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Nanofabrication technologies: high-throughput for tomorrow's metadevices

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Fabrication fundamentals

1. Serial versus parallel? ***Most are currently fabricated by serial writing….***

2. Additive or subtractive?

3. Feature size required.

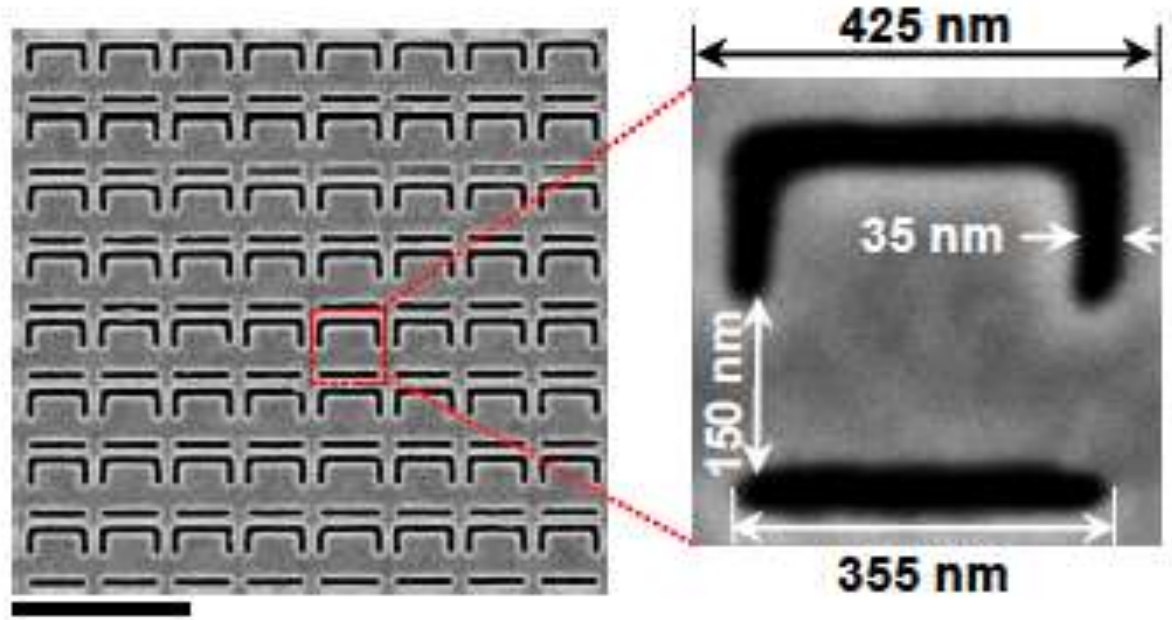
4. One-off demonstration (journal paper) or ***volume production (in the shops by next Christmas…)***

5. What material?

6. ***Cost***….(+ normalise to 150mm diameter wafer)

7. ***Time*** to fabricate

1. Serial fabrication times via FIB



- 1.2 seconds per metamolecule:
- **$0.002 \mu m^3 /s$**
- For a 20 micron x 20 micron device, it took 20-30 mins....
- ...and cost ~£50 in the ZI cleanroom

For a 150mm wafer :
£1,300,000,000 and 2,521 years

S. Savo et al., *Phys. Rev. B* 85, (2012).

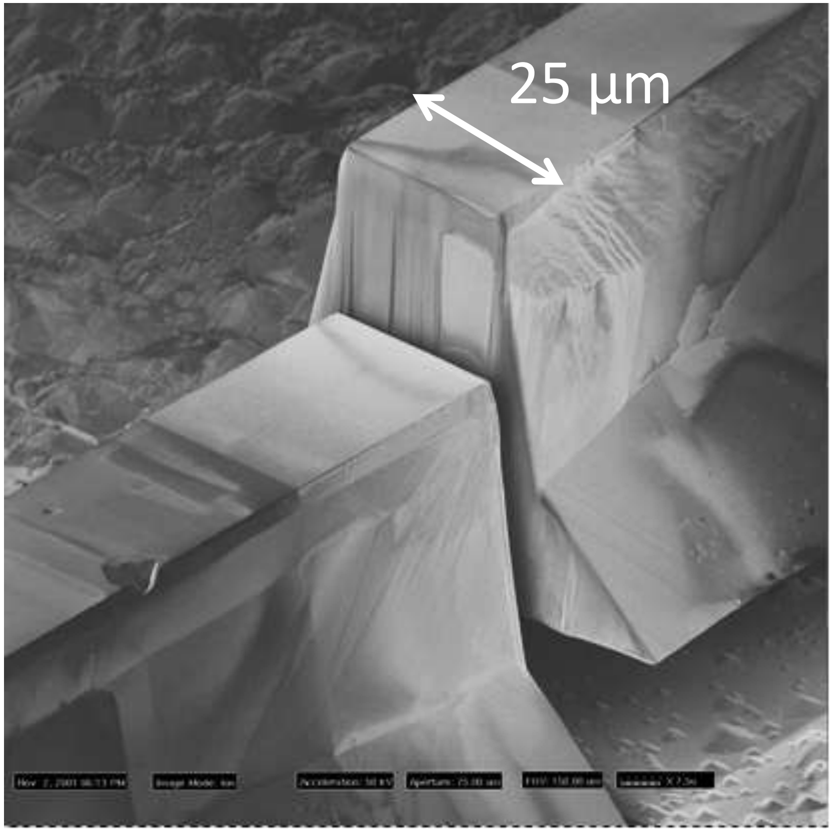
FIB machining times: stainless steel

Table 3
Results of design of experiments for MRR and surface roughness.

Sr. no.	MRR ($\mu m^3/s$)	Surface roughness, *Ra* (nm)
1	0.0106	41.9
2	0.0141	35.6
3	0.2944	59.4
4	0.3193	56.1
5	0.2511	58.5
6	0.2653	68.5
7	0.0067	18.1
8	0.0062	36.6
9	0.0059	32.3
10	0.0093	12.3

Bhavsar et al. Precision Engineering (2014)

$LiNbO_3$ (RWE FIB feasibility grant: EPSRC 2001)



FIB slicing of $LiNbO_3$ cantilever: ~2000µm ^{3} in 1 hour

(**0.5µm³ /s**)

FIB is a very slow and expensive manufacturing technology

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2. Serial writing via e-beam:

- Exposing 50% area of a 150mm diameter wafer.
- Assumed dose is 200µC/sq. cm, appropriate for ZEP 520A, a widely used high resolution resist.

Feature size/nm	**Spot size/nm**	**Beam current /nA**	**Time (hours)**
250	25	25	**172**
100	10	12	**358**
50	5	2	**2150**

2150 hours = 3 months….. (***10^4 times faster than FIB…)***

For mass production, a different strategy is needed

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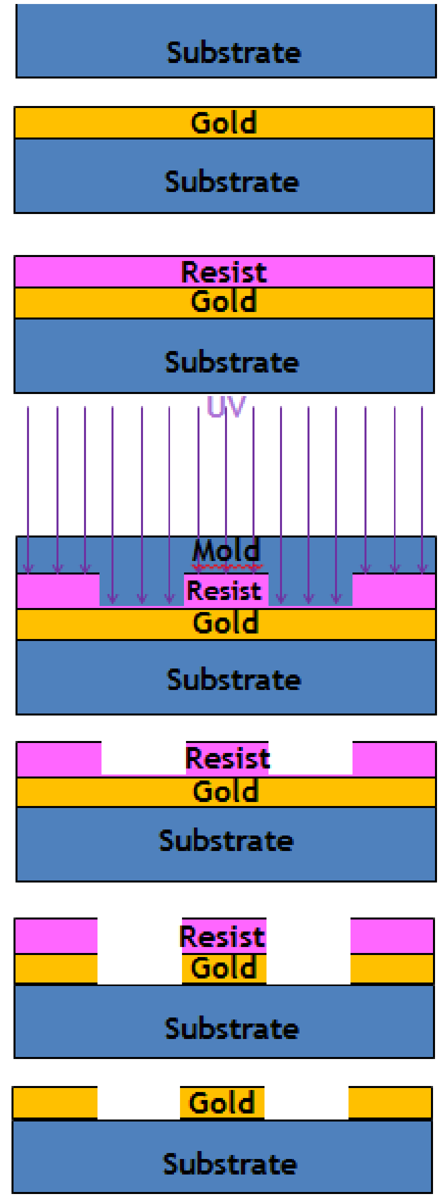
- Micro-contact printing/soft lithography/nano-imprint lithography?
- Parallel writing/image-based fabrication?
- Direct-write/direct print techniques?
- + newer laser-based techniques

For mass production, a different strategy is needed

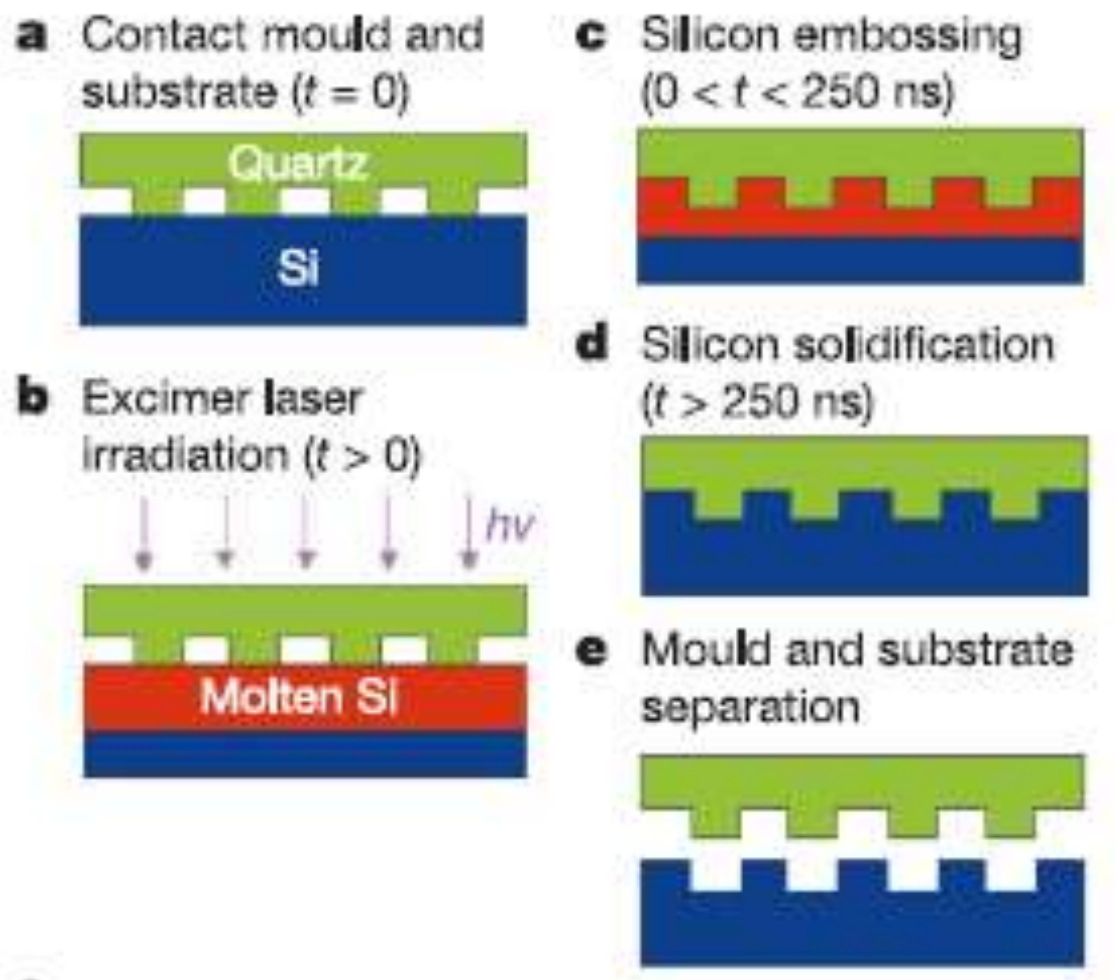
- Micro-contact printing/soft lithography/nano-imprint lithography?
- Parallel writing/image-based fabrication?
- Direct-write/direct print techniques?
- + newer (unproven) laser-based techniques

Nanoimprint lithography

- Clean substrate
- Deposit gold
- Apply resist
- Press mold into resist and cure (by UV exposure or heat depending on resist)
- Remove the mold
- Etch (remove material
- Remove remaining resist

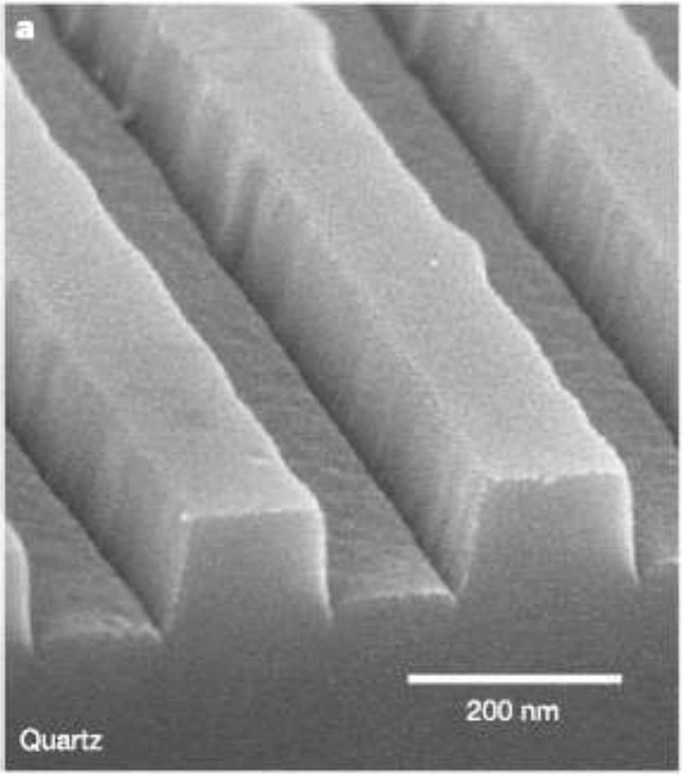


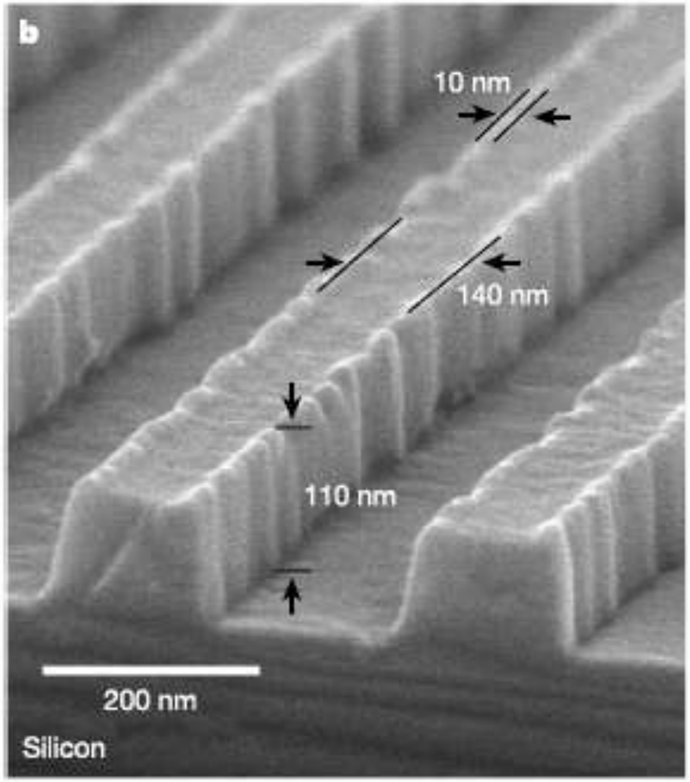
Imprinting into Si: LADI.
Laser assisted direct imprint



Chou, SY et al NATURE Volume: 417 2002

The mould and the imprint





Quartz master

Silicon

But….you do need the master….
+Issues of wear, release, and 'only' 2.5D

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For mass production, a different strategy is needed

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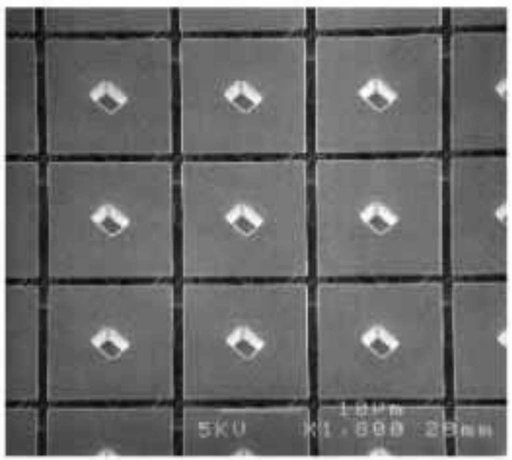
- Direct-write/direct print techniques?
- + newer laser-based techniques

Parallel writing/image-based fabrication
- Laser ablation

- Fast, single shot (ns-fs per image).
- Need ~ 1J /cm^2 laser fluence
- Ablation depths of 30-100 nm per shot.
- Areas of 50μm^2 (fs pulses), and few mm^2 (ns pulses)
- All materials will ablate
- Every shot can have a unique pattern/position

Digital Multimirror Devices (DMD) for laser-based Manufacturing

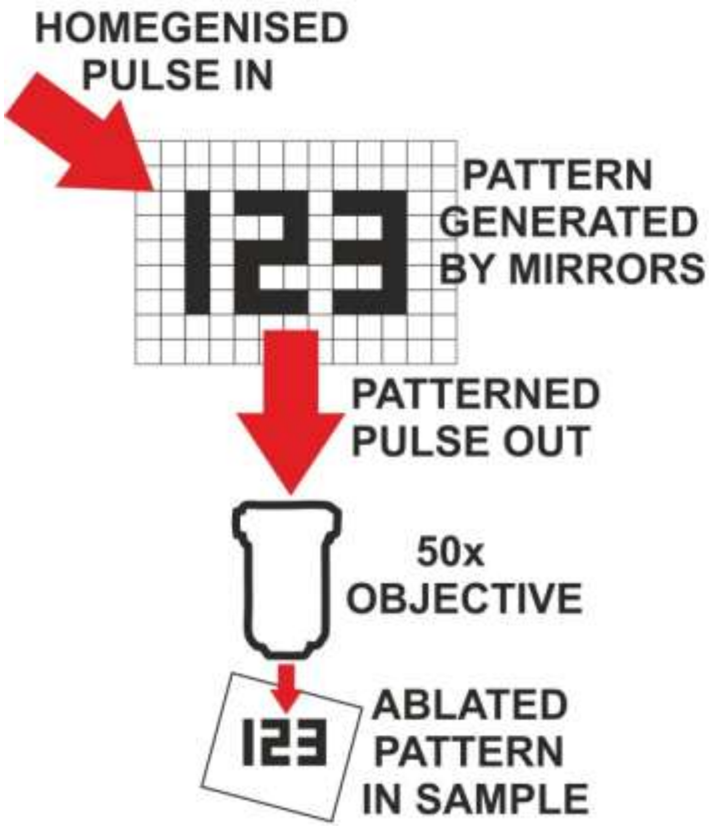
Use programmable mirror arrays to pattern the spatial profile of a laser pulse for applications in **subtractive** and **additive** manufacturing.



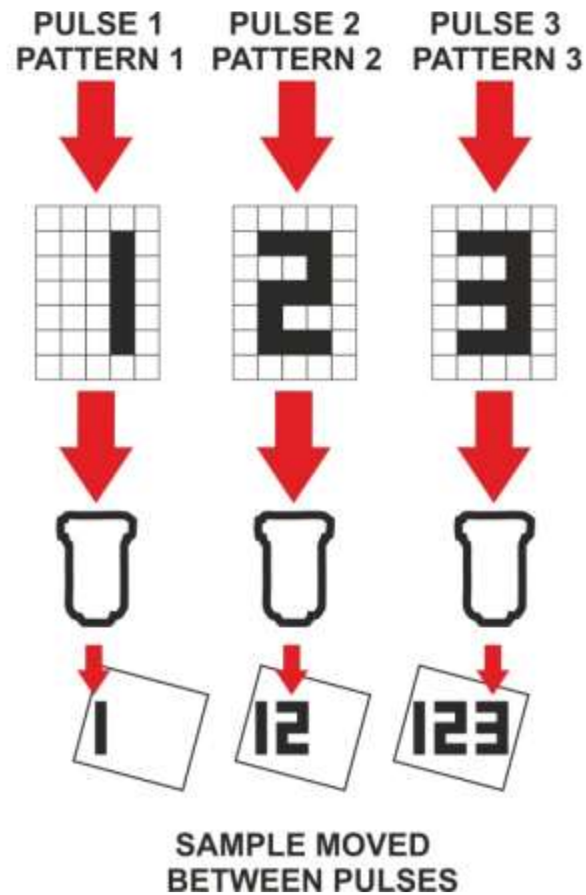
- Array of ~ 1 million individually controlled ~7µm wide mirrors
- Operates across the visible and NIR region
- Can be used as an ***intensity*** spatial light modulator (SLM)

Patterning and laser machining/processing

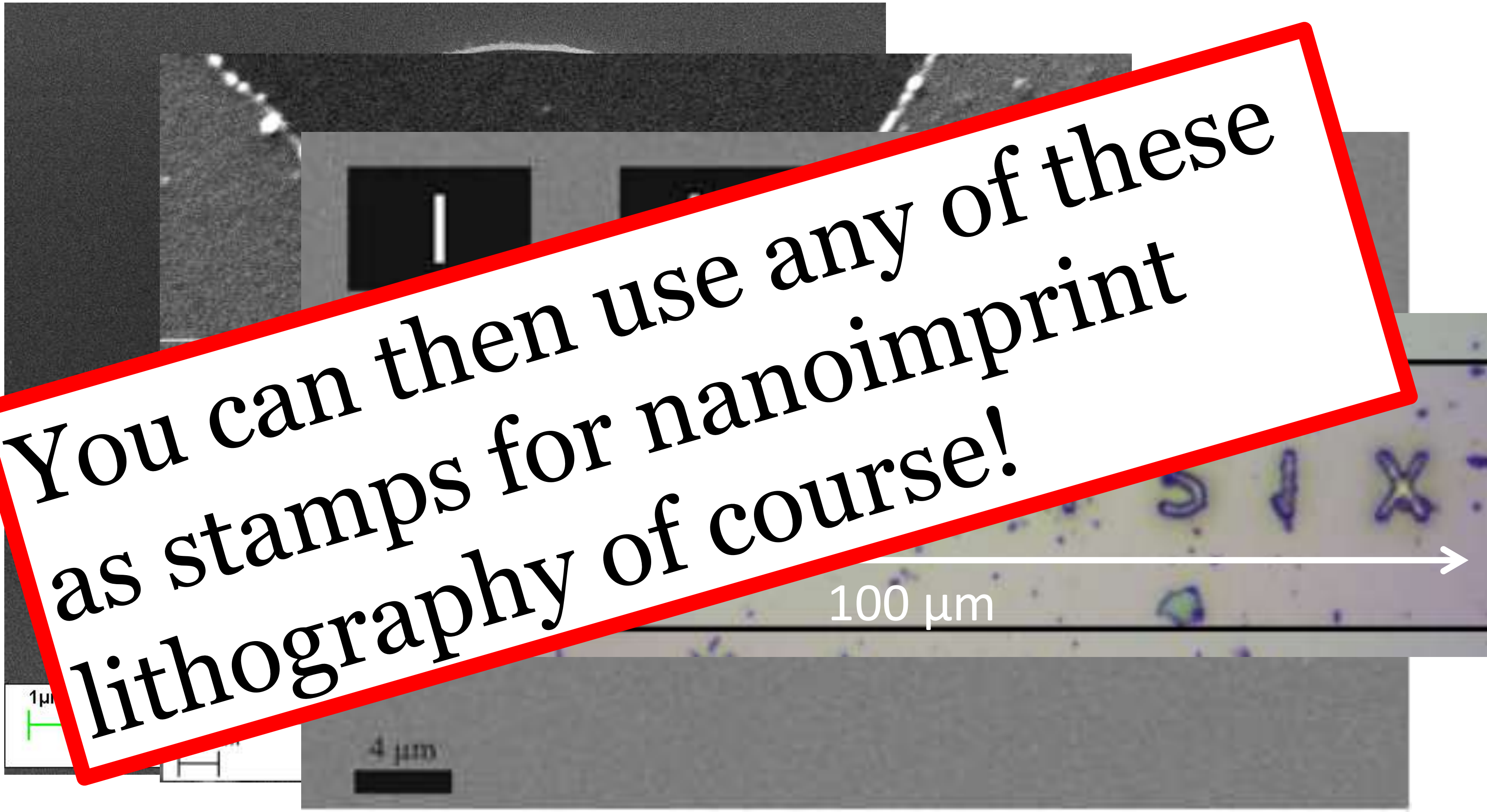
Option 1: single pattern/ single pulse



Option 2: step and repeat



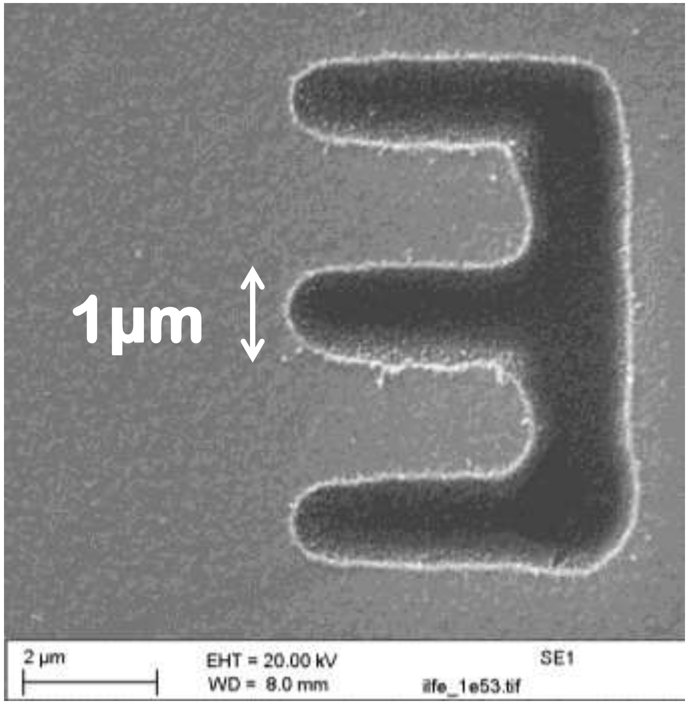
1 Ablative removal:



You can then use any of these as stamps for nanoimprint lithography of course!

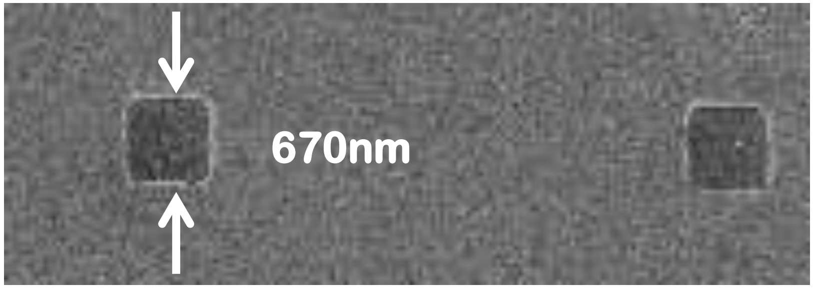
Semiconductors **Metals/alloys** **Diamond**

Close-ups:



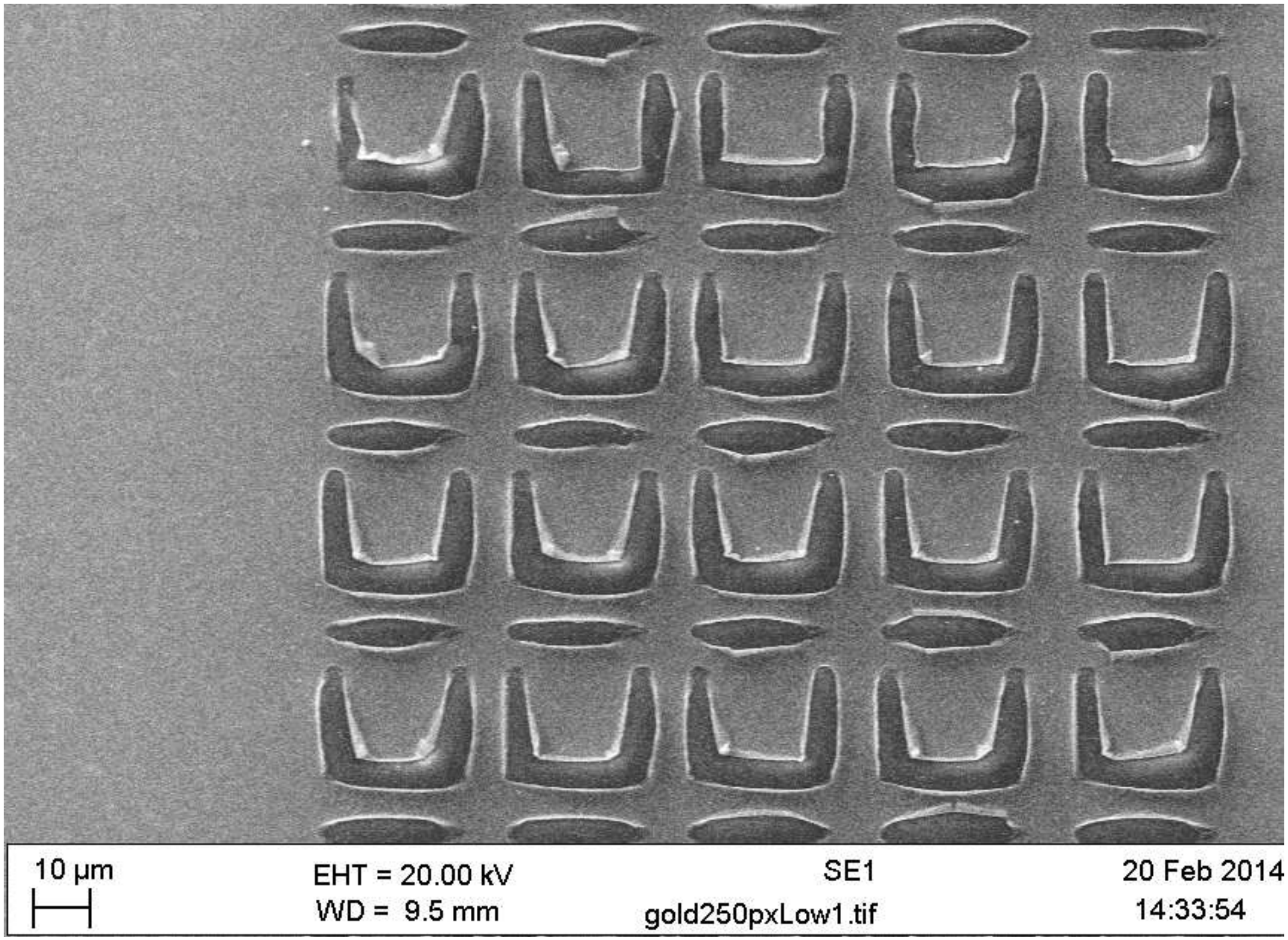
This took 150 fs

= machining rate of ~1µm^3 /150fs



= 3.3 quadrillion times faster than a FIB

Laser-ablated split ring trial: 30 nm Au films



Each split ring is single shot, and takes 1ms

So far, ~25 µm sizes, but can go smaller to the ~µ scale

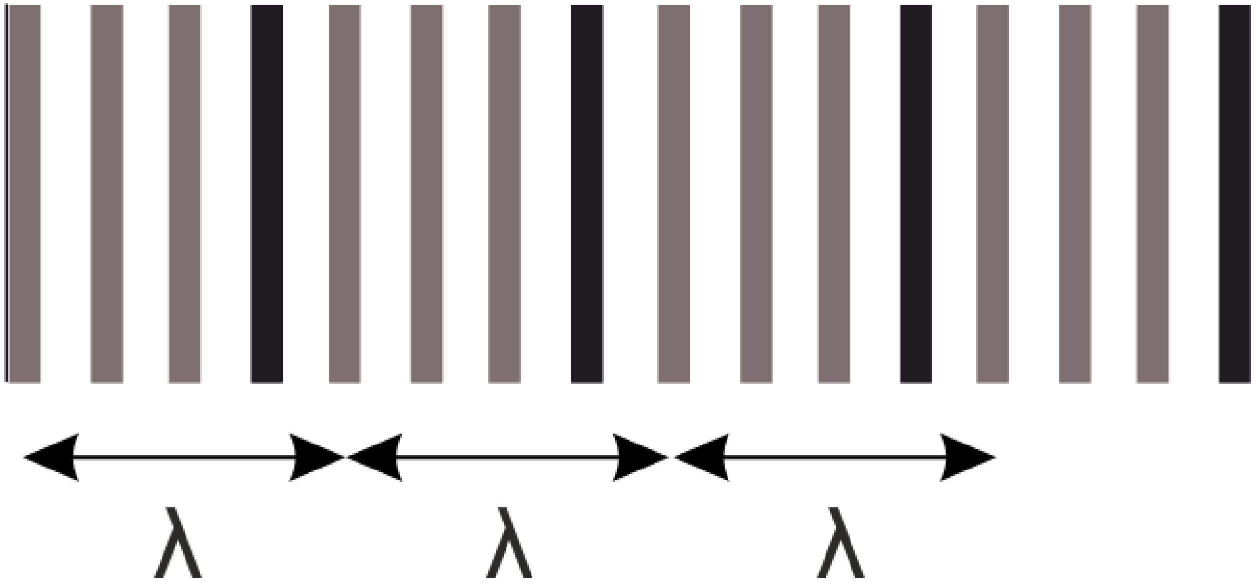
And can you 'beat' the diffraction limit?

FEATURE SIZE

- Single pulse (150fs) ablation, using λ=800nm
- Have seen ~100nm single feature size

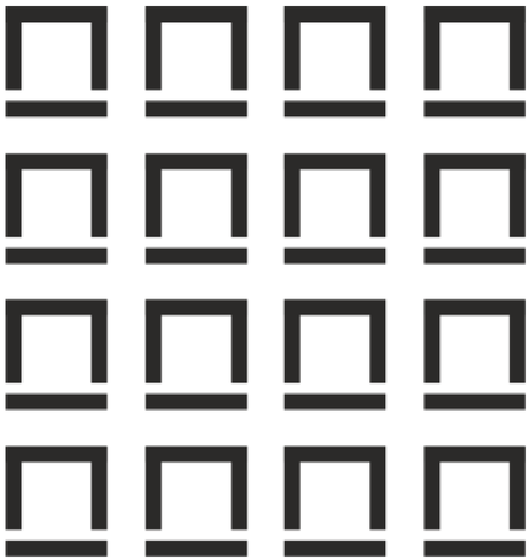
RESOLUTION

- Ability to *resolve* or *ablate* close adjacent features
- Limited by λ (800nm)
- We've achieved 700nm
- Cannot beat diffraction limit



N pulses, can give λ/N resolution

‘Beating’ the diffraction limit (in 8 shots)

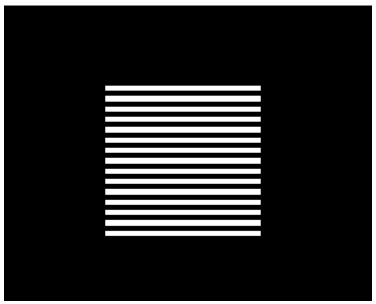


Final split ring structure would have << λ features

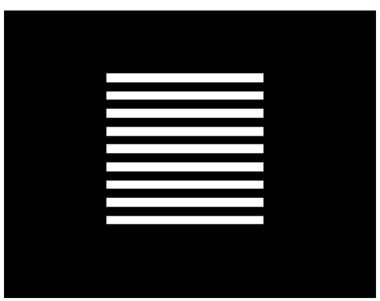
How fast can you do this?

Direct writing of gratings: 6300 Gratings, Actual time = ~4 minutes, best possible time = 6.3 seconds

How they appear on the DMD

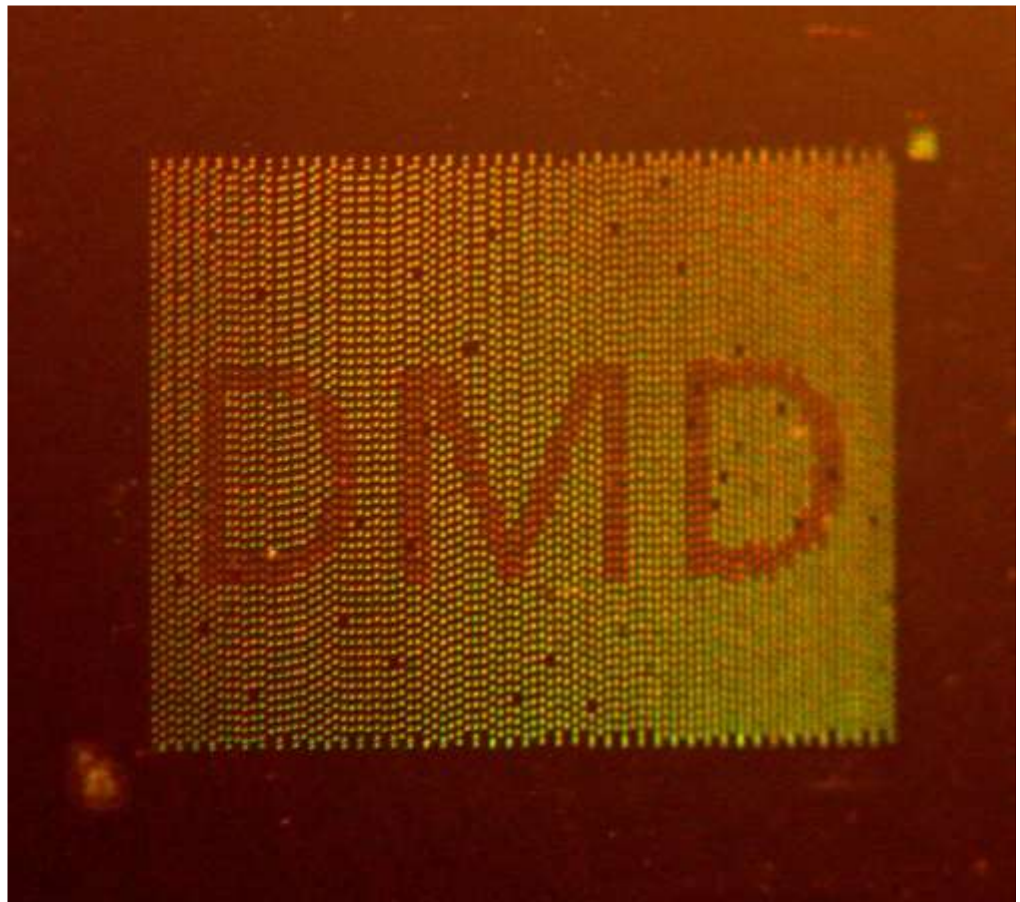


Each line 10 pixels wide

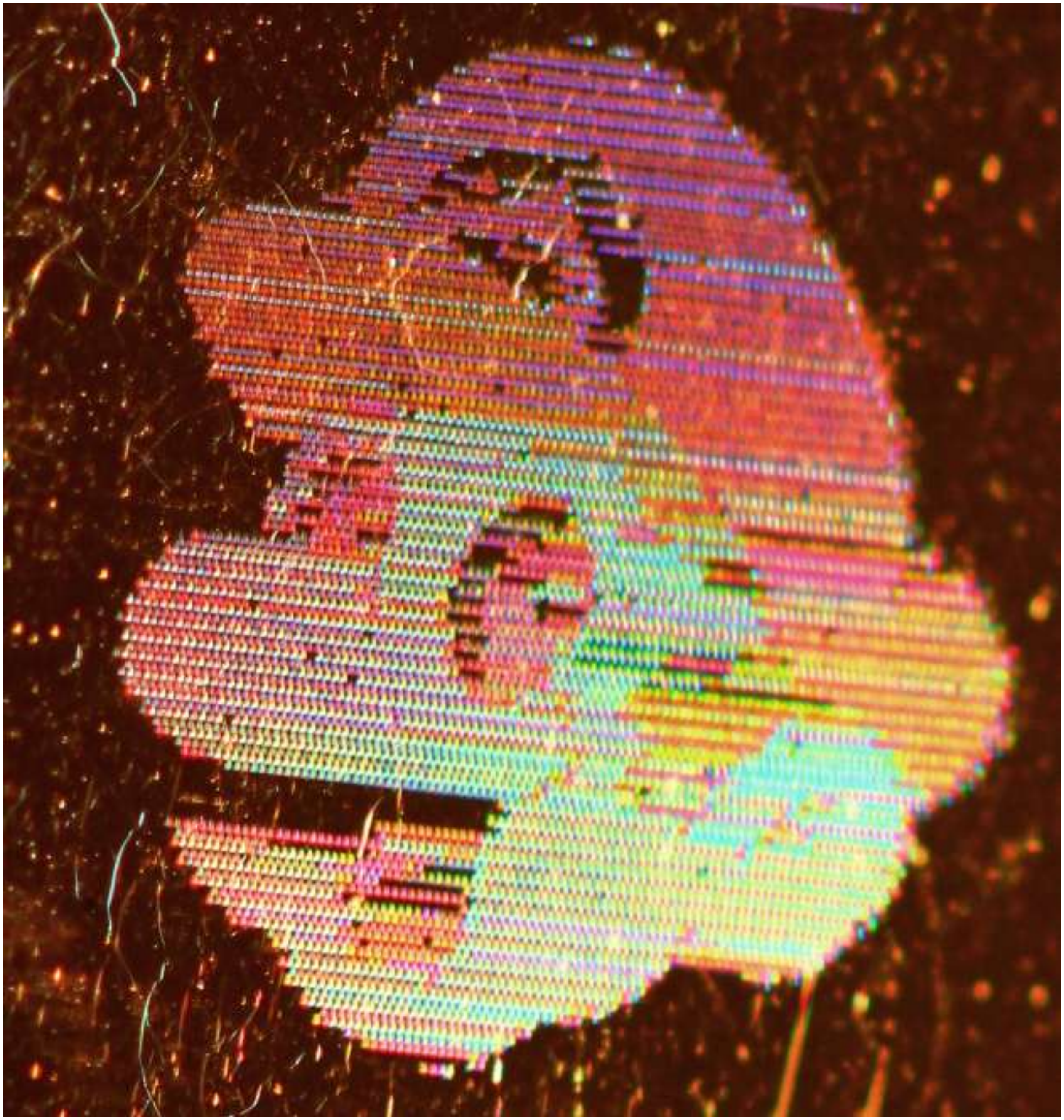


Each line 17 pixels wide

4.5x3.5mm total area, each pixel in image a grating of 30x30μm



Any image can be displayed on DMD for each pixel of course, not just gratings (though they look macroscopically attractive).



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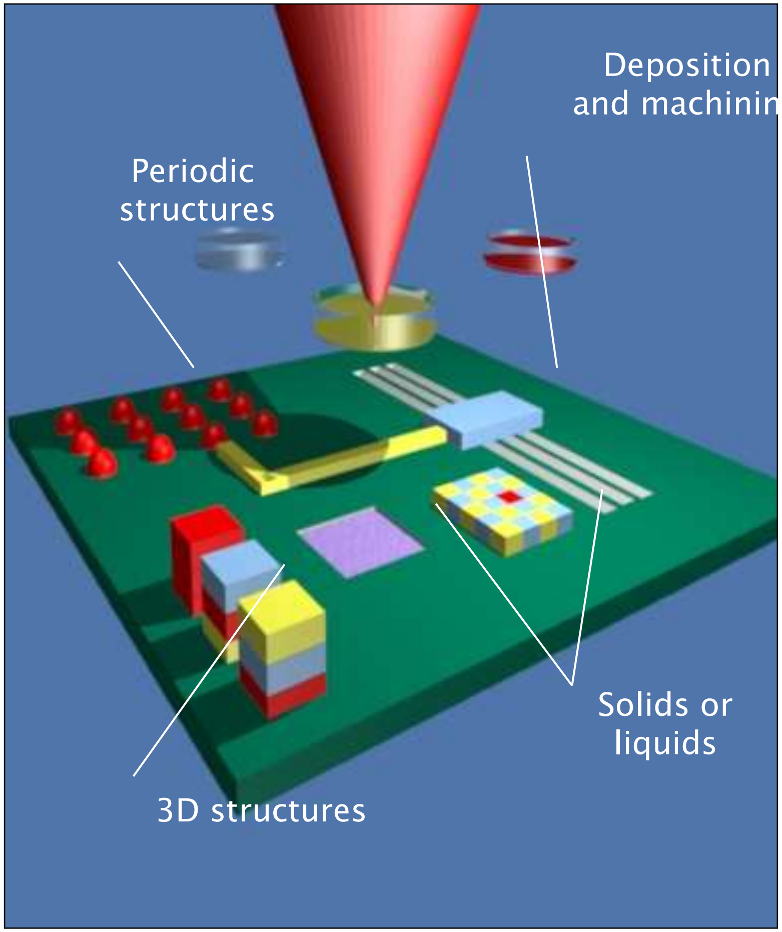
Direct writing/printing of metal (**serial**)

Renishaw: AM250 laser melting (metal 3D printing) machine – but large scale…

	AM250
Max. part building area	245 mm x 245 mm x 300 mm (X, Y, Z) (360 mm Z axis by request)
Build rate*	5 cm^3 - 20 cm^3 per hour
Layer thickness	20 µm - 100 µm
Laser beam diameter	70 µm diameter at powder surface
Laser options	200 W
Power supply	230 V 1 PH, 16 A

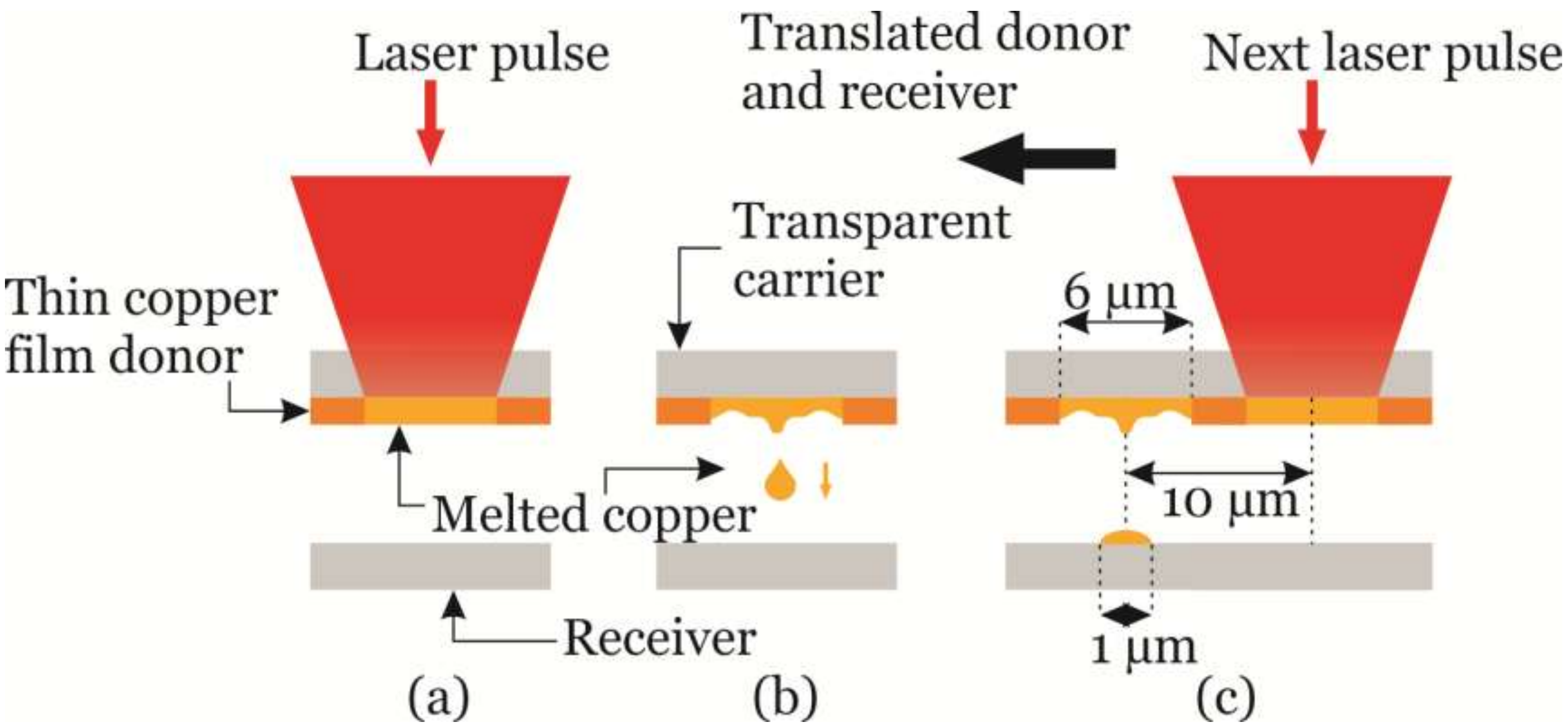
The power of Additive Manufacturing

Additive printing via Laser-induced forward transfer, LIFT



- Ultrashort regime → can ablate most source film materials.
- Deposition onto wide range of receiver materials and geometries.
- Fast and relatively simple.

Metal printing with LIFT (**serial**): donor replenishment

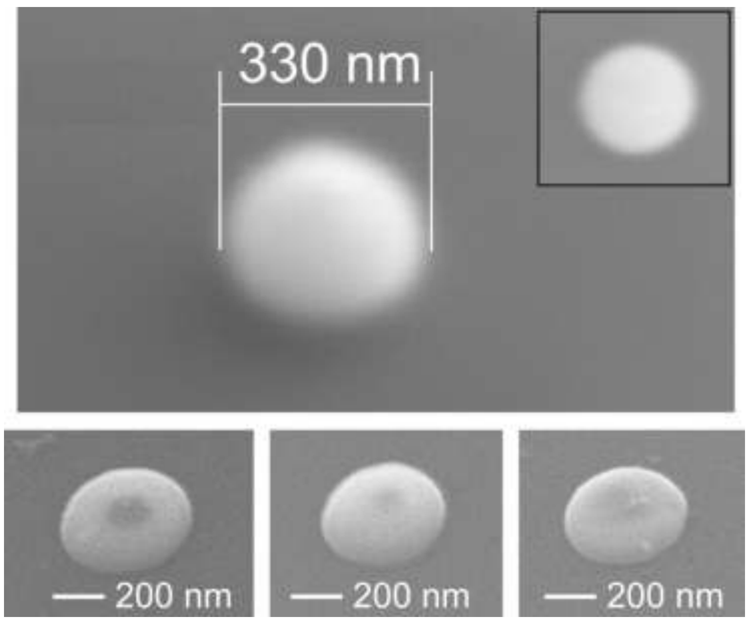


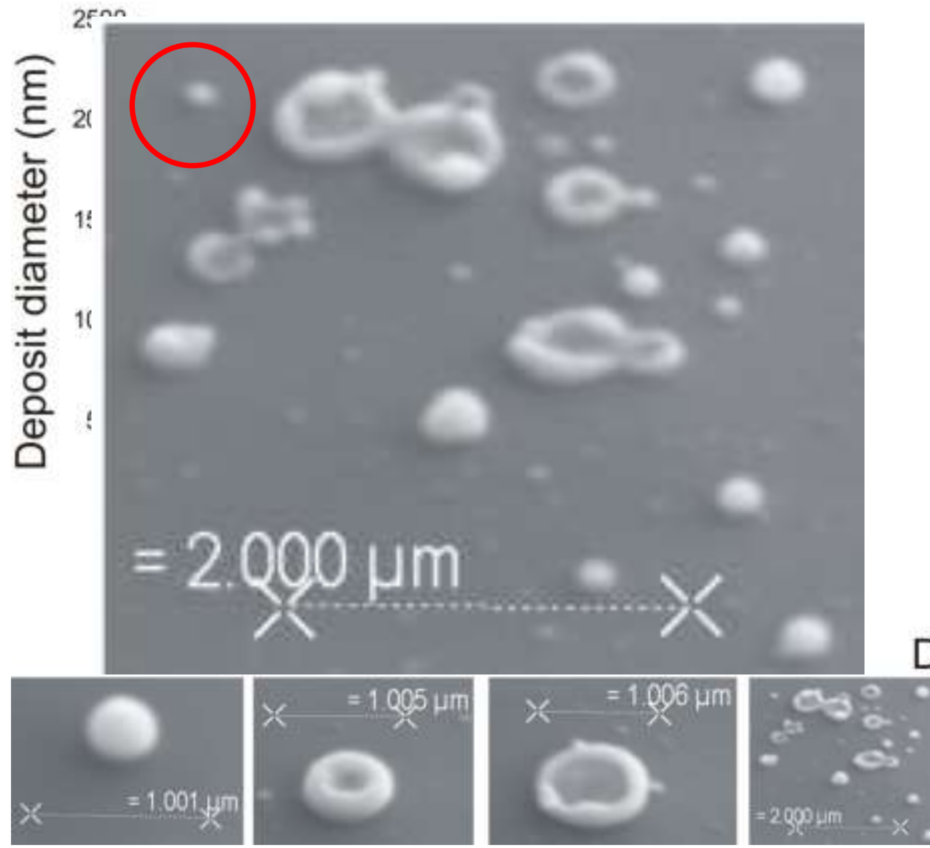
Nanodroplets: printing of metals

Details:

Donor – 30 nm Cr (i.e. comparable to absorption depth at 800 nm).

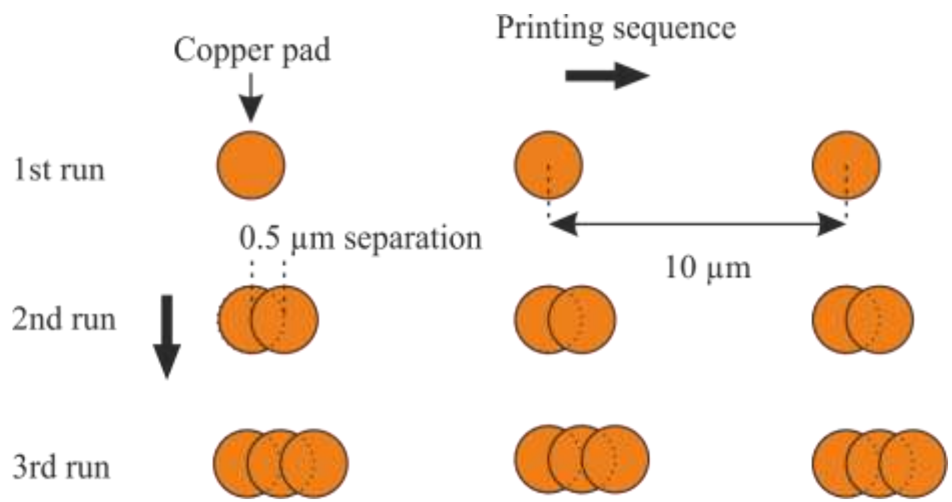
Donor-receiver separation <5 μm, controlled by Mylar spacers.





D.P. Banks, C. Grivas, J.D. Mills, I. Zergioti, and R.W. Eason, *Appl. Phys. Lett.* 89, 193107 (2006).

Printing overlapping process



1st run: Donor and receiver translated together .

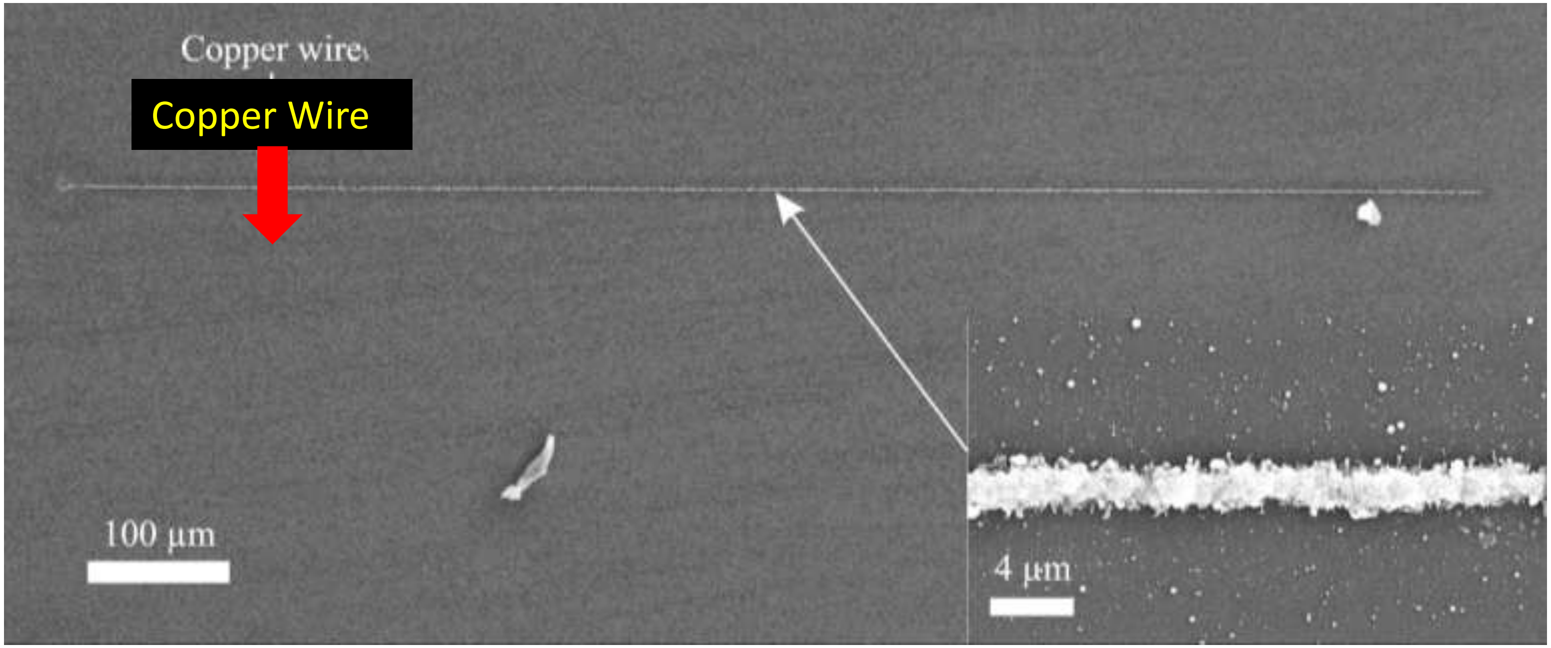
New undisturbed region of the donor used in LIFT process.

2nd run: Receiver was translated by 0.5 µm with respect to the laser focus, for next print run.

Nth run: After n sets of replenishments, a 1 mm long wire is produced.

Printing of 1 mm long wire

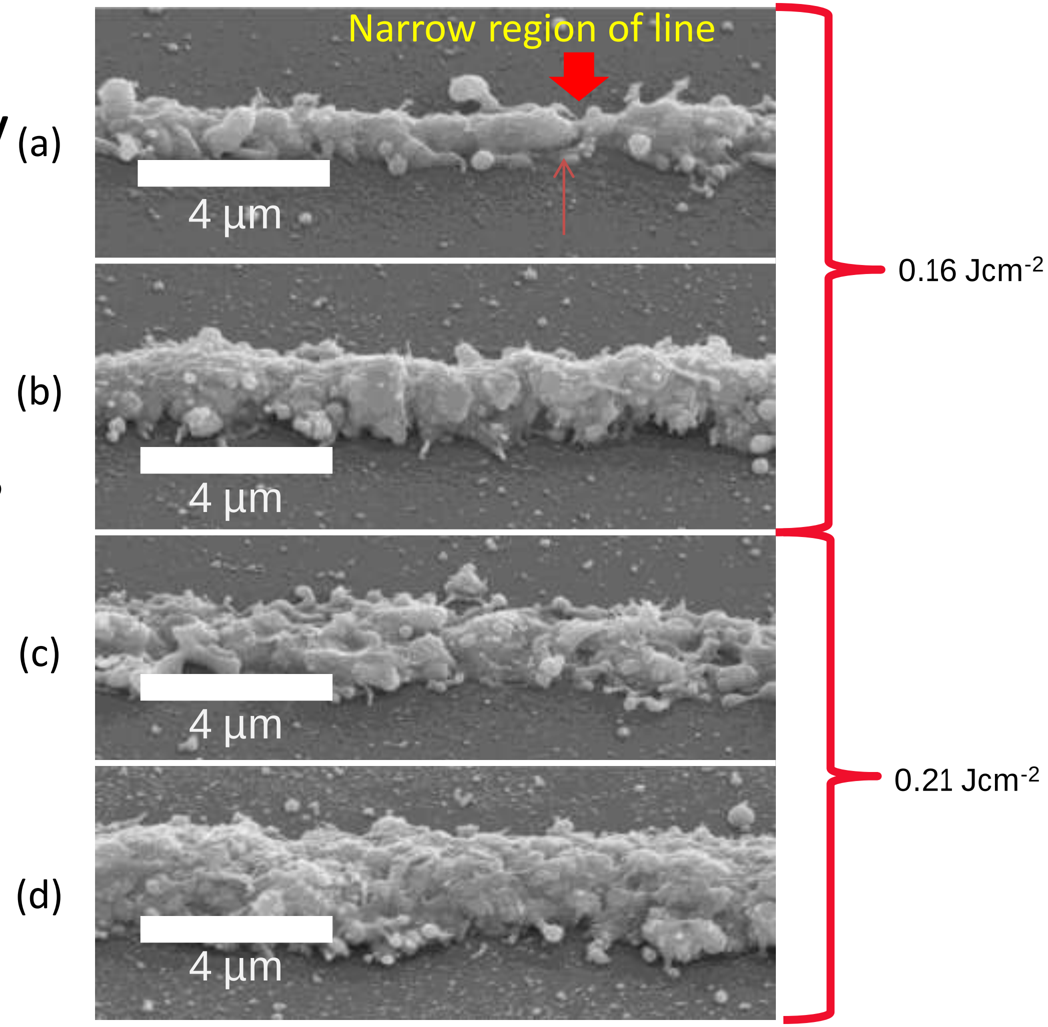
- 1.6 µm wide, 800 nm high, 1 mm long copper wire.
- No sintering process needed.
- Took **10 mins**, but could be 10 s with automated software



Grant-Jacob et al, *Optical Materials Express* 2013

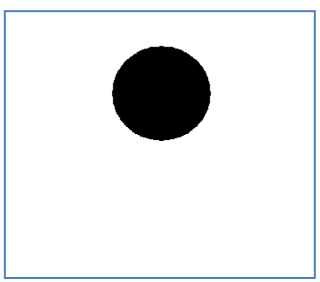
Printing of multiple lines

- Lower laser pulse energy densities produce thinner wires
- Rapid fabrication possible over large areas
- Higher energy densities produced greater splatter

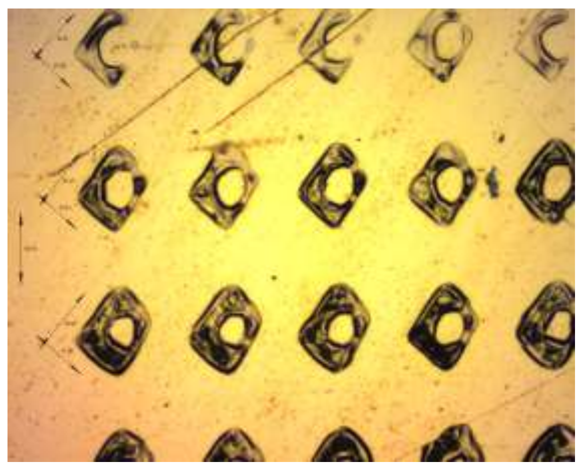


Spatial shaping of the laser pulse:
Texas Instruments **DMD mirror arrays**
(Parallel/image-based fabrication)

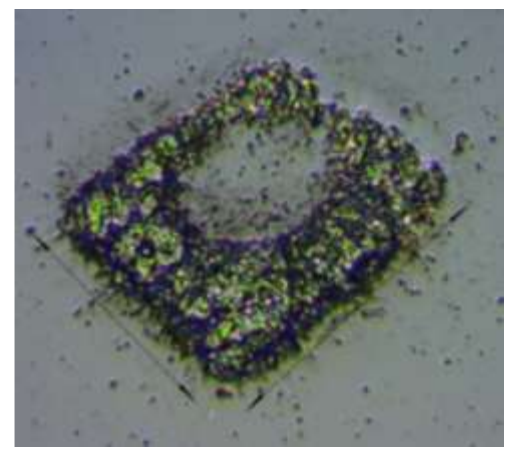
40μm x 40μm



Pattern on the DMD

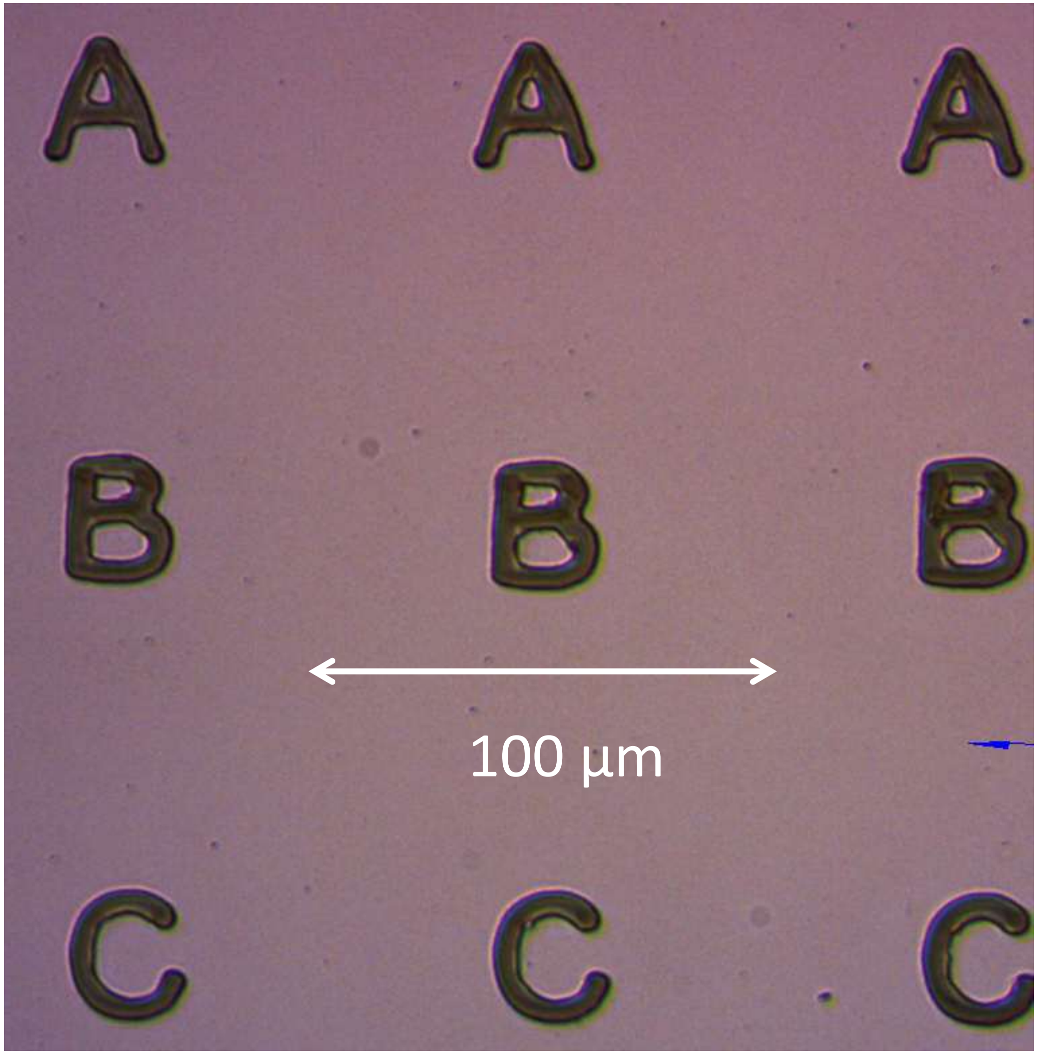


Pattern on the donor film



Final LIFTed feature (Au on Si).

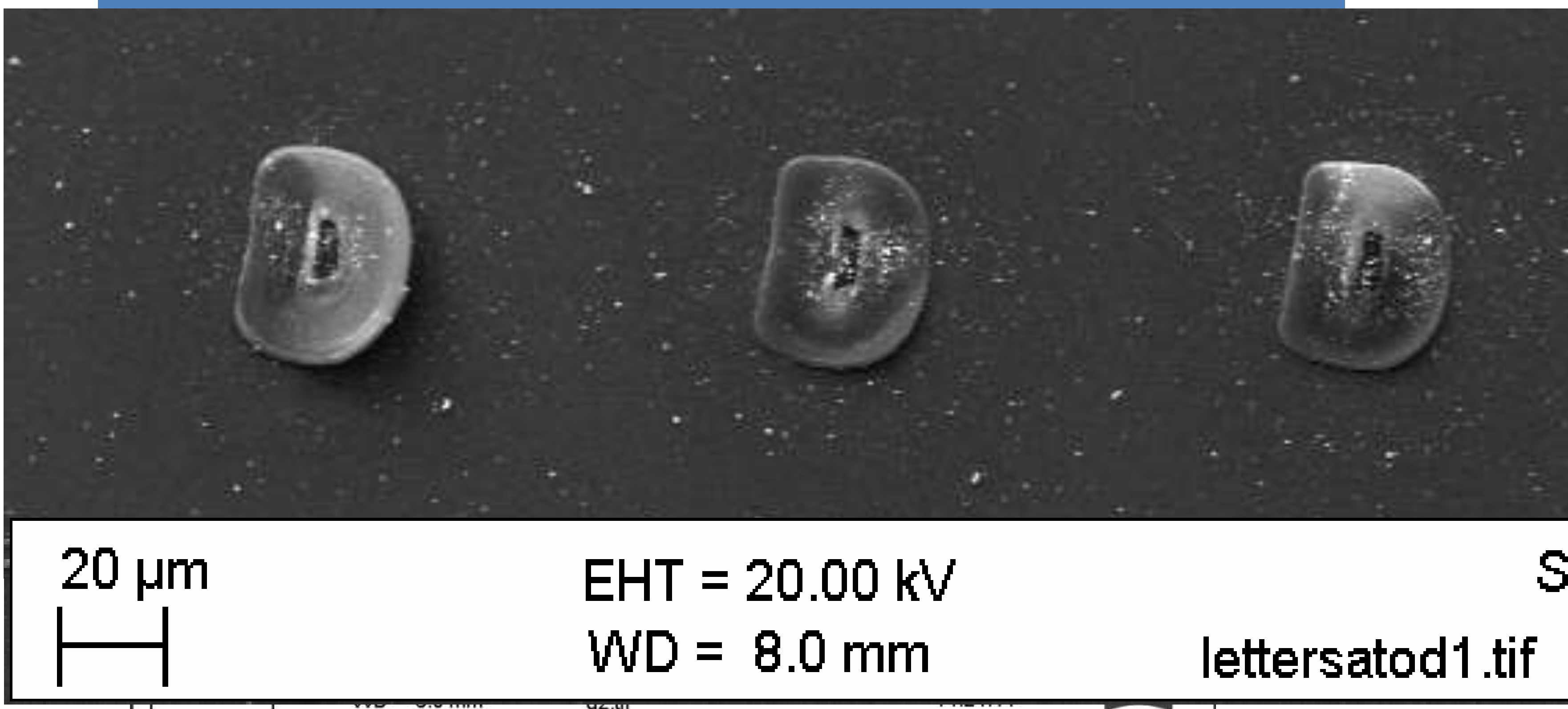
700nm thick Si films: the donor



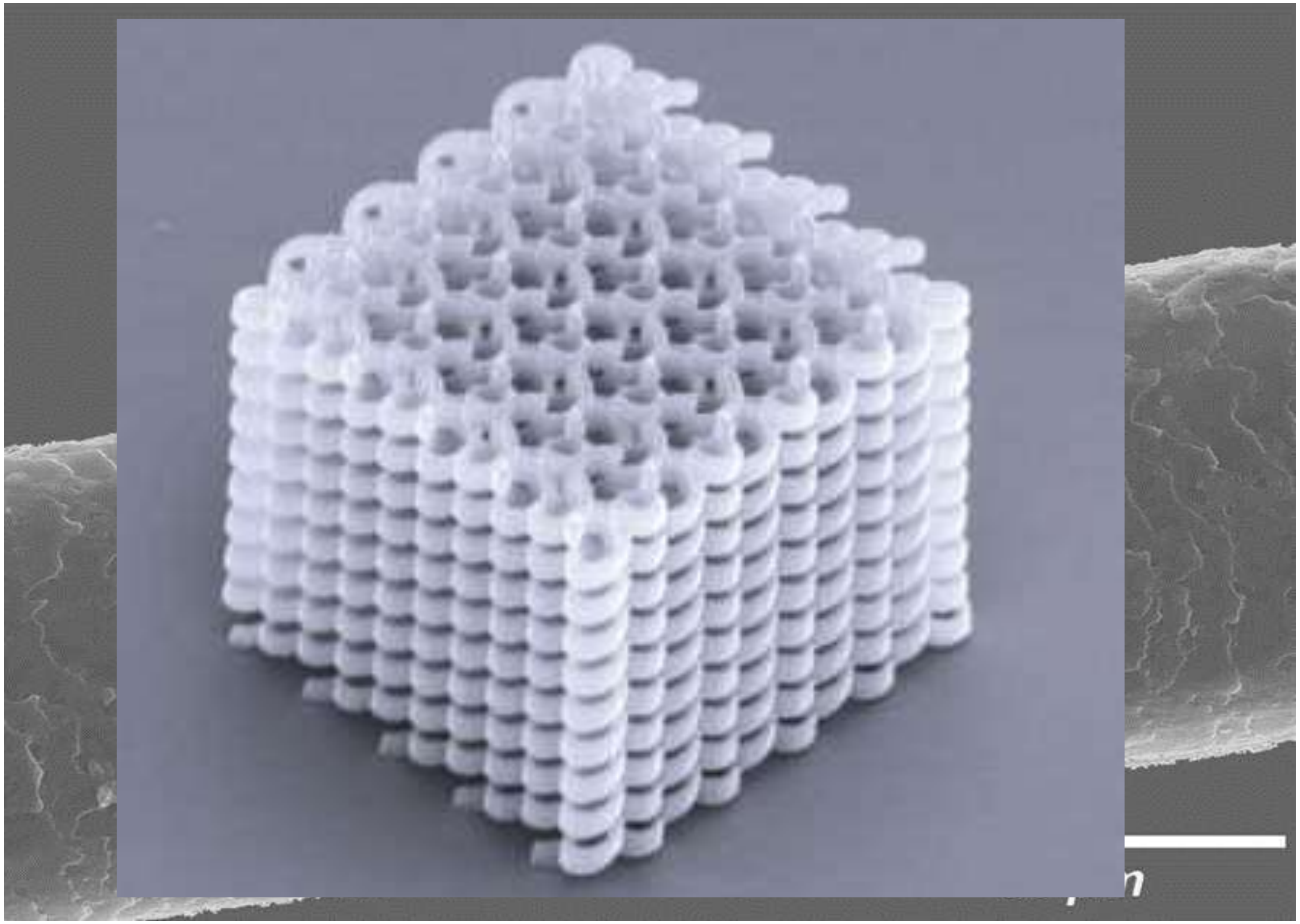
Most recent DMD LIFT results

New laser 3D printing facility…An ORC breakthrough

New 3D printing technology!

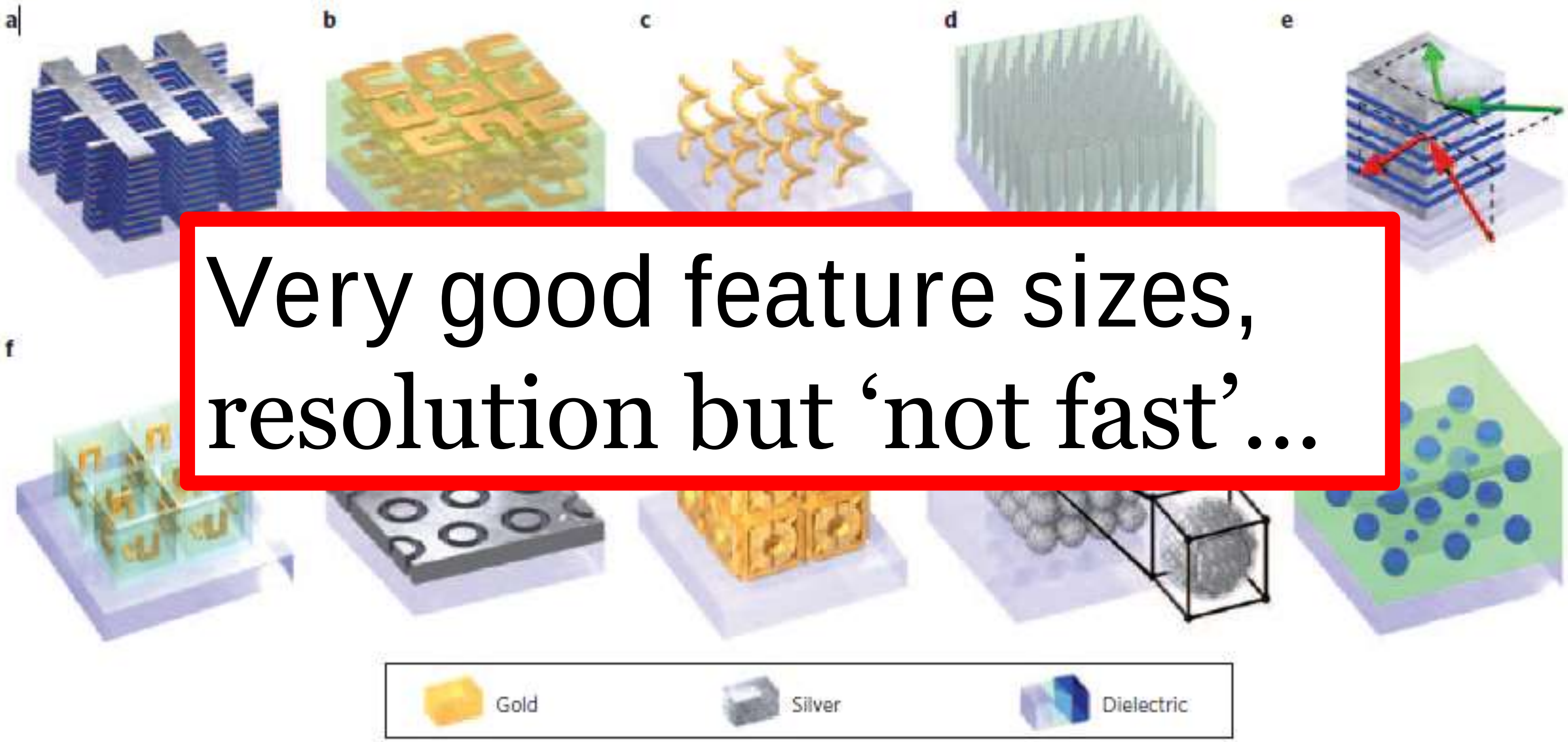


Multiphoton writing (serial printing)



Laser Zentrum, Hannover, + Nanoscribe....many others

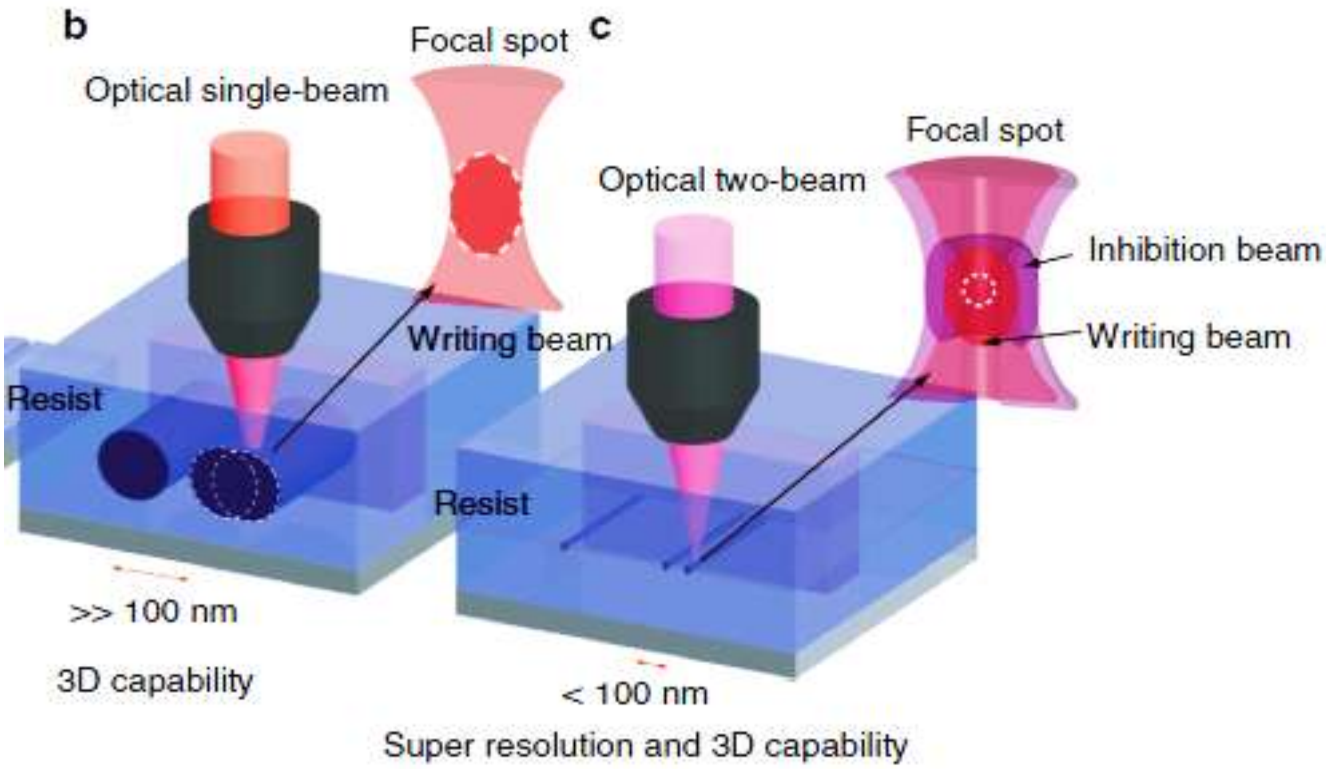
The full potential….but all serial processing



Very good feature sizes, resolution but ‘not fast’…

Soukoulis and Wegener, Nature Photonics, 2011

Current size record: 3-d two-photon writing: 9nm feature size (serial however)



52nm two-line resolution: scanning speeds of up to 160µm/s

Gan et al, (Min Gu) Nature comms 2013

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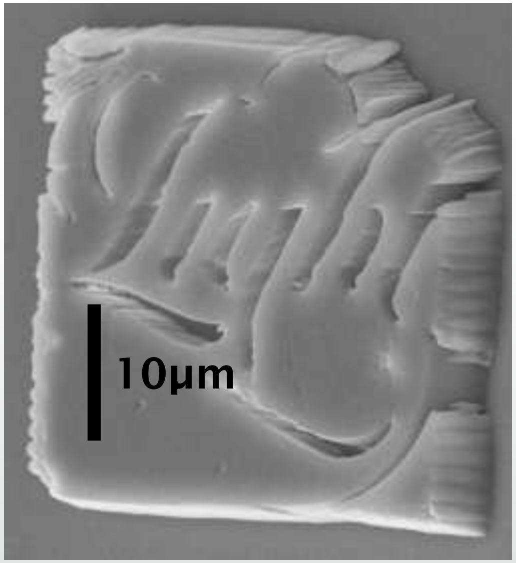
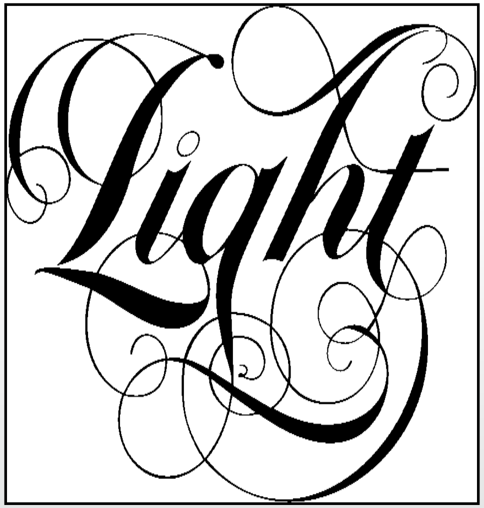
We have adopted an **image-based approach** for multiphoton printing

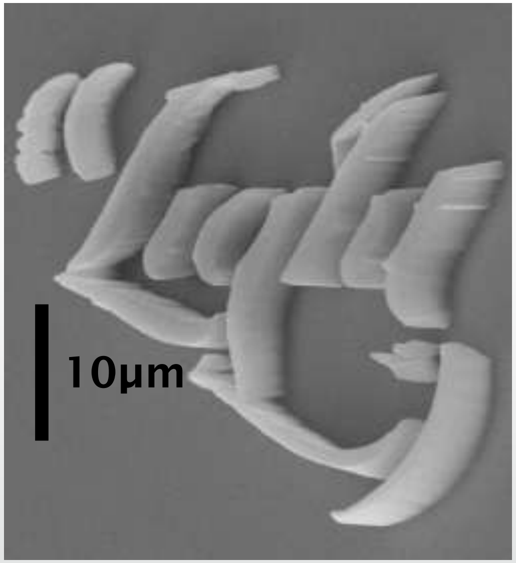
Feature size can be ~400nm (~λ/2)

+ contrast

- contrast



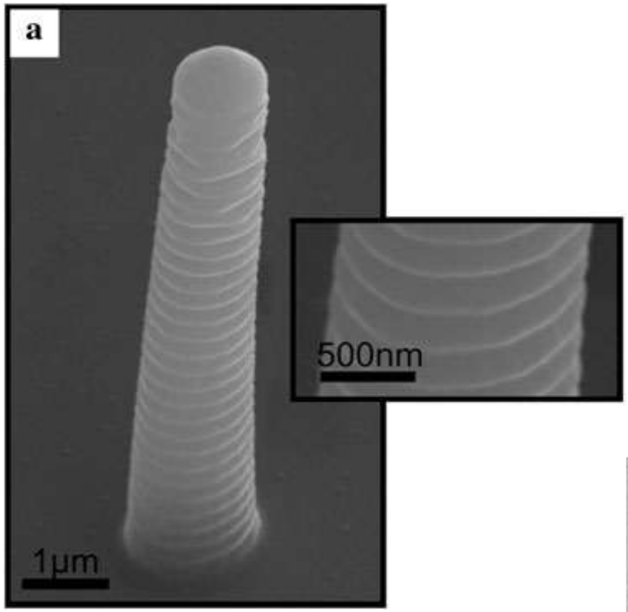


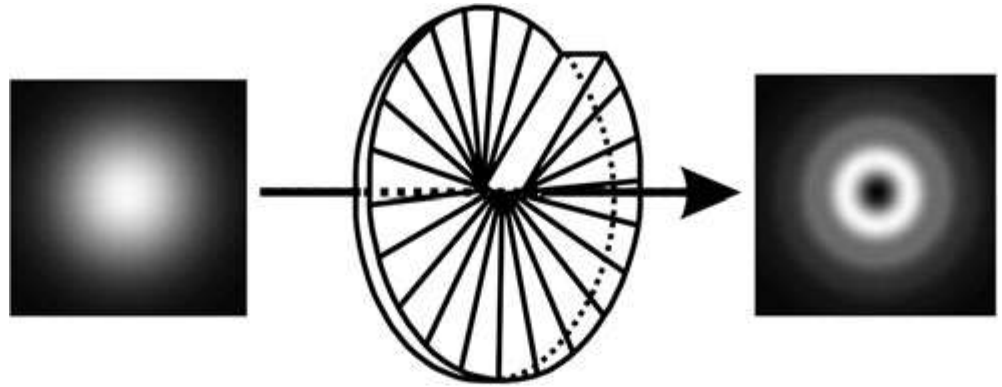


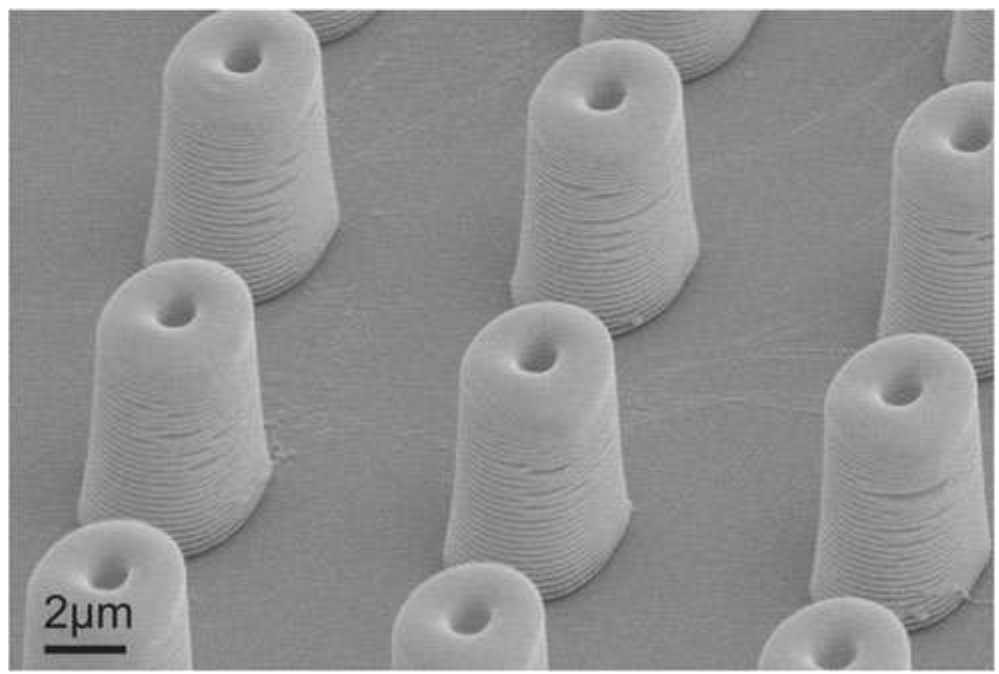
Arbitrary structures can be printed at < λ feature sizes, in a single shot

Mills et al,
Optics Express 2013

Single shot: 3-d structuring







Mills et al, Appl Phys A, 2012

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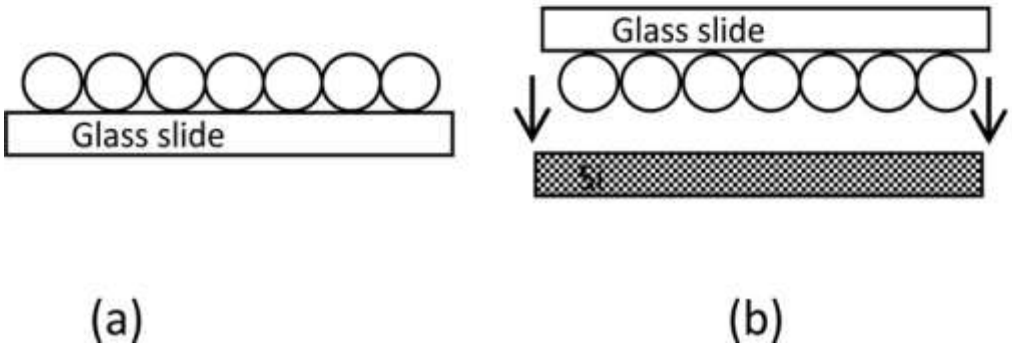
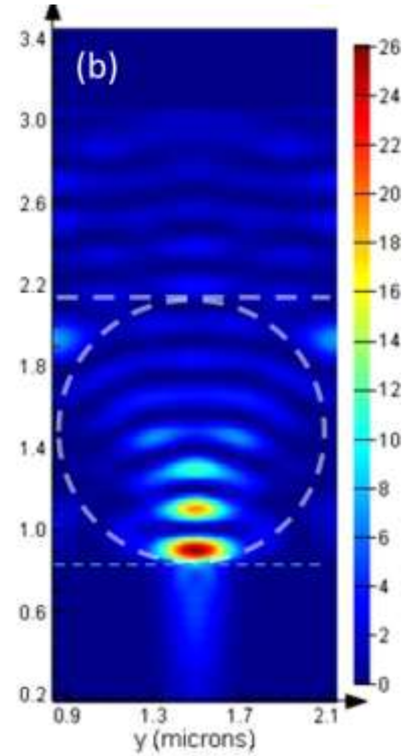
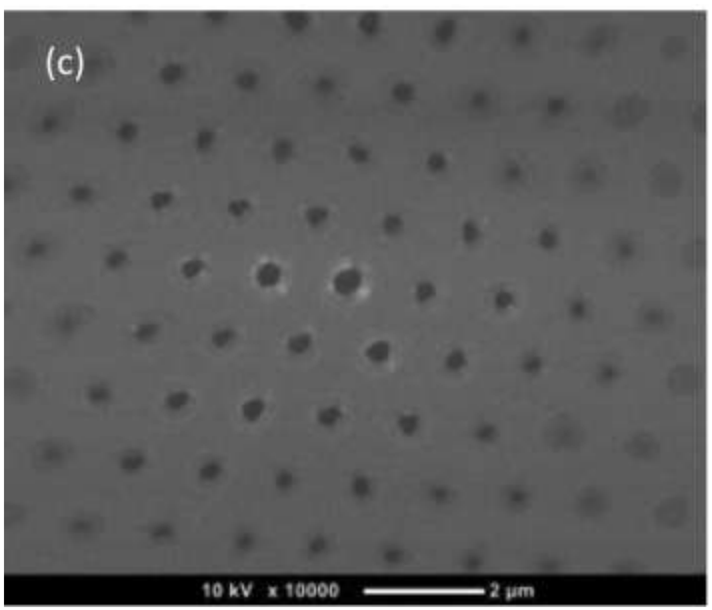
- + newer laser-based techniques **with some potential...?**

Micro-sphere array for nanohole production.







Xxx Sedao et al, JAP, 112, (2012)

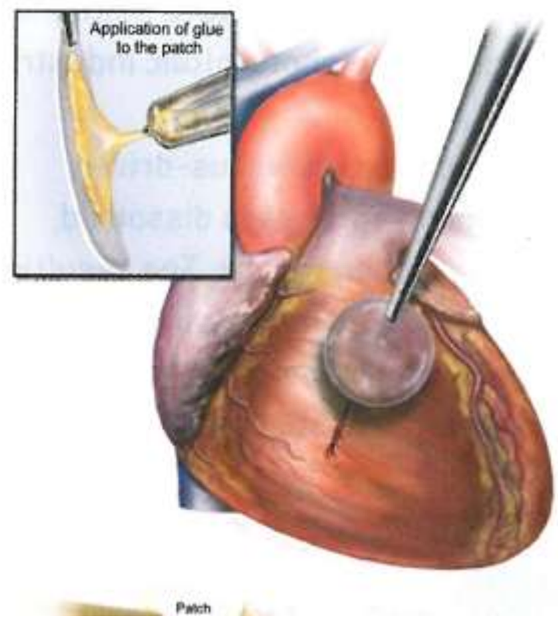
Single shot, and maybe only one shot possible!

Light-activated processes

BIOMEDICAL

Light-Activated Glue **Mends Heart**

To make surgical heart repairs less invasive, surgeons need tools and materials that can work in confined, wet spaces. A team of physicians and biomedical engineers based in Massachusetts has developed a light-activated glue that binds to blood vessel walls and beating heart tissue (Sci. Transl. Med. **6**, 218ra6).



Optics and photonics news March 2014

Light-activated etching?

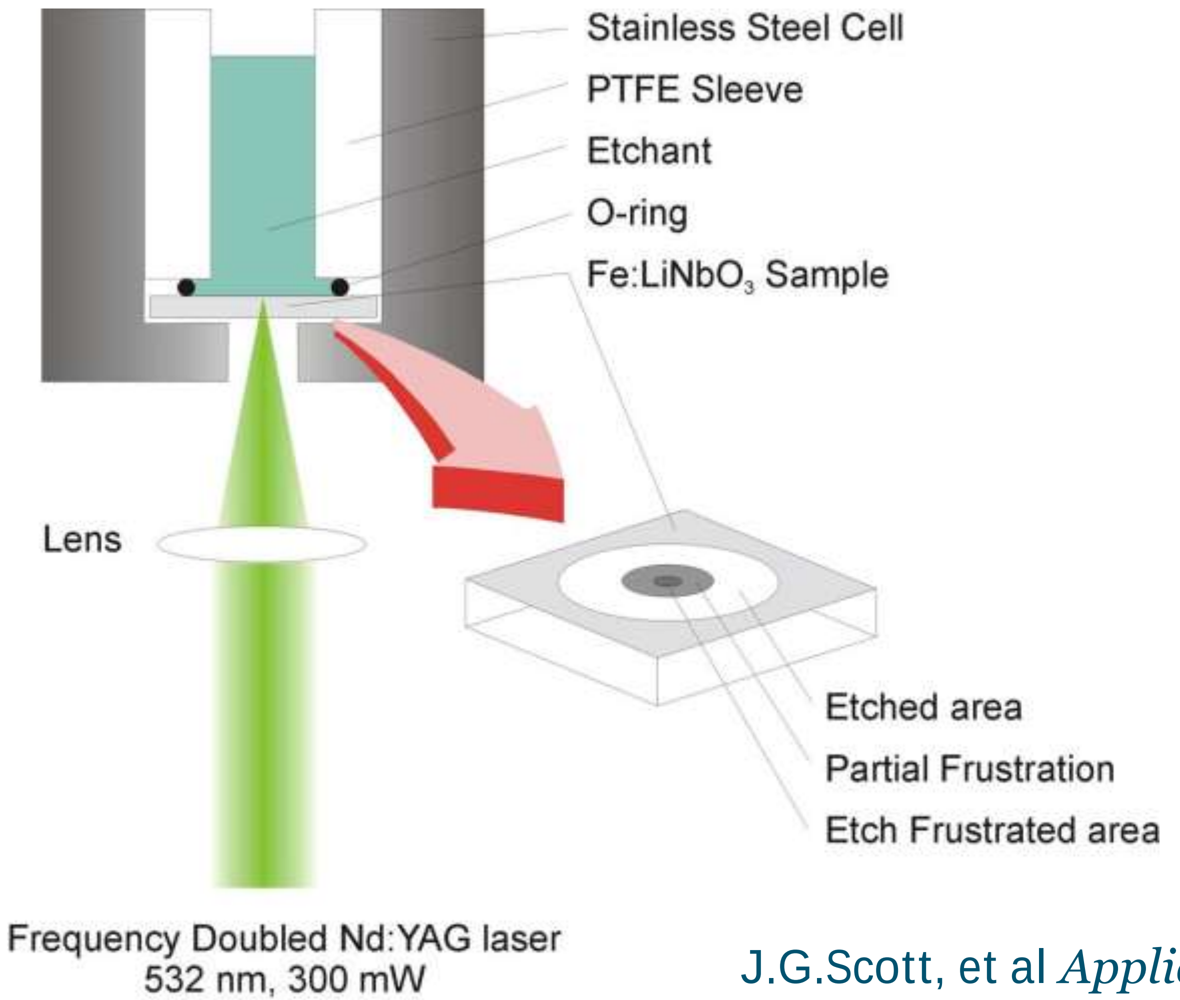
Spin coat a film onto a substrate

Scan laser in the desired pattern over the interface between film and substrate

Laser light photodissociates the film to produce reactive (acid) species

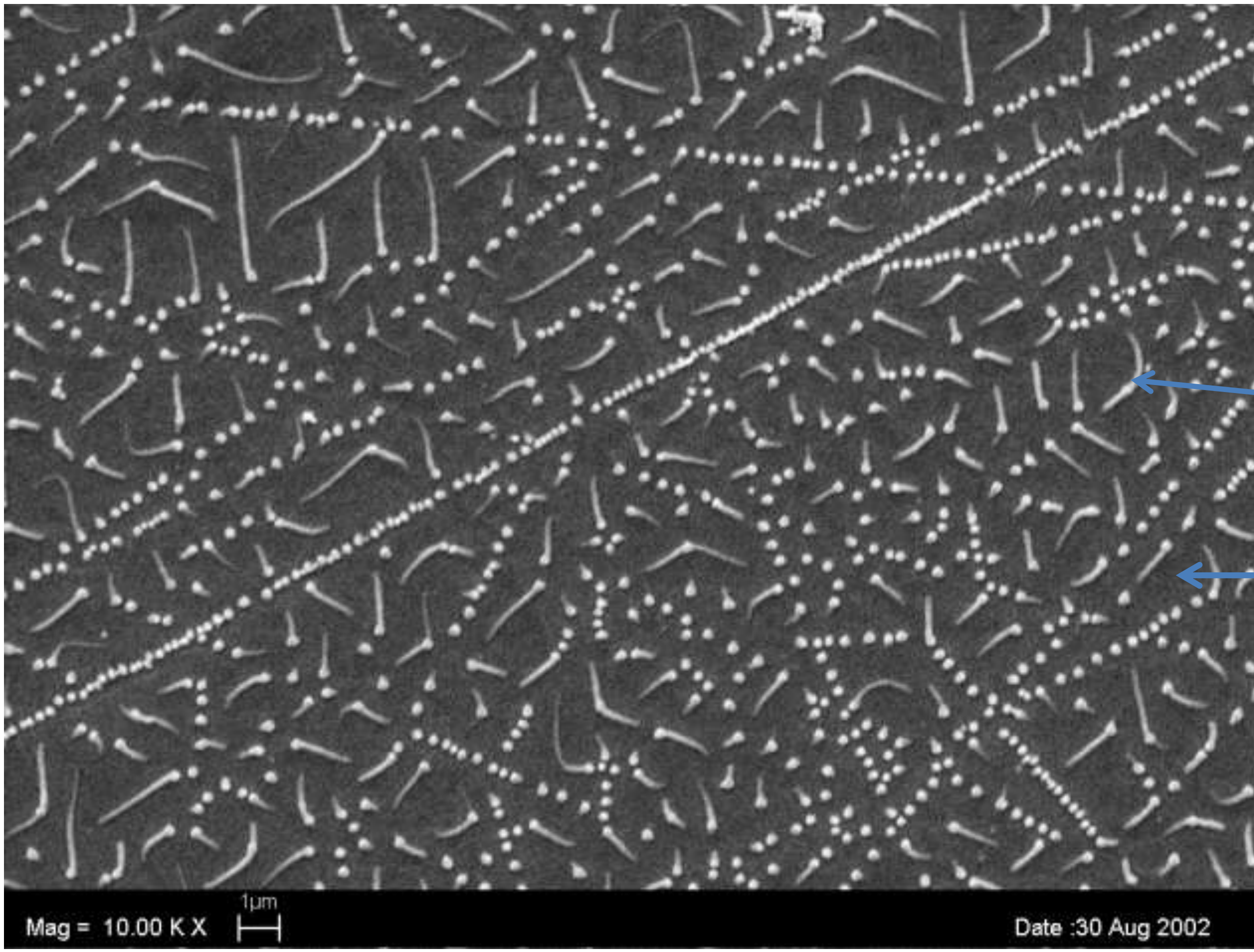
Control etching depth and diffusion length by material design.

Light-activated etching in $LiNbO_3$: light+ acid



J.G.Scott, et al *Applied Surface Science* 2004

Early stages : light + acid environment

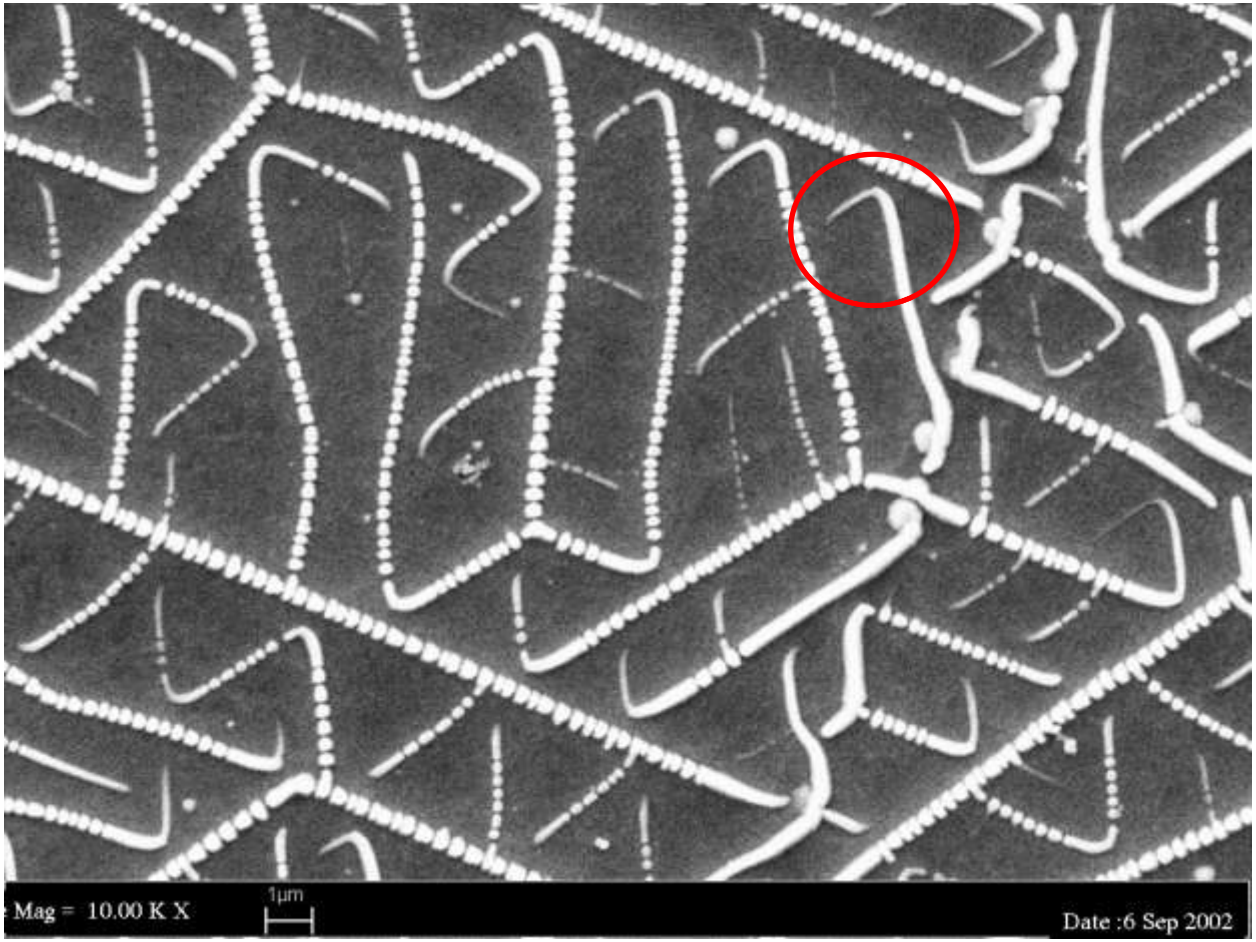


Ferroelectric domains

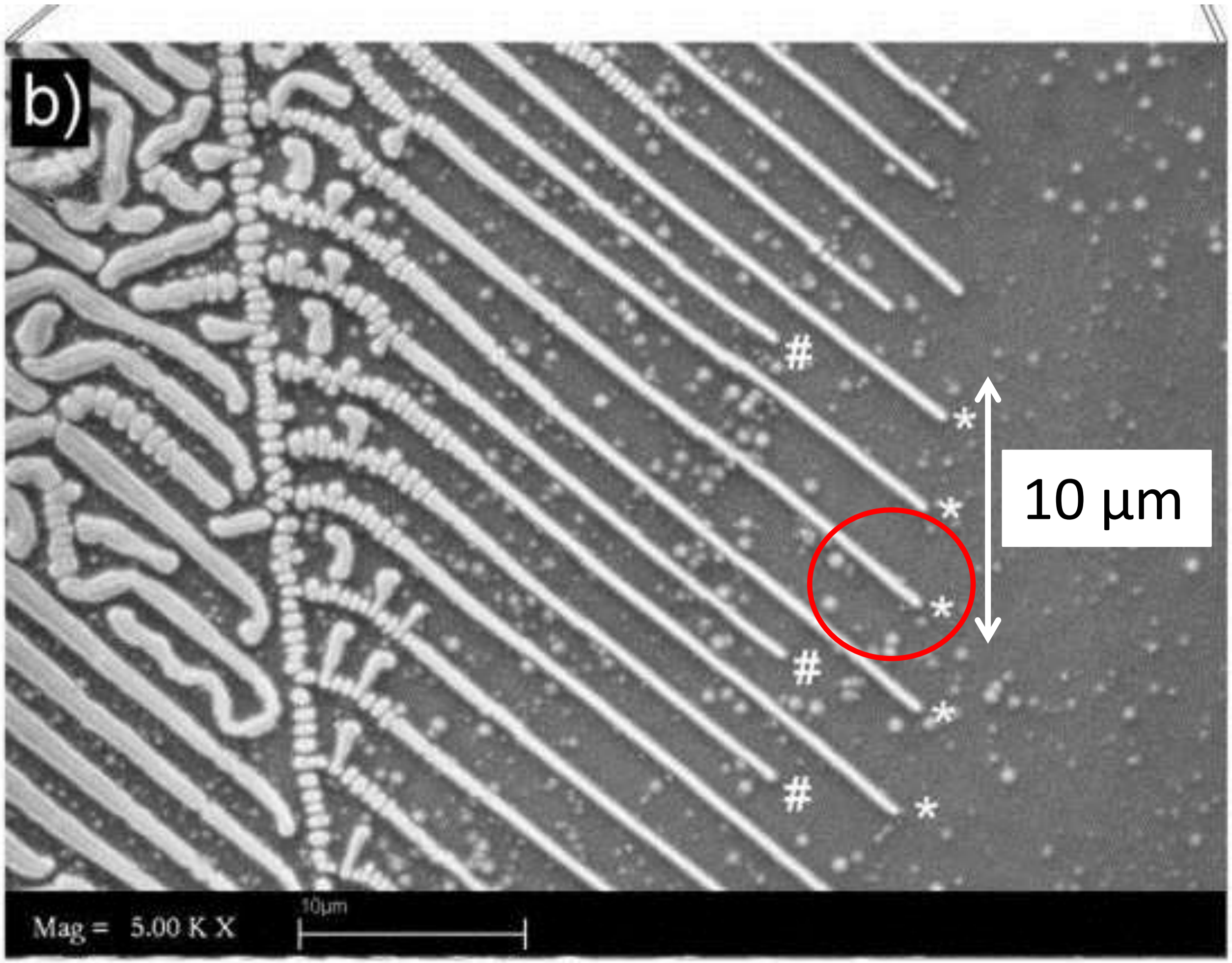
+z

-z

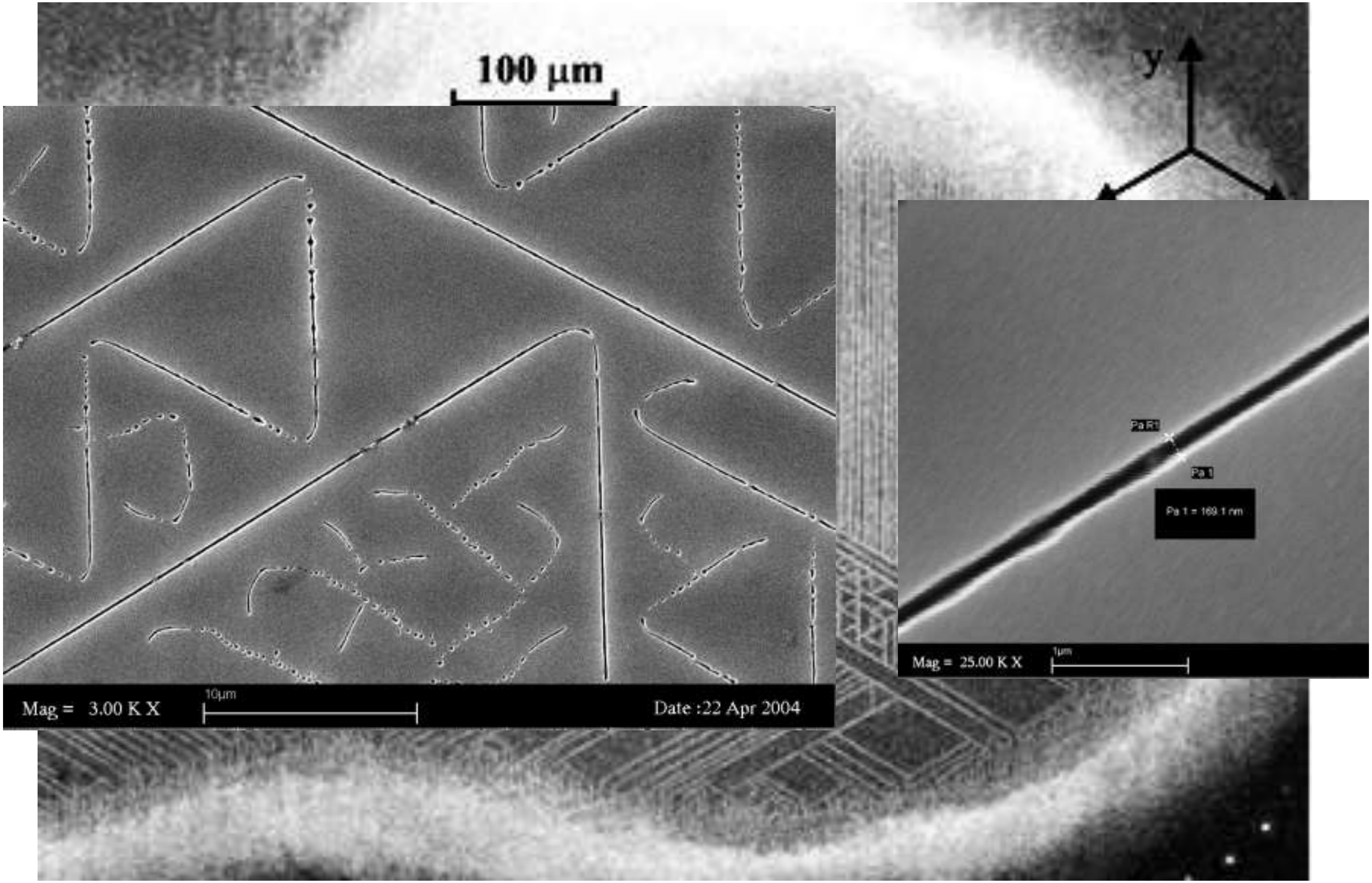
Self-organisation



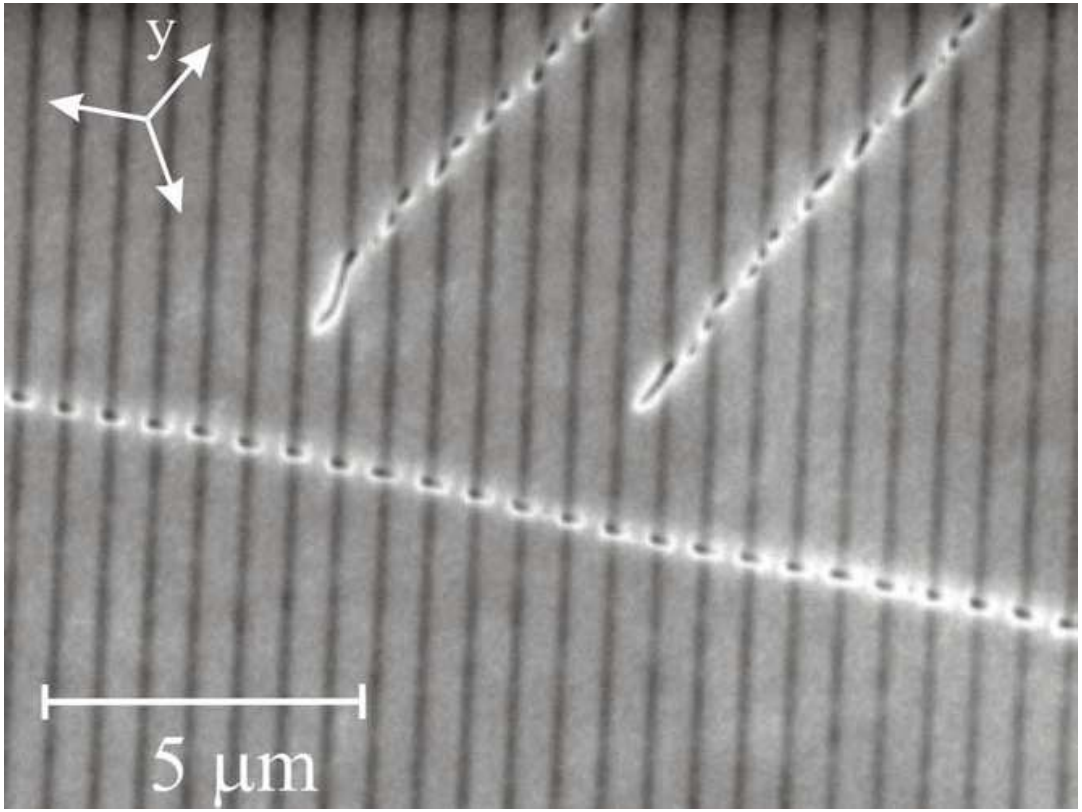
Unidirectional…

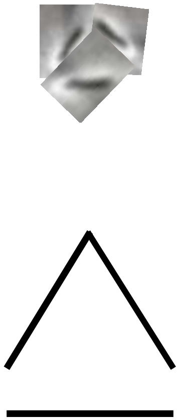


light *then* etching...



‘Regular’ features; illuminated via a phase mask





= split ring....

But...unquantified chance of success...!

UNIVERSITY OF Southampton
Optoelectronics Research Centre

To conclude…

1. Adopt **parallel** technologies.
2. **Additive** and **subtractive** both work.
3. Can achieve **sub λ features**.
4. Mass/volume production (more) possible…
5. Metals, polymers, semiconductors, crystals…
6. **Single shot** 3-D structures achievable.