Phase change memory as a next-generation memory for storage-class memory and neuromorphic computing

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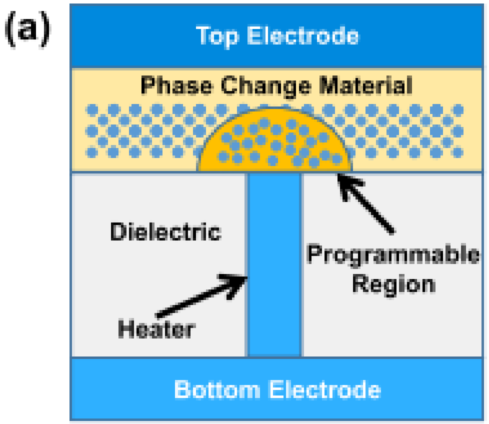
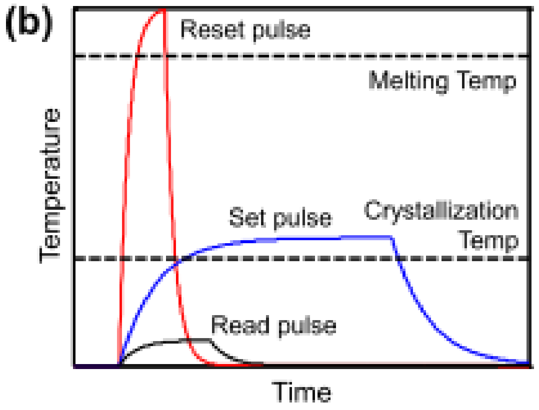
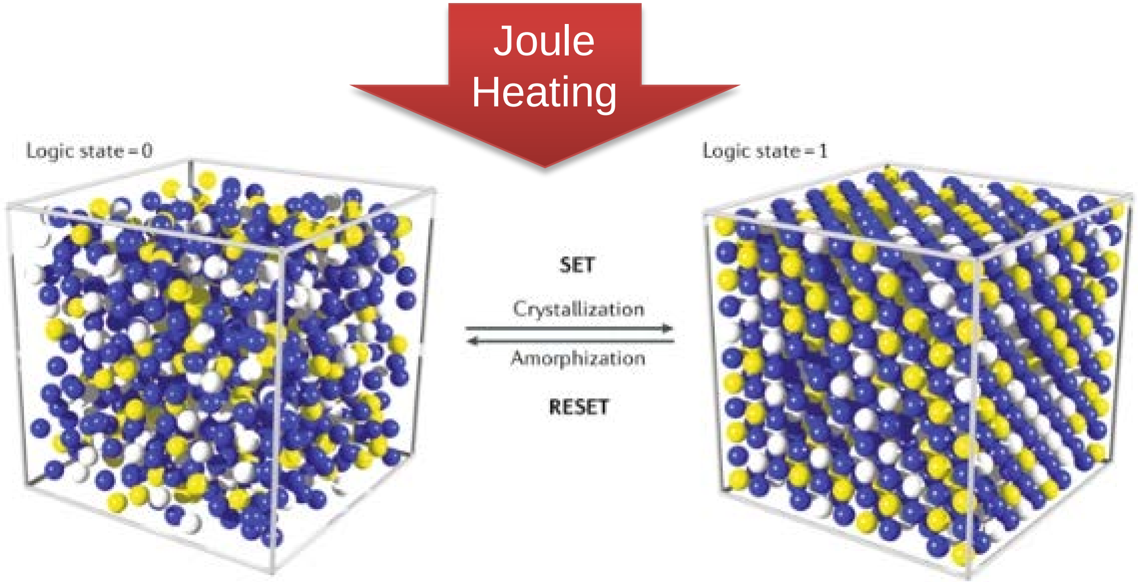
Phase Change Memory (PCM)

Cross-section view



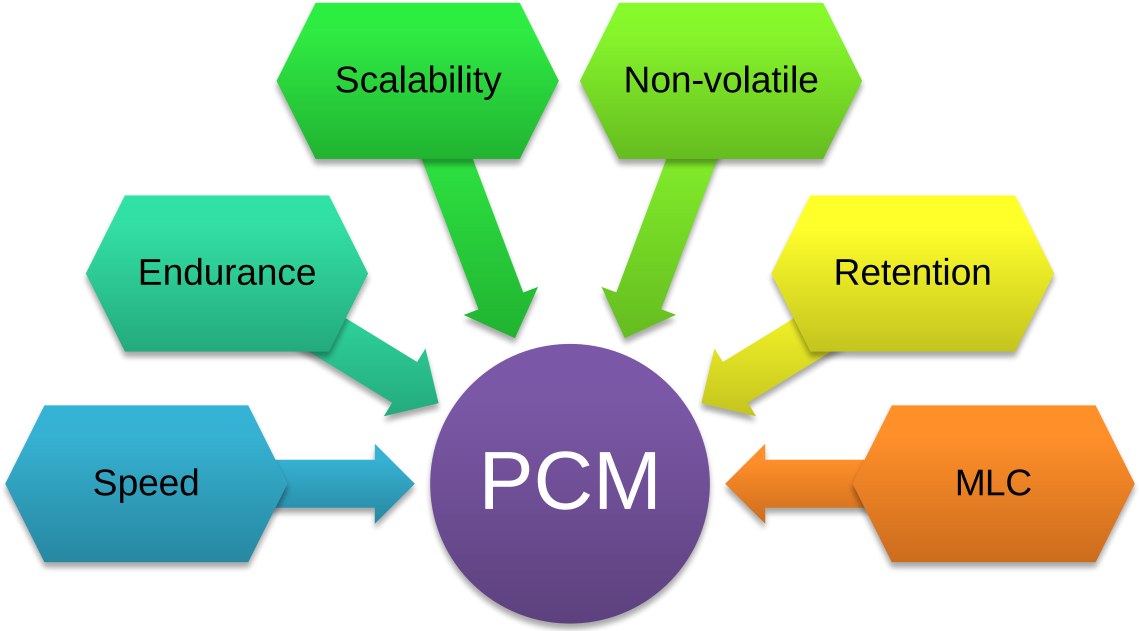
Electric pulse



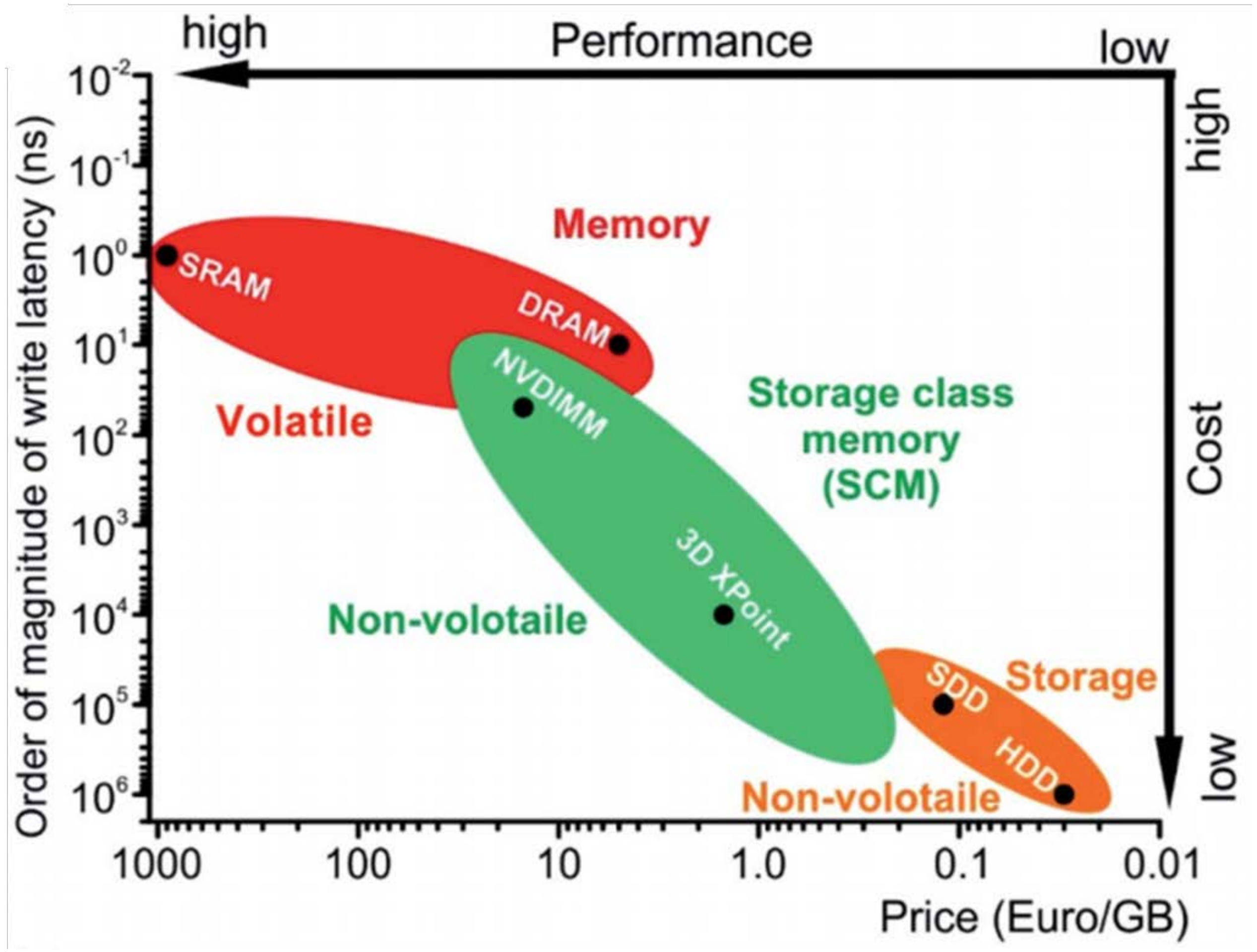


Zhang, Wei, et al. "Designing crystallization in phase-change materials for universal memory and neuro-inspired computing." *Nature Reviews Materials* 4.3 (2019): 150-168.

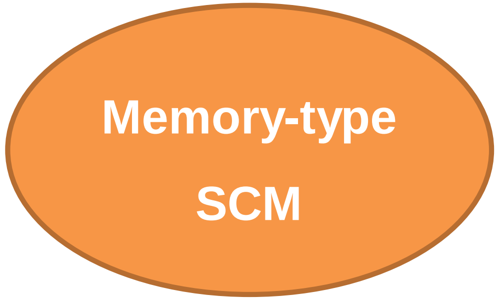
Promising properties



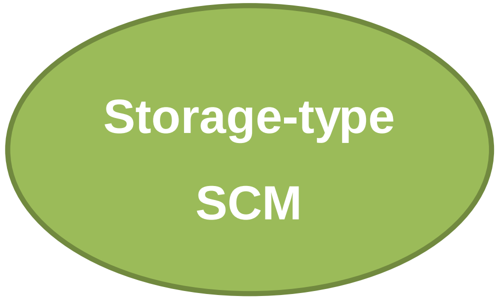
Storage Class Memory (SCM)



[Requirements]



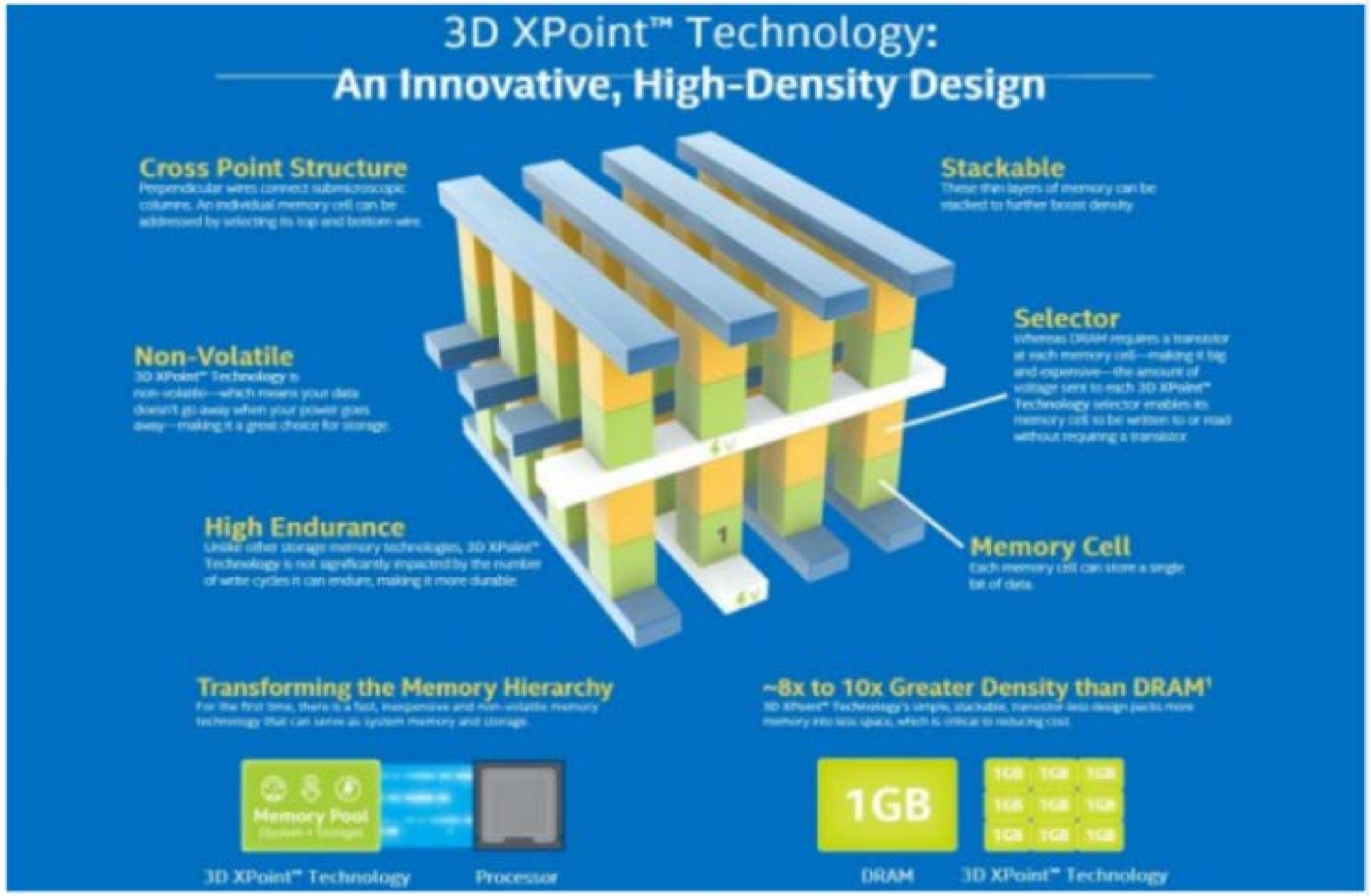
- Low power consumption
- High speed
- High cyclic endurance



- High density (+ MLC)
- High retention
- High cyclic endurance

Storage Class Memory (SCM)

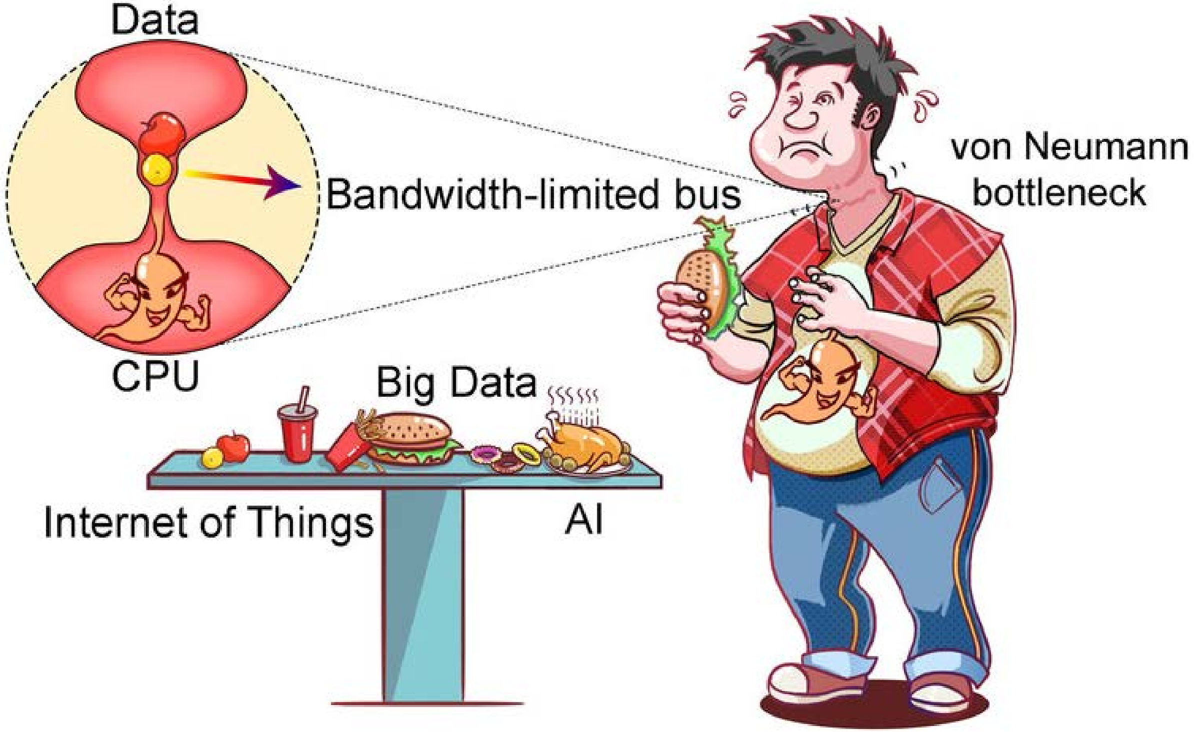
https://www.intel.co.kr/content/www/kr/ko/homepage.html



https://www.extremetech.com/extreme/211087-intel-micron-reveal-xpoint-a-new-memory-architecture-that-claims-to-outclass-both-ddr4-and-nand

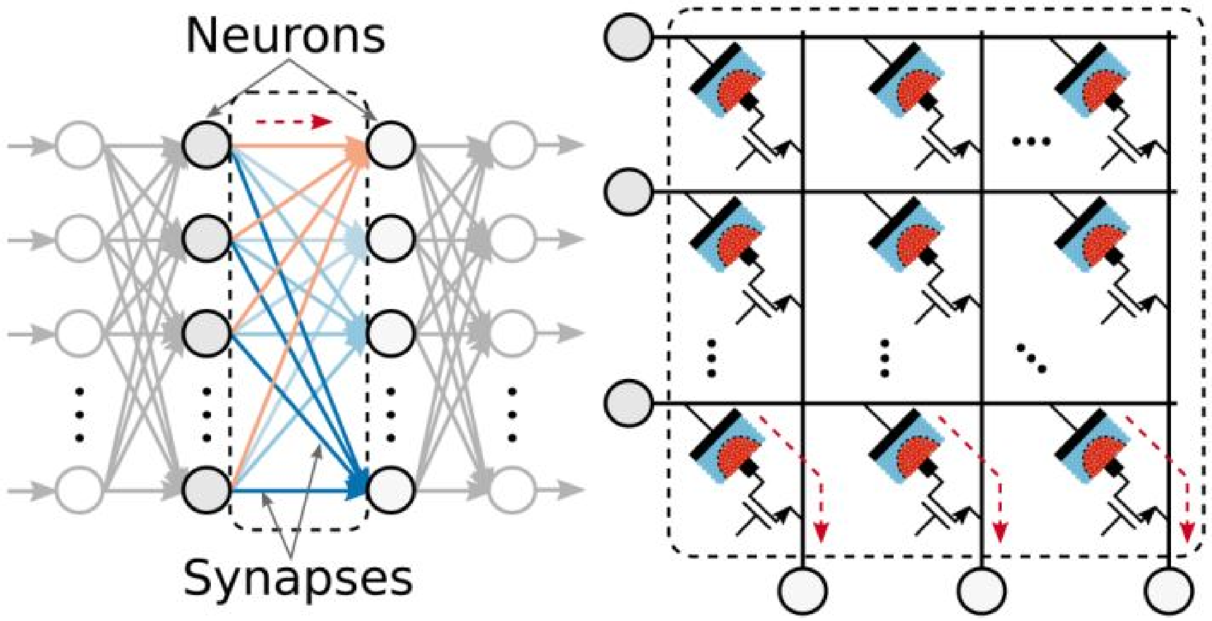
Neuromorphic Computing

- **Limitation of current computing architecture**



https://lt.onlineshopping2021.com/category?name=von%20neumann%20bottleneck

- **New architecture : Neuromorphic computing**



Nandakumar, S. R., *et al.*, *Journal of Applied Physics* 124.15, 2018

[Requirements]

- Large # of memory states
- Low energy (Power↓ & Speed↑)
- High cyclic endurance
- Low variations (D2D, C2C)

Improvements of the power consumption

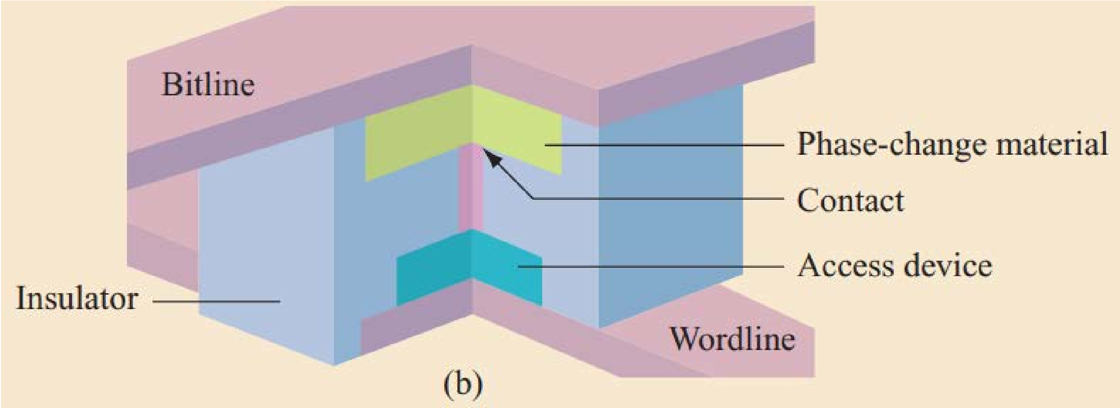
➢ **Cell design approaches**

❖ **Mushroom cell**

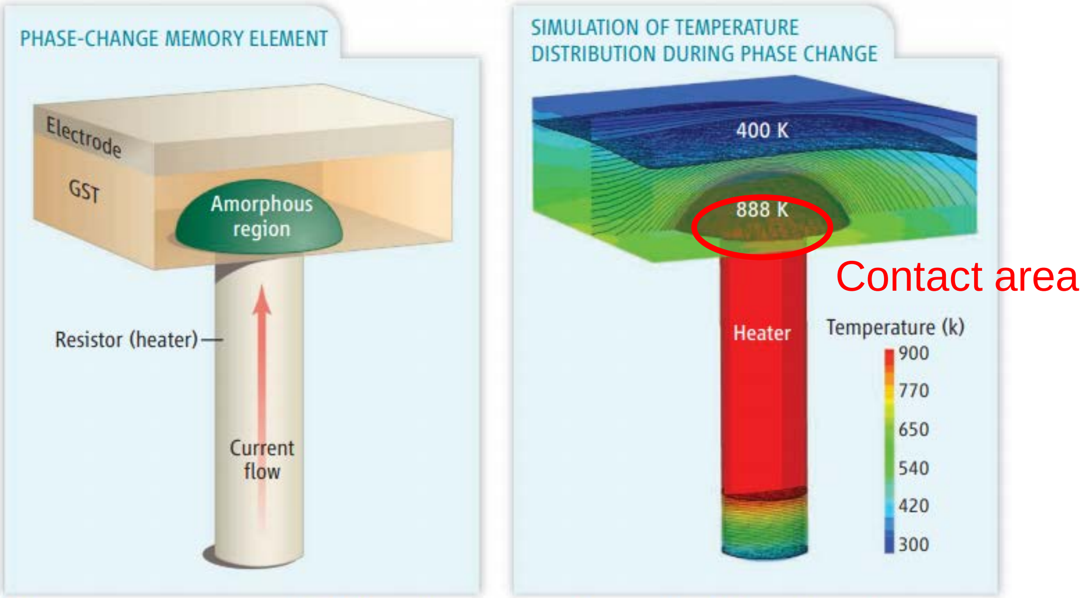
❖ Edge-contact type / μ-trench

❖ Cross-spacer cell

❖ Dash-type / Confined cell



DOI: 10.1147/rd.524.0465



Making resistive memories. (**Left**) Phase-change memory element. (**Right**) Simulation of temperature distribution during phase change.

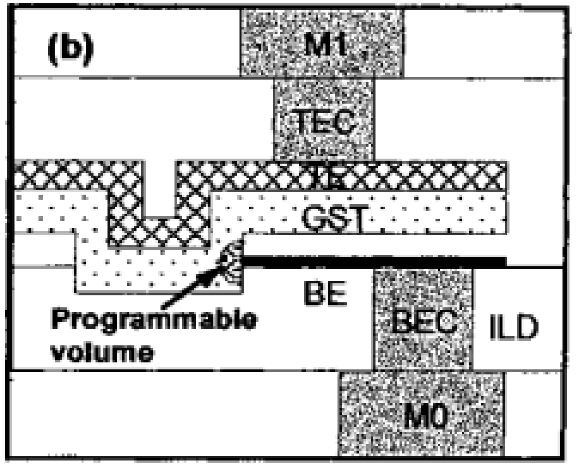
DOI: 10.1126/science.1160231

Improvements of the power consumption

➢ Cell design approaches

- ❖ Mushroom cell
- ❖ **Edge-contact type / μ-trench**
- ❖ Cross-spacer cell
- ❖ Dash-type / Confined cell

Edge-contact type cell



DOI: 10.1109/VLSIT.2003.1221142

✓ **Contact area dependence**

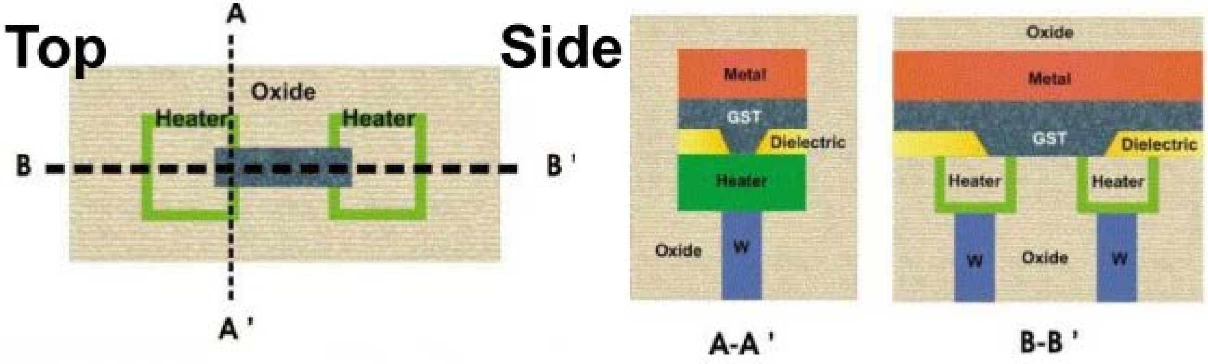
Lithographic feature size

↓

Heater thickness

- I_{Reset} reduction(40~70%)
- But, large area is needed

μ-trench cell

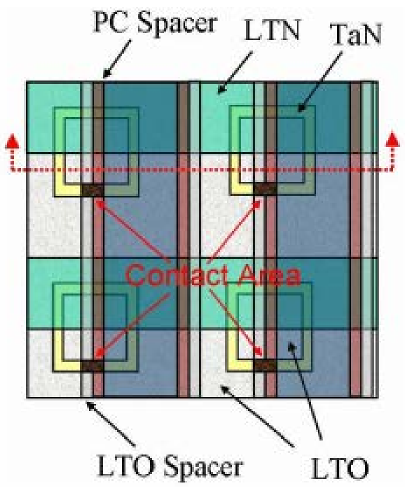


DOI: 10.1109/VLSIT.2004.1345368

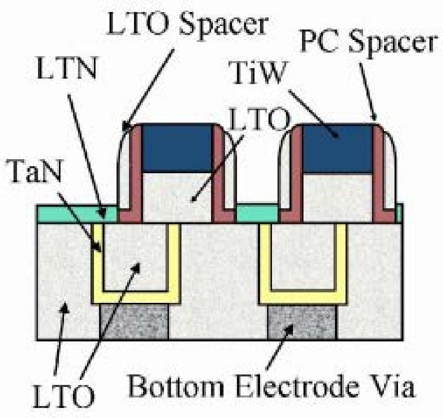
Improvements of the power consumption

➢ Cell design approaches

- ❖ Mushroom cell
- ❖ Edge-contact type / μ-trench
- ❖ **Cross-spacer cell**
- ❖ Dash-type / Confined cell



(a)



(b)

Fig. 1 Schematic diagrams of cross-spacer PCM cell structure (a) top view and (b) side view.

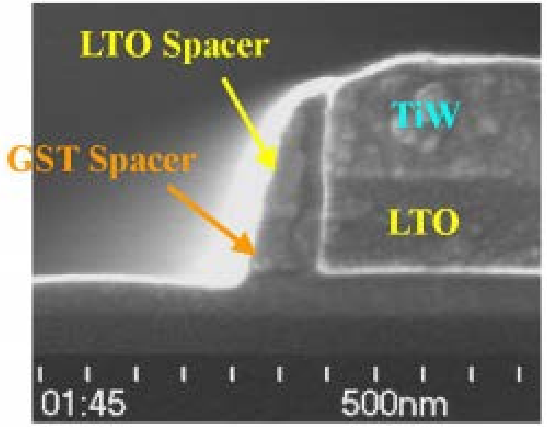


Fig. 2 Top electrode structure with LTO/GST double-spacer on the sidewalls.

Contact area

- ✓ Phase-change layer thickness
- ✓ Heater thickness

➡ I_{Reset} reduction
(50% over μ-trench cell)

DOI: 10.1109/IEDM.2007.4418935

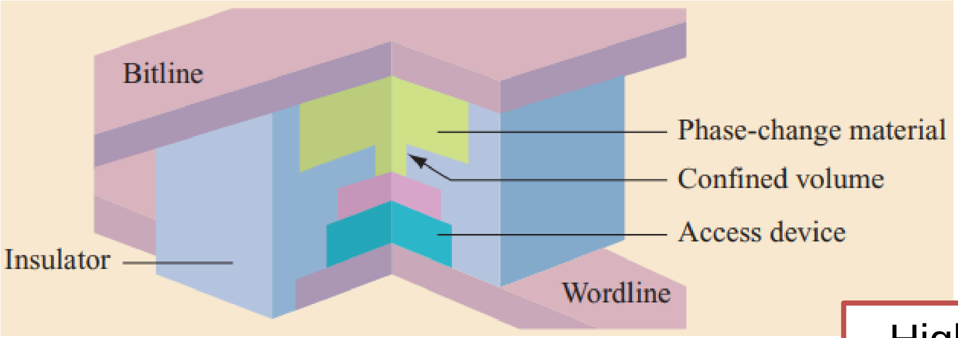
Improvements of the power consumption

➢ Cell design approaches

- ❖ Mushroom cell
- ❖ Edge-contact type / μ-trench
- ❖ Cross-spacer cell
- ❖ **Dash-type / Confined cell**

Confined cell

DOI: 10.1147/rd.524.0465



- High device density
- Power reduction(I_{Reset} ↓)
- Thermal confinement

Dash-type confined cell

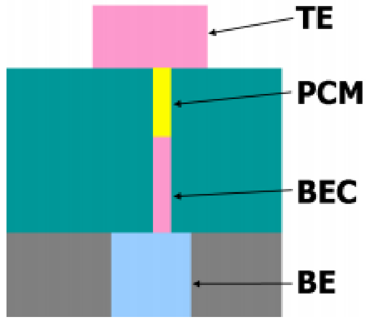


Fig.3 Schematic diagram of dash-confined cell structure for one-dimensional 7.5 nm-scale.

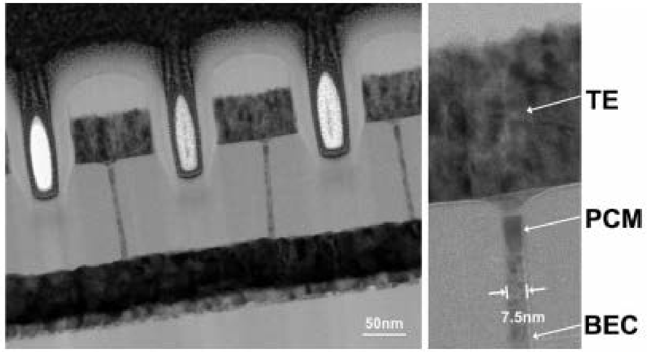
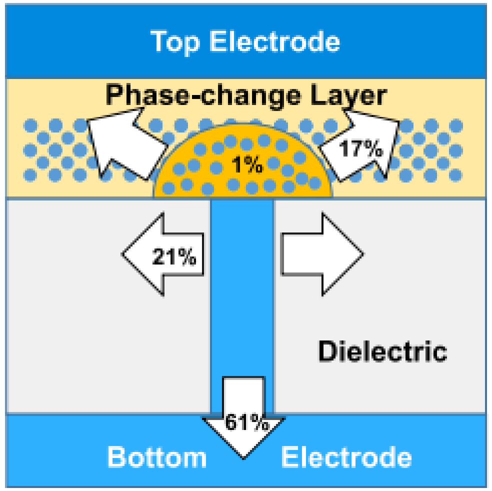


Fig.5 TEM images of dash-type confined cell structure. The width of PCM in the contact is approximately 7.5nm and the PCM was filled perfectly without void.

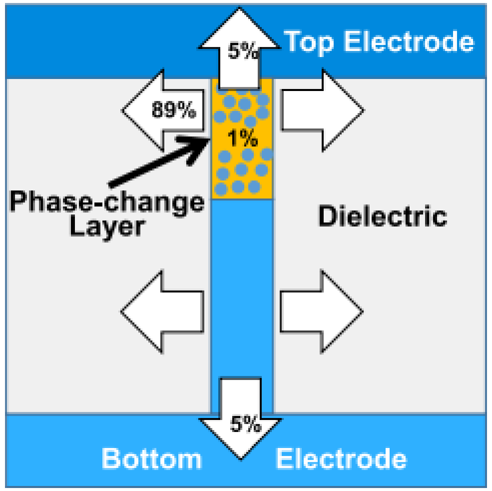
DOI: 10.1109/IEDM.2008.4796654

Improvements of the power consumption

➢ Thermal engineering



Mushroom cell



Confined cell

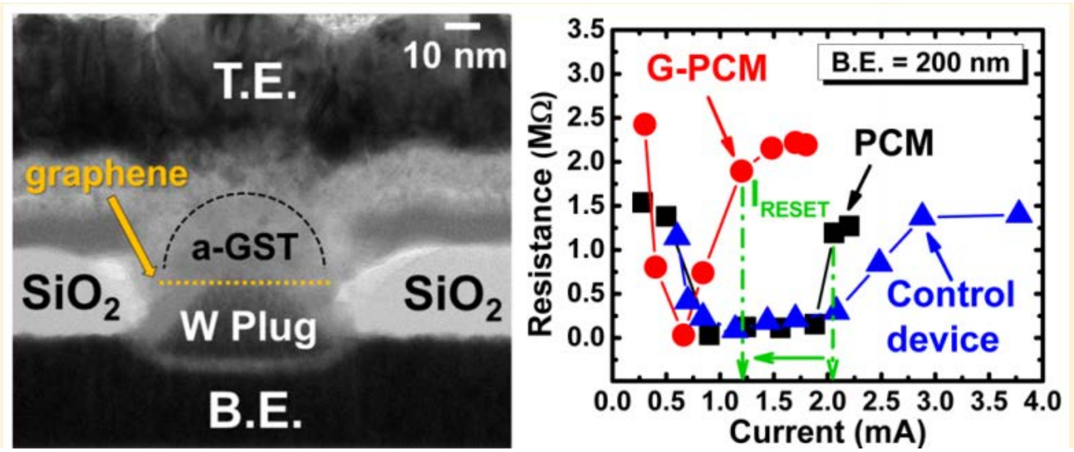
- To reduce the power consumption,
⇒ We should minimize the heat loss!

- In many thermally not optimized devices,
⇒ >99% of the heat is lost to surrounding structure.

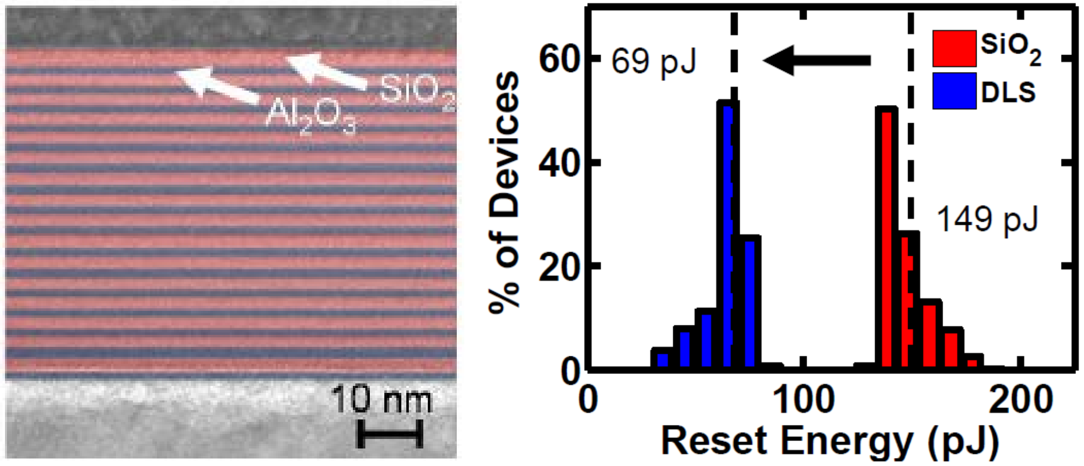
➢ Mushroom cell
→ Heat energy is primarily lost through the bottom electrode.

➢ Confined cell
→ Most of the heat is loss through the dielectric due to large contact.

<u>Use thermally resistive electrode, oxide, boundary.</u>



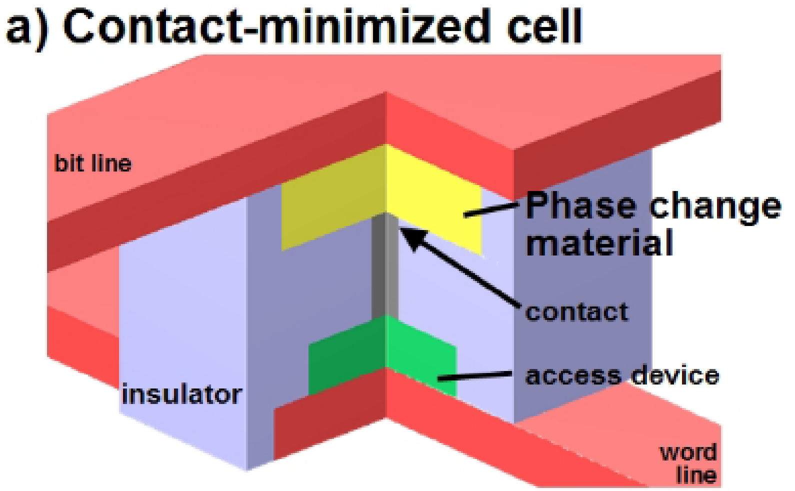
DOI: 10.1021/acs.nanolett.5b02661

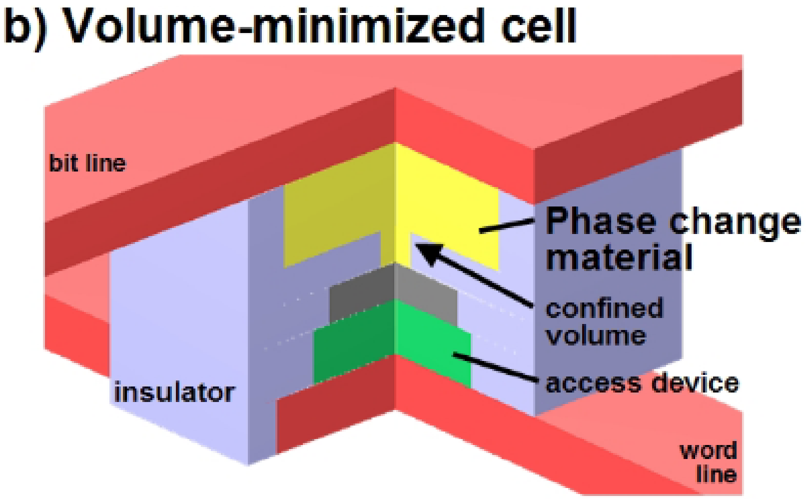


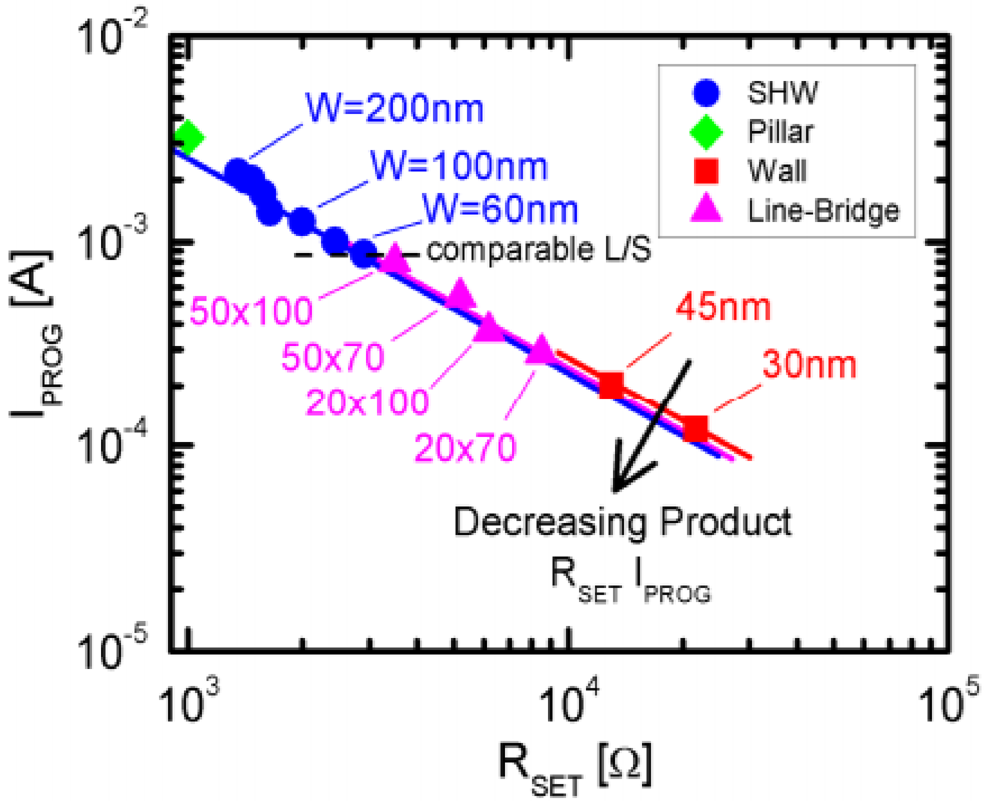
DOI: 10.1109/IMW.2017.7939079

$R_{SET} - I_{RESET}$ trade-off

- **Current PCM structures**





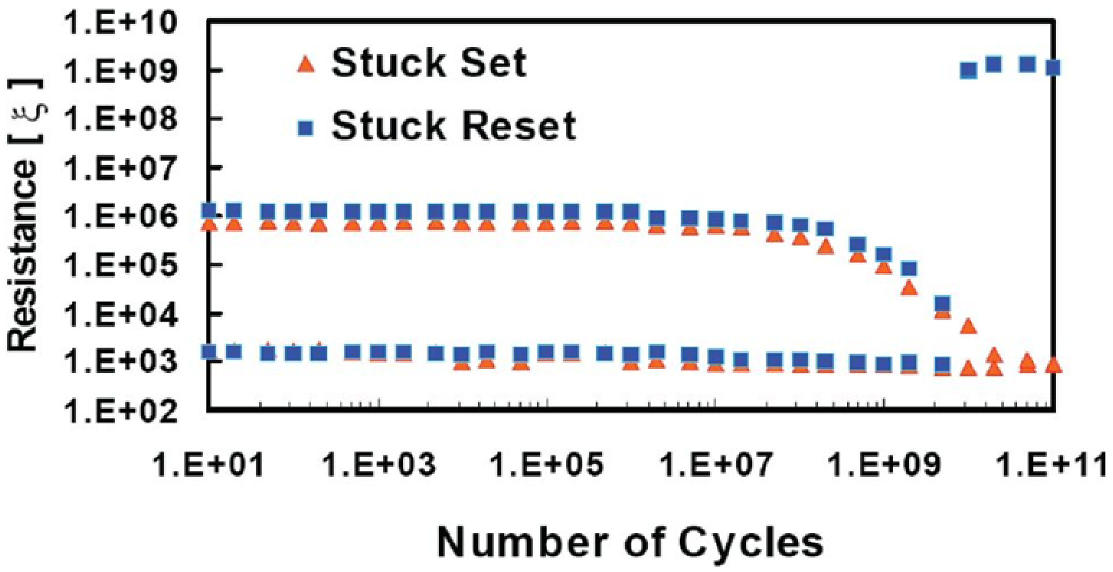


Boniardi, Mattia, et al., *IEDM*, 2014.

- **Reduction of RESET power by increasing R_{th}**
  - Contact / Cell size reduction increases both R_{th} & R_{el}
  - Material doping increases both ρ_{th} & ρ_{el} (by W-F Law)

Improvements of the cyclic endurance

- **Cyclic endurance failure**



Burr, G. W. et al., J. Vac. Sci. Technol., (2010)

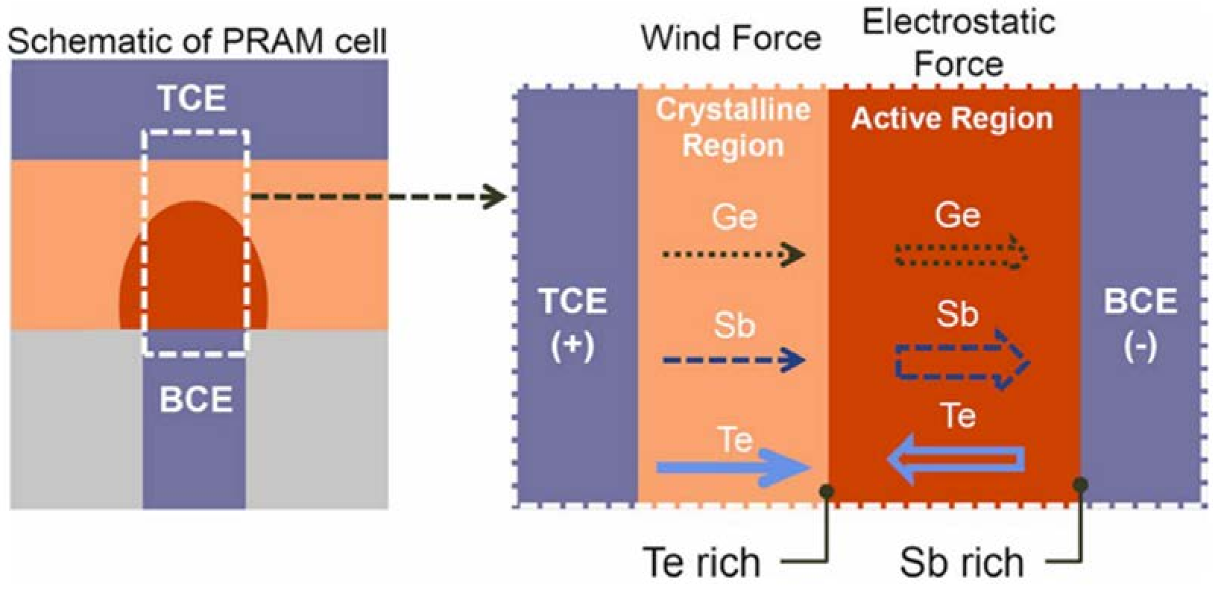
- **Stuck SET**

: Gradual elemental segregation

- **Stuck RESET**

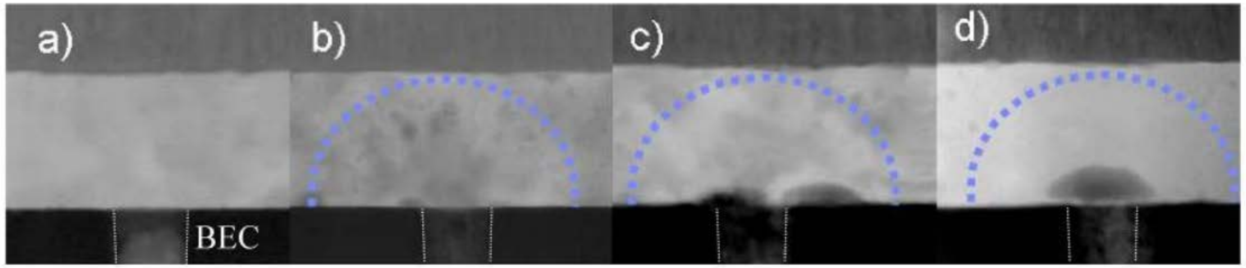
: Void formation near the contact

- Phase segregation



Yang, T-Y. et al., Appl. Phys. Lett., (2009)

- Void formation



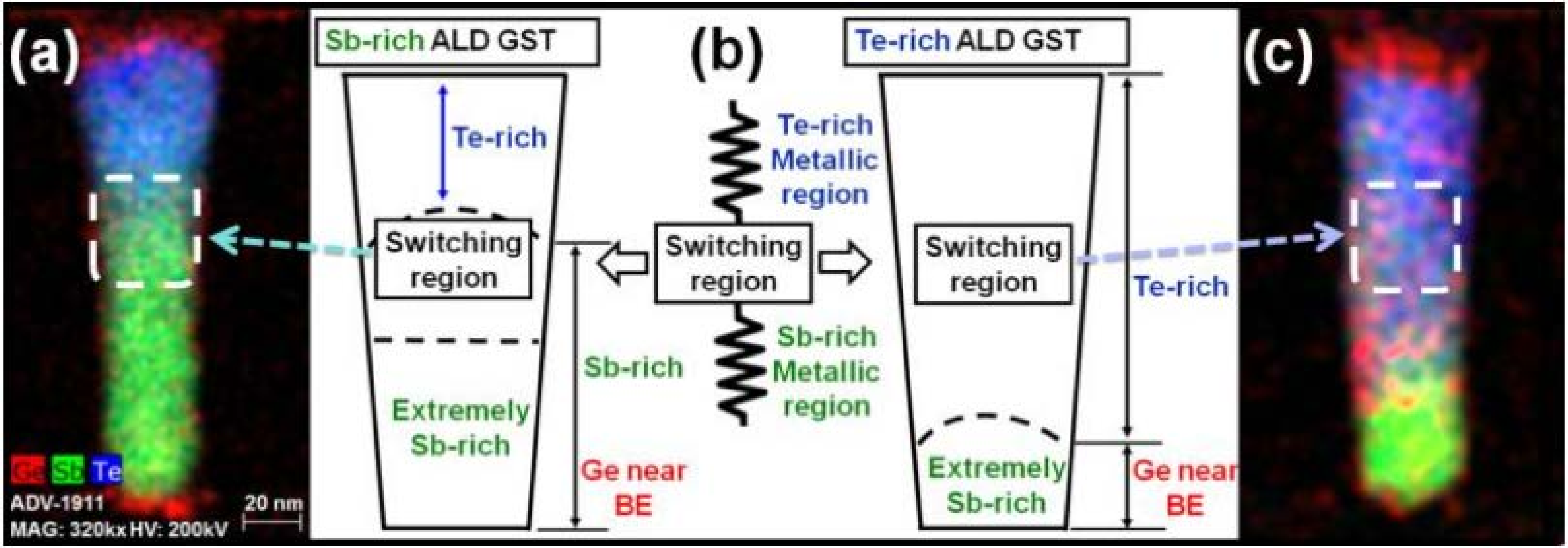
DOI: 10.1109/IMW.2009.5090589

Improvements of the cyclic endurance

- **How to solve stuck-SET failure?**

- Monatomic PCM (ex) Sb only)

- Confined PCM → Immune to the atomic segregation

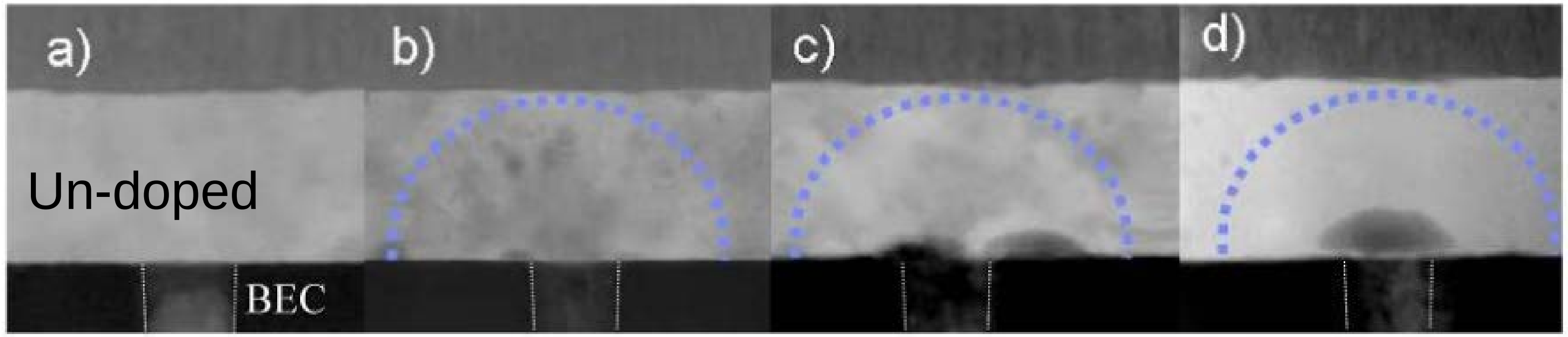


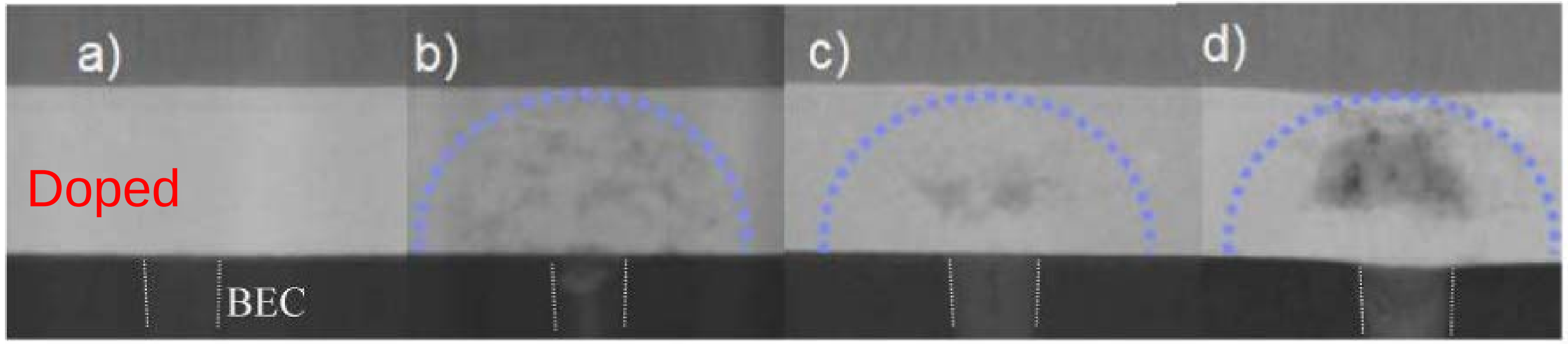
W. Kim *et al.*, *2016 IEEE International Electron Devices Meeting (IEDM)*, 2016

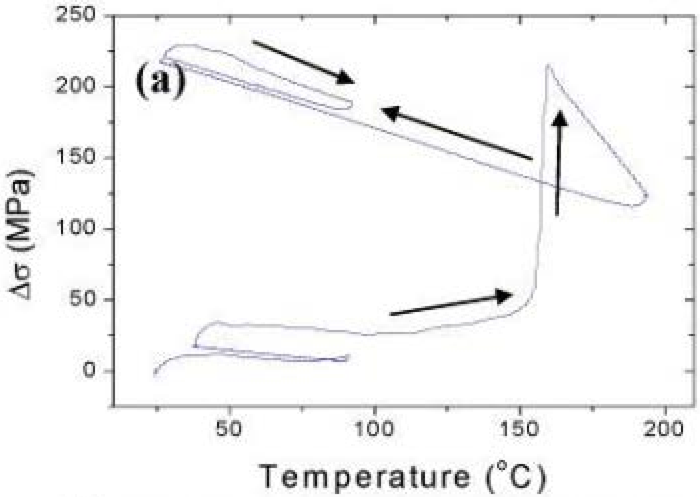
Improvements of the cyclic endurance

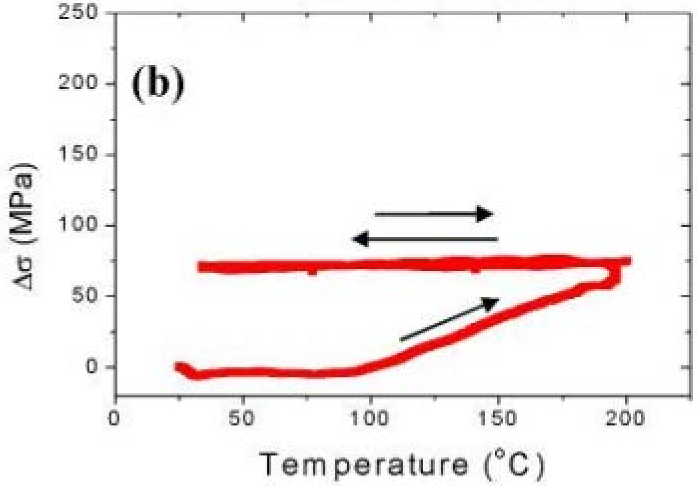
- **How to solve stuck-RESET failure?**

- Material doping (ex) N, O, C, Si)









C. -F. Chen *et al.*, *2009 IEEE International Memory Workshop*, 2009

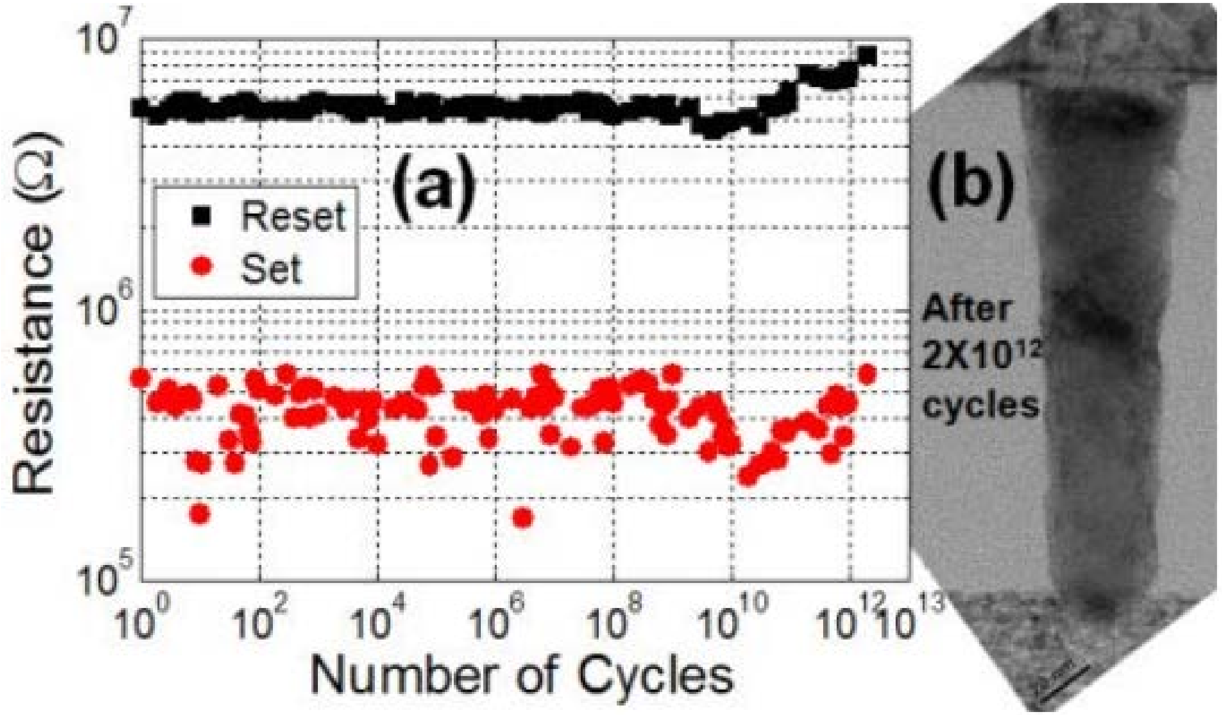
⇒ Reduction of thermal stress by material doping due to the smaller thermal expansion and volume change between phases

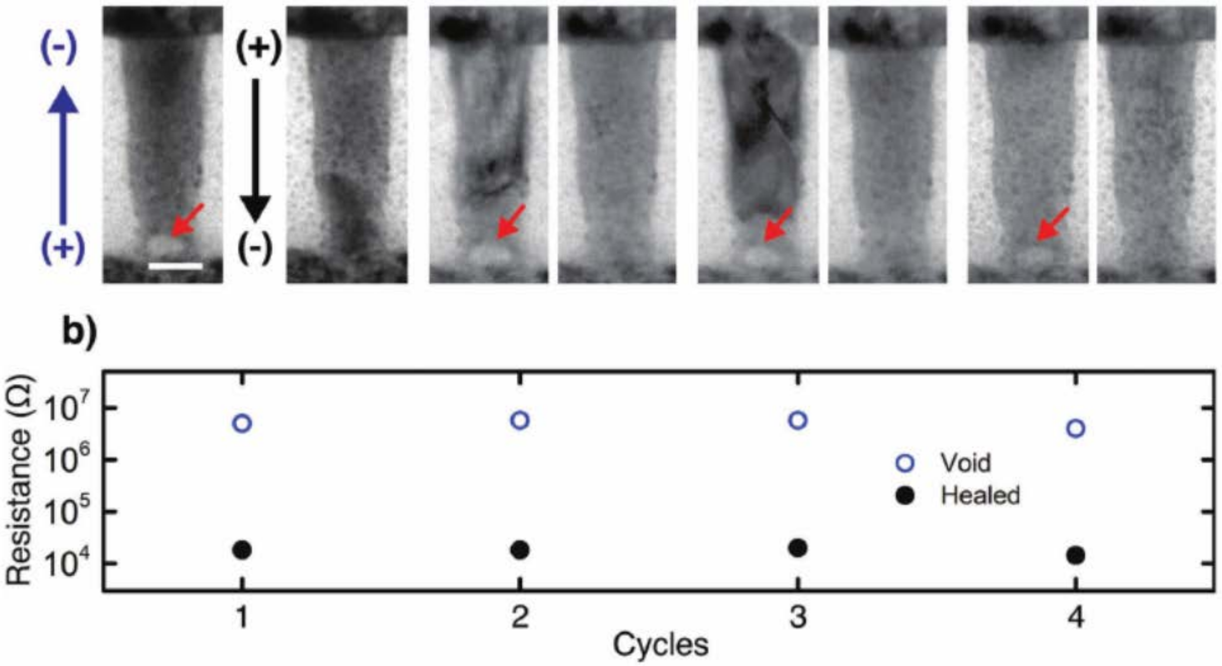
Improvements of the cyclic endurance

- **How to solve stuck-RESET failure?**

- Densifying the as-deposited PCM with high-temperature anneals

- ALD-based confined PCM with metallic liner / Void healing





Xie, Yujun, et al., *Advanced Materials* 30.9, 2018

⇒ However, high electric field formed in the PC material still causes atomic movement in the existing PCM structures and limits further enhancement of the cyclic endurance.

Summary

- Phase-change memory(PCM) is one of the next-generation memory devices as a storage-class memory that can fill the gap between DRAM and NAND flash memory.
- PCM is also used as a synaptic device in neuromorphic computing hardware for more power-efficient operation beyond the existing Von Neumann architecture
- Various studies have been proposed to reduce power consumption, such as reducing the contact size or size of the cell itself by modifying the cell structure, and thermal confinement to reduce heat loss.
- In order to improve endurance, methods such as material doping, structures immune to atomic movement or void-free structure, and pore healing have been proposed.