National Aeronautics and
Space Administration

Toward high-endurance nonvolatile reconfigurable metasurfaces

Hyun Jung Kim (NASA Langley Research Center)

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Hyung Bin Bae and Taewoo Lee

Why is NASA researching reconfigurable metasurfaces?

- “Cutting edge innovations by NASA leaderships seek to refine **scientific instrument into smaller, lighter, more versatile** tools for exploration” – *Karl Hille, chief technologist at NASA’s GSFC*

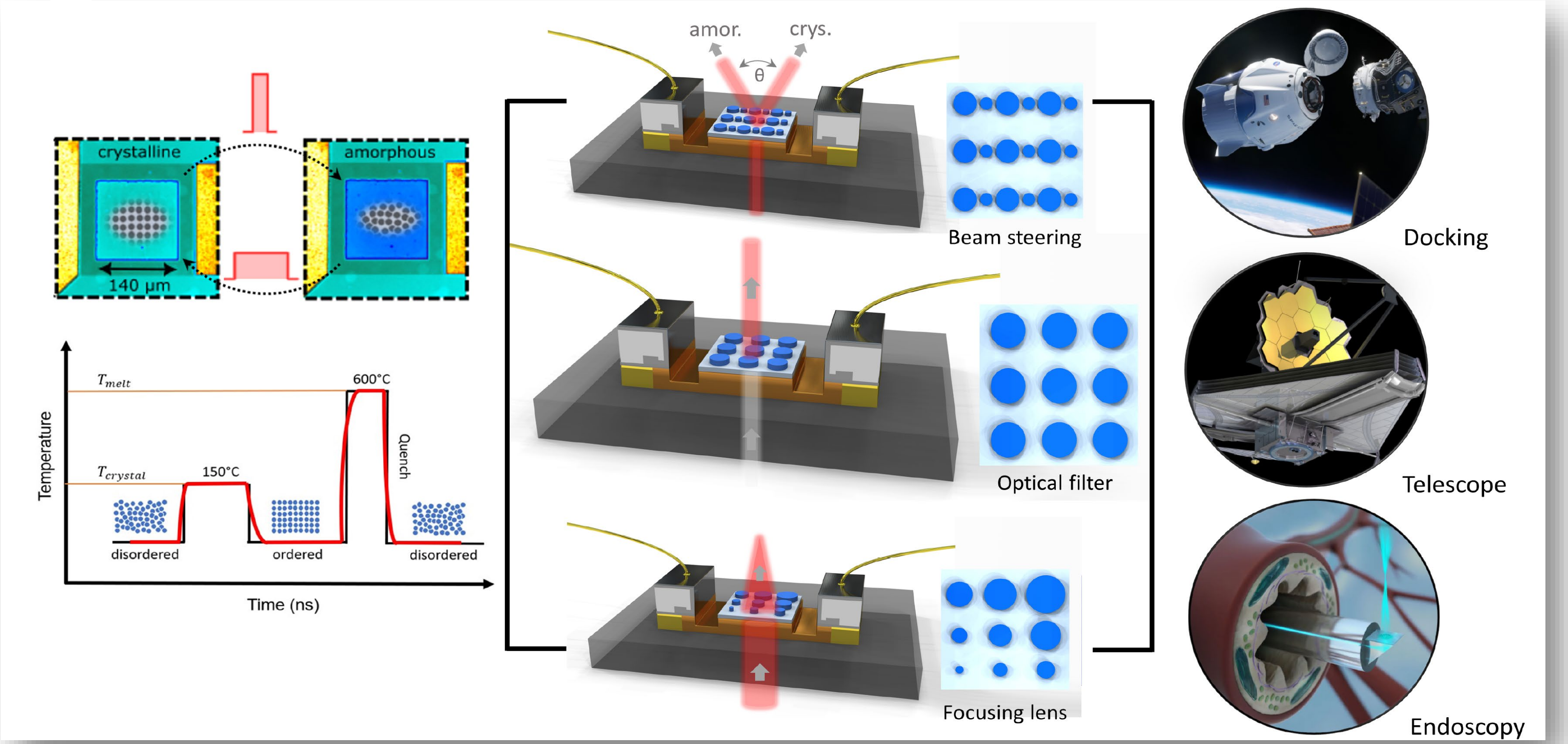
- “**Metasurface optic** technologies are important because of the **precision and versatility** that is offers to LiDAR” – *Cheryl Gramling, assistant chief for technology at GSFC*

- “As recently displayed by the stunning images from the JWST, we often rely on recording the intensity of light (e.g., with a camera) to study the universe. …**Metasurfaces** enable general manipulations of phase, amplitude, and polarization on the nanoscale, thereby providing **ample opportunity** ….and even **enable functionality not possible using conventional technologies** - *Tobias Wenger, researcher at JPL*

- … “NASA scientists are on the cusp of revolutionizing LEO Earth Observing platforms using novel optical **metamaterials to reduce the size, weight and power (SWaP) of existing architectures**."
  – *William Humphreys, chief engineer at LaRC*

  - **Metamaterials** are man-made (synthesized) composite materials whose electromagnetic, acoustic, optical, etc. properties are determined by their constitutive structural materials and their configurations. In the field of electromagnetic research and beyond, metamaterials offer **excellent design flexibility with their customized properties and their tunability under external stimuli**

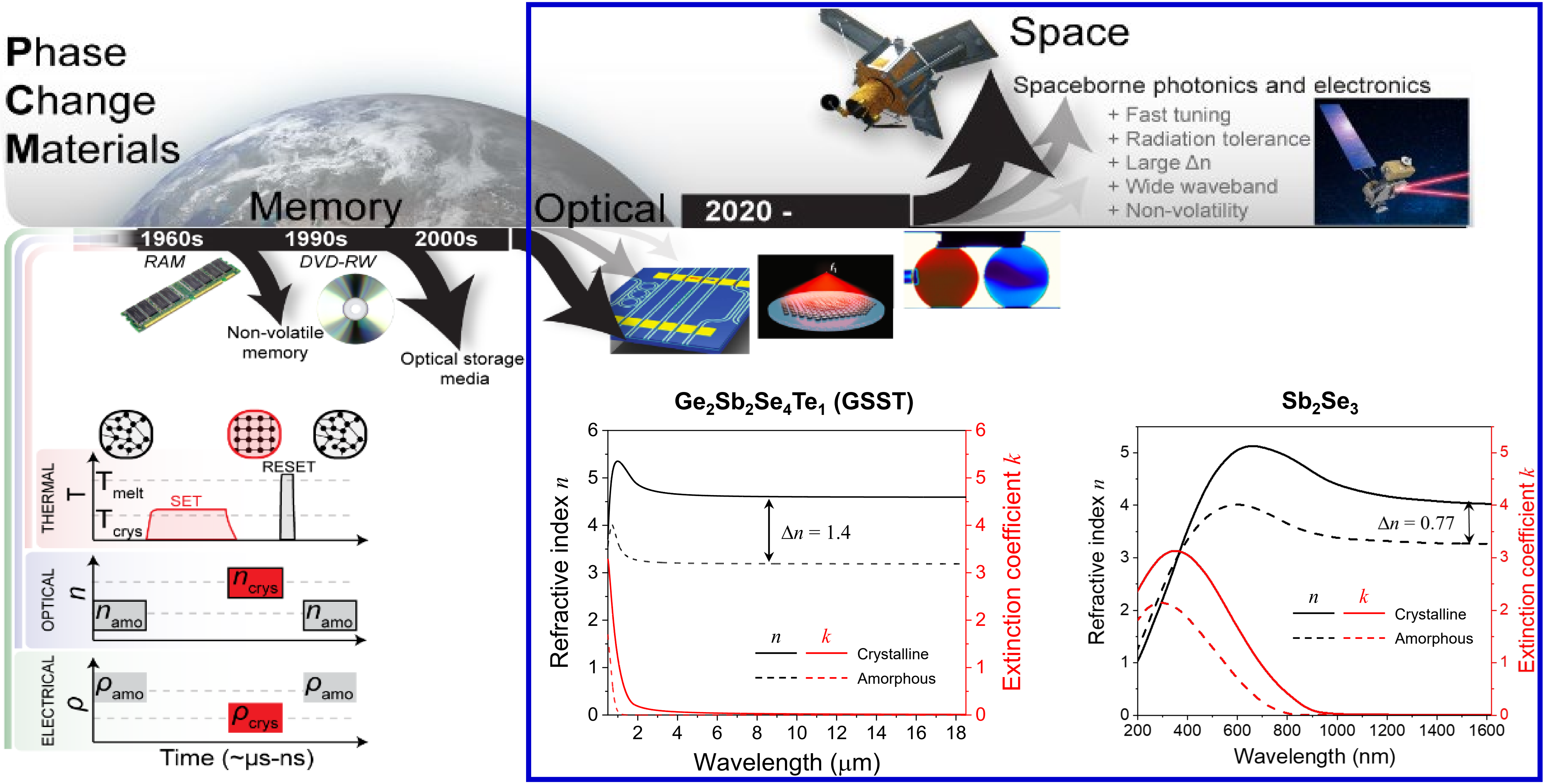
Why is NASA researching nonvolatile reconfigurable metasurfaces?



Mission Need

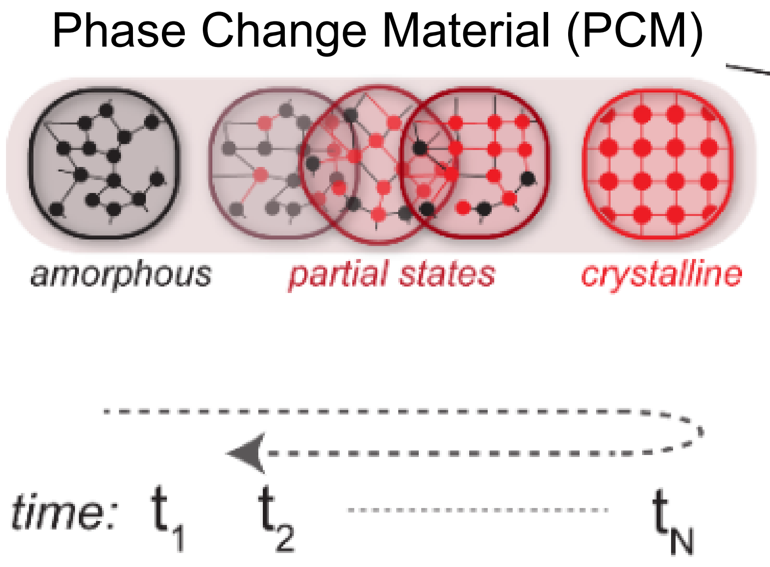
<u>Metasurface-based optics</u> capable of generating actively-tunable focus, arbitrary optical wavefronts at **<u>ultrafast speeds, with sub-wavelength resolution, and without moving parts</u>**.

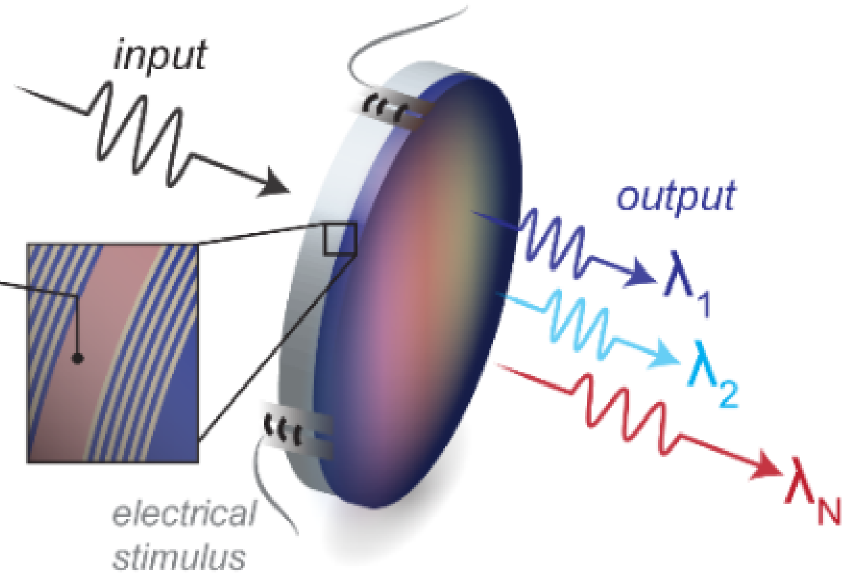
PCM-based reconfigurable metasurfaces

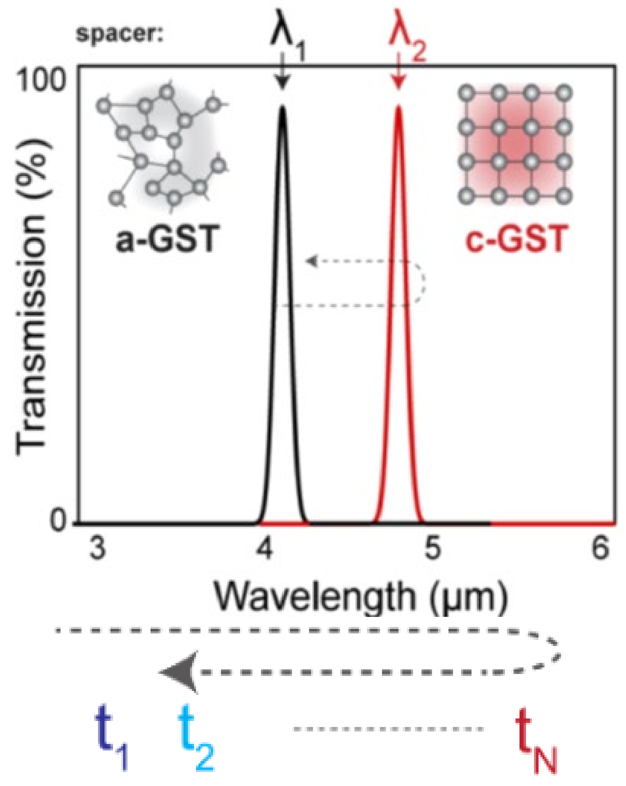


Exploiting the extraordinary refractive index contrast in PCMs to unprecedented functionalities in photonic components

An example: PCM-based Actively Tunable Filter

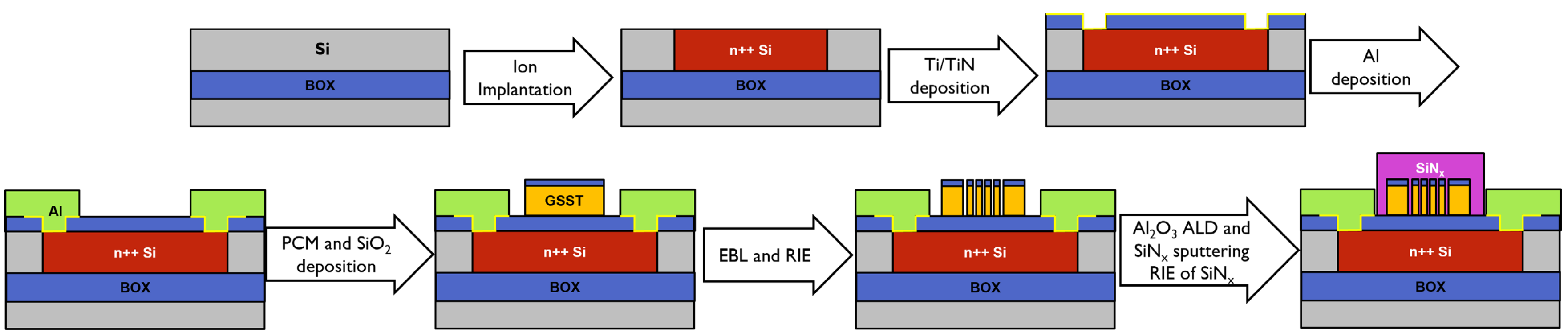


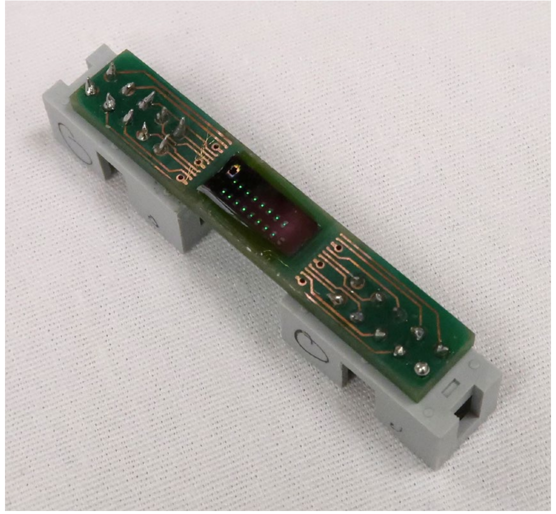




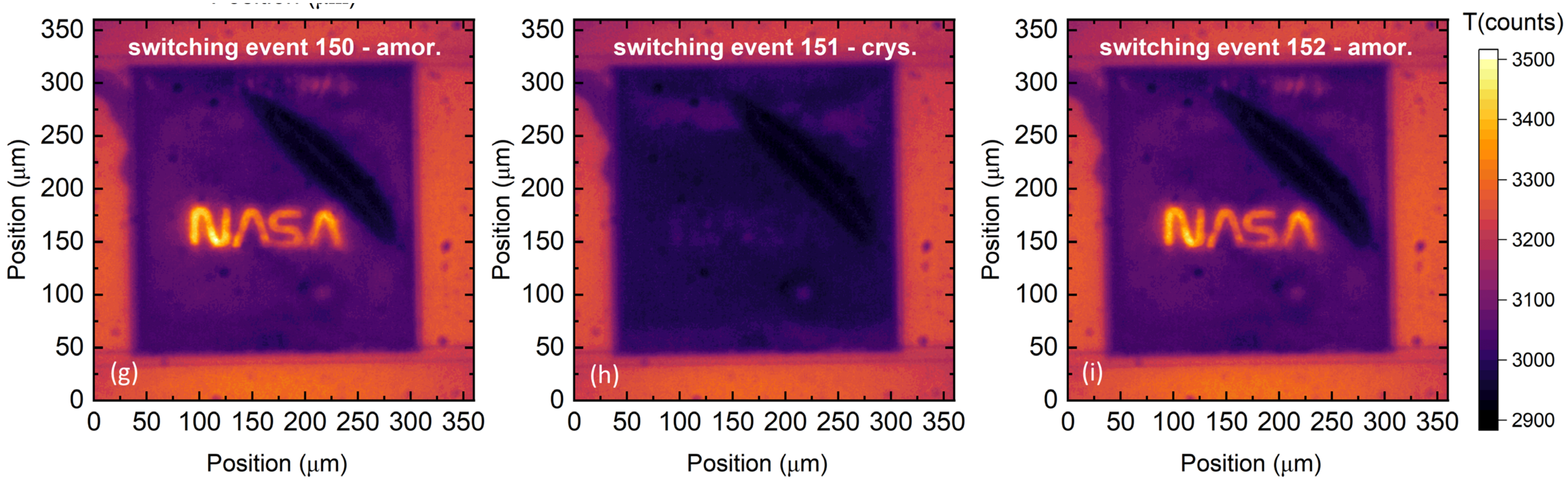
- ✔ Ultrafast (ns) switching
- ✔ Tunable narrowband filtering
- ✔ Wide waveband coverage

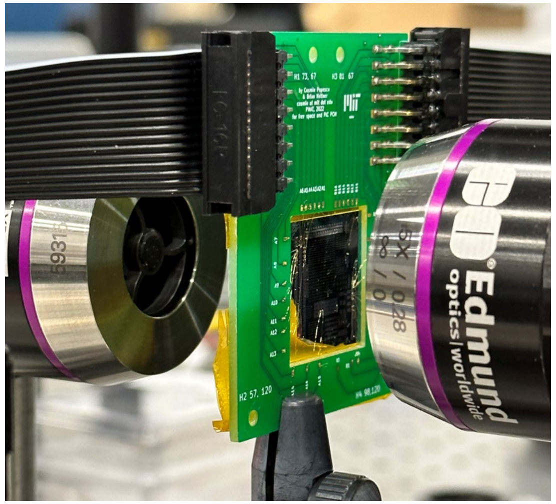
Reshaping light using PCM-based tunable filters



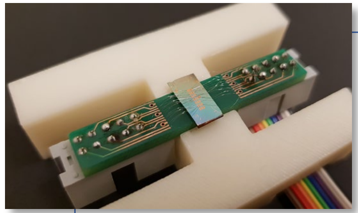


Packaged PROWESS filter

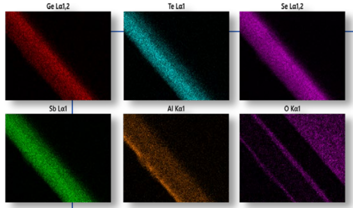




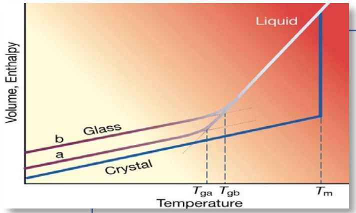
PROWESS- tunable k-space optic



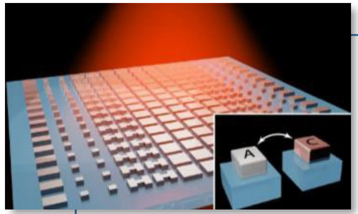
Electrical switching of PCM metasurfaces



Long live PCMs: mitigating failure mechanisms

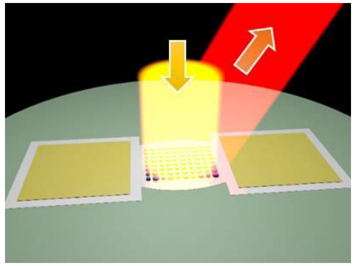


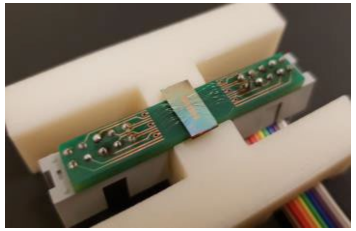
Beware the pitfalls: thermal modeling of PCMs [EL12.08 / 10:15am talk]



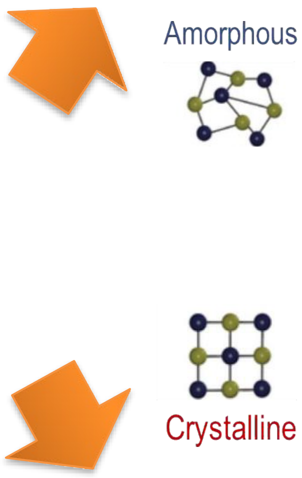
Reshaping light using PCM metasurfaces

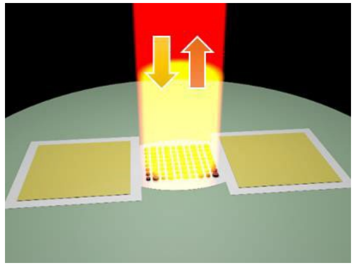
Electrical switching of PCM metasurfaces





Nat. Nanotechnol.
16, 661 (2021)





Optics in 2021

Metasurfaces Embracing a Phase Change

RESEARCHERS

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1. Y. Zhang et al. Nat. Commun. **10**, 4279 (2019).
2. M.Y. Shalaginov et al. Nat. Commun. **12**, 1225 (2021).
3. Y. Zhang et al. Nat. Nanotechnol. **16**, 661 (2021).
4. Y. Wang et al. Nat. Nanotechnol. **16**, 667 (2021).

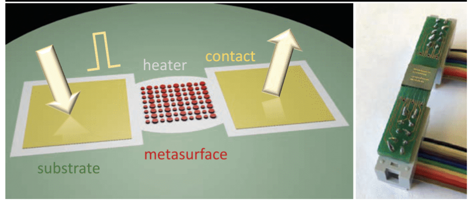
Recent progress in nanophotonics has enabled planar optical systems, termed metasurfaces, that hold potential to enable agile light manipulation and provide size, weight, power and cost (SWaP-C) benefits compared with traditional optics. Active metasurfaces, the optical properties of which can be modulated post-fabrication, have attracted a surge of interest in recent years, given their broad potential applications in imaging, sensing, display and optical ranging. A cohort of non-mechanically switchable meta-devices has been already demonstrated; however, most of them either operate within a limited tun-

metasurfaces made of optical phase-change materials. More specifically, we have synthesized a new class of nonvolatile chalcogenide alloys, $Ge_2Sb_2Se_4Te_1$, exhibiting giant index contrast as well as broadband transparency in both amorphous and crystalline states.[1]

Capitalizing on this material platform and metasurface design innovation, we demonstrated an all-dielectric varifocal metalens in mid-infrared.[2] By annealing the entire metasurface, we showed that the lens shifted its focal plane between the distances of 1.5 mm and 2 mm and produced multi-depth imaging with diffraction-limited resolution and a

record half-octave spectral shift with a large relative optical contrast exceeding 400%. By exploiting the same device architecture, we also prototyped a polarization-insensitive deflector for beam steering.

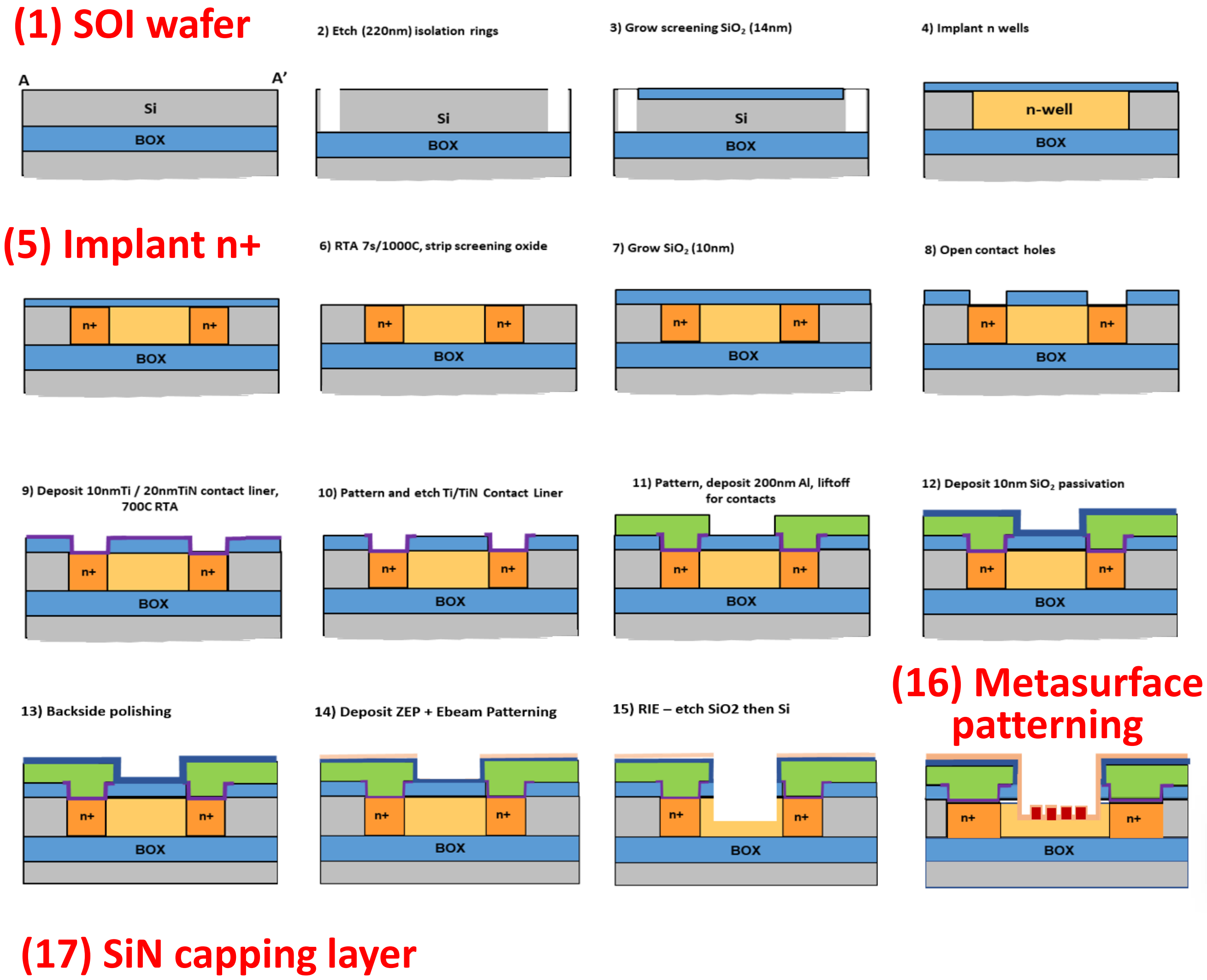
Our advances in phase-change-material meta-optics demonstrate that active metasurfaces can achieve optical quality on par with conventional precision bulk optics involving mechanical moving parts. The work points to exciting applications fully unleashing the SWaP-C benefits of active-metasurface optics. OPN

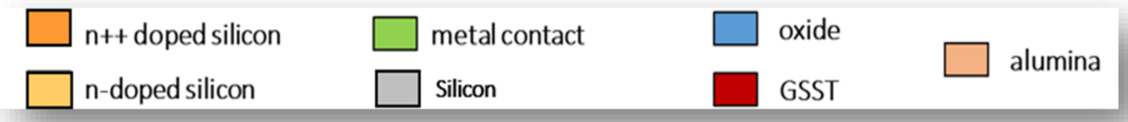


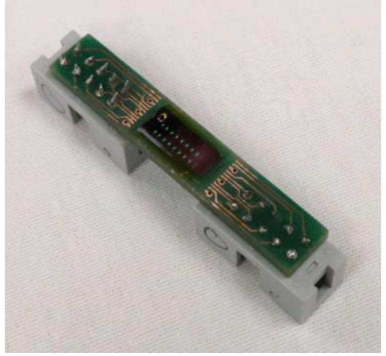
Top: Rendering of a $Ge_2Sb_2Se_4Te_1$ varifocal metalens. The focal-spot position is shifted by changing the crystallinity of the phase-change-material meta-atoms collectively. Bottom: Illustration of an on-chip, electrically switchable metasurface with beam-steering functionality, and photograph of a metasurface chip wire-bonded onto a custom-made printed circuit board.

? **Lifetime: 50 cycles**

Electrical switching of PCM metasurfaces





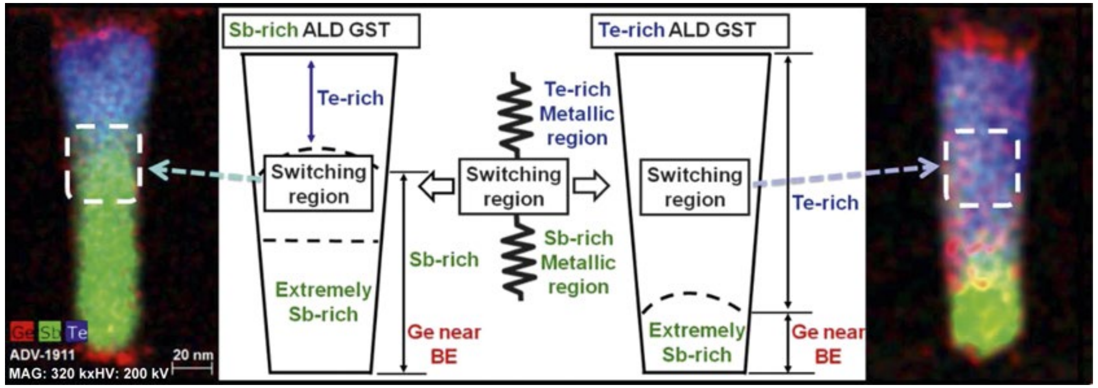


Packaged PCM metasurface devices

Failure mechanism of electronic PCMemories

Driving Force	Voltage-Bias Polarity Dependence	Atomic Motion			Working Phase	Force Intensity
		Ge	Sb	Te		
Incongruent melting	No	Ge-rich "solid" phase	Sb,Te-rich "liquid" phase		Solid, liquid	–
Wind force (by hole carrier)	Yes	Toward (–) electrode	Toward (–) electrode	Toward (–) electrode	Dominant in solid	Gentle
Electrostatic force	Yes	Toward (–) electrode	Toward (–) electrode	Toward (+) electrode	Dominant in liquid	Strong

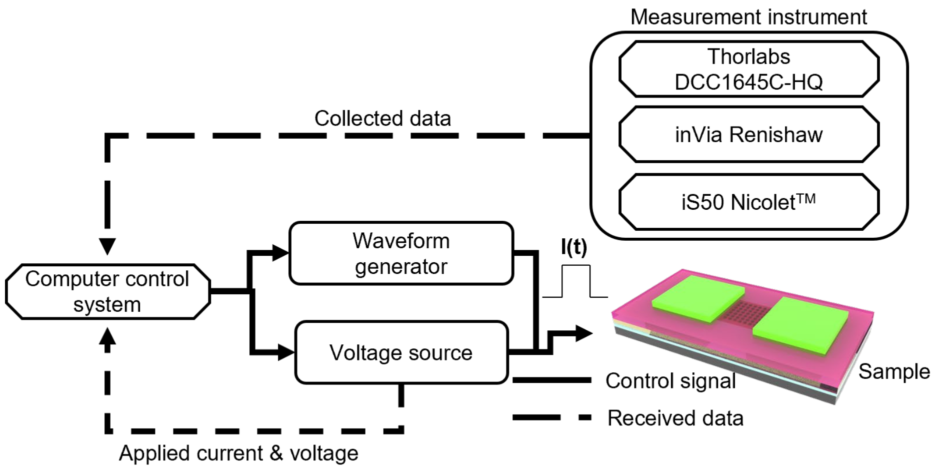
Not relevant to optical PCMs!

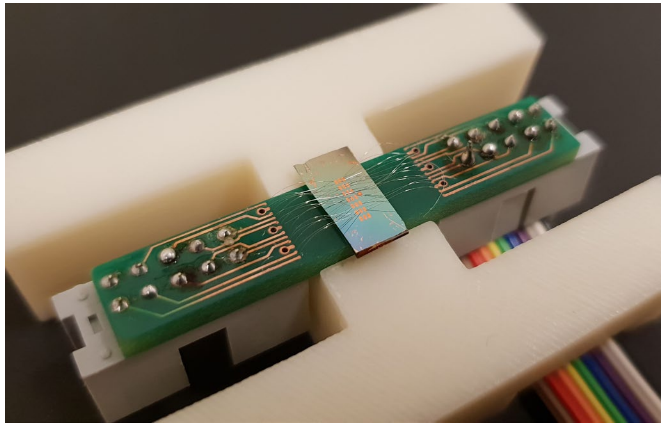


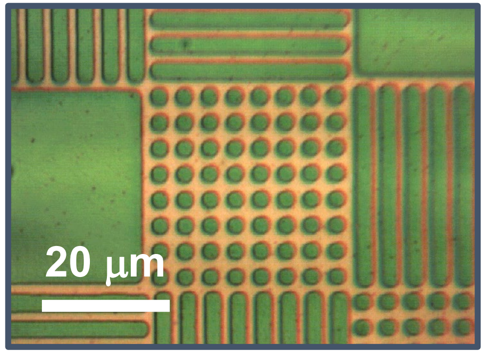
Electromigration induced void formation and elemental segregation

MRS Bull. **44**, 710-714 (2019)

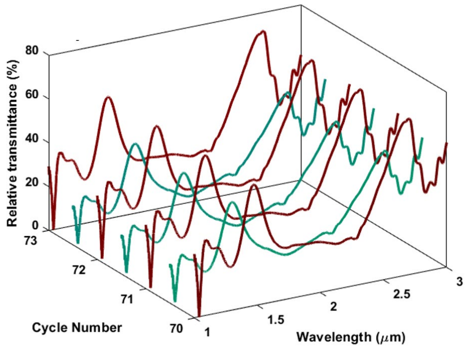
Multimode in-situ characterization platform



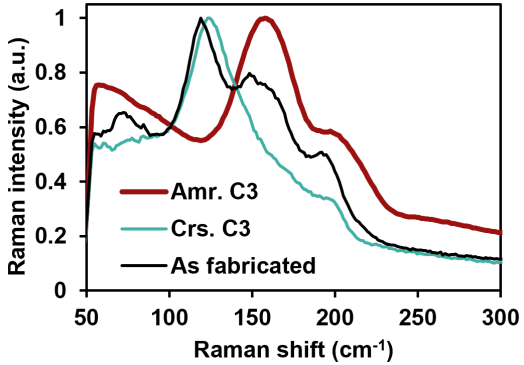




Imaging

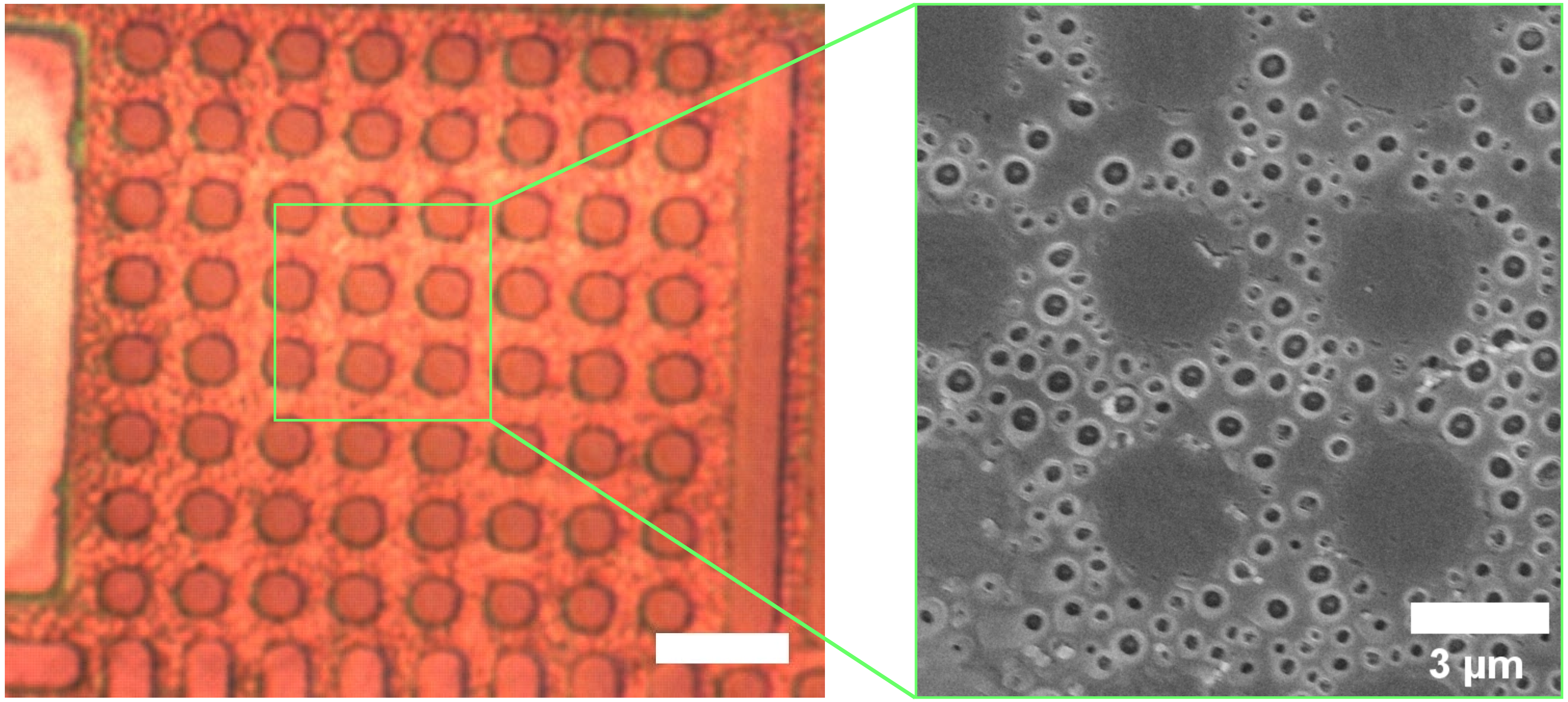


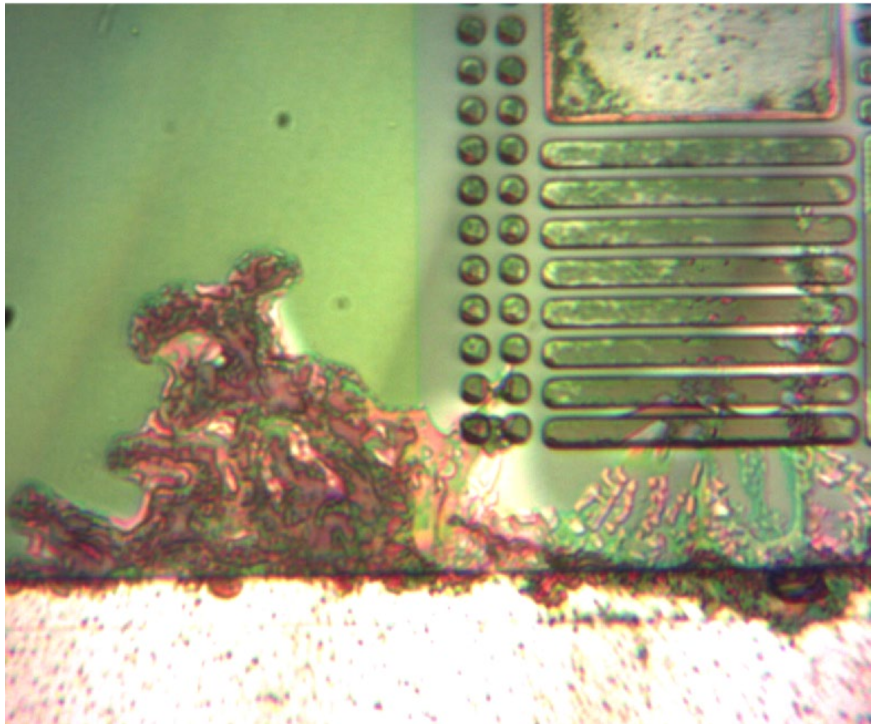
Micro-FTIR



Raman spectroscopy

H-release from SiN capping layer & Electromigration of metal contacts

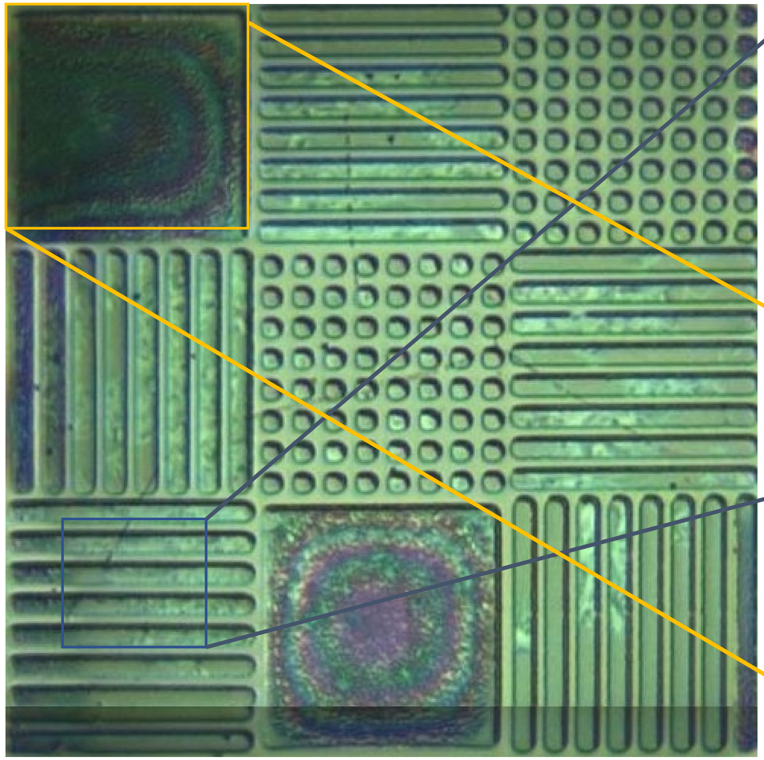


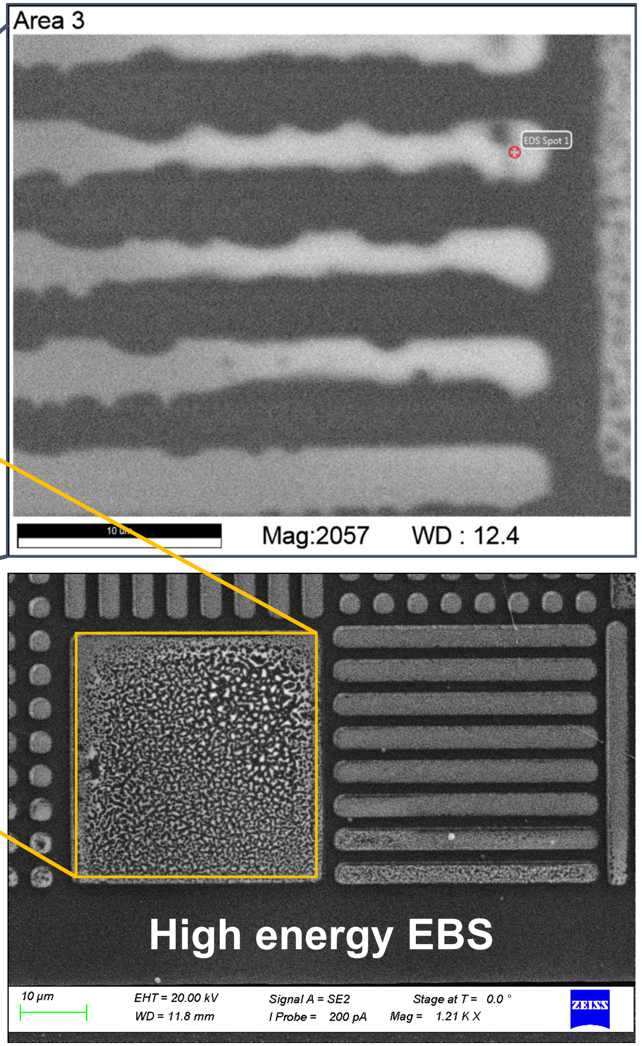


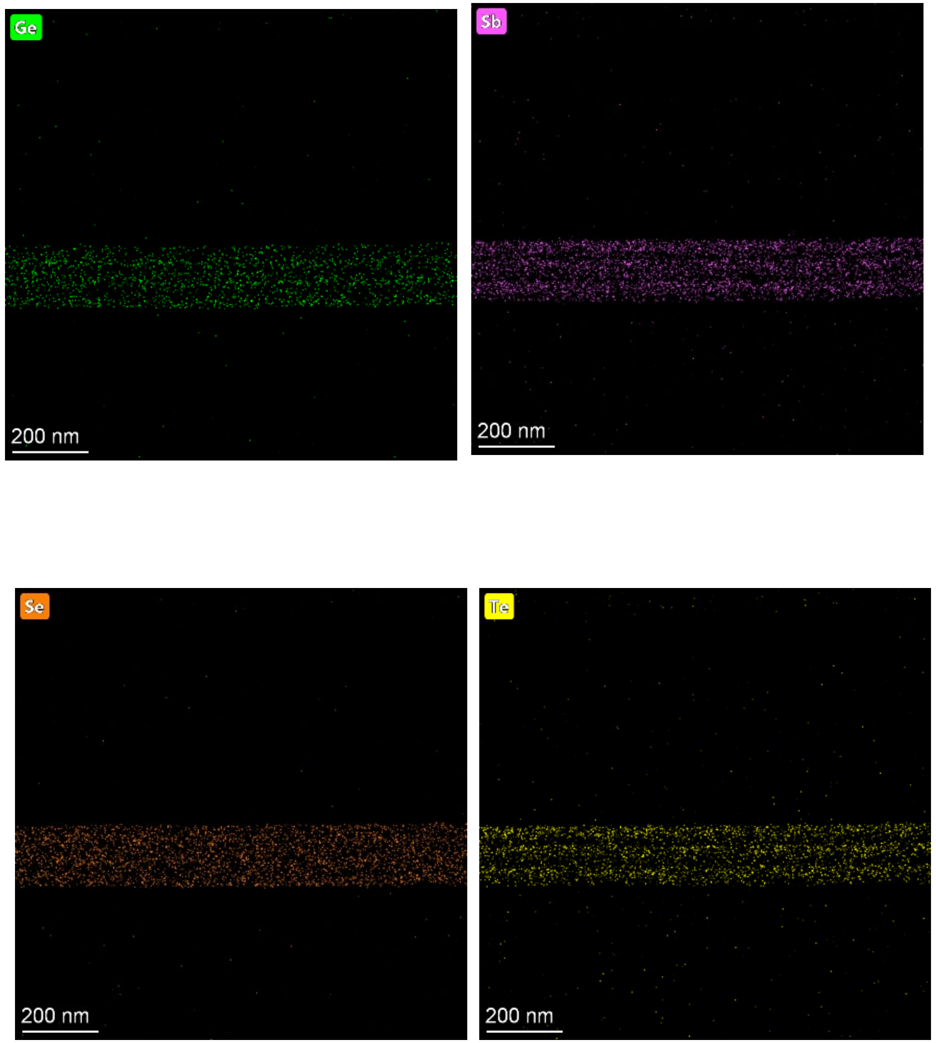
Switching from PECVD SiN to H-free sputtered SiN

Using AC bias voltage

Morphological instability & Compositional non-uniformity

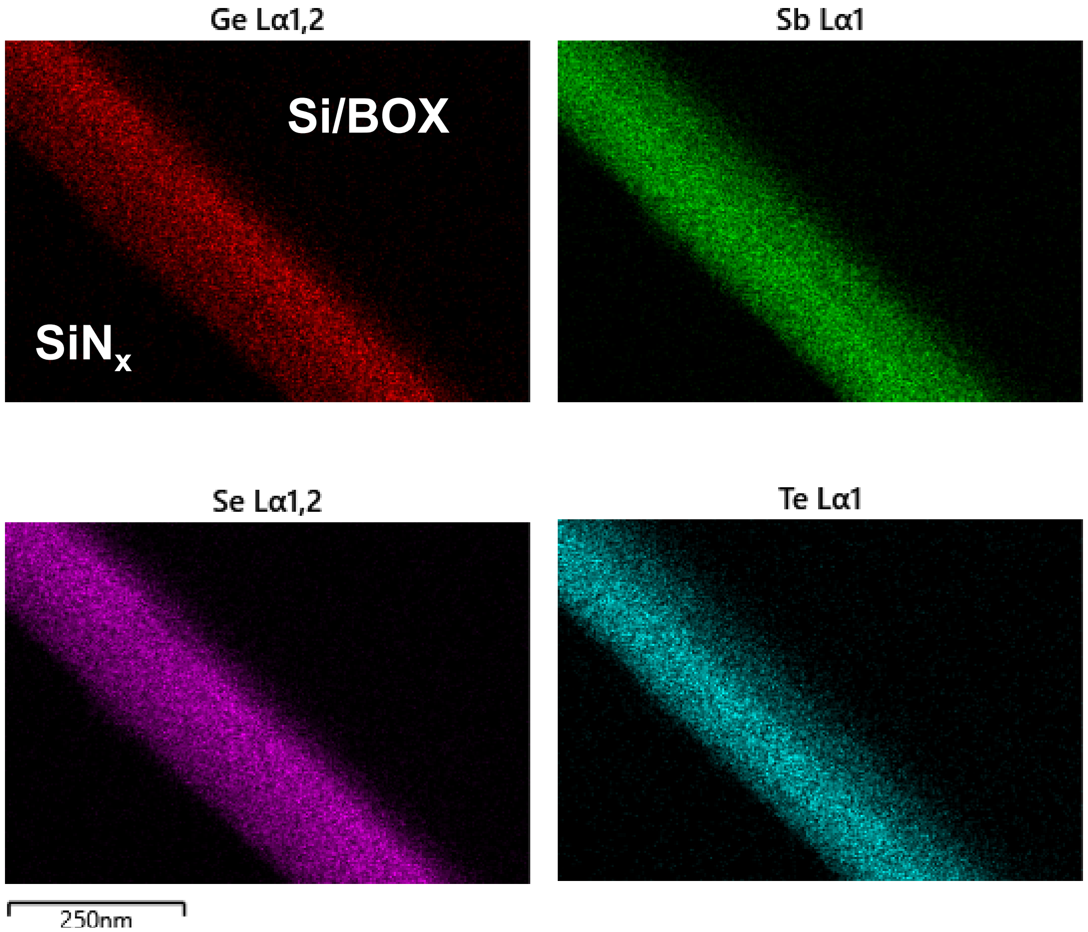


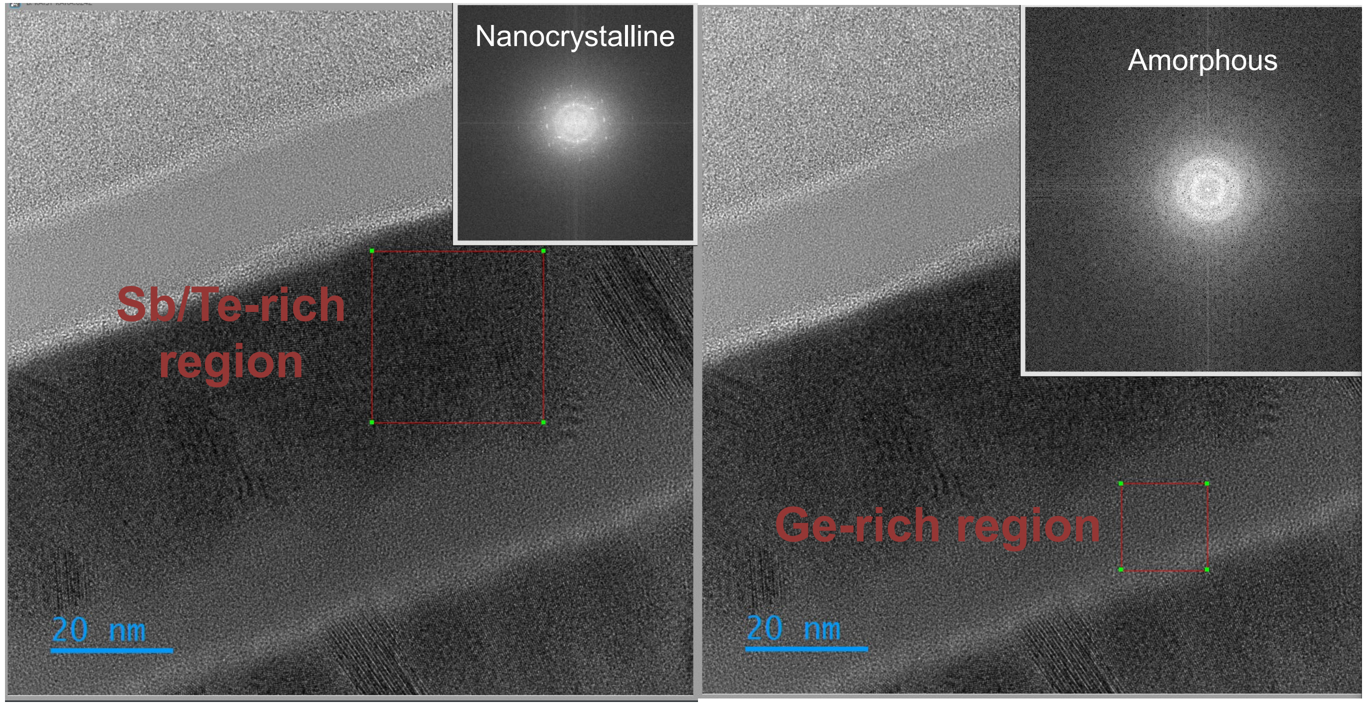




Optimize PCM structure geometry

Elemental segregation during cycling





Ge segregation prevents crystallization

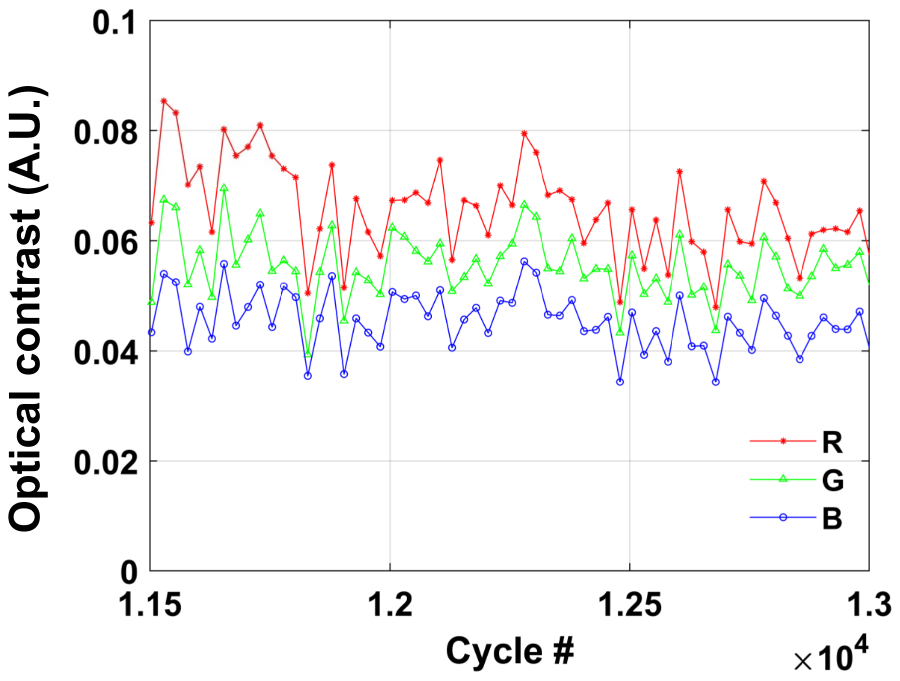
Ge migrates to high-T region whereas Sb and Te moves to low-T region

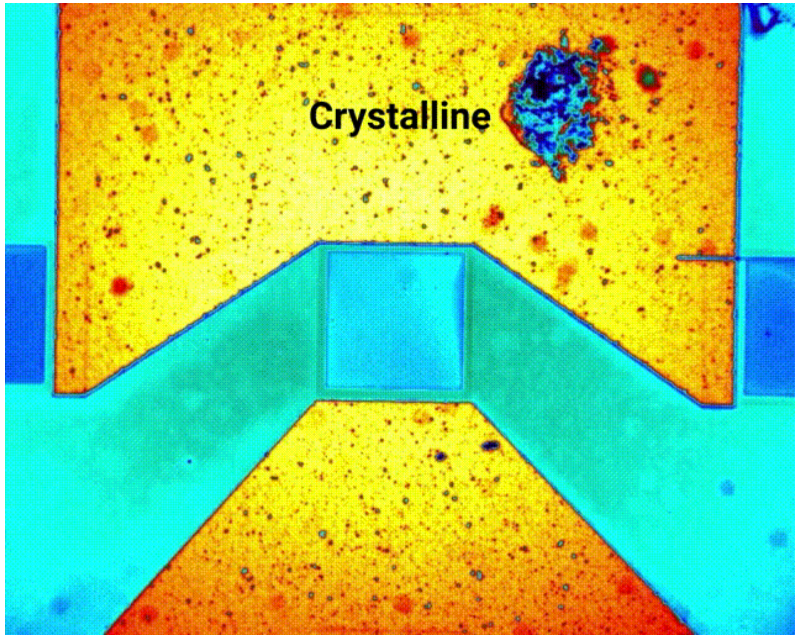
Increasing liquid phase dwell time

Endurance improvement in large-volume optical PCM switching

PCM switching volume: ~ 4,000 μm^3

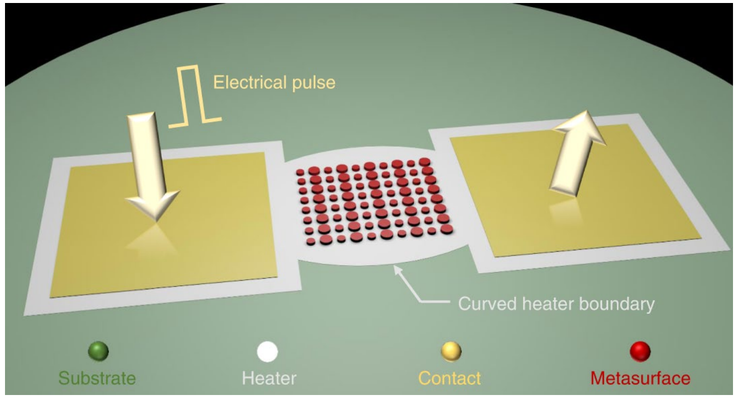
100 million times larger than that in PCMemories!

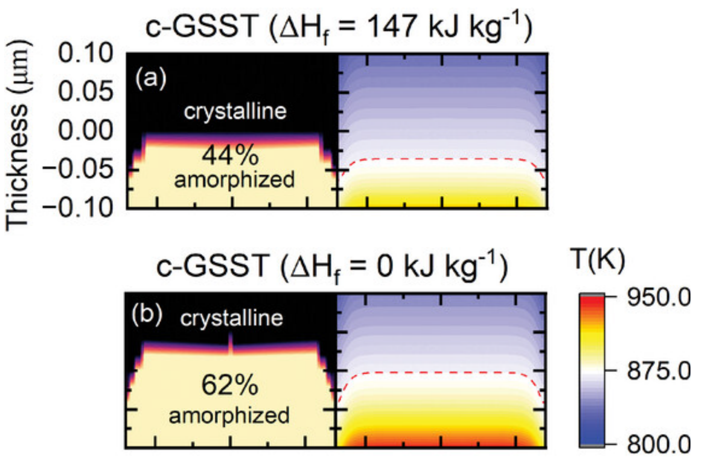




Large-area PCM switching with endurance of over 60,000 cycles

Thermal modeling of PCM devices

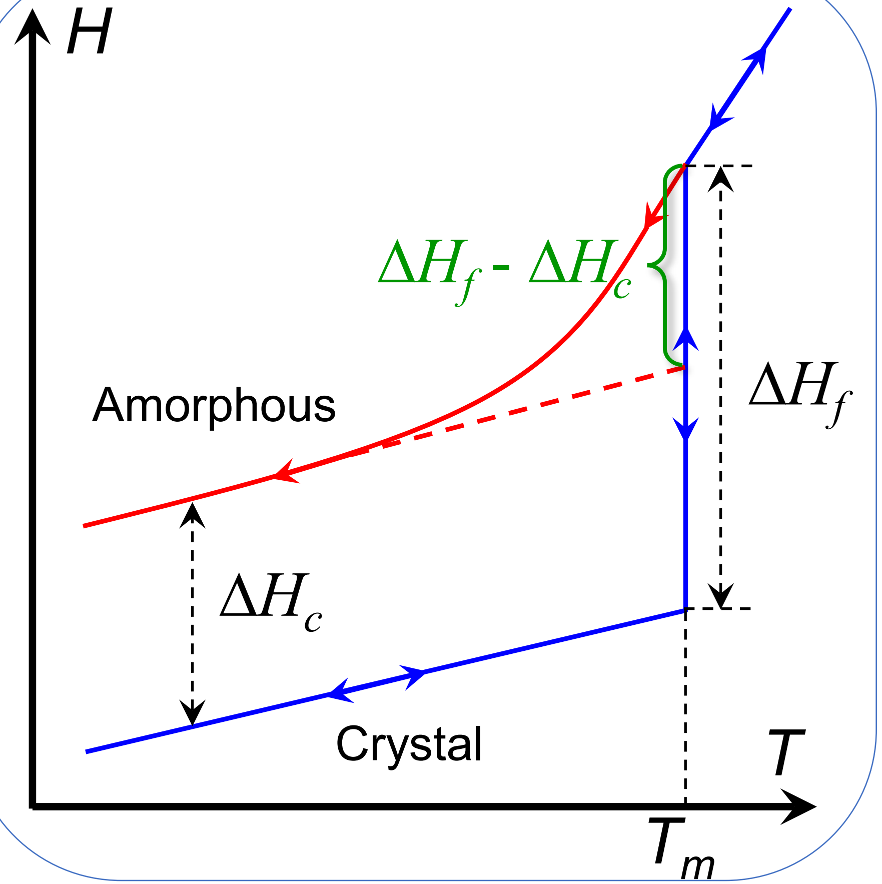




Thermal modeling is critical to device optimization and improving endurance

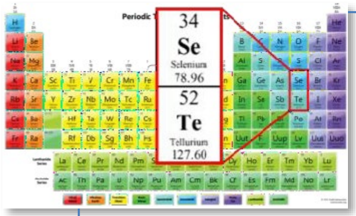
	Si	SiO_2	Si_3N_4	am-GSST	cry-GSST	Graphene	Al_2O_3	Au
Density [kg m^{-3}]	2329	2203	3100	5267	5267	2250	3900	19 300
Specific heat [J kg^{-1} K^{-1}]	700	740	700	275	351	420	900	129
Thermal conductivity [Wm^{-1} K^{-1}]	150	1.38	20	0.2	0.4	160[90]	30	317
Relative permittivity	–	–	–	–	–	4.708	–	6.9
Electrical conductivity [S m^{-1}]	–	–	–	–	–	$1/(d \cdot R_{sh})$	–	45.6×10^6

Constants?

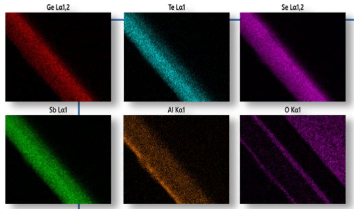


- ❑ **Fundamental behavior studying on the effect of enthalpy of melting on solidification of PCMs as part of controlling phase change kinetics** (Small, https://doi.org/10.1002/smll.202304145, 2023)
- ❑ **Scaling up phase change material-based devices**

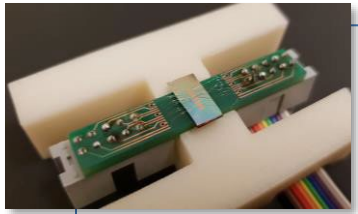
Summary



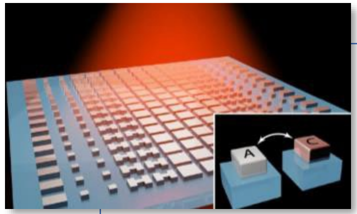
With their low optical loss, large index change and switching volume, **PCMs are an ideal materials for active / reconfigurable metasurface optics**



Electrically reconfigurable PCM photonic circuits and metasurfaces have been demonstrated leveraging Si foundry processing

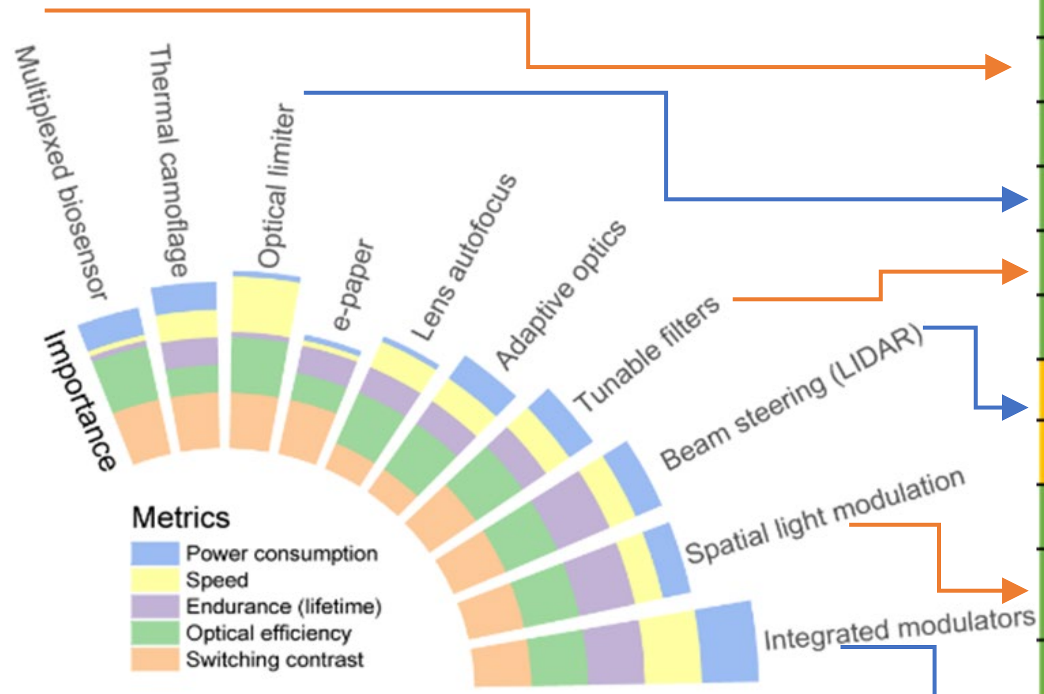


Understanding and **mitigating failure mechanisms** enable electrical switching of PCM metasurfaces over tens of thousands of cycles (and likely more)



Temperature dependence of heat capacity and thermal conductivity of PCMs must be accounted for to enable **accurate thermal modeling**

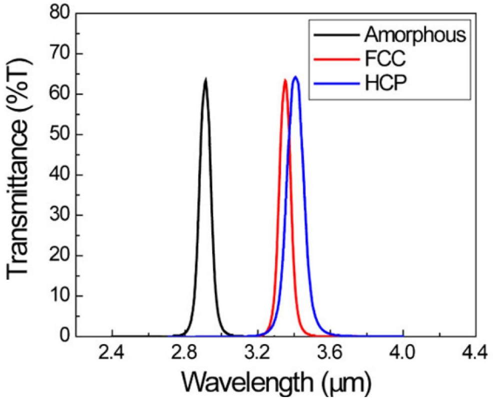
Application-driven trade study



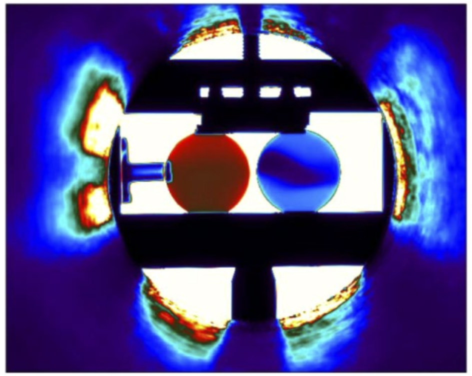
Optical contrast (relevant metrics)	Optical loss suppression	Endurance (cycling lifetime requirement)	Speed (bandwidth requirement)	Power consumption
Extinction ratio		10^7	1 kHz	
Full 2π phase tuning range		10^9	10 Hz	
Field-of-view and image contrast		10^{10}	30 Hz	
Full 2π phase tuning range		$10^{10\ d}$	100 Hz	
Full 2π phase tuning range		10^3	1 Hz	Nonvolatile or capacitive
Full 2π phase tuning range		10^8	1 kHz	
Image contrast		$10^{10\ d}$	30 Hz[g]	
Color saturation and image contrast		10^7	1 Hz	Nonvolatile or capacitive
Full 2π phase tuning range		10^5	1 Hz	
Modulation contrast		10^{18}	10 GHz	
Full 2π phase tuning range		10^9	100 Hz [94]	
Isolation ratio		$10^{18\ h}$	10 GHz	
Extinction ratio		10^3	> 1 GHz	Nonvolatile
Dynamic range		10^8	10 Hz	

References (H. J. Kim *et al.*)

P-ACTIVE tunability & gas sensing

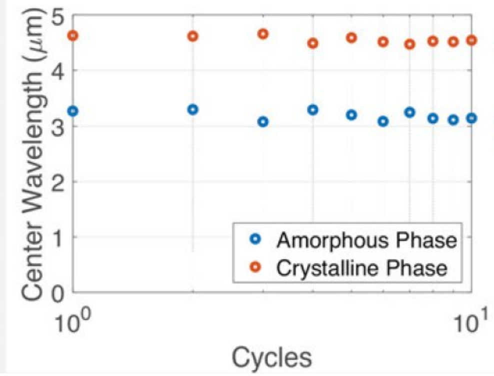


Optica ***7***(7) 746 (2020)



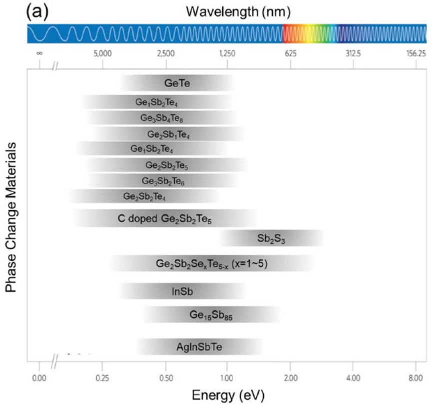
Optics Express ***28***(7), 10583 (2020)

Reliability test



Optical Eng. ***60***(8) (2020)

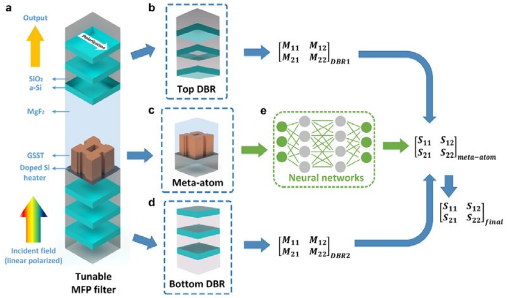
PCM-net database



J. Phys. Photo. ***3***, 024008 (2021)

A Multi-Spectral Imaging Pyrometer Patent *Applica.(2022)*

DNN design



Nanophotonics ***11***(17), 4149 (2022)


NASA/TP–20220019141

P-ACTIVE Project Report

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NASA ***TP-20220019141****(2022)*


Optics in 2021

Metasurfaces Embracing a Phase Change

ACS, highlight (2022)

Vision to sub-system

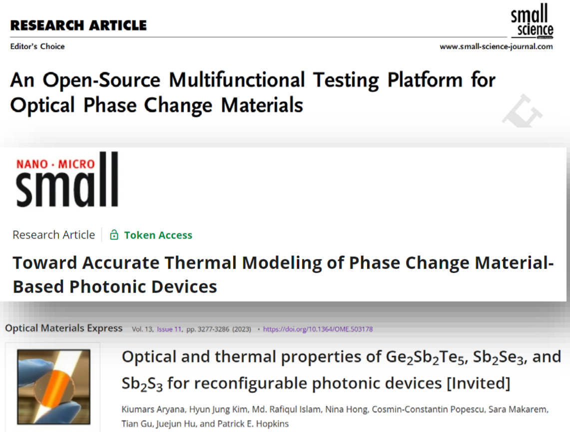

nature photonics

Review Article

Reconfigurable metasurfaces towards commercial success

Nature Photonics ***17***(48) (2023)

2023 -


RESEARCH ARTICLE

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An Open-Source Multifunctional Testing Platform for Optical Phase Change Materials

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Toward Accurate Thermal Modeling of Phase Change Material-Based Photonic Devices

Optical Materials Express

Optical and thermal properties of $Ge_2Sb_2Te_5$, Sb_2Se_3, and Sb_2S_3 for reconfigurable photonic devices [Invited]

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