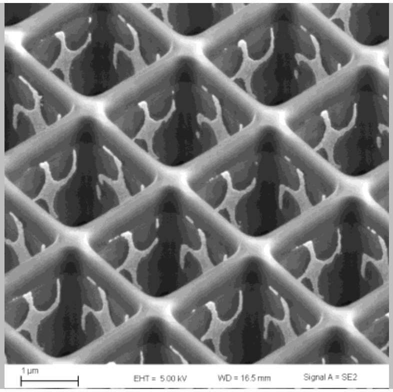
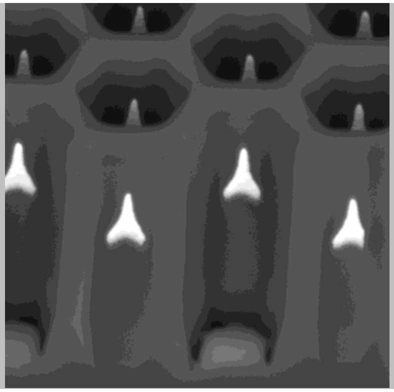
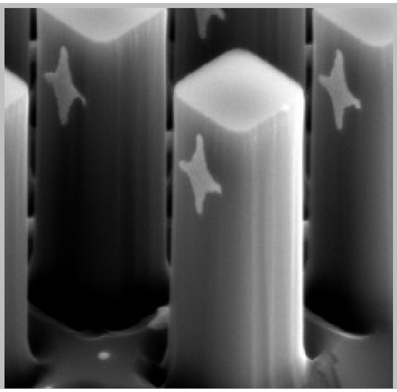
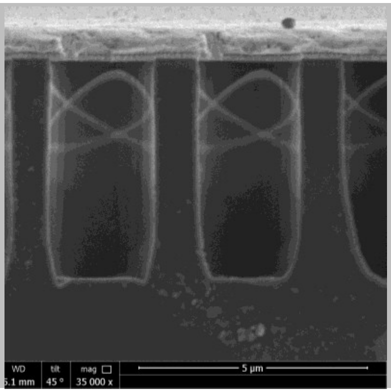
Exceptional service in the national interest

SAND2015-7791C









Fabrication and Characterization of Micron-Scale 3D Metamaterials

D. Bruce Burckel

dbburck@sandia.gov

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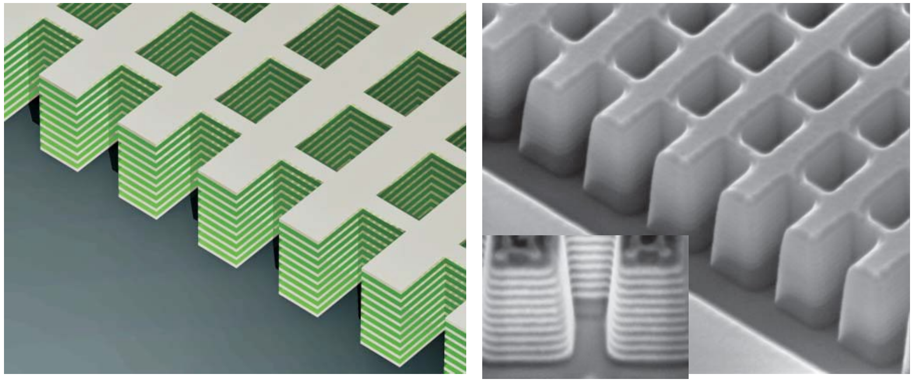
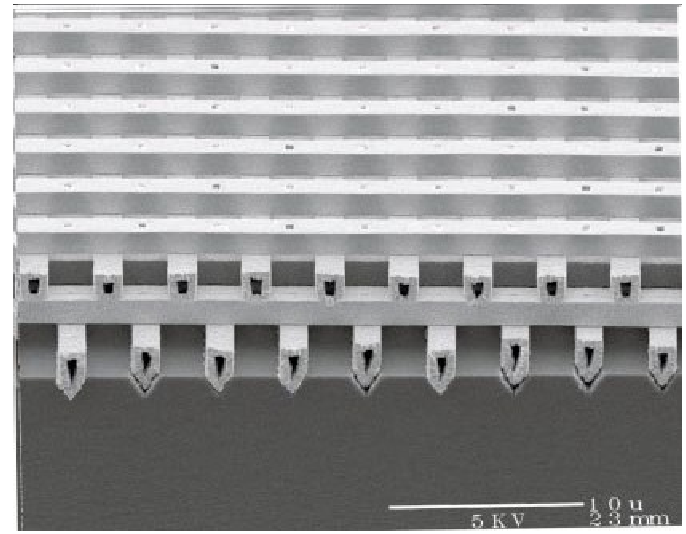
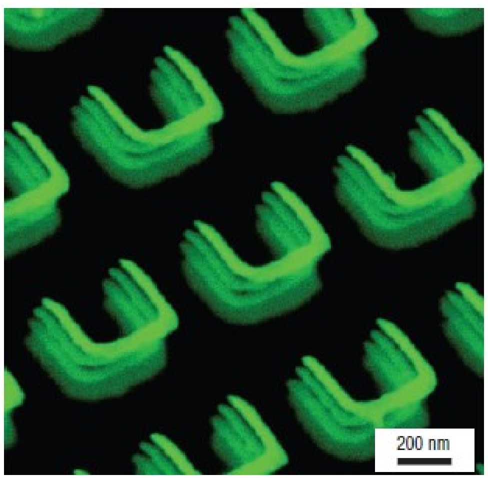
3D in the Microscopic Sense



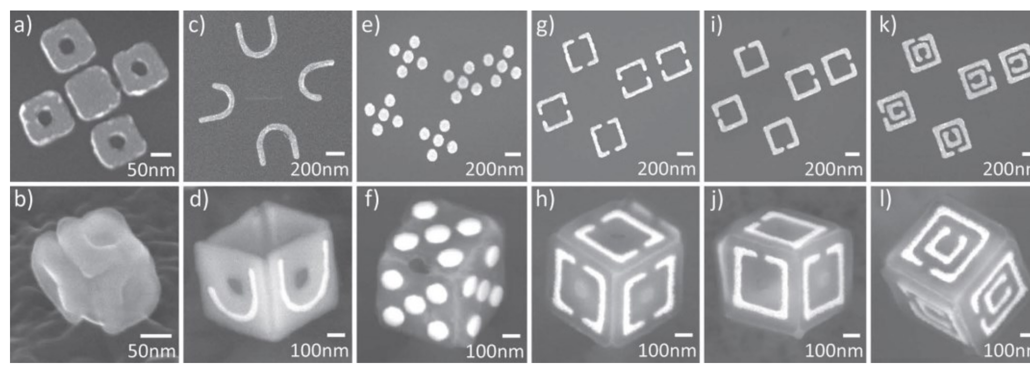
Valentine, et al. Nature, **455**, 376 (2008)



Fleming, et al. Nature, **416**, 52 (2002)

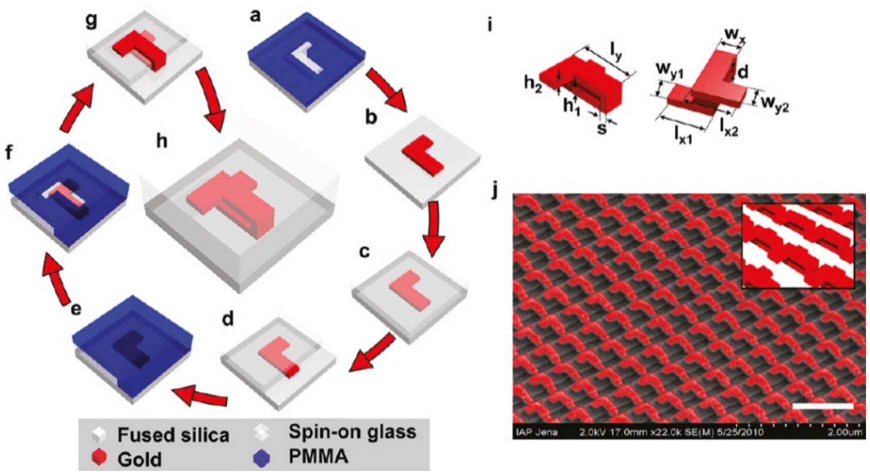


Liu, et al. Nature Materials **7**, 31(2008)

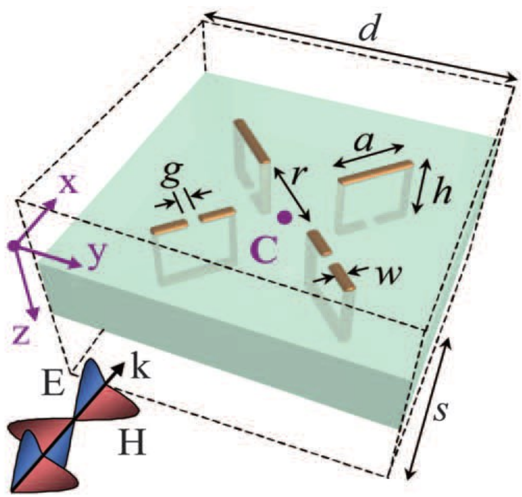


Cho, et al. Small **325**, 1943(2011)

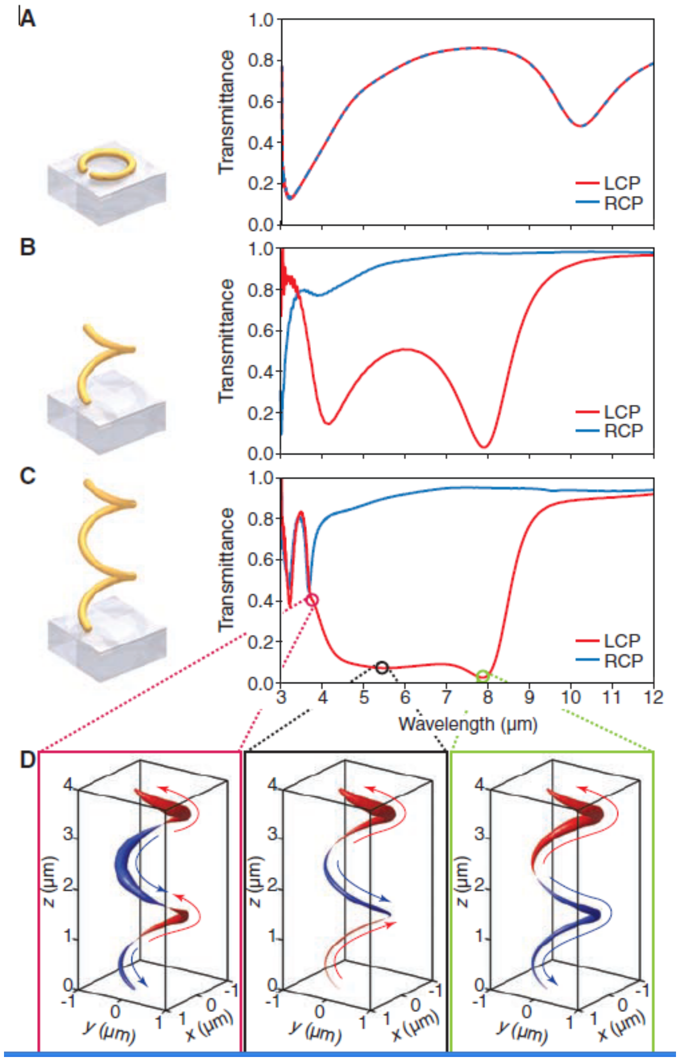
3D in the Meta-Atom Sense



Helgert, et al. Nano Letters **11**, 4400 (2011)



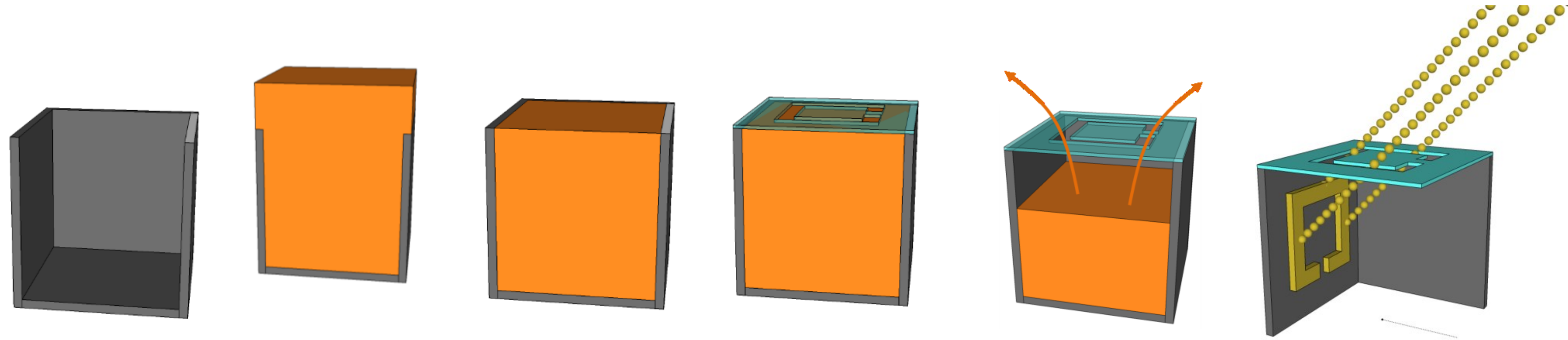
Kaelberer, et al. Science **330**, 1510 (2010)



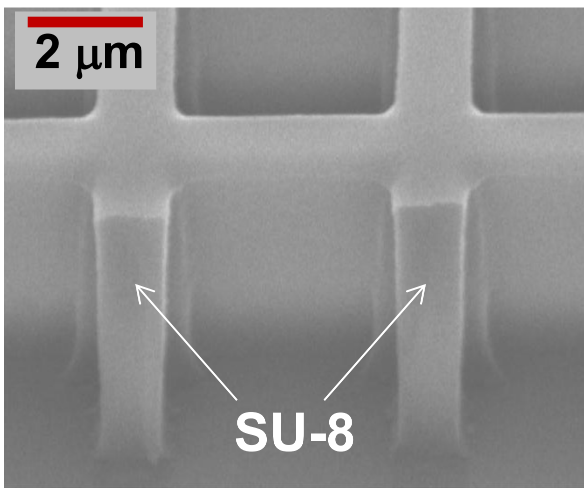
Gansel, et al. Science **325**, 1513 (2009)

Polymer-Based MPL

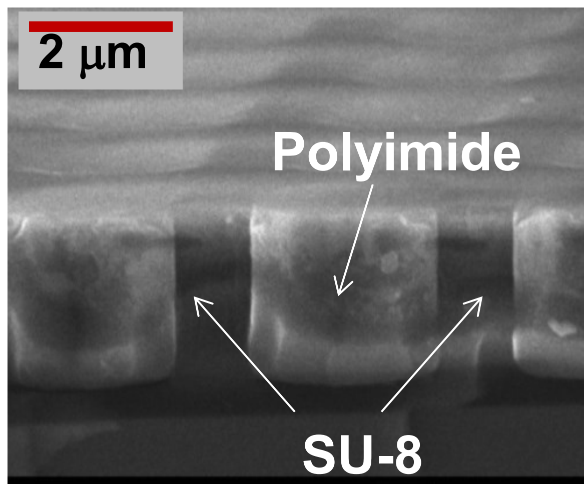
Polymer-Based MPL Process Flow



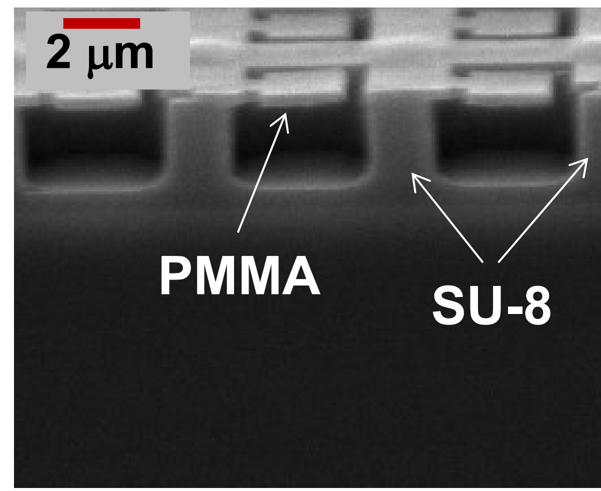
Create Cavity | Sacrificial Backfill | Planarize Backfill | Deposit/Pattern Membrane | Dissolve Out Backfill | Directional Processing



Create Cavity

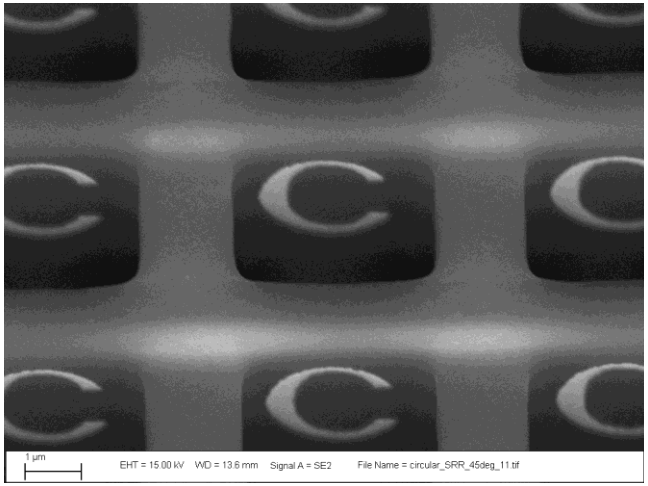


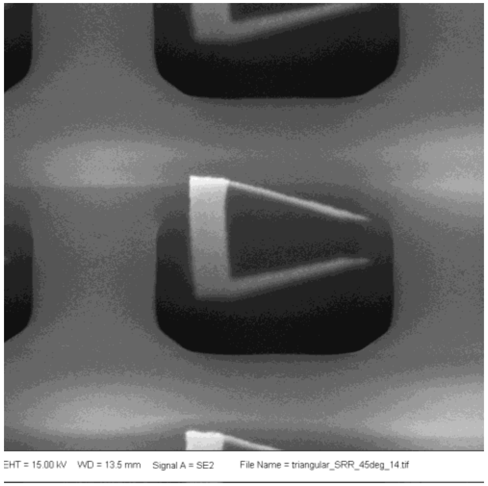
Planarize Backfill

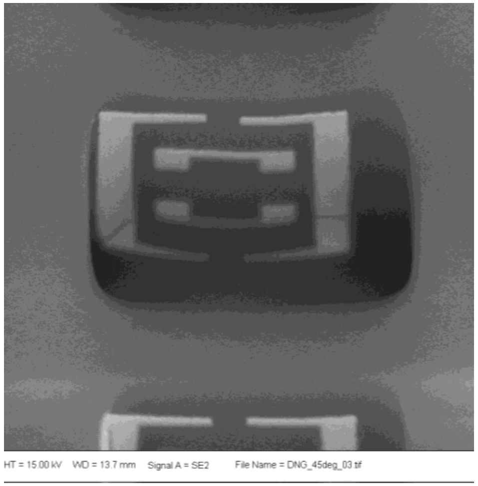


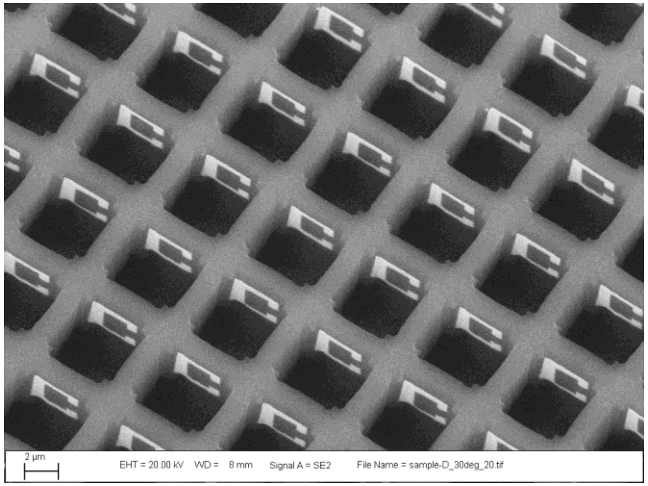
Dissolve Out Backfill

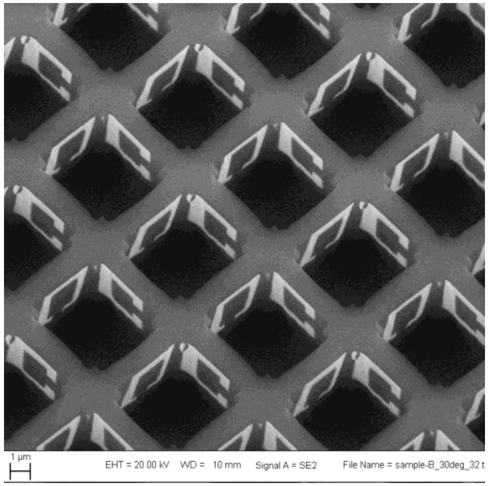
Polymer-Based MPL Structures

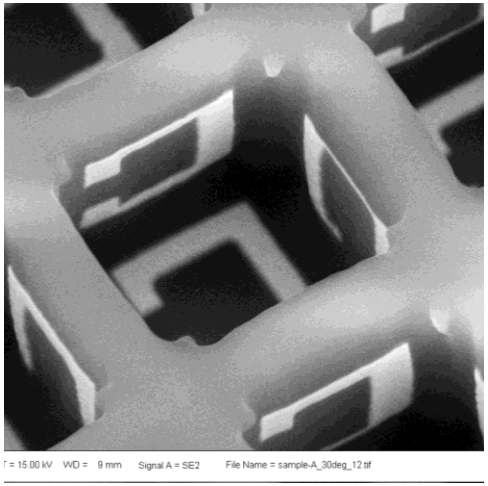




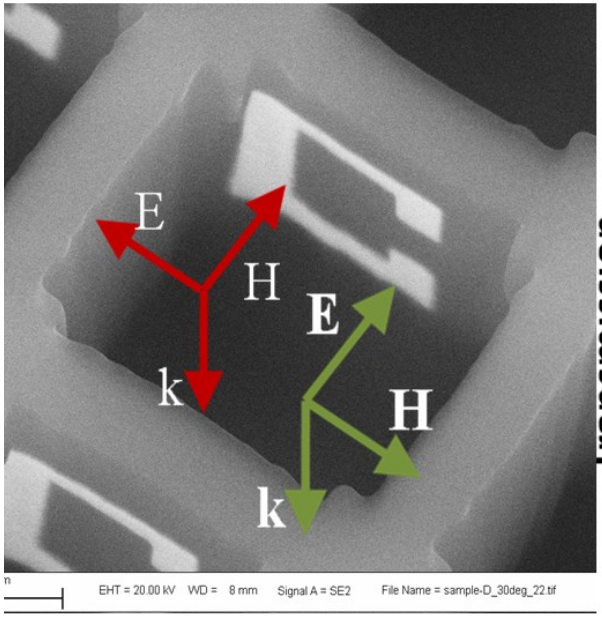


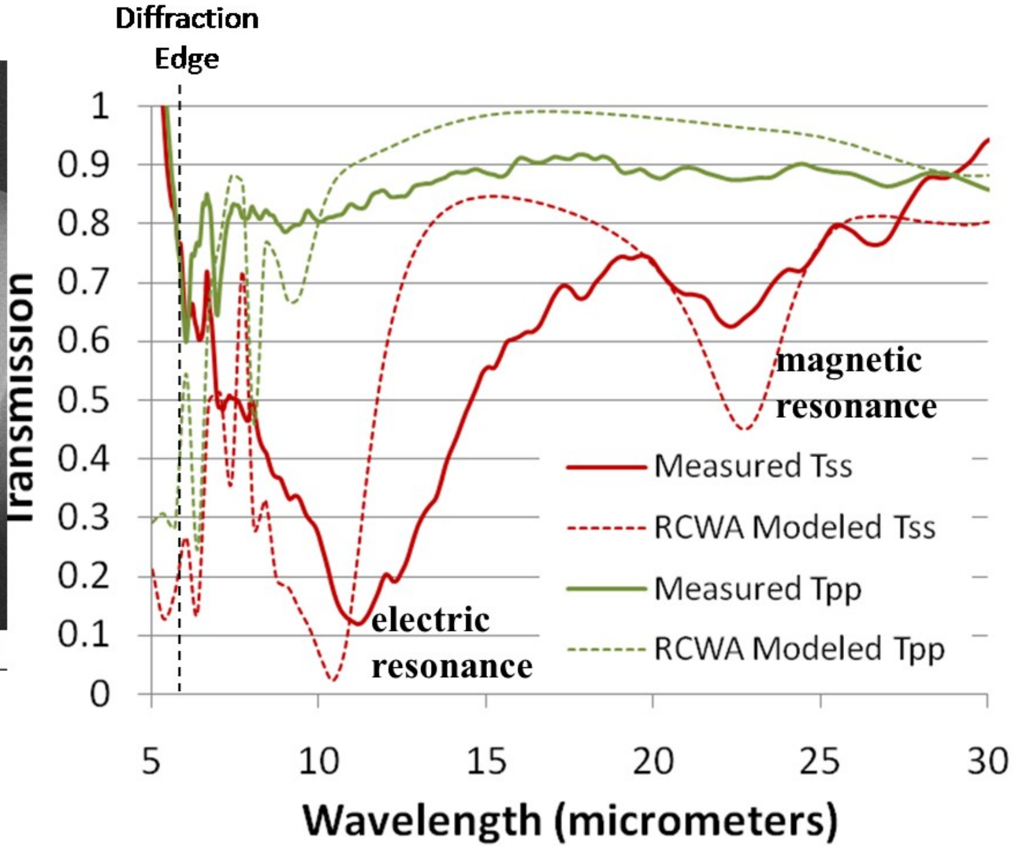






Polarized Transmission of Magnetically Excited SRR Array





S-polarization

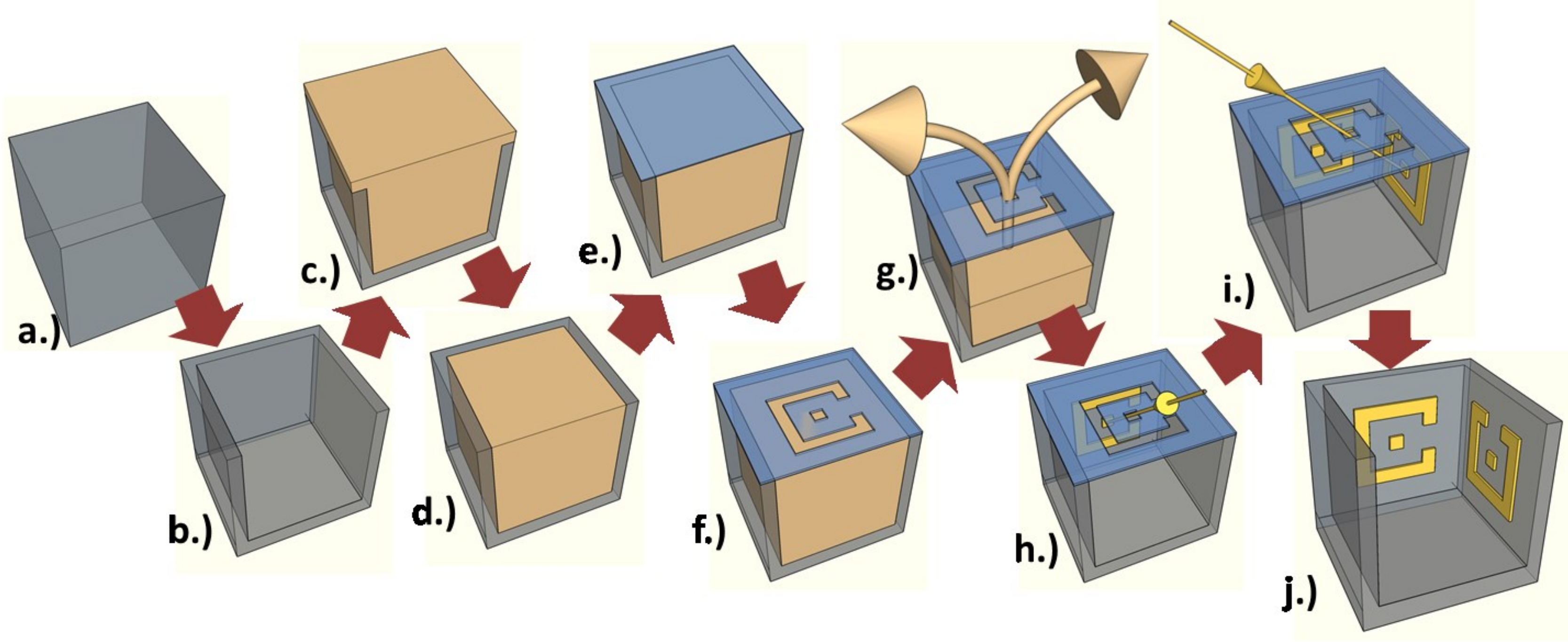
- B-field excites lowest SRR resonance --- magnetic excitation
- E-field excites second order resonance --- electric excitation

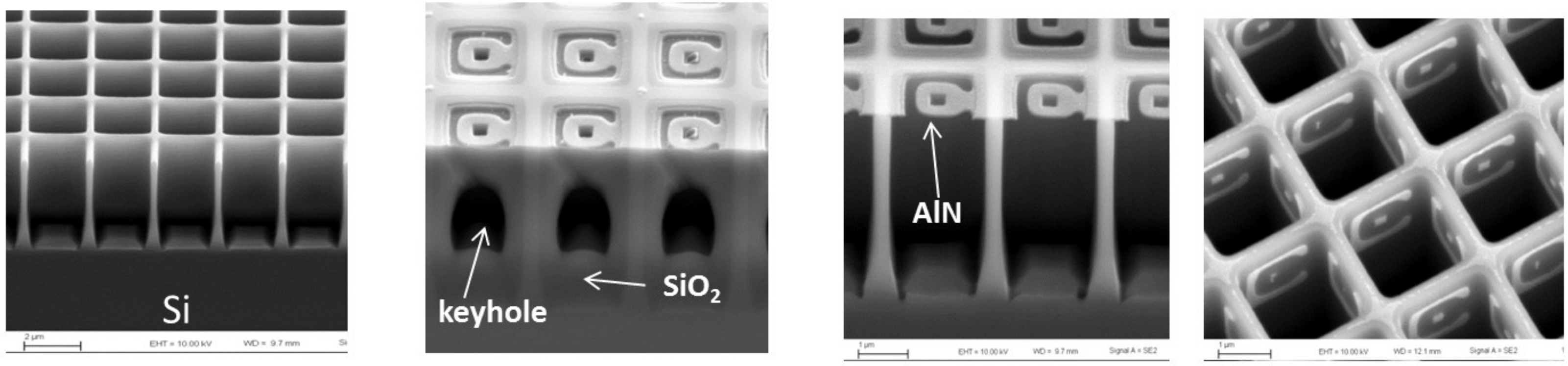
P-polarization

- can't couple to any SRR resonances

CMOS-Compatible MPL

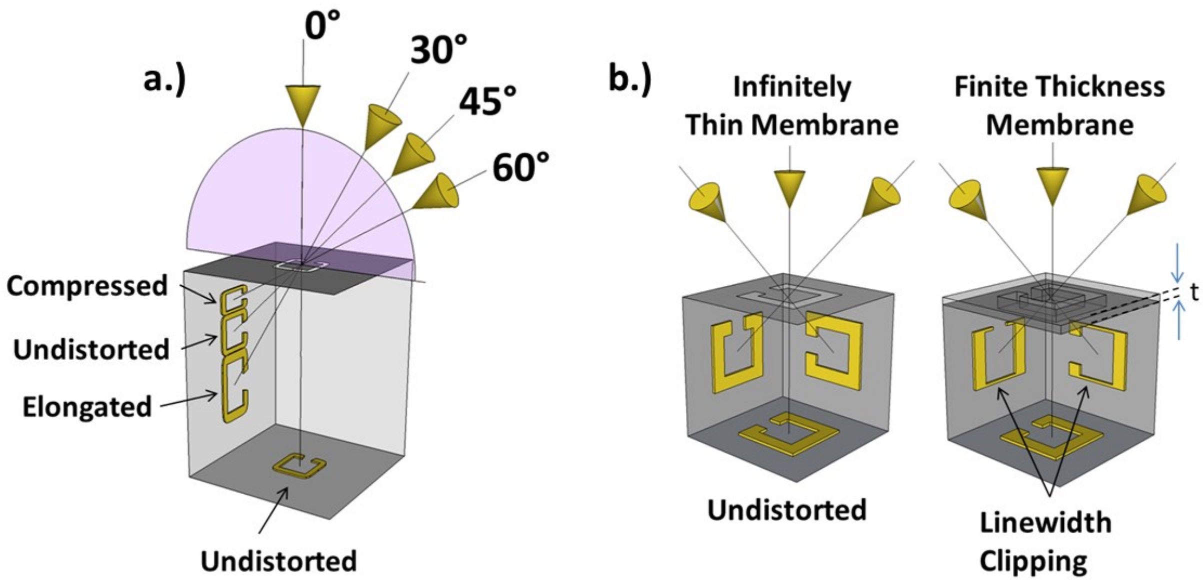
CMOS Compatible MPL

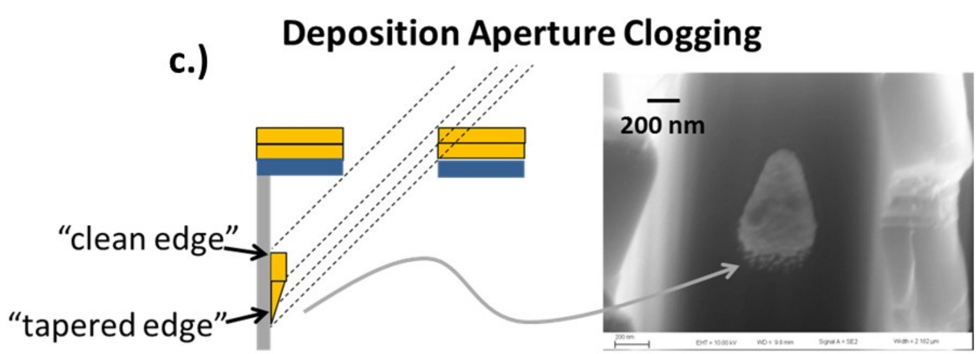




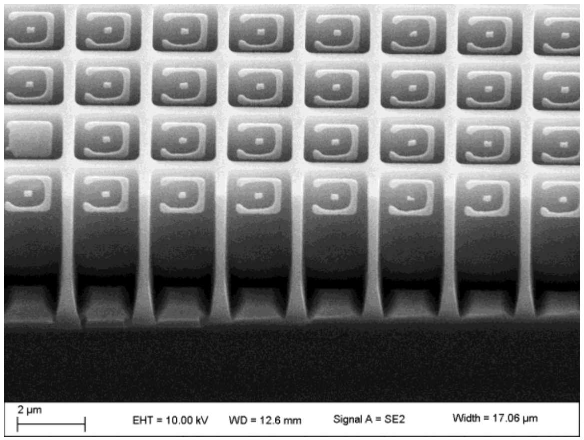
k.) l.) m.) n.)

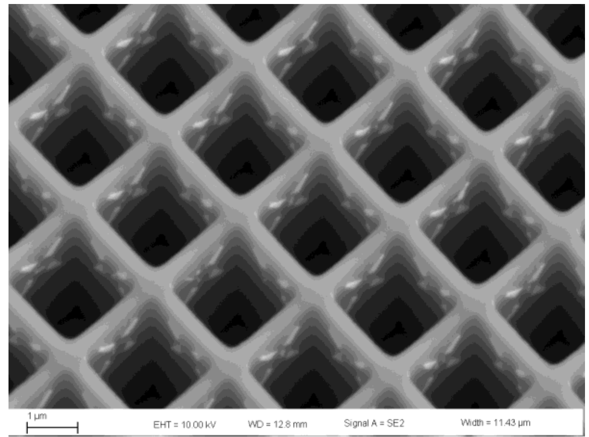
Sources of Pattern Distortion

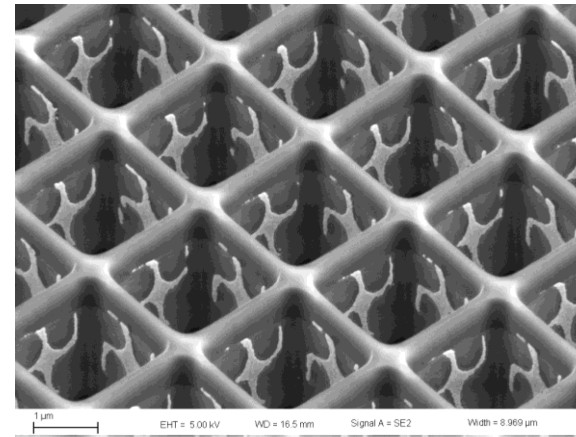


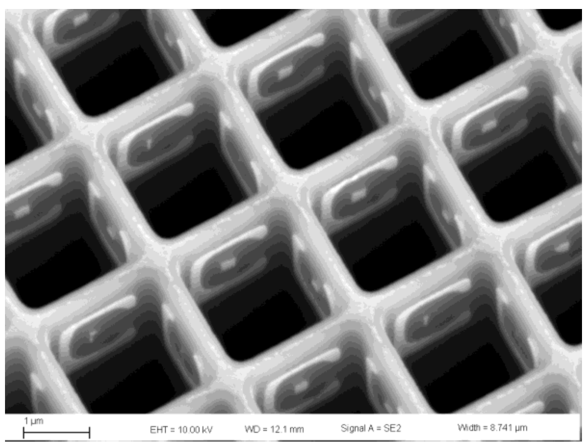


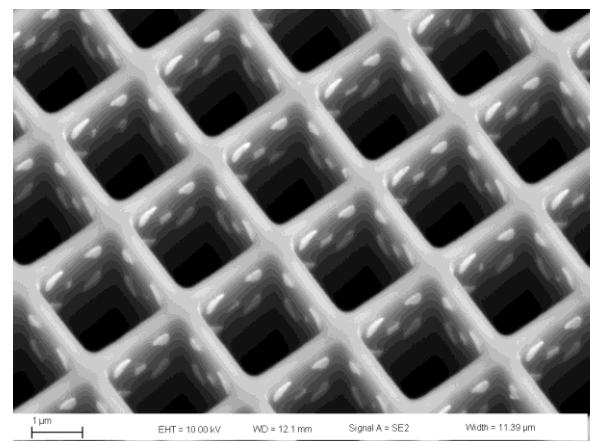
3D µm-scale Metamaterials



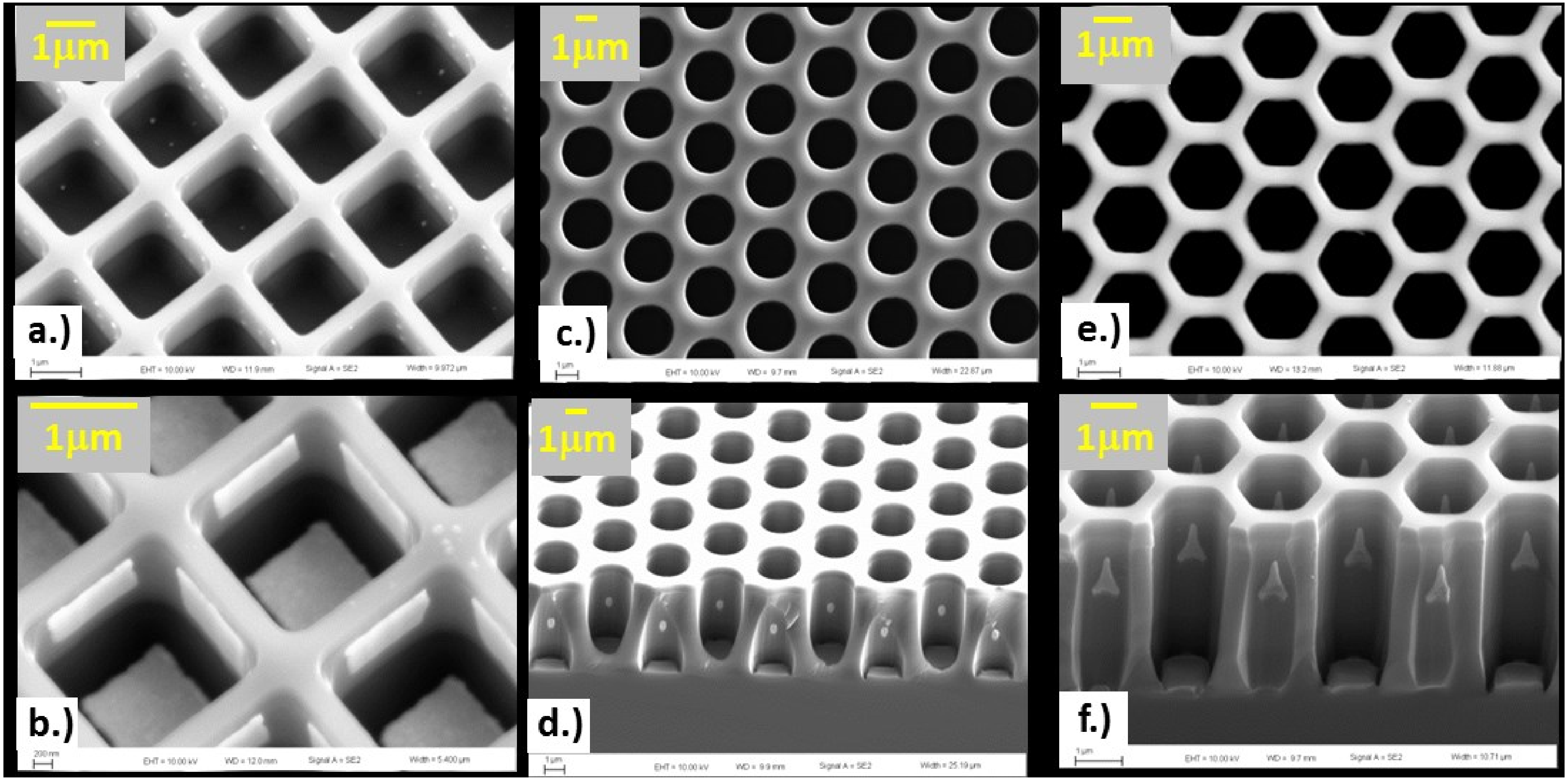








3D μm-scale Metamaterials



3D μm-scale Artificial Dielectrics

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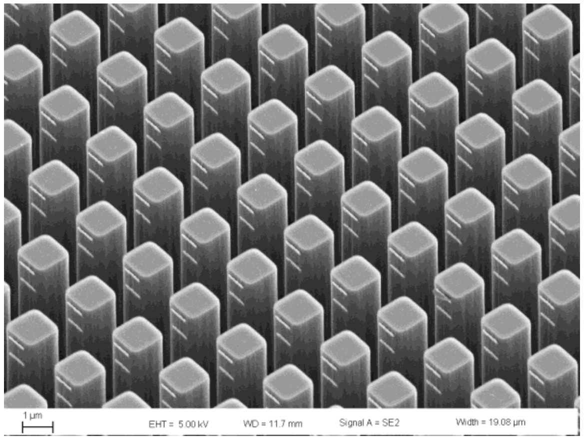
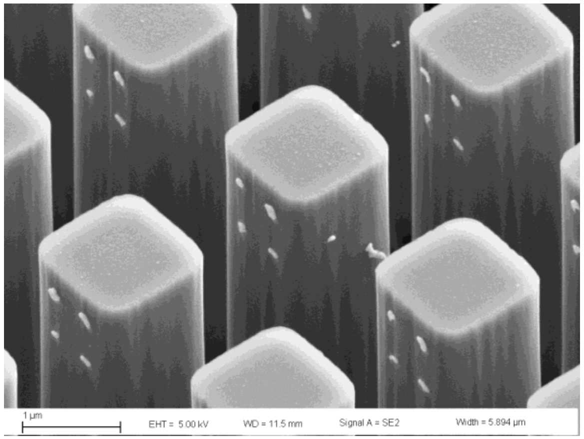
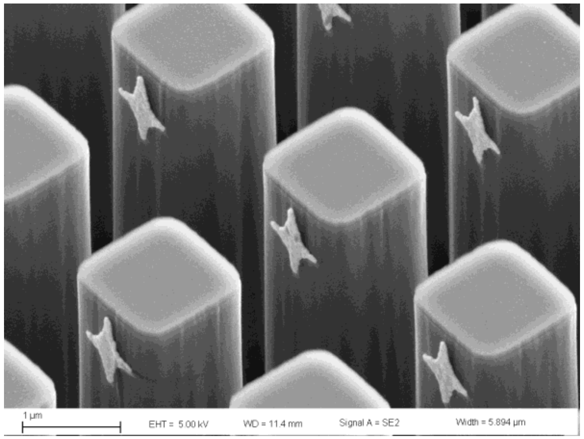
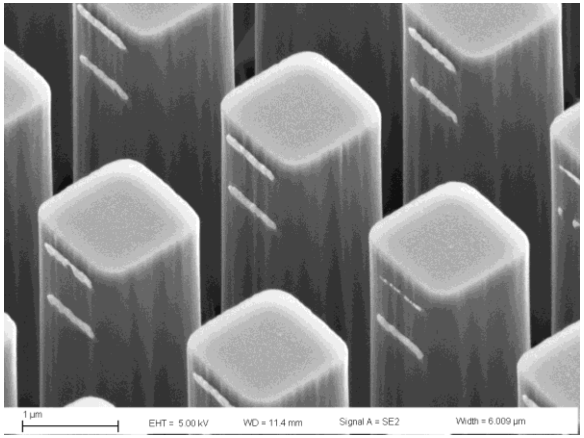
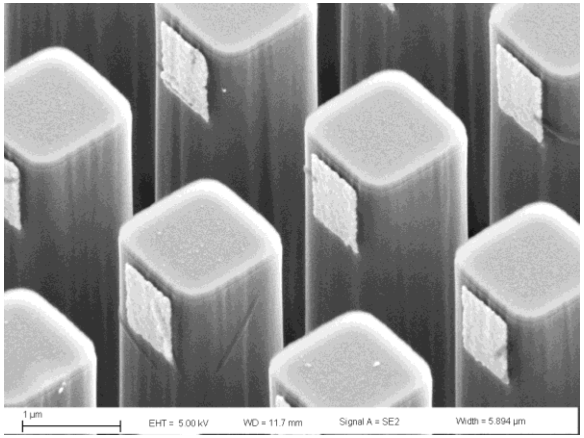
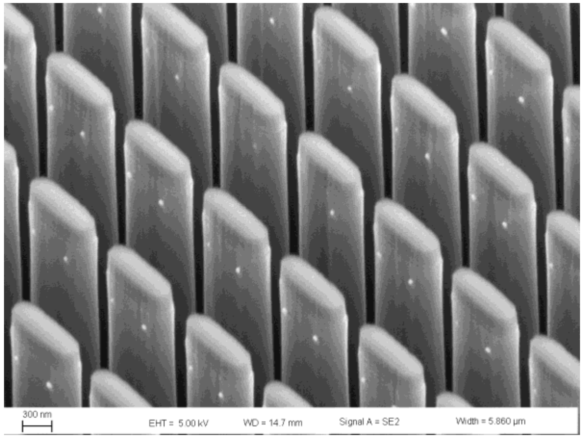




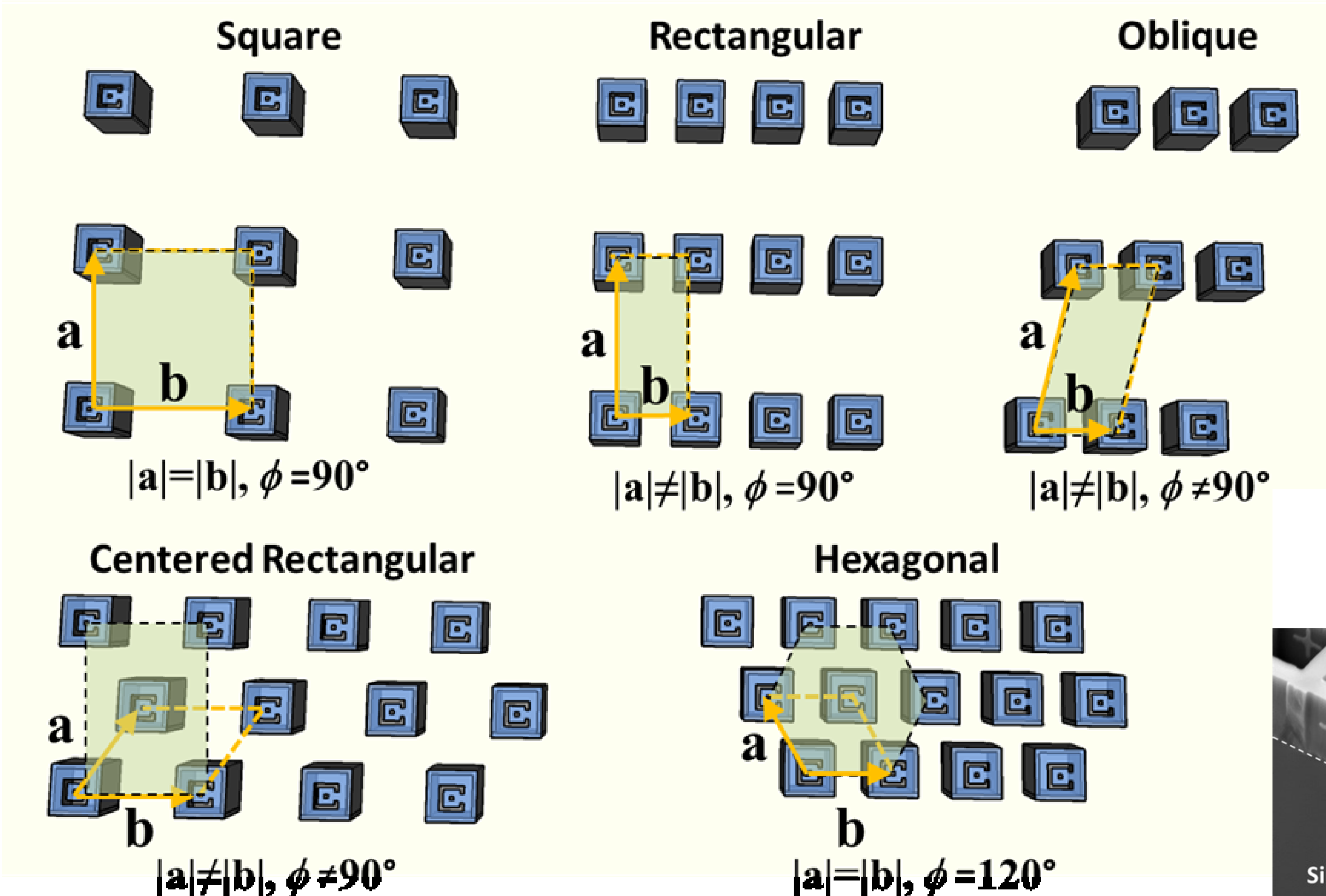








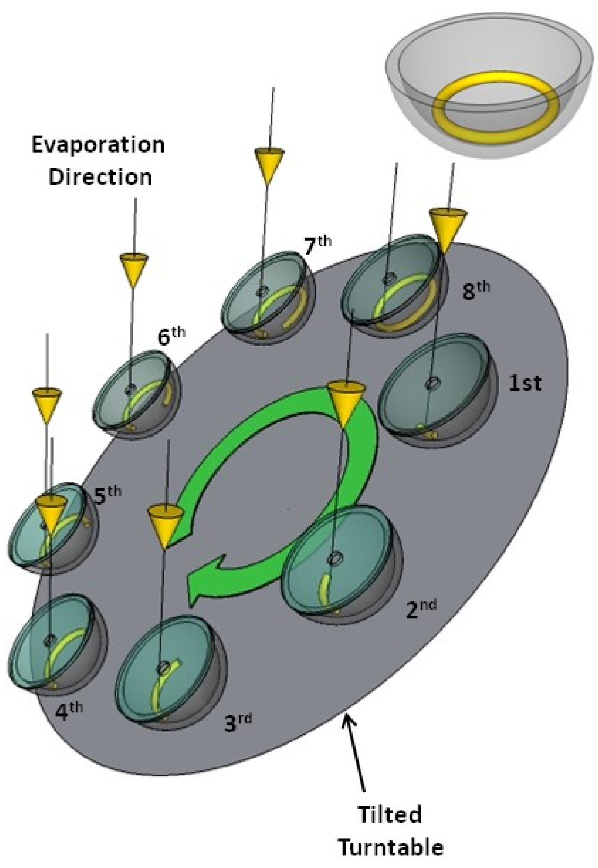
2-D Lattice + Basis



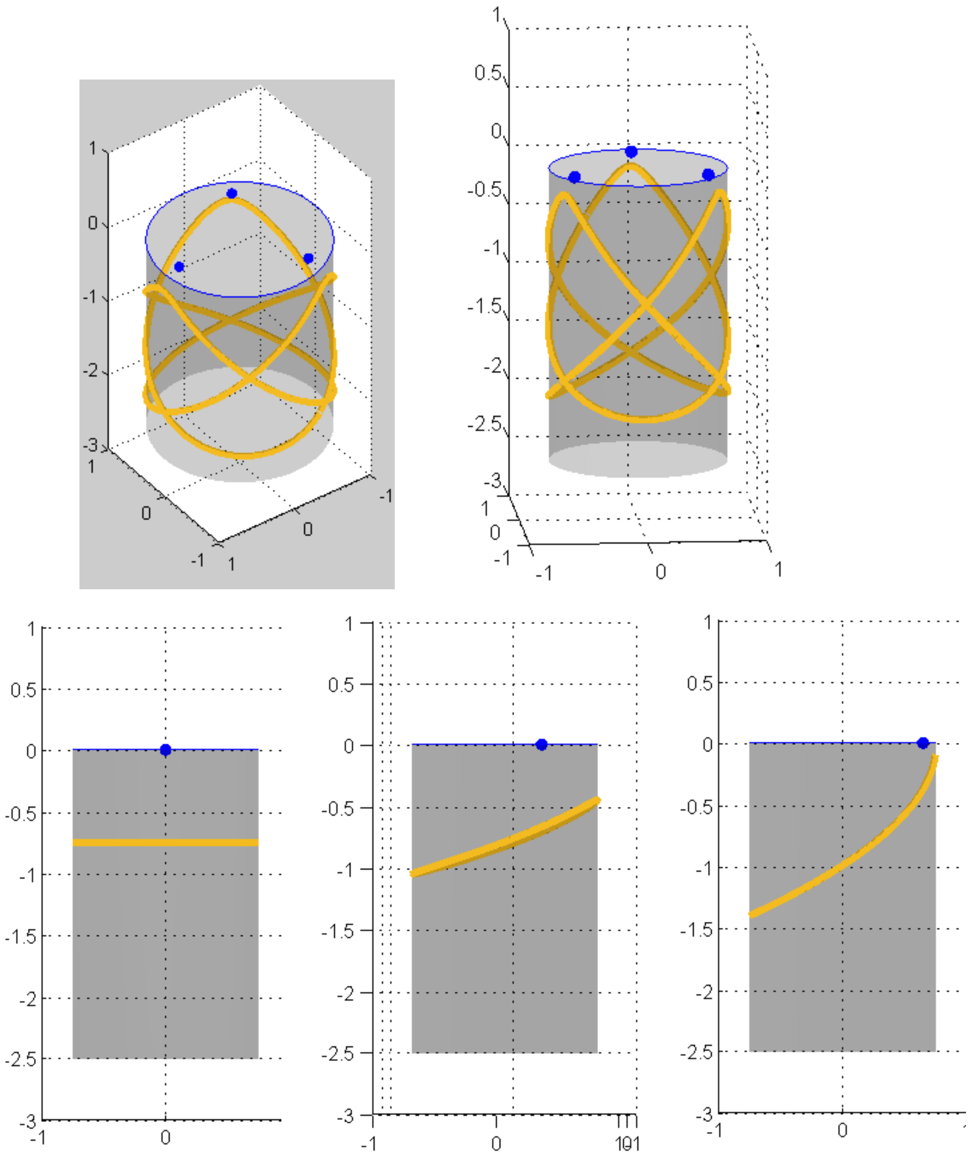
Path to all 14 3D Bravais Lattices?

Dynamic MPL

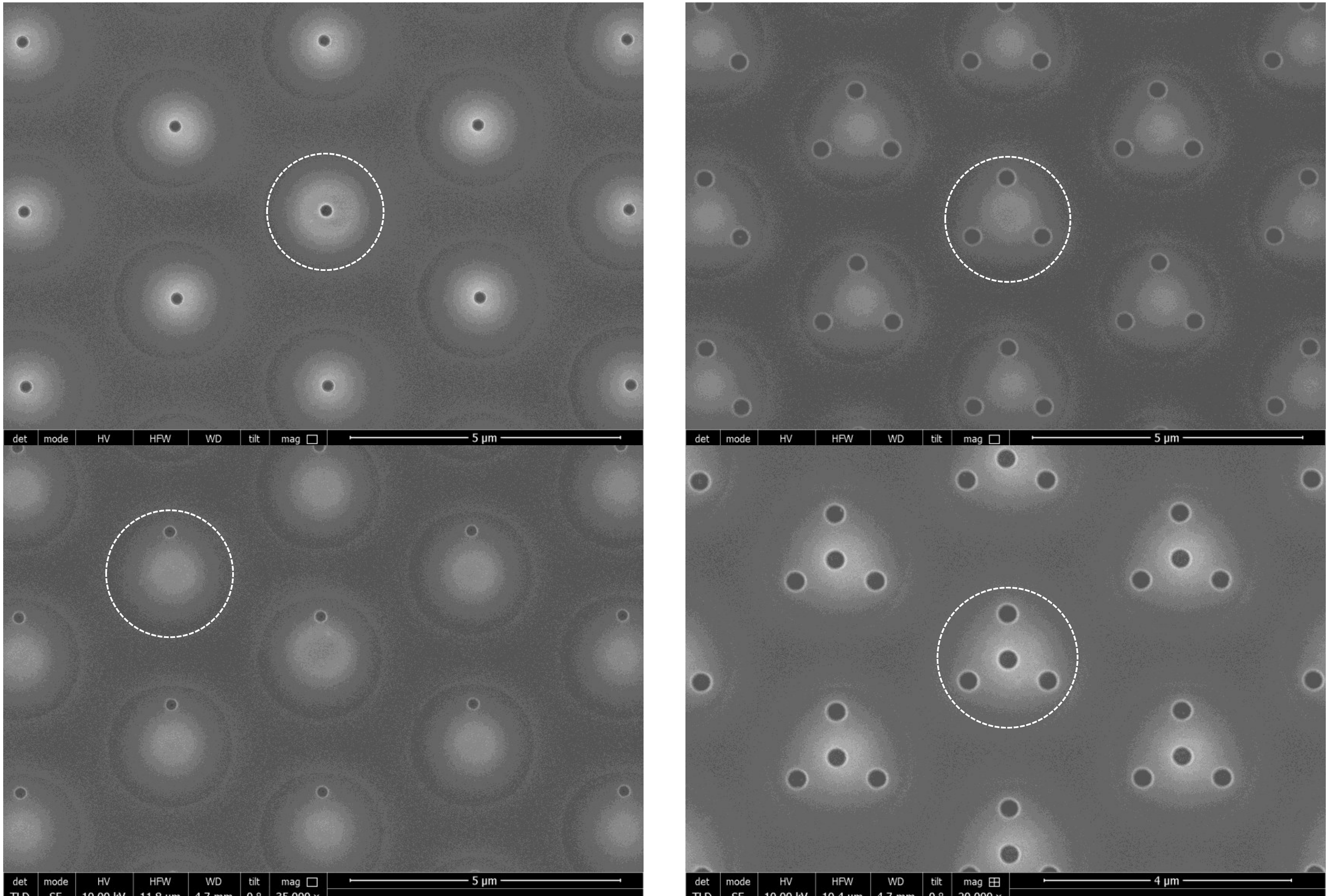
Dynamic MPL



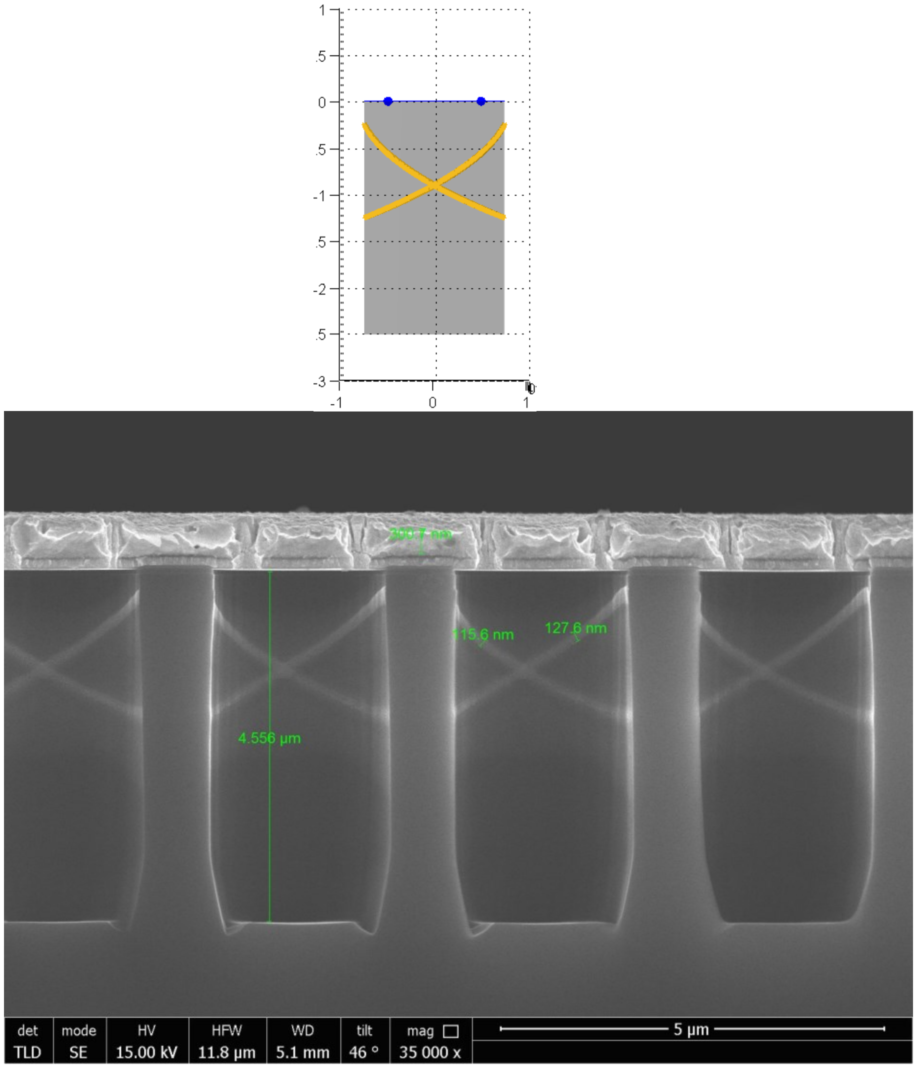
Evaporation Direction
7th
8th
6th
1st
5th
2nd
4th
3rd
Tilted Turntable



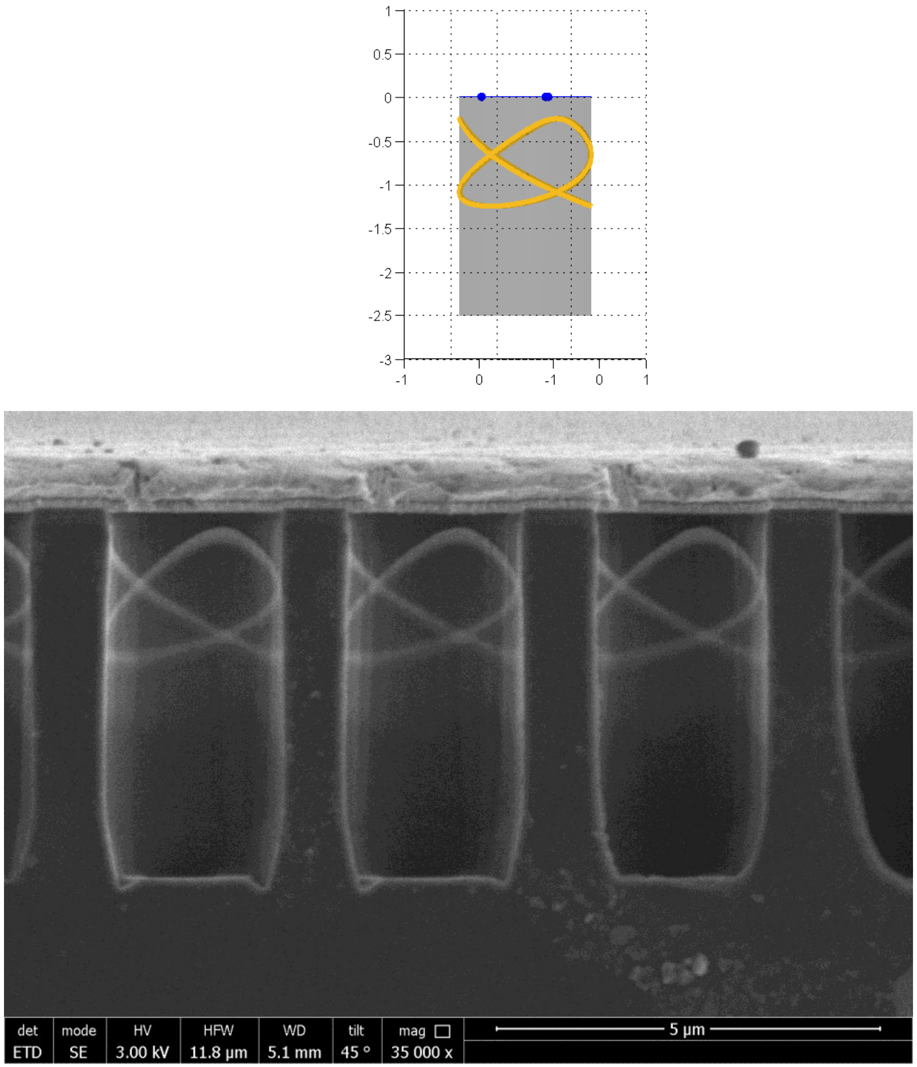
Dynamic MPL


det mode HV HFW WD tilt mag
5 µm
det mode HV HFW WD tilt mag
5 µm
det mode HV HFW WD tilt mag
TLD SE 10.00 kV 11.8 µm 4.7 mm 0 ° 35 000 x
5 µm
det mode HV HFW WD tilt mag
TLD SE 10.00 kV 10.4 µm 4.7 mm 0 ° 20 000 x
4 µm

Dynamic MPL



2- Aperture

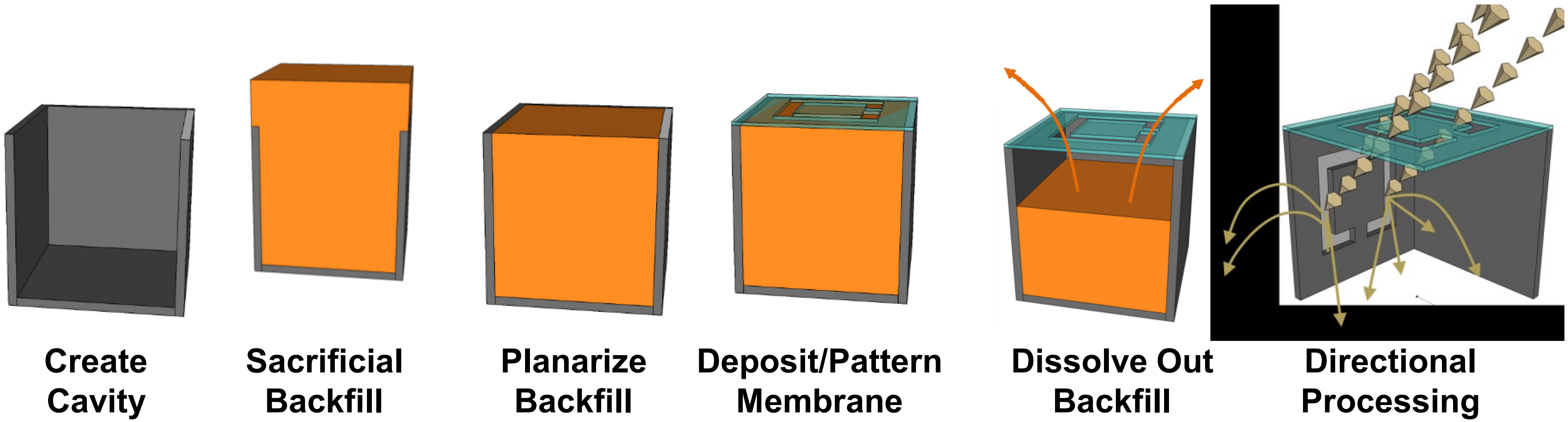


3- Aperture

Etching with MPL

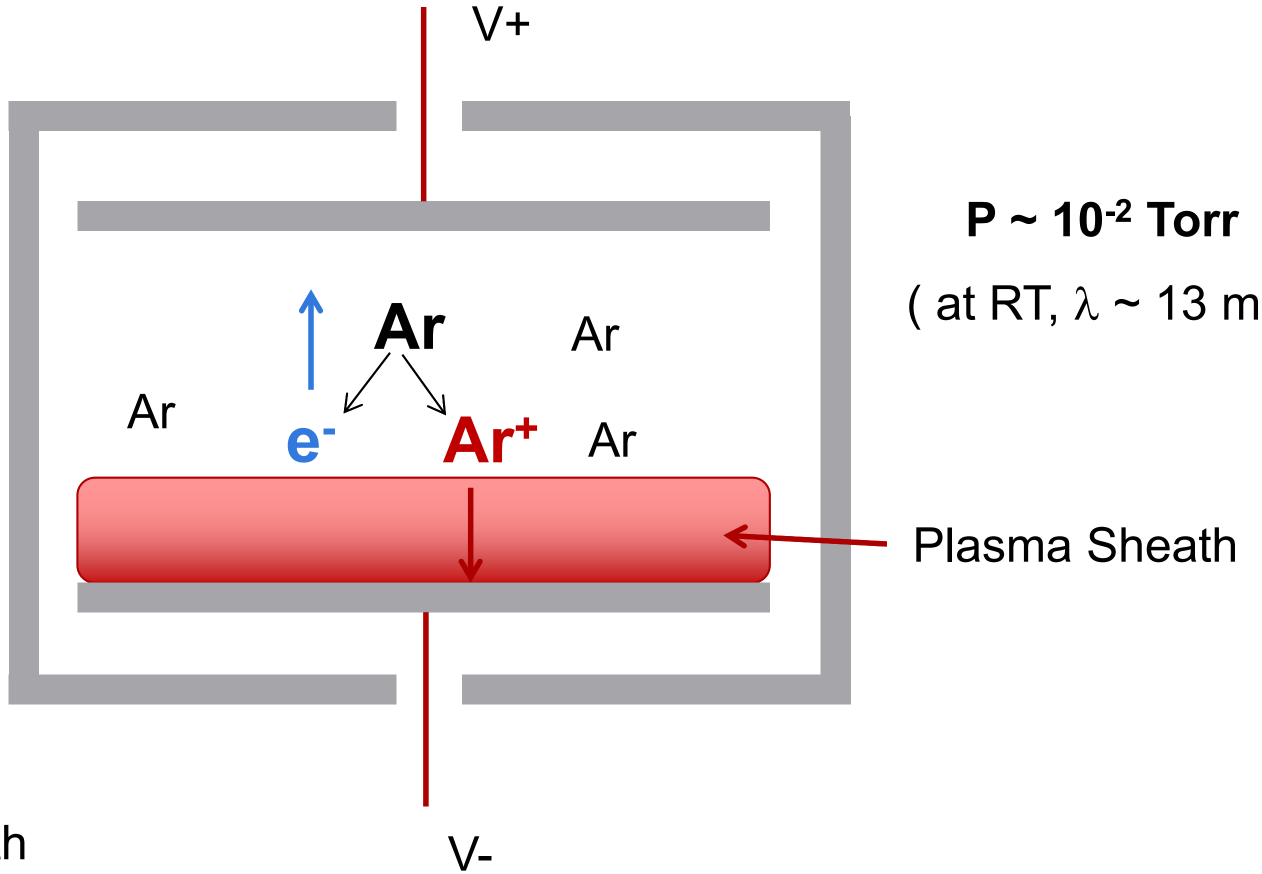
MPL Process Flow for Etching

Question: Since dry etching is also a low-pressure operation, can we directionally etch sidewalls in an MPL-centric process flow?



Directional Processing - Actual

Plasma Etching



P ~ 10^{-2} Torr

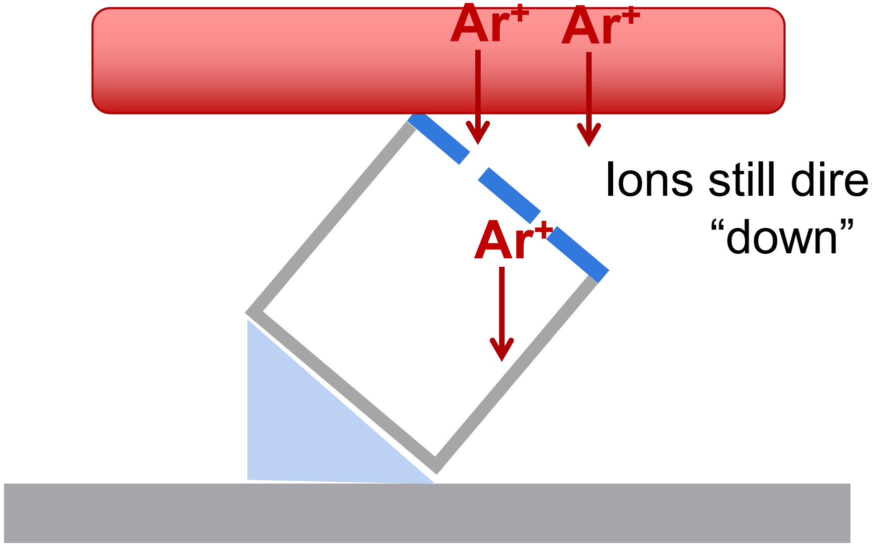
(at RT, λ ~ 13 mm)

Most of the voltage drop occurs across the plasma sheath located at the platen

Plasma Sheath Conforms to Die

What You Would Like

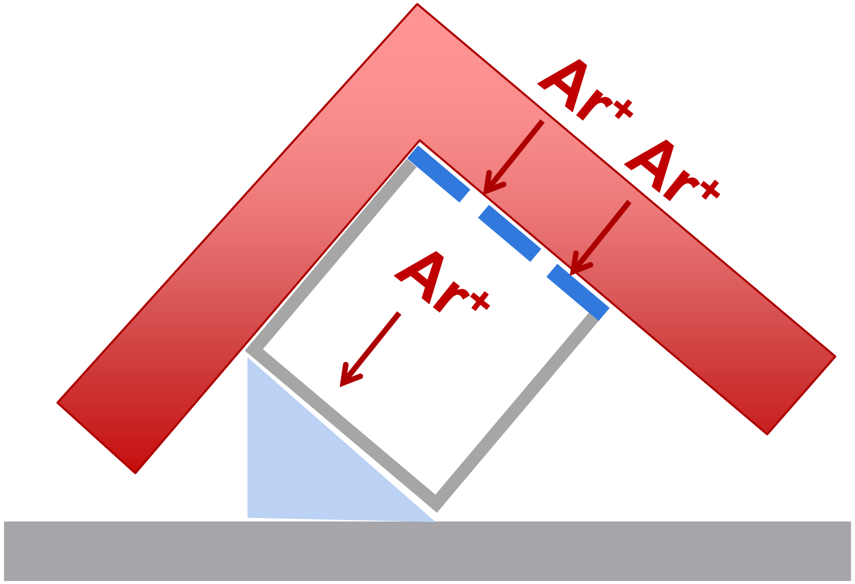
Unperturbed plasma sheath



Ions still directed "down"

What You Get

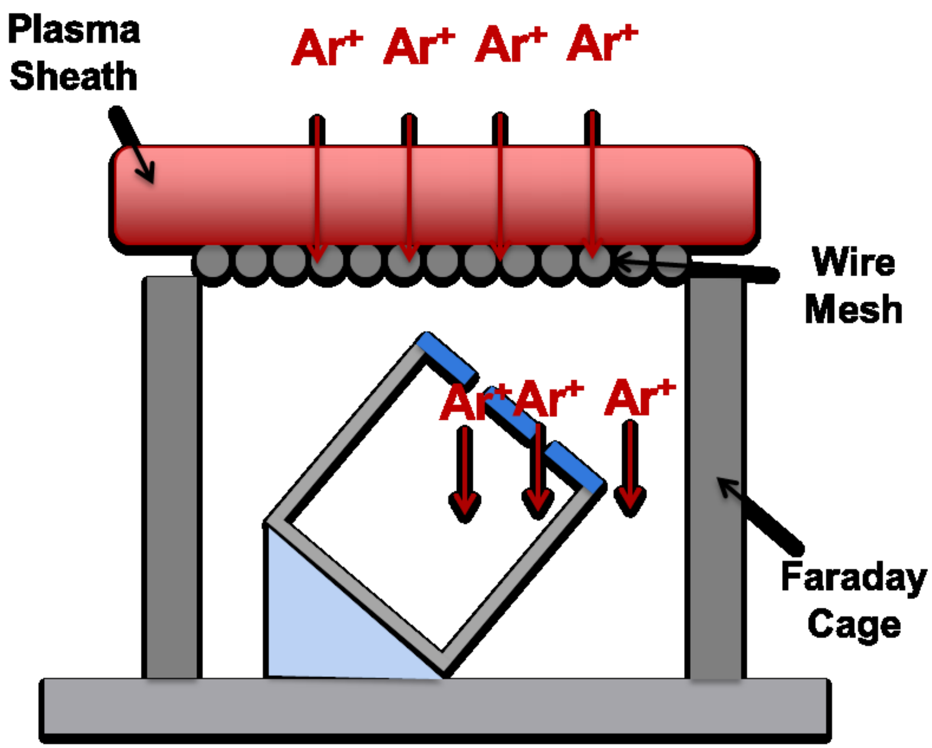
Plasma sheath conforms to tilted die



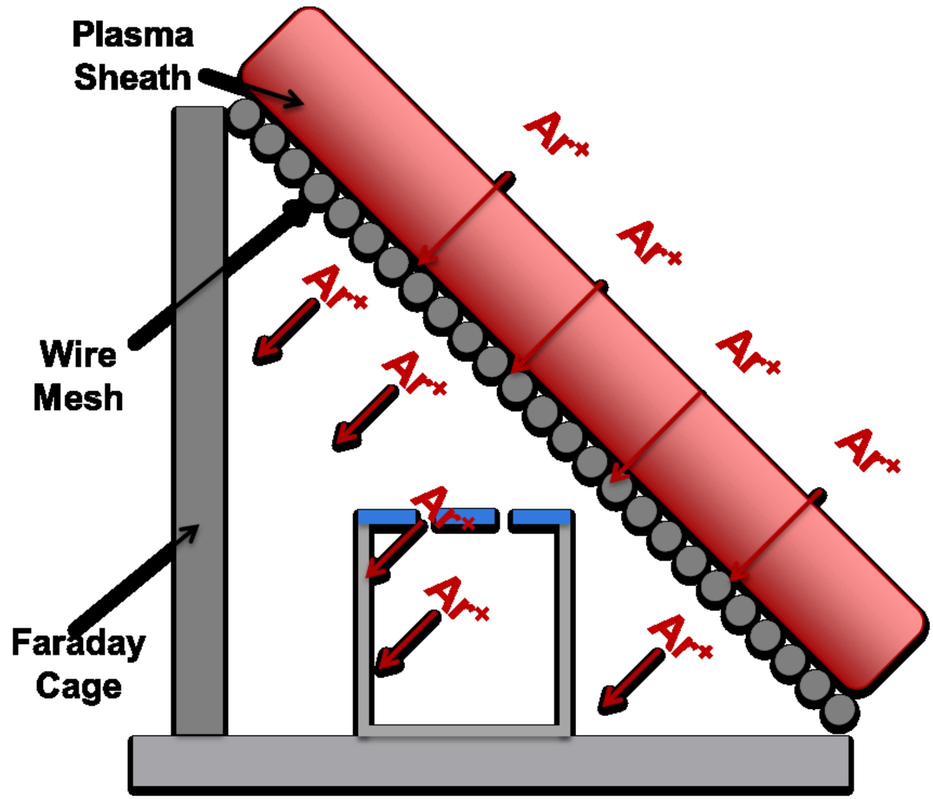
Ions tilted wrt platen -
still predominately etch floor

Use Faraday Cage to Reorient The Plasma Sheath

Planar Faraday Cage



Tilted Faraday Cage

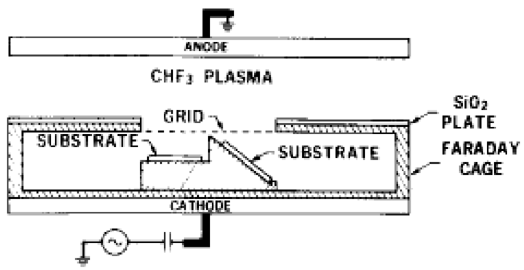


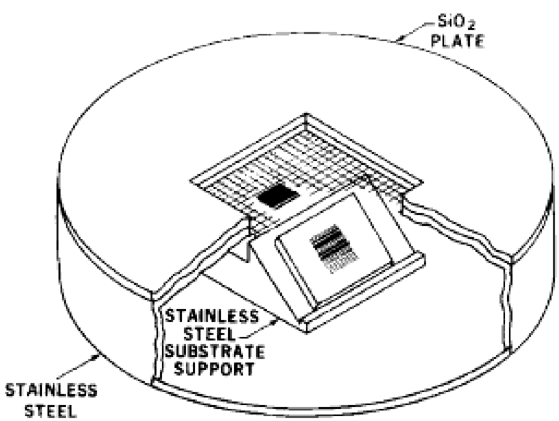
Oblique Directional Etching in the Literature

Directional reactive ion etching at oblique angles

G. D. Boyd, L. A. Coldren, and F. G. Storz
Bell Laboratories, Holmdel, New Jersey 07733

(Received 13 December 1979; accepted for publication 24 January 1980)

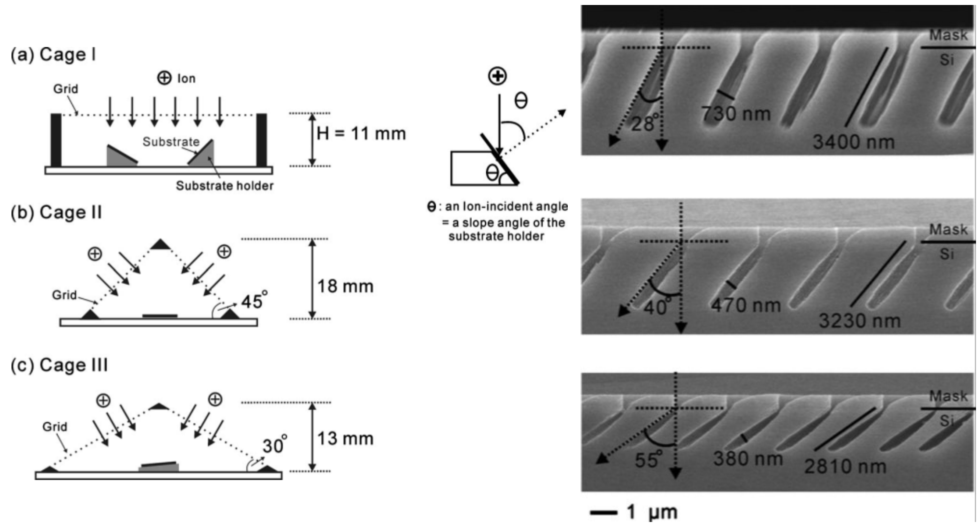


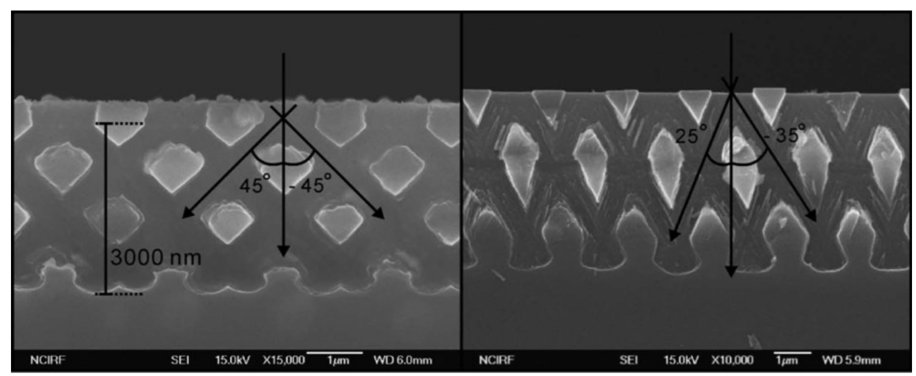


D222 Journal of The Electrochemical Society, 156 (7) D222-D225 (2009)
0013-4651/2009/156(7)/D222/4/$25.00 © The Electrochemical Society

Oblique-Directional Plasma Etching of Si Using a Faraday Cage

Jin-Kwan Lee,[a] Seung-Haeng Lee,[a] Jae-Ho Min,[a] Il-Yong Jang,[a] Chang-Koo Kim,[b,*] and Sang Heup Moon[a,z]



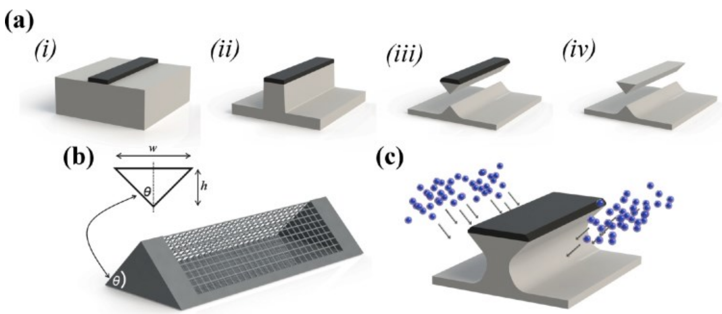


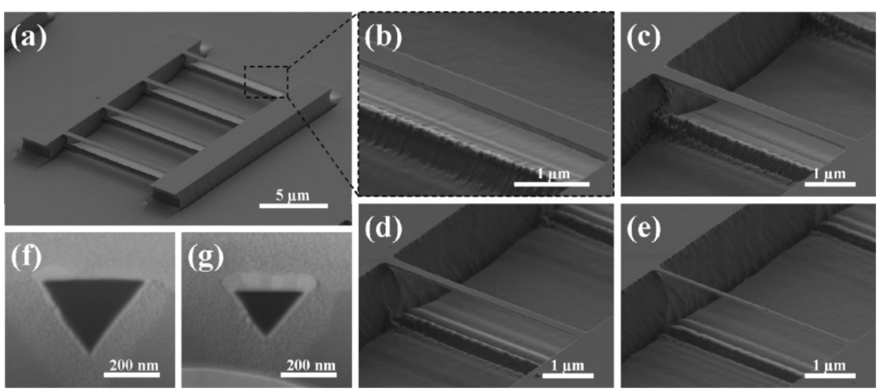
Oblique Directional Etching in the Literature

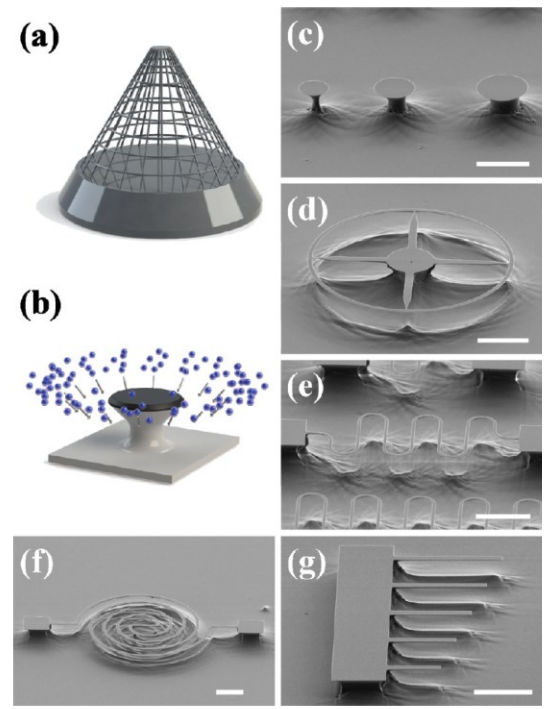
NANO LETTERS
Letter
pubs.acs.org/NanoLett

Free-Standing Mechanical and Photonic Nanostructures in Single-Crystal Diamond

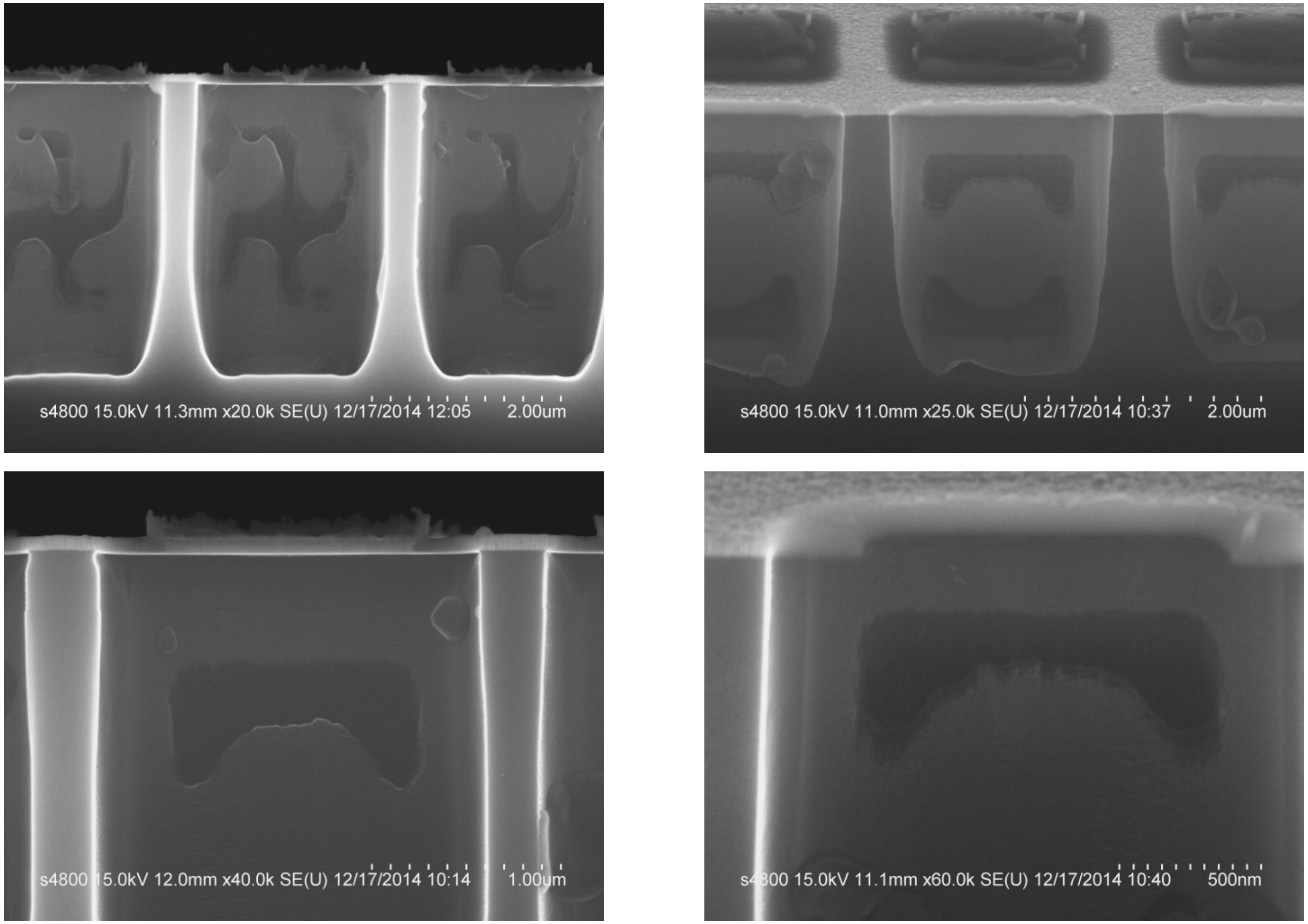
Michael J. Burek,[†] Nathalie P. de Leon,[‡,§] Brendan J. Shields,[‡] Birgit J. M. Hausmann,[†] Yiwen Chu,[‡] Qimin Quan,[†] Alexander S. Zibrov,[‡] Hongkun Park,[†,§] Mikhail D. Lukin,[‡] and Marko Lončar*,[†]





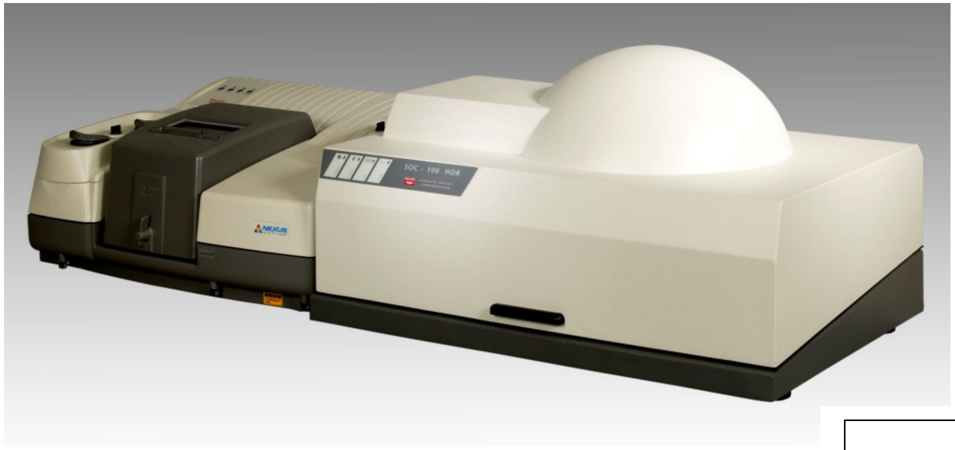


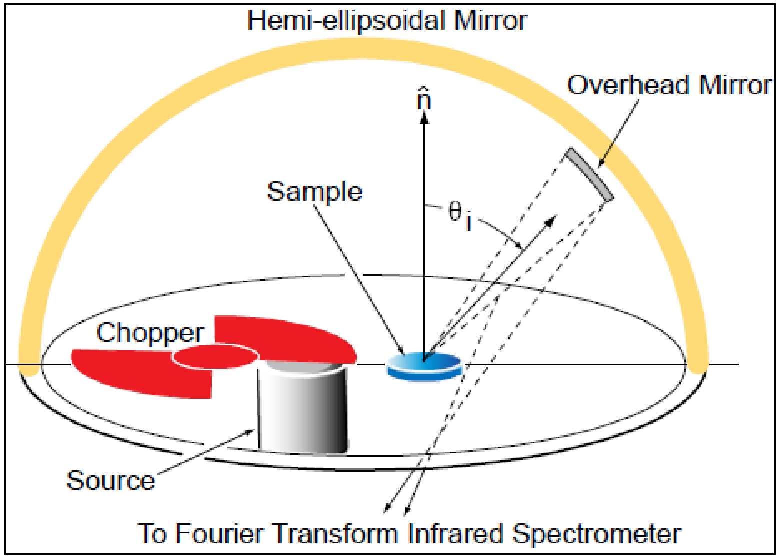
MPL-Etching


s4800 15.0kV 11.3mm x20.0k SE(U) 12/17/2014 12:05 2.00um
s4800 15.0kV 11.0mm x25.0k SE(U) 12/17/2014 10:37 2.00um
s4800 15.0kV 12.0mm x40.0k SE(U) 12/17/2014 10:14 1.00um
s4800 15.0kV 11.1mm x60.0k SE(U) 12/17/2014 10:40 500nm

Optical Characterization

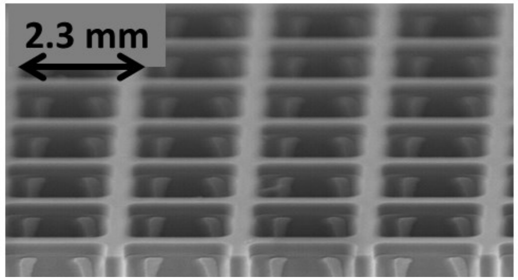
Hemispherical Directional Reflectometer

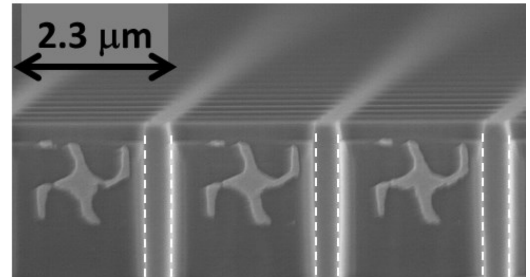


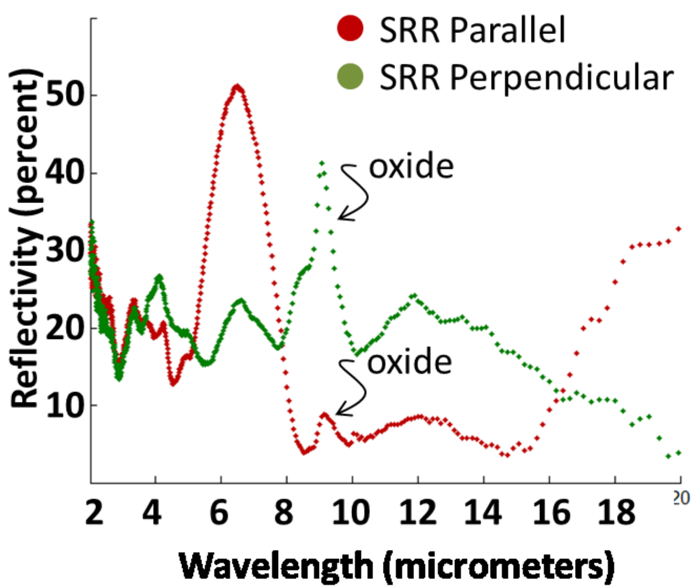


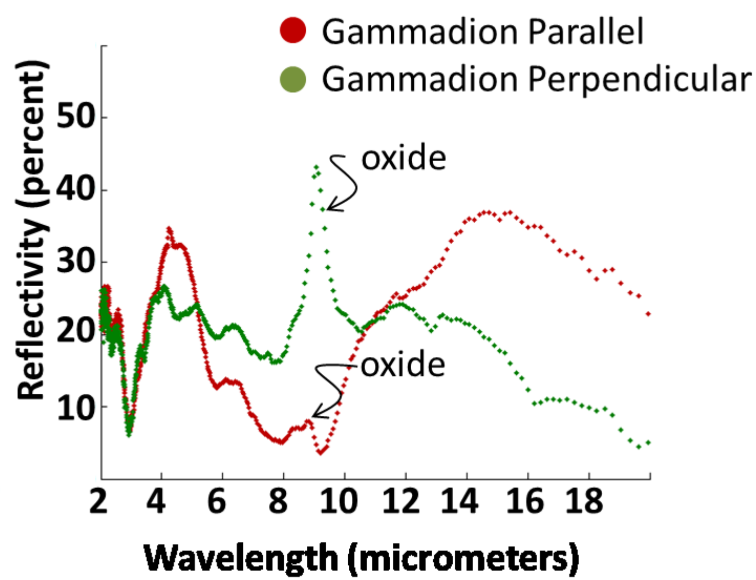
Polarization Dependent Reflectivity

Sandia National Laboratories



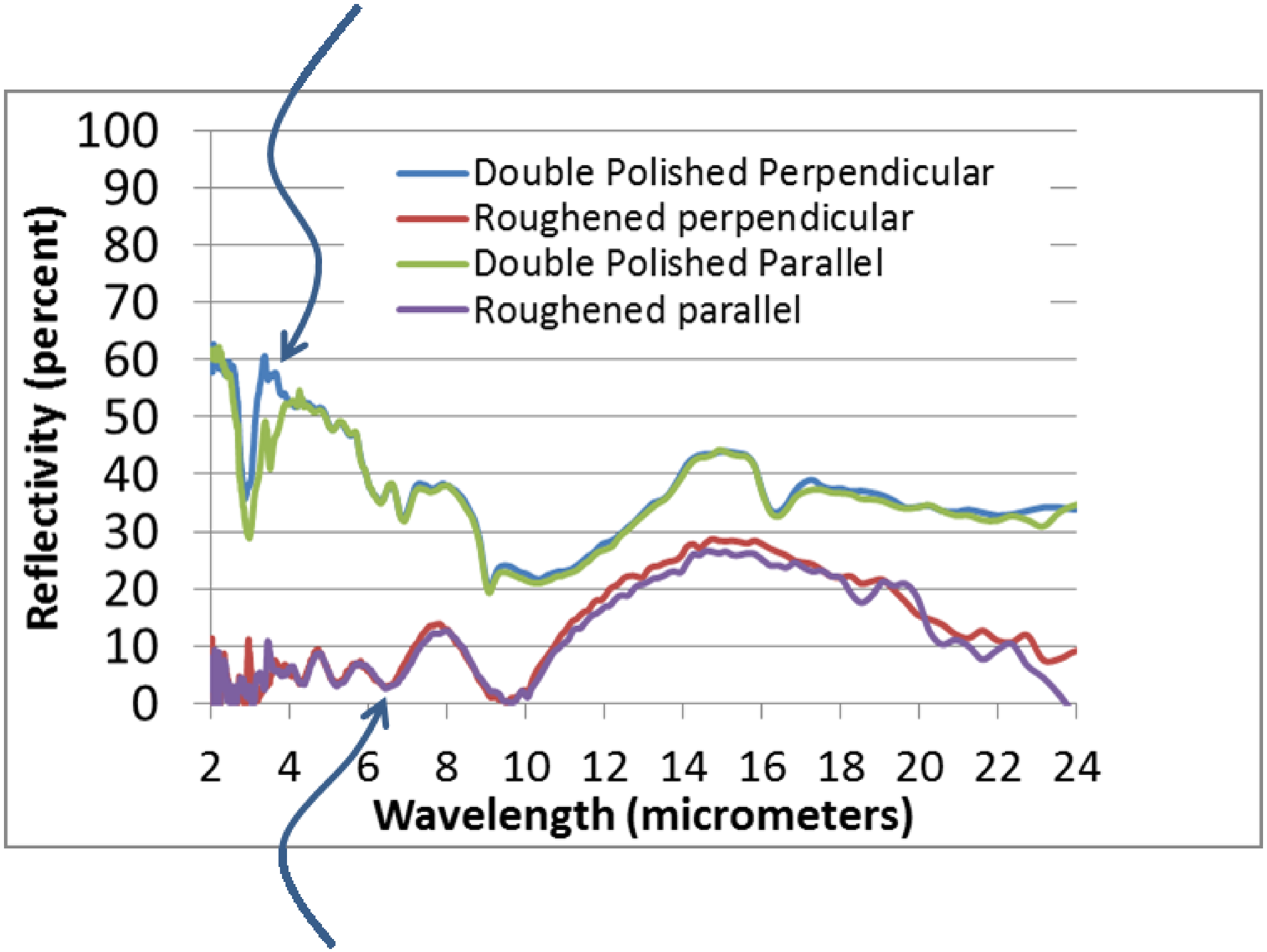






Measured Data – Naked Boxes

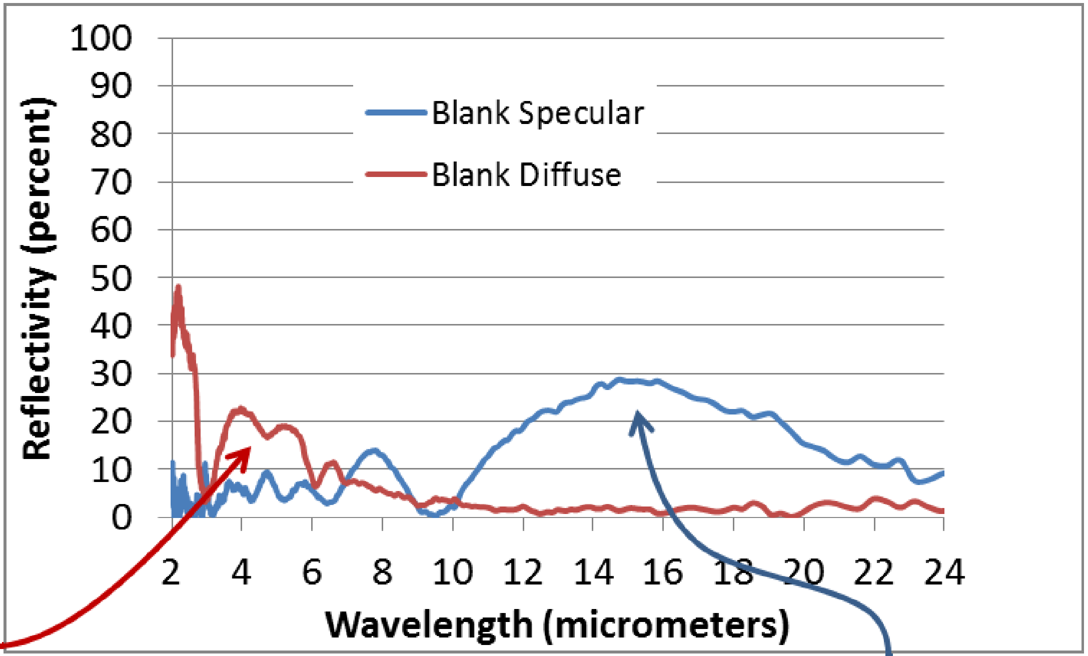
Total reflectivity = Diffuse + Specular Signals



Specular reflectivity

Measured Data – Naked Boxes

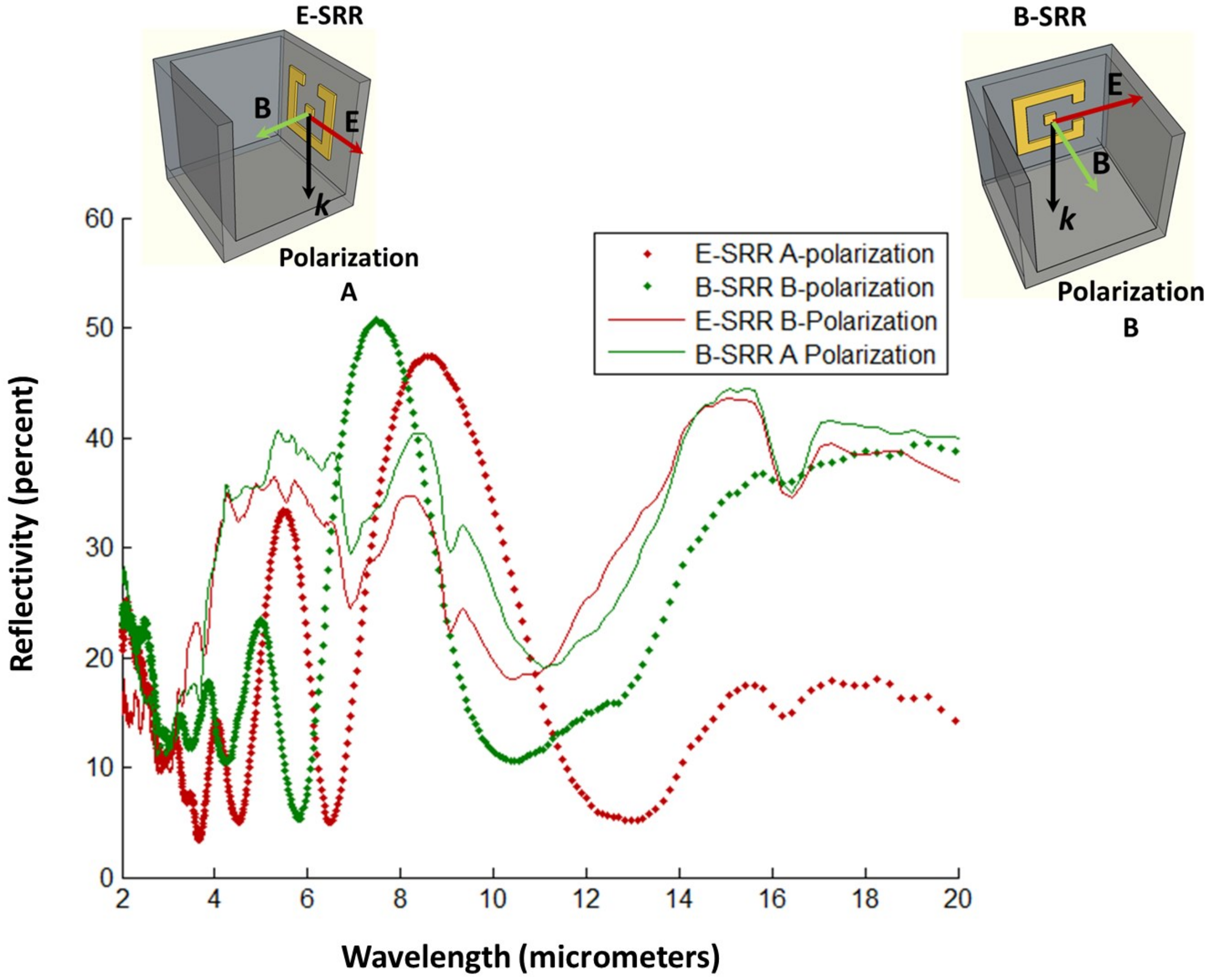
Roughened Back



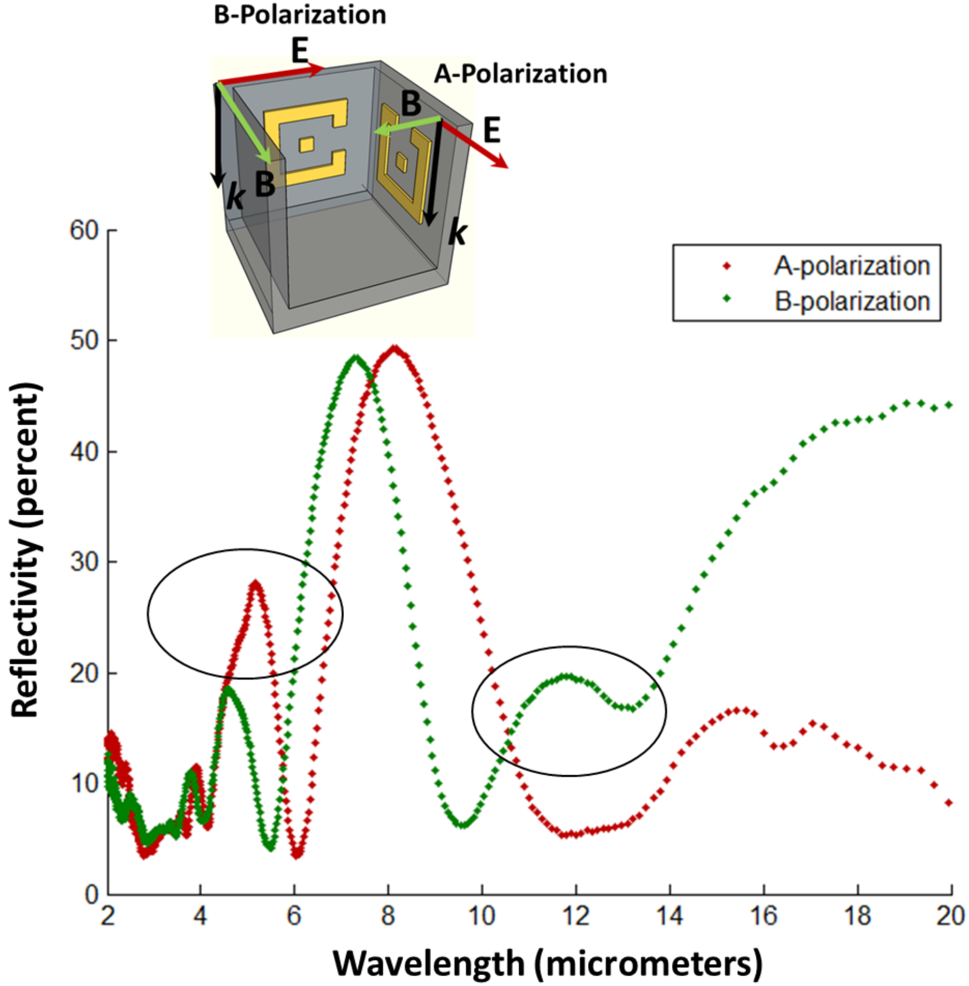
Diffuse signal carries significantly more energy at short wavelengths than specular (diffraction + scatter)

Specular signal carries significantly more energy at long wavelengths than diffuse

Polarization Dependent Reflectivity



2-SRR Basis



B-Polarization
E
A-Polarization
B
E
B
k
k
A-polarization
B-polarization
Reflectivity (percent)
Wavelength (micrometers)
0
10
20
30
40
50
60
2
4
6
8
10
12
14
16
18
20

Conclusions

- MPL is capable of creating all 5 2D-Bravais Lattices.
- Using Layer-by-layer techniques access to all 14 3D-Bravais Lattices is possible.
- Dynamic MPL is capable of creating complex 3D traces inside the unit cell.
- MPL can be extended to etching using a Faraday cage.
- CMOS compatible structures show significantly reduced material absorption and obvious polarization dependent resonances.
- Roughening the backside is important to remove contribution of backside scattering in silicon substrate due to IR transparency of silicon.

Collaborators : Patrick S. Finnegan, Paul Davids, M. David Henry, Rob L. Jarecki, and Paul J. Resnick

QUESTIONS?

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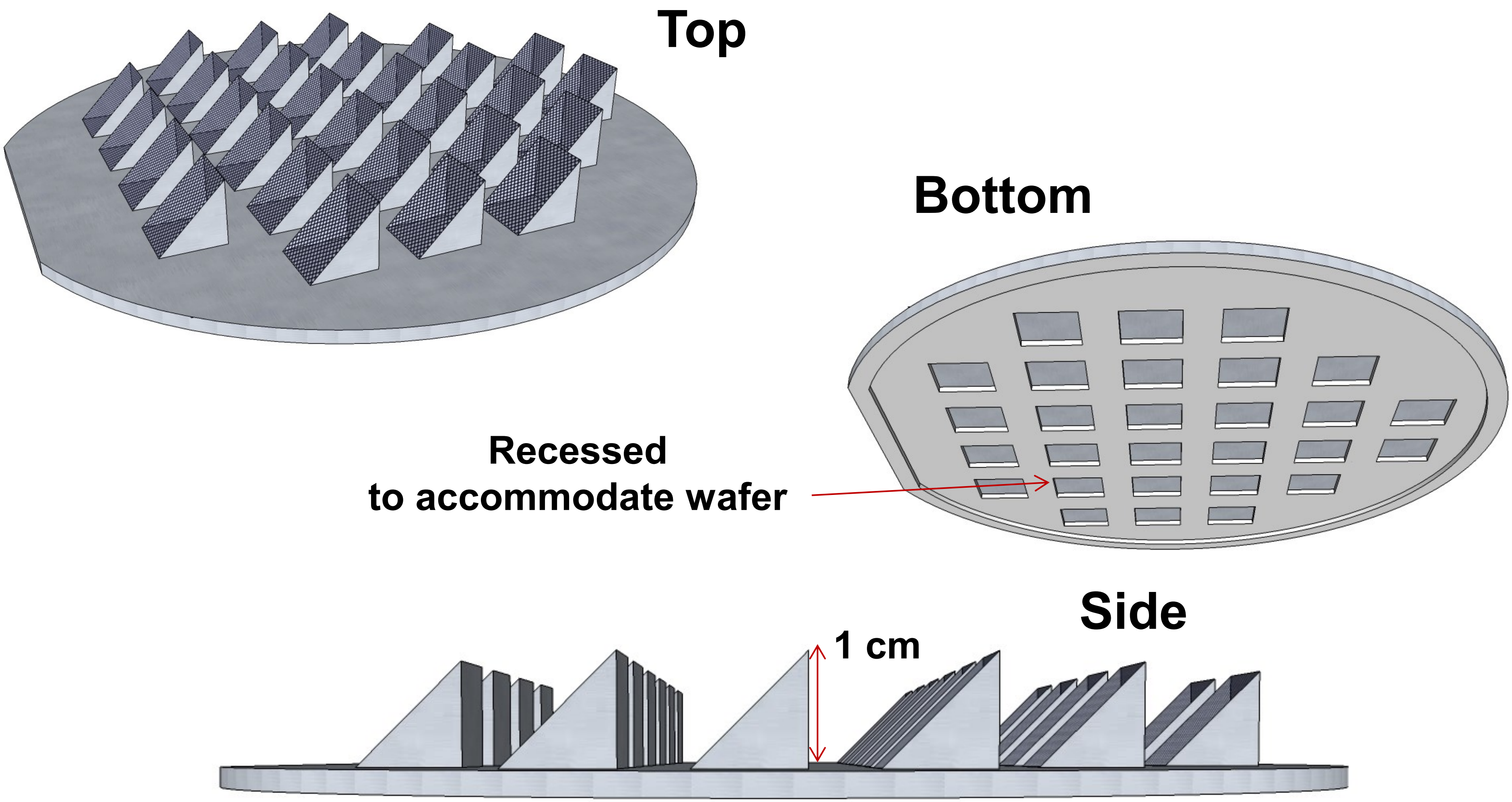
BACKUP SLIDES

Wafer Scale Oblique Angle Etching Fixture



Polymer Based MPL

Sandia National Laboratories