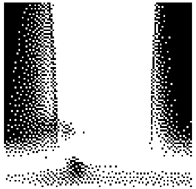
Re-cap: IJP and limits



- Viscosity vs surface tension
- Capillary & nozzle
- Non-reacting components in ink

- What to do if you want to :
  - Print viscous / solid materials?
  - Create a reaction of 2 component ink on the surface?
  - Get higher resolution?

MICRO-413

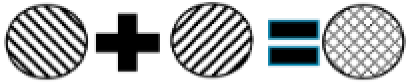
Advanced additive manufacturing methods

Reactive IJP
EHDP
LIFT

Spring semester 2024

Reactive printing

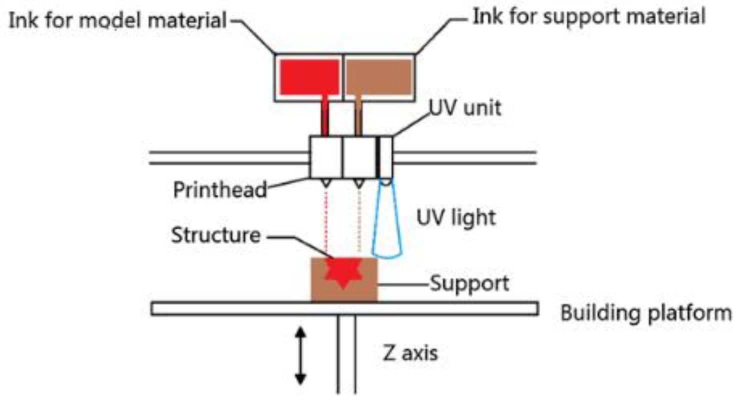
Reactive printing

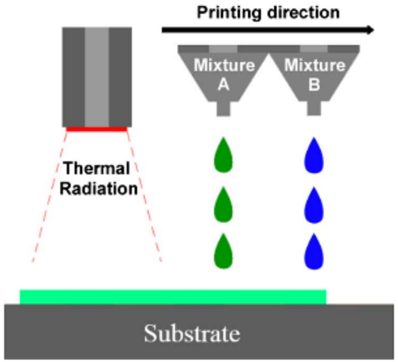


Reactive inkjet printing involves adding one reactant to another to form a product.

From the book: Reactive Inkjet Printing— An Introduction P.J. Smith and A.Morrin

Reactive printing

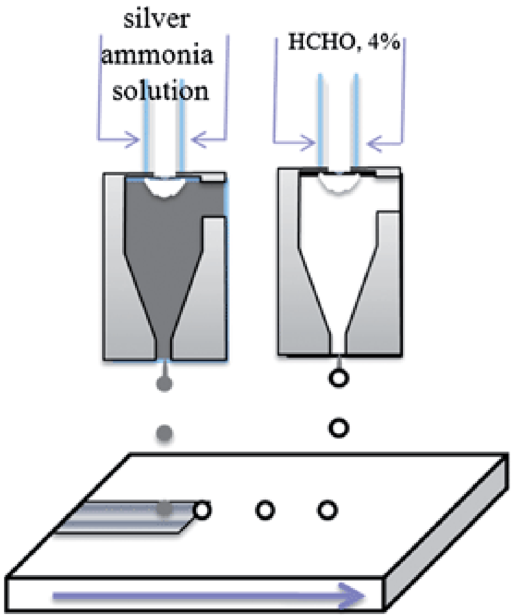




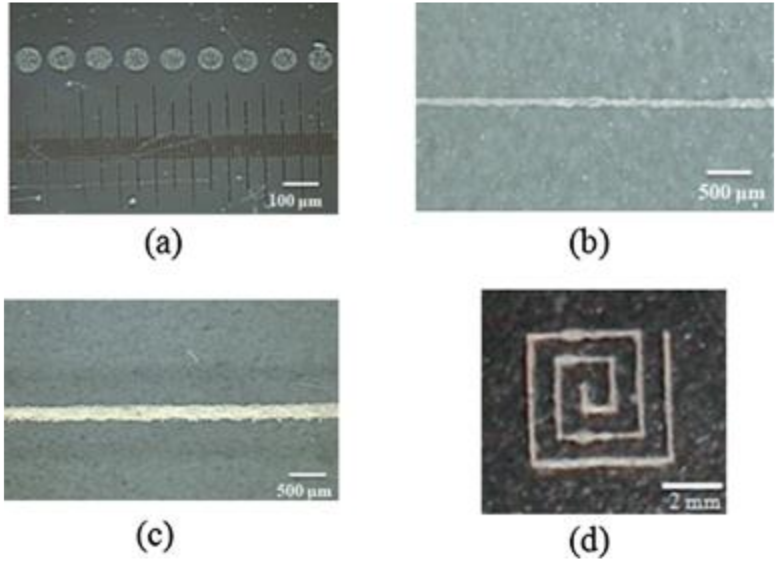
Example of Material Jetting System based on photo-polymerisation

From the book: Reactive Inkjet Printing— An Introduction P.J. Smith and A.Morrin

Reactive printing of conductive silver



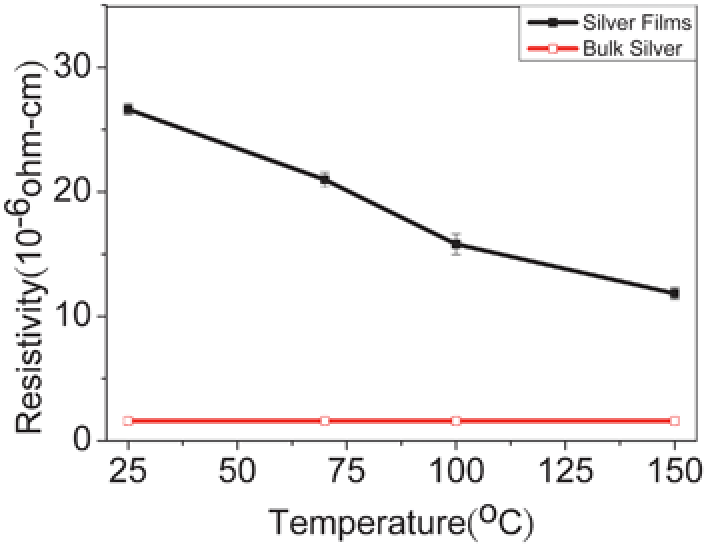
Formaldehyde and silver ammonia to generate silver *in situ*



(a) a row of silver dots of 80 µm diameter, (b) a silver line of 100 µm width, (c) a silver line of 250 µm width, and (d) an RFID antenna pattern

J. Mater. Chem., 2011,21, 18799-18803

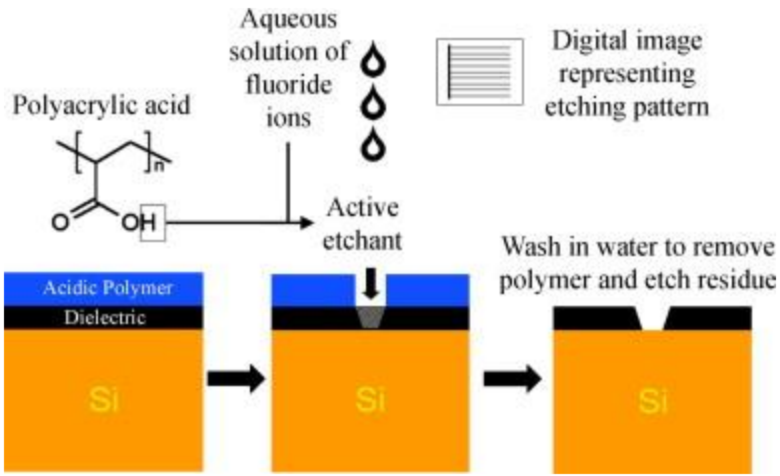
Reactive printing of conductive silver



Dependence of resistivity on temperature for printed silver films after sintering for an hour.

J. Mater. Chem., 2011,21, 18799-18803

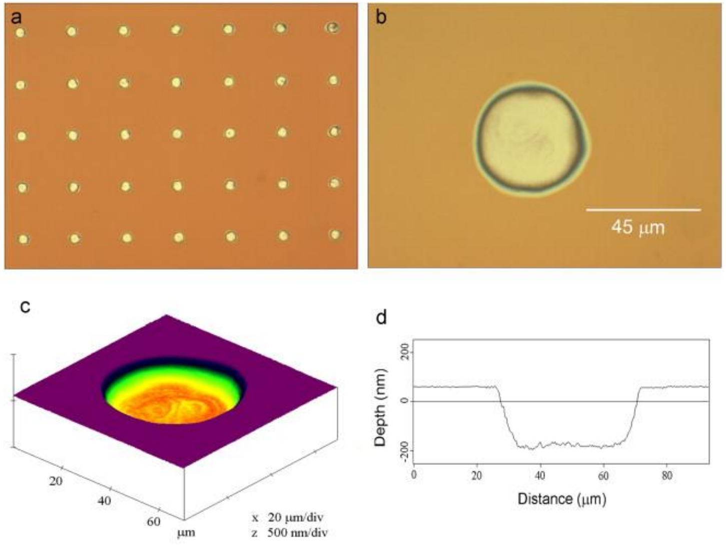
Reactive printing (dielectric etching)



Schematic showing the use of the direct etching method to form a pattern of openings in a dielectric layer formed on a silicon wafer.

Solar Energy Materials and Solar Cells
Volume 93, Issue 10, October 2009

Reactive printing (dielectric etching)



(a) An array of hole openings etched in a ~270 nm thick SiO_2 layer, thermally grown on a polished silicon wafer. (b) A magnified view of one of the holes from (a). (c) An AFM profile and (d) An AFM cross-section of the hole depicted in (b).

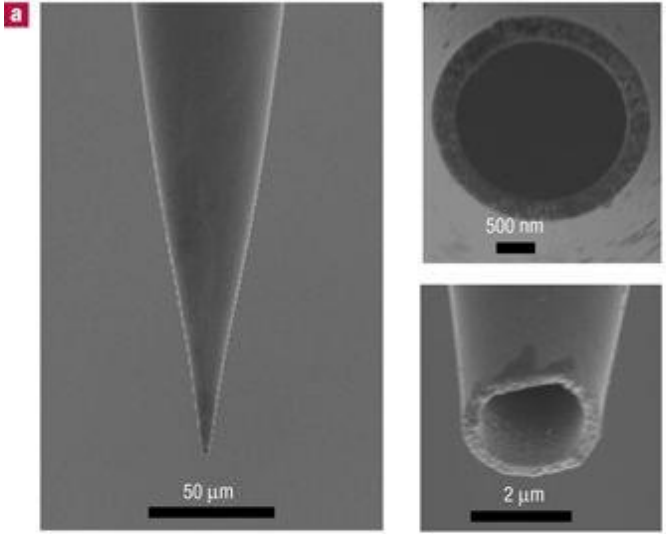
Solar Energy Materials and Solar Cells
Volume 93, Issue 10, October 2009

In-flight drop merging

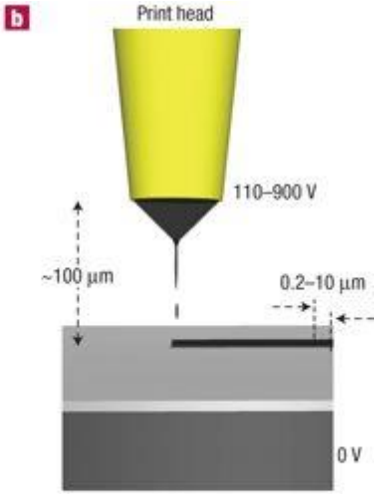
Electro Hydro Dynamic (EHD) printing

3D nanometer scale printing

Electro hydro dynamic printing (smaller than the nozzle size)



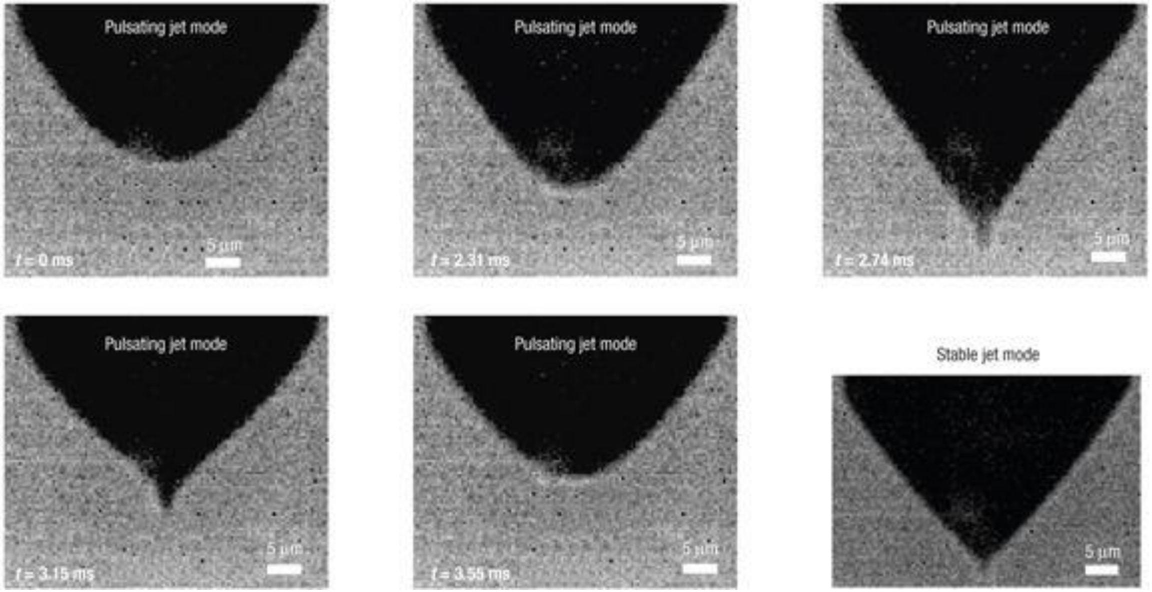
gold-coated glass microcapillary nozzle
(2 µm internal diameter)



Nozzle and substrate configuration for printing

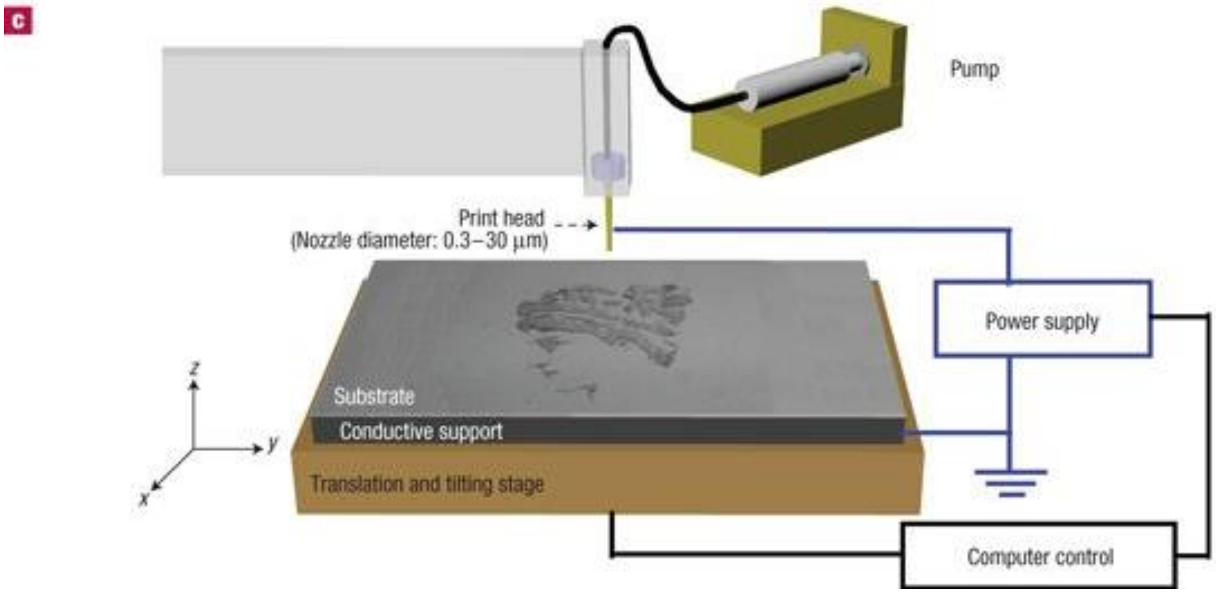
Nature Materials volume 6, pages 782–789 (2007)

EDH printing liquid tip



high-speed camera images of liquid at nozzle under electric field
V/H ~ 9 V/um
66,000 fps

EDH printing



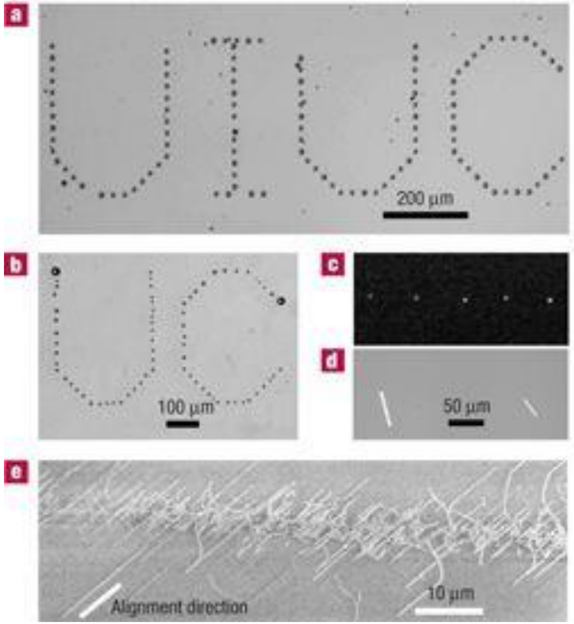
Nature Materials volume 6, pages 782–789 (2007)

EDH printing of functional polymer

nozzles with internal diameters of 30 µm

a) PEDOT/PSS

b) photocurable polyurethane



c) Si NP (3 nm)
4 µm dots

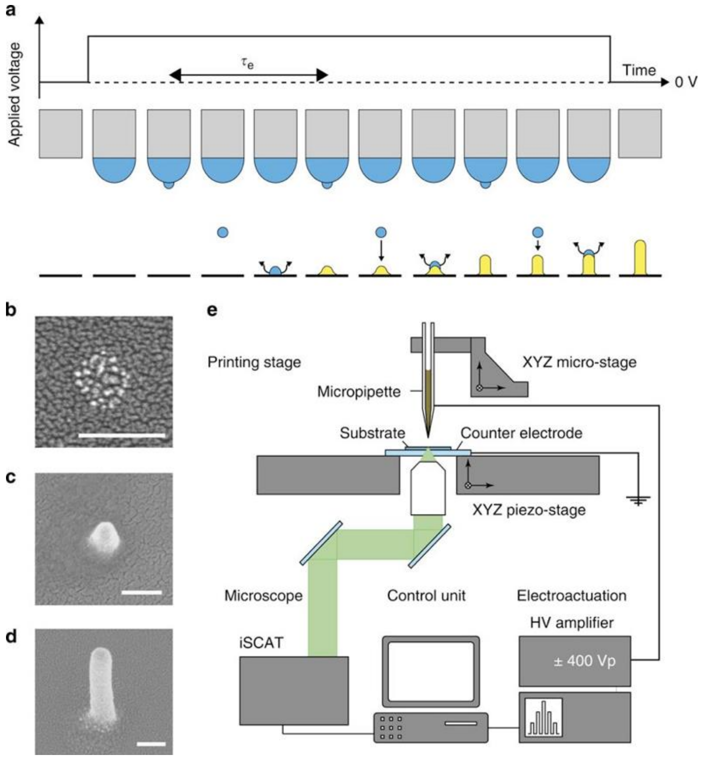
d) single-crystal Si rods (thickness: 3 µm, length: 50 µm, width: 2 µm

e) aligned SWNTs grown by CVD

The average dot diameter is 10 µm

3D EHD printing

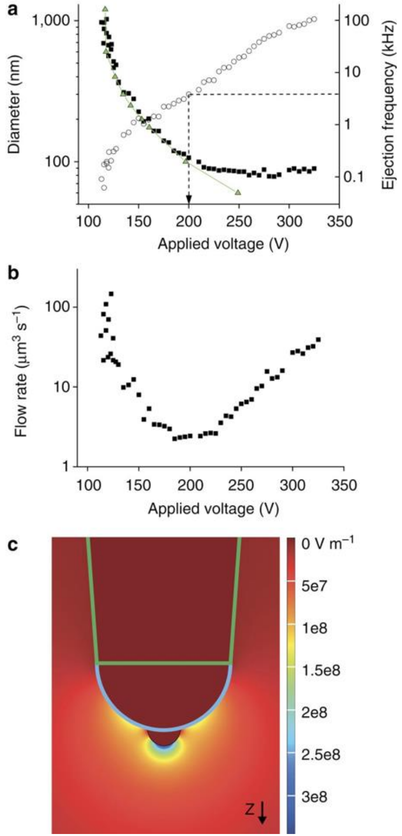
a) Growth of liquid meniscus
b) Single drop
c) Small pillar
d) Higher pillar
e) Set up schematics



Galliker, P. et al. Direct printing of nanostructures by electrostatic autofocussing of ink nanodroplets. Nat. Commun. 3:890 doi: 10.1038/ncomms1891 (2012)

3D EHD printing

a) Drop diameter and drop ejection frequency as f(V)
b) Flow rate as f(V)
c) Numerical simulation around nozzle

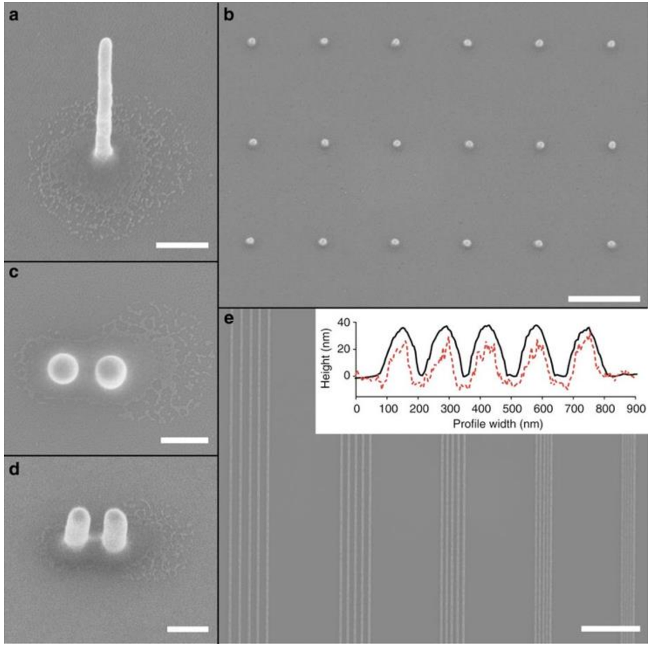


Galliker, P. et al. Direct printing of nanostructures by electrostatic autofocussing of ink nanodroplets. Nat. Commun. 3:890 doi: 10.1038/ncomms1891 (2012)

3D EHD printing

Au nanostructures

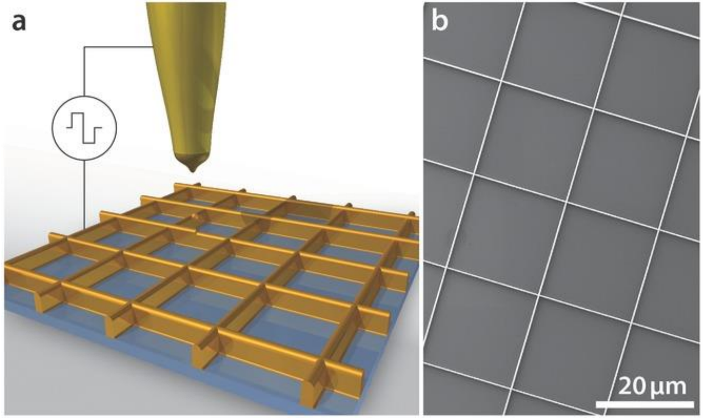
a) Au nanopillar 50 nm
b) 80nm dots printed on 1um lattice
c) Au nanopillar close pitch
d) Tilted view of c)
e) Printed tracks with pitch sizes of 250, 200, 150, 100 and 75 nm



Galliker, P. et al. Direct printing of nanostructures by electrostatic autofocussing of ink nanodroplets. Nat. Commun. 3:890 doi: 10.1038/ncomms1891 (2012)

3D EHD printing

Fine and sparse grids made out of tall nanowalls are excellent transparent conducting electrodes

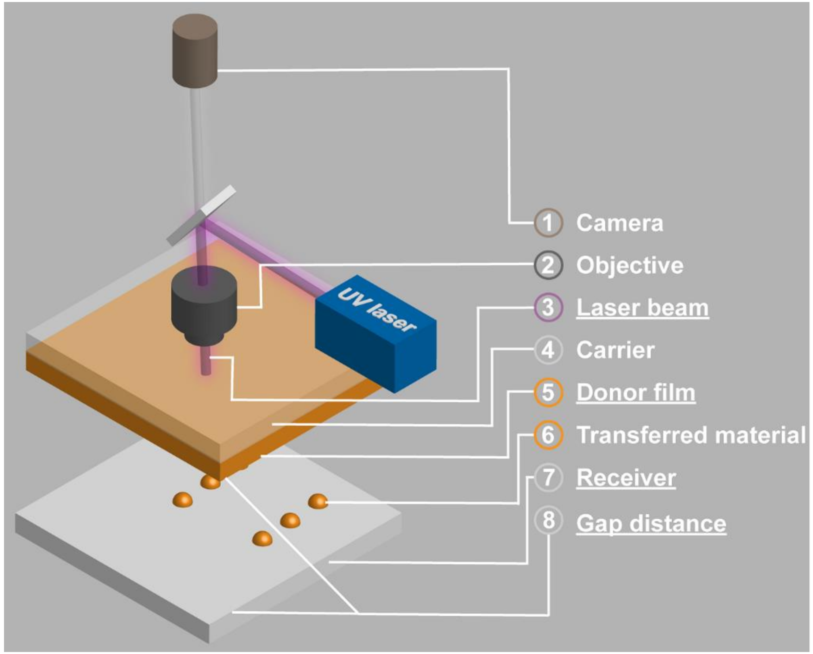


Schneider et al. ETHZ 2015
https://doi.org/10.1002/adfm.201503705

Laser induced forward transfer

LIFT

LIFT basics

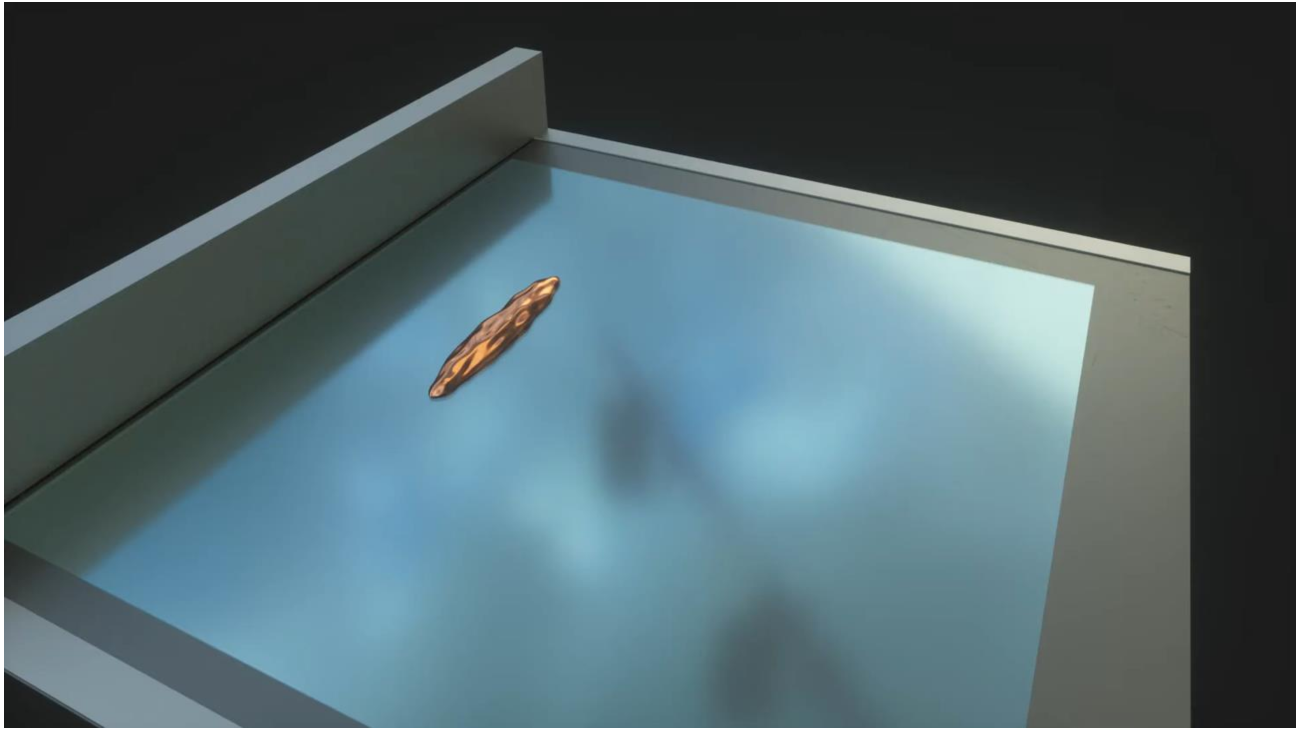


Schematic illustration of a typical LIFT system

- Additive manufacturing technique
- Interaction between laser and material
- Transfer of materials

Advantages:

- Mask free
- Nozzle free
- Non contact
- Material diversity



https://www.youtube.com/watch?v=5tnO2T07oR4

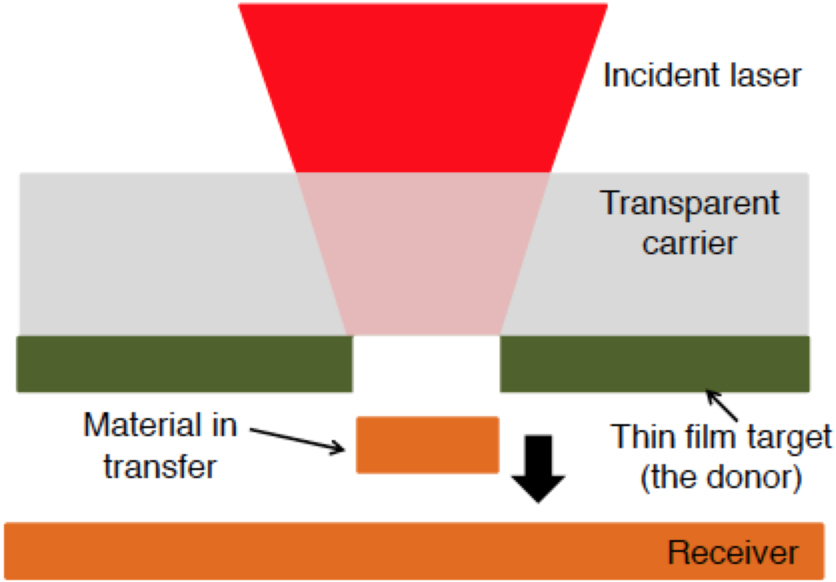
Why laser "Printing"?

- Thin films of almost any material can be deposited with high lateral resolution, making structuring unnecessary.
- Possibly "solvent-free"
- No nozzle which could clog
- All type of materials can be deposited, from liquid to solid.

History: Transfer of layers with lasers

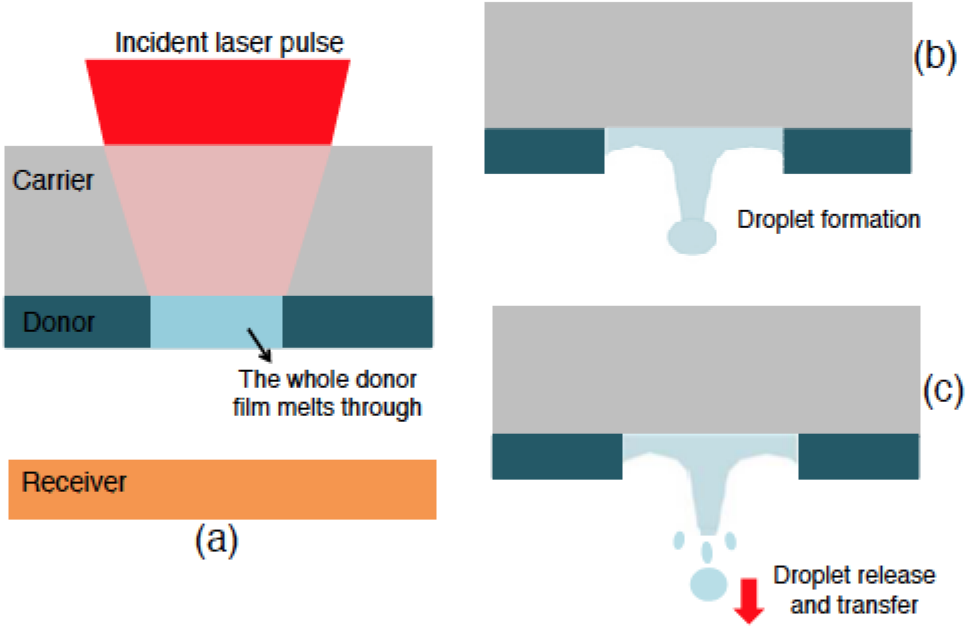
- First papers: Laser Writing (LR) and Material Transfer Recording (MTR) (R. S. Braudy in Proceedings of IEEE Oct. 1969, p. 1771, and M. Levene et al. in Appl.Optics 9, 2260 (1970).
- Then Laser Induced Forward Transfer (LIFT), i.e. transfer of Cu. (J. Bohandy et al., J. Appl. Phys. 60, 1538 (1986)).
- Also called laser direct write methods see e.g.: C.B. Arnold, P. Serra, and A. Piqué, MRS Bull. 32, 23 (2007)

General principle of LIFT



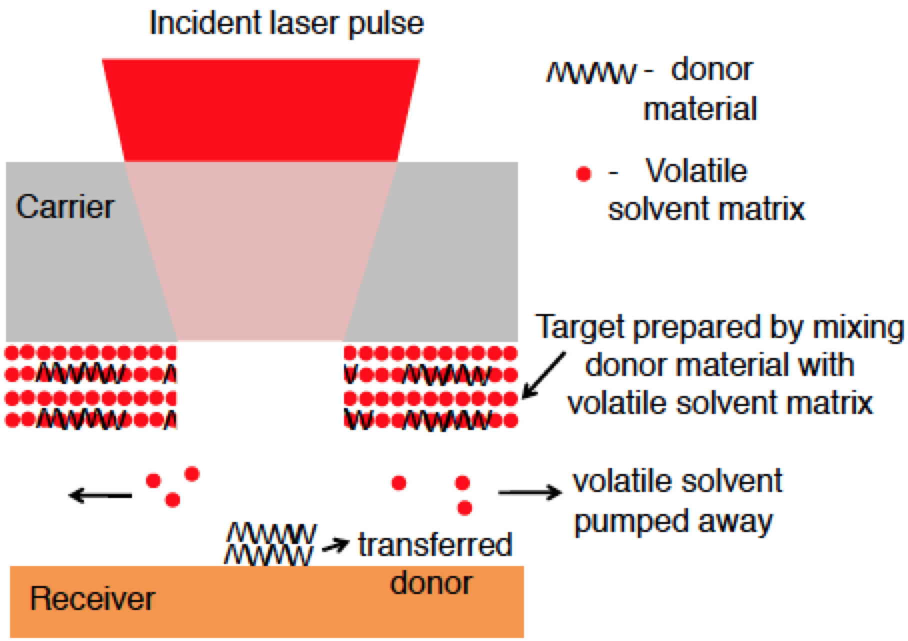
Kamalpreet Kaur
PhD thesis U. Southampton June 2011

Nanodroplet growth and transfer



Kamalpreet Kaur
PhD thesis U. Southampton June 2011

Matrix-Assisted Pulsed Laser Evaporation-DirectWrite (MAPLE-DW)



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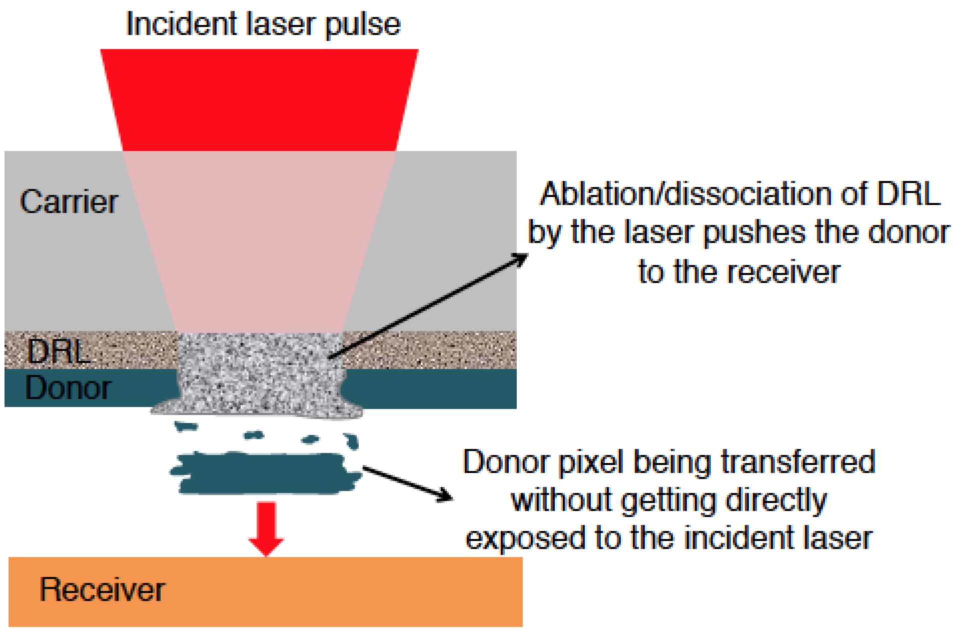
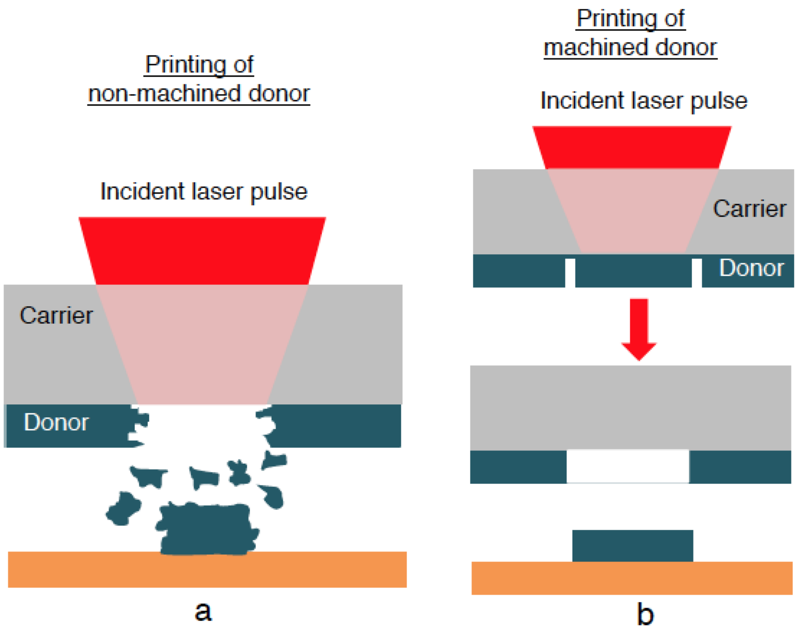
PhD thesis U. Southampton June 2011

Matrix-Assisted Pulsed Laser Evaporation-DirectWrite (MAPLE-DW)



Kamalpreet Kaur
PhD thesis U. Southampton June 2011

Lift of a pre-machined donor film



Kamalpreet Kaur
PhD thesis U. Southampton June 2011

Governing equation for LIFT process-**heat conduction equation**

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = S(z,t)$$

ρ-density of the donor material; C_p-heat capacity at constant pressure; T-temperature; t-time

k-thermal conductivity; $S(z,t)$-heat source

Beer-Lambert Law for the laser-material interaction

$$\mathrm{S(z,t)} = \alpha \times (1-\mathrm{R})\mathrm{I_0(t)} \exp(-\alpha z)$$

Temporal evolution of the laser pulse intensity

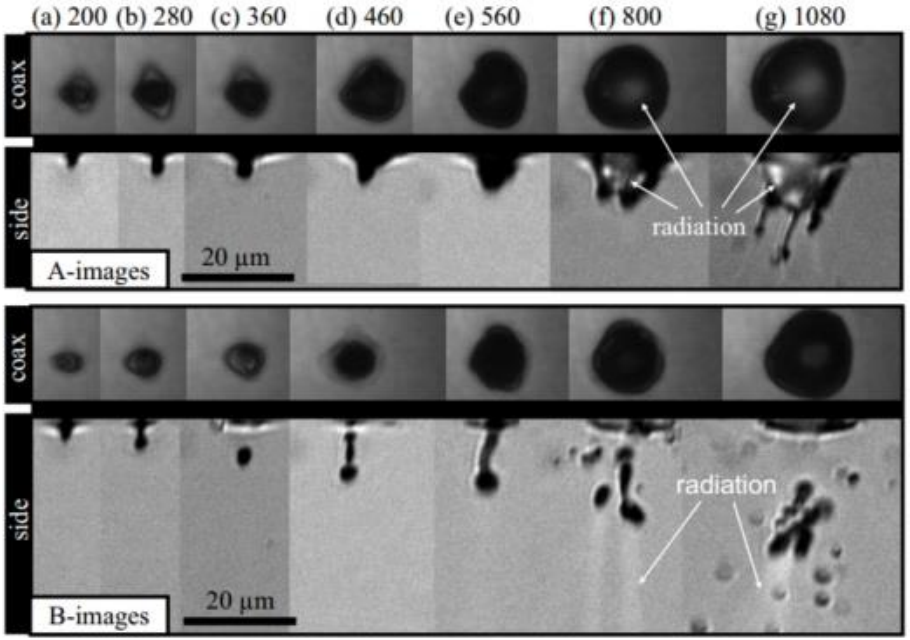
$$I_0(\mathrm{t}) = \frac{2\mathrm{F}\sqrt{\ln 2}}{\sqrt{\pi}\tau} \exp(-4\ln 2(t/\tau)^2)$$

Definition of laser fluence

$$F = \frac{E}{(\pi D^2/4)}$$

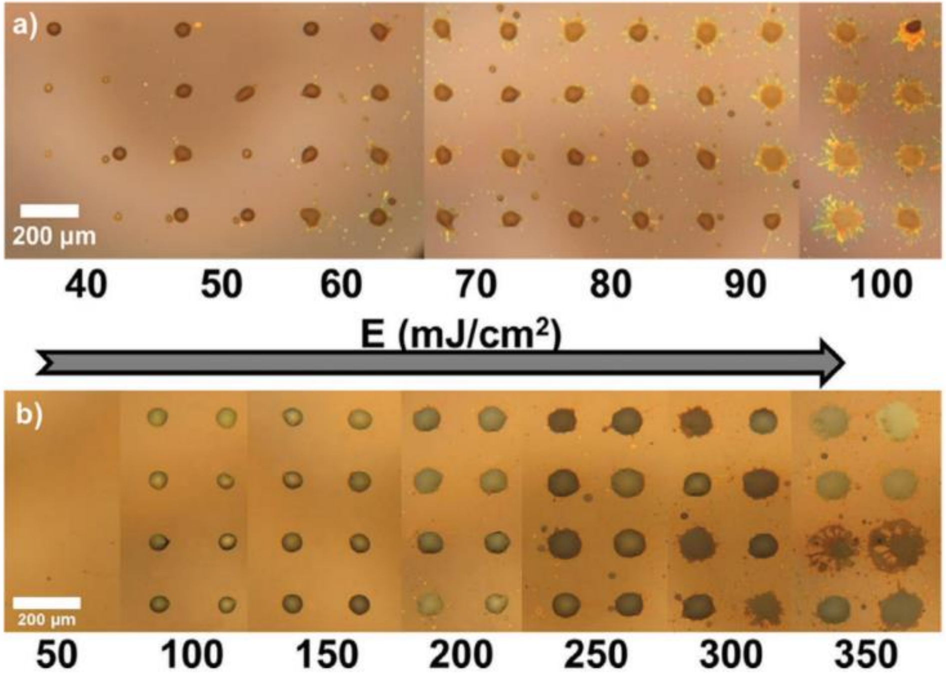
- absorption coefficient of the donor material
- reflectivity of the donor material
- thickness of the donor material
- laser energy
- laser pulse duration
- laser spot diameter

R. Pohl, et al. Phys. Rev. Appl., 2015
M. Sharam, Kumar. Diss. R. Inst. Technol., 2013



Visualization of ns-LIFT ejection process of 200 nm thick gold taken at 300 ns (A-images) and 800 ns (B-images) after the ejection under different laser fluence. Laser fluence increases from 200-1080 mJ/cm^2.

Pohl. *Laser-induced forward transfer of pure metals,* PhD thesis, 2015

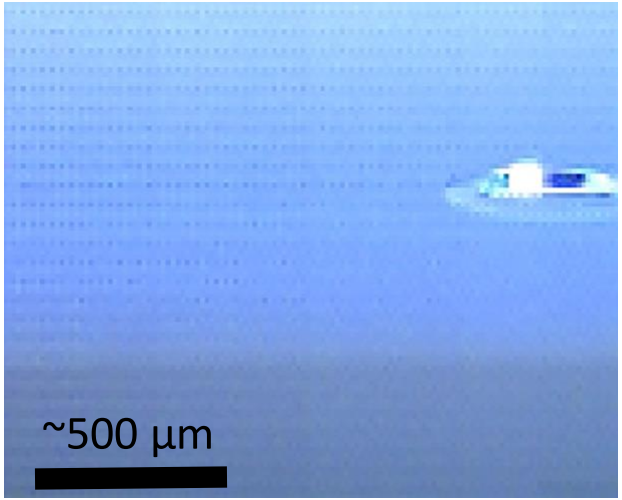


Evolution of the droplets morphology with laser fluence during LIFT of a Ag ink on a silicon dioxide on silicon receiver substrate a) with no DRL and b) with a Ti-DRL.

M. Makrygianni, et al. *Appl. Surf. Sci.*, 2014

Time resolved imaging of a Ag-nano-particle paste transfer as function of viscosity

300 000 fps camera



wet transfer
(1.99 µs)

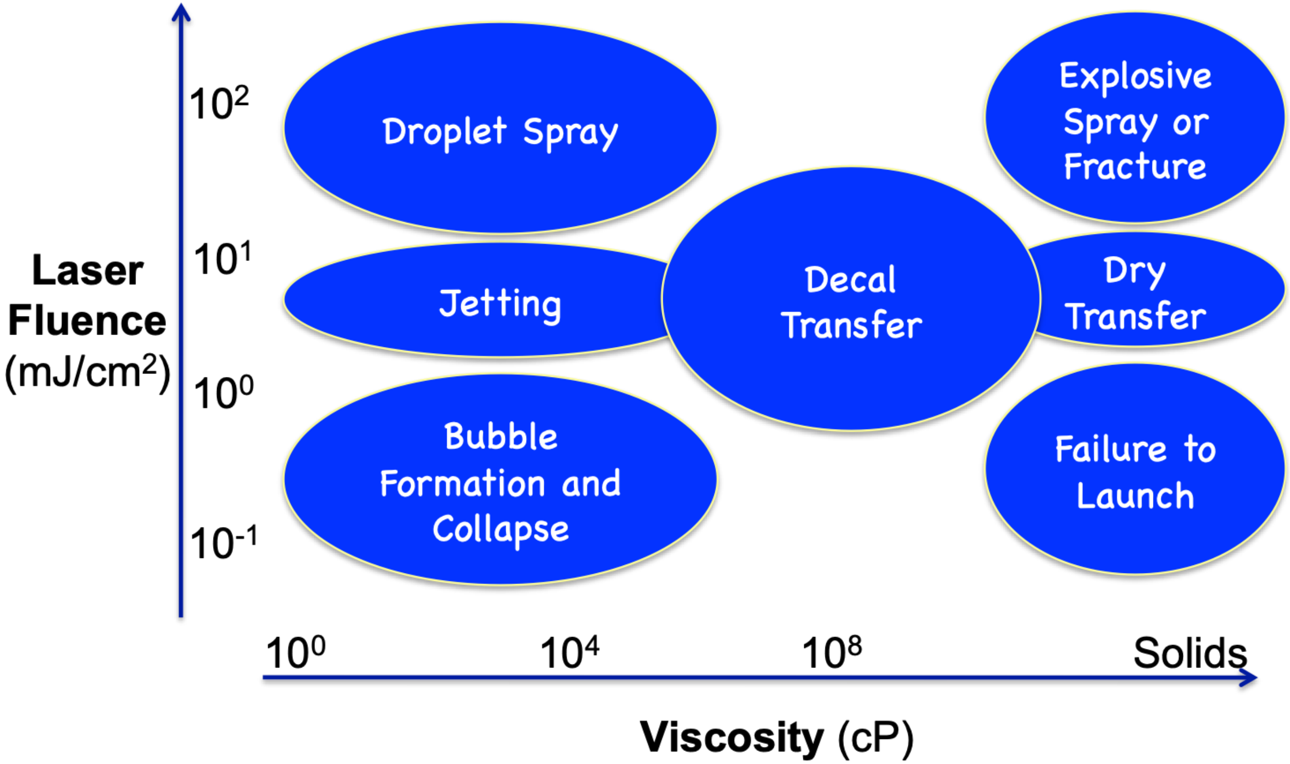
“Decal” transfer
(1.99 µs)

Dry transfer
(1.96 µs)

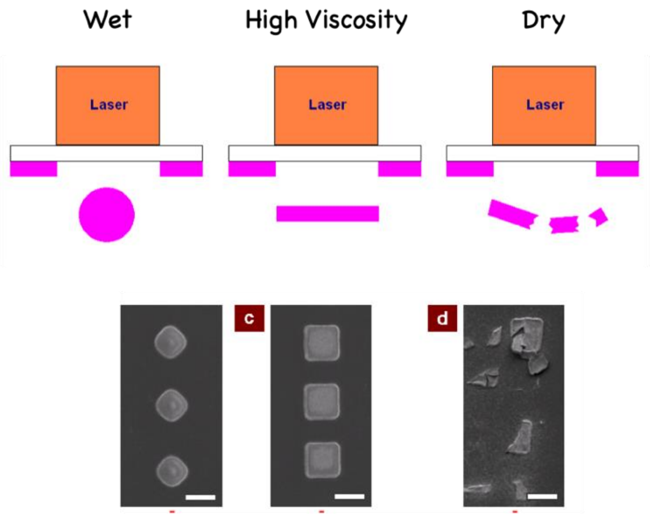
Decal = decalcomania
https://en.wikipedia.org/wiki/Decalcomania

slide adopted from A.Pique

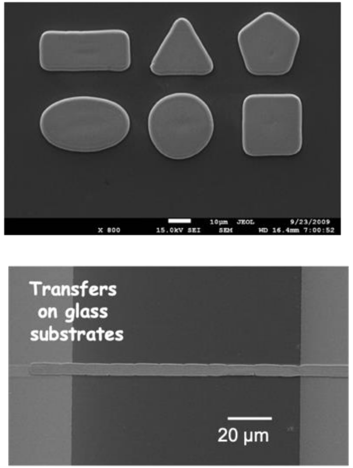
Laser Transfer as Function of Viscosity



What is "DECAL"?



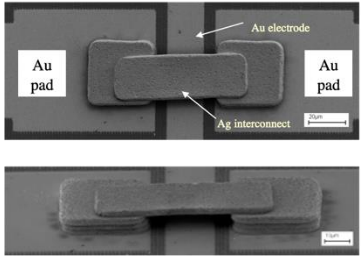
"Decal" transfer

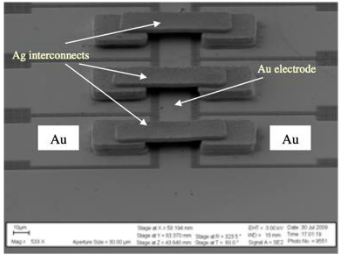


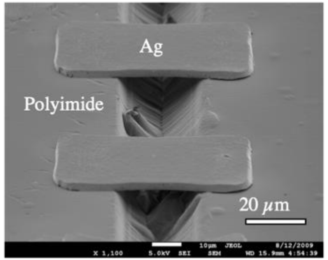
Decal maintains the original beam geometry (gap 5-50 µm)
Ag nanoink: 3 – 7nm, η ≈ 105 cP, 80 wt% solids loading content
Ag nanoparticles allow for efficient laser to nanoink energy coupling

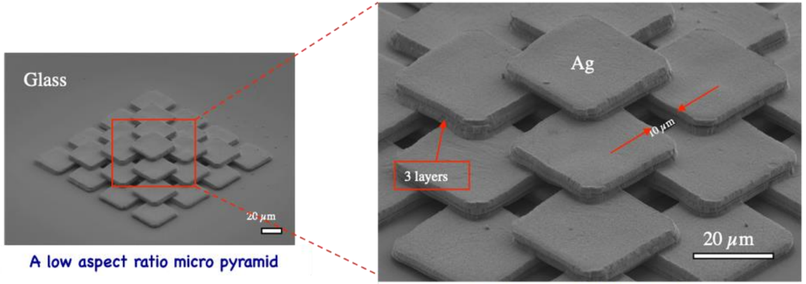
Auyeung, et al., J. of Laser Micro/Nanoeng. 2, (2007) 21
Piqué, et al. J. Laser Micro/Nanoeng., 3 (2008) 163.

3D and Free Standing Structures



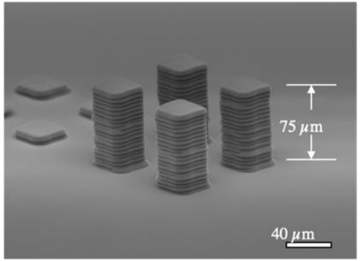






A low aspect ratio micro pyramid

Multilayer scaffold structure

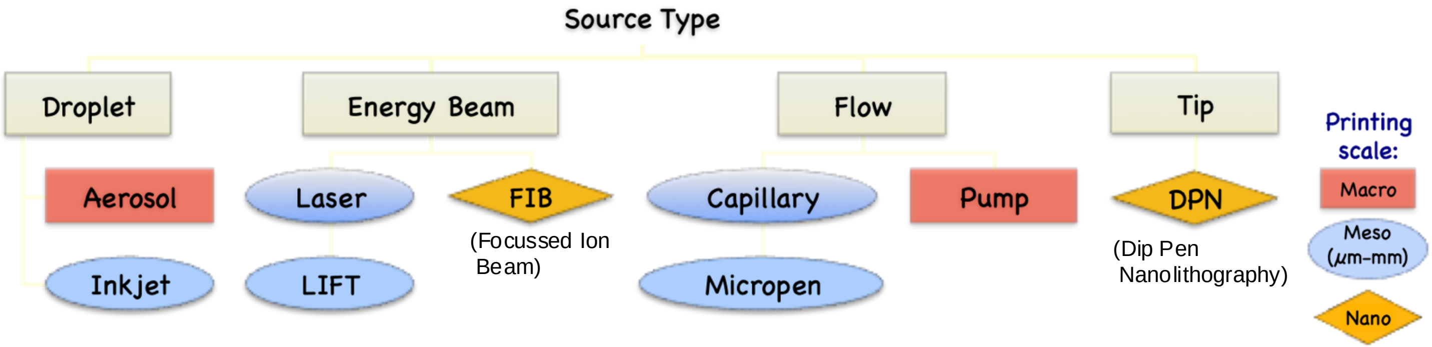


slide adopted from A.Pique

Versatility of LIFT

Transferred materials range from **biomaterials** (DNA, fungal (Trichoderma) conidia, rat Schwann and astroglial cells, pig lens epithelial cells, salmon sperm DNA, living human osteosarcoma, embryonal carcinoma cells, etc.), **metals, or "complex" organic materials** (inorganic inks or pastes, organic polymers) and even biological solutions (microliter volume). The feasibility of the technique for depositing these materials has been proven through the fabrication of diverse functional devices such as microbatteries, solar cells, organic light-emitting diodes, or biosensors.

Various printing techniques
Digital Microfabrication Techniques



Digital µ-fabrication techniques allow the discrete processing of functional materials for the prototyping, customization and/or repair of microelectronic systems.

slide adopted from A.Pique