Fabrication of Si, Si3N4 & InGaAsP Optical Metasurfaces with Dry Etching

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Etch Instructor: Guy Lavallee and Shane Miller

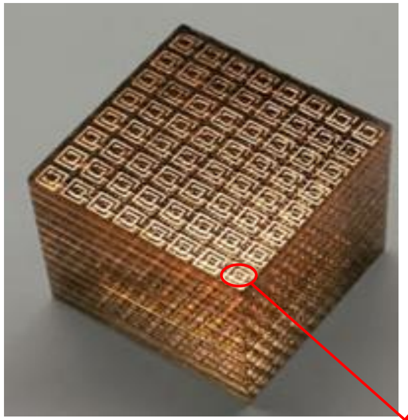
Outline

- **Background**
- **Optical Metasurfaces based on Dry etching**
  - aSi wafer scale metalens fabricated by dry etch
  - Si3N4 double-layer achromatic metalens fabricated by dry etch
  - III-V OAM and BIC lasers fabricated by dry etch
- **Summary**

Metasurface – Tailoring light properties *in the nanoscale*

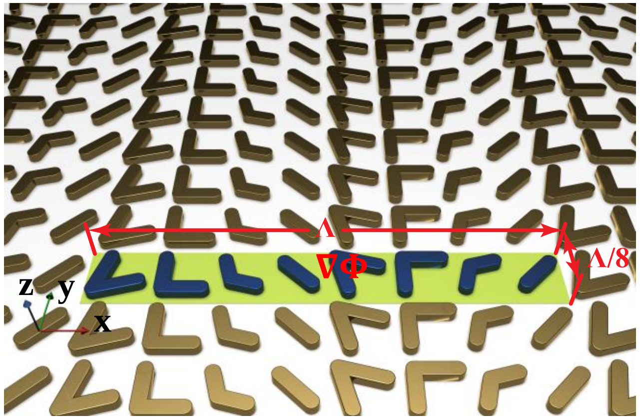
Bulk material

Bulk metamaterial



Meta atoms

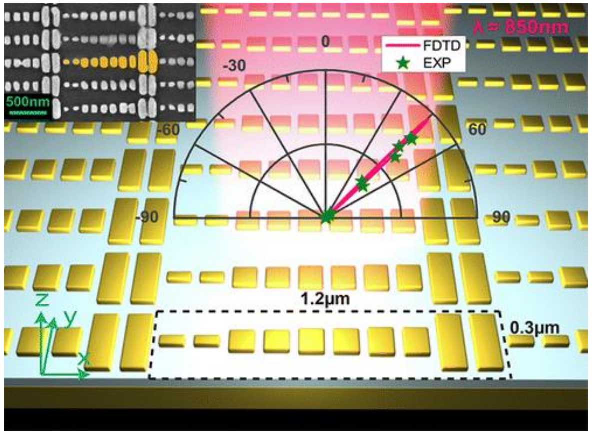
Metasurface



X. Ni, et al. Science, (2012)

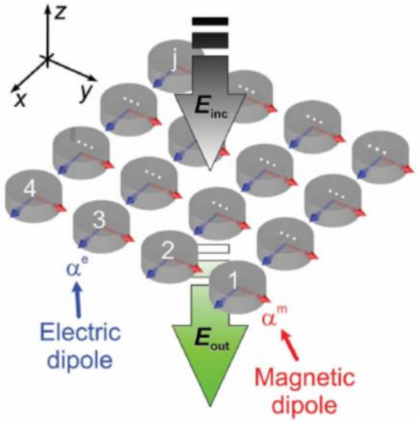
- Low loss, small footprint, easy fabrication and integration, low cost, etc.

Plasmonic resonance



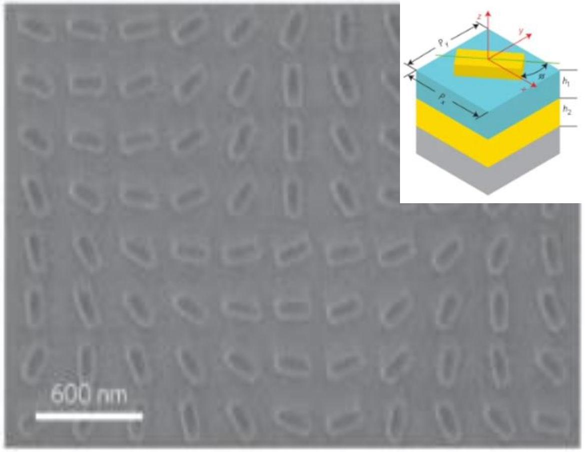
S. Sun, et. al. Nano Lett., (2012)

Mie resonance



M. Decker, et al. Adv. Opt. Mat., (2015)

Pancharatnam–Berry phase



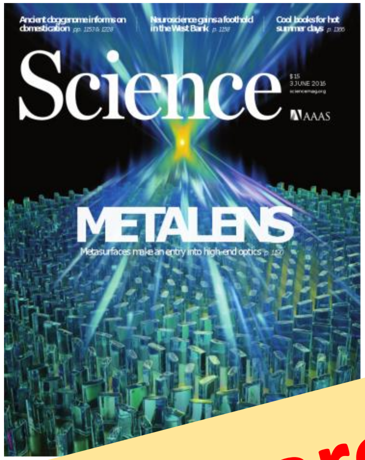
G . Zheng, et al. Nat. Nanotech. , (2015)

Applications of metasurfaces

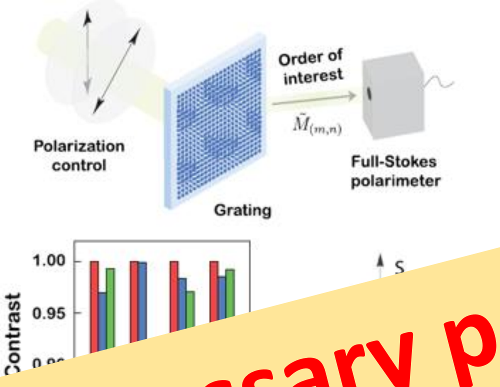
Invisibility cloaking

X. Ni, et al., Science, (2015)

Meta-lens



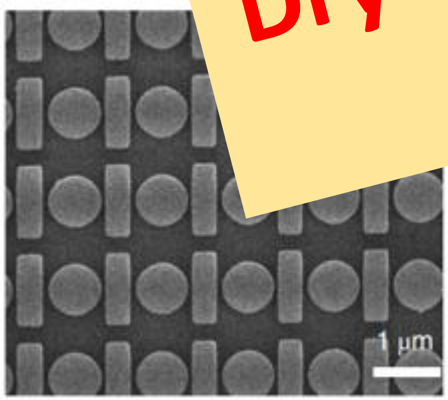
Polarization imaging



Hologram and OAM

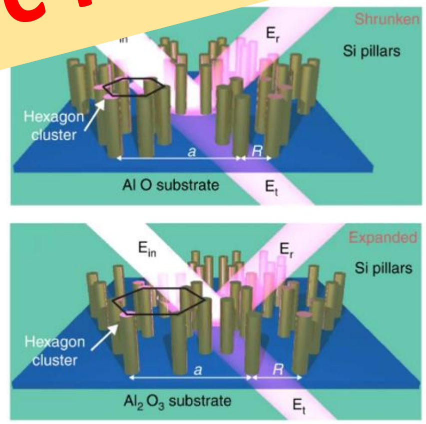
Ren, et al. Nat. Commun., (2019)

Dry etching are necessary part for dielectric metasurfaces!



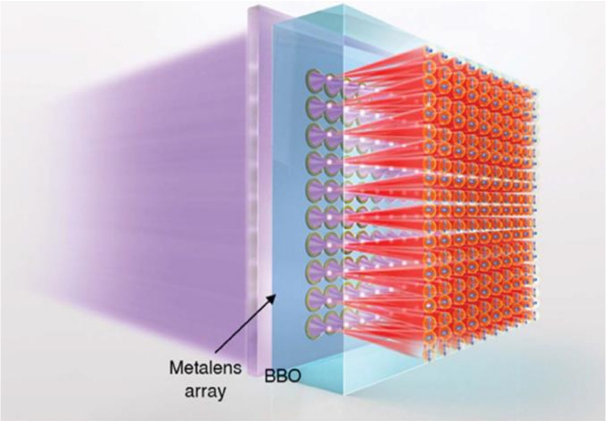
H. Liu, et al. Nat. Phys., (2018)

ics



M. A. Gorlach. et al. Nat. Commun., (2018)

Quantum Optics



L. Li et al., Science, (2020)

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Seeing colorful world with Lenses

Cellphone

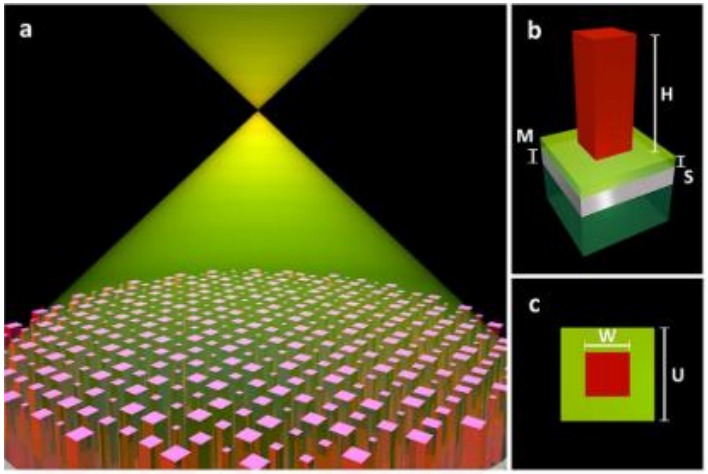
Digital Camera

Conventional lenses: Bulky, Heavy

Expensive, Hard to fabricate

Metalens: lightweight, ultrathin

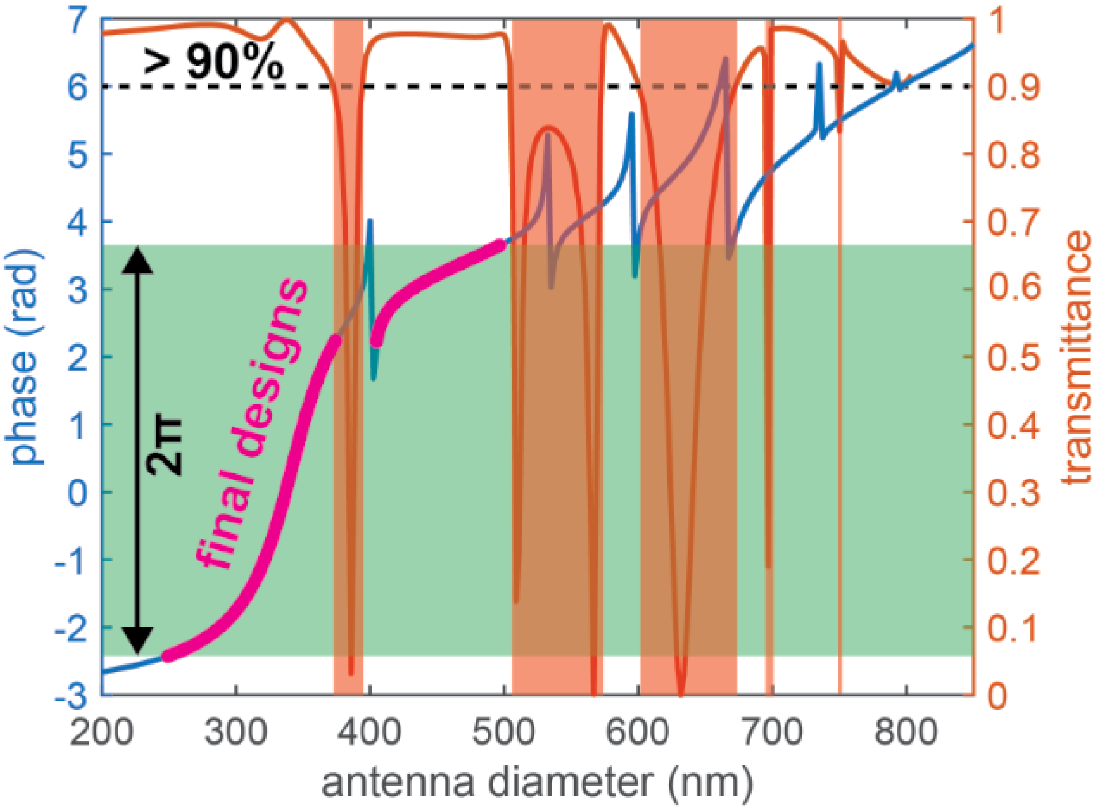
Hubble Space Telescope

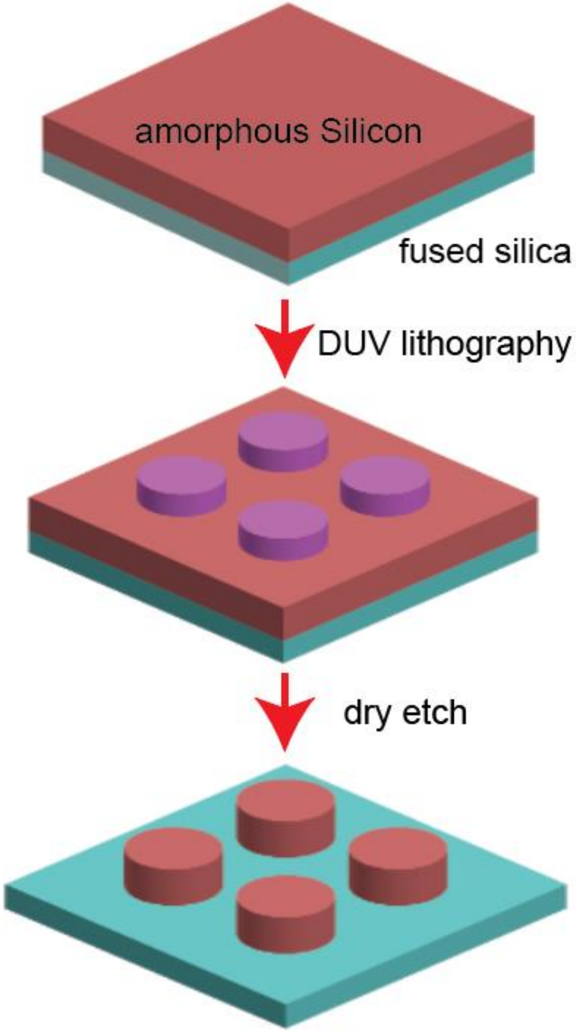


Nano Lett. 2017, 17, 1819–1824

Dielectric metalenses: Low loss, strong light confinement

Design and fabrication of wafer-scale metalens



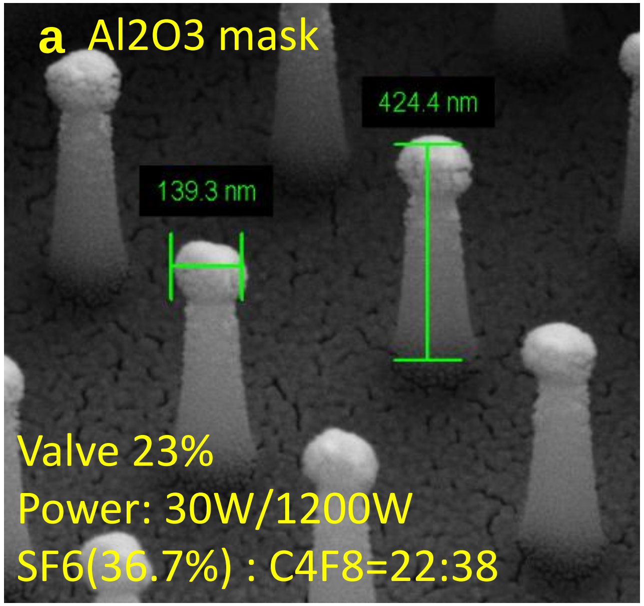


Required phase profile：

$$\varphi(r) = -\frac{2\pi}{\lambda}[\sqrt{(r^2 + f^2)} - f]$$

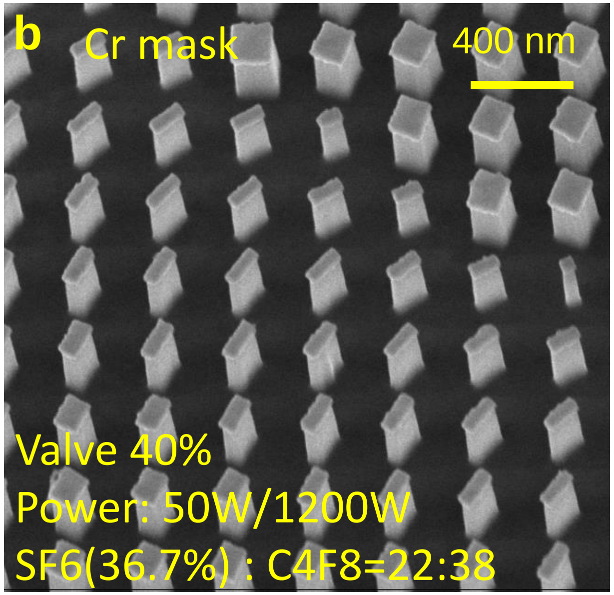
aSi Metalens with different mask and etching recipe

Alcatel Speeder 100 SiO_2



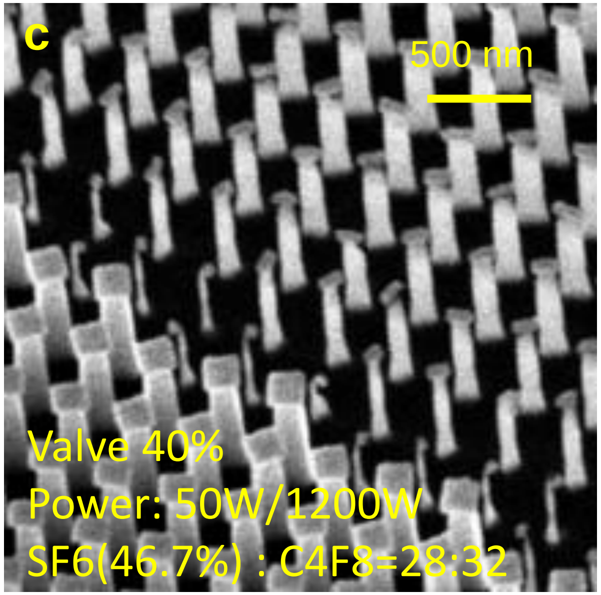
Al2O3 mask

Valve 23%
Power: 30W/1200W
SF6(36.7%) : C4F8=22:38

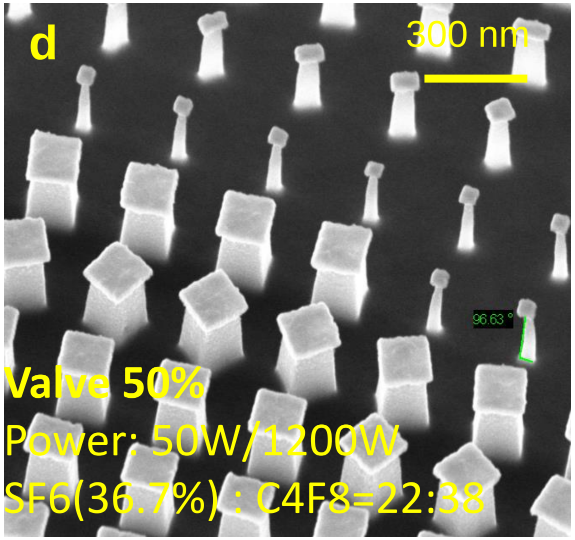


Cr mask

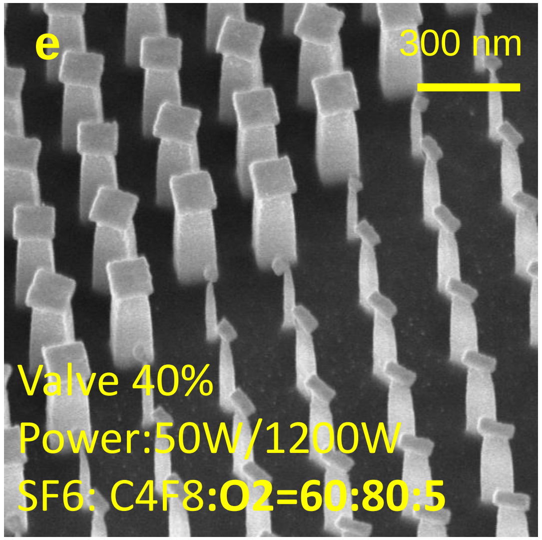
Valve 40%
Power: 50W/1200W
SF6(36.7%) : C4F8=22:38



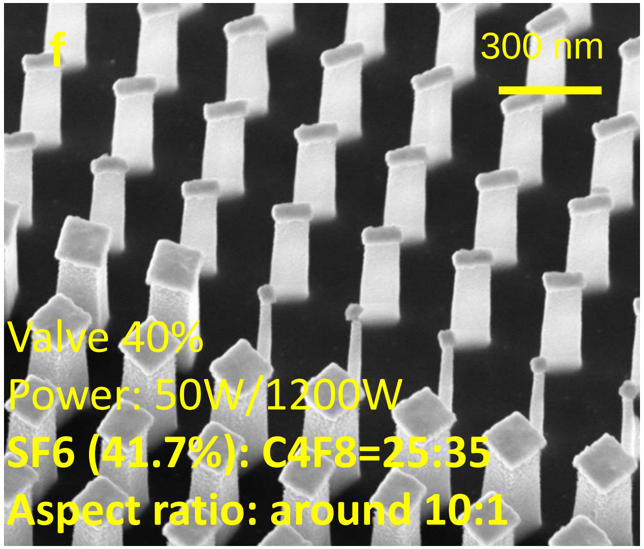
Valve 40%
Power: 50W/1200W
SF6(46.7%) : C4F8=28:32



Valve 50%
Power: 50W/1200W
SF6(36.7%) : C4F8=22:38



Valve 40%
Power:50W/1200W
SF6: C4F8:**O2=60:80:5**

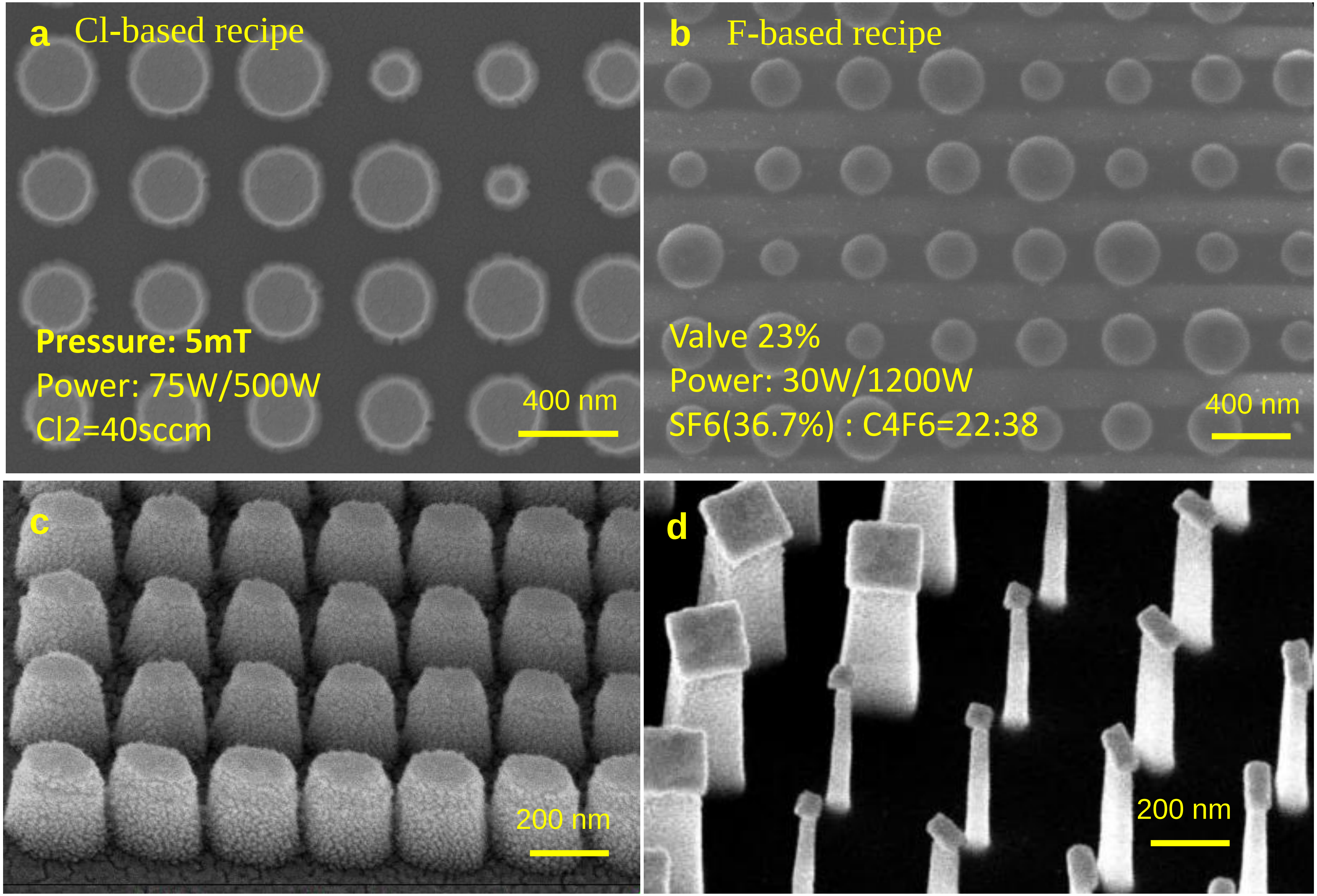


Valve 40%
Power: 50W/1200W
SF6 (41.7%): C4F8=25:35
Aspect ratio: around 10:1

aSi Metalens with different etching gas

Plasma-Therm Versalock

Alcatel Speeder 100 SiO_2



Cl-based recipe

Pressure: 5mT
Power: 75W/500W
Cl2=40sccm

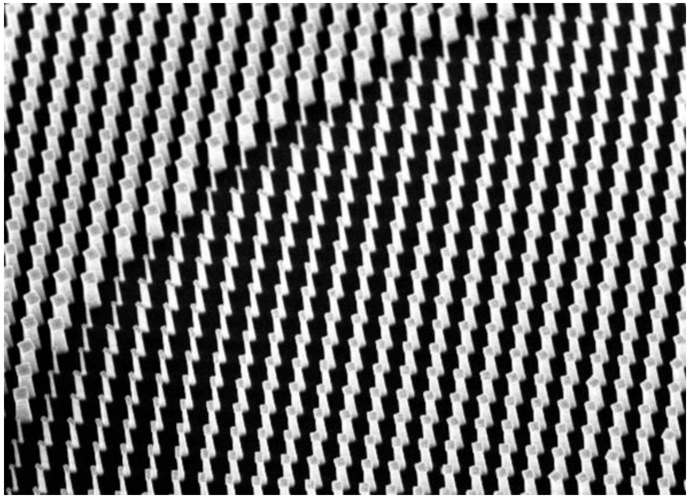
F-based recipe

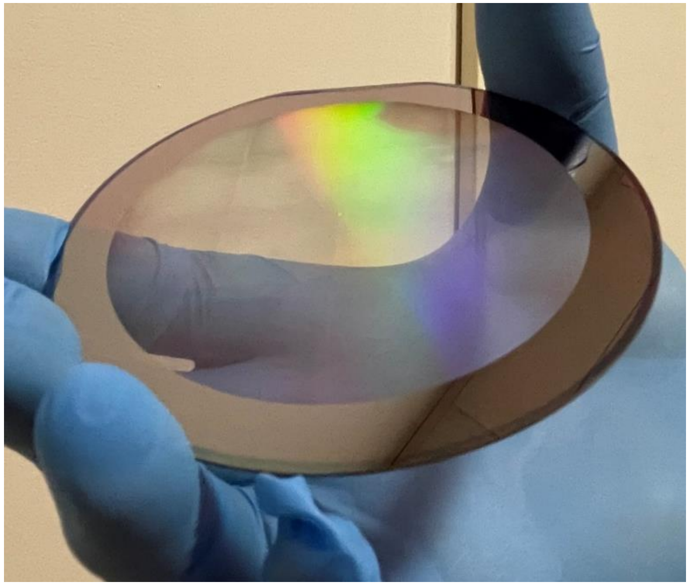
Valve 23%
Power: 30W/1200W
SF6(36.7%) : C4F6=22:38

By courtesy of Yao Duan

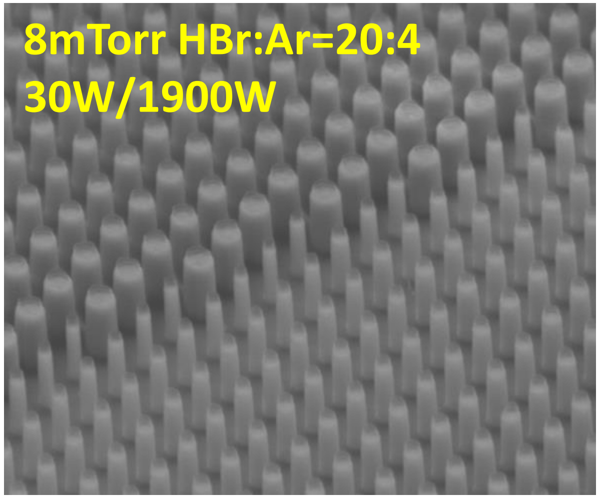
Wafer-scale Metalens

Alcatel Speeder 100 SiO_2

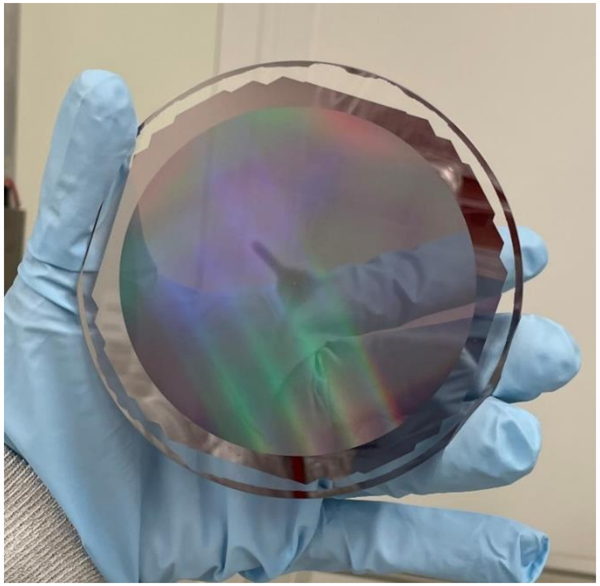




Oxford Cobra



8mTorr HBr:Ar=20:4
30W/1900W



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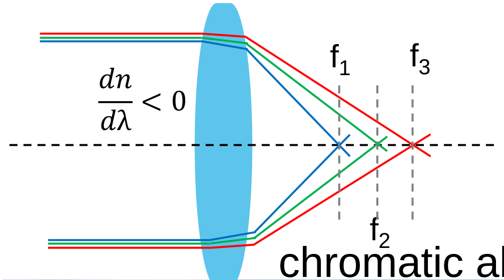
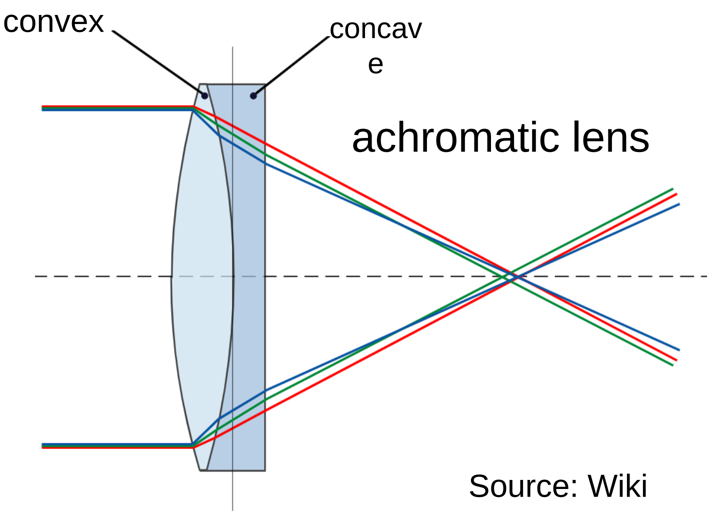
- **Summary**

Metalens – lightweight, manipulate aberration



chromatic aberration

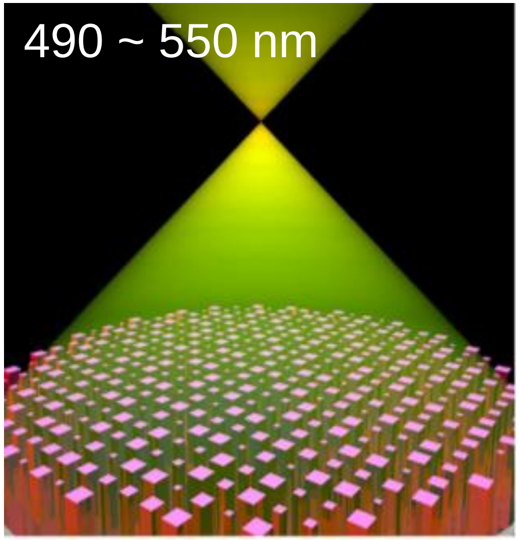

Source: Wiki



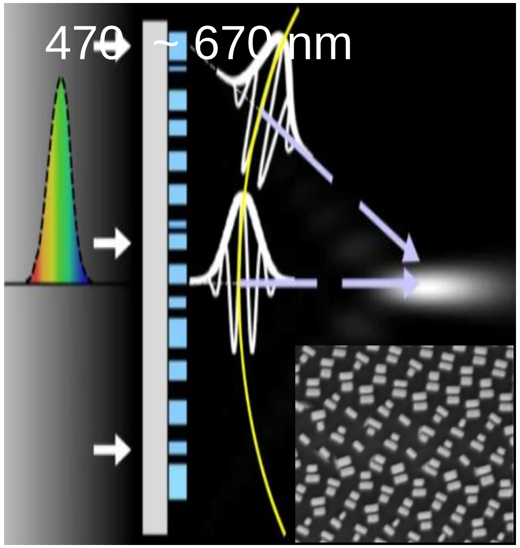
achromatic lens

Source: Wiki

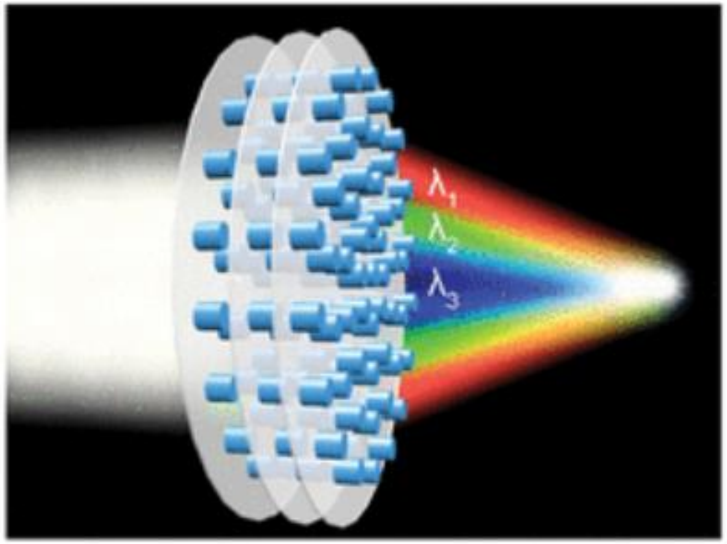
- metalens: metaphotonic device which can function like normal lens



Nano Lett.17.3 (2017)

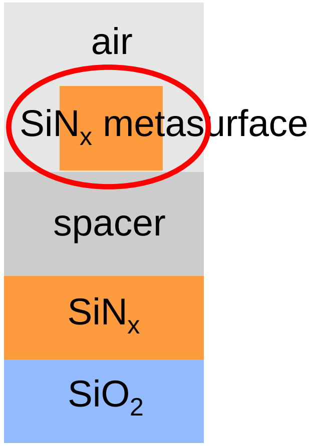


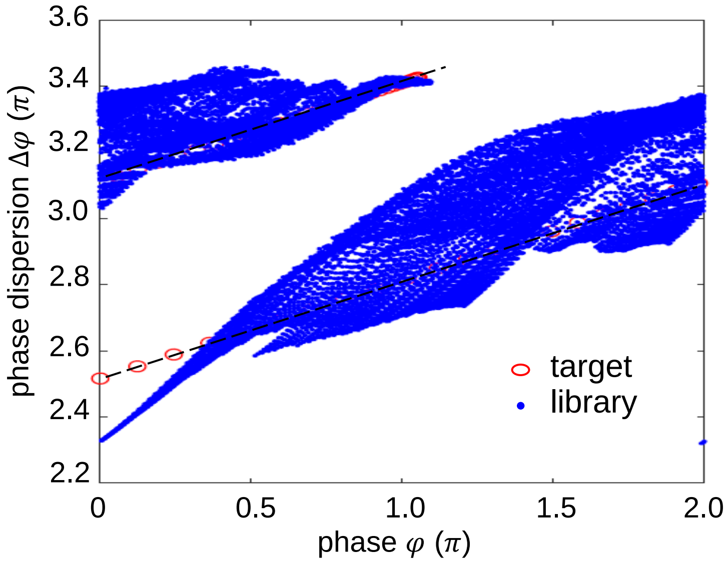
Nat. Nanotechnol. 13.3 (2018)



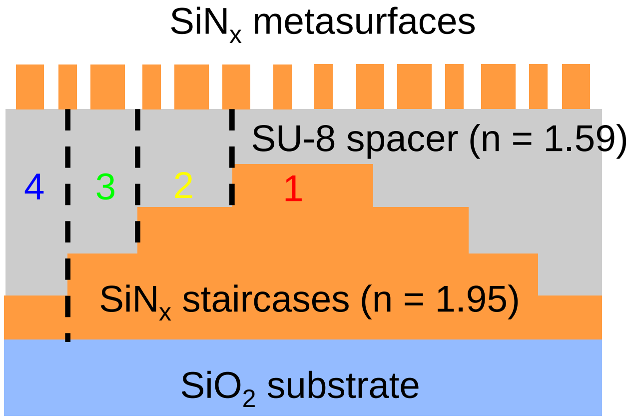
Nano Lett. 18.12 (2018)

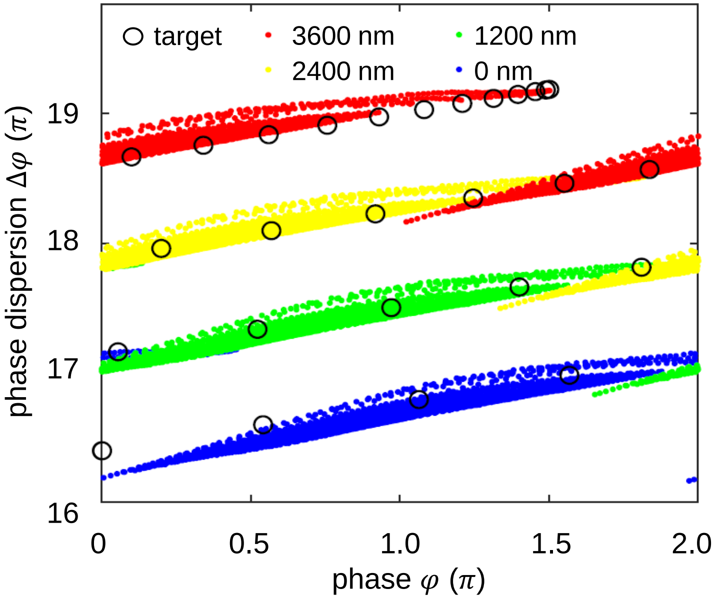
Design Principle





metasurface
fine tuning





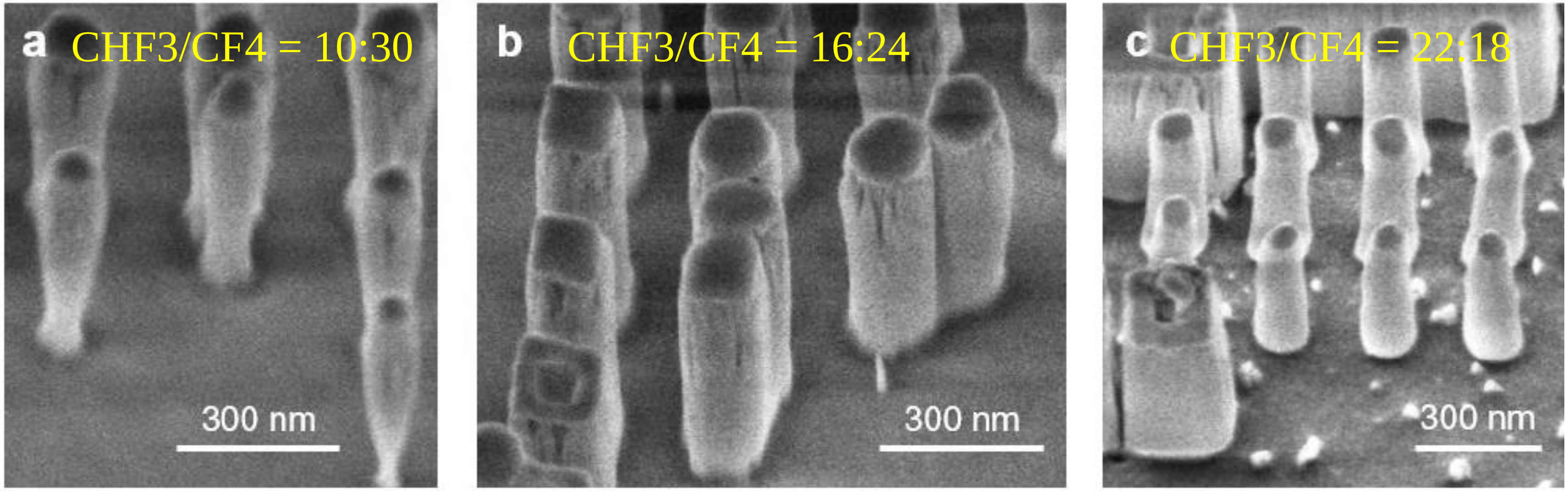
staircases
rough tuning

By courtesy of Shengyuan Chang

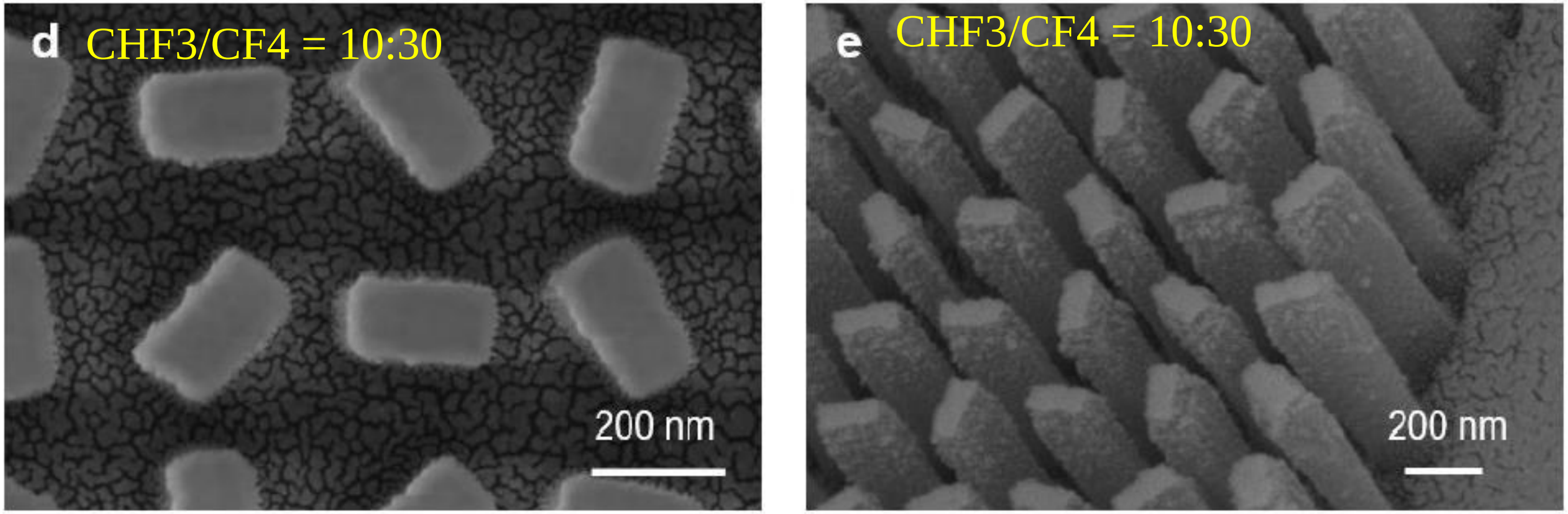
Different SiNx etching with different etching recipe

Plasma-Therm Versalock

Low dispersive SiNx

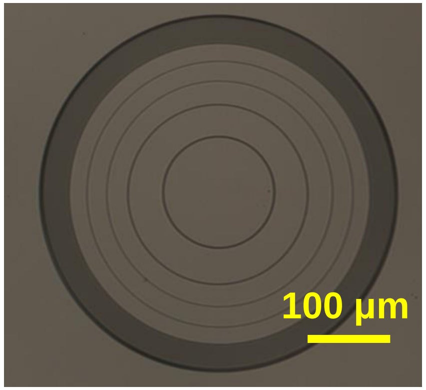


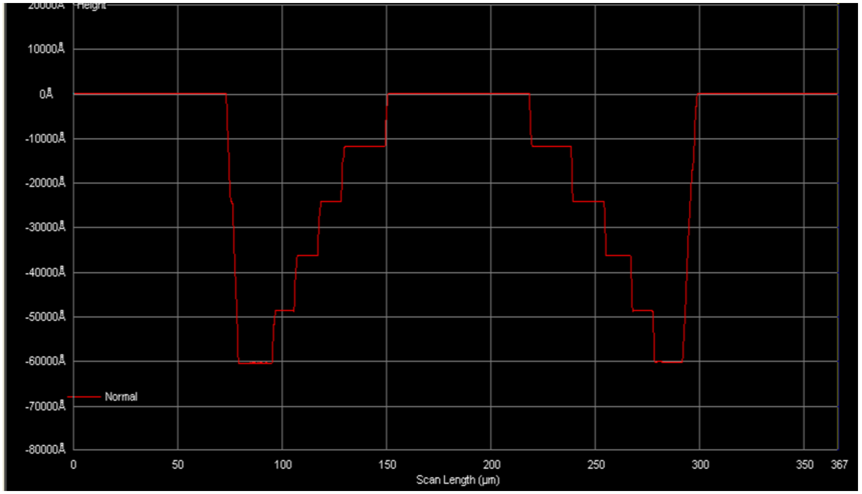
high dispersive SiNx

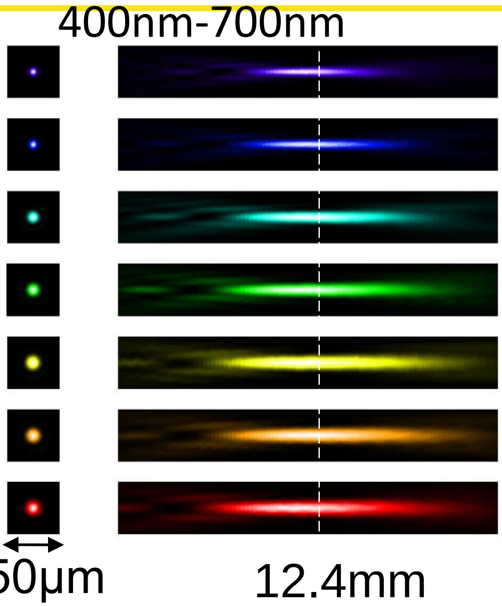


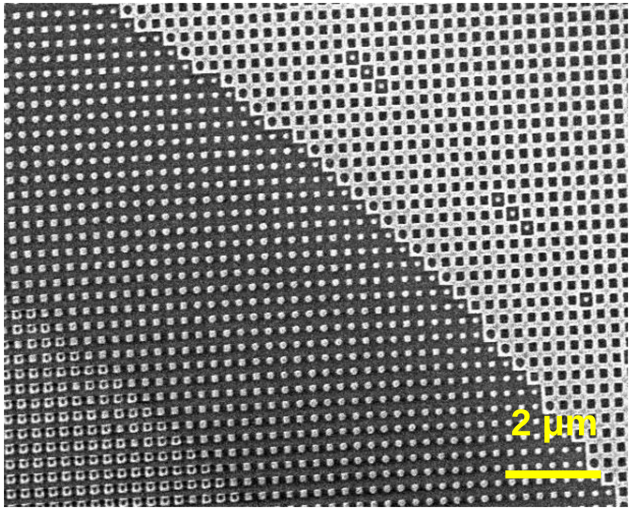
By courtesy of Yao Duan

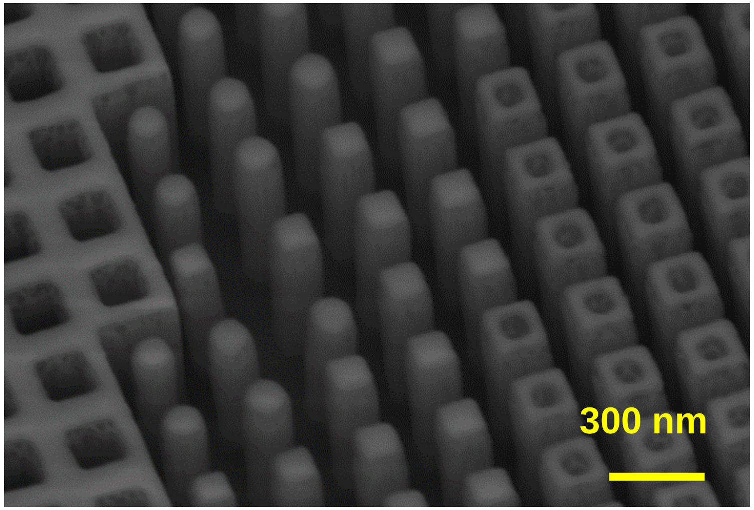
SiNx metasurfaces with different etching recipe

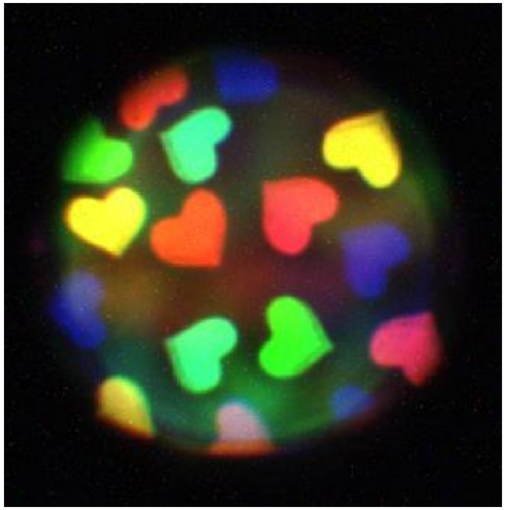












Plasma-Therm Versalock

By courtesy of Yao Duan and Shengyuan Chang

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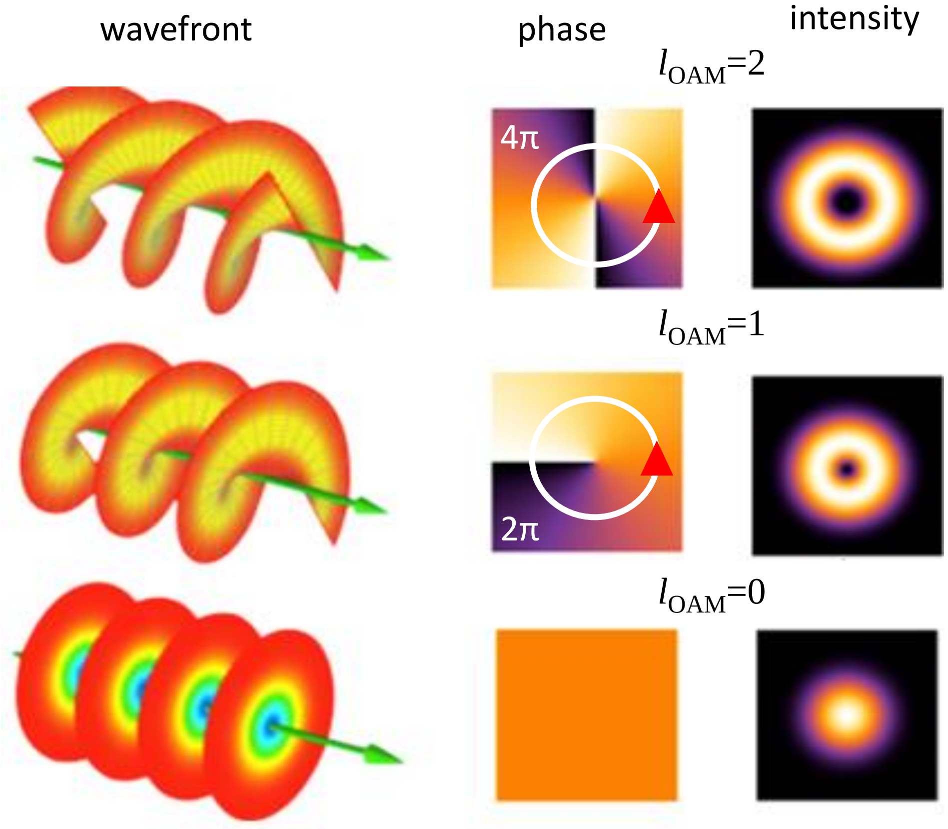
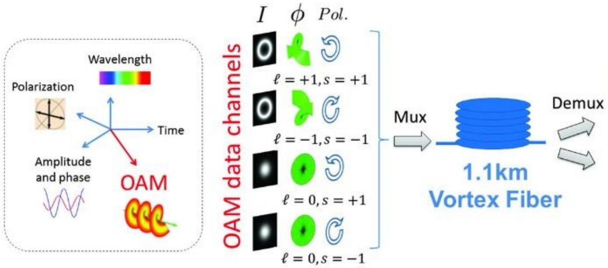
Orbital angular momentum

Light with **orbital angular momentum (OAM)** has an **azimuthal** phase term $e^{il\varphi}$, travelling with a twisted helical wavefront.



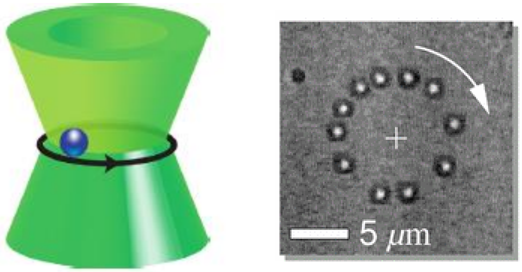
https://en.wikipedia.org/wiki/Orbital_angular_momentum_of_light

Optical communication



B. Nenad, et al. *Science* (2013)

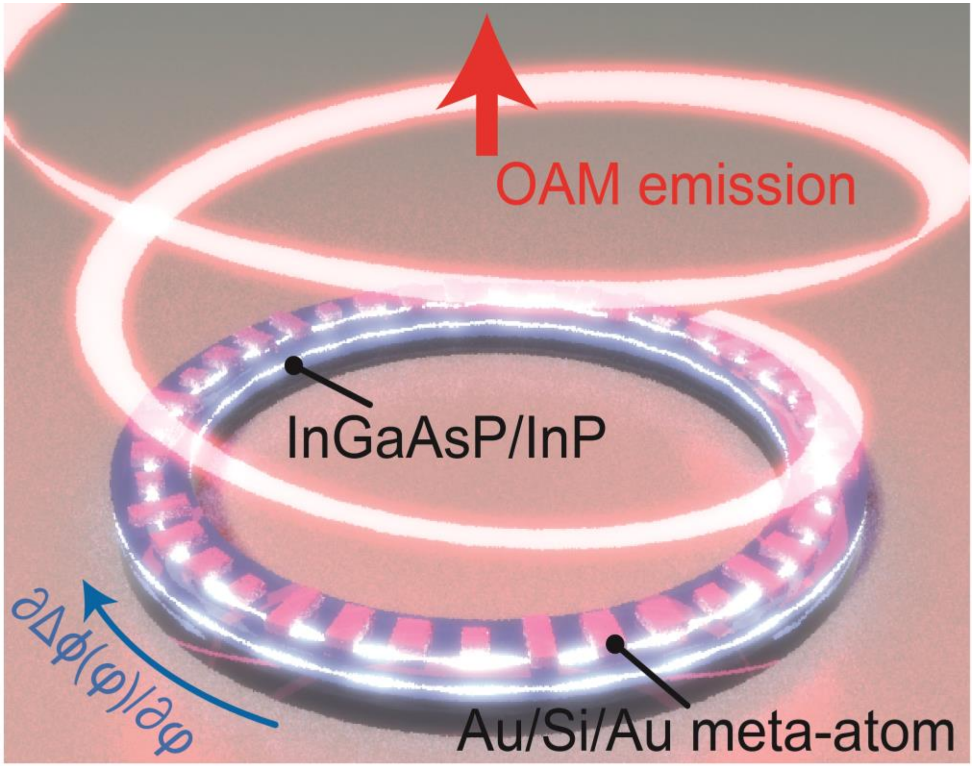
OAM trapping and manipulation

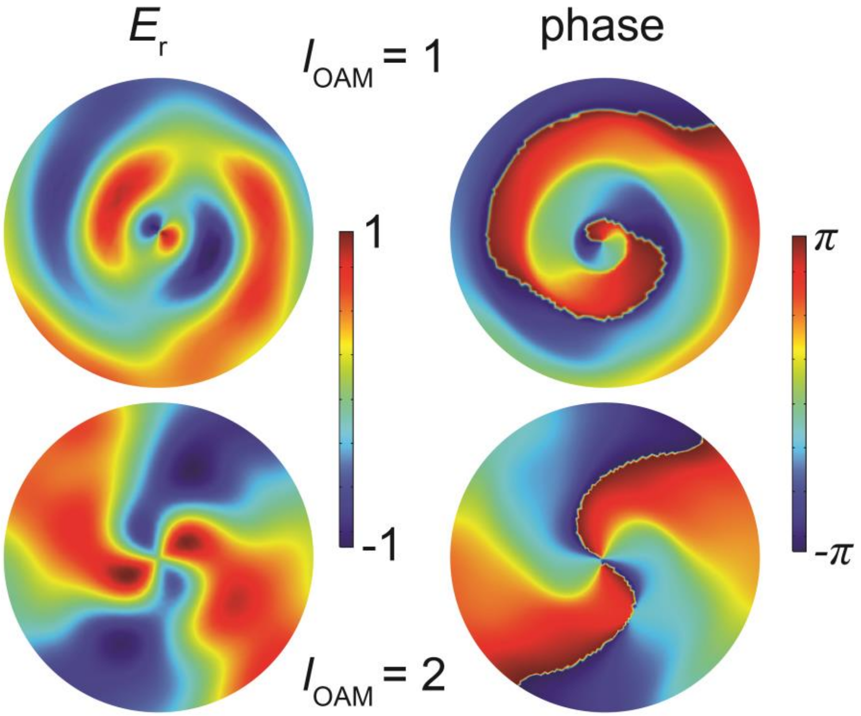


J. E. Curtis, and D. G. Grier. *PRL.* (2003)

By courtesy of Xuexue Guo

Integrated OAM microring lasers





$$l_{OAM}\varphi = \phi_{OAM} = \phi_{CCW} + \phi_{ms} = \beta_{\mathrm{CCW}}R\varphi - \frac{2\pi}{\Lambda}R\varphi.$$

$$l_{OAM} = M - N$$

$M - WGM\ order$

$N - number\ of\ supercells$

- Breaking CW and CCW mode degeneracy with asymmetric phase gradient
- OAM order can be tuned

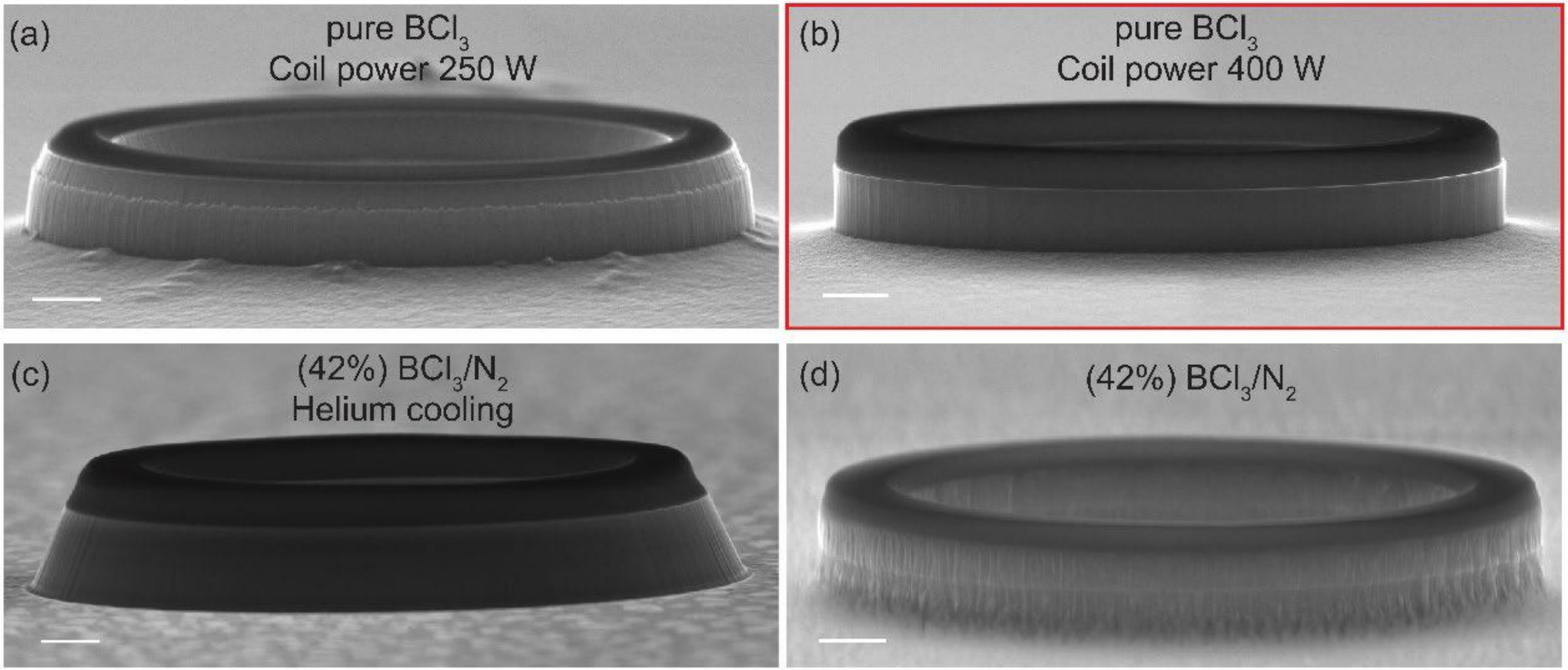
Science advances 6.29 (2020): eabb4142.

By courtesy of Xuexue Guo

InGaAsP/InP Microrings with different etching recipes

Convention method: CH4/H2/Ar ---- slow etch rate and chamber contamination

BCl_3 30 sccm, 2 mT, chuck power: 200W, chuck temperature: 80 °C, no helium cooling

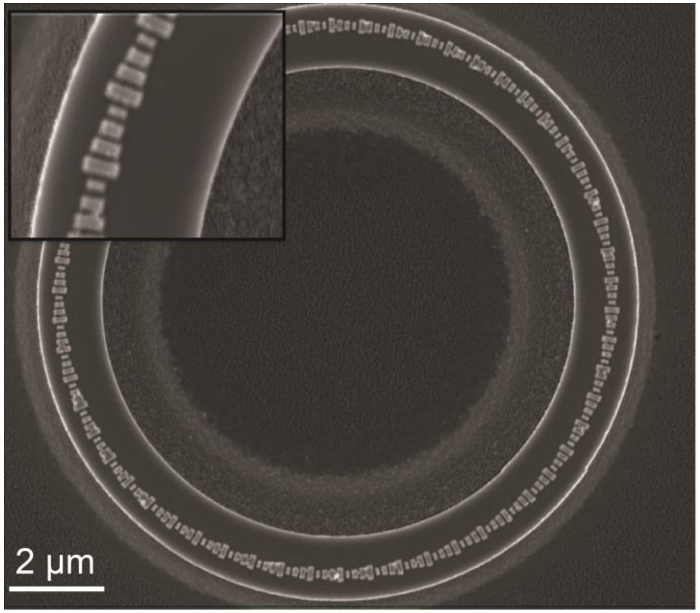


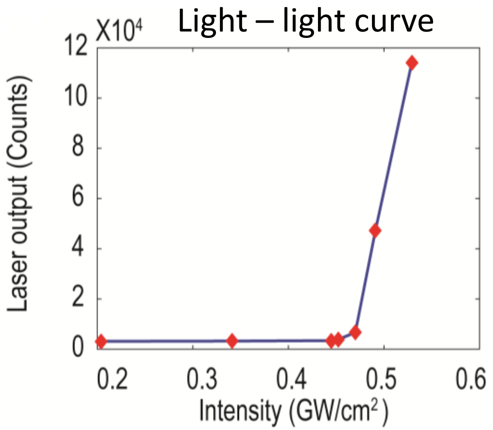
Scale bar: 1 μm.

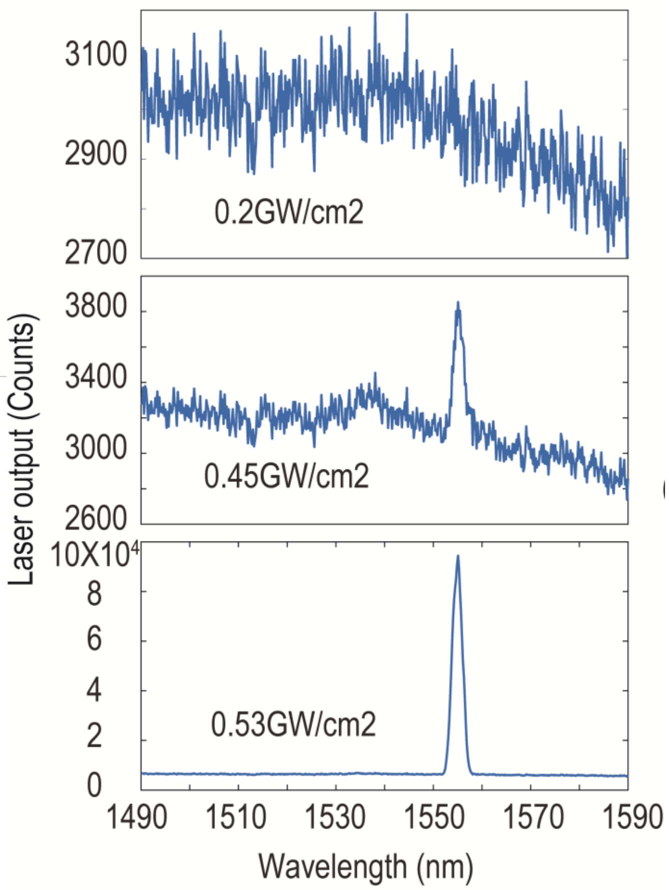
ULVAC NE-550 Etching System

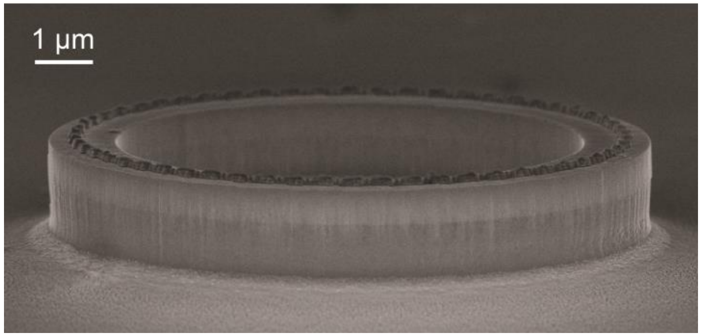
By courtesy of Xuexue Guo

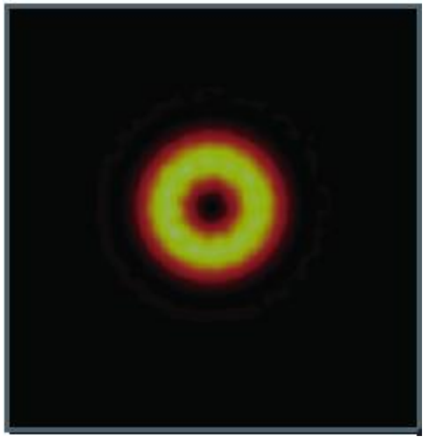
Characterization of OAM microring laser











The microring consists of a 500-nm InGaAsP multi-quantum-well layer, a 1-µm InP layer and an array of metasurfaces with N = 58 supercells.

Science advances 6.29 (2020): eabb4142.

By courtesy of Xuexue Guo

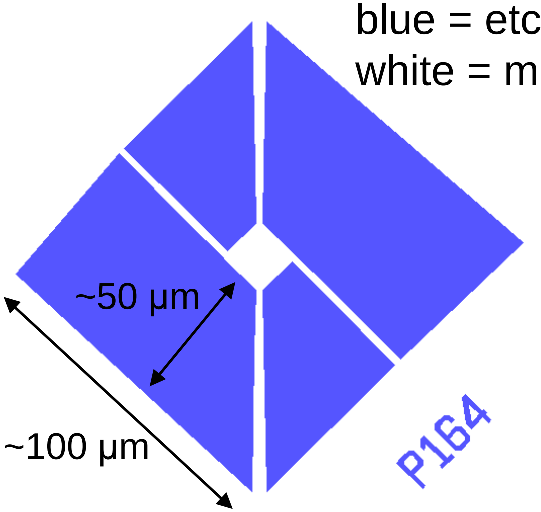
Suspended MQW Structures

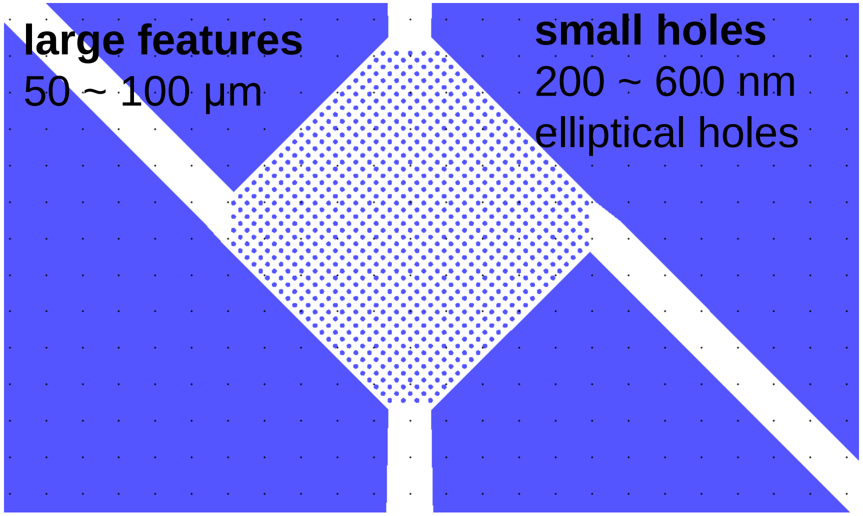
- Objective:
  - Suspended InGaAsP structures for laser purpose
  - elliptical holes with axis diameter varying from 200 nm to 600 nm

InGaAsP (505 nm)
InP (1000 nm)
InGaAs (100 nm)
InP substrate

- Bulk blue region must penetrate InGaAs layer (> 1605 nm)
- holes region must be moderate deep for promoting wet etch (>1000 nm)

blue = etched
white = mask





By courtesy of Yao Duan

Dry Etch in Cl-Based Chemistry

Proper window: 190 ~ 250 ℃

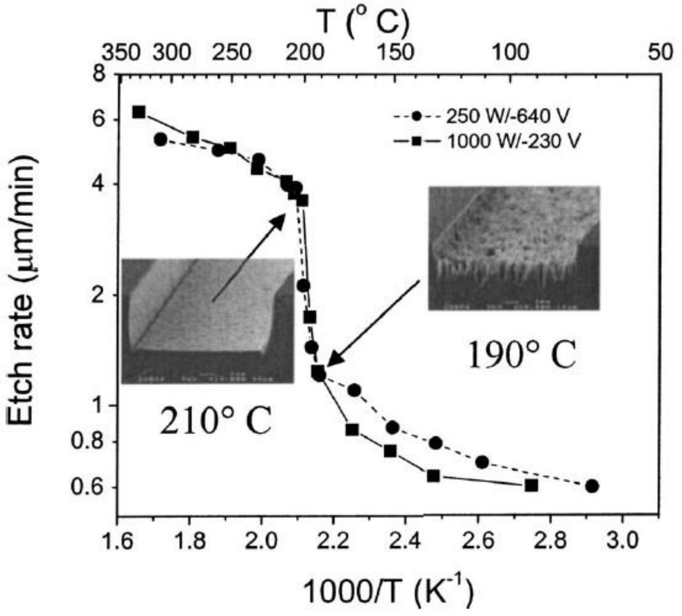
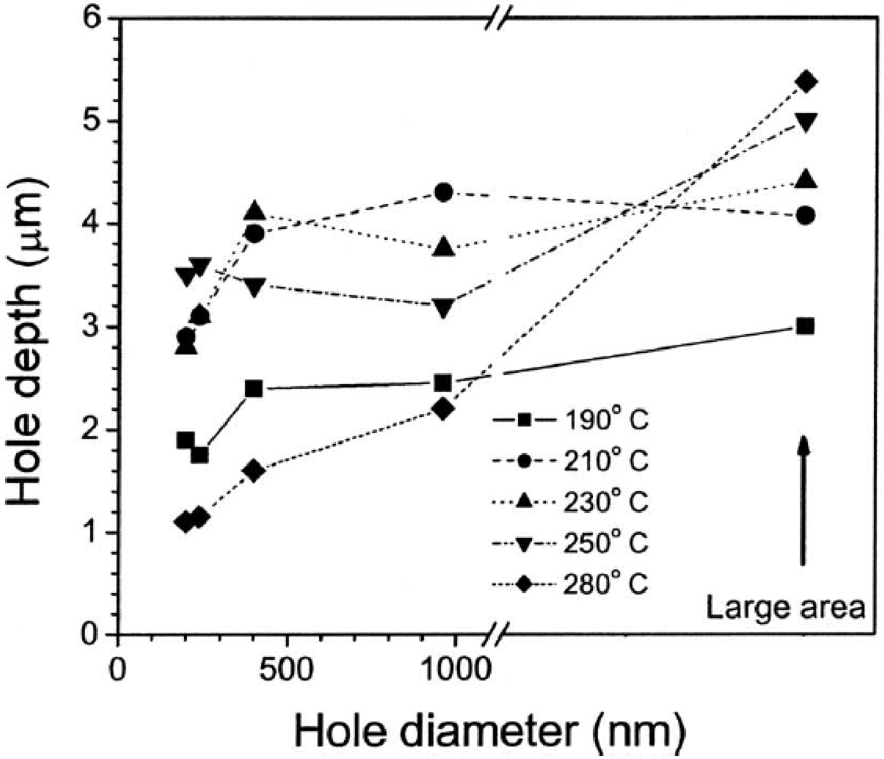


FIG. 2. Arrhenius plots of the etch rate for process 1 (250 W/−640 V) and process 2 (1000 W/−230 V). The temperatures used are the real estimated temperatures of the sample. Insert SEM micrographs show surfaces etched with process 2.



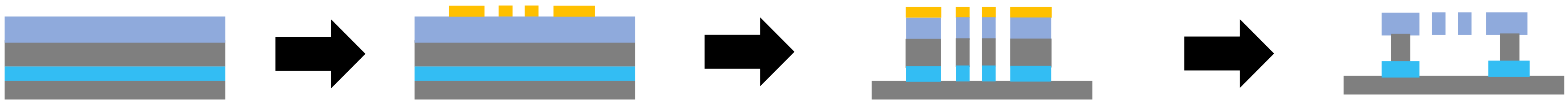
Carlström C F, et al. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena, 2008, 26(5): 1675-1683.

Etch rate is very slow < 190 ℃

Etch lag is large > 280 ℃
(on Si carrier wafer)

Control RIE lag

Suspended InGaAsP photonic crystal



InP wafer

E-beam litho & Cr etch
(resist = ZEP520)

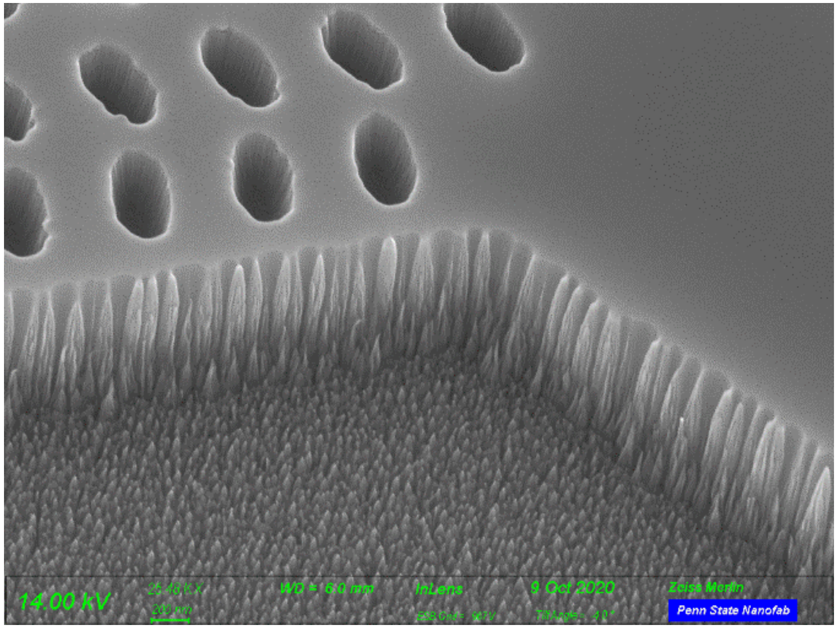
InP dry etch

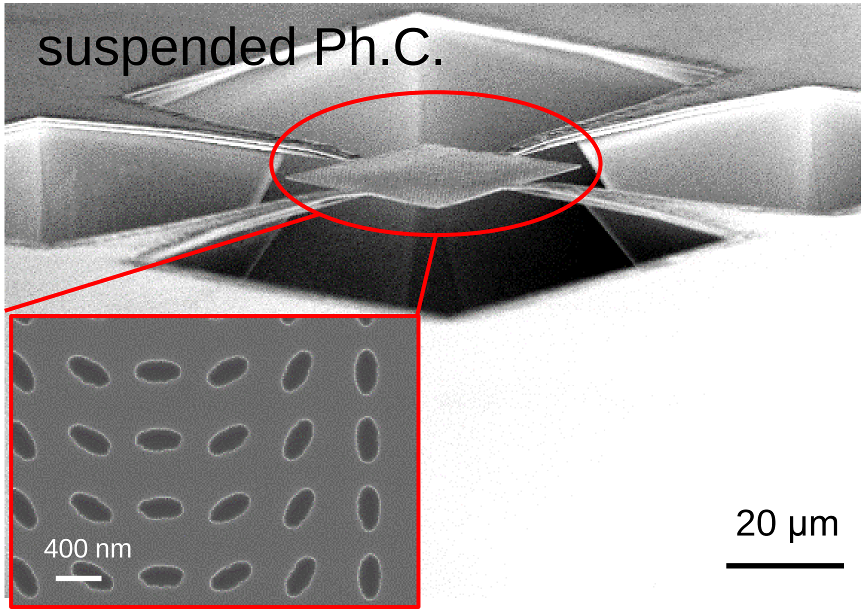
HCl wet etch

🟦	InGaAsP	⬛	InP	🟦	InGaAs	🟥	ZEP-520	🟨	Cr

BCl3 = 25 sccm, Cl2 = 5 sccm, 3 mTorr, ICP = 220W, chuck = 100 W, T = 110 C, He Cooling (PFC) = 4.5 Torr, etch time = 225s

large trenches = 3.8 um
holes = 1.17 um

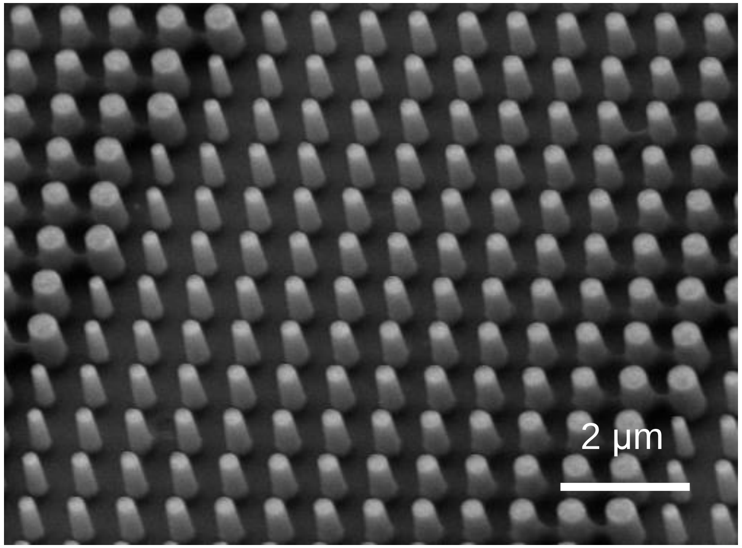




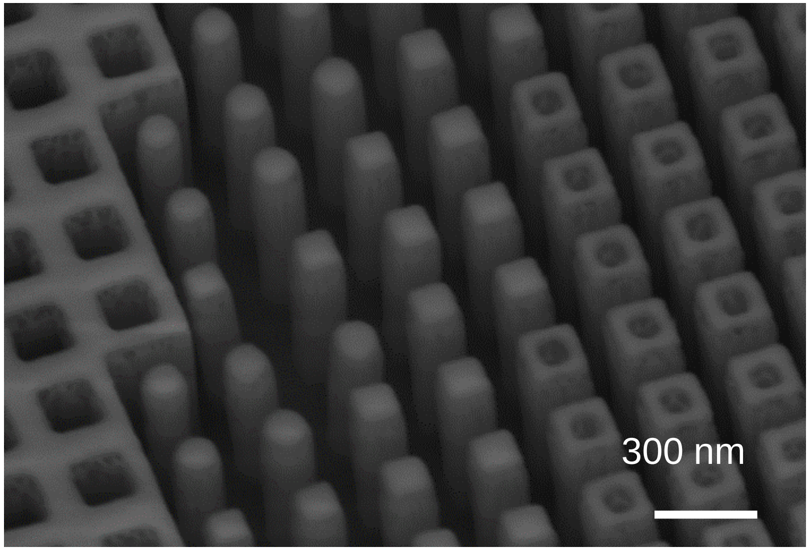
By courtesy of Yao Duan

Summary

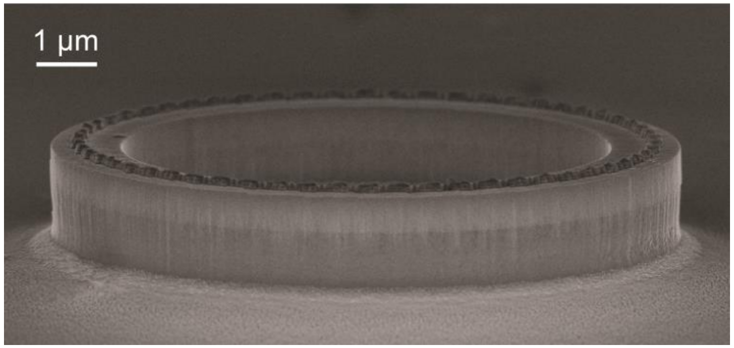
aSi wafer-scale metalens



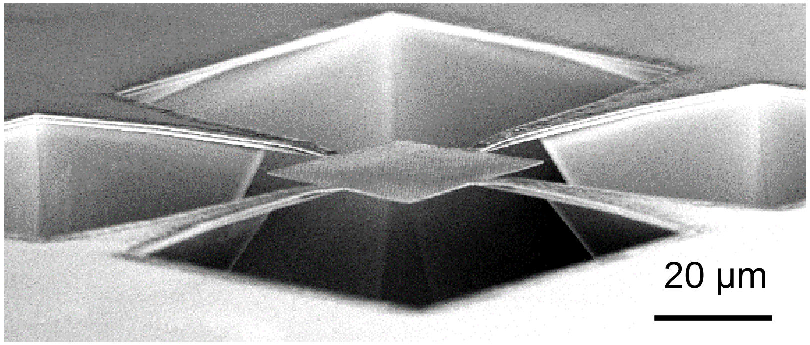
Si3N4 double-layer achromatic metalens



InGaAsP OAM laser



InGaAsP suspended photonic crystal



Acknowledgements

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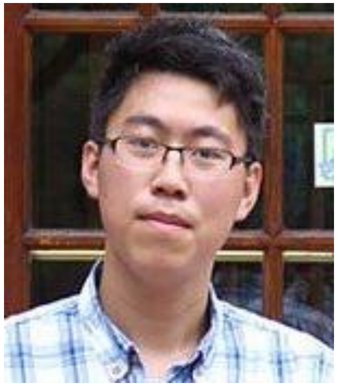

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