Laser-induced forward transfer:

A novel laser-based deposition process for PCBs?

James Shaw-Stewart

PAUL SCHERRER INSTITUT

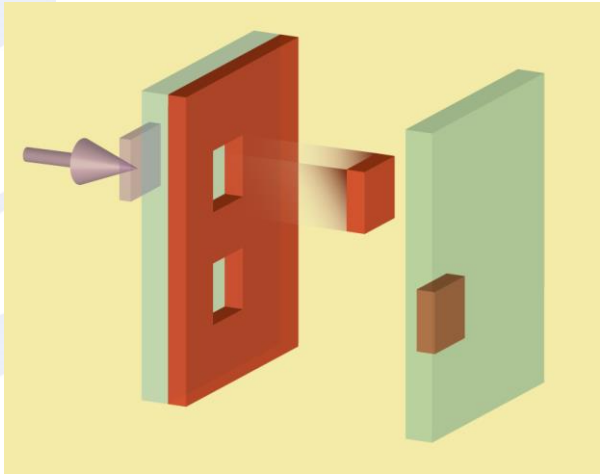
PSI

ETH zürich

EMPA

Materials Science & Technology

M-SOLV Limited



Coventry University

Laser-induced forward transfer:

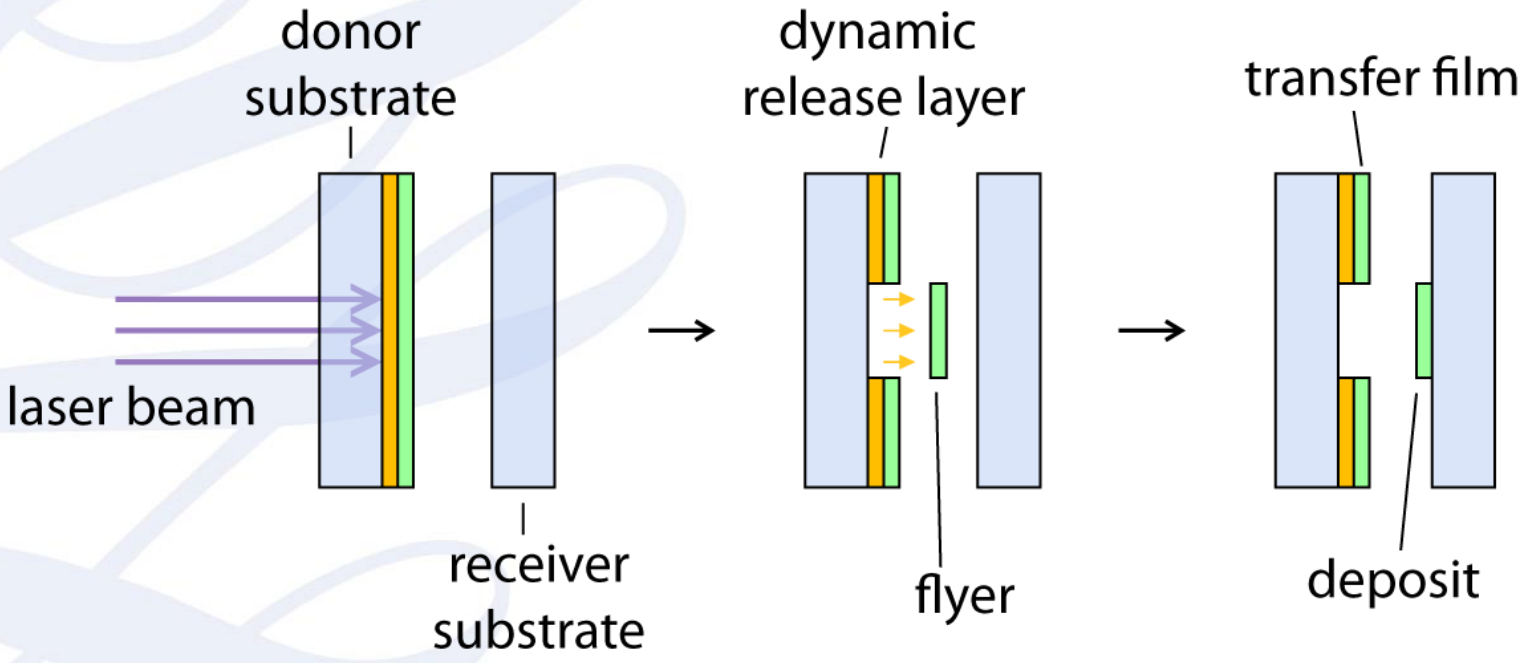
A novel laser-based deposition process for PCBs?

Content

- Introduction to the LIFT process
  - Solid LIFT
  - Liquid LIFT
- Examples of LIFT applications
  - Organic semiconductors (prior experience)
  - Biomaterials (cells)
  - Sensors
  - Capacitors
  - Flip-chip packaging
  - Metal interconnects
- Something a bit different
  - M-Solv's Scanned Mask Imaging (SMI) system

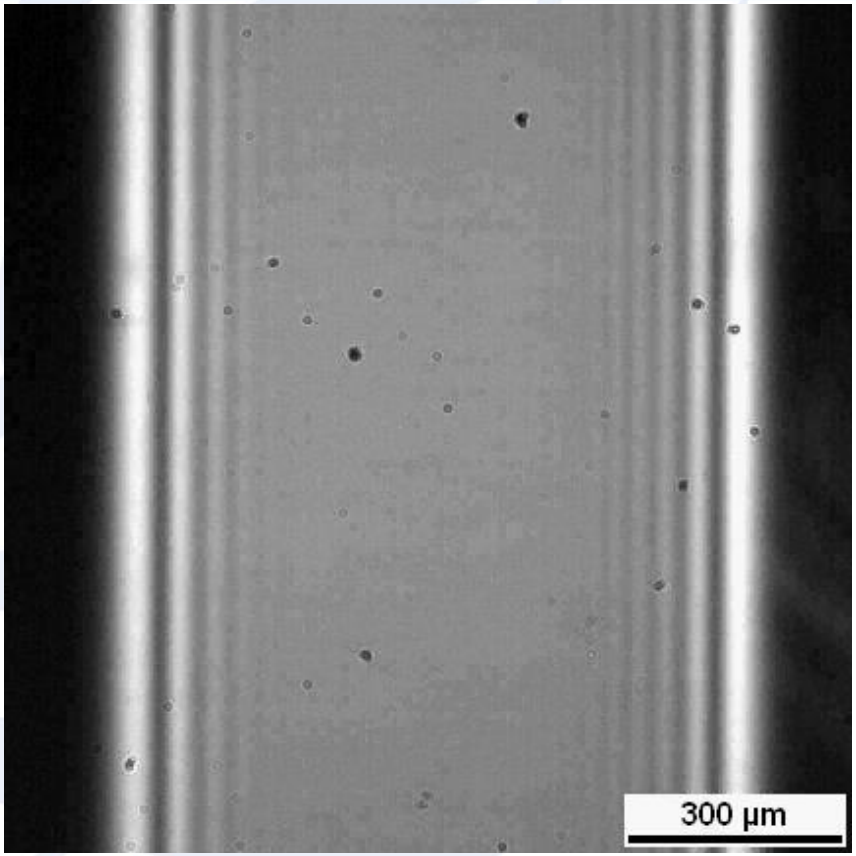
Laser-induced forward transfer

– A photosensitive layer which is sacrificially ablated by the laser beam, in order that the transfer material may be propelled forward as a **flyer**:

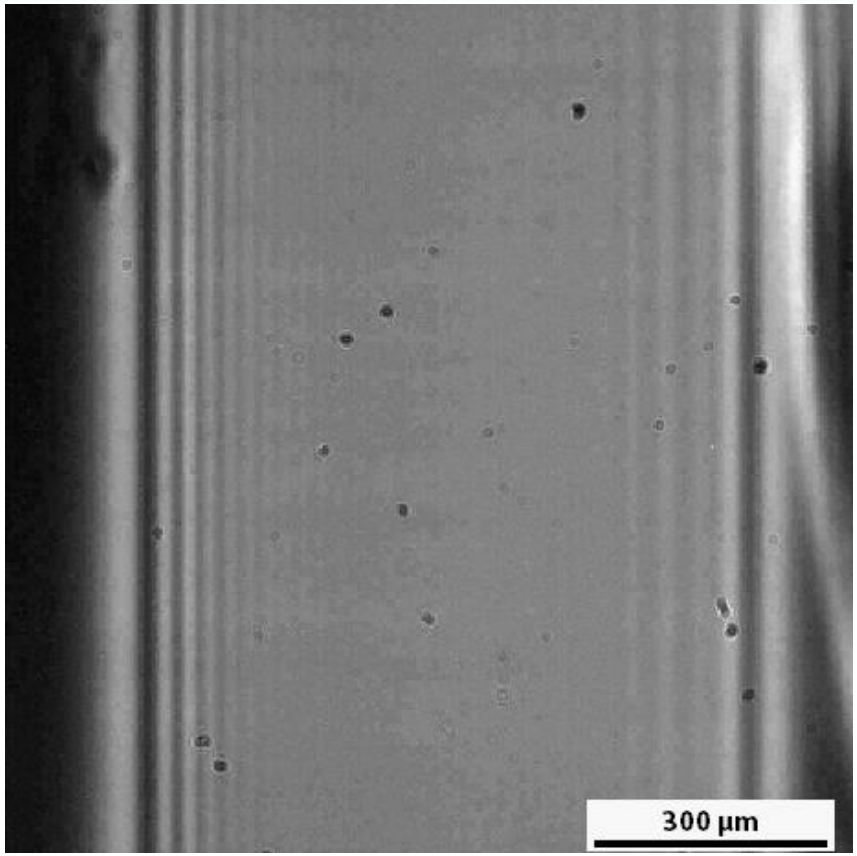


Early shadowgraphy experiments

At atmosphere



At low pressure



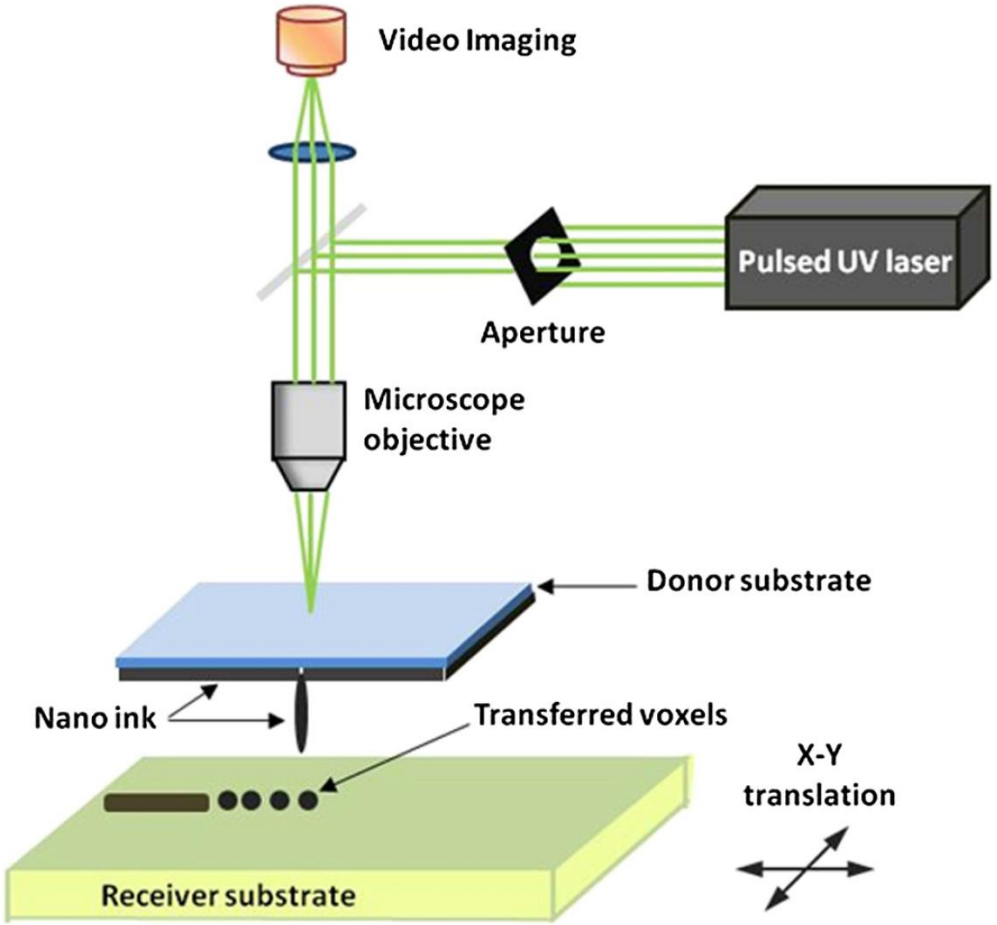
Φ = 270 mJ/cm^2

Fardel et al. 2010

350 nm triazene

80 nm aluminium

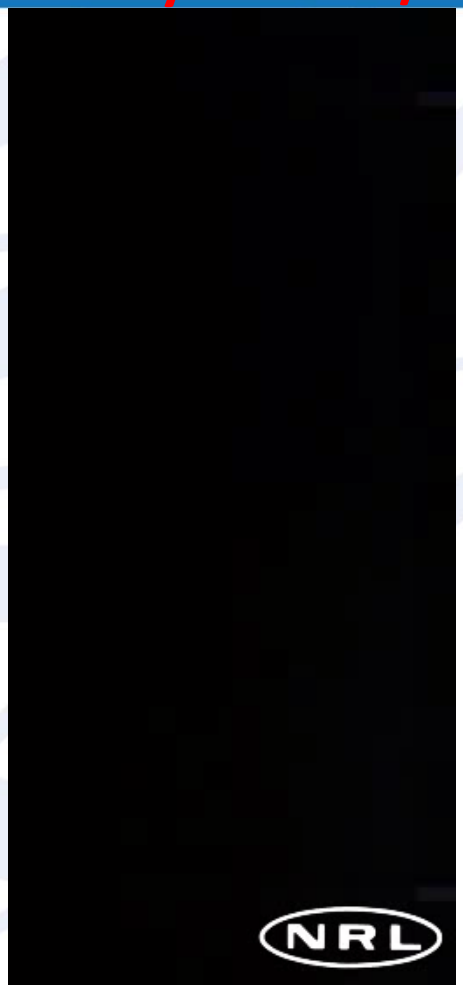
Liquid LIFT

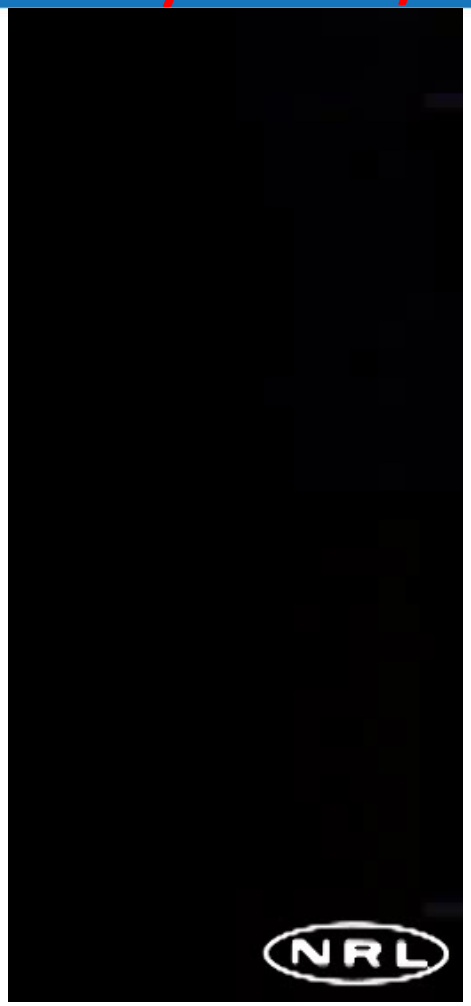


[Kim et al. 2014]

Liquid lift

Low viscosity – 78 mJ/cm² **High viscosity – 42 mJ/cm²**

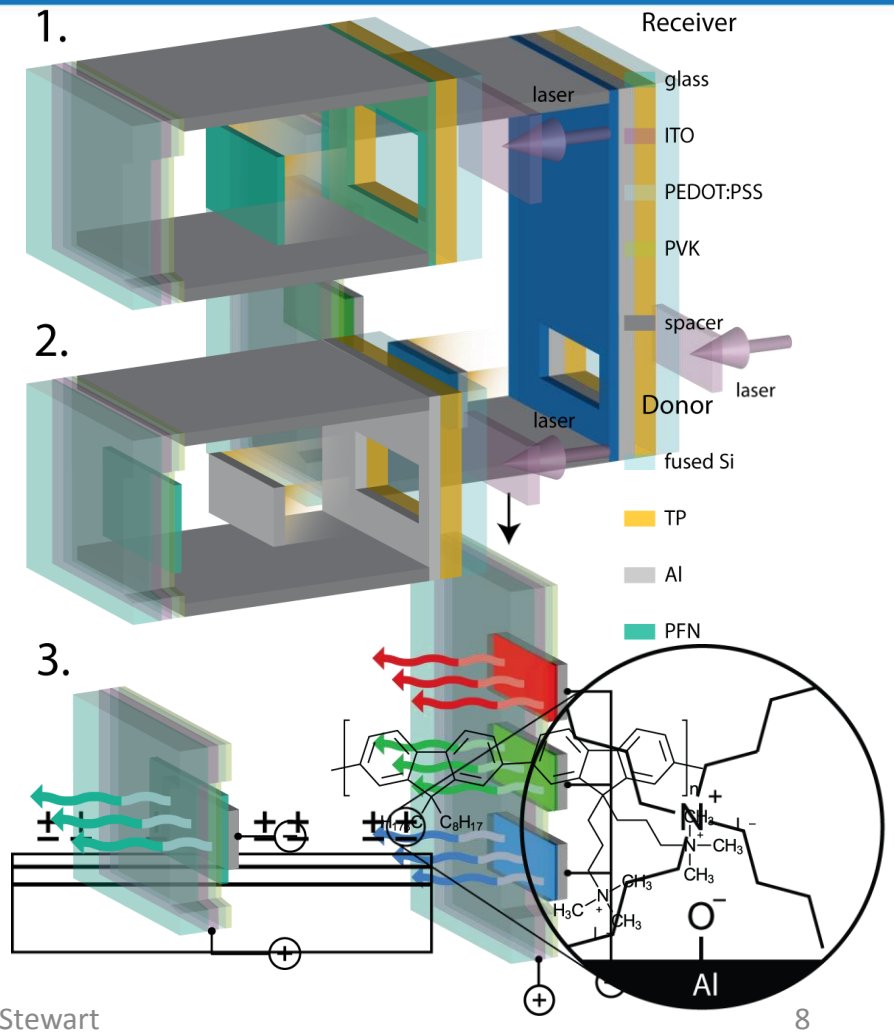




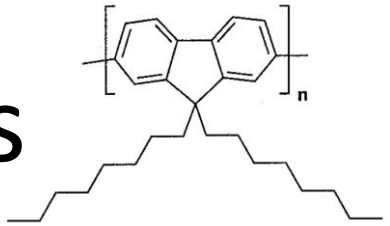
Mathews et al. 2013

OLEDs

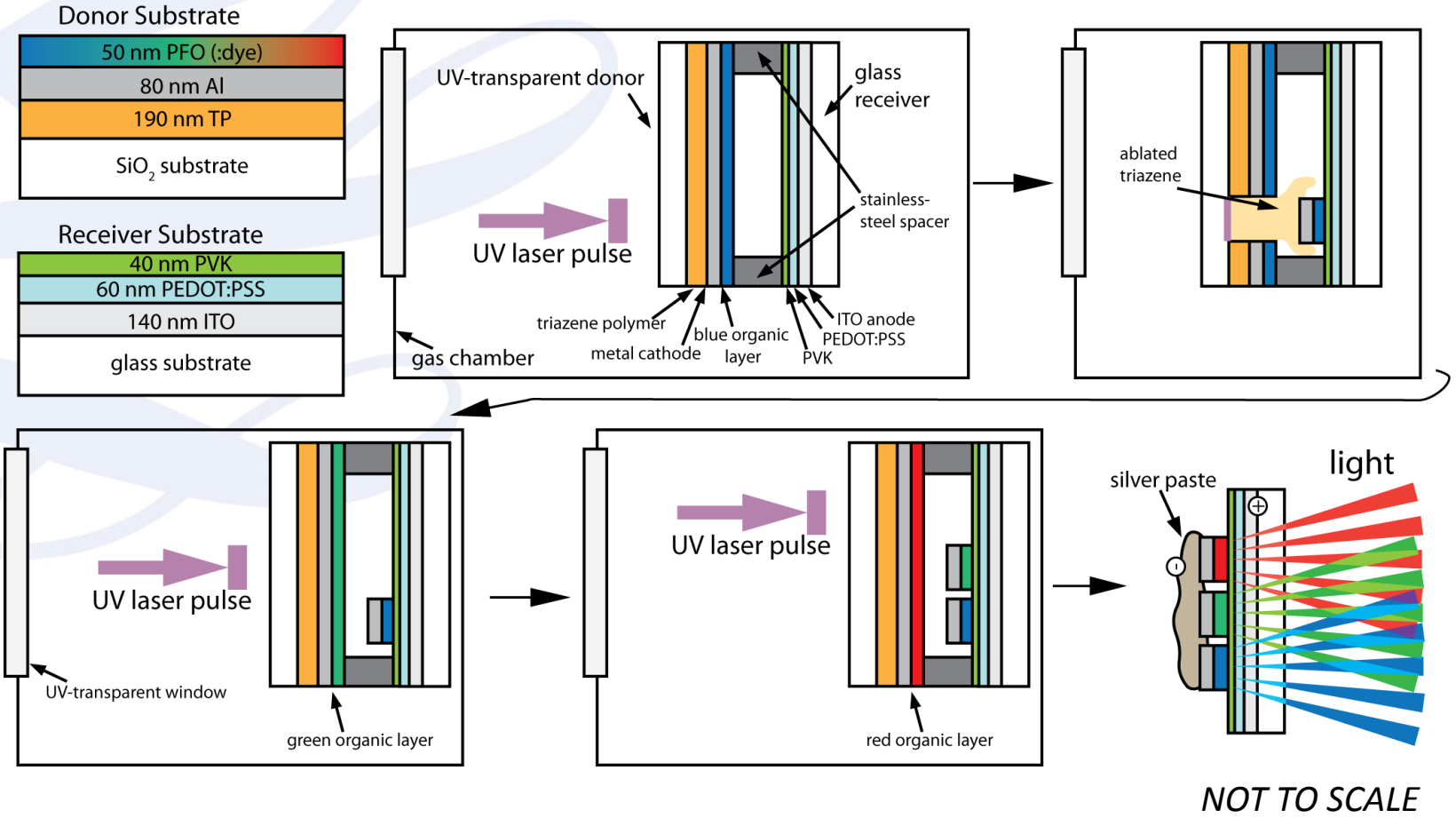
- Different types of OLEDs can be fabricated by LIFT:
  - PLEDs
  - PhOLEDs
  - SMOLEDs
- Charge injecting and transporting layers can be added to improve performance.
  - More flexibility is available in terms of surface modification.
- Sequential layer-by-layer deposition of a working PLED has been demonstrated.



Optimized PFO devices



[Shaw-Stewart et al. (2012)]

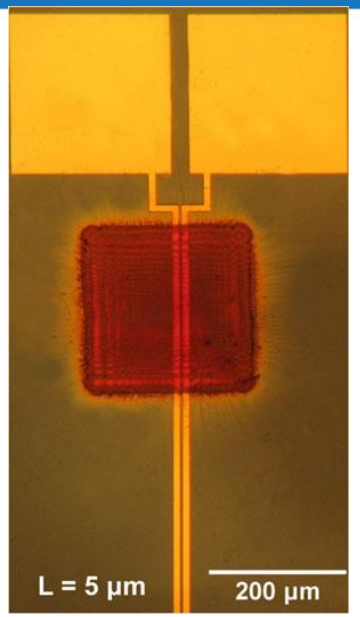


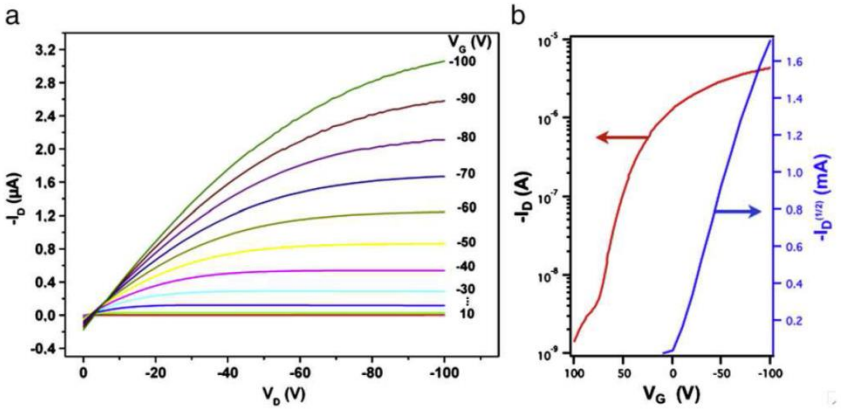
- All at 1 mbar, with 12 µm gap

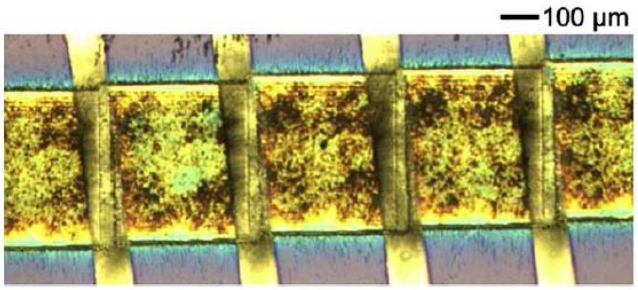
Thin film transistors

- Concurrently, as part of the e-LIFT FP7 project, a lot of work was carried out on the transfer of organic TFT materials

[Makrygianni et al. (2013)]

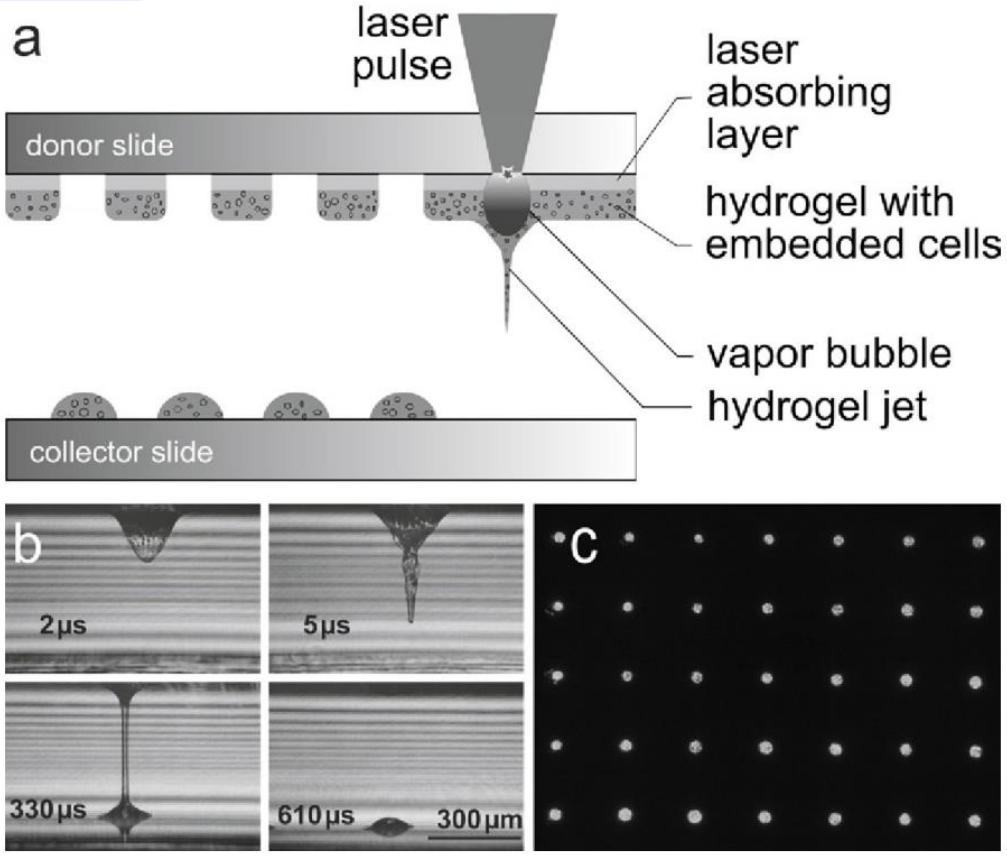






[Rapp et al. (2012)]

Biomaterials

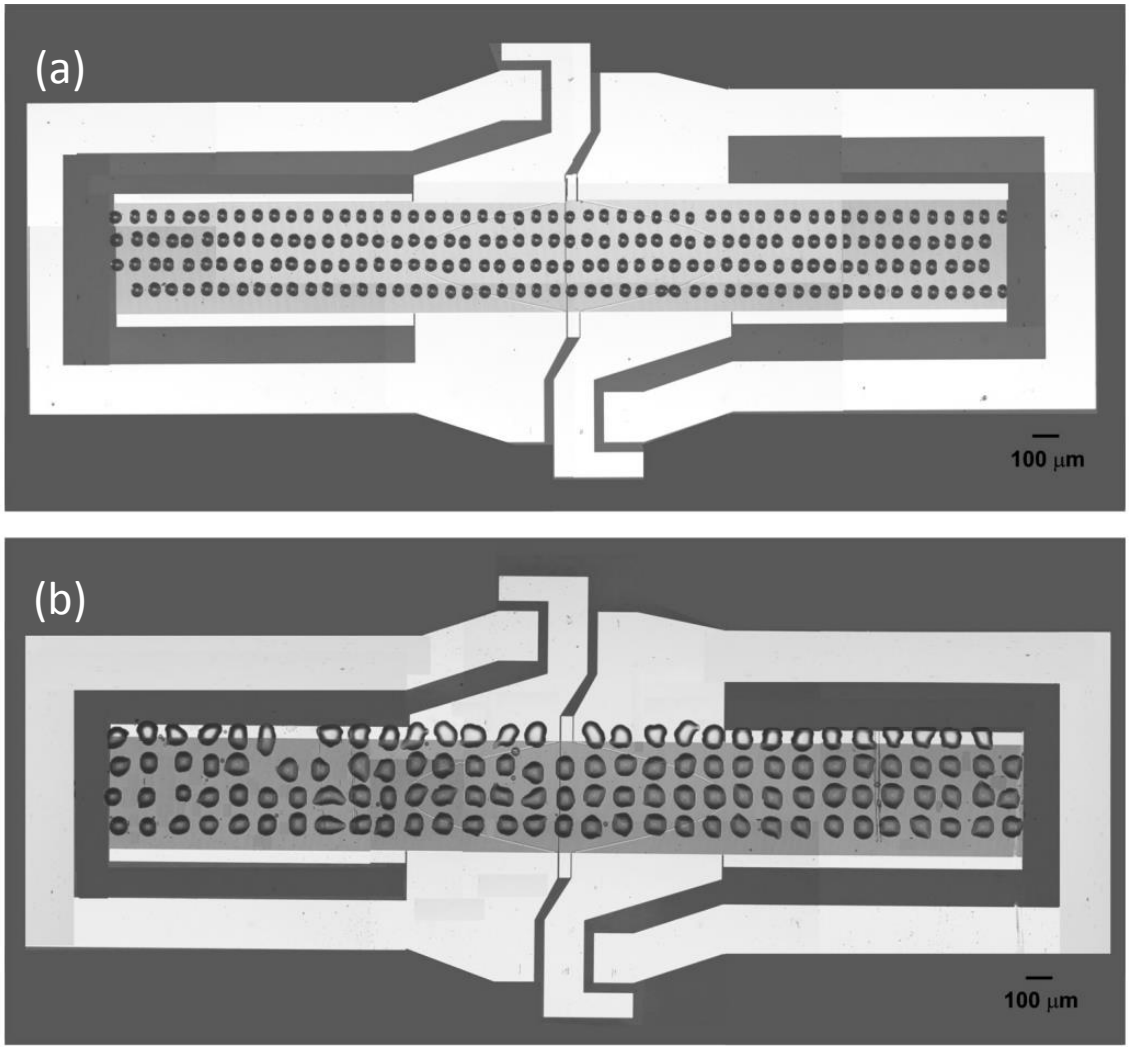


[Koch et al. 2015]

a) Schematic sketch of laser-assisted bioprinting (LaBP) setup
b) Shadowgrams of a hydrogel jet being deposited
c) Tightly controlled lateral positioning of the deposited droplets, of diameter 80 µm

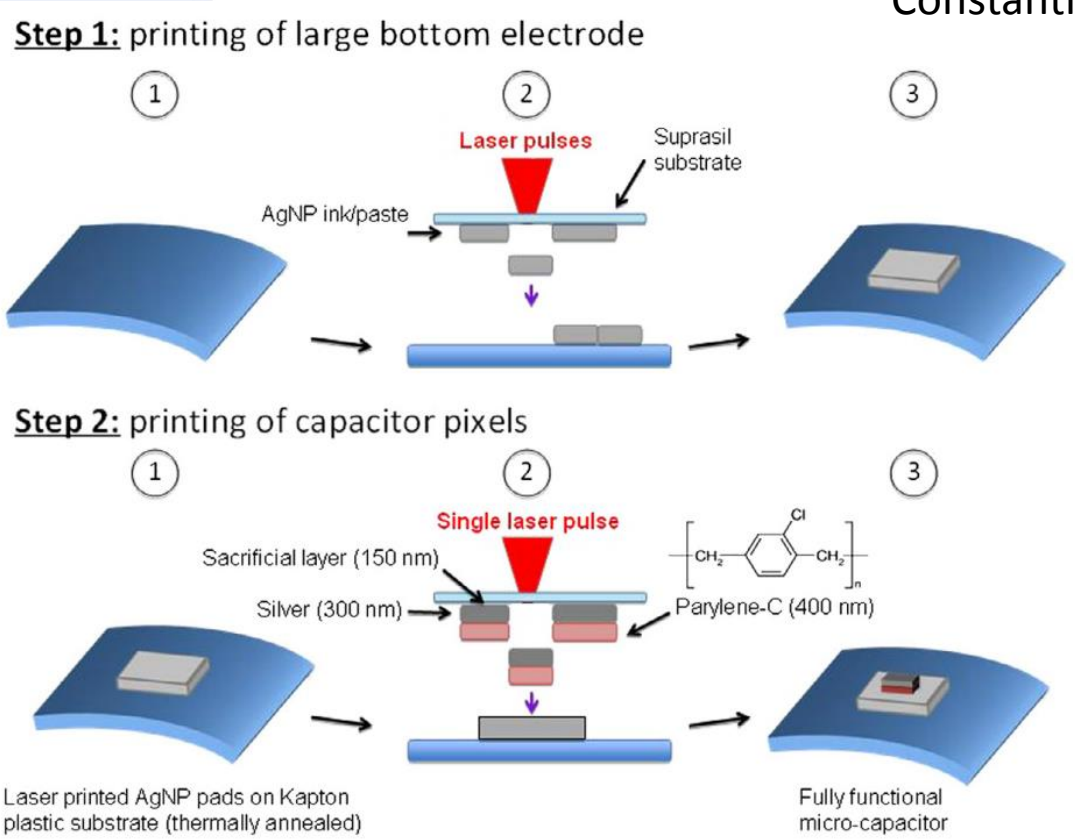
Sensors

- Fabrication of SAW odor sensors
- Active bovine odorant binding protein deposited from solutions with:
  a) 50% glycerol
  b) 20% glycerol



Capacitors

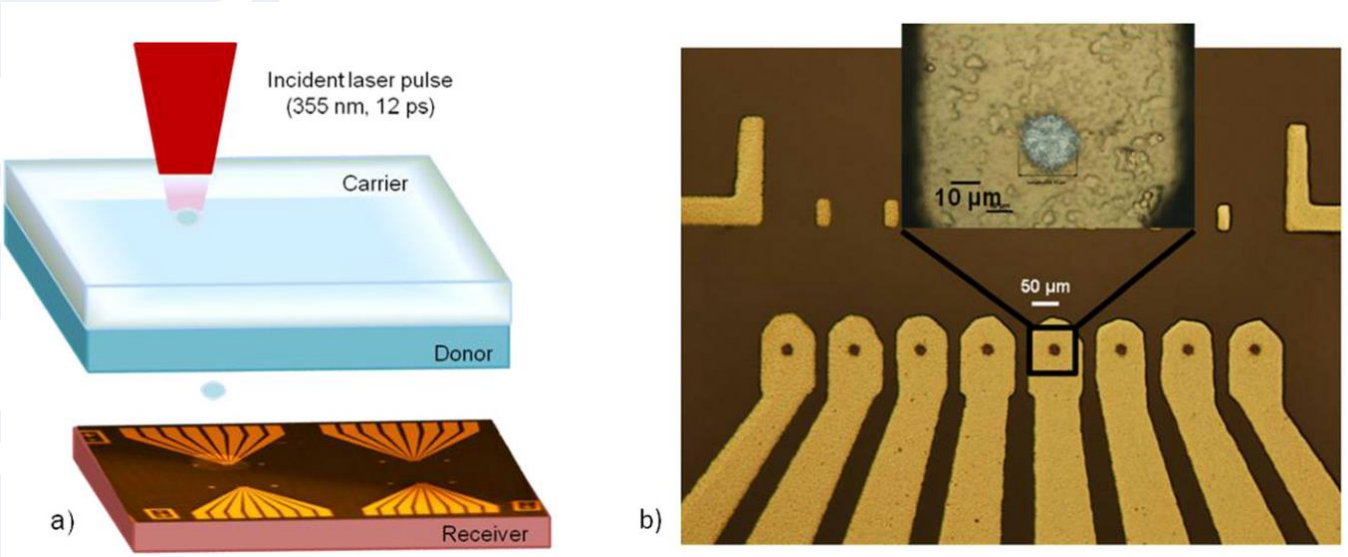
Constantinescu et al. 2015



- A hybrid process using both liquid and solid LIFT

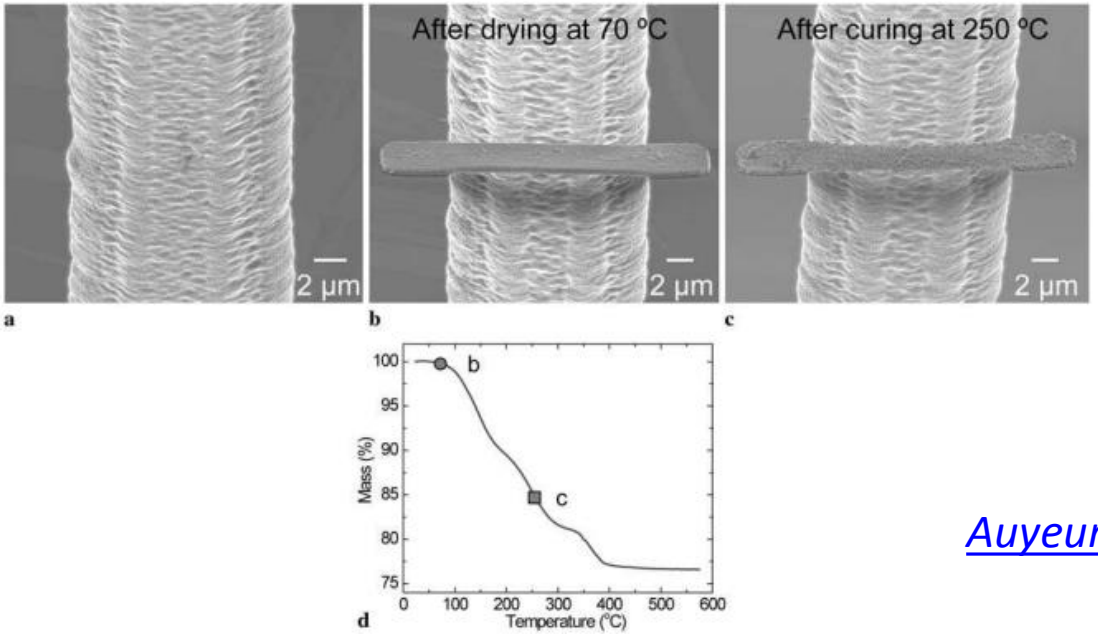
Flip-chip microbumps

[Kaur et al. 2014]



- LIFT of both pastes and solid metals have been used for the fabrication of microbumps
- The most successful process so far uses a solid indium precursor

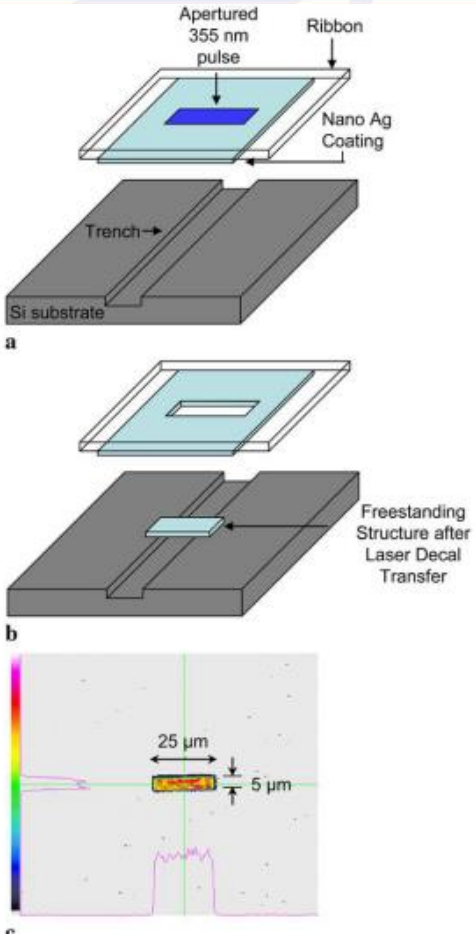
Laser printing of metals

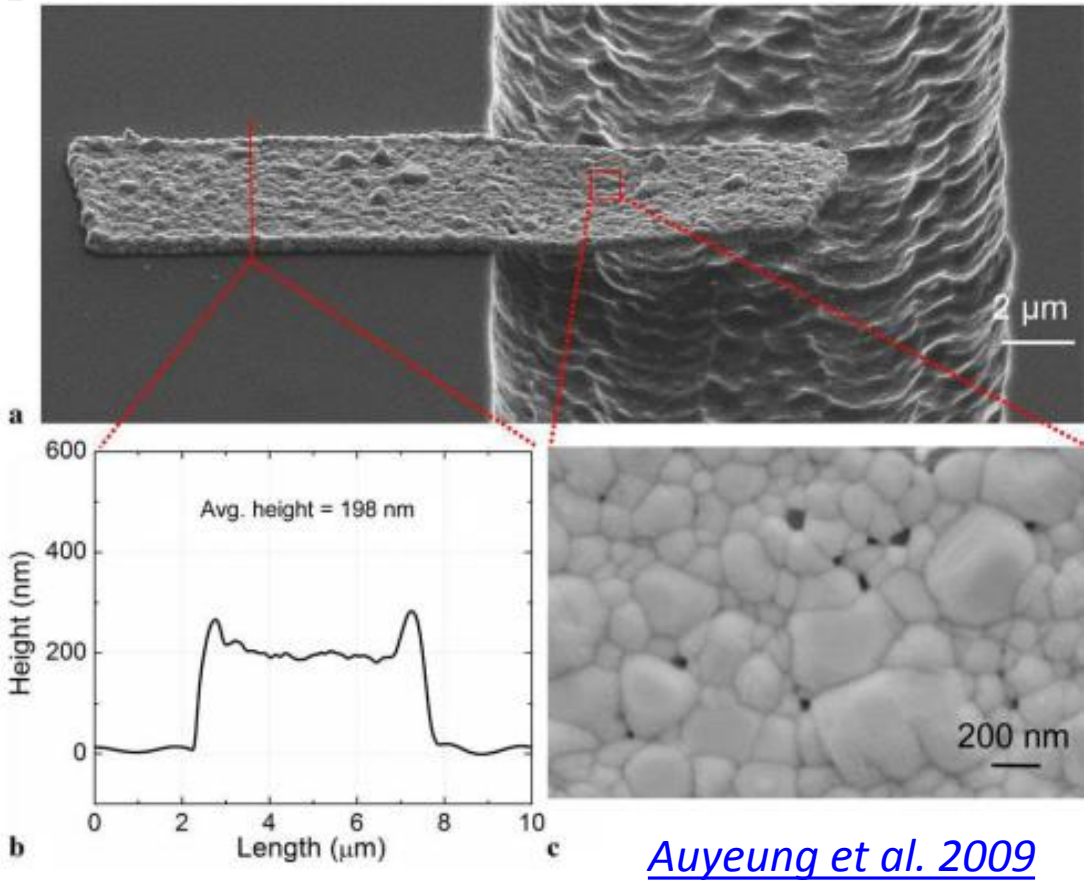


[Auyeung et al. 2009]

- A lot of the work has been pioneered by a group from the US, at the Naval Reserarch Laboratories
- They termed their process “laser decal transfer”

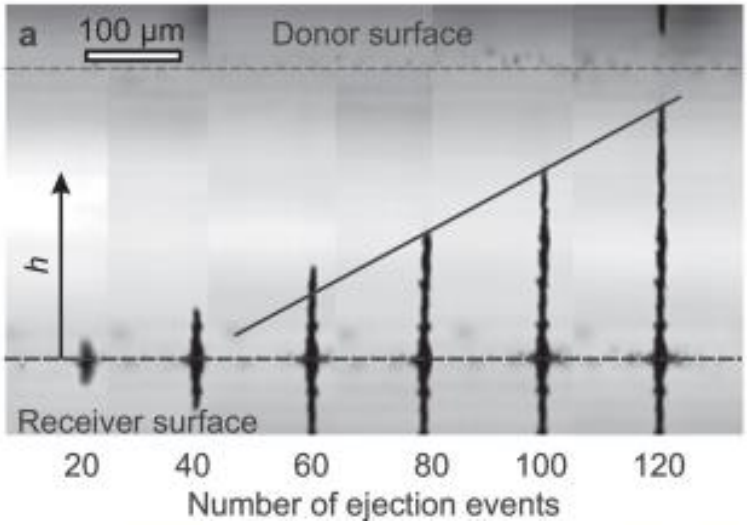
Laser decal transfer of microbridges and microcantilevers



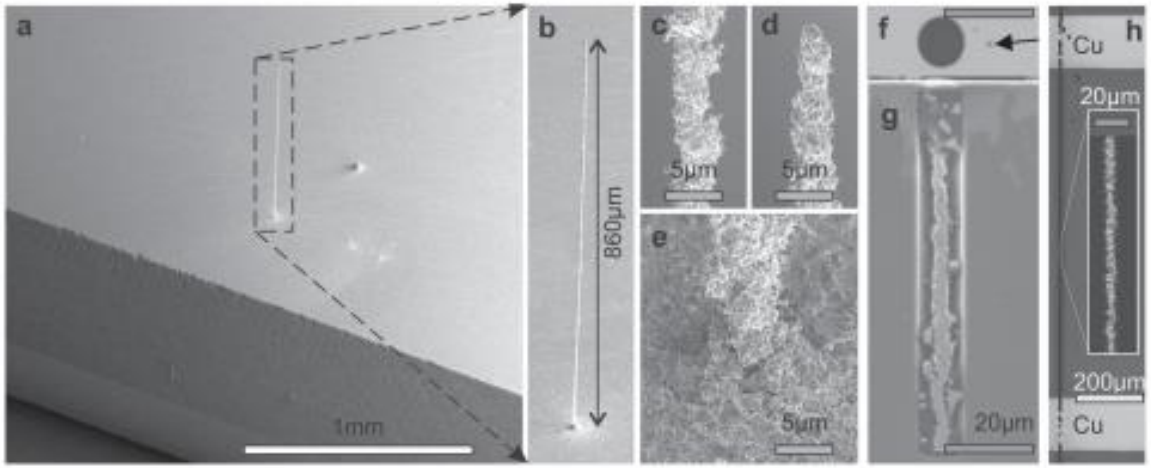


[Auyeung et al. 2009]

3D deposition of metal



[Visser et al. 2015]

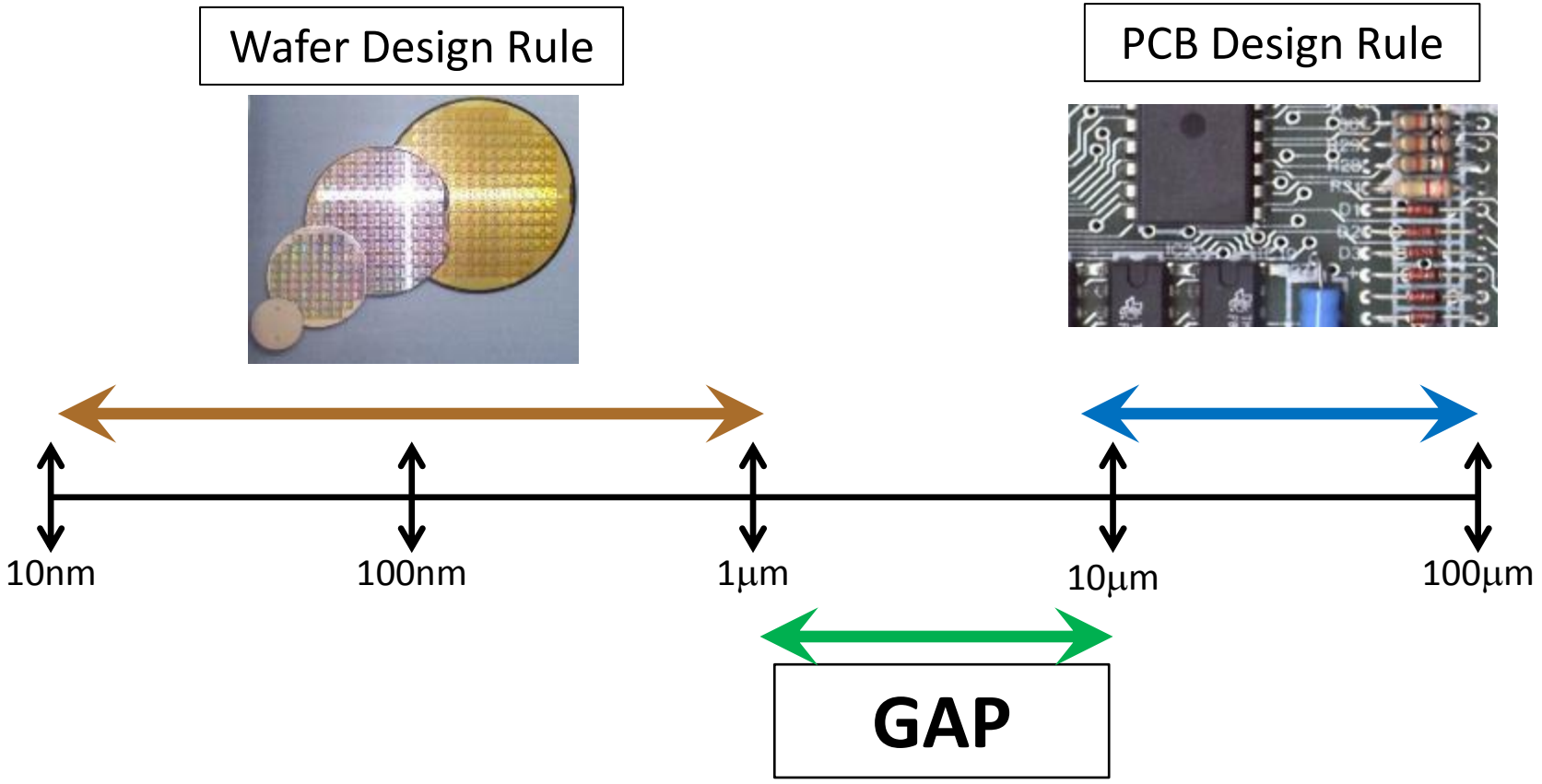


With even more work on the nature of deposition from varying all the available parameters, extreme aspect-ratio Cu structures have been deposited from a solid copper donor

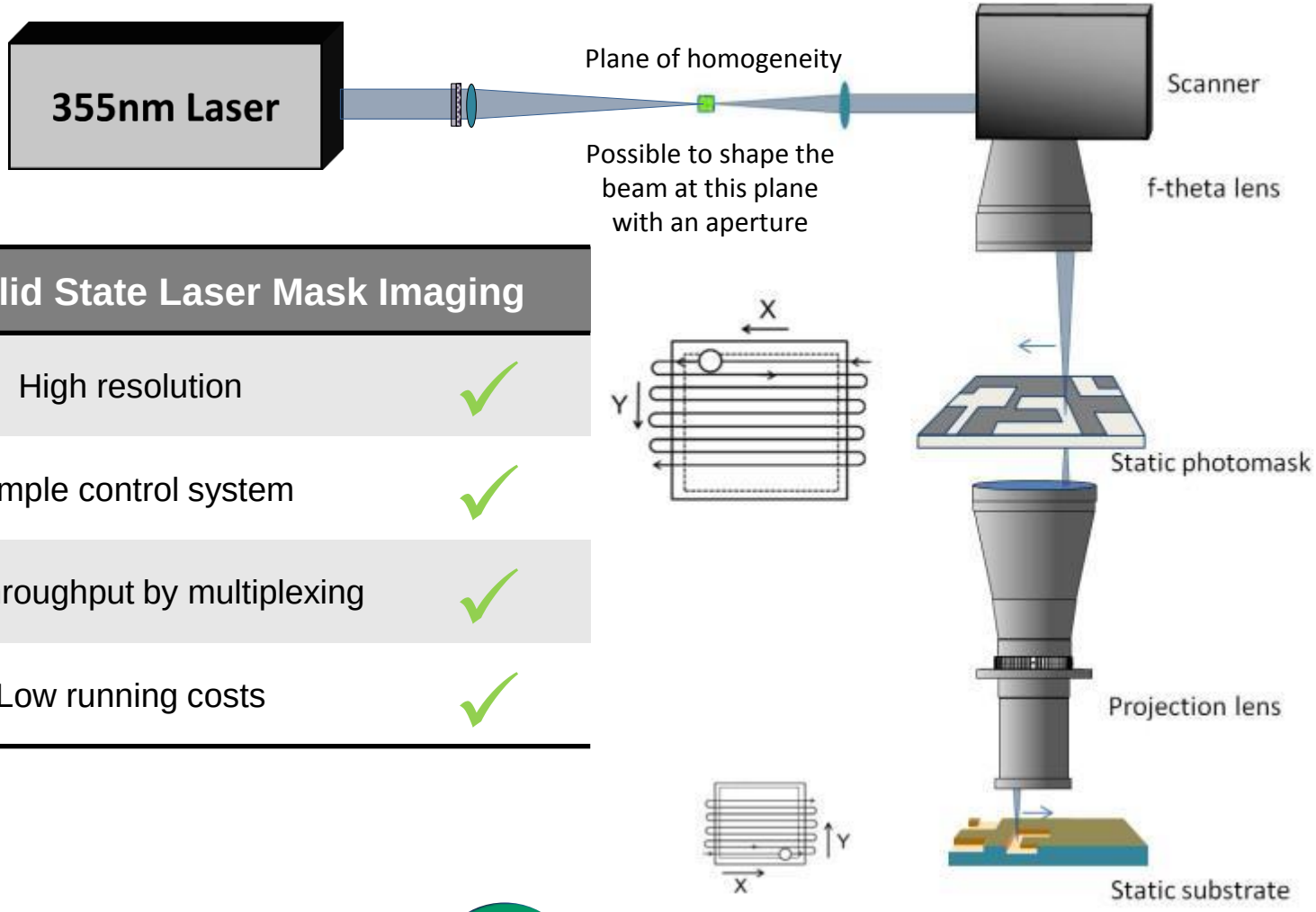
Something a bit different…

- Scanned mask imaging (SMI)
- David Myles at M-Solv has developed this novel technique for laser imaging
- Cost effective solid-state lasers, with excimer-style beam uniformity…

Advanced Packaging Technology Gap

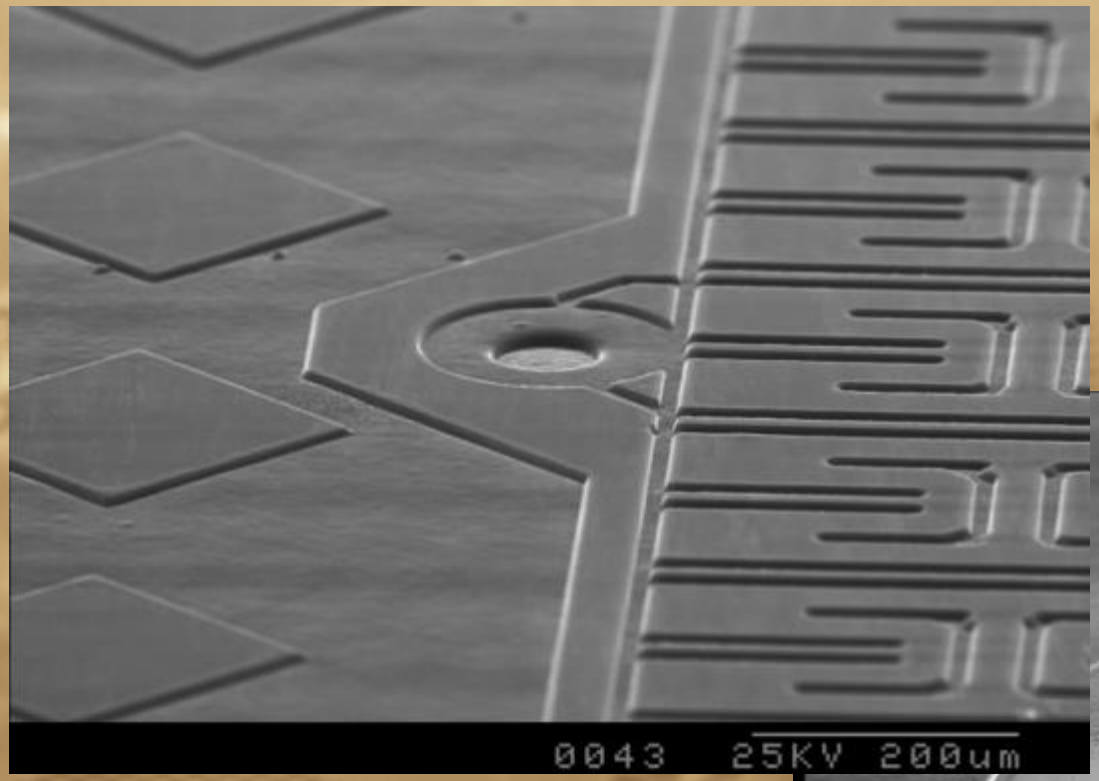


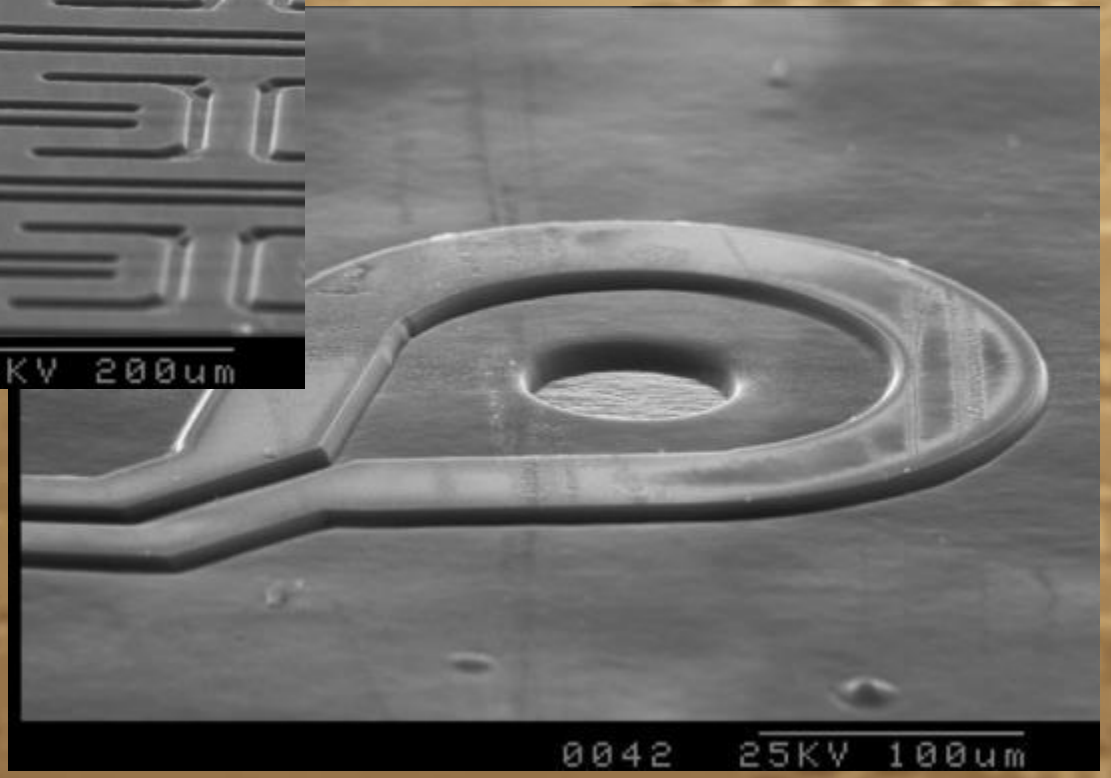
Scanned Mask Imaging



Multi-Mode Solid State Laser Mask Imaging	
High resolution	✓
Simple control system	✓
High throughput by multiplexing	✓
Low running costs	✓

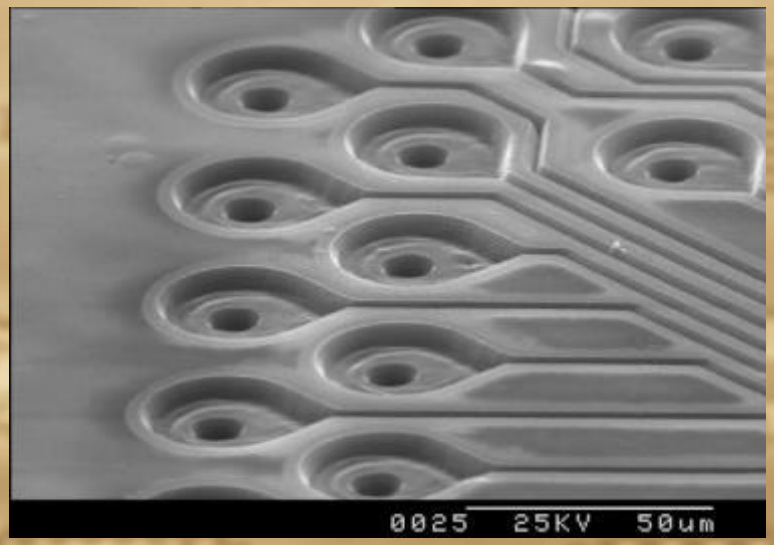
Scanned Mask Imaging Results

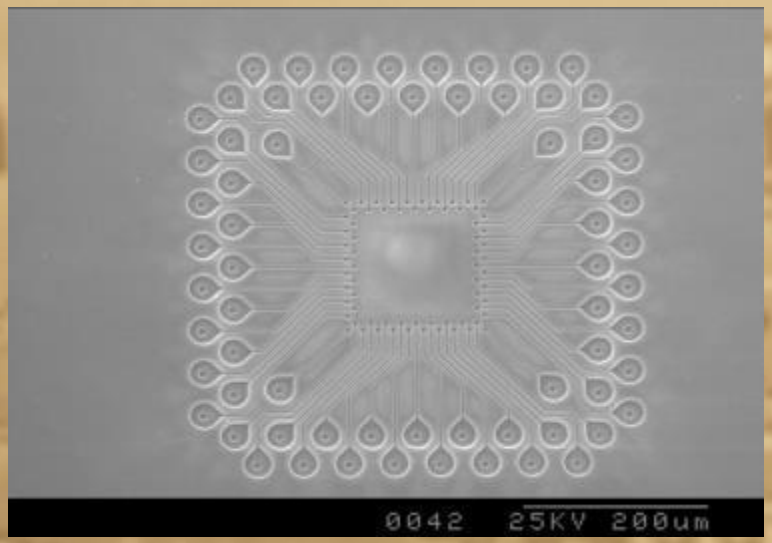


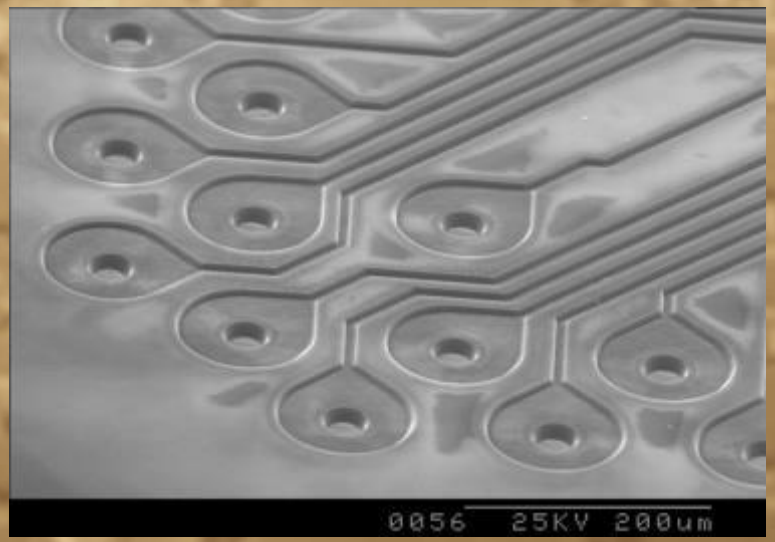


Ground planes, 180µm capture pads, 80µm vias and 16µm traces

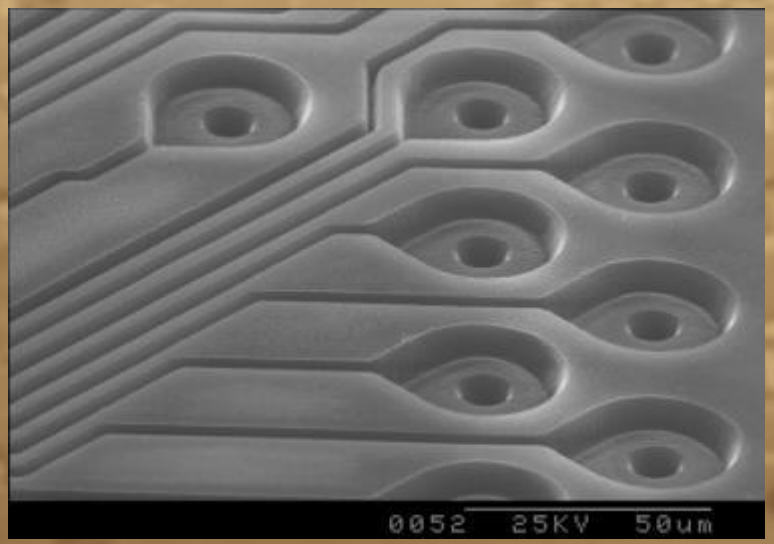
Scanned Mask Imaging Results





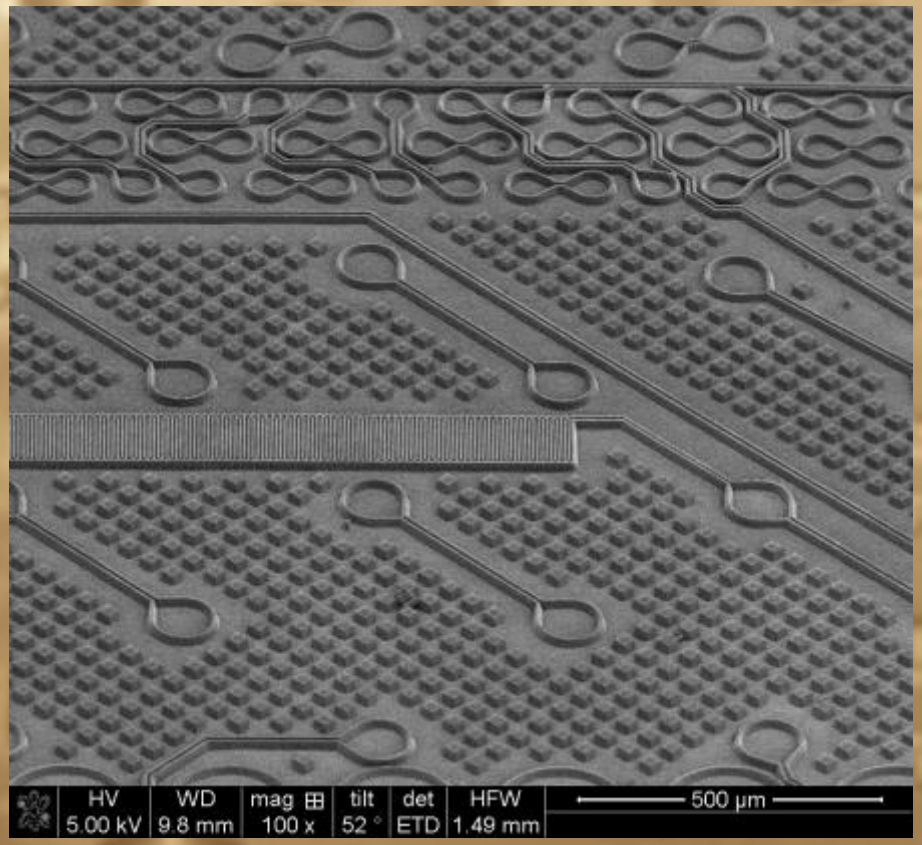


10µm L/S traces and 33µm vias

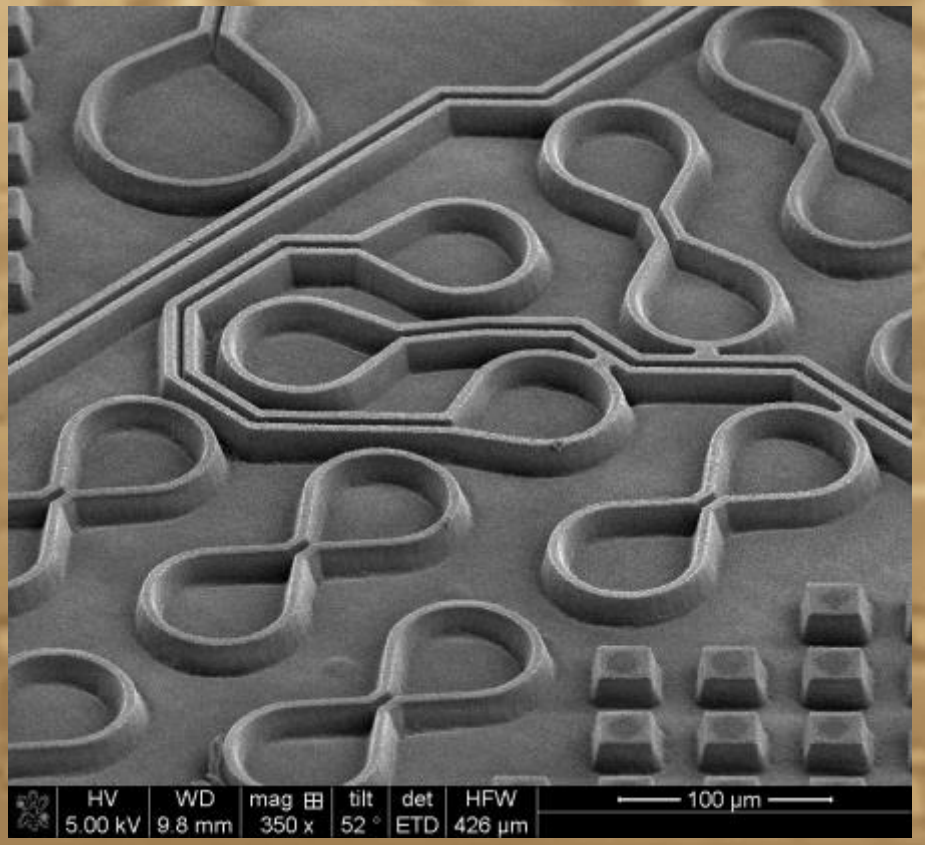


3µm L/S traces and 10µm vias

Scanned Mask Imaging Results



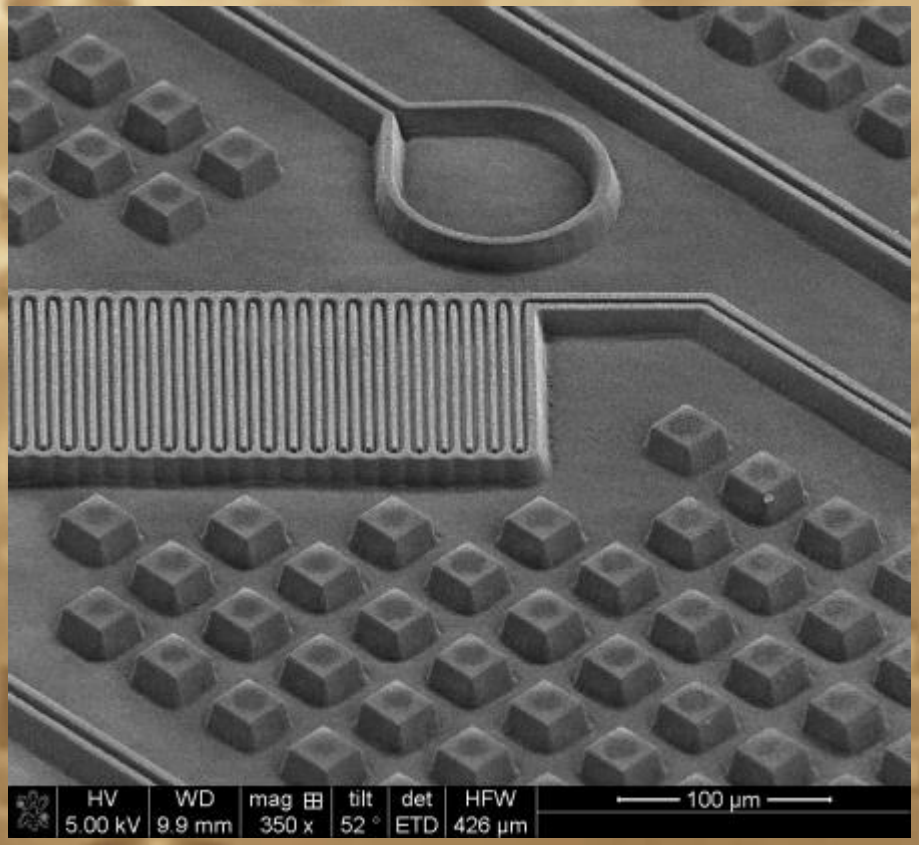
3µm L/S serpentine traces and ground planes

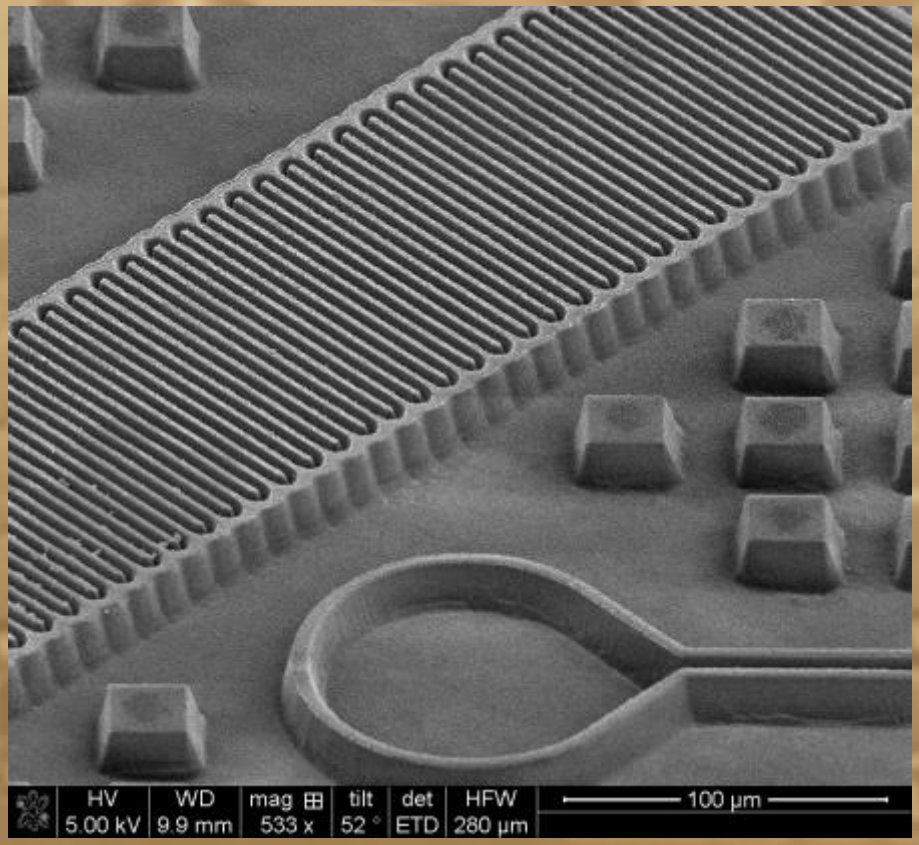


5µm traces and ground planes

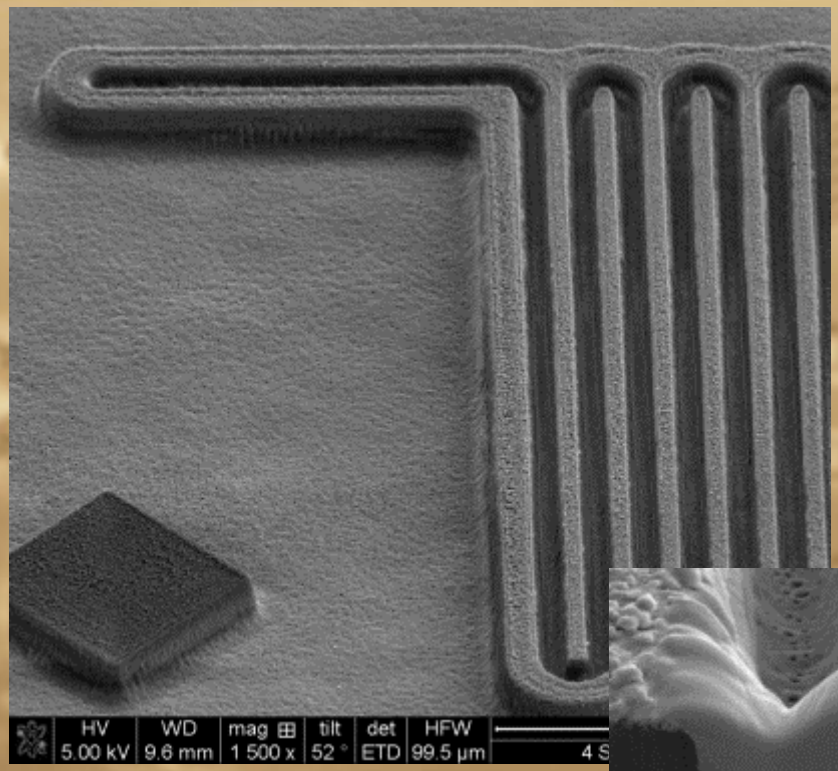
Scanned Mask Imaging Results

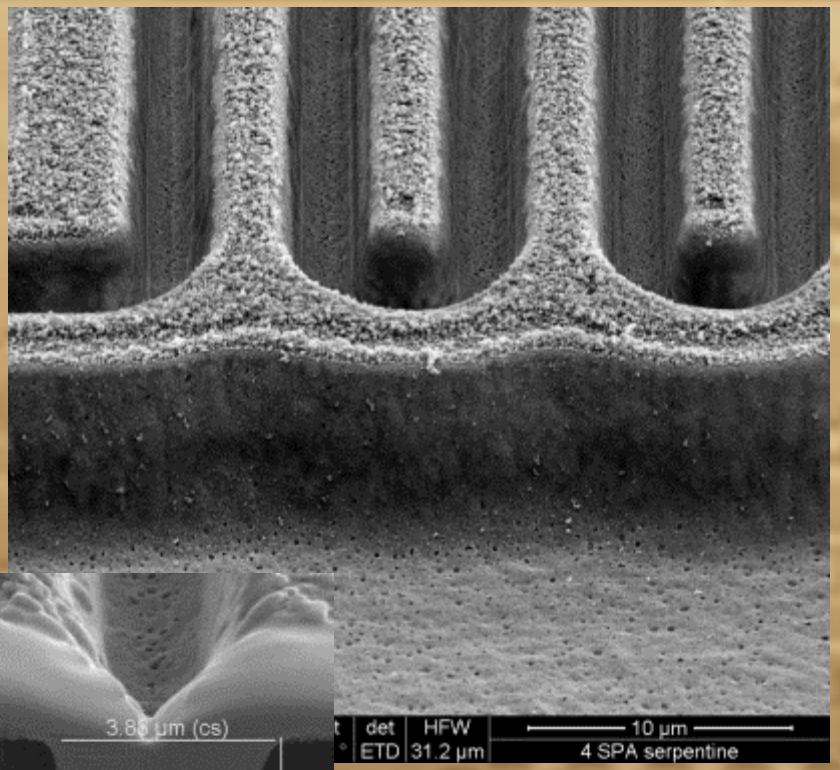
3um Line:Space Serpentine

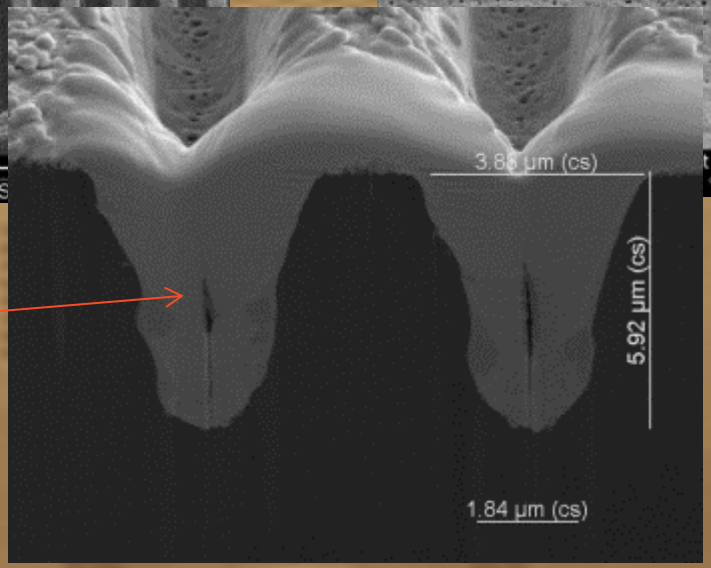




Scanned Mask Imaging Results



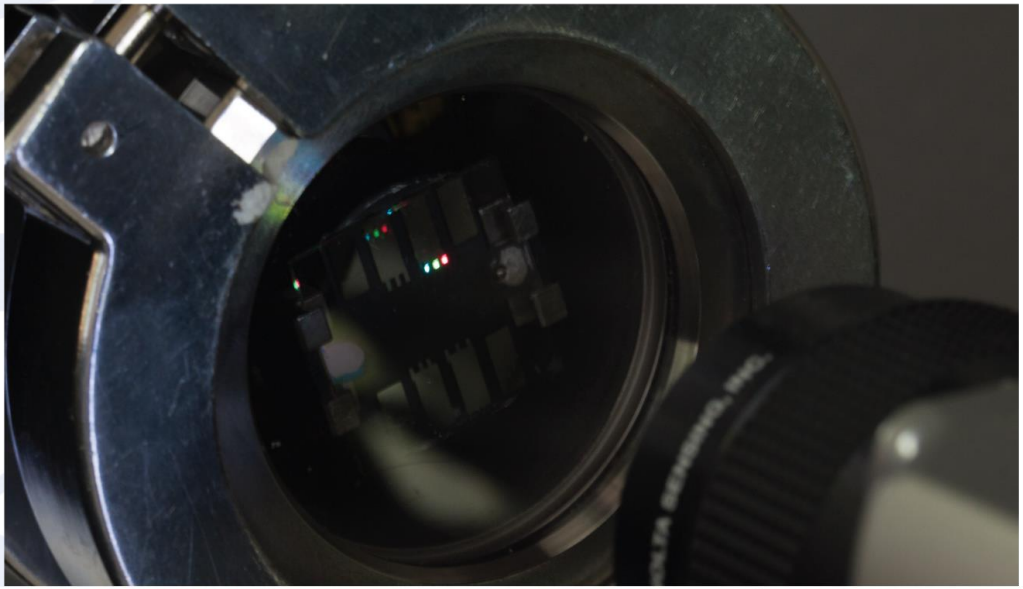


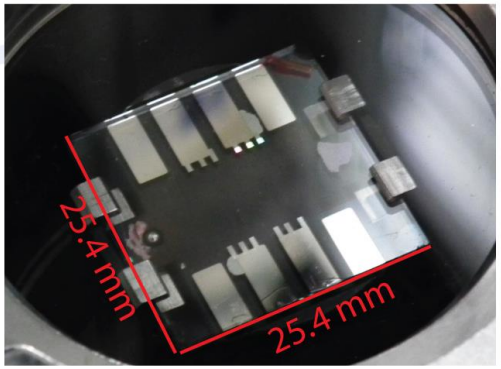


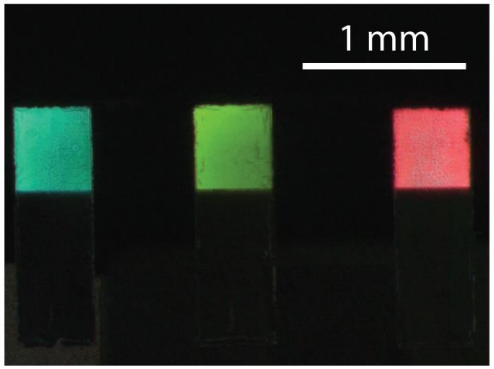
Platinum

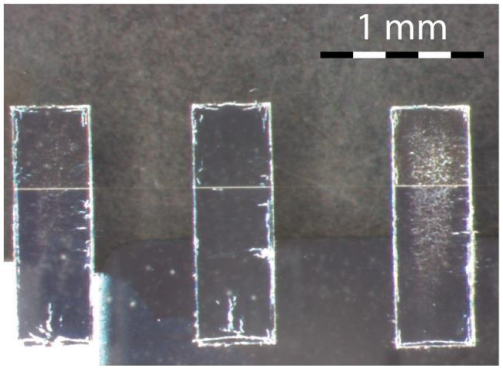
FIB cross-section

THANK YOU!









References

[1] R. Fardel, M. Nagel, F. Nüesch, T. Lippert, and A. Wokaun, "Laser-induced forward transfer of organic LED building blocks studied by time-resolved shadowgraphy," *J. Phys. Chem. C*, vol. 114, no. 12, pp. 5617–5636, 2010.

[2] H. Kim, T. E. Sutto, and A. Piqué, "Laser materials processing for micropower source applications: A review," *J. Photonics Energy*, vol. 4, no. 1, 2014.

[3] S. A. Mathews, R. C. Y. Auyeung, H. Kim, N. a. Charipar, and A. Piqué, "High-speed video study of laser-induced forward transfer of silver nano-suspensions," *J. Appl. Phys.*, vol. 114, no. 6, p. 064910, 2013.

[4] J. Shaw Stewart, T. Lippert, M. Nagel, F. Nuesch, and A. Wokaun, "Red-green-blue polymer light-emitting diode pixels printed by optimized laser-induced forward transfer," *Appl. Phys. Lett.*, vol. 100, no. 20, pp. 203303–203304, 2012.

[5] M. Makrygianni, E. Verrelli, N. Boukos, S. Chatzandroulis, D. Tsoukalas, and I. Zergioti, "Laser printing and characterization of semiconducting polymers for organic electronics," *Appl. Phys. A*, vol. 110, no. 3, pp. 559–563, Aug. 2013.

[6] L. Rapp, A. K. Diallo, S. Nénon, A. P. Alloncle, C. Videlot-Ackermann, F. Fages, M. Nagel, T. Lippert, and P. Delaporte, "Laser printing of a semiconducting oligomer as active layer in organic thin film transistors: Impact of a protecting triazene layer," *Thin Solid Films*, vol. 520, no. 7, pp. 3043–3047, 2012.

[7] L. Koch, S. Michael, K. Reimers, P. M. Vogt, and B. Chichkov, "Bioprinting for Skin," in *3D Bioprinting and Nanotechnology in Tissue Engineering and Regenerative Medicine*, L. G. Zhang, J. P. Fisher, and K. W. Leong, Eds. 2015, pp. 281–306.

[8] A. Palla-Papavlu, A. Patrascioiu, F. Di Pietrantonio, J.-M. Fernández-Pradas, D. Cannatà, M. Benetti, S. D'Auria, E. Verona, and P. Serra, "Preparation of surface acoustic wave odor sensors by laser-induced forward transfer," *Sensors Actuators, B Chem.*, vol. 192, pp. 369–377, 2014.

[9] C. Constantinescu, L. Rapp, A. K. Diallo, C. Videlot-Ackermann, P. Delaporte, and P. Alloncle, "Microcapacitors with controlled electrical capacity in the pF-nF range printed by laser-induced forward transfer (LIFT)," *Org. Electron.*, vol. 20, pp. 1–7, 2015.

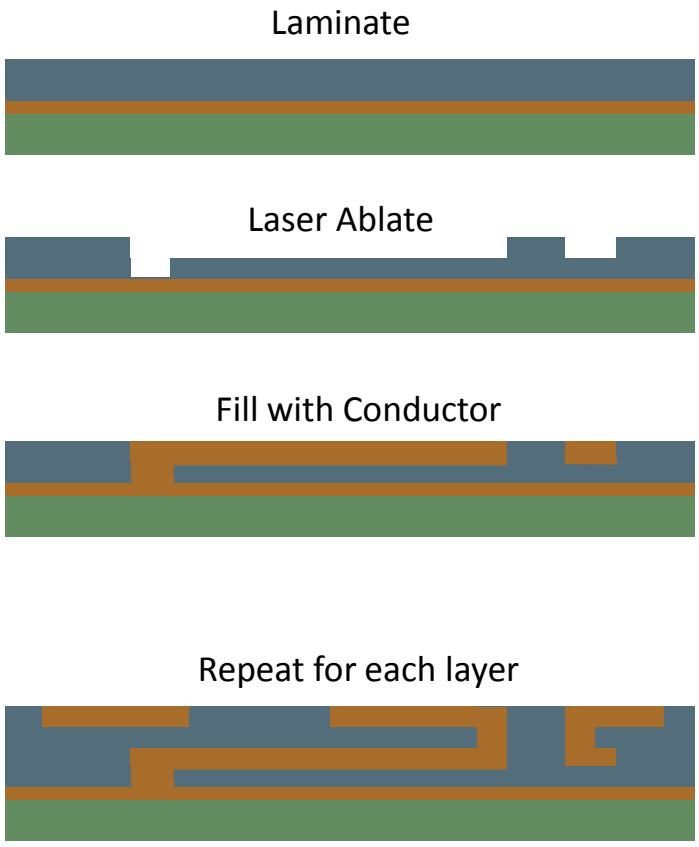
[10] K. S. Kaur, J. Missinne, and G. Van Steenberge, "Flip-chip bonding of vertical-cavity surface-emitting lasers using laser-induced forward transfer," *Appl. Phys. Lett.*, vol. 104, no. 6, p. 061102, Feb. 2014.

[11] R. Auyeung, H. Kim, A. Birnbaum, M. Zalalutdinov, S. Mathews, and A. Piqué, "Laser decal transfer of freestanding microcantilevers and microbridges," *Appl. Phys. A Mater. Sci. Process.*, vol. 97, no. 3, pp. 513–519, 2009.

[12] C. W. Visser, R. Pohl, C. Sun, G.-W. Römer, B. Huis in 't Veld, and D. Lohse, "Toward 3D Printing of Pure Metals by Laser-Induced Forward Transfer," *Adv. Mater.*, vol. 27, no. 27, pp. 4087–4092, 2015.

Advanced Packaging Market Trends and Requirements

IC Substrates



Benefits of Laser Embedded Conductor Technology:

- Higher resolution than Conventional PCB manufacturing technologies, enabling the total layer count to be reduced, thereby reducing the size and cost of the package.
- Wiring **and** vias made in a single process.
- Near padless vias allow more routing space, further reducing the total layer count.
- Embedding conductors improves surface planarity within a multi-layer substrate, reducing warpage issues.
- No requirement for photo-chemistry or blind-via drilling equipment.
- Superior Cu adhesion due to “3-point anchoring”.
- Standard low K, low CTE organic dielectrics may be used.

HERIOT WATT UNIVERSITY

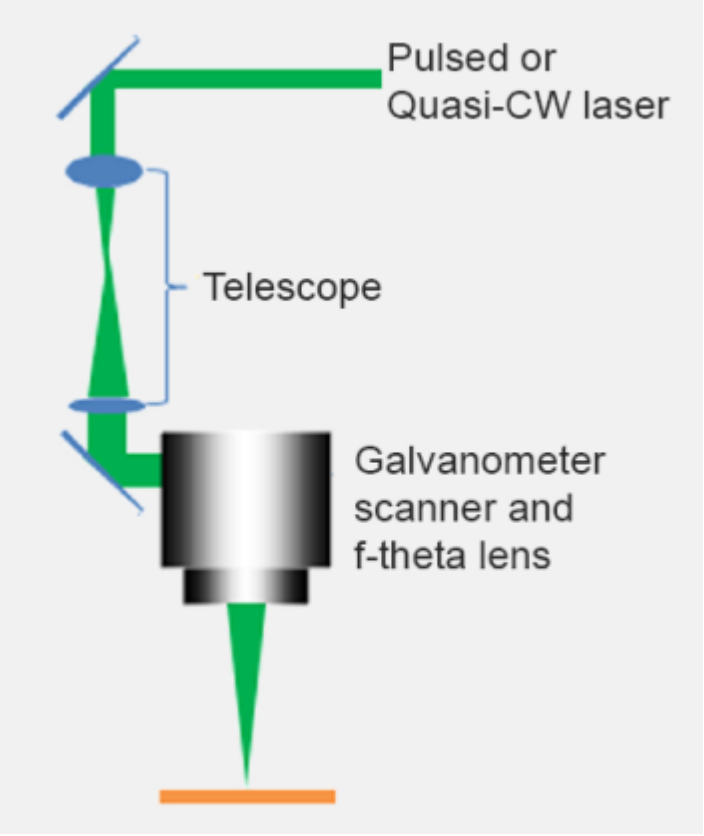
iMAPS

M-SOLV Limited

Conventional Pulsed UV Laser Ablation Methodologies

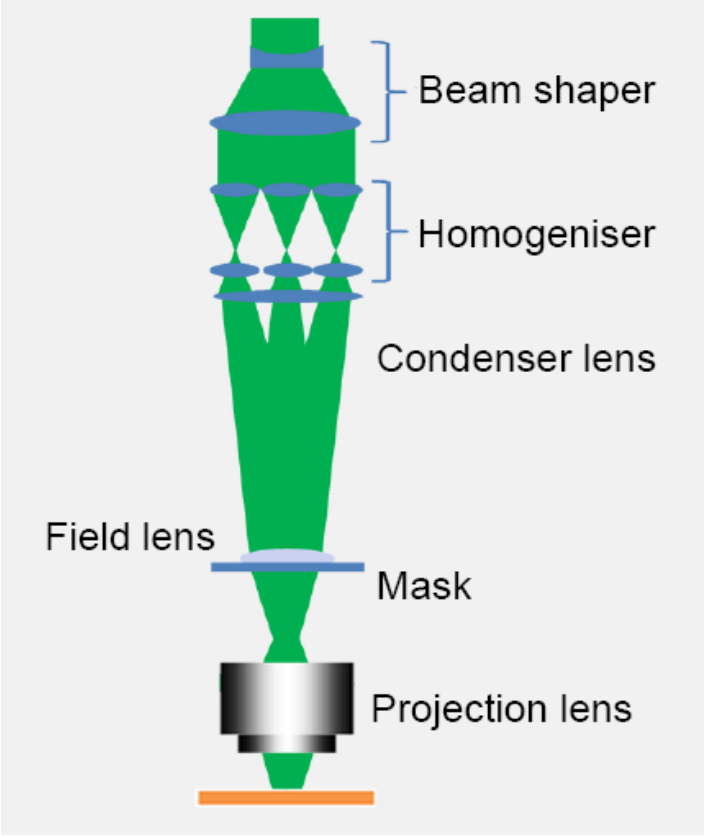
Conventional Pulsed UV Laser Ablation Methodologies

Direct Write Solid State Systems	
Flexible	✓
Low running costs	✓
Complicated control systems	✗
Low throughput	✗
Low resolution	✗



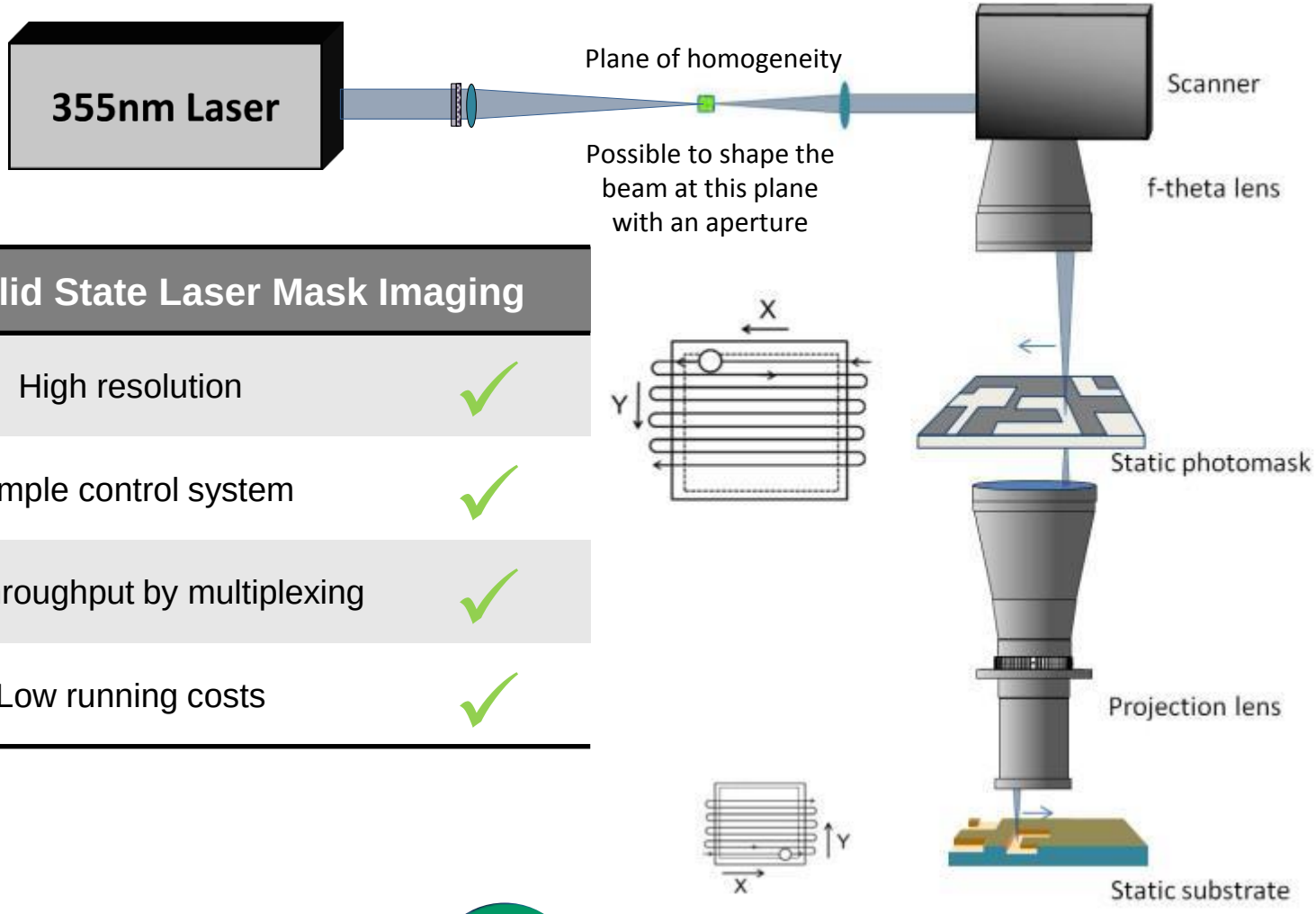
Conventional Pulsed UV Laser Ablation Methodologies

Excimer Laser Imaging Systems	
High resolution	✓
High throughput	✓
High running costs	✗ ✗ ✗



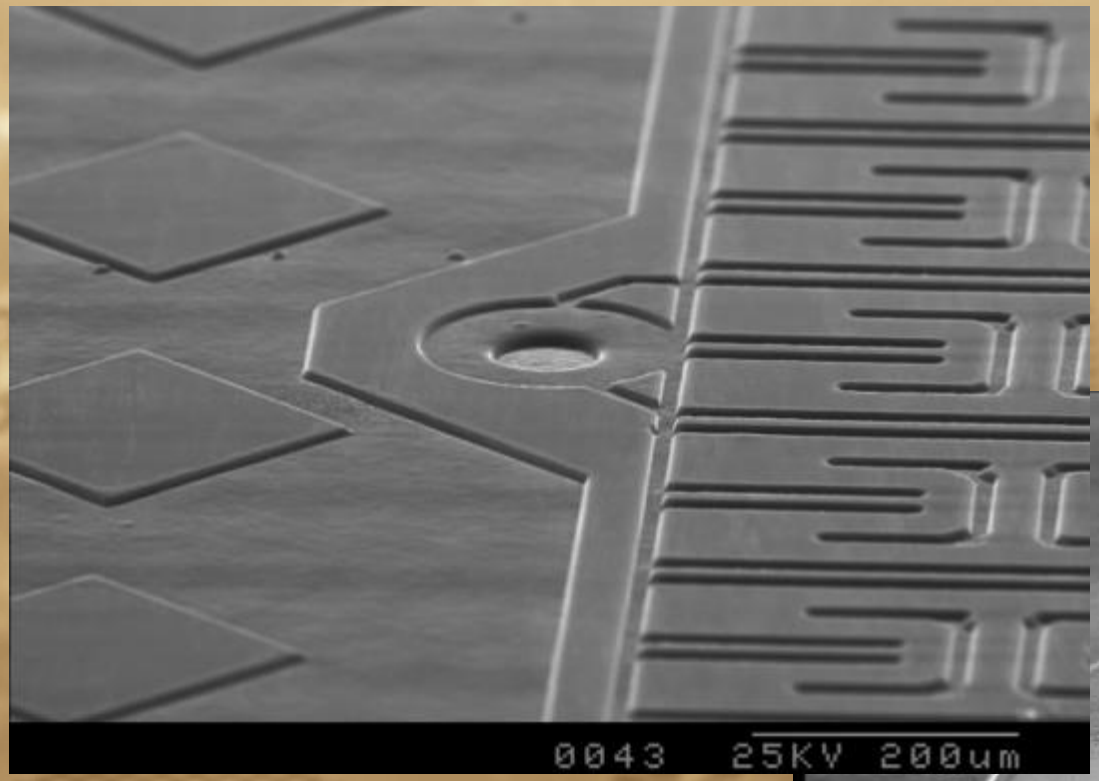
A **New** Methodology - Scanned Mask Imaging

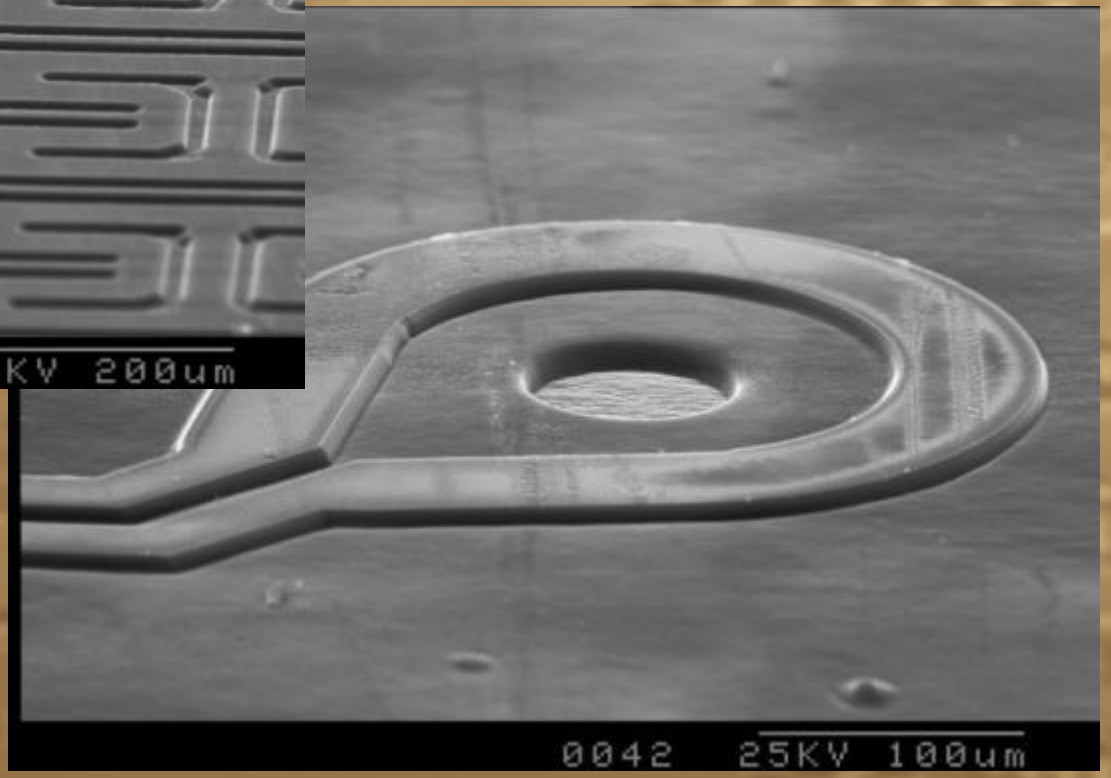
Scanned Mask Imaging



Multi-Mode Solid State Laser Mask Imaging	
High resolution	✓
Simple control system	✓
High throughput by multiplexing	✓
Low running costs	✓

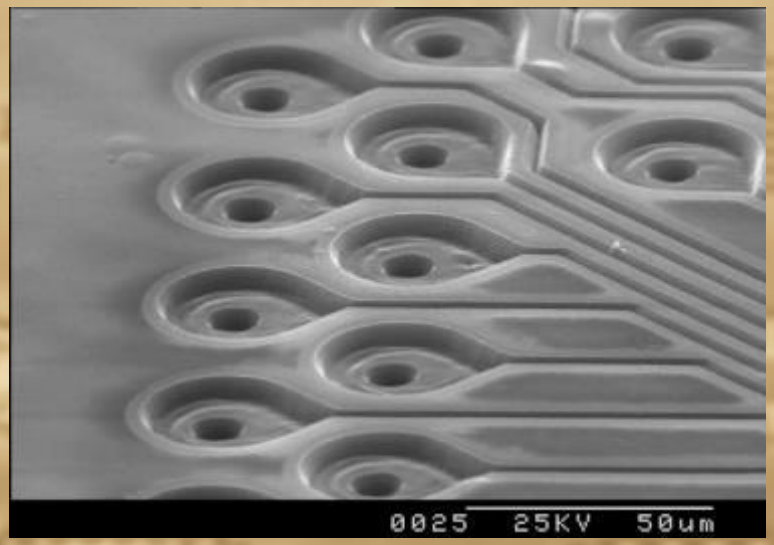
Scanned Mask Imaging Results

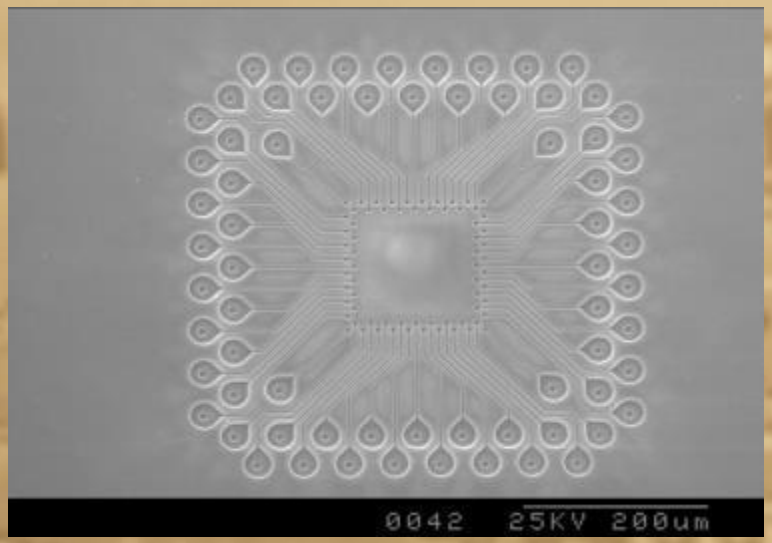


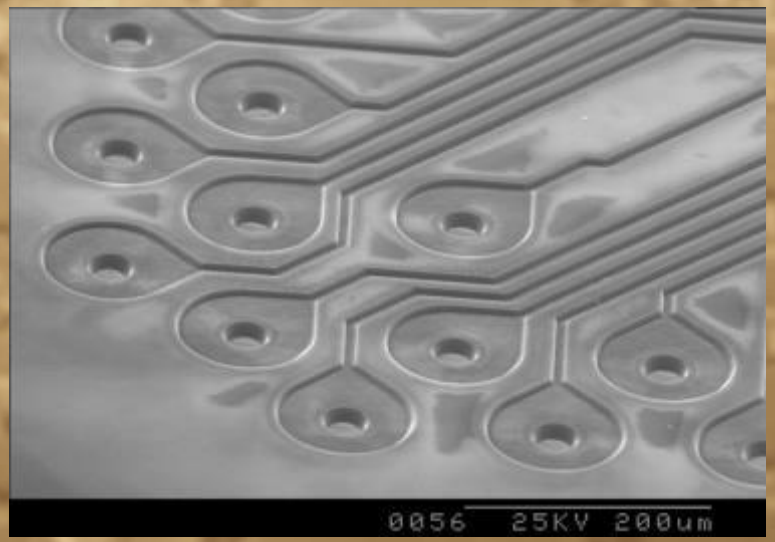


Ground planes, 180µm capture pads, 80µm vias and 16µm traces

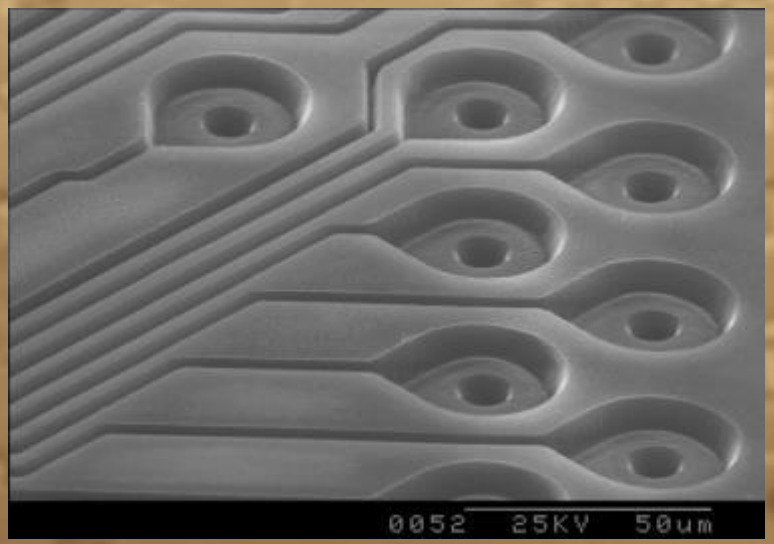
Scanned Mask Imaging Results





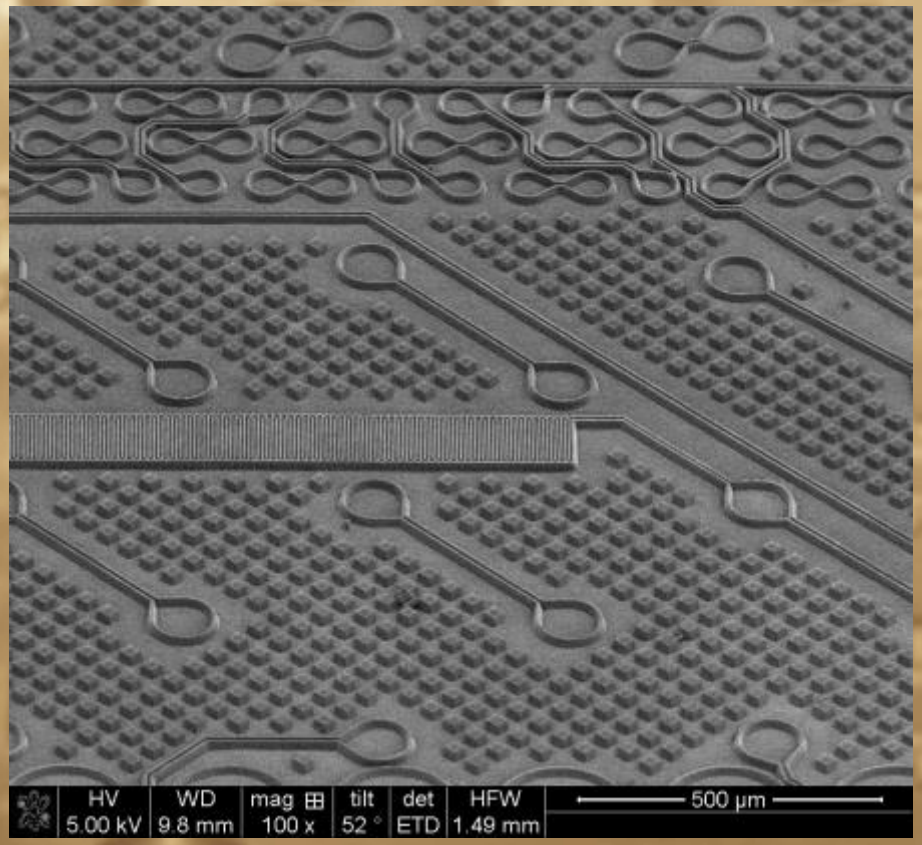


10µm L/S traces and 33µm vias

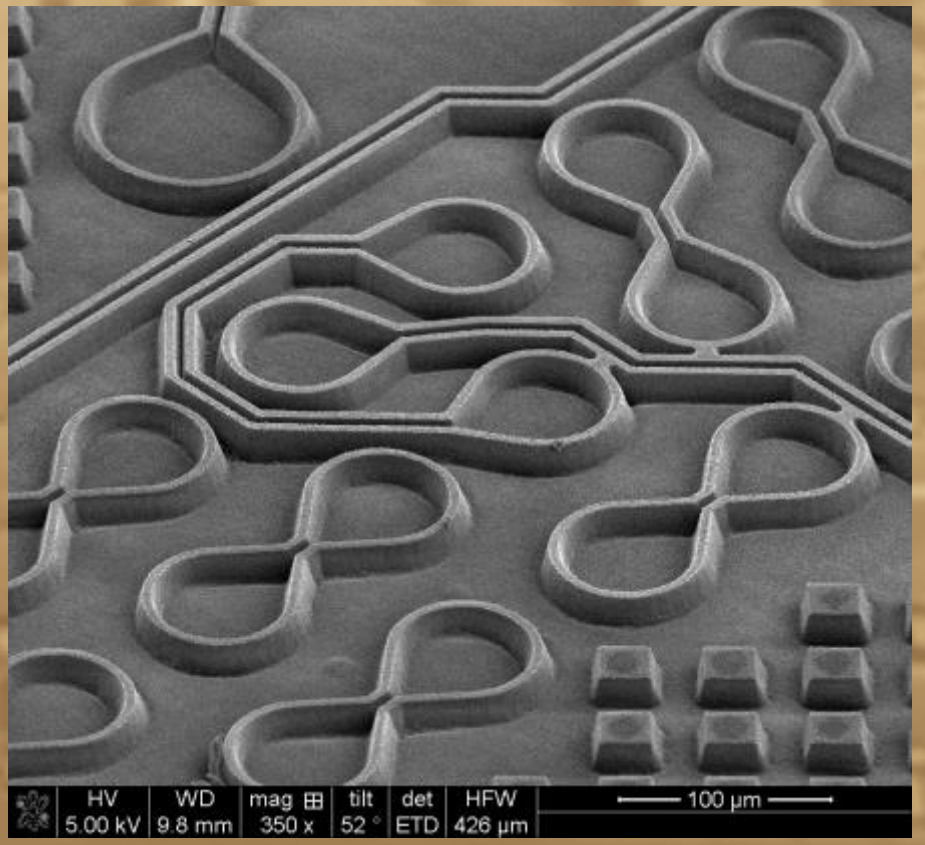


3µm L/S traces and 10µm vias

Scanned Mask Imaging Results



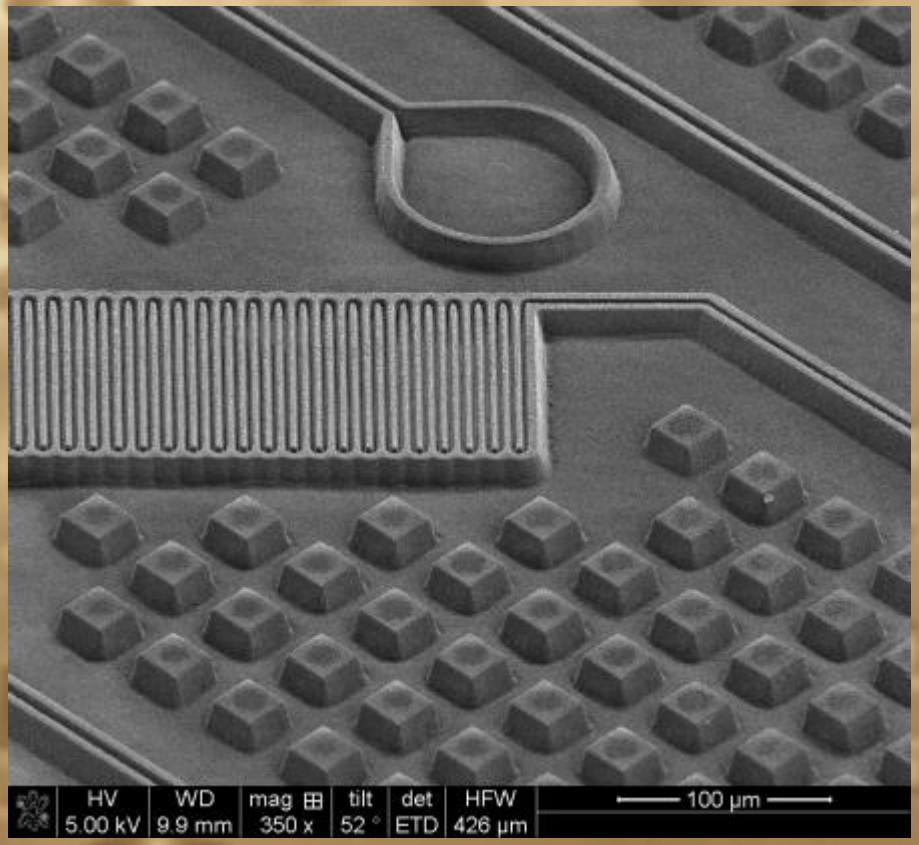
3µm L/S serpentine traces and ground planes

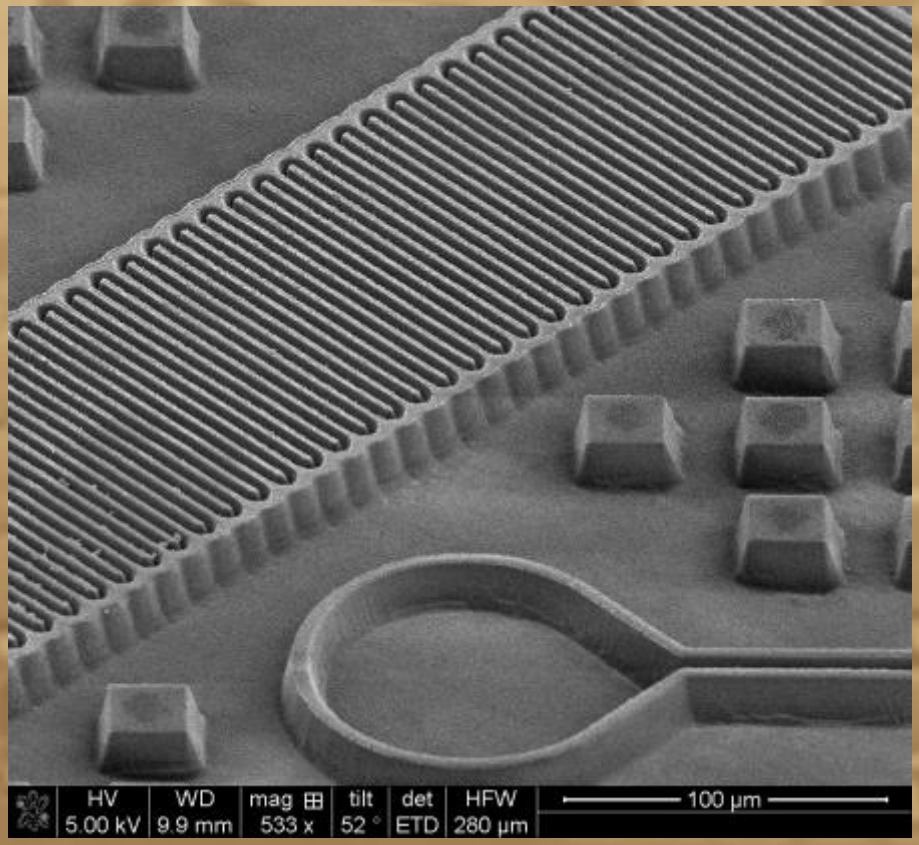


5µm traces and ground planes

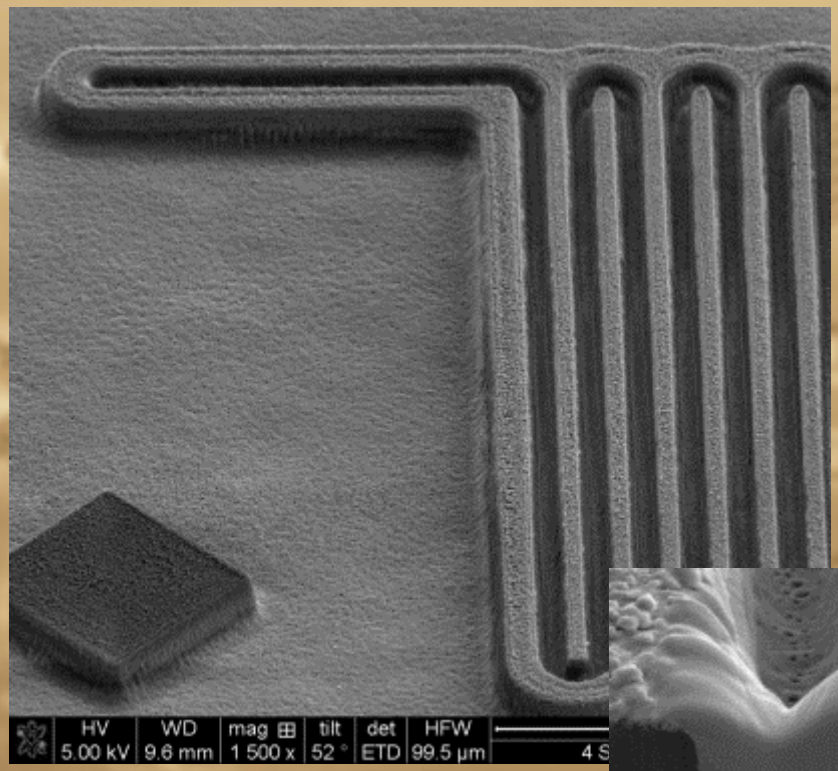
Scanned Mask Imaging Results

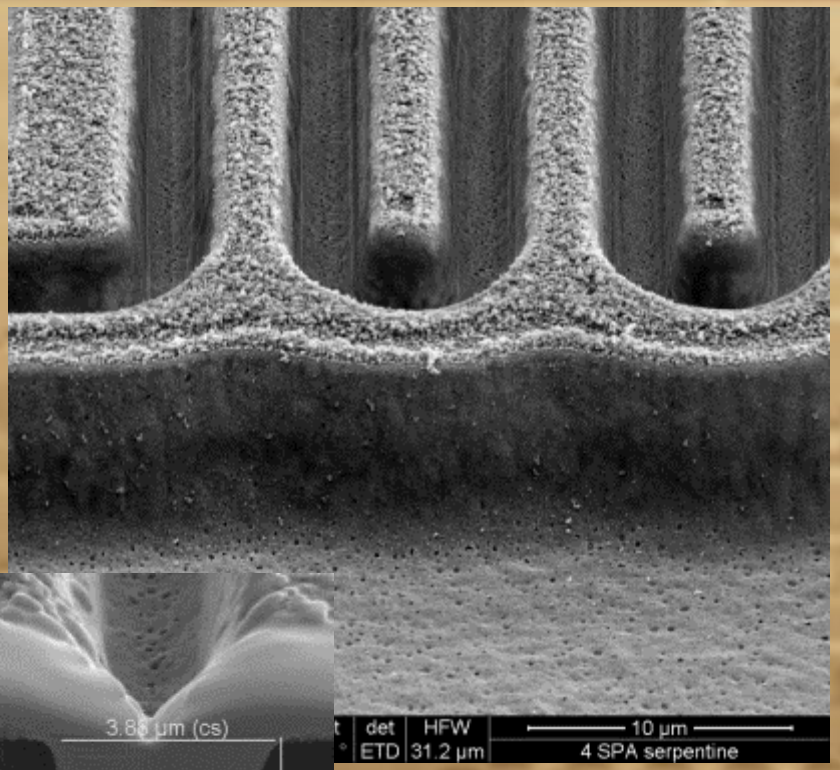
3um Line:Space Serpentine

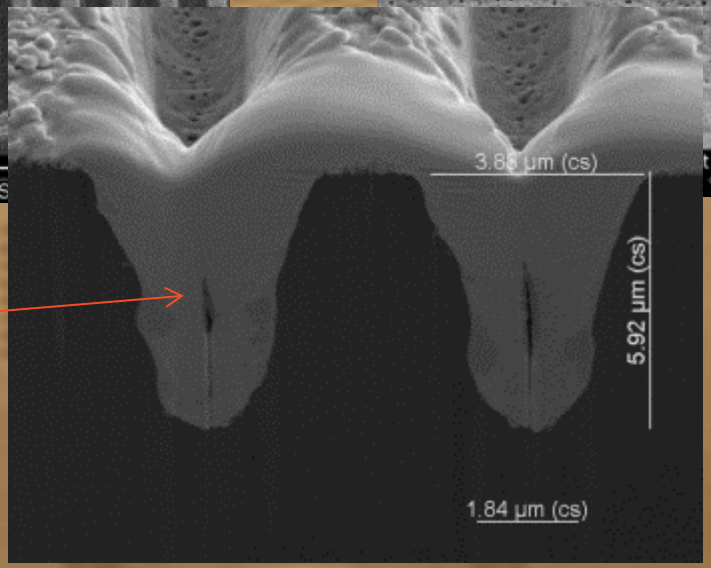




Scanned Mask Imaging Results





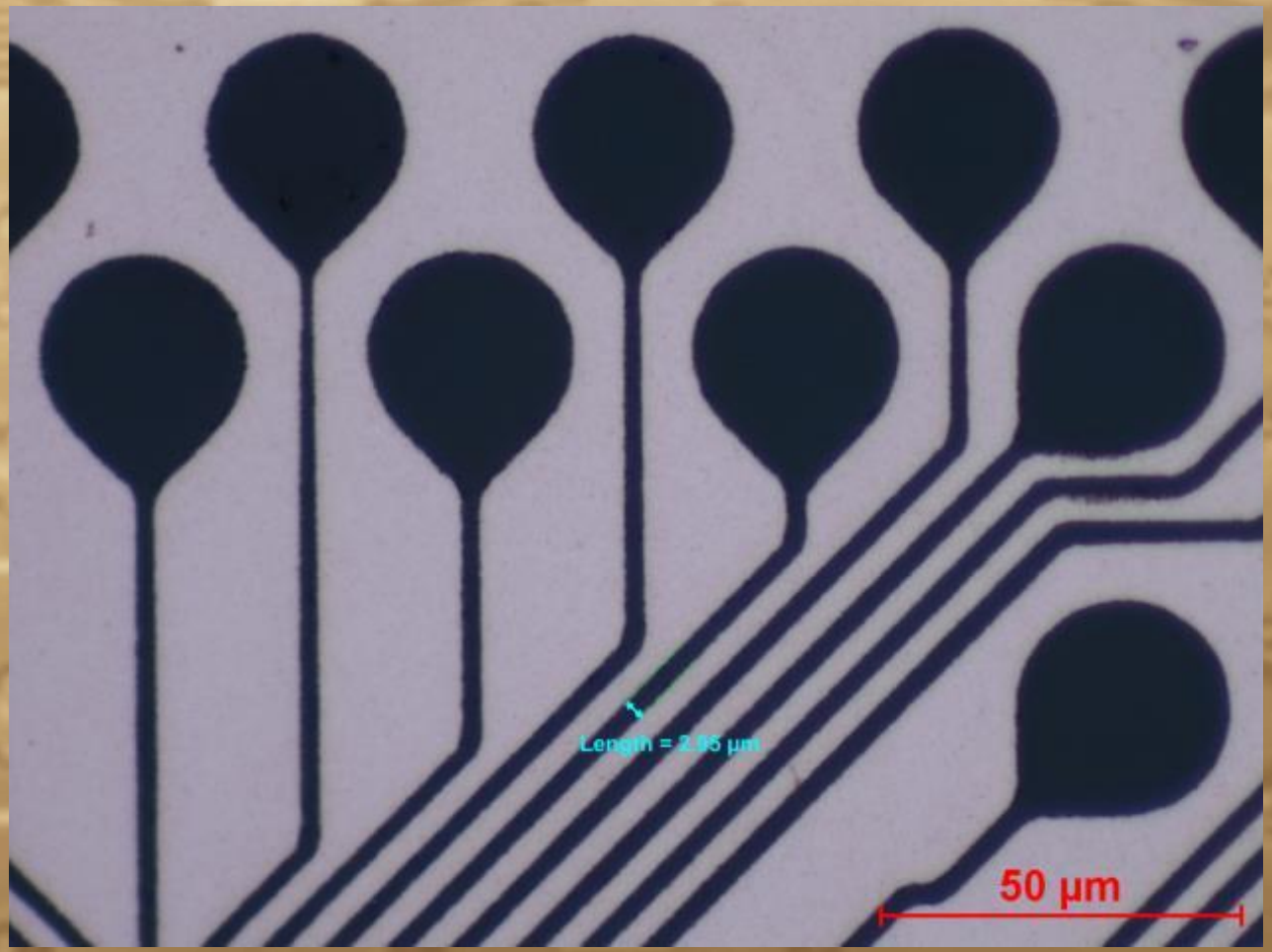


Platinum

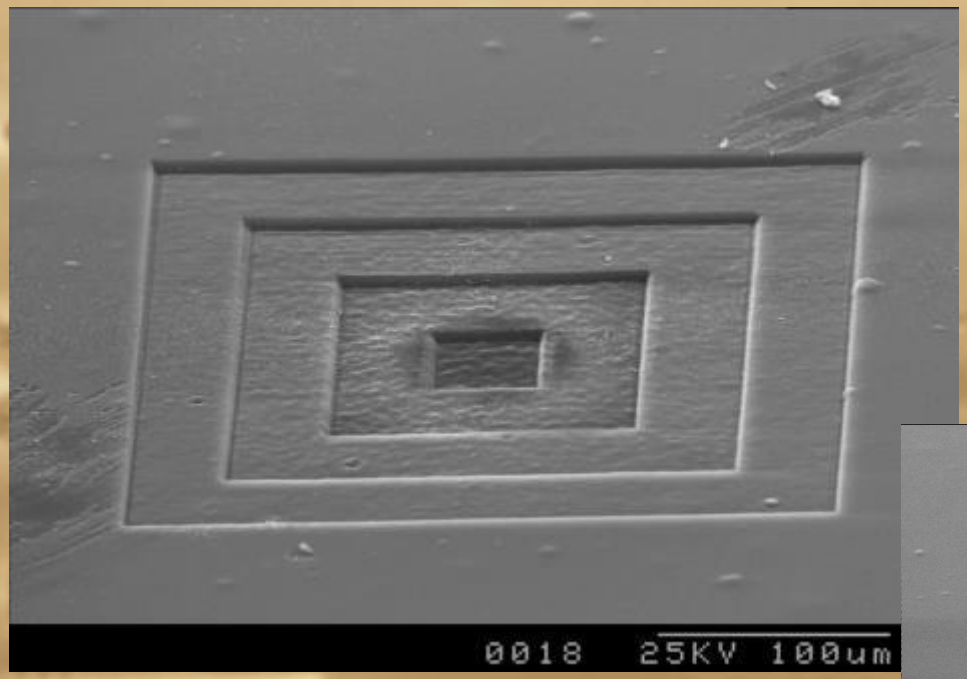
FIB cross-section

Alternative Uses for Scanned Mask Imaging

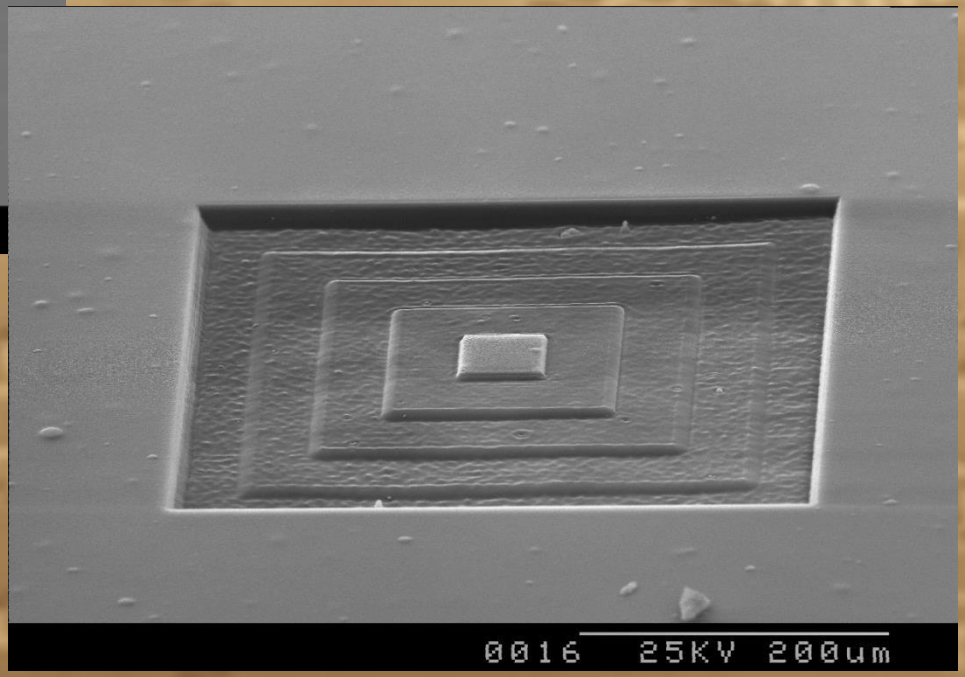
Resist Exposure



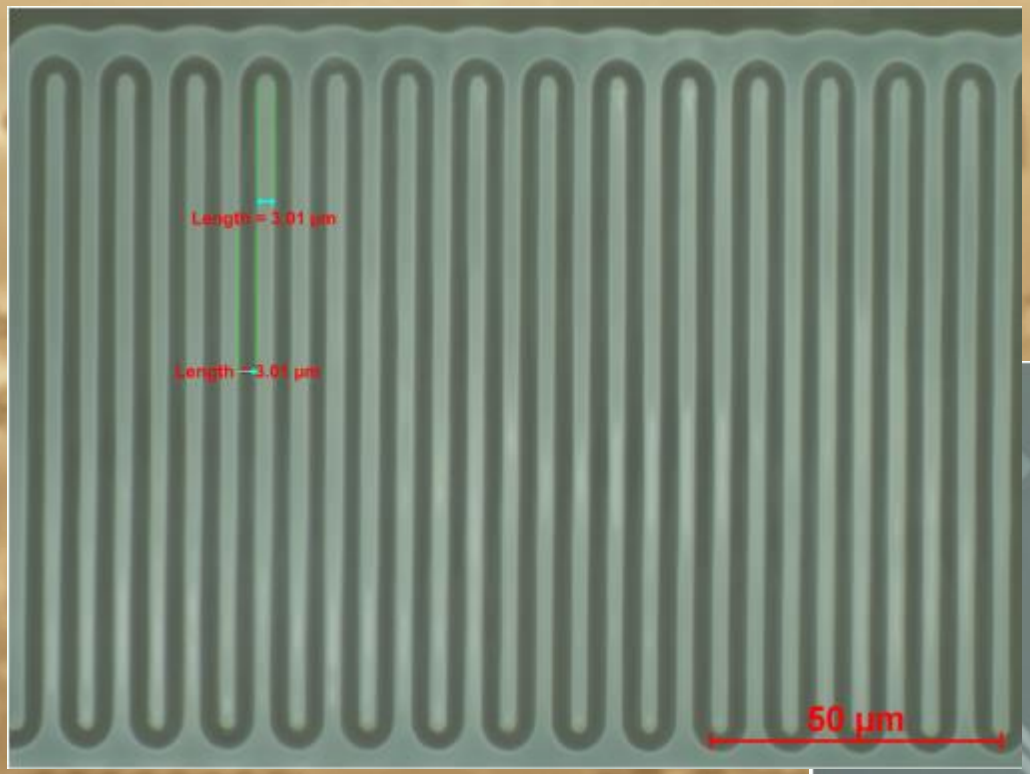
Alternative Uses of SMI



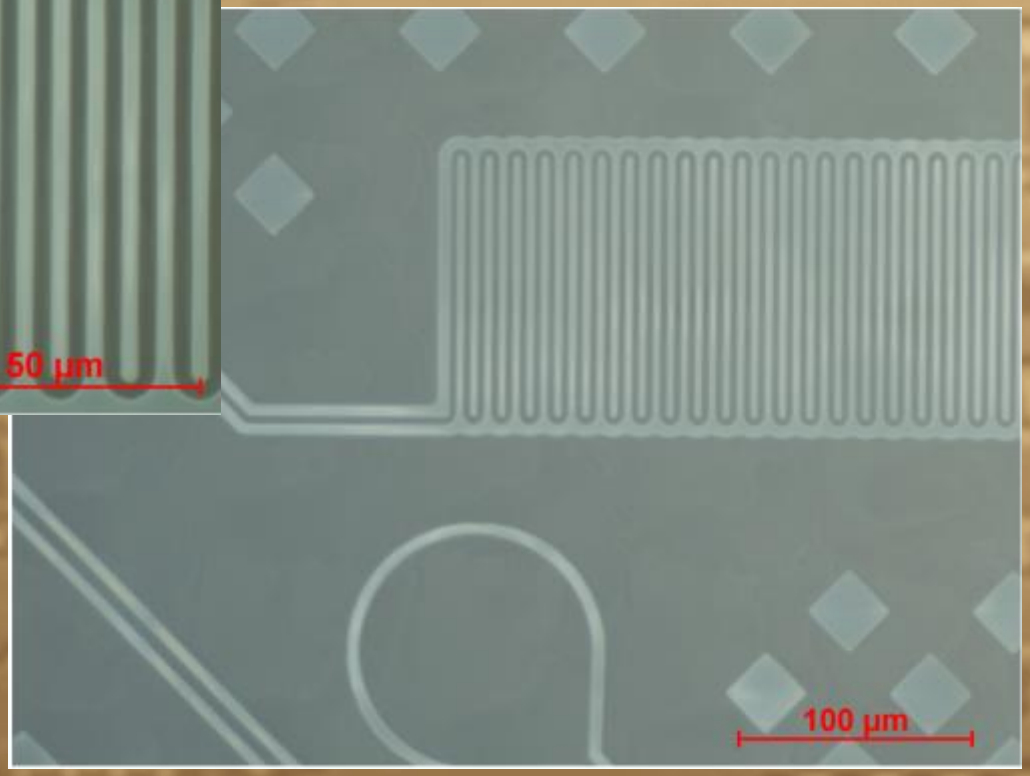
Micro-machining



Alternative Uses of SMI



ITO Patterning



3um L/S
Darker areas are where ITO is removed by laser ablation

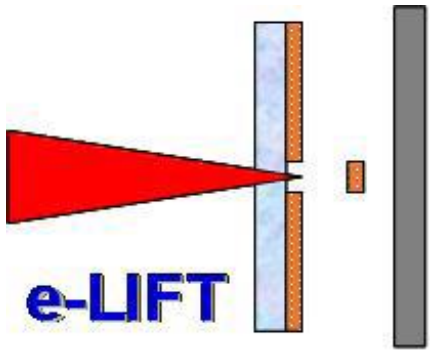
Acknowledgements

- Doctorvater:
  - Professor Alexander Wokaun (ETHZ & PSI)
- Supervisors
  - Professor Thomas Lippert (PSI & ETHZ)
  - Professor Frank Nüesch (Empa & EPFL)
  - Dr. Matthias Nagel (Empa)
- Experimental colleagues:
  - Dr. Romain Fardel (PSI)
  - Dr. Thomas Mattle (PSI)
  - Ylenia Maniglio (Empa)
  - Pascal Frank (Konstanz)
  - Dr. Valentina Dinca (Bucharest)
  - Dr. Alexandra Palla-Papavlu (Bucharest)

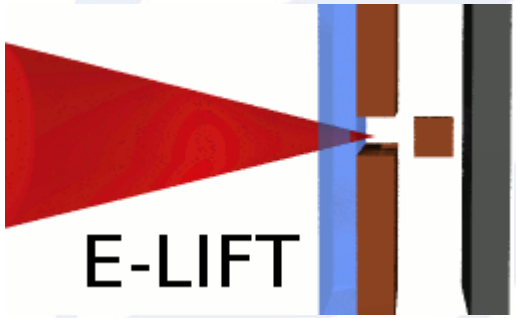
- Funding:
  - Swiss national science foundation (SNF)

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

  - EU e-LIFT project



e-LIFT http://www.e-lift-project.eu/

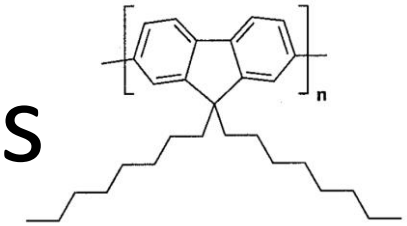


- Laser printing of organic/inorganic material for the fabrication of electronic devices
- 3 year project from 2010-2012
- €4.2M budget project

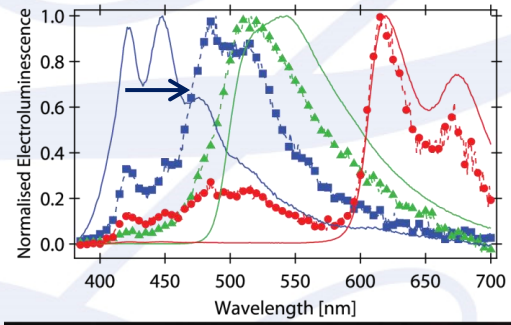
PARTNERS

- CNRS - LP3 (FR)
- ARMINES - EMSE (FR)
- Paul Scherrer Institut (CH)
- EMPA (CH)
- National Technical University of Athens (GR)
- University of Barcelona (SP)
- University of Southampton - ORC (UK)
- INFLPR (RO)
- CNR - IDAC (IT)
- Laser Micromachining Limited (UK)
- ACXYS Technologies (FR)
- MICROSENS S.A. (CH)
- TAGSYS (FR)
- BIOSENSOR S.R.L. (IT)
- Toplink Innovation (FR)

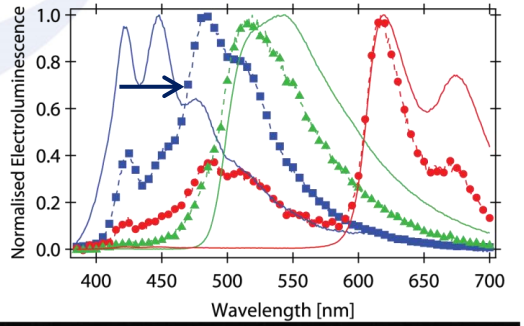
Optimized PFO devices

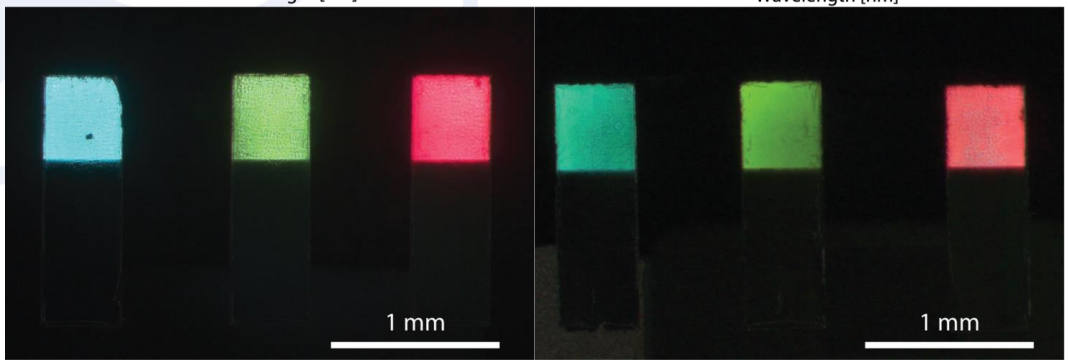


With tba (tetrabutylammonium)



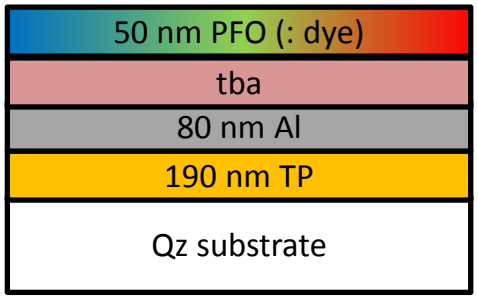
Original



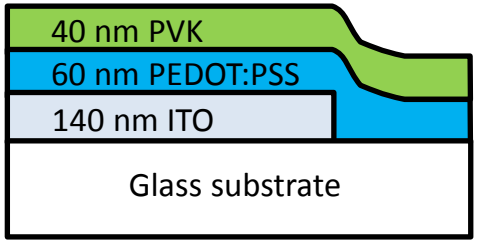


- Blue LIFTed device
- Green LIFTed device
- Red LIFTed device
- Blue conventional (Ca) device
- Green conventional (Ca) device
- Red conventional (Ca) device

Donor Substrate



Receiver Substrate

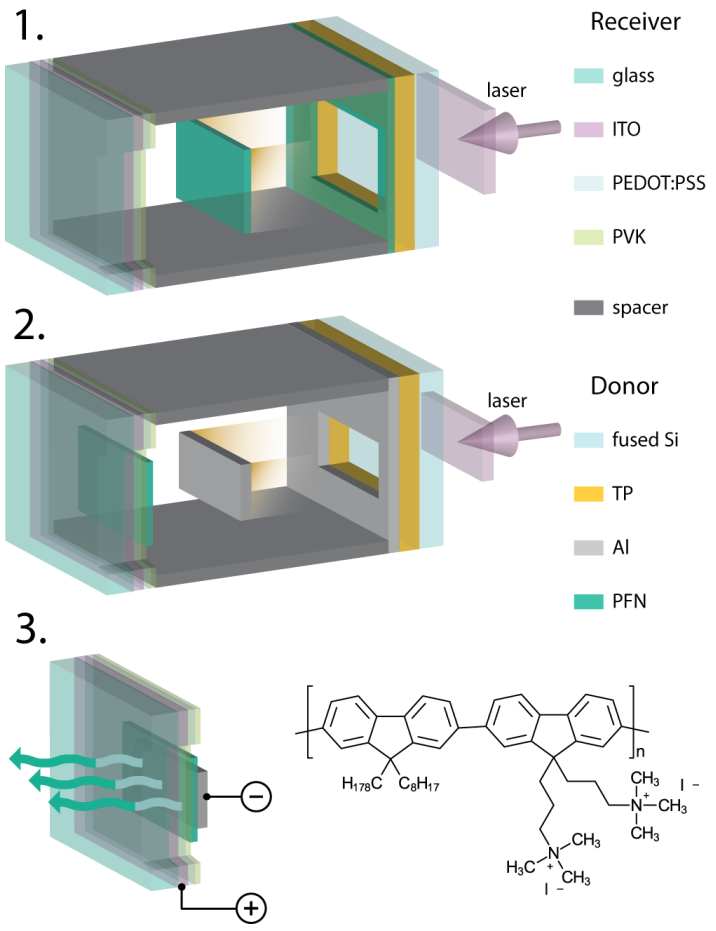


- Good tri-colour LIFTed OLEDs
- Only blue EL spectrum is a bit shifted

Two-step transfer

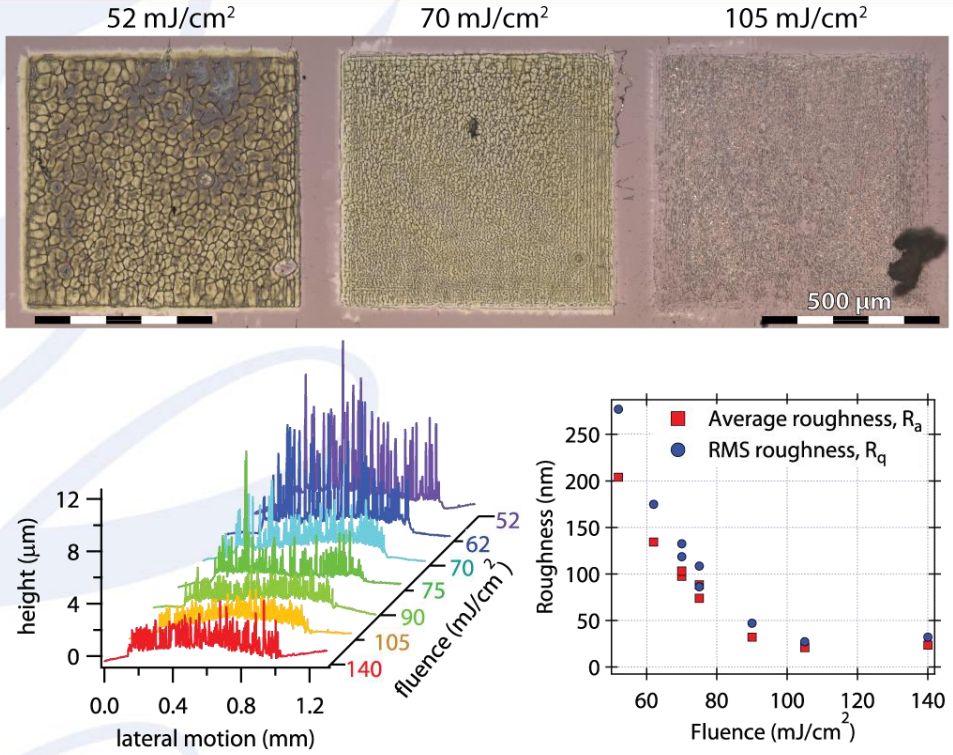
- Sometimes solution processable materials may be incompatible
- First demonstration of functional devices with two components deposited separately by LIFT

1. Single-layer polymer (PFN) pixel transferred
2. Al pixel transferred
3. Device operation



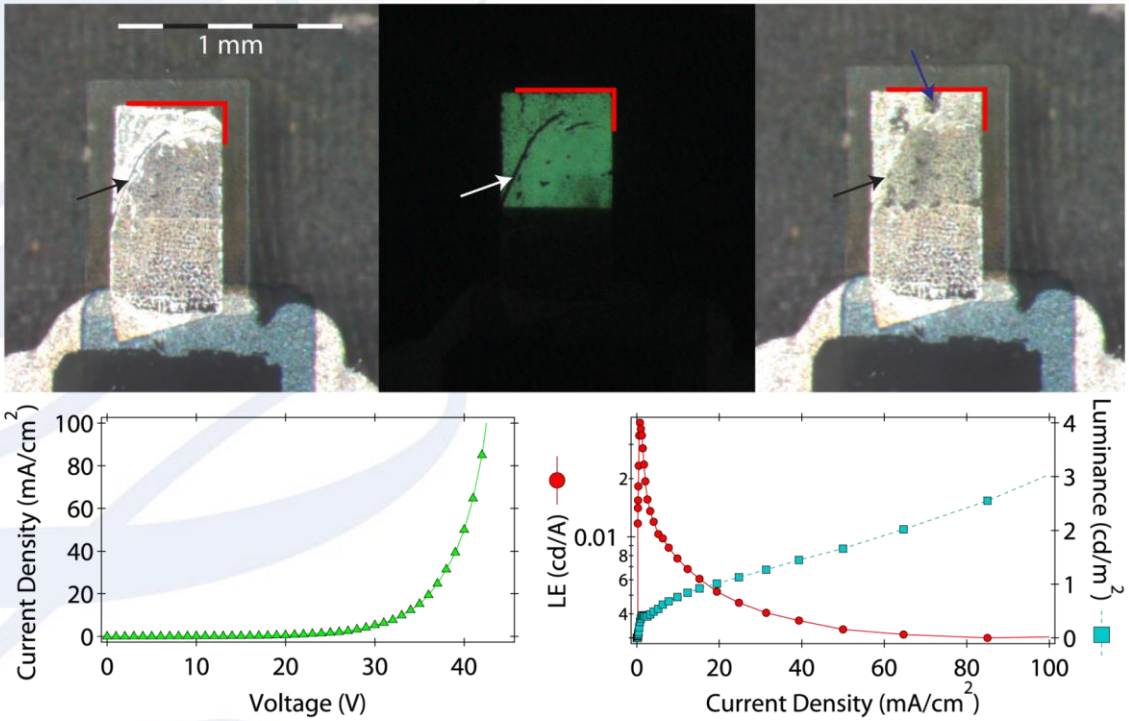
NOT TO SCALE

PFN morphology



- Single-layer polymer (PFN) pixel roughness decreases as the fluence for transfer increases

Functional pixels



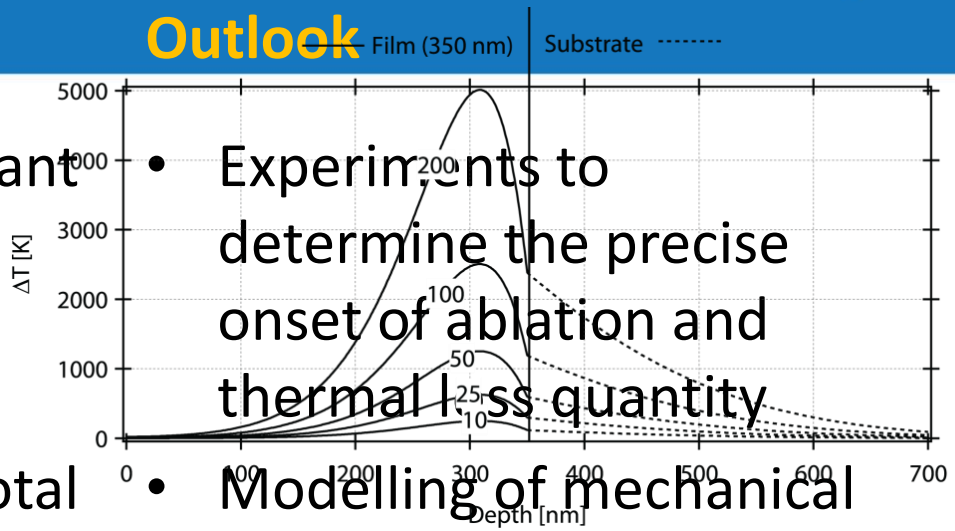
- Devices are not perfect, but are functional
- Luminances up to 15 cd m^{-2} were obtained

Understanding of LIFT process

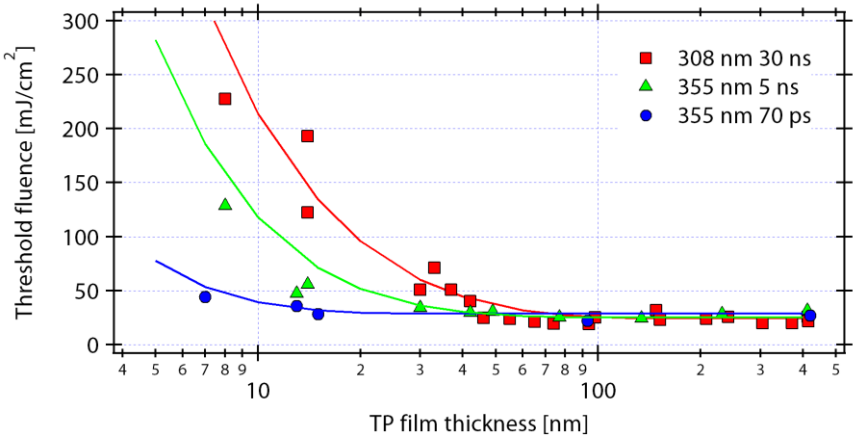
Conclusions

- Thermal loss is a very significant energy loss mechanism.
- Flyer velocity has been modelled using an energy balance that quantifies the total energy loss.
- The laser pulse length has a significant effect, probably due to thermal losses.
  - Ps pulses have higher effective absorption than ns, and more efficient energy transfer

Outlook

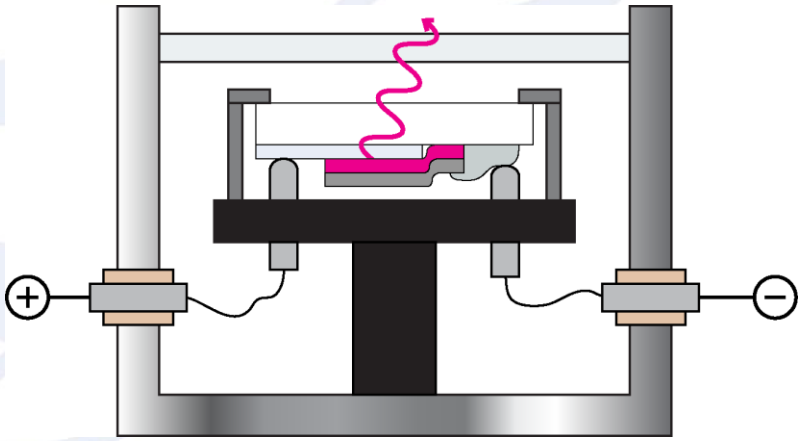


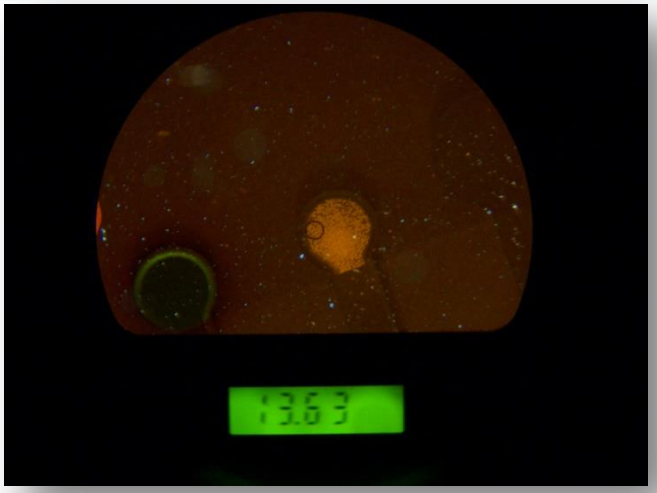
- Experiments to determine the precise onset of ablation and thermal loss quantity
- Modelling of mechanical loss mechanisms, such

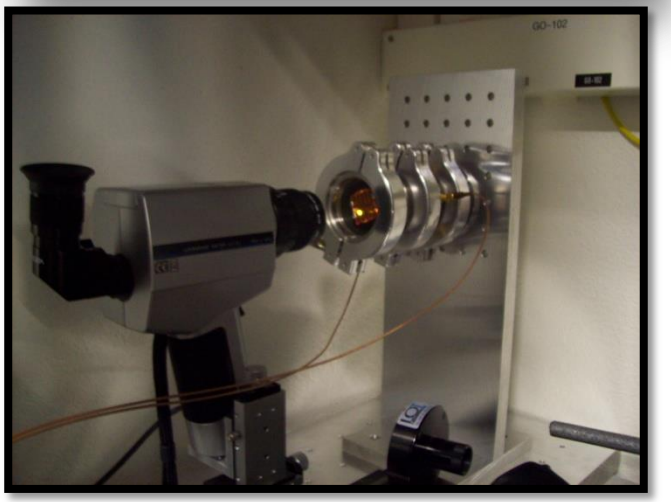


OLED device characterisation

- Done at Empa, using a Minolta **luminance-meter** and a Keithley **source-meter**, combined with a sample-holder that keeps the sample in an inert N_2 environment



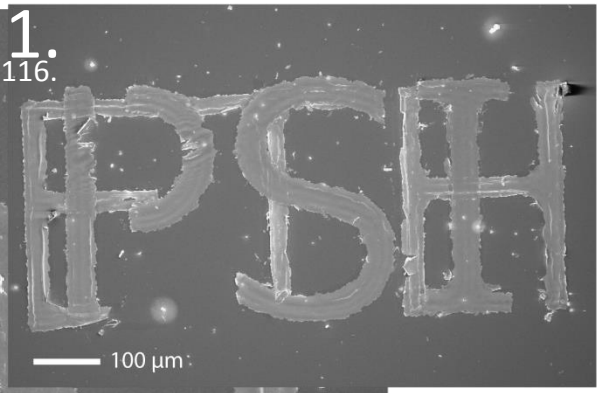




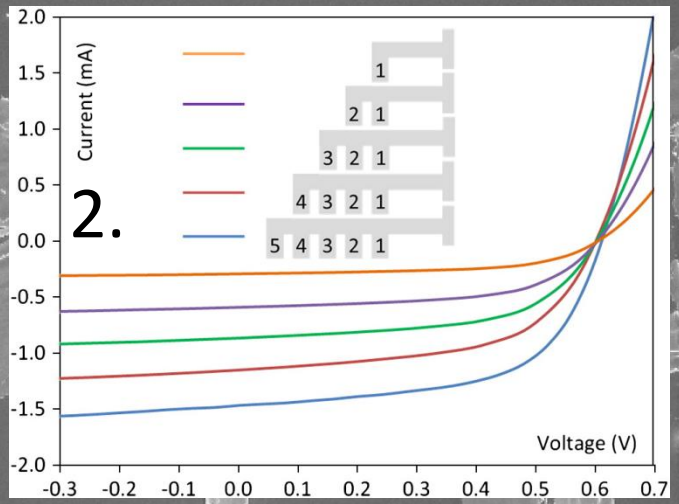
Other applications

Wang et al. (2013). "Fast Chemical Imaging at High Spatial Resolution by Laser Ablation Inductively Coupled Plasma Mass Spectrometry." Analytical Chemistry 85(21): 10107-10116.

- Other applications include:
  1. Scientific research
  2. Organic photovoltaic arrays
  3. Cleaning



1.



2.

100 µm

3.