SAND2011-3540C

Larger Scale Fabrication of Nanometer to Micron Sized Periodic Structures in 2D and 3D: Approaches and Trends

G.R. Bogart
Sandia National Laboratories
Phononics 2011
May 29-June 2, 2011
Santa Fe, NM USA

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Sandia National Laboratories

Periodic Structures in 2D and 3D for Photonic/Phononic Application

Past 20 years research, fabrication and processing have focused on optical band gap structures looking for large photonic band gaps and photon control.

Why Phononics?

•Renewed interest in the past few years in mechanical waves passing through air, liquids, and solids (elastic waves). Like Photonic crystals and photon manipulation, phononic crystals can be used to manipulate acoustic or elastic waves.

•Obvious uses: Sound attentuation, acoustic filters, acoustic super lenses (ultrasound), thermal management, energy harvesting.

•Sonic and ultrasonic crystals are macroscopic and can be manufactured in large scales with conventional processing techniques, hypersonic crystals require 3D periodic patterns created at the micron to nanometer scale.

Congratulations! You Made It!!

The next possible questions:

Can you make more?

And how soon can I get them??

Wow! It's so tiny!!   I need it bigger. Can I get a few square meters?

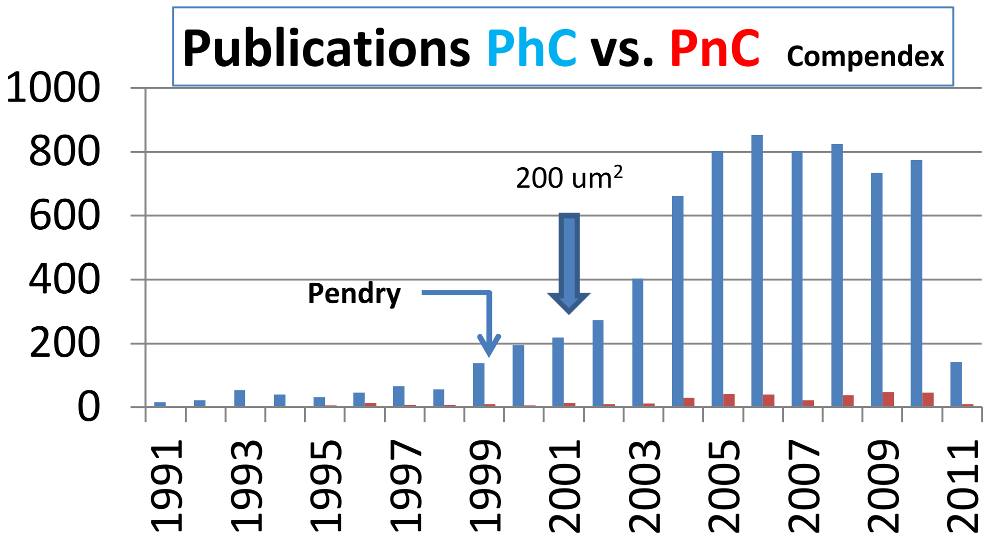
How much does it cost?

I've done some calculations…can you make it out of ______?

Where do you begin?

Fabrication of Photonic vs. Phononic Crystals: Some Perspective

Crystal Type	Photonic	Phononic
Medium to control	Light/Photons	Sound/Elastic Waves
Element Pitch	nm – um	nm – meters
2D (Slab)	Yes	Yes
3D (Bulk)	Yes	Yes



Large area in 2001
Several hundred square microns. Generally technique limited due to element size.
Search Terms: Photonic, or phononic crystal, fabrication

Fabrication of Photonic vs. Phononic Crystals: Some Perspective

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Medium to control	Light	Sound
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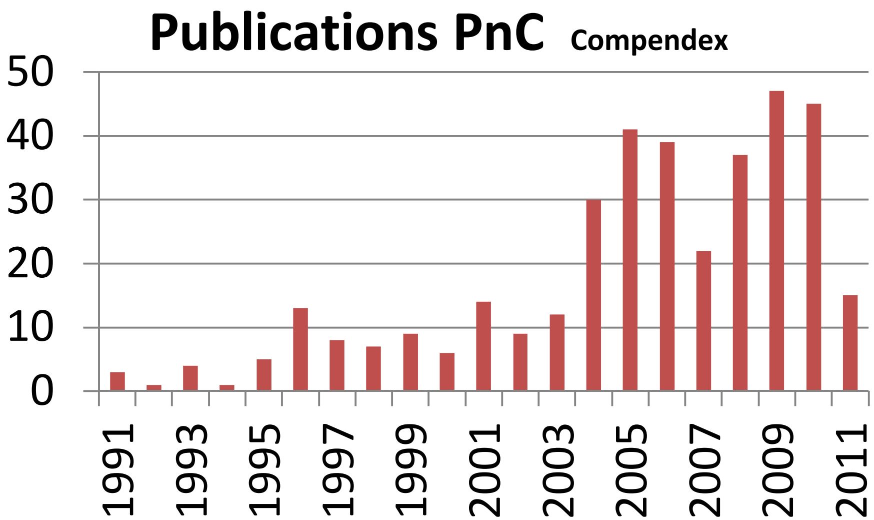
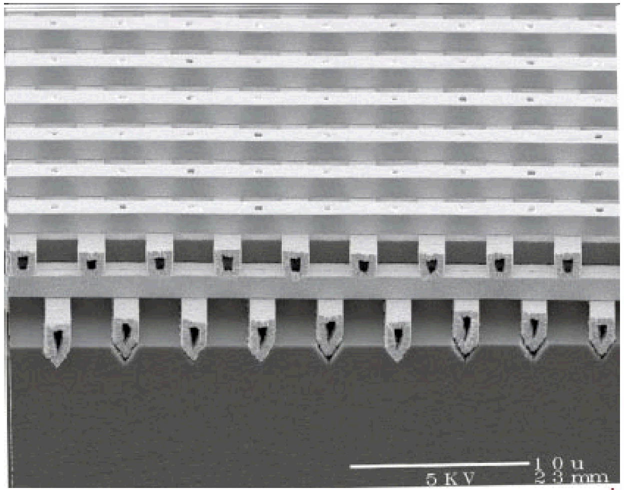


Large area dimension in 2011 is substantially larger. PnC element sizes are more easily fabricated than photonic in some applications (long wavelengths). Other limitations come in to play.

Traditional Approaches for PhC or PnC :

Top-down processing in the semiconductor fab. What works for PhC should work for PnC

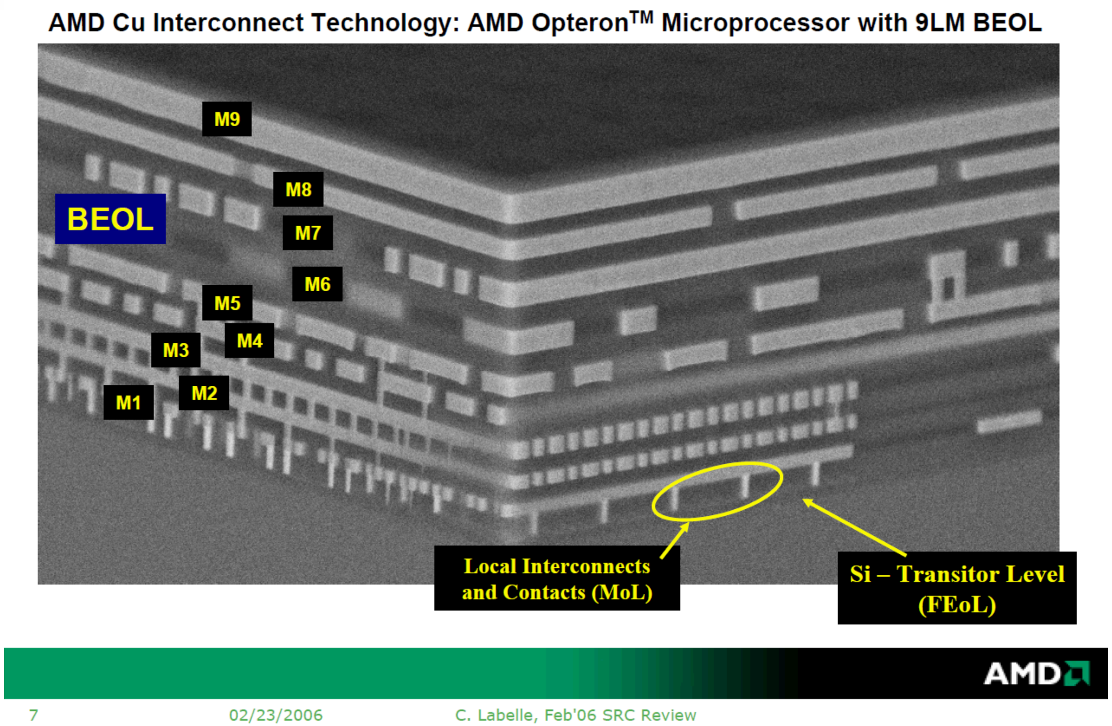
- Single print area can be large (EUV 26mm x 33mm field size)
  - ➢Field stitching for larger areas
- Leverage existing pattern transfer processes
  - ➢Speed and know how/ flexibility
- Limited set of materials
- Front end (geared toward small features) vs. Back end



J. Fleming, SNL 2002

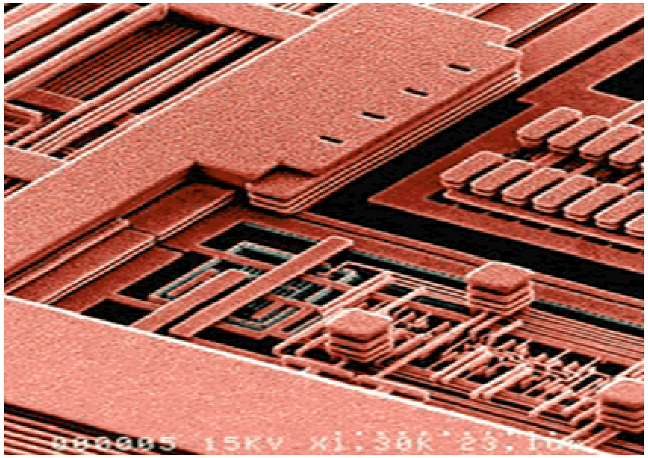
~1um on 4um pitch Tungsten from PolySi

More Metal, More Layers, More Molding, More Stress



William H. Dresher, Ph.D., P.E.

http://www.copper.org/publications/newsletters/innovations/2006/01/copper_nanotechnology.html

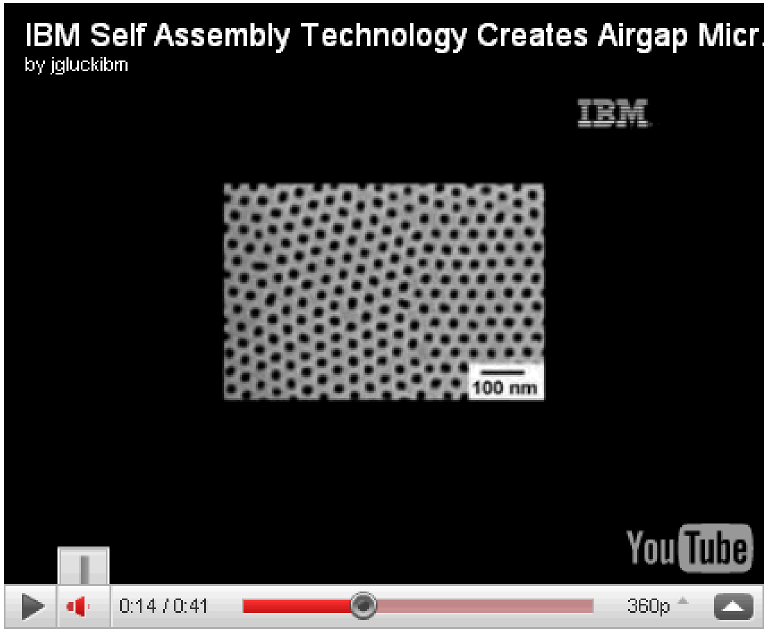


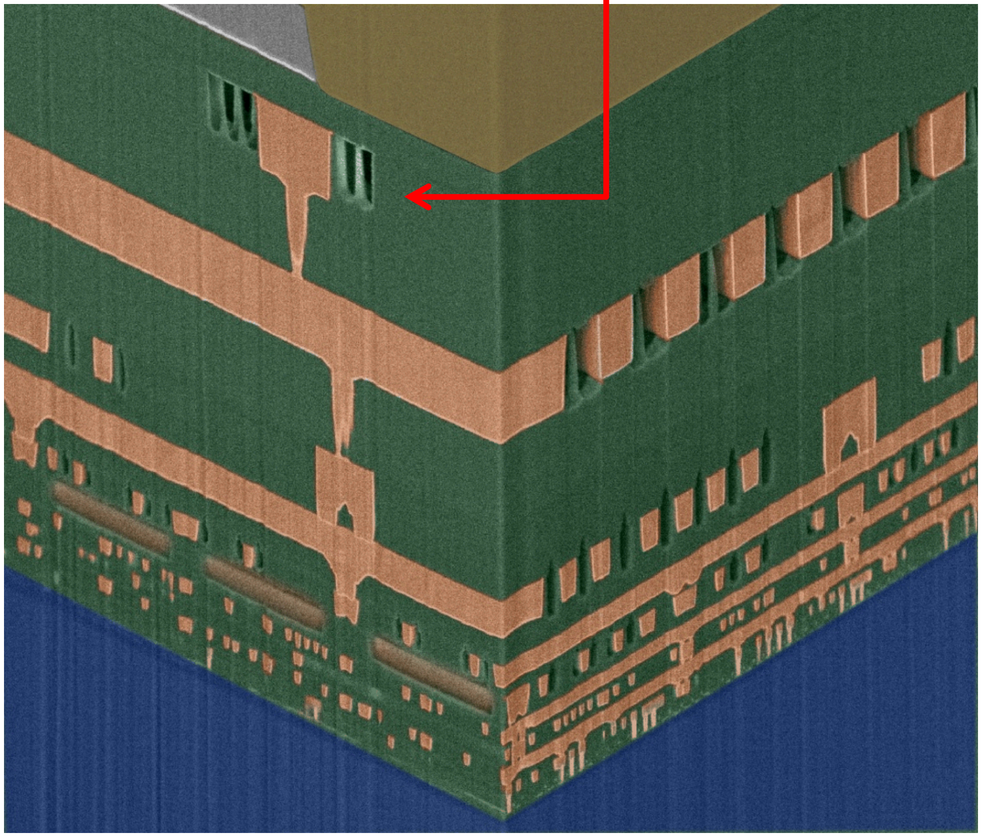
C. Labelle, Feb SRC Review, 2006.

11 layers of metal at the 65nm node with inductors and solenoids fabricated

http://www.electroiq.com/index/display/semiconductors-article-display/296969/articles/solid-state-technology/volume-50/issue-7/departments/technology-news.html

IBM Self-Assembly of Diblock Copolymer for Air Gaps
Dan Edelstein, May 2007





Self-assembled tiny holes allow for pinch off in CVD Deposition.

http://www-03.ibm.com/press/us/en/presskit/21463.wss

Stamping and Printing for High Volume/Low Cost Scaling

•~2nd Century China printing with wood block stamps

•~11th Century China: printing using clay tablets

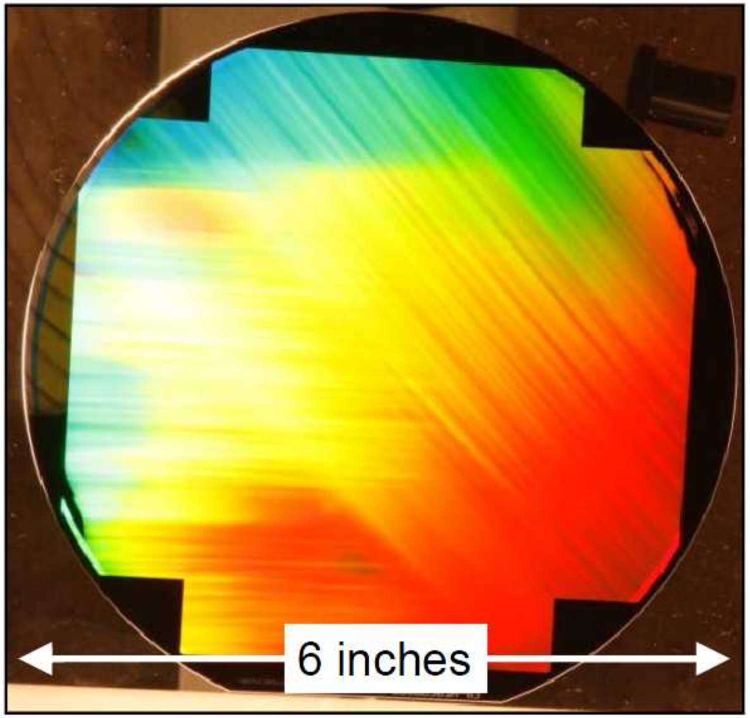
•Signet rings or cylinders: Much earlier by the Egyptians and others ~4000 BC. Mesopotamia: Between Tigris and Euphrates rivers

•Gutenberg: Printing press, ~1450 A.D.

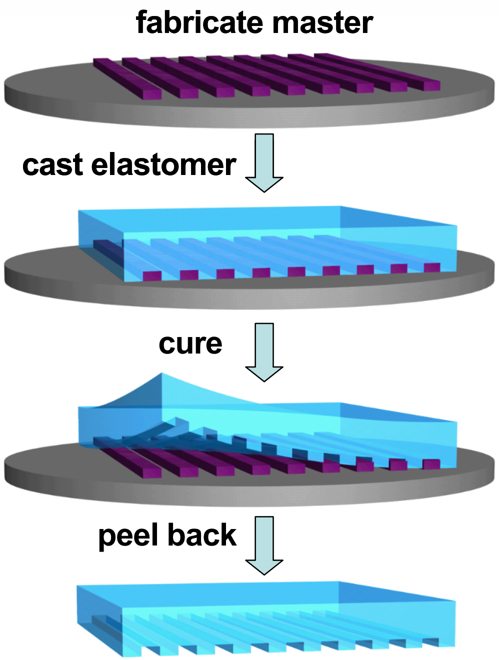
•Nano-imprint Lithography, ~1995 Chou, et. al. Currently being leveraged by semiconductor fabricators.

http://previous.presstv.ir/photo/20090302/ahmadi-nastaran20090302124546109.jpg
(Ancient cylinder seal found in Iran

Printing and Stamping Large Area 3D "Fishnet" Negative Index Materials



D. Chanda, J. A. Rogers, UIUC, G.R. Bogart SNL Nature Nanotech In Press

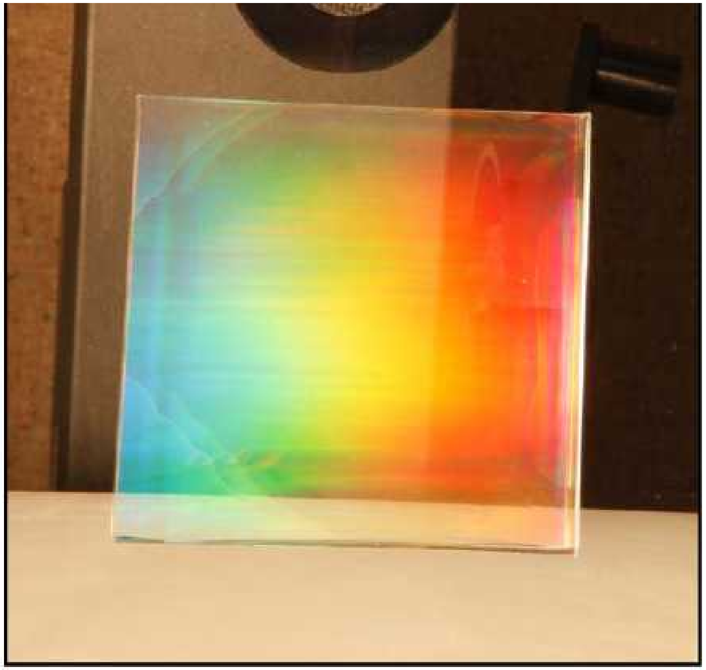


Large effort to make the master.
Less effort to make the stamp

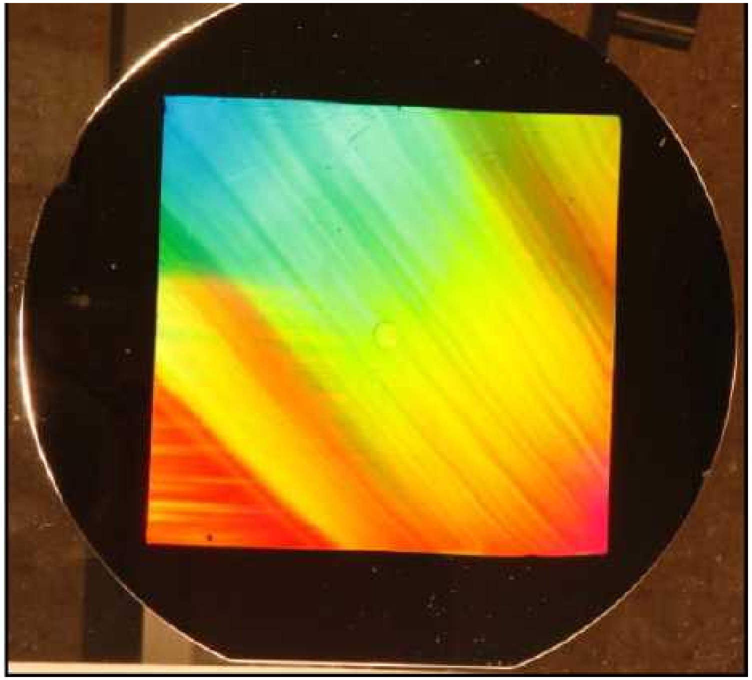
Material issues: Polymer shrinkage, thermal stability, CD control, topography. Flat surface to curved surface transfers?
Rapid and reproducible pattern transfer down to the nanoscale or better.
The cost is still in the mold master.

Soft Molds for Pattern Transfer

Soft silicone mold



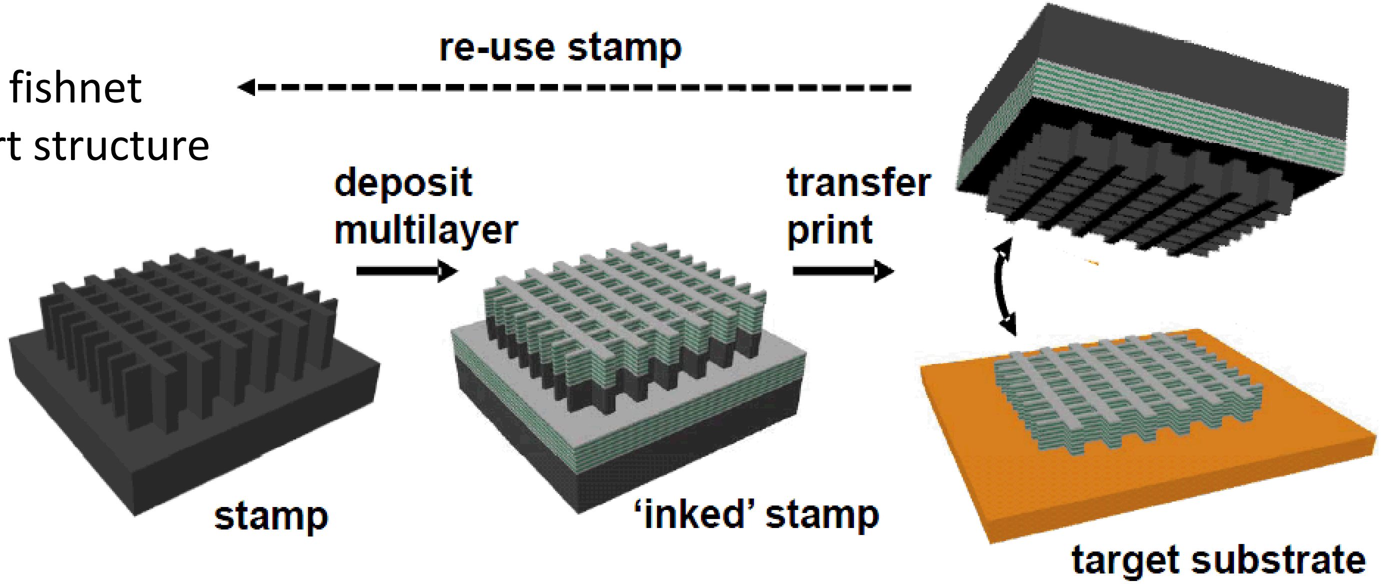
Pattern transferred to silicon wafer using traditional resist/etch

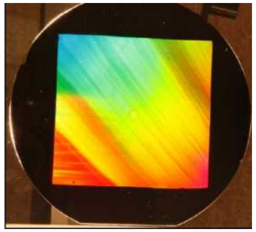


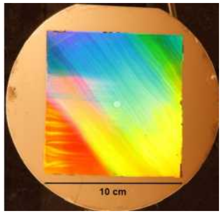
D. Chanda, J. A. Rogers, UIUC, Bogart SNL   Nature Nanotech In Press

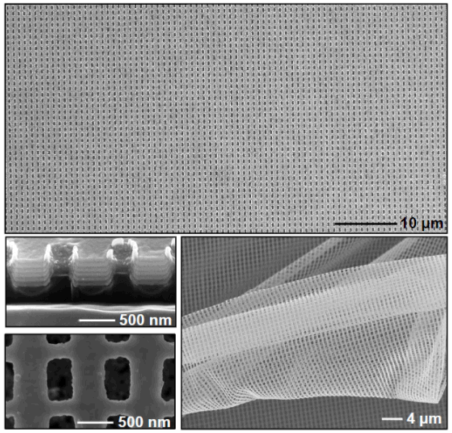
Large Area NIM Fabrication

Raised fishnet support structure



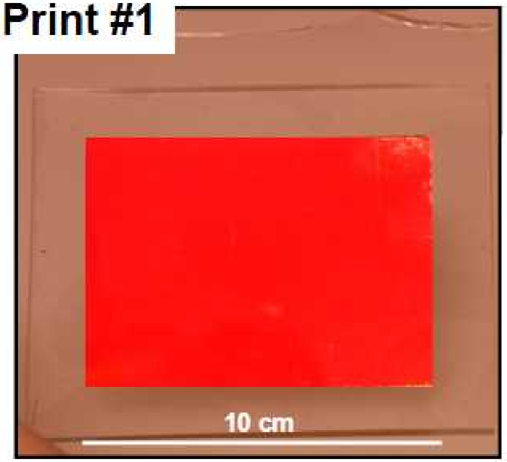




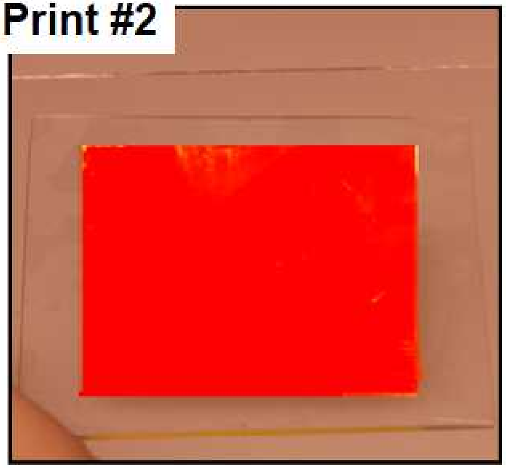


Multiple 2D NIM Structures Using Same Hard Silicon Wafer Stamp

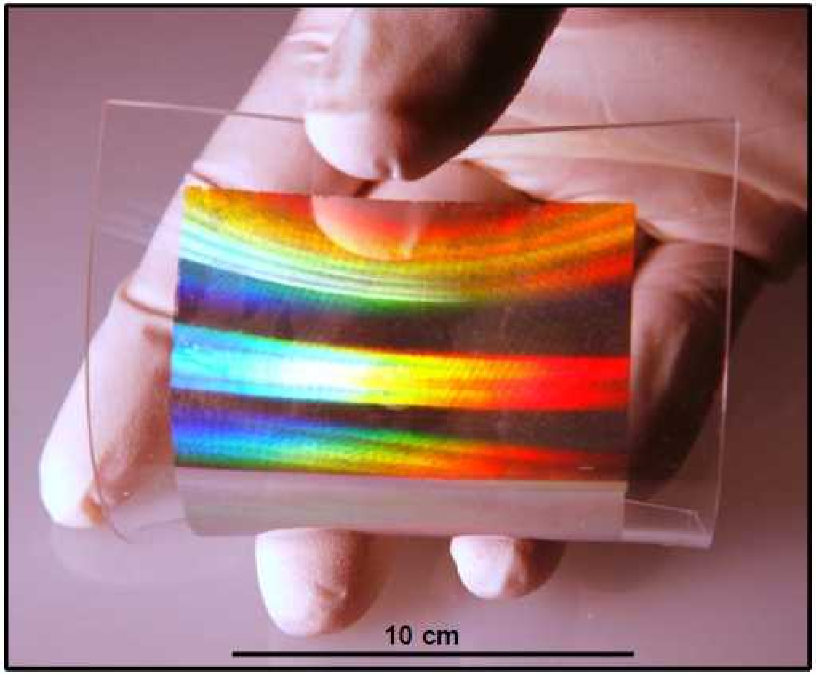
Print #1



Print #2



Low-Cost, Plastic Substrate

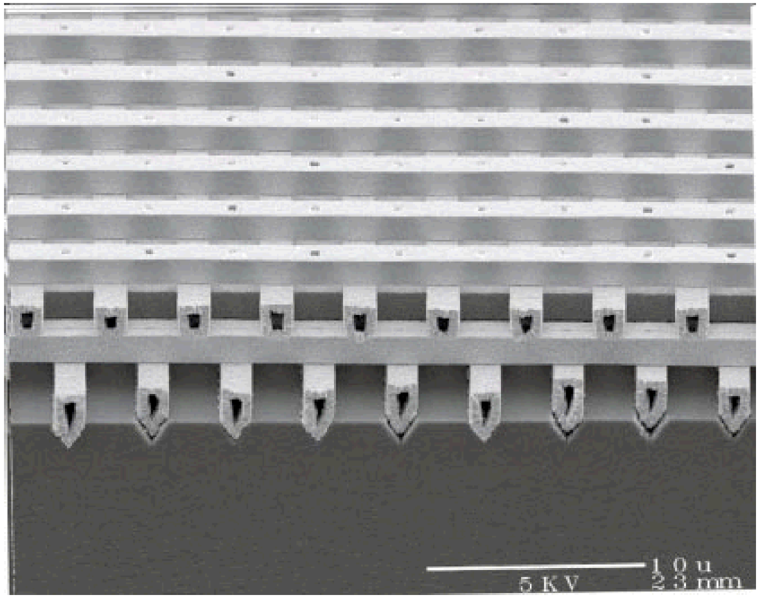


Nature Nanotech, in press

Phase Mask Lithography For Stamped 3D Structures

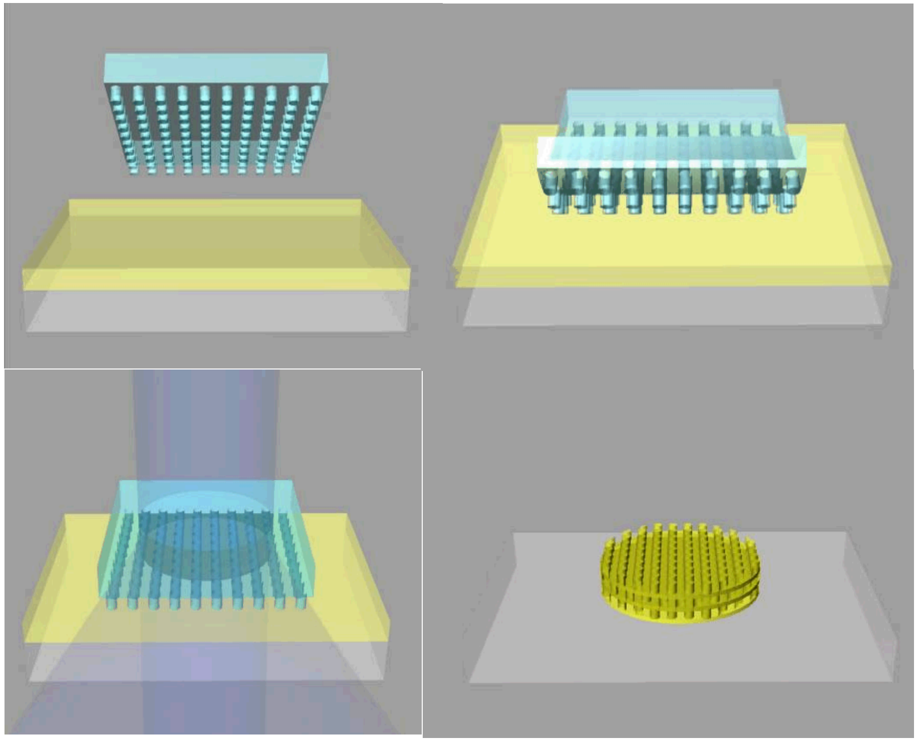
J. Fleming, SNL 2002

~1um on 4um pitch   Tungsten from PolySi



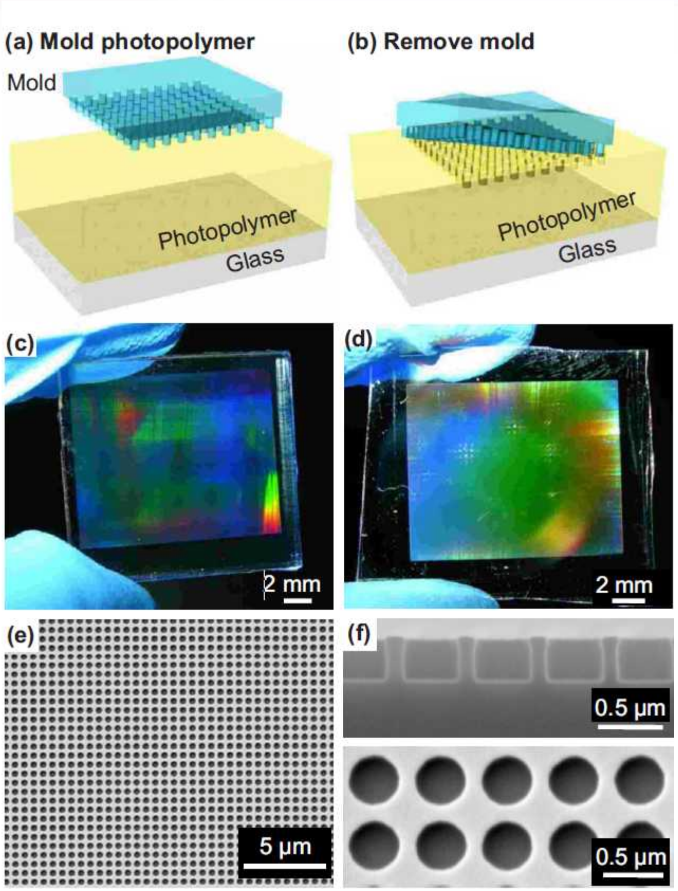
Layer by layer 3D
Extent of effort is
very high.

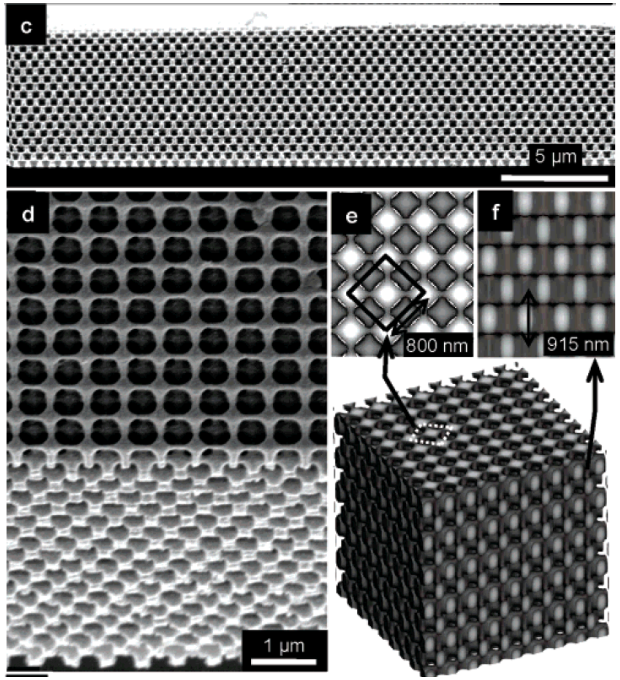
Can we get 3D structures in one shot?



Less effort and lower cost

Phase Imprint Lithography for 3D Structures



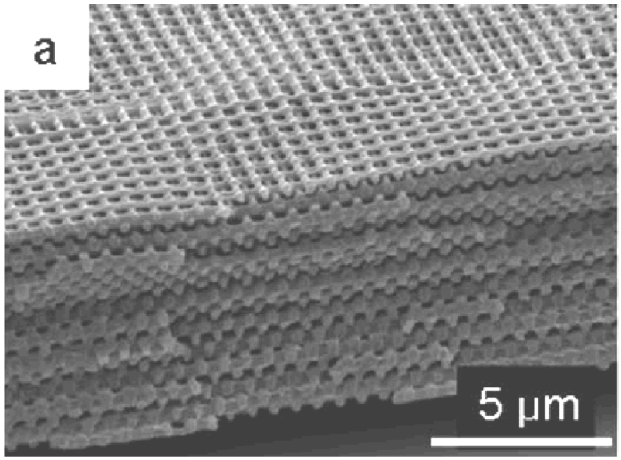


Simple Process: Stamp, Expose, Develop
Mask (optical phase delay) integrated into the resist.

Efficient phase mask design requires modeling both forward and backward

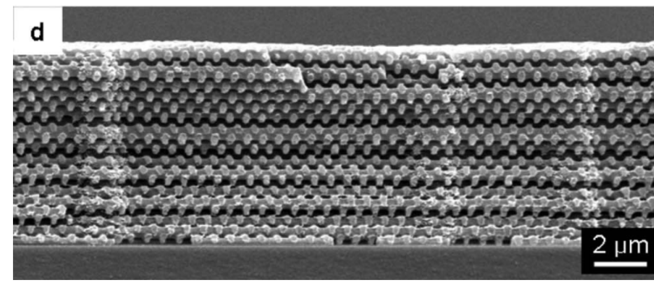
Shir et. al. *J. Phys. Chem. B, Vol. 111, No. 45, 2007*

Improved Processing: Layer by Layer to Single Step With Other Materials



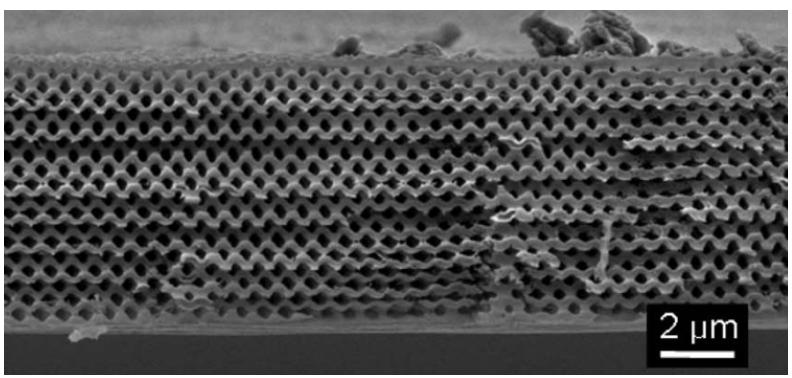
Polymer

Inverse
Silicon
Wood Pile
Structure



Silicon
Using ALD
and CVD

~3D: large
area but
not very
thick



J. Vac. Sci. Technol. B, Vol. 28, No. 4, Jul/Aug 2010 D. Shir, et.al

Electron Beams: Proven Technology but Oh So SLOW???

• Current e-beam litho speed - writing a single 300-mm wafer at 60-nm half pitch still takes 20 hours

However:

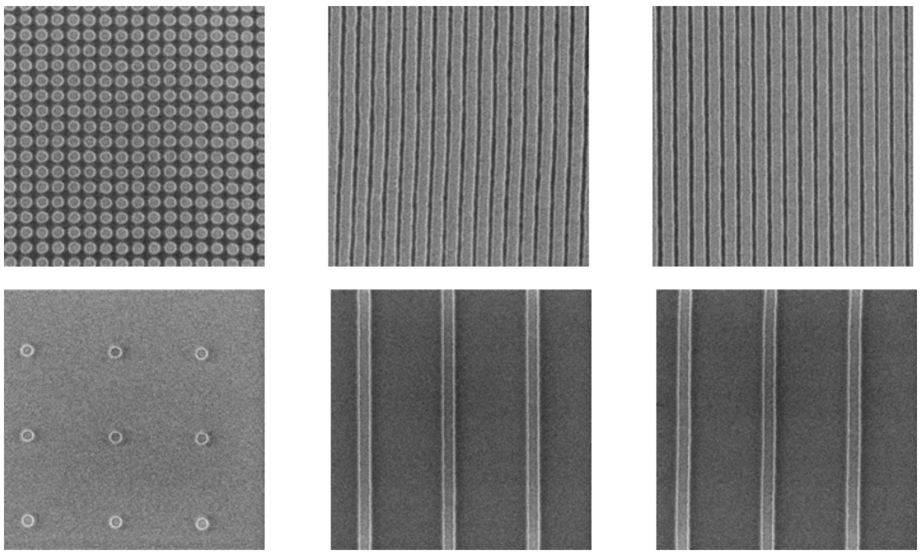
• NuFlare and others make e-beam direct write photo mask writers for flash imprint lithography mold masters.

• Projection Mask-Less Lithography (PLM2) technology has a goal of building E-beam direct write systems that offer 256,000 programmable electron multi-beams of 5 keV energy.

• Mapper e-beam has a throughput goal for its tools of 10 wafers per hour and then cluster 10 tools together in a system that can write 100 wafers per hour. Current tools feature 13,000 electron beams that can be individually switched on and off by means of an optical blanker array and a movable stage.

Multiple E-Beam Direct Write Lithography System by MAPPER for High Throughput Templates

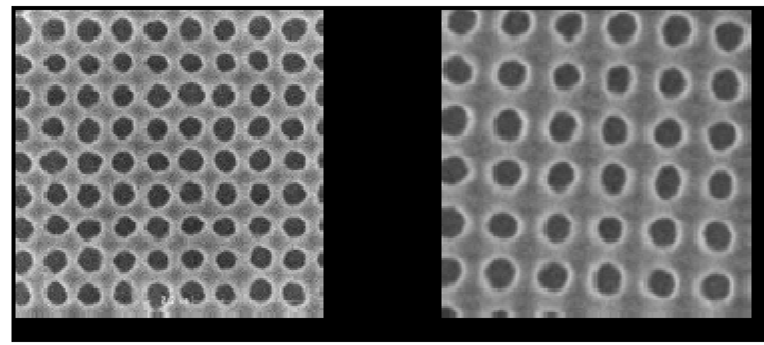
*www.**mapperlithography**.com Delft, Netherlands*

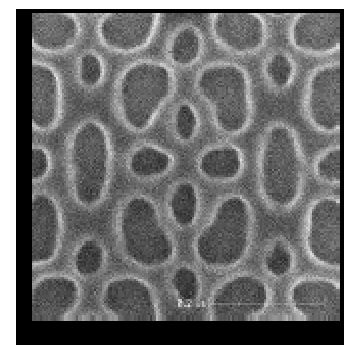


45 nm structures (solated and dense)

Figure 8 Dense and isolated 45 nm exposures in PMMA at MAPPER's S005 machine. (Center trenches are 'horizontal trenches' and right trenches are 'vertical trenches')

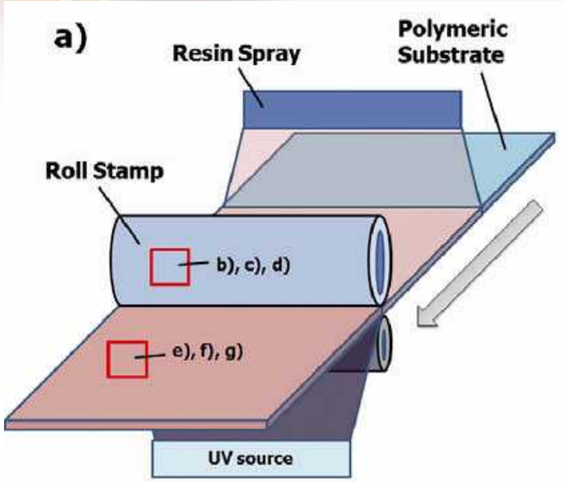
Wieland, et al. 2010 Proc. of SPIE Vol. 7637 76370F-2





Easily Programmable defects

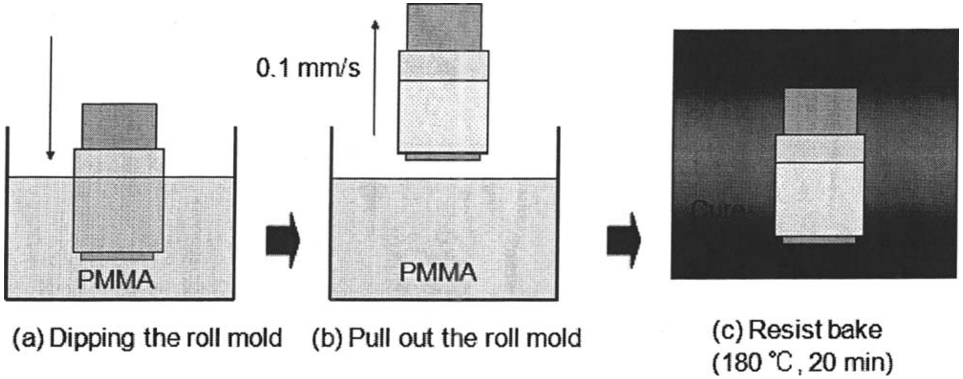
E-Beam Fabricated Stamps Mounted to Rollers

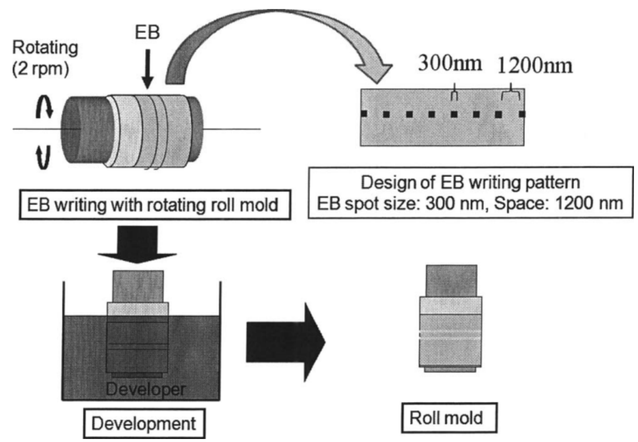


Microelectronic Engineering 86 (2009) 642–645
Seon-Yong Hwang, Sung-Hoon Hong, Ho-Yong Jung, Heon Lee
*

Flexographic (plate on a roller)

E-beam direct write on a roller!



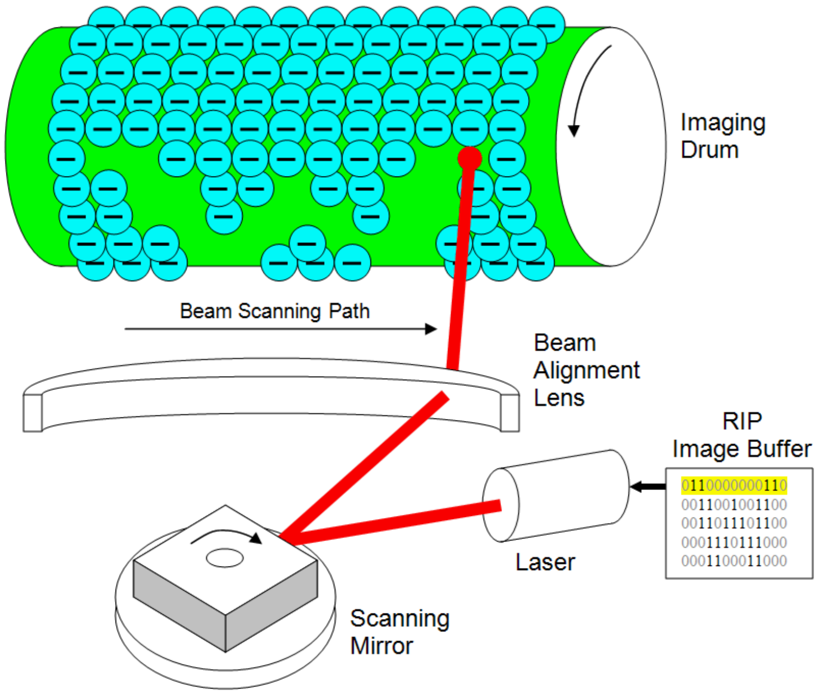


Taniguchi and Aratani, J. Vac. Sci. Technol. B 27,,6…, Nov/Dec 2009

Where Could Direct Write E-beam be Headed?

Desk top E-beam printer?

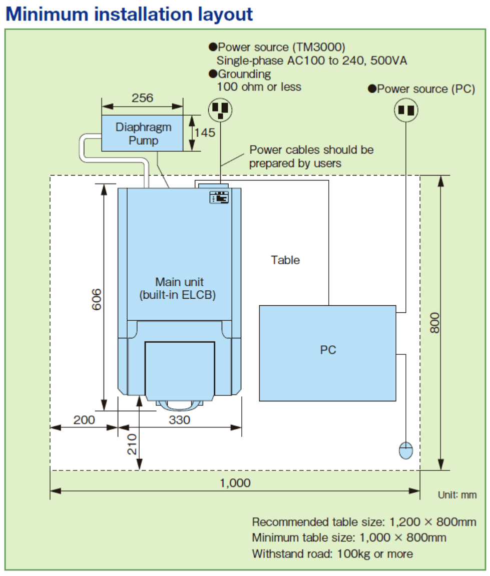
Typical Laser Printer Design:
Full activation with deactivation in DW mode.



Wikimedia

Hitachi TM3000 (1'x2')

Image from Brochure as of presentation date
Table Top Electron Microscope



Sandia
National
Laboratories

Additive Technologies: 3D Printers With Plastic Materials for Rapid Prototyping/Mock Ups

Liquid or Powder

Commercial Systems
150um resolution

Other Than Commercial Vendors

- 50um resolution claim using a DLP projector

http://blog.sculpteo.com/2011/04/08/homemade-high-resolution-3d-printer/ Junior Veloso (Singapore)

Nickel plated Plastic

SLARMOR

Stereolithography

Viper

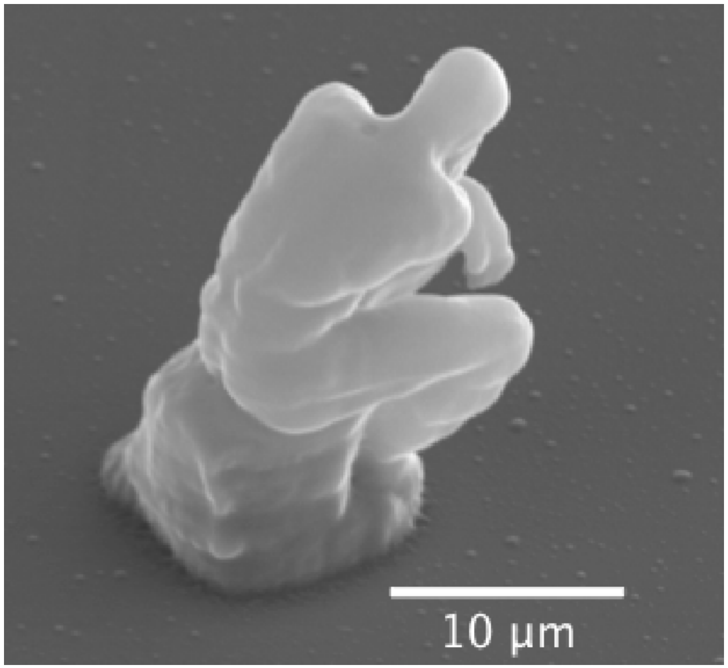
FineLine

SLArmor

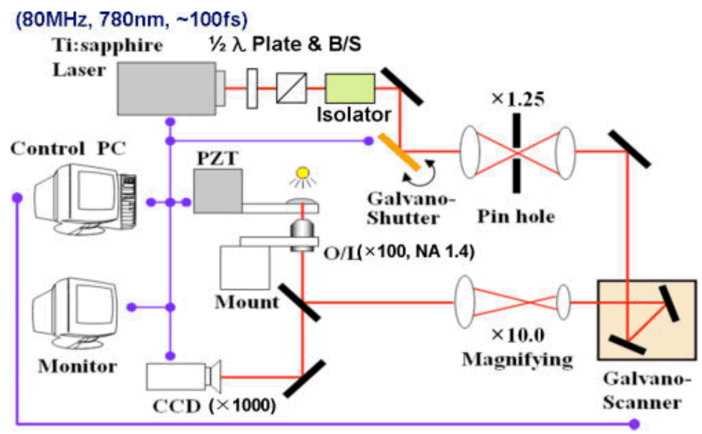
NR: 0.015"
HR: 0.010"

http://www.finelineprototyping.com/services/materials.php

3D Direct Write Lithography: Two Photon Stereo Lithography



Sang-Hu Park et al.,
Laser & Photon. Rev. 3, No. 1–2, 1–11 (2009)



Resolutions typically 100's nm Limited more by voxel (volume element of exposure beam) size and polymer chemistry

Other 3D Direct Write Structures Using 2-Photon Exposure

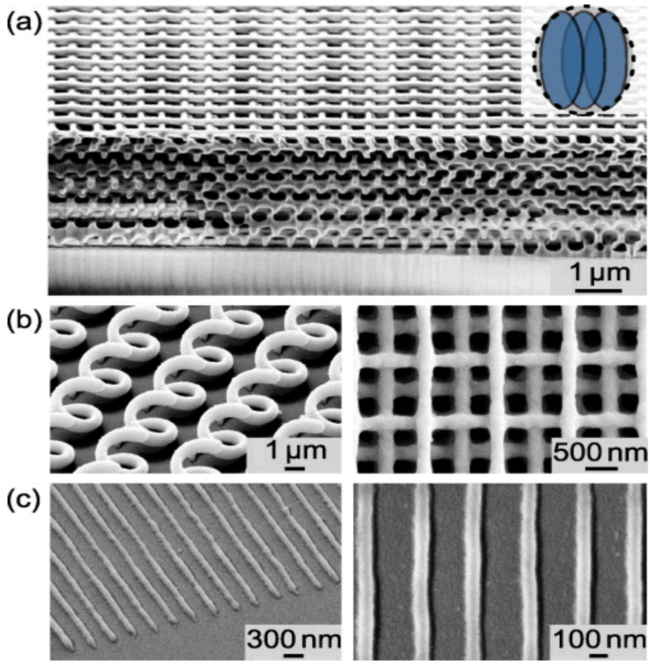


FIG. 2. The gallery of electron micrographs of structures fabricated by 532 nm cw-DLW. (a) 24 layers of a = 500 nm rod spacing woodpile cut by focused-ion-beam milling to reveal the three-dimensional interior IP-L photoresist. (b) Oblique view of SU-8 photoresist...

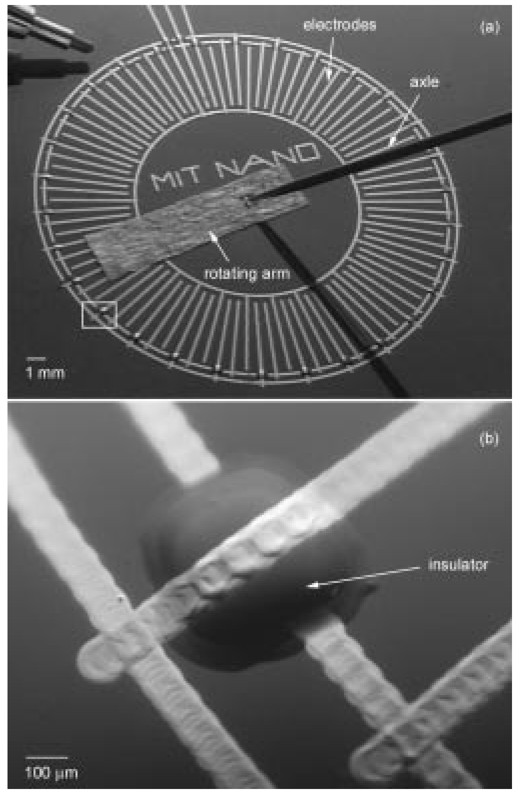
Thiel, M.; Fischer, J.; von Freymann, G.; Wegener, M , Appl. Phys. Lett. 97, 221102 (2010) American Institute of Physics

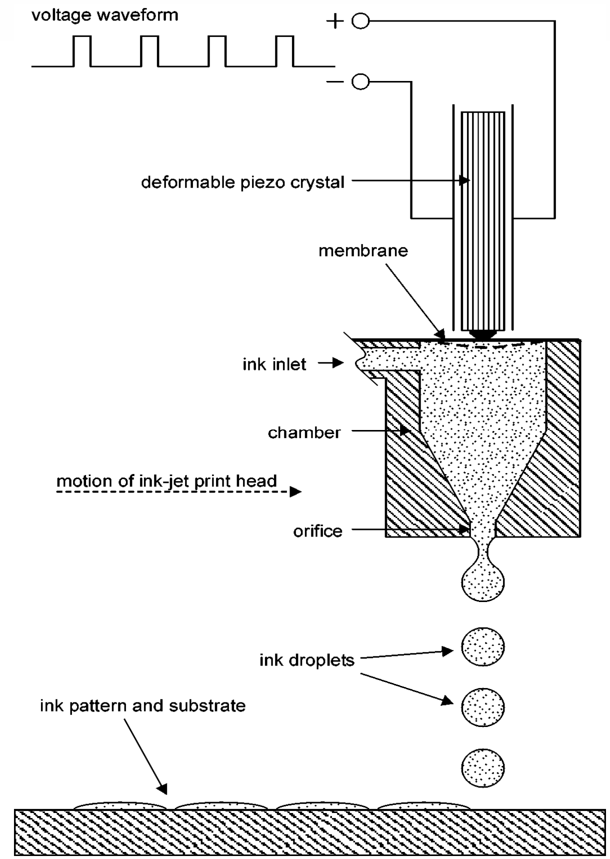
Where to now?

- •Super Resolution Imaging and Lithography
- •Based on Microscopy technique to image single molecules using fluorescent dyes.
- •Developed by Stefan Hell, Max Planck Institute.
- •Promise of sub-100nm structures in one direction.
- •Improvements in polymer chemistry and beam shaping may achieve that in all three.
- • Martin Wegener’s Group (*Universität Karlsruhe: Karlsruhe, Germany)*

Ink-Jet Printing: Some Early Work

< 100um final size perhaps to 20um Positional accuracy better than +/-5um.
Solvent issues
Particle size issues (CdSe)
1-100nm Lower melting points
Sintering temp 300C
Rheology issues
Multi-layer demonstrated





Fuji

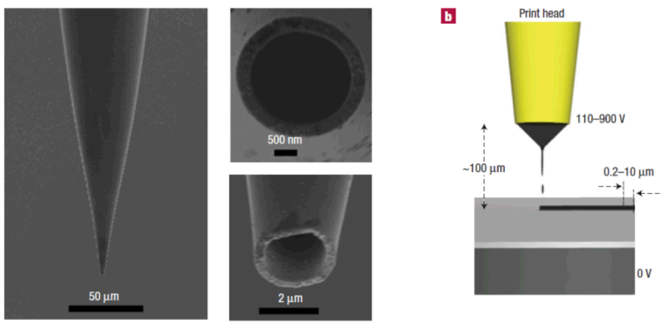
Dimatix Materials Printer DMP-2800

http://www.dimatix.com/divisions/materials-deposition-division/printer_cartridge.asp

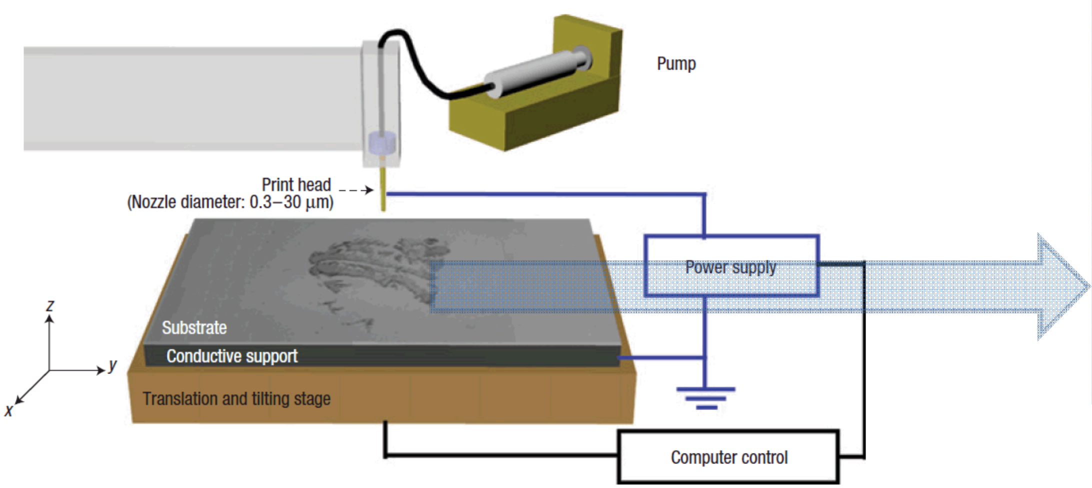
JMEMS, VOL. 11, NO. 1, FEBRUARY 2002
Sawyer B. Fuller, Eric J. Wilhelm, and
Joseph M. Jacobson MIT 2002

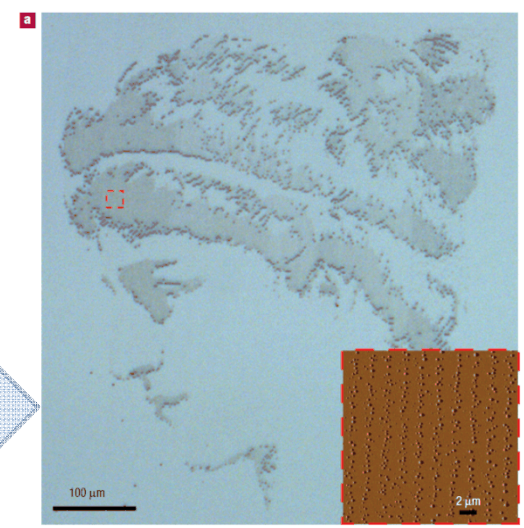
Electrohydrodynamic Ink-Jet Printing

E-jet printing: Uses electric fields rather than acoustic/thermal methods to create fluid flow
Graphic arts dot diameters to 20um. Resolution approaching 0.5um. Printing speeds vary ~100um/sec



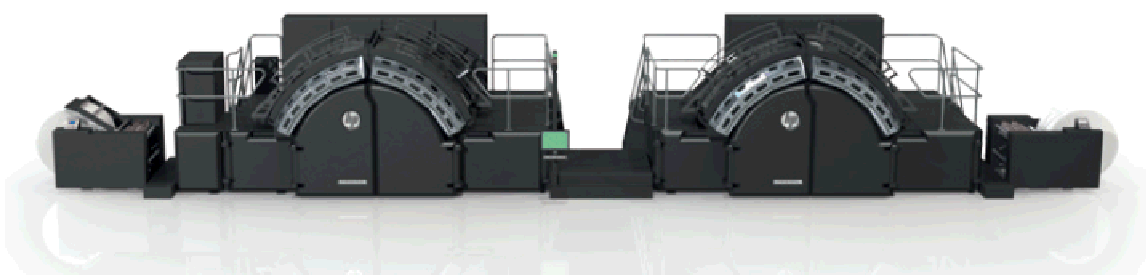
Dispensed nanoparticles in solution
Au, Si, Ferritin for aligned SWNT growth, SWNT themselves. Substrates: Glass, Silicon,





Park, et al. Nature Nanomaterials
October 2007, V6, PP 782-789

Where is Inkjet Technology Headed?



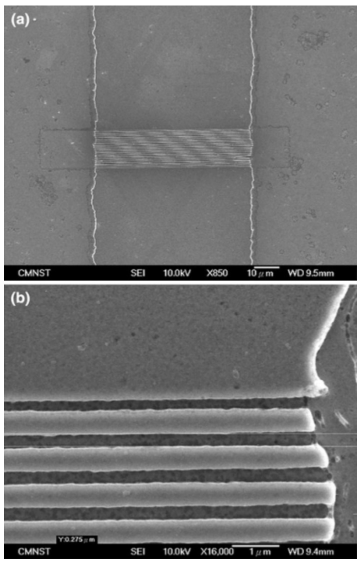
HP T400 Color Inkjet Web Press

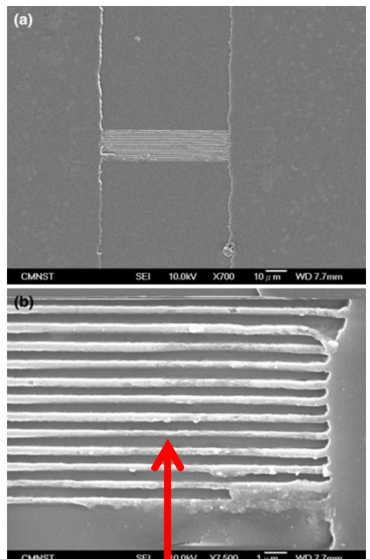
Create new business opportunities with a whole new class of digital production

Instead of different colors (12) have different materials

Picoliter (current) to Femtoliter drop sizes

Subtractive Technologies: Machining and Injection Molding (Drill and Fill)





- Sesame seed sized pellet produces 520 micro molding components
- Microfluidics slots to 0.5 micron (0.000019")
- Total part length of 0.060" (1.5mm)
- Gate diameters as low as 0.002" (0.05mm)
- Overall part weight of 0.00012 grams

Microsyst Technol (2010) 16:941–946

C.-H. Chang W.-B. Young (&)
Department of Aeronautics and Astronautics,
National Cheng Kung University,
Tainan 70101, Taiwan, ROC

http://www.mtdmicromolding.com/micro-molding

0.5 um channel on 1 um pitch

Materials:

“Spruce” Goose aka H-4 Hercules
Wikimedia Commons

Materials mentioned so far:
Silicon, copper, aluminum, tungsten, (CMOS fab) plastics, silicone, exotic polymers, mixed matrix, biologicals, ceramics, glass.

Choice depends on:
1. Technology you choose to work in
2. Materials you have available
3. Materials defined by the design

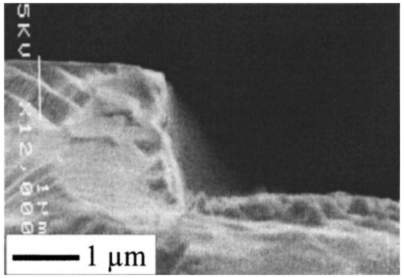
Lithium Niobate and Processing

Why $LiNb0_3$? excellent electro-optical, acousto-optical, and nonlinear optical properties.

Very difficult to process but the payoffs are high.

- Pyroelectric
- Piezoelectric

Leverage the optoelectronics industry?
Main processes are etching. Wet and Dry
Wet: Isotropic etch in HF
Dry: Anisotropic but generally rough due to LiF residues generated from fluorine based plasma chemistries.

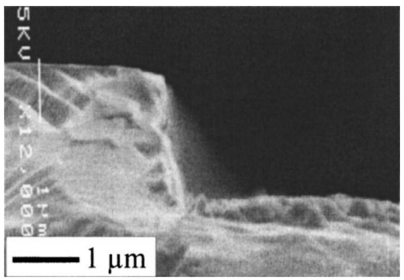


Hu et. al. , J. Vac. Sci. Technol. A, Vol. 24, No. 4, Jul/Aug 2006

Processing of LiNbO3 Lags Other Optical Materials

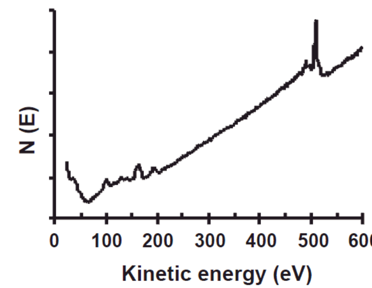
Proton Exhange Processing:

Lithium is substituted with hydrogen to eliminate non-volatile etch species for dry etch processing. (Benzoic acid melt)

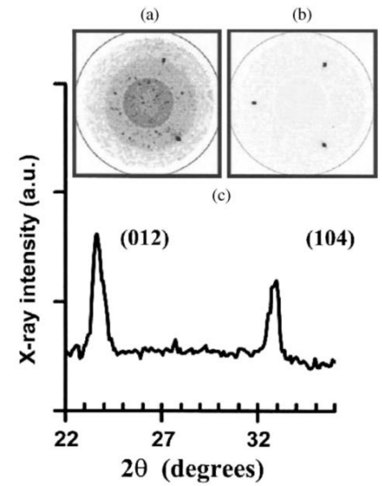


Hu et. al. , J. Vac. Sci. Technol. A, Vol. 24, No. 4, Jul/Aug 2006

CVD: Alcoxide precursor deposition, processing, then annealing. High processing temps.



2. Auger electron spectra of amorphous $LiNbO_3$ films



V. Joshkin et al. / Journal of Crystal Growth 259 (2003) 273–278

Damage 2um below surface

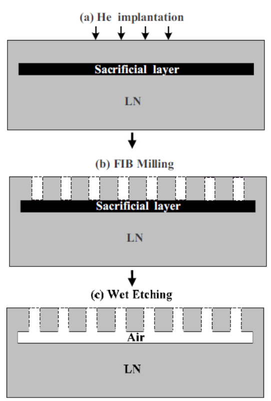
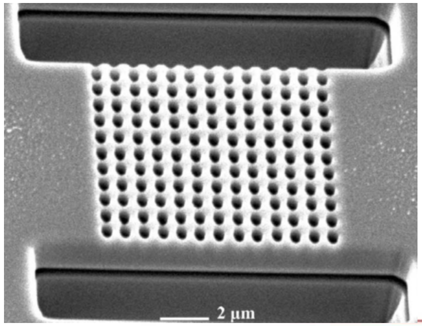


FIG. 1. Illustration of the process steps to create suspended structures in LN using ion implantation, FIB milling, and selective wet etching.

Si et al, J. Vac. Sci. Technol. B 28,,2..., Mar/Apr 2010

Ion implantation with FIB milling and wet etching allow for suspended membranes.



Summary

Location: Rome, Oregon, USA Credit: Ellen Findlay Herdegen

From Sign Spotting Calendar
April 11, 2011
Ellen Findlay Herdegen
Rome, Oregon USA

- Have a vision and dream big!!
- Plan Ahead: Begin thinking about fabrication methods AT the time of design not just the materials.
- Pick appropriate technologies to start with. Don't design with "a hope" that the technology you choose to work in will improve by the time you need it.
- Don't forget to look at current technologies for advanced implementations and also keep your eyes open for improvements in the tried and true fabrication methods

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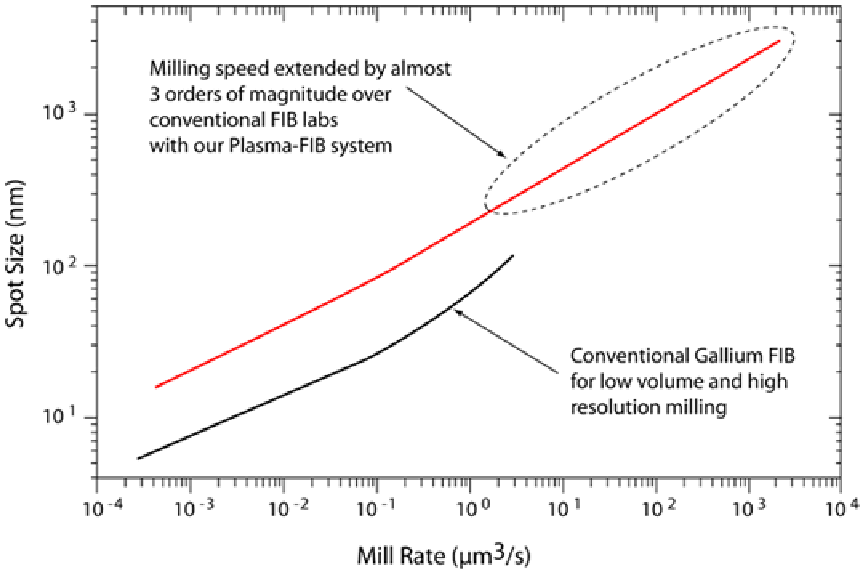
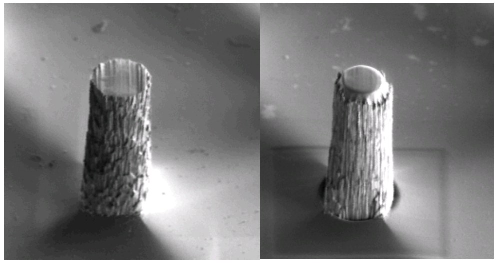
Amy Rein, SNL
Bruce Burckel, SNL
Victor Katsap, NuFlare
Penny Moore, SNL
Anthony Farino, SNL

Emerging Trends

Fast FIB (gas ions not liquid metals)

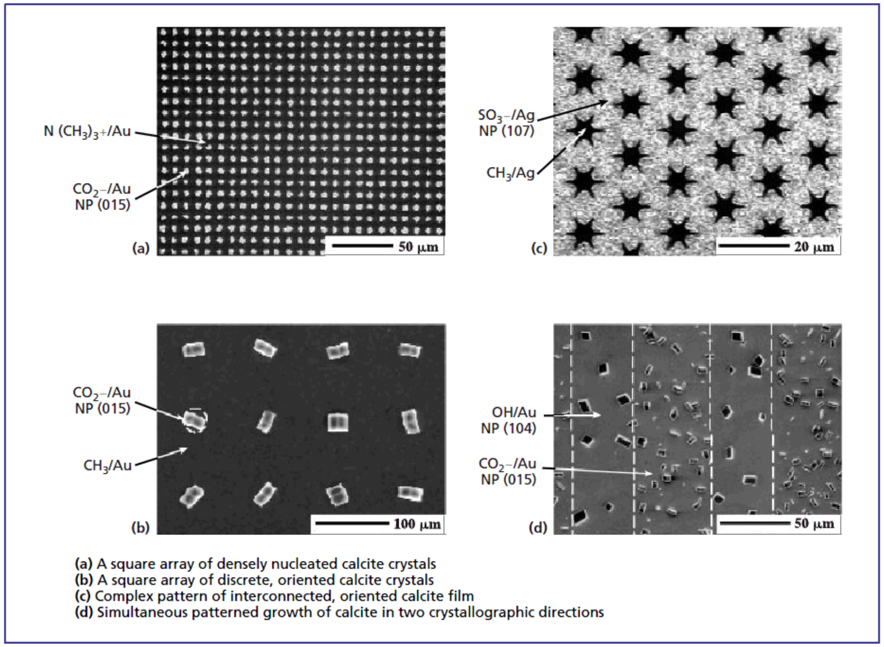


www.oregon-scientific.com Former division of FEI



DRIE pillar Shaping 30 sec

Selective Crystal growth (Zeolites, biomimetics)



(a) A square array of densely nucleated calcite crystals
(b) A square array of discrete, oriented calcite crystals
(c) Complex pattern of interconnected, oriented calcite film
(d) Simultaneous patterned growth of calcite in two crystallographic directions

Figure 6.
Scanning electron micrographs showing the controlled crystallization of calcite on patterned SAMs.

J. Aizenberg, Bell Labs Technical Journal 2005 P. 138

Phase Mask Master Design Using Modeling

If I have a 3D structure, what does the 2D phase mask need to look like?

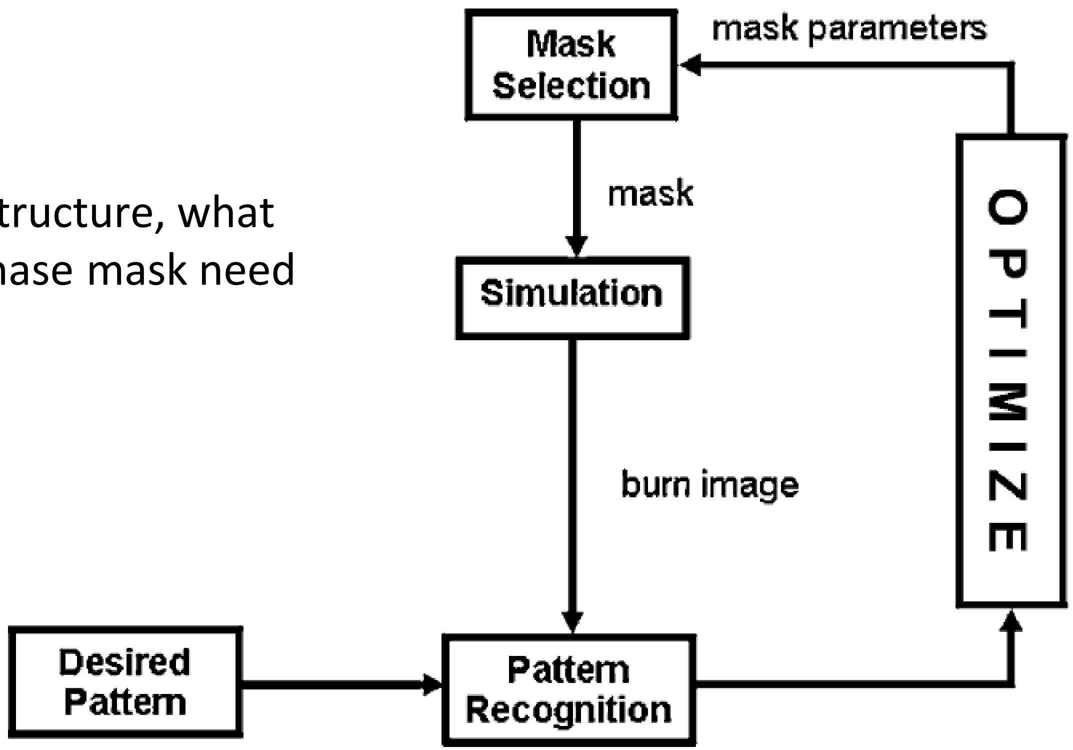
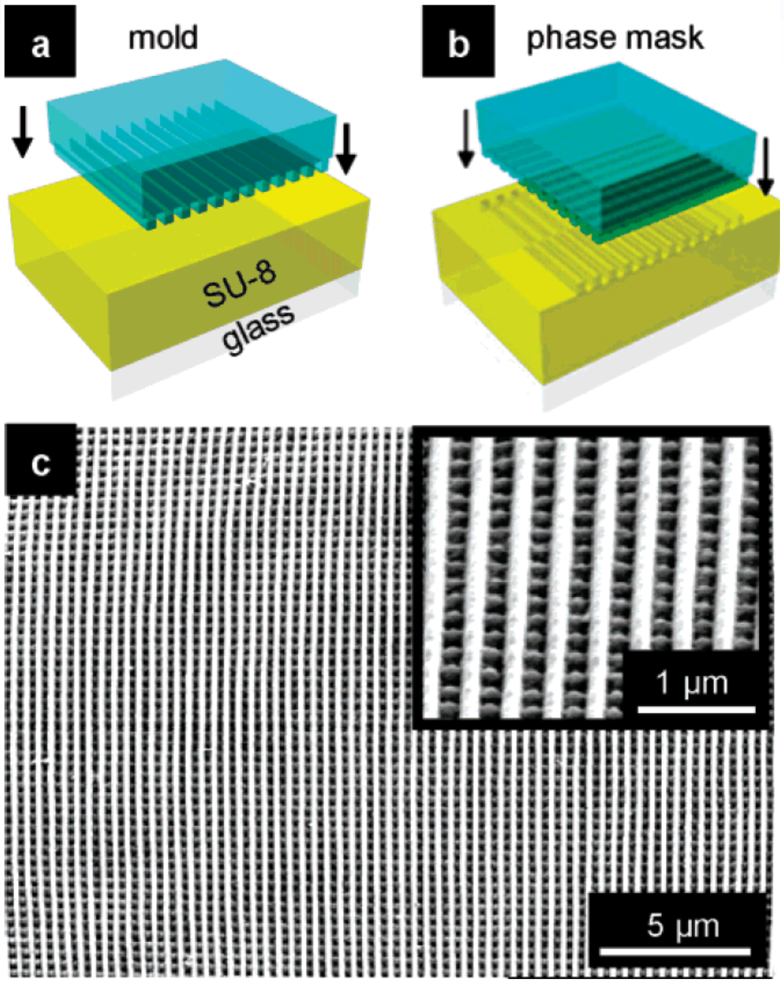


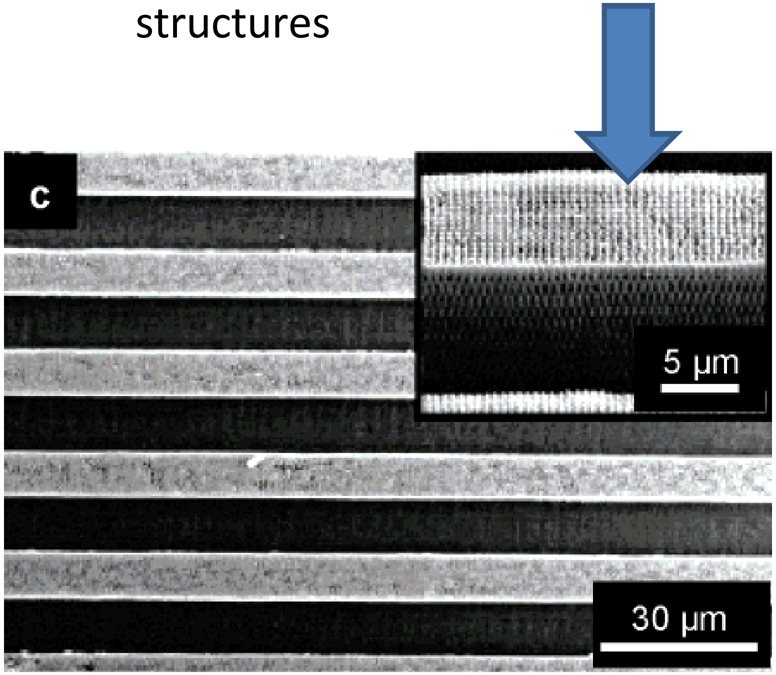
Fig. 1. Schematic illustrating the components of the integrated tool.

M.F. Su et al. / Photonics and Nanostructures – Fundamentals and Applications 6 (2008) 69–80

Multiple Phase Mask Imprints



Periodic structures within periodic structures



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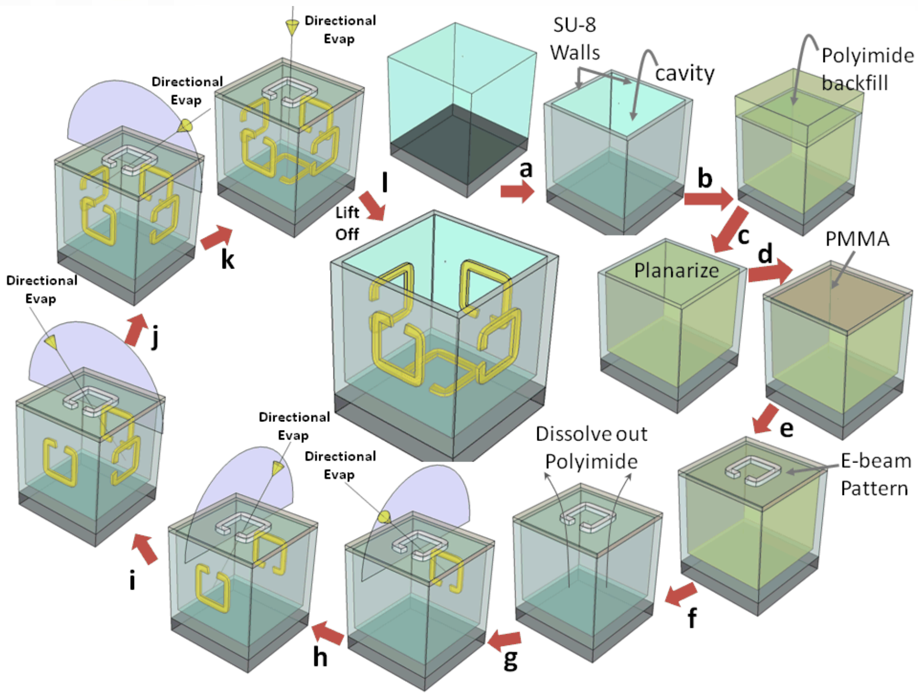
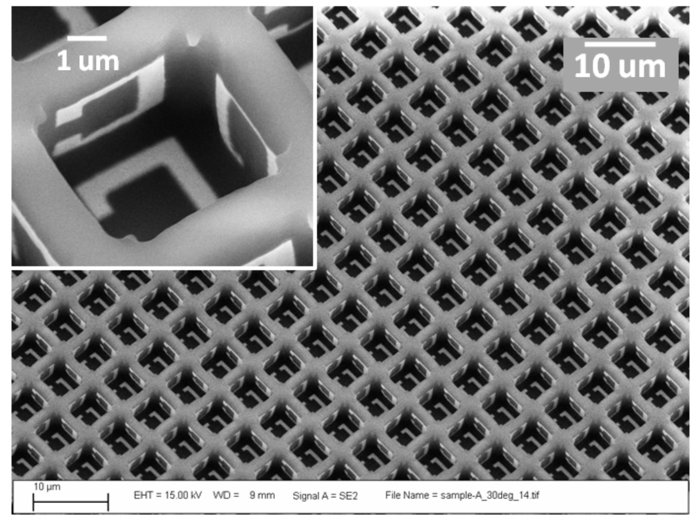
Membrane Projection Lithography
Scaled Metamaterial at 6um with 5 walls patterened



D. Bruce Burckel, Joel R. Wendt, Gregory A. Ten Eyck, James C. Ginn, A. Robert Ellis, Igal Brener, and Michael B. Sinclair, “Micrometer-Scale Cubic Unit Cell 3D Metamaterial Layers” Advanced Materials, vol 22, pp 5053-5057, (2010).



Angled evaporation with a suspended stencil. 5mm x 5mm current size. Resonator 0.7um width. Process could be adapted to traditional CMOS tool set.

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