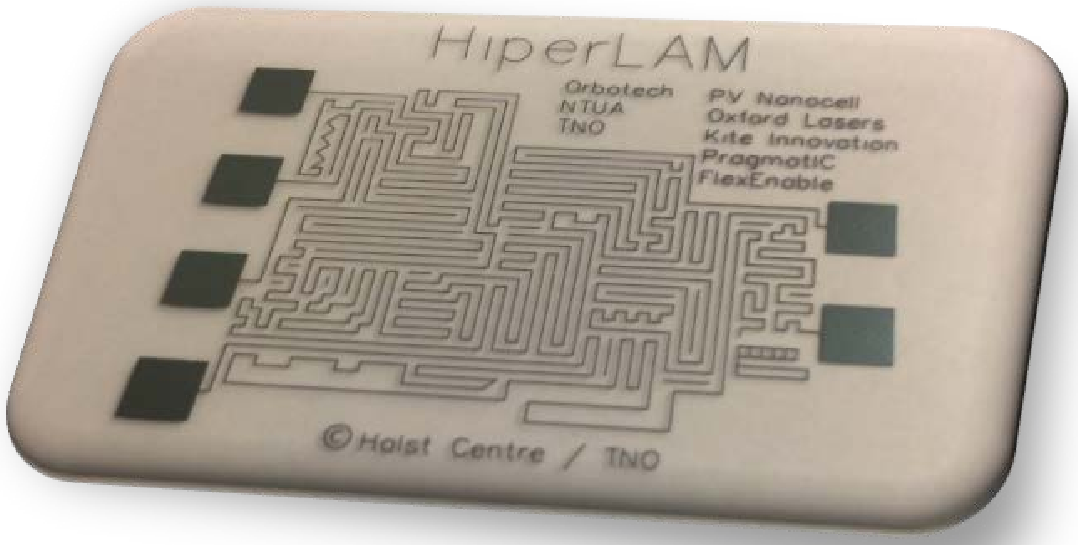
High speed laser printing and sintering of flexible RFID antennas and fingerprint sensors

I. Theodorakos[1], F. Zacharatos[1], M. Makrygianni[1], A. Kalaitzis[1], O. Koritsoglou[1], J. Ankri[2], A. Schwarzbaum[2], A. Melamed[2], M. Giesbers[3], G. Arutinov[3], S. Tuohy[4], D. Arnaldo[4], N. Braz[4], R. Geremia[4], D. Karnakis[4], S. Melamed[5], A. Kabla[5], F. de la Vega[5], D. Kariyapperuma[6], B. Cobb[6], R. Price[6], P. Too[7], S. Norval[7] and
I. Zergioti[1]

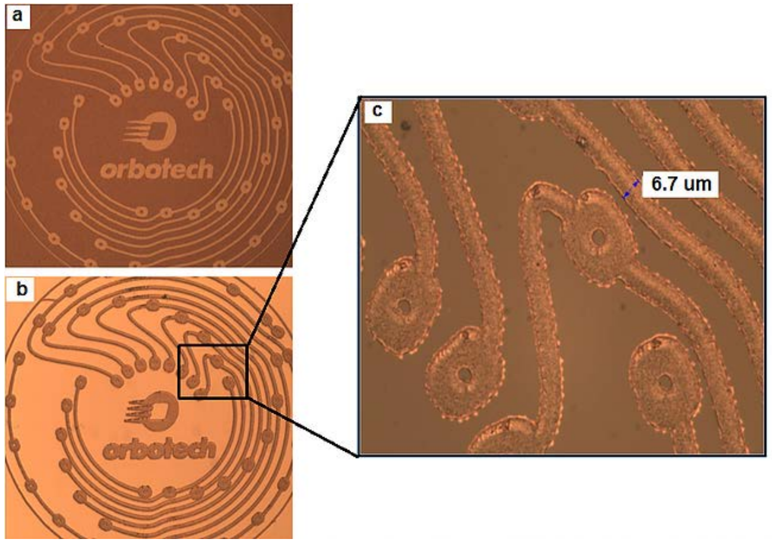
[1] NTUA, Athens, Greece, [2] Orbotech Ltd., Israel, [3] TNO Eindhoven, The Netherlands, [4] Oxford Lasers Ltd., Didcot, UK, [5] PV Nano Cell Ltd, Israel, [6] PragmatIC, Cambridge, UK, [7] FlexEnable Ltd, Cambridge, UK

HiperLAM

High Performance Laser-based Additive Manufacturing
H2020-FOF-2016-2020



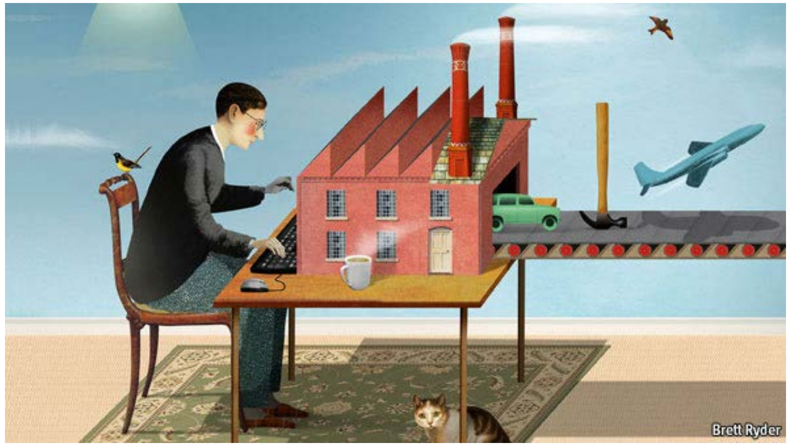
Laser Printing of metal Nanoparticle inks for flexible electronics

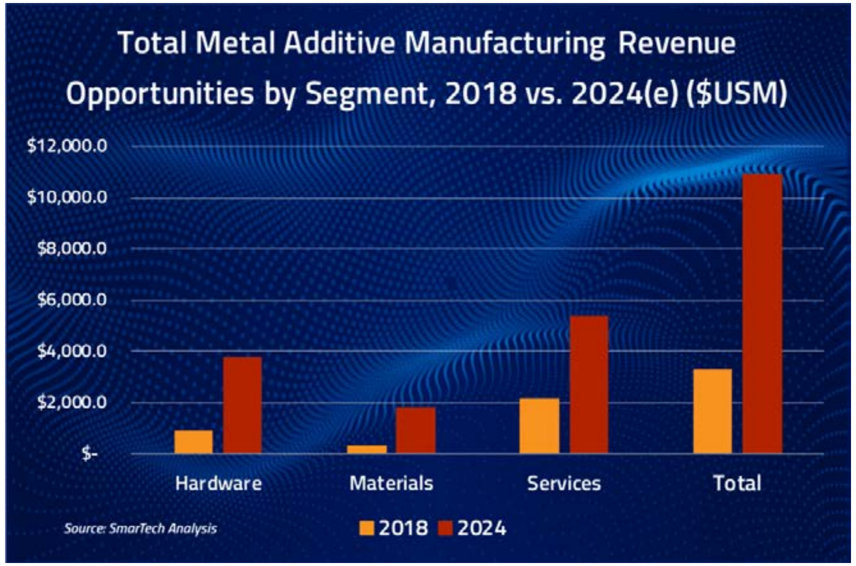


Laser Sintering of metal Nanoparticle inks for flexible conductive patterns

Additive Manufacturing

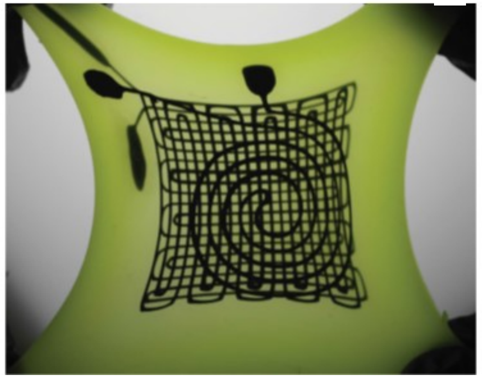
“Additive Manufacturing has the potential to revolutionize the way we make almost everything” US President Barack Obama, 2013, at National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio





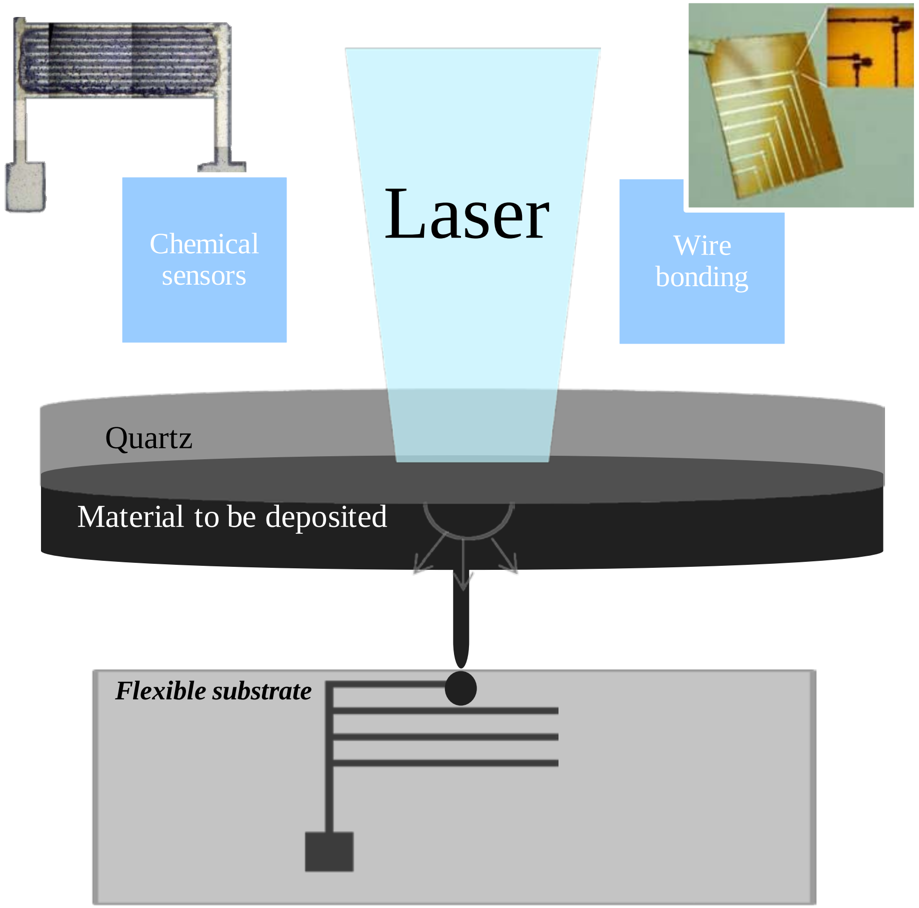
Flexible Circuits

Stretchable sensors

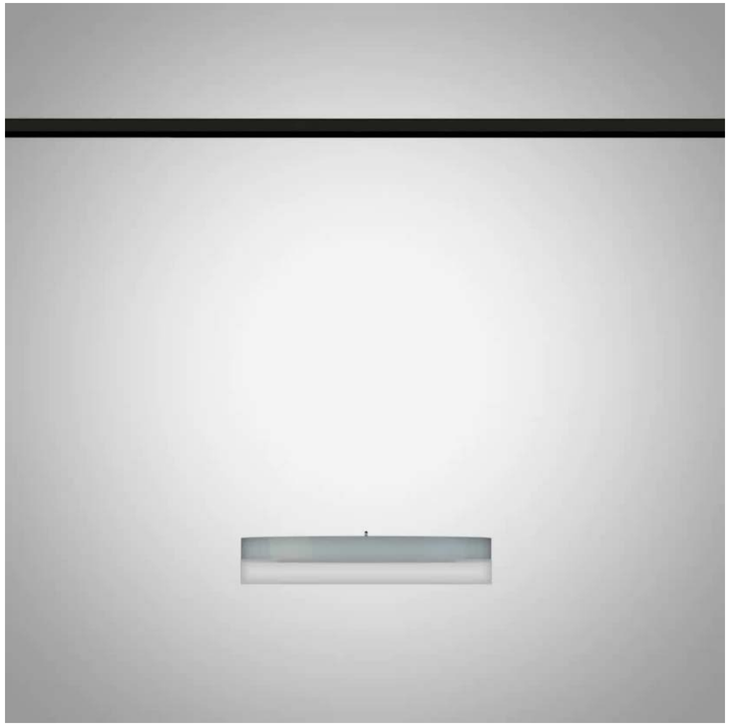


Touch Screens

Laser Induced Forward Transfer30



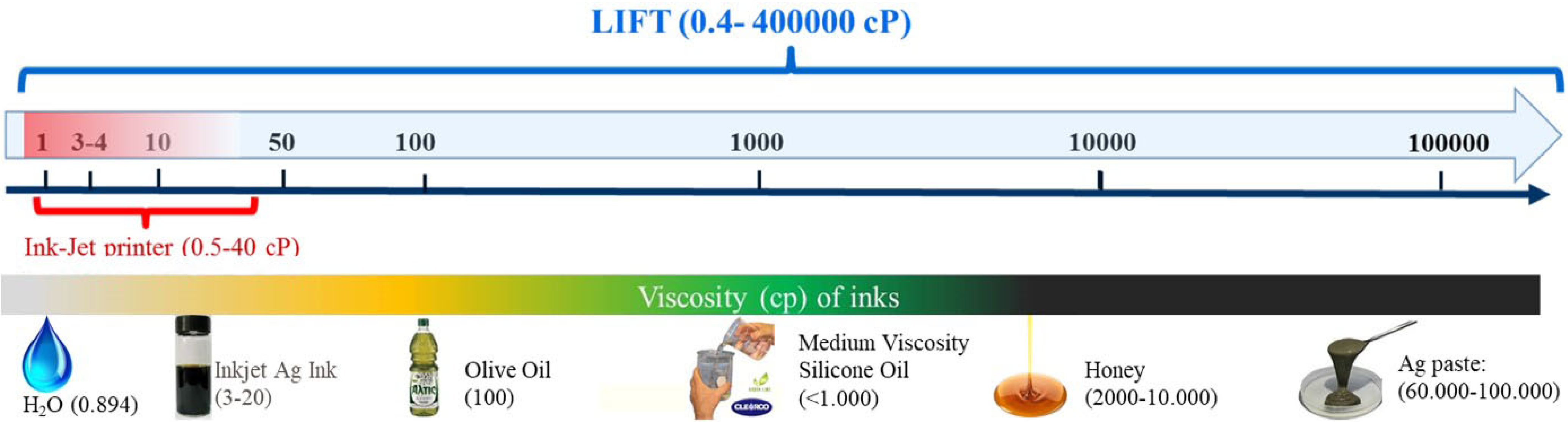
- Printing in solid and liquid phase
- Spatial resolution down to 10 μm for liquid and sub-micron for solid phase
- Printing of inorganic, organic, biological materials



LIFT advantages

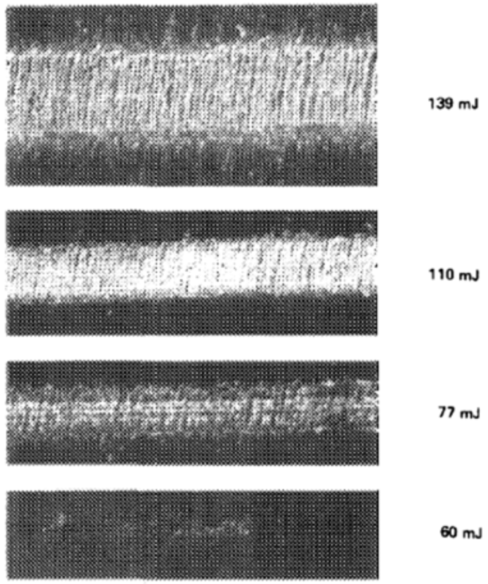
- Drop-on-demand printing, non-contact printing
- Compatible with a wide range of materials
- No limitations in materials viscosity (0.4–500000cP)
- No use of nozzles, no additives
- Receiver substrate independent (flexible, polymer materials, etc.)

Inkjet printing typically handles low viscosity inks (1-15 mPa.s) and even with piezoelectric actuation, inks up to 100 mPa.s viscosity can be processed.



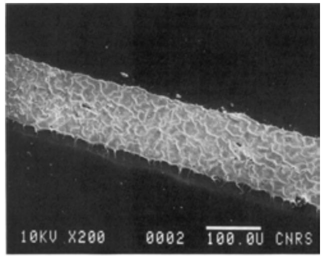
LIFT of metallic nanoparticles

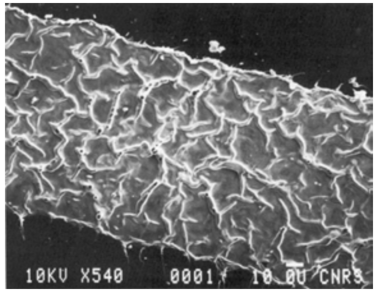
LIFT of Cu



Bohandy *et al.* J. Appl. Phys. 60, 1538, (1986)

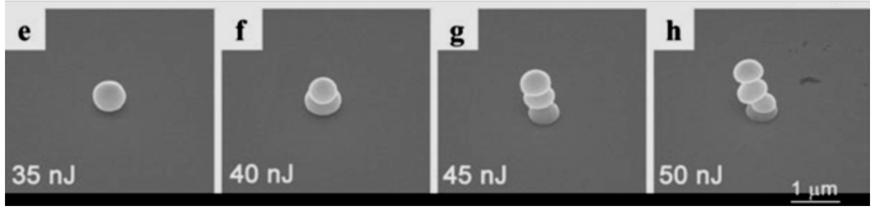
LIFT of high Tc superconducting films





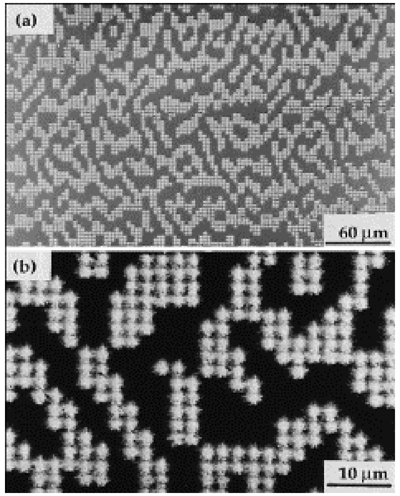
E. Fogarassy et al., J. Mater. Res., Vol. 4, 5, (1989)

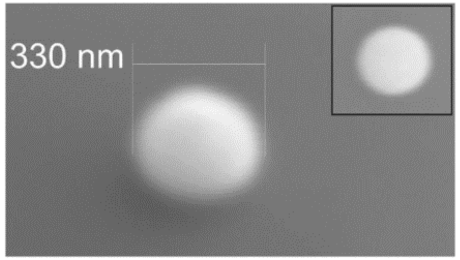
LIFT of Au



Kuznetsov et al., Appl Phys A, 106:479–487, (2012)

Nanoscale droplets of Cr

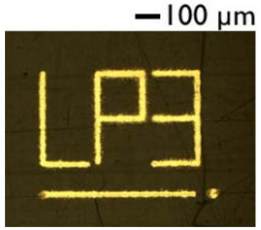




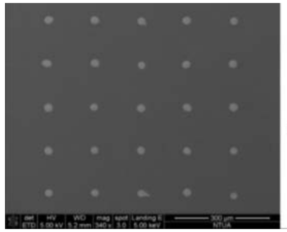
Banks *et al.* Appl. Phys. Lett. **89**, 193107 (2006)

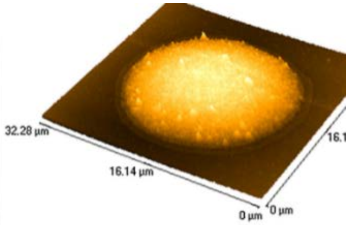
I. Zergioti *et. al.* Appl. Surf. Sci. 127-129, 601 (1998)

Ag-NPs inks



L. Rapp, J. Ailuno, A.P. Alloncle and P. Delaporte, Optics Express , vol. 19 , no. 22, pp. 21563, (2011)

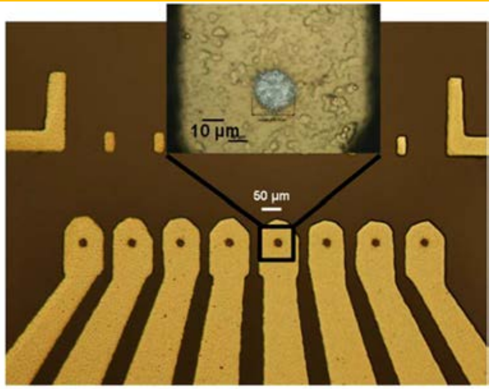




M. Makrygianni, I. Kalpyris, C. Boutopoulos, I. Zergioti, Applied Surface Science 297 (2014) 40–44

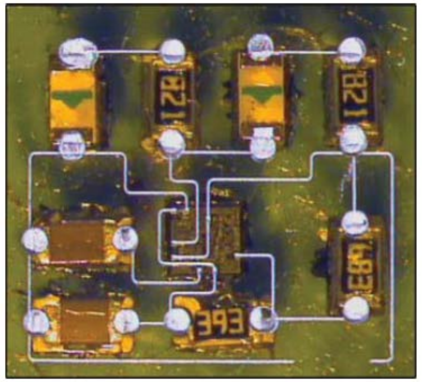
LIFT for device components and interconnects

Flip-chip bonding



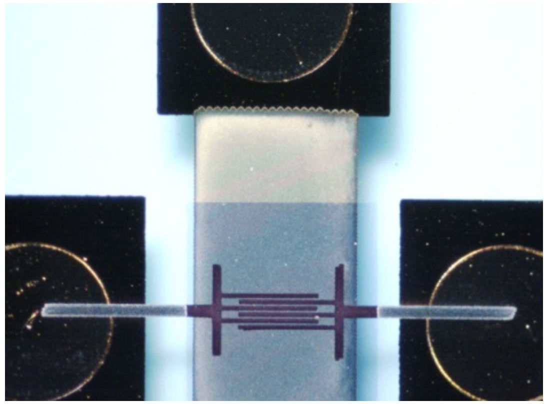
Kaur et al., Appl. Phys. Lett. 104, 061102 (2014)

Printing of electronic components



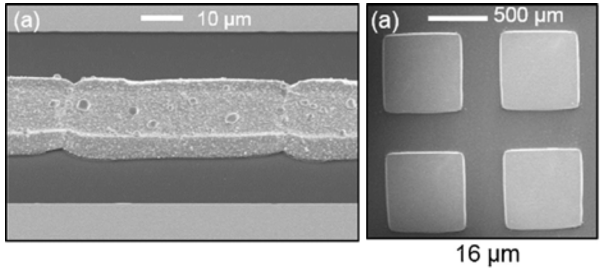
C.B. Arnold, P. Serra, A. Pique, MRS Bulletin, 32, (2007)

Interdigitated Ag electrodes for OTFTs



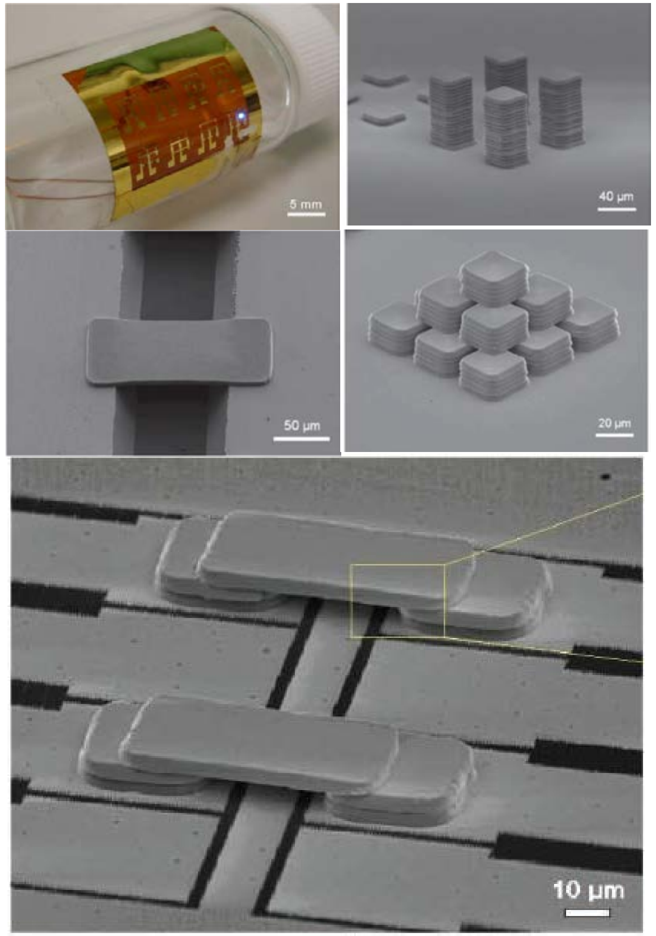
H. Kim, R.C.Y. Auyeung, S.H. Lee, A.L. Huston and A. Pique, J. Phys. D: Appl. Phys., vol. 43, (2010)

Silver nanopaste for microwave interconnects



E. Breckenfeld et al. Applied Surface Science 331, 254-261, (2015)

Printing Silver Nanopastes for interconnect bonding of Au pads

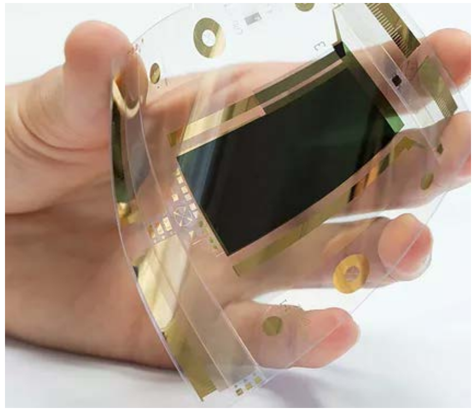


Wang et al., Adv. Mater., 22, 4462–4466, (2010)

Applications

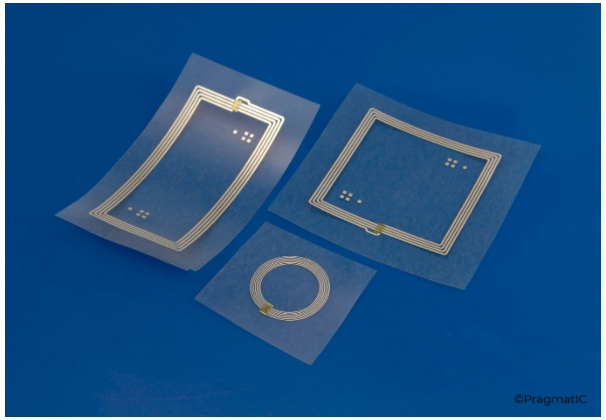
Fingerprint sensor

FlexEnable
Truly flexible electronics



RFID Antenna

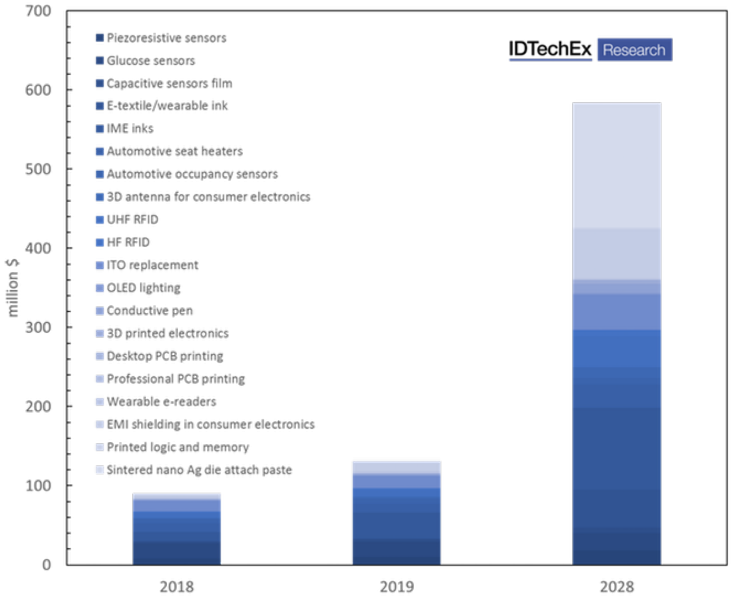
PragmatIC®



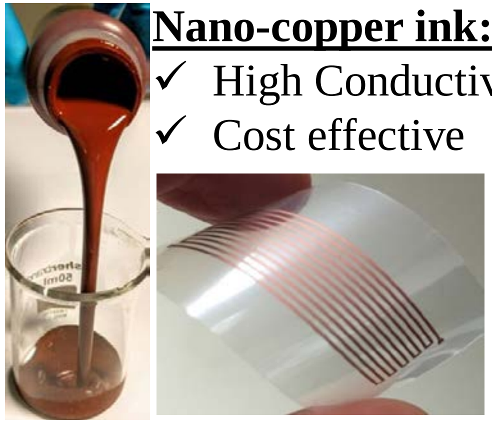
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP
FoF Factories of the Future Public Private Partnership

The HIPERLAM Project is an initiative of the Photonics and Factories of the Future Public Private Partnerships and received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 723879

Nanoparticle metal inks for Printed Electronics



Nano-silver ink/paste:
- ✓ High Conductivity
- ✓ Stability

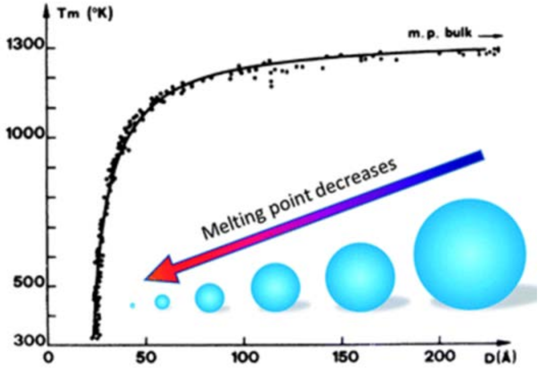


Nano-copper ink:
- ✓ High Conductivity
- ✓ Cost effective

www.prometheanparticles.co.uk

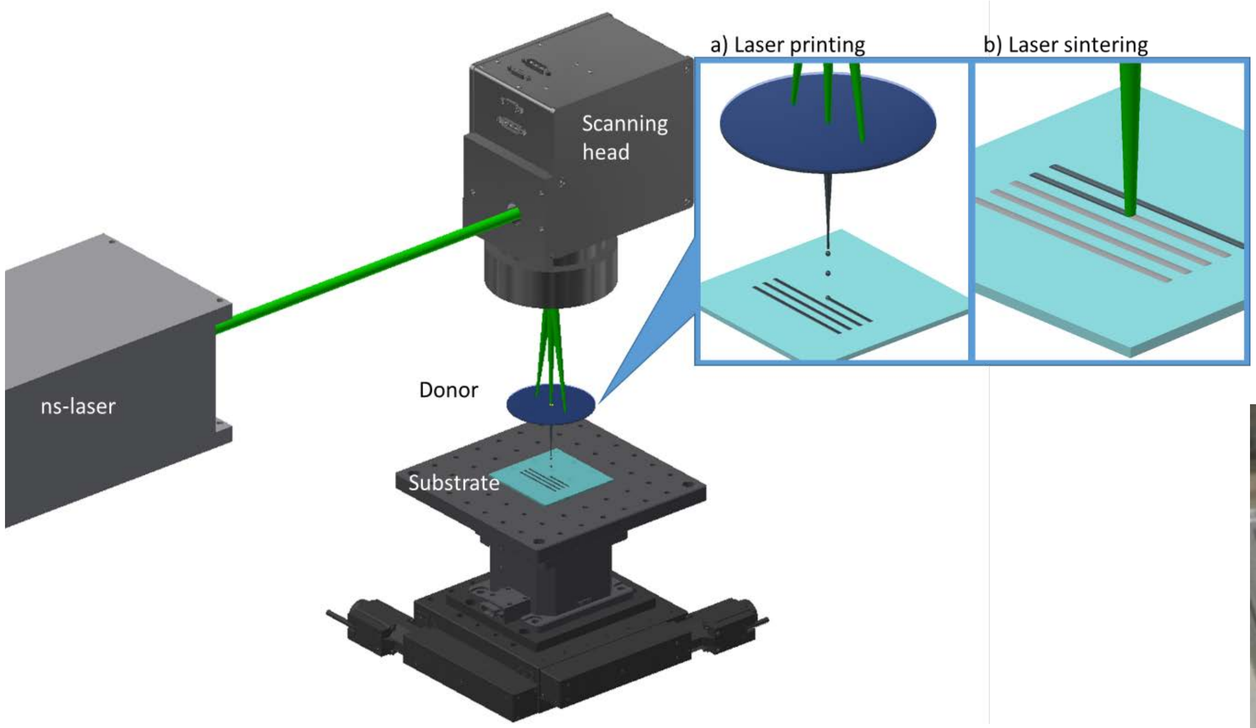
Requirements and Challenges
- Good Printability
- Good adhesion to specific substrates
- High resolution
- Long shelf life

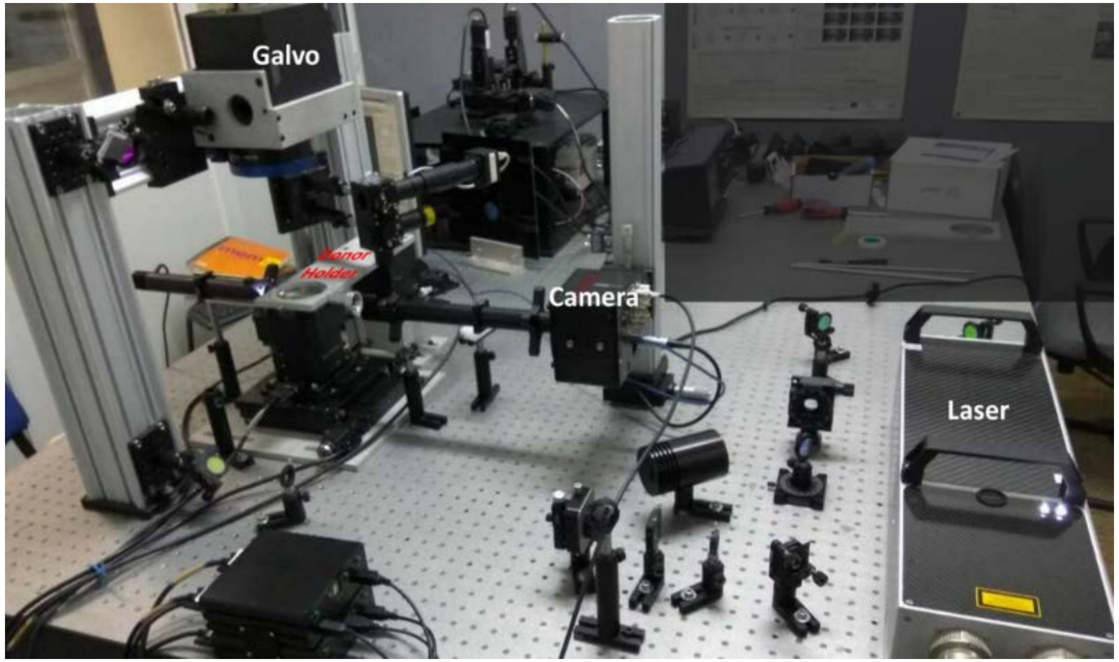
Melting point vs. particle diameter of gold nanoparticles



C. Yang et al. / J. Mater. Chem. C **1**, 4052-4069 (2013)

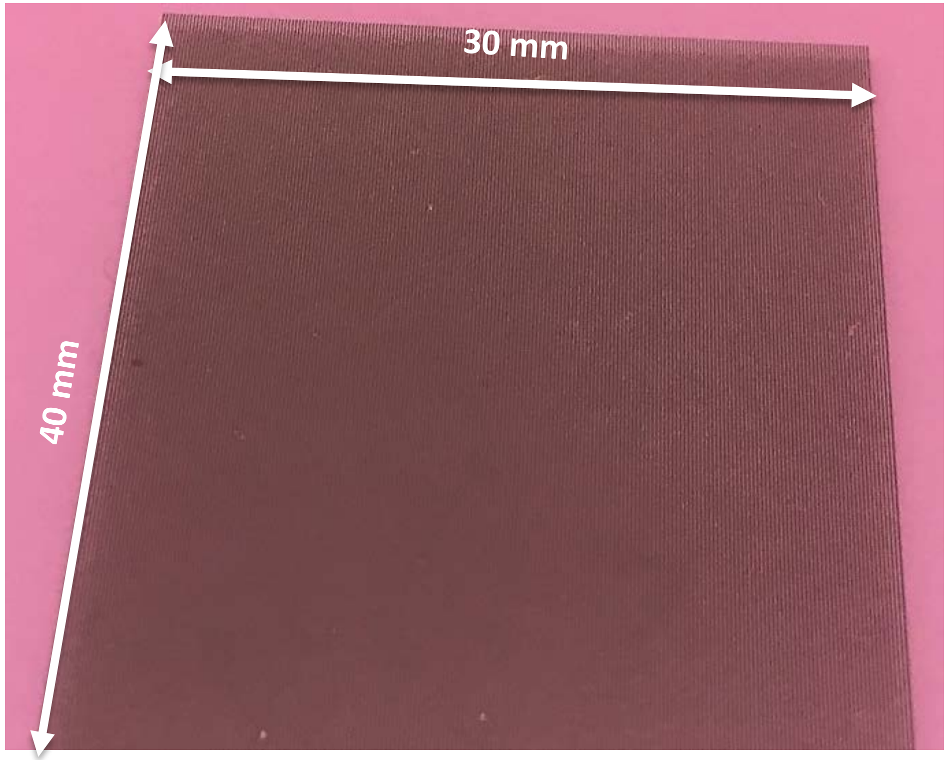
Experimental set-up for laser printing and sintering

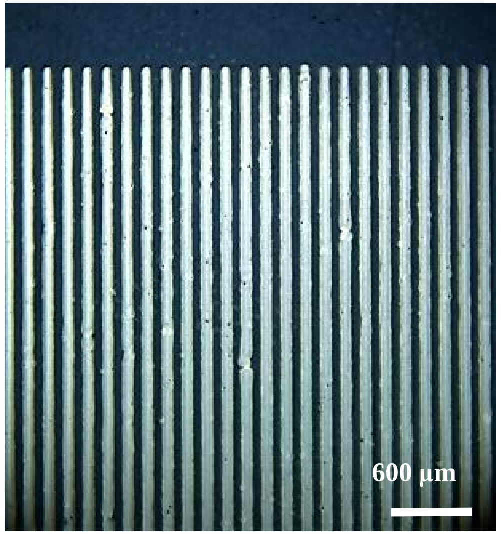




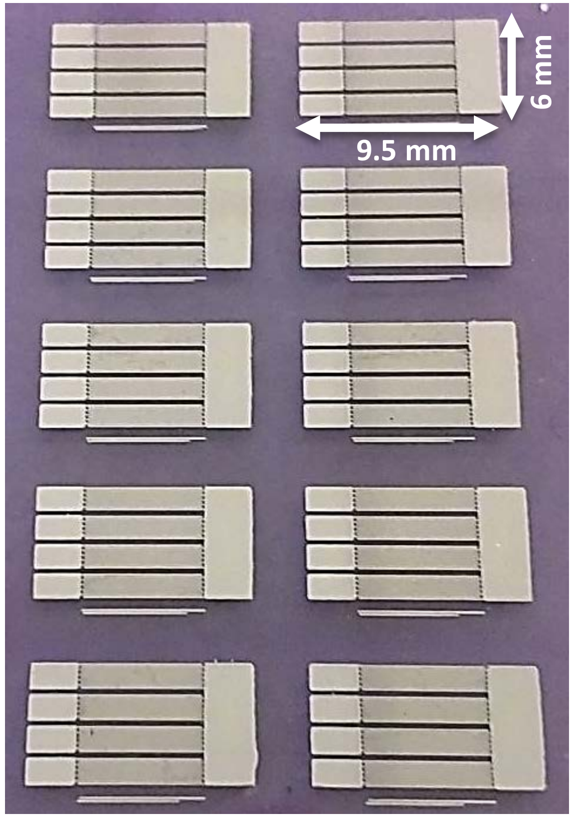
- High power ns laser at 20 W, tunable up to 500 KHz, 20-200ns
- Galvo scan lab: sub-micron step resolution, size, 5 m/sec speed

LIFT: Large area printing on flexible substrates

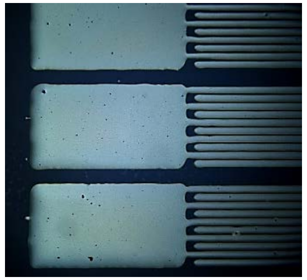


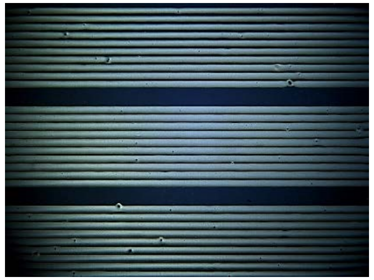


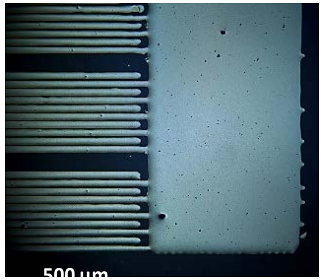
Lines’ width ~ 90 µm
Lines’ gap ~ 60 µm



Lines’ width ~ 90 µm
Lines’ gap ~ 20 µm

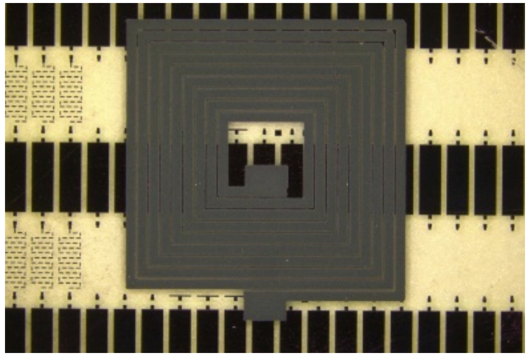


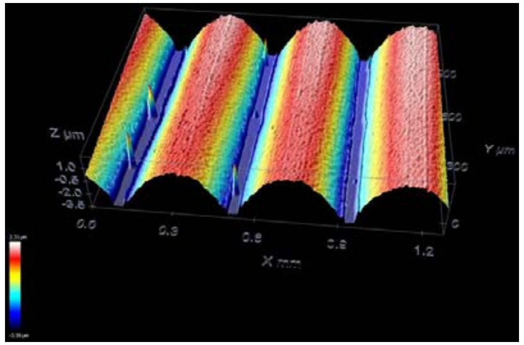


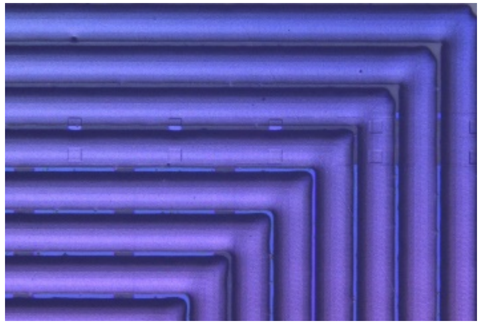


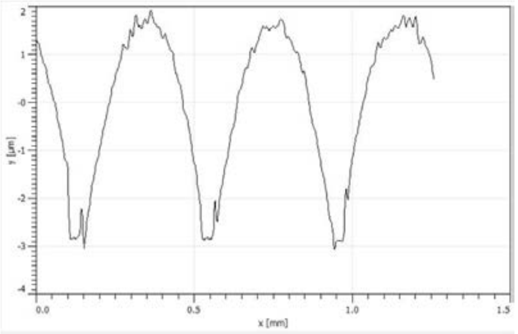
On-chip Ag antennas on flexible integrated circuits

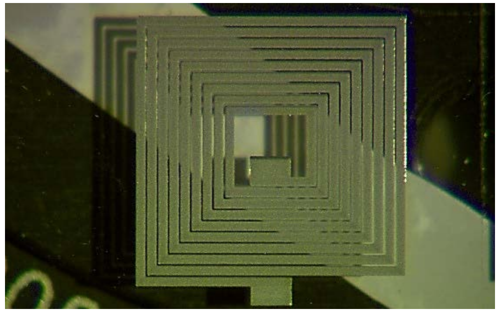
Laser printed and laser sintered RFID antennas with low overall resistance < 30 Ω, with from factors designed for High Frequency band applications .

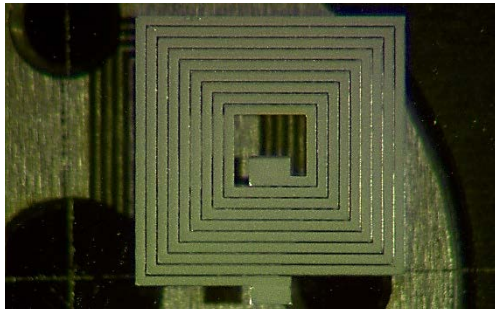


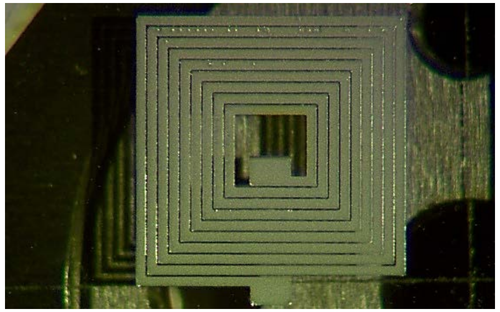


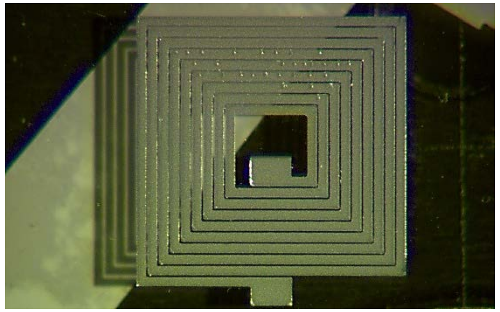










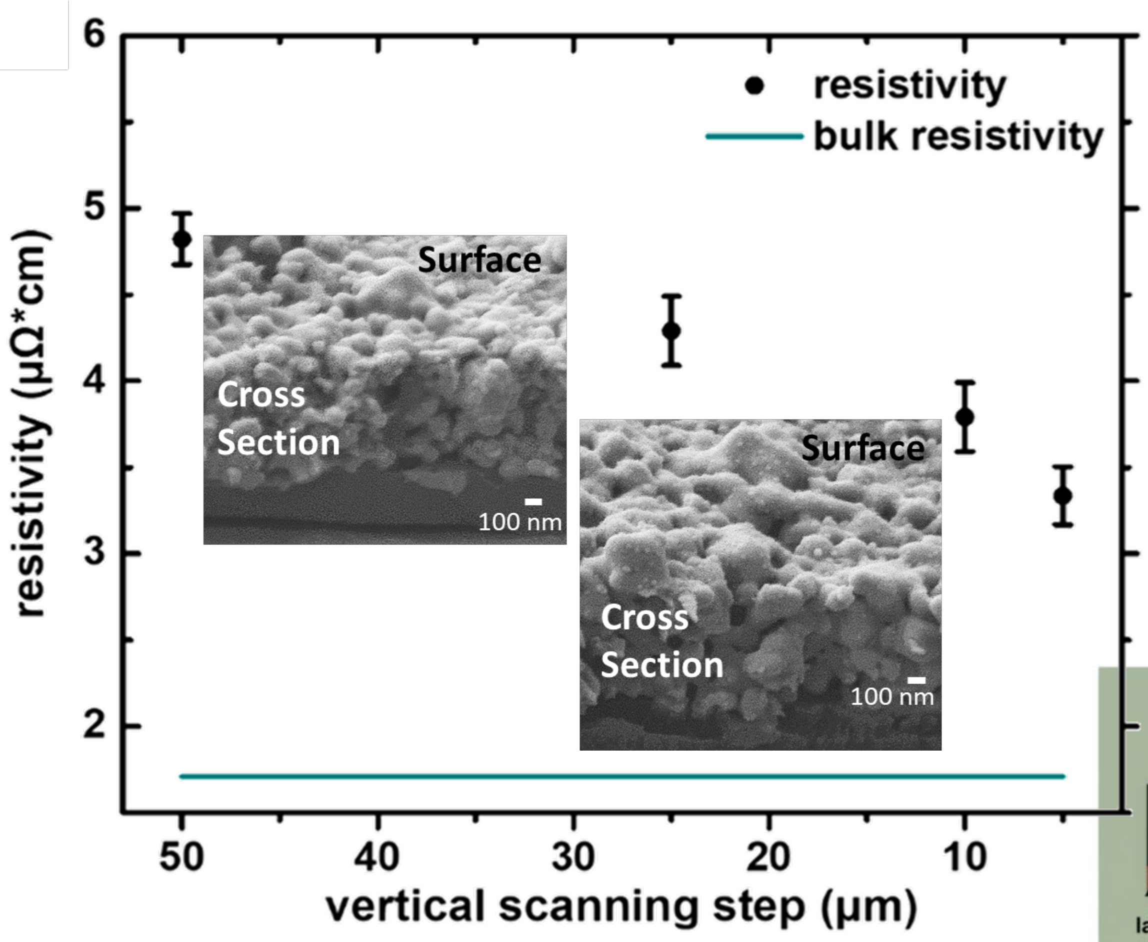


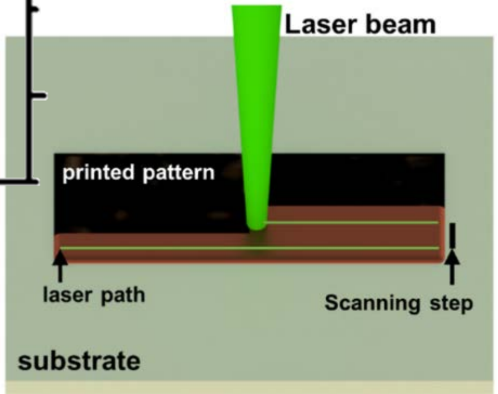
<u>Dimensions</u>
10x10 cm^2 RFID total area
Line width= 350 μm
Line height ~ 4.5 μm

The laser printing & sintering process window spans across a vast range of conditions yielding functional antennas

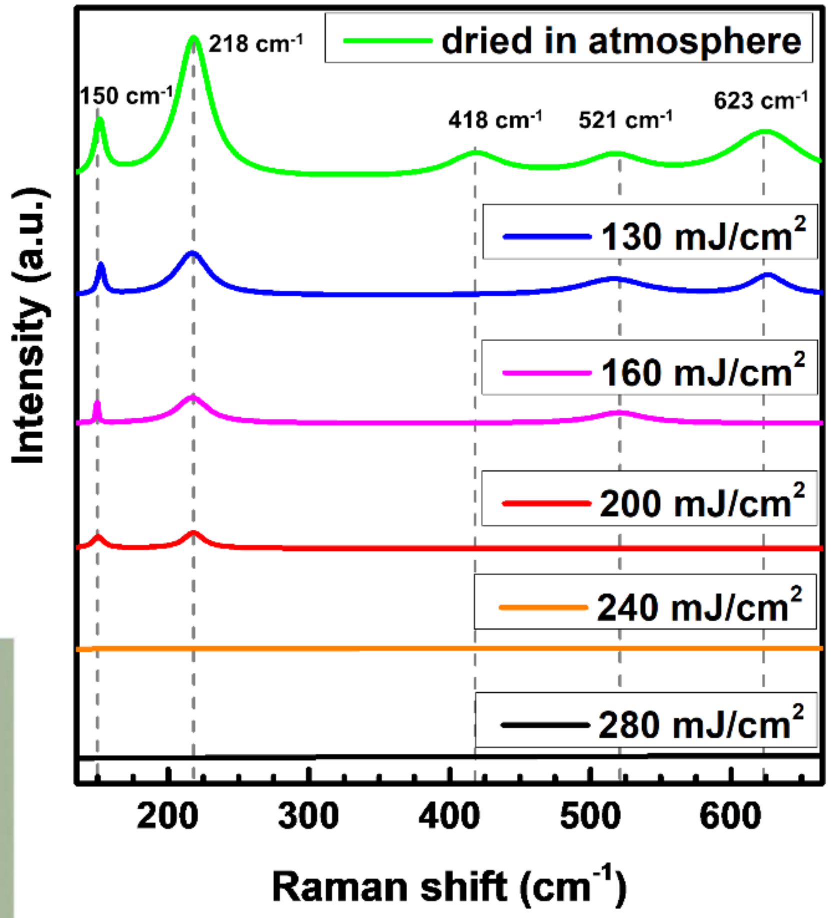
Laser printed & laser sintered Cu micro-electrodes

2x Bulk resistivity achieved





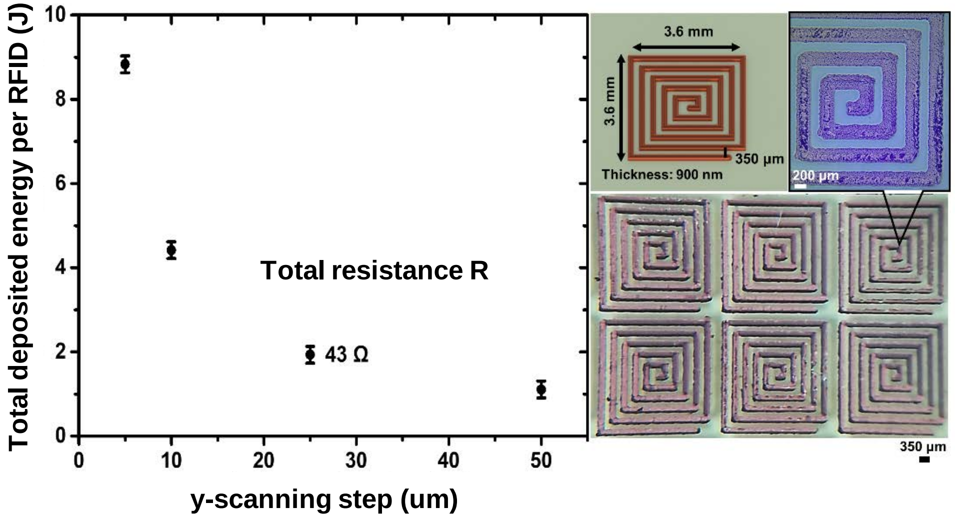
Raman study



150/218/418/521/623 cm^{-1}, Cu_2O peaks

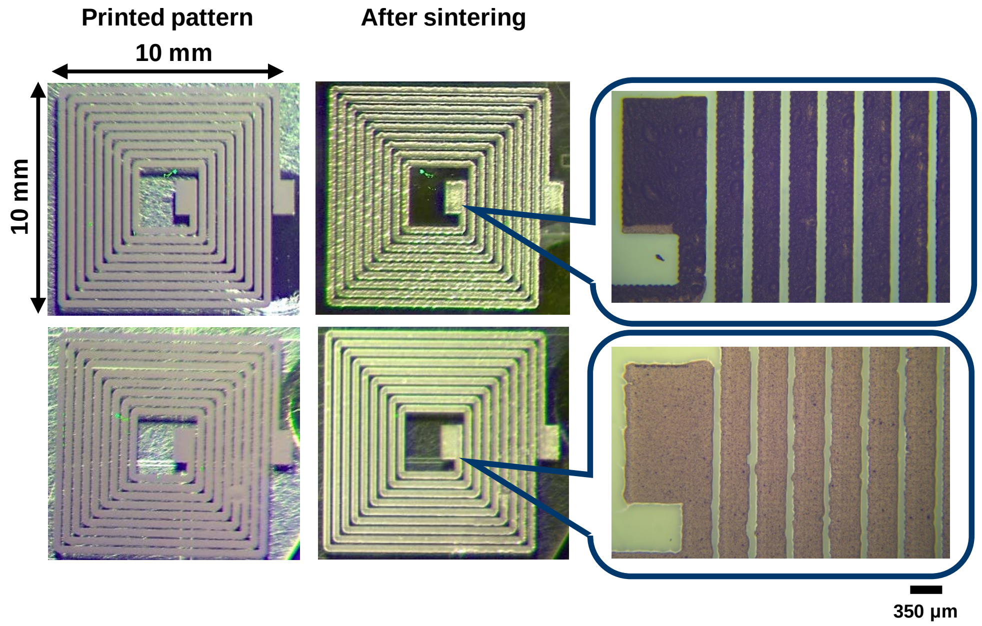
On-chip Cu antennas on flexible integrated circuits

Near Field RFID system



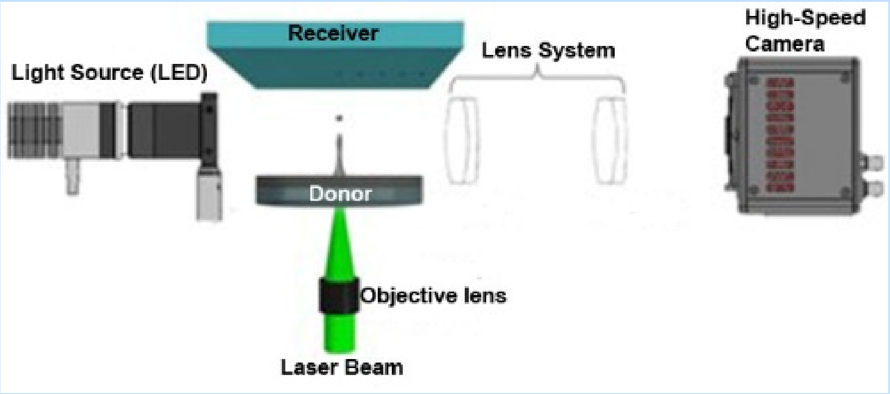
Cu patterns produced by laser printed and laser sintering are a low cost alternative to Ag patterns. The reported work demonstrates that in terms of resistivity, laser printed Cu patterns may be even superior to similar Ag patterns fabricated by laser processing.

RFID antennas design for HF band



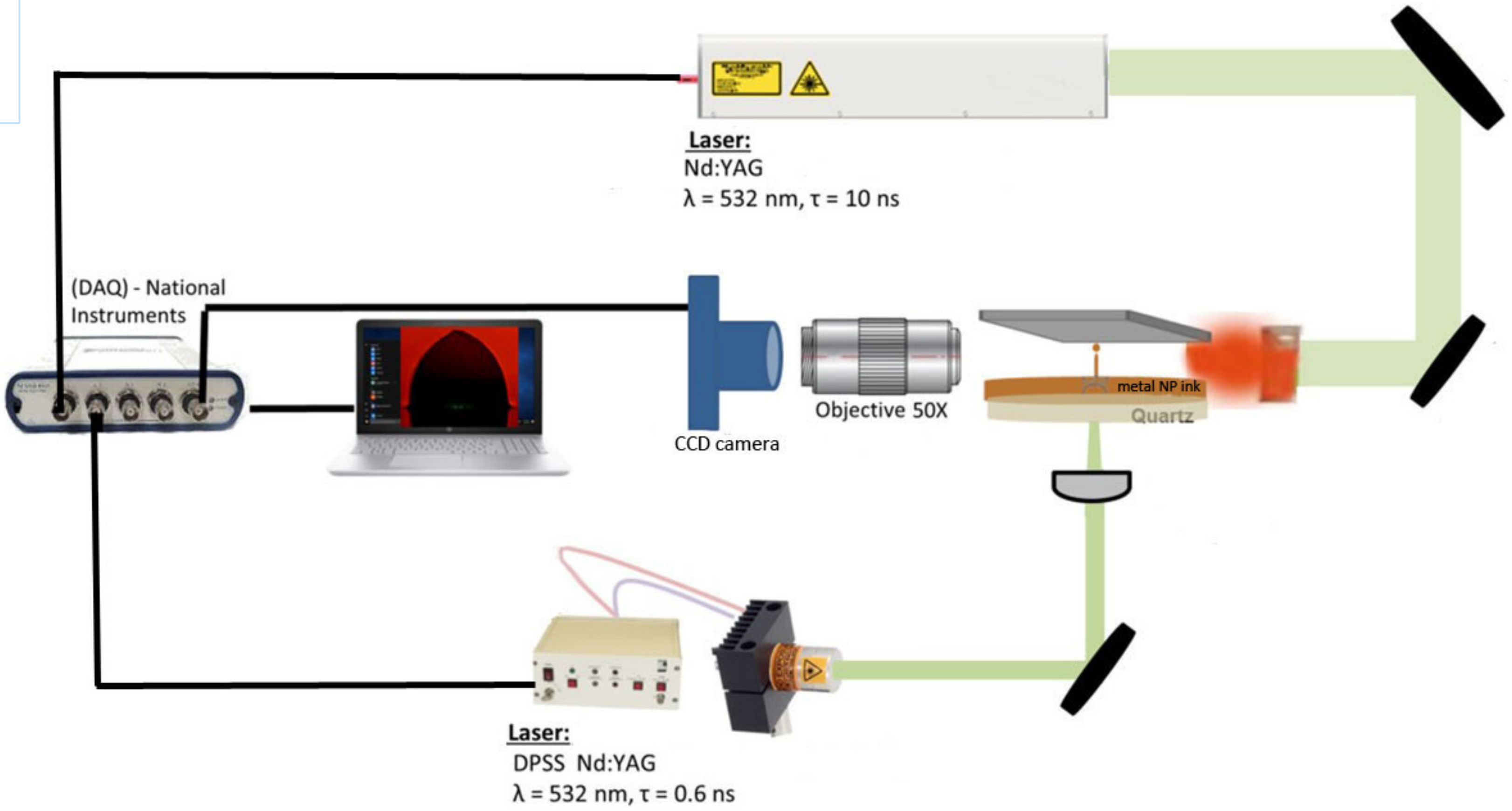
"Copper micro-electrode fabrication using laser printing and laser sintering processes for on-chip antennas on flexible integrated circuits", O. Koritsoglou et al., Optical Materials Express, **9**(7) 3046-3058 (2019).

TWO SETUPS - Time-resolved Imaging setup

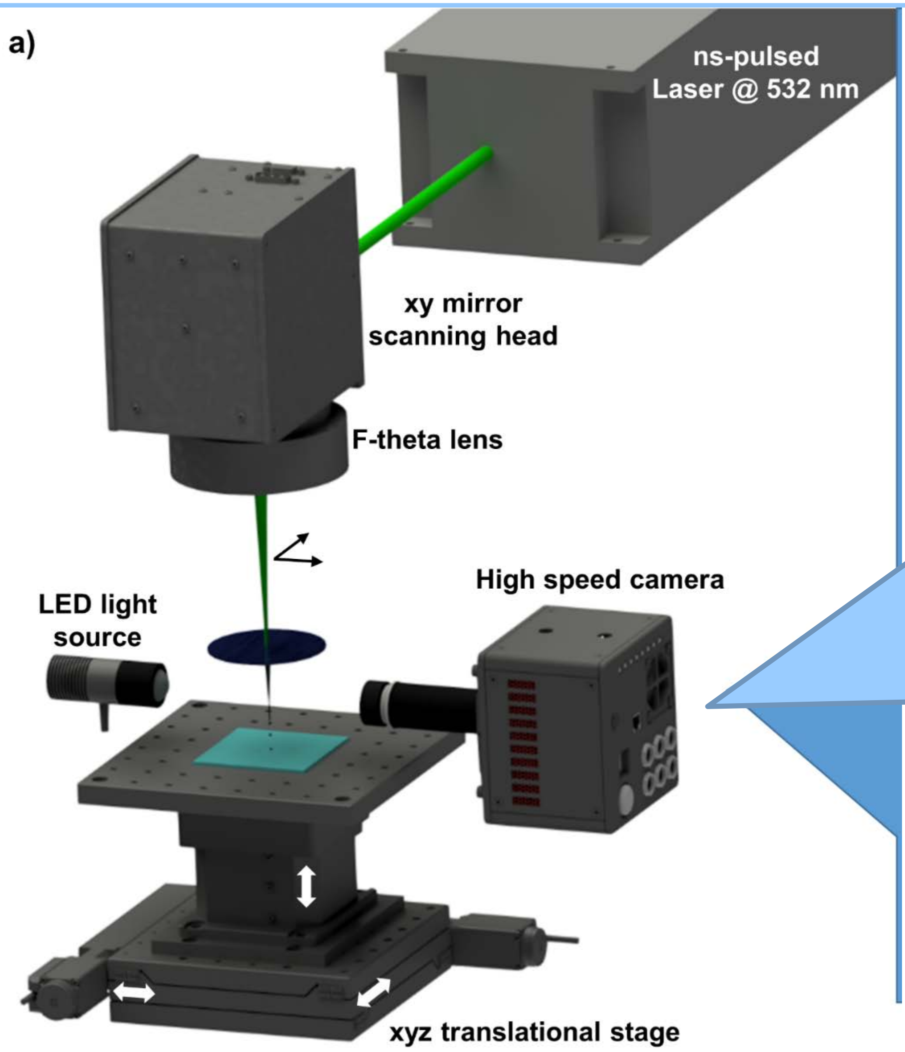


High speed visualisation 500kfs

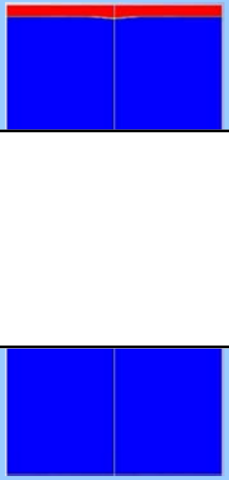
EARLY-STAGE (ns to μs)



Visualization using high speed camera

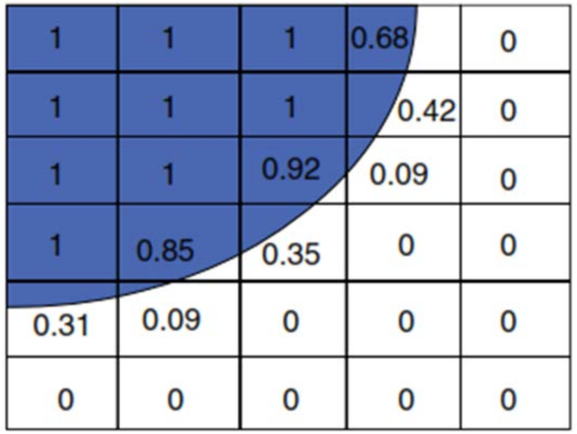


Viscosity @ 1 s^{-1} [cP]: 550 7400 170000



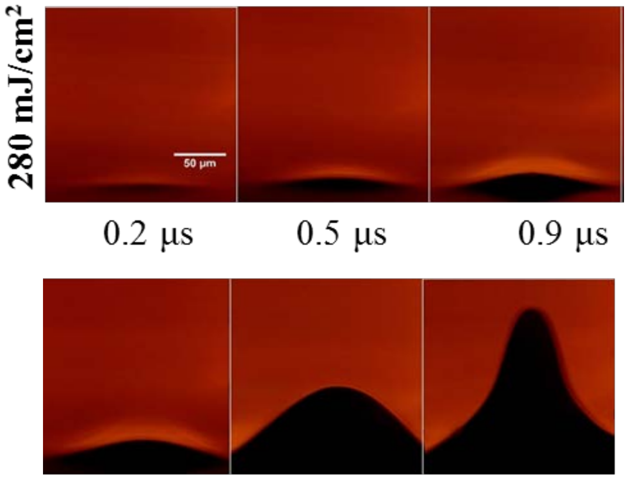
Simulation with ANSYS Fluent

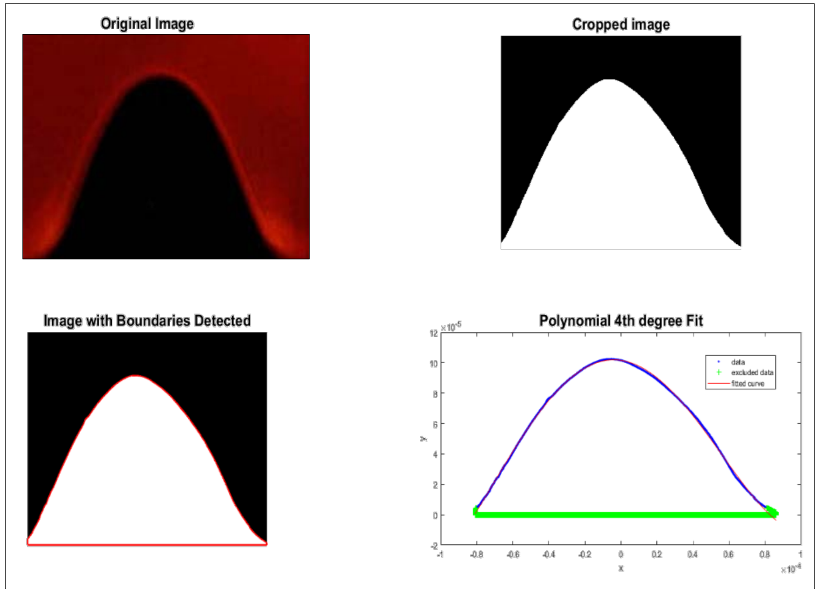
Simulation: Initialization & Methods



Example of VOF interface tracking

- 2-D Axisymmetric, transient model
- Volume of Fluid (VOF) model to track the ink-air interface
- Solving the Navier- Stokes equation for incompressible flow
- Simulating the laser pulse effect with a deforming boundary
- Deformation rate based on experimental time-resolved data (spatial and temporal evolution of ink bubble)





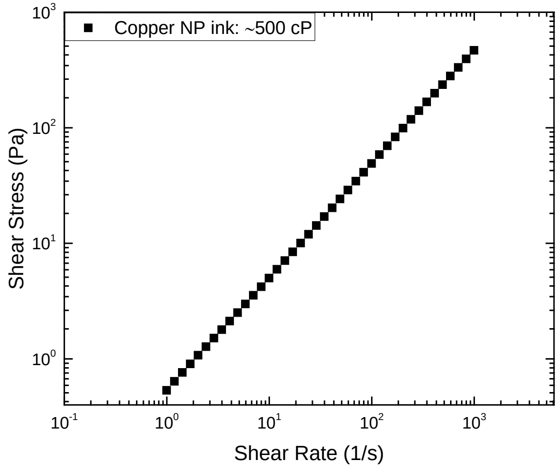
Detection and extraction of ink bubble's spatial profile.

Ag NP ink,

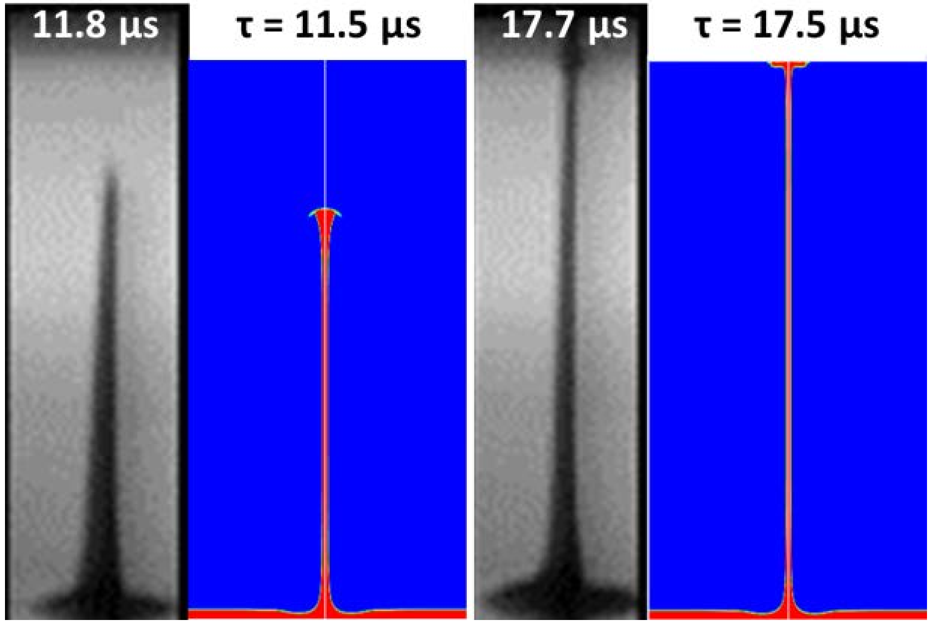
μ >50000 cP

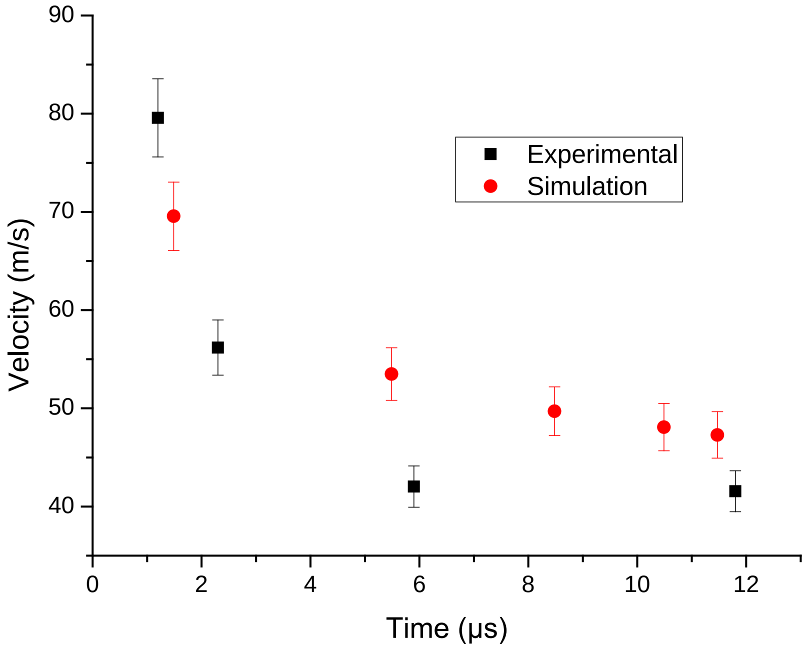
Newtonian ink: Correlation between simulation & experimental printing results

Newtonian fluids follow Newton's law of viscosity: $\tau = -\mu \frac{dv}{dy}$

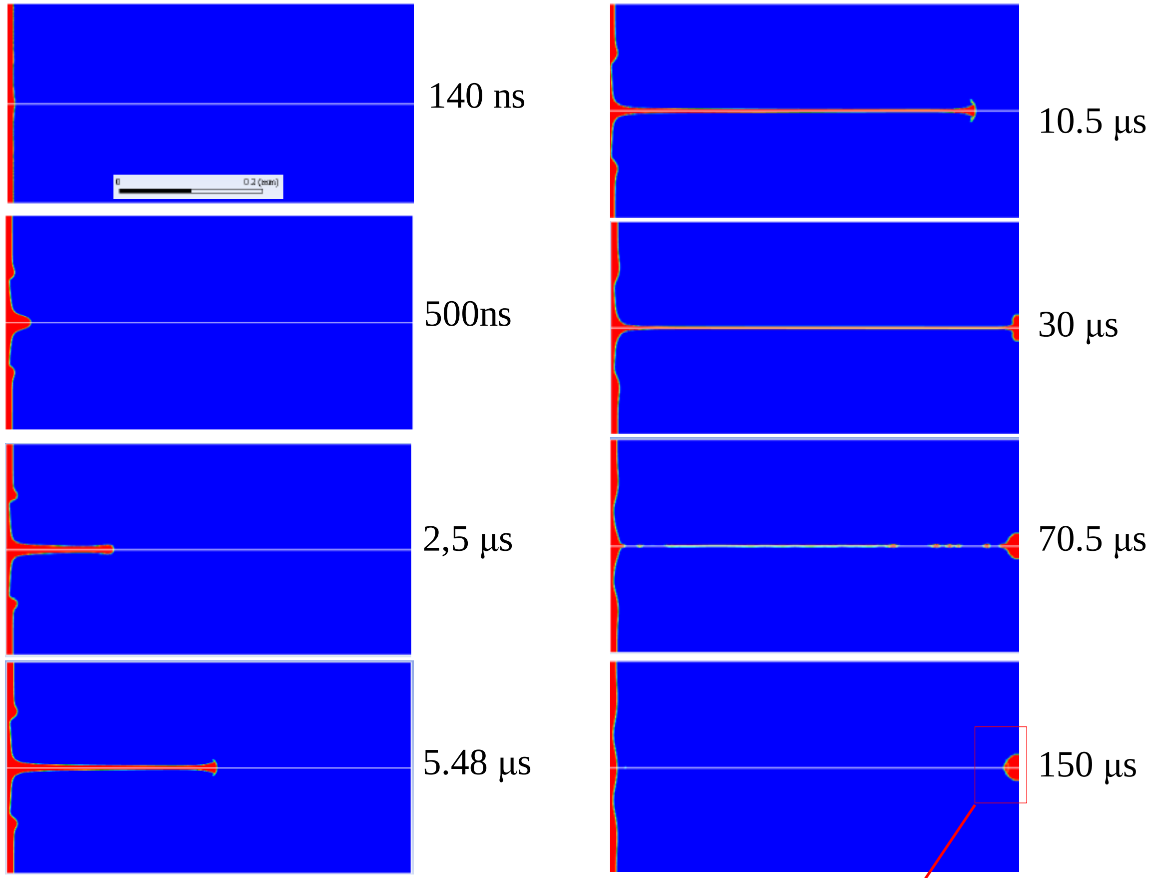


τ: shear stress, μ: viscosity of fluid,, dv/dy: shear rate (rate of strain)

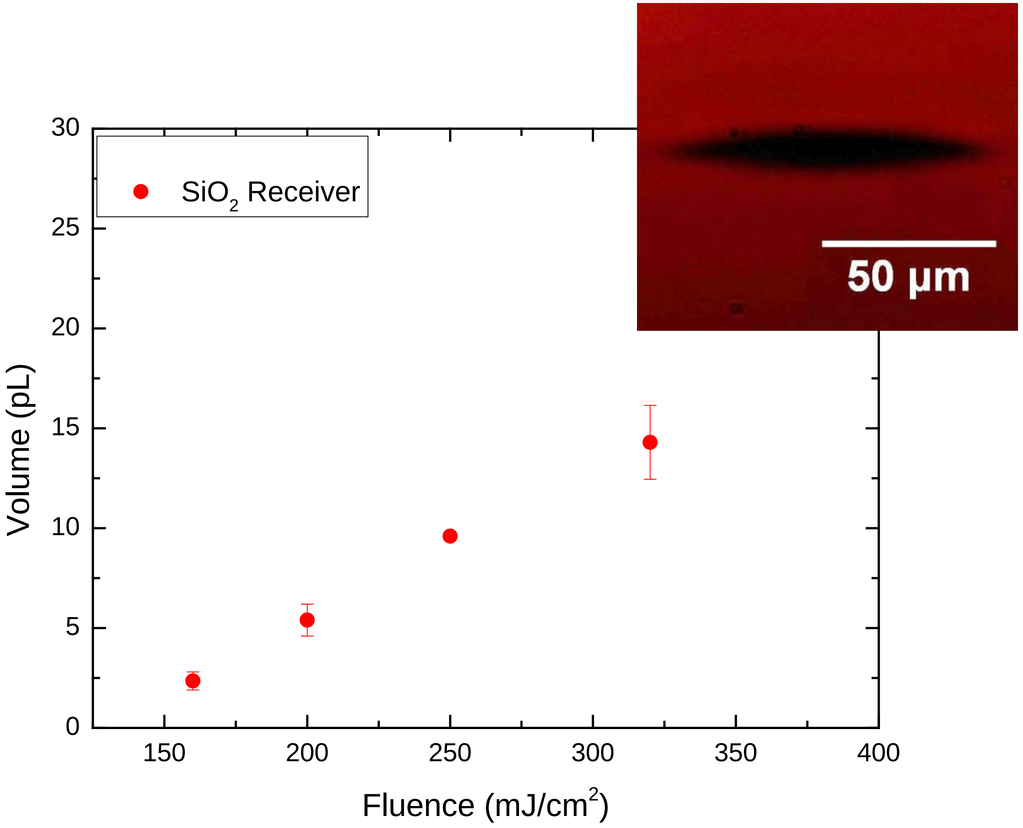




Newtonian ink: Correlation between simulation & experimental printing results



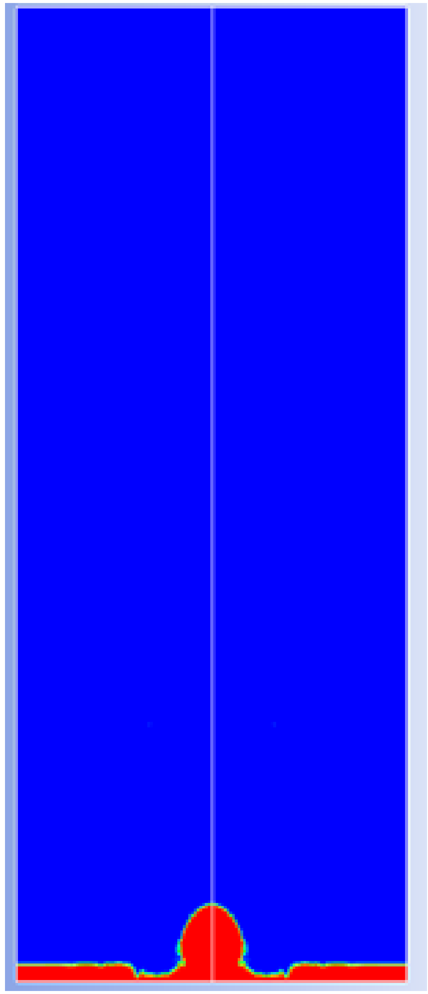
Droplet Volume ~14pL

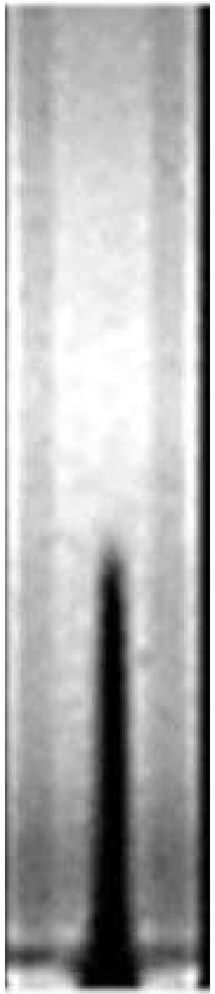


Simulation of non-Newtonian inks

If Non-Newtonian fluids are assumed to have constant viscosity during LIFT

Simulation not successful



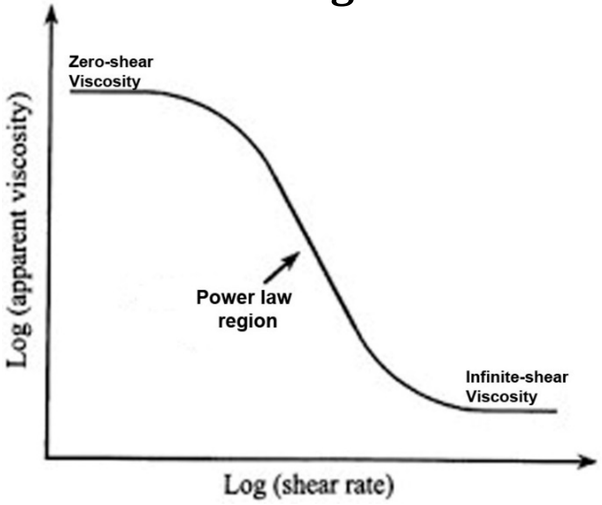


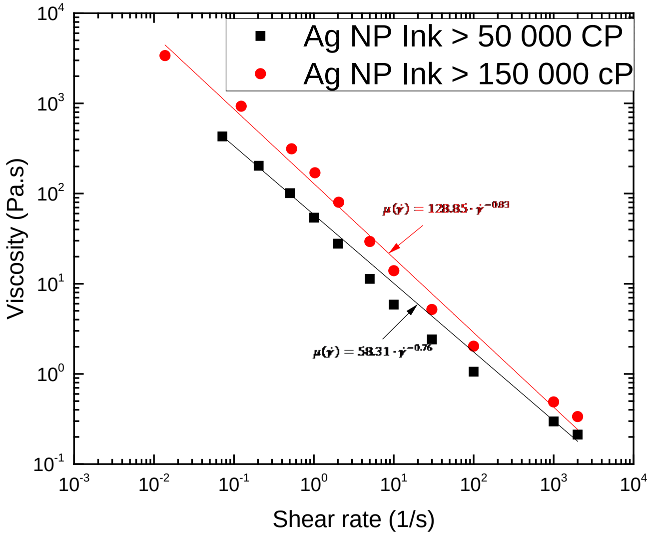
$\tau = 5\ \mu s$

Non-Newtonian fluids

Non-Newtonian (shear-thinning) behavior for our Ag NP inks exhibit

Shear Thinning Behavior





DURING LIFT

- **Negligible temperature effect**
- **High velocity gradients 10-100 m/s**
- **Result in high shear rates ~ 10^5 - 10^6 s^{-1}**

Viscosity dependent on shear rate:

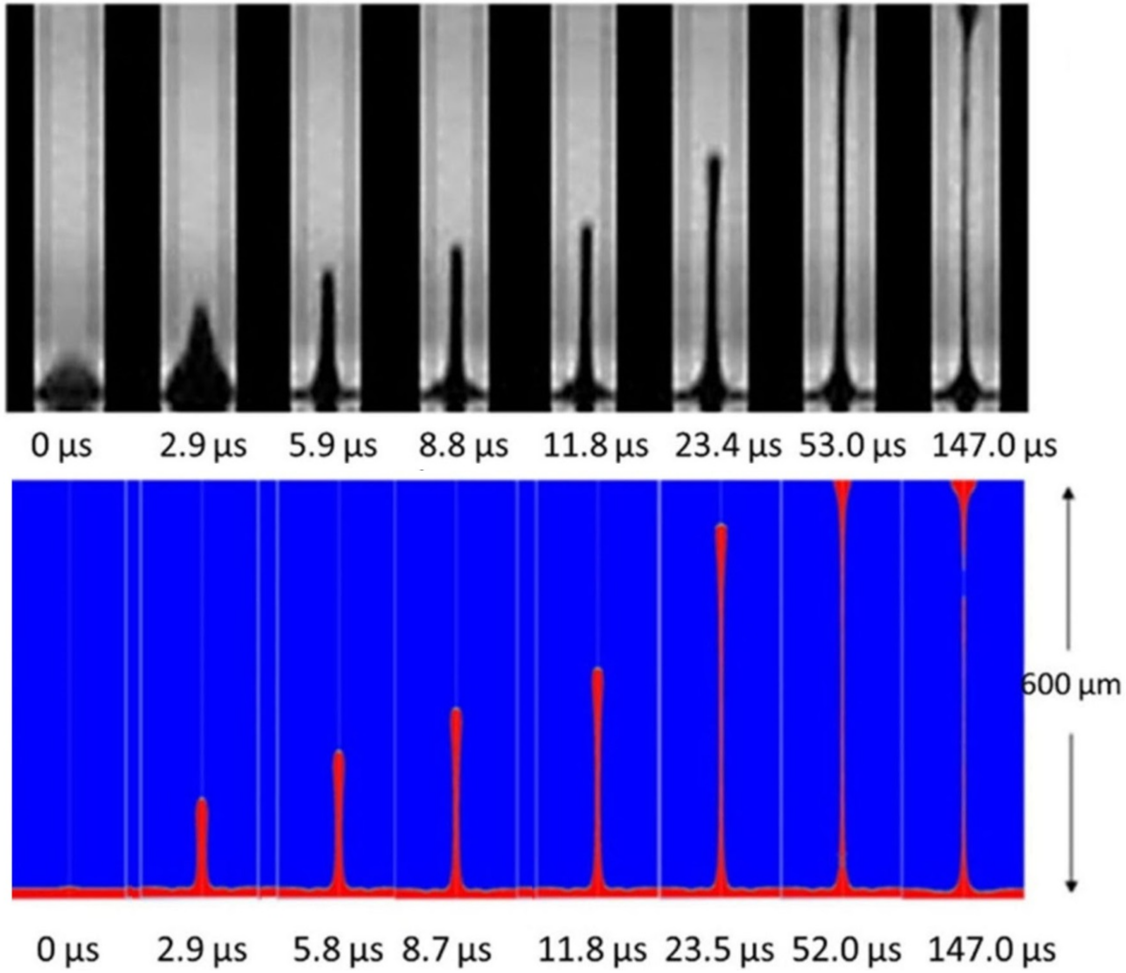
$$\mu(\dot{\gamma}) = \alpha * \dot{\gamma}^n,$$

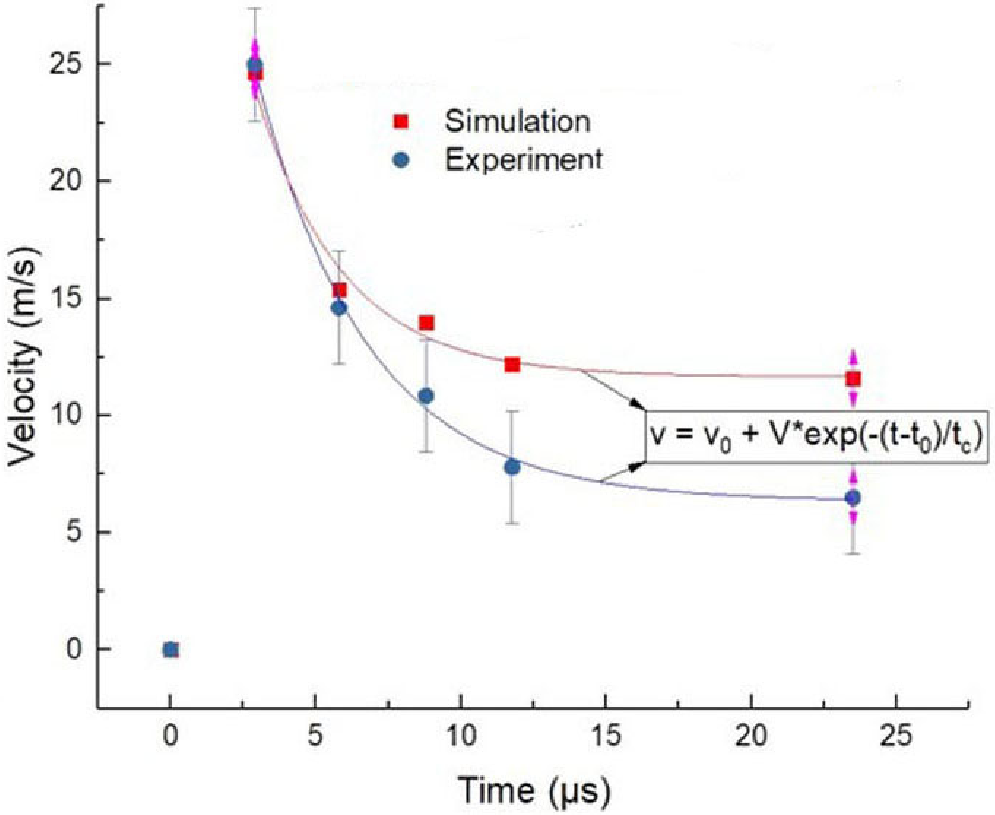
α: measure of the average viscosity,

$\dot{\gamma}$: shear rate, n: Power Law exponent

Non-Newtonian ink: Correlation between simulation & experimental results

Ag NP ink: >50000 cP





In Conclusion…

- High spatial resolution and high speed printing, potential for 3D processing
- Large area printing on flexible substrates
- DRL-free LIFT printing, employing inks of both Newtonian and non-Newtonian character
- Ejection mechanism for both type of inks: imaging with time-resolved and high-speed experiments.
- Building the simulation tool to predict printing quality.

Acknowledgments

Dimitra Tsakona, MSc
Elena Margariti, MSc
Kostas Andritsos, MSc
Mado Lofotheti, MSc
Marianna Trigazi, MSc
Maria Dimadi
Christina Kryou, PhD Student
Ioannis Theodorakos, PhD Student
Agamemnon Kalaitzis, Engineer
Olga Koritsoglou, MSc
Dimitra Mandala, MSc
Dr. Simos Papazoglou,
Dr. Marina Makrygianni
Dr. Filimon Zacharatos
Dr. Marianneza Chatzipetrou
Dr. Chrysa Chandrinou

Prof. A. Hatziapostolou
Prof. D. Tsoukalas

The HIPERLAM Project is an initiative of the Photonics and Factories of the Future Public Private Partnerships and received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 723879

*A. Kabla, S. Melamed, F. de la Vega, **PVNanocell***
*G. Arutinov, M. Giesbers, **TNO***
*S. Tuohy, D. Karnakis, **Oxford Lasers***
*P. Too, S. Norval, **FlexEnable***
*R. Price, B. Cobb, D. Kariyapperuma, **PragmatIC***
*A. Schwarzbaum, A. Melamed, **Orbotech***
*E. Trabut, A. Dron **MODUS Innovation***