PAUL SCHERRER INSTITUT

PSI

Helmut Schift :: Head Polymer Nanotechnology Group :: Paul Scherrer Institut

More (than Moore) applications based on nanoimprint lithography

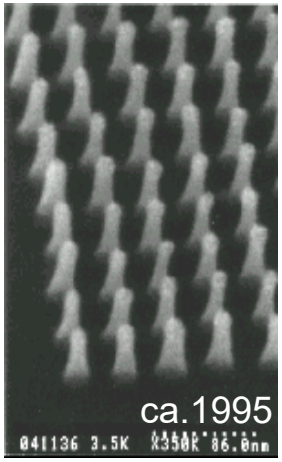
IFAME 2016, Daejeon, Korea, August 18, 2016

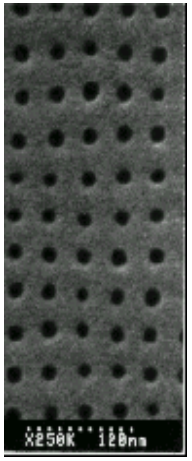
20 Years of Nanoimprint lithography (NIL)

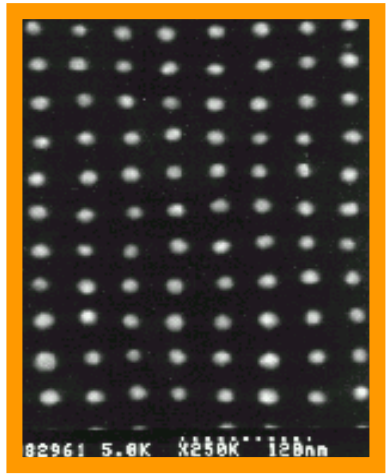
Stephen Y. Chou, Princeton

PRINCETON UNIVERSITY

Applied Physics A
Materials Science & Processing



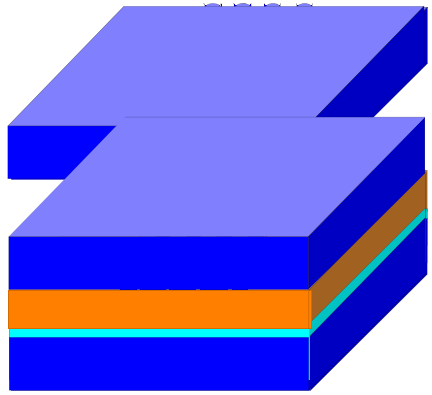




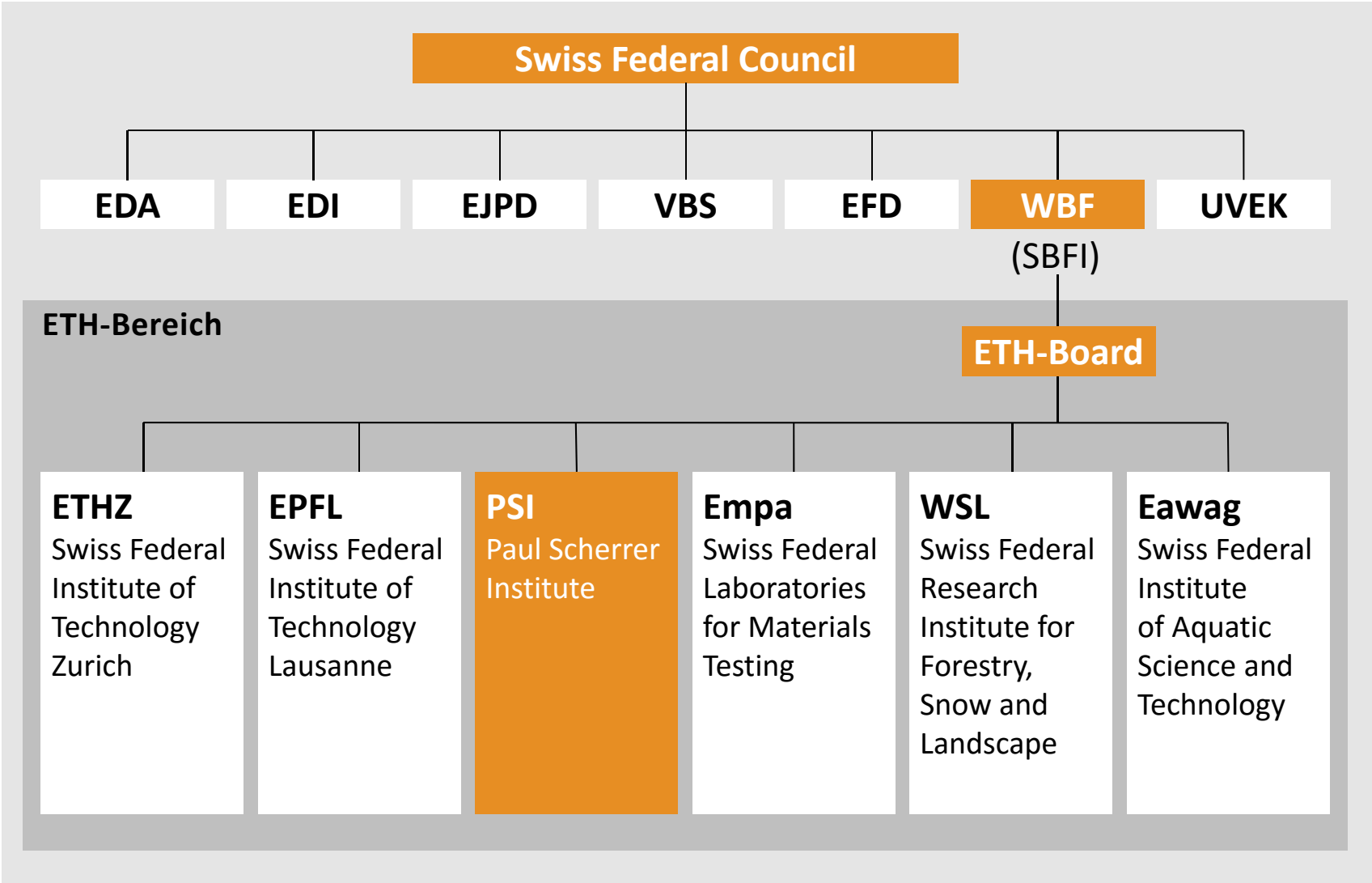
The Nanoimprint "Invention"

"Until 20 years ago, nanolithography by a mechanical method was unthinkable. Not only do mechanical methods use a completely different physical principle from the traditional lithography [wave/particle interactions (e.g., photons, electrons) with matter]; but also mechanical methods were perceived, at that time, to be applicable only for large scale structures, not for nanoscale."

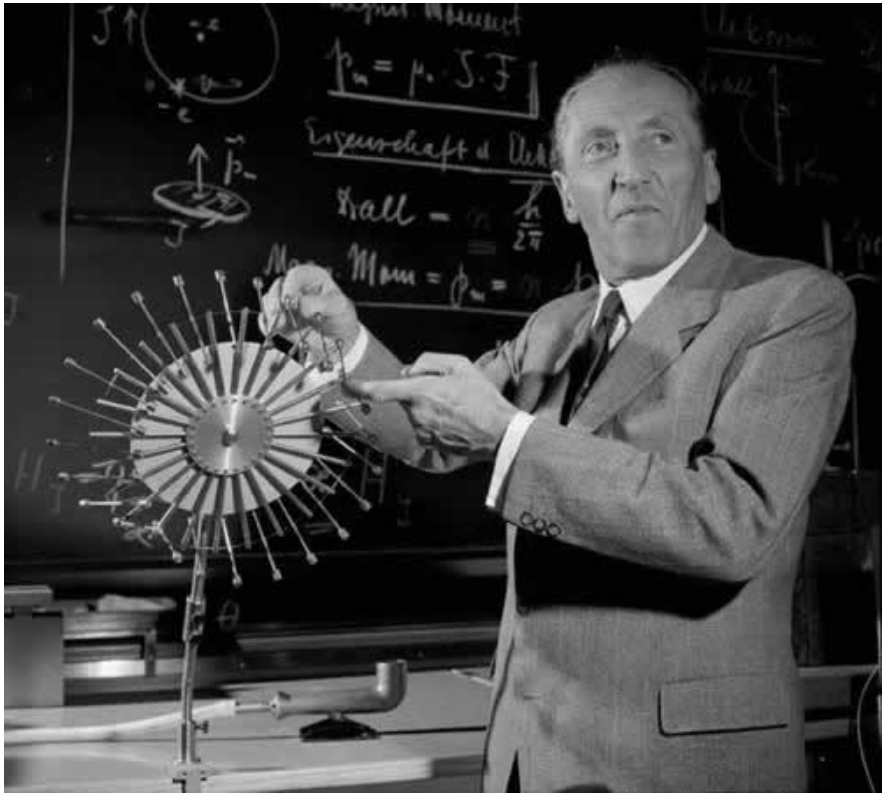
Appl. Phys. A (2015) 121:317–318



Paul Scherrer Institut :: Political Embedment



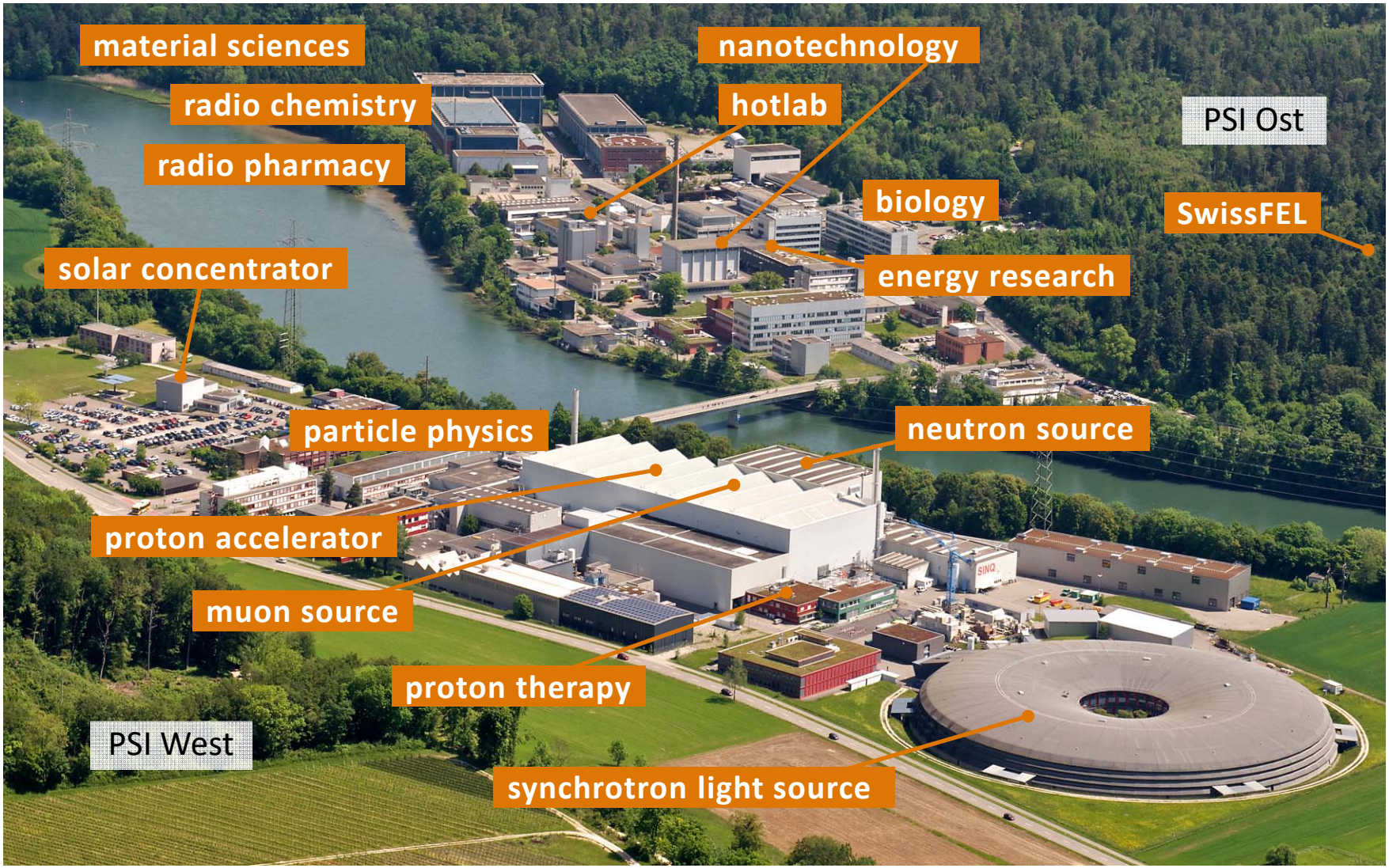
Paul Scherrer (1890–1969)



- Physics and mathematical studies at ETH Zürich, at Königsberg and Göttingen (Germany)
- 1920: professorship in experimental physics at ETH Zürich, from 1927 director of Physikalisches Institut. Known for his excellent lectures
- Research into X-ray scattering on crystals, liquids and gases. Later research focus: nuclear physics
- 1946: president of the Schweizerische Studienkommission für Atomenergie
- involved in the foundation of CERN

Aerial View

← Basel Germany ↑ Aarau/Bern ↓ Zürich →

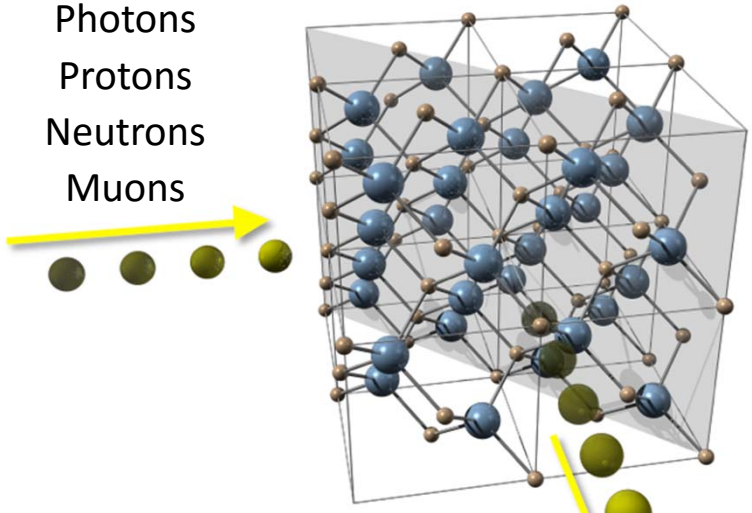


Large Research Facilities at PSI

Research at large facilities

Synchrotron lightsource SLS
Neutron source SINQ
Muon source SμS

Photons
Protons
Neutrons
Muons

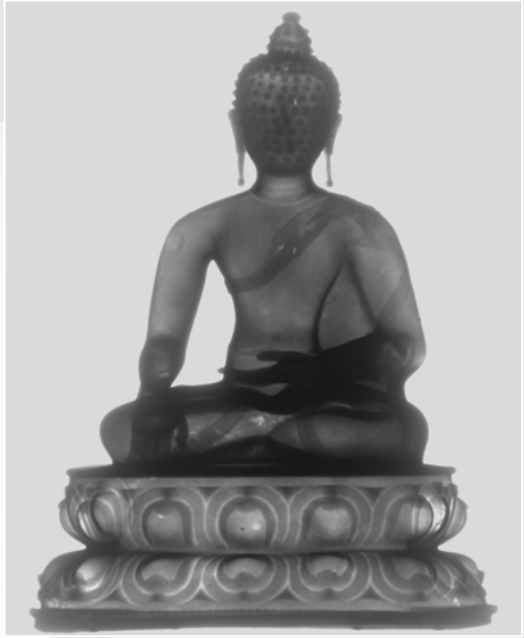


Microscopic insights into materials

Neutron Radiography – X-rays

Neutron Radiography

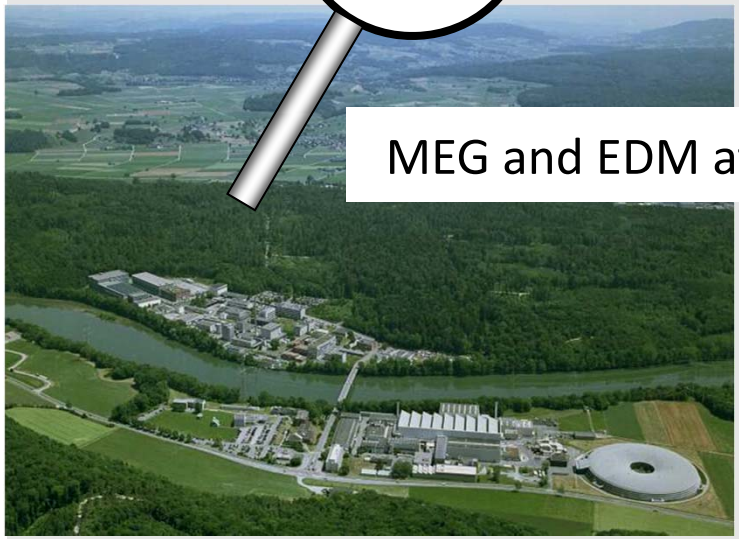
X-rays



Particle Physics :: PSI and CERN

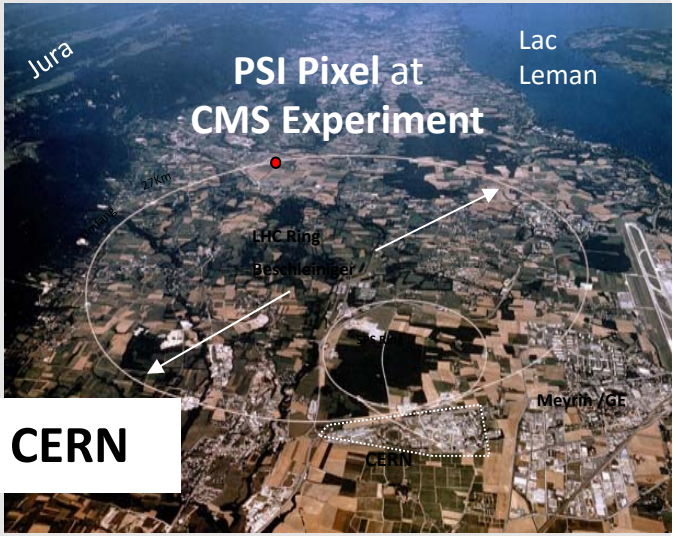
Are there any physics beyond our standard models?
New particles? New forces?

extreme prec ision



MEG and EDM at **PSI**

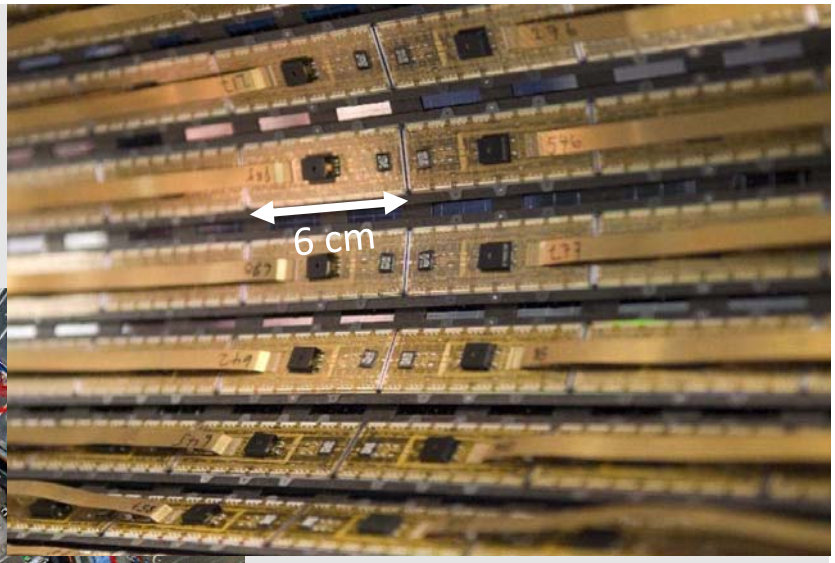
extreme energies

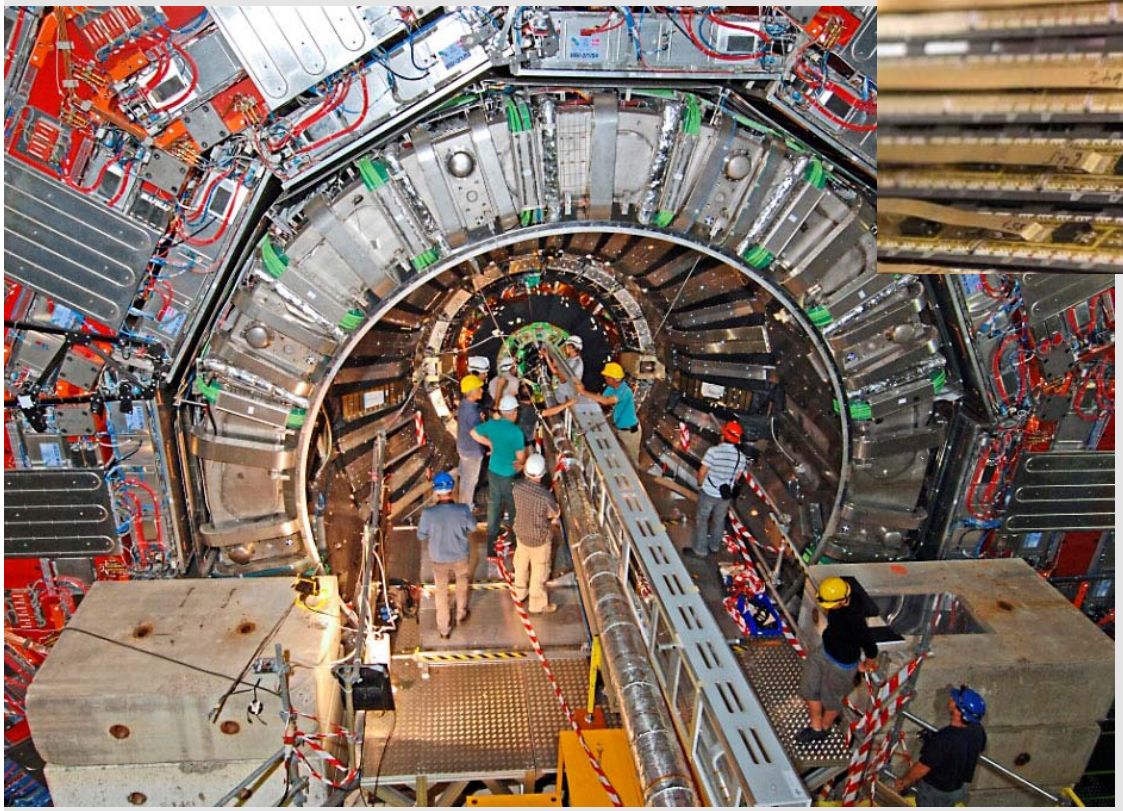


LHC at **CERN**

LHC: CMS Detector co-developed at PSI

The pixel detector played a mayor role in the discovery of the Higgs particles.



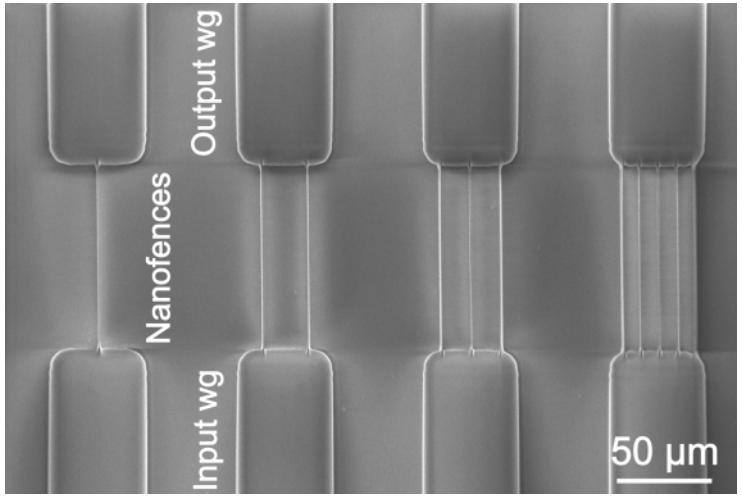


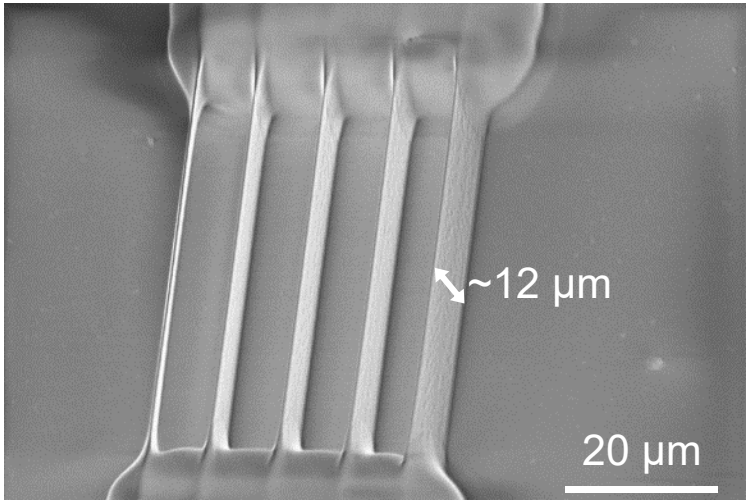
PSI development: digital pixel particle camera for **CERN**: 48 mega pixel, 40 million images per second.

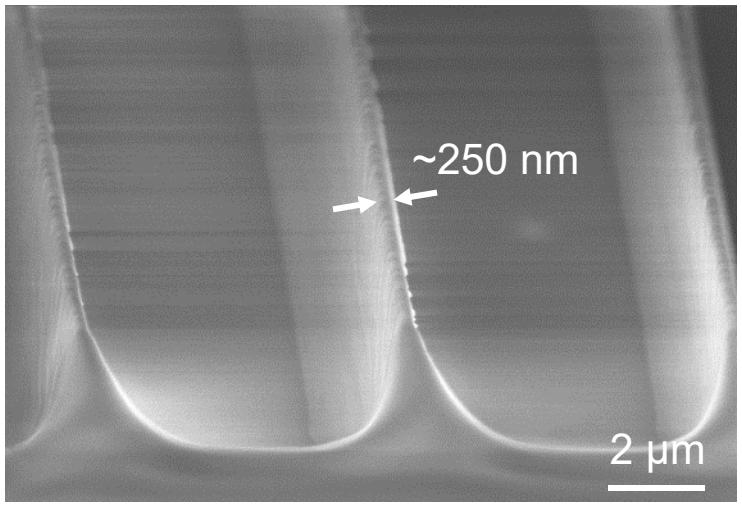
Photonic nanofences: Fabrication results

Direct fabrication of structures

- Fast prototyping
- Smallest structures ~250 nm
- High aspect ratios (> 40:1)
- Structures up to millimeters long
- High design flexibility
- Straightforward combination of micro and nanostructures



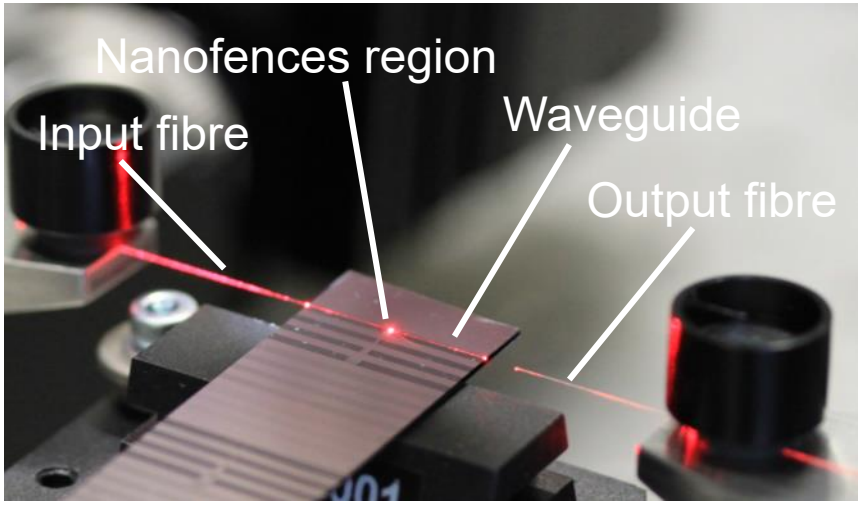




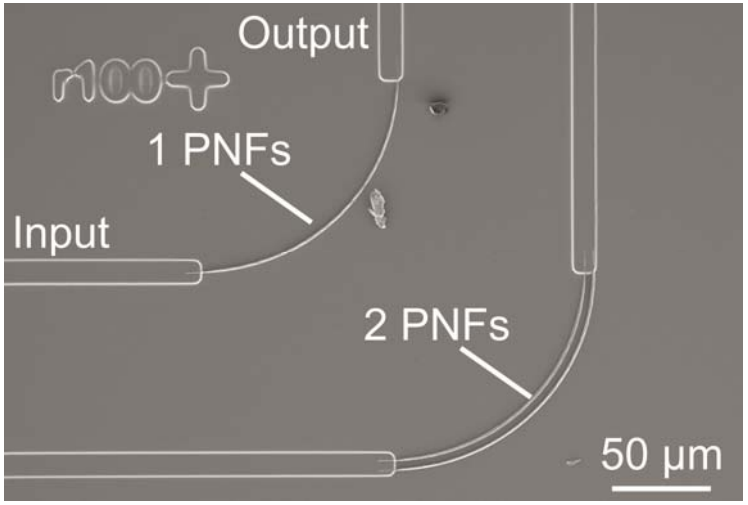
High aspect ratio > 40:1 achieved (5:1 needed)

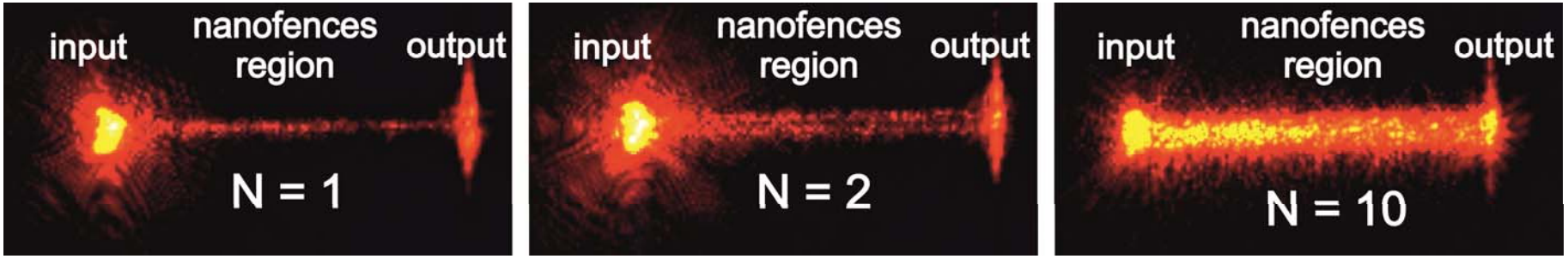
Photonic Nanofences: Coupling and guiding light

Direct coupling of light



Bent PNFs





Efficient direct coupling of light from standard waveguides to photonic nanofences
Propagation losses in the range of semiconductor photonic nanowires

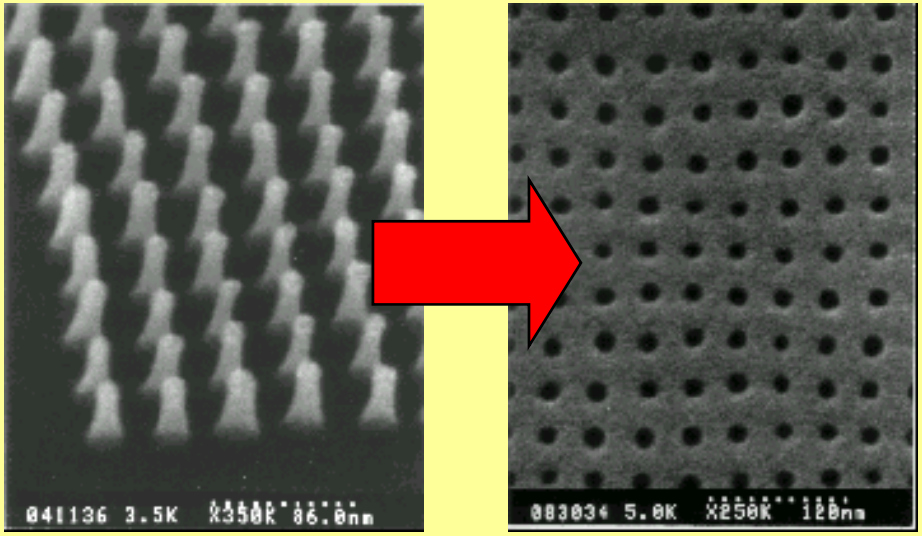
V.J. Cadarso et al. TBP, ACS Nano 2015

Outline

- Nanoimprint in the context of advances in mechanical engineering
- NIL is a Next Generation Lithography – true, but not only!
- Is NIL More Moore or More than Moore?
- Non-IC applications, more than Moore – front runners
- What a researcher can contribute
- … and More NIL to come

Nanoimprint and Nanomolding by Mechanical Identation

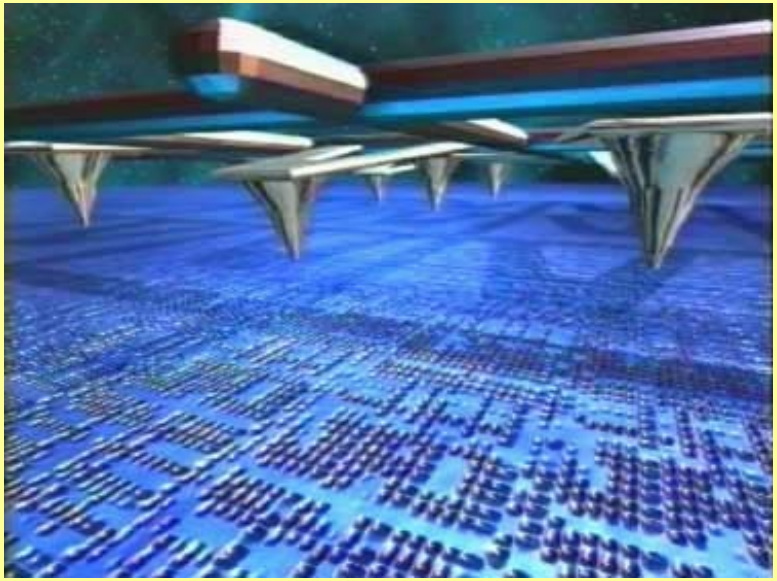
Nanoimprint Lithography



Molding of resist by thermal imprint. The viscous polymer assumes the shape of the stamp by squeezed flow.

S.Y. Chou, P. R. Krauss and P. J. Renstrom, *Appl. Phys. Lett.* **67**(21), 3114 (1995).
P.R. Krauss and S.Y. Chou , *Appl. Phys. Lett.* **71**(21), 3174 (1997).

Scanning Probe Indentation



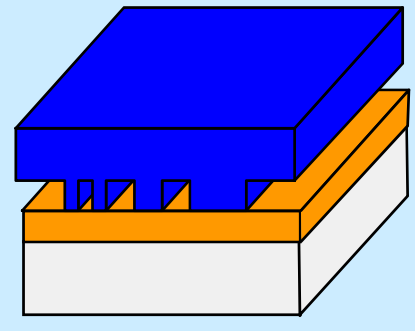
Indentations are generated using an array of heatable SPM tips.

H. J. Mamin and D. Rugar, *Appl. Phys. Lett.* **61**, 1003 (1992)

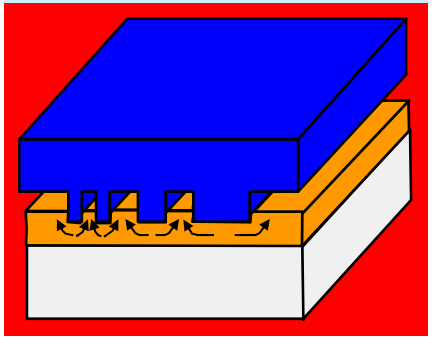
P. Vettiger et al. *Microelectr. Eng.*, **46** (1-4) 101 (1999)

Thermal-NIL + Window Opening + Pattern Transfer

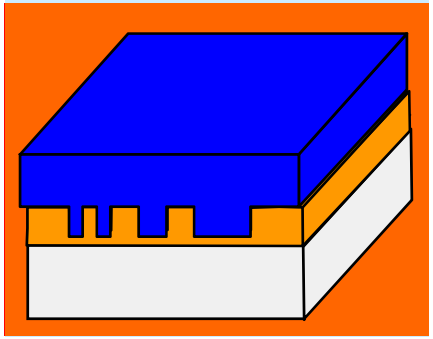
Replica molding (imprint)



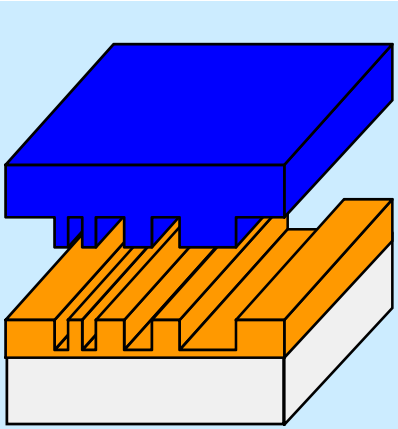
positioning of
stamp and heating



thermoplastic
squeeze flow

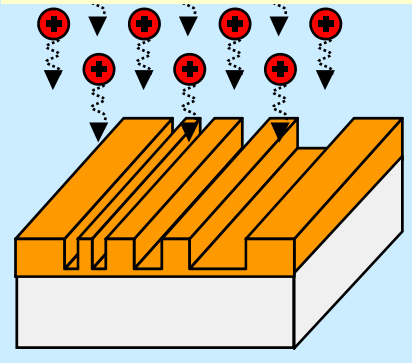


cooling and
hardening

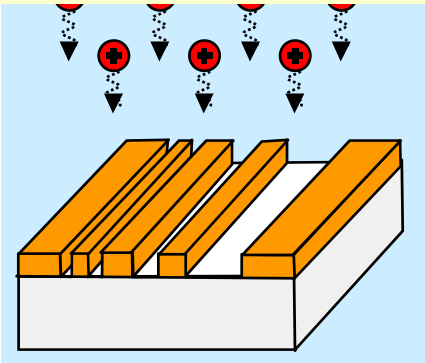


demolding

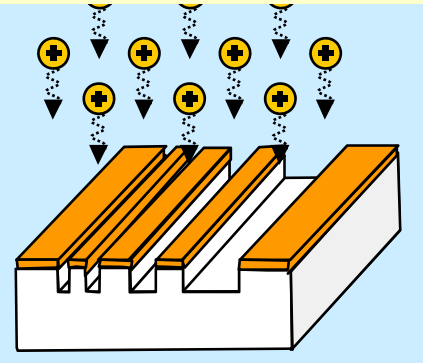
Pattern Transfer (residual layer etch AND substrate etching)



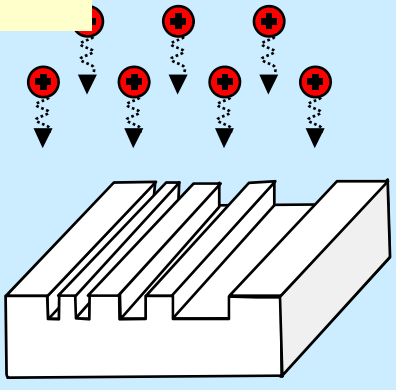
residual layer
RIE etch



substrate window
opening

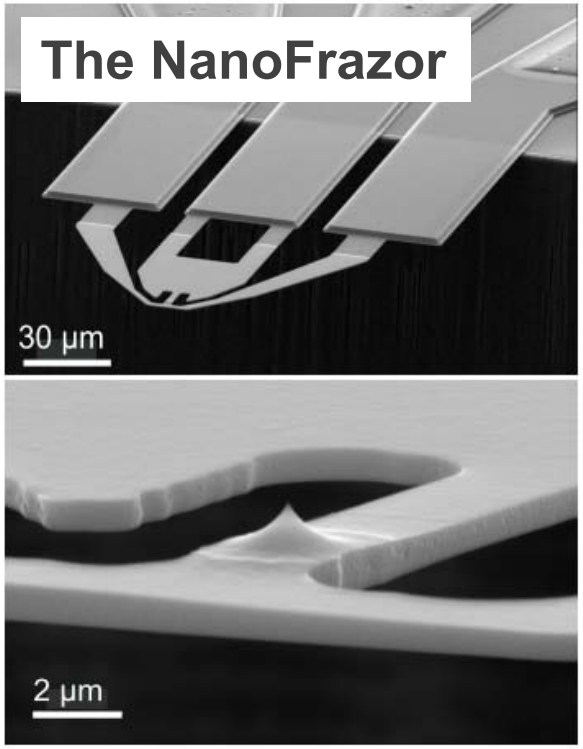


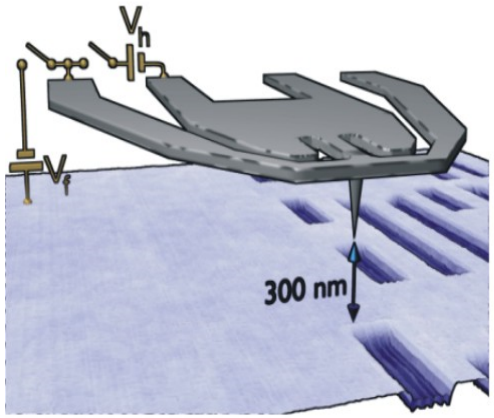
pattern transfer
Into substrate (RIE)

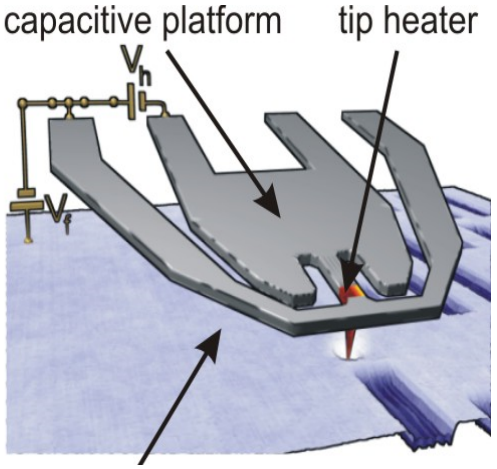


removing of
resist

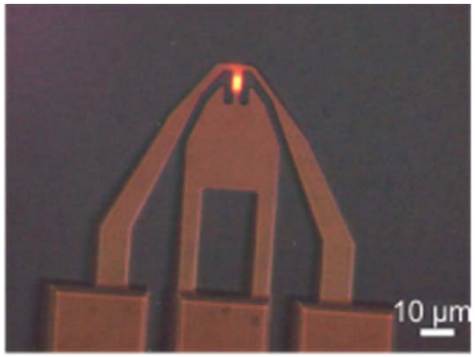
Serial lithography with thermal cantilevers







Thermal sensor for measuring topography in special AFM imaging mode



Heating of the tip:

Microheater: 2x2 µm^2 area with higher electric resistivity (lower dopant concentration in Si) heats up to 1000 ºC

Replication Technology –
the BIG Advantages of Molding

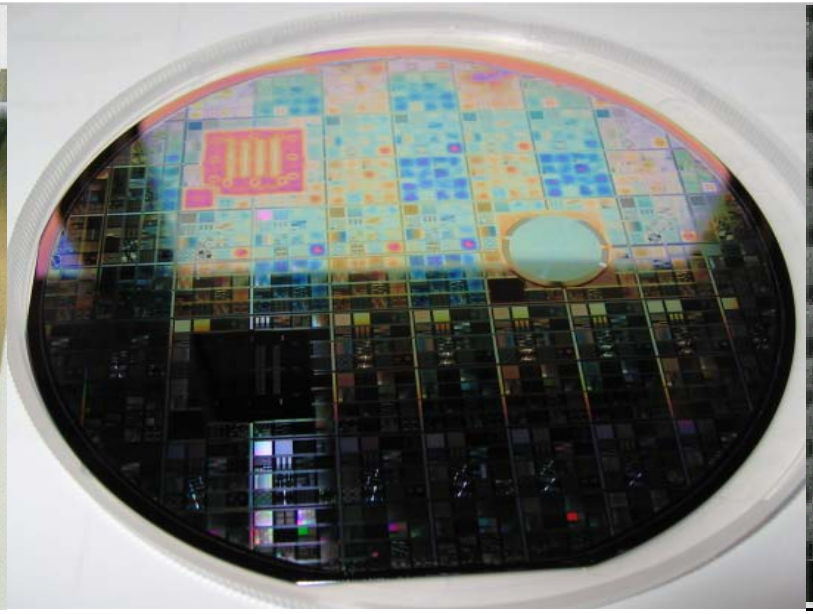
- Freedom of materials: polymer as template
- **3D patterning: molding of complex shapes**
- Small and big structures in one step

+ Working stamp fabrication by replication

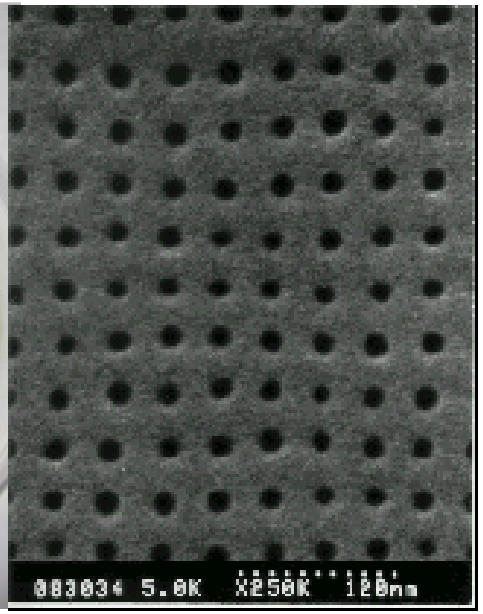
+ Hybrid manufacturing schemes

Low-cost

Throughput



Parallel



Resolution

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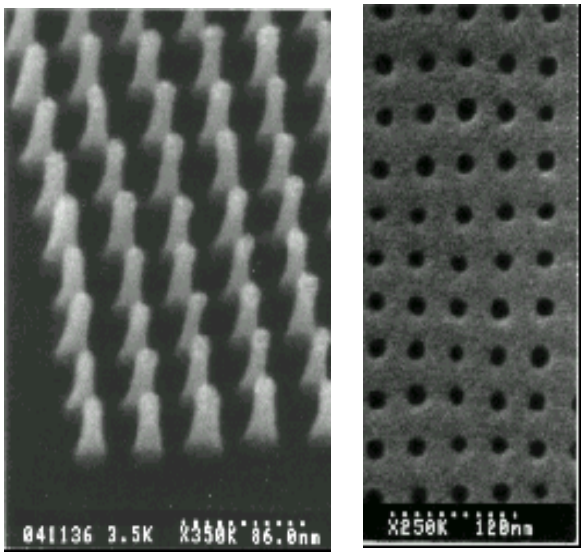
- … and More NIL to come

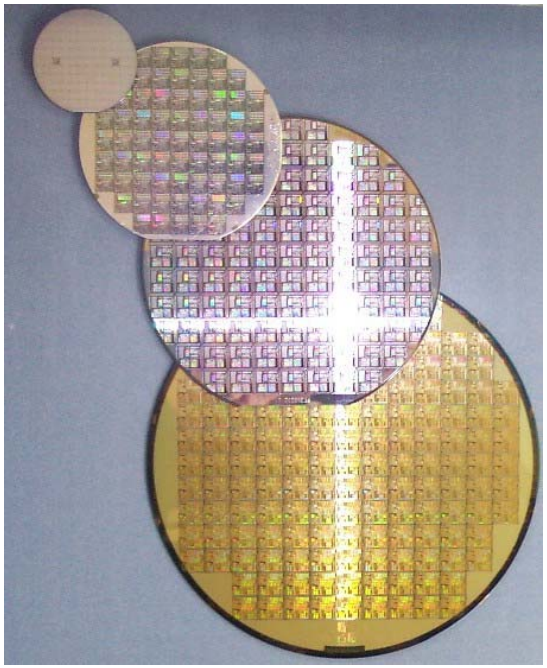
What is the Unique Selling Point (USP) of NIL?

Resolution
no physical limit
→ <10 nm demonstrated

Large area
Scalable
→ large stamps / S&R (Polymer/Mineral)

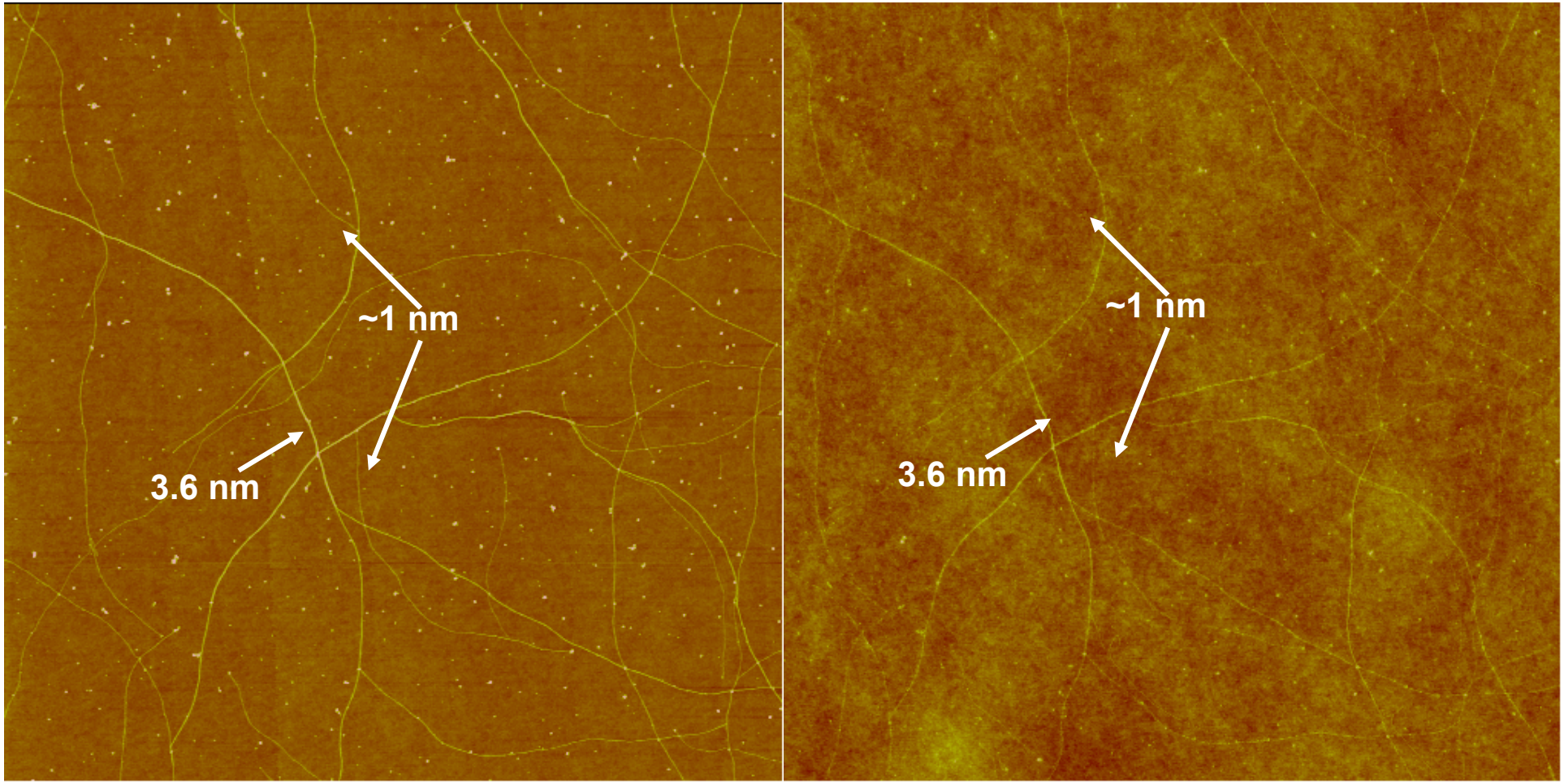
Cost / availability
Simple tools / materials
→ standardization





Note: This has to be proved for applications – against competing (lithography) processes

Polymer Imprint Lithography With Molecular Scale Resolution

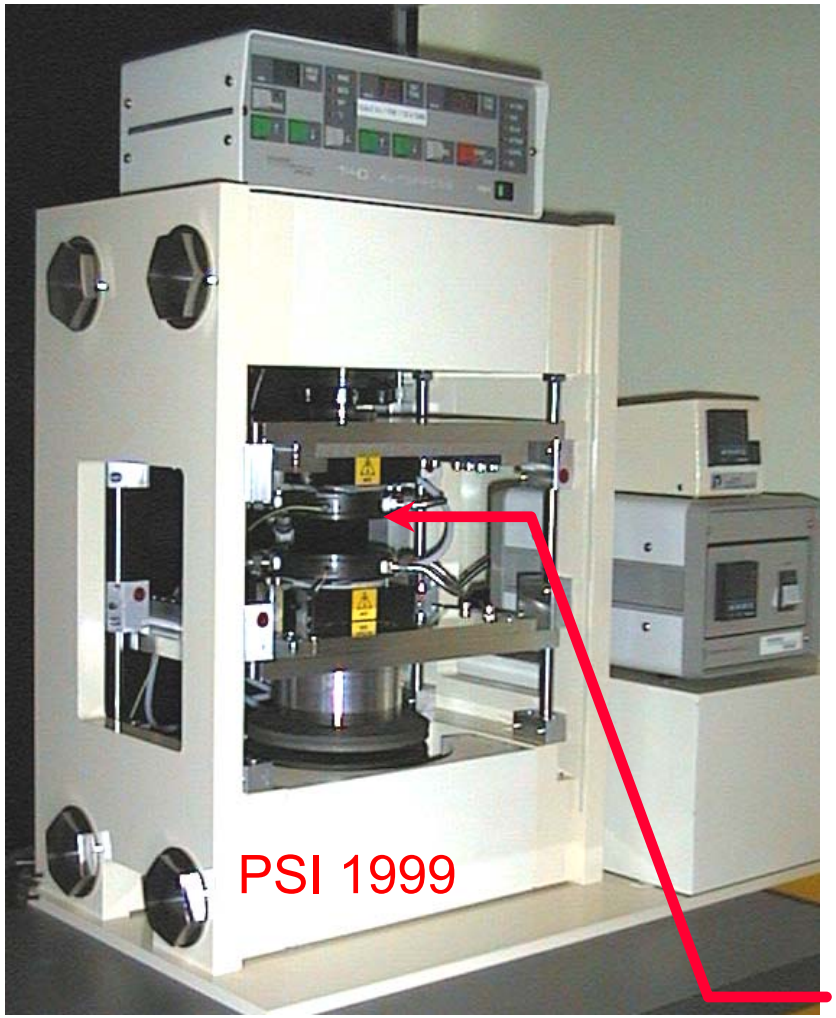


Master, 10x10 µm with single nanotubes

Polymer Imprint, 10x10 µm

IEEE Trans. Nanotechn. **5**, 301 (2006).

Hot Embossing Equipment (in PSI)



embossing press from Specac

hydraulic press for nanolithography machine parameters:

- press : hydraulic (oil)
- lateral resolution : < 50 μm
- stamp : 15 x 15 mm^2, up to 100 mm wafers, substrate silicon spincoated PMMA (thermoplast)
- samples : up to 100 mm wafers
- temperature : up to 280 °C
- applied force : up to 40 kN
- conditions : ambient, laminar flow (clean room)
- heating : electrical
- cooling : water / air
- control : automatic

process area for sample and mold insert

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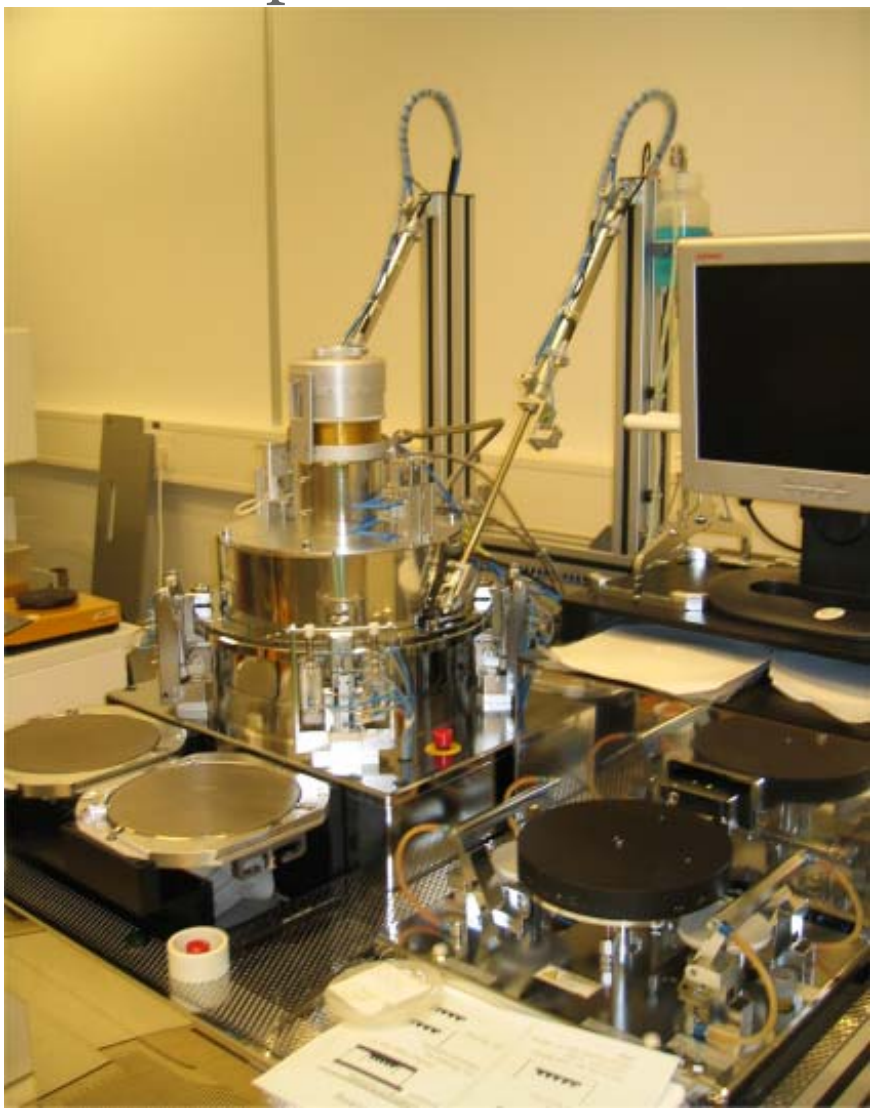
Nanoimprint Machines from EVG 620



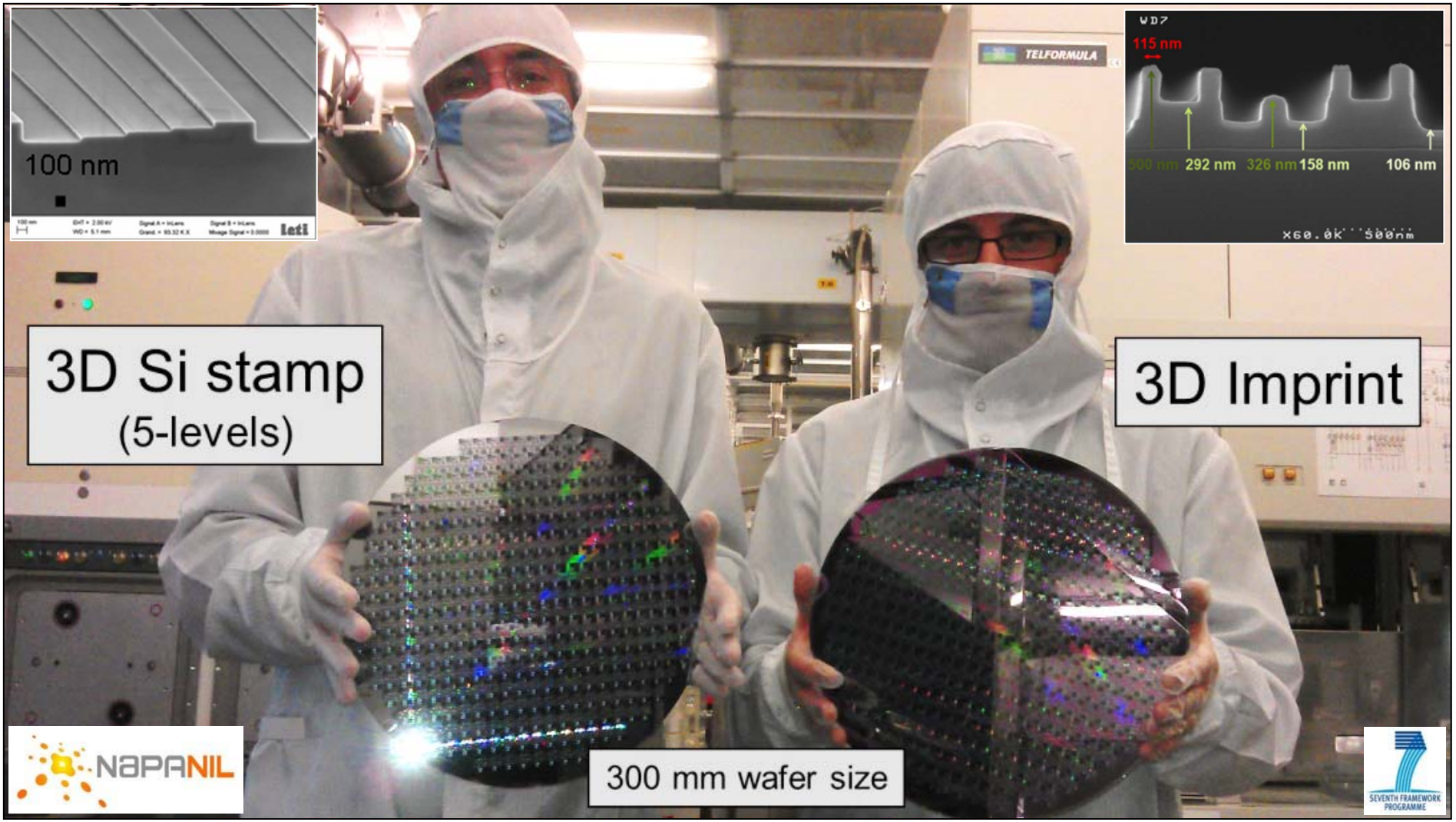
8” imprint bonder in LETI / Grénoble

- imprint under vacuum
- alignment separately in mask aligner

(+) good accessability, usable for anodic bonding

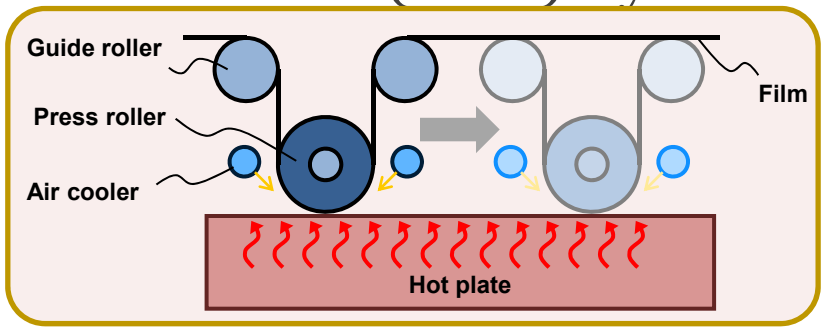
(-) low pressure, speed (no water cooling)

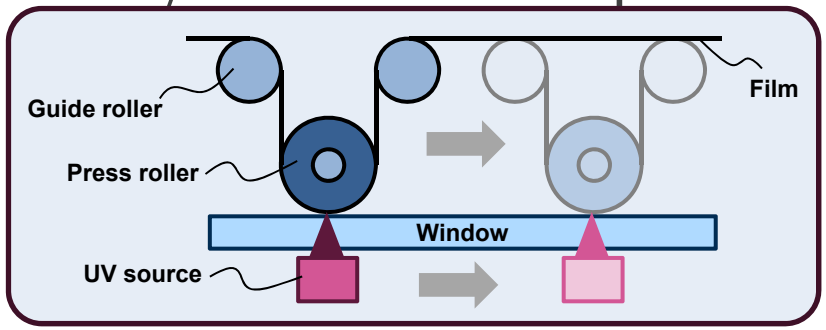
Large Area 3D Imprint Capabilties (Plate-to-Plate)

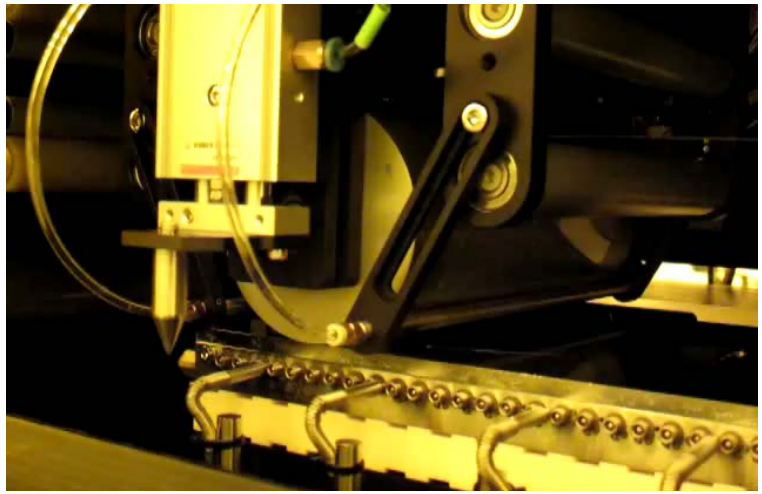


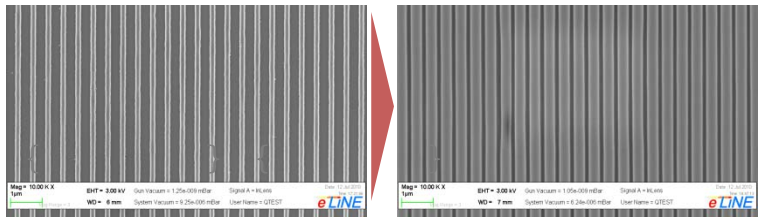
With courtesy of Stéfan Landis & Vincent Reboud (LETI-CEA, France)

Roll-to-Roll (R2R) System: Thermal/UV-assisted Imprint





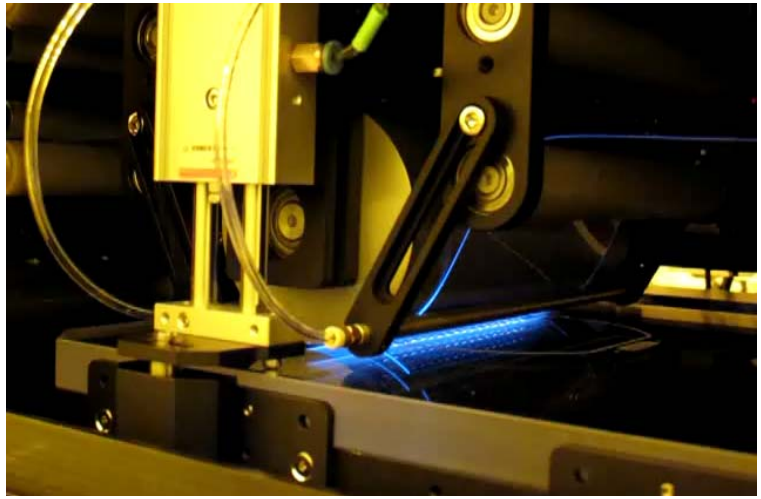


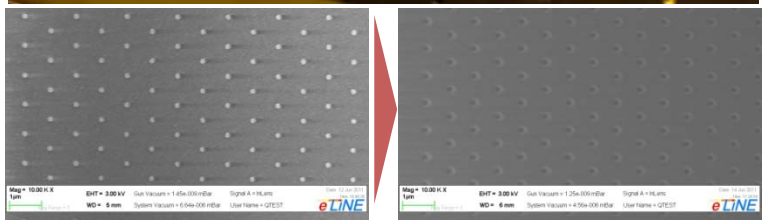


180 nm-width and 470 nm-pitch line pattern on a **Si stamp**

Transferred pattern on a PC film by the **thermal-RNIL system**

Thermal-RNIL Mode





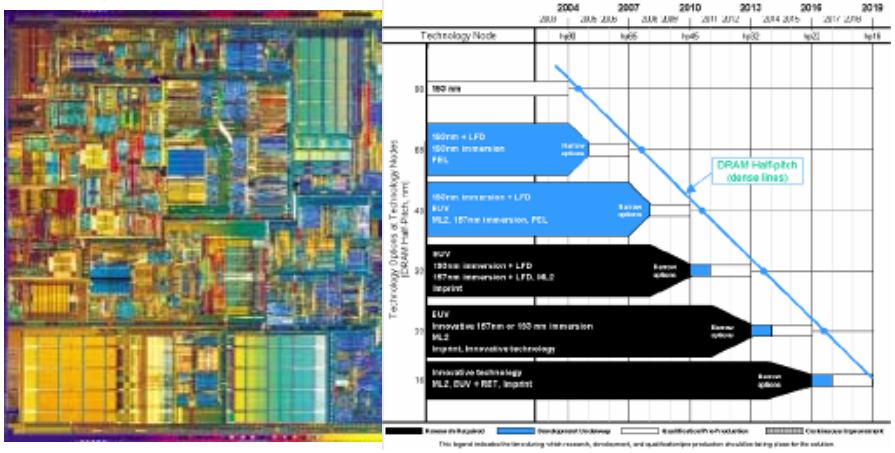
140 nm-diameter and 1 um-pitch dot array on a **PUA/glass stamp**

Transferred pattern on a PC film by the **UV-RNIL system**

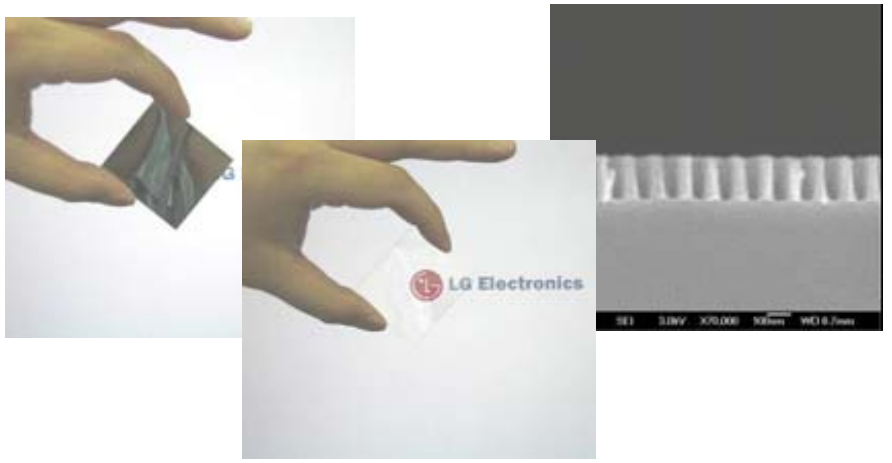
UV-RNIL Mode

Nanopatterning – Main NIL Applications

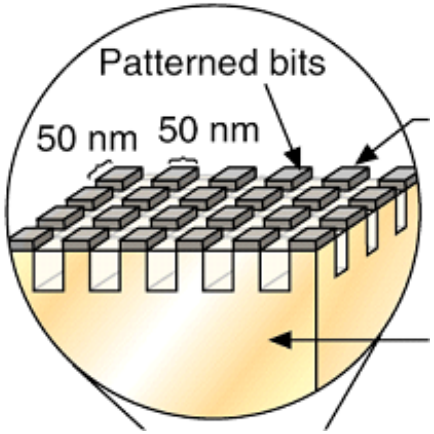
High End Microelectronic Chips

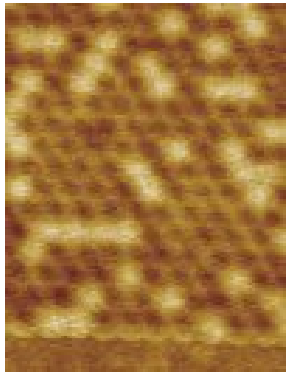


Wire Grid Polarizer

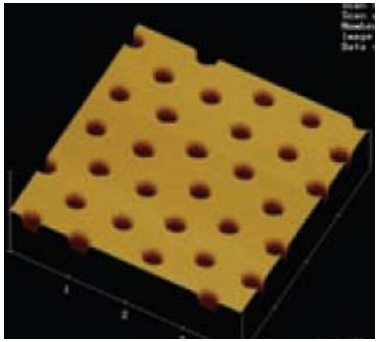


Patterned Magnetic Media

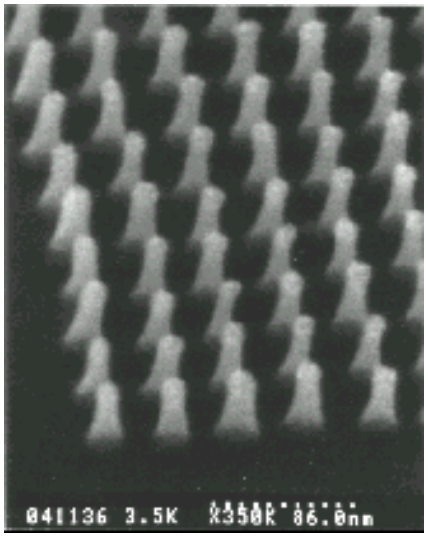


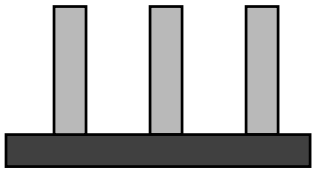


High Brightness LEDs

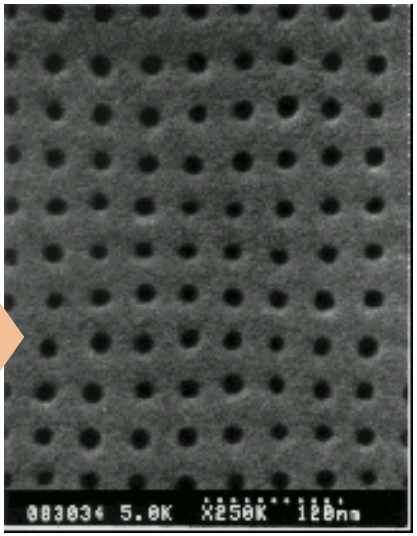


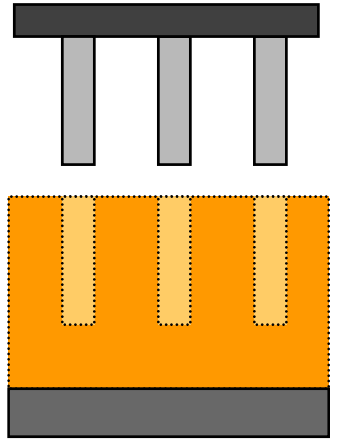
Fabrication of Nanodots in Metal



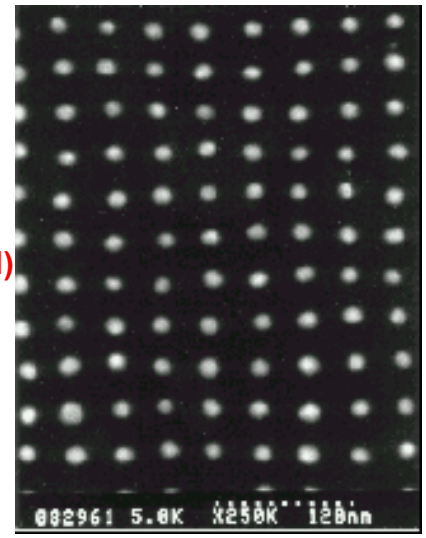


Hot Embossing Lithography





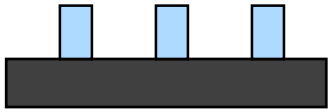
master:
embossing stamp
- fabrication with e-beam exposure and RIE
- material: Si or SiO_2 (not specified)
- size: down to 10 nm
- period: 40 nm
- depth: 60 nm



Lift-off

molded structure
- material: PMMA on Si

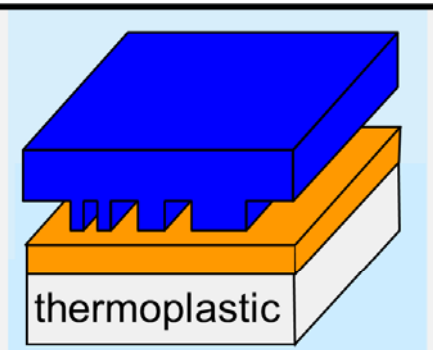
metal dots
- material: not specified
- excellent uniformity over 1 square inch

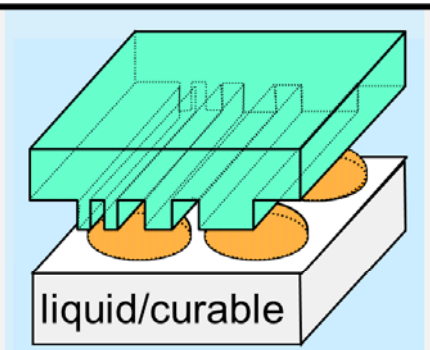


Source: S. Chou, NSL, 1998

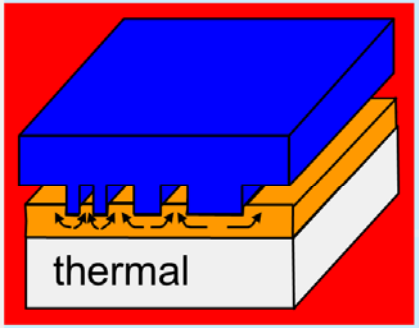
Replication (thermal, UV-, step&repeat and roll-to-roll NIL)

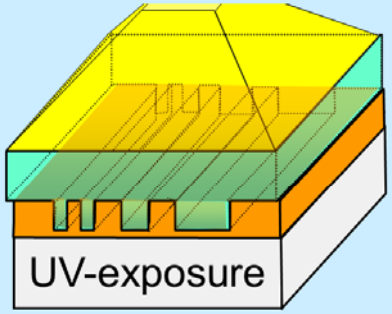
Stamp alignment
on resist coated substrate
spin-coated film
or dispensed droplets



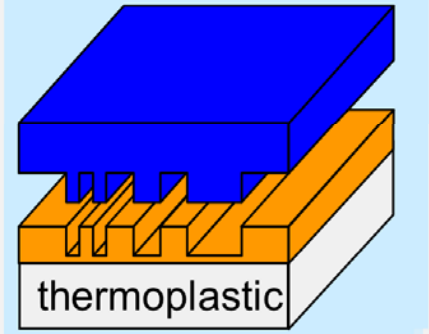


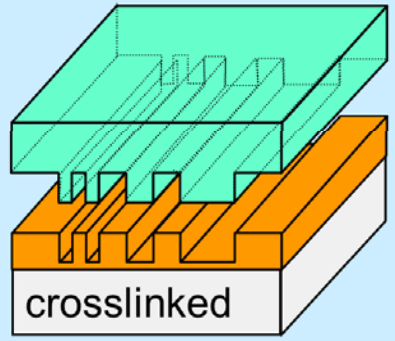
Thermal or UV-light assisted nanoimprint
viscous squeeze and capillary induced flow



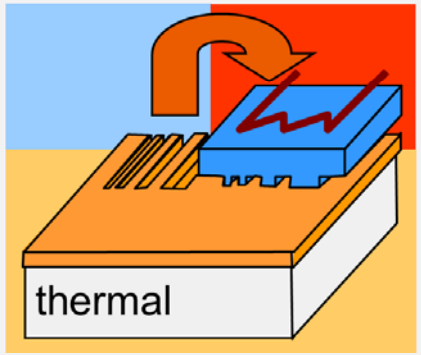


Demolding
stamp detachment from molded resist (thickness contrast) and re-use

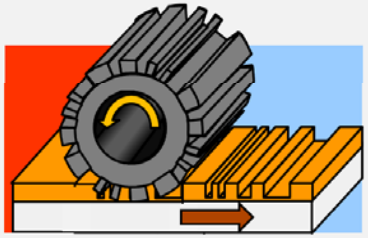




Lateral area enhancement
by step&repeat



Roller imprint
roll-to-role / roll-to-plate

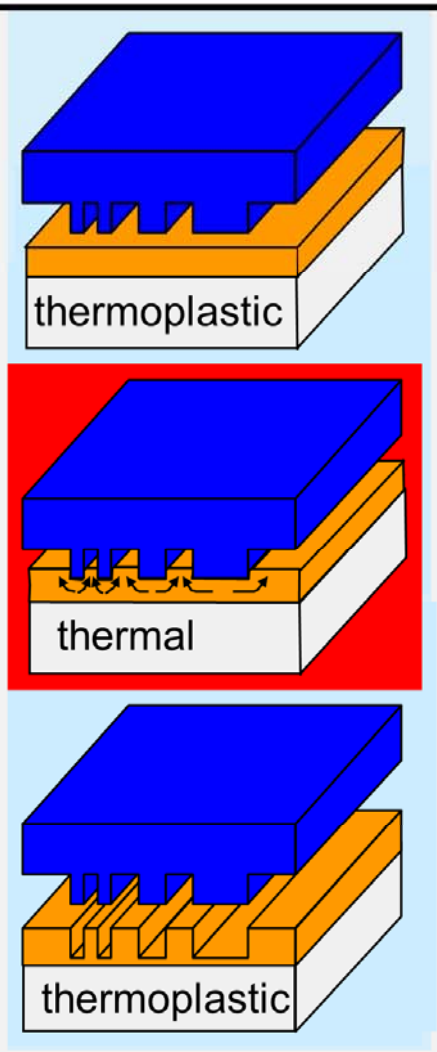


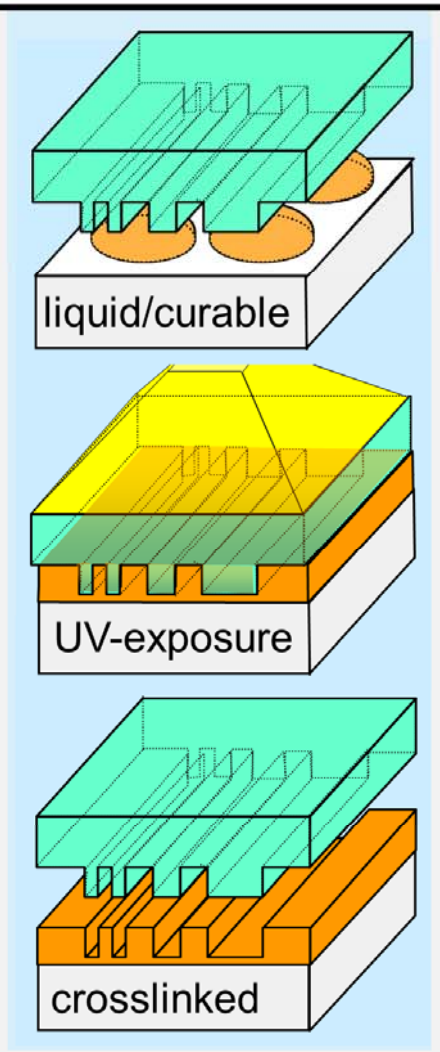
Replication (thermal, UV-, step&repeat and roll-to-roll NIL)

Stamp alignment
on resist coated
substrate
spin-coated film
or dispensed droplets

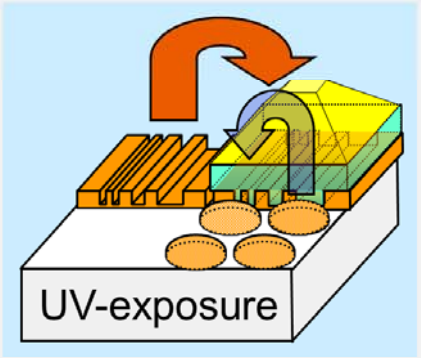
Thermal or
UV-light assisted
nanoimprint
viscous squeeze and
capillary induced flow

Demolding
stamp detachment
from molded resist
(thickness contrast)
and re-use

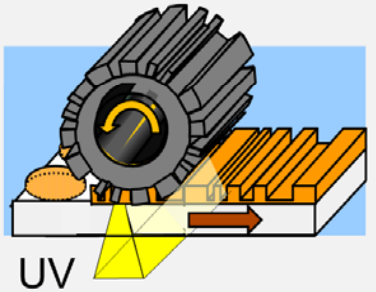




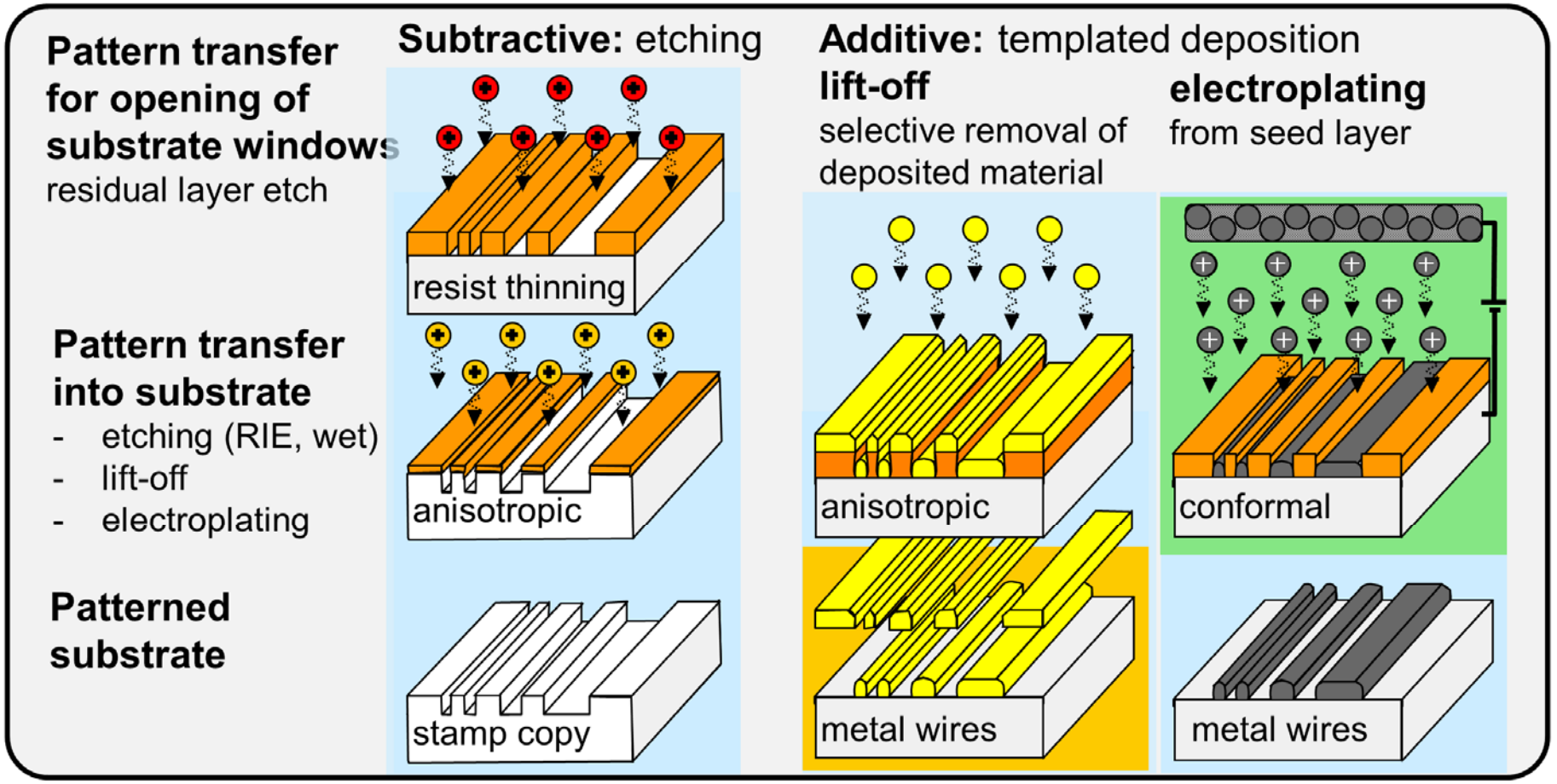
Lateral area
enhancement
by step&repeat



Roller imprint
roll-to-role / roll-to-plate



Pattern transfer (window opening and substrate patterning)

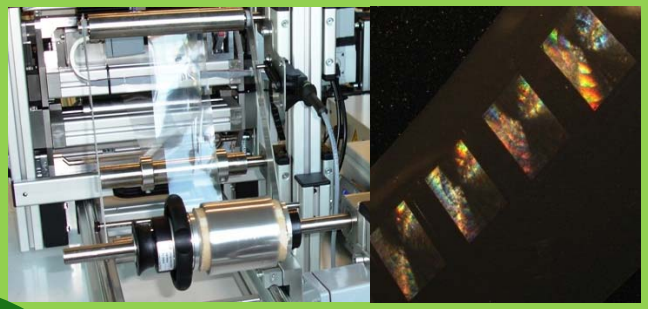


NOTE: Only pattern transfer makes NIL a true «lithography»

Replication toolbox

Thermal / UV nanoimprint

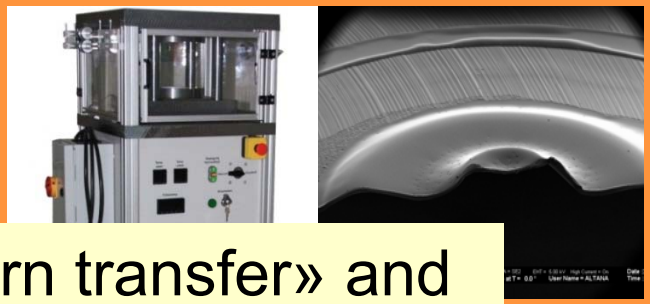
Roll-to-roll thermal imprint



Replication technology toolbox

Injection molding

Microthermoforming



NOTE: There are «lithographic pattern transfer» and «direct-use» functional material applications

Outline

- Nanoimprint in the context of advances in mechanical engineering
- NIL is a Next Generation Lithography – true, but not only!
- Is NIL More Moore or More than Moore?
- Non-IC applications, more than Moore – front runners
- What a researcher can contribute
- … and More NIL to come

Moore's law – the 'inner law' of growth

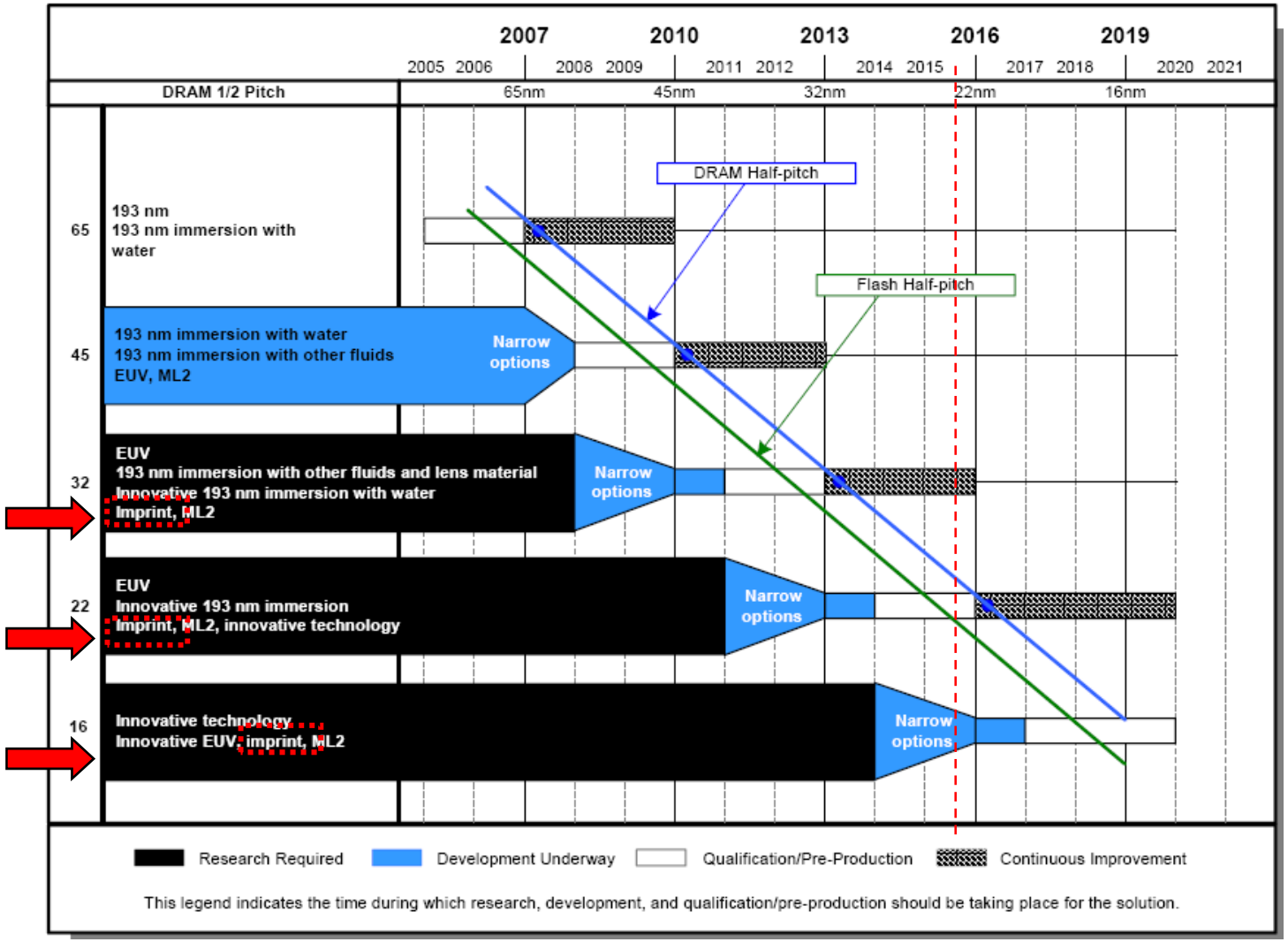
for (integrated circuit) microchip manufacturing

Moore's law: roadmap defined 1965 by Gordon Moore (INTEL)
transfer of economic rules into the world of lithography
«The number of transistors has to double every 18 months»

⇨ engineers are forced to do a technological advancement

PAUL SCHERRER INSTITUT

Lithography Roadmap – Moore's Law



Draft of 2006 update to ITRS

Optical Lithography

through the 45 nm node; and possibly beyond

Imprint Lithography

appears on the roadmap as a potential solution at the 32 nm node

SEMATECH

Lithography Exposure Tool Potential Solutions

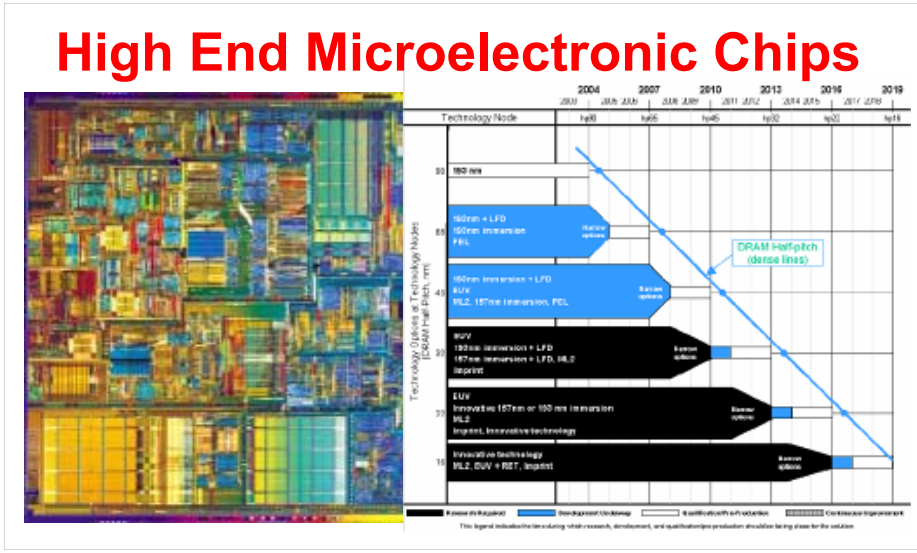
2009-10: Intel announces 32 for 2009 and 22nm for the end of 2011; 14 nm for 2016

20 Years of Nanoimprint lithography (NIL)

PRINCETON UNIVERSITY

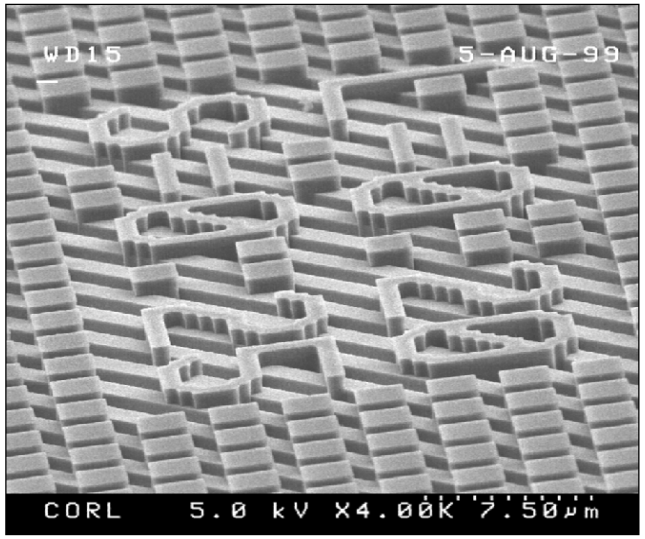
Applied Physics A
Materials Science & Processing

Stephen Y. Chou, Princeton

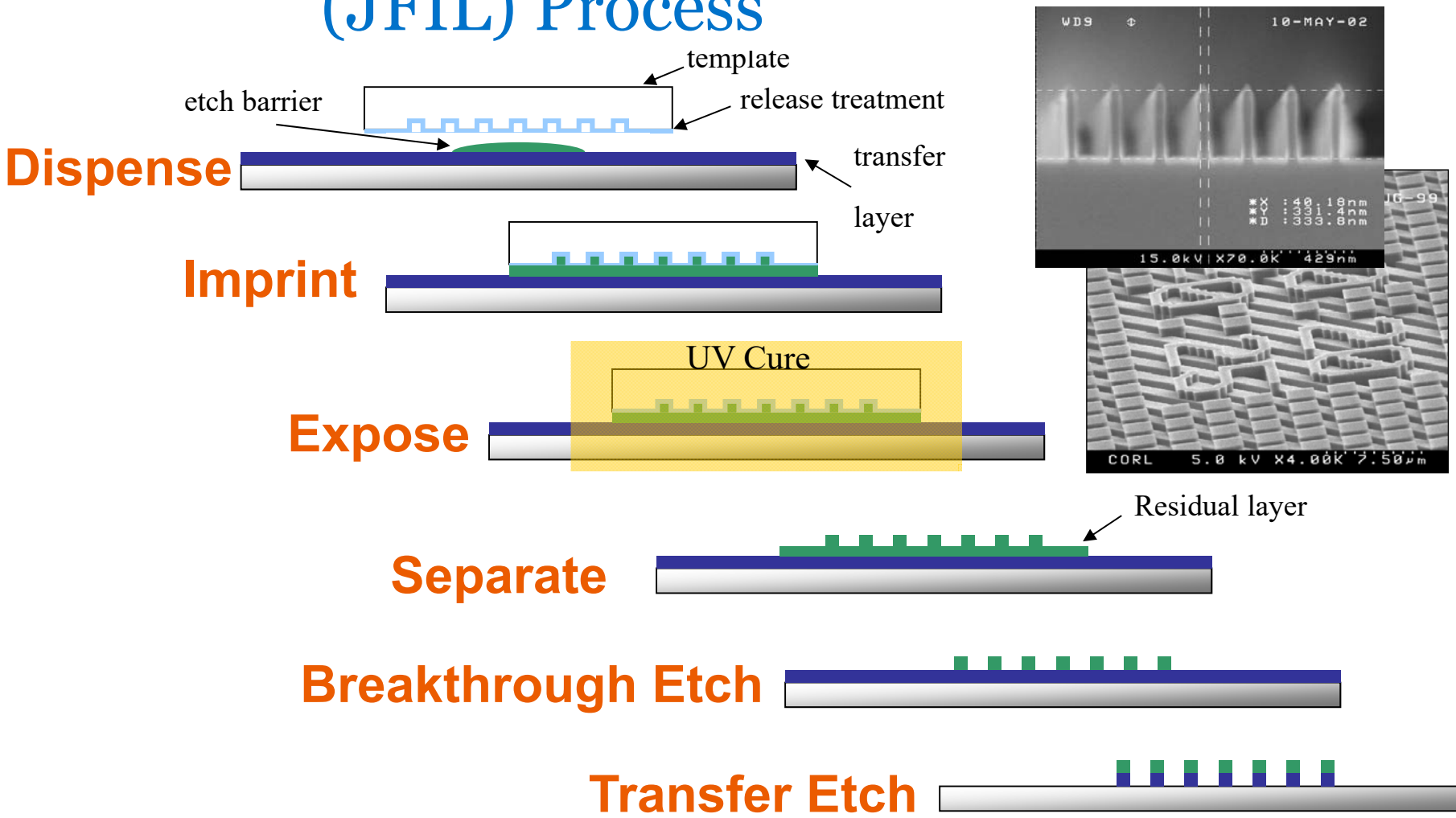


"MIT's Technology Review named nanoimprint lithography one of "ten emerging technologies that will change the world". The magazine wrote in 2003 that "ultimately, nanoimprinting could become the method of choice for cheap and easy fabrication of nano features in such products as optical components for communic-ations and gene chips for diagnostic screening.."

Appl. Phys. A (2015) 121:317–318



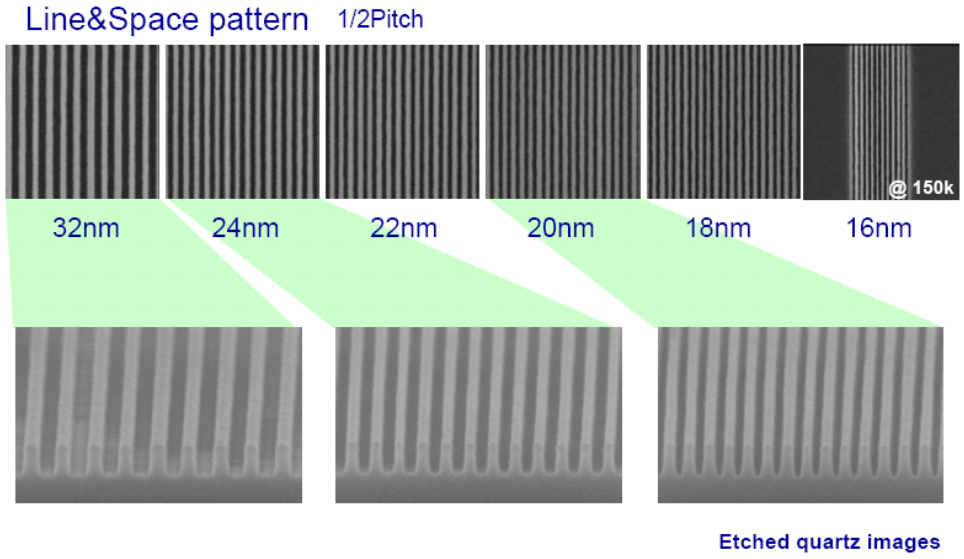
Jet and Flash Imprint Lithography (JFIL) Process

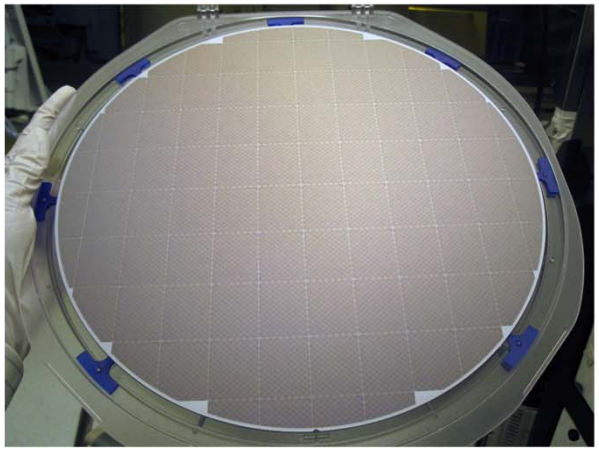


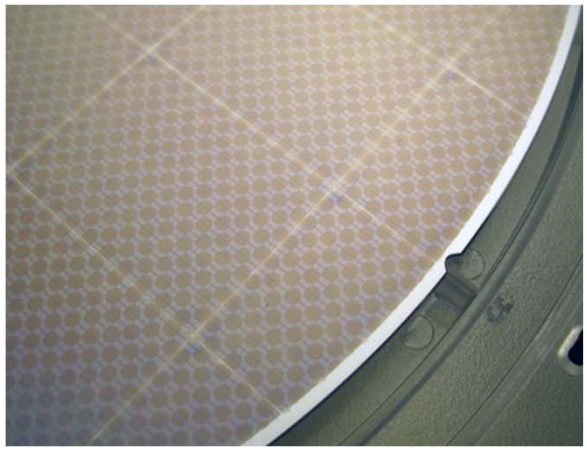
SFIL/JFIL was commercialized by Molecular Imprints Inc (MII)

Courtesy Grant Willson, University of Texas at Austin

Canon acquired Molecular Imprints in 2015







- ⇨ Fast «jetting» of resist
- ⇨ Dust filtering (micro-environment)
- ⇨ Cluster of 4 machines for 60 wafers per hour
- ⇨ Overlay, yield and homogeneity over 300 mm wafers

Courtesy Doug Resnick, Canon Nanotechnology

Moore's law – the 'inner law' of growth

for (integrated circuit) microchip manufacturing

Moore's law: roadmap defined 1965 by Gordon Moore

transfer of economic rules into the world of lithography

«The number of transistors has to double every 18 months»

⇨ engineers are forced to do a technological advancement

More Moore: NIL as a next generation lithography

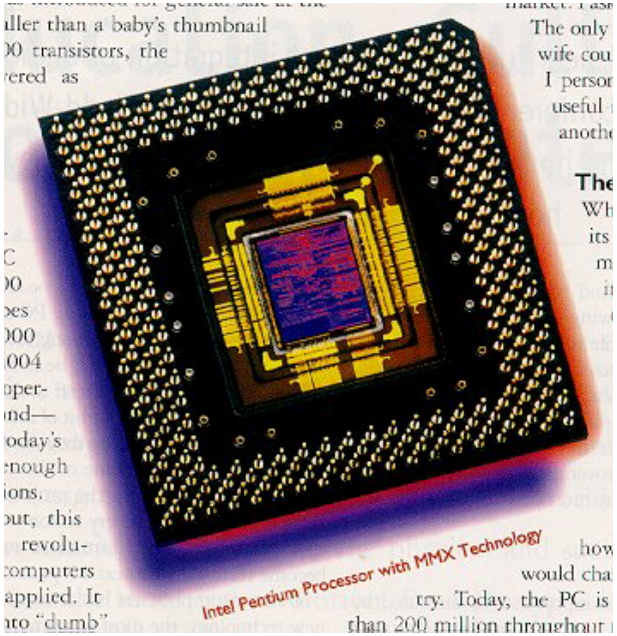
«The number of transistors has to double every 18 months»

⇨ NIL is forced to obey Moore's law (resolution, defectivity)

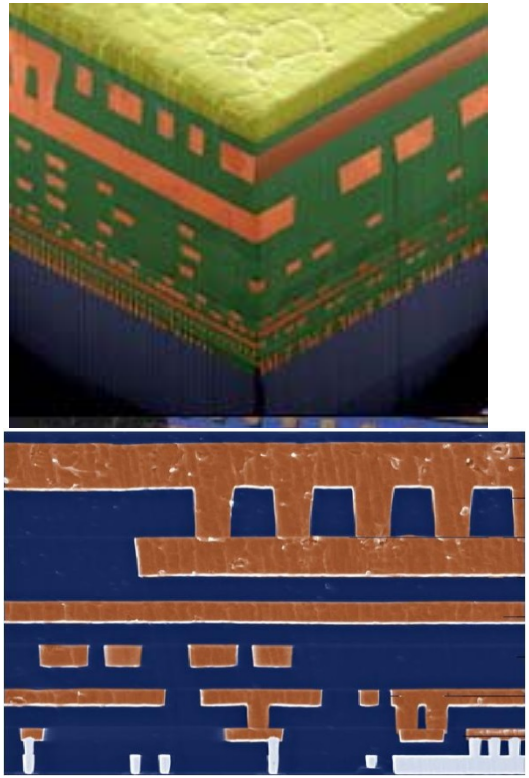
⇨ Different priorities (defectivity), resolution not much smaller than with DUV

⇨ NIL has to be cheaper than other high-end lithographies

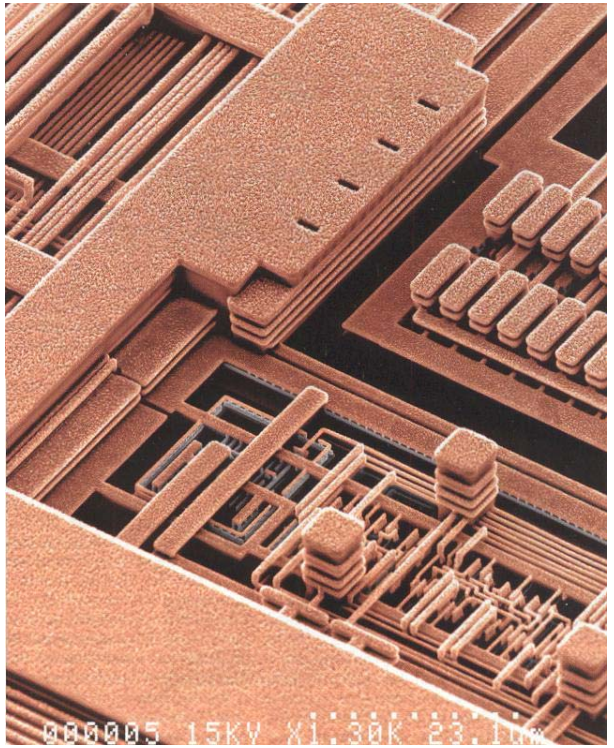
Integrated Chips – Interconnect Layer



Intel Pentium Processor



IBM copper interconnect
with six metal layers
(year: 1998)



IBM CMOS 0.12 mm
Dual Damascene process

Nanoimprint needs to
be used for transistors
with smaller gate lengths – or for the interconnect layer

http://www-03.ibm.com/chips/about/technology/makechip/interconnect/

Moore's law – the 'inner law' of growth

for (integrated circuit) microchip manufacturing

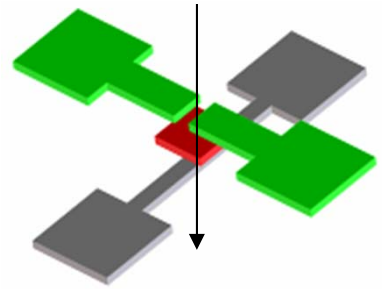
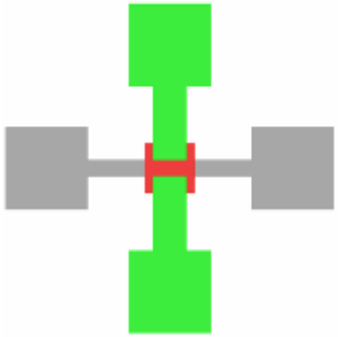
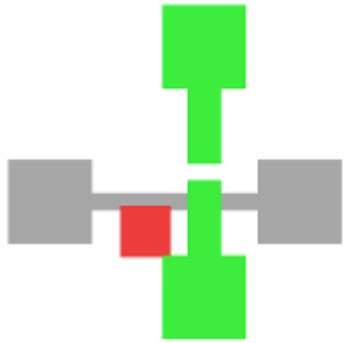
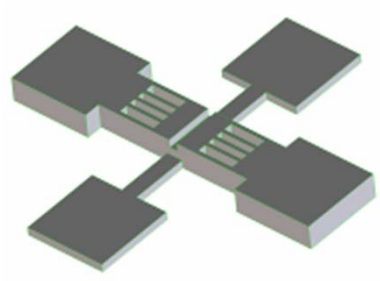
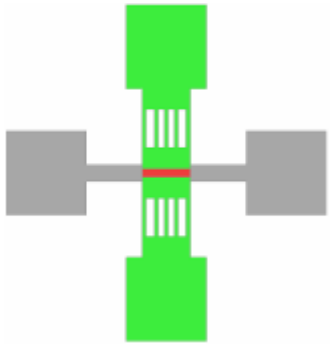
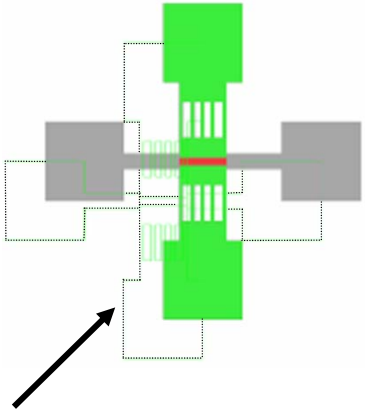
More than Moore: NIL with multilayer approach (with benefits)

«The number of transistors has to double every 18 months»

⇨ NIL is forced to obey Moore's law (resolution, defectivity) at a much lower price (cost of ownership)

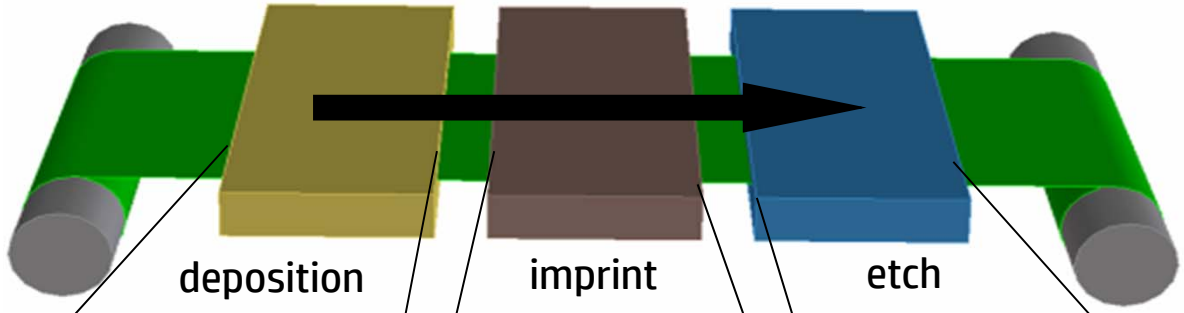
BUT NIL does not only replace single lithographic steps, but also has added value by reducing the number of process steps

SAIL: Self-Aligned Imprint Lithography

Photolithography	 Multiple masking and alignment steps required	 Different mask used to pattern each layer	 Process distortion of 200ppm results in 20µ misalignment over 10cm
SAIL	 SAIL encodes multiple patterns and alignments into thickness modulations of a monolithic masking structure	 Single mask used to pattern all the layers multiple times	 No misalignment because mask distorts with substrate

Carl Taussig, HP Labs

SAIL: Self-Aligned Imprint Lithography

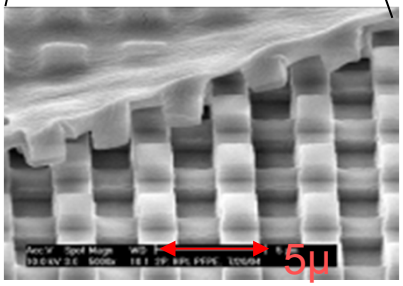


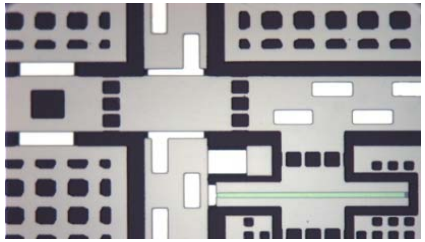
SAIL Process flow is radically different from typical thin film

Vacuum deposition of metals, dielectrics, & semiconductors

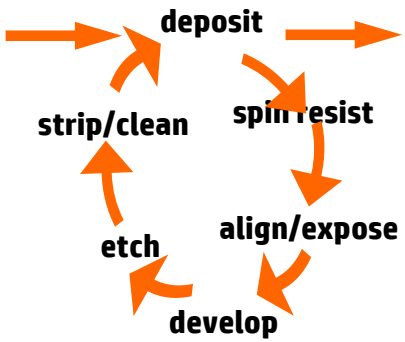
Multiple mask levels imprinted as single 3D structure

Patterning completed w/ wet & dry processes

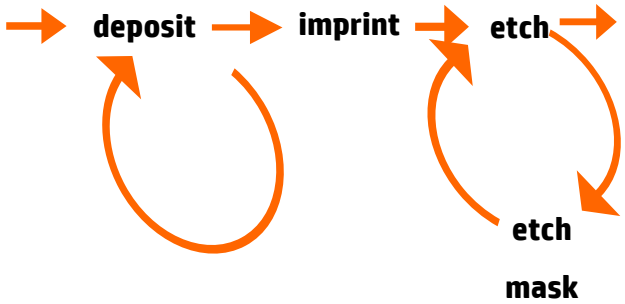




Conventional Photo-Litho



SAIL



Carl Taussig, HP Labs

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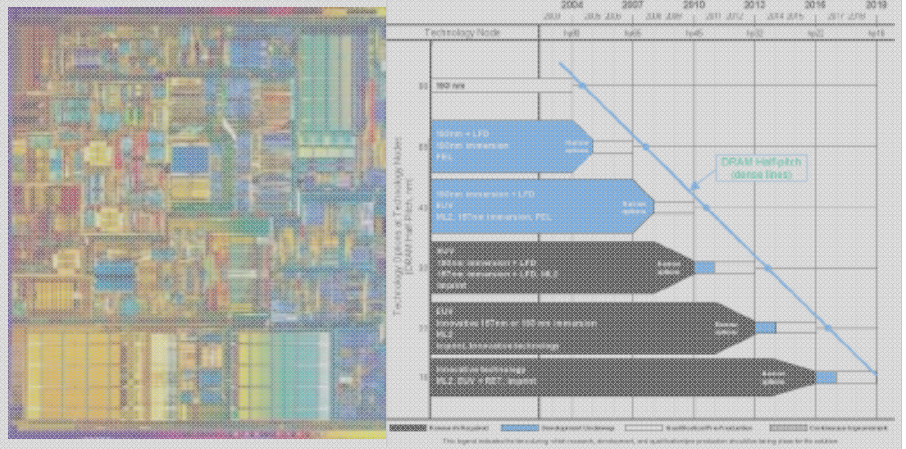
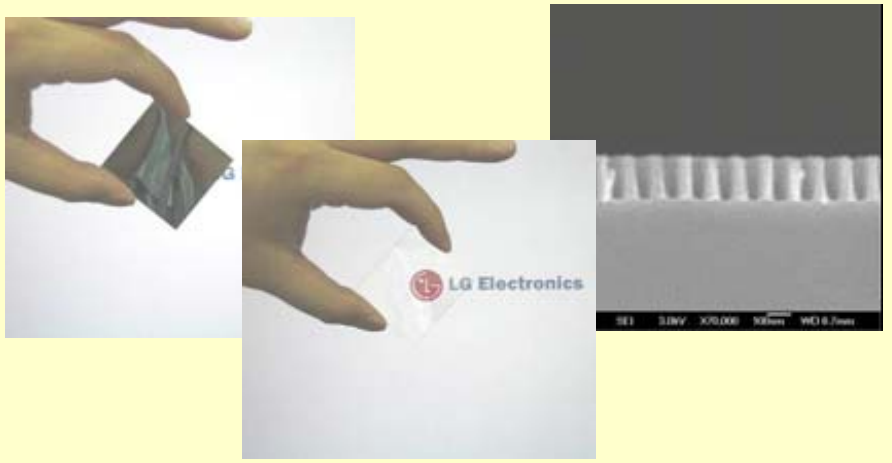
Nanopatterning – Main NIL Applications

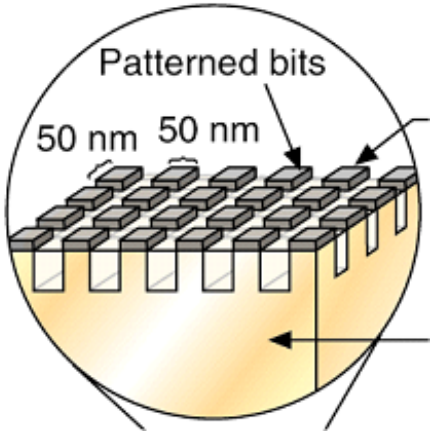
High End Microelectronic Chips

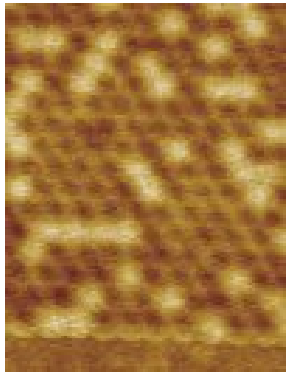


Wire Grid Polarizer

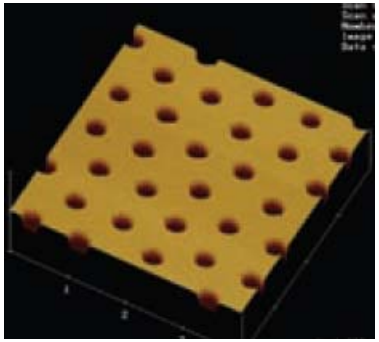


Patterned Magnetic Media





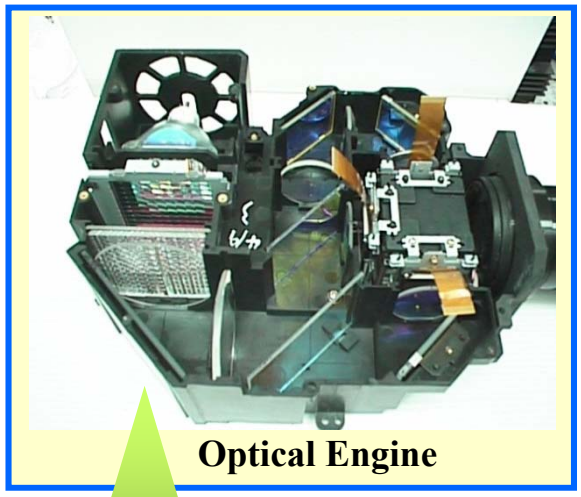
High Brightness LEDs



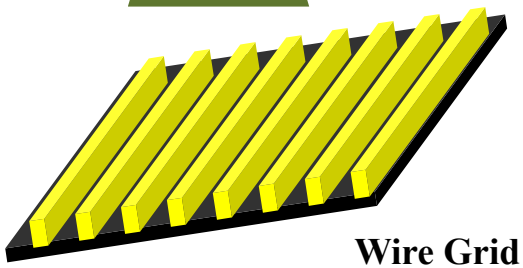
Wire Grid Polarizer in Projection Display

Wire grid polarizer is being increasingly adapted in micro-display projection TV as a core optical component.

LCD/LCoS Projection TV



Optical Engine

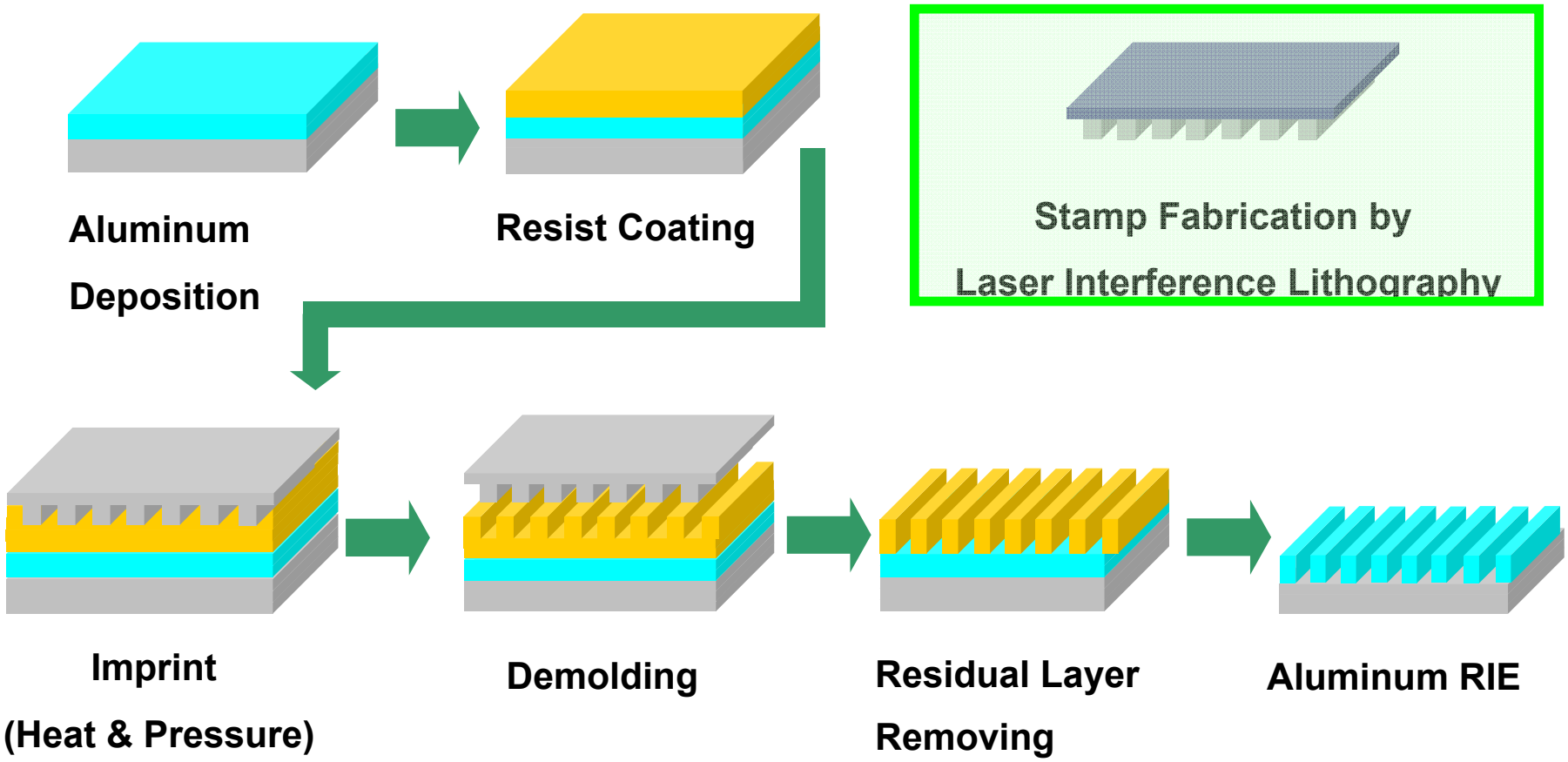


Wire Grid Polarizer

LG Electronics

나노메카트로닉스기술개발사업단
Center for Nanoscale Mechatronics & Manufacturing

Fabrication Procedure



LG Electronics

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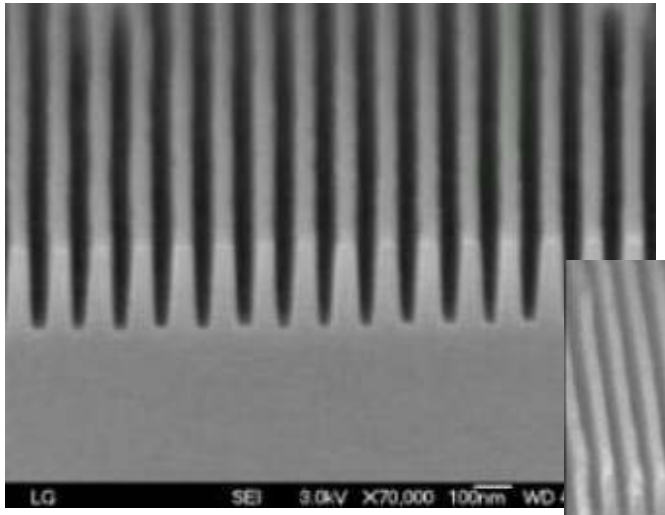
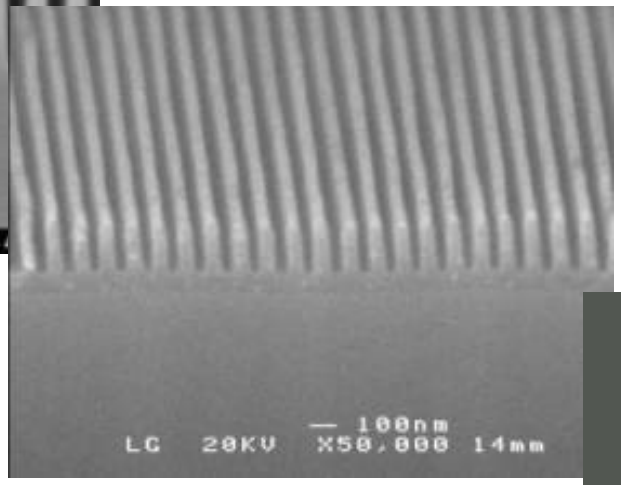
Center for Nanoscale Mechatronics & Manufacturing

50 nm Half-pitch Gratings

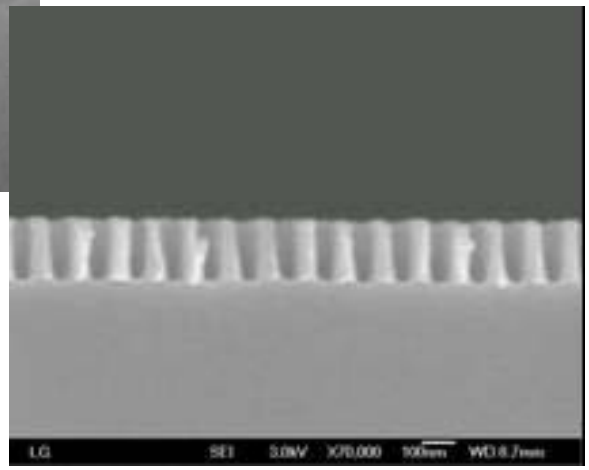


Fabrication of 50 nm Half-pitch Wire Grid Polarizer Using Nanoimprint Lithography, NNT 2004

Stamp with 50 nm half-pitch grating



Imprinted polymer pattern



50 nm half-pitch Al grating

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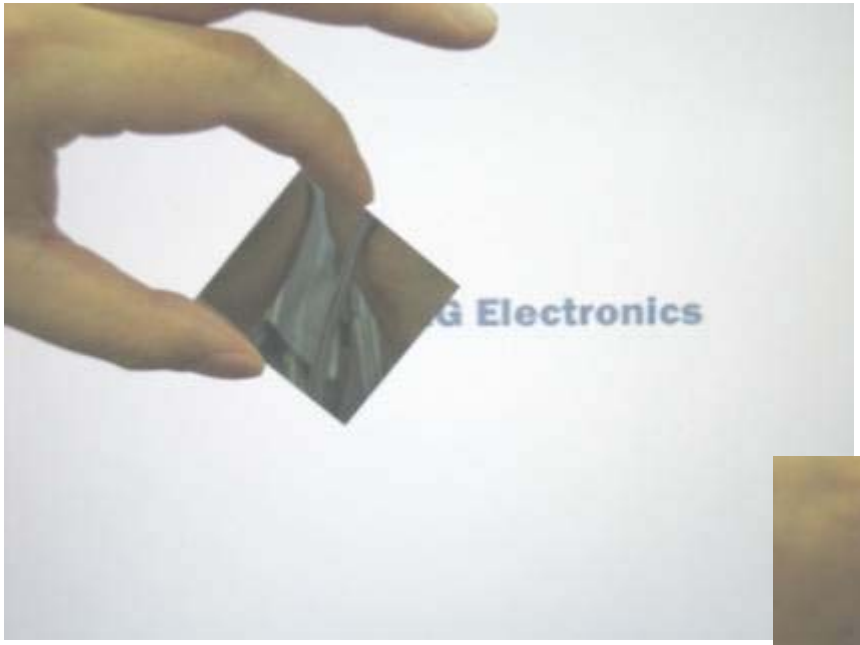
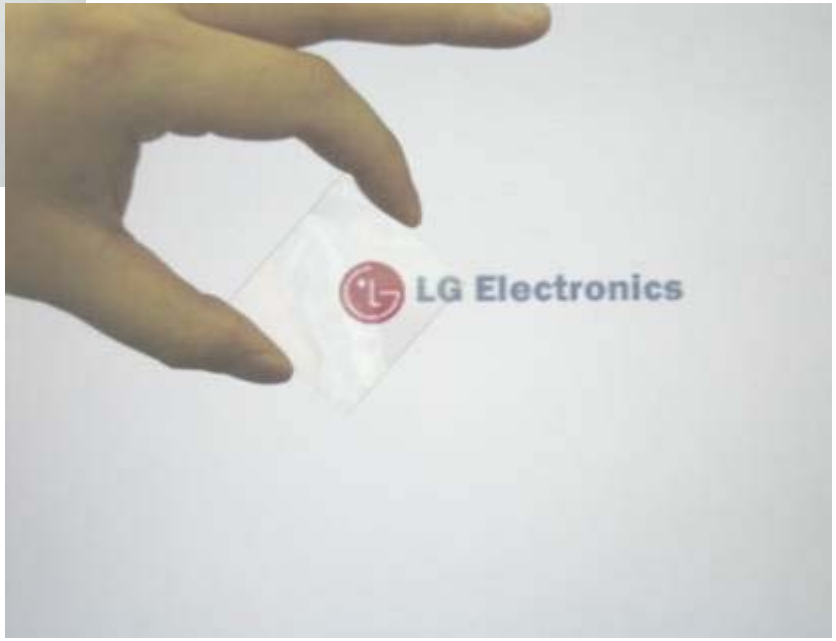
Center for Nanoscale Mechatronics & Manufacturing

Ki-Dong Lee, Devices & Materials Lab.
LG Electronics Institute of Technology

Performance of Fabricated Polarizer





Extinction Ratio > 2,000

Transmission > 85 %

at λ = 450 nm

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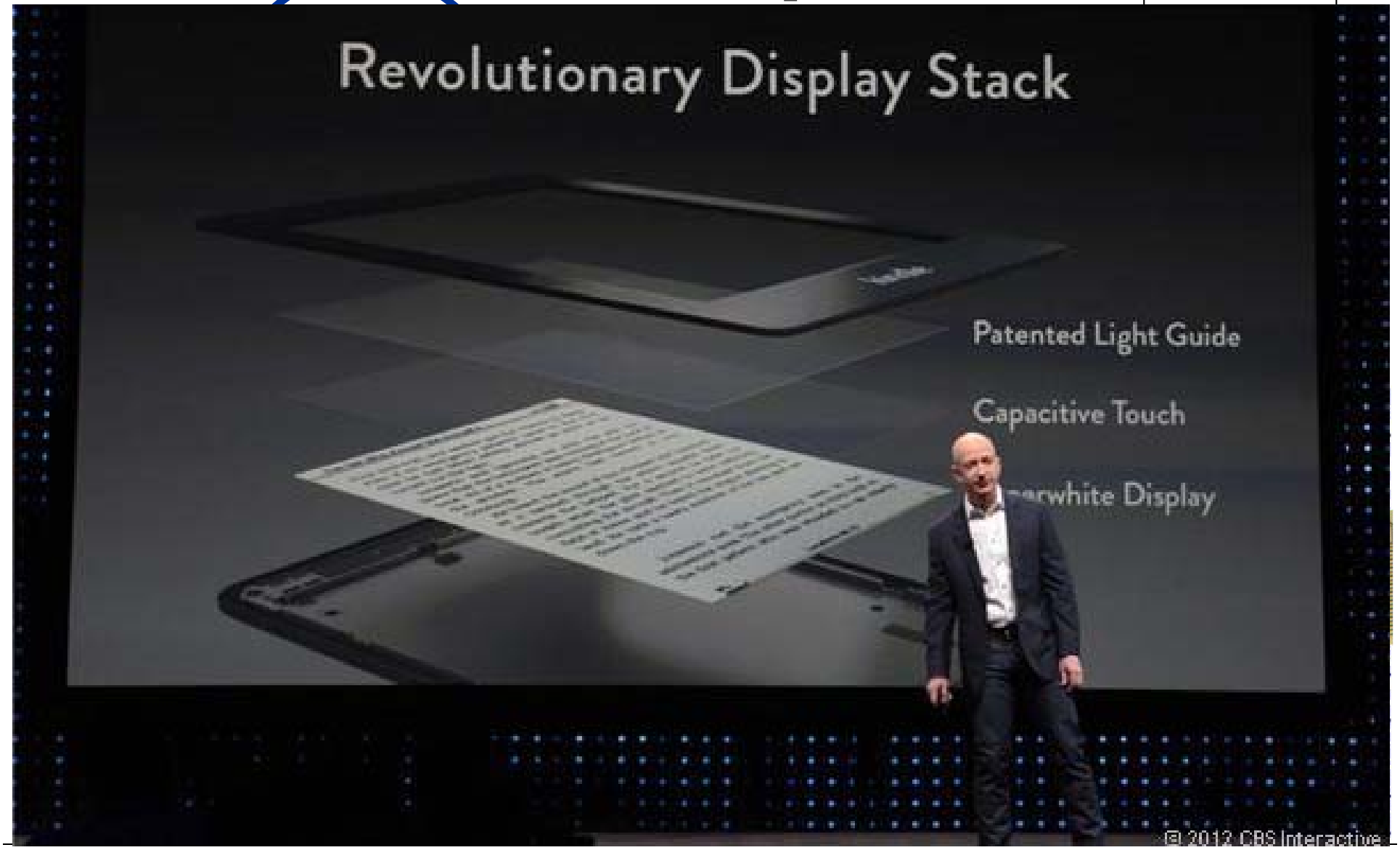
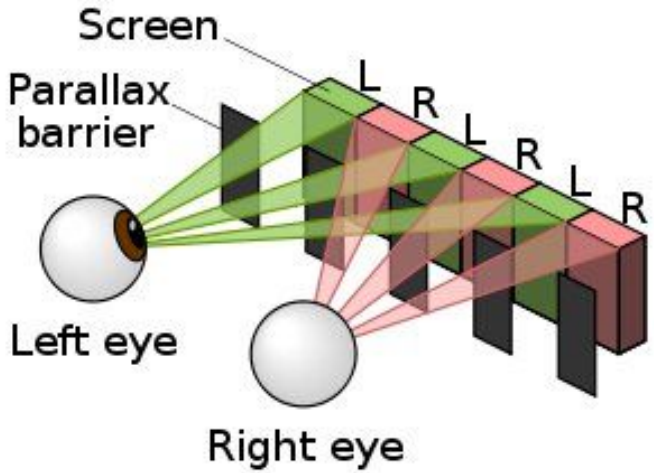
Center for Nanoscale Mechatronics & Manufacturing

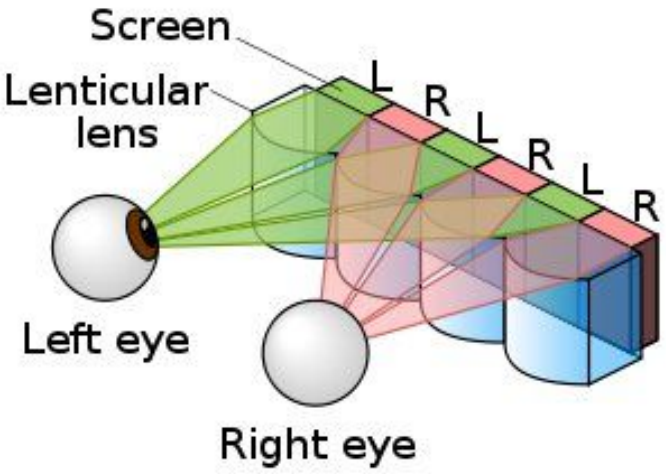
Industrial Demonstrators: Example 1 PDOE

Backlight



EyeFly 3D Screen Protector from Nanoveu



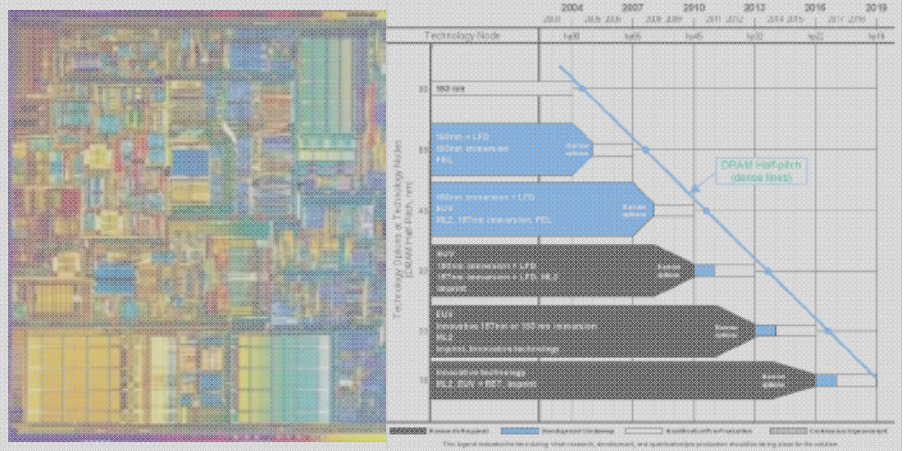


Structure Origination with Interference Lithography

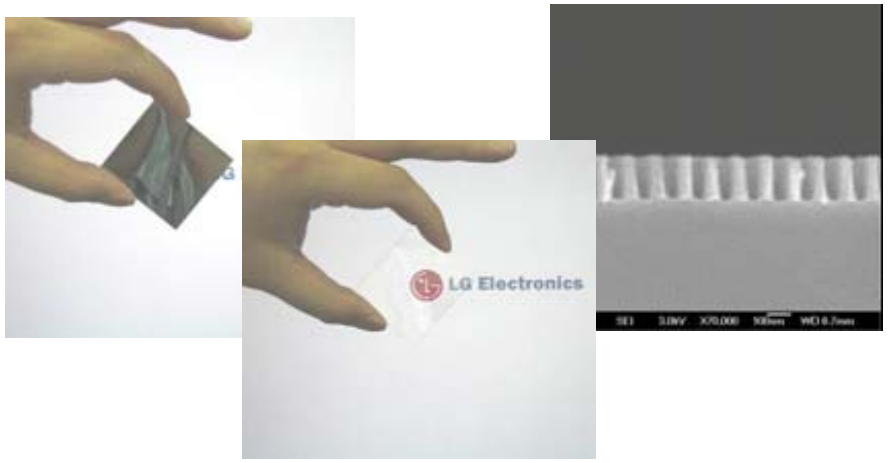
- Maximum substrate size: 1.2 x 1.2 m²
- Exposure times: up to 5 h
- Optical path lengths: up to 20 m
- Acceptable instabilities: < 20 nm
- Extreme stability requirements for building and set-up

Nanopatterning – Main NIL Applications

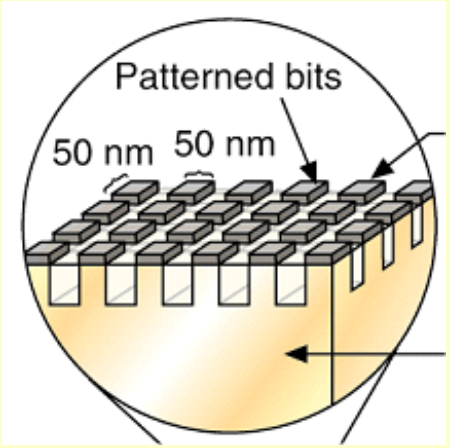
High End Microelectronic Chips

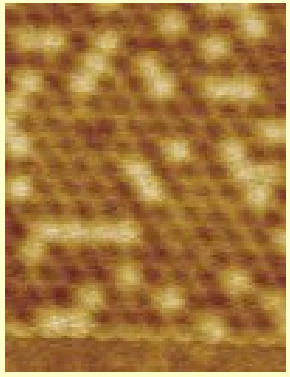


Wire Grid Polarizer

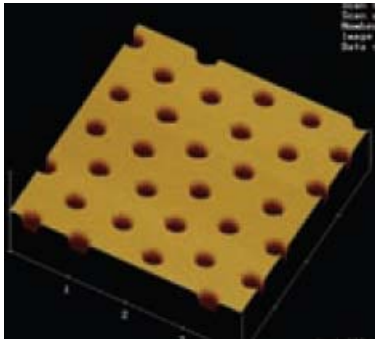


Patterned Magnetic Media

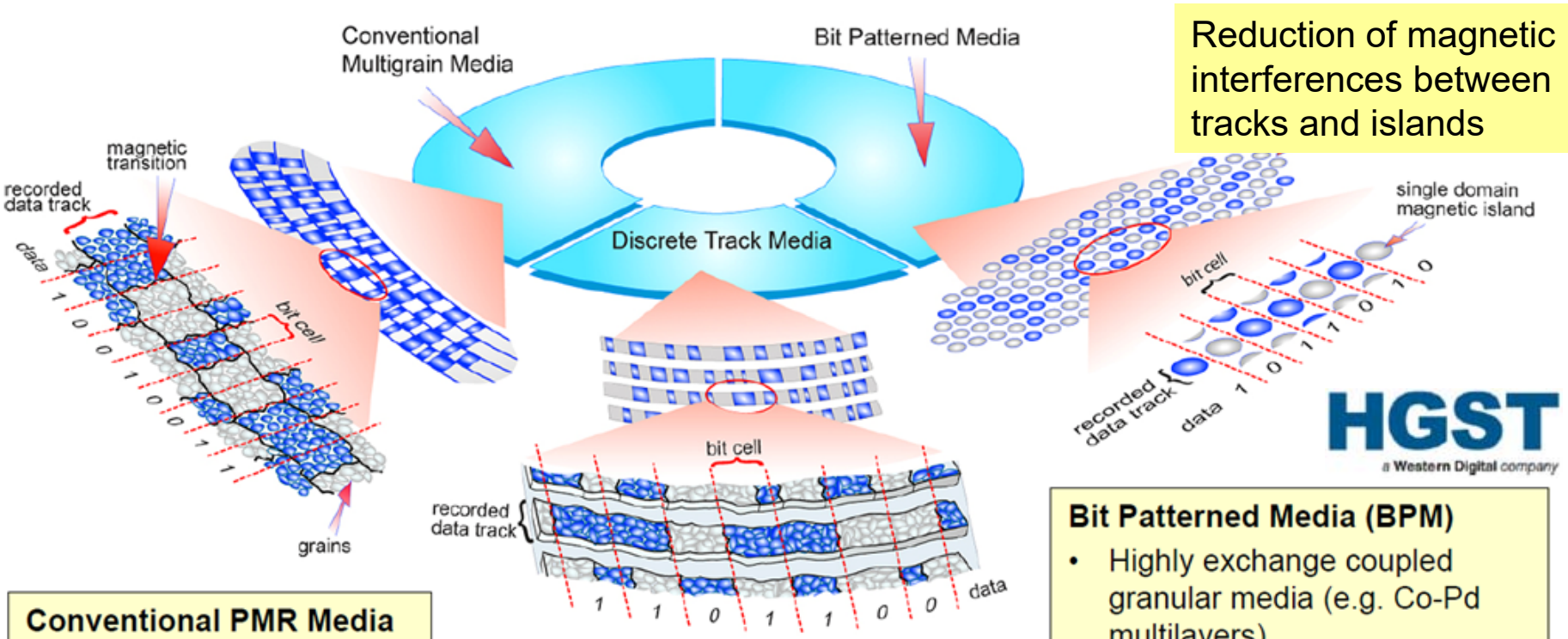




High Brightness LEDs



Conventional granular, discrete track, and bit patterned



Reduction of magnetic interferences between tracks and islands

Conventional PMR Media

- Continuous granular recording layer
- Multiple grains per bit
- Boundaries between bits determined by grains
- Thermal stability unit is 1 grain (~ 6 nm diam.)
- Reaching its limits

PMR = perpendicular magn. rec.

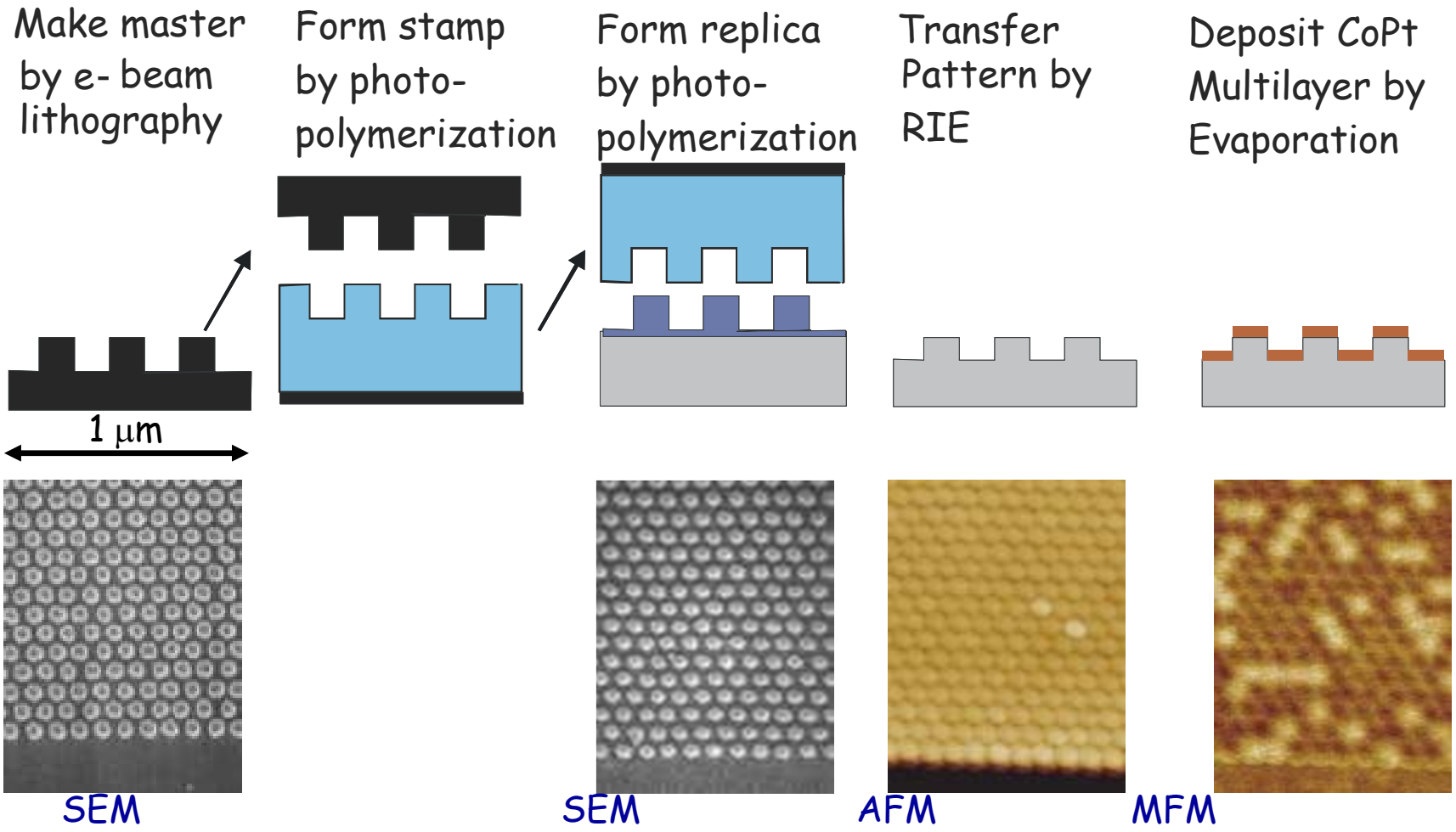
Discrete Track Media (DTM)

- Conventional PMR media, with patterned tracks
- Multiple grains per bit
- Eliminates track edge noise and reduces adjacent track interference
- Thermal stability unit is still 1 grain (~ 6 nm diam.)
- Modest areal density gain possible

Bit Patterned Media (BPM)

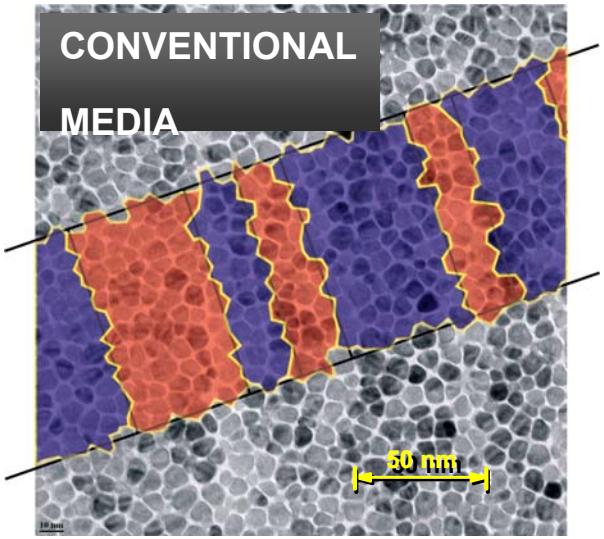
- Highly exchange coupled granular media (e.g. Co-Pd multilayers)
- Multiple grains per island, but each island is a single domain particle
- Bit locations determined by lithography
- Therm. stab. unit is 1 island (~15 nm diam.)
- Substantial areal density gain should be feasible

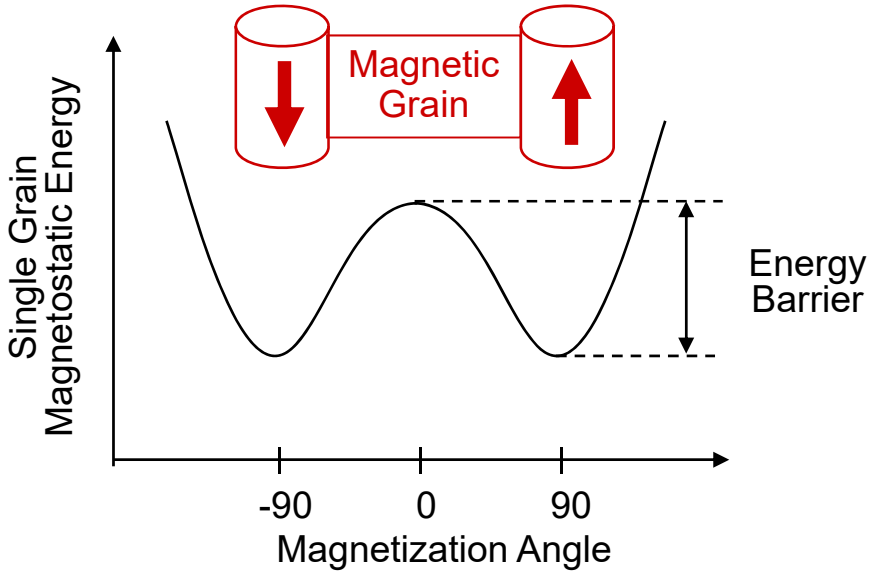
Magnetic Islands by Nanoimprinting



Source: Hewlett Packard, NNT2004

The problem: thermal stability, write-ability, and density





Magnetic Stability: $\frac{\text{energy barrier}}{\text{thermal energy}} \propto \frac{\text{anisotropy x volume}}{k_B \text{ x temperature}} = \frac{K_u V}{k_B T} > 70$

PROBLEM:

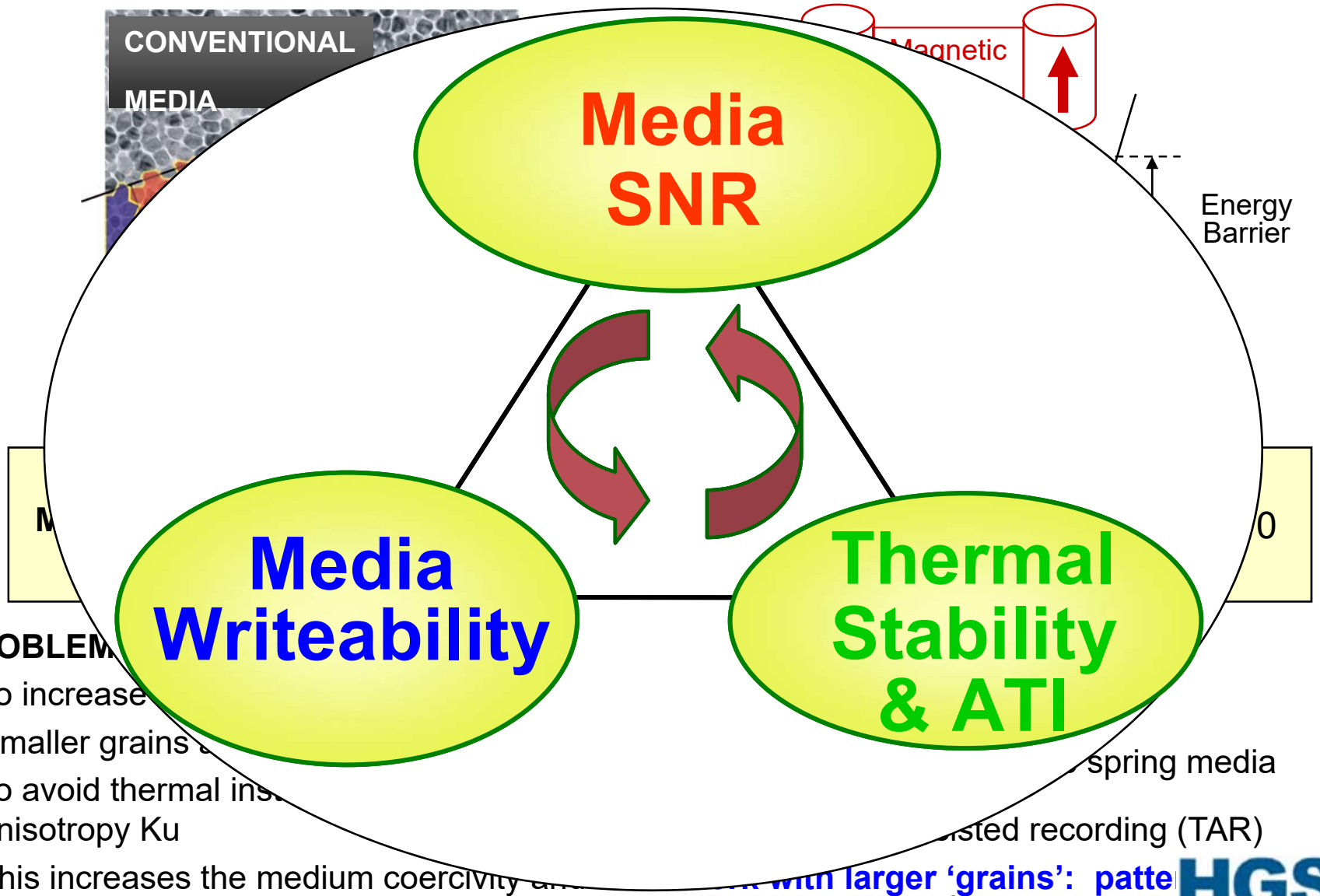
- To increase density, need smaller grains
- Smaller grains are thermally unstable
- To avoid thermal instability, increase grain anisotropy Ku
- This increases the medium coercivity and makes the medium more difficult to write

SOLUTIONS:

- Work with higher anisotropy:
  - Capped and exchange spring media
  - Thermally assisted recording (TAR)
- **Work with larger 'grains': patterned media**

HGST
a Western Digital company

The "Trilemma"



PROBLEM

- To increase
- Smaller grains
- To avoid thermal ins
  anisotropy Ku
- This increases the medium coercivity
  makes the medium more difficult to write

spring media

isted recording (TAR)

with larger 'grains': patte

ATI: adjacent track interference

SNR: signal to noise ratio

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BPM Requires Features Smaller Than Semiconductors

International Technology Roadmap

Figure LITH3B Flash Potential Solutions

	First Year of IC Production	2011	2012	2013	2014	2015	2016	2017	2018	2019
	Flash ½ Pitch (nm) (un-contacted Poly)(f)	22	20	18	17	15	14	13	12	11
32	193 nm DP									
22	193 nm DP									
16	193nm MP									
	EUV									
	Imprint									
11	EUV higher NA / EUV + DP									
	193nm MP									
	DSA + Litho									
	EUV (new wavelength)									
	Imprint									
	Innovation									

NAND Flash Time Line

Narrow Options

Narrow Options

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required

Development Underway

Qualification / Pre-Production

Continuous Improvement

6-9 nm needed

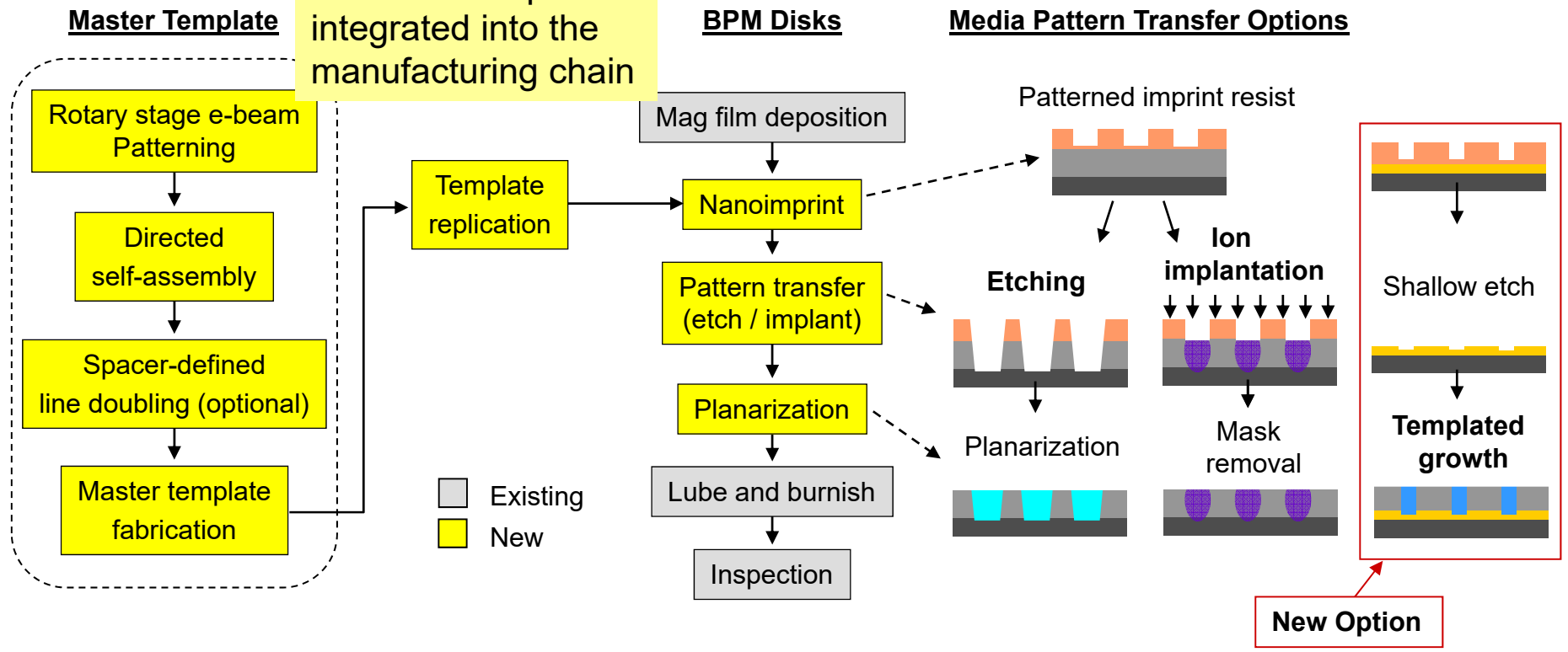
Compared to semiconductor manufacturing, we need:

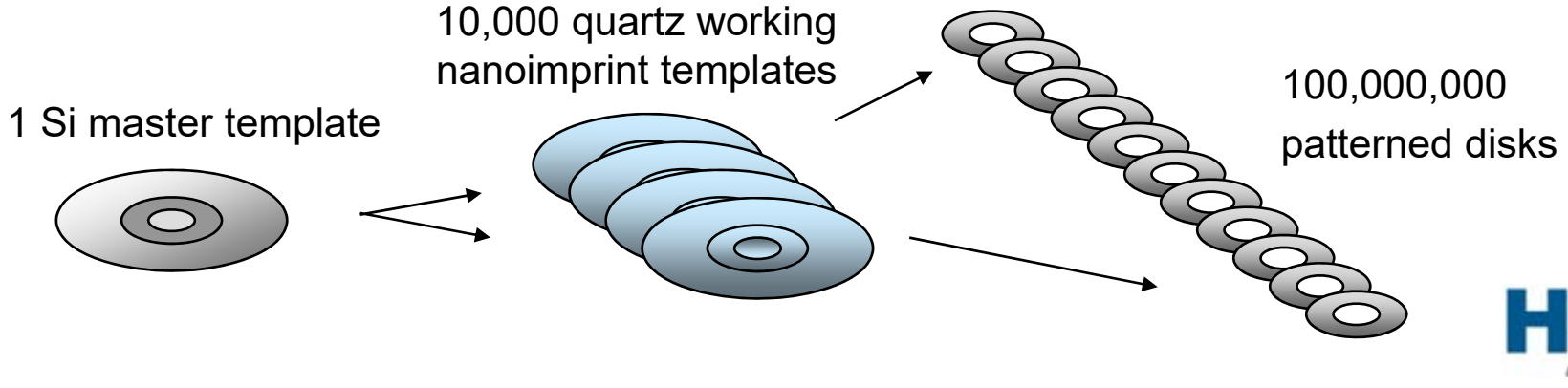
- **Smaller features sooner**
- **Higher volume (10^9 disks/year)**
- **Lower cost target (< $5/disk total; < $1 for patterning)**
- **Periodic features; simple patterns**
- **No overlay**

HGST a Western Digital company

BPM High Volume / Low Cost Fabrication Strategy

Additional steps are integrated into the manufacturing chain





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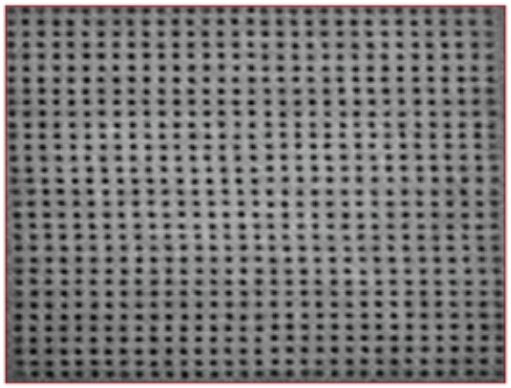
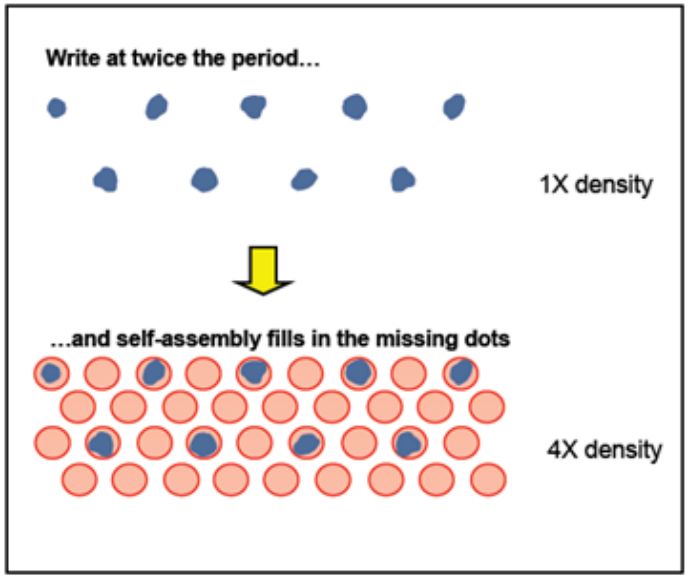
Master pattern lithography roadmap

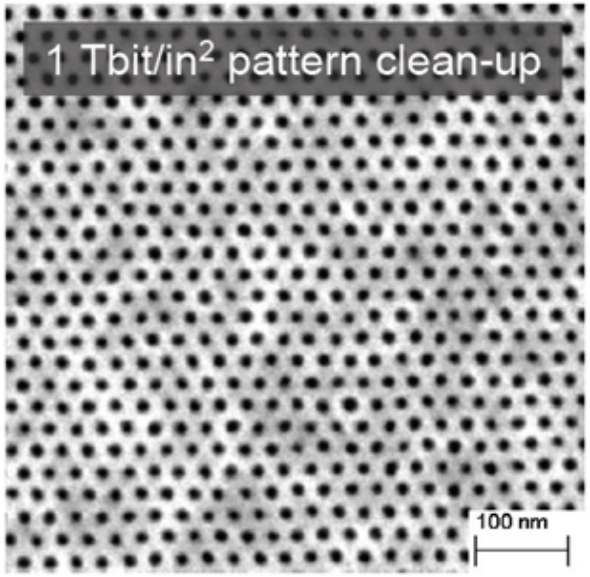
E-beam lithography



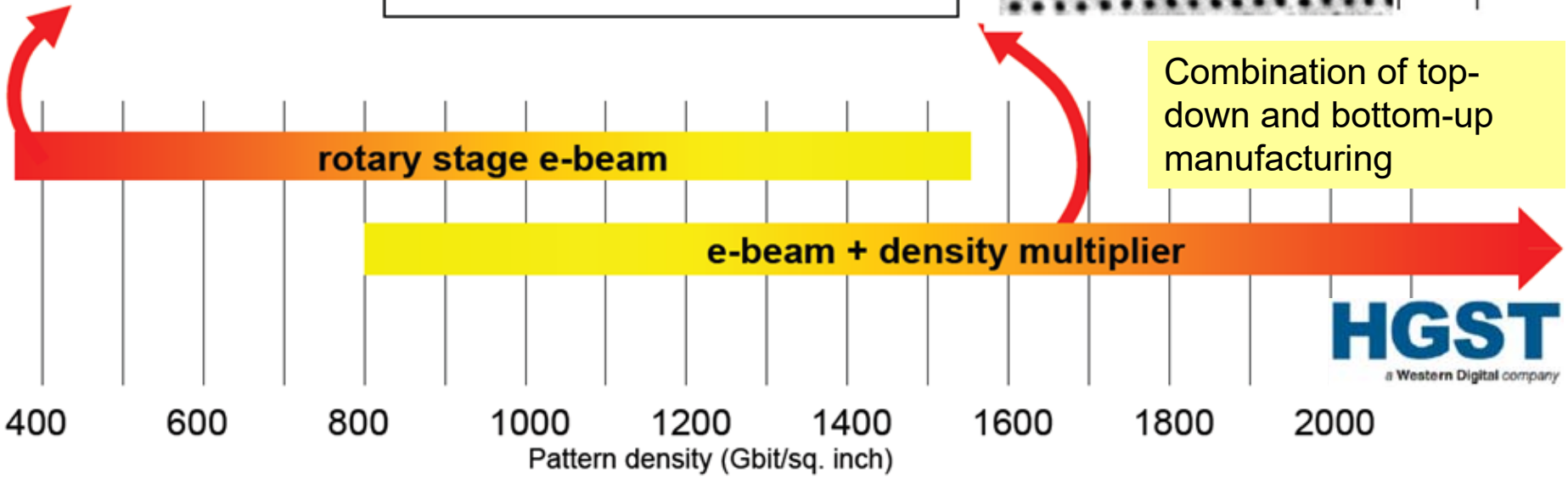
720 Gbit/in² (30 nm period):
Holes etched in Si master mold
(Leica VB-6 100 kV w/ PMMA, cold ultrasonic develop; RIE pattern transfer)

e-beam prepattern + block copolymer self-assembly

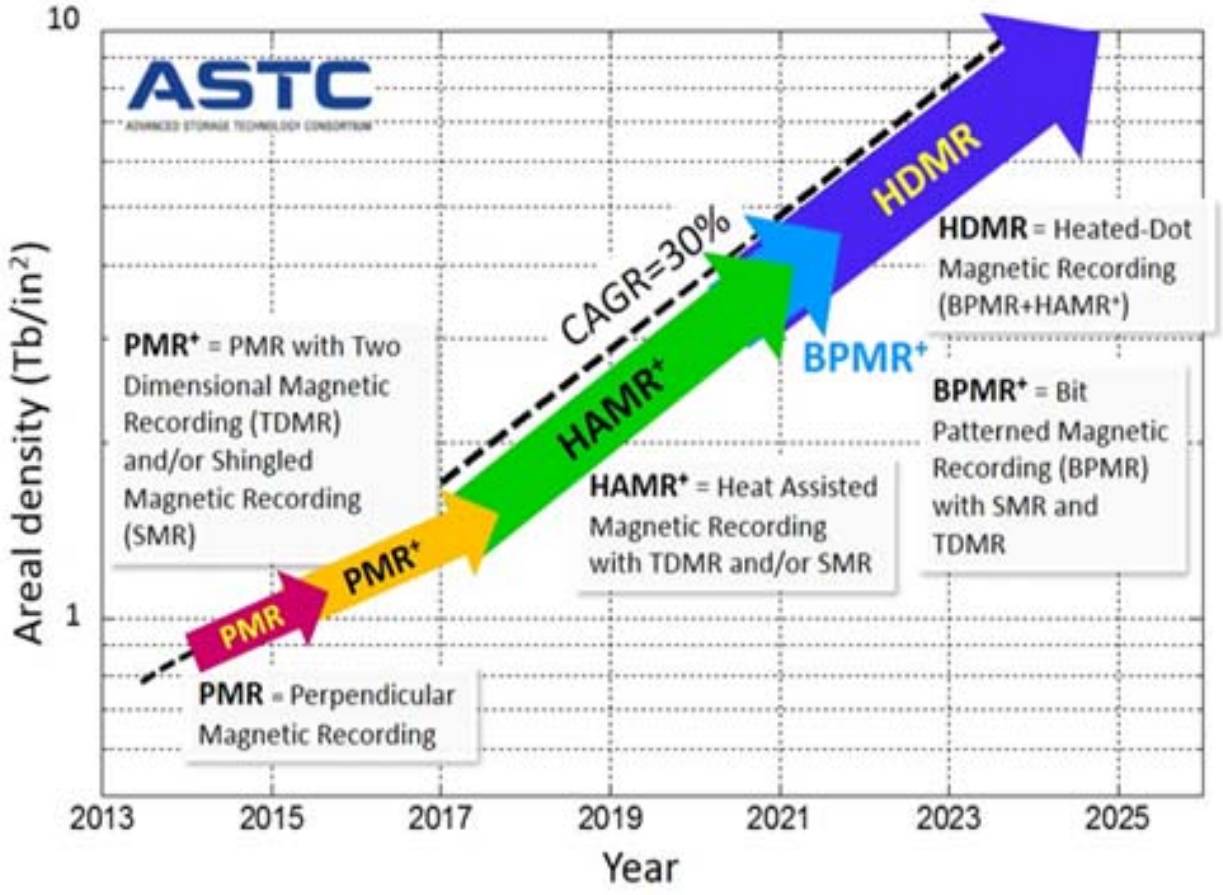




Combination of top-down and bottom-up manufacturing



BPM-Status: it is on in the industry roadmap

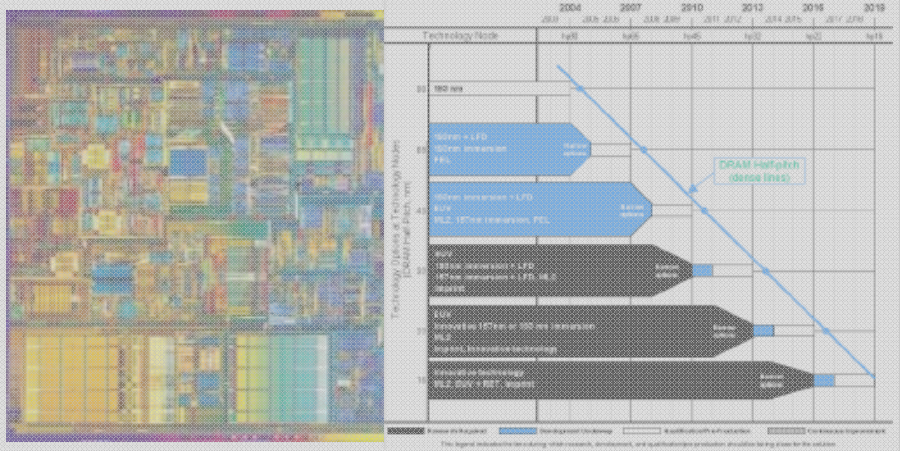


Bit-patterned media is on the ASTC industry roadmap for post-2020

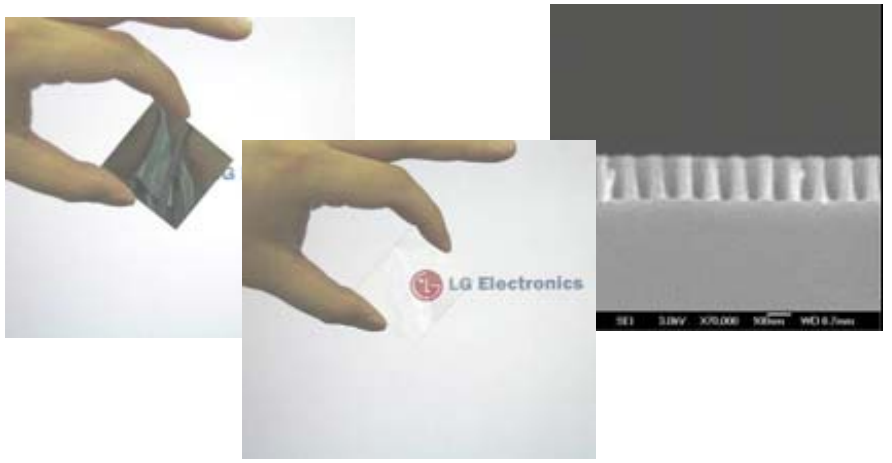
WesternDigital (HGST): BPM «on hold» (last publication 2015)
Seagate: still active in BPM (last publication 2015)
Toshiba: ? (last publication 2010)

Nanopatterning – Main NIL Applications

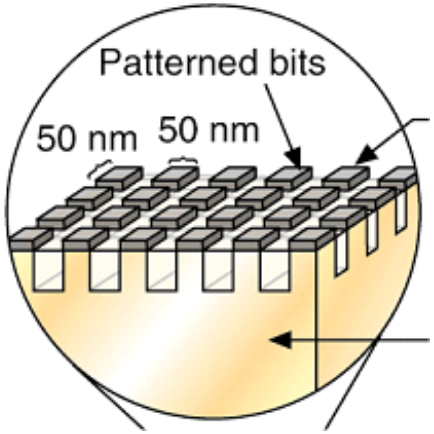
High End Microelectronic Chips

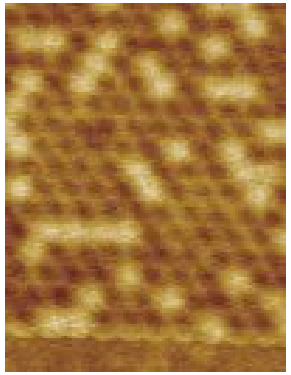


Wire Grid Polarizer

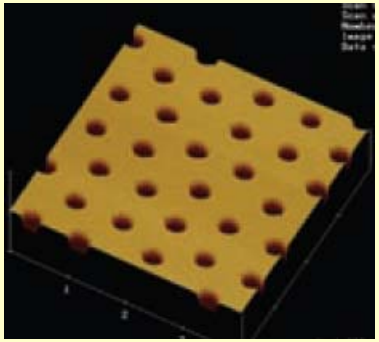


Patterned Magnetic Media





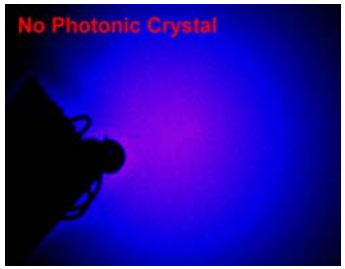
High Brightness LEDs

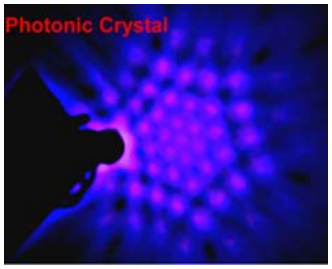


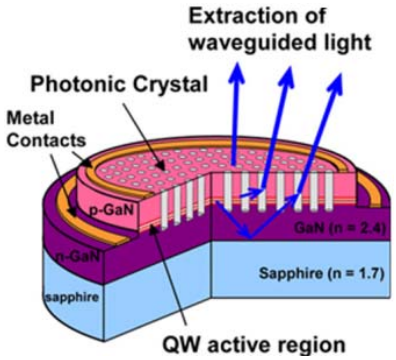
Different concepts for the realization of high-brightness LEDs

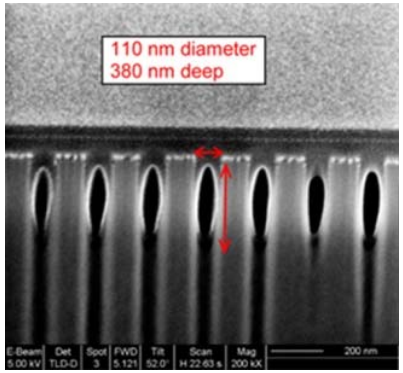
1. Photonic crystals

High aspect ratios in GaN necessary (>3:1)



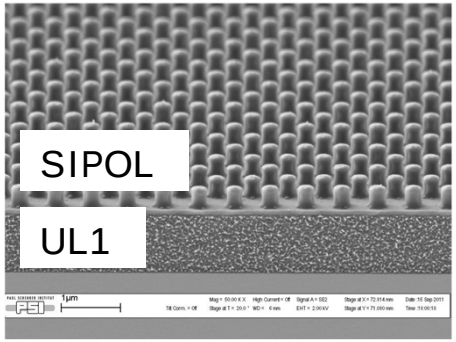


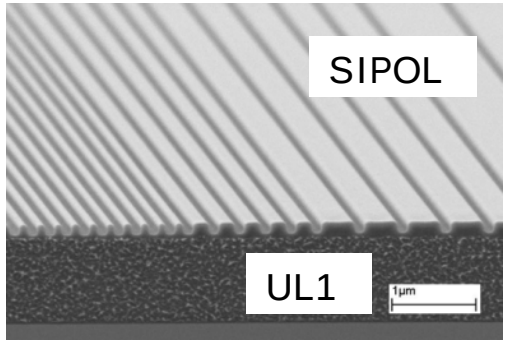


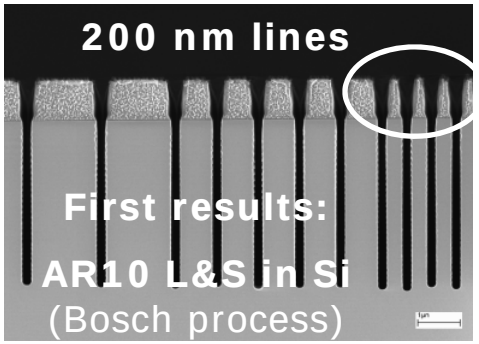


DL Barton and AJ Fischer SPIE Newsroom **2006**
doi:10.1117/2.1200603.0160

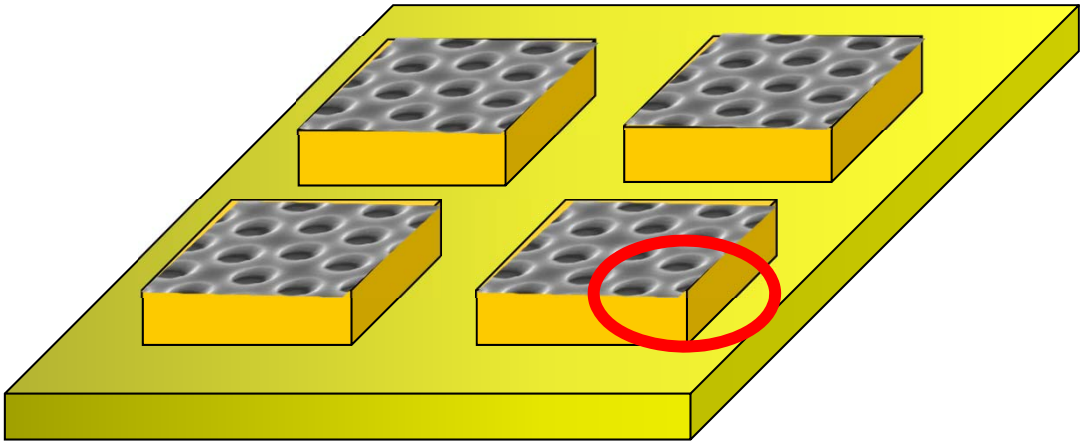
e.g. SIPOL in a bilayer approach

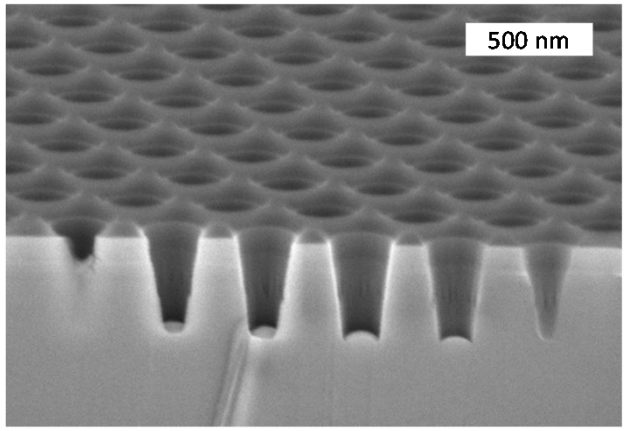






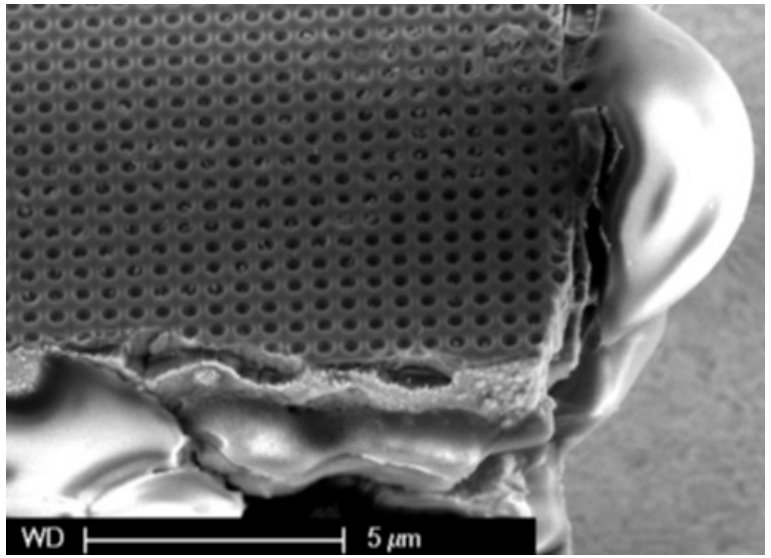
Patterning LEDs on sub-mount





Separated LED chips

- Test LEDs
- Place individual LEDs
- Spray coat sol-gel resist
- Flexible stamp
  ➔ Imprint on top of LEDs
- Etch GaN



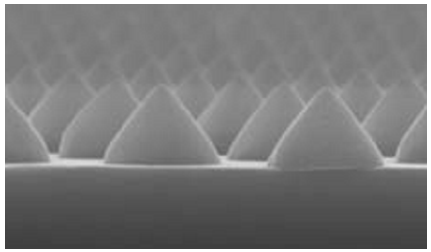
Courtesy of: M. Verschuuren, Philips Research, Eindhoven

Different concepts for the realization of high-brightness LEDs

2. Nano-Patterned Sapphire Substrates (NanoPSS)

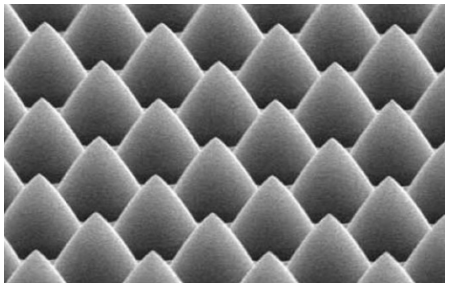
Concept with the widest use in industry

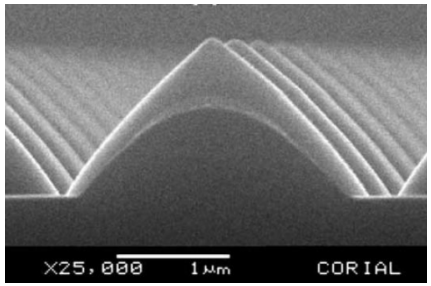
Hemispheres, cones, triangles, hexagons, etc…



Y-C Lee and S-H Tu *Rec Adv in Nanofabrication Techn and Appl* 173 **2011** 196

- mr-NIL 6000E, mr-I 9000M
- **PSS-specific Photo-NIL resist prototypes** (PDMS compatibility)



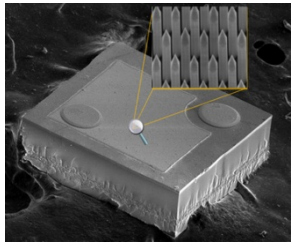


www.corial.net

3. Nano-wire approach

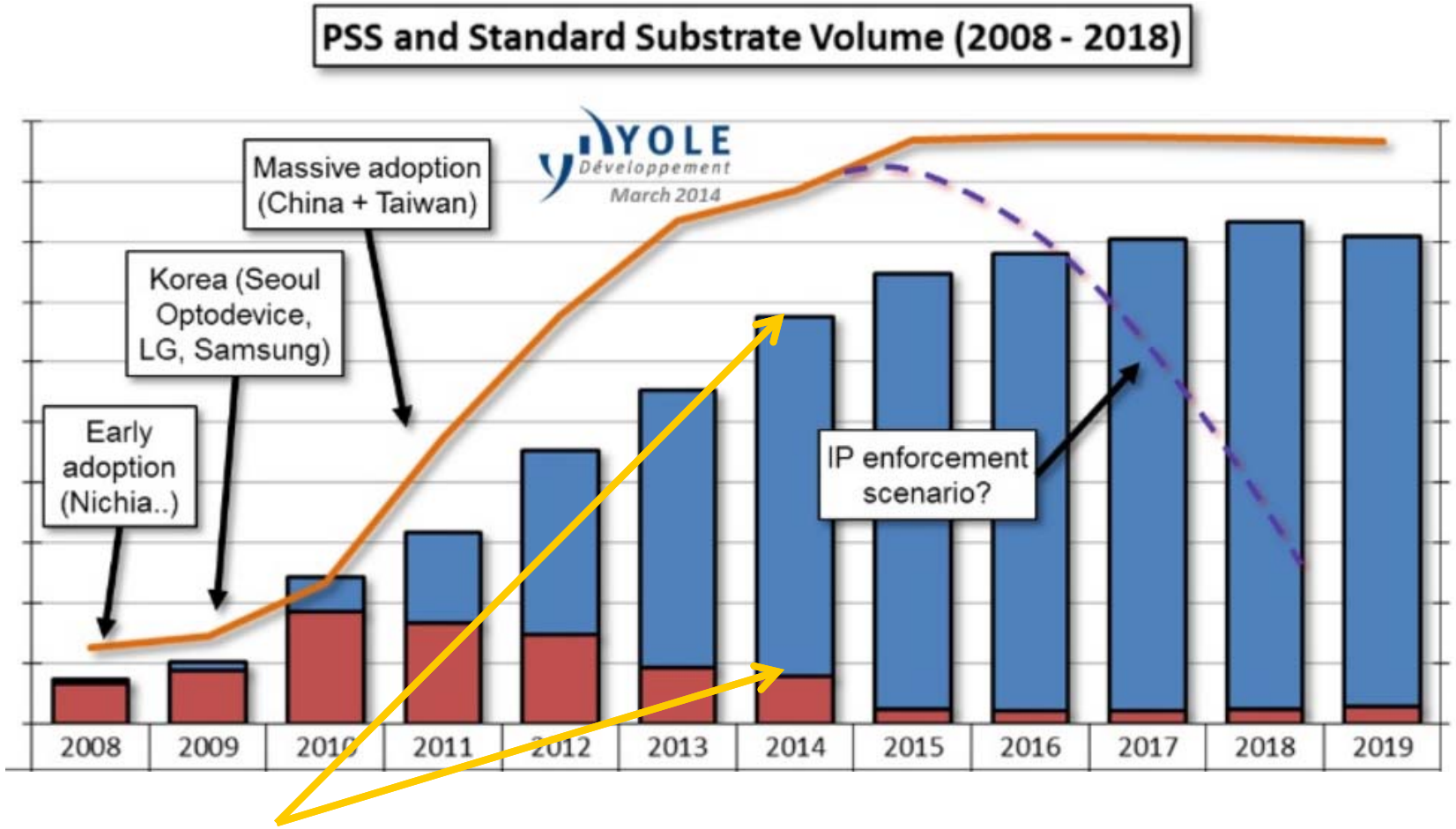
True white light LED chip possible without the need of an additional phosphor

mr-NIL 6000E, mr-I 9000M



www.glo.se

Nano-Patterned Sapphire Substrates (NanoPSS)



87% of fabricated LEDs in 2014 are processed on PSS

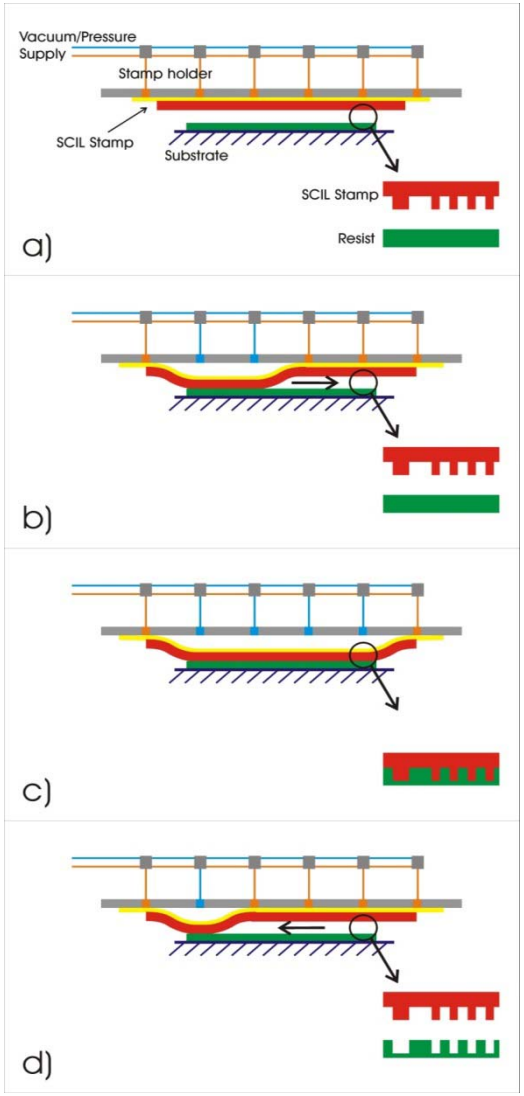
PSS: optical Lithography ⇨ **Nano-PSS requires NIL**

Source Yole Developpement LED Frontend Manufacturing Trends **2014**

Nanoimprint Machines from SÜSS : MA8-SCIL

MA8-SCIL tool:

- Substrate Conformal Imprint Lithography (SCIL)
- Composite soft stamps
- Demonstrated with UV-curable resists and Sol-gel materials
- Semiautomatic tool
- 1000 W lamp
- 6 & 8 inch system
- Alignment system

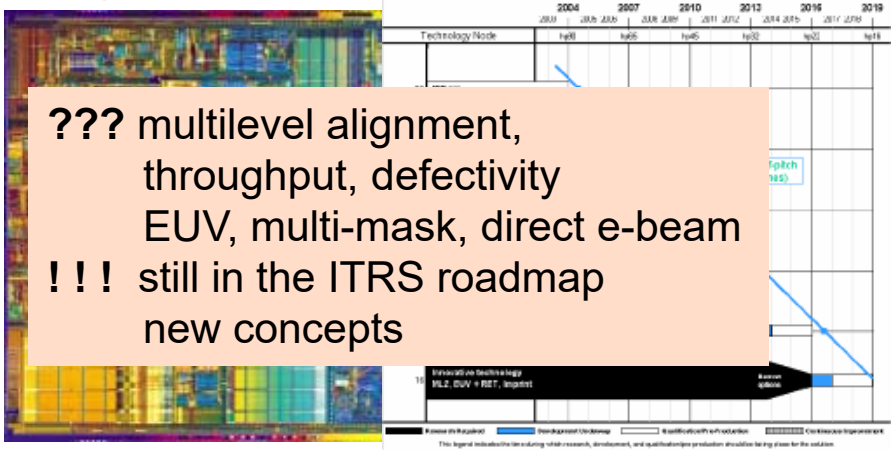


6”-8” imprint tool at AMO / Aachen
- UV imprint of large areas
- alignment

(+) molding and demolding
(-) layered stamp needed

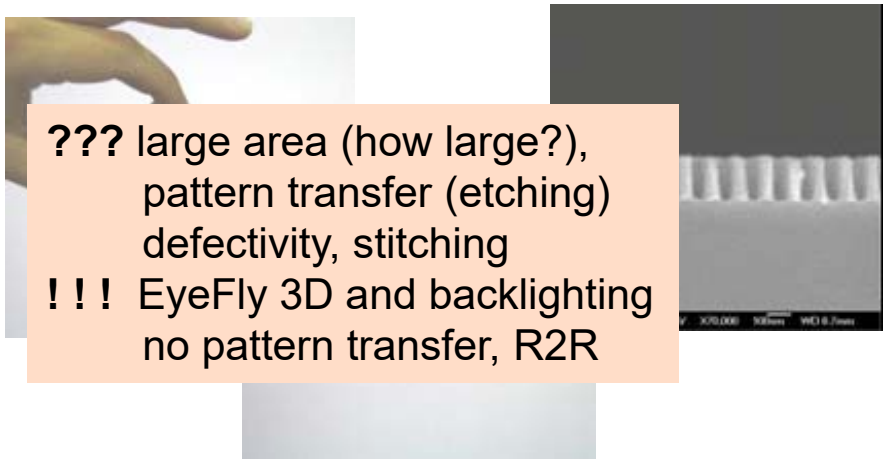
Nanopatterning – Main NIL Applications

High End Microelectronic Chips



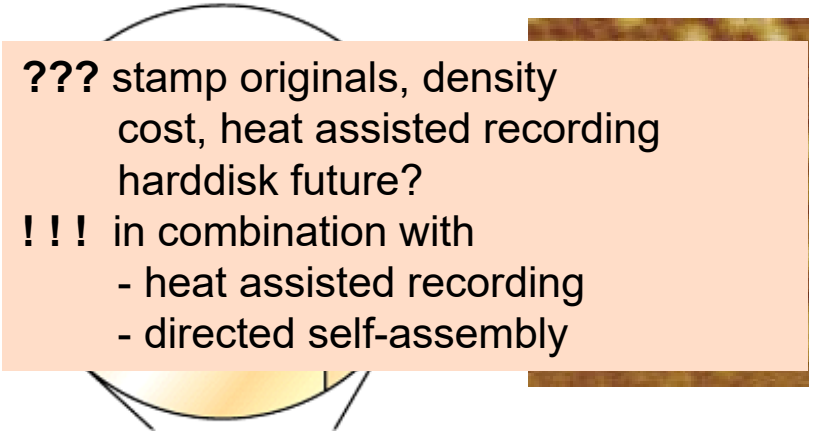
??? multilevel alignment,
throughput, defectivity
EUV, multi-mask, direct e-beam
! ! ! still in the ITRS roadmap
new concepts

Wire Grid Polarizer



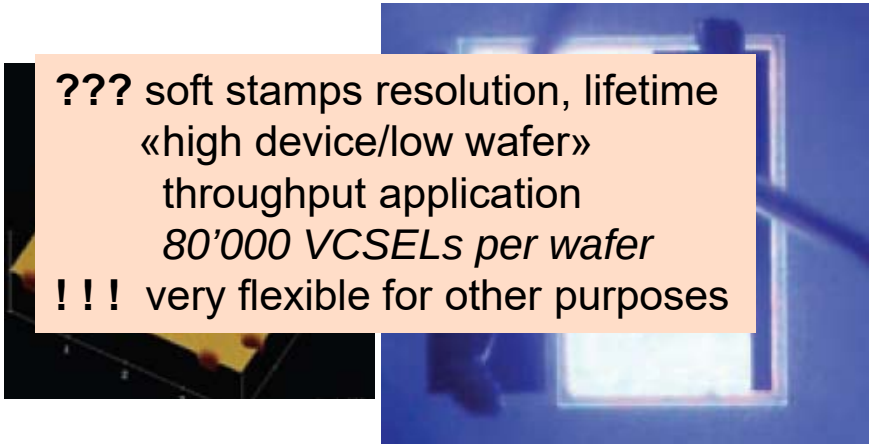
??? large area (how large?),
pattern transfer (etching)
defectivity, stitching
! ! ! EyeFly 3D and backlighting
no pattern transfer, R2R

Patterned Magnetic Media



??? stamp originals, density
cost, heat assisted recording
harddisk future?
! ! ! in combination with
- heat assisted recording
- directed self-assembly

High Brightness LEDs



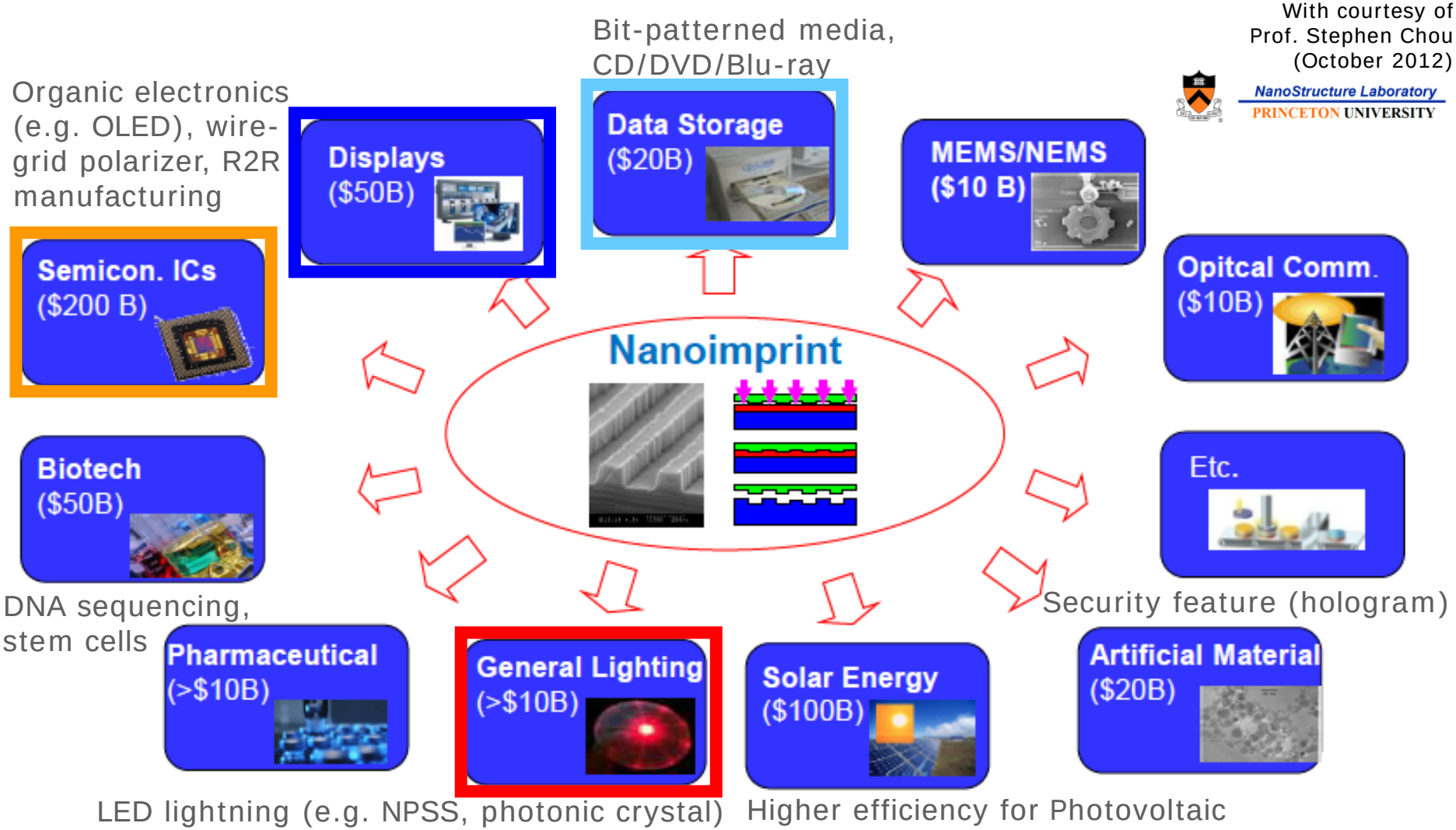
??? soft stamps resolution, lifetime
«high device/low wafer»
throughput application
80'000 VCSELs per wafer
! ! ! very flexible for other purposes

Nanoimprint enables Multi-billion Dollar Industries

Easy 3D patterning of functional materials using NIL technology

With courtesy of
Prof. Stephen Chou
(October 2012)

NanoStructure Laboratory
PRINCETON UNIVERSITY



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Outline

- Nanoimprint in the context of advances in mechanical engineering
- NIL is a Next Generation Lithography – true, but not only!
- Is NIL More Moore or More than Moore?
- Non-IC applications, more than Moore – front runners
- What a researcher can contribute
- … and More NIL to come

Application Examples (non-IC)

Electronics

- High brightness LEDs
- Photovoltaics
- Energy Storage (Li-Ion Batteries)
- Thin Film Transistors (TFTs)
- Lasers
- Structuring of Graphene
- Nanostructured Photoelectrodes

Pharmaceutics/Bioapplications

- Plasmonic Biosensors
- Titanium Implants

Optics

- Wire Grid Polarizers (WGPs)
- Metamaterials
- Sub-15 nm metal gratings
- Microlenses with nanostructures

Data storage

- Bit patterned (magnetic) media
- Crossbar storage

MEMS/NEMS

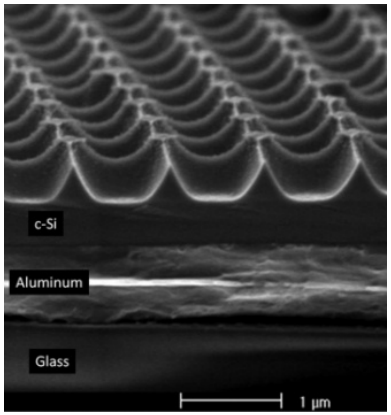
- Write/read heads
- Microcantilevers / -membranes

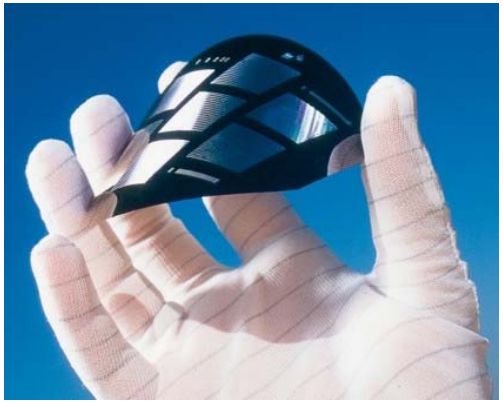
- Micro- and nanofluidics (μTAS, DNA sequencing, …)
- Biomimetic structures

- Fishnet transparent electrodes
- Structural colors
- Backlight display waveguides
- Light redirection for lighting
- Liquid crystal cells for displays

Nanopatterning – Main NIL Applications

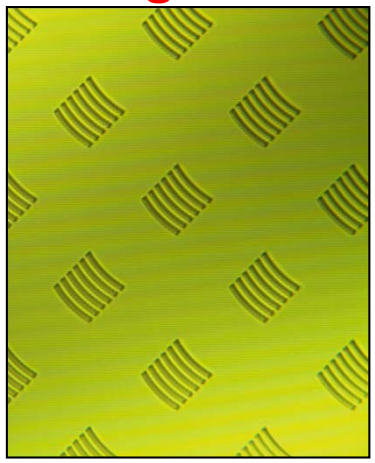
Photovoltaics



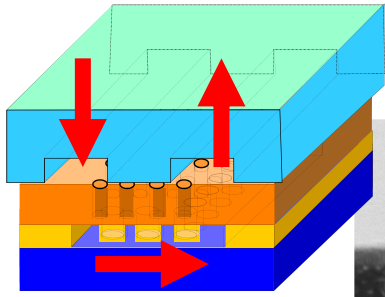


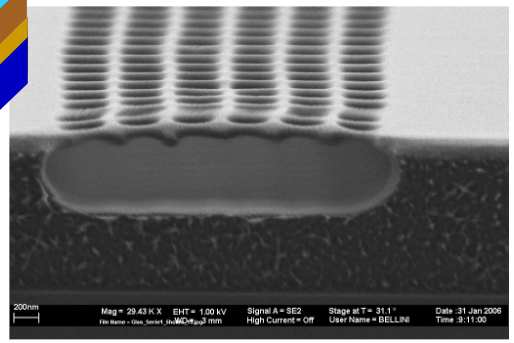
Transparent electrodes

Backlight Display Waveguides



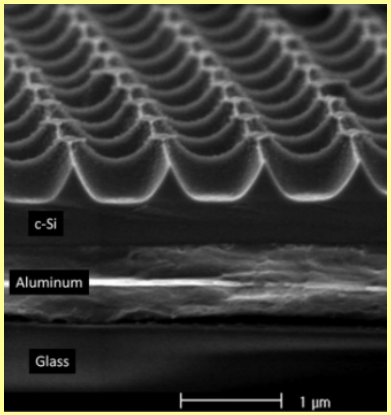
Nano-Fluidic Devices





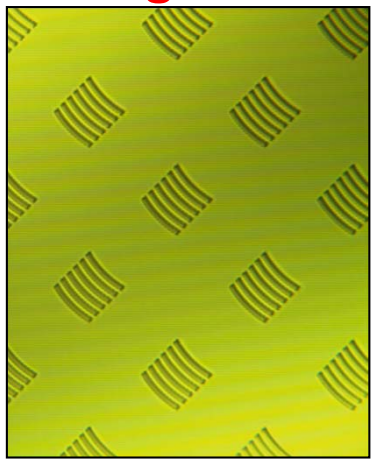
Nanopatterning – Main NIL Applications

Photovoltaics

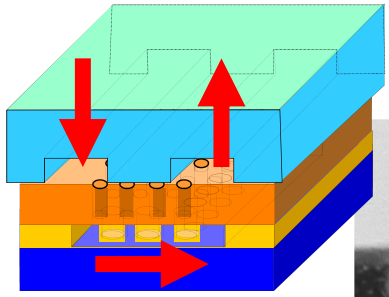


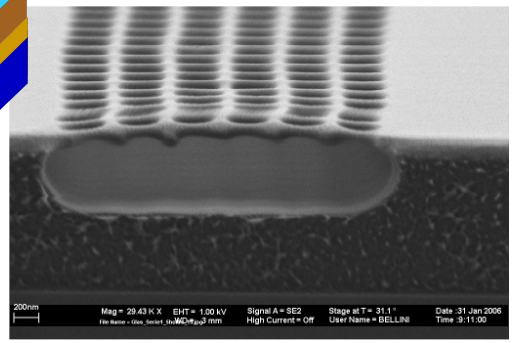
Transparent electrodes

Backlight Display Waveguide



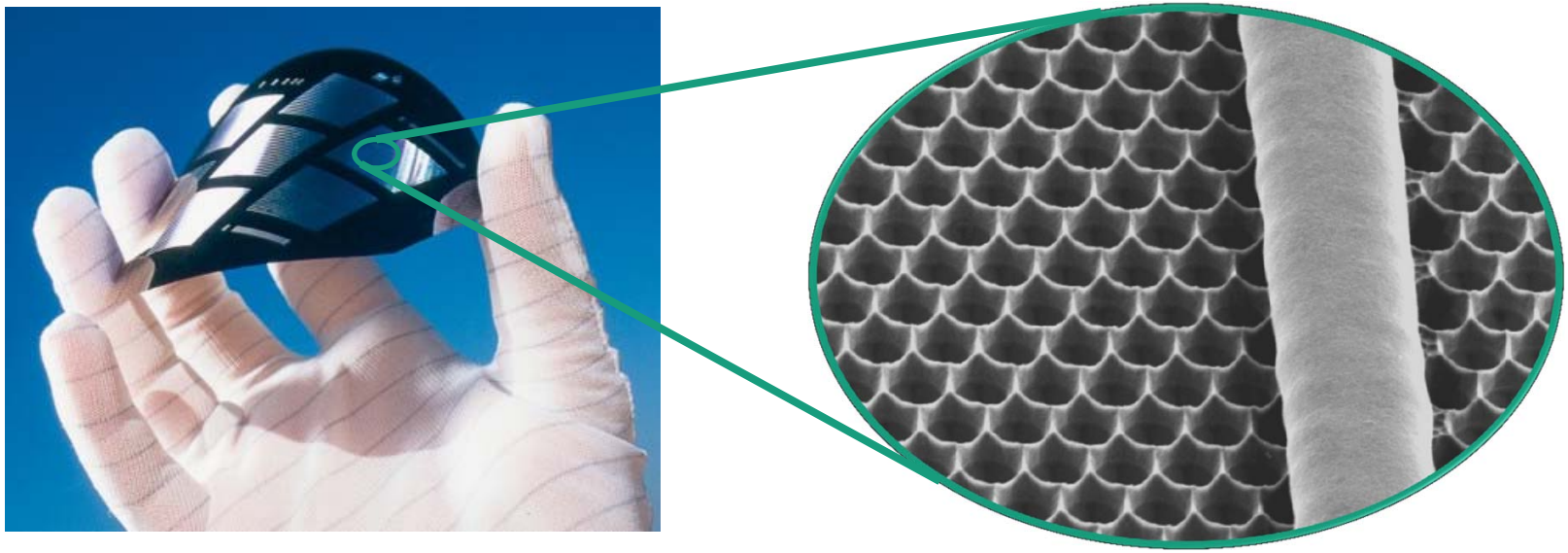
Nano-Fluidic Devices



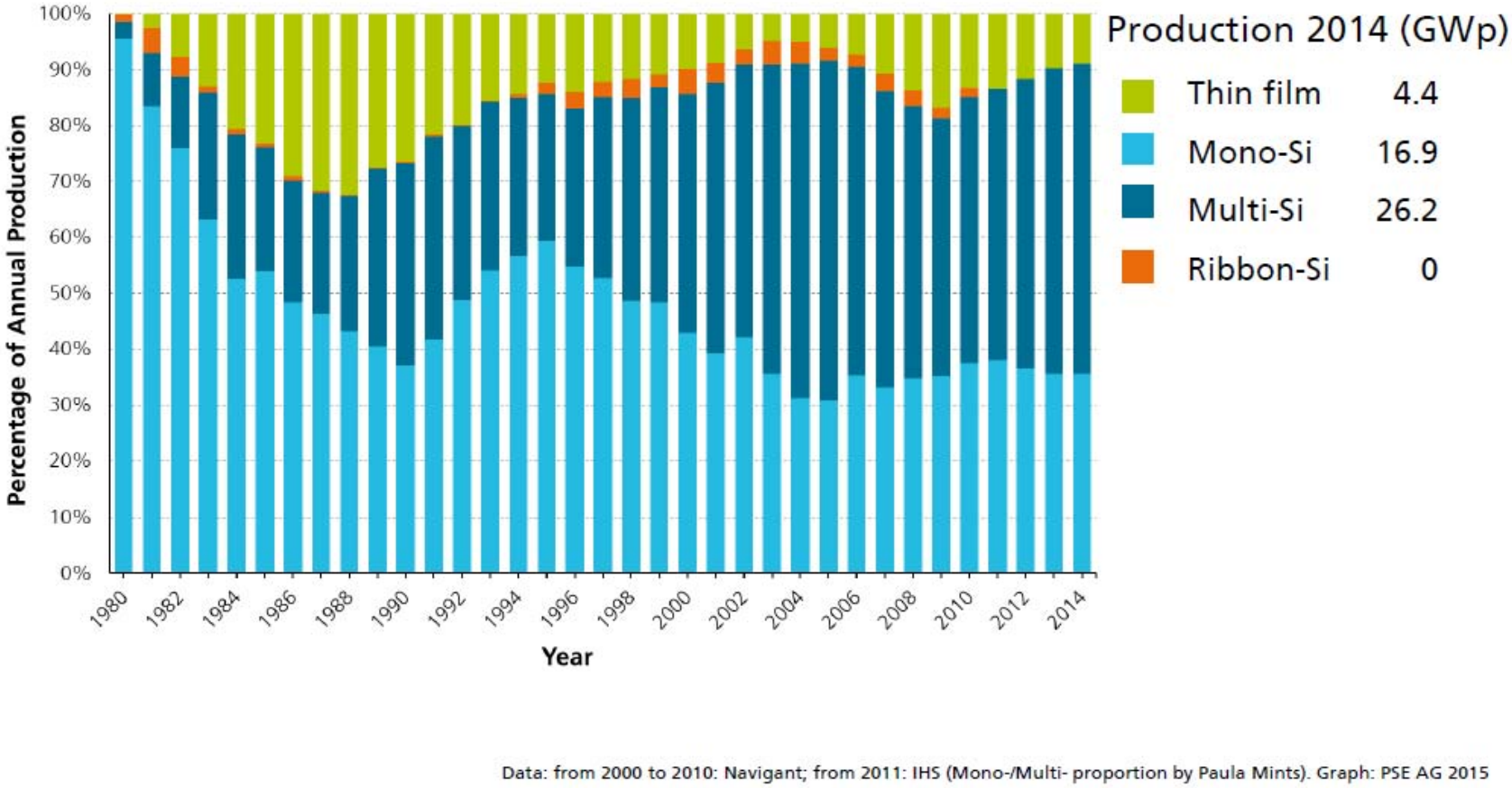


Photon Management Structures for Solar Cells

- Thin solar cells ⟷ high quantum efficiencies
- Photon management structures of increasing importance for solar cells
- Challenge: cost effective production of very precise structures on large areas



Facts and Trends – Technology Shares



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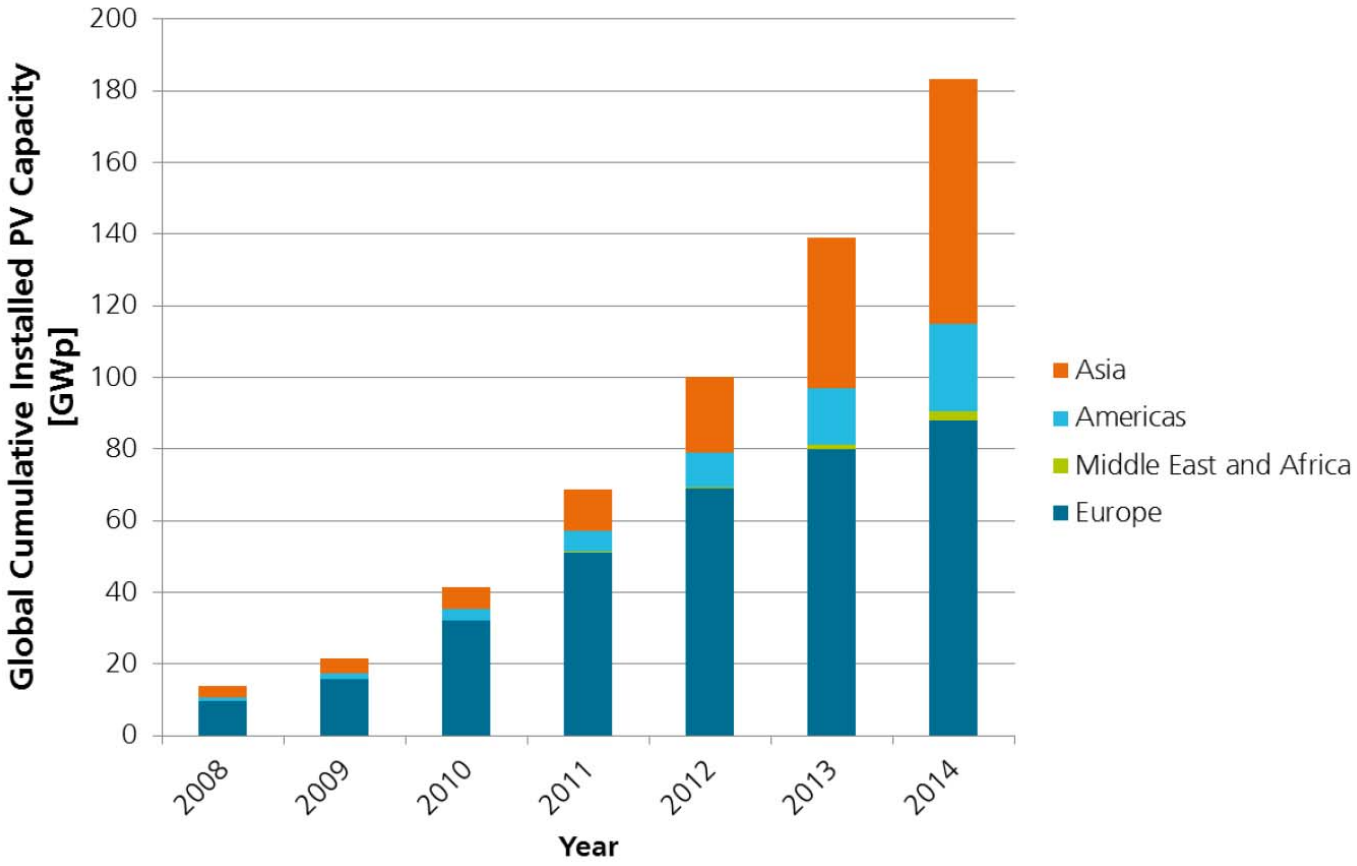
Facts and Trends – Market Volume



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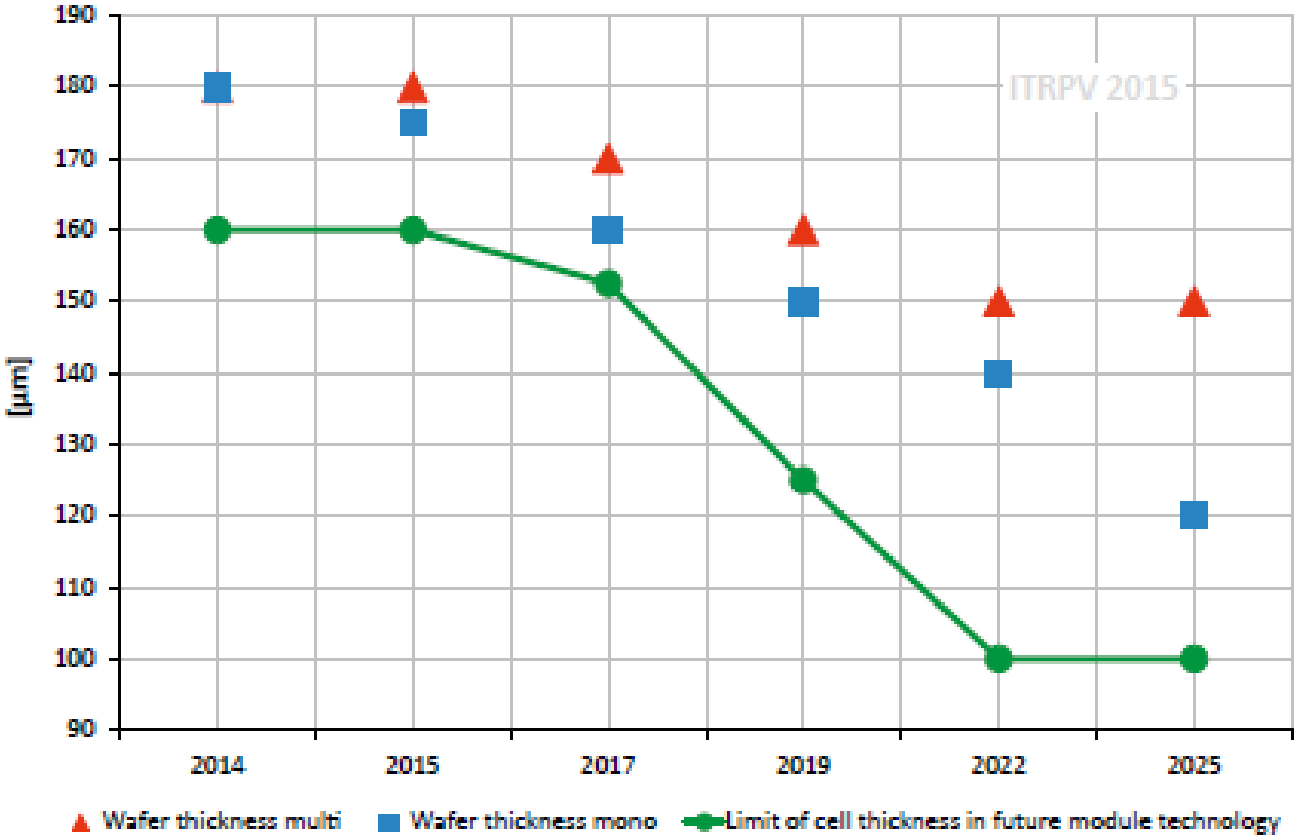
Facts and Trends – Wafer Thicknesses

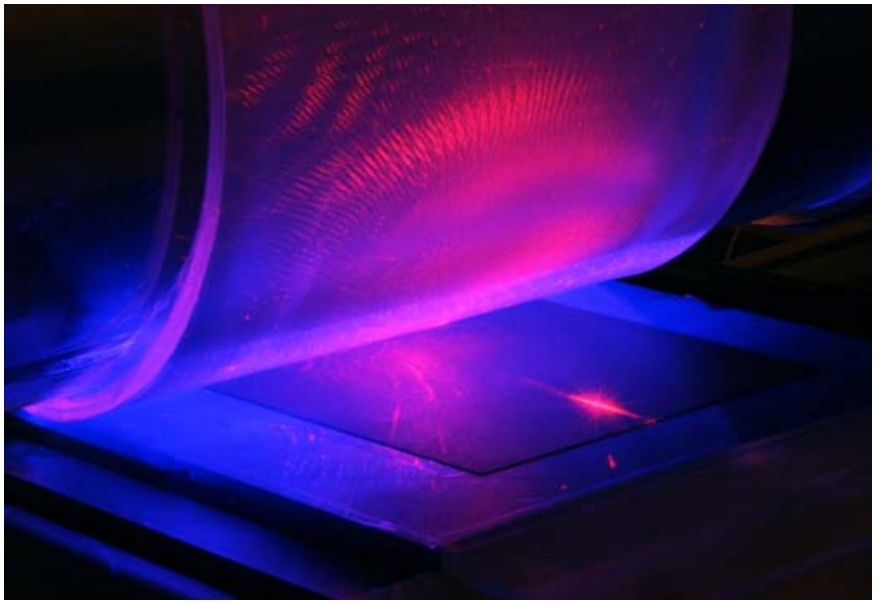


Quelle: ITRPV, Revision 1, July 2015

Nanoimprint Lithography - Roller-Tool

Replication of Photonic Structures

- UV-exposure throughout flexible stamp
- Imprinted area: 156 x 156 mm²
- Excellent adaptability to rough surfaces
- Homogeneous and low residual layer thickness (< 100 nm)
- Successfully tested on very thin wafer substrates (50 µm)



H. Hauser et al., IEEE Journal of Photovoltaics, 2 (2),114-122 (2012)

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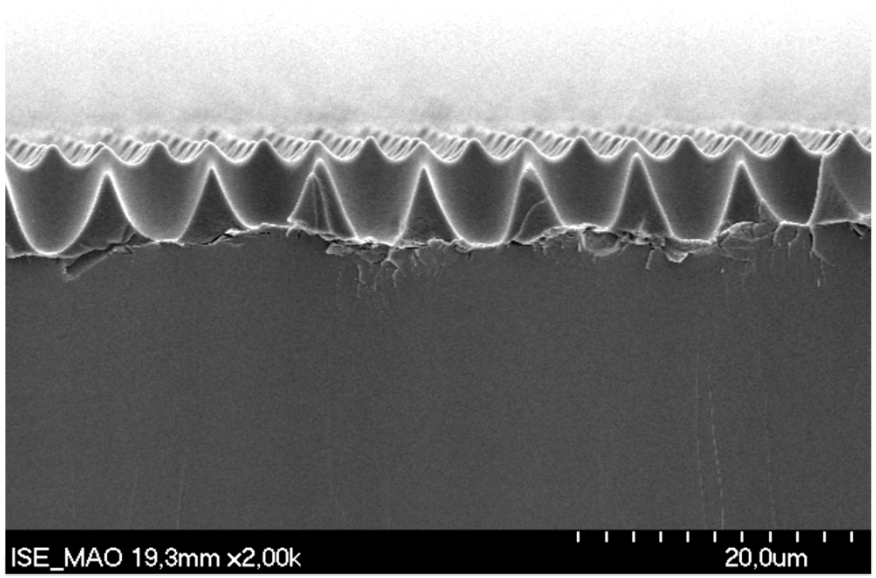

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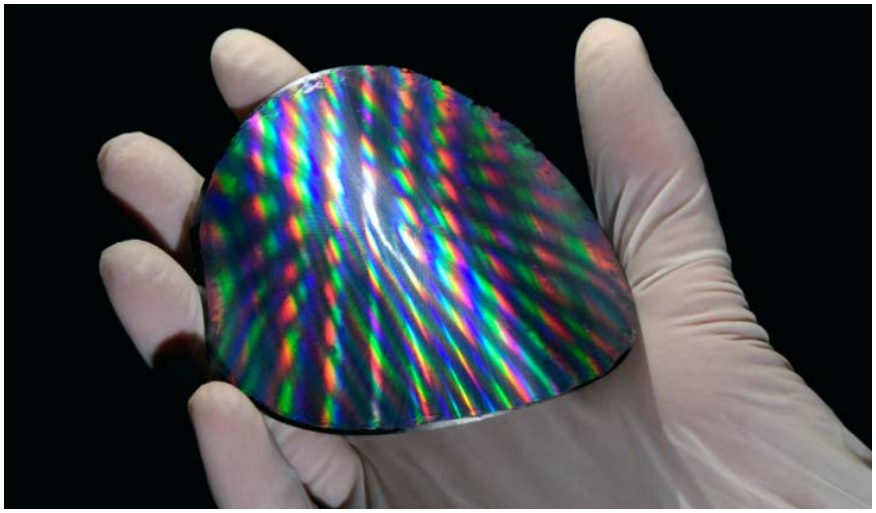
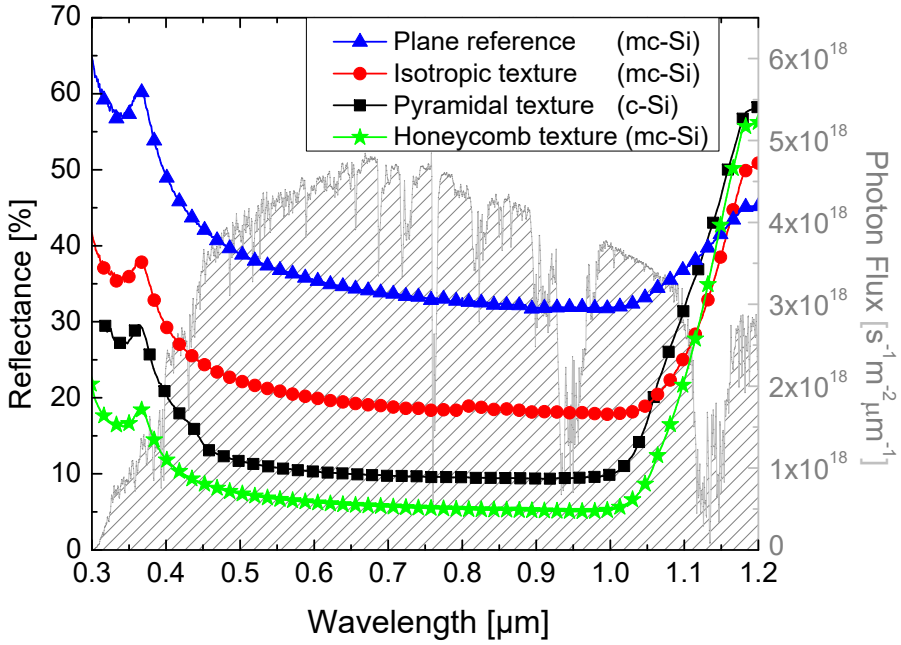


H. Hauser et al., IEEE Journal of Photovoltaics, 2 (2),114-122 (2012)

Honeycomb Front Side Texture for Silicon Solar Cells

- Excellent optical performance even outperforming pyramidal textures (shown without ARC) [1]
- J_{sc} of 40.6 mA/cm² demonstrated on FZ material (2 x 2 cm²) [2]
- This corresponds to an optical efficiency η_{opt} of 87.5 % (electrons out / photons in)



[1] A. K. Volk et al., accepted for publication in IEEE Journal of Photovoltaics, (2015)

[2] H. Hauser et al., IEEE Journal of Photovoltaics, 2(2), 114–122 (2012).

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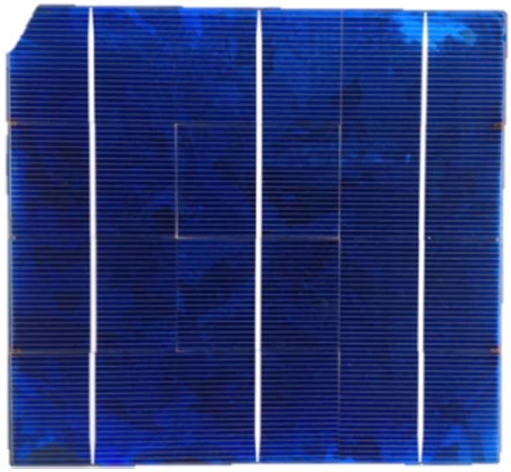
Honeycomb Front Side Texture for Silicon Solar Cells

- Al-BSF Solar Cells
  - 156 x 156 mm^2
  - Standard ARC
  - In-line capable texturing
  - Screen printed metallization
- Best Cell Results [1]



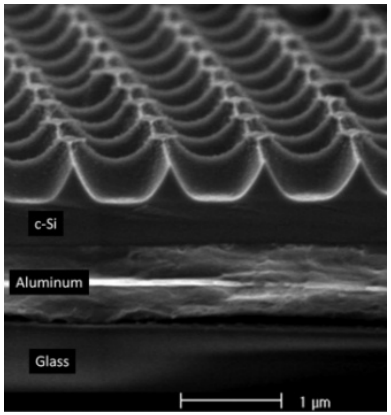
	V_{OC} [mV]	J_{SC} [mA/cm²]	FF [%]	η [%]
ISO-Texture Cell	618.3	35.0	79.3	17.3
HC-Texture Cell	618.4	36.2	79.5	17.8
HC-Texture Cell (5 x 5cm^2)	620.0	37.5	76.7	17.9

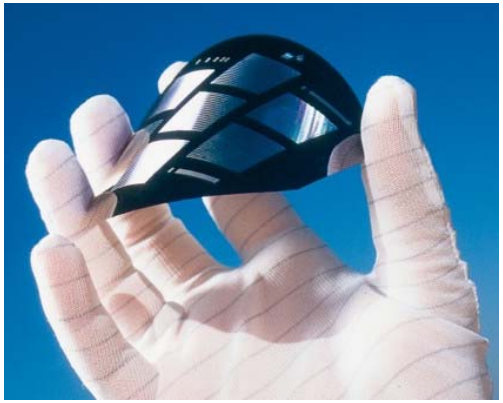
[1] A. Volk et al, IEEE Journal of Photovoltaics, 99, 1-7 (2015)

ISO=isotropically etched, HC = honeycomb, ARC = antireflexion, BSF=Back surface field

Nanopatterning – Main NIL Applications

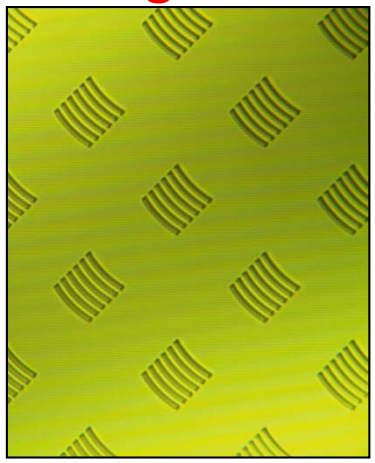
Photovoltaics



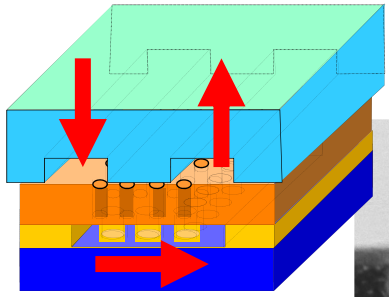


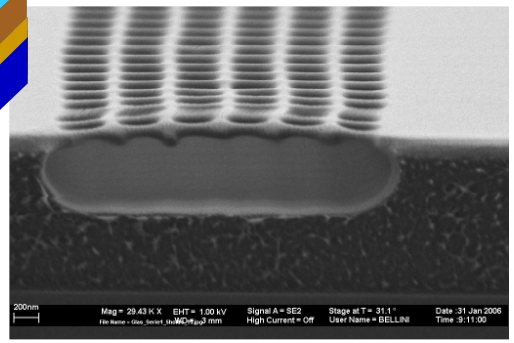
Transparent electrodes

Backlight Display Waveguide



Nano-Fluidic Devices





NIL for Transparent Electrodes

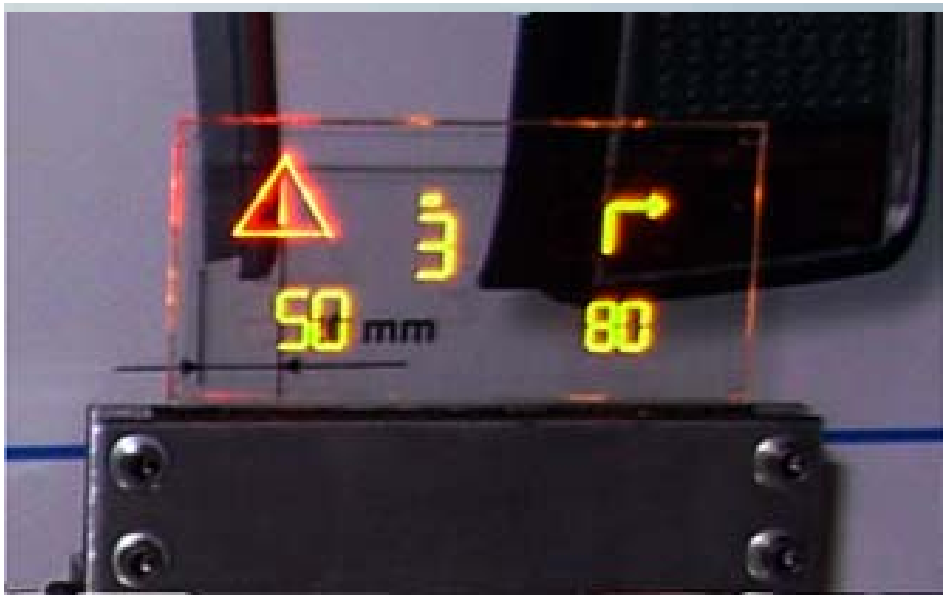
Head-up Displays integrating an emissive array of LED dice onto a transparent substrate unlike conventional HUD, which are virtual, in the emissive HUD the emitting layer is integrated into the transparent substrate.

Advantages of eHUD

- **Installation volume required**
  <100ml (standard HUD 3-4 liters)
- **High luminance: >5000cd/m2**
- **Potentially low cost: <30% standard HUD**
- **Image: real, monochrome or multi-color,**

CURRENT LIMITATIONS

- **High resistivity TCOs** (>10 Ohm square for a 100nm ITO film) with limitation on the layout of the display
- **Light reflection on windshield and pixeled** information (interference with primary driving task, not clear images)
- **Substrate costs**

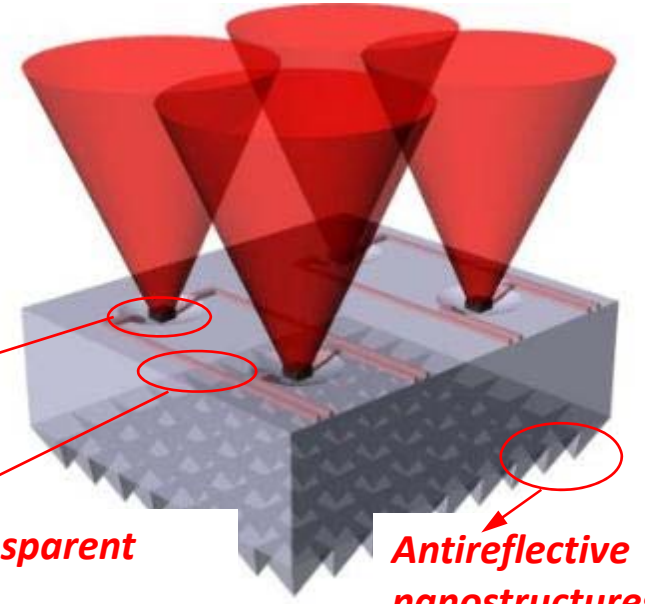


emissive HUD with integrated diodes

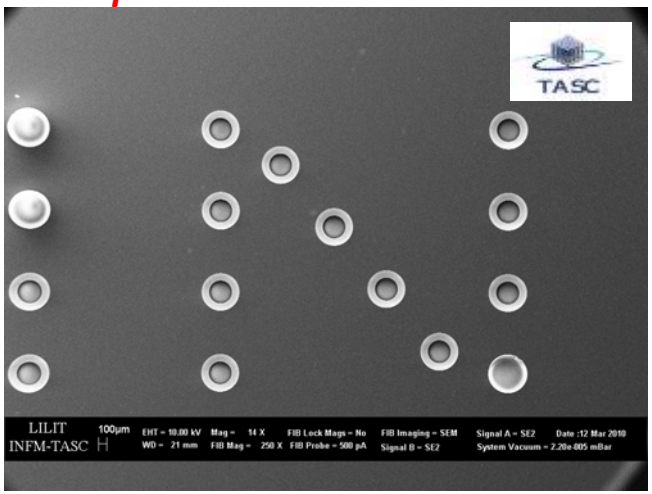
NIL for Transparent Electrodes

NaPANIL IMPROVEMENTS

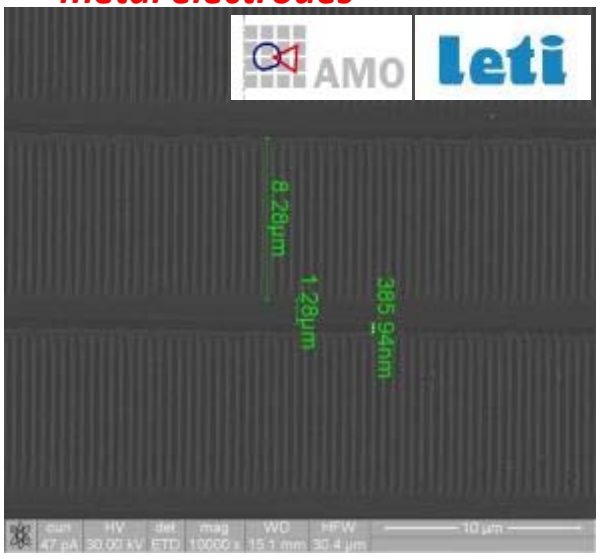
- Increased transparency of conductive wires
- Lower operative voltage and power consumption
- Flexible substrates
- Increased optical performances (antireflection, light control) with enhanced safety and comfort
- Low cost processes



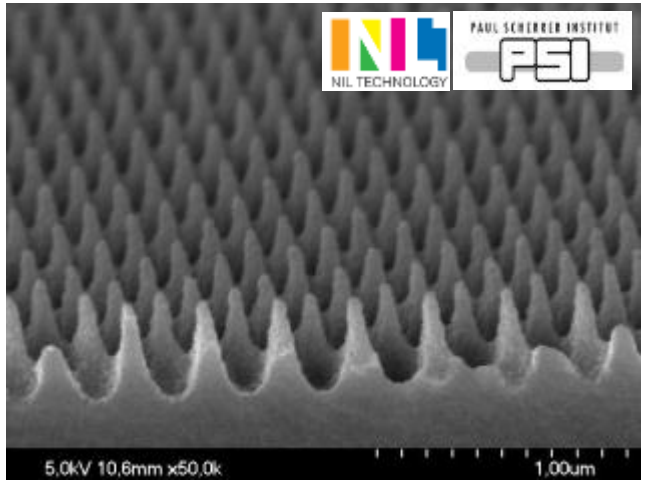
3D micropatterning of parabolic micromirrors



Nanopatterning of transparent metal electrodes

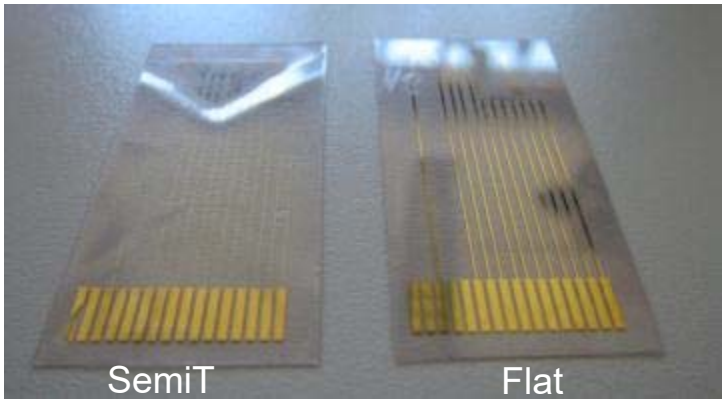


Antireflective nanostructures

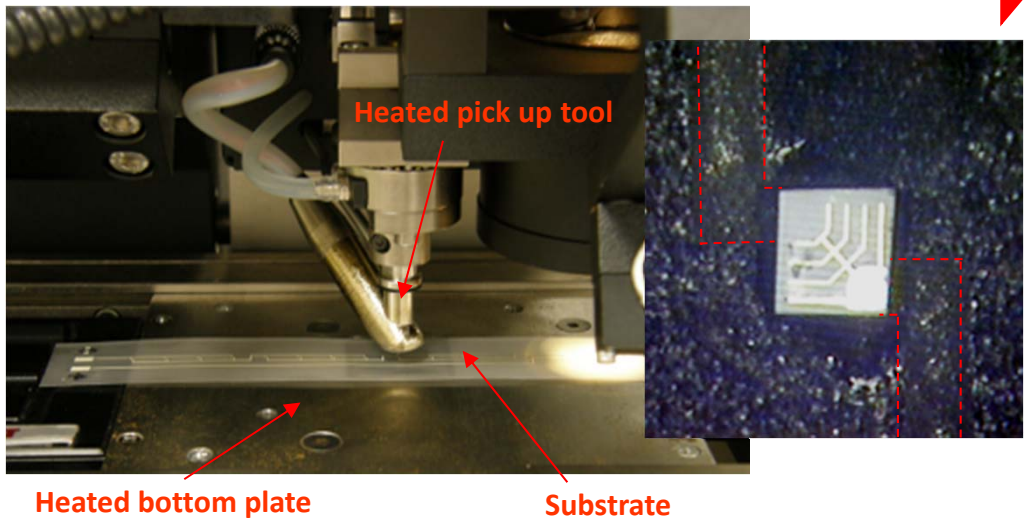


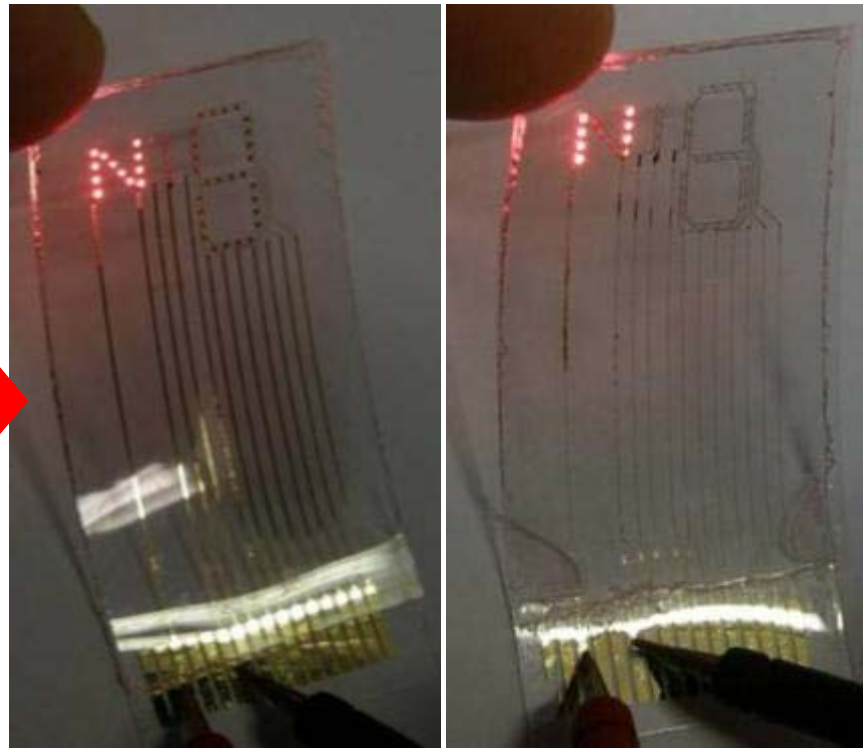
NIL for Transparent Electrodes

eHUD prototype integrating double side patterned plastic substrate



LEDs bonding optimization using flip-chip technology





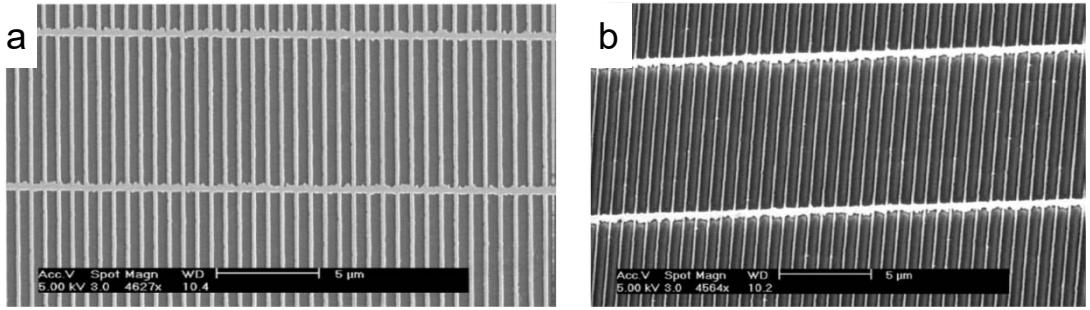
Flat

SemiT

NIL for Transparent Electrodes

eHUD prototype integrating double side patterned plastic substrate

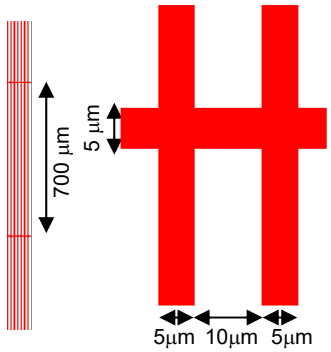
State of the art

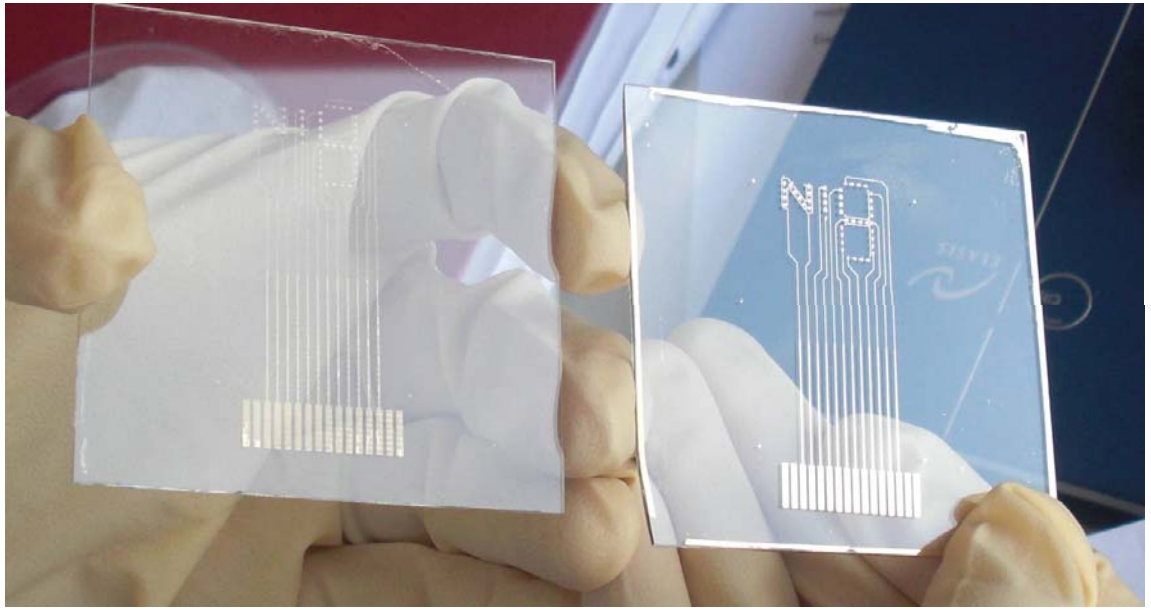


Nanoimprinted semitransparent Metal Electrodes and their application in organic light-emitting diodes

Myung-Gyu Kang and *L. Jay Guo*, *Adv. Mater.* **2007**, *19*, 1391–1396

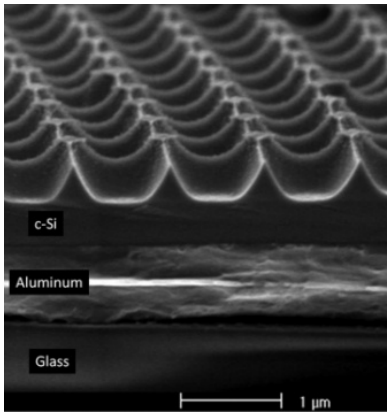
It also works with micrometer sized semi-transparent tracks

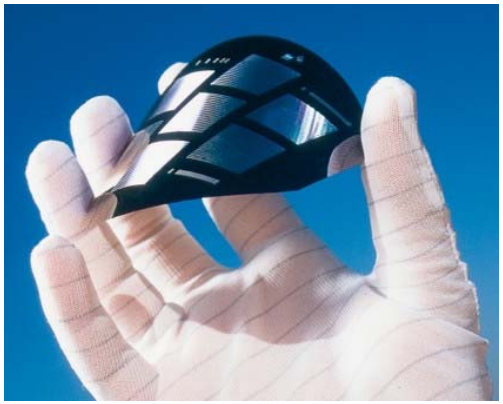




Nanopatterning – Main NIL Applications

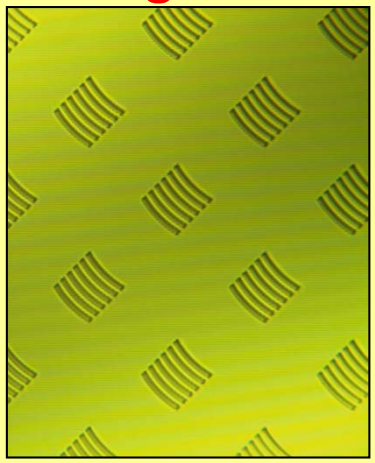
Photovoltaics



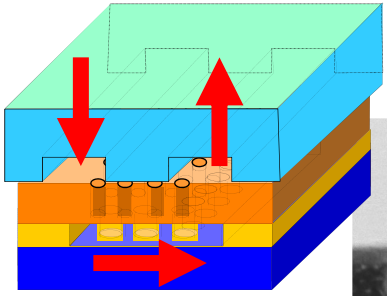


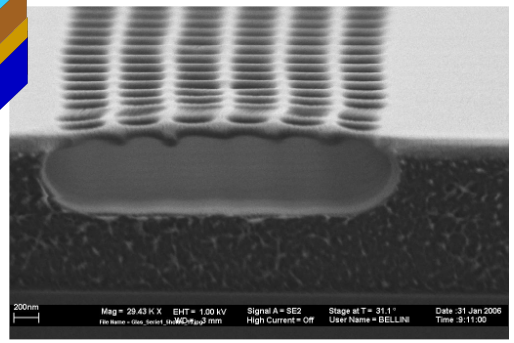
Transparent electrodes

Backlight Display Waveguide

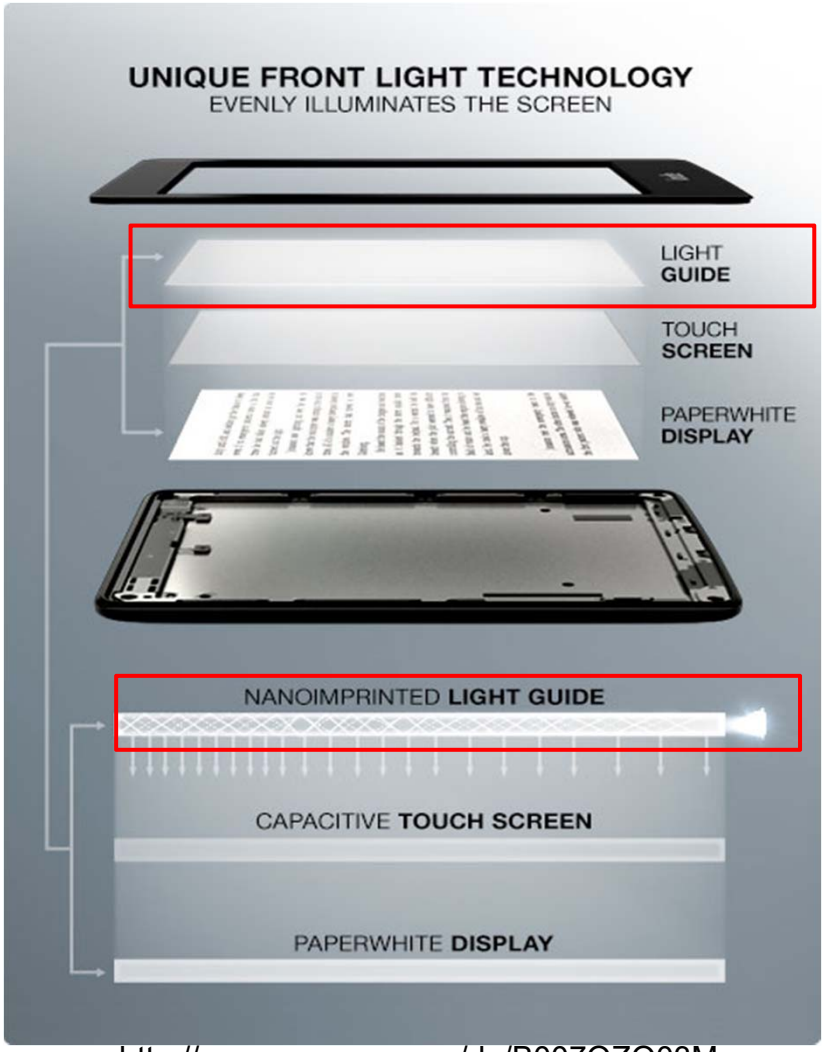


Nano-Fluidic Devices





Manufacturing of Displays with integrated Illumination



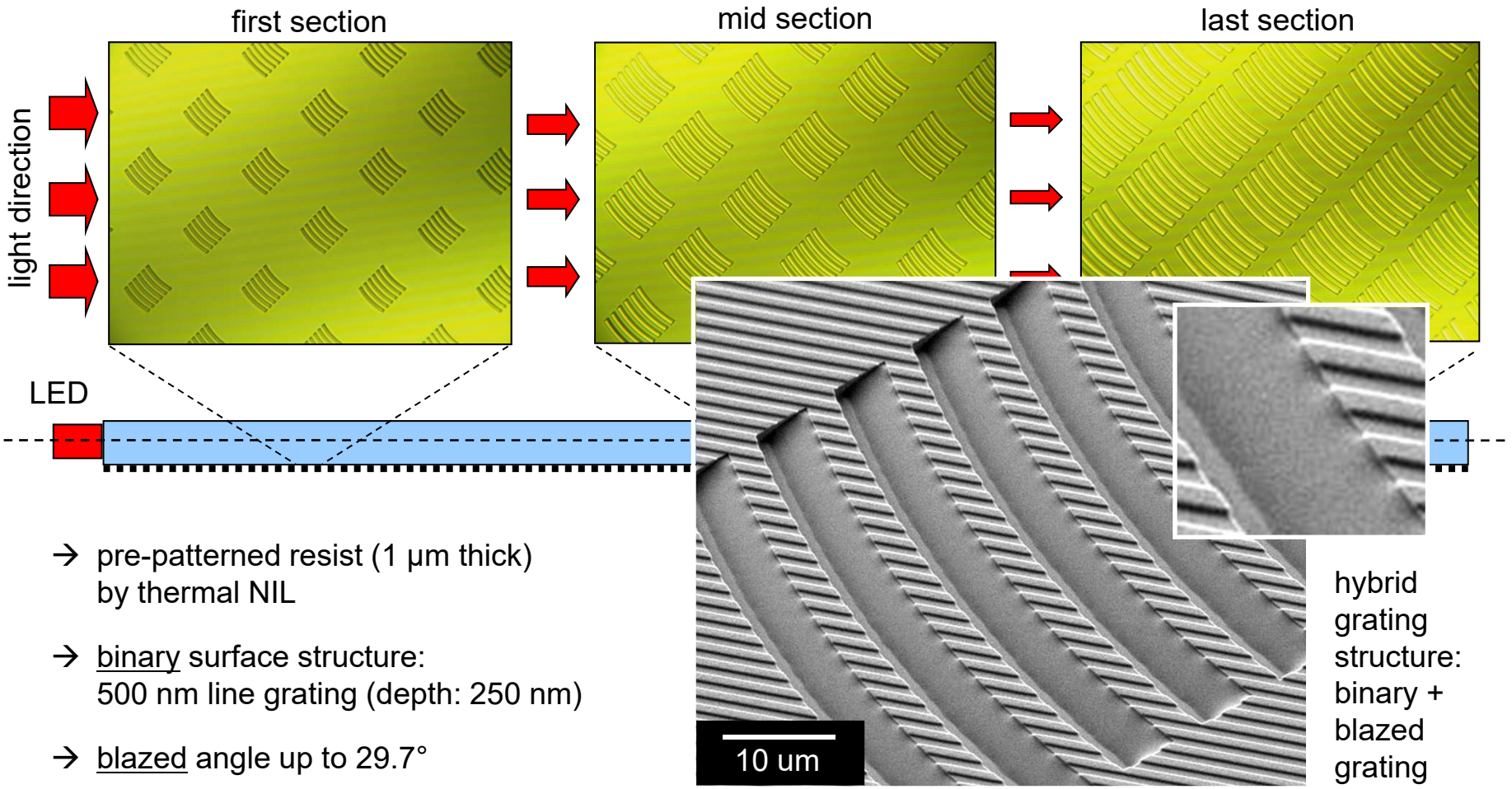
But: e-paper displays do not have backlight illumination

Solution: illumination with frontlight, with light coming from top side onto e-ink

http://www.amazon.com/dp/B007OZO03M

Fabrication of hybrid gratings by selective thermal reflow

Pixelized lightguide surface for backlighting devices: outcoupling elements and anti reflective pattern



→ pre-patterned resist (1 µm thick) by thermal NIL

→ binary surface structure: 500 nm line grating (depth: 250 nm)

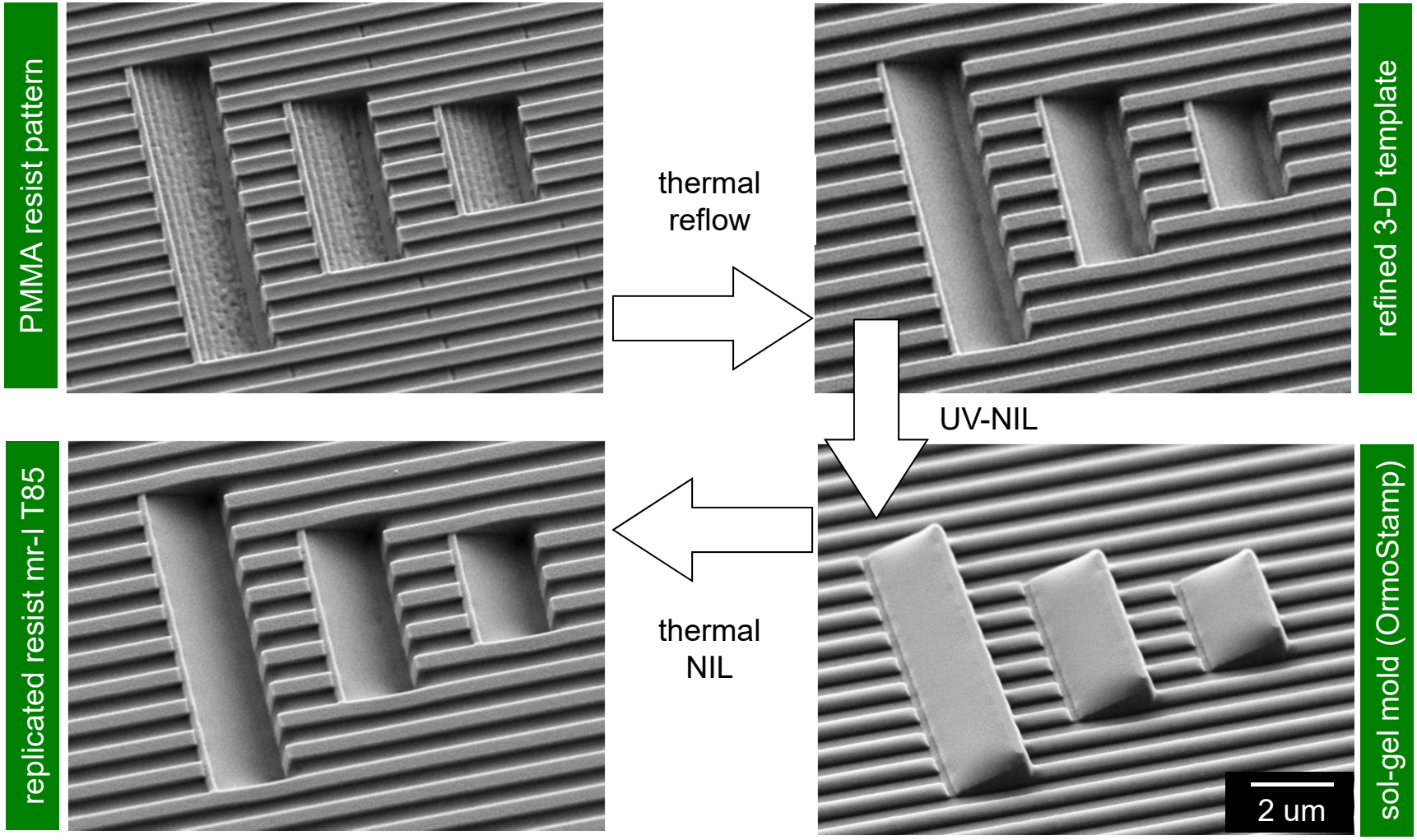
→ blazed angle up to 29.7°

hybrid grating structure: binary + blazed grating

Kari Rinko, Light outcoupling structure for a lighting device, Patent application: US 2008/0225393 A1

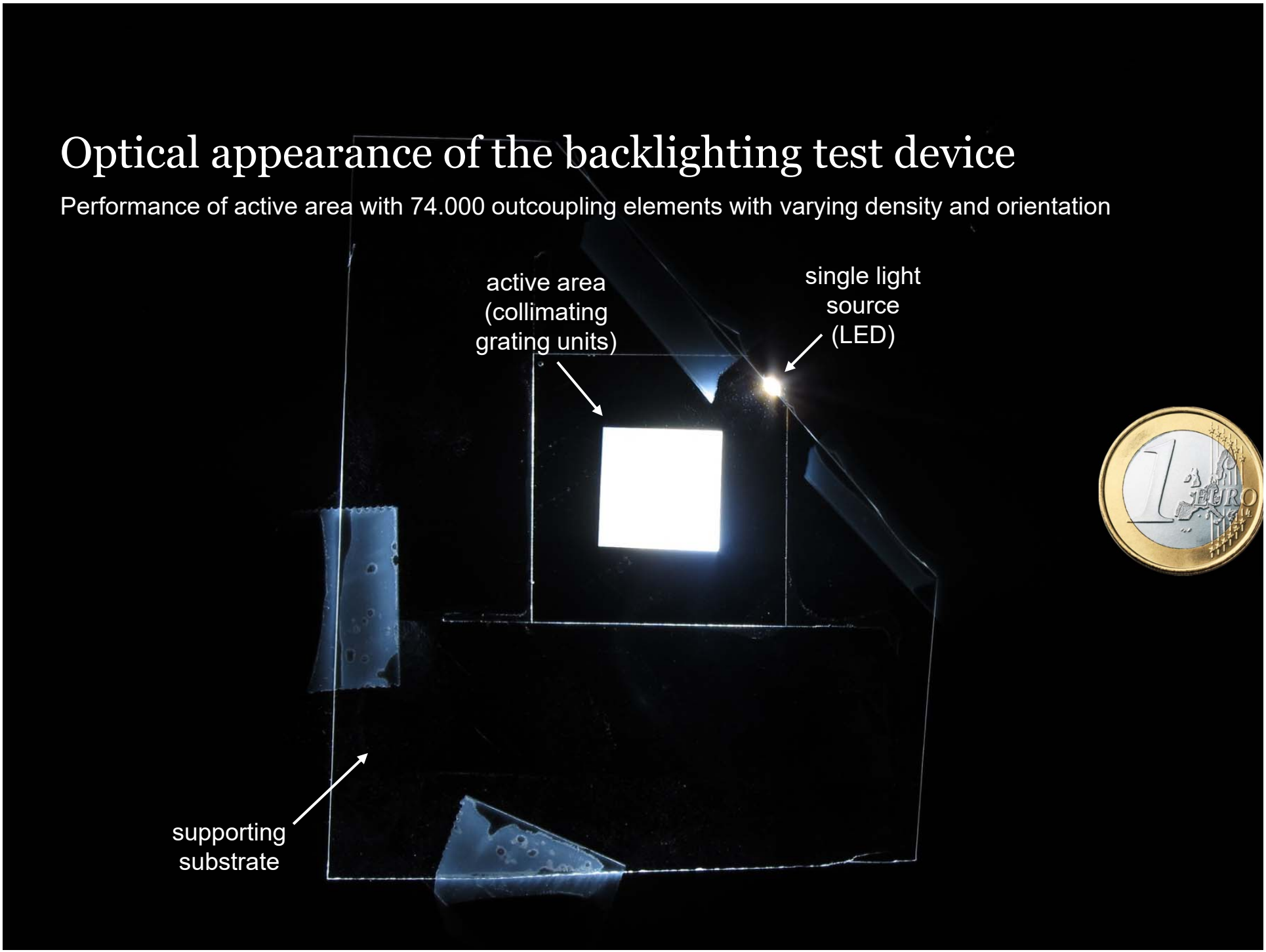
Fabrication of hybrid gratings by selective thermal reflow

3-D pattern are copied into a sol-gel material and repeatedly replicated into a polymer resist



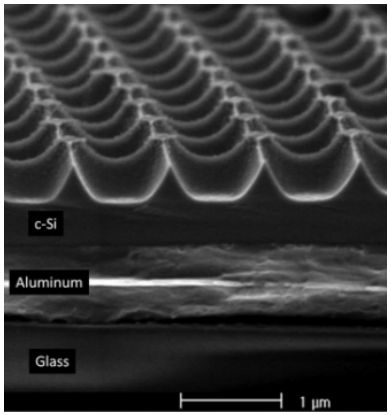
Optical appearance of the backlighting test device

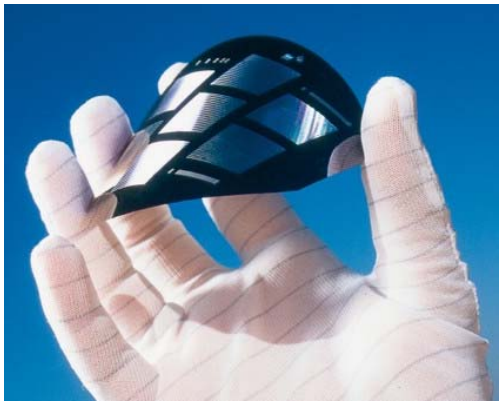
Performance of active area with 74.000 outcoupling elements with varying density and orientation



Nanopatterning – Main NIL Applications

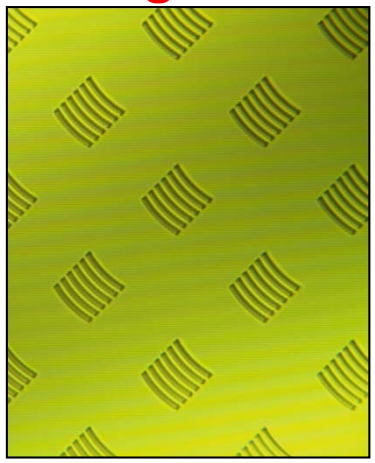
Photovoltaics



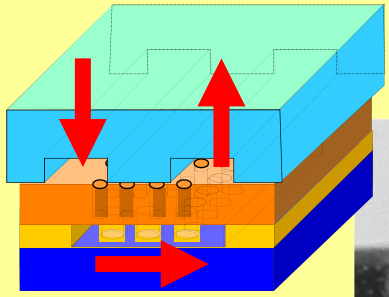


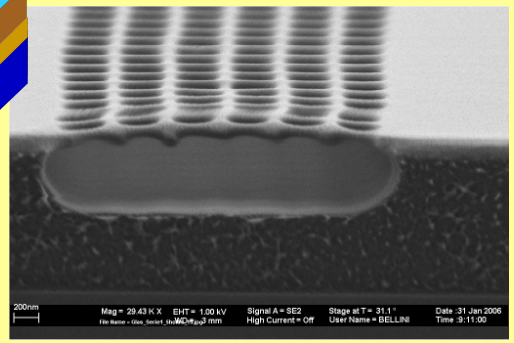
Transparent electrodes

Backlight Display Waveguide



Nano-Fluidic Devices

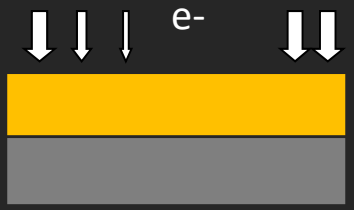




Fabrication processes for nanofludics

LIGA + NIL: Grey scale EBL +THERMAL REFLOW

e-beam exposure

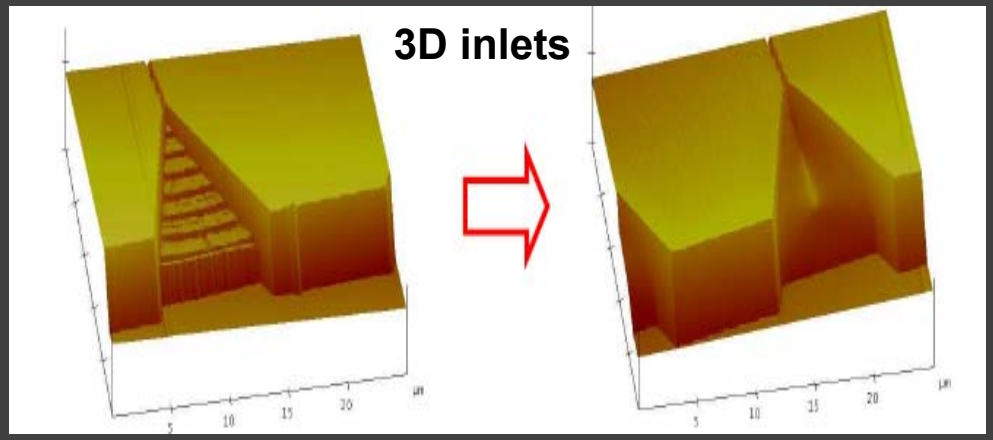


Development

Thermal reflow: T~Tg

16/08/2016

101



Funnel from

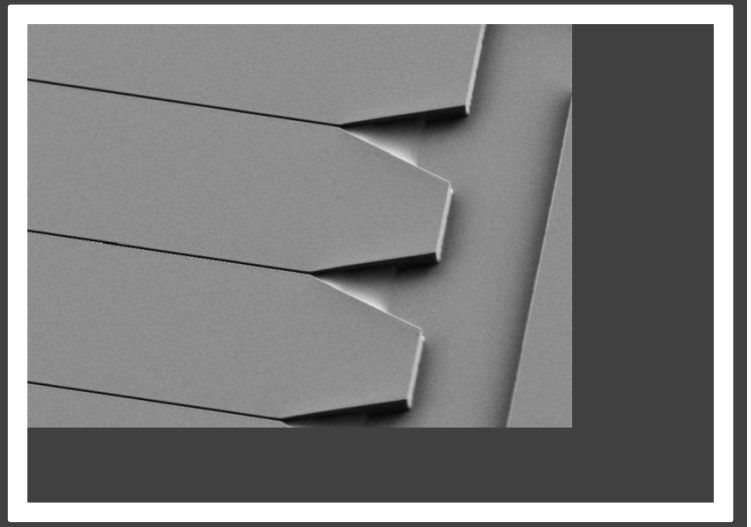
- 1 μm to
- 20 nm

channel

FIB

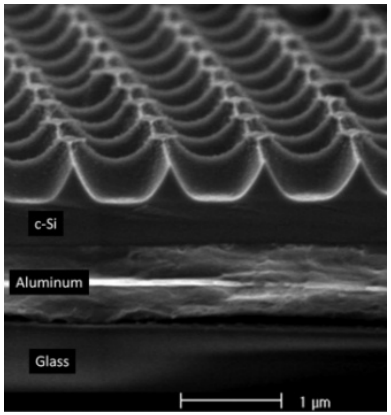
Grey scale EBL + thermal reflow

- Ultra smooth structures
- No steps
- High reproducibility
- High throughput

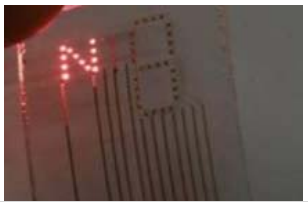


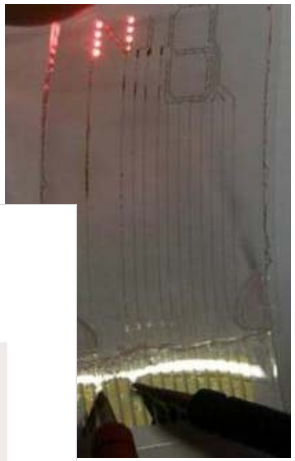
Nanopatterning – Main NIL Applications

Photovoltaics

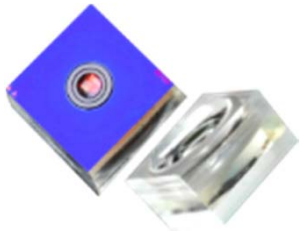


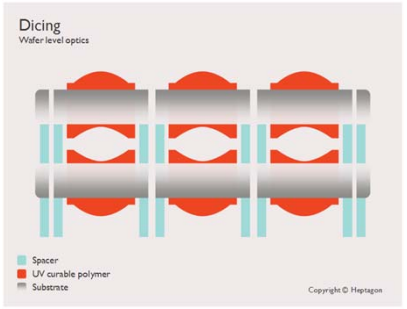
Transparent electrodes



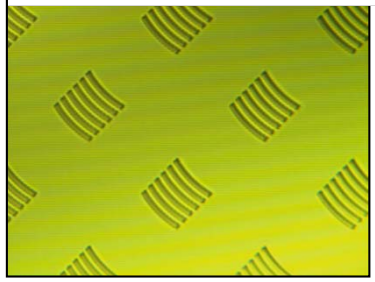


Micro-optical systems

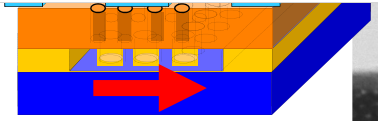


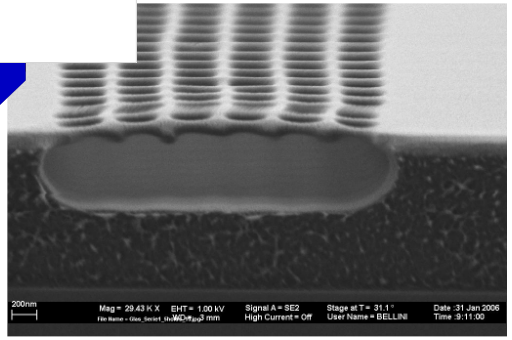


Backlight Display



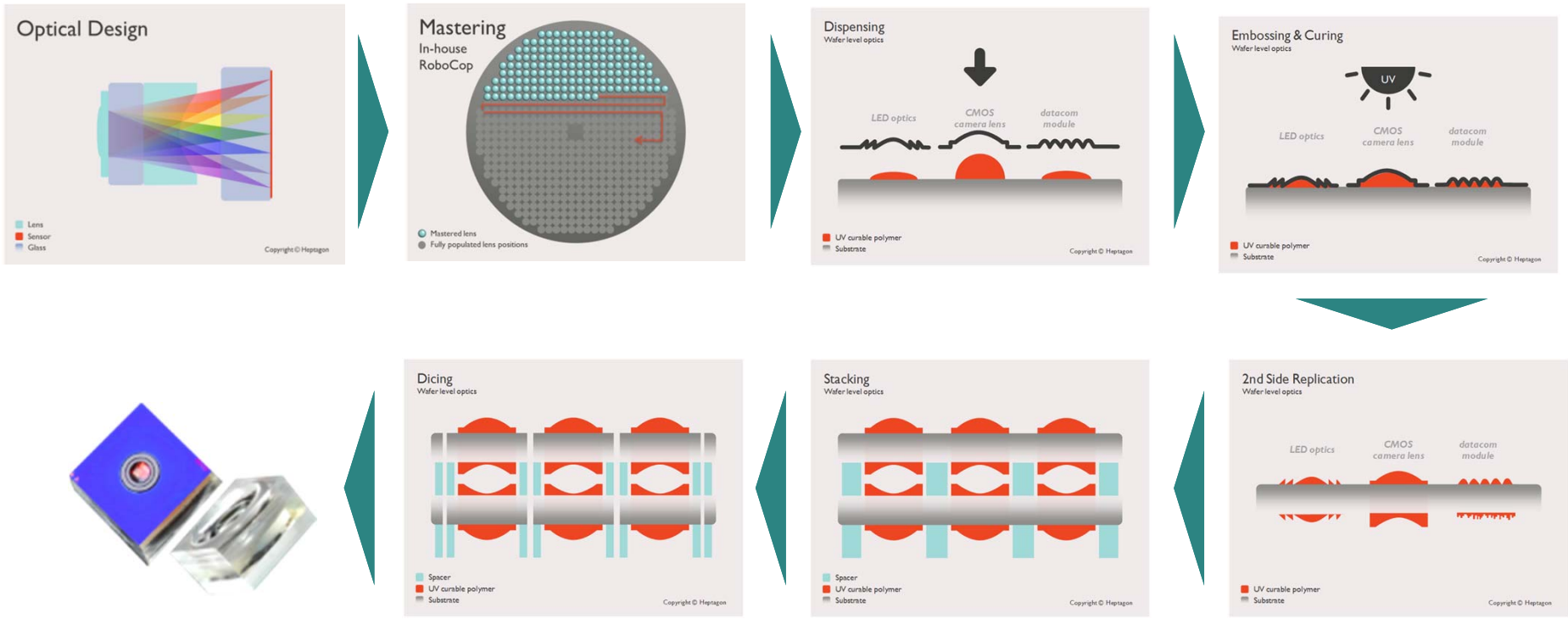
ces





HEPTAGON microsystems in smart devices

UV Replication Process



NOTE: Most of the lenses are still «micro», but the techniques are ready to be adapted to nanopatterning

Wafer Level UV Replication Technology

Micro Optics

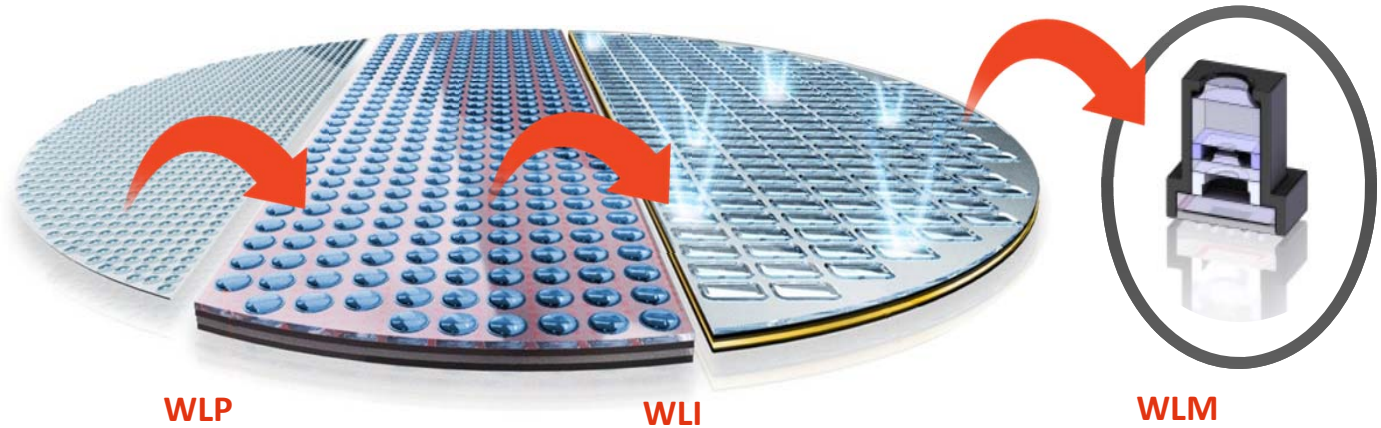
- Precision stacking
- Spacer technology
- Advanced packaging technologies

Micro Modules

- Non imaging modules
- New advanced packaging methods
- Reconstructed PCBs
- Electronics

Imaging Solutions

- Miniatureized camera technology
- 3D Systems
- ToF sensor technology
- 3D software



WLO
Wafer Level Optics

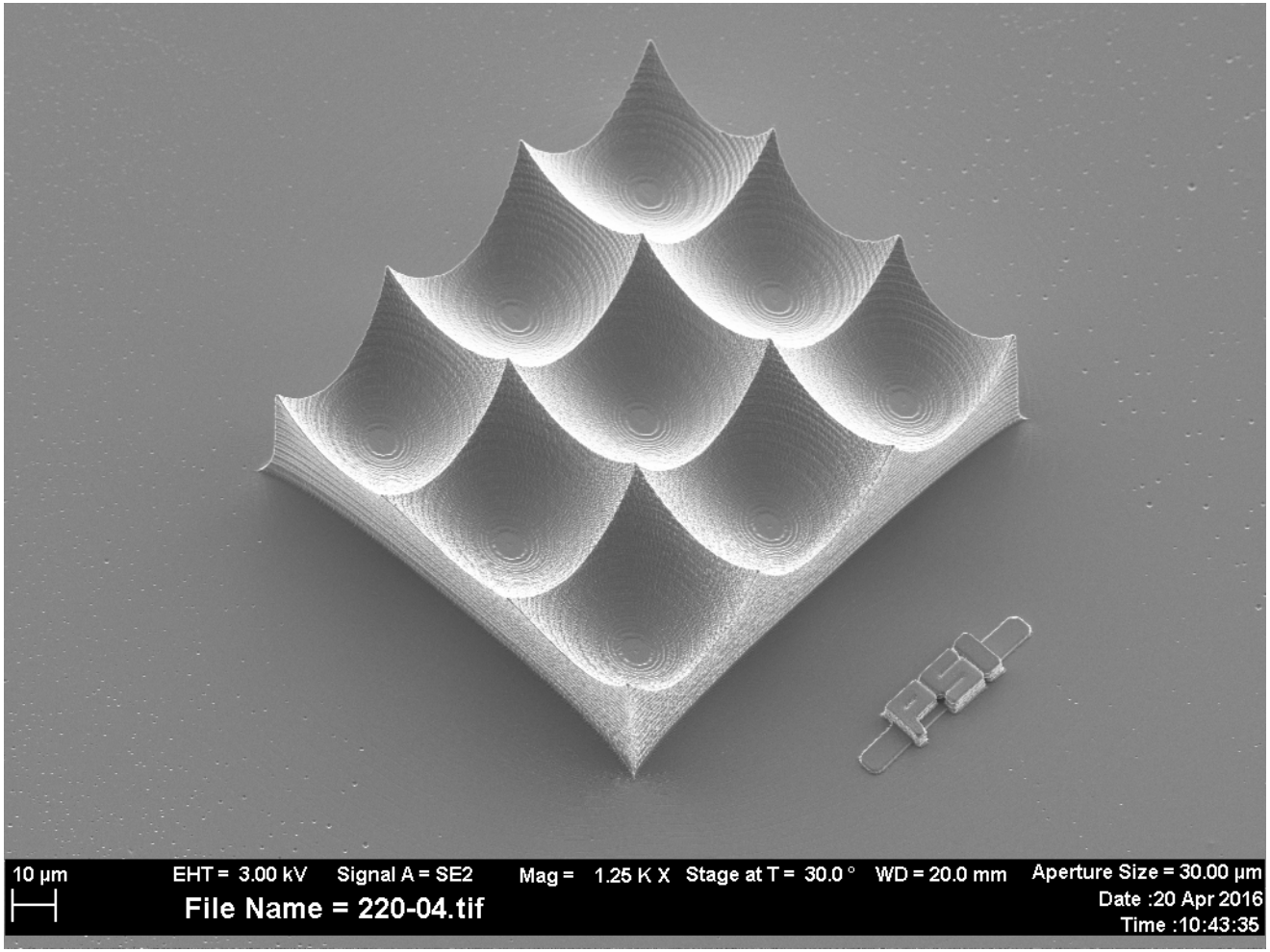
WLP
Wafer Level Packaging

WLI
Wafer Level Integration

WLM
Wafer Level Modules

Motivation

Surfaces of microstructures are typically «rough» in different dimensions

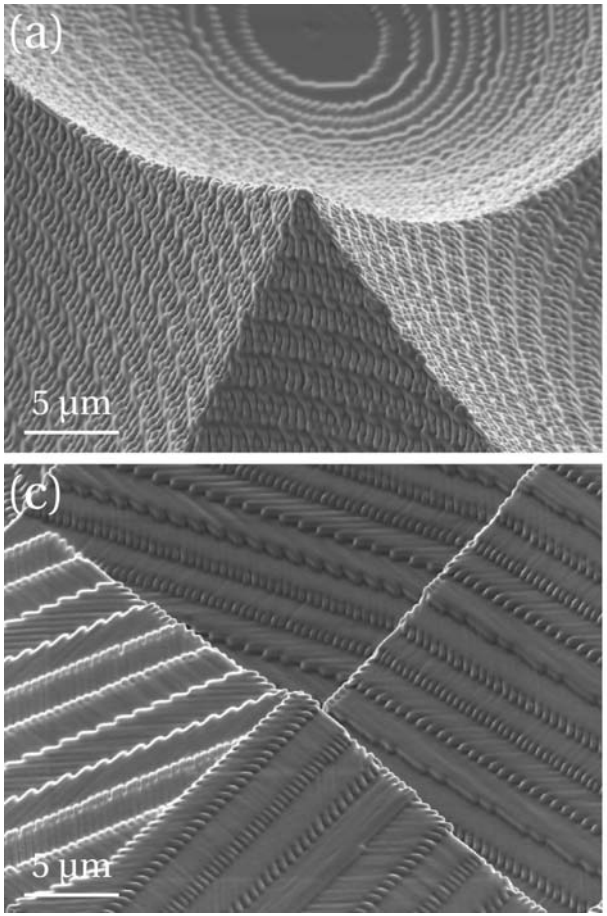


Test structure: Micro-lens array (3x3) concave 50 µm x 50 µm x 50 µm (each)

Motivation

Distinction between structural details and unwanted «nano»roughness

Rough surface

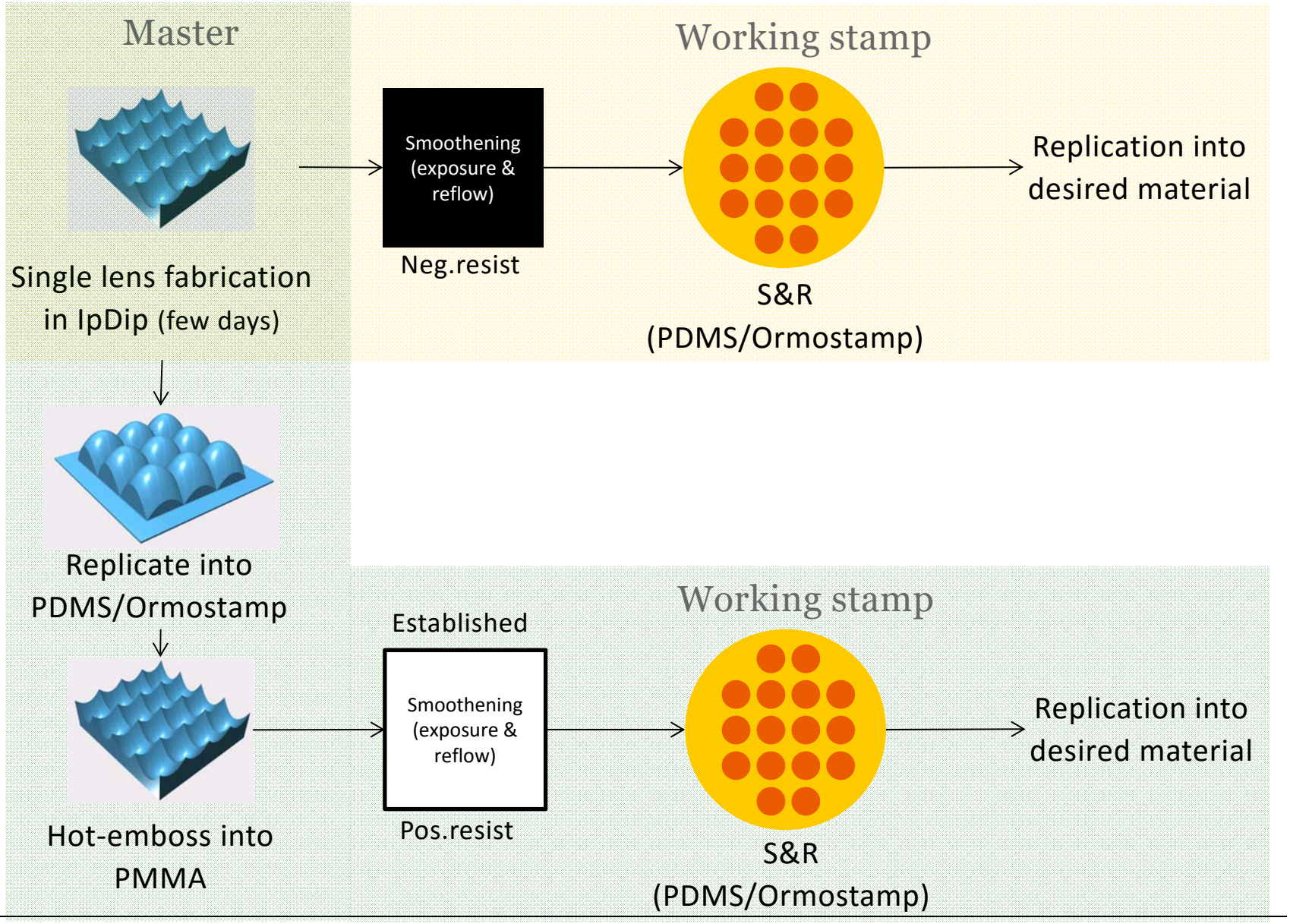


Concave lenses

Tiled slopes

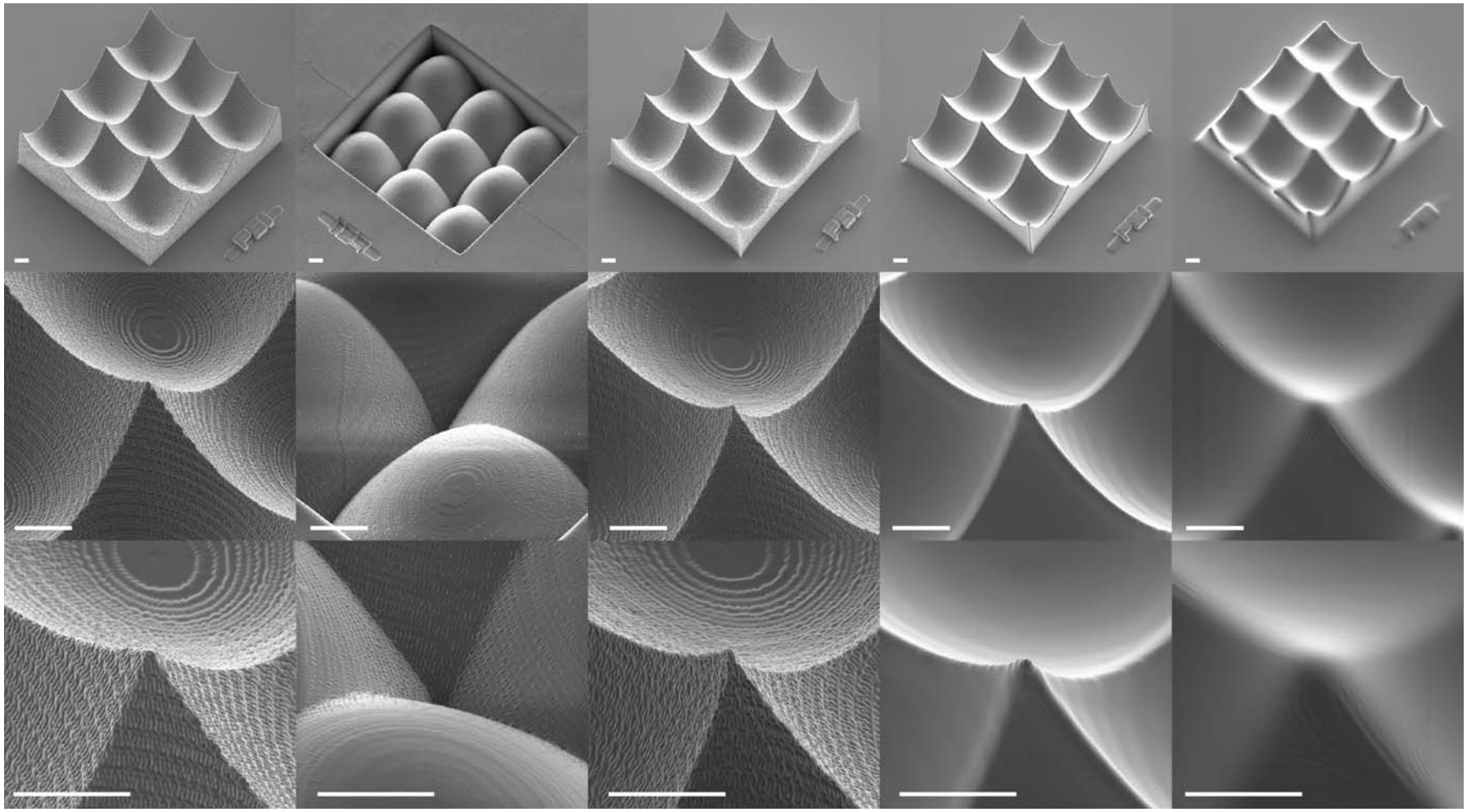
Segments intersection: sharp <1 µm tips («high aspect ratio»)

Process flow with NanoScribe MLA



Micro lens array

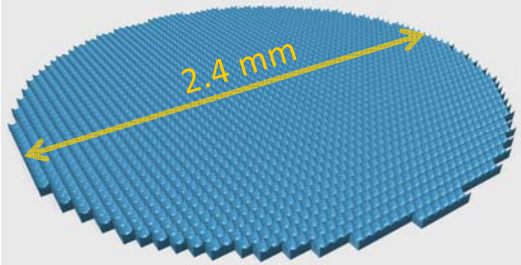
IpDip UV PDMS PMMA Reflow (exp) Reflow (no exp)

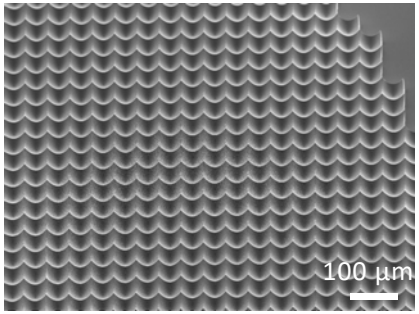


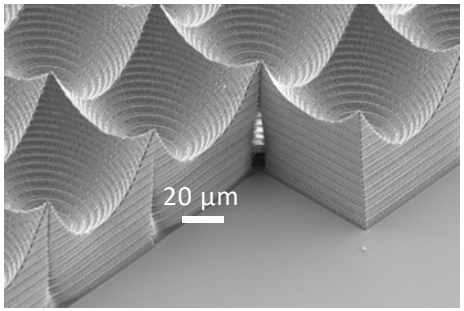
Scale = 10 µm

Device (48 hours writing)

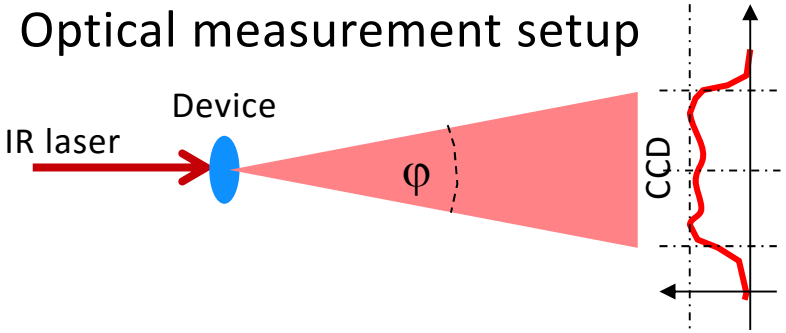
Master fabrication





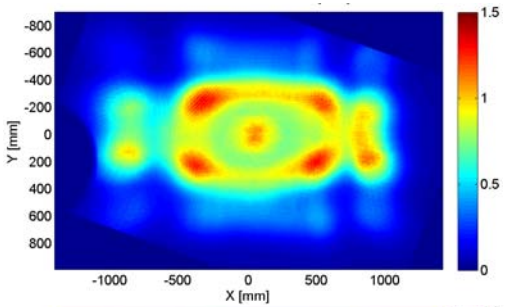


Optical measurement setup

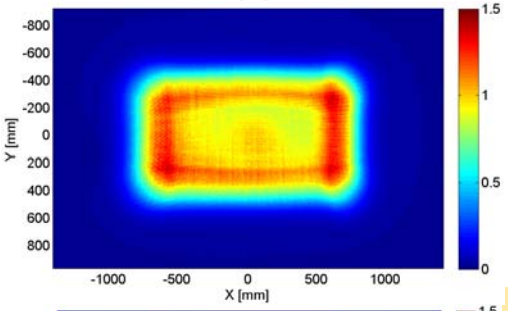


FOI: Field of illumination given by angle φ_x

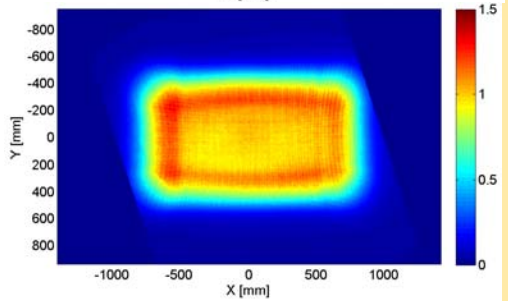
Intensity variation: standard deviation by Sigma



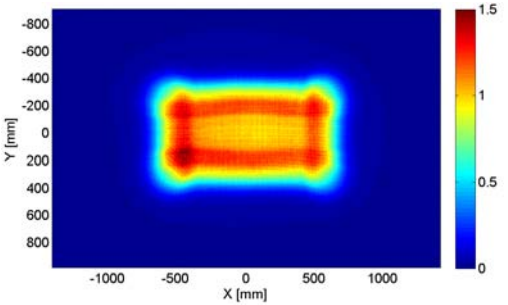
IpDip Master
x-FOI (75%) = 61.5°
Sigma = 10%



PMMA as embossed
x-FOI (75%) = 75°
Sigma = 10%

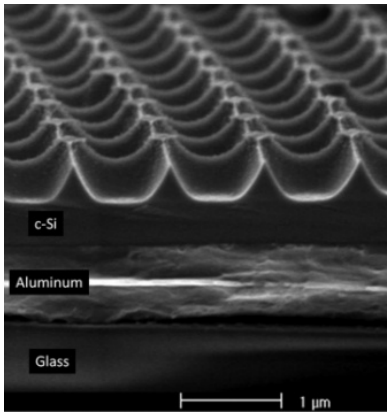


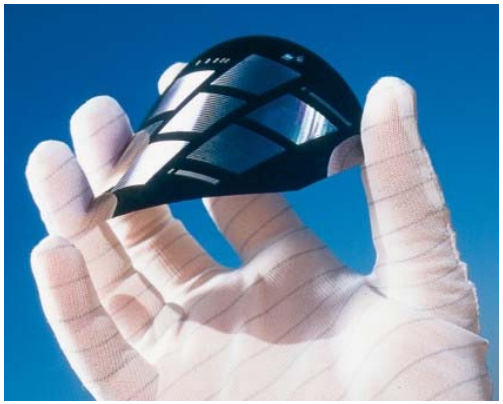
PMMA exp+reflow
x-FOI (75%) = 74.5°
Sigma = 5%



PMMA no exp reflow
x-FOI (75%) = 63.2°
Sigma = 7%

Photovoltaics





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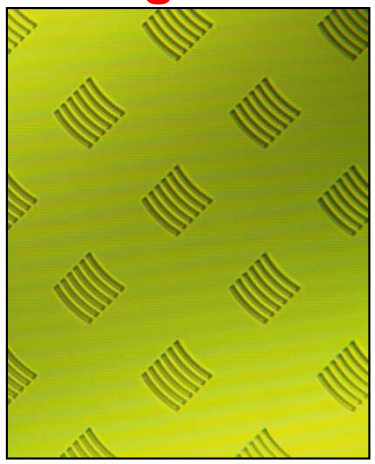
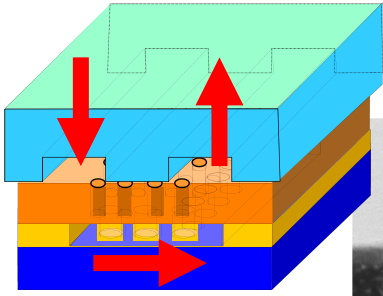
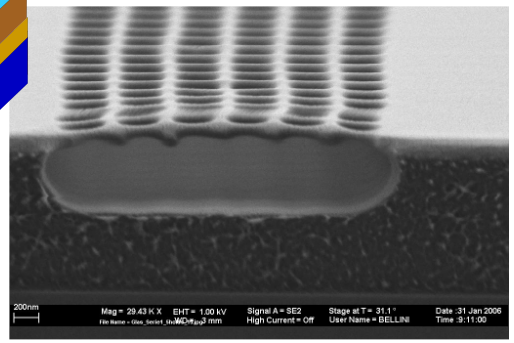


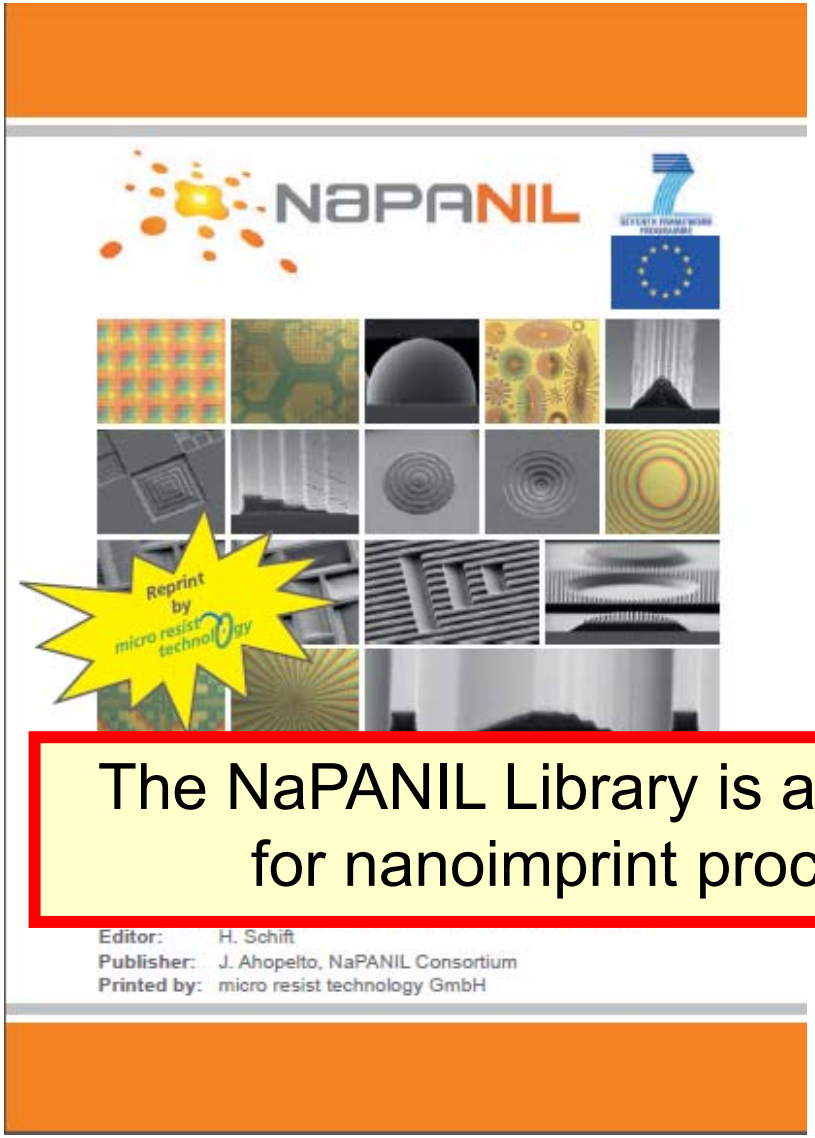
Nano-Fluidic Devices

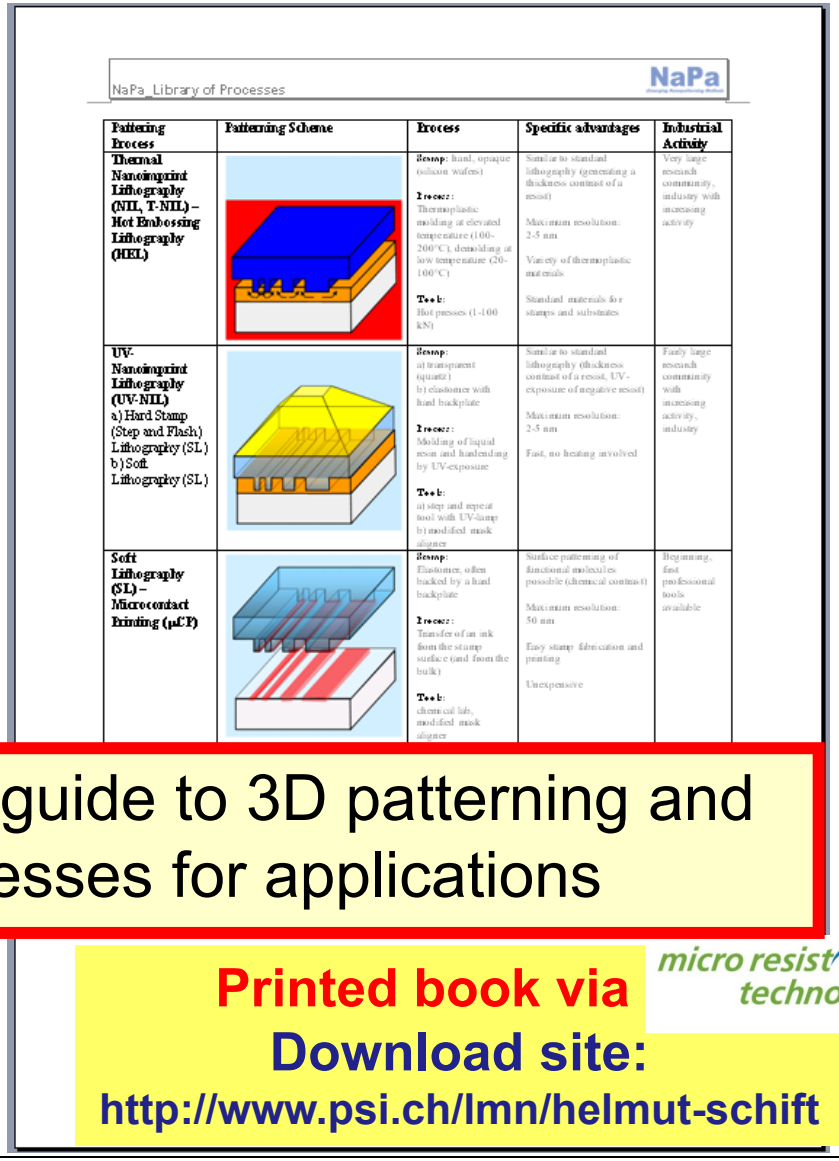




NaPANIL: Dissemination of Results

NaPa Library of Processes: A Guide to Nanopatterning





The NaPANIL Library is a guide to 3D patterning and for nanoimprint processes for applications

Printed book via micro resist technology

Download site:
http://www.psi.ch/lmn/helmut-schift

PAUL SCHERRER INSTITUT

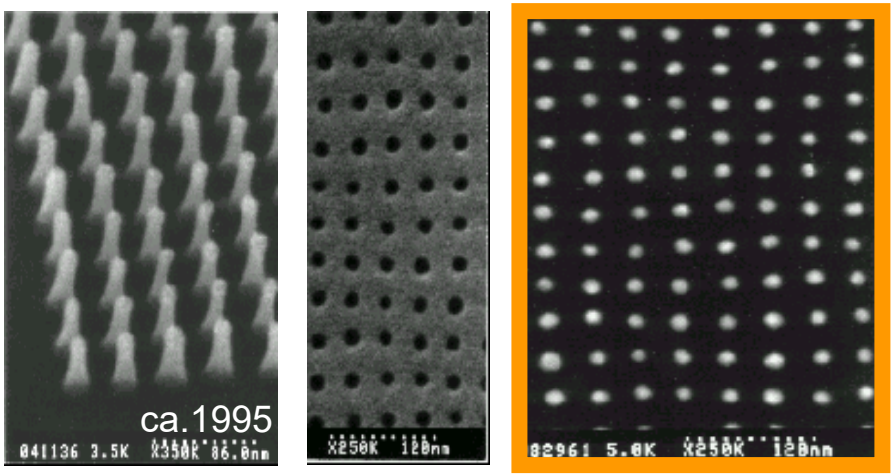
Outline

- Nanoimprint in the context of advances in mechanical engineering
- NIL is a Next Generation Lithography – true, but not only!
- Is NIL More Moore or More than Moore?
- Non-IC applications, more than Moore – front runners
- What a researcher can contribute
- … and More NIL to come

20 Years of Nanoimprint lithography (1995-2015)

PRINCETON UNIVERSITY

Applied Physics A
Materials Science & Processing



The Nanoimprint "Invention"

Stephen Y. Chou, Princeton

"Looking forward, clearly it is just a beginning in nanoimprint. Nanoimprint will continue to grow rapidly in academic research, making new discoveries and inventions, will exponentially grow in many industrial sectors (existing ones and future new adopters) and in revenue, and will have increasingly greater impact to modern technologies and our society. If the history of nanoimprint is any indication, we have not seen anything yet.."

Appl. Phys. A (2015) 121:317–318

Acknowledgement

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- Arne Schleunitz
- Jens Gobrecht,
- V. Guzenko
- Nachiappan Chidambaram

Particularly to:

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CRF CENTRO RICERCHE FIAT

Fraunhofer

PHILIPS

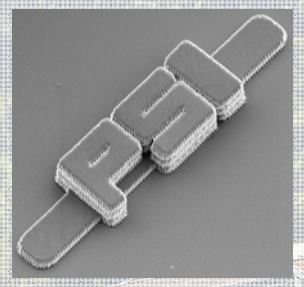
M. Vogler (mrt) and M. Altana

micro resist technology

HEPTAGON™

…

and all our colleagues in partner institutes and companies



NaPANIL