



**Seeing glass in a new light:
Chalcogenide glass-enabled
integrated photonics**

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Anu Agarwal

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Nonreciprocal & nonlinear optics

ACS Photonics **5**, 5010 (2018)

Photon. Res. **6**, B37 (2018)

Opt. Express **27**, 13781 (2019)

On-chip Sensing

Appl. Phys. Lett. **114**, 051103 (2019)

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Chalcogenide photonics

Metasurfaces

Nat. Commun. **9**, 1481 (2018)

Flexible photonics

Nat. Photonics **8**, 643 (2014)

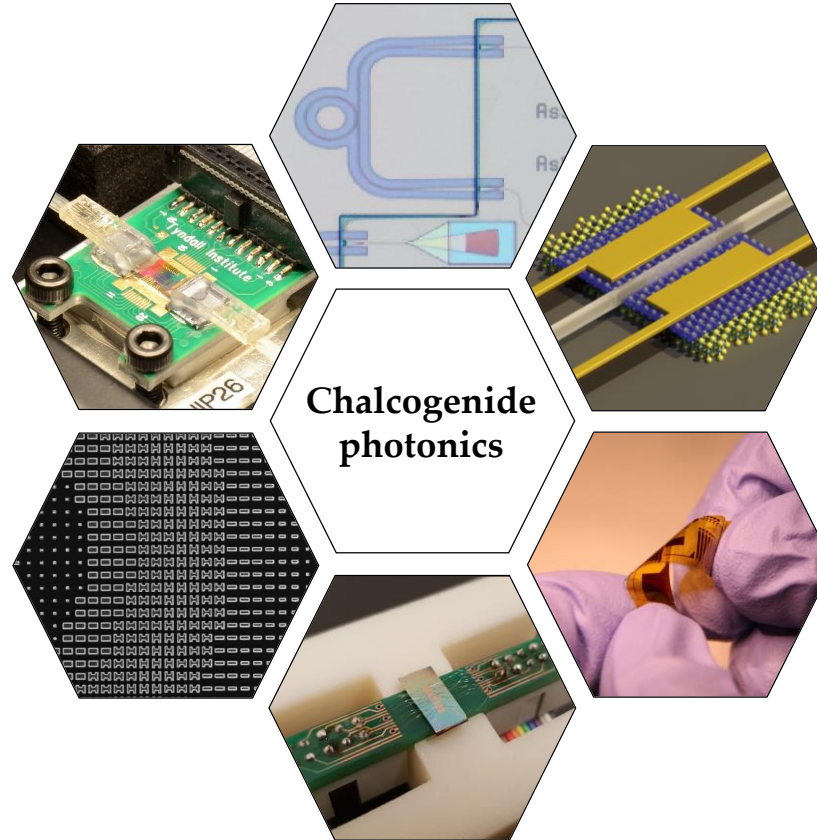
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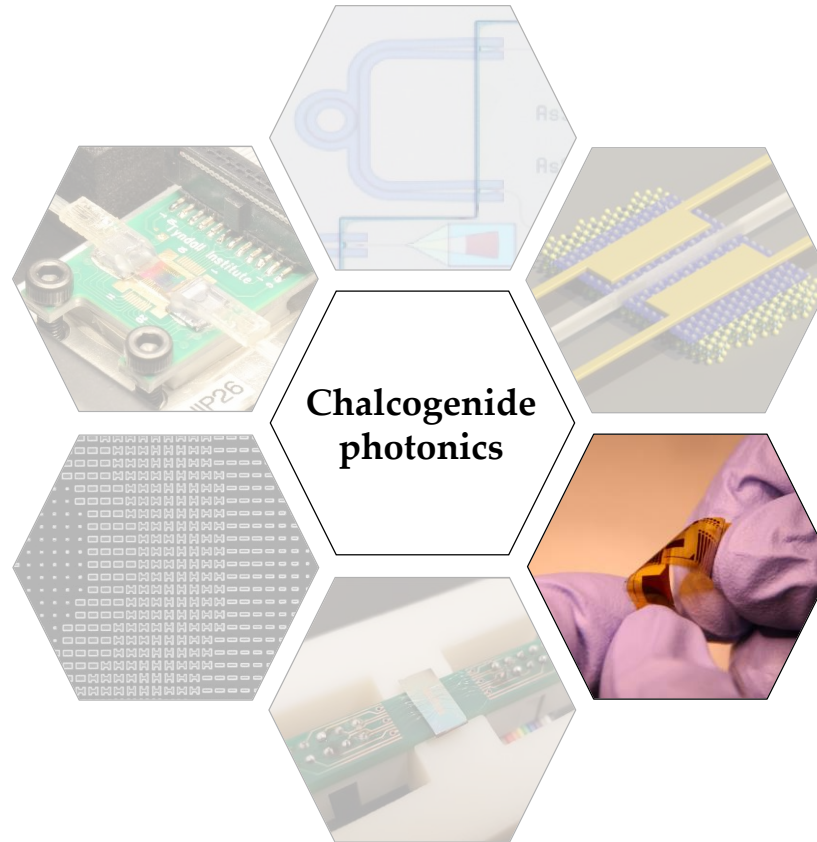
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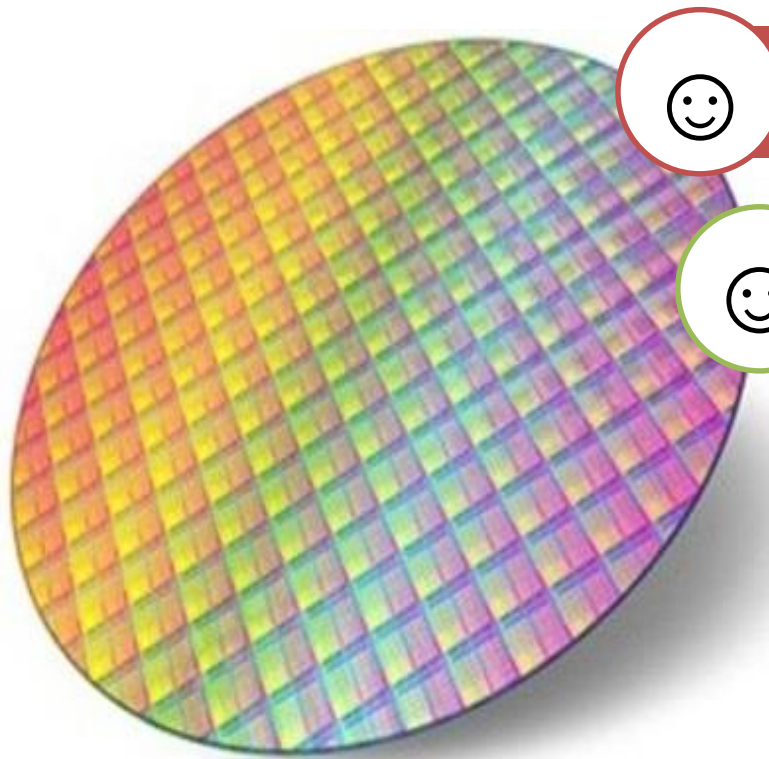
Optical phase change materials

Nat. Commun. (2019)

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ChGs enabling substrate-agnostic integration



Epitaxy-free deposition



Low deposition temperature

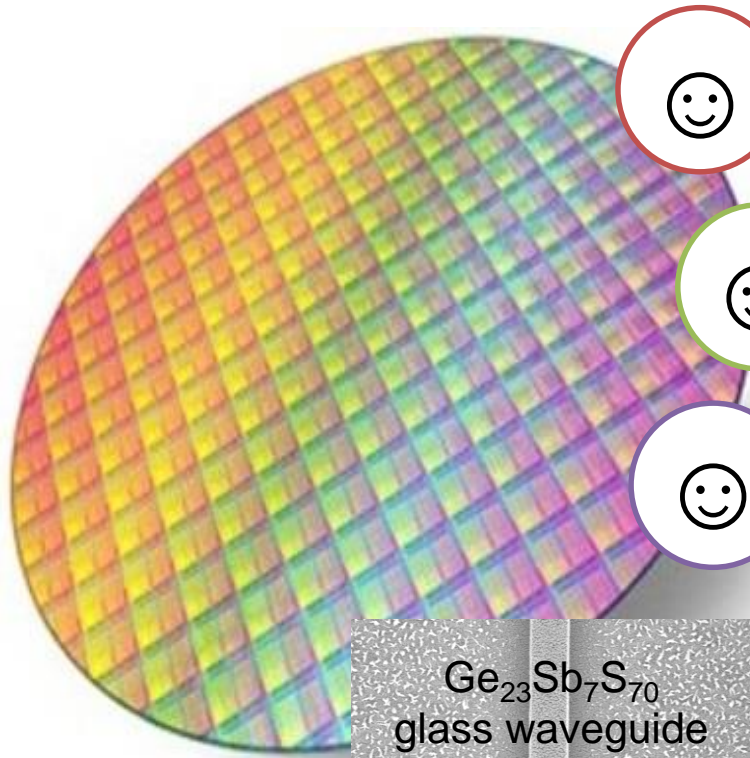
B	C	N	O	F
Al	Si	P	S	Cl
Ga	Ge	As	Se	Br
In	Sn	Sb	Te	I
Tl	Pb	Bi	Po	At



Weaker
inter-atomic
bonds

Room temperature
processing

ChGs enabling substrate-agnostic integration



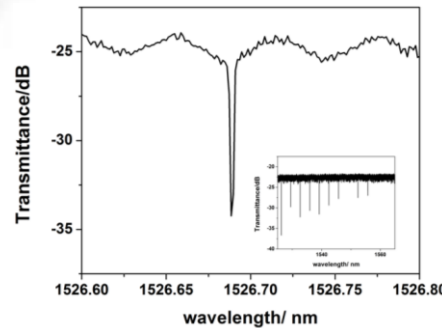
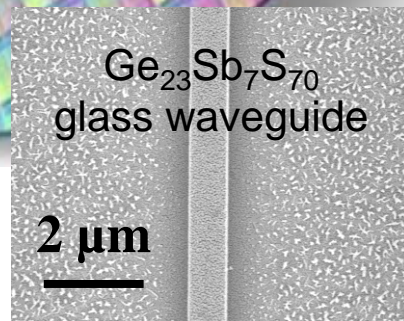
Epitaxy-free deposition



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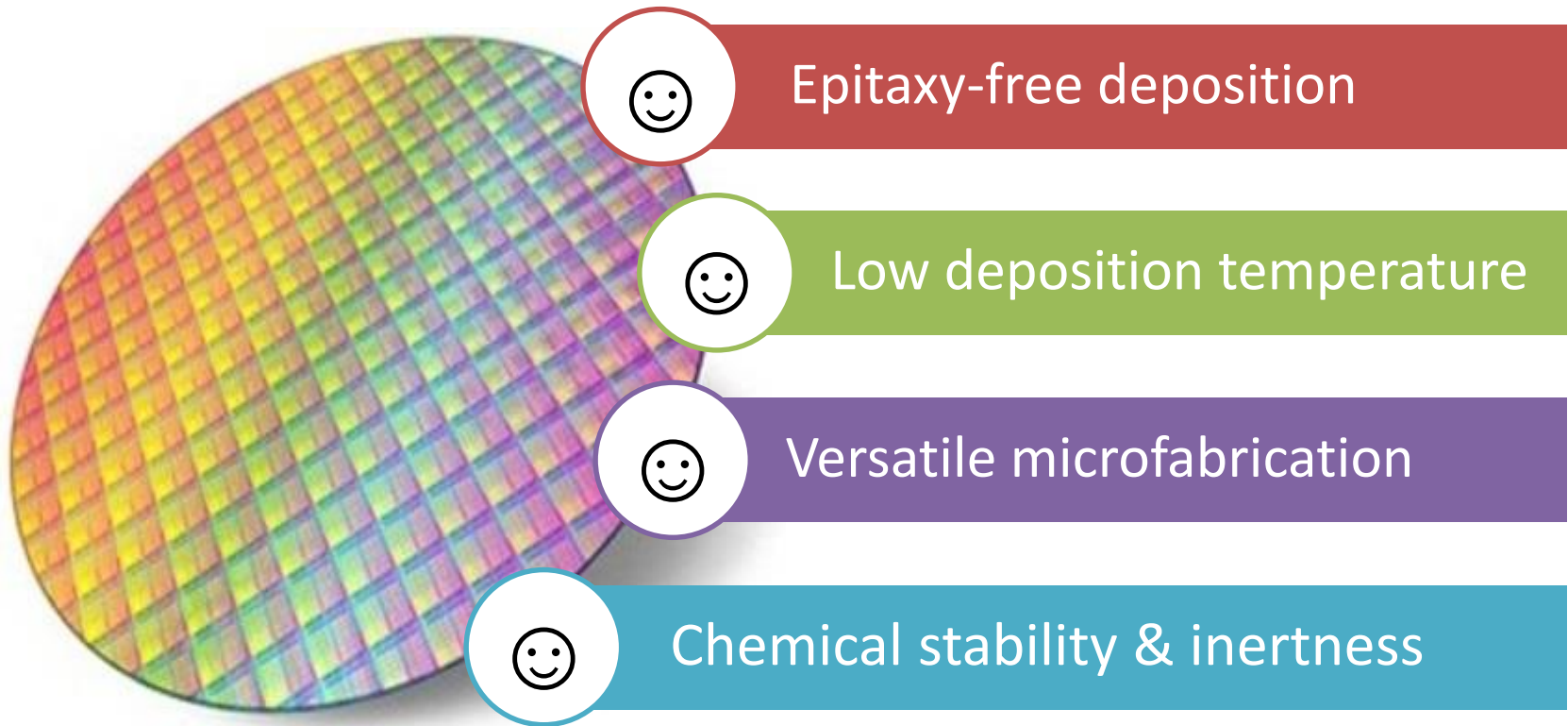
Versatile microfabrication



Waveguide loss:
0.5 dB/cm
Cavity Q-factor:
 1.2×10^6

Opt. Lett. **41**, 3090 (2016)

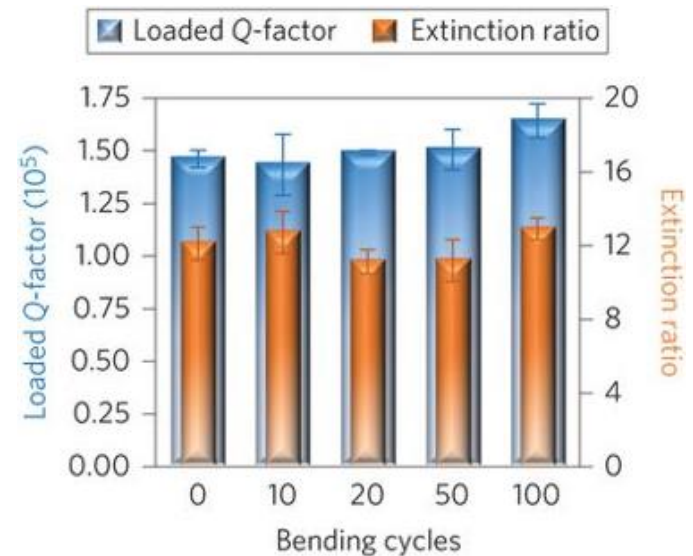
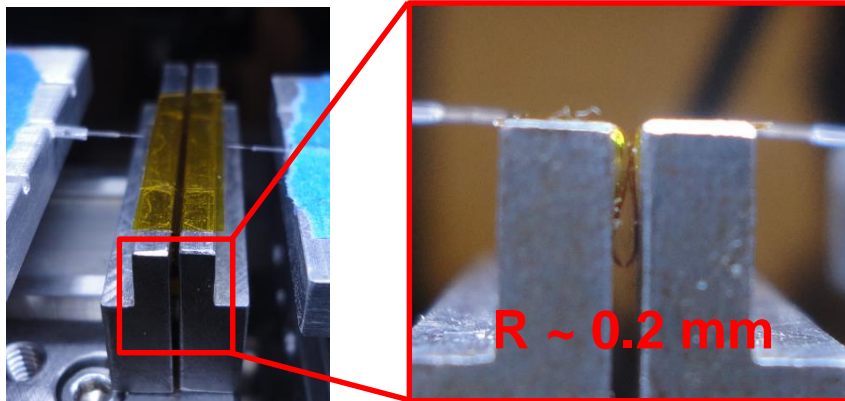
ChGs enabling substrate-agnostic integration



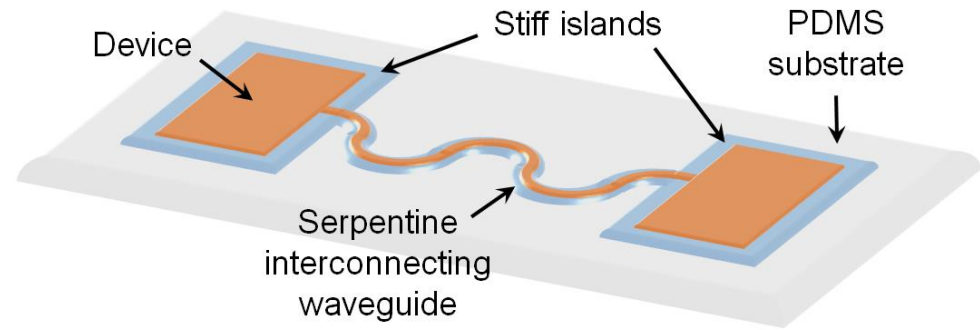
ChG can function as a passivation coating for 2-D materials

Integrated flexible chalcogenide glass photonic devices

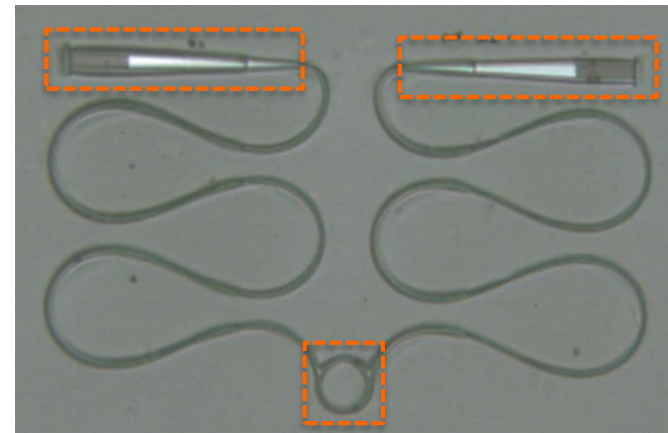
Lan Li^{1†}, Hongtao Lin^{1†}, Shutao Qiao^{2†}, Yi Zou¹, Sylvain Danto³, Kathleen Richardson^{3,4}, J. David Musgraves⁴, Nanshu Lu² and Juejun Hu^{1*}



Making stretchable photonics out of rigid glass

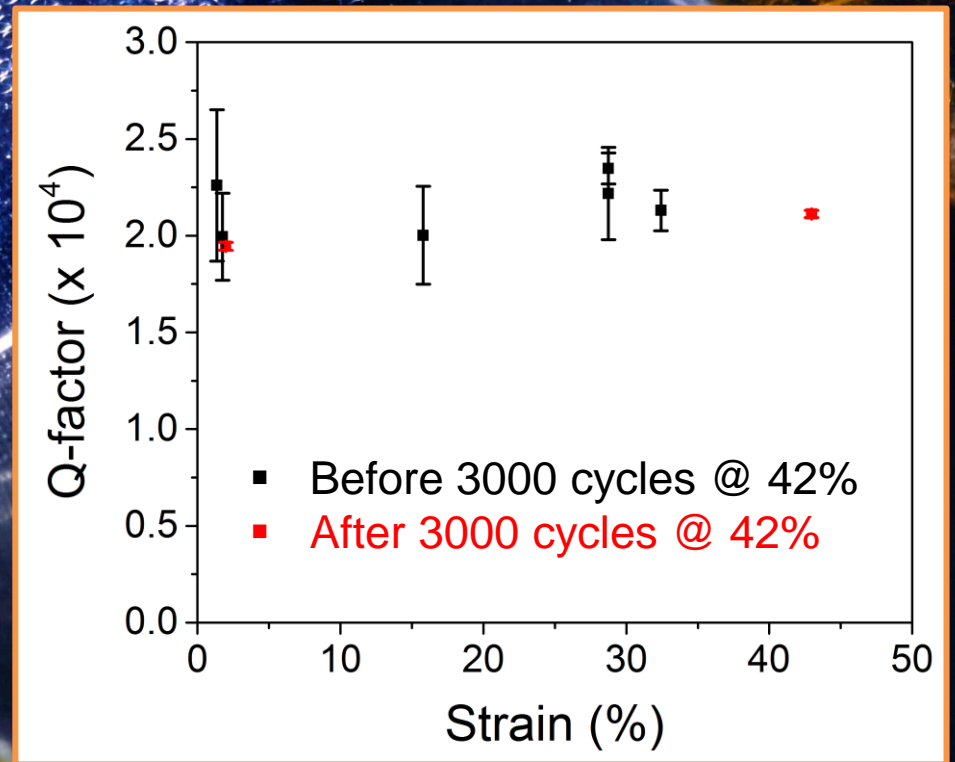


Devices on locally stiffened islands interconnected by serpentine waveguides



Resonator

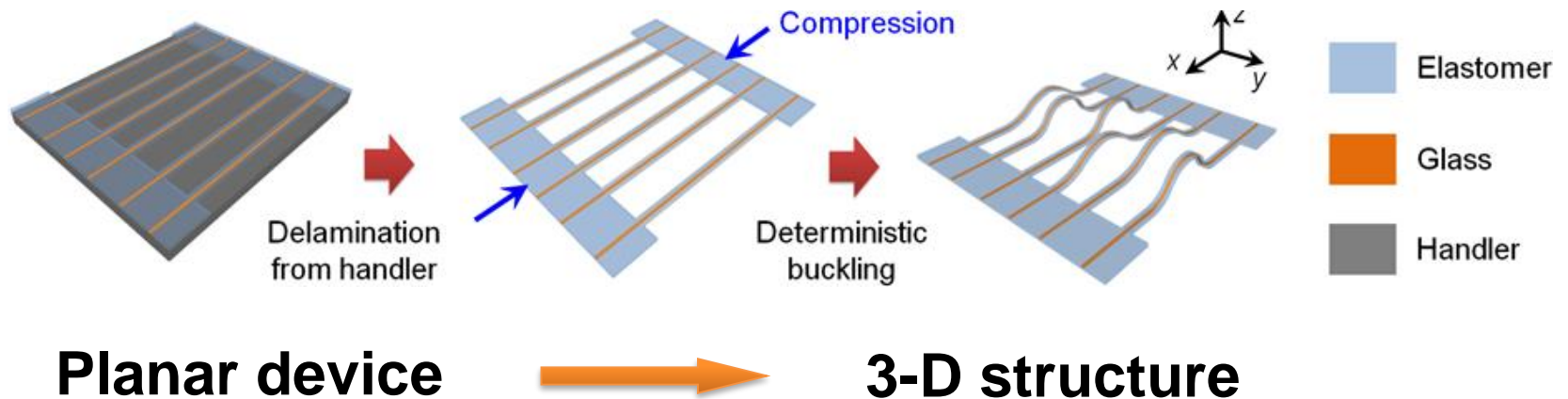
Grating coupler



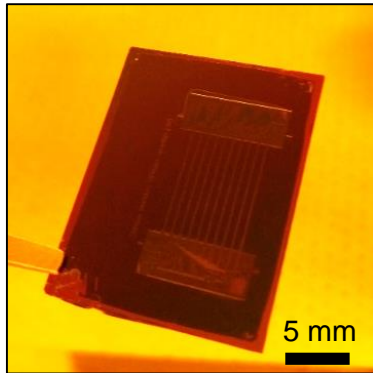
The world is not flat but rather 3-D



Create 3-D photonics from planar structures via deterministic deformation



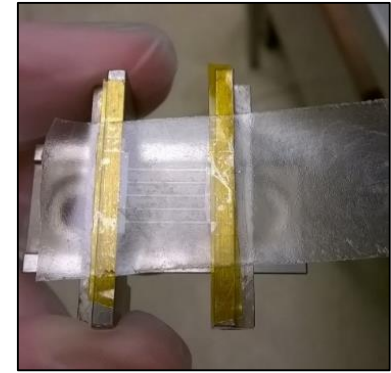
3-D photonic fabrication



On substrate



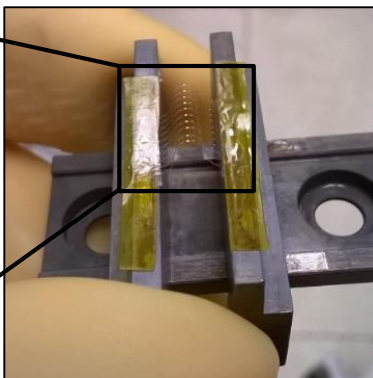
Delamination



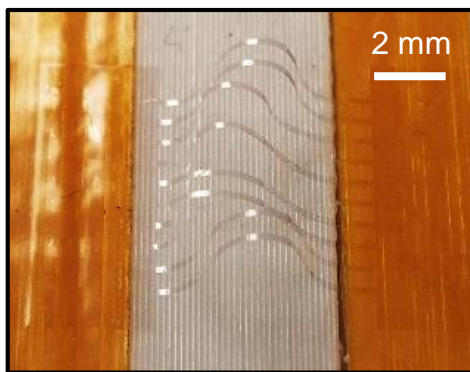
On stage



Tape removal

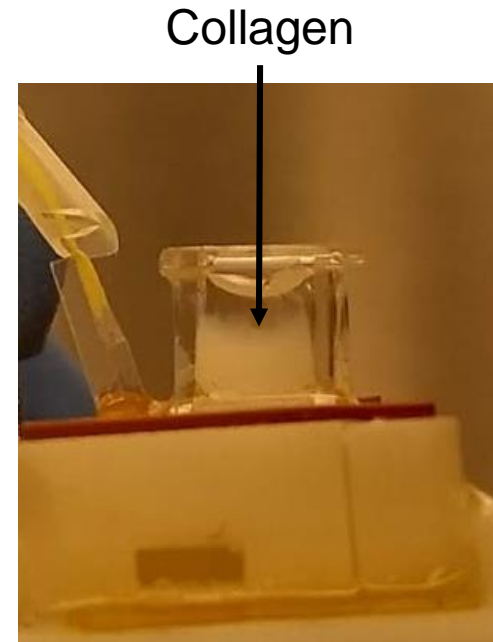
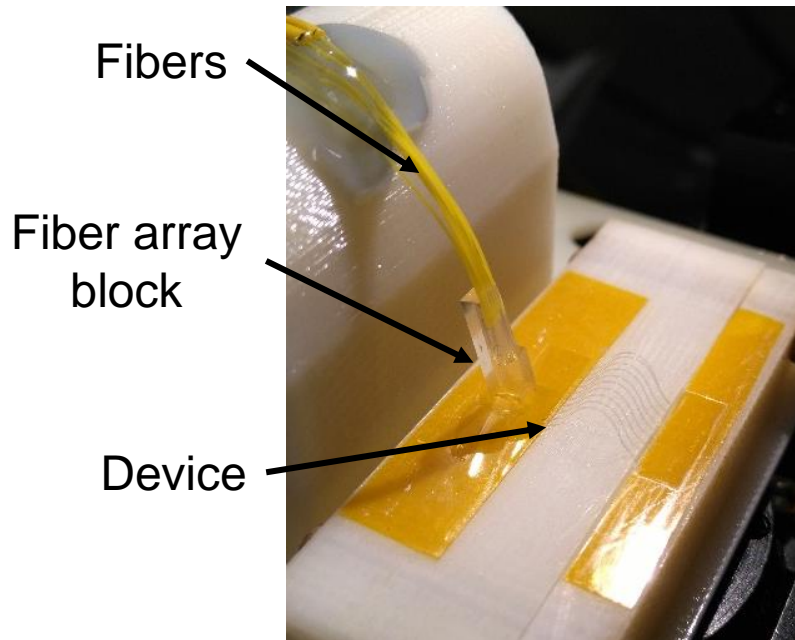


After buckling



3-D structure

A sensor for 3-D stress mapping in soft materials



A 3-D stress sensor with force sensitivity down to 10 nN

Photon. Res. **8**, 194-201 (2020)

Nonreciprocal & nonlinear optics

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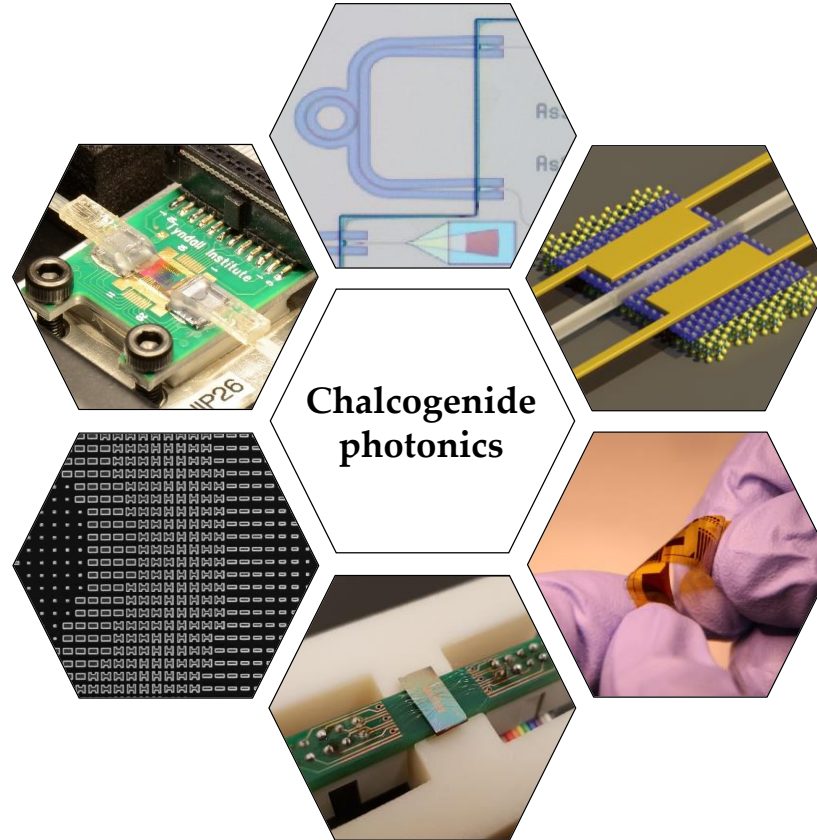
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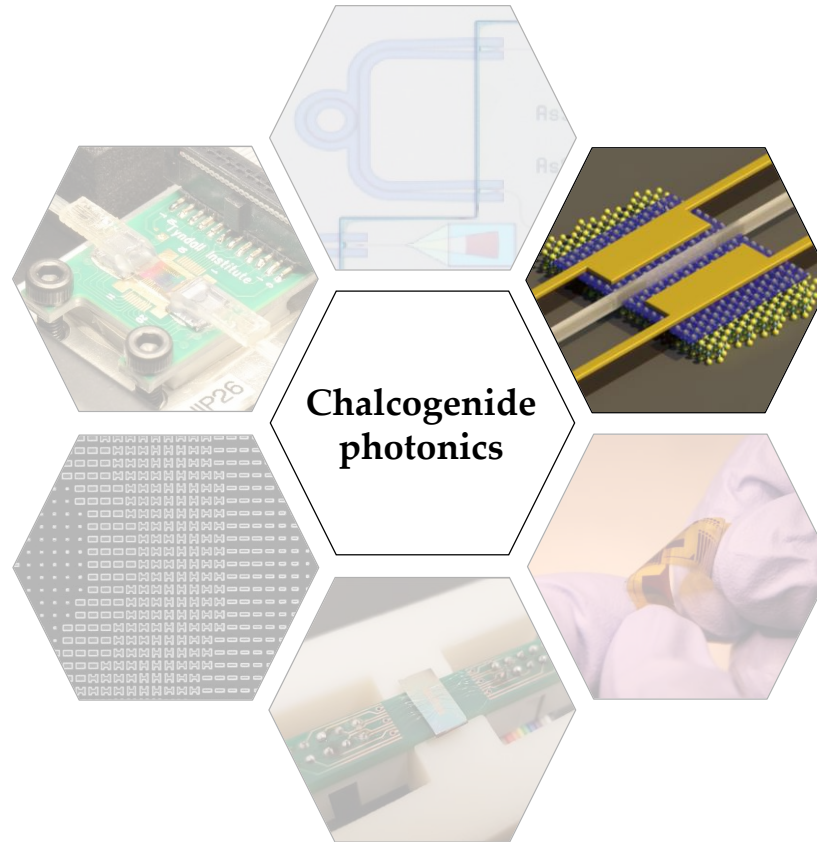
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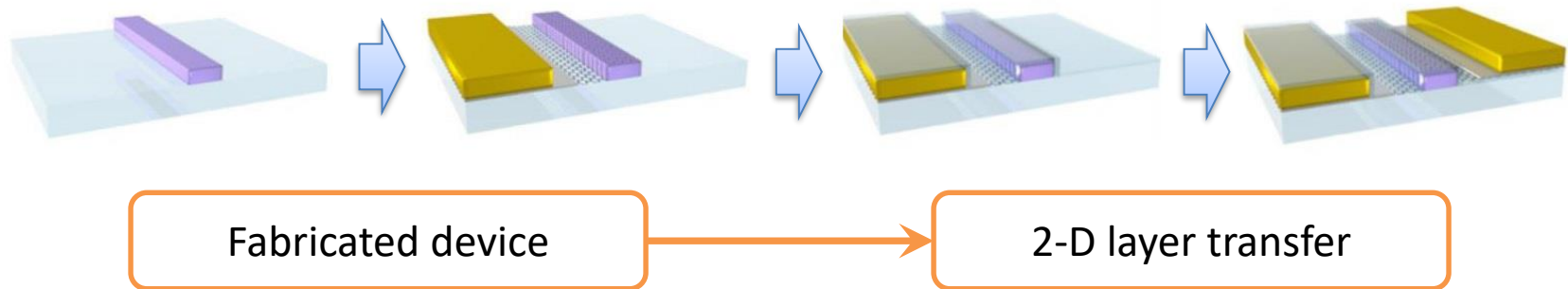
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Opt. Lett. **43**, 94-97 (2018)



Photonic integration of 2-D materials relies on hybrid transfer

Nature **474**, 64-67 (2011)



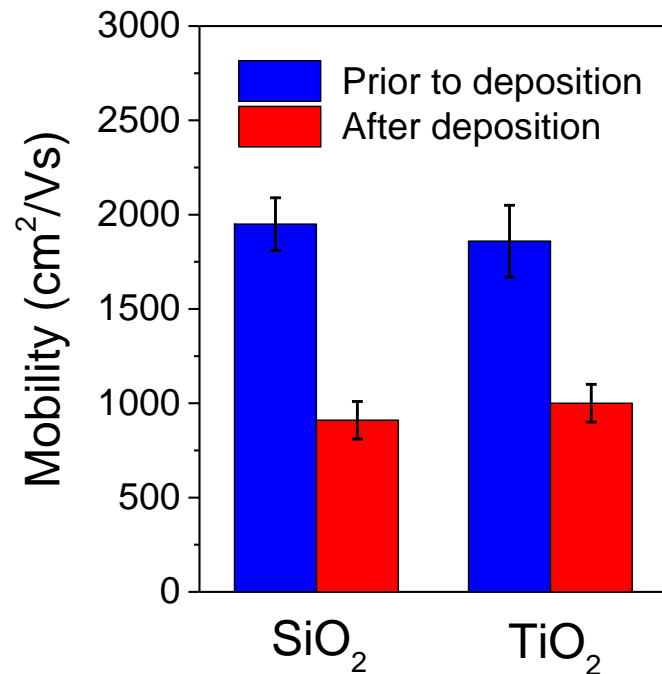
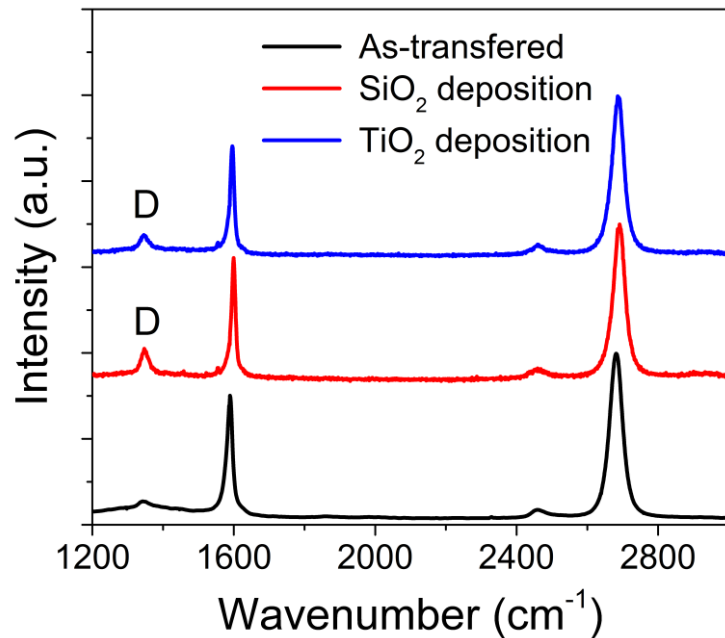
Hybrid transfer:

- ✗ 2-D layer rupture at pattern edges
- ✗ Weak evanescent interaction
- ✗ Limited throughput and integration capacity

Monolithic integration:

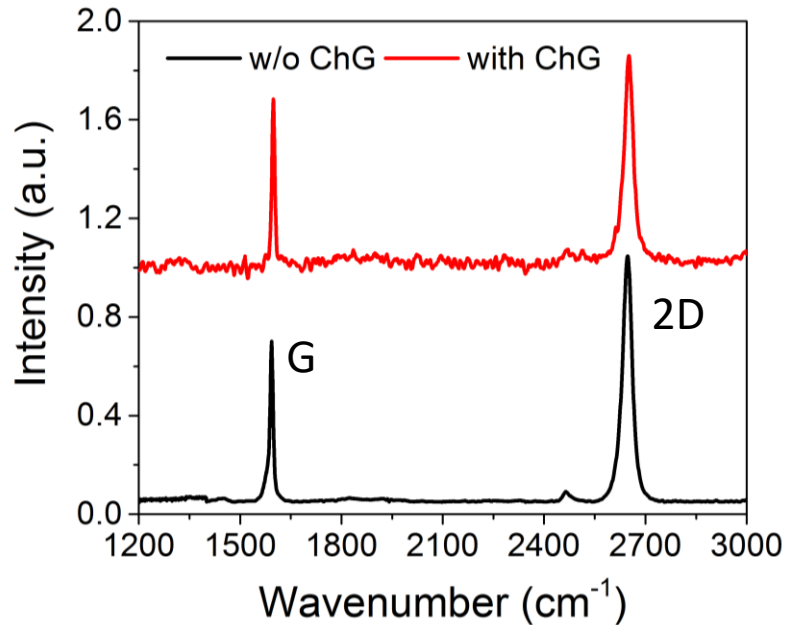
- ✓ Improved yield and throughput
- ✓ Flexible 2-D layer placement
- ✓ Superior alignment accuracy
- ✗ Material degradation

Thick dielectric growth on graphene is difficult due to its inert surface

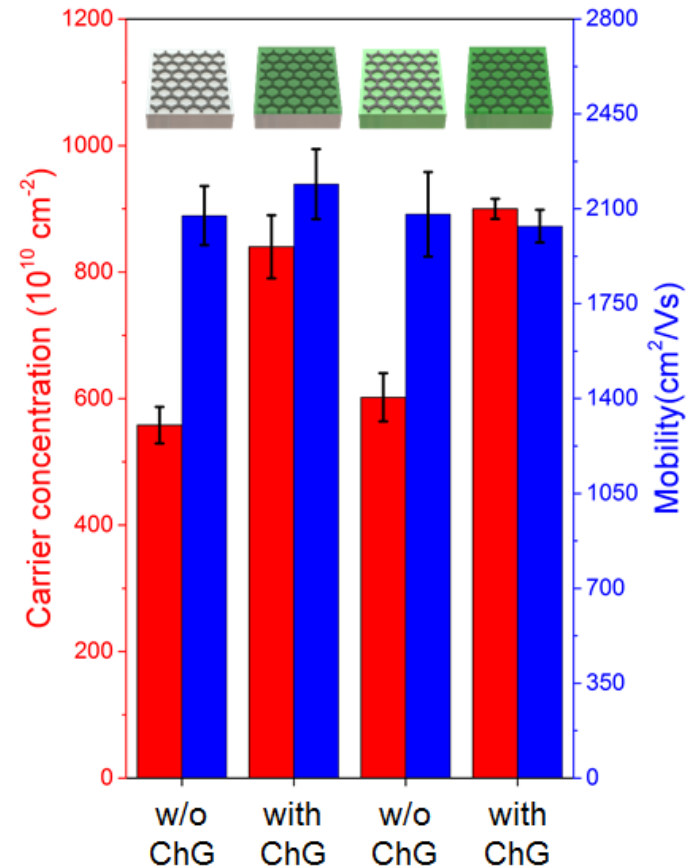


- × Direct dielectric deposition often results in defect formation which degrades graphene properties
- × Atomic layer deposition: low throughput for optical devices

Compatibility of ChGs with graphene

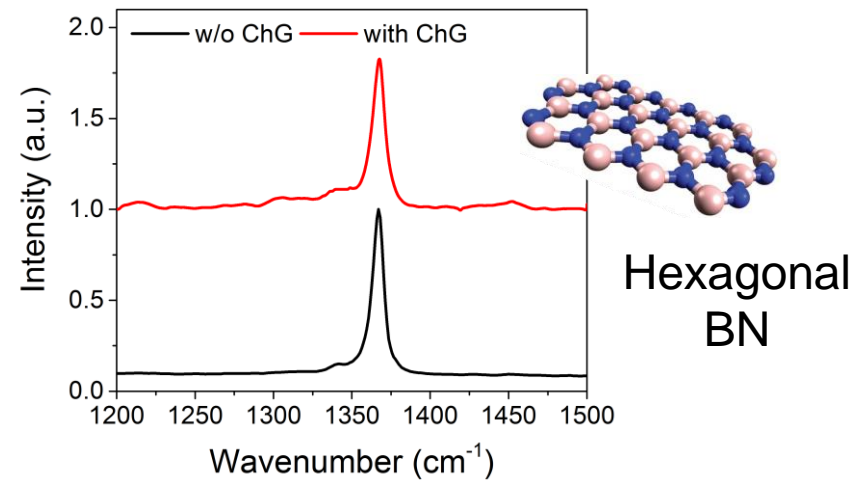
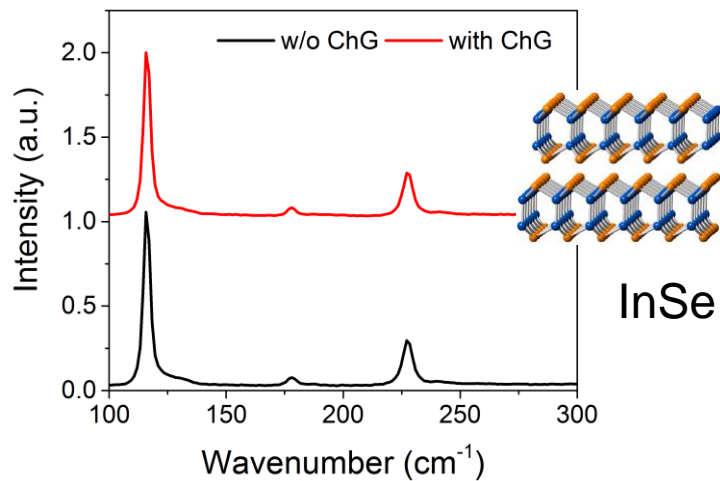
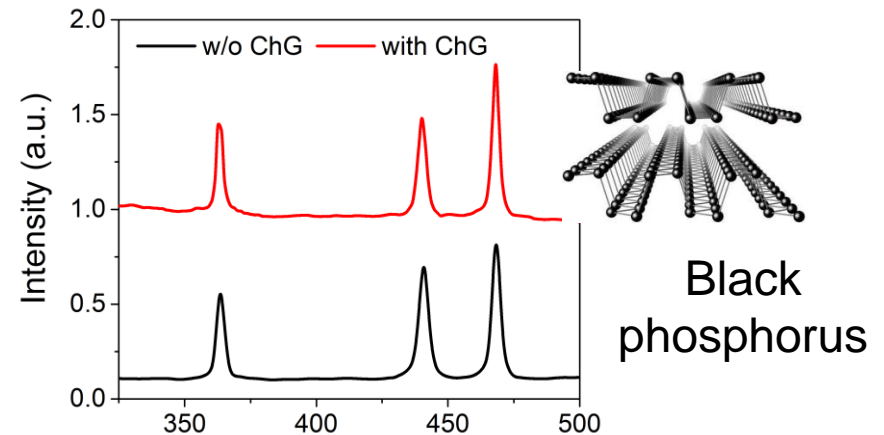
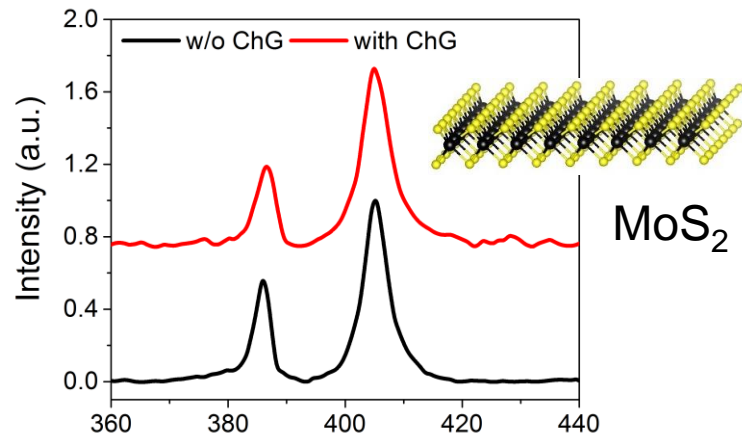


ChG maintains the structural and optoelectronic properties of graphene

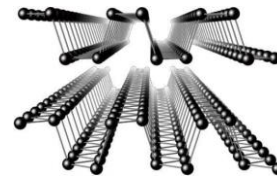
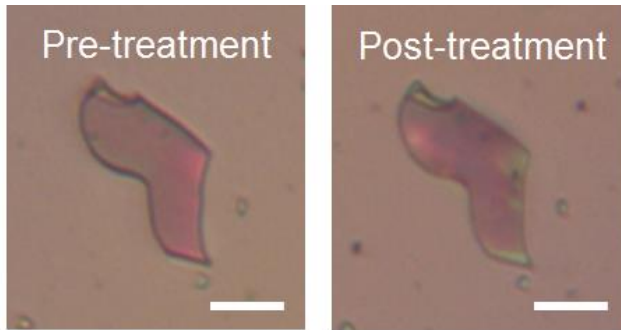


Nat. Photonics 11, 798 (2017)

Compatibility of ChGs with other 2-D materials



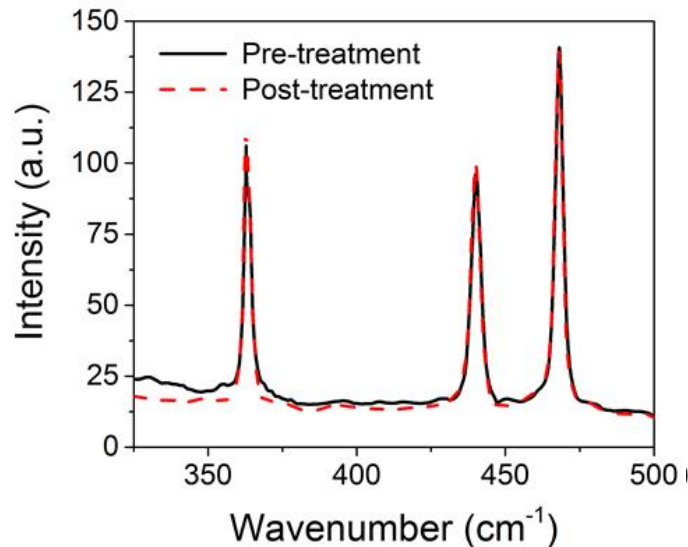
ChGs as a passivation layer for 2-D materials



Black phosphorus

The multifunctional ChG material

- ✓ Broadband light guiding medium
- ✓ Passivation layer for 2-D materials
- ✓ Gate dielectric



30 nm
Ge₂₃Sb₇S₇₀
glass film

Nat. Photonics 11, 798 (2017)

Nonreciprocal & nonlinear optics

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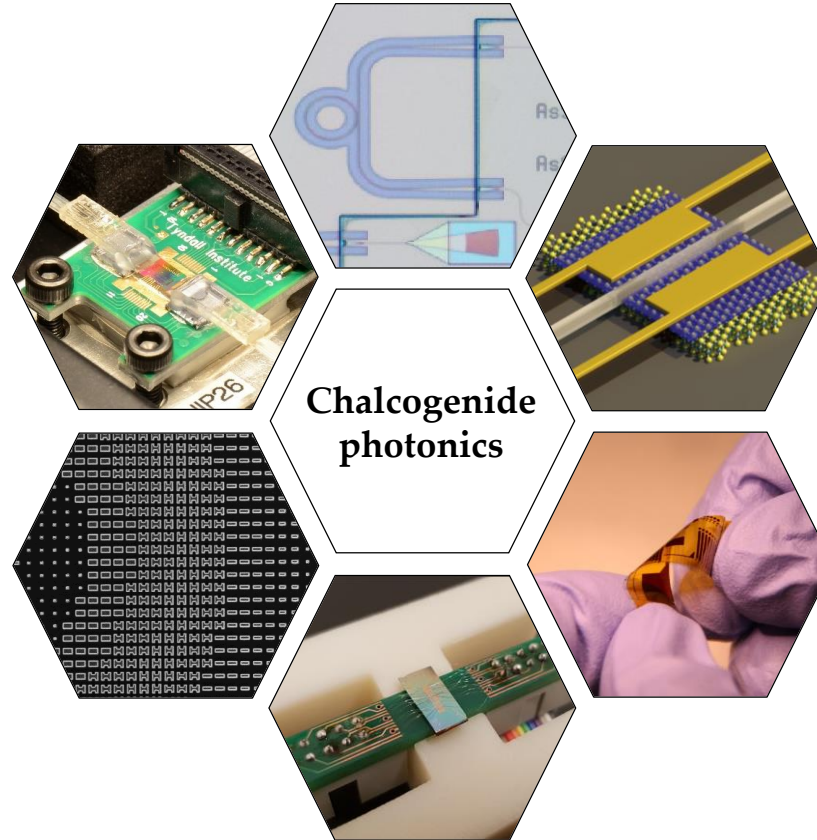
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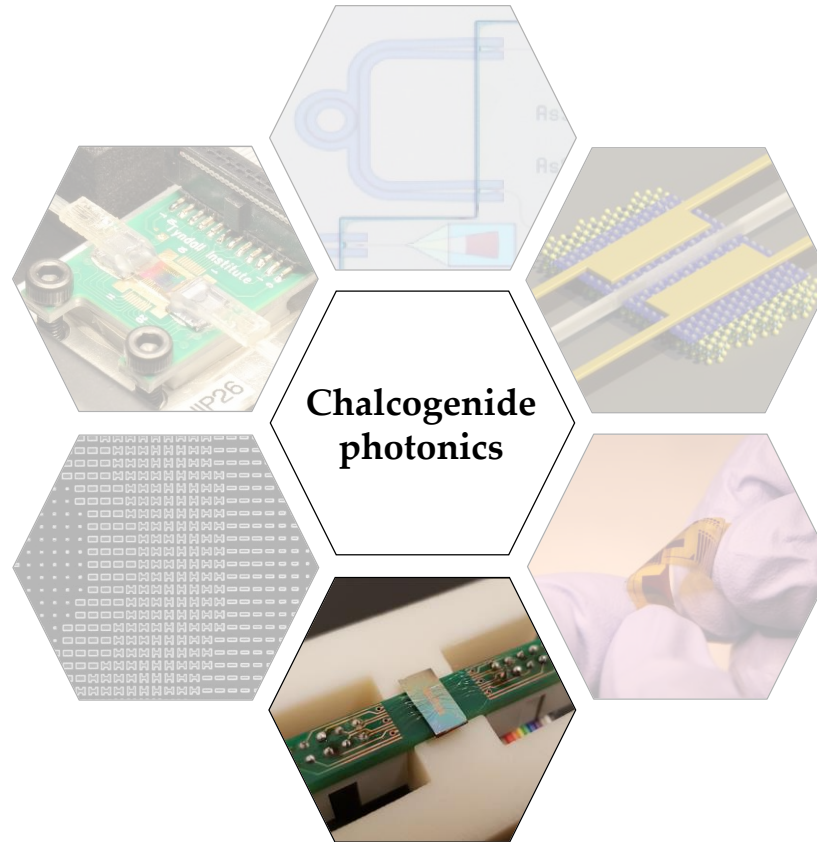
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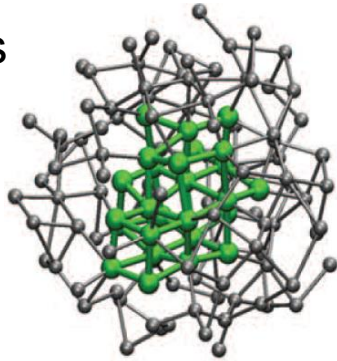
Nat. Commun. (2019)

Opt. Lett. **43**, 94-97 (2018)



Optical phase change materials (O-PCMs)

Amorphous



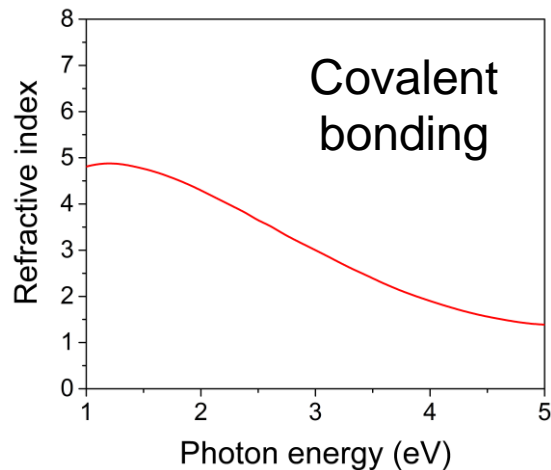
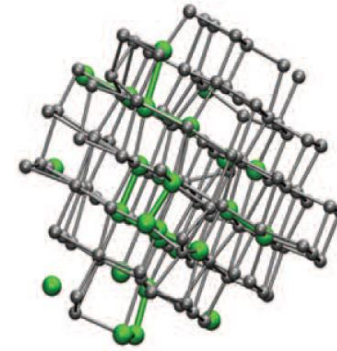
Quench



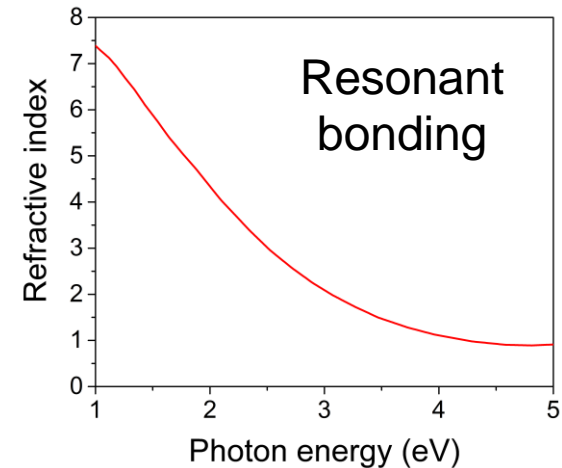
Anneal



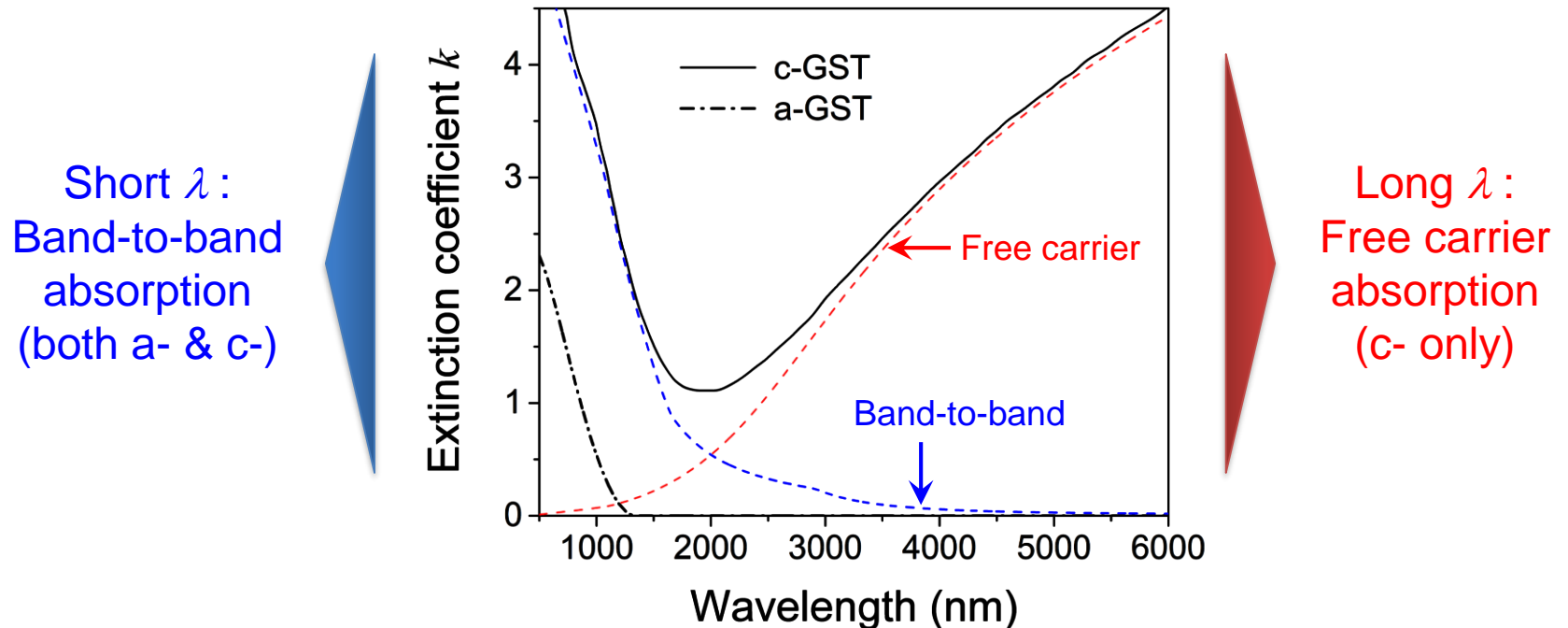
Crystalline



Index change
 $\Delta n > 1$

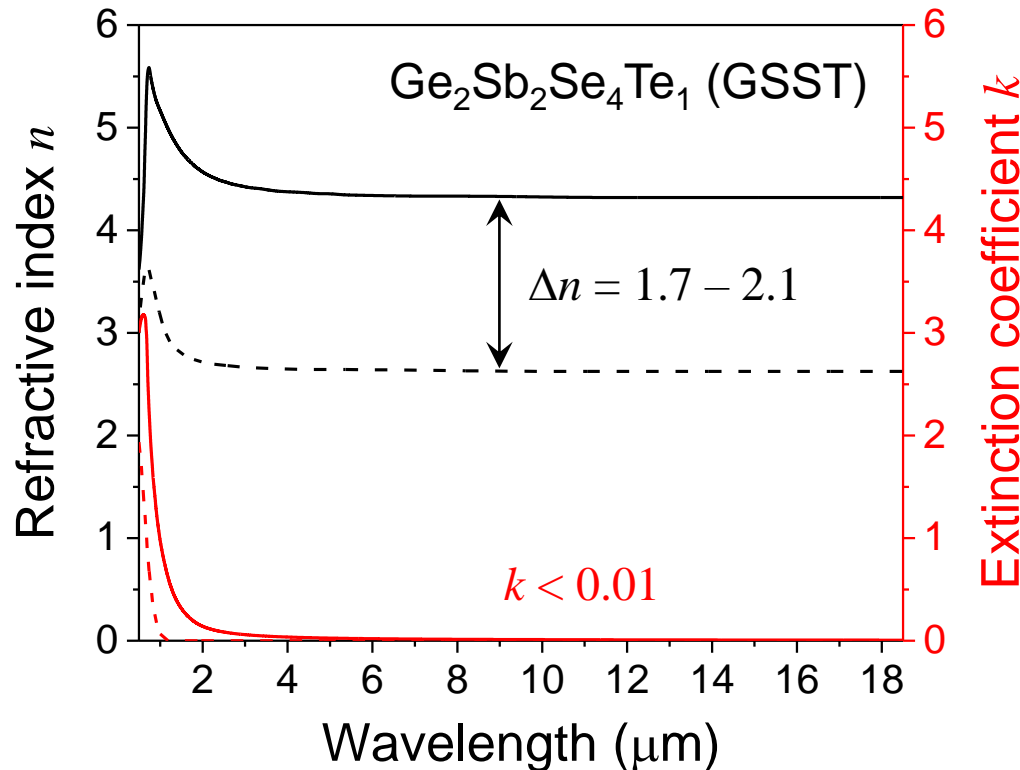


Traditional O-PCMs (Ge-Sb-Te) are optically lossy



Optical losses in O-PCMs are bound by interband absorption at short wavelength and free carrier absorption at long wavelength

GSST: an extreme broadband transparent phase change alloy

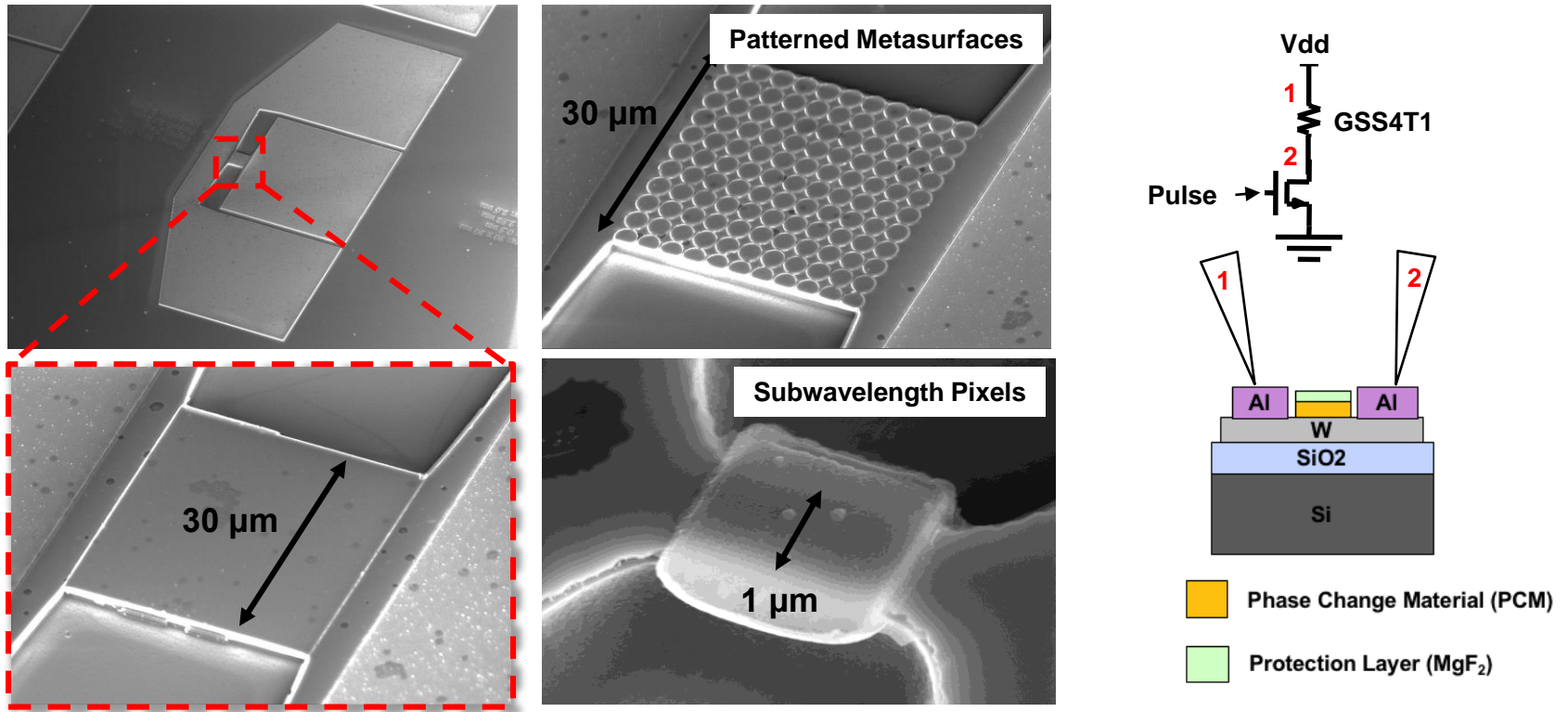


- ✓ Index change:
 $\Delta n = 1.7 - 2.1$
- ✓ Loss: $k < 0.01$
1 – 18.5 μm (a)
4 – 18.5 μm (c)

FOM **100x** higher
than GST-225

Nat. Commun. **10**, 4279 (2019)

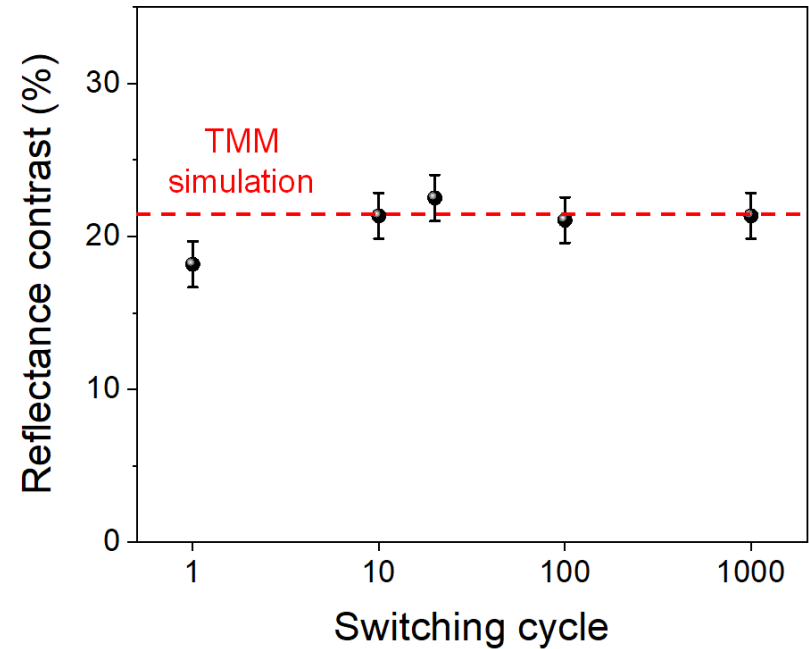
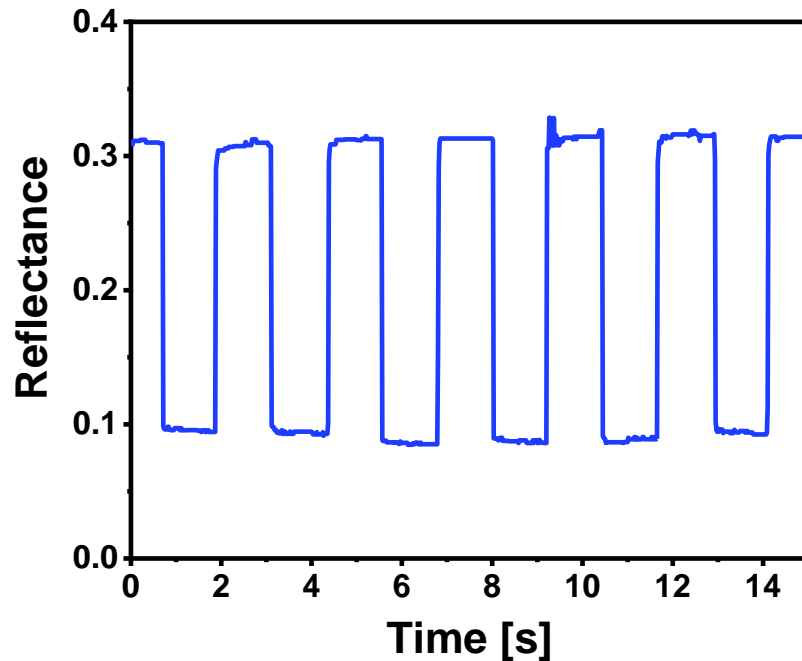
Free-space reflective light modulator pixel



Nat. Commun. **10**, 4279 (2019)



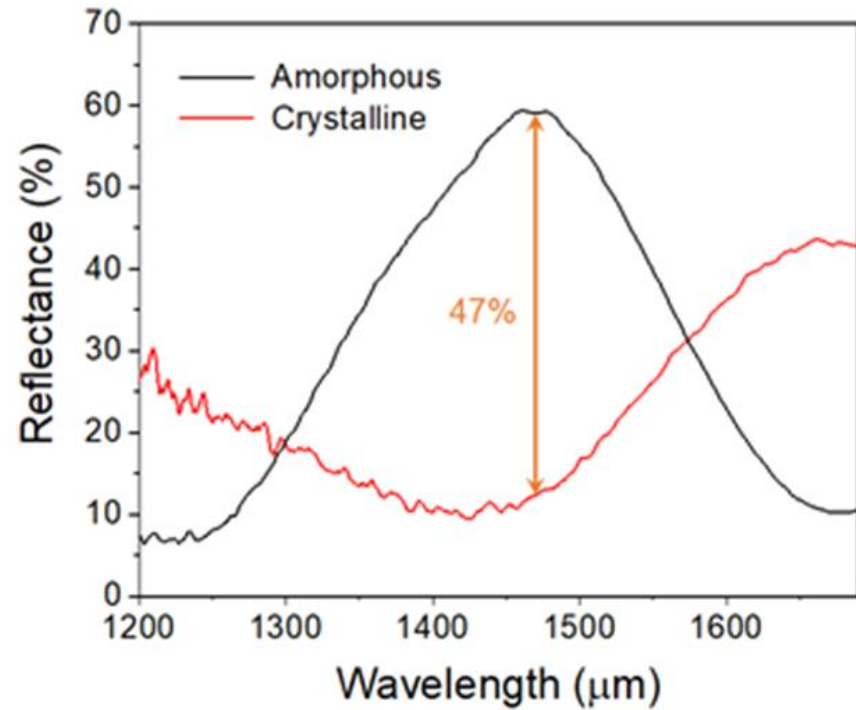
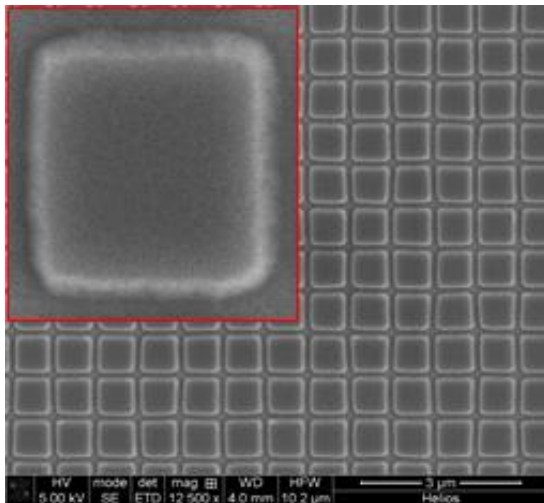
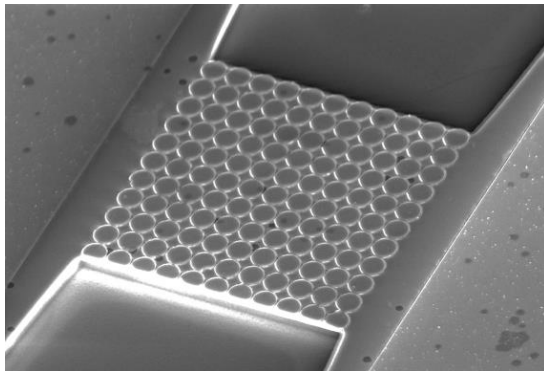
Switching of free-space reflective pixel



**22% absolute
reflectance contrast**

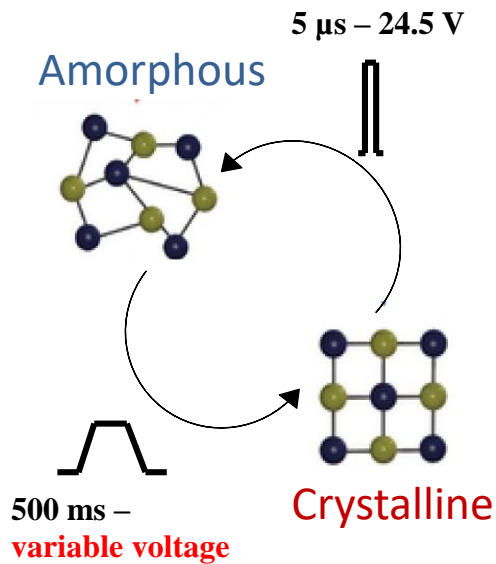
**Consistent 1,000 cycle
switching**

Electrically switchable metasurface based on GSST

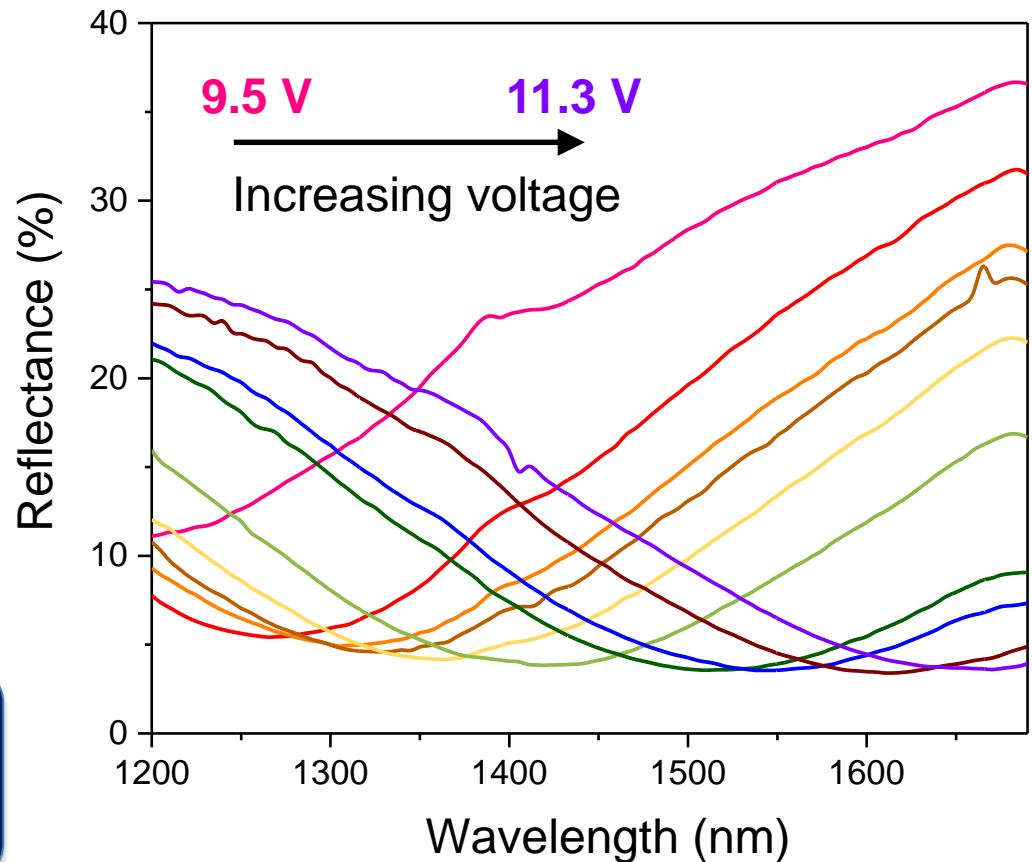


First demonstration of electrically switchable metasurface based on O-PCMs

Switchable metasurface: multi-state operation



**Half-octave (480 nm)
spectral tuning**



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