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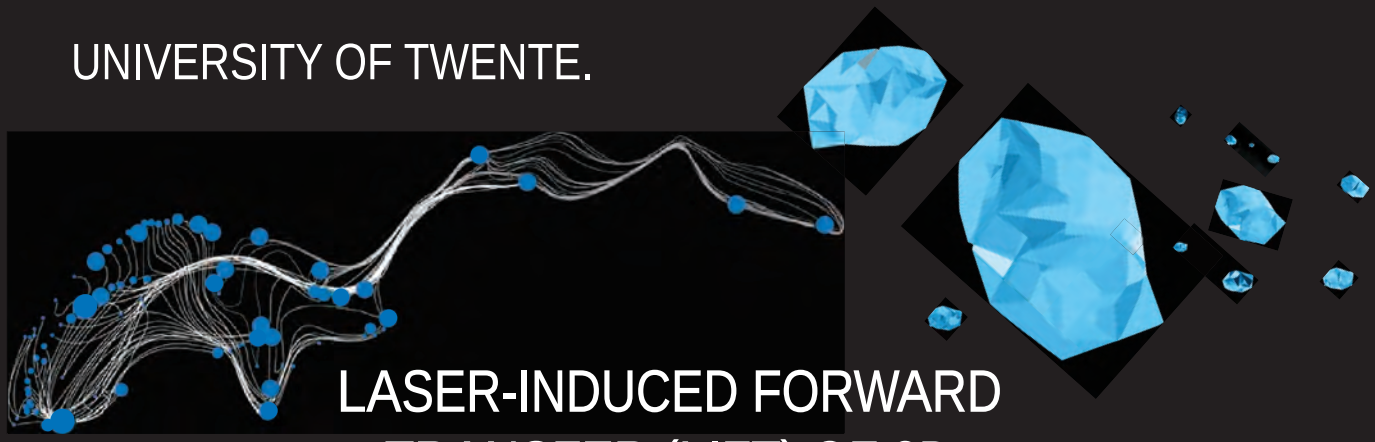

LASER-INDUCED FORWARD TRANSFER (LIFT) OF 3D MICRO-STRUCTURES

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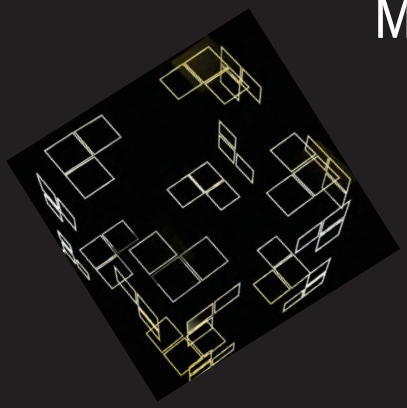
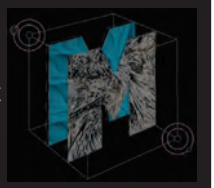
Matthias Feinaeugle & Ralph Pohl
g.r.b.e.romer@utwente.nl

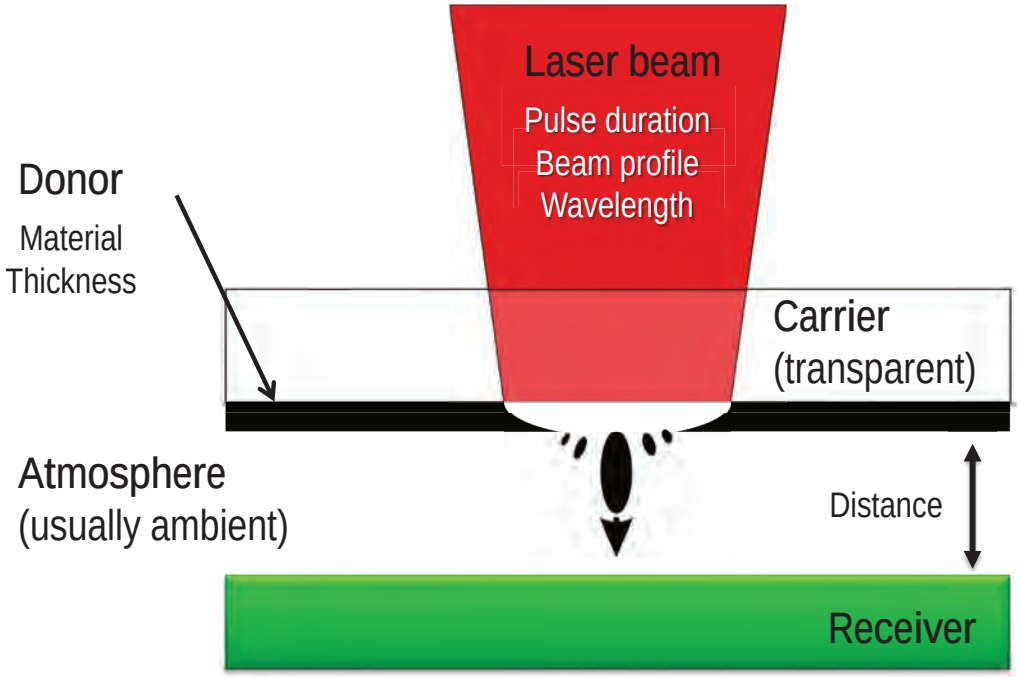


M2i, 4TU, BvM: Meeting Materials 2020
On-line Event
14 & 15 DECEMBER 2020



LASER-INDUCED FORWARD TRANSFER (LIFT)

MICROMETER SCALE ADDITIVE MANUFACTURING TECHNIQUE



LASER-INDUCED FORWARD TRANSFER

TYPICAL PROCESSING PARAMETERS

- Laser source
  - Pulse duration: fs, ps, ns, µs, ms, cw
  - Laser wavelength: UV, Green, IR
  - Spot size: about 1µm to about 100 µm
  - Pulse frequency: about 1 Hz to kHz's
  - Laser fluence (energy) profile: Gaussian (in most cases)
- Thickness donor layer: few 100's nm to 10's of µm
- Donor-receiver distance: a few µm to about 10 mm
- Carrier material: glass, polymer

LASER-INDUCED FORWARD TRANSFER

SOME DONOR MATERIALS USED IN LIFT

- Cu
- Ag
- V
- Cr
- Ti
- Ge
- Sn
- W
- Pd
- Al
- Au
- Ni
- Zn
- Pt

- YBaCuO
- BiSrCaCuO
- PMMA/IR-165 dye
- PMMA
- Diamond/Photoresist
- In_2O_3
- Au/Sn
- Lambda phage DNA
- TiO_2-Au nanocomposite
- Carbon nanotubes
- V2O5
- Luciferase
- PEDOT-PSS
- $FeSi_2$
- Ge/Sn

- DNA, proteins
- Fungi (trichoderma conidia)
- Mammalian cells
- Embryonic cells
- OLED components
- Quantum dot emitters
- Glycerol
- NiCr
- Graphite
- Polyethylene

LASER-INDUCED FORWARD TRANSFER

ADVANTAGES

- Nearly all types of materials can be transferred
  Metals, semiconductors, polymers, organic materials, …
- Transfer of material in any “state”
  Solids, liquids, emulsions, ….
- Donor material is *mostly* unaffected by laser radiation or induced heat, otherwise DRL-LIFT is applied
- High resolution
  Droplets smaller than ∅1μm are possible
- Flexible in (receiver) substrate choice

LASER-INDUCED FORWARD TRANSFER

CHALLENGES

- Quality: not always well defined deposits
  E.g. in the case of metals: contamination due to no single drop transfer—i.e. fragmented droplets
- Quantity: relatively low throughput
  droplet has low volume (e.g. femto- to pico-liter), so pulse frequency needs to be high, but mechatronics is not fast enough (for donor refreshment, donor & receiver positioning)

CONTENTS

- Laser-induced Forward Transfer (LIFT)
- EJECTION CHARACTERISTICS
- LIFT of 2½D structures (pillars)
- LIFT of 3D structures

LIFT OF METALS

MORPHOLOGY OF DEPOSITS

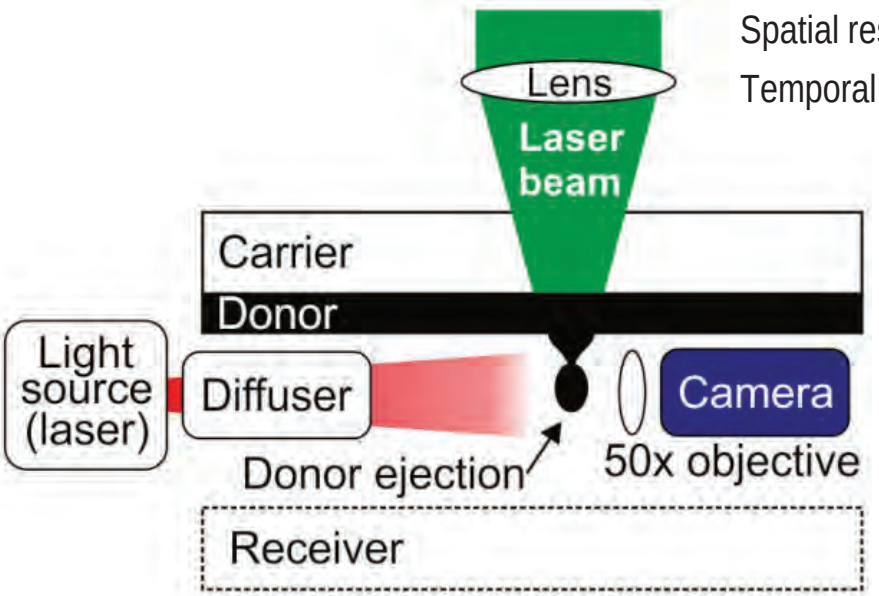
Donor material: Cu, 200nm, donor-receiver gap 25 µm
Conditions: τ = 7 ps, λ = 515 nm, *d* = 9µm spot diameter

Typical deposited features for 3 fluence regimes, $F = E_p / A$

Fluence at threshold	Transition fluence	High fluence

LIFT OF METALS

IMAGING SETUP (SHADOWGRAPHY)



Spatial resolution about ±1um

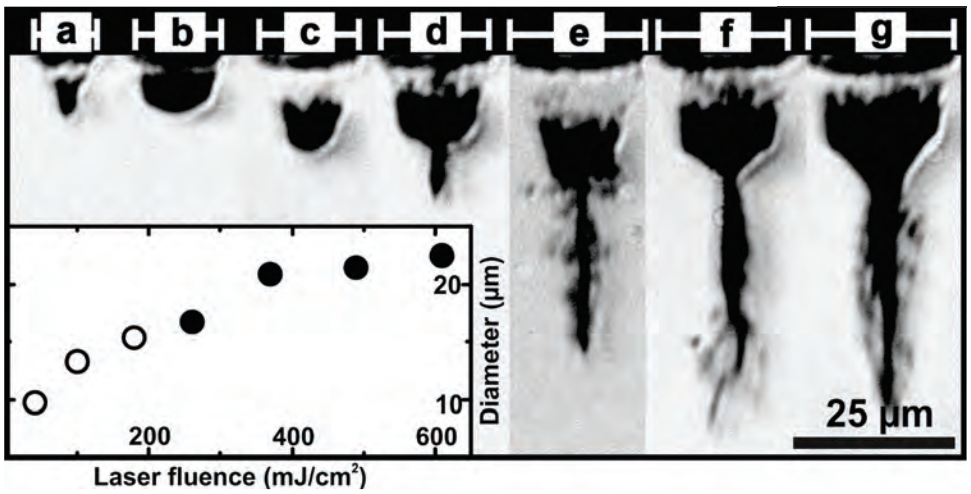
Temporal resolution <50ns

LIFT OF METALS

EJECTION AS FUNCTION OF FLUENCE (FLUENCE SERIES)

Threshold *F* "cap" | Transistion *F* *"jet"* | High *F* *"spray"* | Donor "hole"

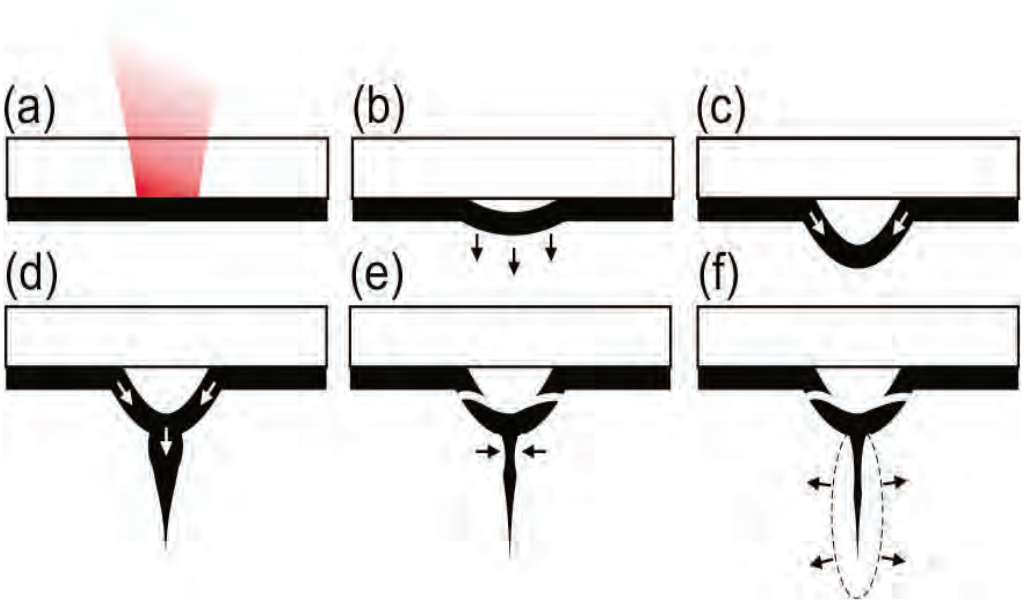
200nm Cu



Less controlled – more material

LIFT OF METALS

SEQUENCE OF PHYSICAL PHENOMENA DURING HIGH FLUENCE LIFT



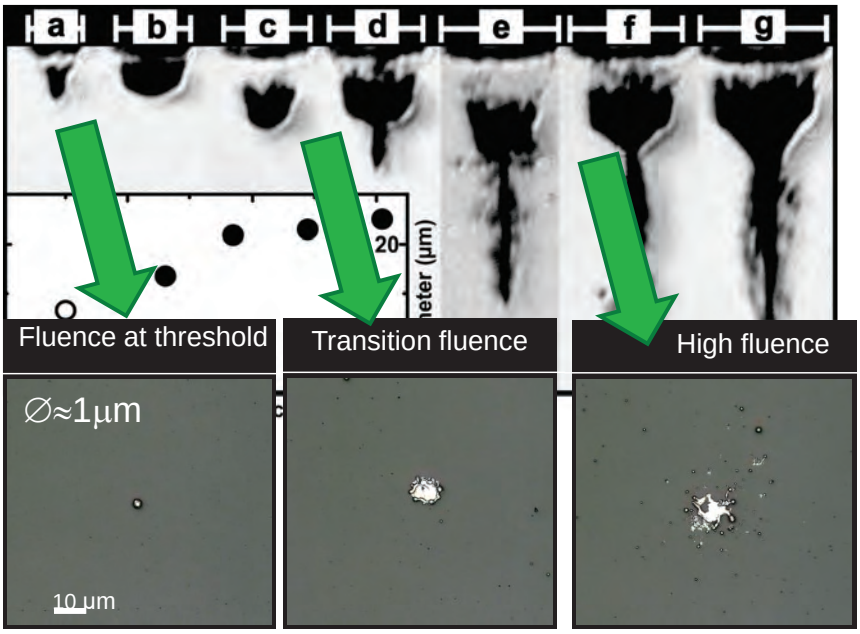
LIFT OF METALS

EJECTION TYPE DETERMINES MORPHOLOGY OF DEPOSIT

Thresh. *F* *"cap"*

Transistion *F* *"jet"*

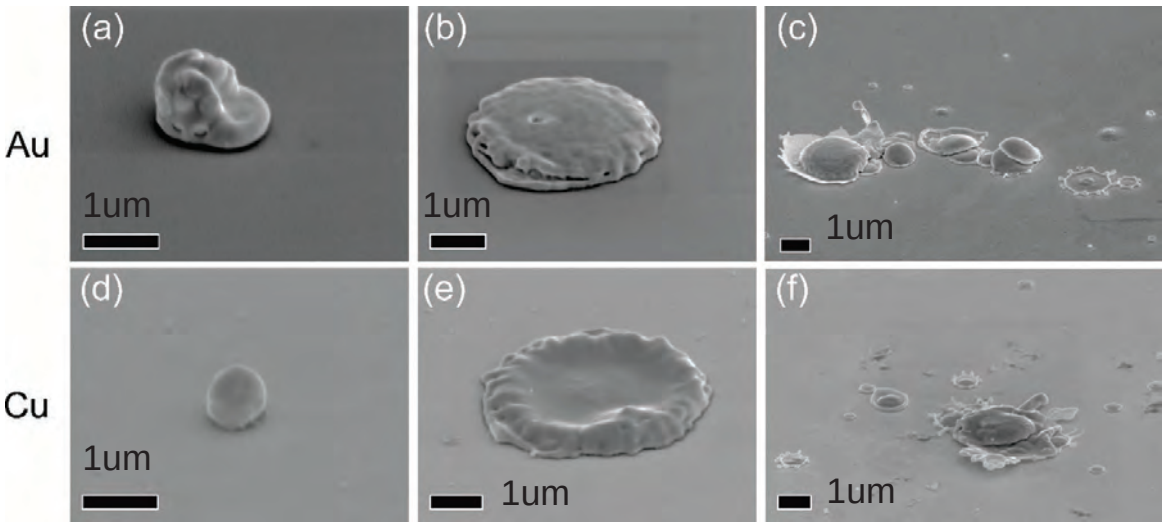
High *F* *"spray"*



LIFT OF METALS

FLUIDICS OF DEPOSITING DROPLETS

Khojasteh et al. (2016)



SEM images on a receiver. Deposits are representative for threshold 140±30 mJ cm^{-2} (a) and 200±30 mJ cm^{-2} (d), optimized working condition 190±30 mJ cm^{-2} (b) and 280±30 mJ cm^{-2} (e) and a fluence level larger than 50% above threshold (c,f).

Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

LIFT OF METALS

VIDEO OF EJECTION AT THRESHOLD FLUENCE

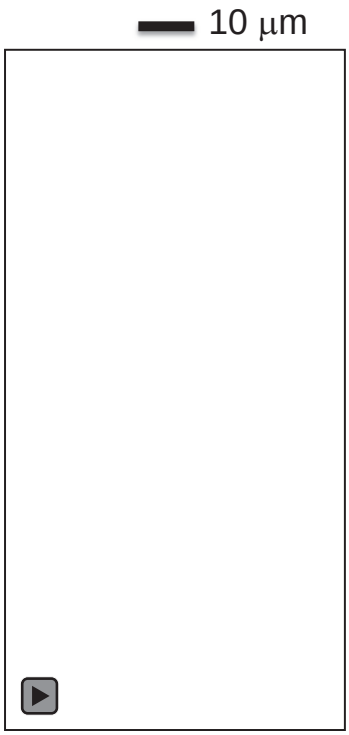
Printing of many droplets on same location = pillar

Processing conditions:

- Low laser fluence
- τ = 7 ps
- λ = 515 nm
- *d* = 9µm spot diameter
- Donor-receiver gap: 25 µm

Donor (moves up as pillar grows)

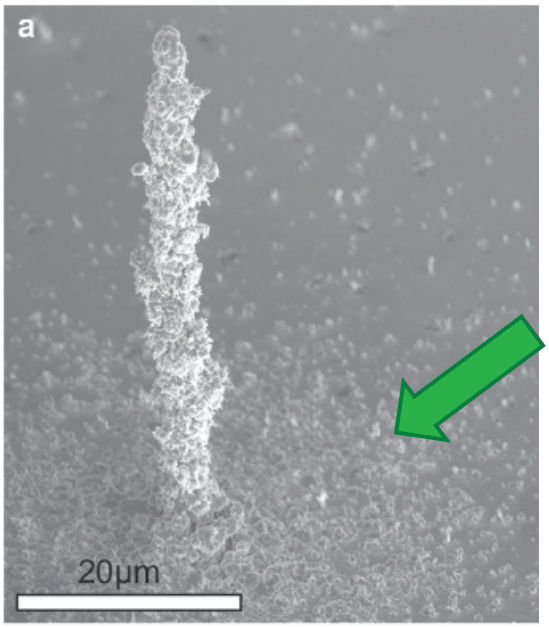
Receiver (droplets pile up)



LIFT OF METALS

EVEN IN THE CASE OF CAP EJECTION: DEBRIS (CONTAMINATION)

Pillar printed using “cap” ejections



Debris (contamination)

Source: Visser et al. (2015)

LIFT OF METALS

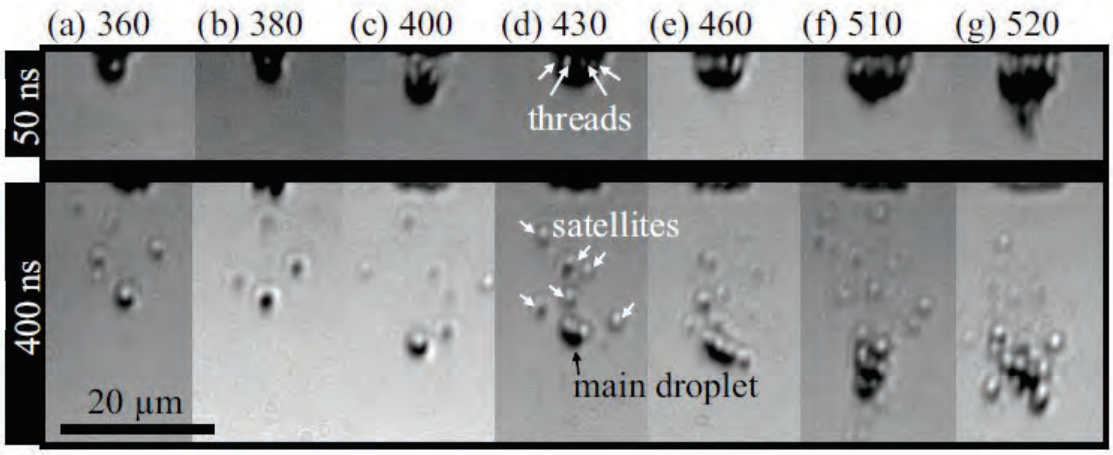
ORIGIN OF DEBRIS (CONTAMINATION)

Two images of same ejection:

Fluence [mJ/cm^2] →

1st image →

2nd image →



Source: Pohl (2015) PhD-thesis

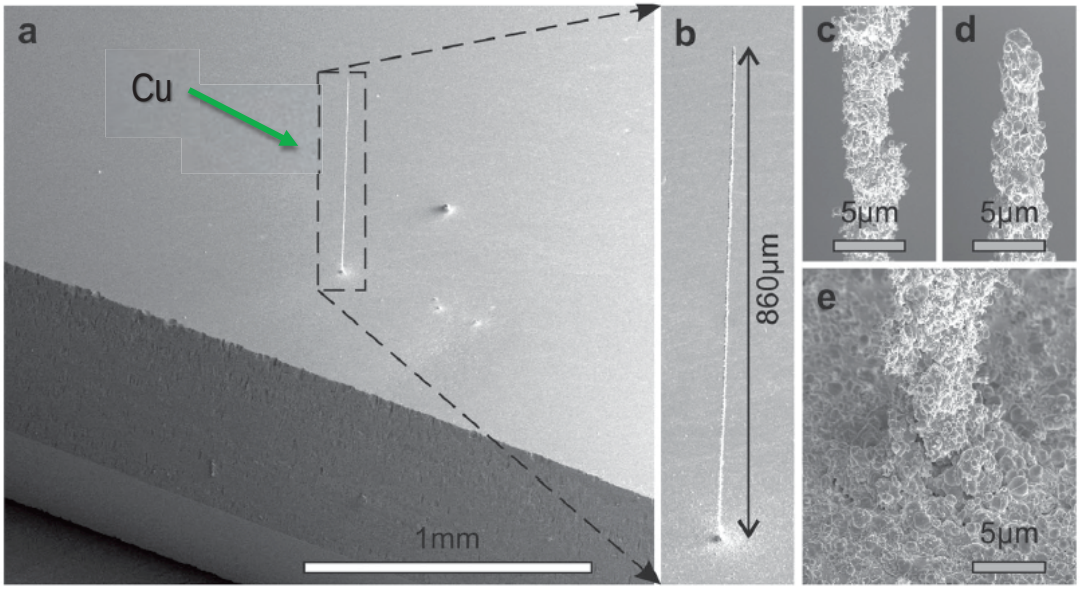
“Threads” are ”trailing” the ejection of the cap

CONTENTS

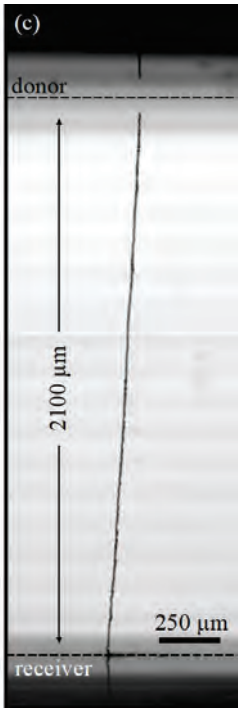
- Laser-induced Forward Transfer (LIFT)
- Ejection characteristics
- LIFT OF 2½D STRUCTURES (PILLARS)
- LIFT of 3D structures

2D & 2½D METALLIC MICROSTRUCTURES

REPRODUCIBILITY OF CU LIFT PRINTED PILLARS

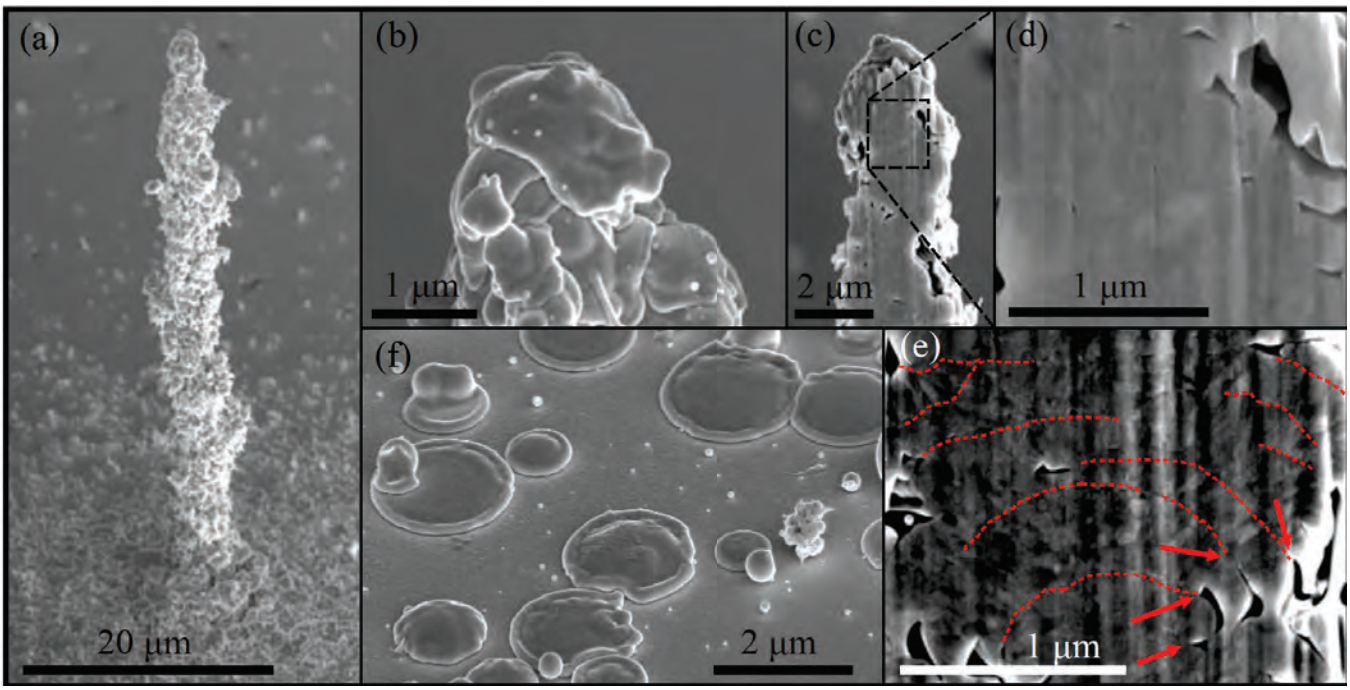


Source: Visser et al. (2015) Adv. Mat.



2D & 2½D METALLIC MICROSTRUCTURES

MORPHOLOGY OF CU LIFT PRINTED PILLARS



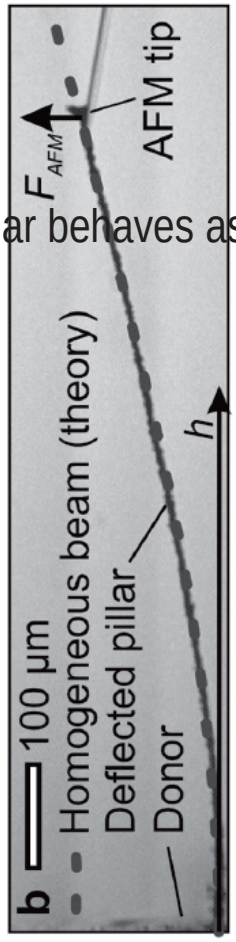
Source: Visser et al. (2015) Adv. Mat.

2D & 2½D METALLI RUCTURES

MECHANICAL PROPERTIES

Mechanically, the pillar behaves as a solid beam of Cu

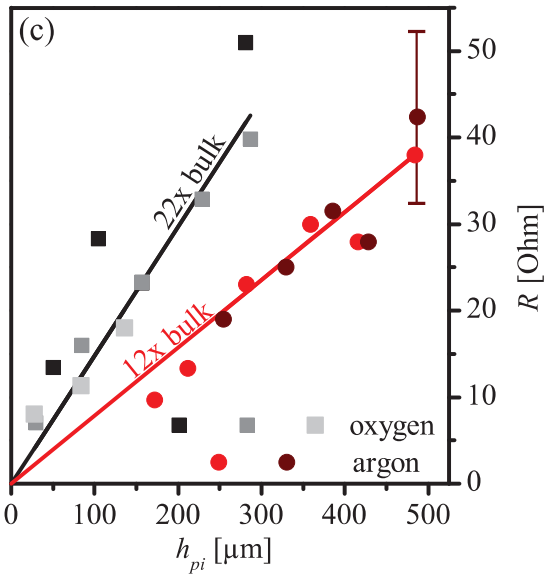
Source: Visser et al. (2015) Adv. Mat.



2D & 2½D METALLIC MICROSTRUCTURES

ELECTRICAL PROPERTIES OF CU PILLAR

Electrical resistance as a function of the pillar length



Source: Visser et al. (2015) Adv. Mat.

This properties are suitable for out-of-plane electrode manufacturing

CONTENTS

- Laser-induced Forward Transfer (LIFT)
- Ejection characteristics
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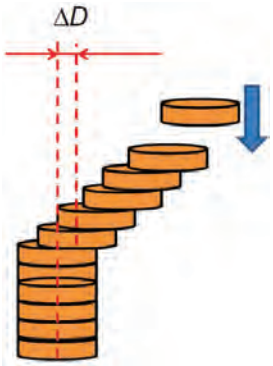
- LIFT OF 3D STRUCTURES

3D METALLIC MICROSTRUCTURES

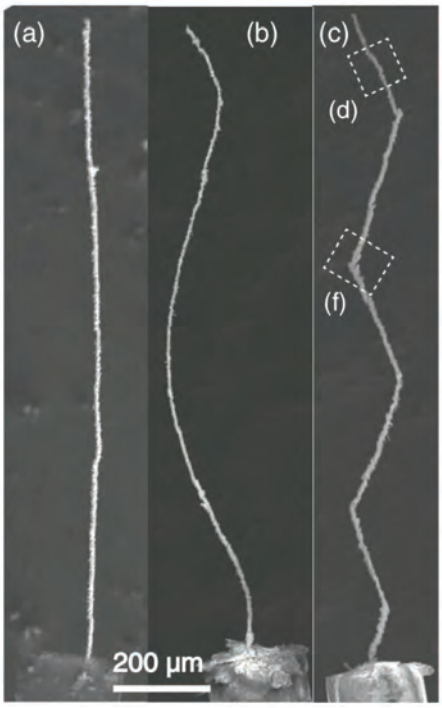
INCLINED PILLARS

Maximum inclination angle (without support) is ~30 degrees



Zenou et al. (2015)

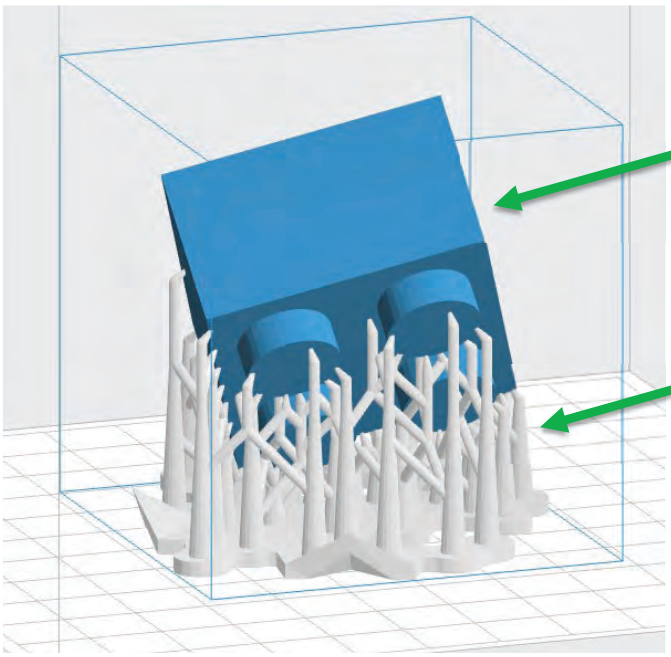
Somewhat larger inclination angles can be achieved by tiling the receiver



Source: Lou et al. (2017)

3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES



Product

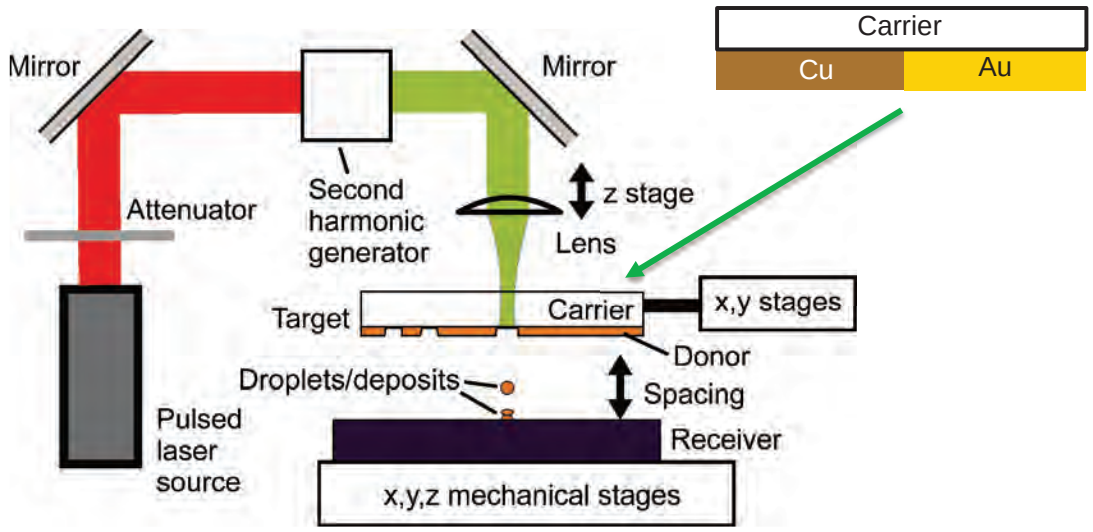
Support structures (removed after Printing)

Source: Wikimedia Commons

3D METALLIC MICROSTRUCTURES

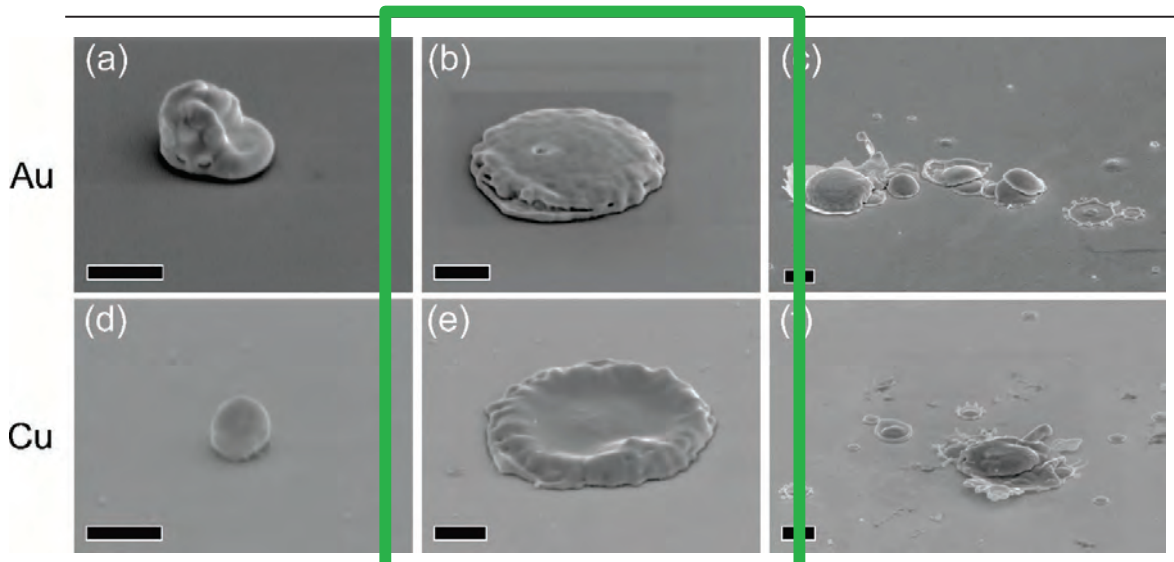
LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES

- In our setup: **one carrier with two materials**: Au and Cu (sacrificial)
- After LIFT printing Cu is etched with aqueous ferric chloride: $FeCl_3$(aq)



3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES



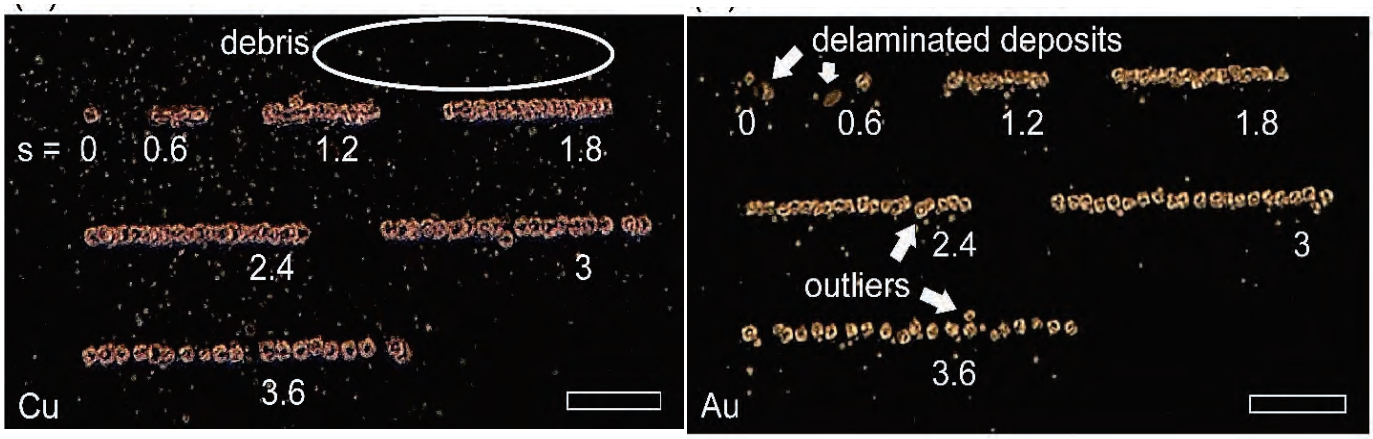
SEM images on a receiver. Deposits are representative for threshold 140±30 mJ cm^{-2} (a) and 200±30 mJ cm^{-2} (d), optimized working condition 190±30 mJ cm^{-2} (b) and 280±30 mJ cm^{-2} (e) and a fluence level larger than 50% above threshold (c,f). The scale bar is 1um.

Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES

Optimization of **deposit spacing** [um] in printed **lines**

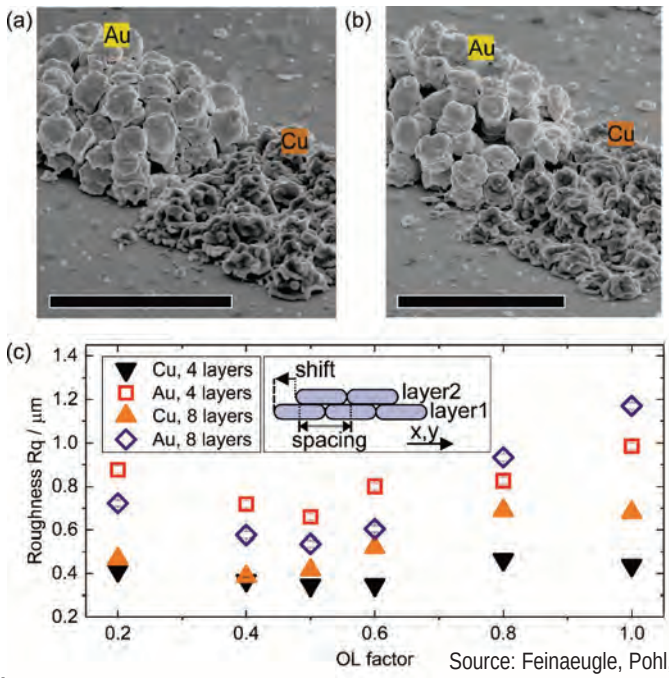


Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES

Optimization of deposit spacing in a **layer** and **stacked layers**



Au: 4 x 4 x 4 deposits
Cu: 5 x 5 x 4 deposits

Stacking layers
optimizing relative shift between subsequent layers

Porosity
- Au: up to 50%
- Cu: < 15%

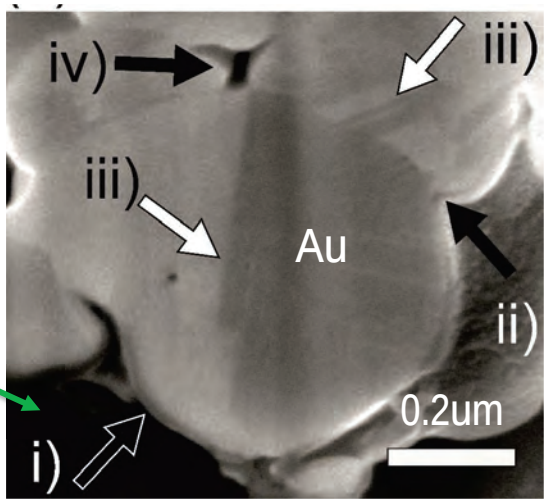
Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES

SEM image of cross-section from **etched stack of Au-Cu deposits**

No more Cu



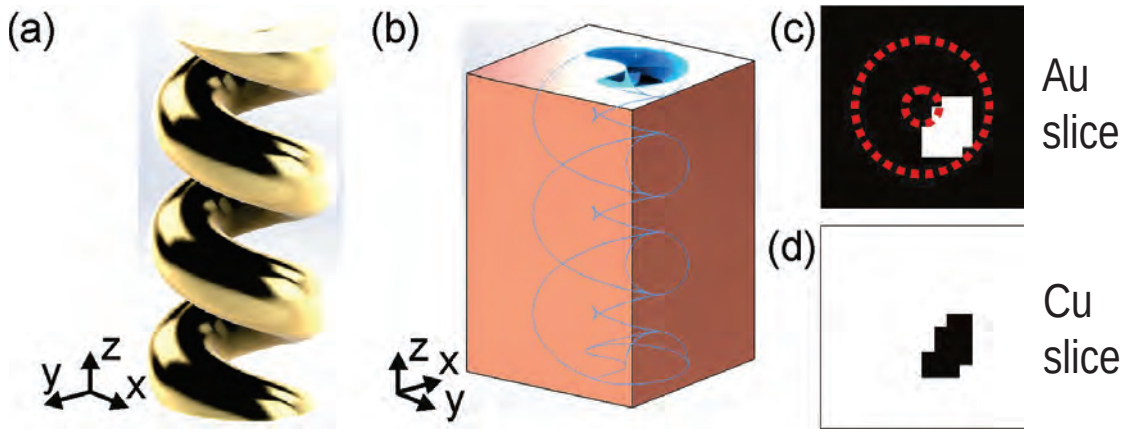
Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

i. (former) Cu-Au interface
ii. Au-Au inter-deposit boundary
iii. line features within deposits
iv. inter-deposit void

Preliminary EDS analysis of Au-Cu stacks after LIFT <u>do not hint at interfaces with undesired formation of intermetallics</u>. The analysis suggests that potential intermixed volumes of Au-Cu did not occur.

3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES



Model of targeted 3D structure (helix) in Au

Model of Au Helix in Cu cuboid

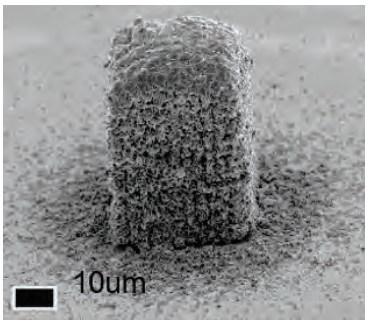
Examples of Slices of Au and Cu layers

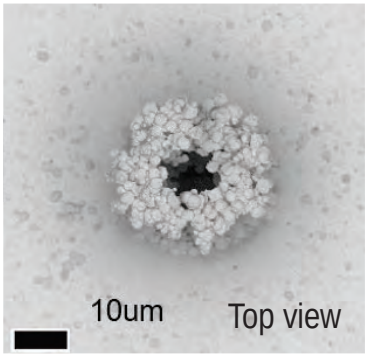
Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

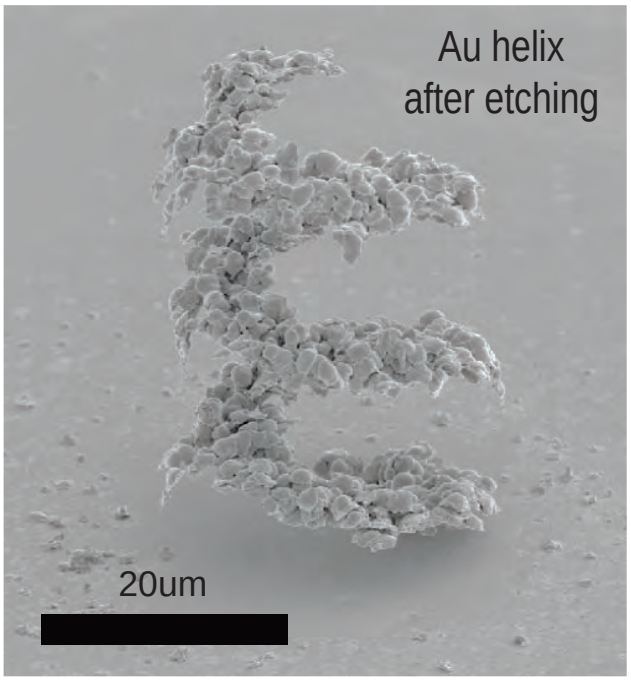
3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES

Encapsulated Au helix in Cu cuboid before etching



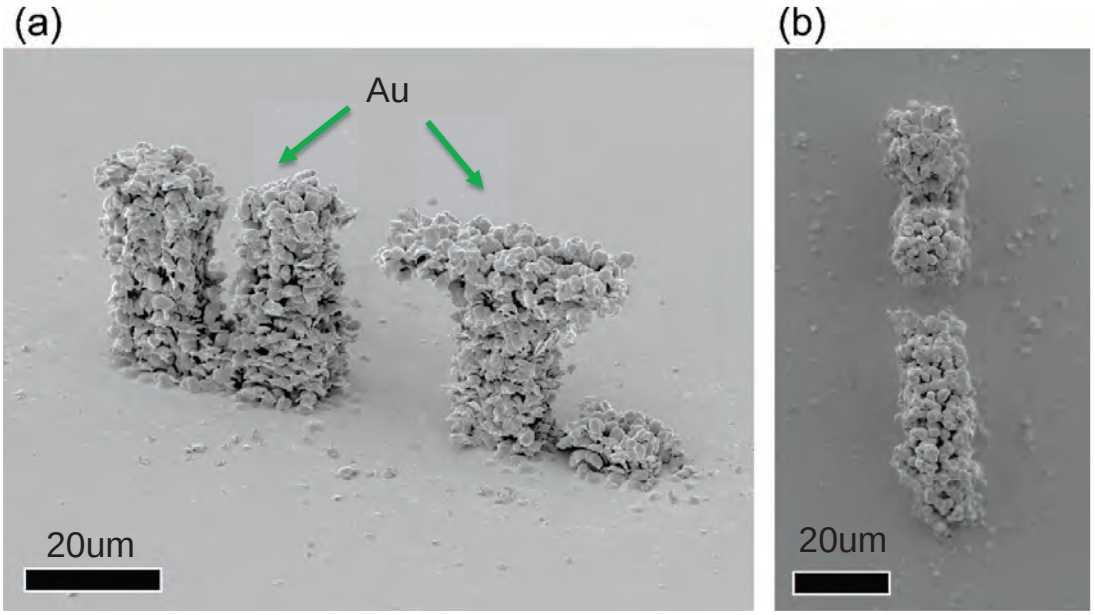




Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

3D METALLIC MICROSTRUCTURES

LIFT PRINTING OF COMPLEX FREE-STANDING 3D METALLIC STRUCTURES



Source: Feinaeugle, Pohl, Bor, Vaneker, Römer (2018)

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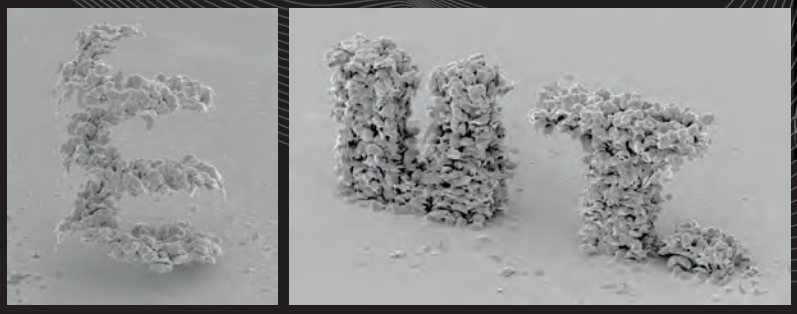
SUMMARY LIFT OF 3D MICRO-STRUCTURES

- LIFT is a high resolution 3D Additive Manufacturing technique
- Allows printing of nearly any material
- Print quality is governed by many physical processes & parameters



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