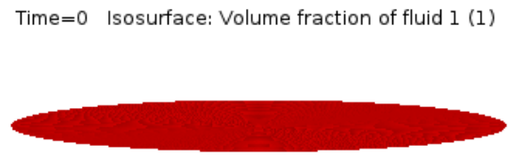




Numerical simulation

Low viscosity: ~mPa·s





Ink

$\rho = 1030\ kg/m^3$

$\mu = 1,7\ mPa{\cdot}s$

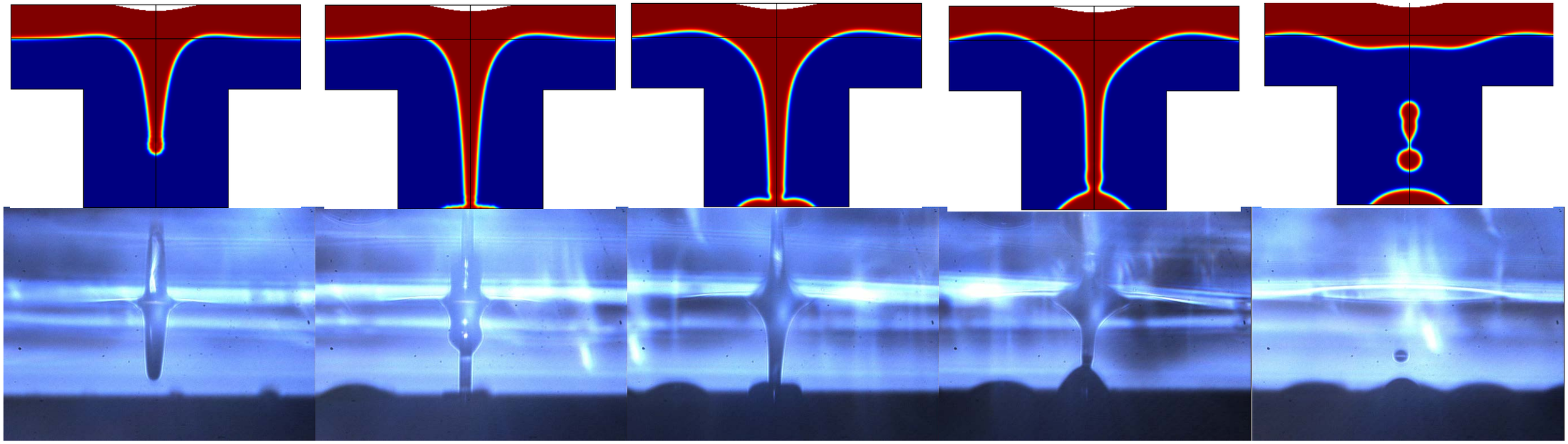
$\gamma = 40,79\ mN/m$

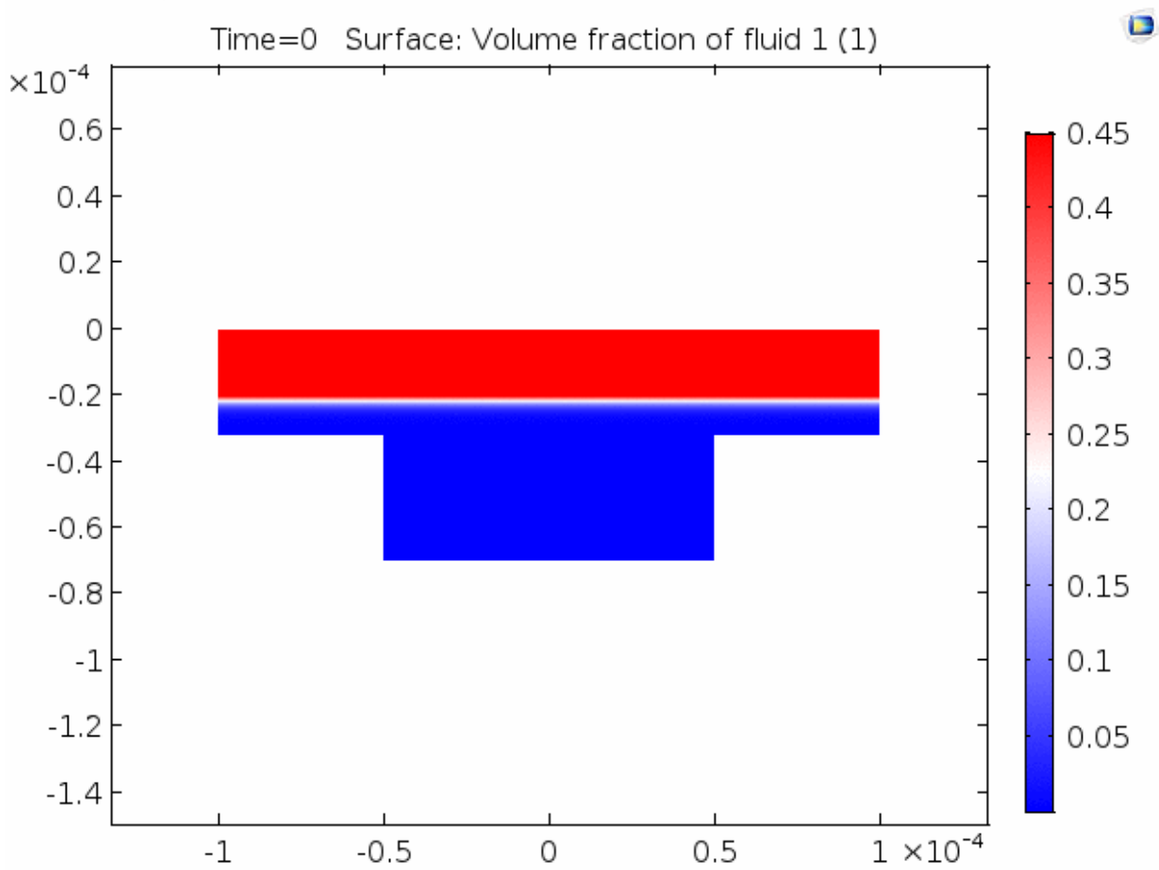
$E_p = 5,5\ \mu J$

Numerical simulation

Water – glycerol, 40%weight
$\rho = 1103{,}2\ kg/m^3$
$\mu = 3{,}63\ mPa{\cdot}s$
$\gamma = 70\ mN/m$

$E_p = 20\ \mu J$



Ammonium alginate solution (3.37%)		
Density (kg/m³)		1.05e3[kg/m^3]
Viscosity Non-Newtonian Power Law		$\mu_1 = m(\dot{\gamma})^{n-1}$ $\dot{\gamma} = \max\left(\sqrt{\mathbf{D}:\mathbf{D}}, \dot{\gamma}_{min}\right), \quad \mathbf{D} = \frac{1}{2}\left[\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right]$
	m (Pa·s)	13
	n	0.5
	$\dot{\gamma}_{min}$ (1/s)	0.01
Surface Tension (N/m)		40.79e-3

E = 10 uJ
Thickness = 20 um
Gap = 50 um