DTU Fotonik
Institut for Fotonik

SAOT
erlangen
graduate school in
advanced optical technologies

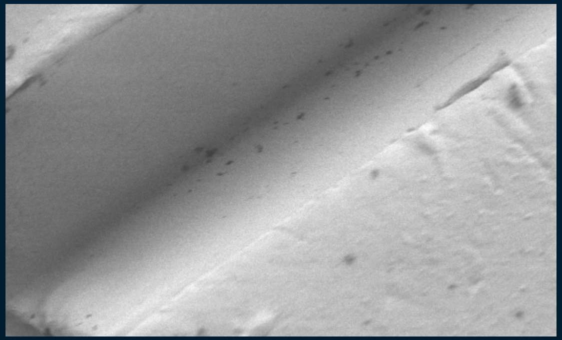
PURDUE
UNIVERSITY

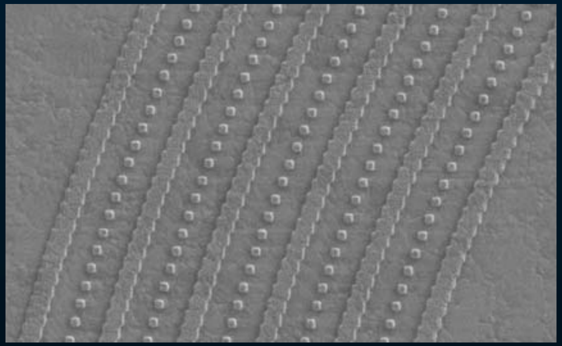
FABRICATION APPROACHES FOR MAKING PHOTONIC METAMATERIALS

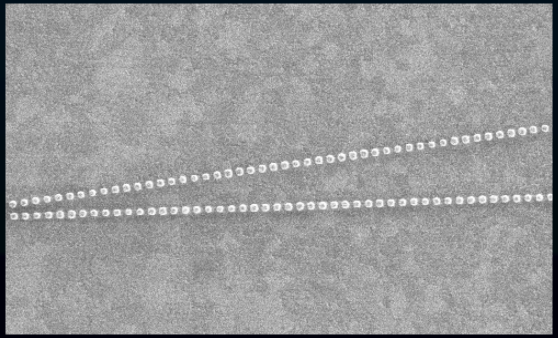
Alexandra Boltasseva

Purdue University
Technical University of Denmark
SAOT Erlangen University

OUTLINE







- First negative index metamaterials
- Fabrication techniques
- 2D metamaterials
- 3D metamaterials
- Outlook

FUTURE OF NANOPHOTONICS

NANOPHOTONICS

❾ NEXT STEP PLASMONICS

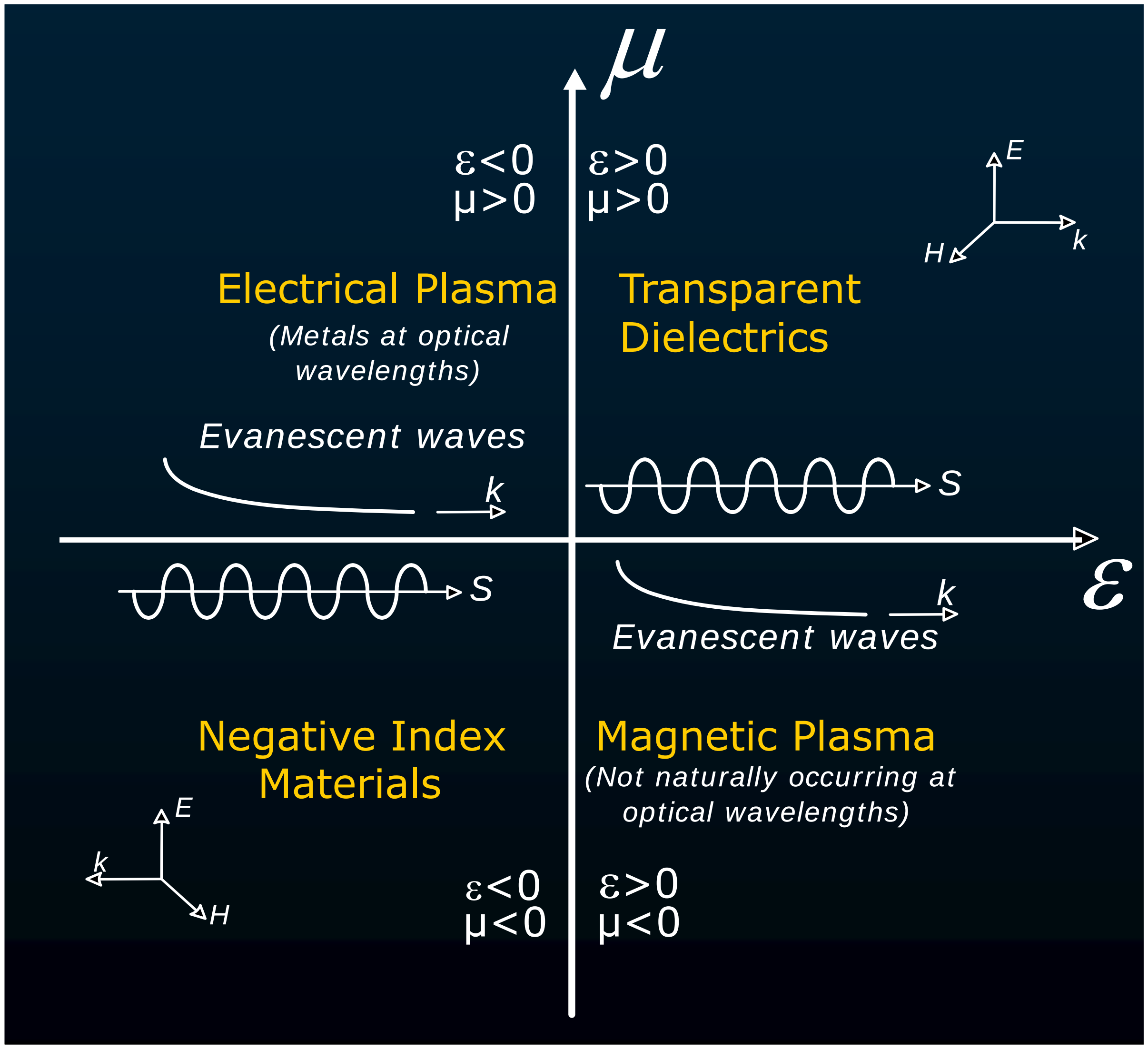
Negative ε

❾ NEXT STEP METAMATERIALS

Engineering of optical space

$\varepsilon \leq 0$

$\mu \leq 0$



$\varepsilon<0$
$\mu>0$

Electrical Plasma

(Metals at optical wavelengths)

Evanescent waves

$\varepsilon>0$
$\mu>0$

Transparent Dielectrics

Evanescent waves

Negative Index Materials

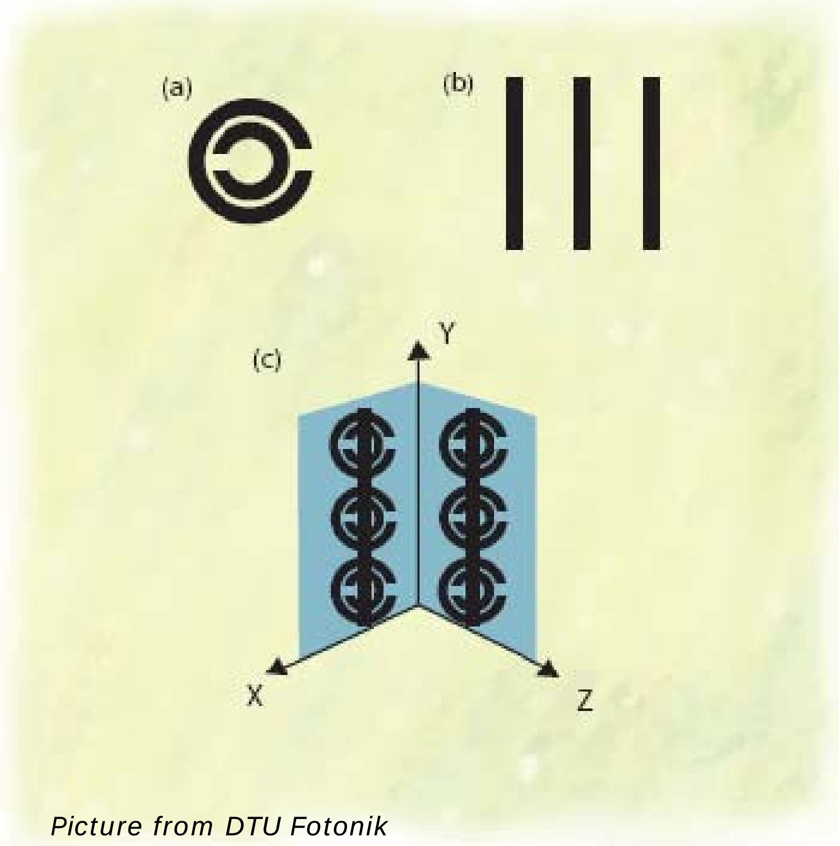
$\varepsilon<0$
$\mu<0$

Magnetic Plasma

(Not naturally occurring at optical wavelengths)

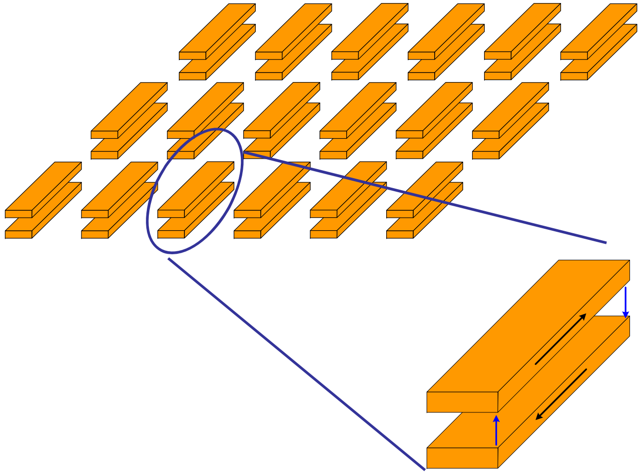
$\varepsilon>0$
$\mu<0$

METAMATERIALS



Picture from DTU Fotonik

J. B. Pendry, (1996, 1999)

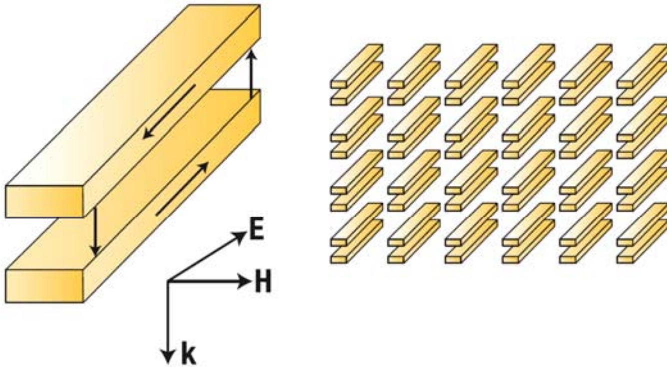


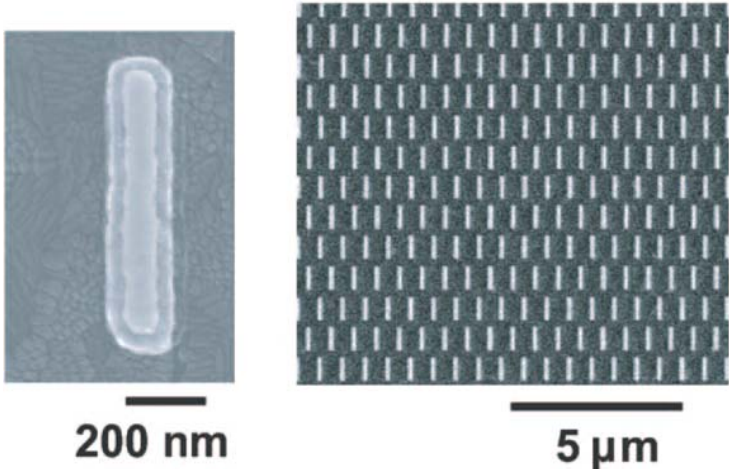
V. Shalaev (Purdue)

Metamaterial with artificially structured "atoms"

FIRST NEGATIVE INDEX MMs

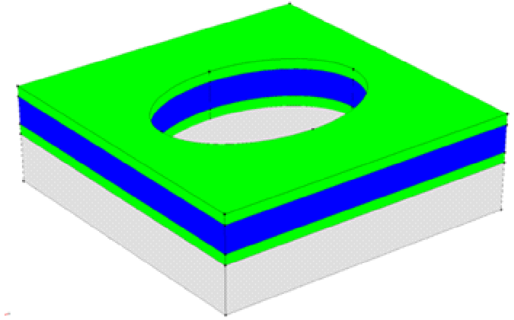
n' **≅ - 0.3** **λ = 1.5 µm**

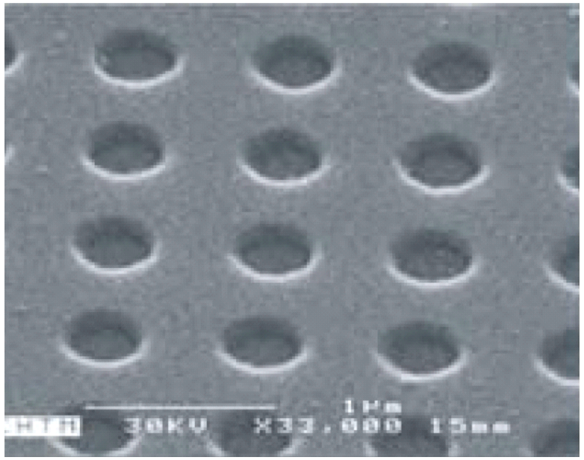




Paired rods

n' **≅ - 2** **λ = 2 µm**





Fishnet

V. M. Shalaev, et. al., Optics Letters 30, 3356 (2005)
S. Zhang, et. al., Phys. Rev. Lett. 95, 137404 (2005)

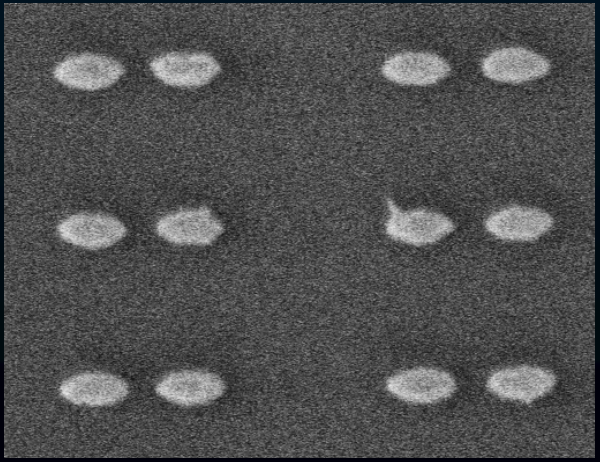
FABRICATION

Making Metal-Dielectric Structures:

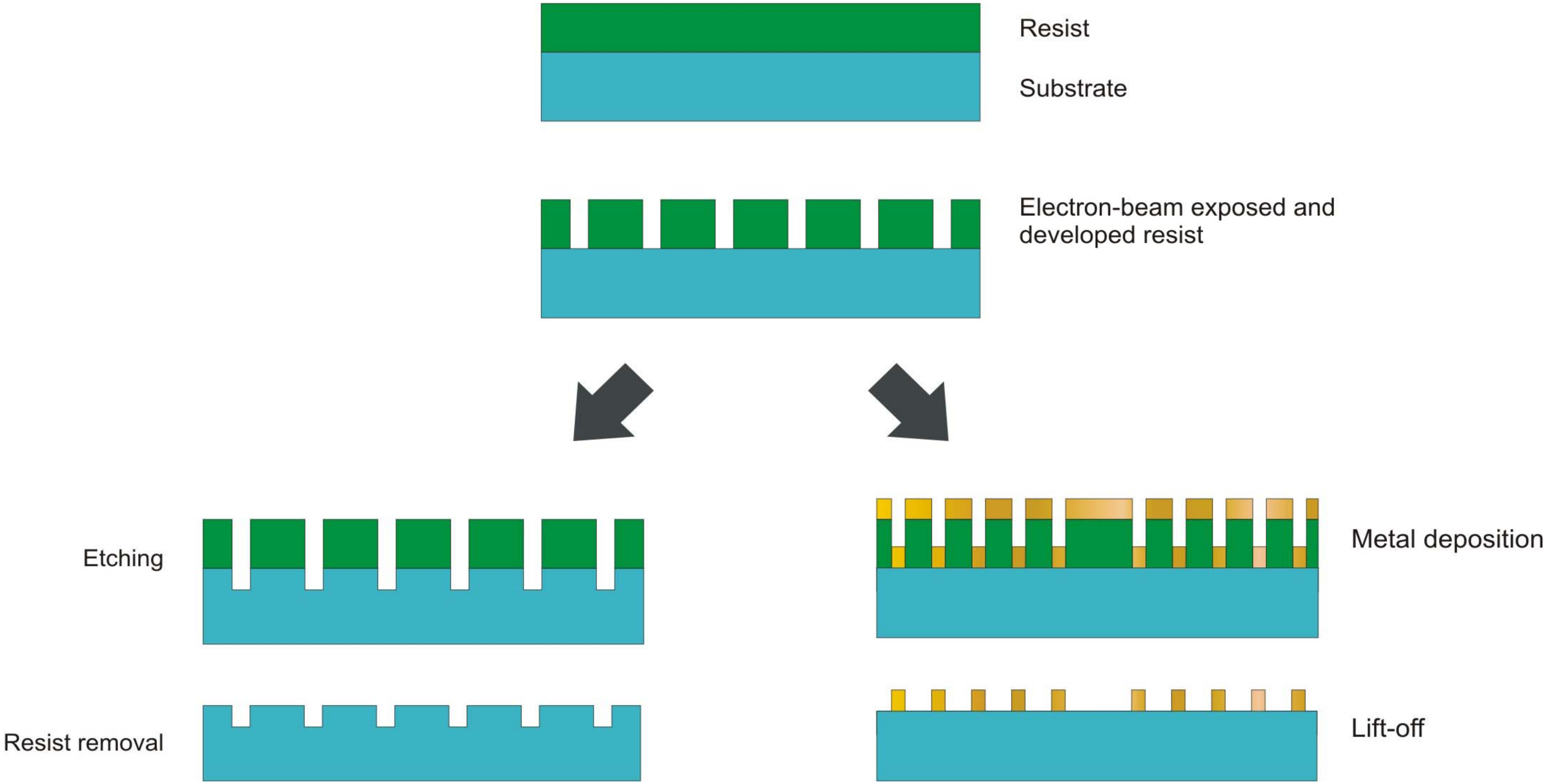
- Subwavelength (nm-scale) patterning
- High precision
- High throughput / Low cost
- Reproducibility
- Robustness
- Flexibility

Performance:

- Uniformity
- Low roughness (loss issue)



LITHOGRAPHIC PATTERNING



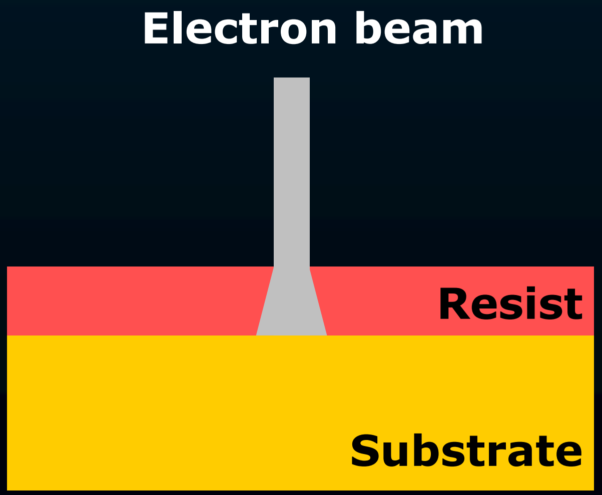
FABRICATION TECHNIQUES

High (100- or sub-100 nm) Resolution

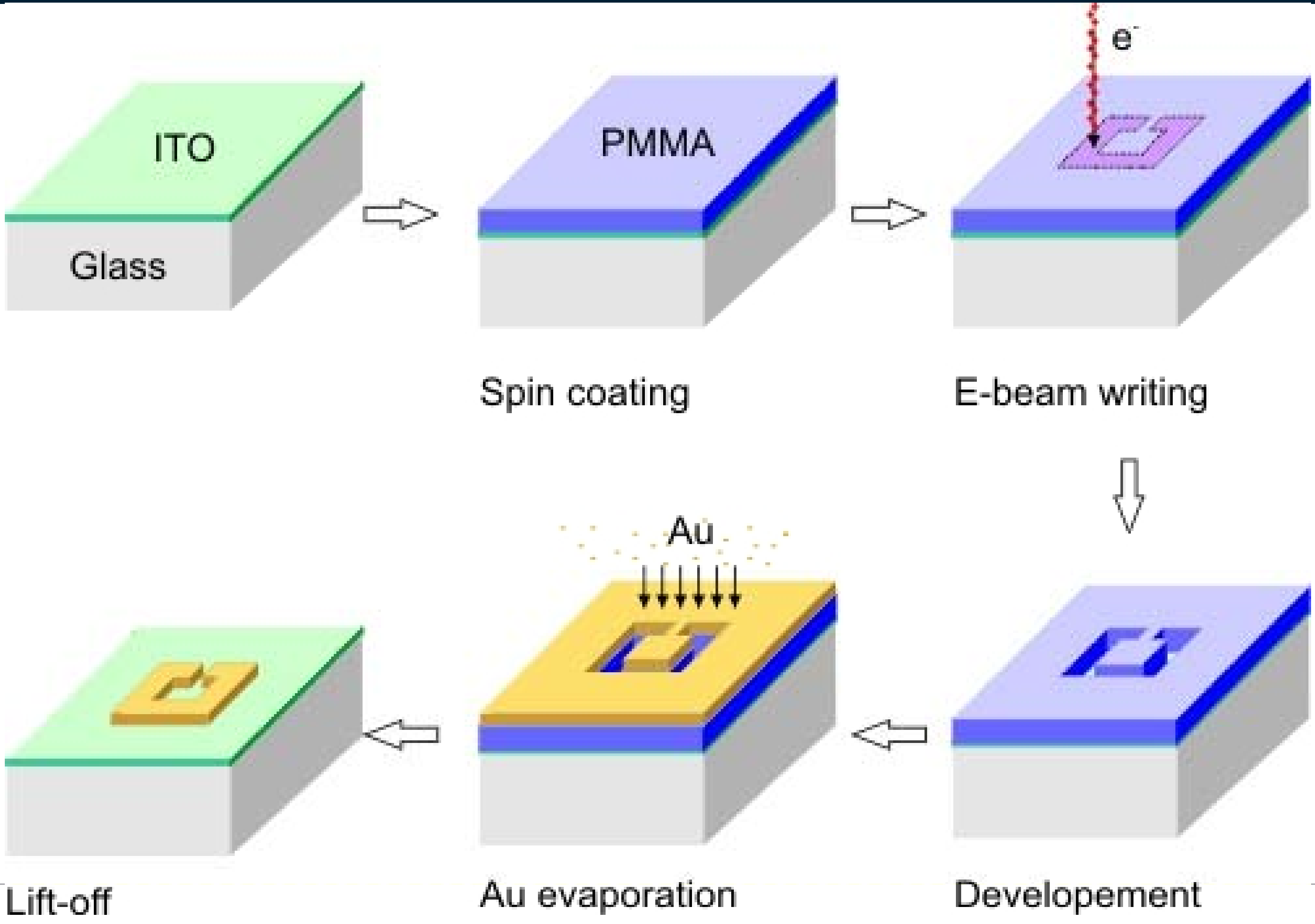
- Electron Beam Lithography

- High resolution
- Flexible

- *Serial / Small areas / Low throughput*
- *Time-consuming / High cost*

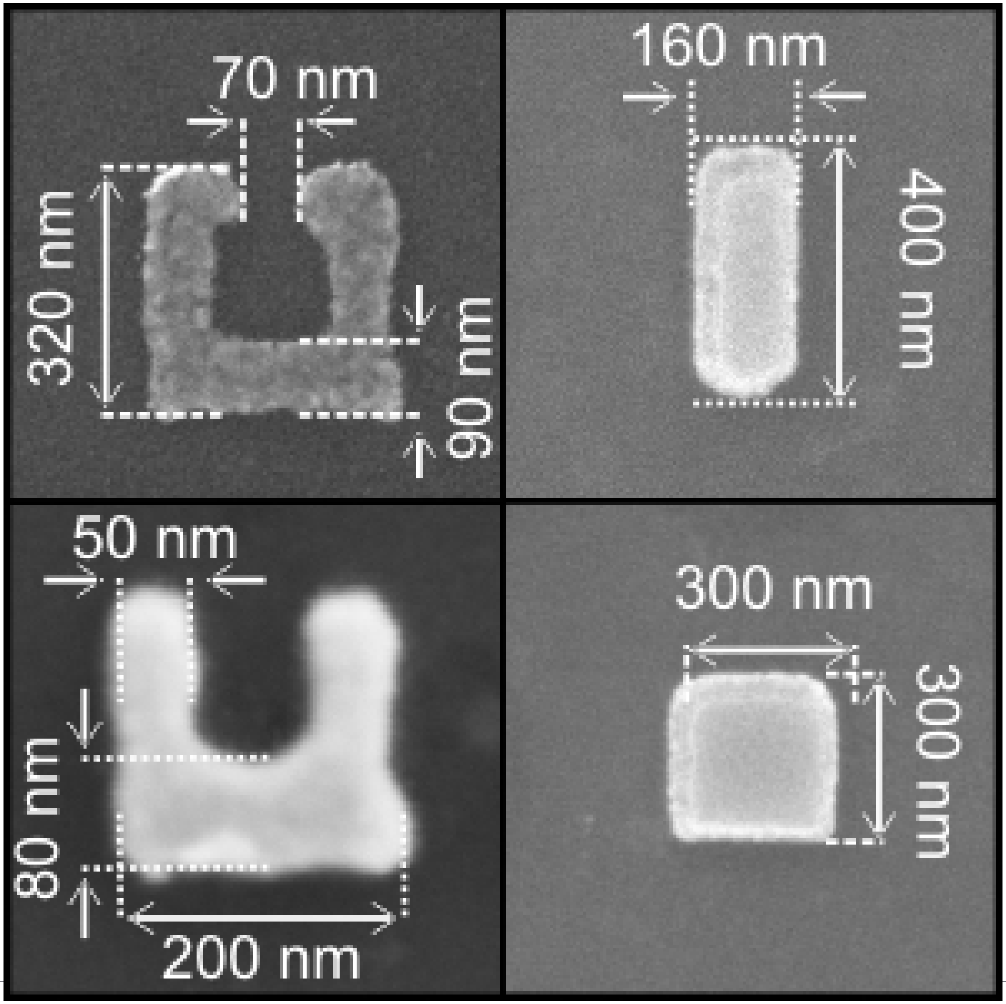


EBL FABRICATION



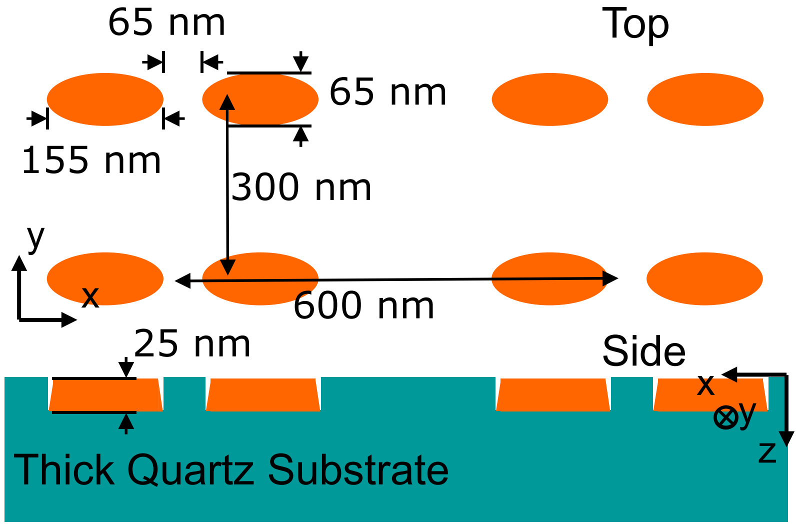
From http://www.aph.uni-karlsruhe.de/wegener/
Group of Martin Wegener

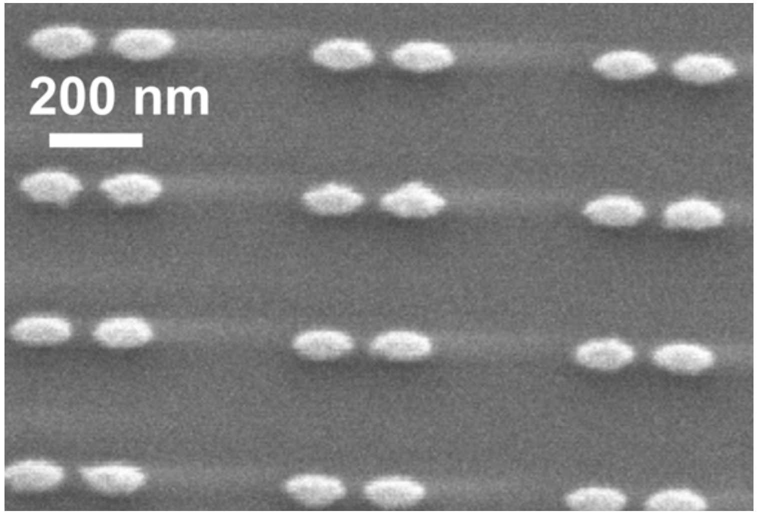
EBL FABRICATION

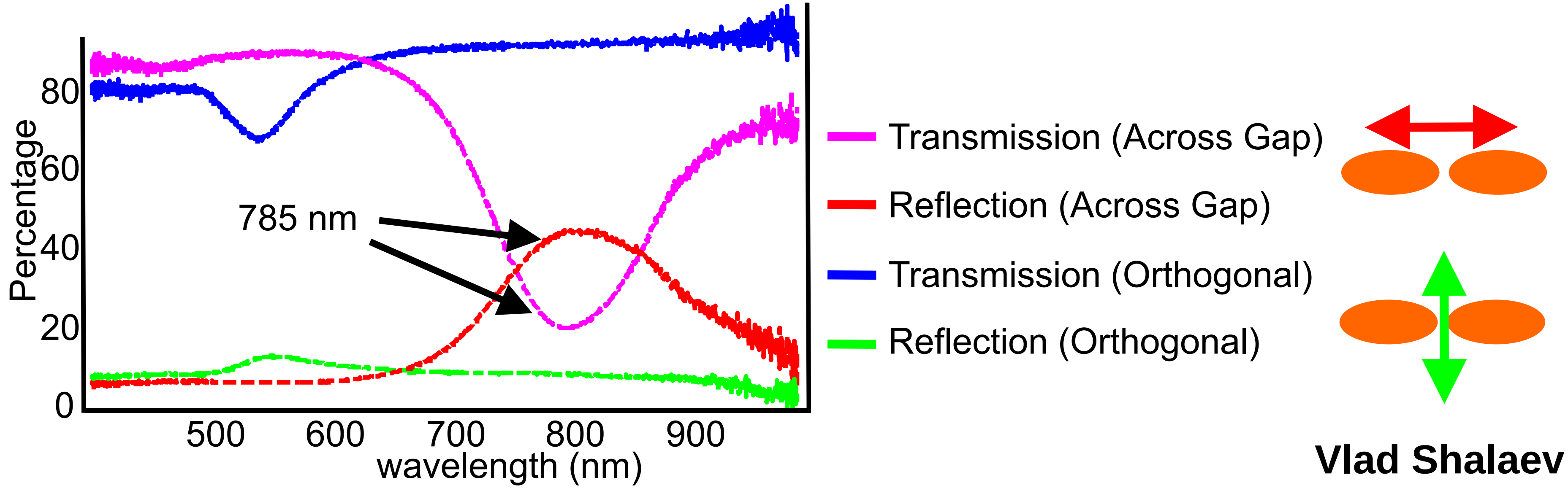


From http://www.aph.uni-karlsruhe.de/wegener/
Group of Martin Wegener

EXAMPLE: NANOANTENNAE

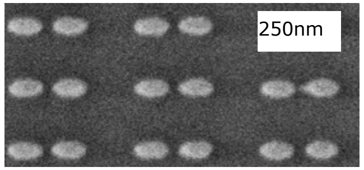




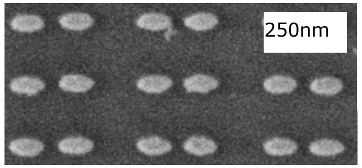


Vlad Shalaev

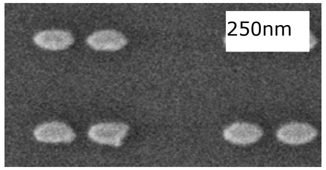
NANOANTENNAE SAMPLES



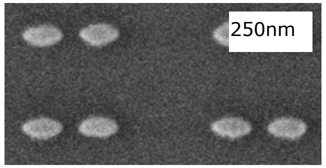
G1: 110 / 55 / 30 / 200 / 400



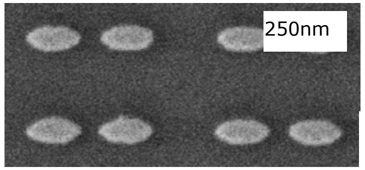
G2: 110 / 55 / 40 / 200 / 400



G3: 120 / 70 / 40 / 300 / 600

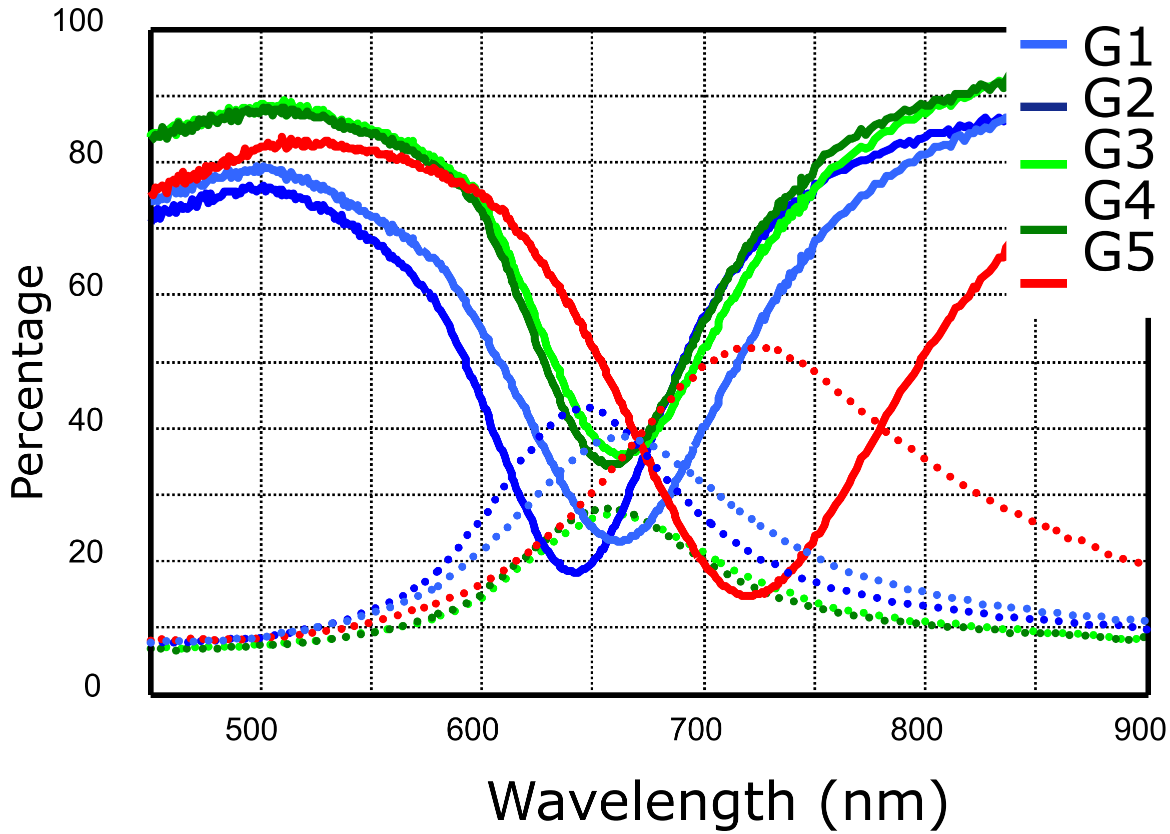


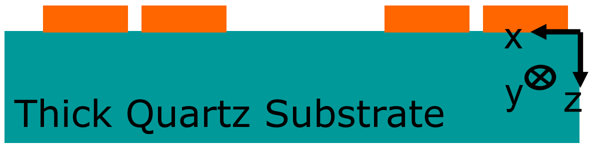
G4: 120 / 70 / 50 / 300 / 600



G5: 160 / 80 / 55 / 300 / 600

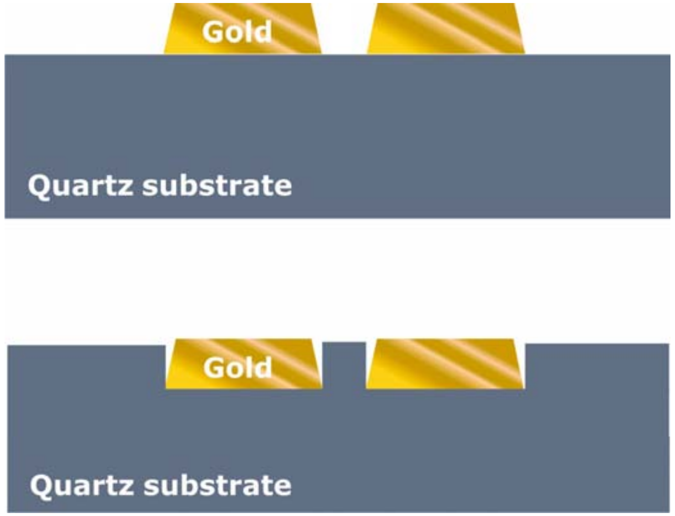
X polarized before dielectric

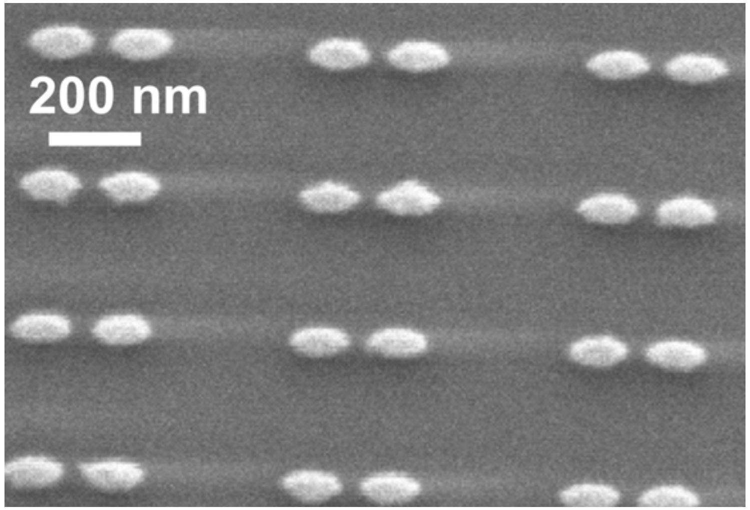


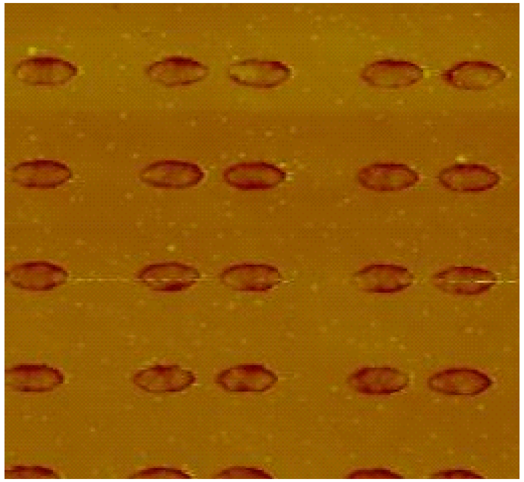


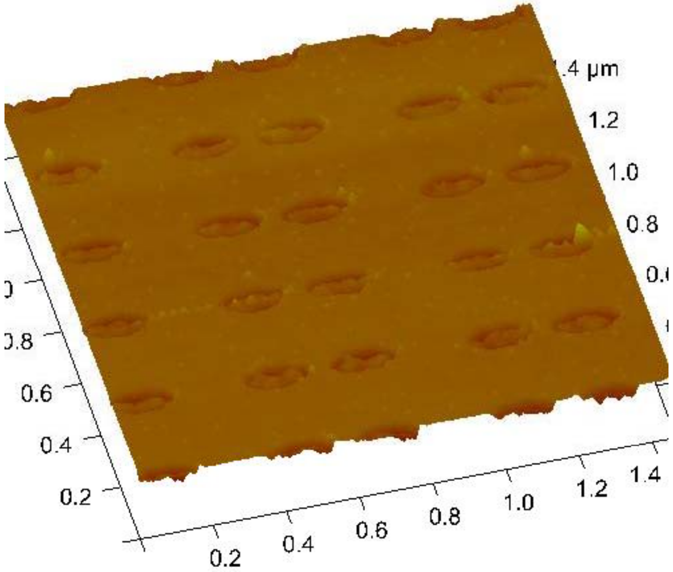
Bakker et al, OE 15, 13682 (2007),
Bakker et al, APL 92, 043101 (2008), Liu, et al, Metamaterials (2008)

E-BEAM BASED FABRICATION





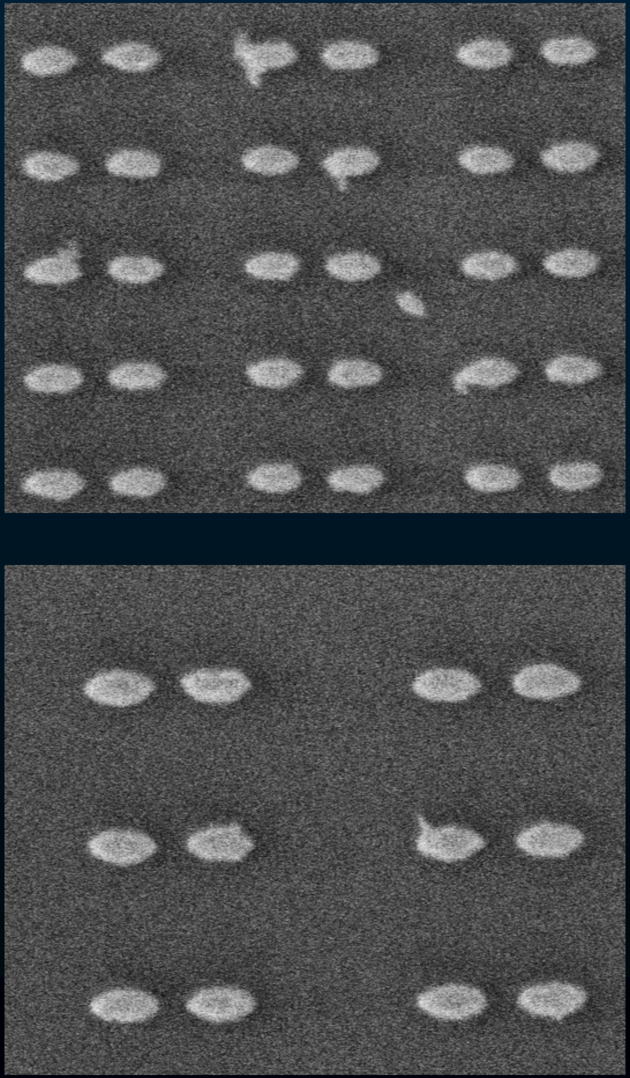




E-BEAM BASED FABRICATION

- Technology
  - High quality
  - Flexible
  - High cost
  - *Small gaps are hard to reproduce'*

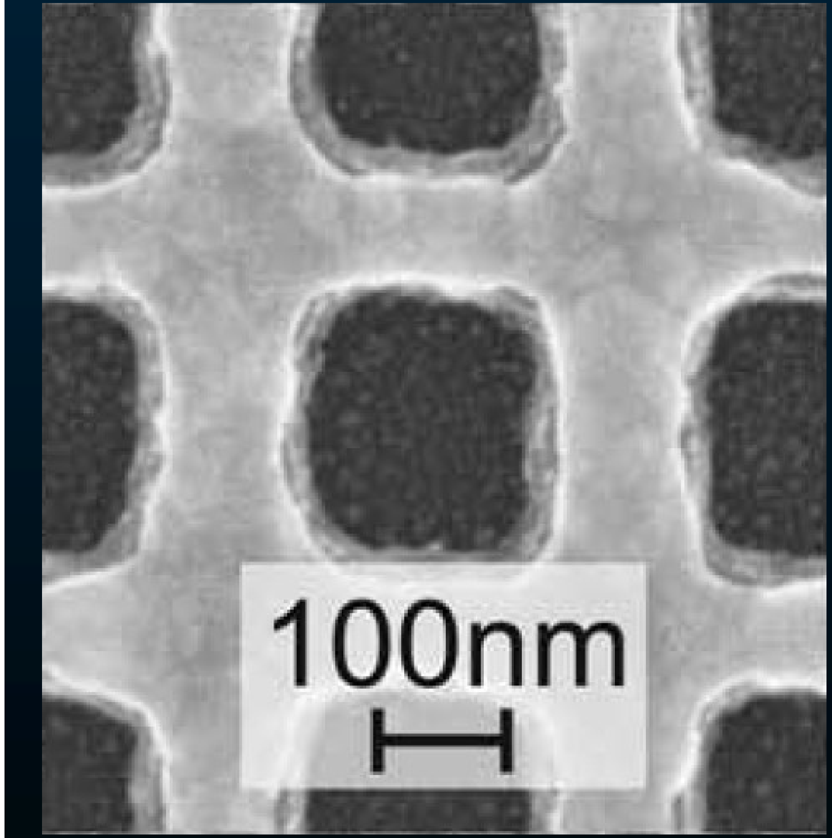
- Chemical methods

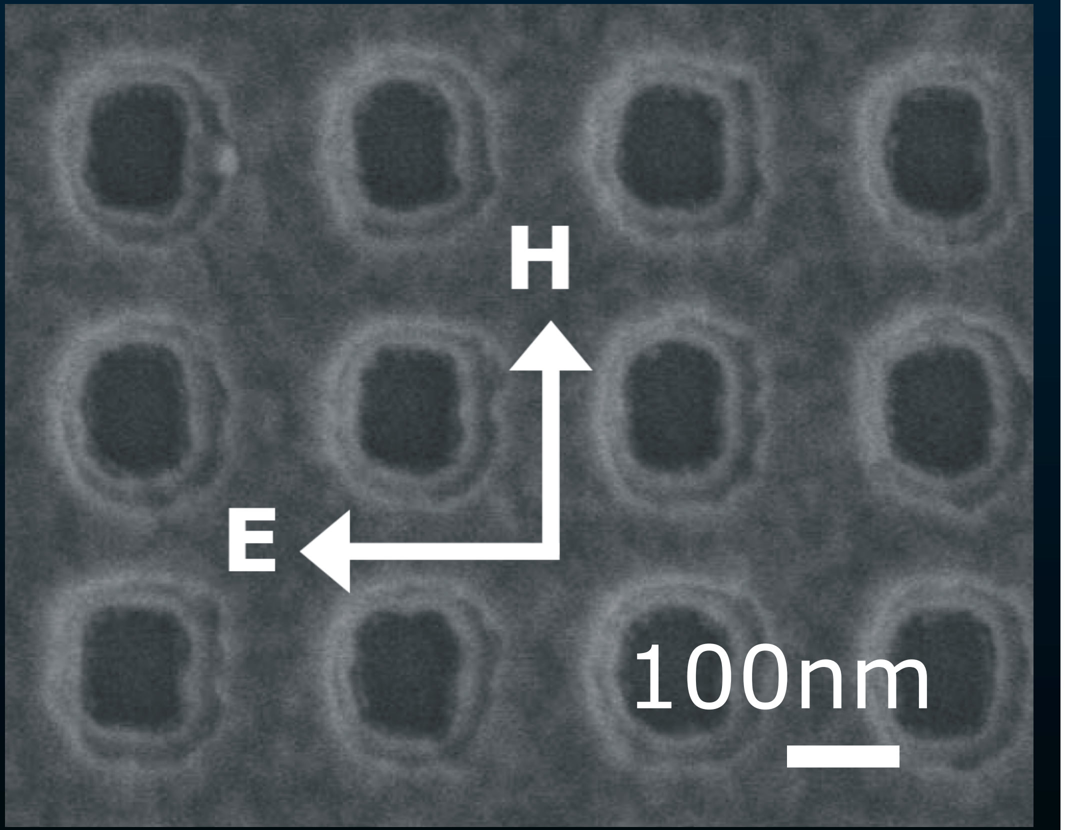


EBL FABRICATION

$n' \cong -0.6$ **$\lambda = 780$ nm**

$n' \cong -0.9$ **$\lambda = 770$ nm**
$n' \cong -1.1$ **$\lambda = 810$ nm**





Karlsruhe – group of Martin Wegener
Purdue – group of Vlad Shalaev

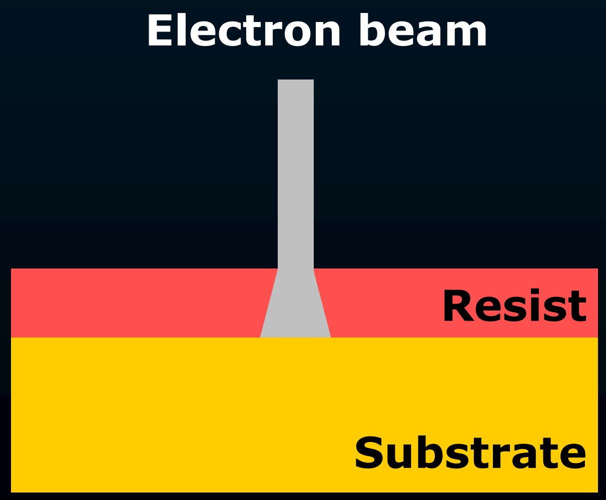
FABRICATION TECHNIQUES

High (100- or sub-100 nm) Resolution

- Electron Beam Lithography

- High resolution
- Flexible

- *Serial / Small areas / Low throughput*
- *Time-consuming / High cost*



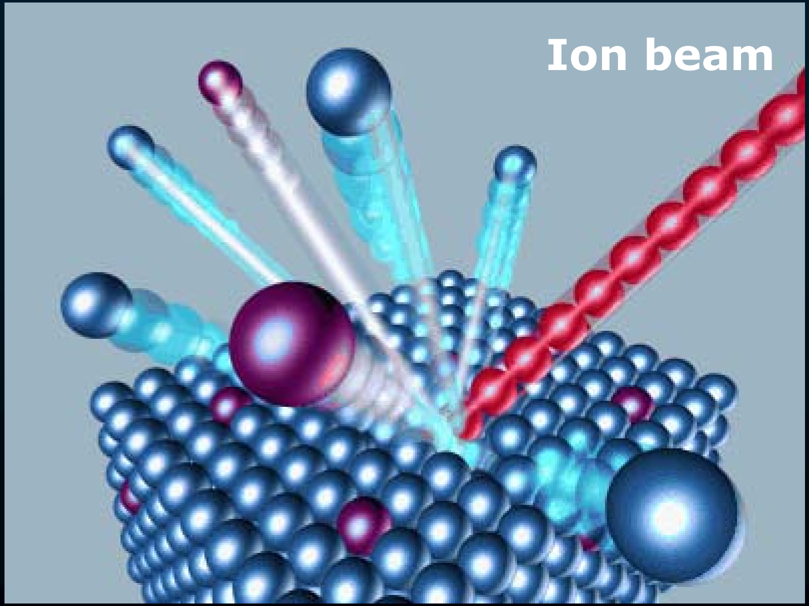
FABRICATION TECHNIQUES

High (100- or sub-100 nm) Resolution

- Focused Ion Beam technique

- Rapid prototyping

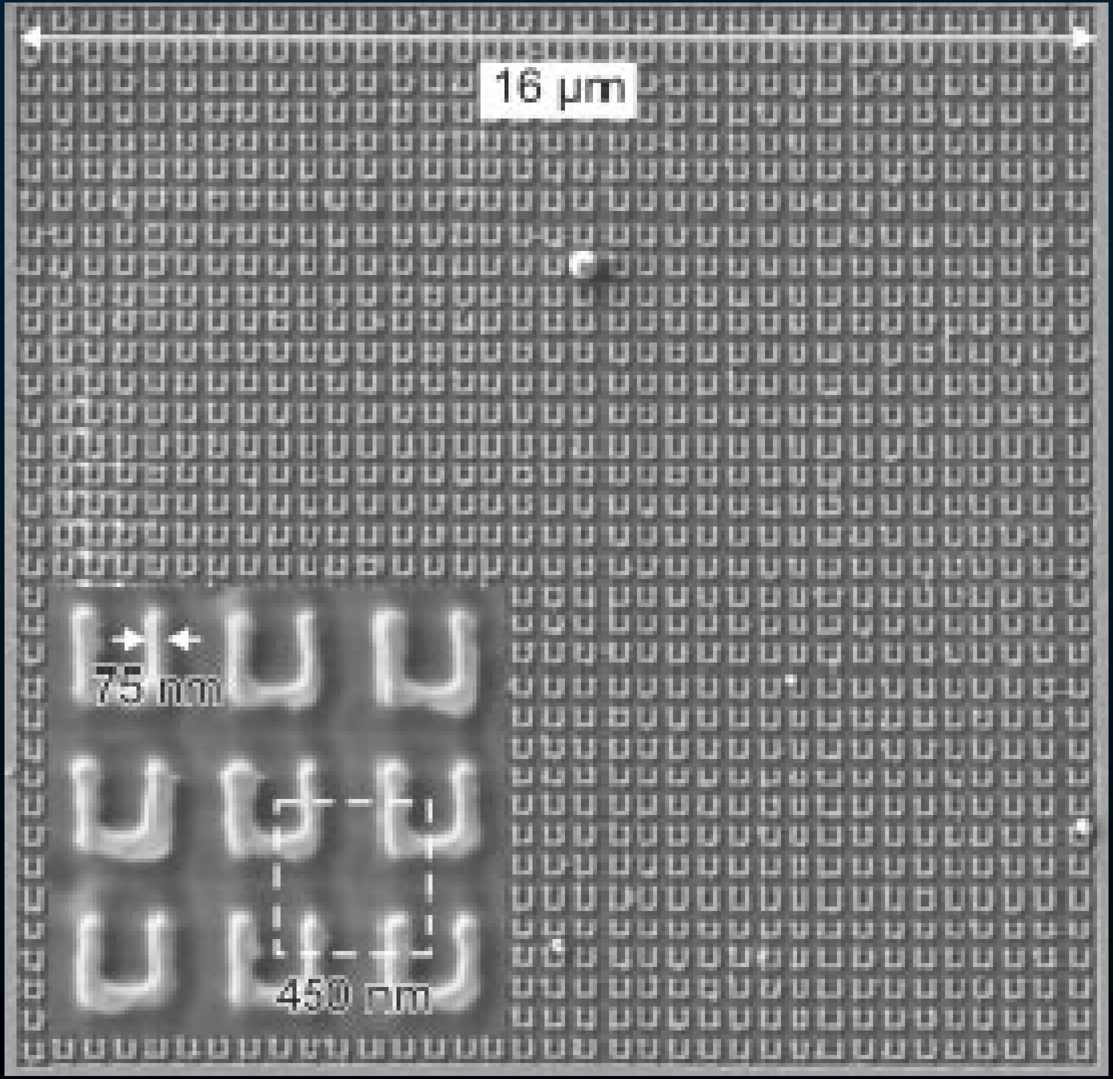
- *Complex*
- *Material limitations*



From http://epswww.unm.edu/iom/SIMSgear.html
Institute of Meteoritics

FOCUSED ION BEAM TECHNIQUE

Negative μ
λ = 2.4 µm



C. Enkrich, et. al., Advanced Materials 17, 2547 (2005)

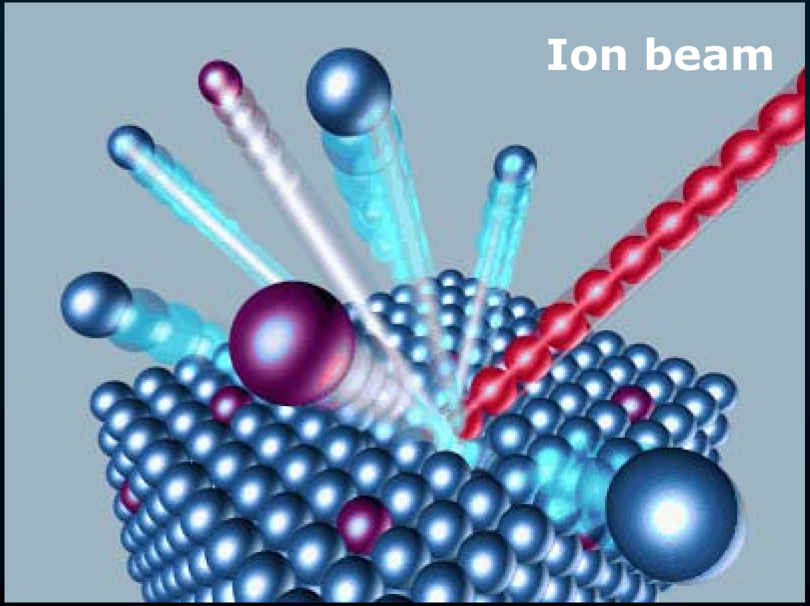
FABRICATION TECHNIQUES

High (100- or sub-100 nm) Resolution

- Focused Ion Beam technique

- Rapid prototyping

- *Complex*
- *Material limitations*



From http://epswww.unm.edu/iom/SIMSgear.html
Institute of Meteoritics

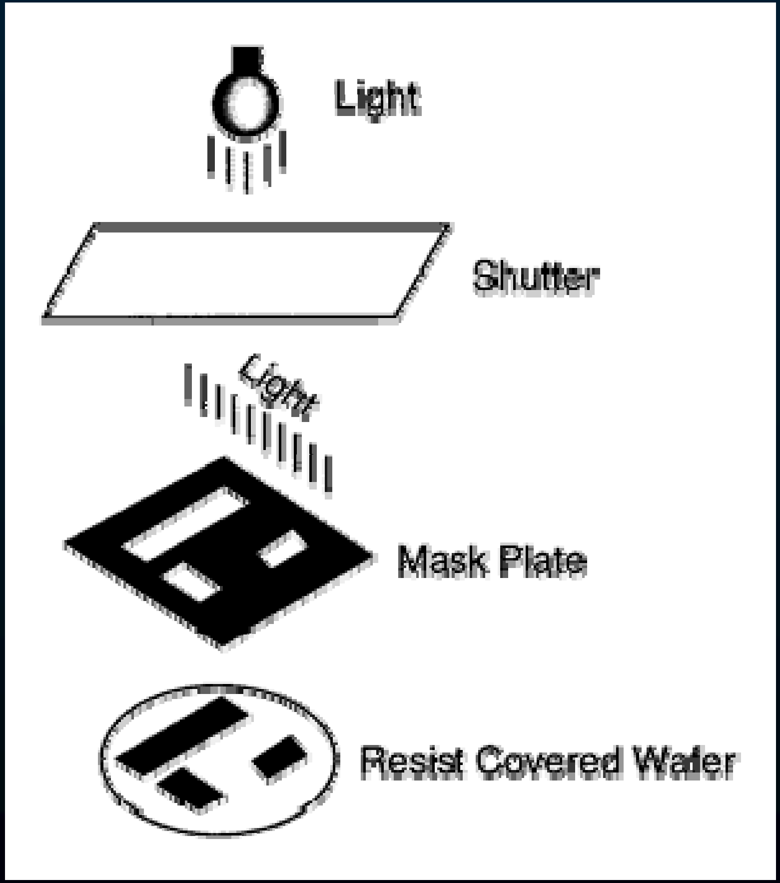
FABRICATION TECHNIQUES

Large-Scale

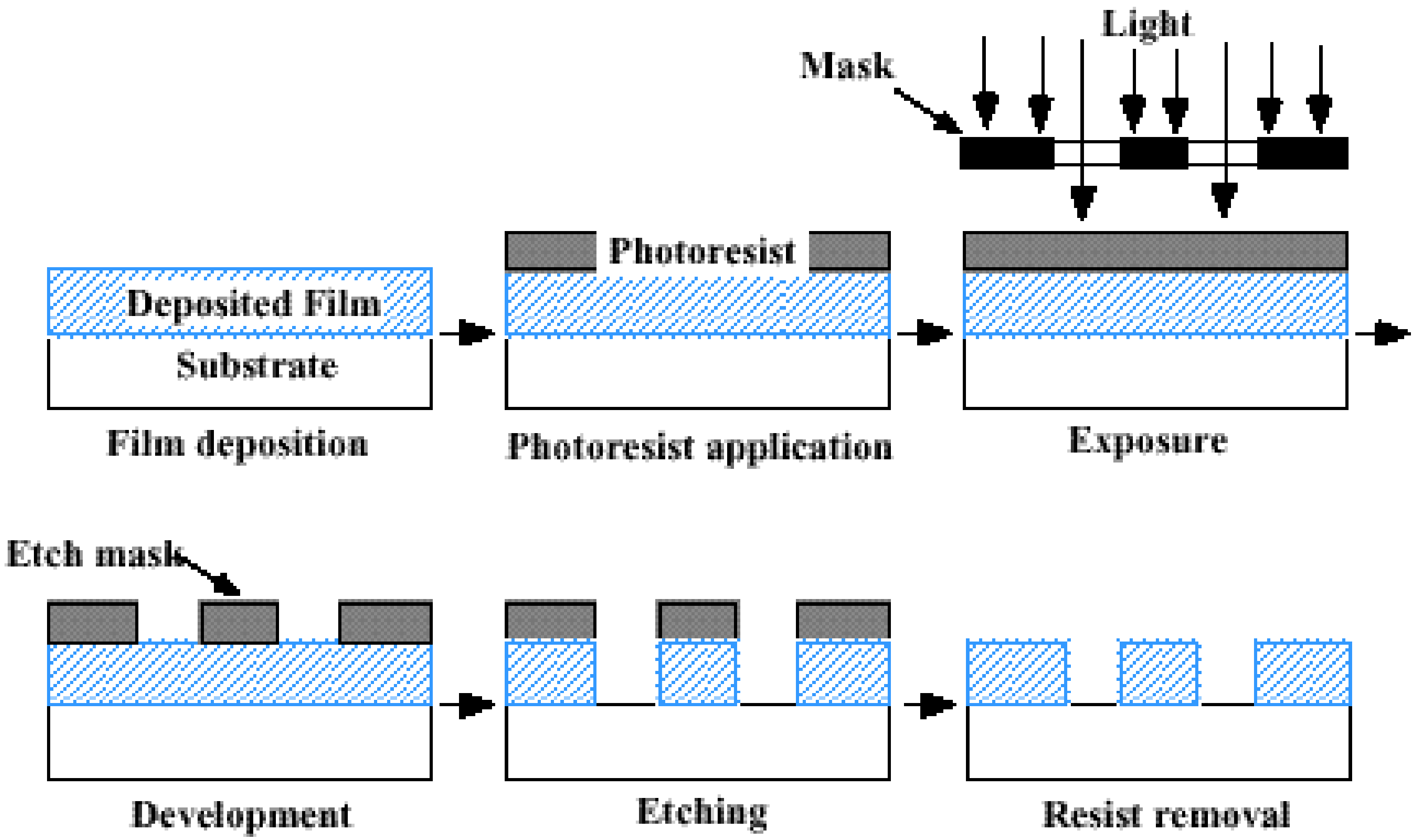
- Photolithography
- Interference Lithography

- Uniformity
- Large-scale
- Possible stacking

- *Low resolution*
- *Not total pattern flexibility*

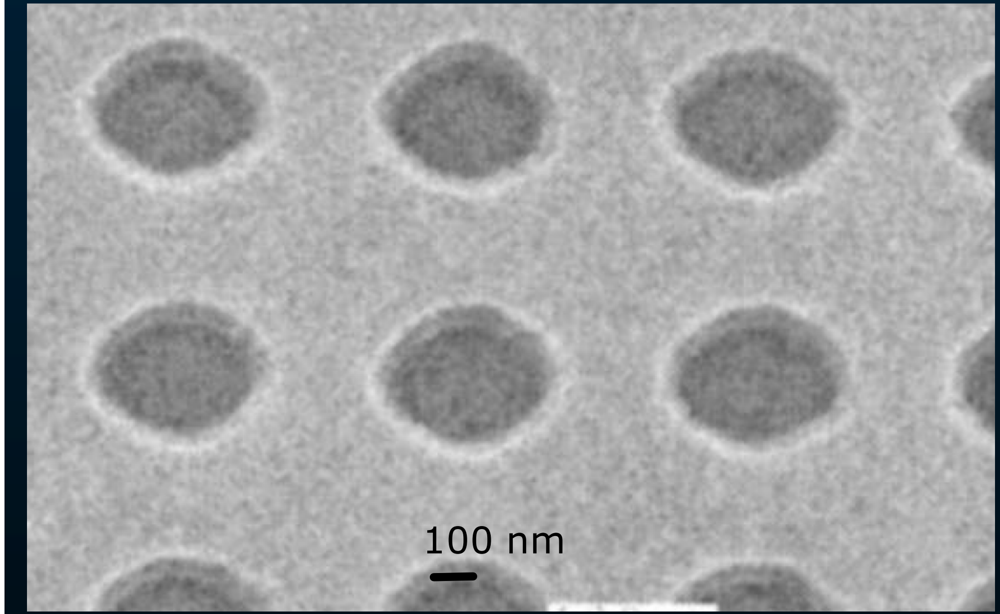


PHOTOLITHOGRAPHY FABRICATION

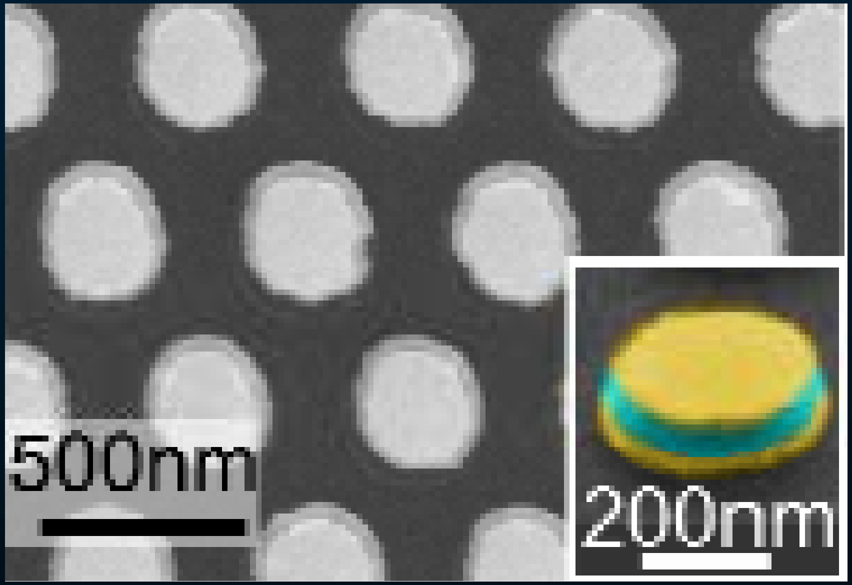


INTERFERENCE LITHOGRAPHY

$n' \cong - -4$ **λ = 1.8 μm**



Negative μ **λ = 1.2 μm**

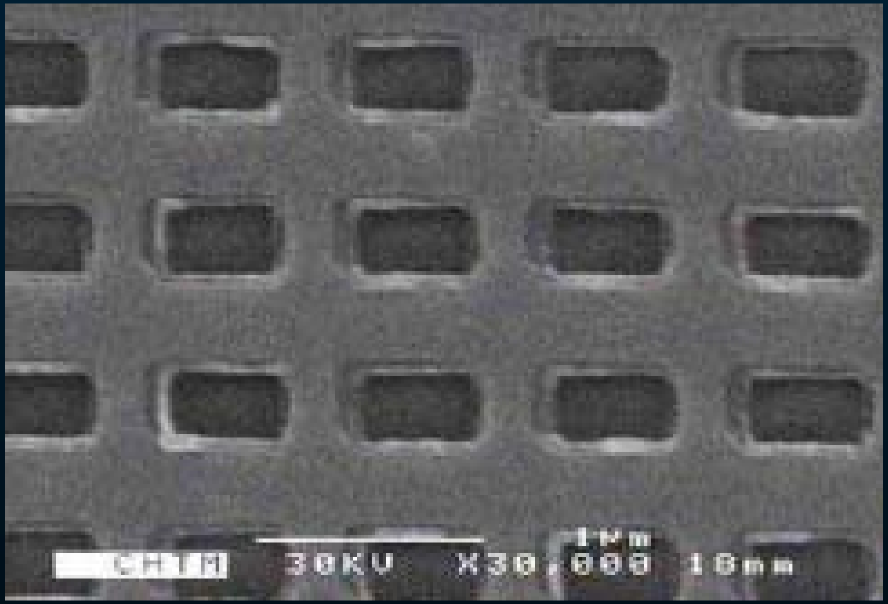


S. Zhang, et. al., Phys. Rev. Lett. 95, 137404-4 (2005)
N. Feth, et. al., Optics Express 15, 501 (2006)

INTERFERENCE LITHOGRAPHY

Negative *n'*

λ = 1.64 – 1.98 µm



Z. Ku, S. R. J. Brueck, Optics Express (2007)

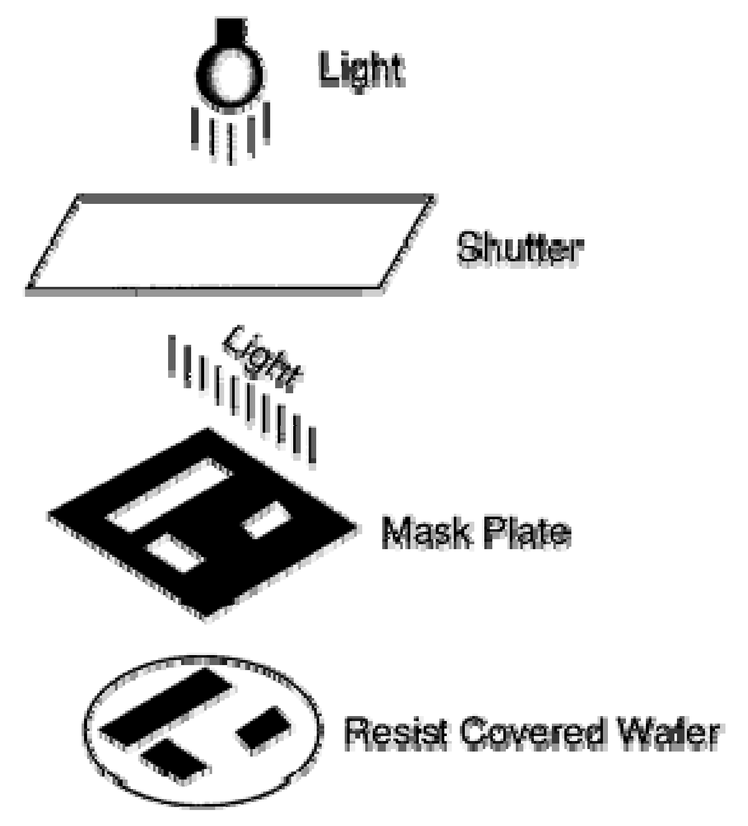
FABRICATION TECHNIQUES

Large-Scale

- Photolithography
- Interference Lithography

- Uniformity
- Large-scale
- Possible stacking

- *Low resolution*
- *Not total pattern flexibility*

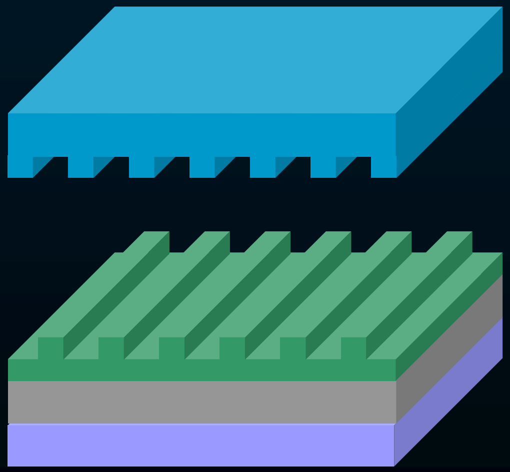


FABRICATION TECHNIQUES

High Resolution + Large-Scale

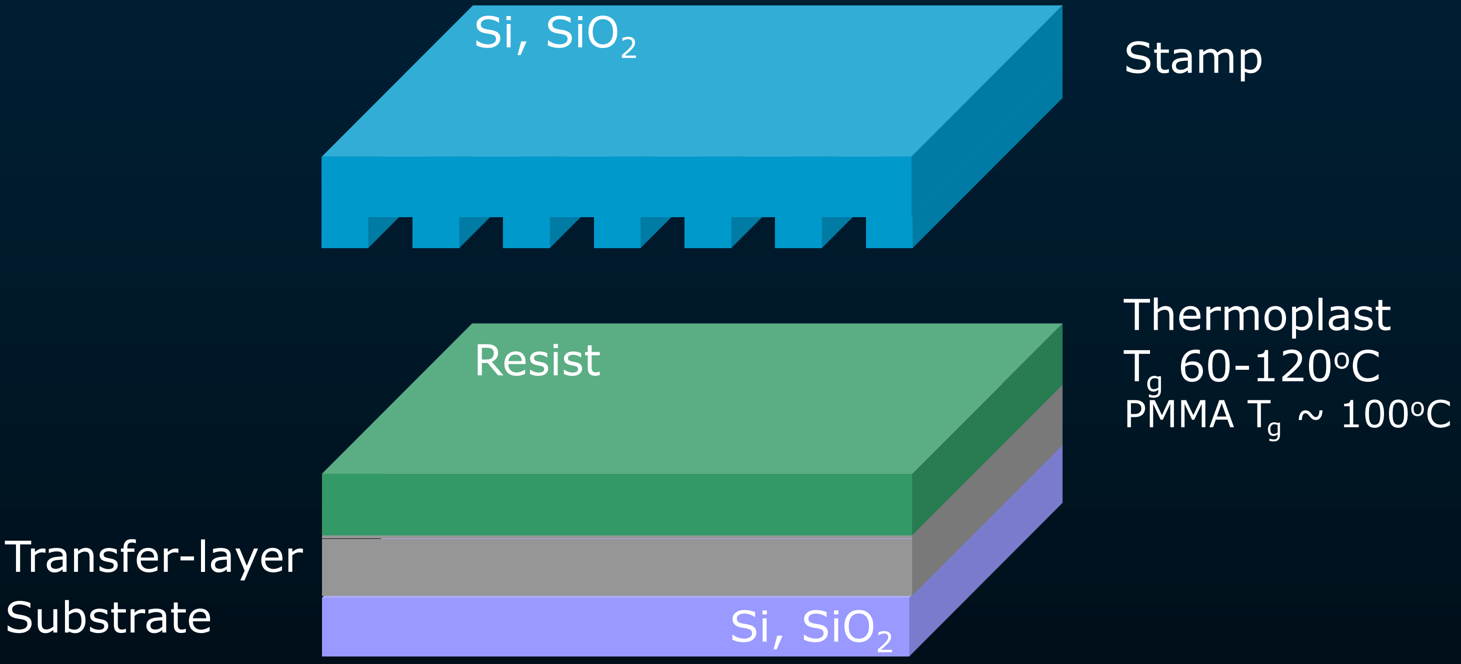
- Nanoimprint

- Unlimited resolution (given by the stamp)
- Planarization of the surface
- Parallel / wafer-scale fabrication
- Simple and cheap process



S.Y. Chou, P.R. Krauss, P.J. Renstrom, Nanoimprint lithography, J. Vac. Sci. Technol. B 14, 4129 (1996)

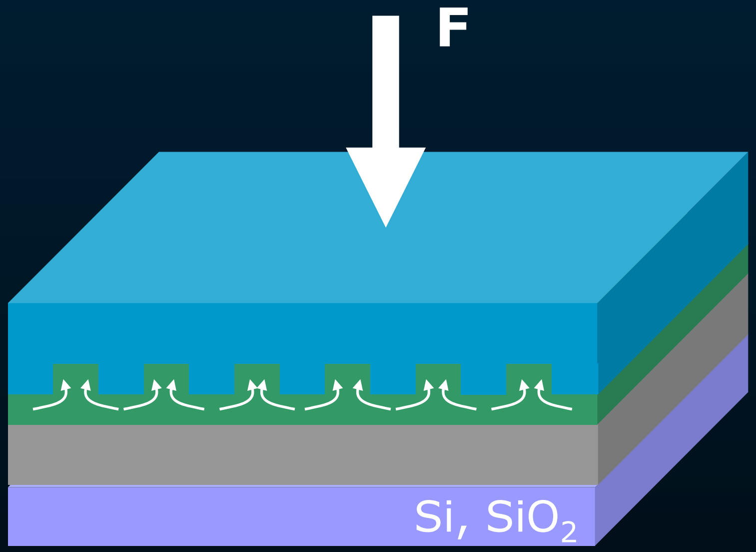
NIL FOR POLYMER MOLDING



Courtesy of A. Kristensen

- Hard stamp
- Substrate with a polymer layer

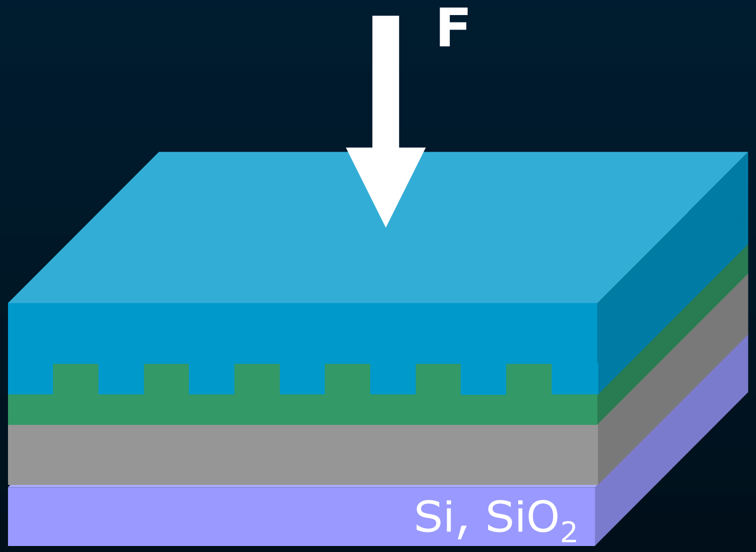
NIL FOR POLYMER MOLDING



Courtesy of A. Kristensen

- Heat
- Pressure

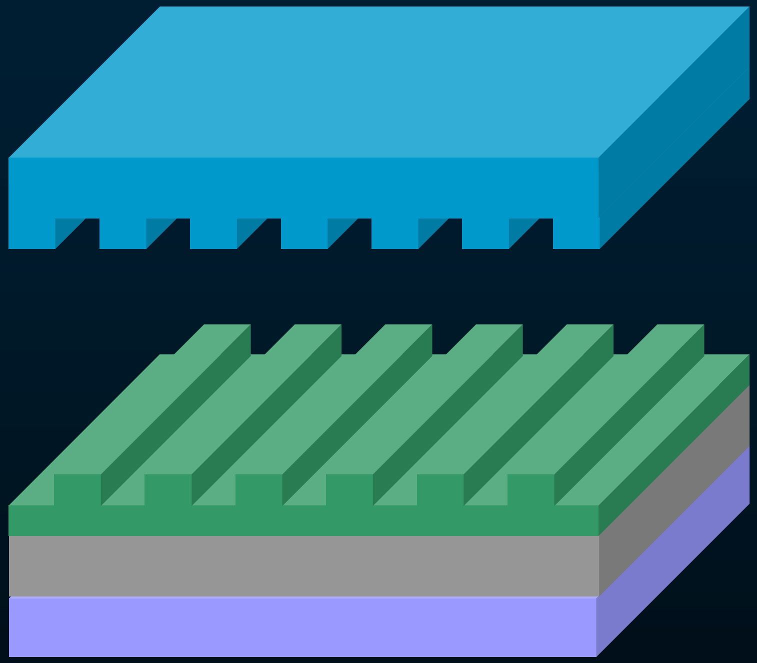
NIL FOR POLYMER MOLDING



Courtesy of A. Kristensen

- Cool down
- Pressure

NIL FOR POLYMER MOLDING



Courtesy of A. Kristensen

- Resist hardened
- Separate

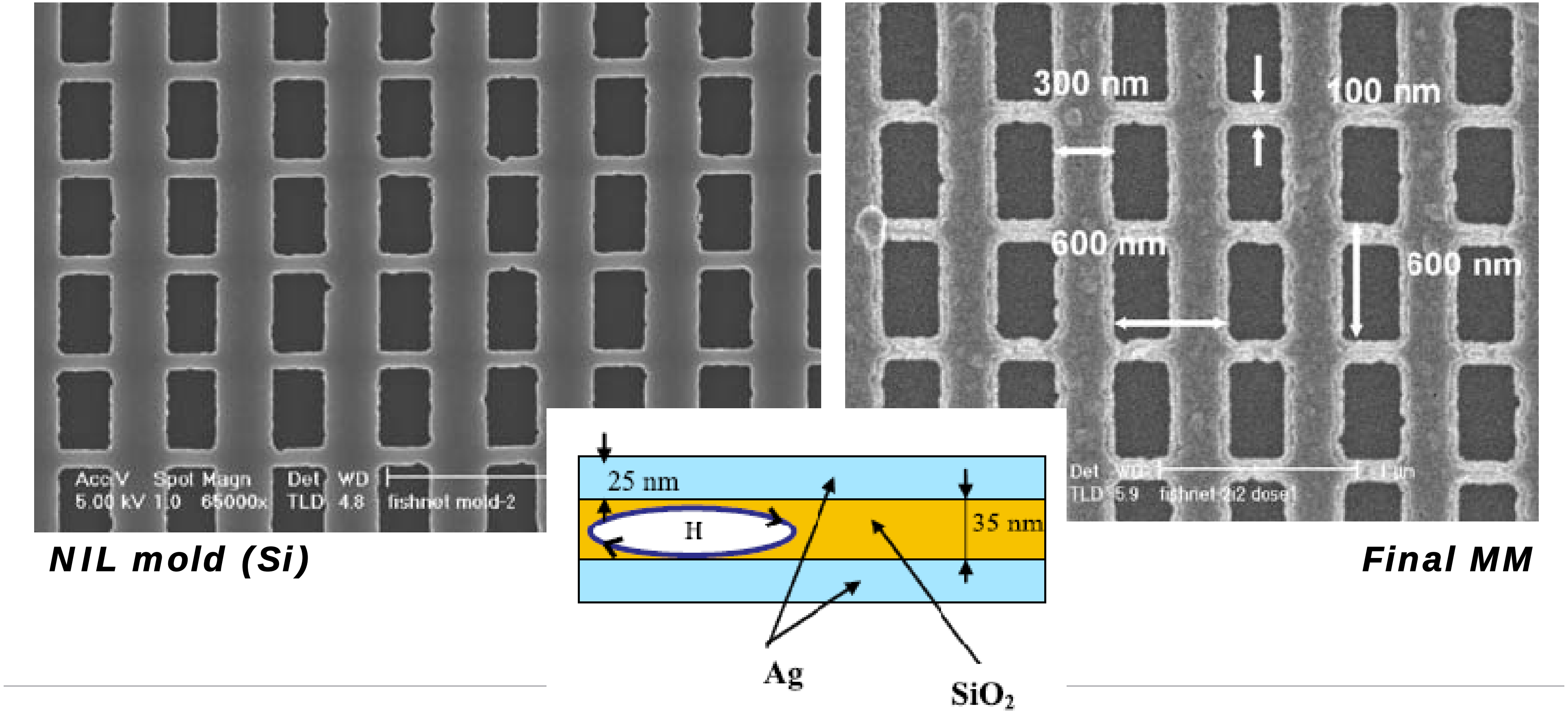
NIL FOR POLYMER MOLDING

Advantages

- Unlimited resolution (given by the stamp fabrication)
- Paralel fabrication process: 1 sample processing at a time, containing several single chips
- Wafer-scale fabrication
- Simple and cheap process

NANOIMPRINT FABRICATION

Negative ε, negative *μ*, negative *n'* ≅ - 1.6 **λ = 1.7 μm**



NIL mold (Si)

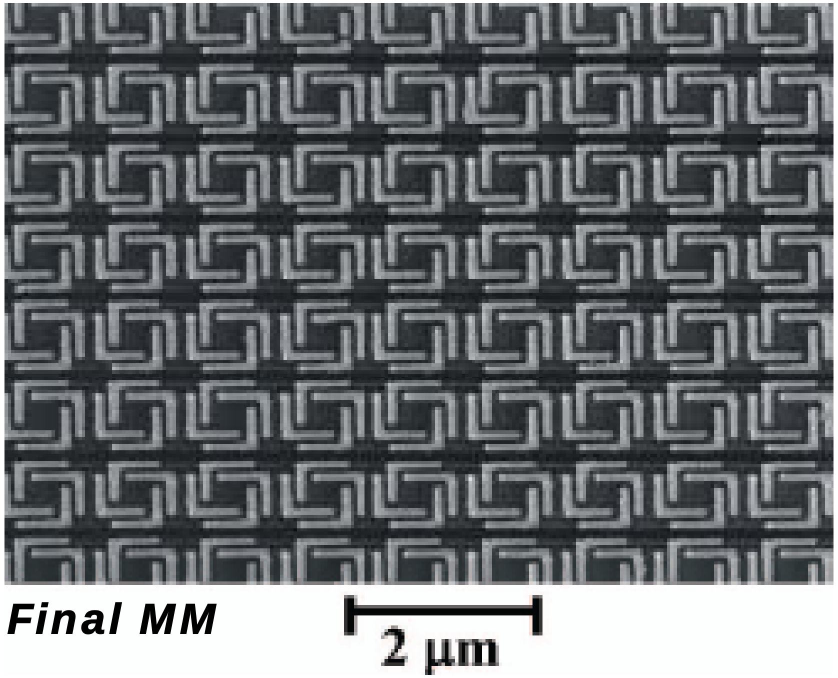
Final MM

W. Wu, E. Kim, E. Ponizovskaya, Z. Liu, Z. Yu, N. Fang, Y.R. Shen, A.M. Bratkovsky, W. Tong, C. Sun, X. Zhang, S.-Y. Wang, R.S. Williams, Appl. Phys. A 87, 147-150 (2007)

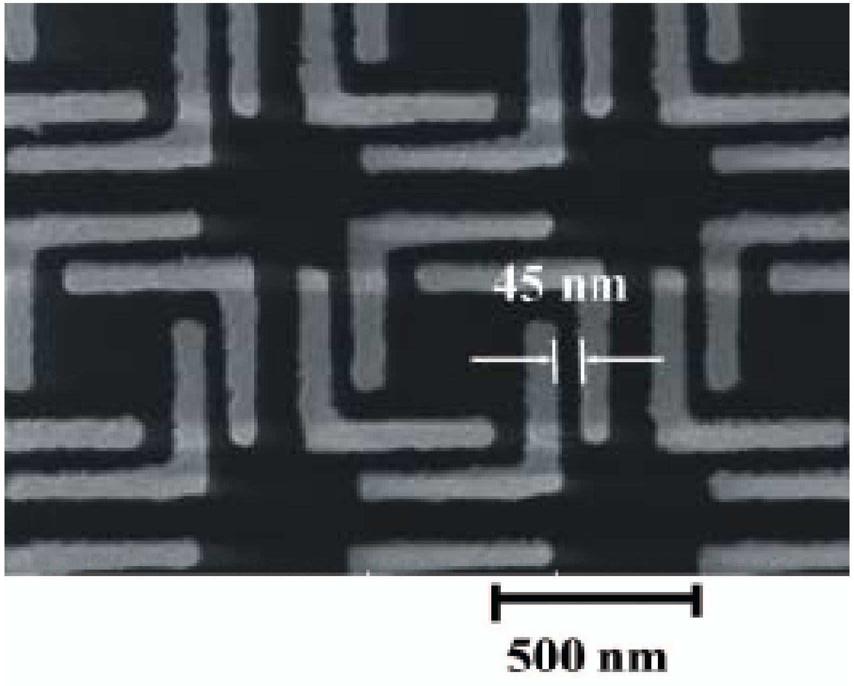
NANOIMPRINT FABRICATION

Negative ε **λ = 3.7 μm**

Magnetic resonance with negative *μ* **λ = 5.25 μm**



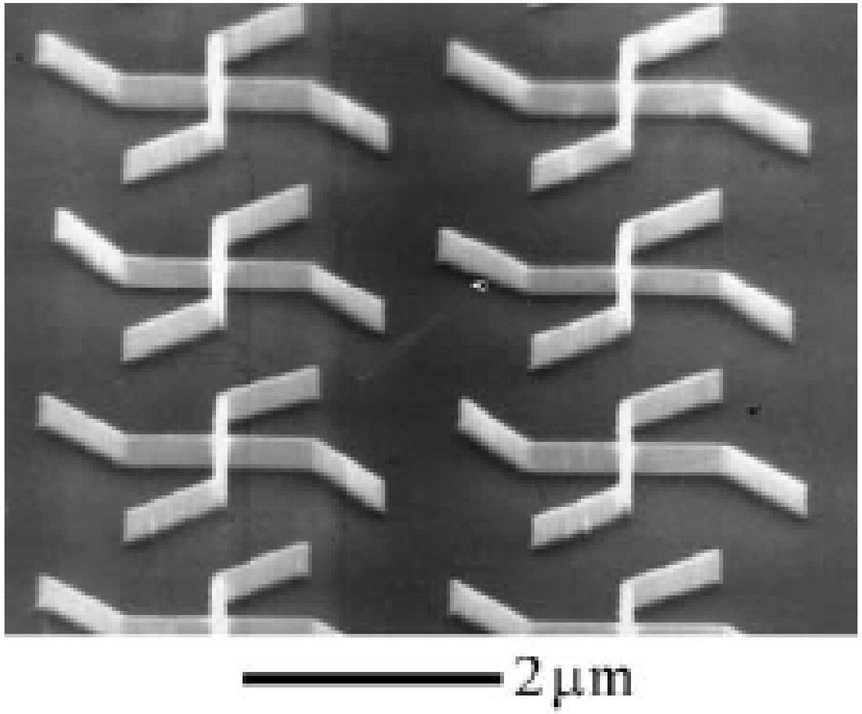
Final MM



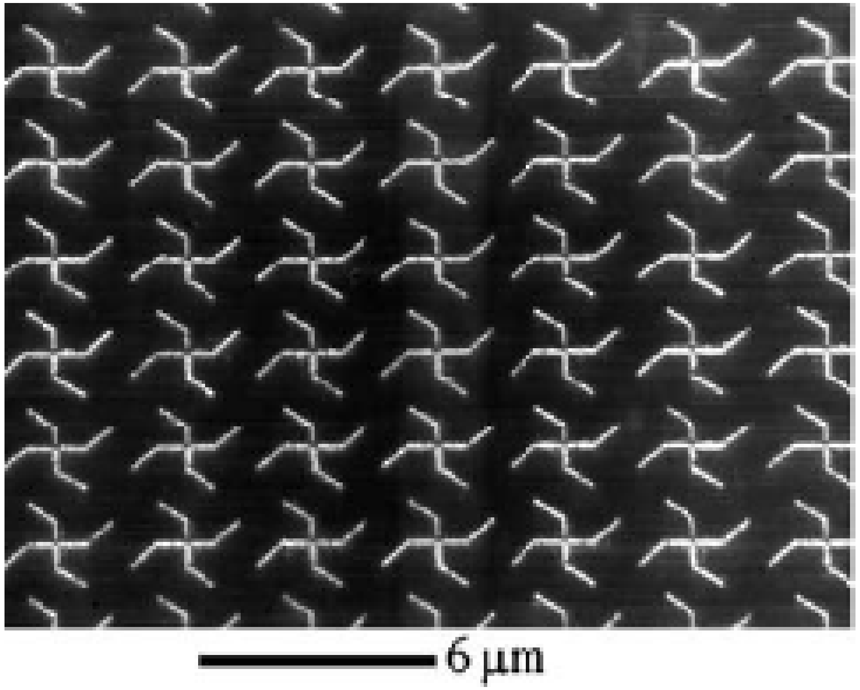
W. Wu, Z. Yu, S.-Y. Wang, R.B. Williams, Y. Liu, C. Sun, X. Zhang, E. Kim, R. Shen, N. Fang, Appl. Phys. Lett. 90, 063107 (2007)

NANOIMPRINT FABRICATION

Planar Chiral MMs for novel polarization effects studies
Room temperature NIL



Si template

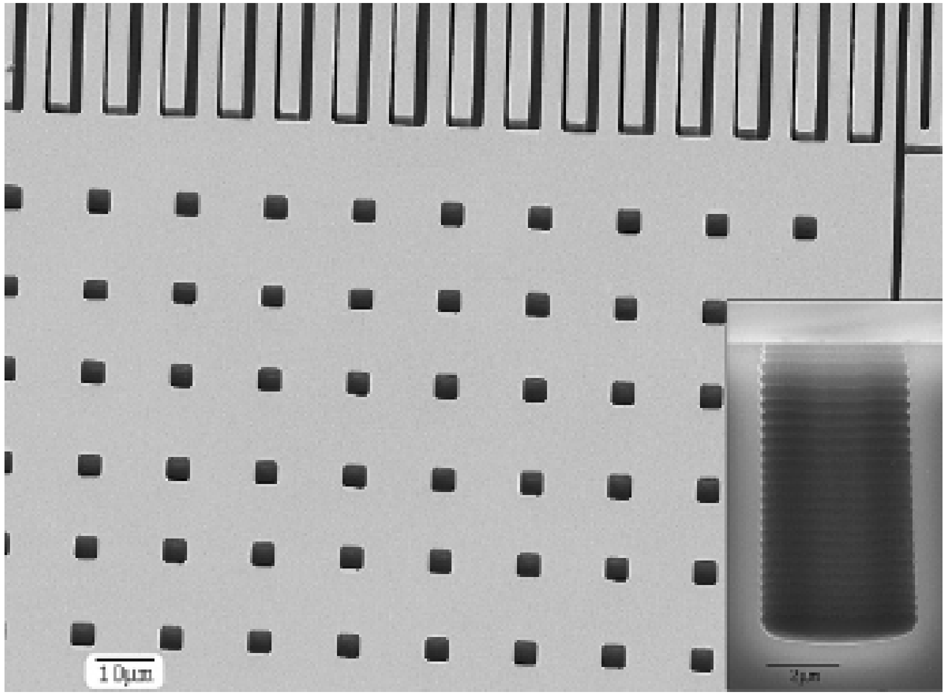


Final chiral MM

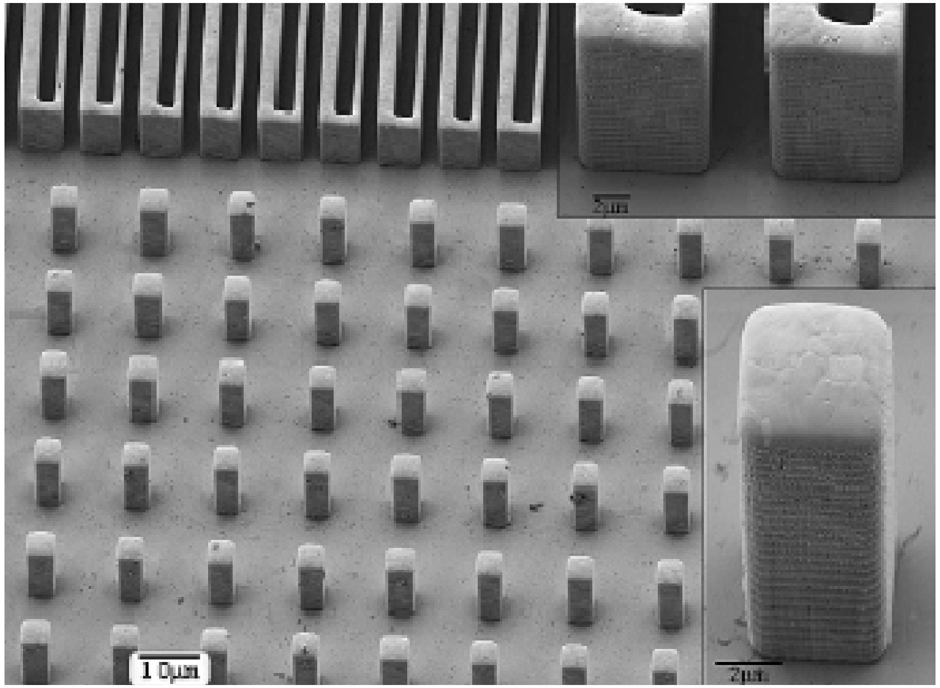
Y. Chen, J. Tao, X. Zhao, Z. Cui, A.S. Schwanecke, N.I. Zheludev, Microelectron. Eng. 78–79, 612 (2005)

DIRECT EMBOSSING

Direct, hot nanoimprinting into metals



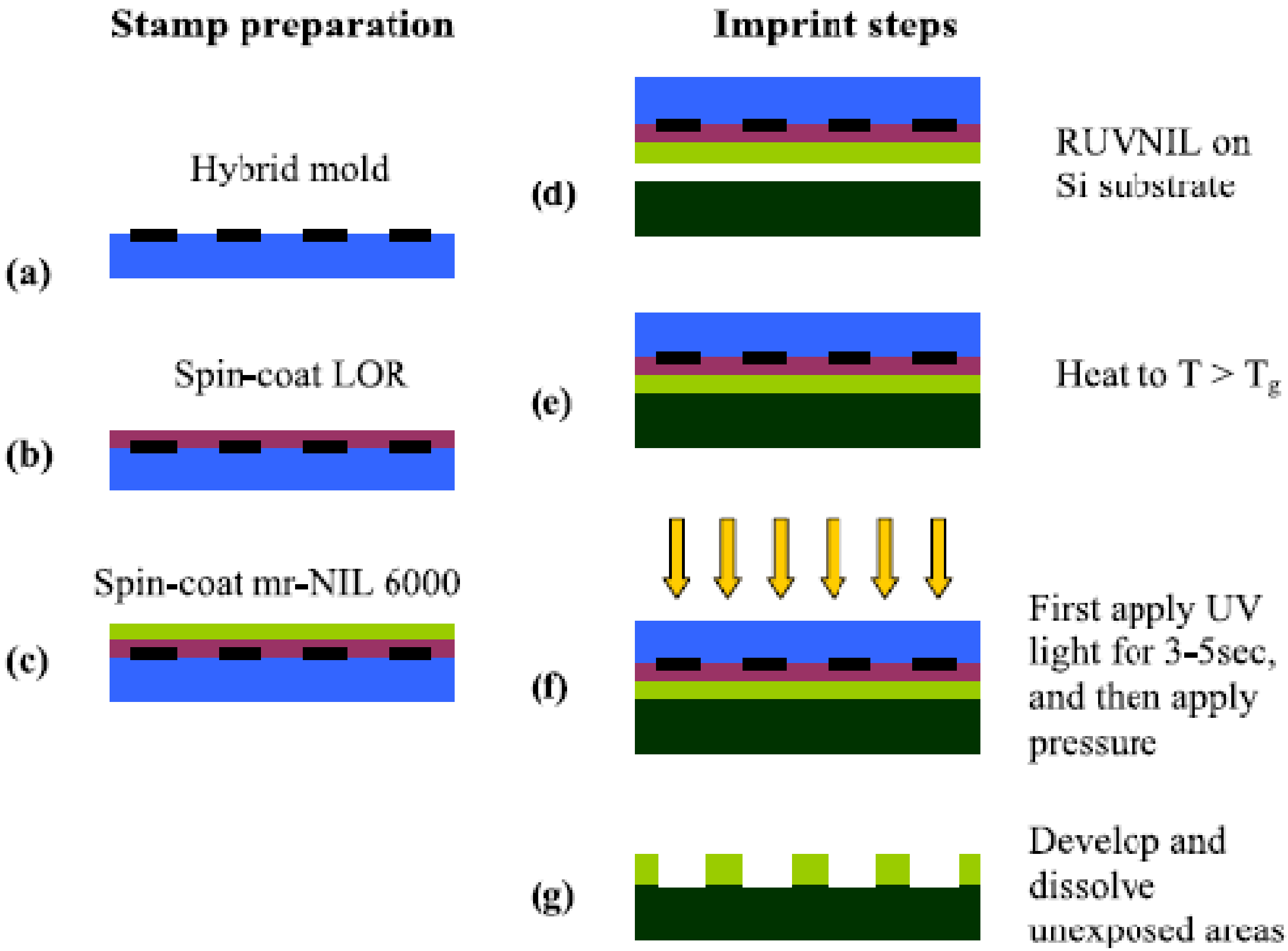
Si mold



Final Ag structure

S.W. Pang, T. Tamamura, M. Nakao, A. Ozawa, H. Masuda, J. Vac. Sci. Technol. B 16, 1145 (1998)
S. Buzzi, F. Robin, V. Callegari, J. F. Loffler, Microel. Engineering 85, 419 (2008)

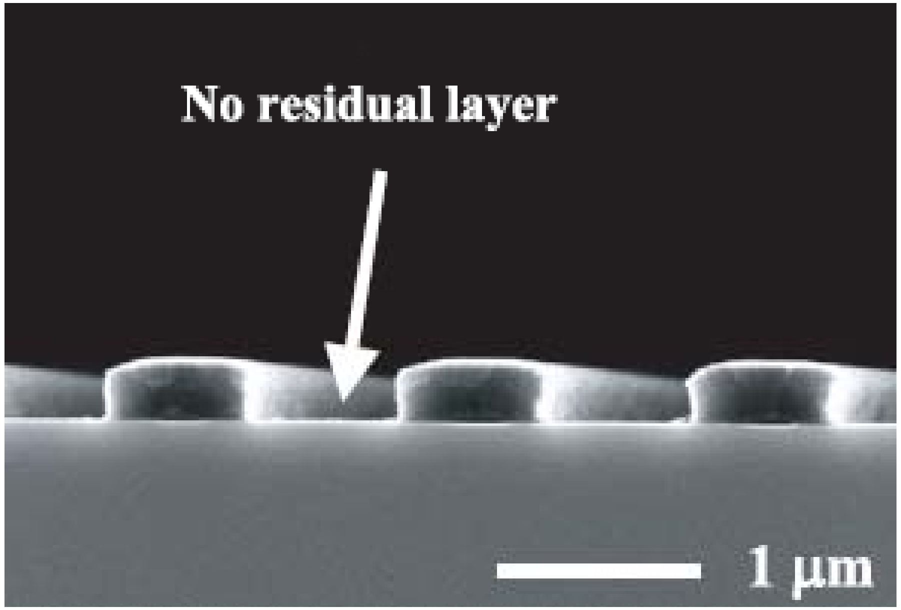
REVERSE-CONTACT NIL



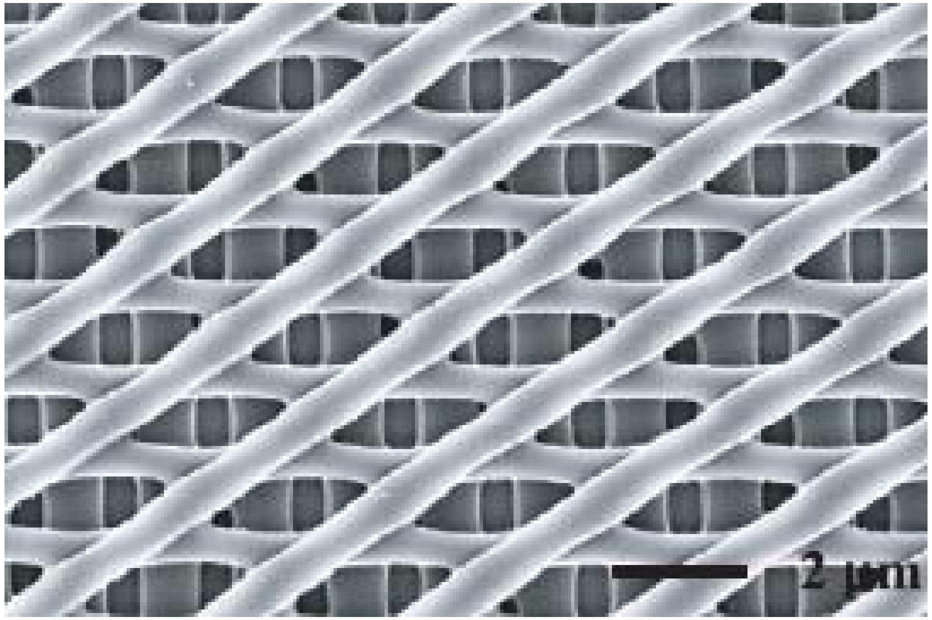
N Kehagias, V Reboud, G Chansin, M Zelsmann, C Jeppesen, C Schuster, M Kubenz, F Reuther, G Gruetzner, C M Sotomayor Torres, Nanotechnology 18, 175303 (2007)

NIL STACKING

Reverse-contact NIL for multilayered structures



Imprinted grating



3-layer polymer woodpile

N Kehagias, V Reboud, G Chansin, M Zelsmann, C Jeppesen, C Schuster, M Kubenz, F Reuther, G Gruetzner, C M Sotomayor Torres, Nanotechnology 18, 175303 (2007)

FABRICATION TECHNIQUES

High Resolution + Large-Scale

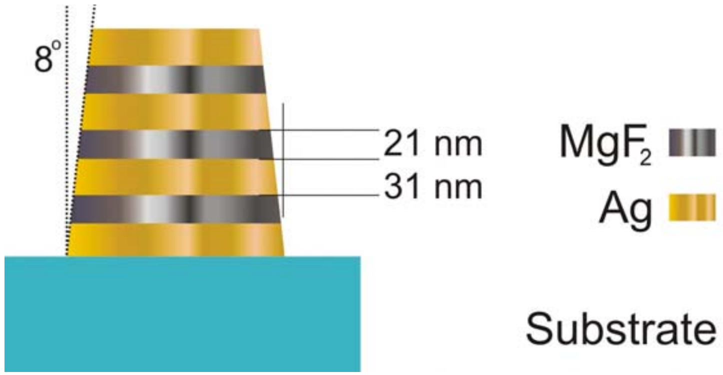
- Nanoimprint
- Unlimited resolution (given by the stamp)
- Planarization of the surface
- Parallel / wafer-scale fabrication
- Simple and cheap process

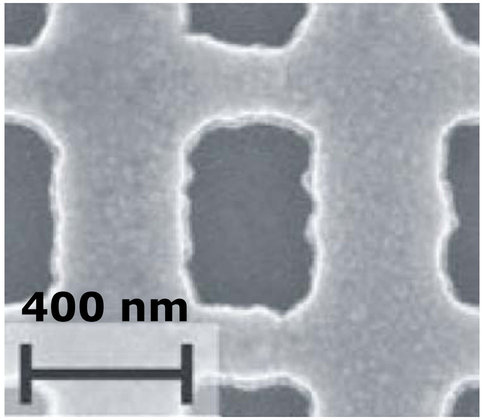
- Soft interference lithography
- Parallel / wafer-scale fabrication

W. Wu, et. al., Applied Physics A 87, 147-150 (2007)
Henzie, et. al., Nature Nanotechn. 2, 549-554 (2007)

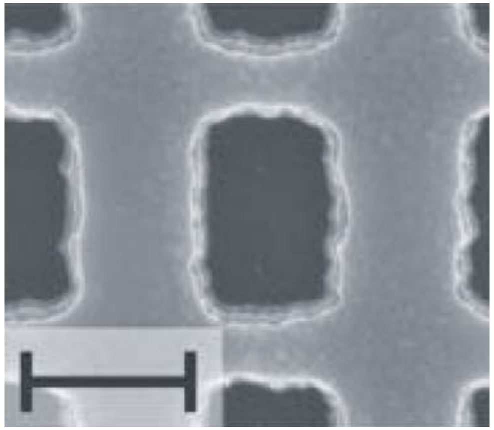
TOWARDS 3D: MULTILAYERS

Negative *n'* ≅ - 1
λ = 1.4 μm

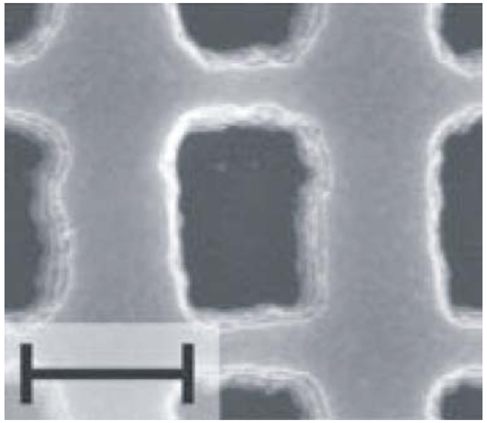




N=1



N=2



N=3

G. Dolling, M. Wegener, S. Linden, Opt. Lett. 32, 551 (2007)

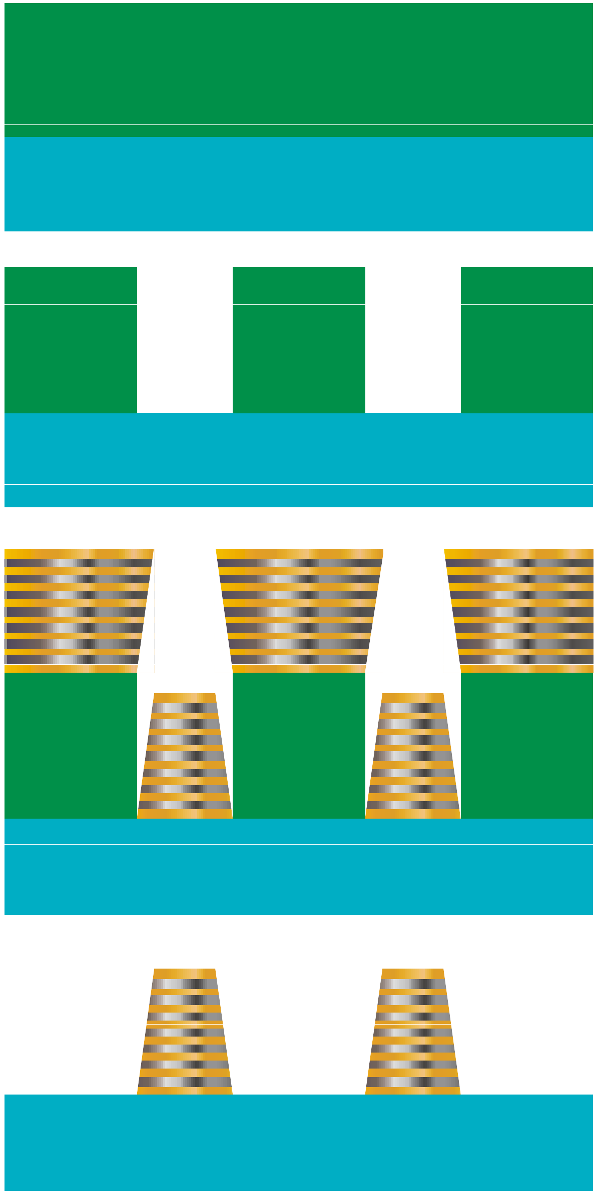
MULTIPLE LAYERS DEPOSITION

Standard Litho
+
Multiple layers deposition

Limitations:

Total thickness

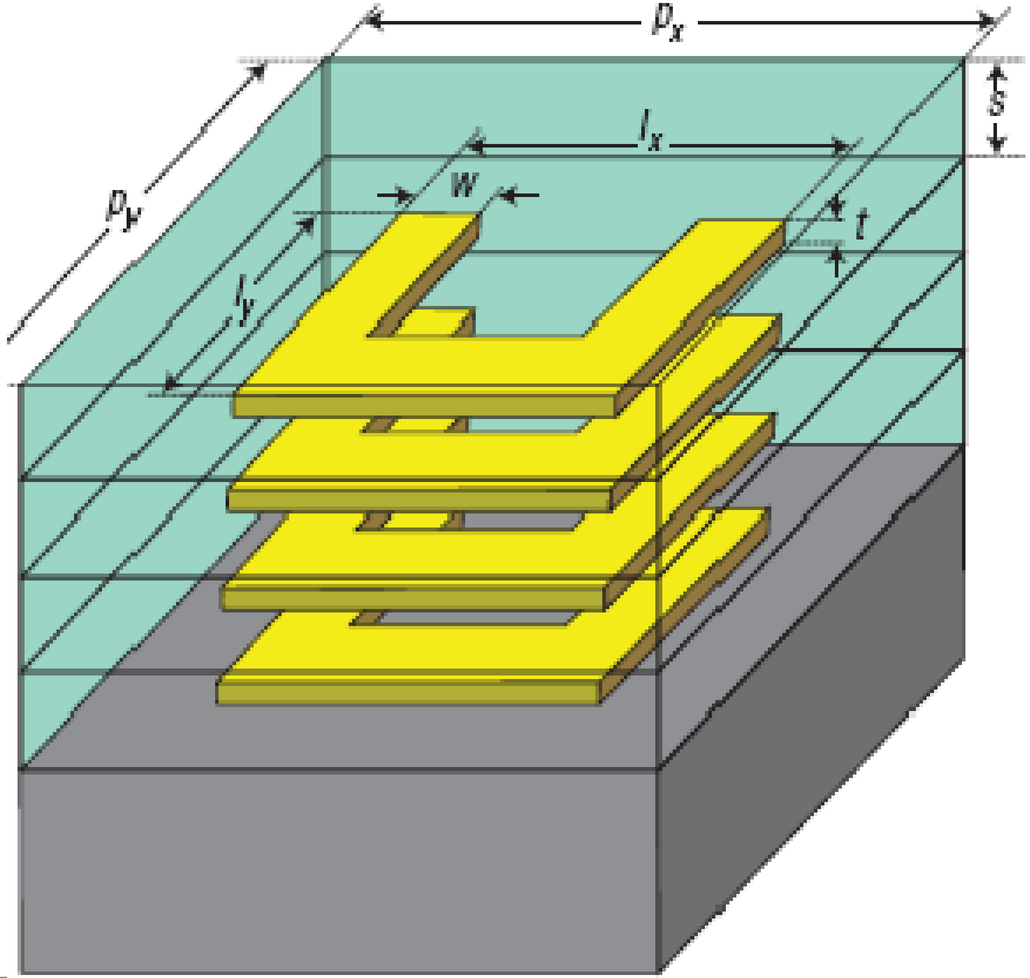
Trapezoidal shape



TOWARDS 3D MM: LAYER-BY-LAYER

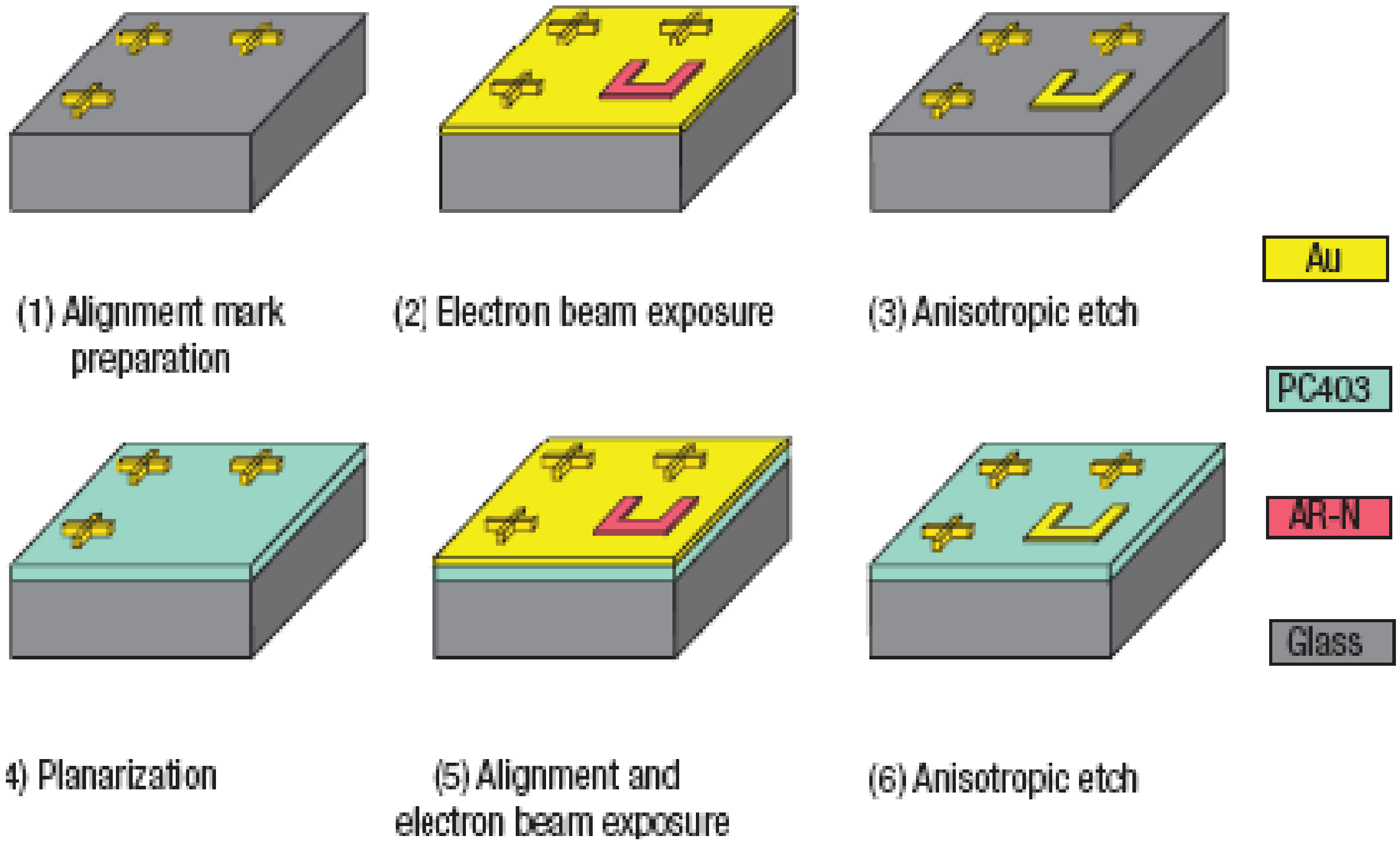
Miltiple lithography steps (layer-by-layer)

Planarization
+
Alignment
+
Stacking



N. Liu, H. Guo, L. Fu, S. Kaiser,H. Schweizer,H. Giessen, Nat. Mater. 7, 31 (2007)

LAYER-BY-LAYER

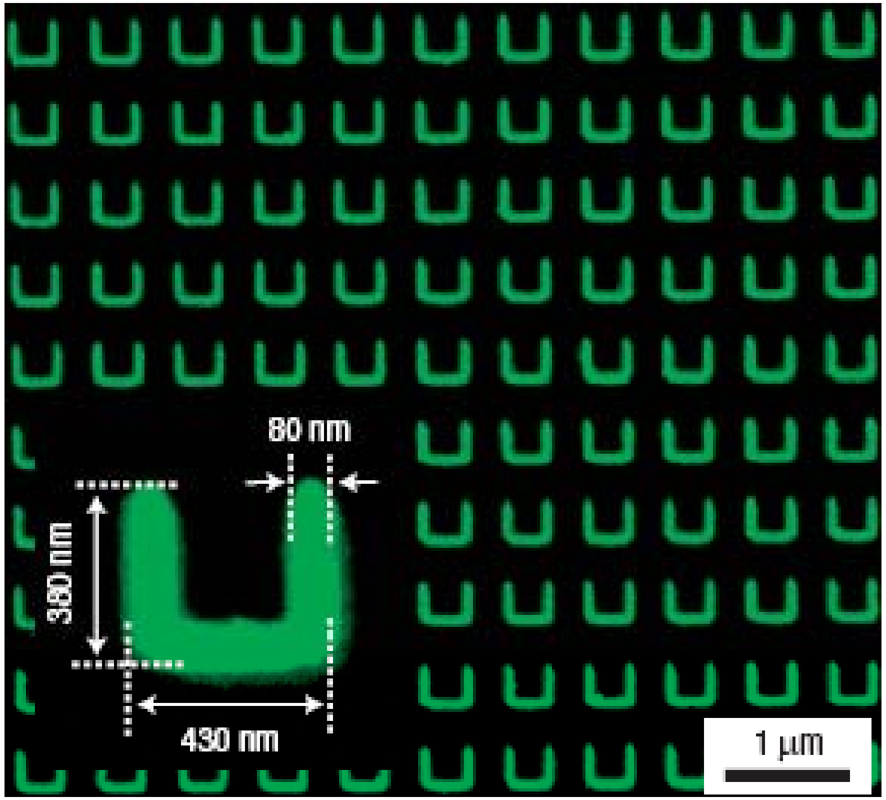


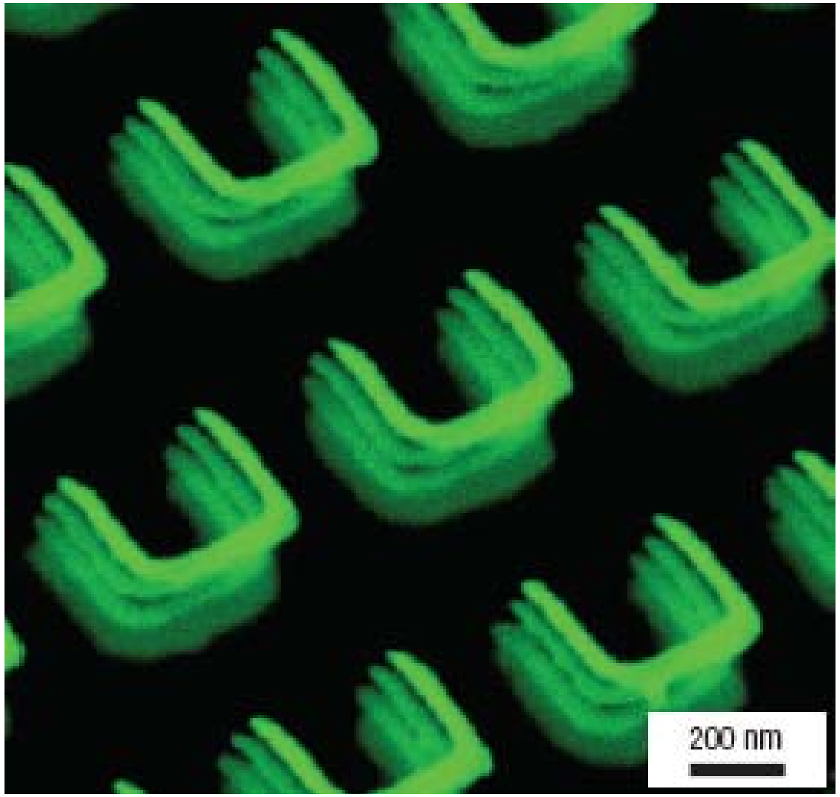
N. Liu, H. Guo, L. Fu, S. Kaiser,H. Schweizer,H. Giessen, Nat. Mater. 7, 31 (2007)

4-LAYER MM

Negative ε
Negative μ

120 THz
200 THz





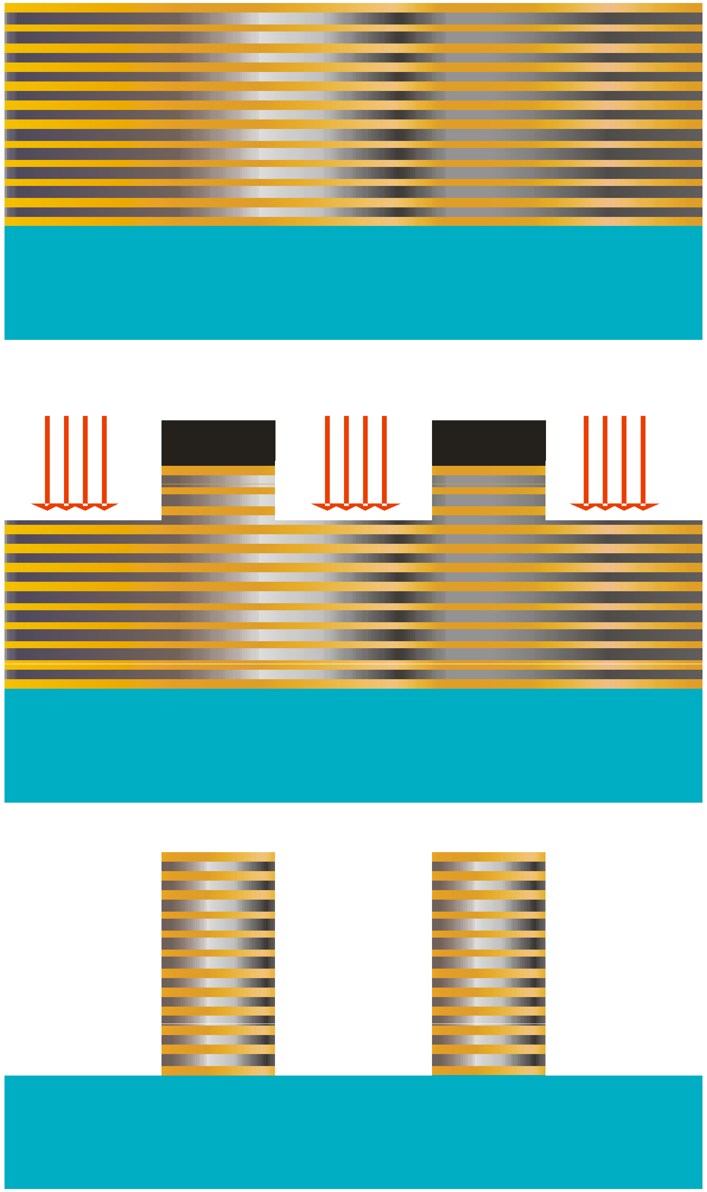
N. Liu, H. Guo, L. Fu, S. Kaiser,H. Schweizer,H. Giessen, Nat. Mater. 7, 31 (2007)

TOWARDS 3D MM

Deep etch
or
Ion milling

Limitations:

Heavy material and process development



Deposited Layers

Substrate

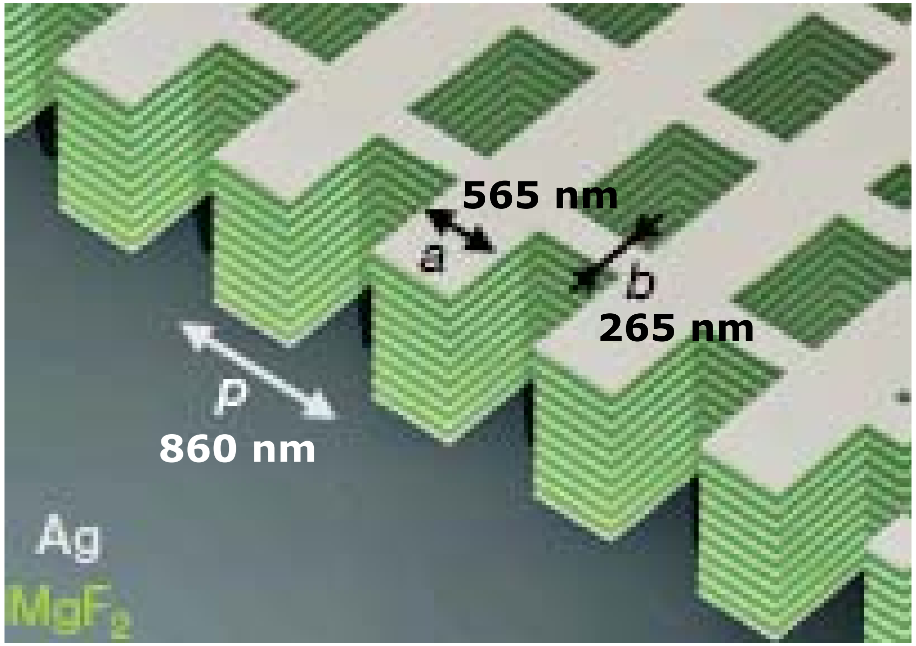
Patterned
Etch Mask

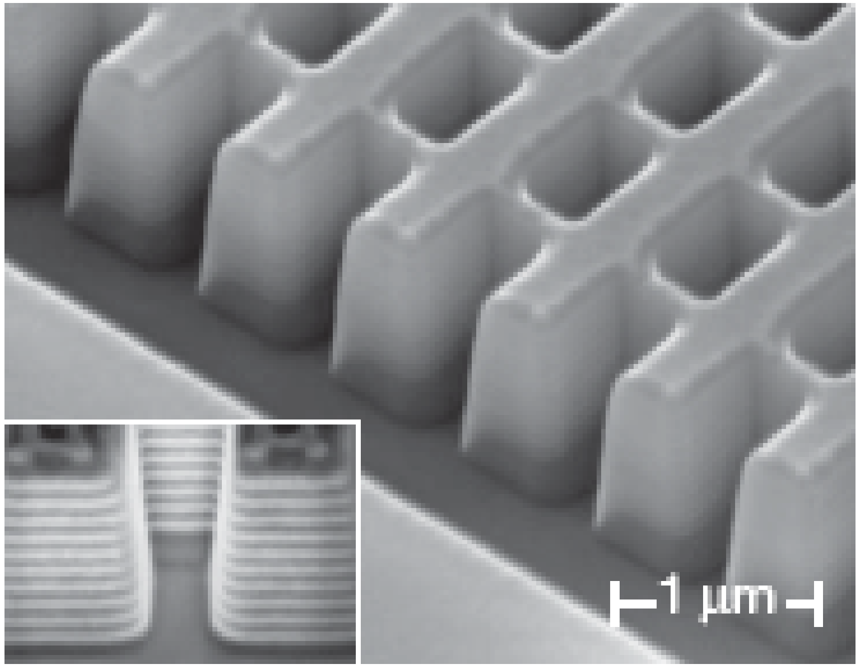
Anisotropic Etch

21-LAYER MM BY FIB

FIB milling fabrication

n = 0.63 ± 0.05 **λ = 1.2 μm**
n = - 1.23 ± 0.34 **λ = 1.775 μm**





J. Valentine, S. Zhang, T. Zentgraf, E. Ulin-Avila, D. A. Genov,
G. Bartal, X. Zhang, Nature, 455, 07247 (2008)

TRUE 3D FABRICATION

Large-Scale

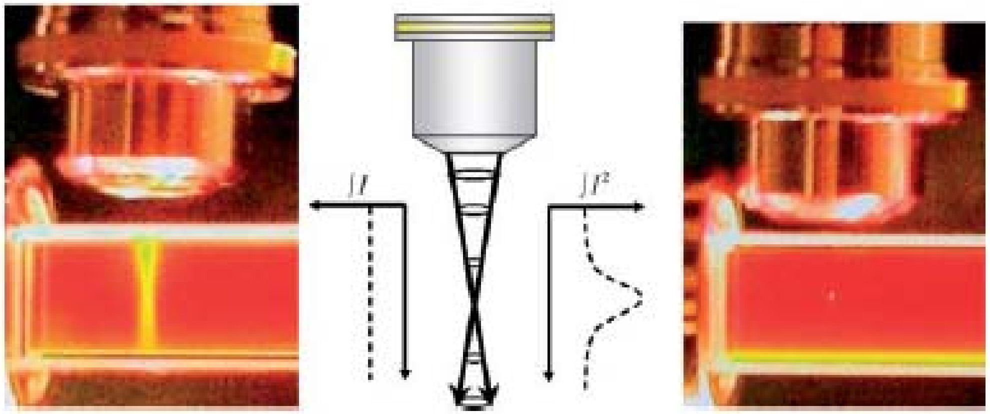
- Two-Photon-Photopolymerization (TPP) Technology
- Direct Laser Writing

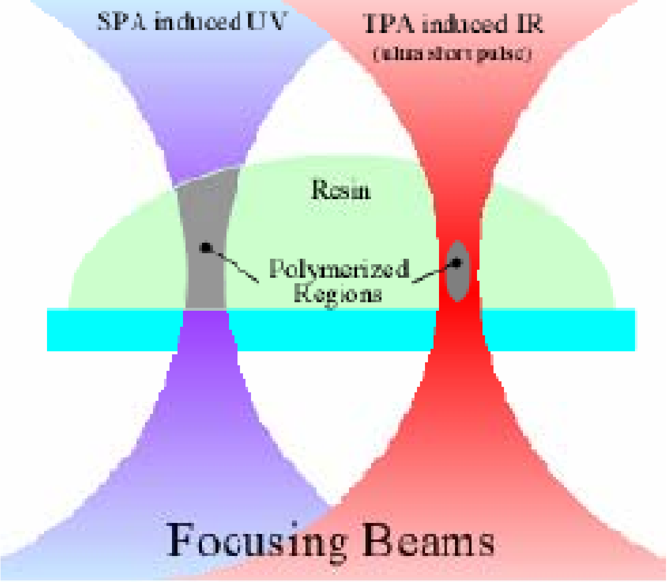
- Large-scale
- Truly 3D

- *Limited resolution*
- *Limited material choice*

S. Kawata, H.-B. Sun, T. Tanaka, K. Takada, Nature 412, 697 (2001)
See for example, review: C. N. LaFratta, J. T. Fourkas,
T. Baldacchini, R. A. Farrer, Angew. Chem. Int. Ed., 46, 6238 (2007)

TWO-PHOTON ABSORPTION



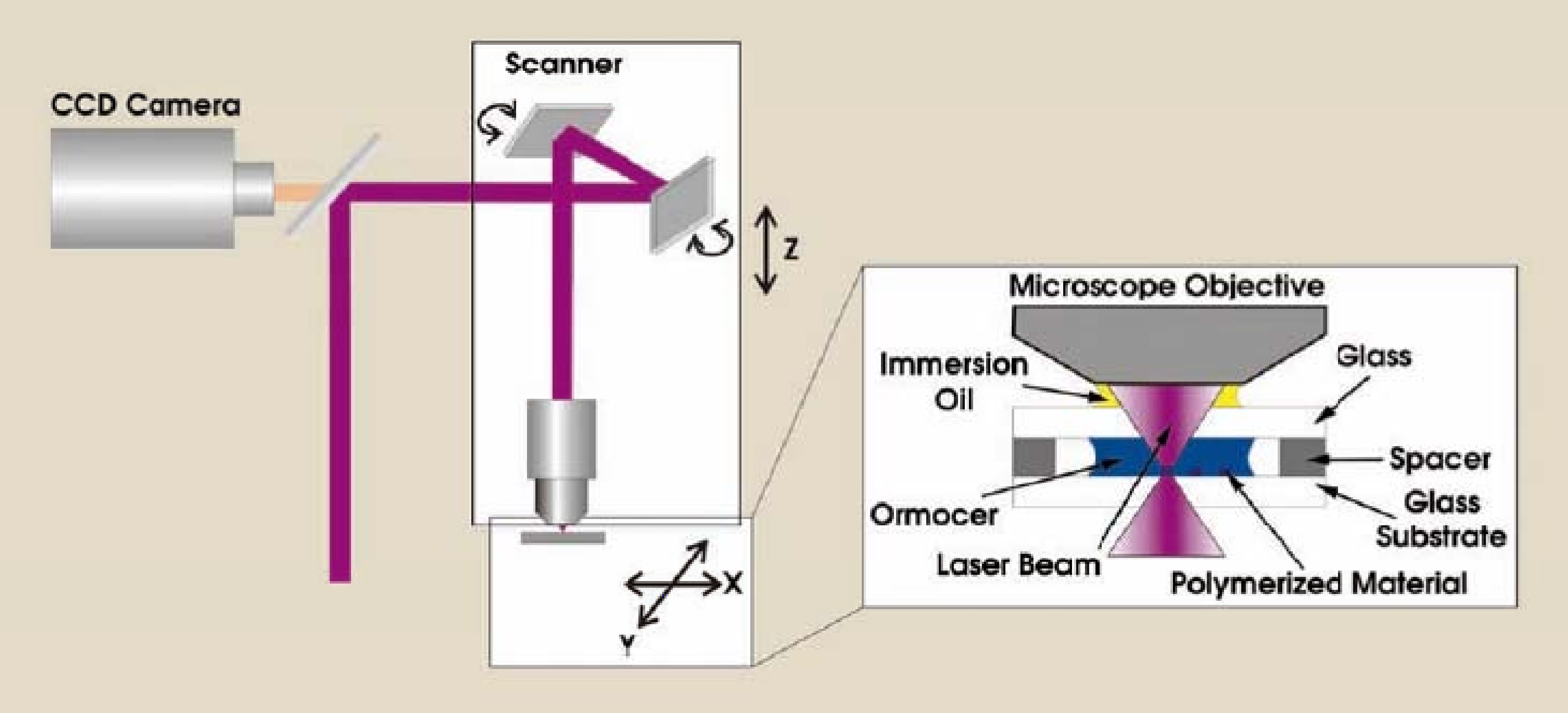


TPA is a third-order nonlinear optical process
TPA rate ~ intensity^2

Resolution:	**150 nm in 2001**
	100 nm in 2006
Surface roughness:	**8 nm (Kawata's group)**

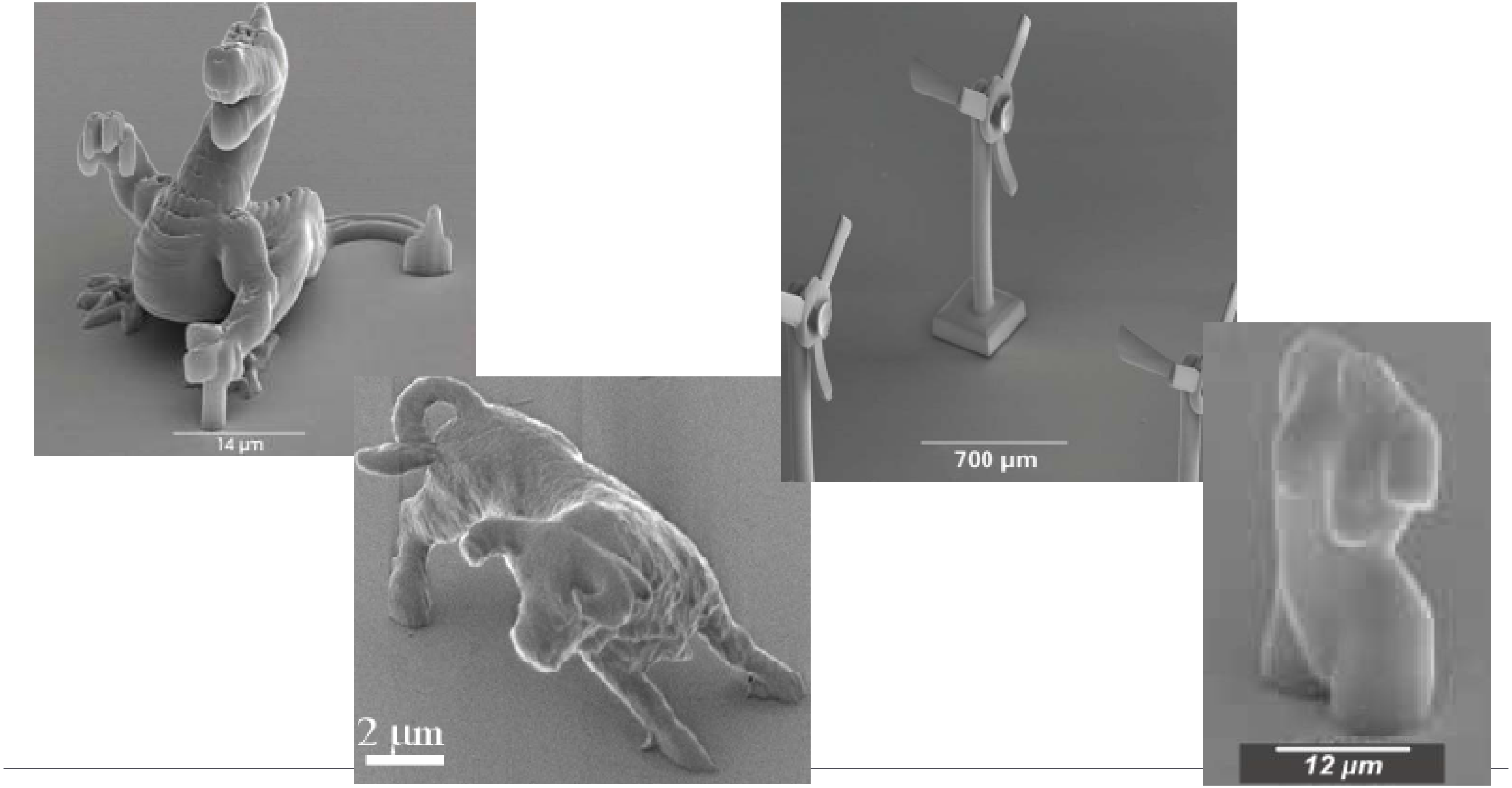
C. N. LaFratta, J. T. Fourkas, T. Baldacchini, R. A. Farrer, Angew. Chem. Int. Ed., 46, 6238 (2007)
Materials today, 10, 6 (2007)

TPP SETUP



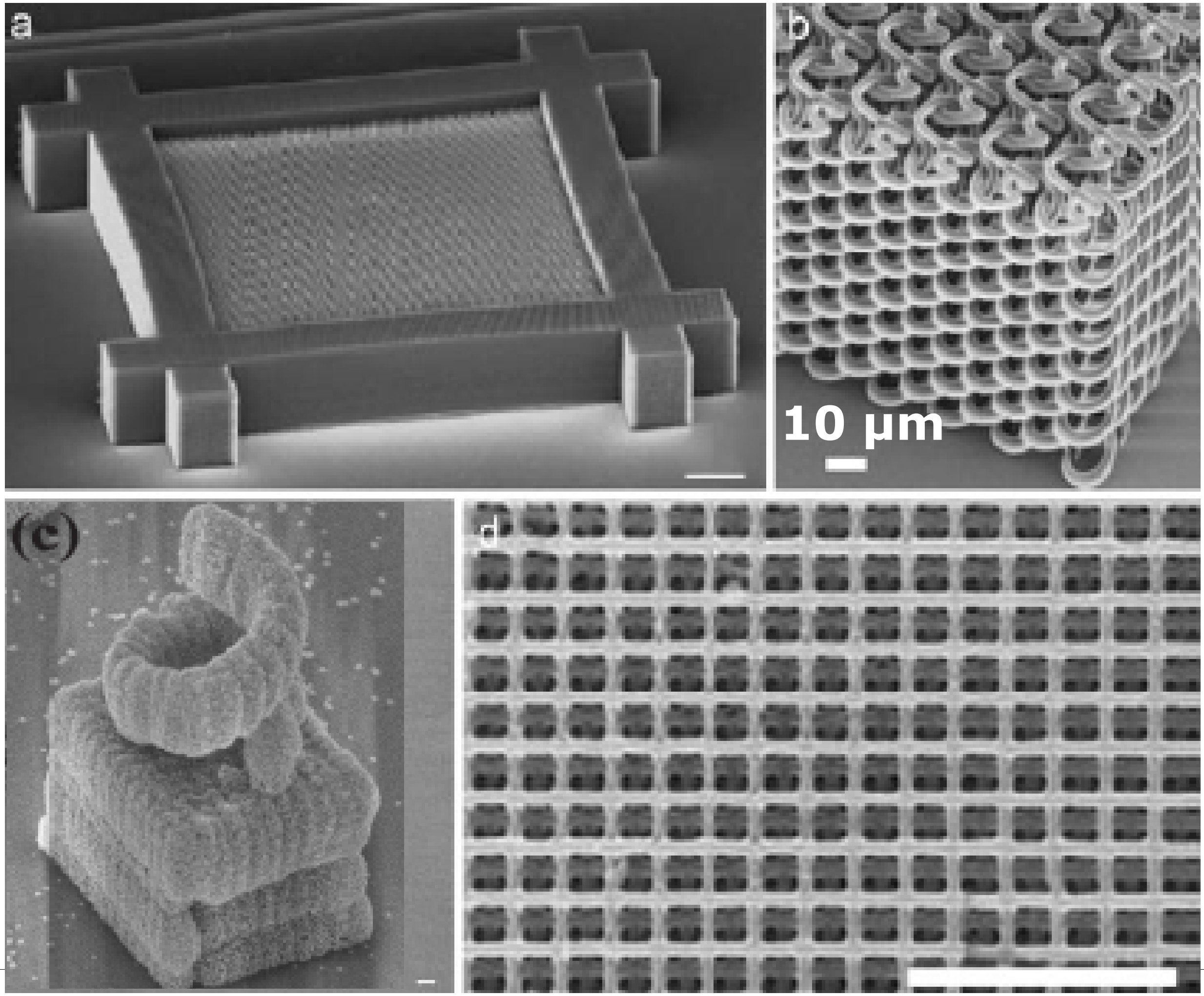
Photonics Spectra

TPP FABRICATED STRUCTURES: FUN



S. Kawata, et. al
B.Chichkov, et. al

TPP FABRICATED STRUCTURES



Nat. Mater.
2004, 3, 444

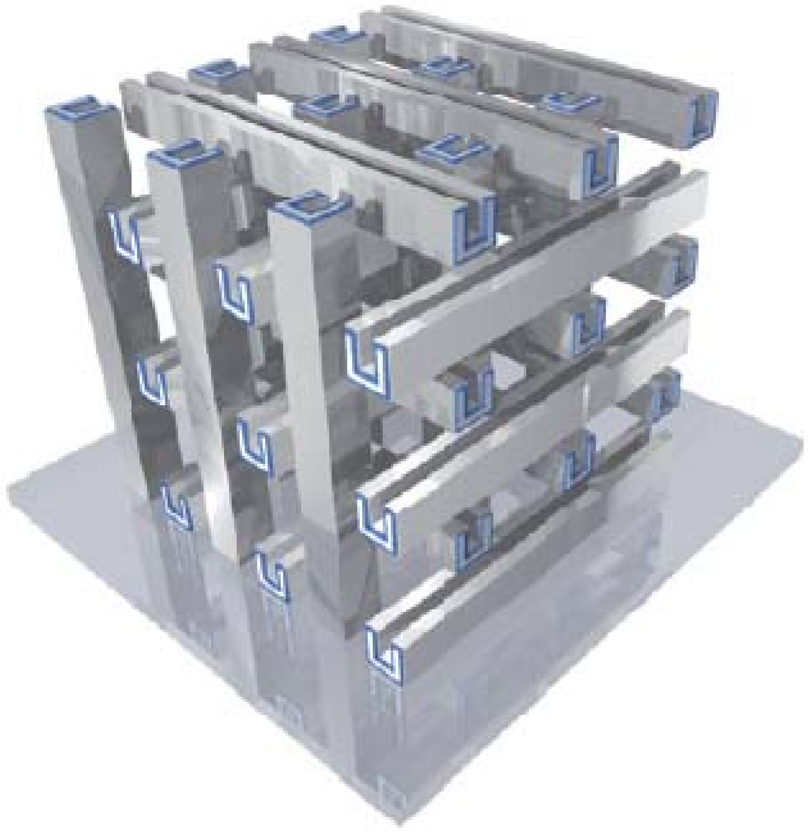
Adv. Mater.
2005, 17, 541

Ag coated
Opt. Express
2006, 14, 800

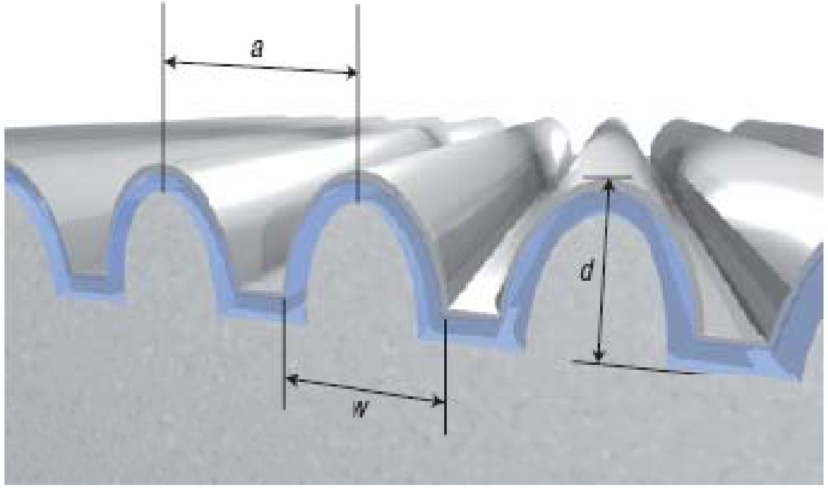
CVD of Si
Adv. Mater.
2006, 18, 457

C. N. LaFratta, J. T. Fourkas, T. Baldacchini, R. A. Farrer,
Angew. Chem. Int. Ed., 46, 6238 (2007)

MMs BY DIRECT LASER WRITING



3D arrangement



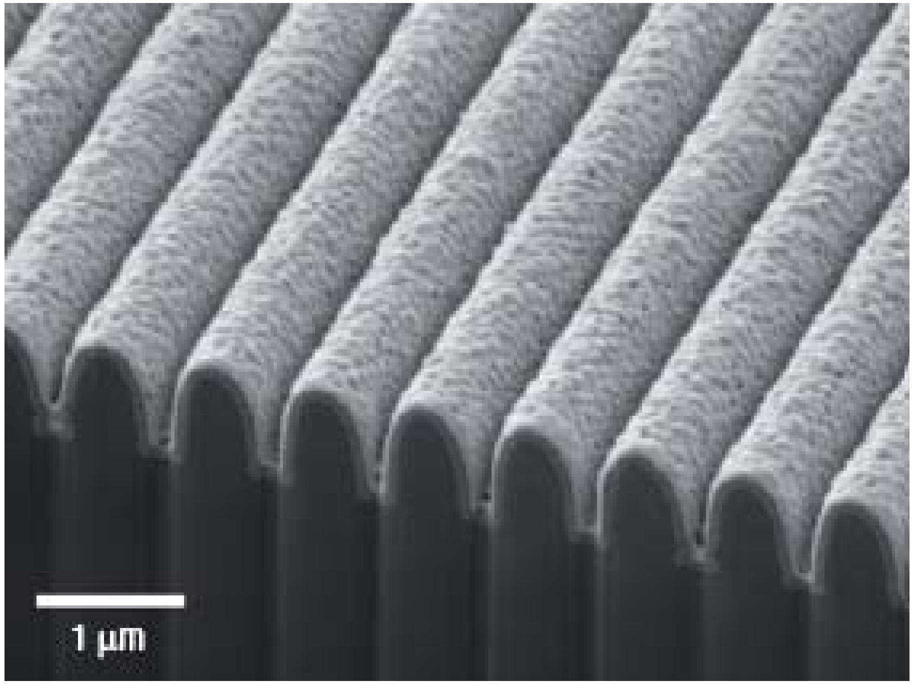
Planar lattice of elongated SRRs

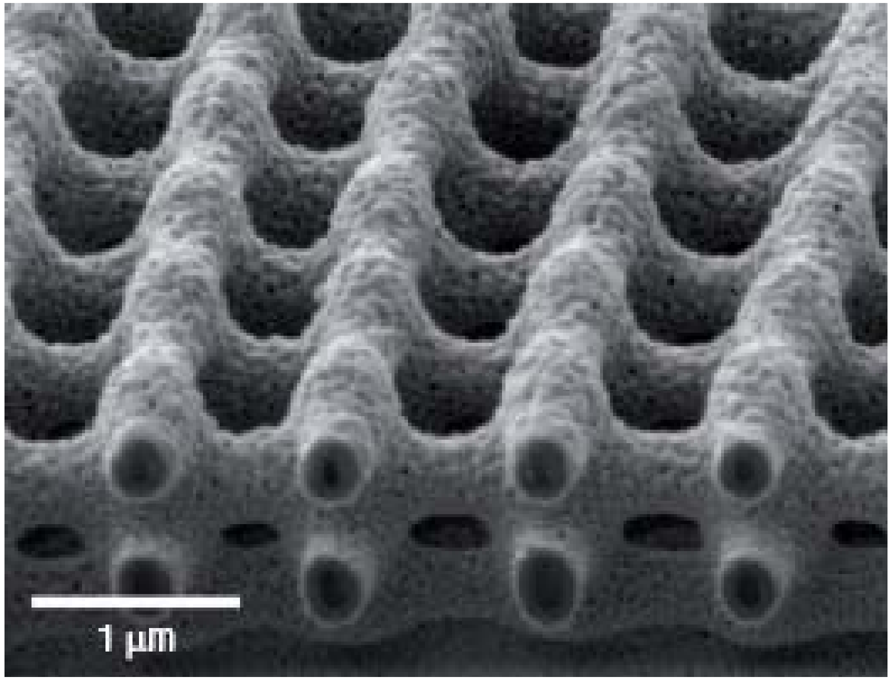
M. Rill, C. Plet, M. Thiel, I. Staude, G. von Freymann,
S. Linden, M. Wegener, Nature Mat. 7, 543 (2008)

DIRECT LASER WRITING + CVD

Direct laser writing + Ag chemical vapour deposition

Magnetic resonance with negative *μ* **100 THZ (λ ~ 3 μm)**



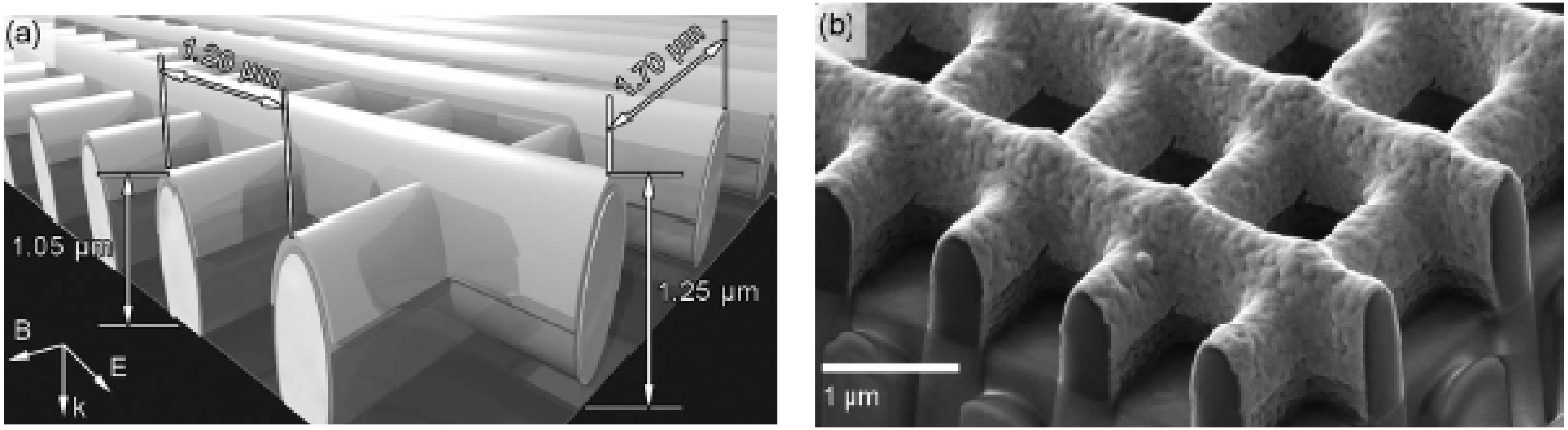


M. Rill, C. Plet, M. Thiel, I. Staude, G. von Freymann,
S. Linden, M. Wegener, Nature Mat. 7, 543 (2008)

DLW + SHADOW EVAPORATION

Direct laser writing + Ag shadow evaporation

Negative *n'* **λ = 3.85 µm**



M. S. Rill, C. E. Kriegler, M. Thiel, G. von Freymann,
S. Linden, M. Wegener, Optics Letters, 34, 19 (2009)

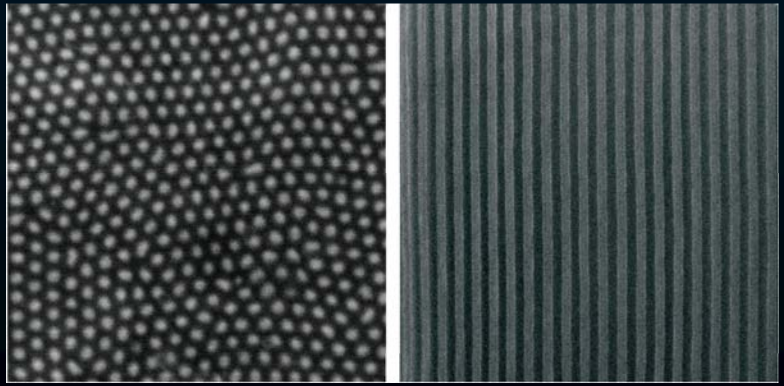
TRUE 3D FABRICATION

Large-Scale

- Electrochemically deposited metal nanowires
- Porous alumina

- Large-scale
- Easy
- Cheap

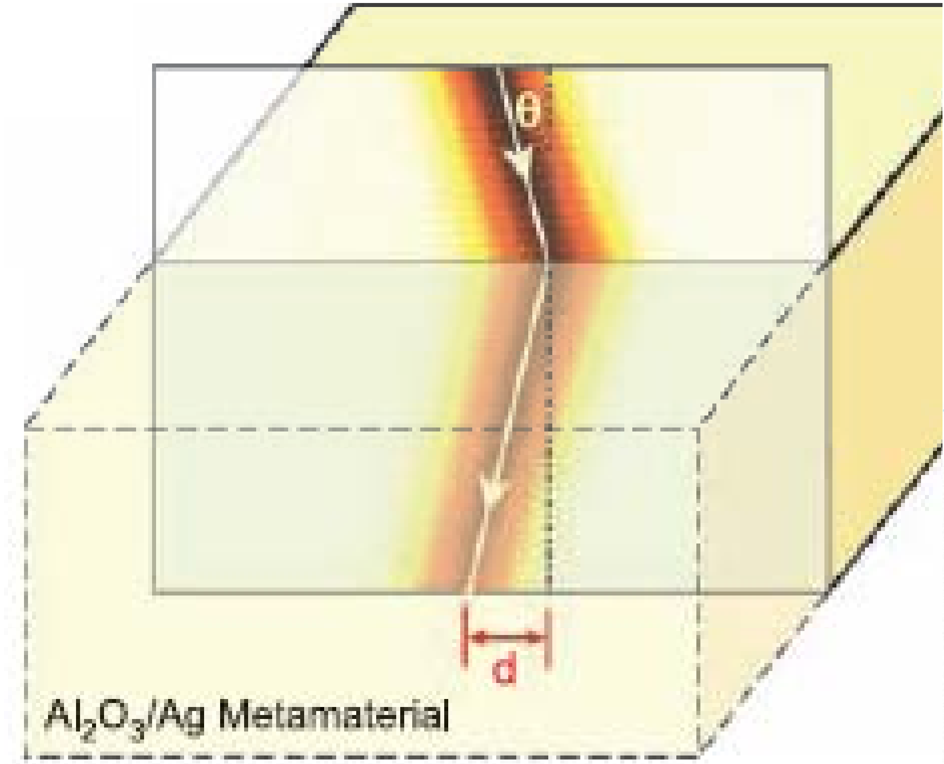
- *Limited flexibility*
- *Limited material choice*

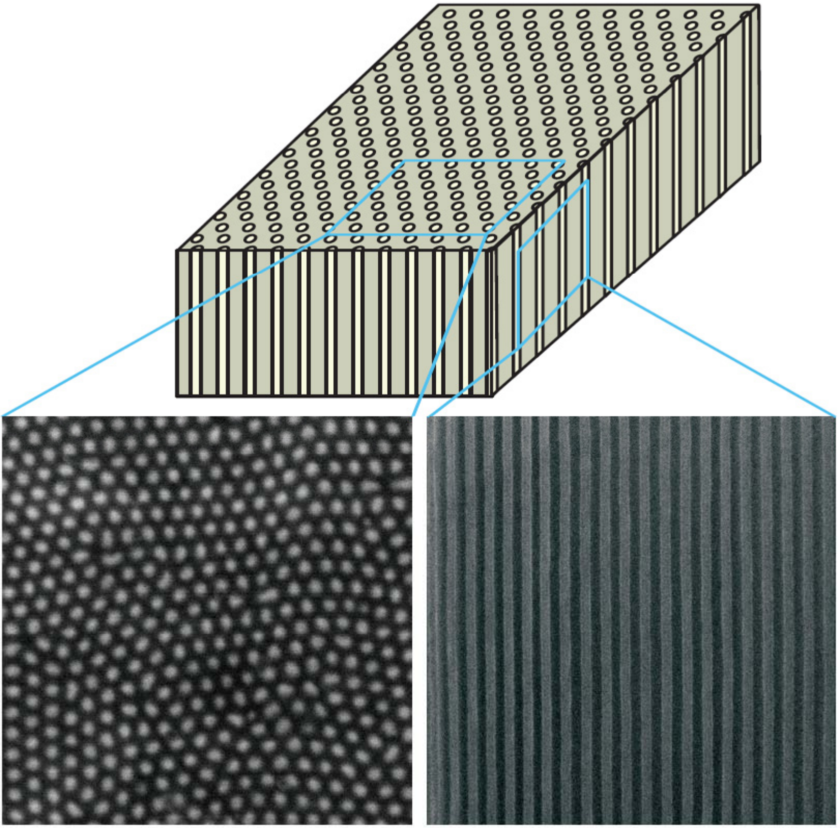


J. Yao, Z. Liu, Y. Liu, Y. Wang, C. Sun, G. Bartal, A. M. Stacy, X. Zhang, Science 321, 930 (2008)

METAL NANOWIRE ARRAYS

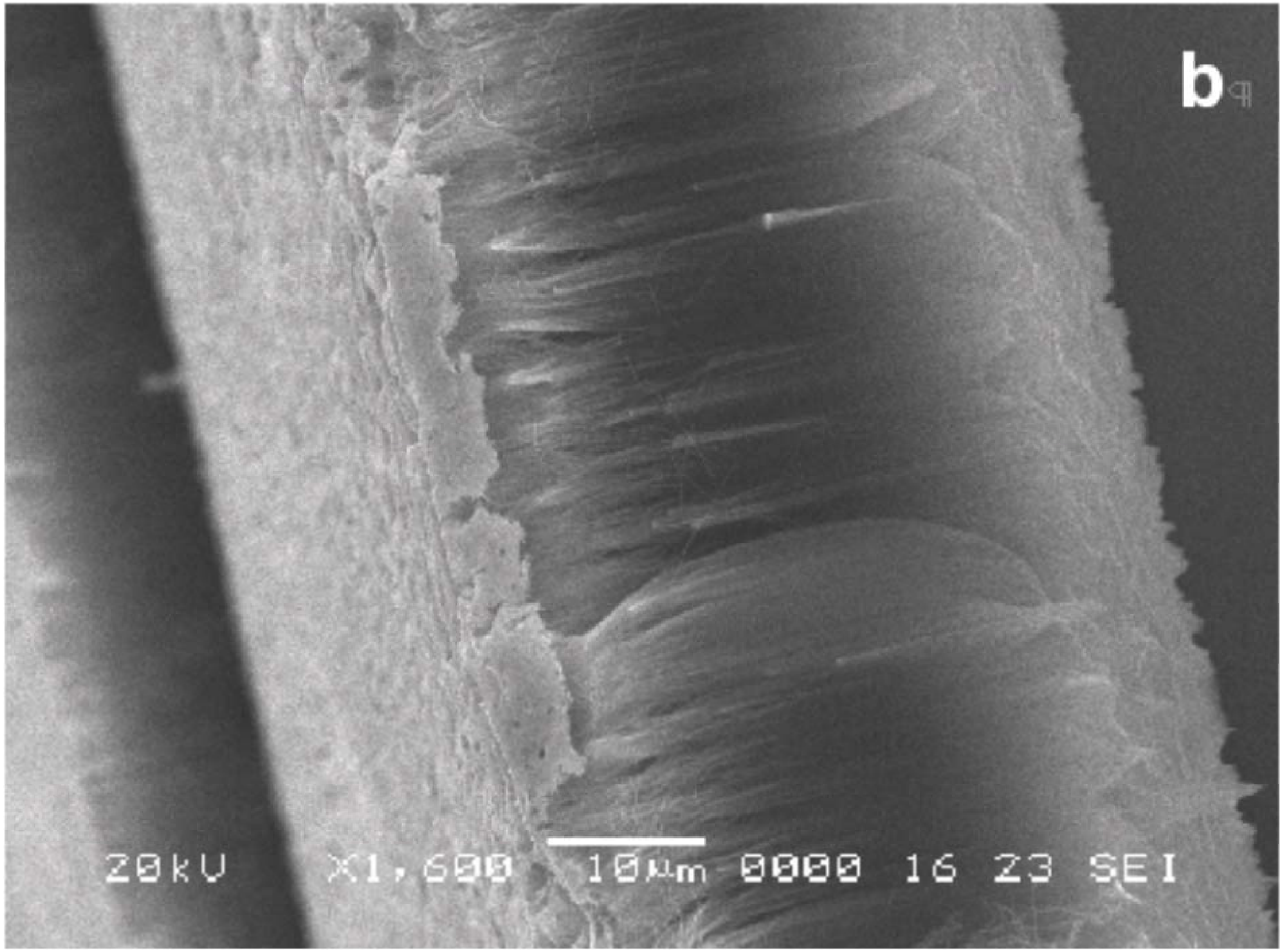
Silver nanowires in porous alumina template
Negative reflection





J. Yao, Z. Liu, Y. Liu, Y. Wang, C. Sun, G. Bartal, A. M. Stacy, X. Zhang, Science 321, 930 (2008)

METAL NANOWIRE ARRAYS



Membrane side wall with silver nanowires

M. Noginov, et. al

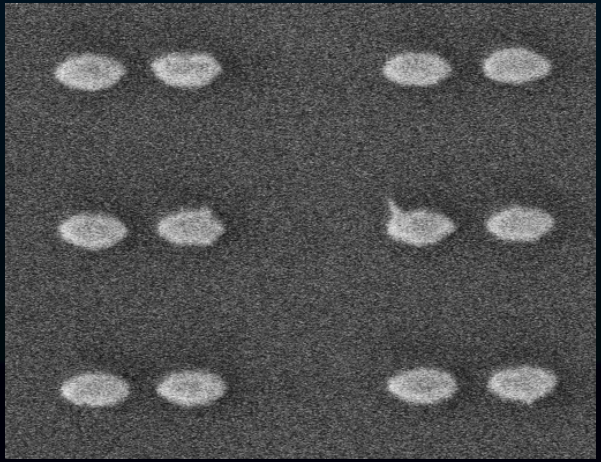
FABRICATION

Making Metal-Dielectric Structures:

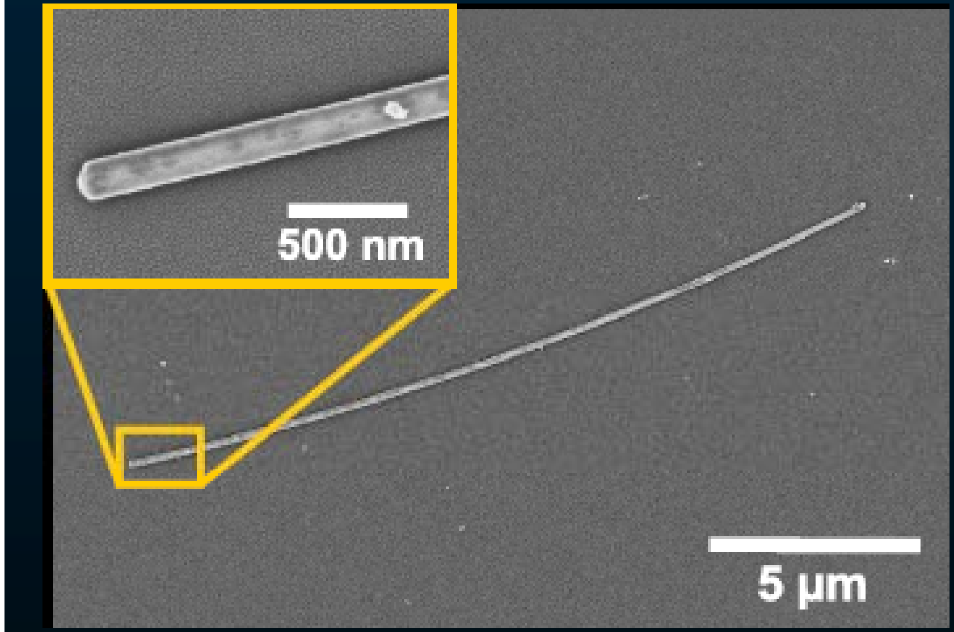
- Subwavelength (nm-scale) patterning
- High precision
- High throughput / Low cost
- Reproducibility
- Robustness
- Flexibility

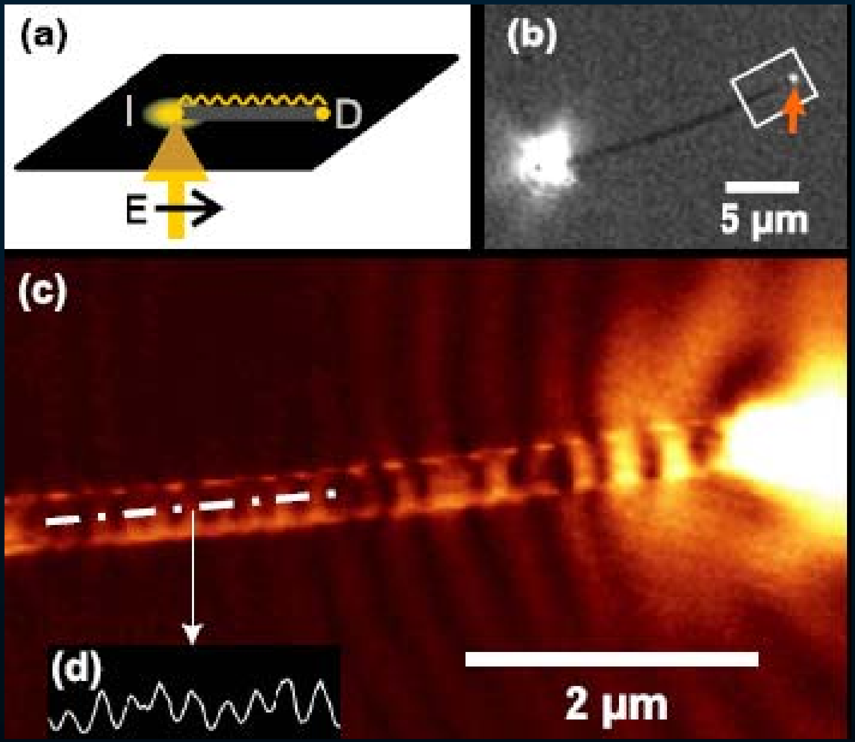
Performance:

- Uniformity
- Low roughness (loss issue)



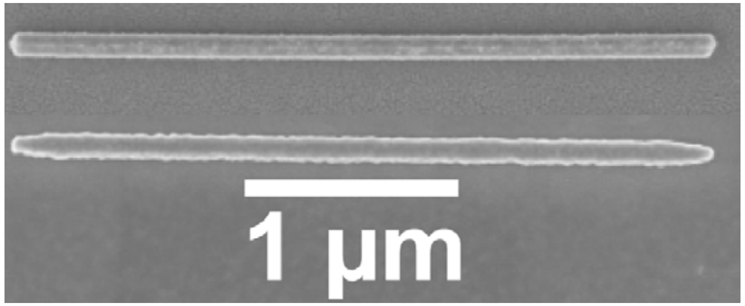
PLASMONIC NANOWIRE RESONATOR

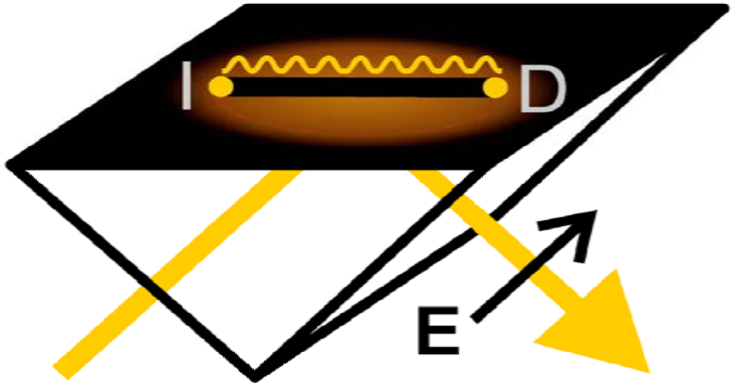


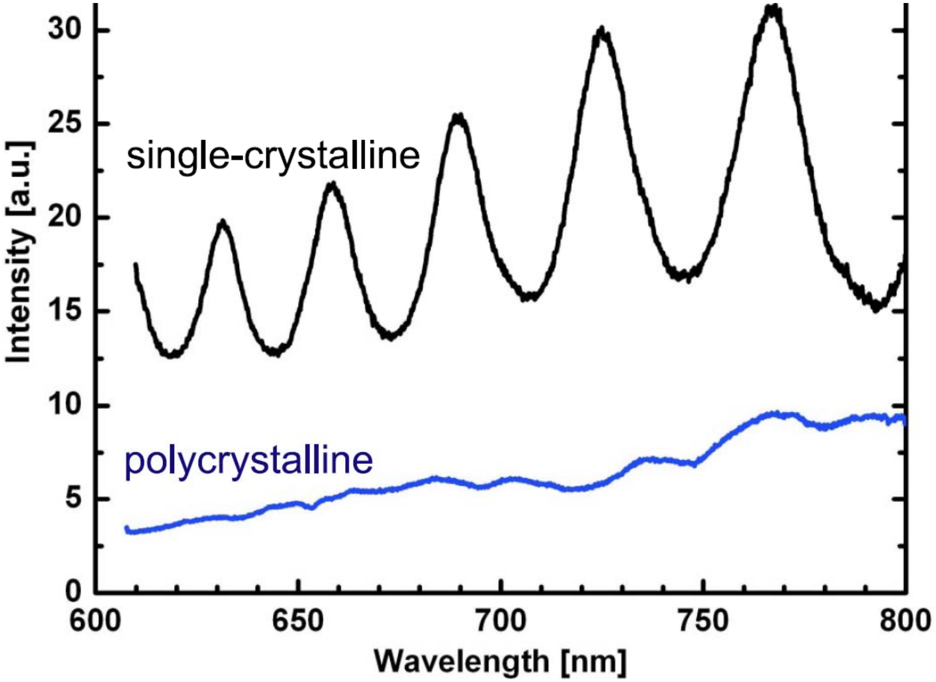


H. Ditlbacher et. al, PRL 95, 257403 (2005)

PERFORMANCE



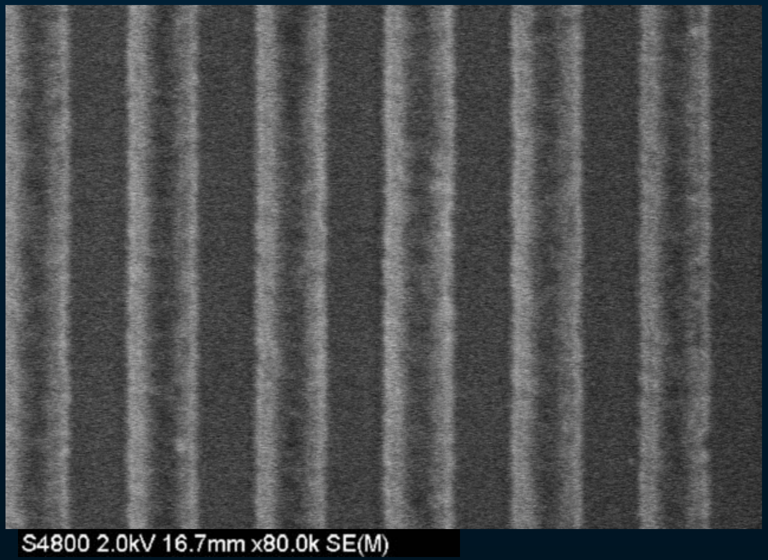


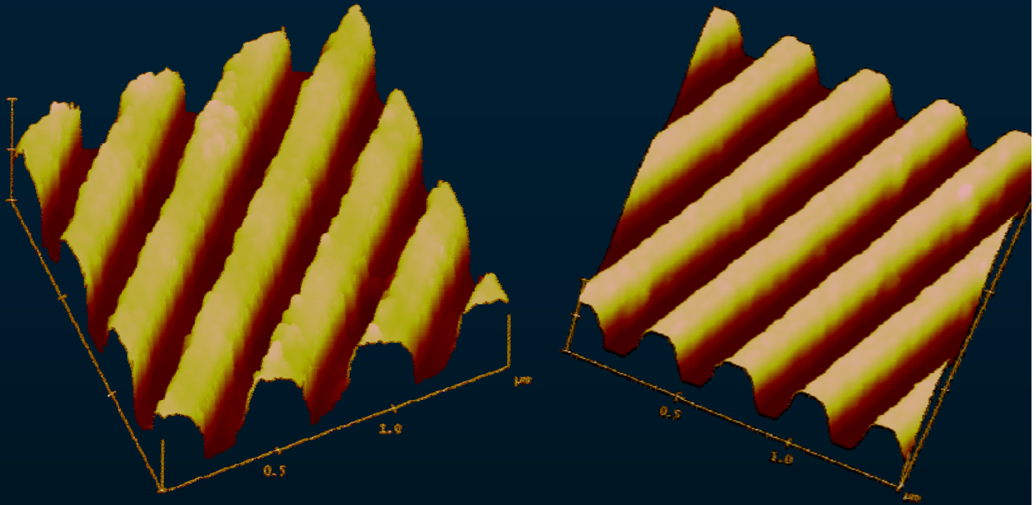


- Plasmonic nanowire resonators
- Planar and chemical fabrication methods
- Minimized damping for well developed wire crystal structure

H. Ditlbacher et. al, PRL 95, 257403 (2005)

COUPLED SILVER STRIPS



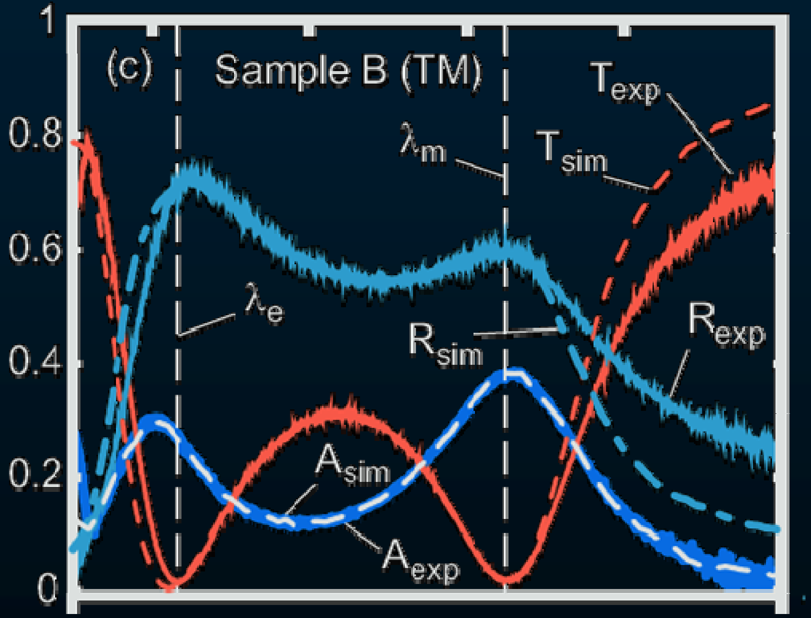


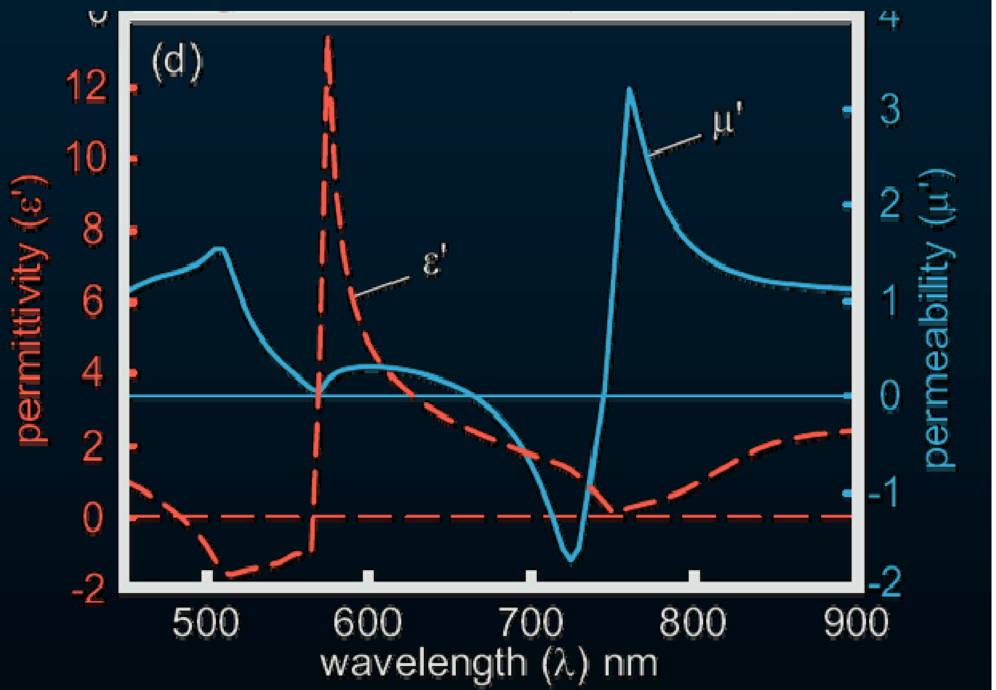
Sample	Silver thickness, nm	Alumina thickness, nm	Deposition rate, Å/s	Roughness, nm
A	30	40	2	2-6
B	35	40	0.5	1.5-2.5

H.K. Yuan, U.K. Chettiar,W. Cai, A.V. Kildishev, A. Boltasseva,
V.P. Drachev, V.M. Shalaev,, Opt. Express 15, 1076 (2007)

NEGATIVE MAGNETISM

$$\varepsilon = 1 - \frac{\omega_p^{\,2}}{\omega^2 + \gamma^2} + i\frac{\omega_p^{\,2}\gamma}{\omega(\omega^2 + \gamma^2)}$$





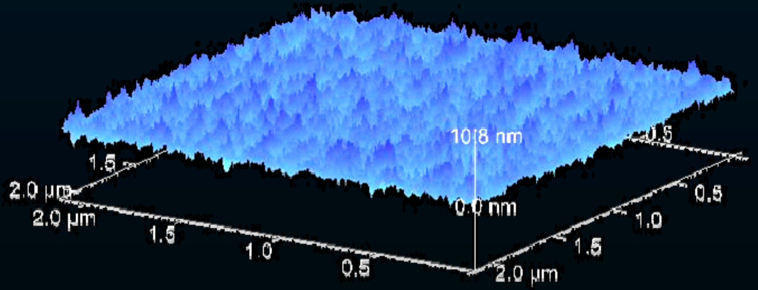
γ **x 4**

μ′ = −1.7
λ = 725 nm

PERFORMANCE

Loss reduction

- **Material choice (new materials)**
- **Thin-film deposition optimization**
- **Surface planarization (imprint, etch)**
- **Post-deposition treatment (annealing)**
- **Planar vs chemical methods**



OUTLOOK

EBL – single-layer MM, 2D plasmonic optics: Areas ~ 100 µm x 100 µm

- High resolution + Flexibility

FIB – MM (up to 10 layers), plasmonics

- High resolution + Rapid prototyping

IL – large-scale MM, stacking, plasmonic components

- Large-scale + High uniformity + Wafer scale / High througput

NIL – plasmonic structures, MM

- High resolution + Wafer scale / High throughput + Flexibility

Chemical methods – plasmonic MM, nanoantennas

- 3D + Large scale + Low cost

Emerging techniques –
New types of soft, contact Litho, TPP DLW, Self-assembly

THANK YOU

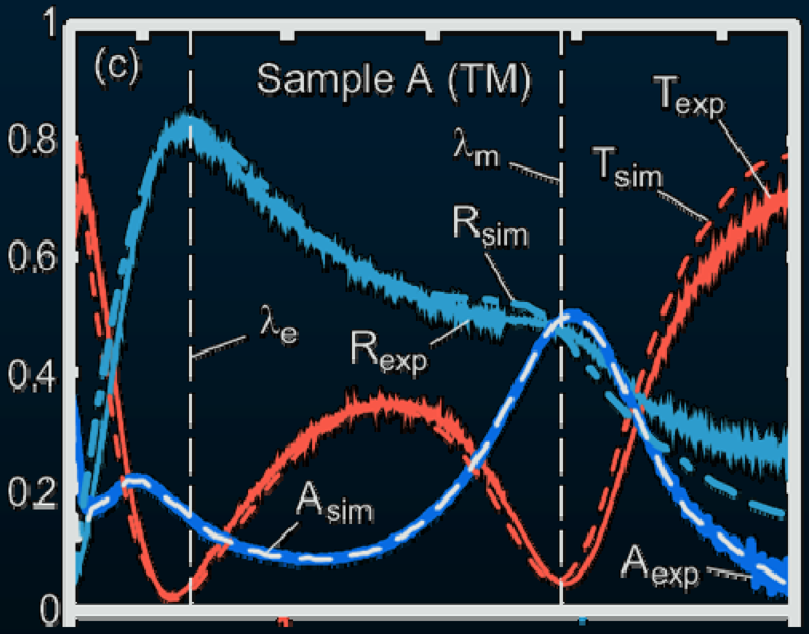
Alexandra Boltasseva
aeb@purdue.edu

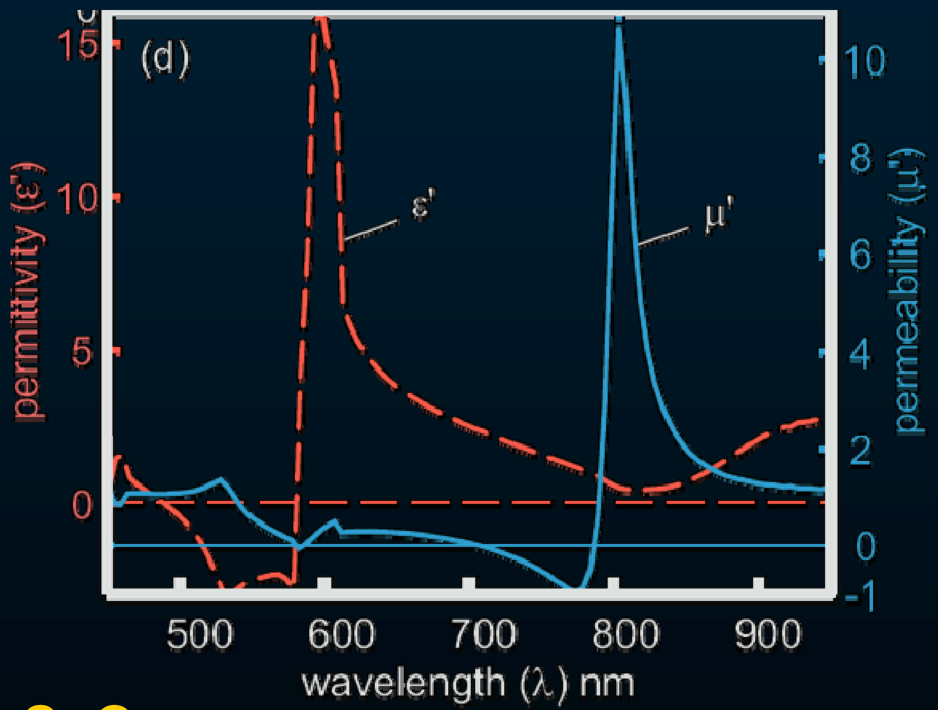
Purdue University
Technical University of Denmark
SAOT Erlangen University

Negative Magnetism in the Visible

$$\varepsilon = 1 - \frac{\omega_p^{\,2}}{\omega^2 + \gamma^2} + i\frac{\omega_p^{\,2}\gamma}{\omega(\omega^2 + \gamma^2)}$$

In the Drude model, relaxation time, γ , is adjusted to obtain a good agreement between experimental and simulated spectra



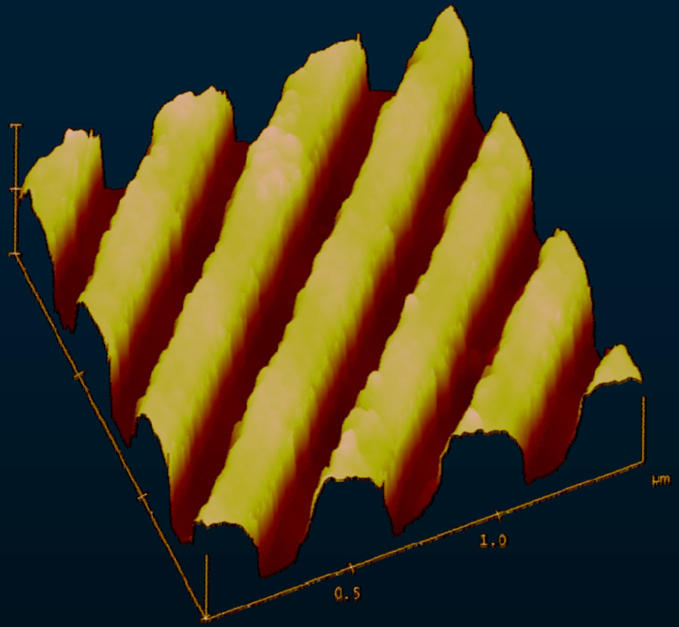


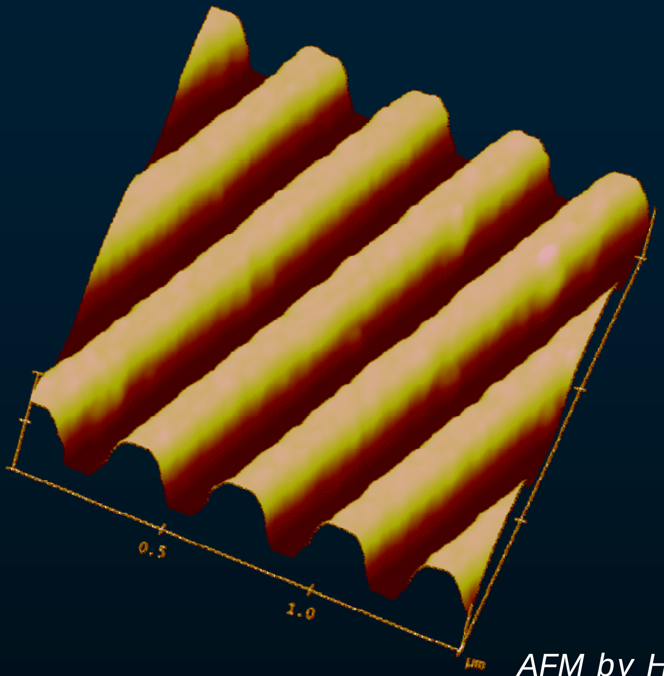
γ x 6

μ′ = –0.9
λ = 770 nm

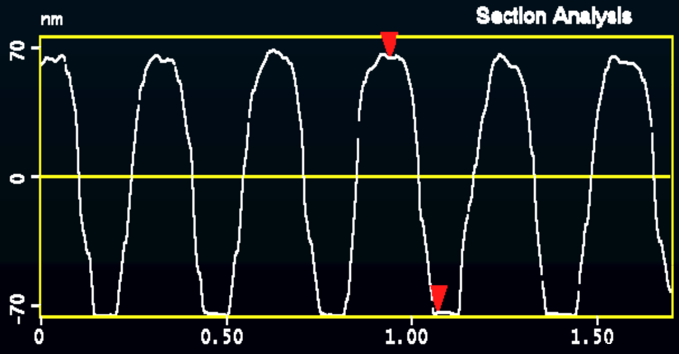
PERFORMANCE

Loss reduction via surface roughness reduction





AFM by H.-K. Yuan

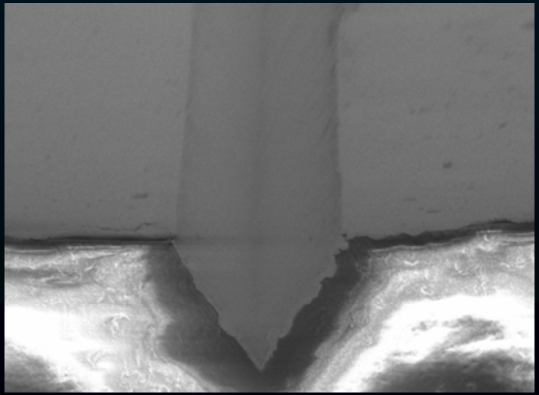


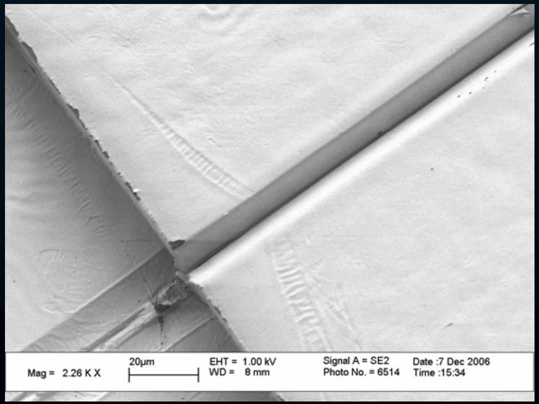
H. K. Yuan, et. al., Optics Express 15, 1076 (2007)

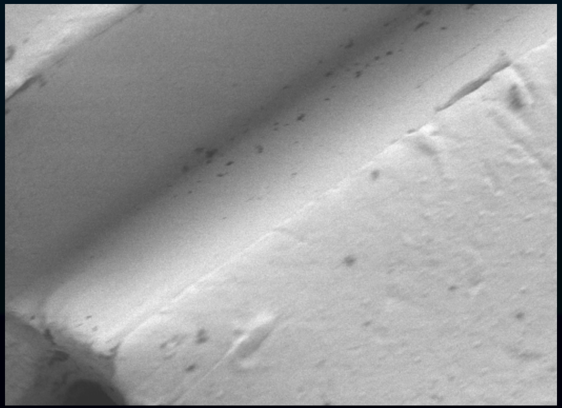
FABRICATED V-GROOVES

V-grooves by NIL-based process

- Parallel, wafer-scale fabrication
- Only standard processes
- Smooth sidewalls
- Shaping (angle change) by stamp oxidation or RIE/oxidation combination
- Adaptable to various designs and devices

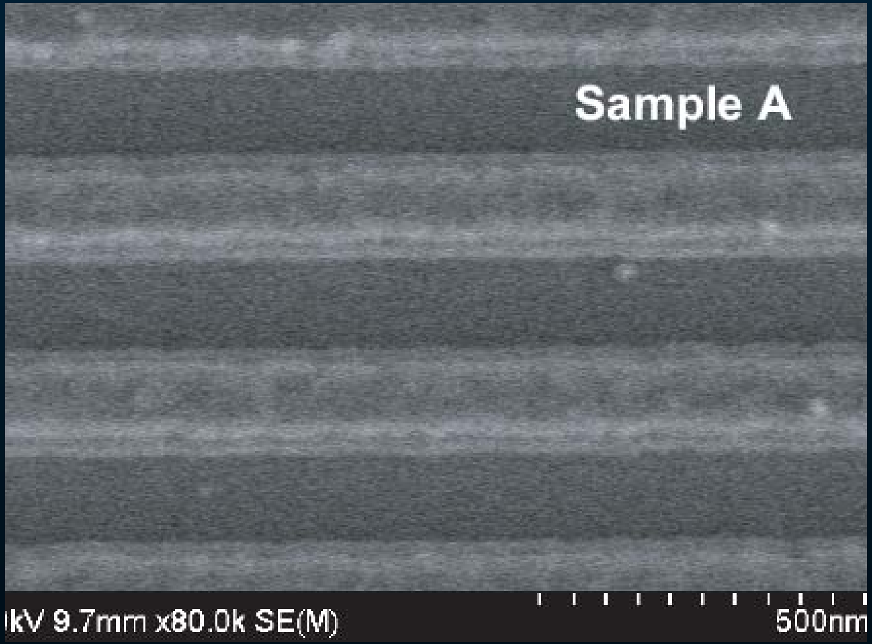


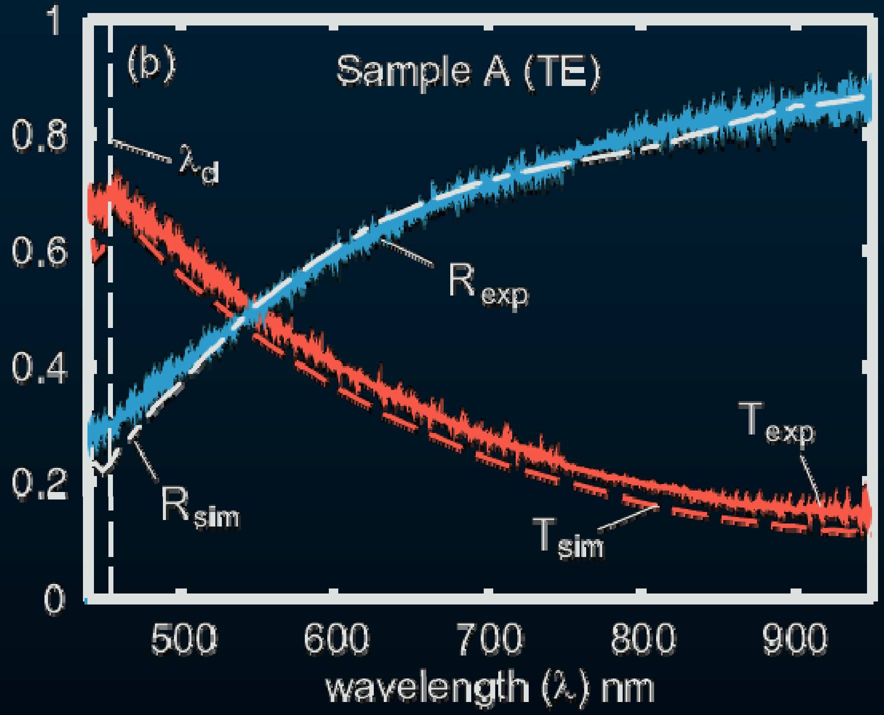




by I. Fernandez-Cuesta

NEGATIVE MAGNETISM

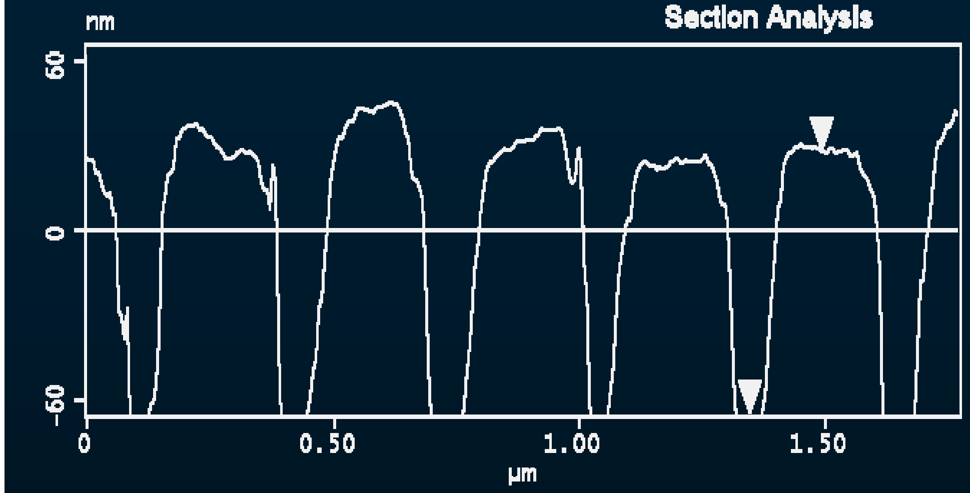




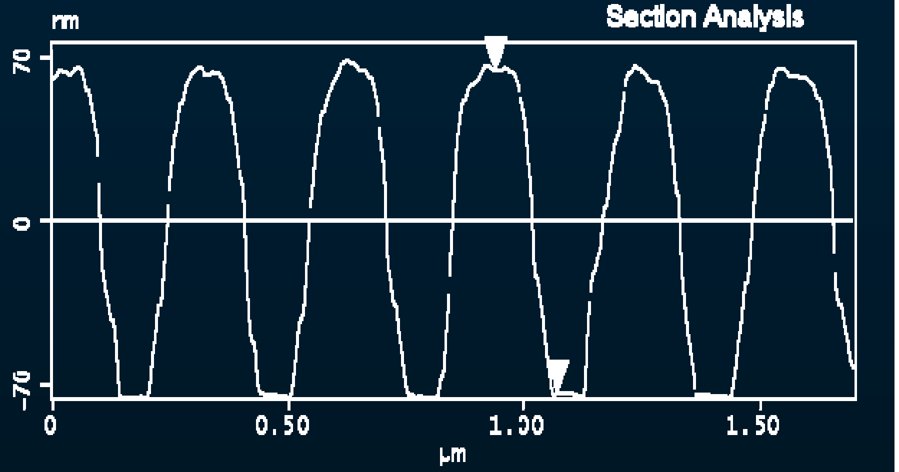
Bulk silver

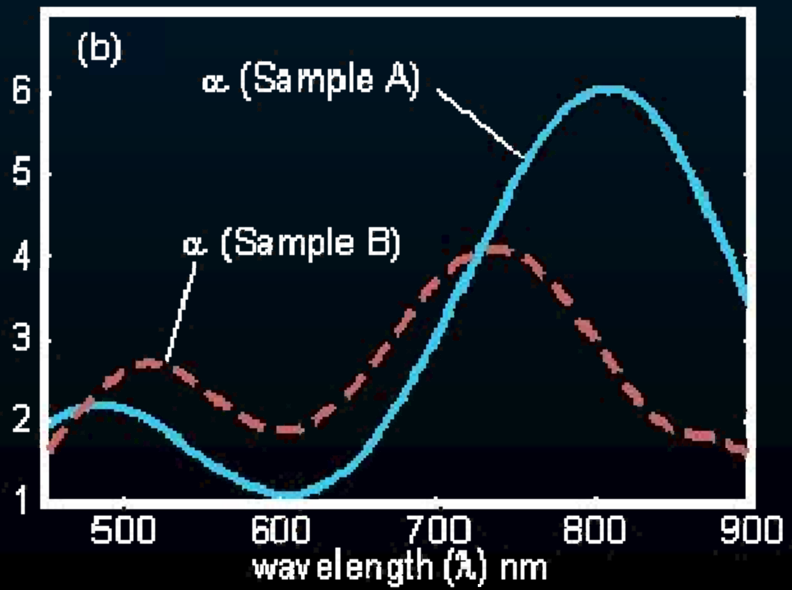
ROUGHNESS AND LOSS

Sample A



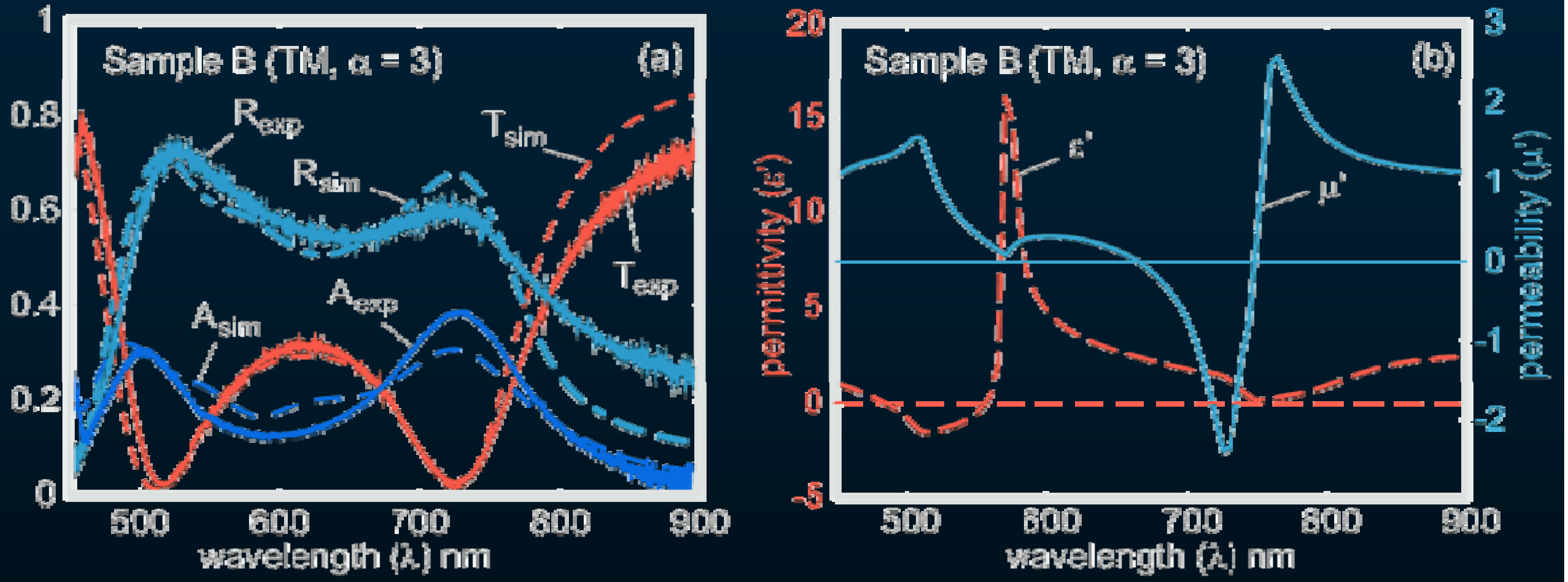
Sample B





LOSS-ADJUSTMENT FACTOR

$$\varepsilon = \varepsilon' + i\alpha\varepsilon''$$



G. Dolling, M. Wegener, C. M. Soukoulis, and S. Linden, Opt. Lett. 32, 53-55 (2007)

Ideal case (α = 1)

"Ideal" sample A	μ′ = −1.0 × **7.8**
"Ideal" sample B	μ′ = −1.7 × **2.4**