The PCM is dead! Long Live O-PCM!

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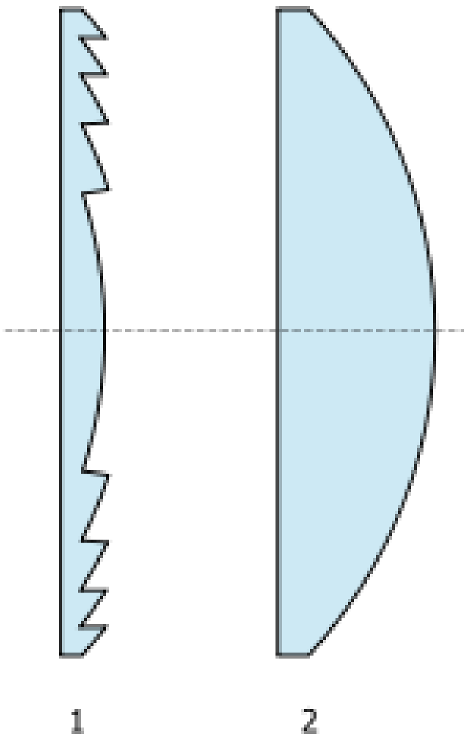
8. KAIST Analysis Center, Korea Advanced Institute of Science and Technology, Daejeon, Korea

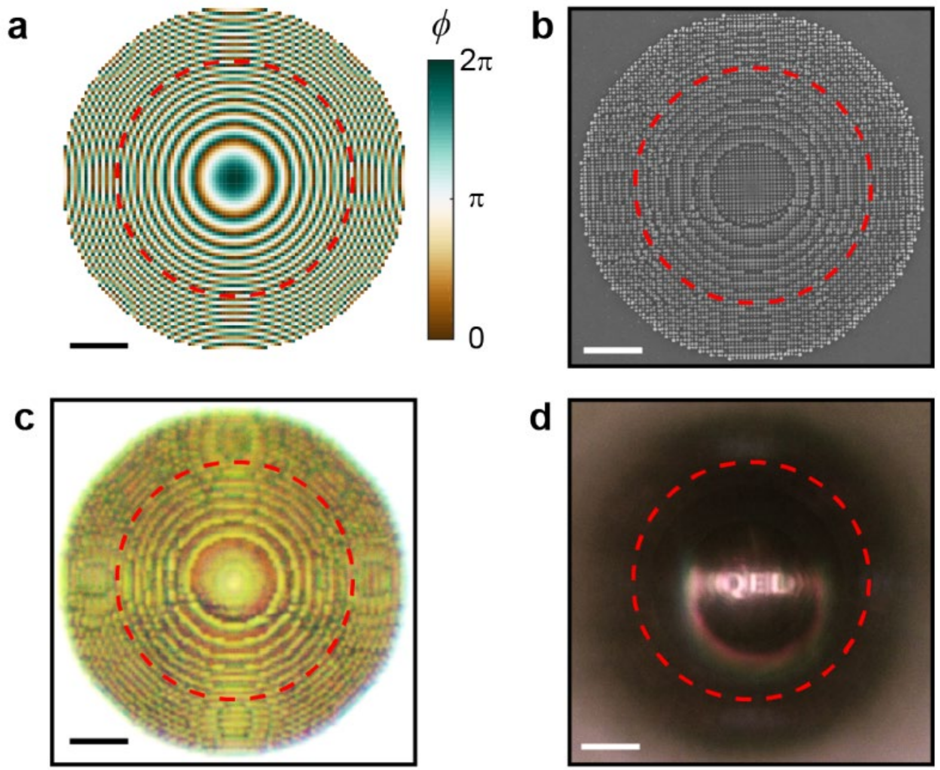
PMAT MIT Lincoln Laboratory University of Central Florida DRAPER NASA

Photonic MATerials

Diffractive optics to sub-wavelength scale E-field phase control



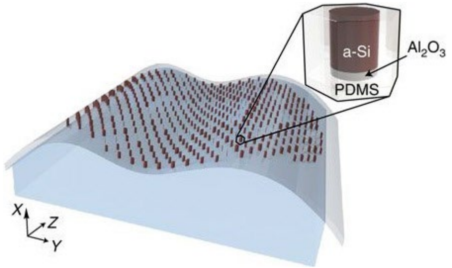
https://en.wikipedia.org/wiki/Fresnel_lens



Nature **10**, 1 (2019)

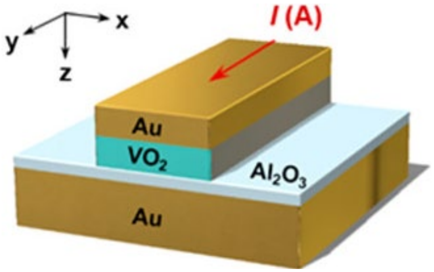
Active Metasurfaces to PCM Metasurfaces

Mechanical



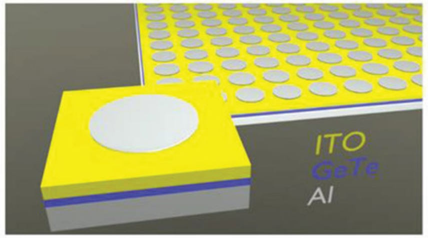
Nat. Commun. **7**, 11618 (2016)

Phase transition



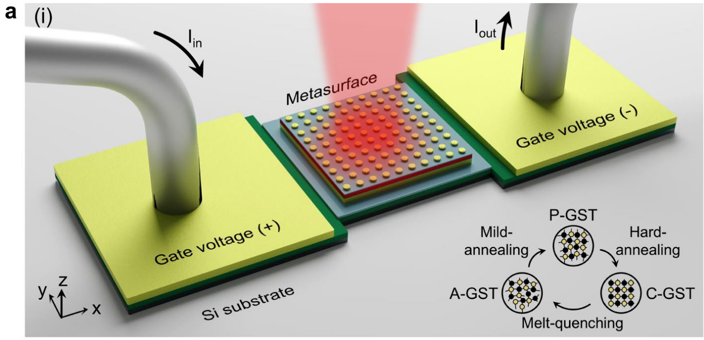
Nano Lett. **19**, 3961 (2019)

GeTe



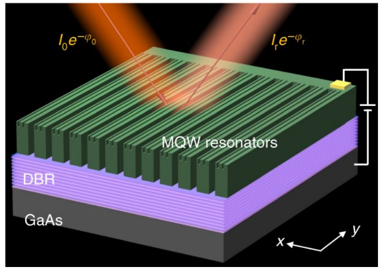
Adv. Opt. Mater. **7**.18 (2019)

$Ge_2Sb_2Te_5$



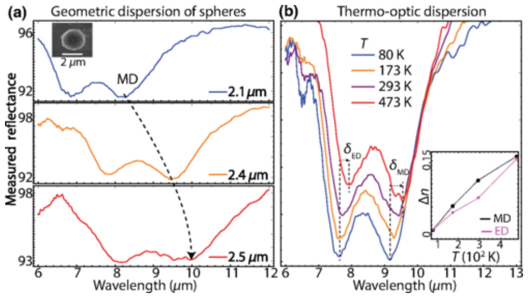
Nat. Comm. **13**, 1696 (2022)

Electro-optic



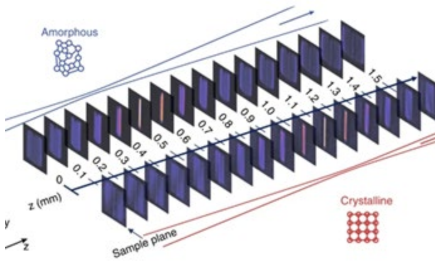
Nat. Commun. **10**, 3654 (2019)

Thermo-optic



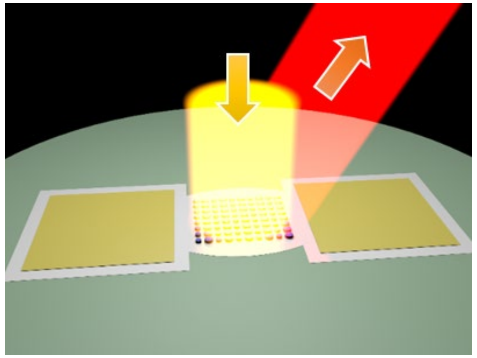
Phys. Rev. Appl. **10**, 044029 (2018)

$Ge_3Sb_2Te_6$



Light Sci. Appl. **6**, e17016 (2017)

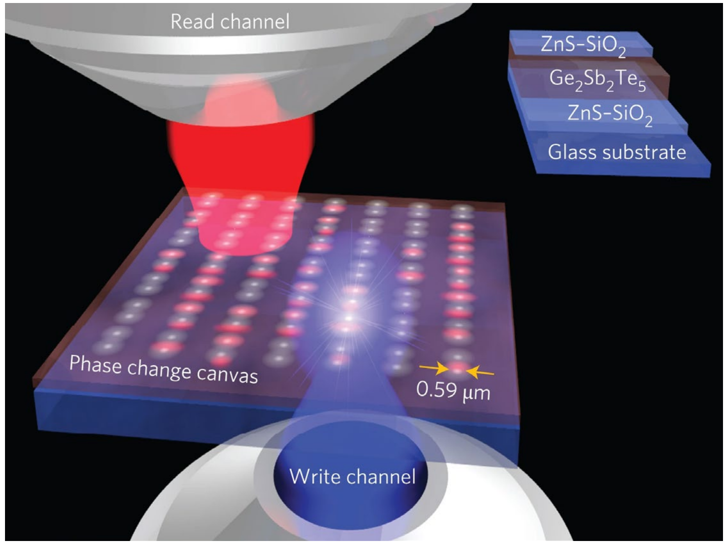
$Ge_2Sb_2Se_4Te$



Nat. Nanotech. **16**, 661-666 (2021)

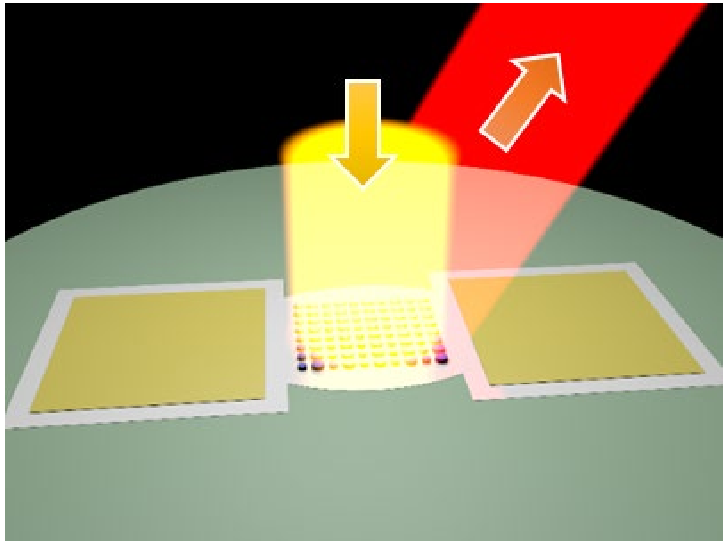
Switching PCM

Laser writing

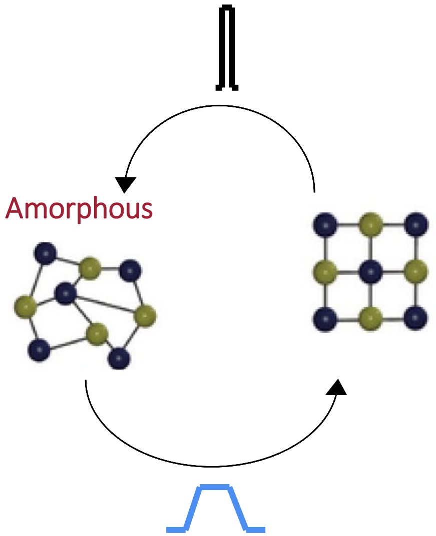


Nat. Photonics **10**, 60 (2016)

Electro-thermal heating

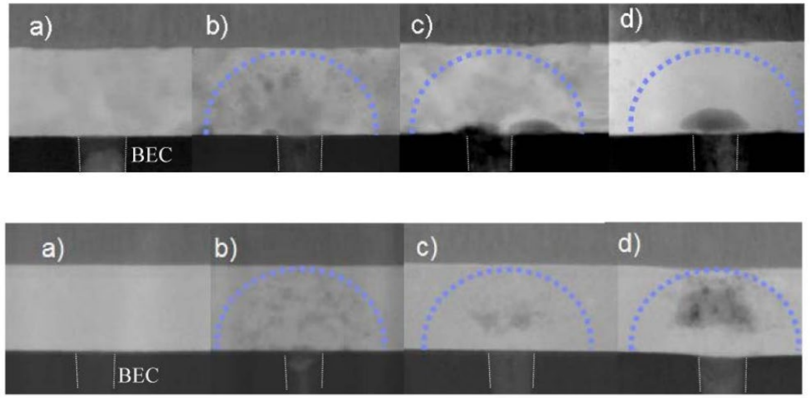


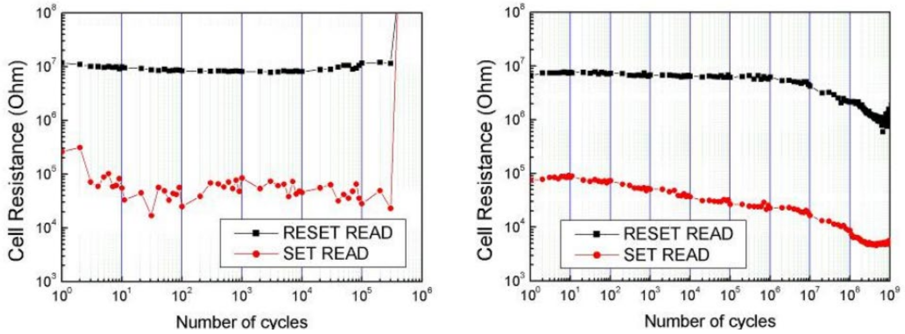
Nat. Nanotech. **16**, 661-666 (2021)



Endurance of PCMs

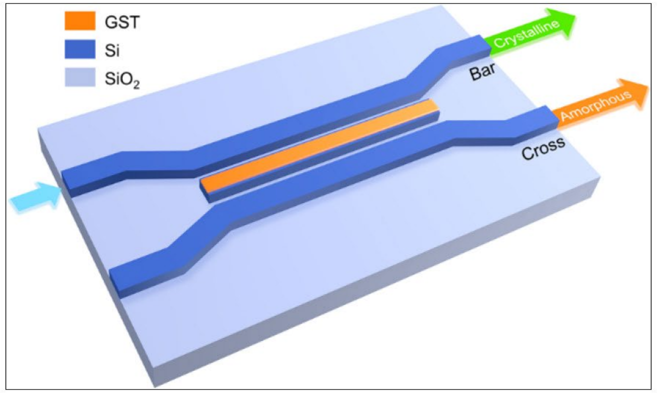
- Electrical phase change memory – resistance
- Optical phase change device – transmission/reflection
    - PCM optical properties





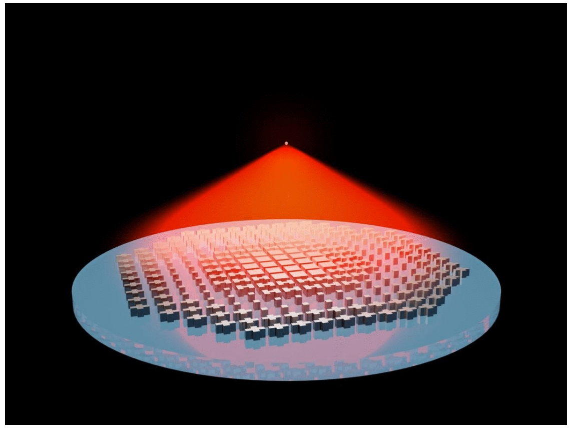
Chen et al. *IEEE Int. Memory Workshop.* (2009)

Photonic Integrated Circuits
Length in the in-plane direction



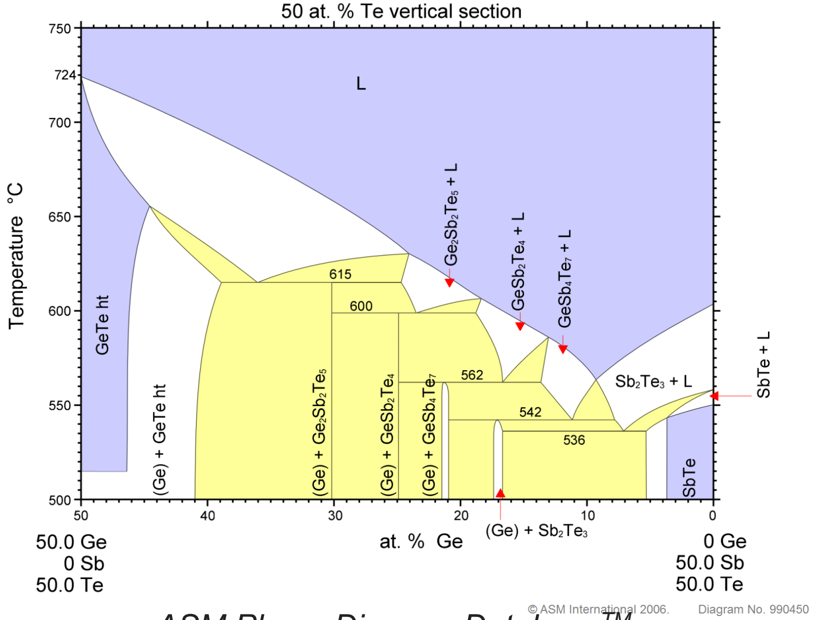
ACS Photonics , **6**, 2, 553−557, (2019)

Free-space optics
Phase accumulation along thickness



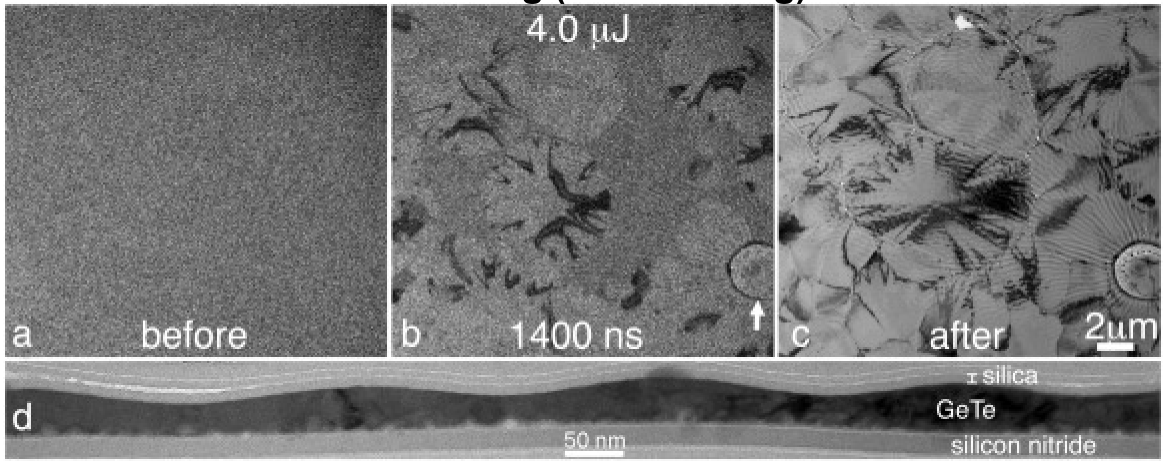
Nat. Commun. **12**, 1225 (2021)

Incongruent melting



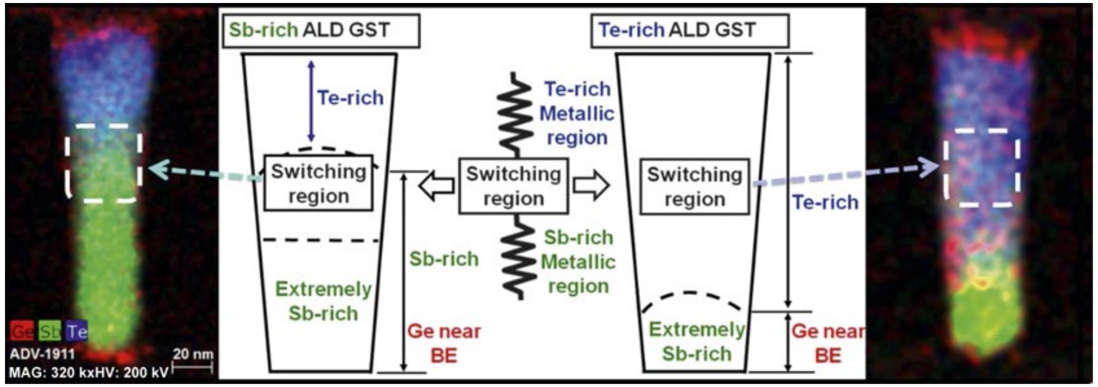
ASM Phase Diagram Database^{TM}

Dewetting (laser heating)



Thin Solid Films **571**. 39-44 (2014)

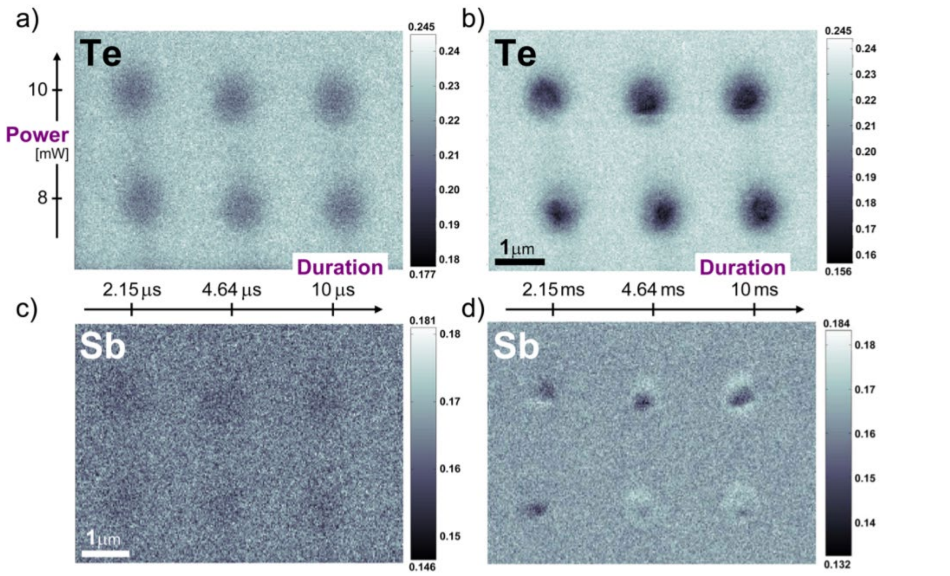
Pore formation and elemental segregation



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

Volatilization

Thermal migration



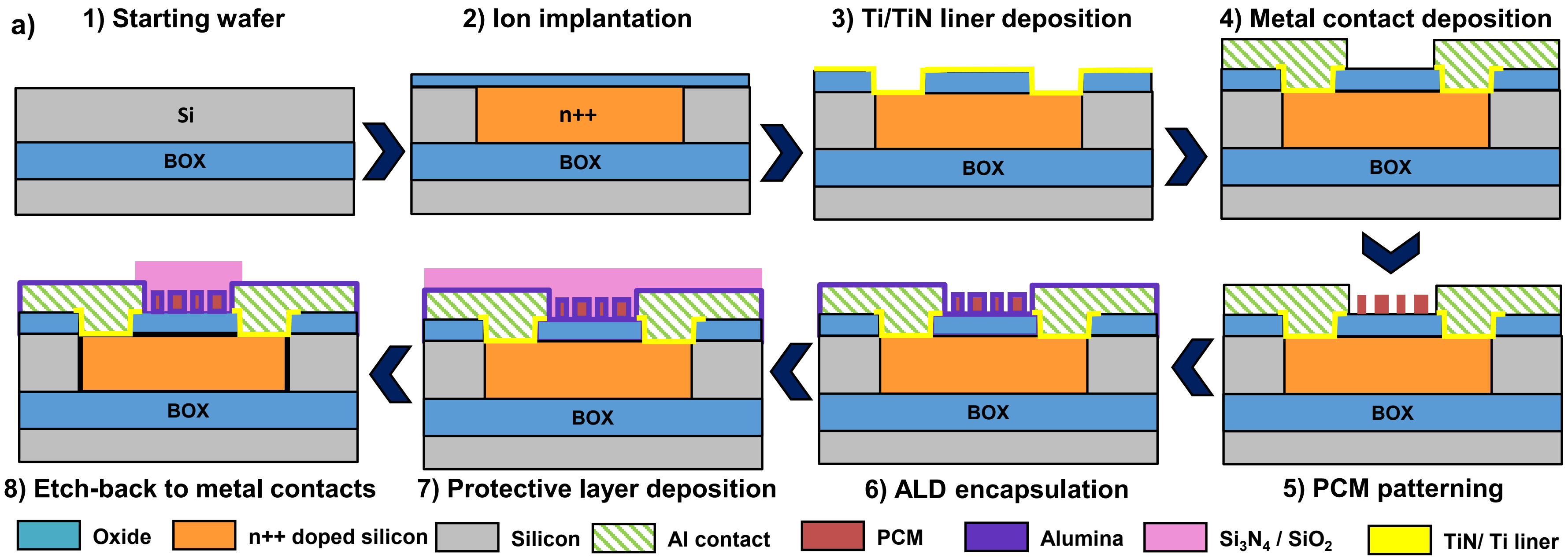
J. Electrochem. Soc. **158** 10 (2011)

PMAT

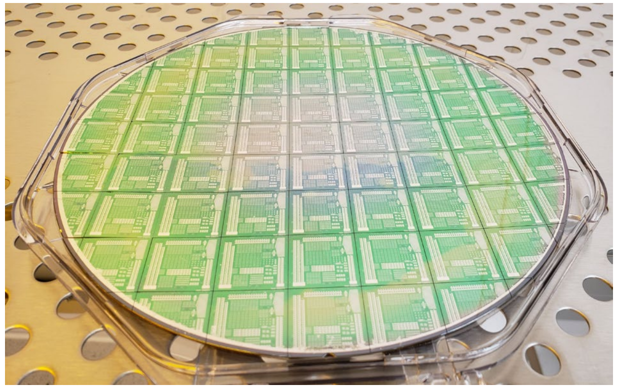
Photonic MATerials

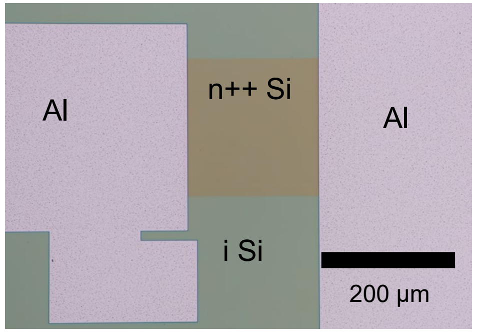
Platform fabrication

a)



e)

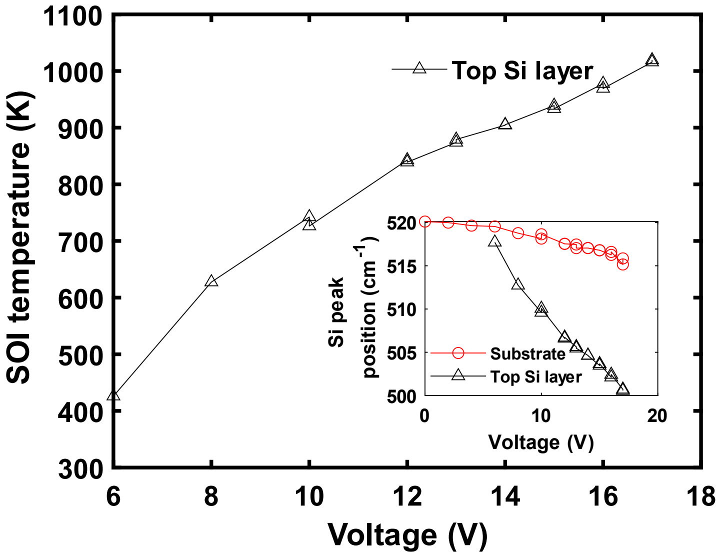




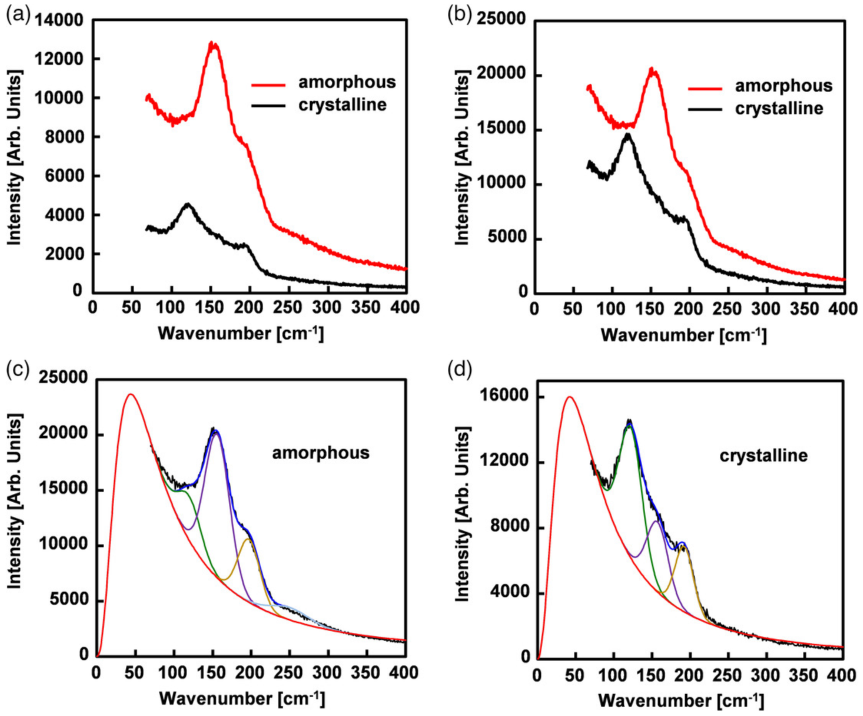
On chip TTT diagrams

Adv. Photonics Research **3**. 10 (2022)

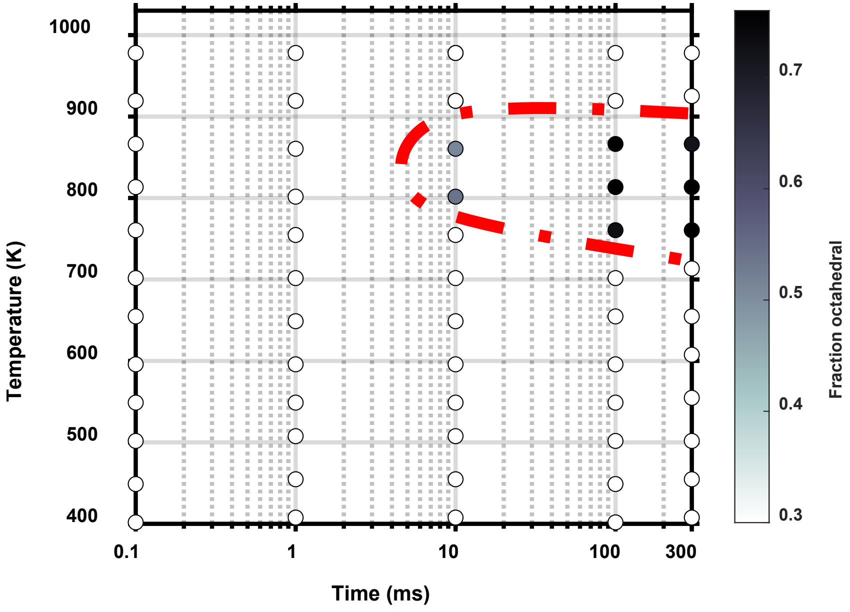
Temperature verification steady state against COMSOL simulations



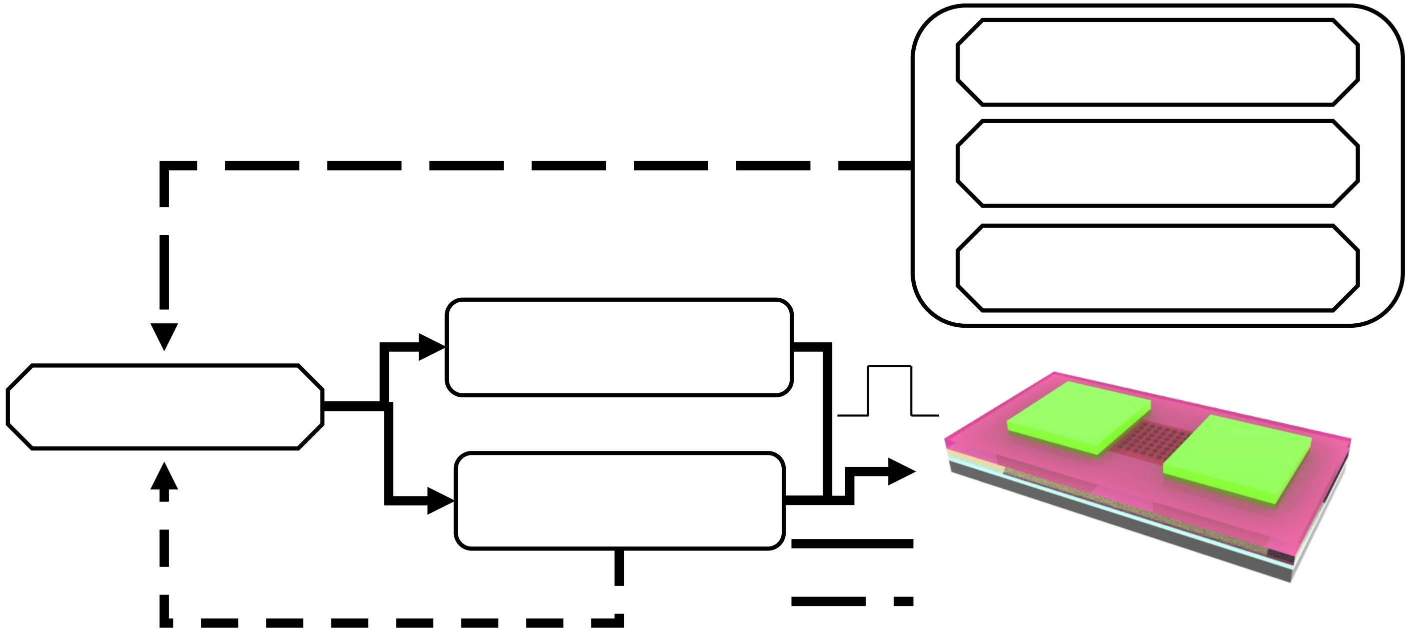
GSST Raman peak fitting Ge-6Se and Ge-4Se

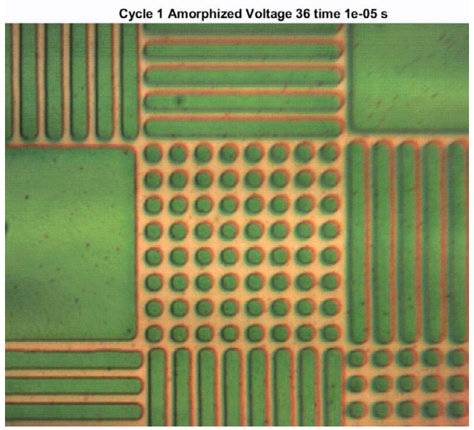


Voltage & Pulse width ⇒ Temperature & Ge-6Se peak



Unraveling failure mechanisms in optical PCMs

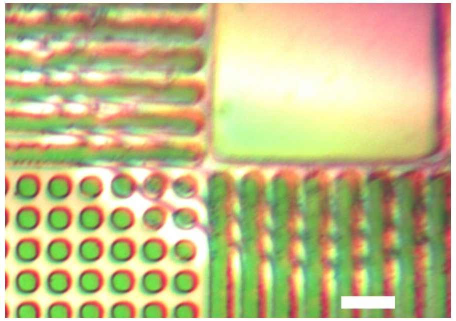




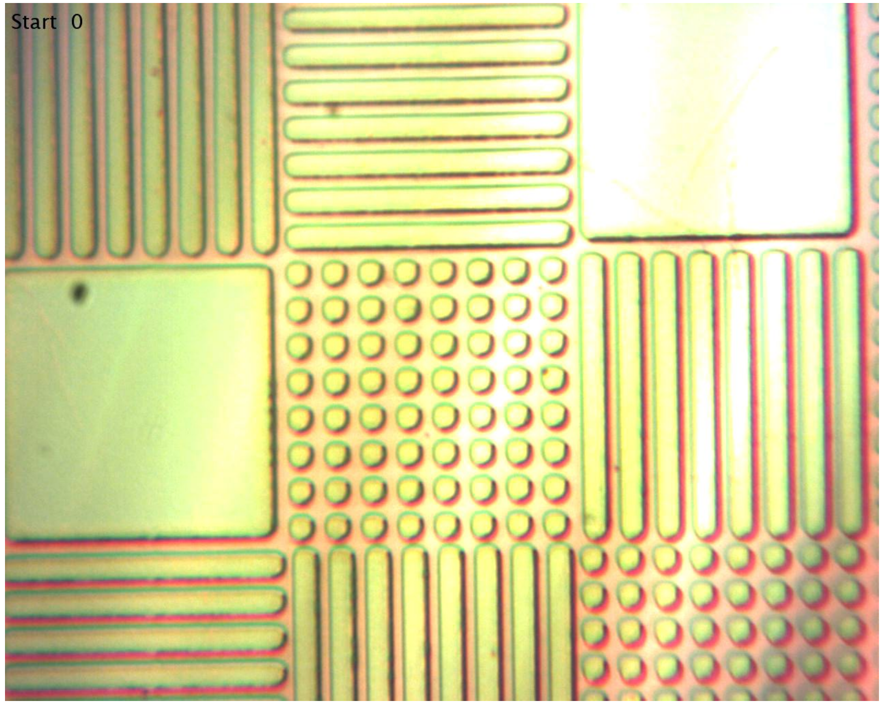
In situ **concurrent structural and optical characterizations**

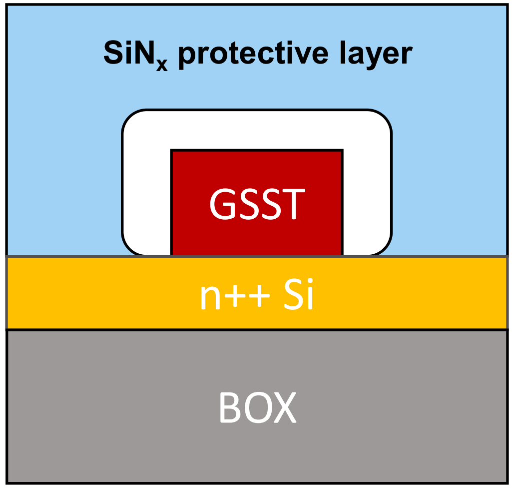
Delamination & Adhesion

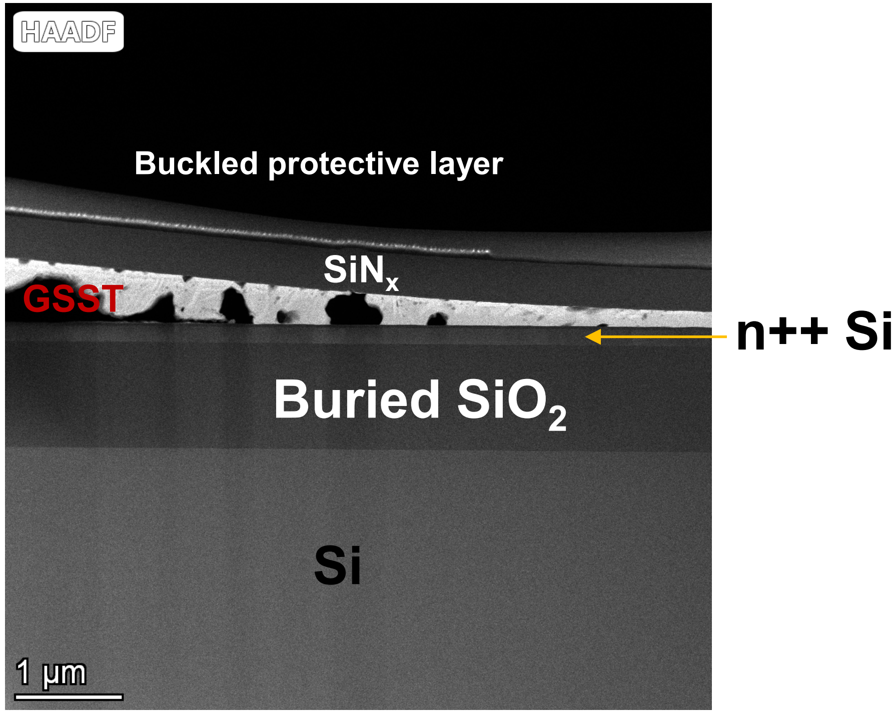
Capping layer delamination



Fringes highlight varying void thickness

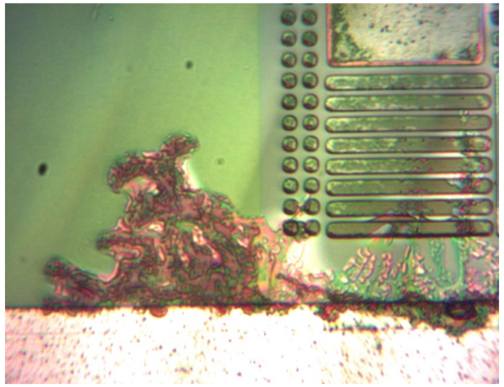




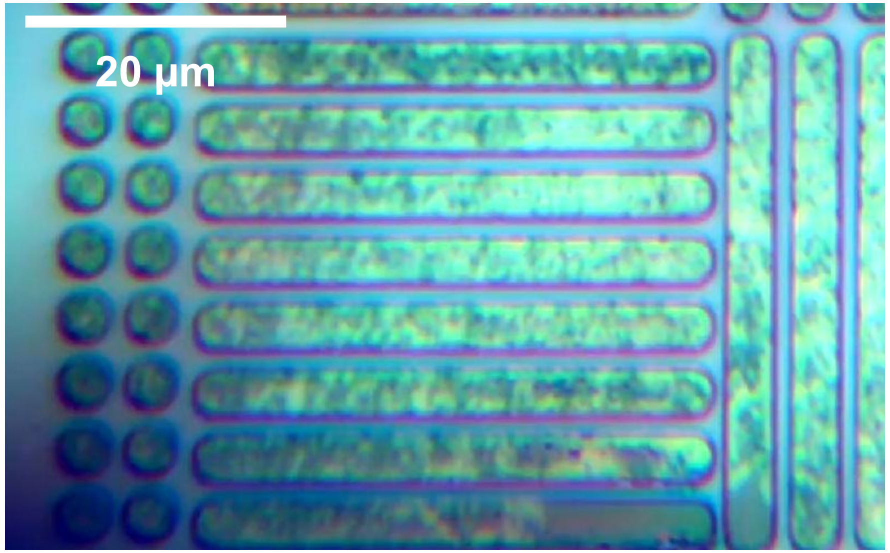


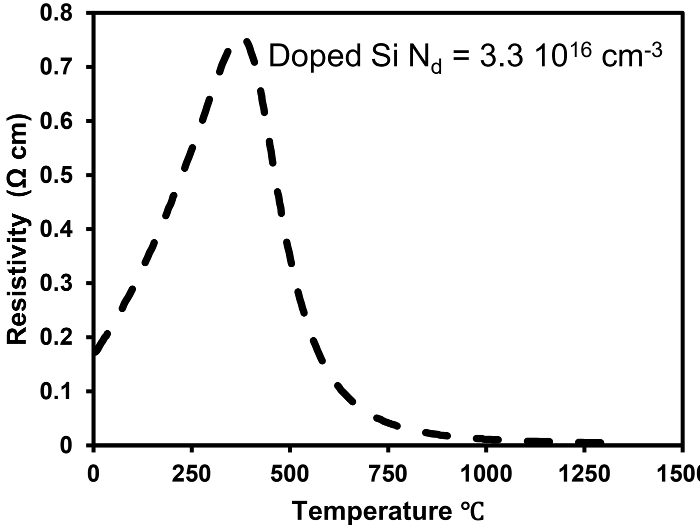
Potential solution:
Restrict dimensions of thin films (e.g. metasurfaces);
Adjust material choice for improved adhesion substrate-PCM and PCM-protective layer

Metal electromigration /Current crowding

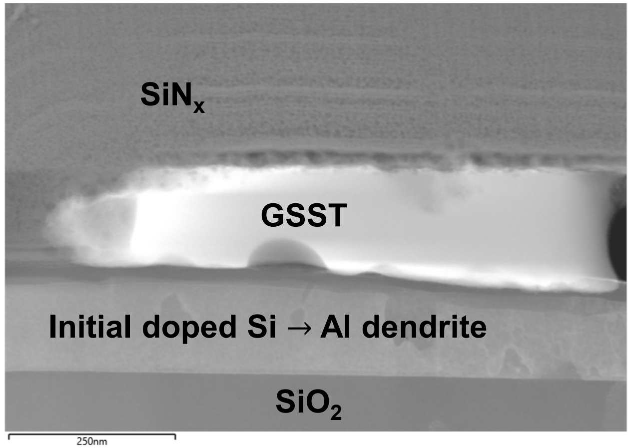


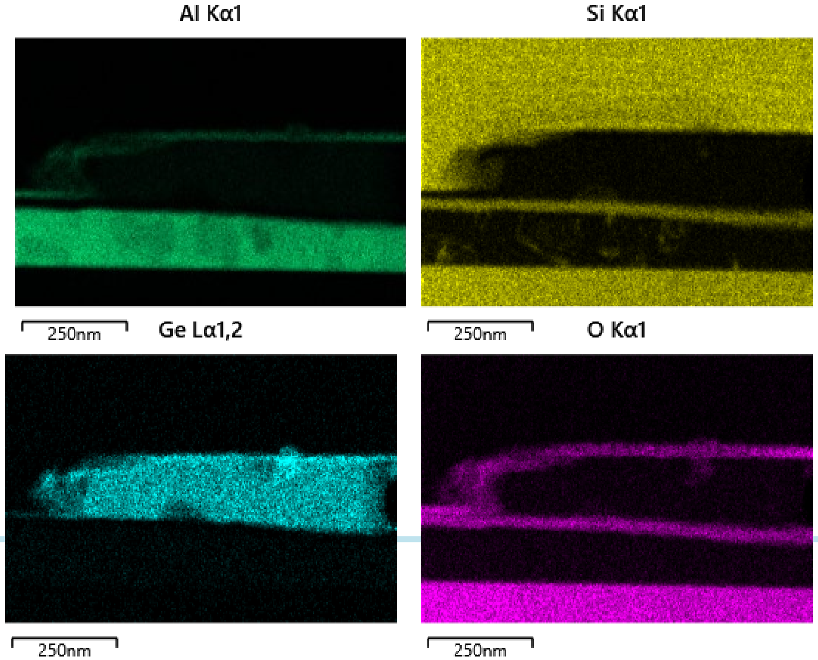
Metal contact electromigration





Cabal, A. R. *ETSIT UMP,* Ph.D. Thesis (2015)





Potential solutions:

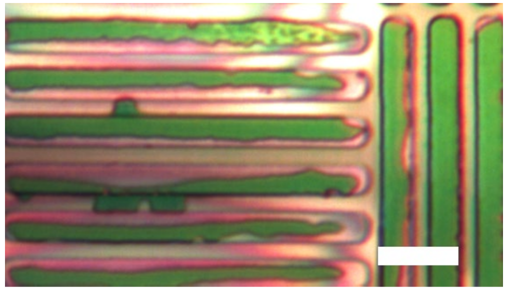
Reshape heater – wider contact region

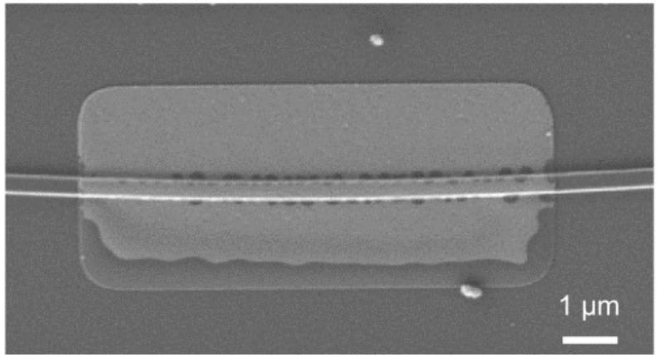
Improved heat sink; Time delay for cooling

Downside: large delay for switching applications

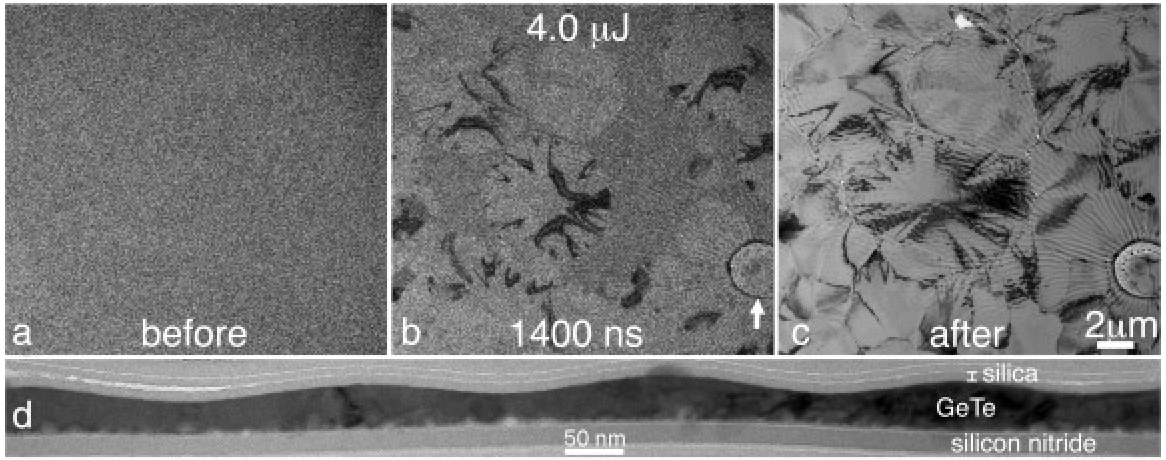
Small device area

Dewetting / fluid instability



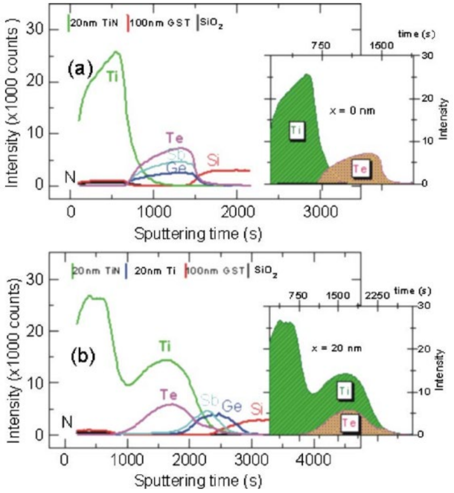


Dewetting of Sb_2Se_3 thin film on Si waveguide



Thin Solid Films **571**. 39-44 (2014)

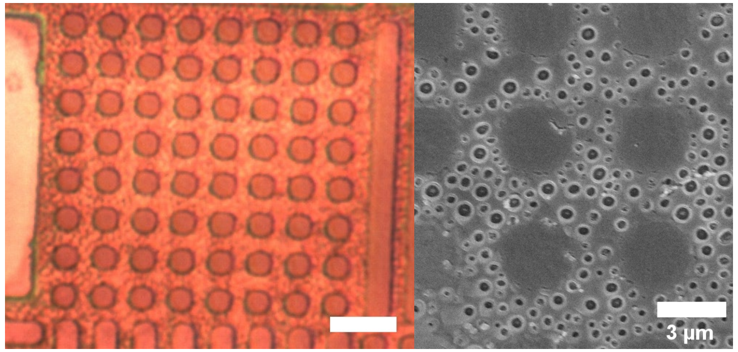
Dewetting & fluid instability



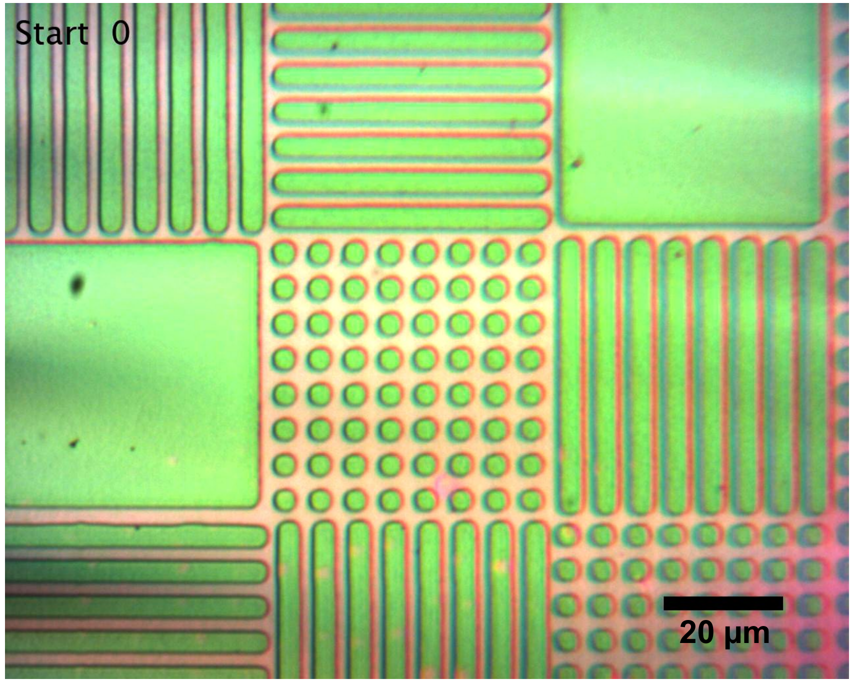
Appl. Phys. Lett. **90**, 051908 (2007)

Potential solutions:
Restrict aspect ratio
Material choice for improved adhesion to substrate
Downside: Potential losses due to adhesion materials (e.g. Ti or TiN) and parasitic reactions ($TiTe_2$ formation)

Damage & pore formation due to H-release

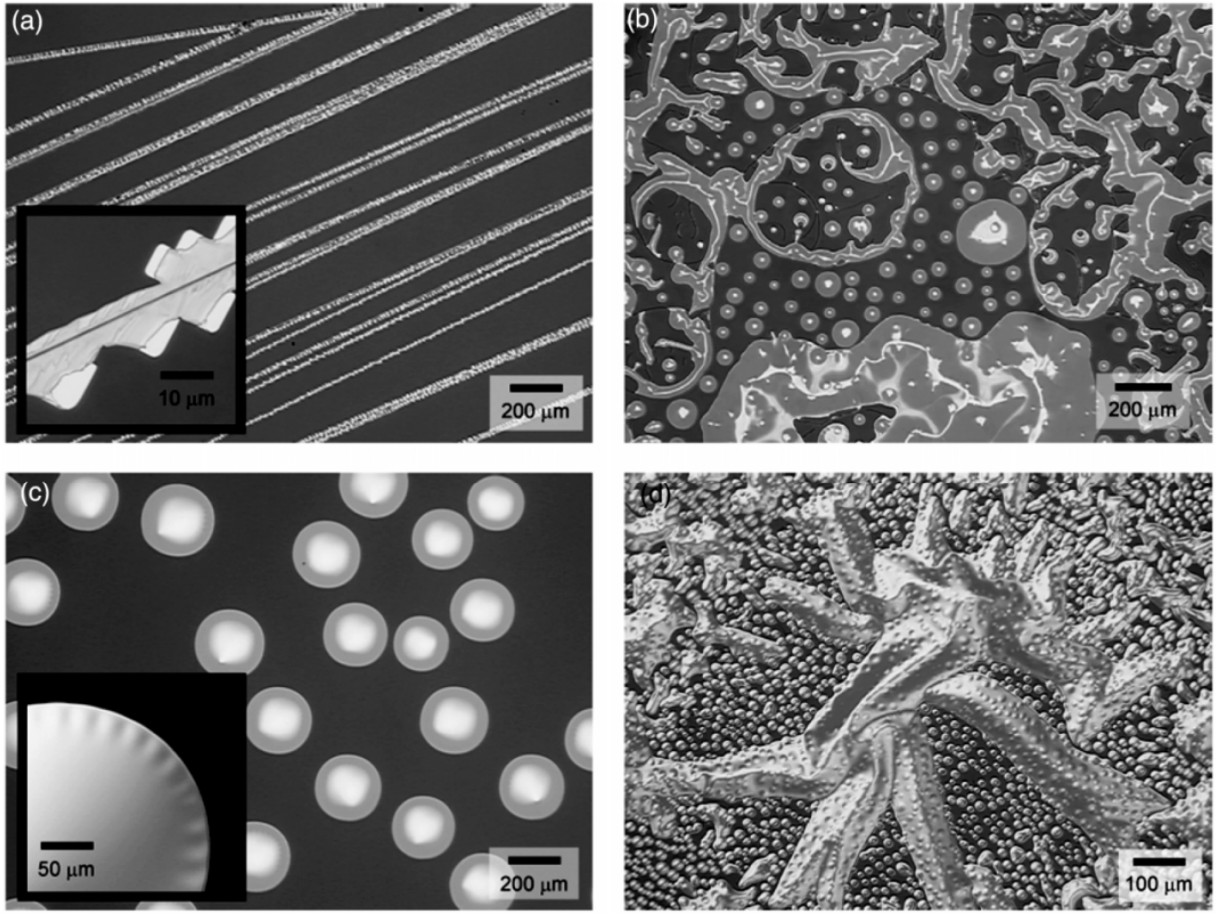


H-release from capping layer



SiN$_x$ on InP

SiN$_x$ on InP

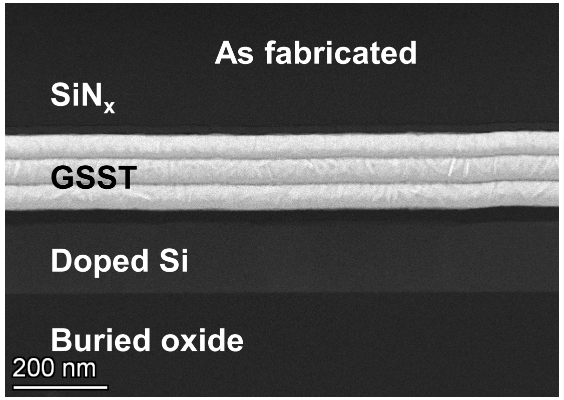


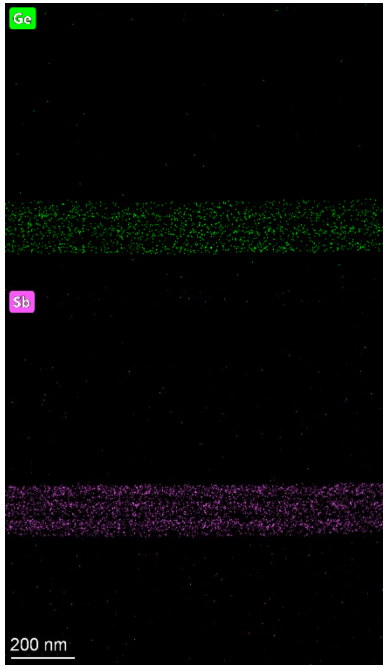
SiN$_x$ on Si

SiN$_x$ on InP

Hughey & Cook, *Thin Solid Films* **460**. 1-2 (2004)

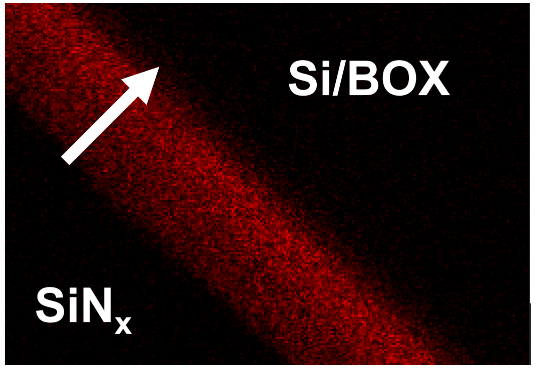
Elemental migration



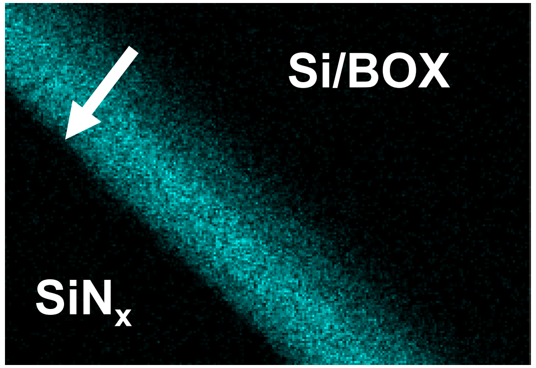


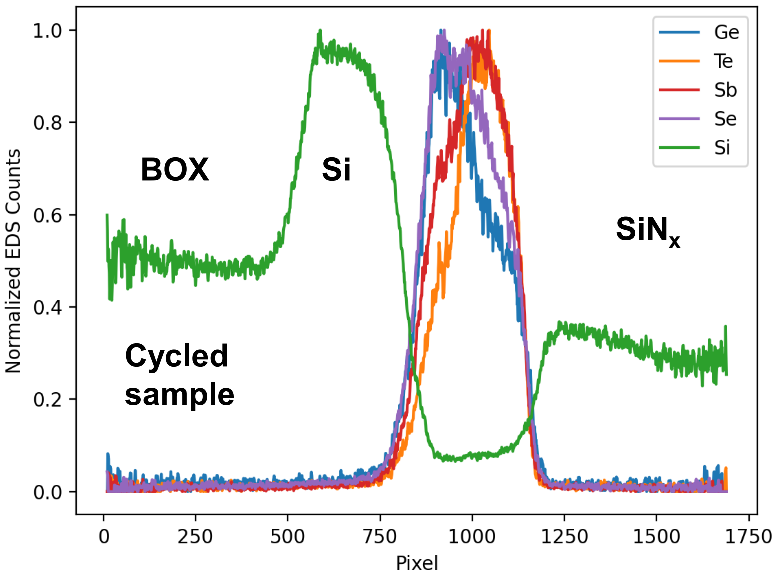
Cycled

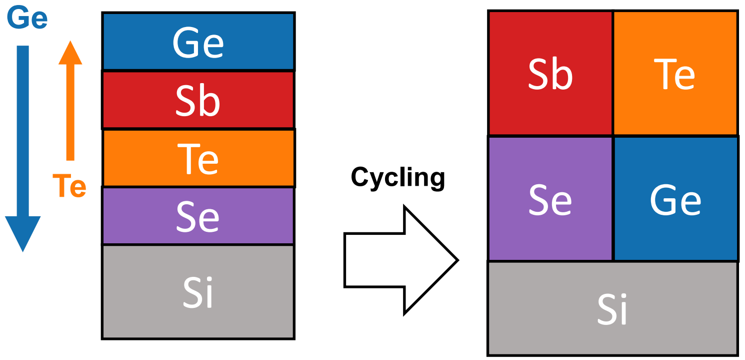
Ge Lα1,2



Te Lα1

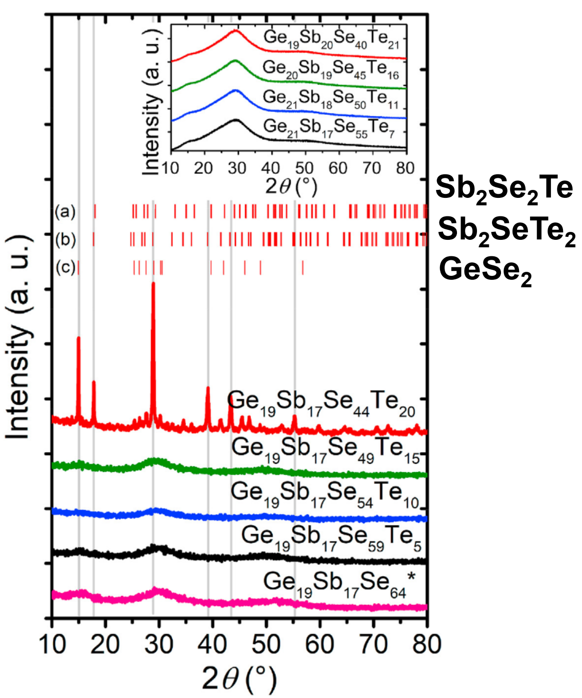






Based on the vapor pressure of the elements.

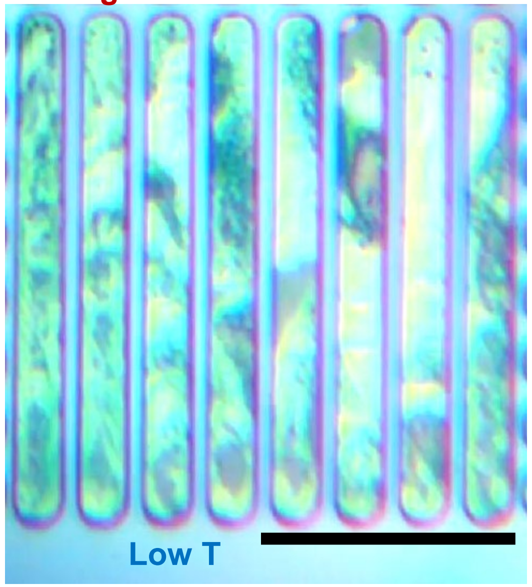
Melt-quench bulk sputter targets



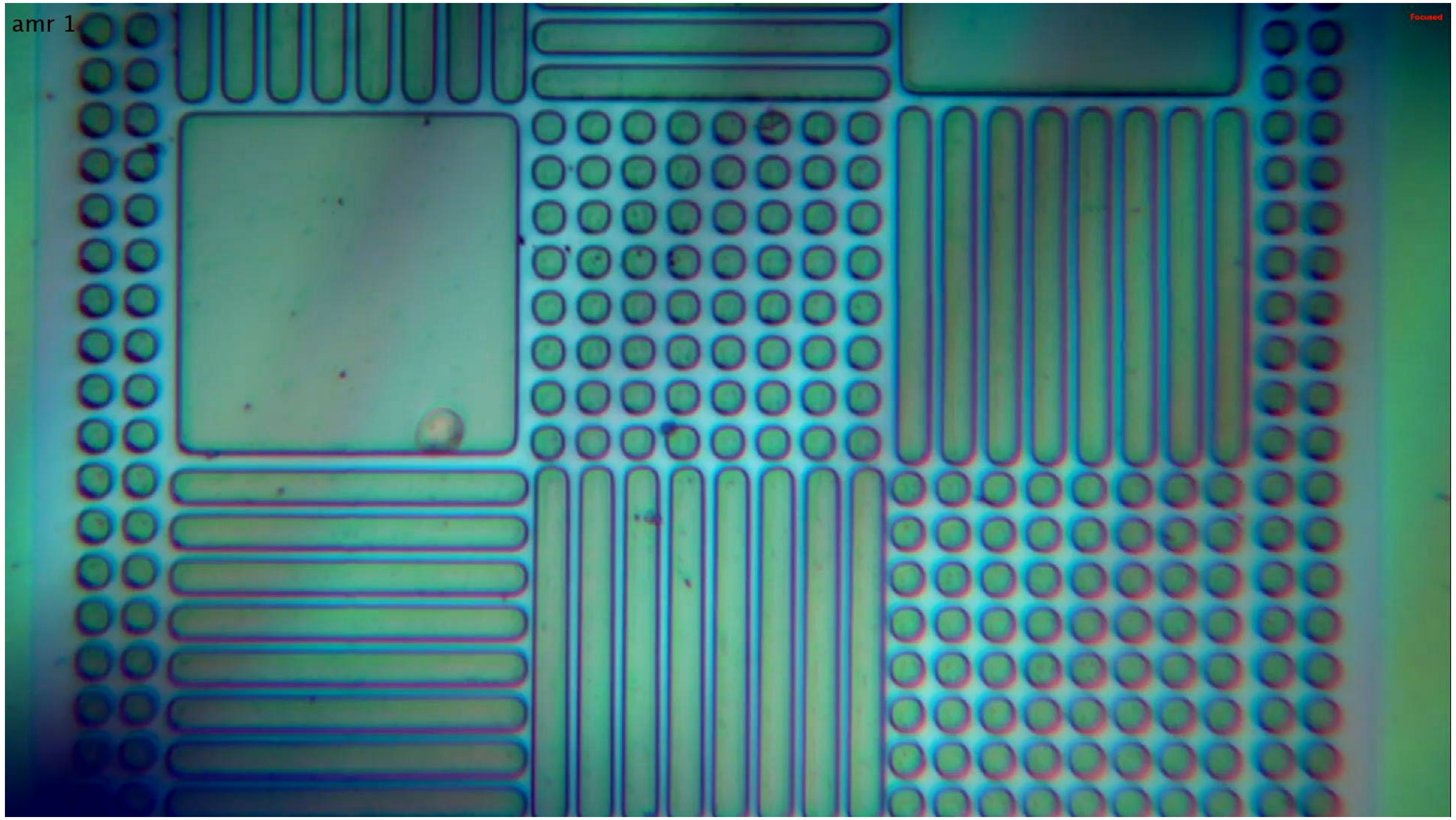
J Materiomics. **8**. 5 (2022)

Potential solution:
Repeated amorphization may remove elemental segregation
Downside: Thermal stresses

Mitigating elemental migration

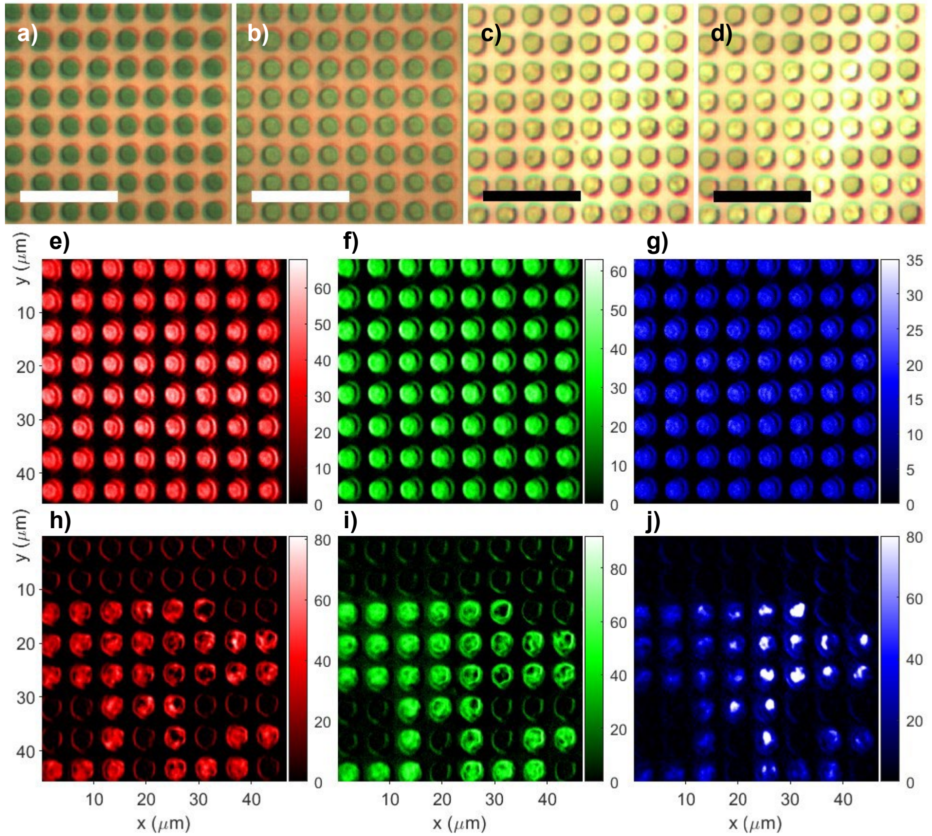


Over-amorphization

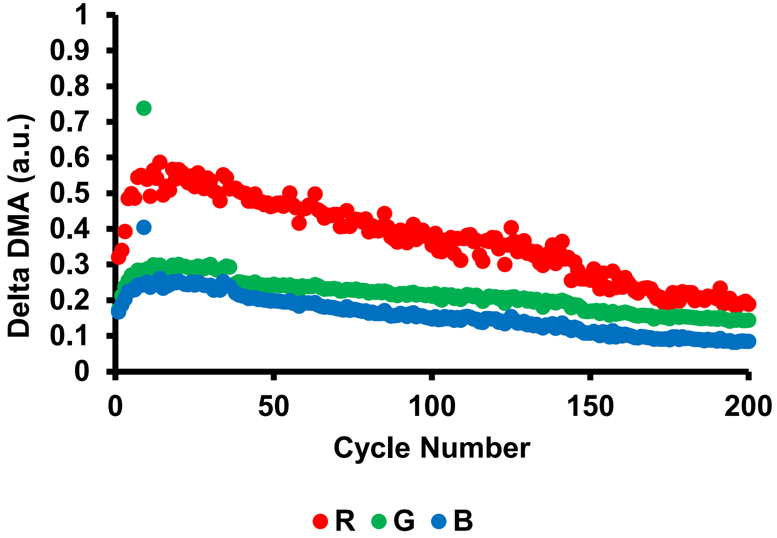


Semi-quantitative analysis for free-space devices

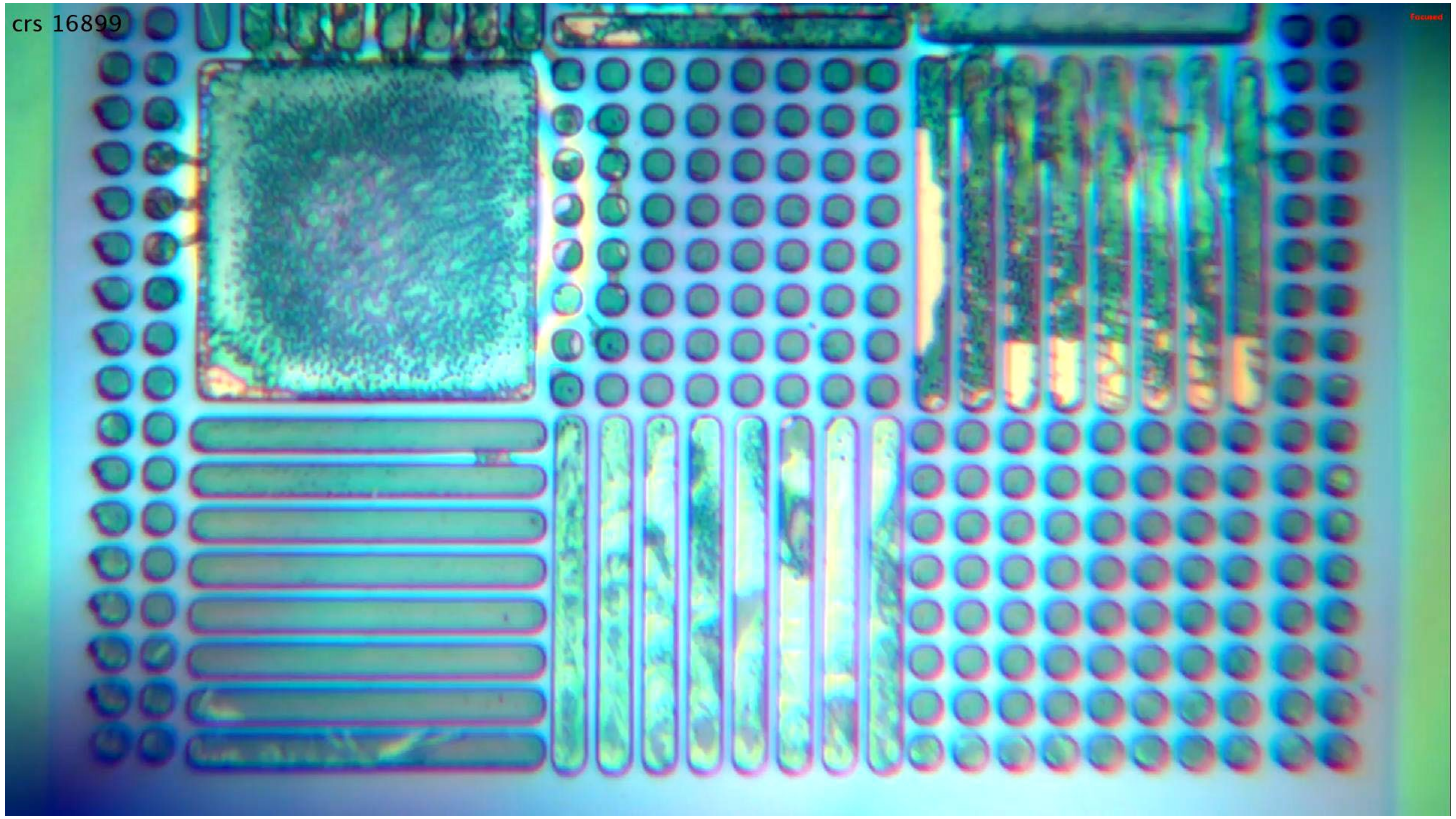
- **Image collection**
    - Amorphous (State 1)
    - Crystalline (State 2)
- **Difference between pixel values**
- **Filter pixels with value above threshold – binary mask**
    - Heuristic approach for threshold selection
- **Average values in filtered (PCM/Switching) region**
- **Normalize by average outside filtered region (Background)**
    - Brightness instability
- **Difference of ratios**
    - Proxy for contrast over time

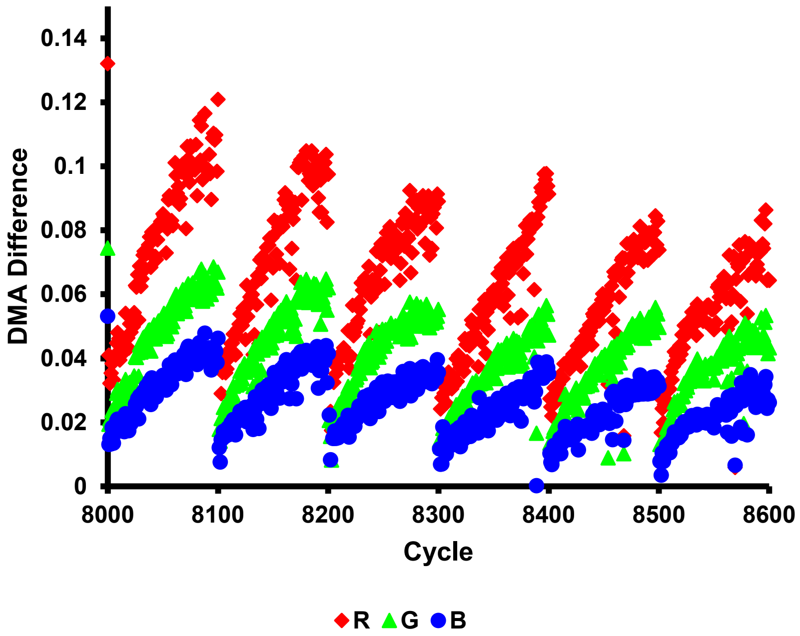


$$\Delta = \left[\frac{\overline{RGB_{PCM}}}{\overline{RGB_{Bckg}}}\right]_{Cr} - \left[\frac{\overline{RGB_{PCM}}}{\overline{RGB_{Bckg}}}\right]_{Am}$$



Repeated longer amorphization pulse (every 100 cycles)

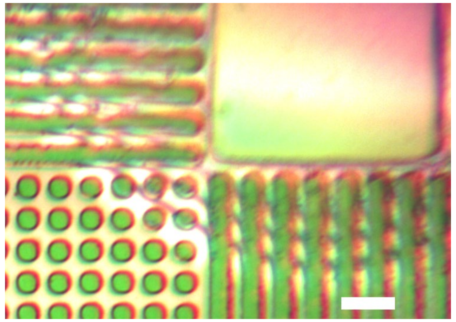




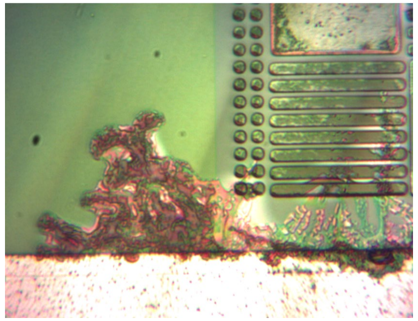
Typical operation below full amorphization

Attempting to remove elemental migration results in losing crystallites that aided in switching, reinitializing the material

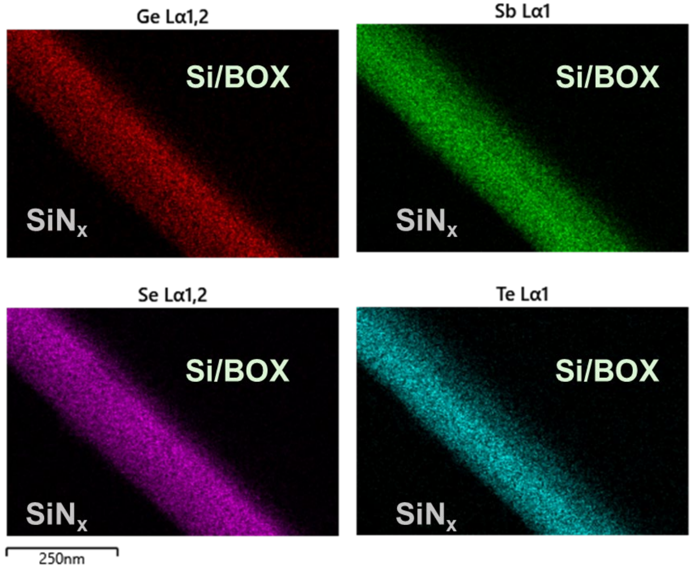
Failure mechanisms in optical PCMs



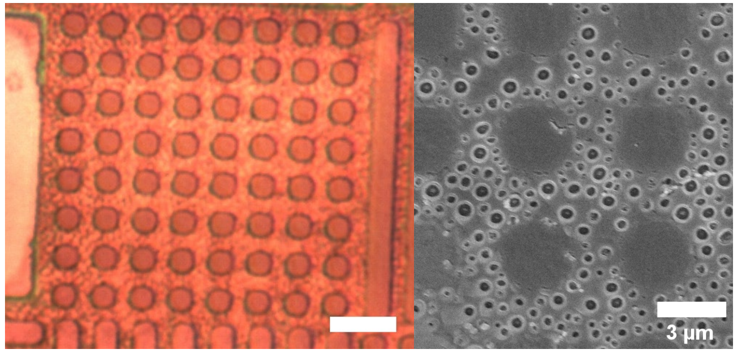
Capping layer delamination



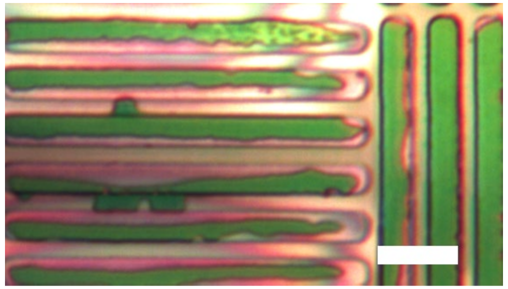
Metal contact electromigration



Thermo-diffusion



H-release from capping layer



Dewetting & fluid instability

Conclusion and Outlook

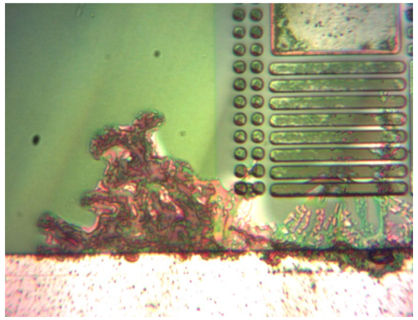
- Cycling guidelines for testing and operation
  - Continuous vs intermittent cycling
  - Heater optimization or limiting PCM operational area
  - Heat sink optimization or cool down time – limit to functionality
  - Testing of extent of amorphization and crystallization – operation in intermediate regions

- Extending life-time
  - Adhesion layers or good wettability between substrate-PCM and PCM-protective layer
  - Reducing stress in protective layers/claddings
  - PCM geometry that does not favor delamination and dewetting

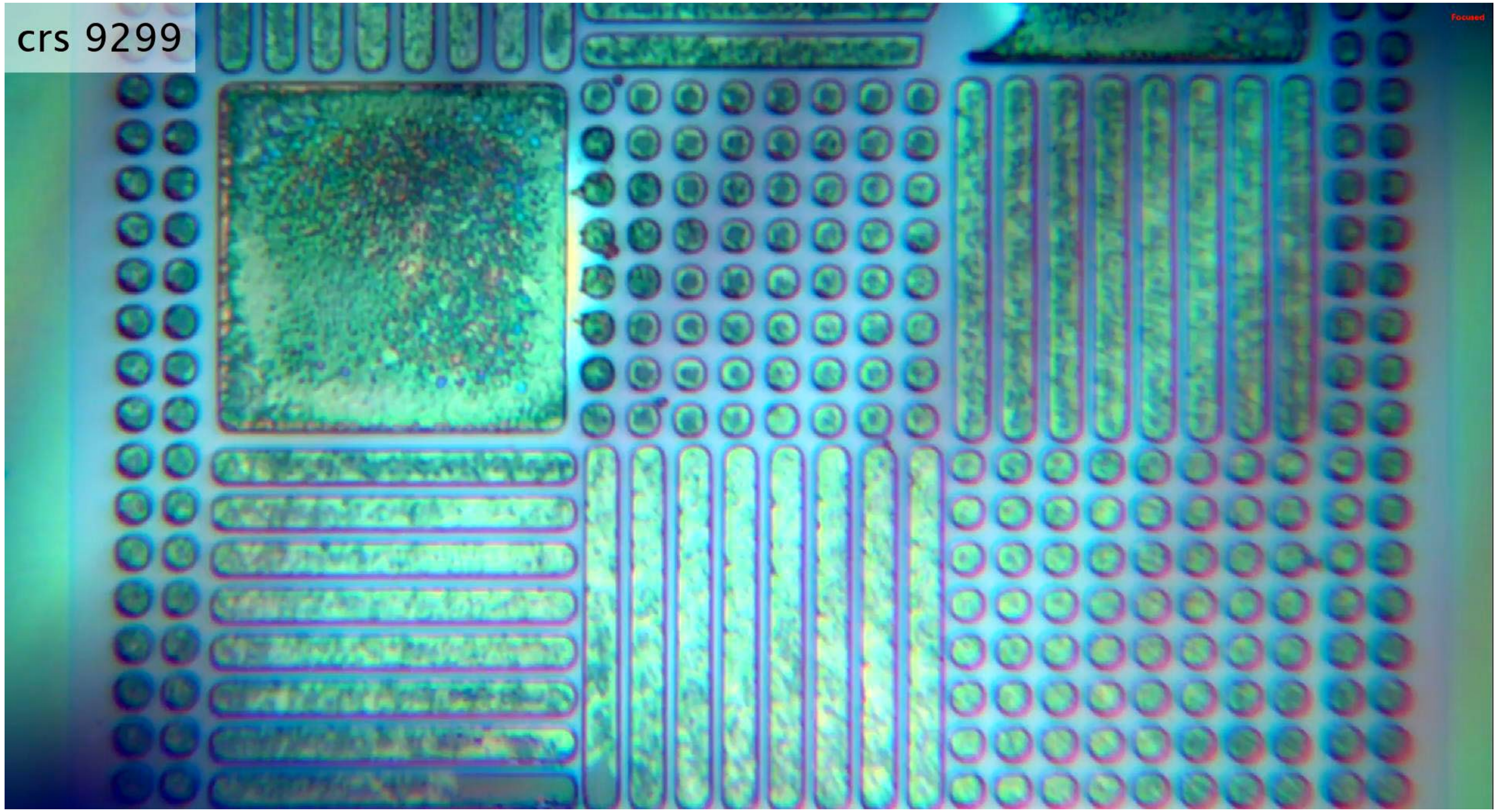
Thank you for your attention!

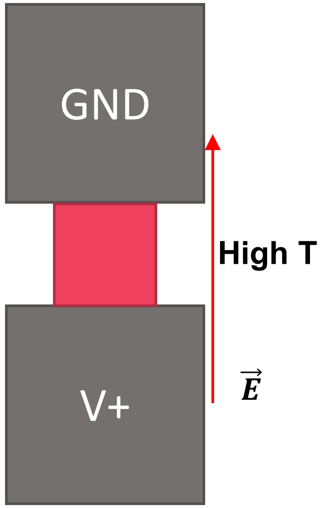
Questions?

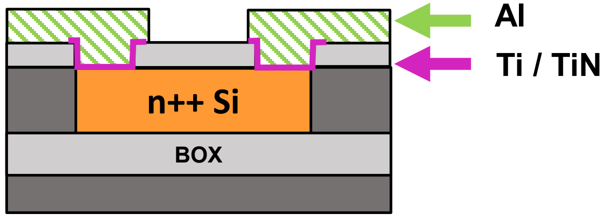
Metal electromigration /Current crowding



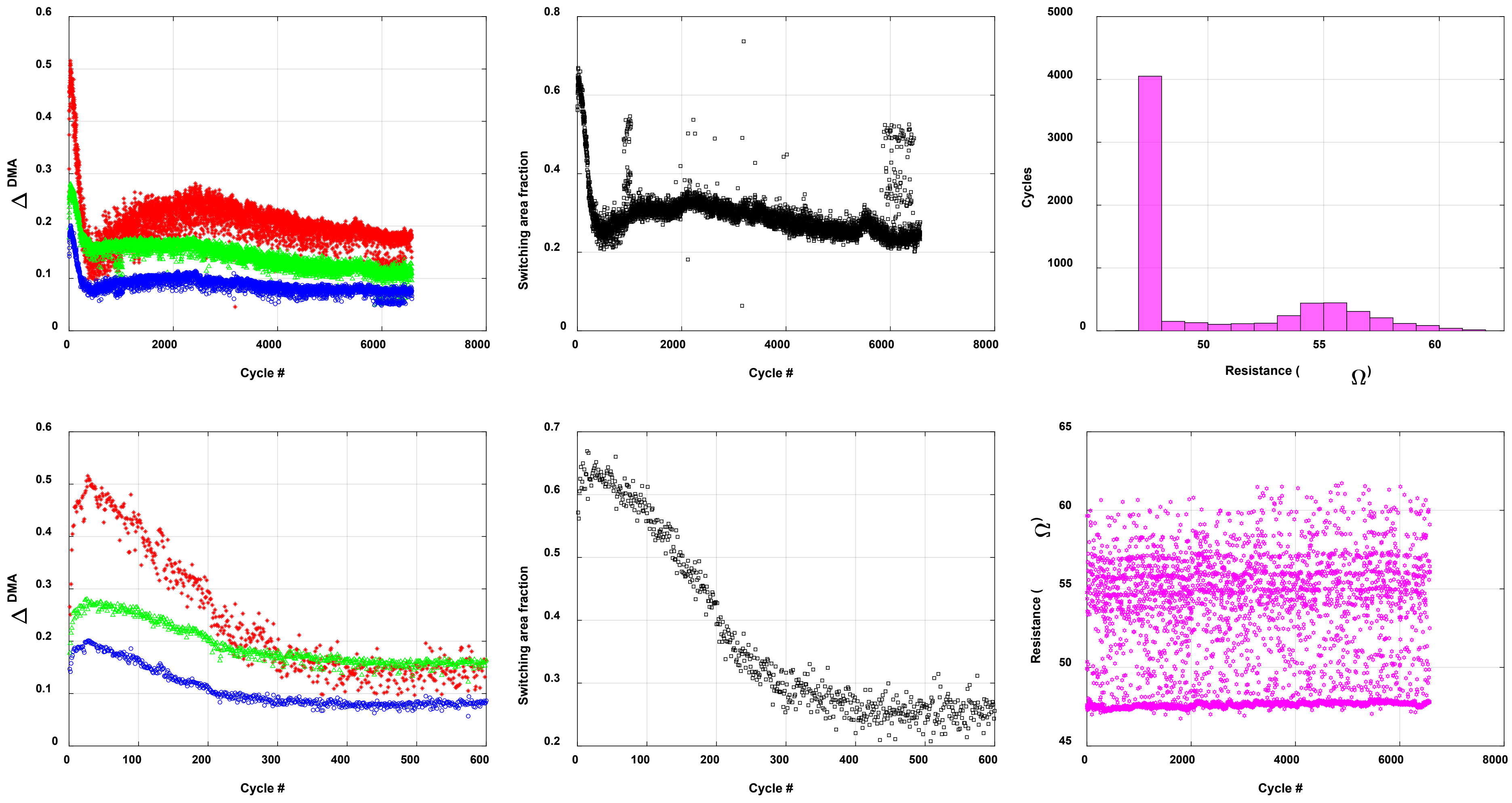
Metal contact electromigration







Endurance test with low/medium amorphization



Parameters:
A 34 V 15 μs
P 8,10,12,14 V, 0.5 s
C 18 V 0.6 s
$\bar{R} = 50\ \Omega$ at 1 V
Cool down wait time avg. 55 s

Hypothesis:

The system will achieve a steady state contrast based on temperatures reached.

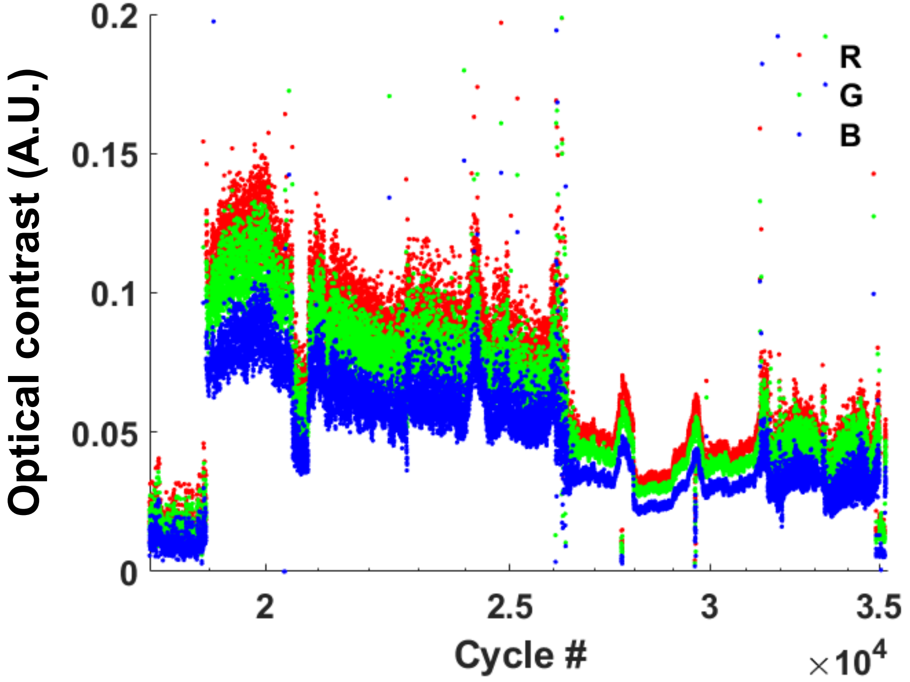
Too high temperatures – stress leads to delamination – loss of device
Too low temperatures – low to no contrast

Underlying mechanism:
Elemental segregation

Endurance improvement in large-volume optical PCM switching

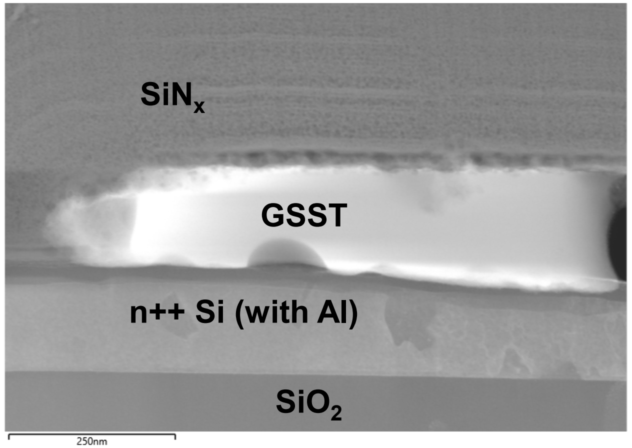
PCM switching volume: ~ 4,000 μm^3

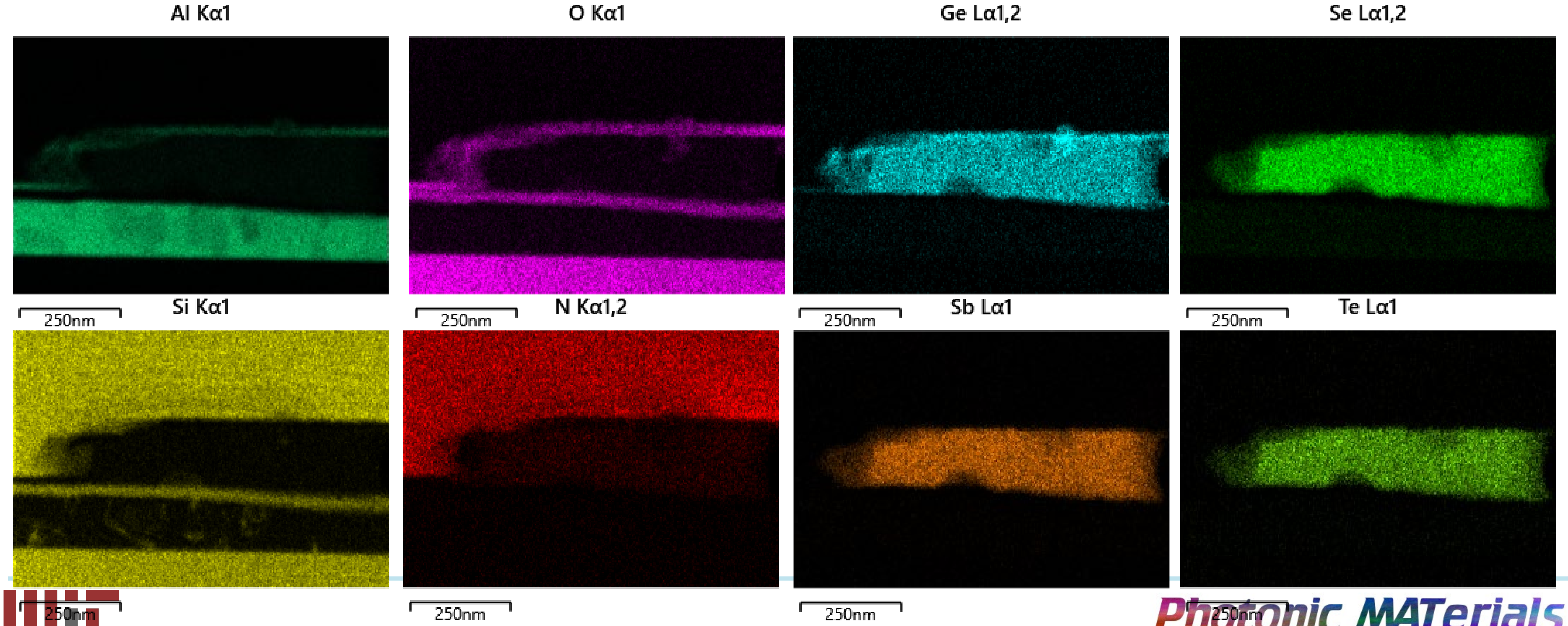
100 million times larger than that in PCMemories!



> 35,000 switching cycles demonstrated

Metal electromigration
Damaged heater





Delamination and preferential adhesion