Plasmonic Color

Presented by:

OSA Optical Material Studies Technical Group

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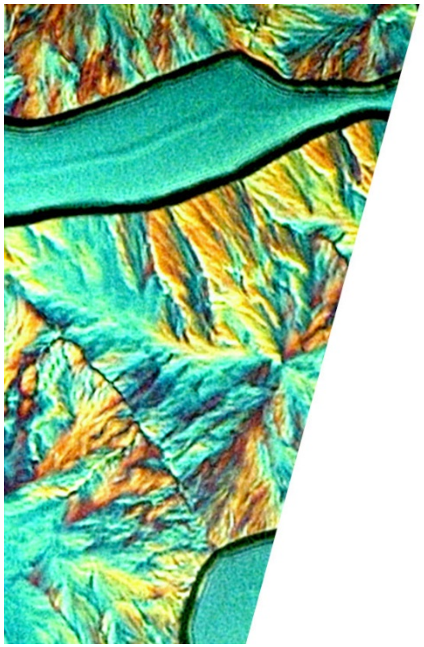

PLASMONIC COLOR WEBINAR

25 October 2018 • 8:30 EDT

OSA Optical Material Studies Technical Group

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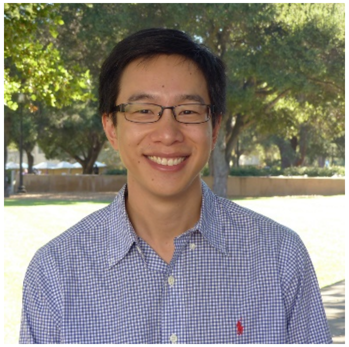
Rice University, USA



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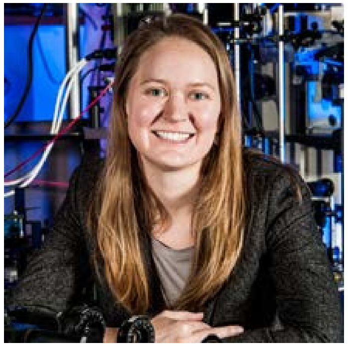

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OSA Optical Material Studies Technical Group

Technical Group at a Glance

- ## Focus
  - "Nano-optical Materials"
  - **1650+** members!
- ## Mission
  - To benefit ***<u>YOU</u>***
  - Webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at guru@rice.edu.
- ## Find us here
  - Website: www.osa.org/OpticalMaterialStudiesTG
  - Facebook: www.facebook.com/opticalmaterial/
  - LinkedIn: www.linkedin.com/groups/8272077

Today's Webinar: ***Plasmonic Color***

Dr. Joel Yang
Associate Professor

Dr. Robert Simpson
Assistant Professor

Singapore University of Technology and Design

Dr. Yang's Short Bio:
SM and PhD in Electrical Engg. & Computer Sci., Massachusetts Institute of Technology
Awards: A*STAR Investigator Award, the MIT Technology Review TR35@Singapore award, and the Singapore Young Scientist Award

Dr. Simpson's Short Bio:
PhD in Optoelectronics Research Center, University of Southampton
JSPS Postdoctoral Fellow at AIST, Japan and ICFO, Spain
Awards: Westminster medal and the AIST president's award

Plasmonic Colors

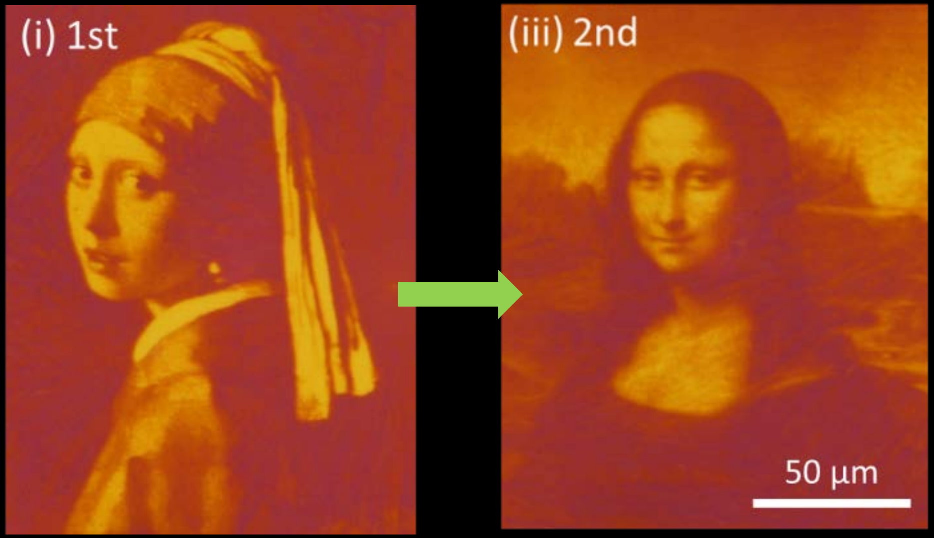
Joel K.W. Yang[1,2] , Robert E. Simpson[1]

[1] Engineering Product Development (EPD), SUTD

*[2] Institute of Materials Research and Engineering (IMRE), A*STAR*

OSA Webinar
25th Oct 2018

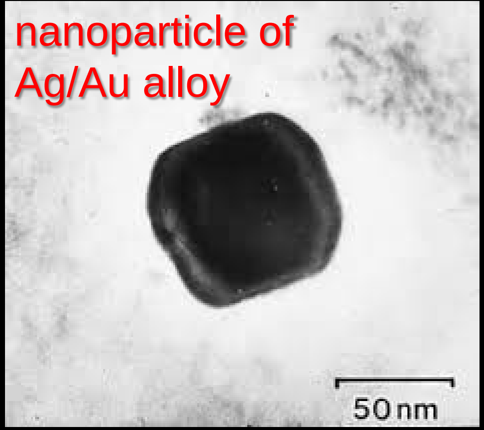
100,000 dpi printing



Phase Change Materials

Brief history of plasmonic colors

Dichroic colors from silver and gold nanoparticles in glass: 4th century AD Lycurgus cup



Michael Faraday's Recognition of Ruby Gold: the Birth of Modern Nanotechnology

His 1857 Lecture to the Royal Society in London

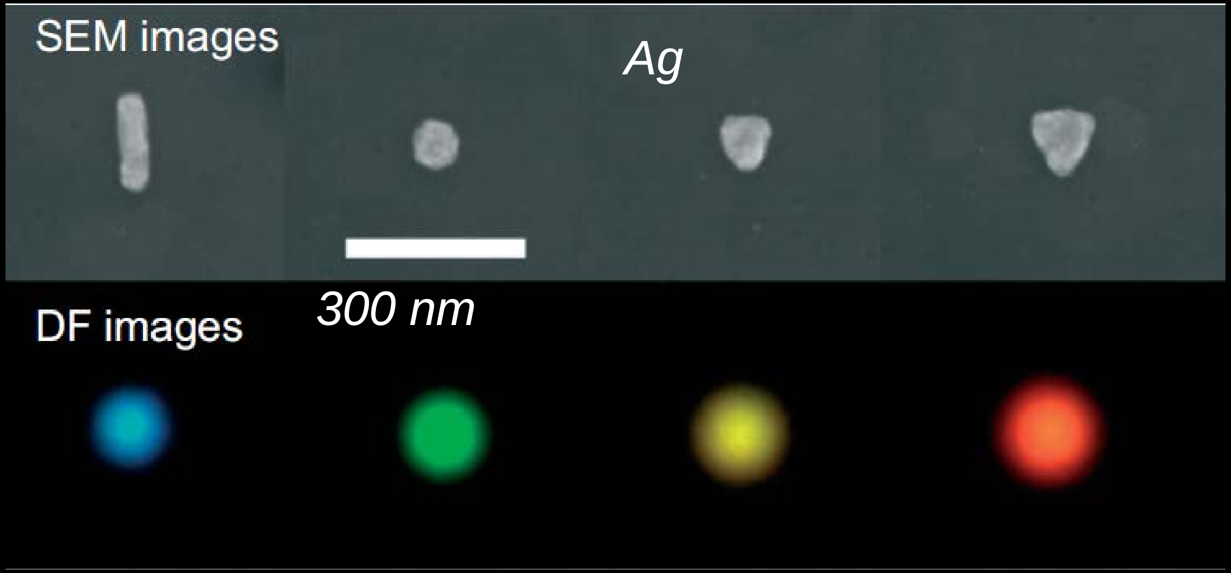
David Thompson
DTThompson@aol.com

Figure 1
Faraday's colloidal ruby gold. Reproduced by Courtesy of the Royal Institution of Great Britain

Freestone, I., Meeks, N., Sax, M. et al. Gold Bulletin (2007)

One Material Many Colors

Geometry-dependent colors



W.A. Murray, W.L. Barnes, Adv. Materials (2007)

Advances in nanotechnology, particularly in lithography:

- E.g. sub-10-nm patterning resolution with electron-beam lithography

J.K.W. Yang, K.K. Berggren, Journal of Vacuum Science & Technology B (2007)

Metallic nanostructures with single constituent materials as universal color "pigment"
Control geometry and structures → control color

How plasmonic colors work

Plasmons: Quasiparticle arising from the collective oscillations of free electrons in a metal, coupled to EM fields.
Requires negative permittivity, relatively & good metallic conductors.
e.g. Au, Ag, Al, Cu, Mg, TiN, etc..

Metallic oscillators on mirrors: Gap plasmons

Geometric Control of Colors

Circuit model: Zhu Di, M. Bosman, J.K.W. Yang, Optics Express (2014)

Other possible geometries

Review: Taejun Lee et al, Nano Convergence (2018)

metal-insulator-metal MIM

Soroosh Rezaei et al, Optics Express (2017)

Review: Fei Ding et al, Nanophotonics (2018)

trench

Zhuo Wang et al, ACS Nano (2017)

Zhuo Wang, Zhaogang Dong et al, Nat. Comm. (2016)

all-metallic protrusions

X.M. Goh et al, ACS Photonics (2016)

Ray J.H. Ng et al, Optics Express (2015)

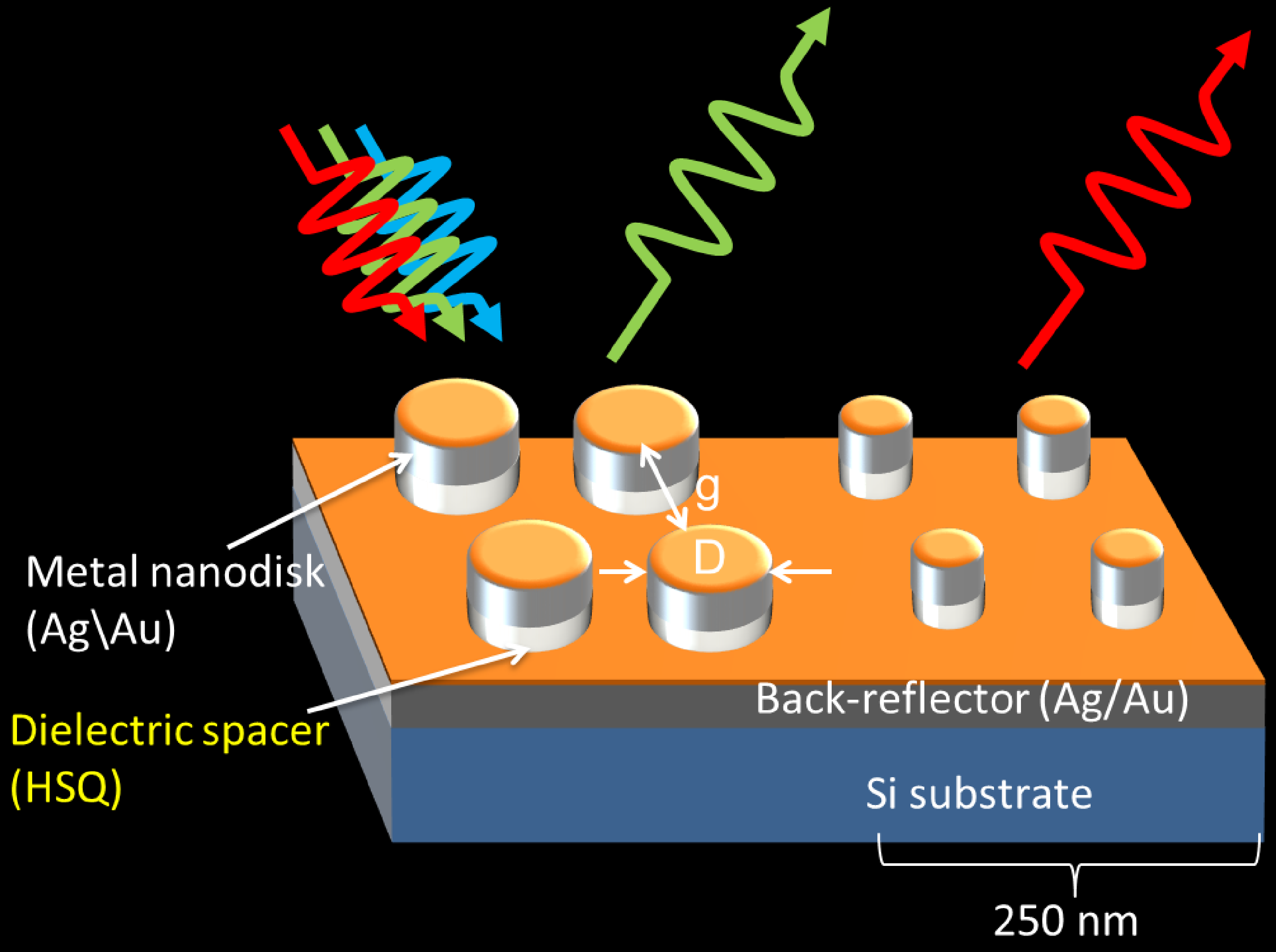
complementary

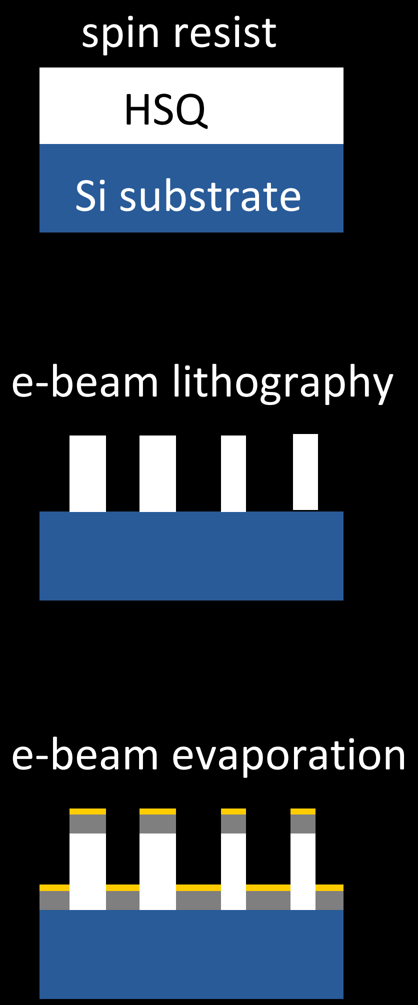
Karthik Kumar et al, Nat. Nano. (2012)

X.M. Goh et al, Nat. Comm. (2014)

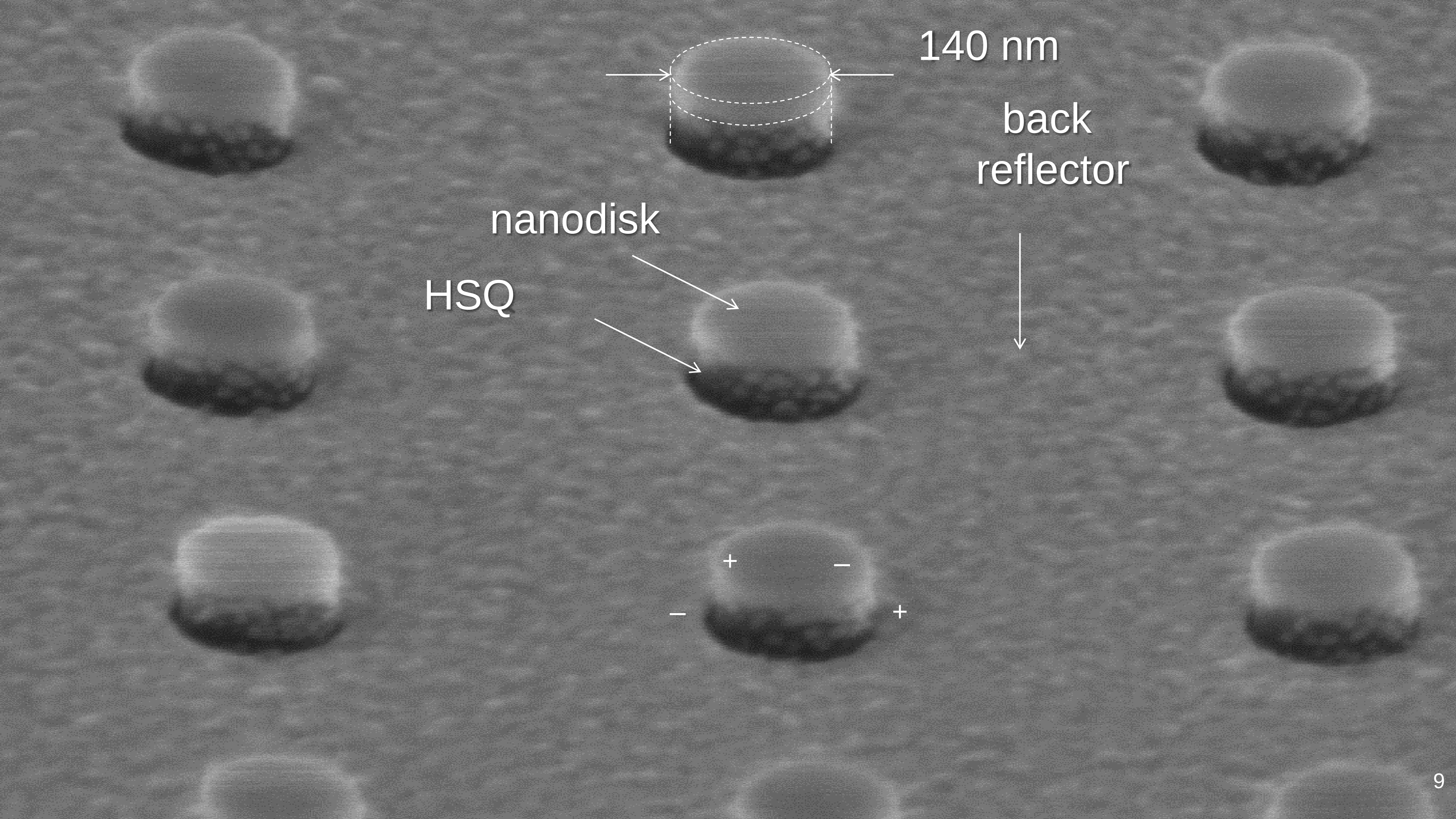
Shawn J. Tan et al, Nano Lett. (2014)

Fabricating High-Resolution Plasmonic Color Prints





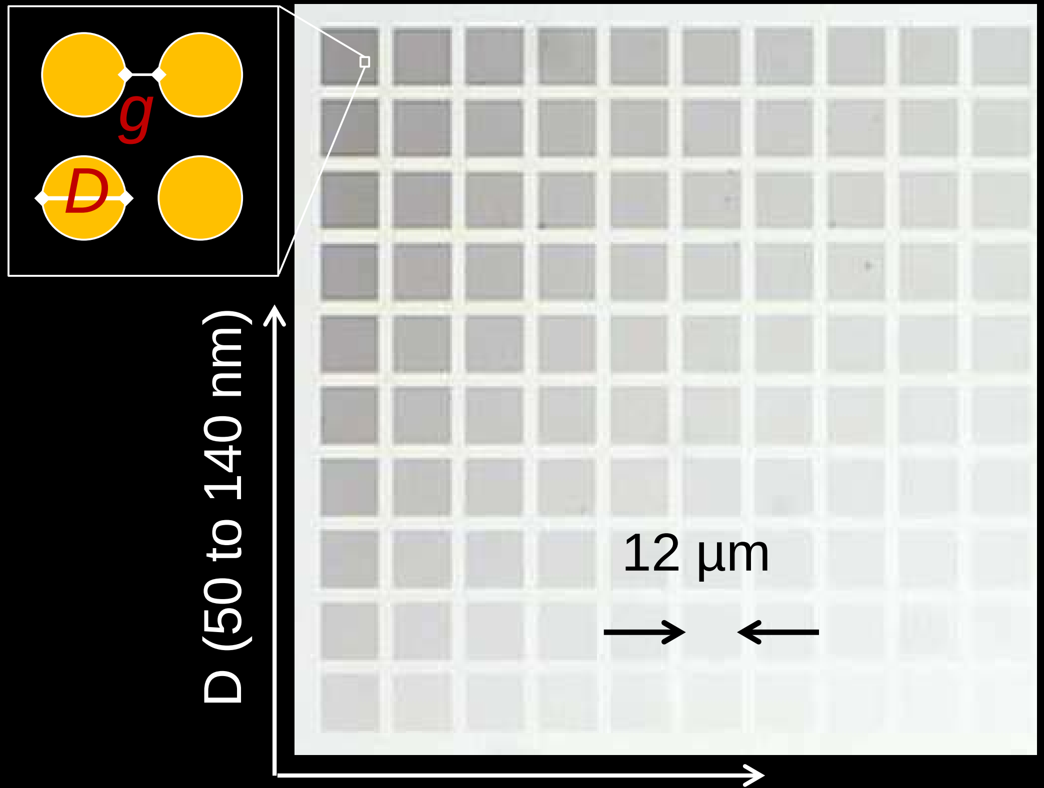
Kumar, Duan, Hegde, Koh, Wei, Yang, Nature Nanotechnology (2012)


140 nm
back reflector
nanodisk
HSQ
+
–
–
+

Printing at the optical diffraction limit ~100,000 dpi

Color information encoded into nanostructure dimensions

Before metal deposition



optical µgraph

Kumar, Duan, Hegde, Koh, Wei, Yang, Nature Nanotechnology (2012)

Printing at the optical diffraction limit ~100,000 dpi

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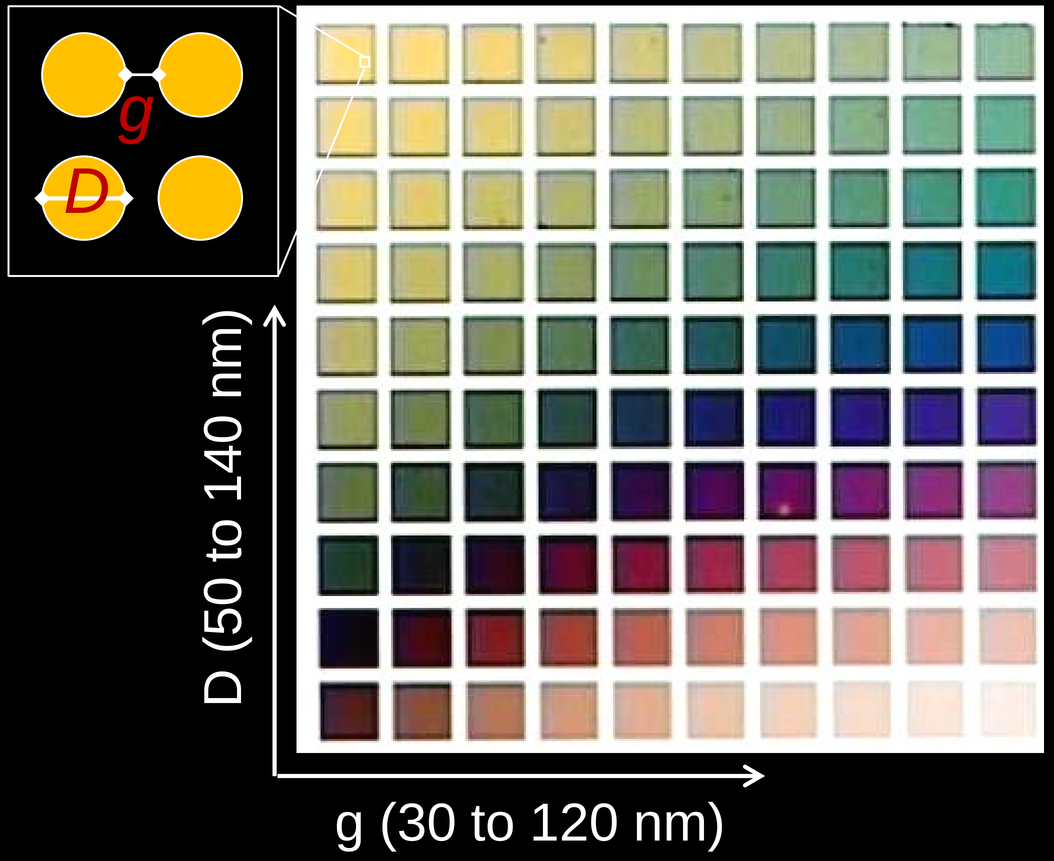


optical µgraph

Kumar, Duan, Hegde, Koh, Wei, Yang, Nature Nanotechnology (2012)

100,000 dpi ~ ultimate resolution

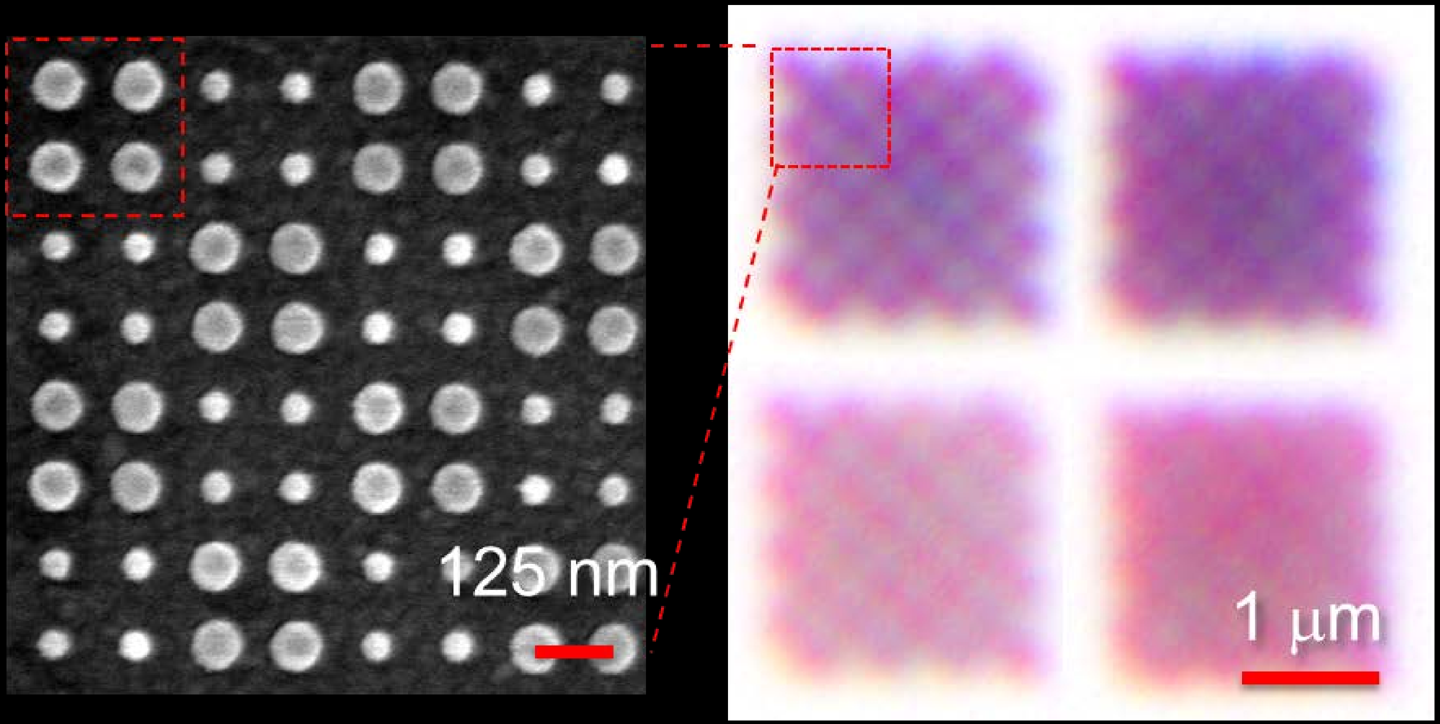
$$d = \frac{\lambda}{2N.A.}$$

Considering green light ~500 nm and a NA of ~1, the Abbe limit is roughly $d = \lambda/2$ = 250 nm

SEM

optical µgraph

250 nm pixels

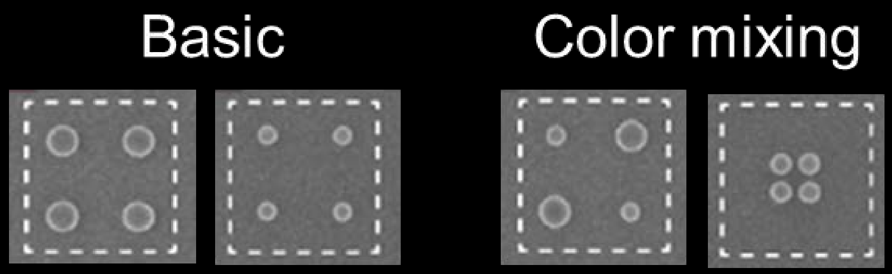


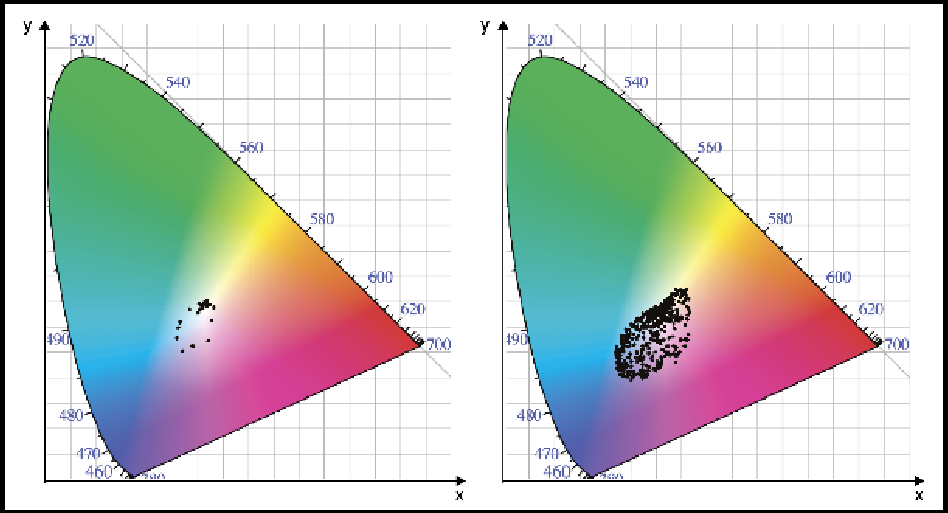
Olympus microscope:

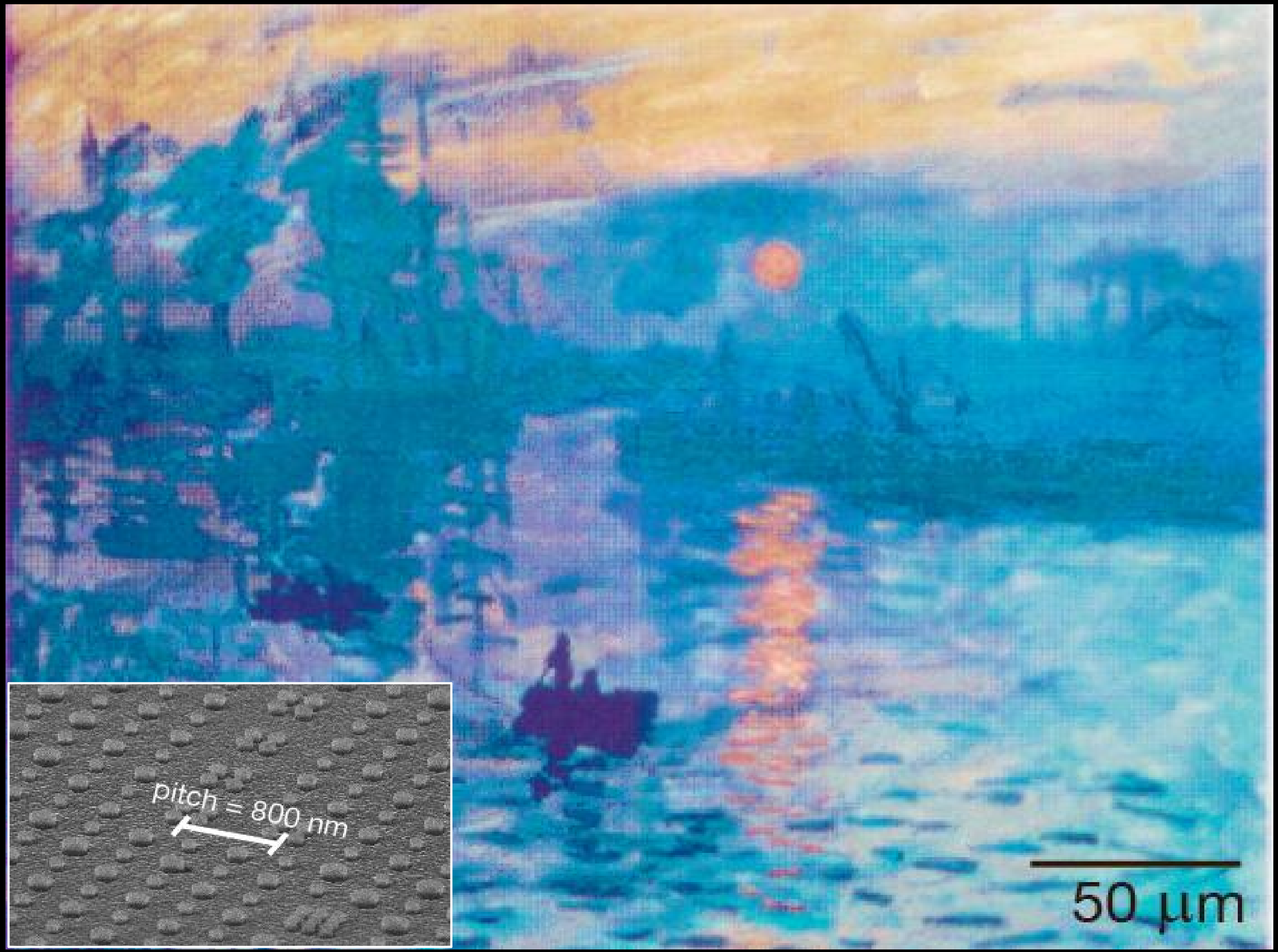
150x mag
0.9 N.A.
objective

Kumar, Duan, Hegde, Koh, Wei, Yang, Nature Nanotechnology (2012)

From Silver to Aluminum: Plasmonic Color Mixing





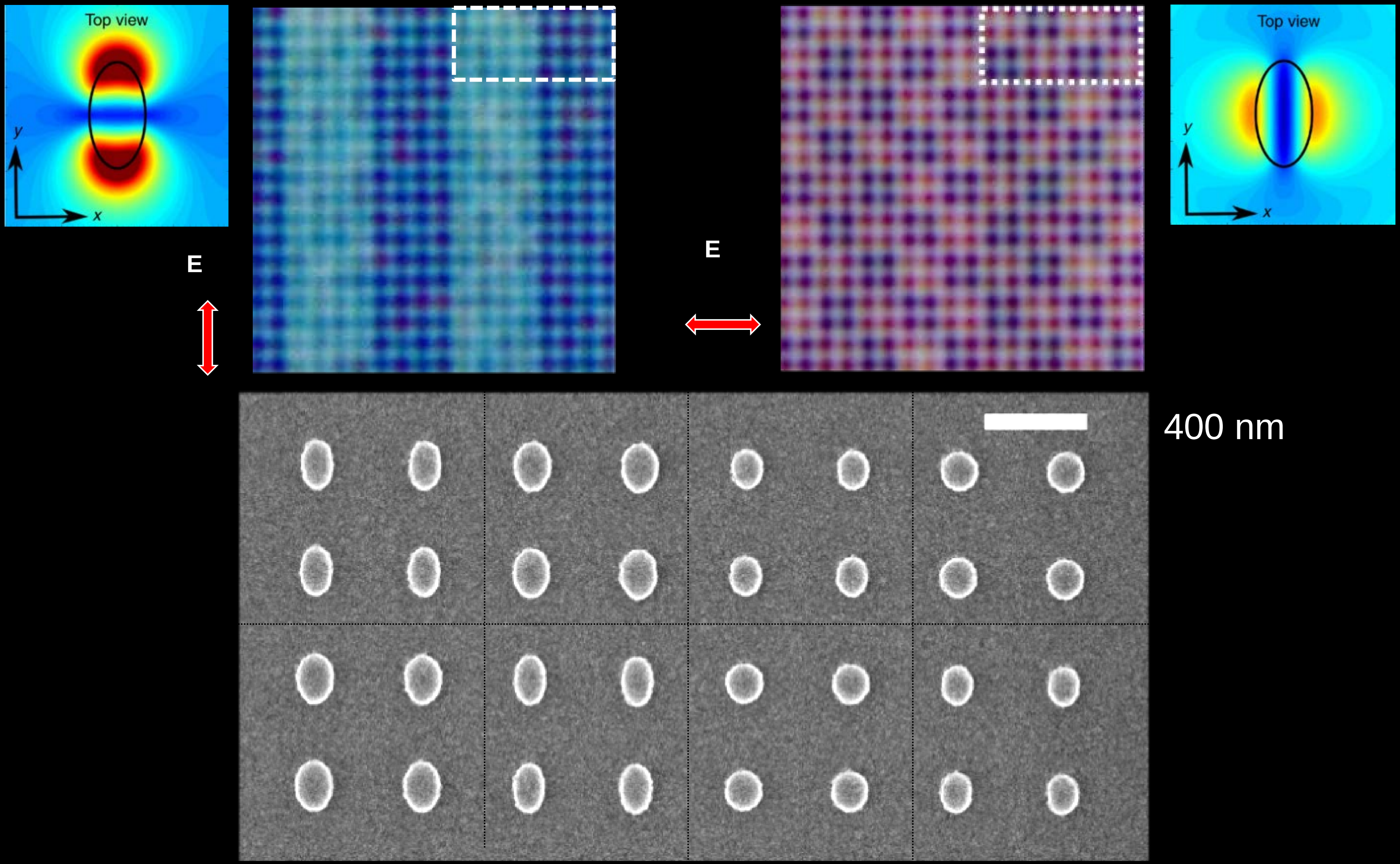


CIE plots showing expanded color gamut when structures are combined within a unit cell

Shawn J. Tan et al., Nano Lett (2014)

From Disks to Ellipses: One structure two colors

Each individual nanostructure can stand alone as a color element.



X.M. Goh et al., Nature Communications (2014)

First 3D Micro Color Stereograms

Overlaid off-set images can be decoupled using polarizers.

Optical microscope set-up	Decoupled Images	3D Microprint

Off-set superimposed prints in orthogonally polarised pixels

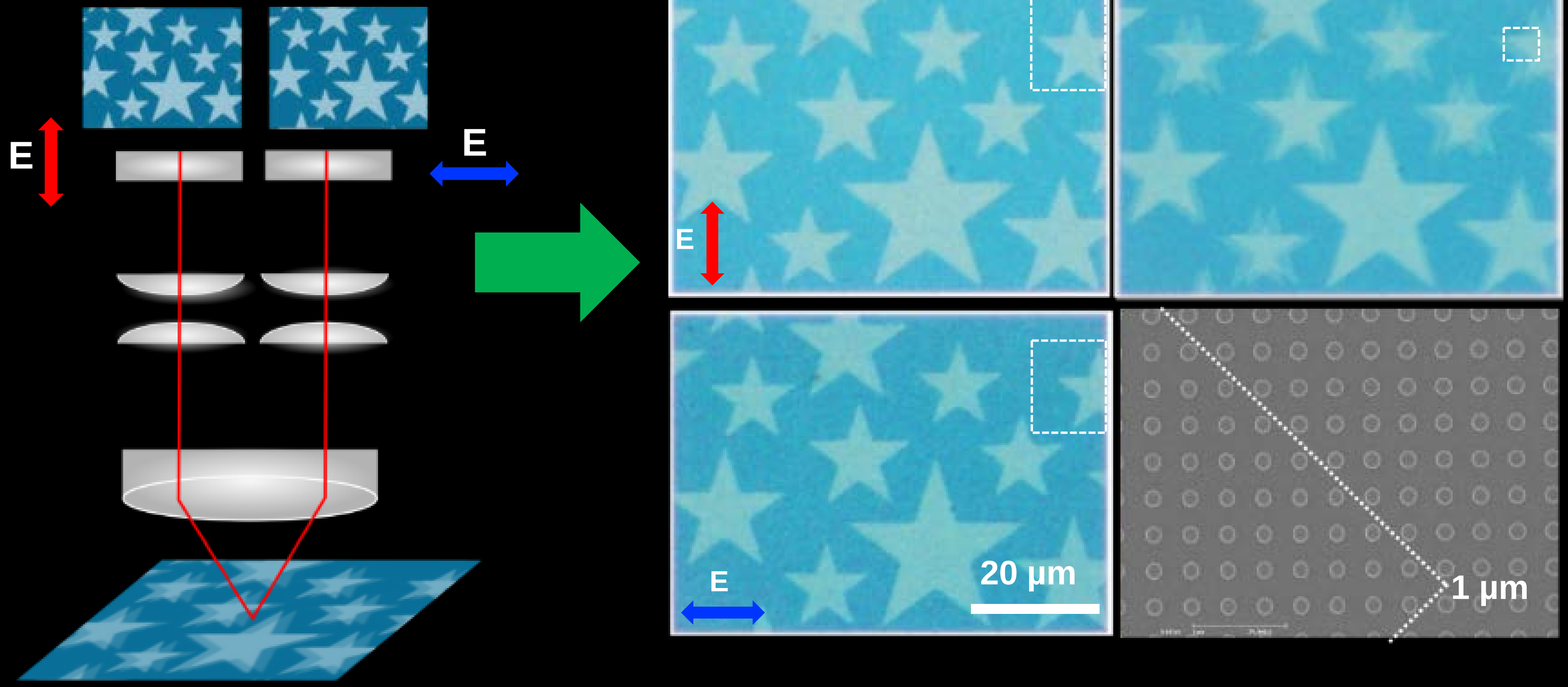


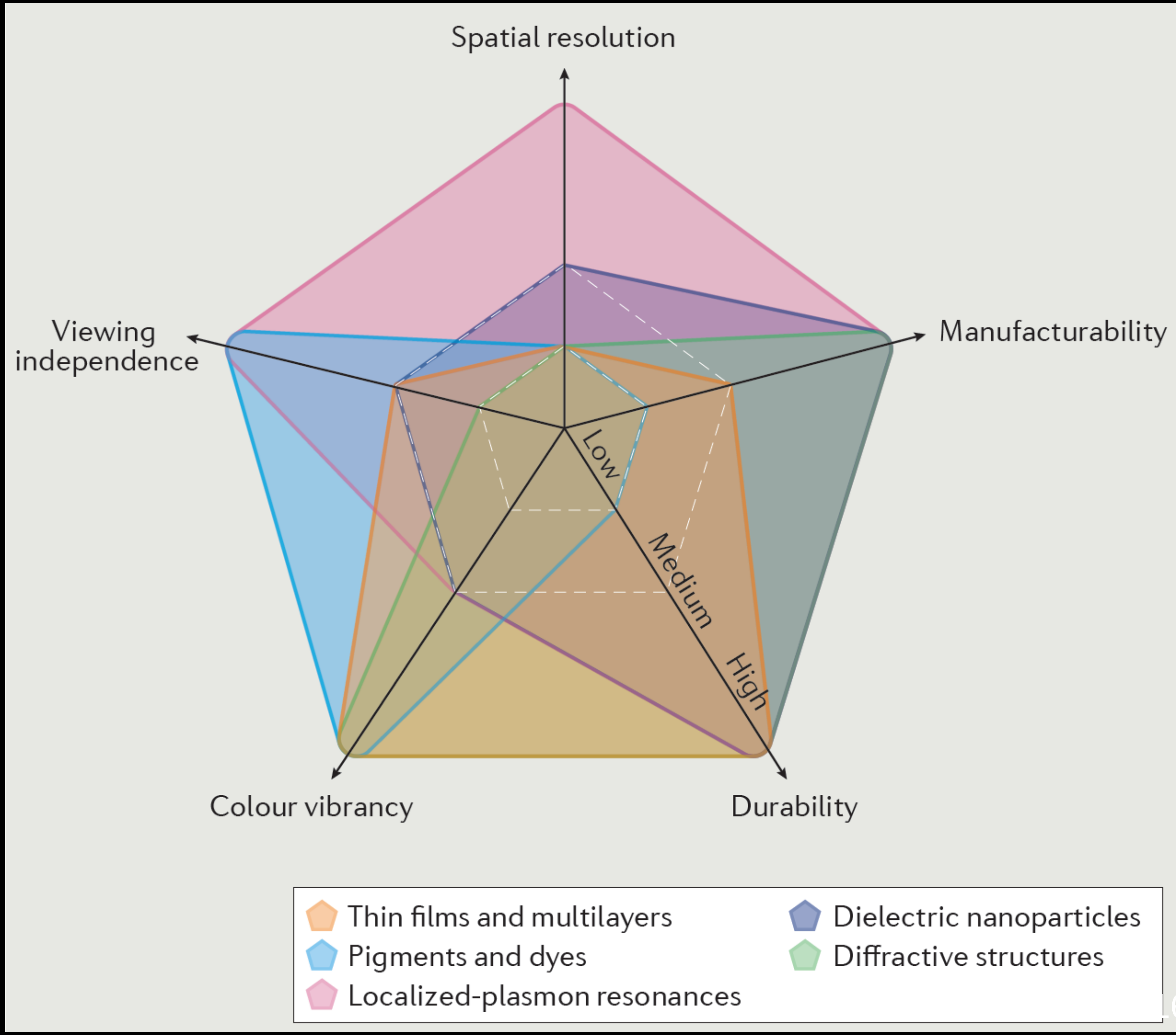
Image with depth perception

X.M. Goh et al., Nature Communications (2014)

Nat. Rev. Mater. **2**, 16088 (2017)

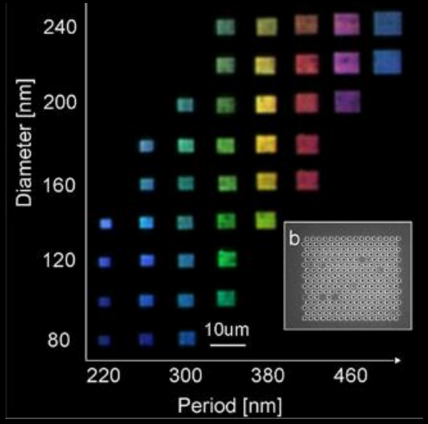
Plasmonic colour generation

Anders Kristensen[1], Joel K. W. Yang[2,3], Sergey I. Bozhevolnyi[4], Stephan Link[5,6], Peter Nordlander[5–7], Naomi J. Halas[5–7] and N. Asger Mortensen[8]



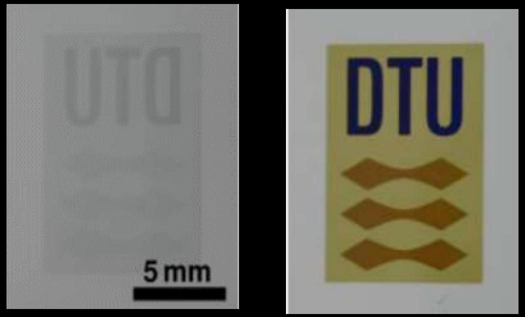
Examples of Applications

Color Filters For High-Digital Cameras



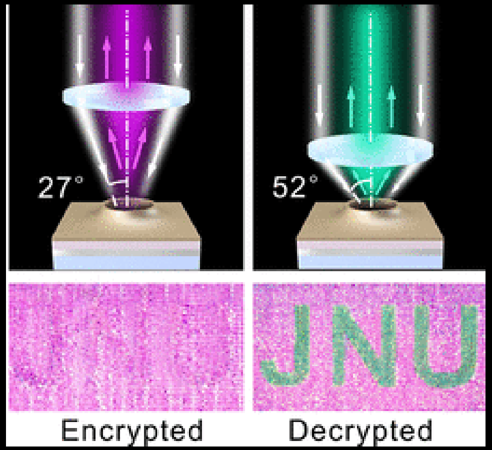
S. Yokogawa et al., Nano Lett (2012) [Atwater, USA]

Colors For Plastic Consumer Products



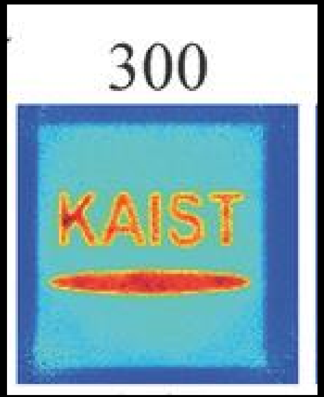
J. S. Clausen et al. Nano Lett (2014) [Kristensen, Denmark]

Encryption using Laser Ablation



D. Hu et al., ACS Nano (2018) [X. Li, China]

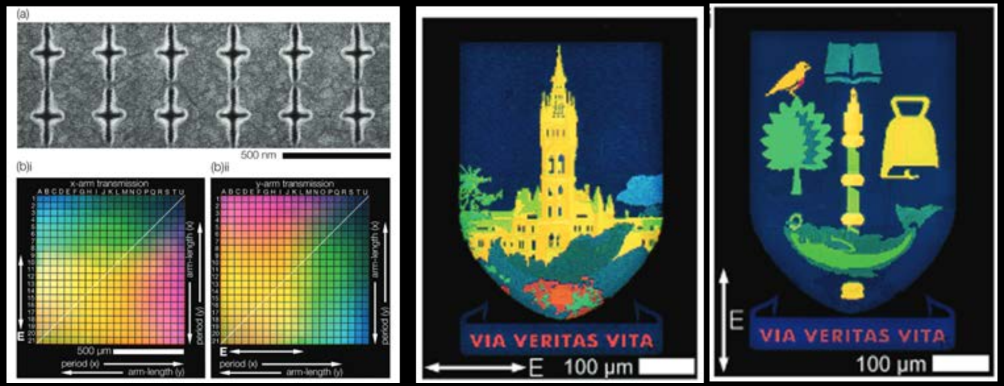
Covert "Colors" in UV



C.H. Lee et al., Adv Opt Mat (2018) [Seo, Korea]

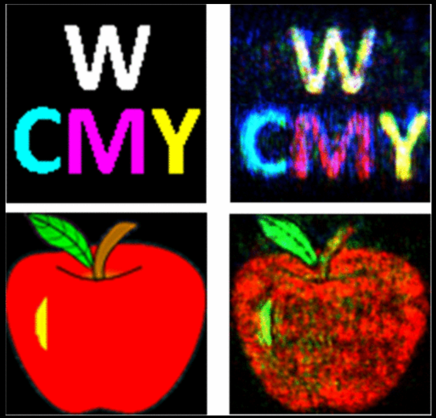
Examples of Applications

Color filters with polarization dependence



E. Heydari, et al. Adv. Funct. Mater. (2017) [Clark, UK]

Plasmonic color holograms

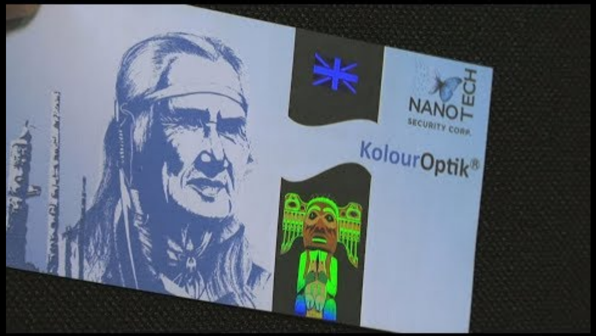


W. Wan et al., ACS Nano (2016) [X. Yang, USA]

Surface decoration

J.M. Guay et al., Nature Comms (2017) [Weck, Canada]

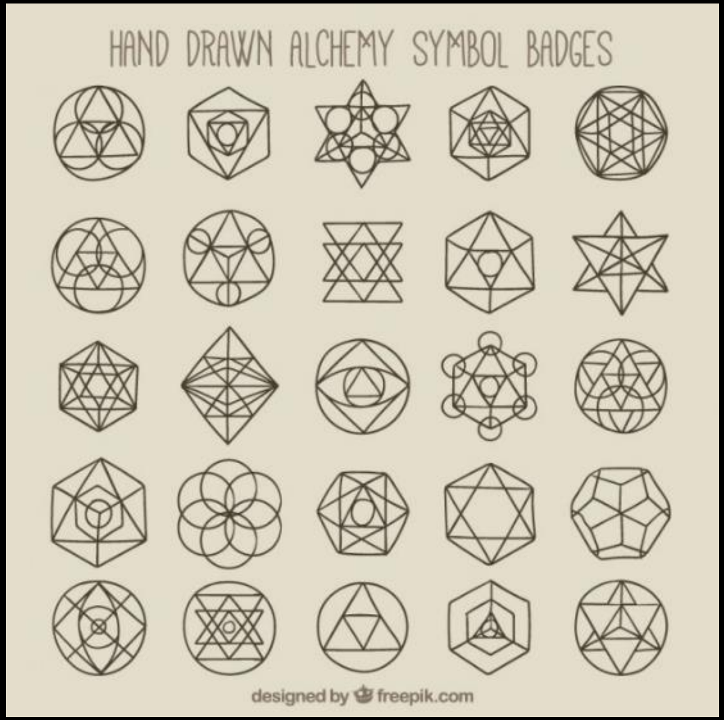
Document Security



Nanotech Security Corp.

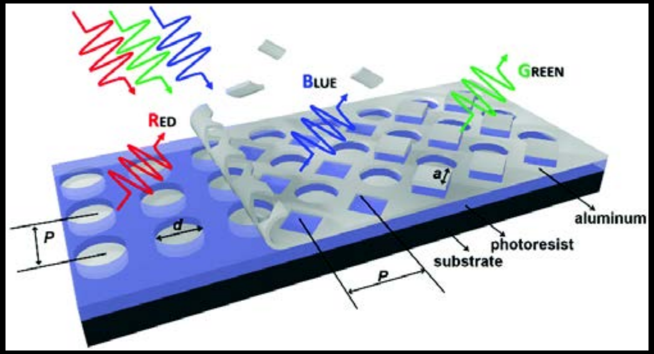
Remaining Challenges

Universal design approach

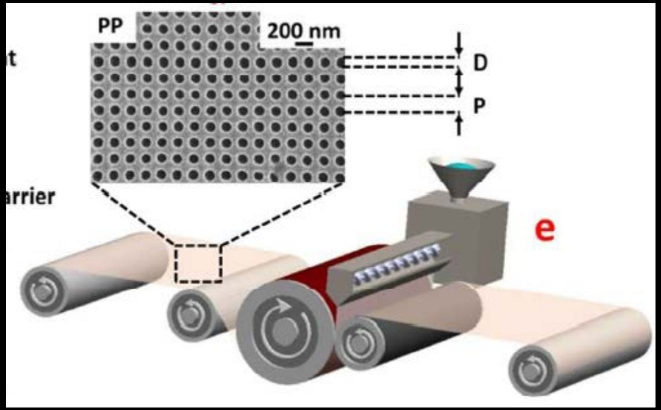


Geometry, Topology, Material, AI/ML

Low cost, large scale



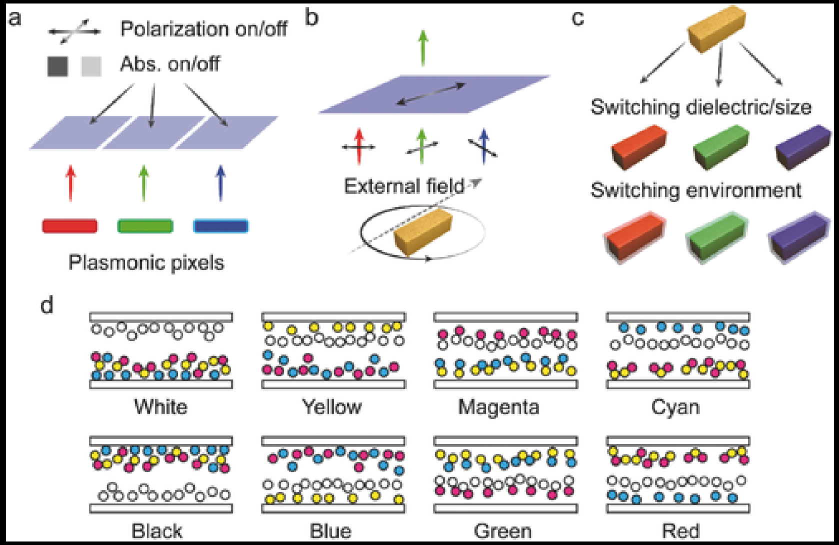
Mahsa Jalali et al. Nanoscale (2016)



S. Murthy et al. Nanoscale (2017)

New lithographic approaches

Dynamically tunable colors



L. Shao, X. Zhuo, J. Wang, Adv. Mater. (2017)

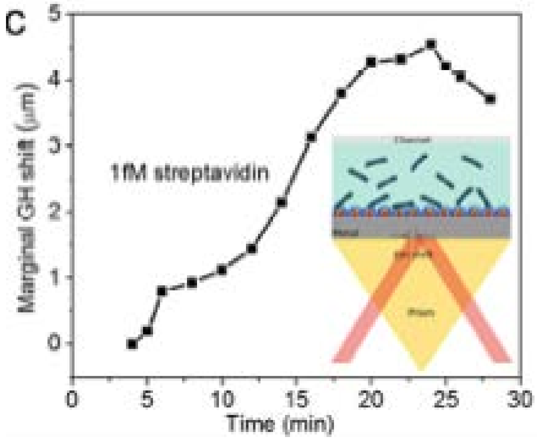
Interactions of plasmonic structures with switchable materials

How can we make switchable plasmonic color?

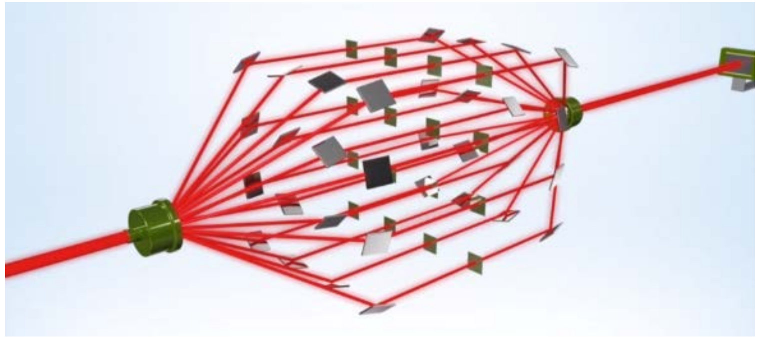
Motivation

Displays

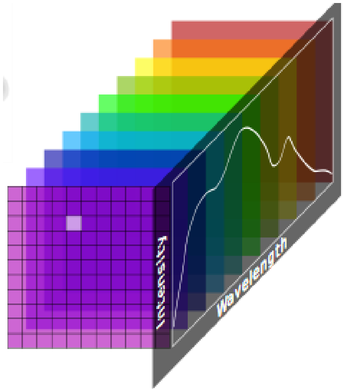
Spectroscopy



Sensing



Processing



Hyperspectral Imaging


Fast Switching


Analogue

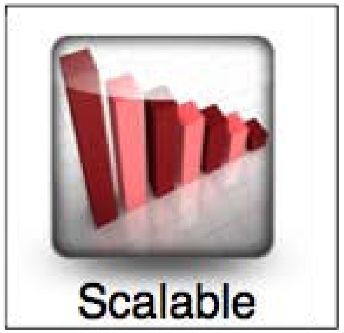

High Contrast

Needs


Energy
Efficient


Low Power


Endurance

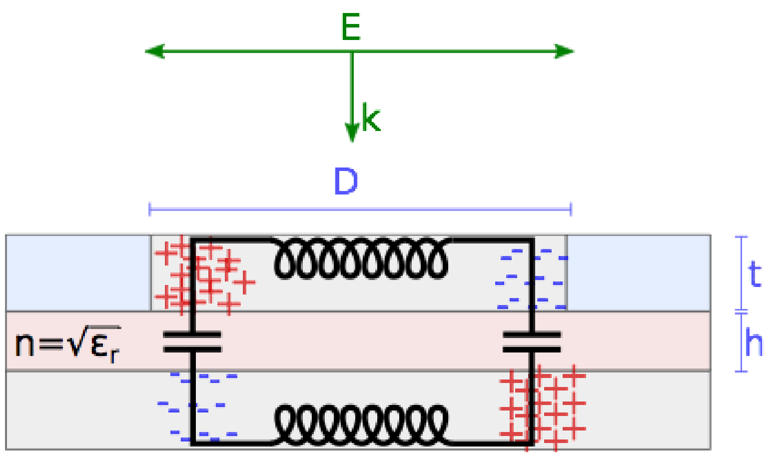

Scalable


Extreme
Environments

Objective

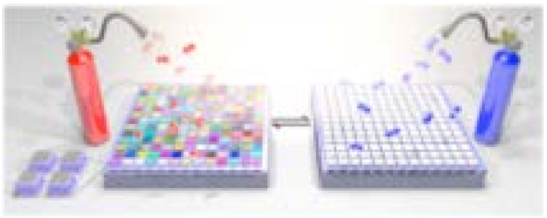
To design tunable plasmonic color materials and structures

Tuning plasmon resonances



$$\lambda_{\mathbf{resonance}} \propto \frac{D}{\sqrt{t \times h/\varepsilon_r}} = n\frac{D}{\sqrt{t \times h}}$$

Reversible Hydrogenation, Index Change

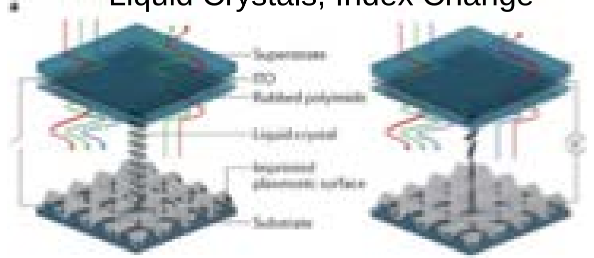


X. Duan, et al., Nat. Commun. (2017)

Electrochromic Polymers, Index Change

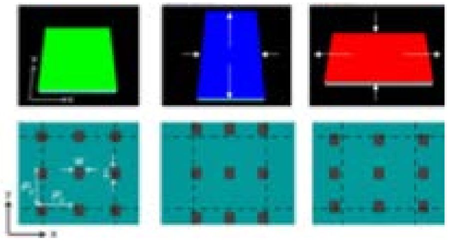
T.Xu, et al., Nat. Commun. (2016)

Liquid Crystals, Index Change



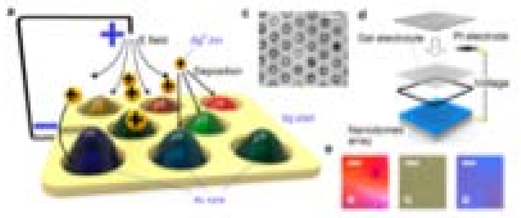
D. Franklin, et al., Nat. Commun. (2015)

Polymeric Stretching, Geometry Change



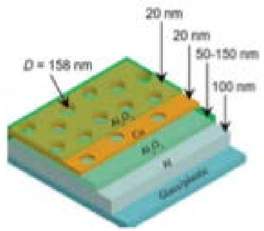
M.L. Tseng, Nano Lett (2017)

Electrochemical, Geometry change



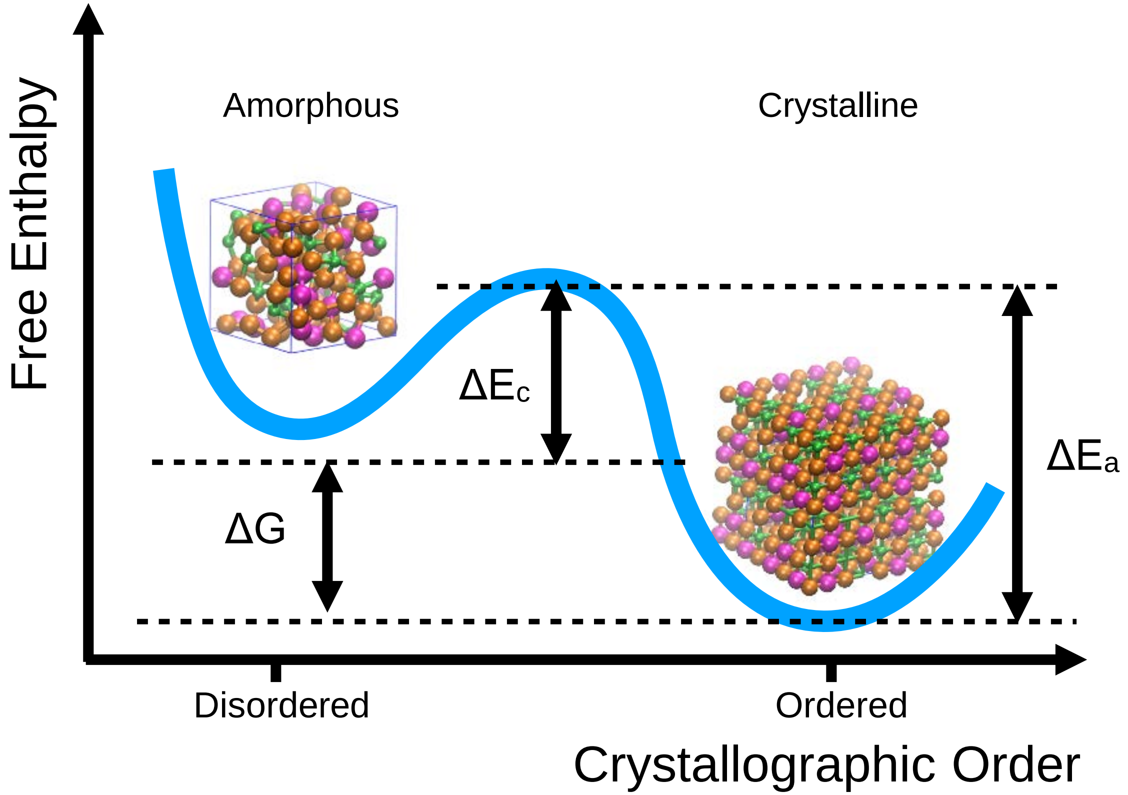
G. Wang et al. ACS Nano, 2016

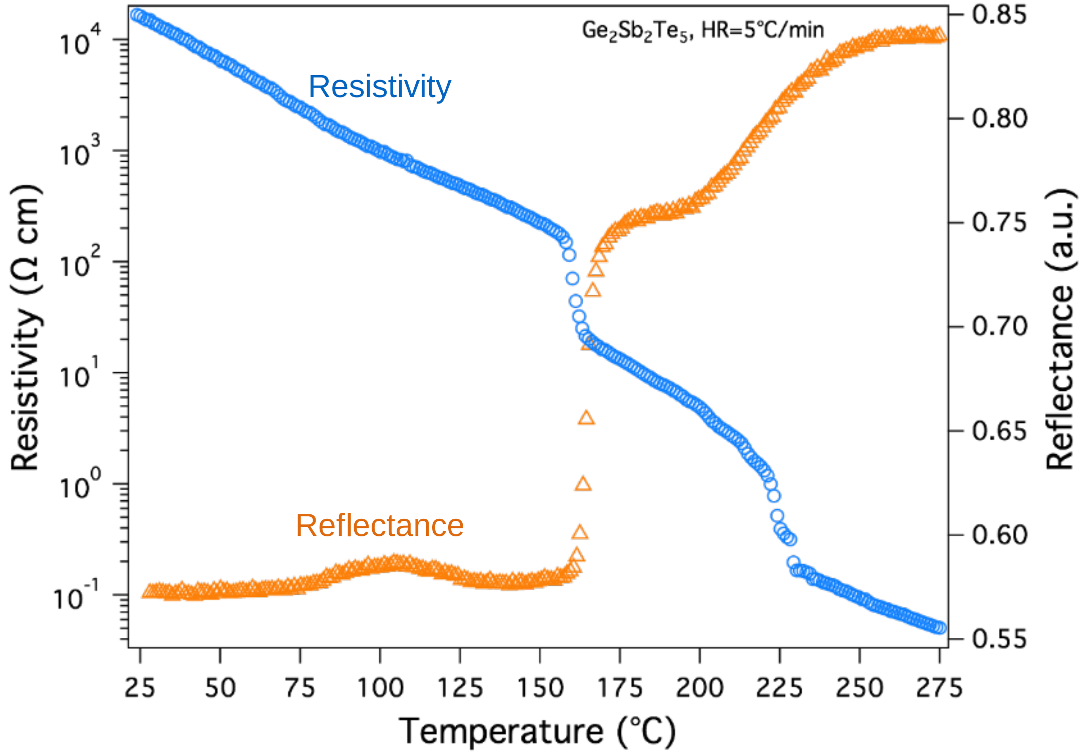
Electrochromic Polymers, Index Change



Kunli Xiong et al., Nano Lett (2017)

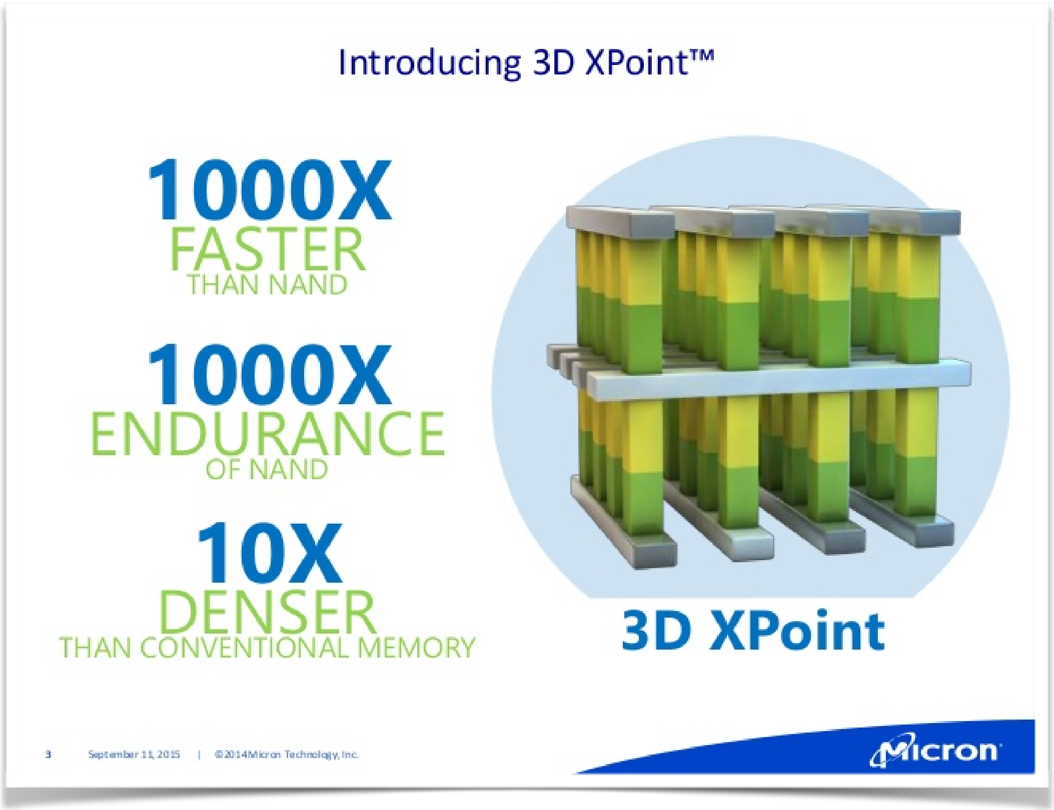
Phase Change Materials





Amorphisation time >5 ps, Recrystallisation >500 ps

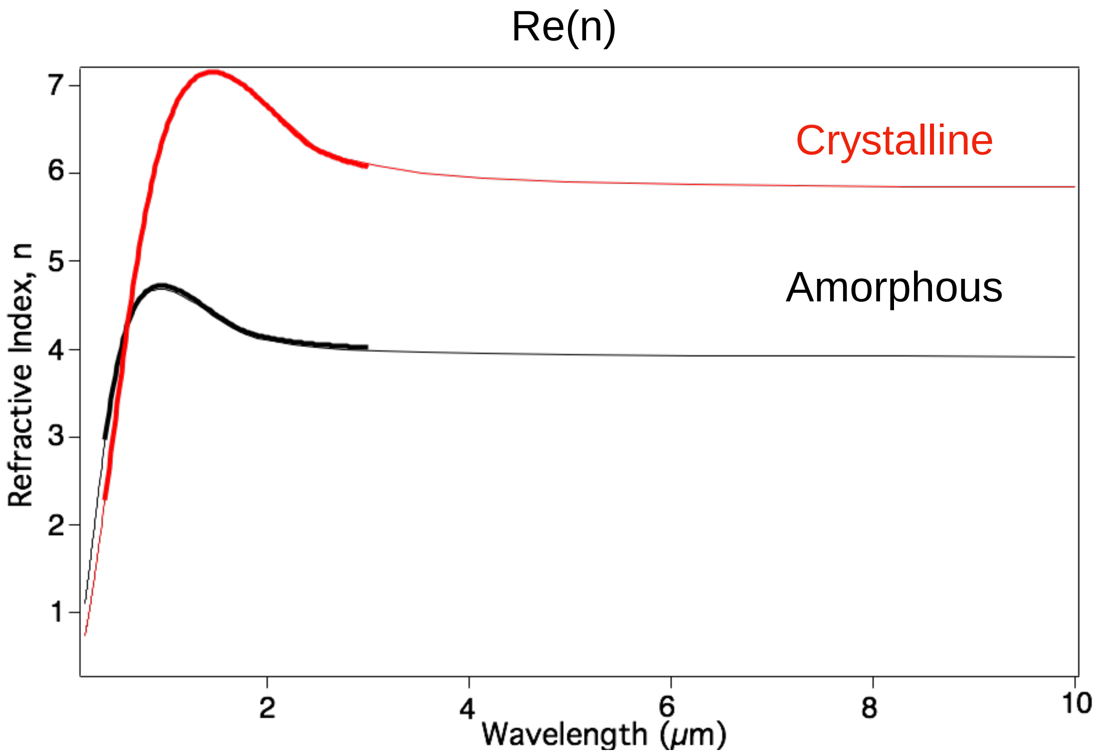
Existing applications

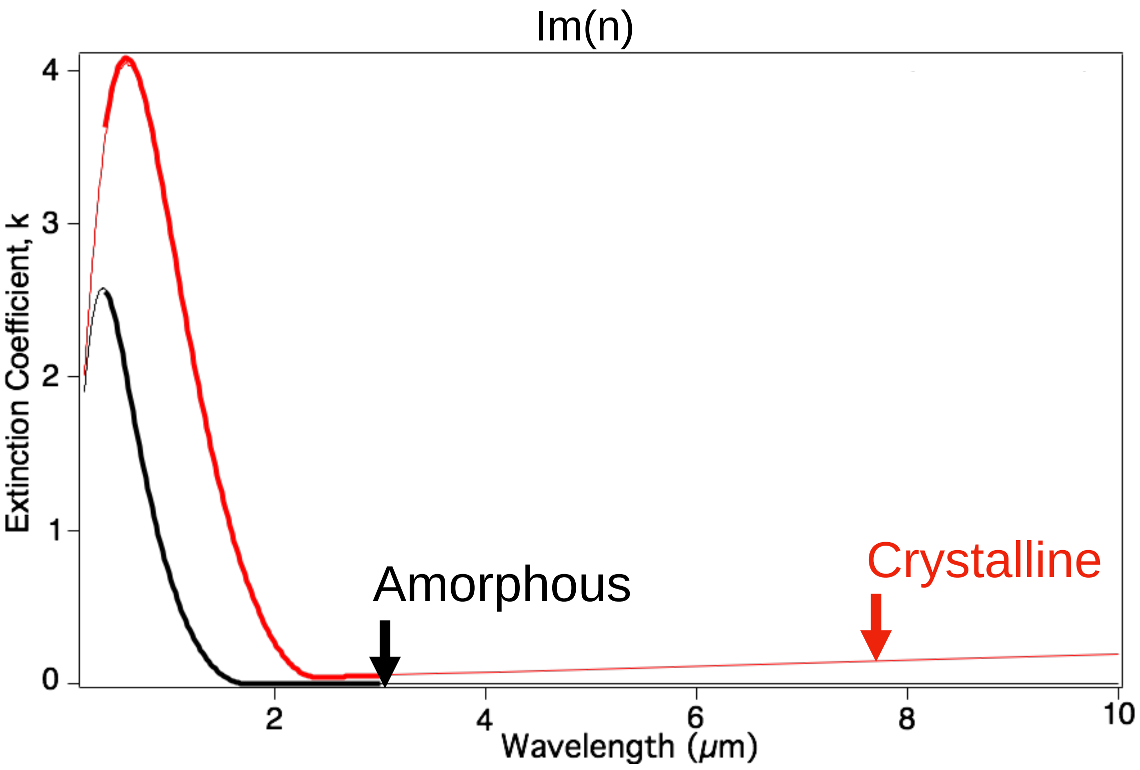


DVD laser wavelength= 658 nm
CD laser wavelength= 780 nm

Are data storage PCMs useful for tuning plasmon resonances?

$Ge_2Sb_2Te_5$ is good for IR

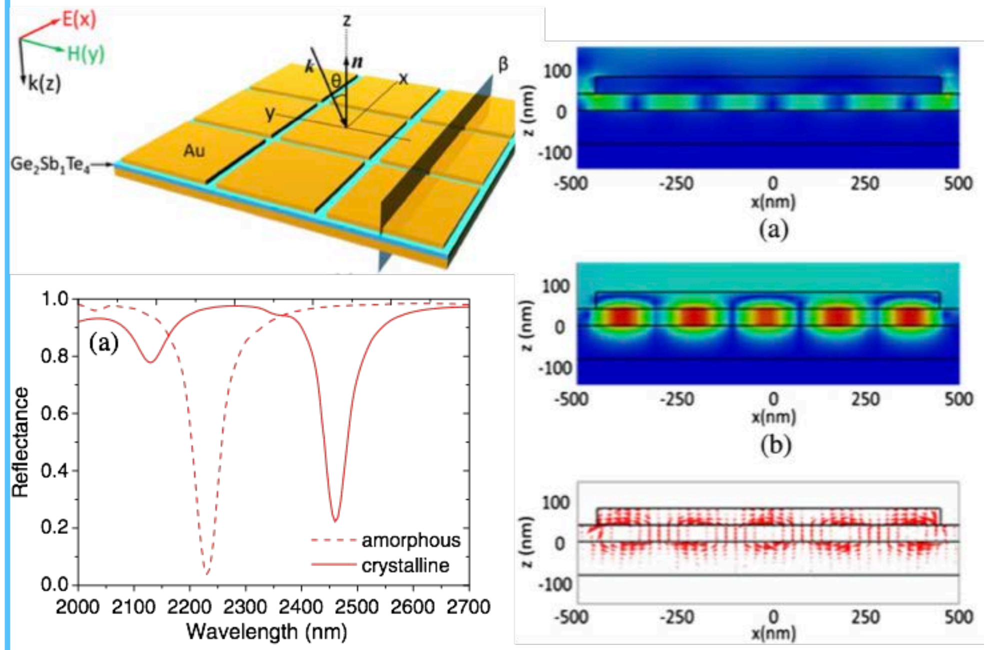




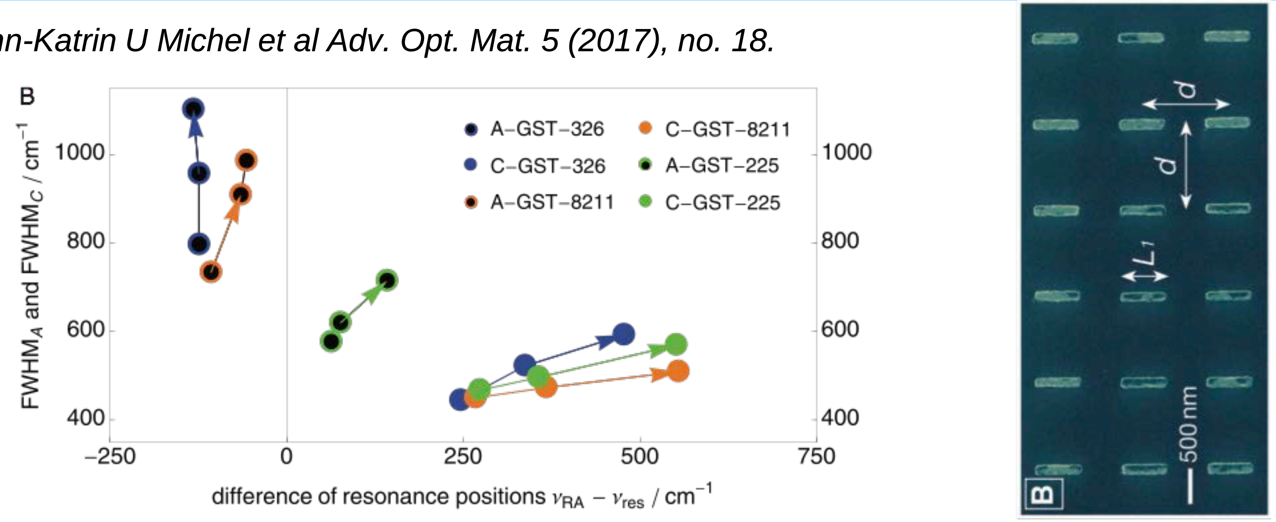
Li Tian Chew, et al., Proc.SPIE 10345 (2017), 10345 – 10345 – 9.

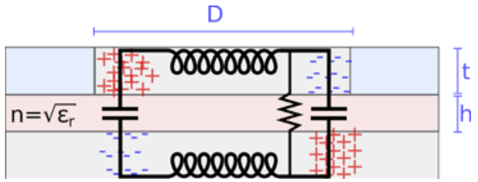
M-IR Plasmonics

Tun Cao et al. , J. Opt. Soc. Am. B 30 (2013), no. 6, 1580–1585.



Ann-Katrin U Michel et al Adv. Opt. Mat. 5 (2017), no. 18.



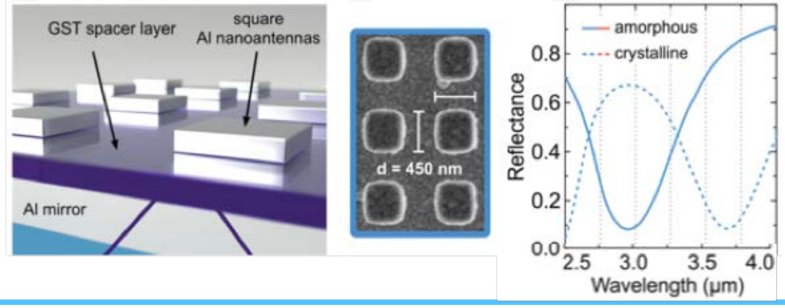


$$Q = R\sqrt{\frac{C}{L}} \propto R\sqrt{\frac{t}{h}}$$

Large R gives higher Q factor

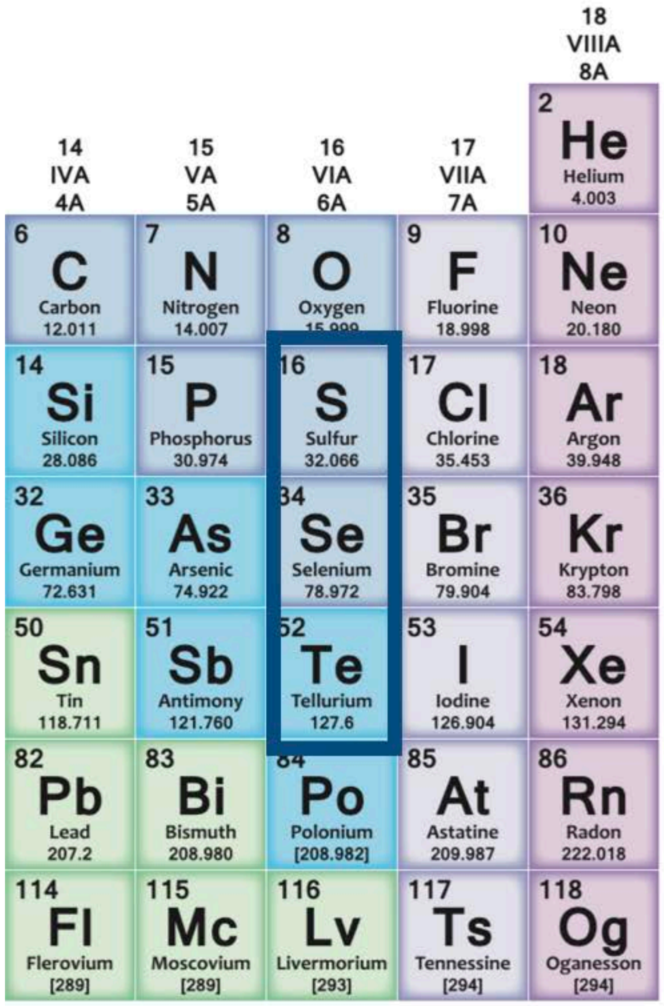
Weiling Dong et al. J. Phys. Chem. C 120 (2016), 23, 12713–12722

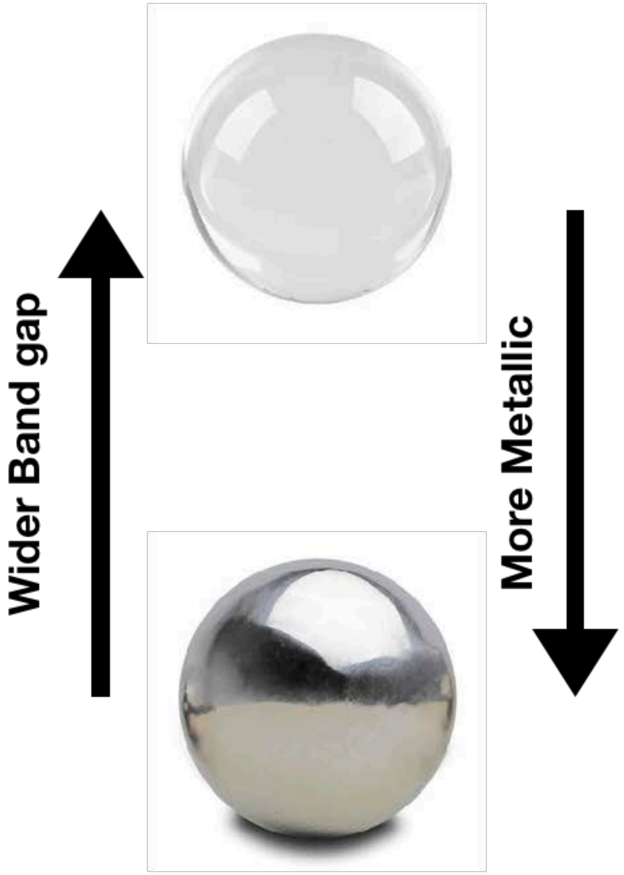
Andreas Tittl, et al, Adv. Mater. 27 (2015), no. 31, 4597–4603.



We need to design new PCMs specially for the visible photonics

Sulphides, Selenides, or Tellurides?





The forgotten PCMs

- Ge–Te–As
- Sn–Te–Se
- Ge–Te–Sn
- Ge–Te
- Ge–Te–Sn–O
- Ge–Te–Sn–Au

- In–Se
- In–Se–Tl
- In–Se–Tl–Co
- Sb–Te
- In–Sb–Te
- Sb–Se–Bi

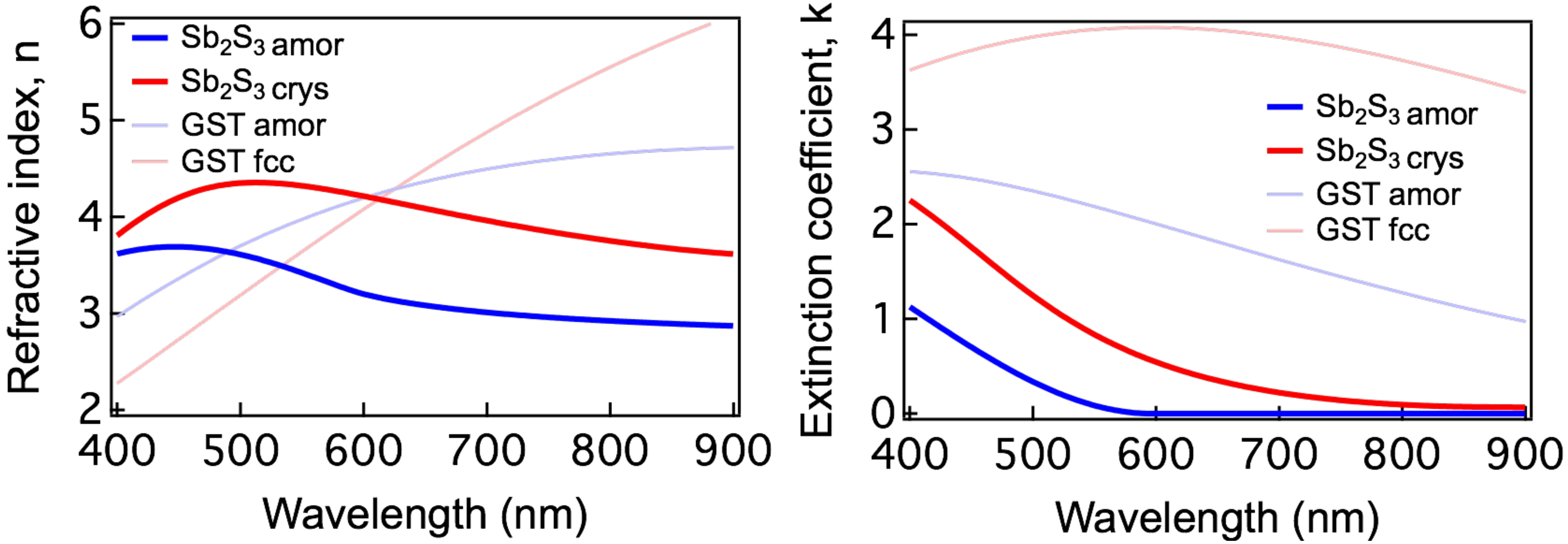
- Ge–Sb–Te–Se
- Ag–In–Sb–Te
- Ga–Te–Se
- Sb-Se
- Sb-S

- Ga-La-S-Cu
- Ga-Sb
- Ge–Te–Ti
- Ge–Sb–Te
- Ge–Te–Sn–Pd

Guo-Fu Zhou, Mat. Sci. & Engineering 304 (2001), 73–80.
P Arun et al. Mat. Res. Bull. 32 (1997), no. 7, 907–913.

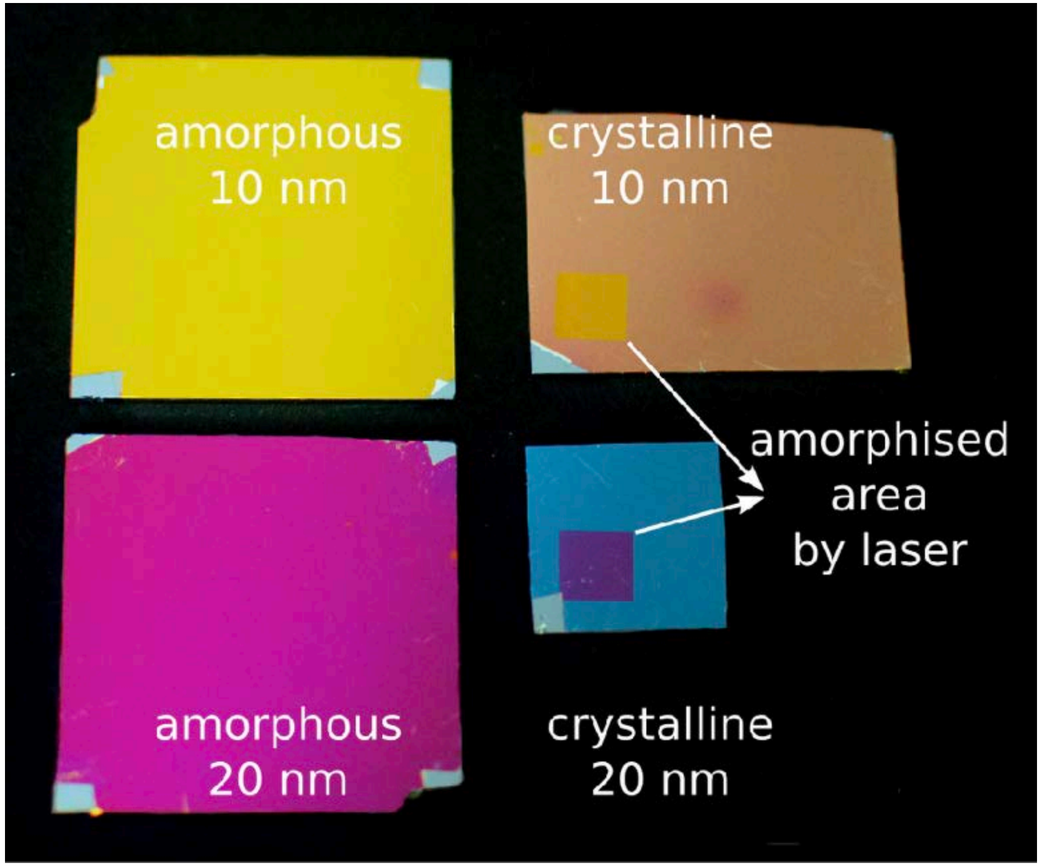
Stibnite (Sb_2S_3)

Sb_2S_3 Refractive Index

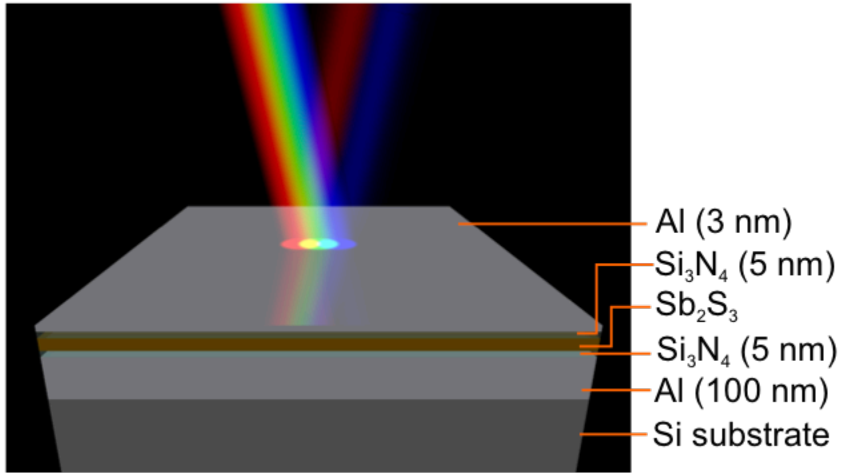


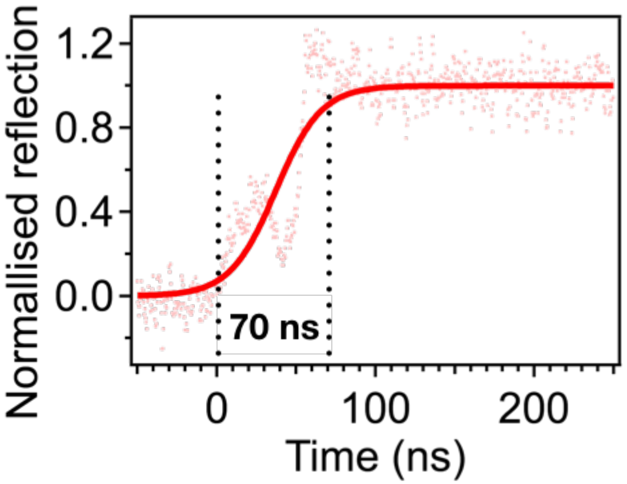
Weiling Dong et al. aXiv [physics. optics] (2018), no. 1808.06459.

Absorption shift

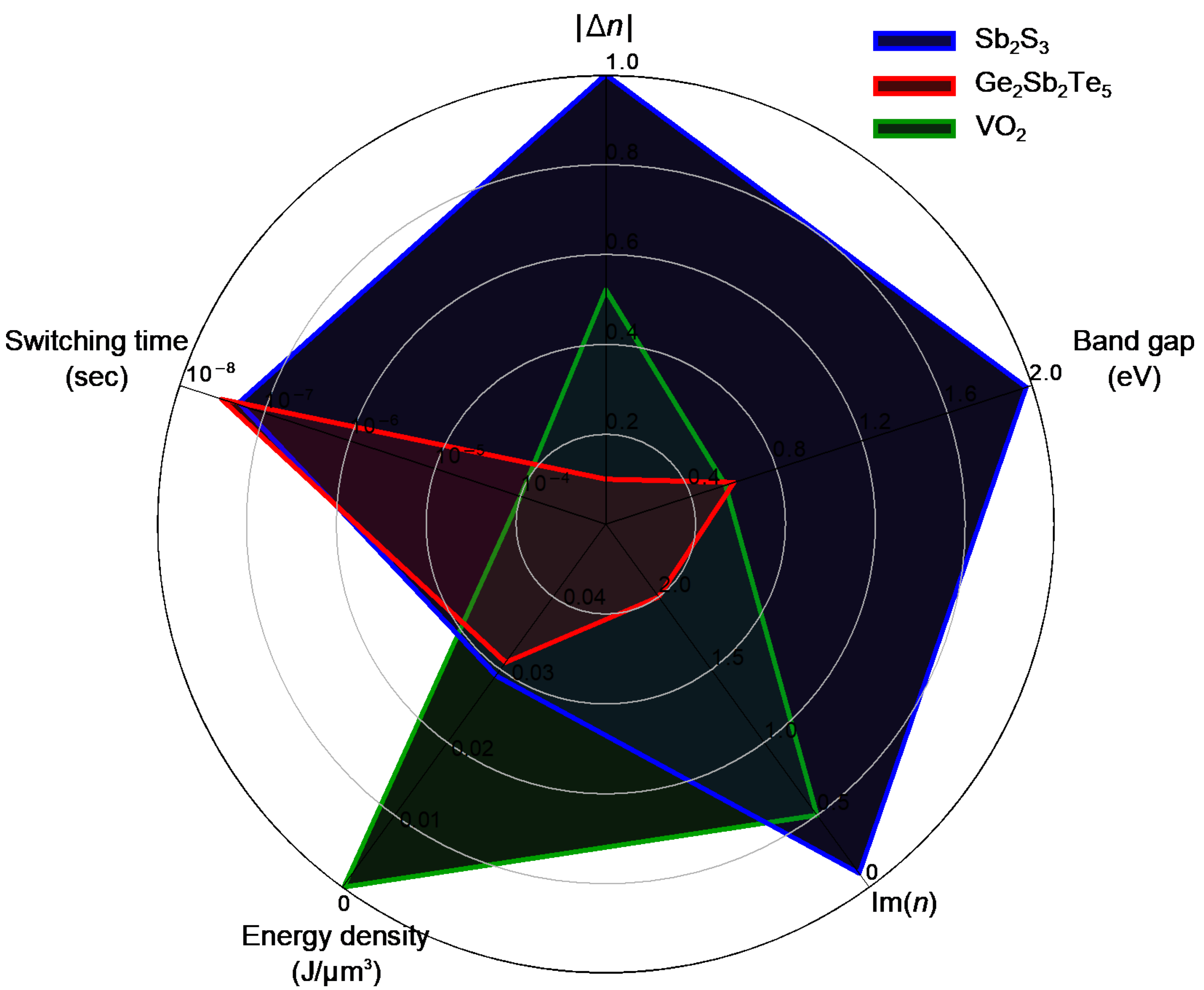


Crystallization and laser amorphisation





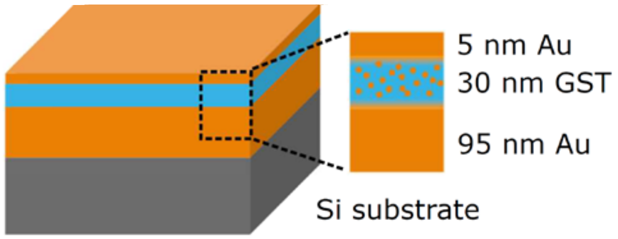
Weiling Dong et al. aXiv Preprint (2018), no. 1808.06459.



Weiling Dong et al. aXiv Preprint (2018), no. 1808.06459.

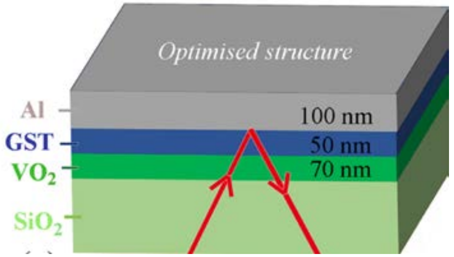
Challenges to be addressed

Diffusion & Reactions



Li Lu et al., arXiv preprint arXiv:1808.08682 (2018).

Analogue refractive index tuning



Yun Meng et al., Appl. Phys. Lett. 113 (2018), no. 7, 071901.
Yun Meng et al. Adv. Opt. Mat. (2018)

More cycles

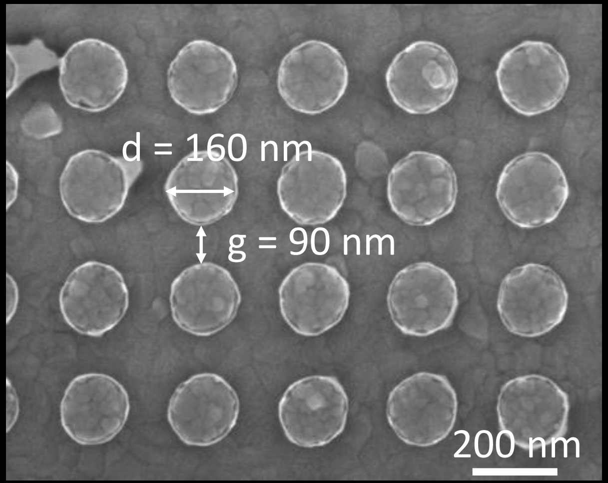
Larger band Gap

Lower switching energy

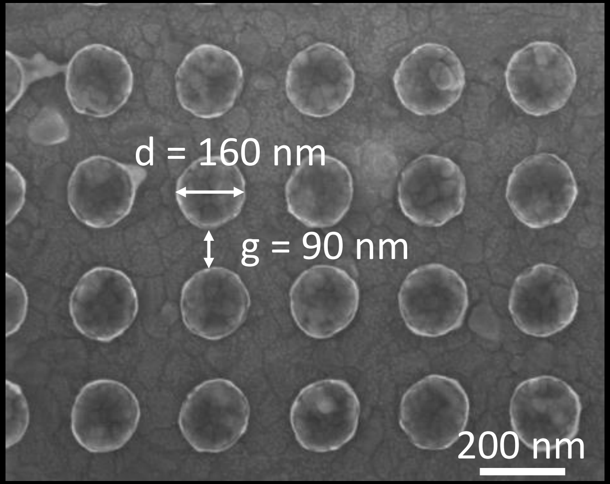
Quenching

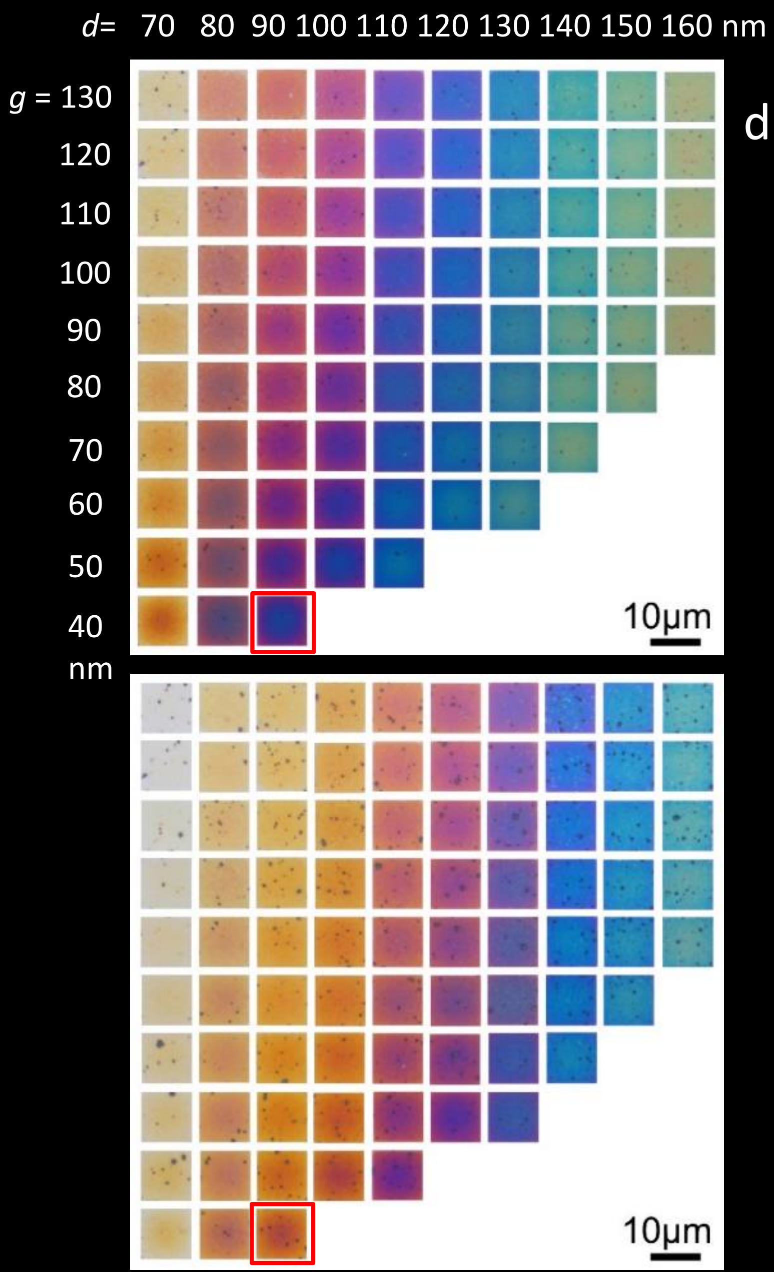
Plasmonic Color Switching with Sb_2S_3

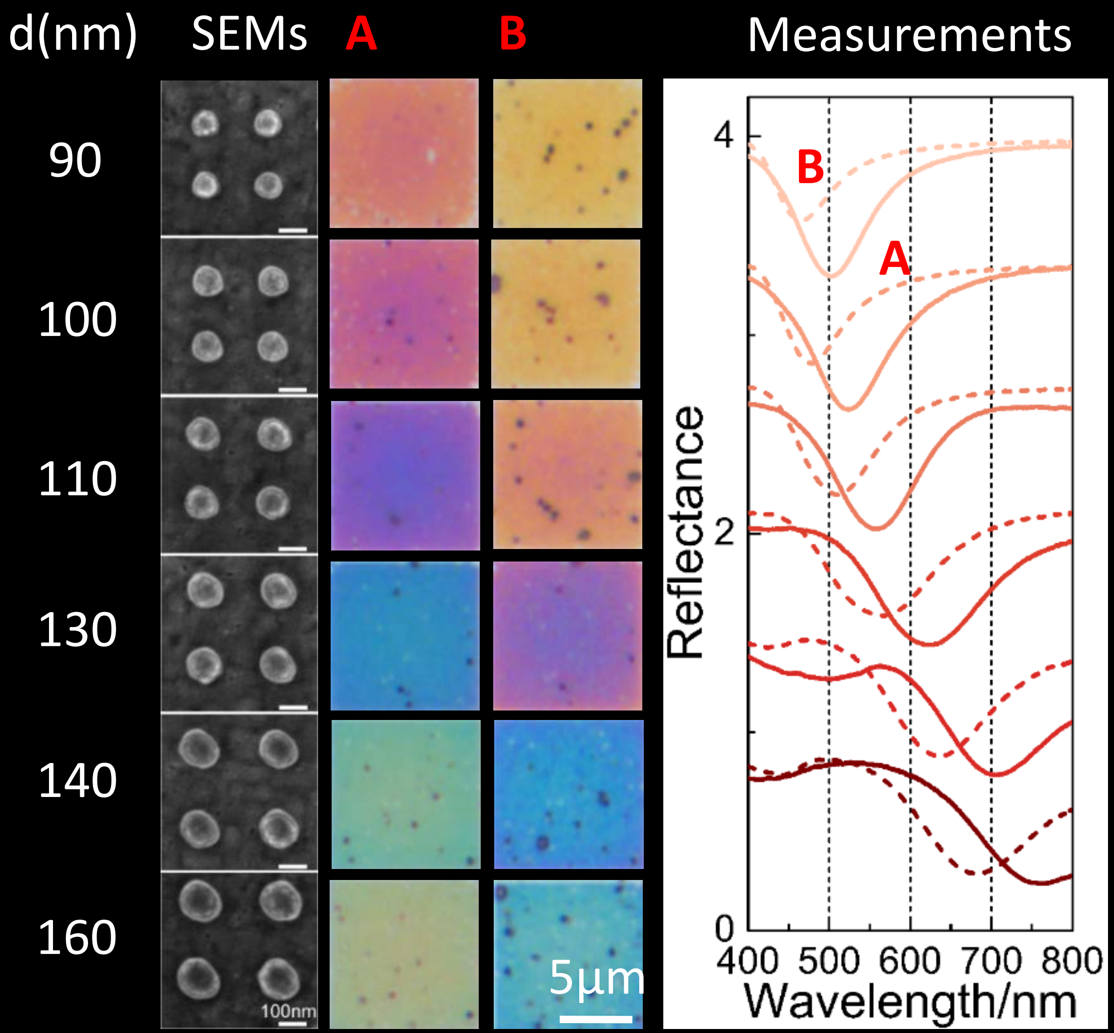
A: As deposited



B: Annealed

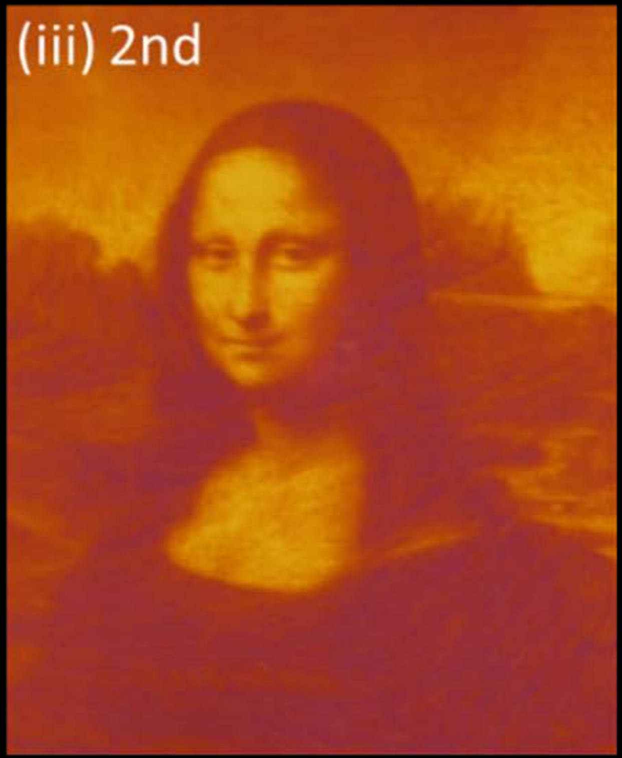






Hailong Liu, Weiling Dong et al., (in preparation)

Rewritable Color Prints

Amorphization	Crystallization	Re-amorphization
		
Girl with a Pearl Earring, Johannes Vermeer, 1665	Sample heated	*Mona Lisa, Leonardo da Vinci, 1503*

Hailong Liu, Weiling Dong et al., (in preparation)

Summary and Outlook

- Plasmonic colors
  - Colors controlled geometry of nanostructured metals
  - Single-step, high-resolution, permanent prints
  - Numerous applications
  - Structural colors based on dielectrics and Fabry-Perot resonances
  - Dynamically tuned colors are needed

- Phase change materials
  - Wide bandgap PCM (e.g. Sb_2S_3) promise high-speed tunable plasmonic color

Yasi Wang et al., Research (2018)

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