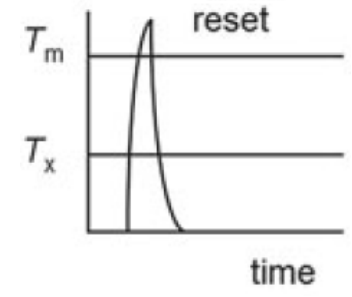
MIT 3.071
Amorphous Materials

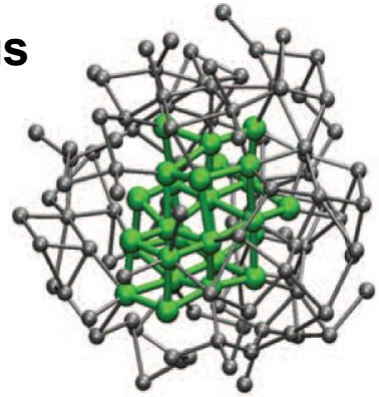
4: Phase Change Data Storage

Juejun (JJ) Hu

Phase change materials

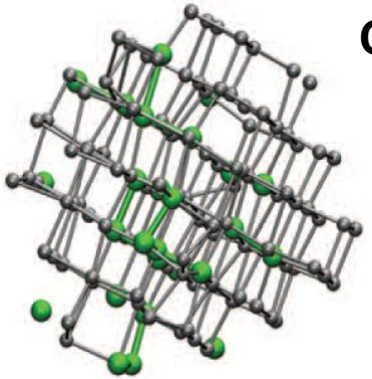


Amorphous

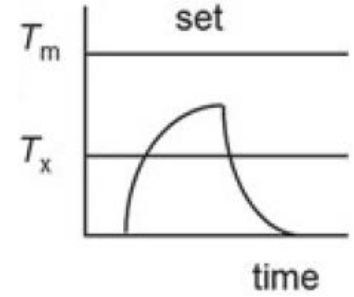


Reset

Set



Crystalline



High electrical resistivity

Low optical reflectance

Low electrical resistivity

High optical reflectance

Key performance metrics

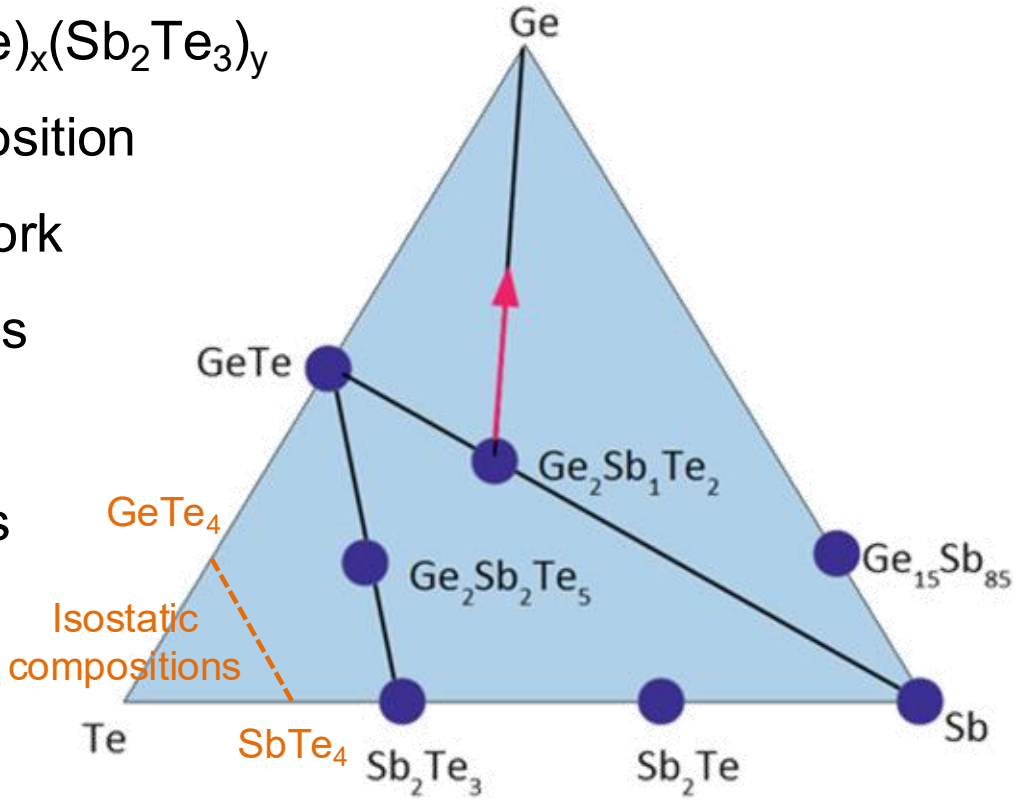
- Data retention
  - Good glass stability
- Programming speed
  - Fast crystallization



- Recording density
  - Size dependence of material properties, driver size
- Endurance (cycle lifetime)
  - Electromigration and phase stability
- Power consumption
  - Enthalpy of melting, heat capacity $Q = \Delta H_m + \int_{RT}^{T_m} C_V dT$
  - Low thermal conductivity

Ge-Sb-Te (GST) phase change alloy

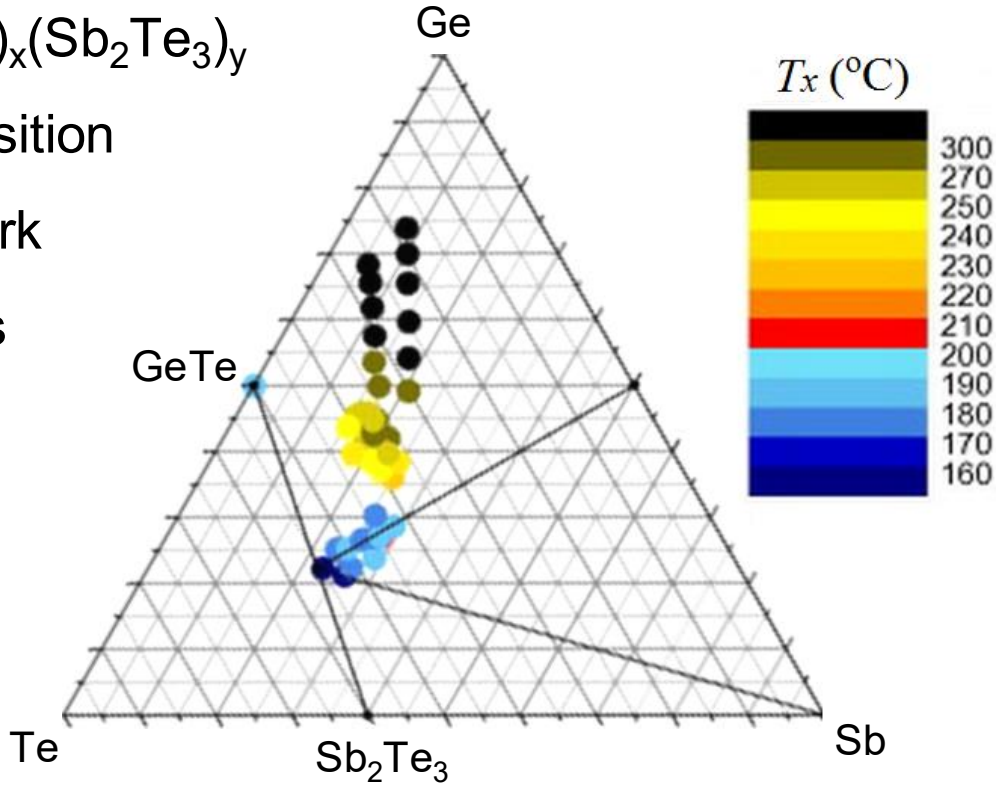
- Pseudo-binary alloy: $(GeTe)_x(Sb_2Te_3)_y$
  - Main commercial composition
  - Stressed rigid 3-D network
- Fast switching compositions
  - $Ge_{15}Sb_{85}$, Sb_2Te
- High thermal stability alloys
  - $(Ge_2Sb_1Te_2)_x(Ge)_y$
- Amorphous: covalent
- Crystal: resonant bonding



Phys. Rev. B **81**, 174206 (2010);
Solid-State Electron. **111**, 27 (2015).

Ge-Sb-Te (GST) phase change alloy

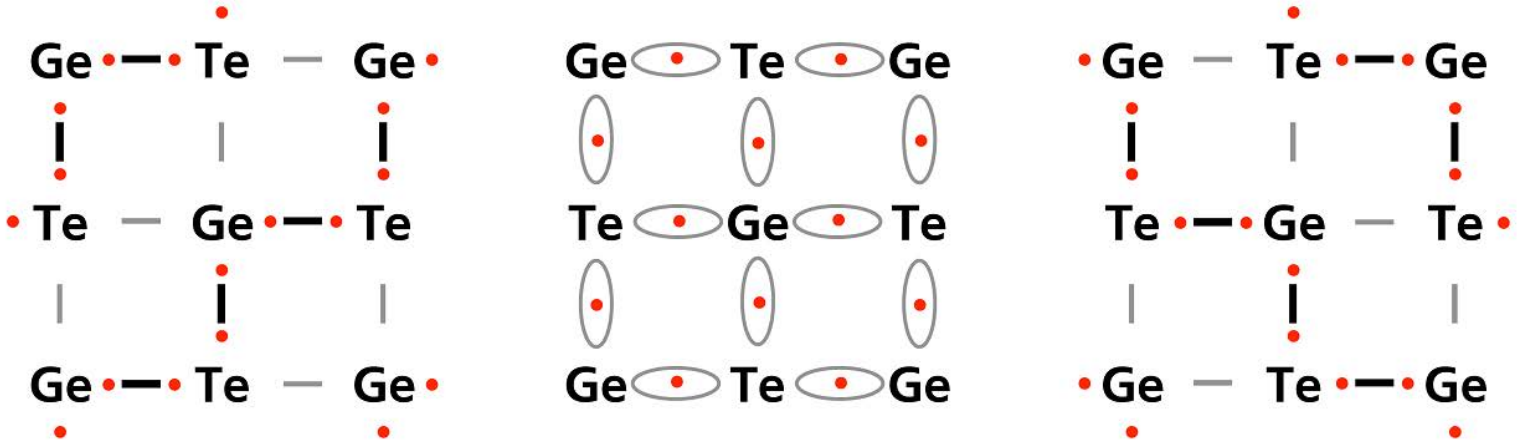
- Pseudo-binary alloy: $(GeTe)_x(Sb_2Te_3)_y$
  - Main commercial composition
  - Stressed rigid 3-D network
- Fast switching compositions
  - $Ge_{15}Sb_{85}$, Sb_2Te
- High thermal stability alloys
  - $(Ge_2Sb_1Te_2)_x(Ge)_y$
- Amorphous: covalent
- Crystal: resonant bonding

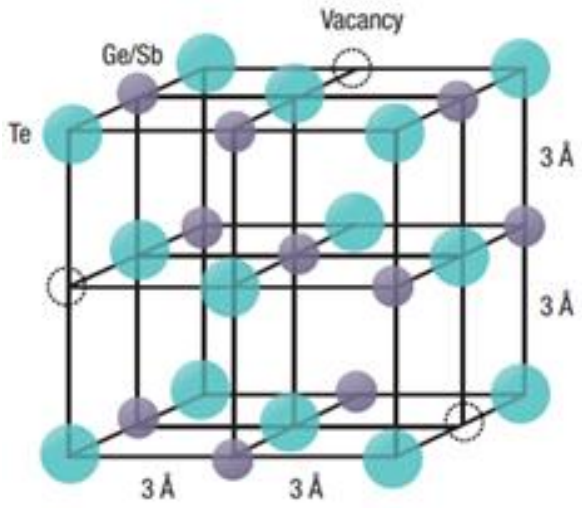


Phys. Rev. B **81**, 174206 (2010);
Solid-State Electron. **111**, 27 (2015).

Fig. 2 in Paola Zuliani, et al, "Engineering of chalcogenide materials for embedded applications of Phase Change Memory," Solid-State Electronics, Volume 111, 2015, Pages 27-.31, https://www.sciencedirect.com. Used with permission

Structure of cubic $Ge_2Sb_2Te_5$ (225) alloy



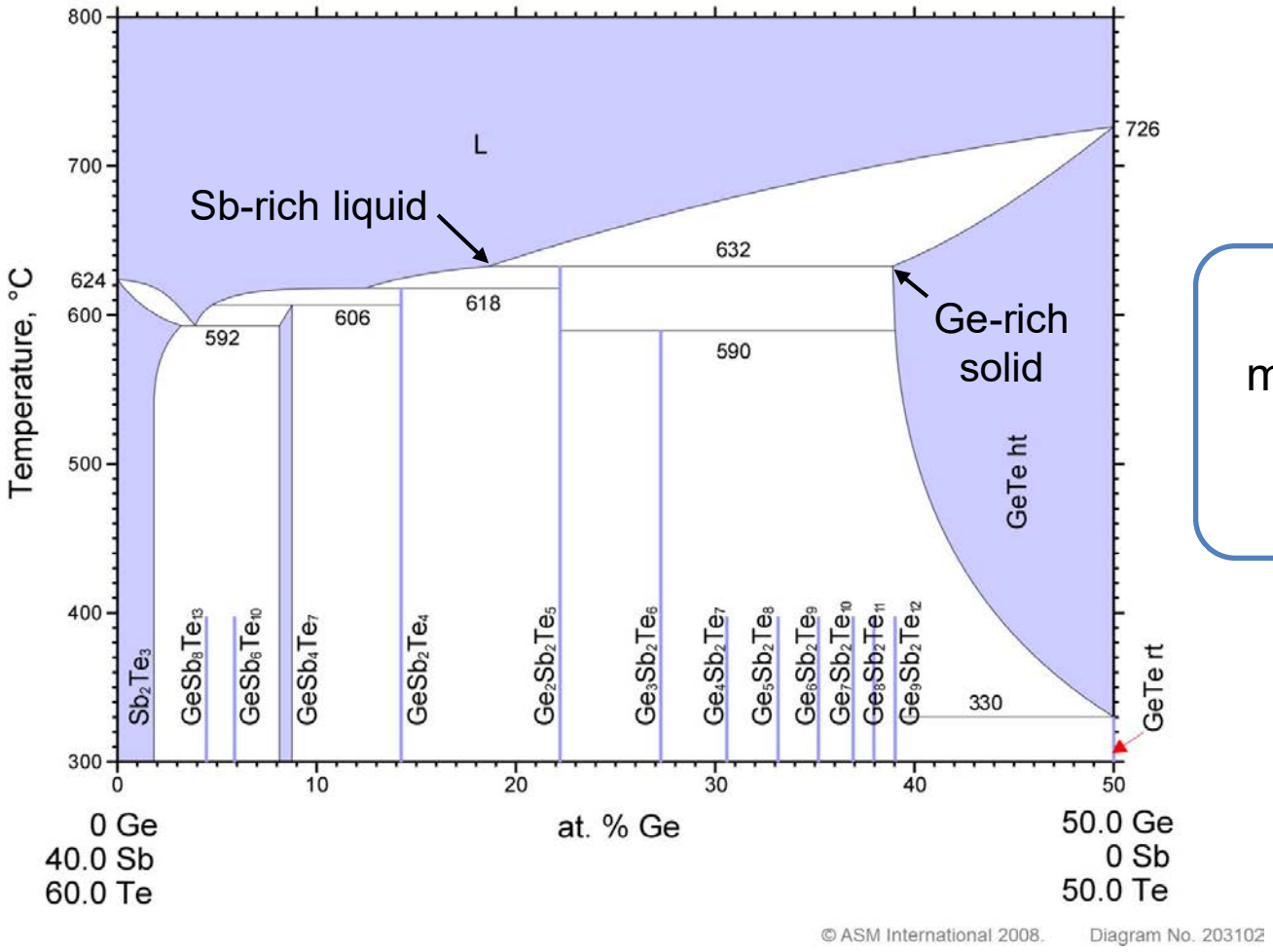


Strong electron delocalization due to resonant (metavalent) bonding

Nat. Mater. **6**, 824-832 (2007)
Adv. Mater. **32**, 1908302 (2020)

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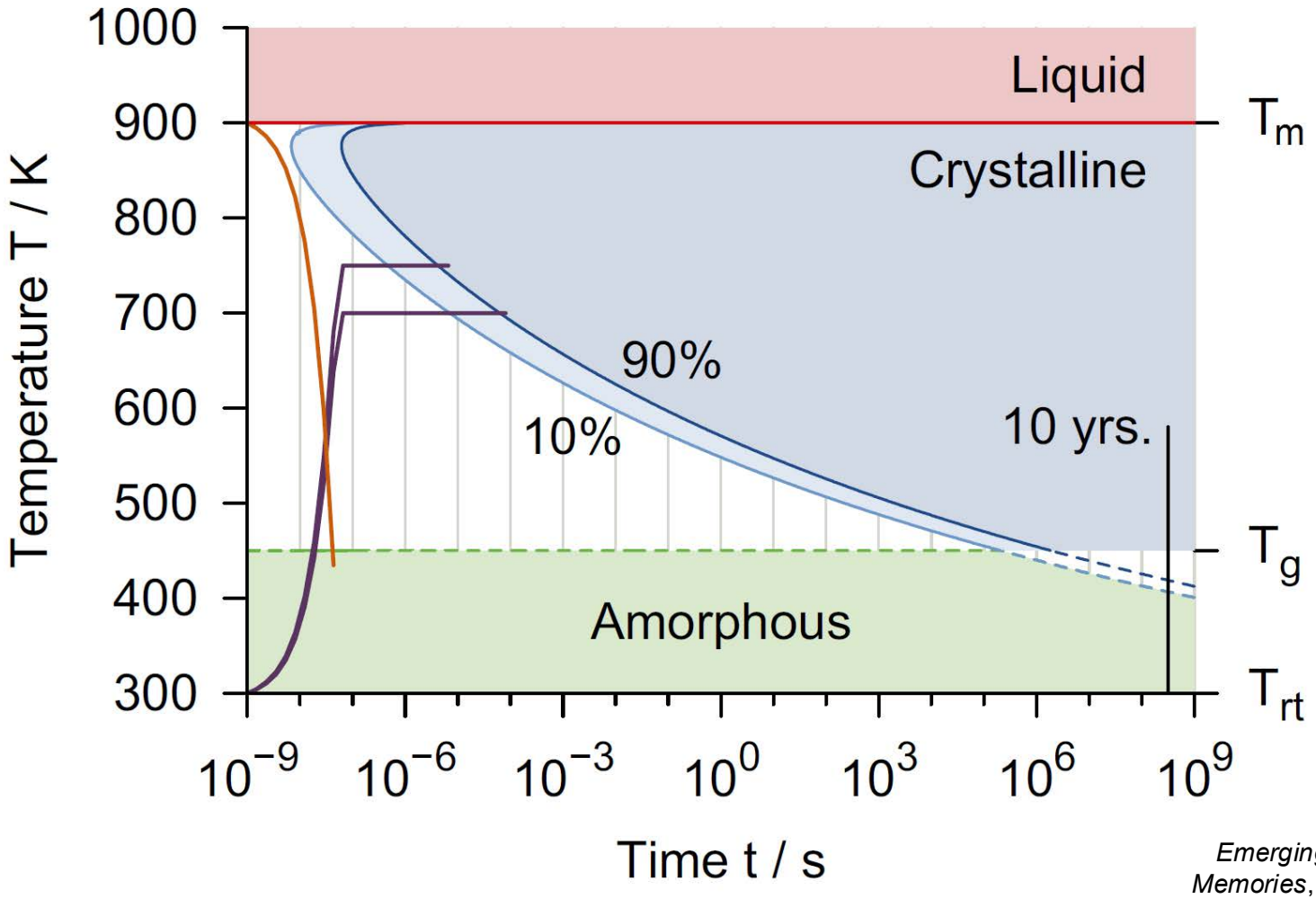
$GeTe$-Sb_2Te_3 pseudobinary phase diagram



Noncongruent melting results in compositional segregation

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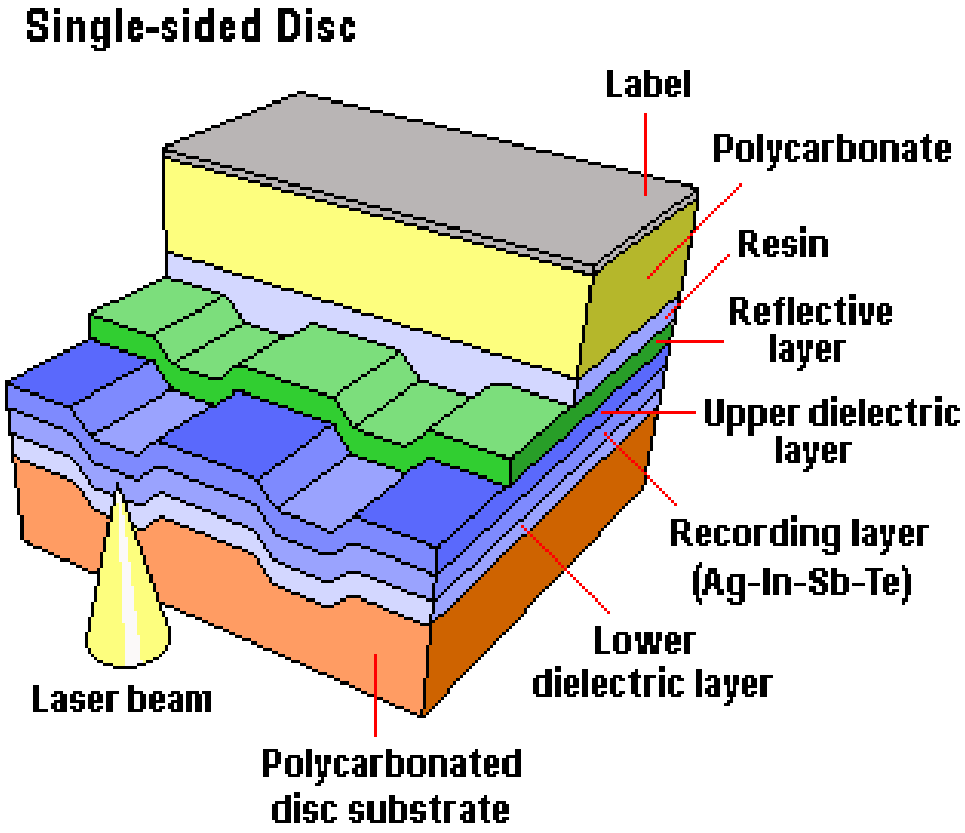
T-T-T diagram of GST phase change alloys



Emerging Non-Volatile Memories, Springer (2014)

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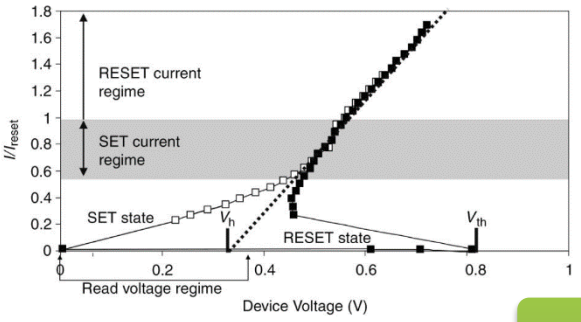
Re-writable CDs and DVDs





Modulation of optical reflectance via laser-induced phase change

Phase change memory (PCM)





Discovery of threshold switching in chalcogenides

1968 Ovshinsky

1970 Gordon Moore

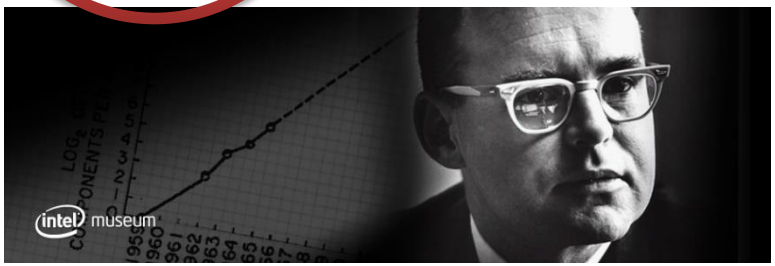
256-bit phase change memory demo

Discovery of rapid switching pseudo-binary GST material

1987 Yamada *et al.*

IBM, Micron, Samsung, …

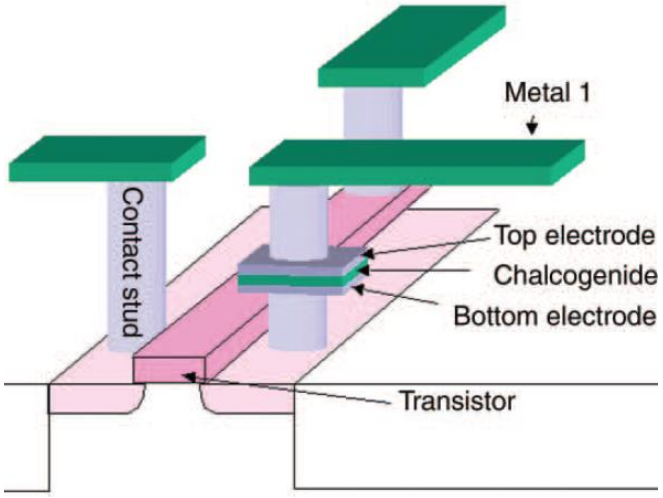
Non-volatile phase change memory module commercialized

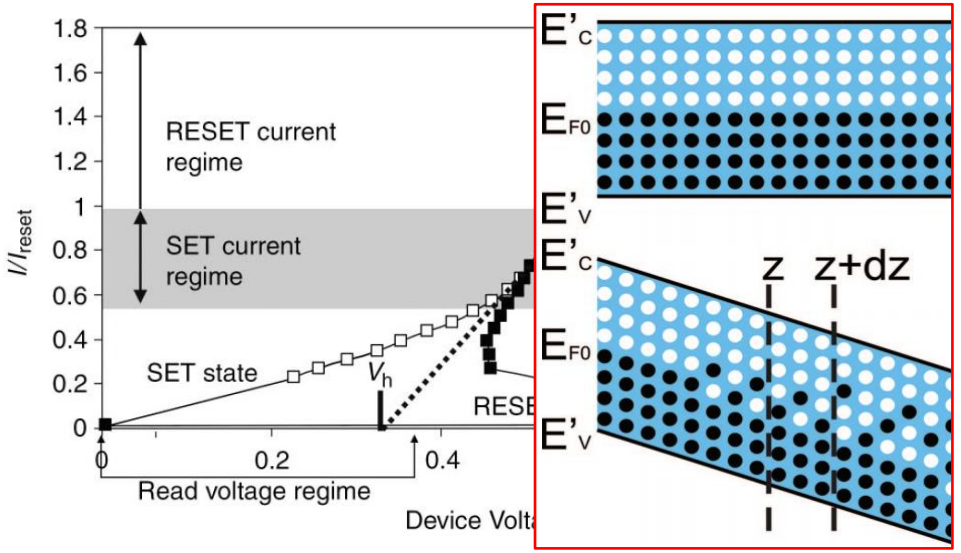


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Phase change memory (PCM)

- Electrodes used for both programming and read-out





- Threshold switching: electric field driven bistability
  - Transient behavior: electronic in nature, no structural change
  - Contributes to reduced SET voltage

S. Hudgens and B. Johnson, *MRS Bull.* (2004); *Phys. Rev. B* **78**, 035308 (2008).

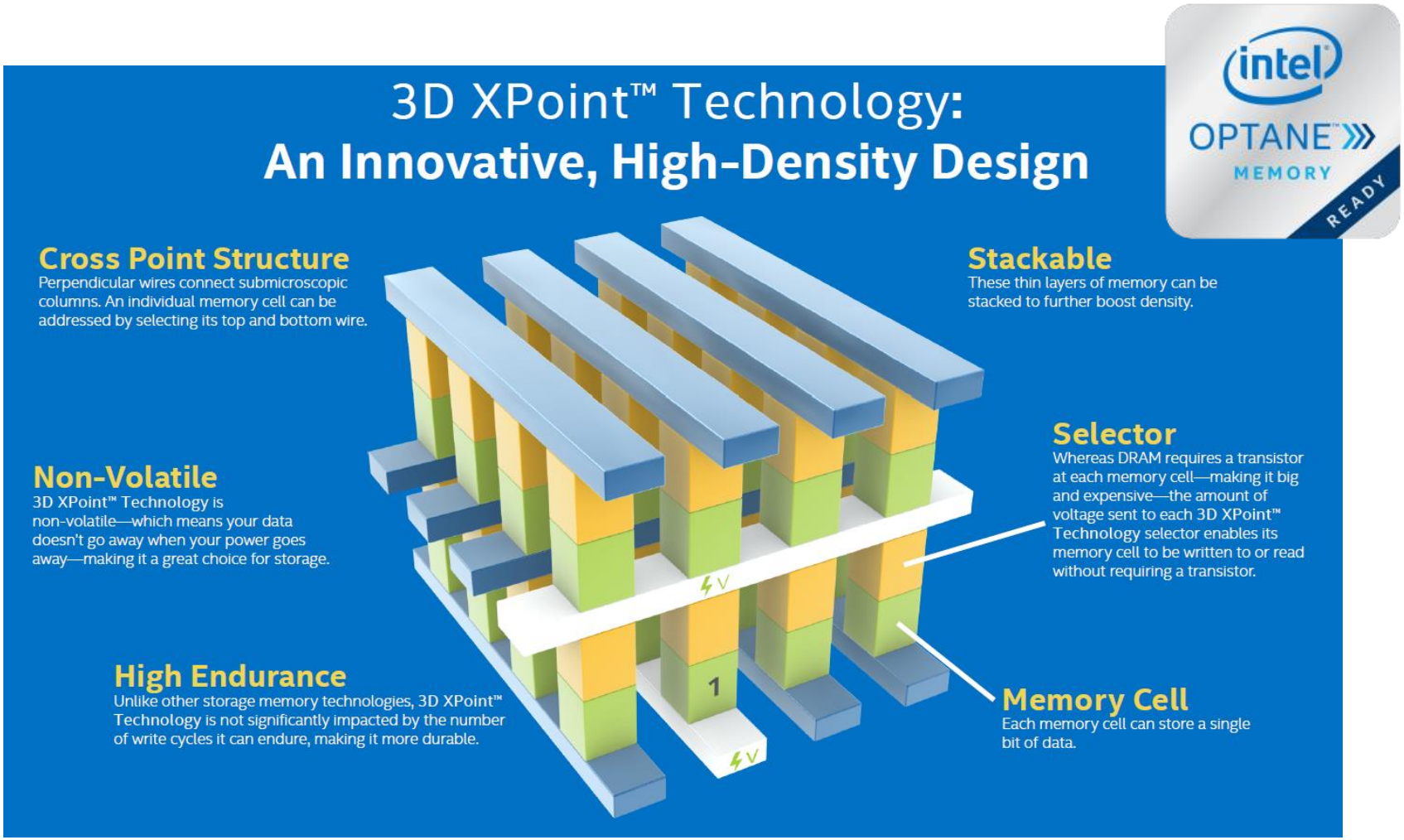
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Where does PCM stand against competitors?

	Memristor	PCM	STT-RAM	DRAM	Flash	HD
Chip area per bit (F^2)	4	8–16	14–64	6–8	4–8	n/a
Energy per bit $(pJ)^2$	0.1–3	2–100	0.1–1	2–4	10^1–10^4	10^6–10^7
Read time (ns)	<10	20–70	10–30	10–50	25,000	5–8x10^6
Write time (ns)	20–30	50–500	13–95	10–50	200,000	5–8x10^6
Retention	>10 years	<10 years	Weeks	<Second	~10 years	~10 years
Endurance (cycles)	~10^{12}	10^7–10^8	10^{15}	>10^{17}	10^3–10^6	10^{15} ?
3D capability	Yes	No	No	No	Yes	n/a

https://news.hpe.com/beyond-dram-and-flash-part-2-new-memory-technology-for-the-data-deluge/

3D XPoint: a likely (?) PCM technology

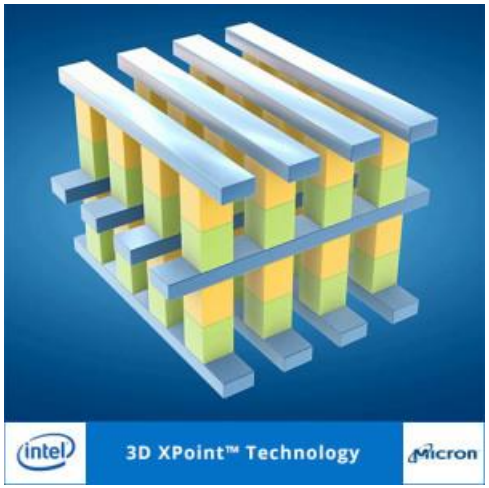


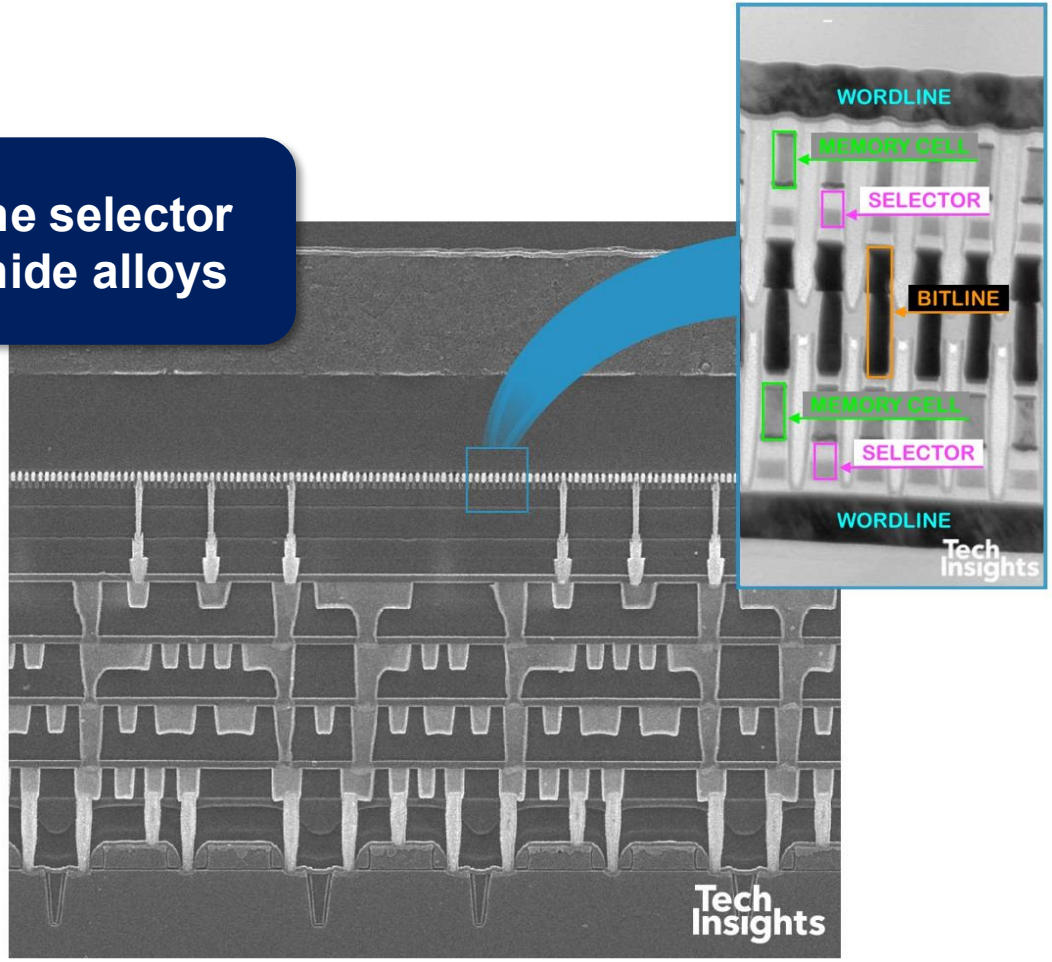
https://www.intel.com/content/www/us/en/architecture-and-technology/optane-technology-animation.html

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Reversing engineering reveals…

Both the memory and the selector are based on chalcogenide alloys





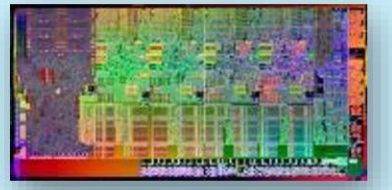
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3D XPOINT™ MEMORY MEDIA

Breaks the memory/storage barrier

MEMORY + **STORAGE**

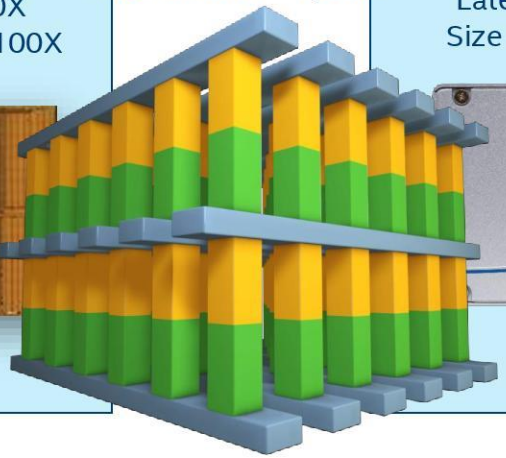
SRAM
Latency: 1X
Size of Data: 1X



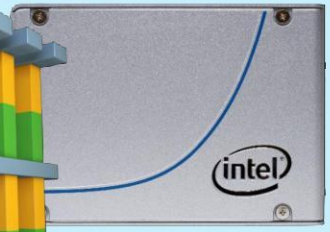
DRAM
Latency: ~10X
Size of Data: ~100X



3D XPoint™
Latency: ~100X
Size of Data: ~1,000X



NAND SSD
Latency: ~100,000X
Size of Data: ~1,000X



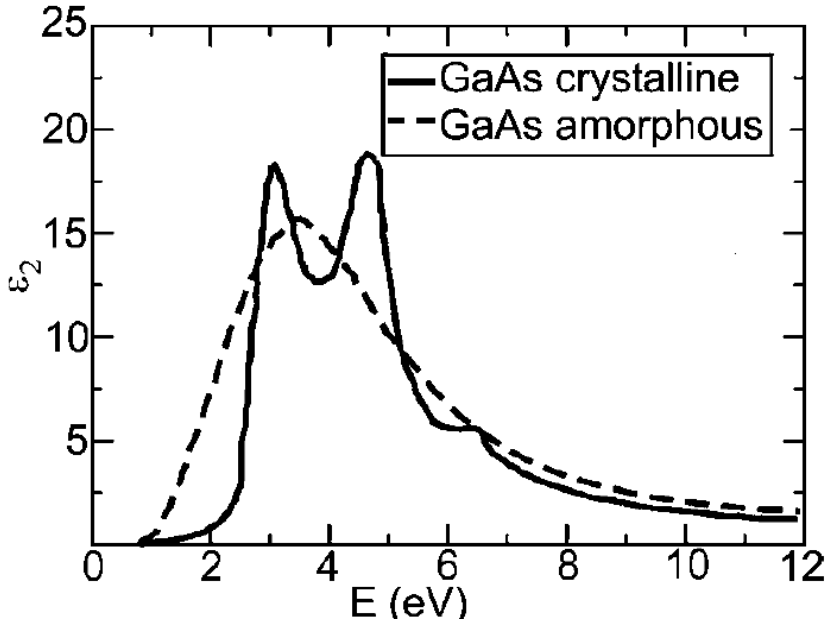
HDD
Latency: ~10 Million X
Size of Data: ~10,000X

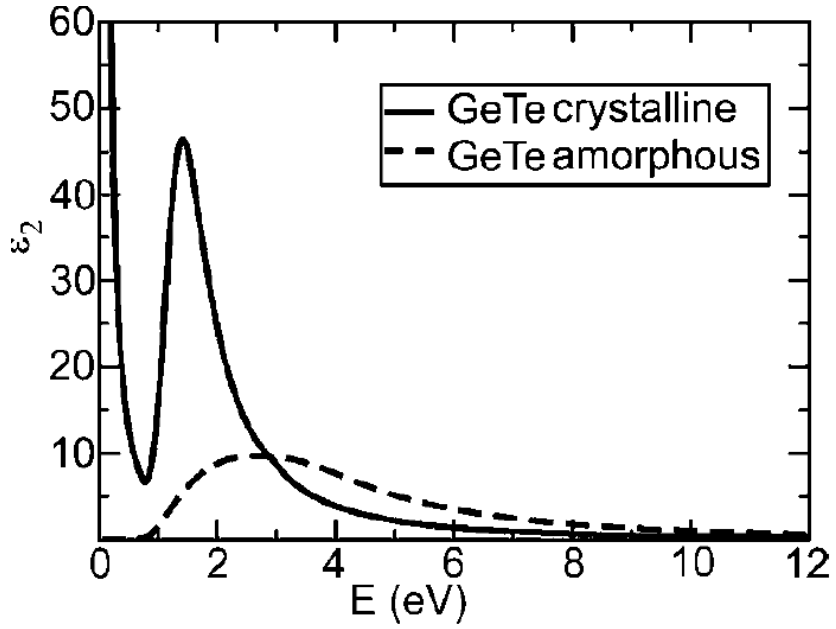


Technology claims are based on comparisons of latency, density and write cycling metrics amongst memory technologies recorded on published specifications of in-market memory products against internal Intel specifications.

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Applications beyond data storage: optics



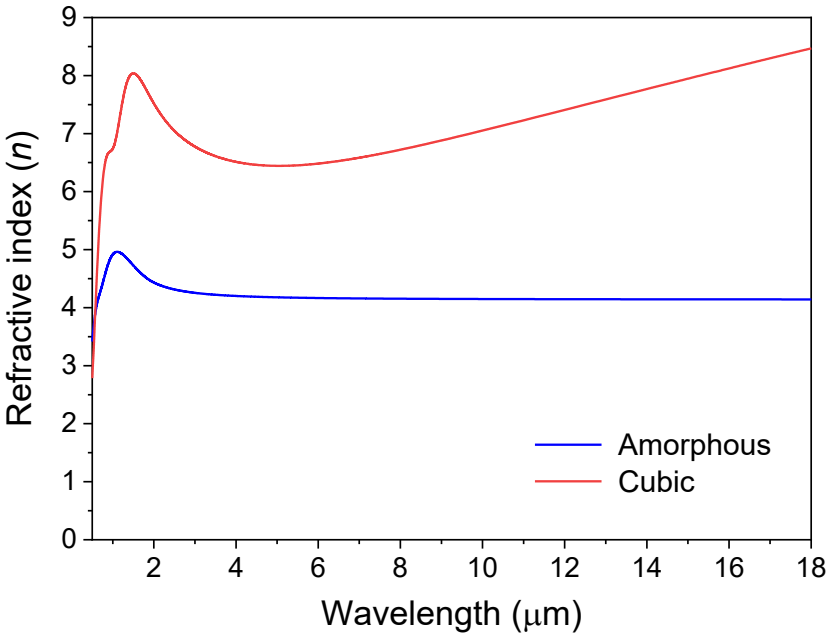


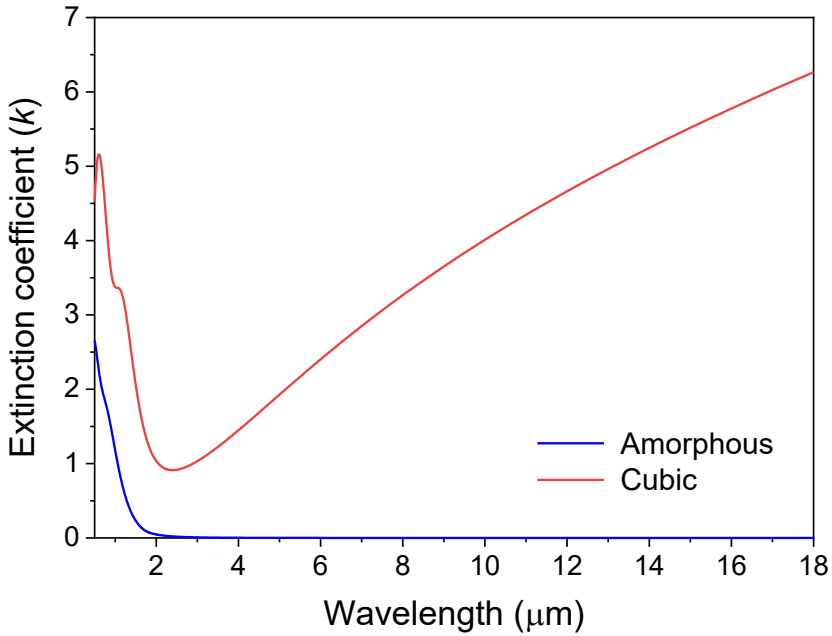
Large optical property contrast in GeTe due to change of bonding type from crystalline (resonance) to amorphous (covalent) phase

Chem. Rev. **110**, 240-267 (2010).

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Optical properties of $Ge_2Sb_2Te_5$ (225) alloy



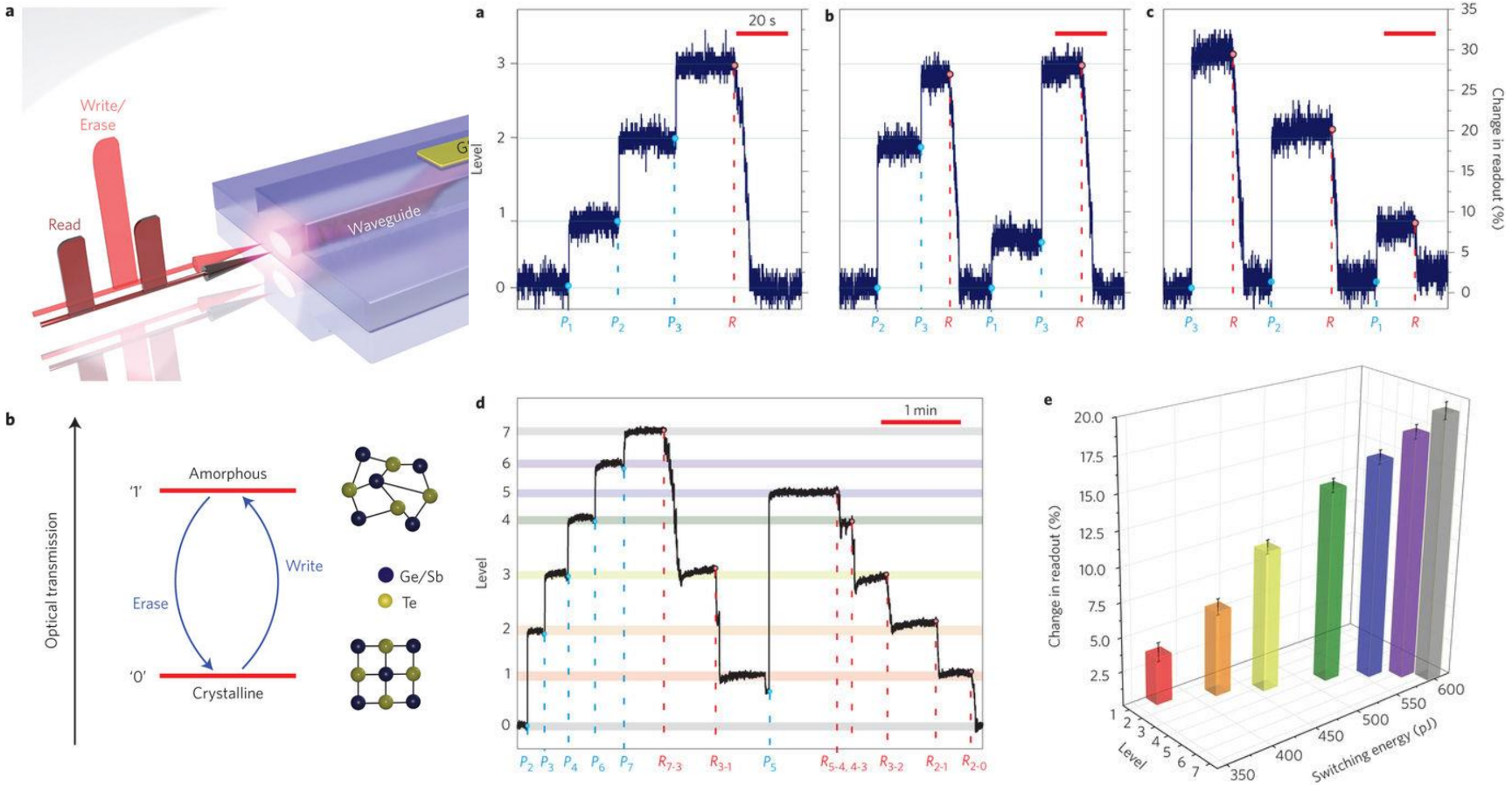


Amorphous state: low-index, reduced loss

Crystalline state: high-index, high loss

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

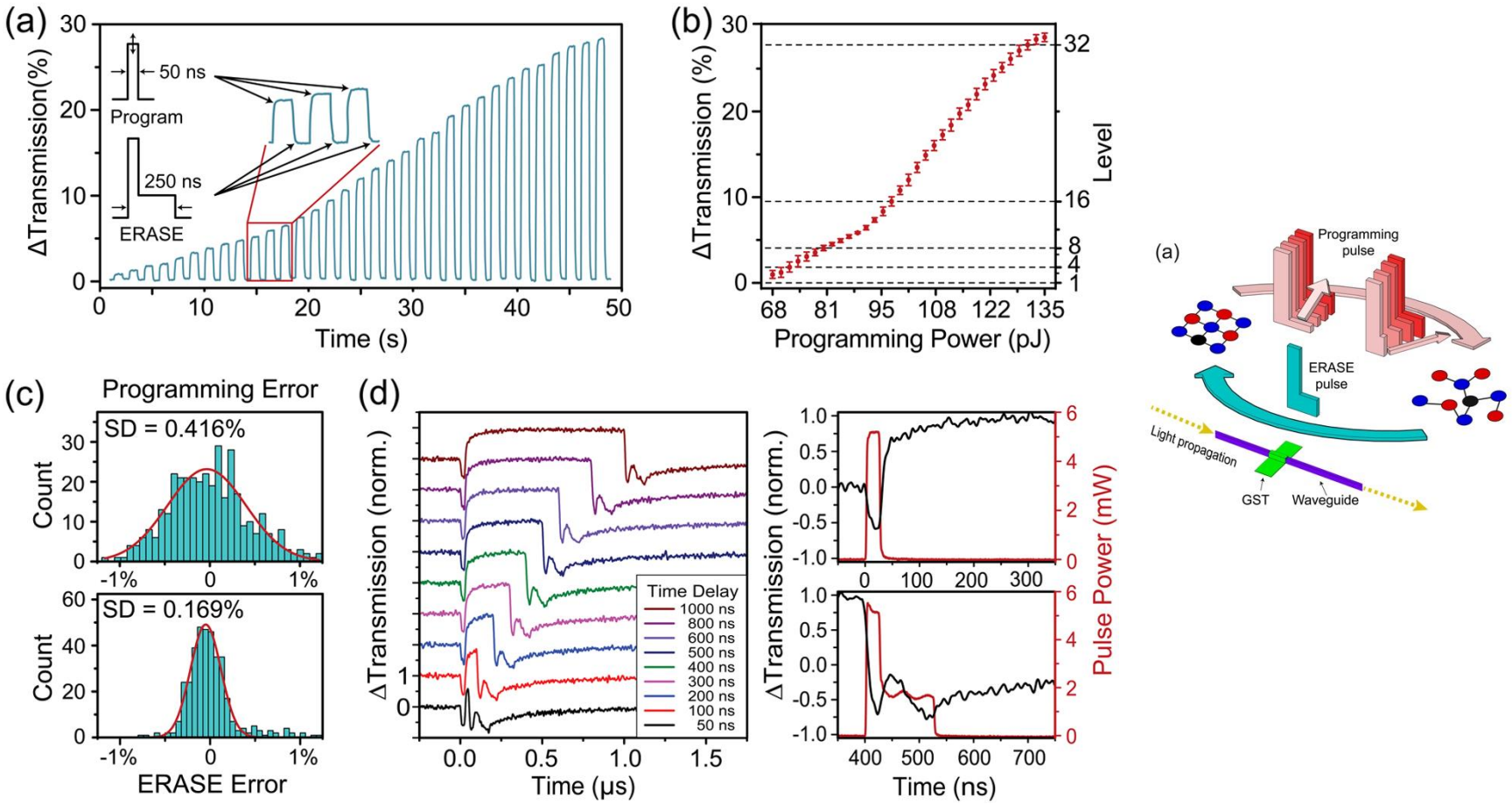
All-optical, multi-level on-chip memory



Nat. Photonics **9**, 725 (2015)

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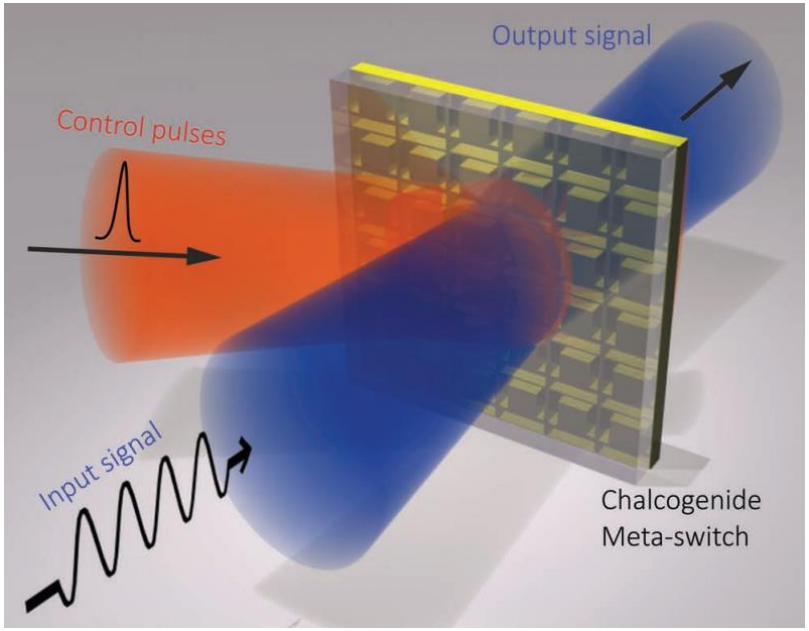
All-optical, multi-level on-chip memory



Optica **6**, 1-6 (2019)

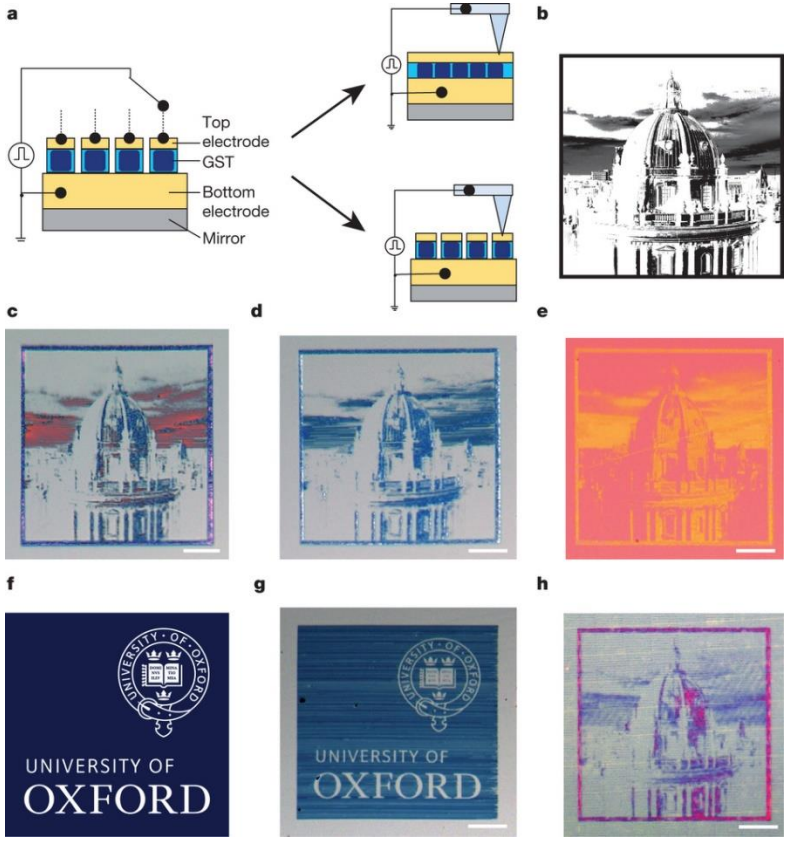
Xuan Li, Nathan Youngblood, Carlos Ríos, Zengguang Cheng, C. David Wright, Wolfram HP Pernice, and Harish Bhaskaran, "Fast and reliable storage using a 5 bit, nonvolatile photonic memory cell," Optica 6, 1-6 (2019). License: CC BY 4.0.

Optical switching and non-volatile display



Optical switch

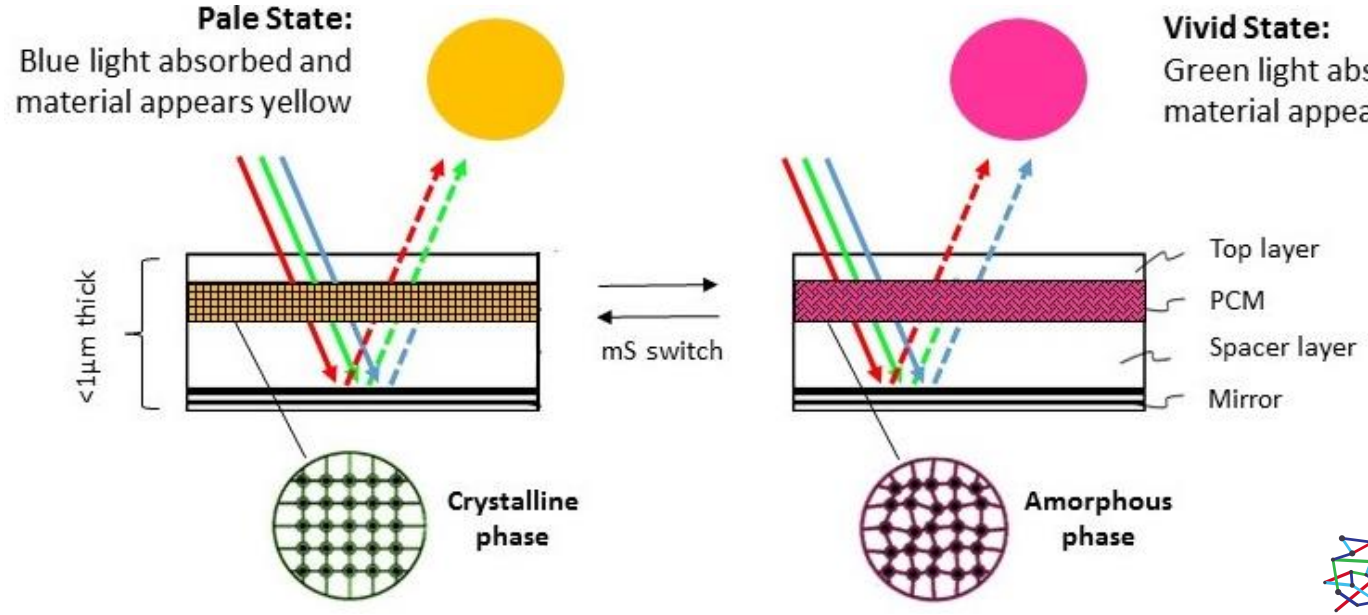
? Applications involving bistable states



Electronic paper display

Nature **511**, 206 (2014); *Adv. Mater.* **25**, 3050 (2013)

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BODLE

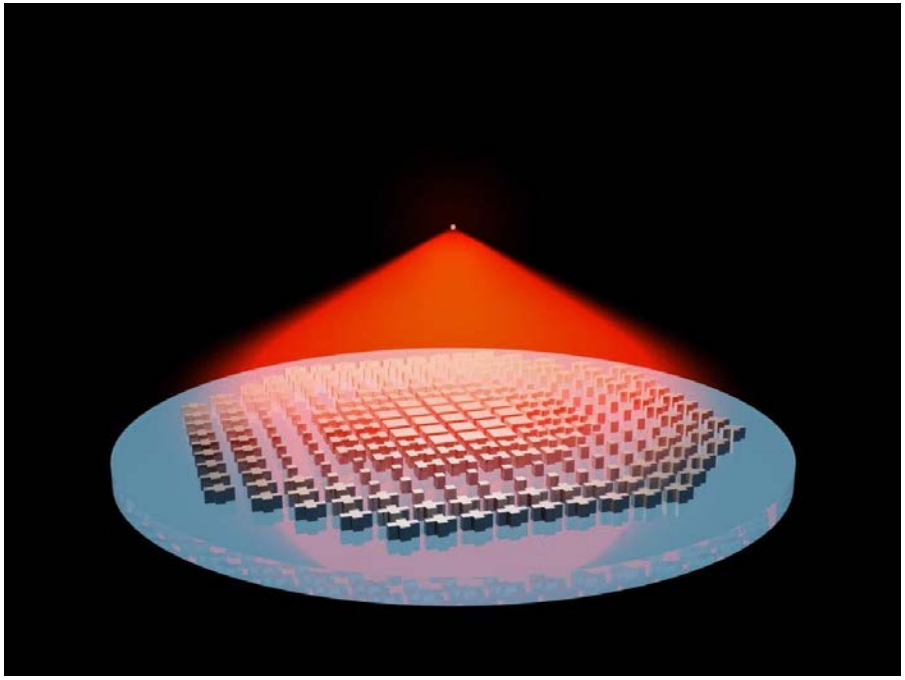


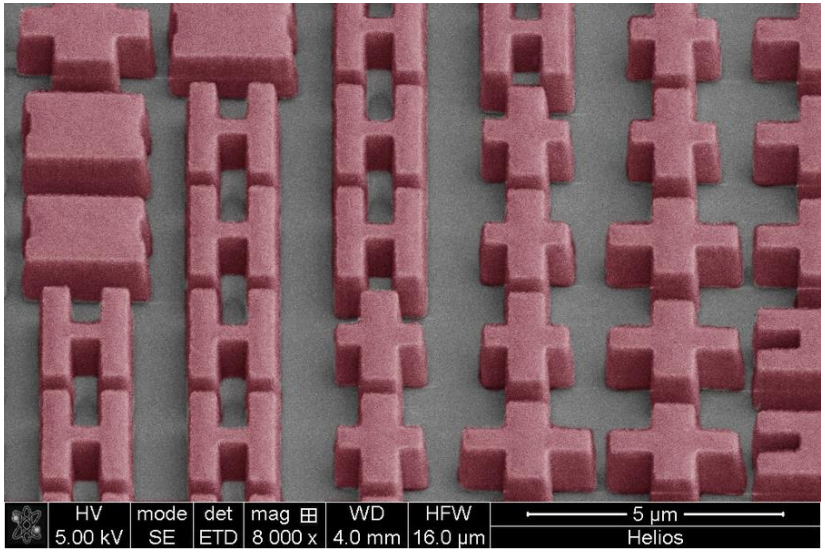
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New "metalens" shifts focus without tilting or moving

The design may enable miniature zoom lenses for drones, cellphones, or night-vision goggles.

Jennifer Chu | MIT News Office
February 22, 2021





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

Fig. 1 in Shalaginov, M.Y., An, S., Zhang, Y. et al. Reconfigurable all-dielectric metalens with diffraction-limited performance. Nat Commun 12, 1225 (2021). License: CC BY.

Further readings

- *Phase Change Materials: Science and Application*, Springer (2009)
  - Google book link
- *Emerging Non-Volatile Memories*, Springer (2014)
  - Download link (MIT certificate required)
- "Phase change materials and phase change memory," *MRS Bull.* **39**, 703 (2014)
- "Designing crystallization in phase-change materials for universal memory and neuro-inspired computing," *Nat. Rev. Mater.* **4**, 150-168 (2019)

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3.071 Amorphous Materials
Spring 2025

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