Stanford University

Methodologies to Study the Scalability and Reliability Physics of Phase-Change Memory

Rakesh Jeyasingh[1], Scott Fong[1], Chiyui Ahn[1], SangBum Kim[1], Jiale Liang[1], Marissa Caldwell[1] Zijian Li[2], Jaeho Lee[2], Elah Bozorg-Grayeli[2], Mehdi Asheghi[2], Kenneth E. Goodson[2], Delia Milliron[3] and H. –S. Philip Wong[1]

[1]Department of Electrical Engineering and [2]Department of Mechanical Engineering, Stanford University, Stanford, CA 94305
[3]Molecular Foundry, Lawrence Berkeley National Labs

11.12.2013

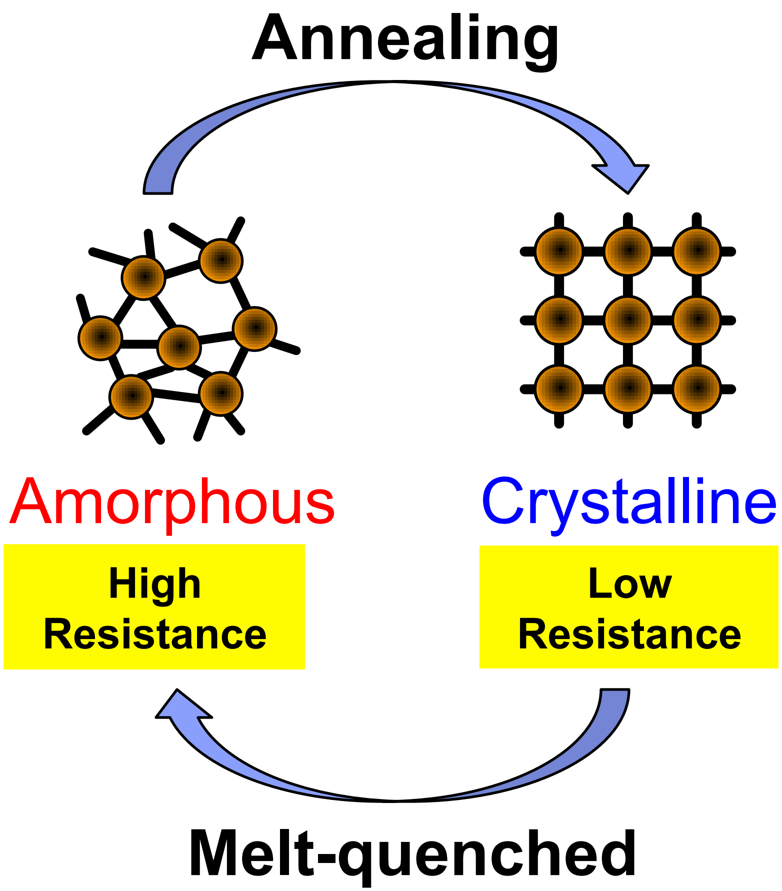
Outline

- **Phase Change Memory (PCM) Basics**
- **Phase Change Material Scaling using GeTe Nanoparticles**
- **1D Thickness Scaling Studies using Additional Top Electrode (ATE) Devices**
- **Programming Current (Electrode) Scaling using CNTs**
- **Micro Thermal Stage (MTS) - An On-Chip Heater and Thermometer to Study PCM Reliability Physics**
- **Conclusion**

Outline

- **Phase Change Memory (PCM) Basics**
- **Phase Change Material Scaling using GeTe Nanoparticles**
- **1D Thickness Scaling Studies using Additional Top Electrode (ATE) Devices**
- **Programming Current (Electrode) Scaling using CNTs**
- **Micro Thermal Stage (MTS) - An On-Chip Heater and Thermometer to Study PCM Physics**
- **Conclusion**

Phase Change Materials



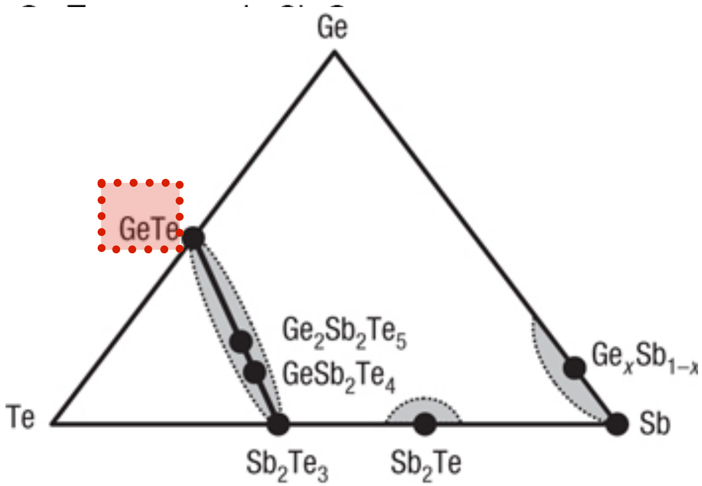
Phase-change materials:

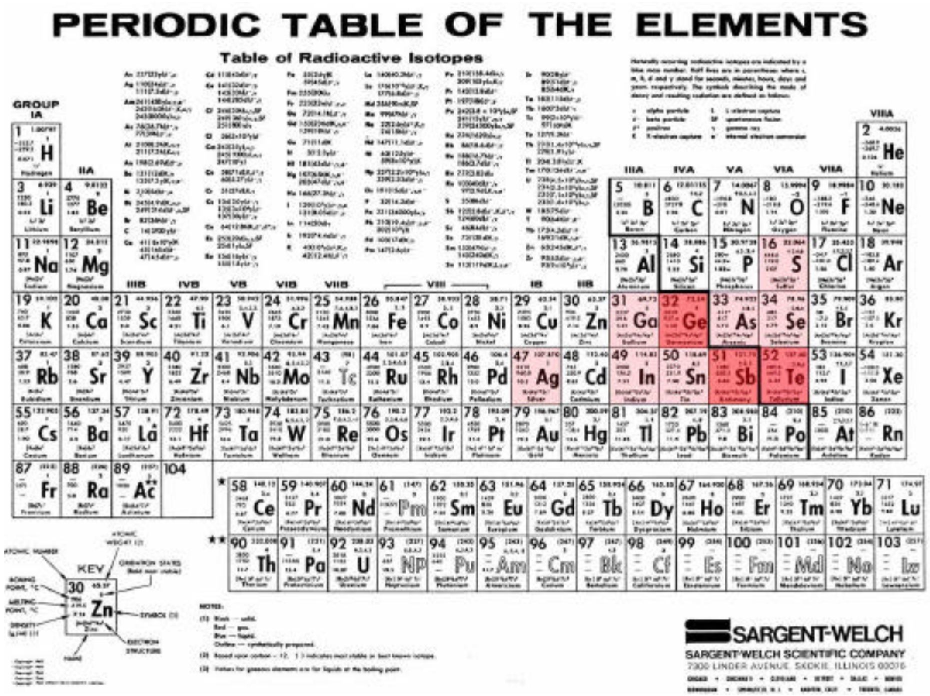
- $Ge_2Sb_2Te_5$ (GST)
- AIST (AgInSbTe)
- GeSb, Sb_2Te, GeTe…

Phase Change Materials

- **Sulphur (S), Selenium (Se) and Tellurium (Te) - group 16 (VIA), are called chalcogens**
- **Chalcogenides - group 16 + group 13-15 namely Arsenic (As), Germanium (Ge), Antimony (Sb), Phosphorus (P) etc.**

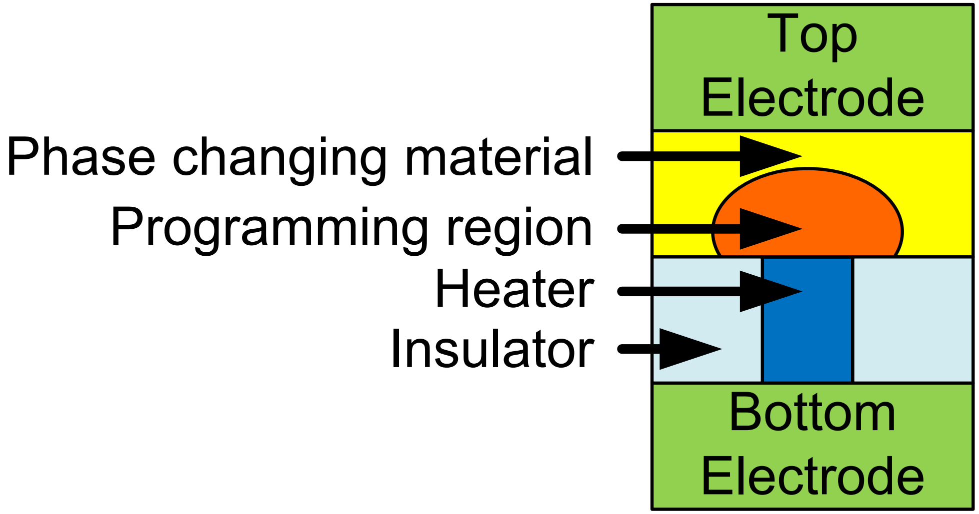
Binary	Ternary	Quaternary
Ga Sb	$Ge_2Sb_2Te_5$	Ag In Sb Te
In Sb	In Sb Te	(Ge Sn)Sb Te
In Se	Ga Se Te	Ge Sb (Se Te)
$Sb_2\ Te_3$	$Sn\ Sb_2\ Te_4$	$Te_{81}Ge_{15}Sb_2S_2$

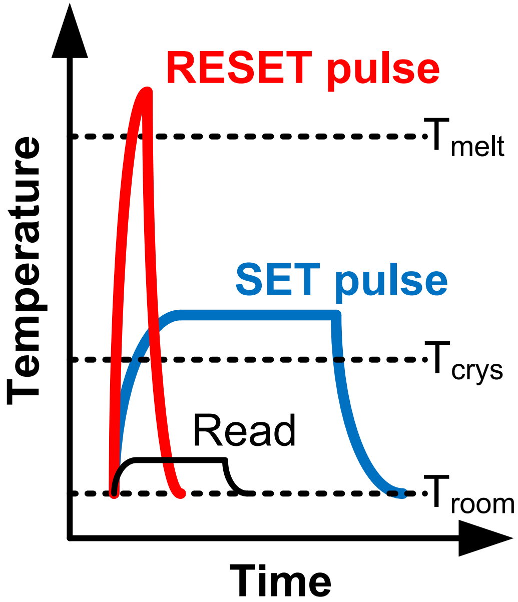




Most reports in the literature uses the $Ge_2Sb_2Te_5$ alloy (GST)

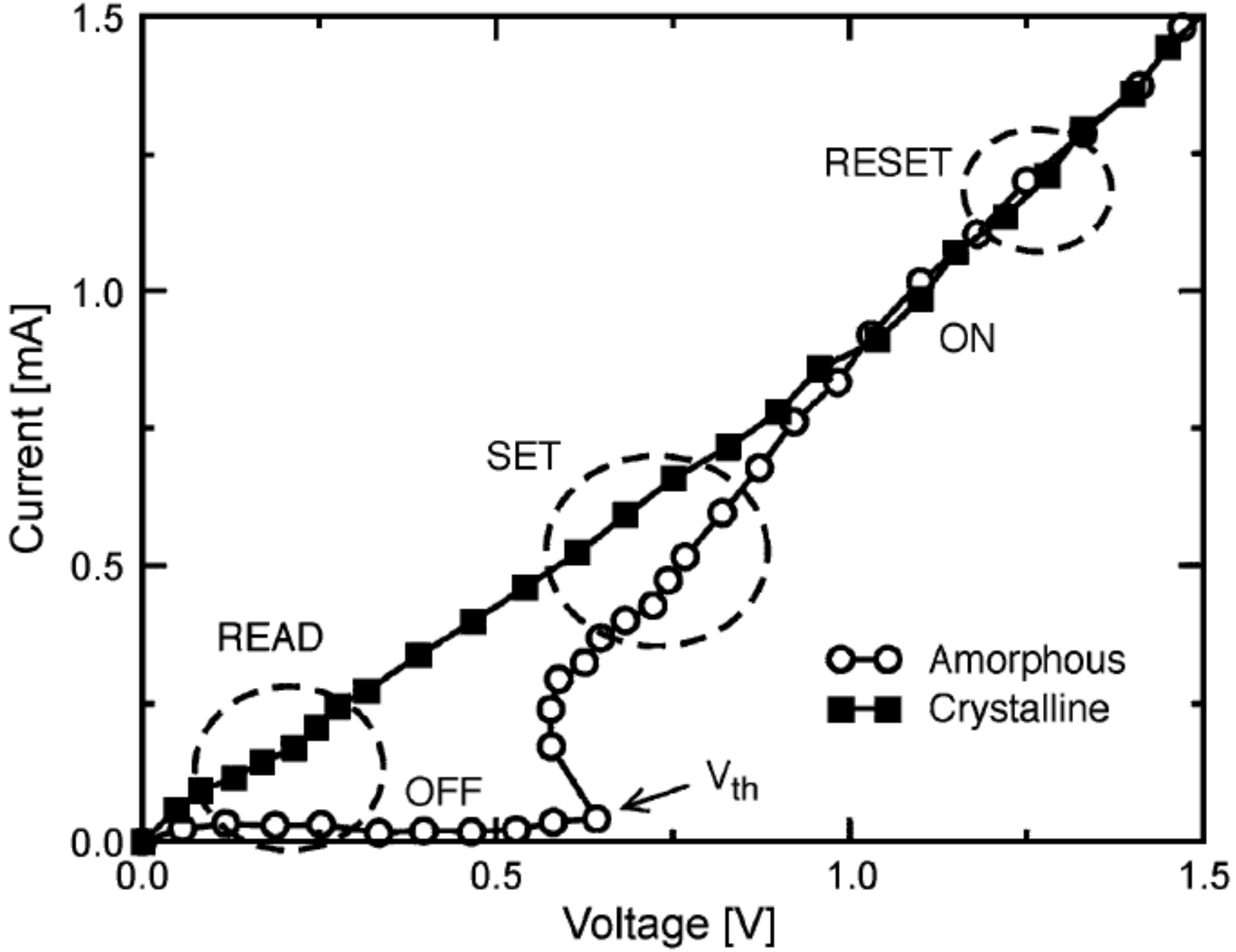
Phase Change Memory





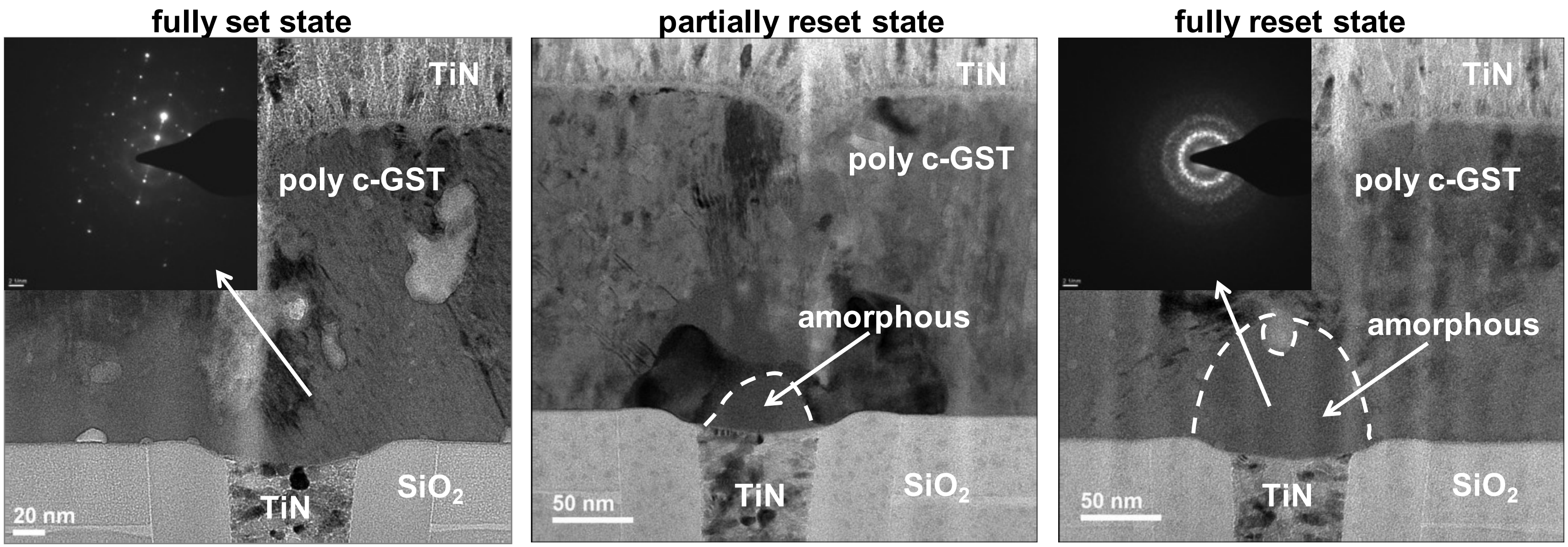
- **Amorphization (RESET): Melt and quench ($T > T_{Melt}$)**
- **Crystallization (SET): Anneal ($T > T_{crys}$)**

PCM Current-Voltage Characteristics



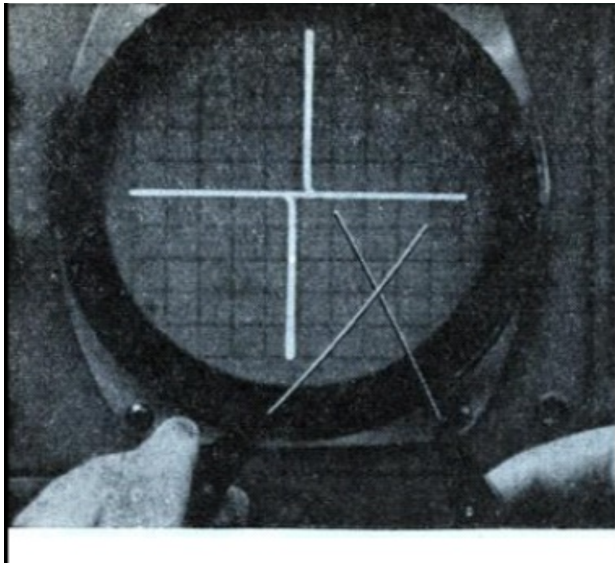
A. Pirovano et al., *IEEE Trans. Electron Devices*, vol. 51, no. 5, pp. 714–719, May 2004.

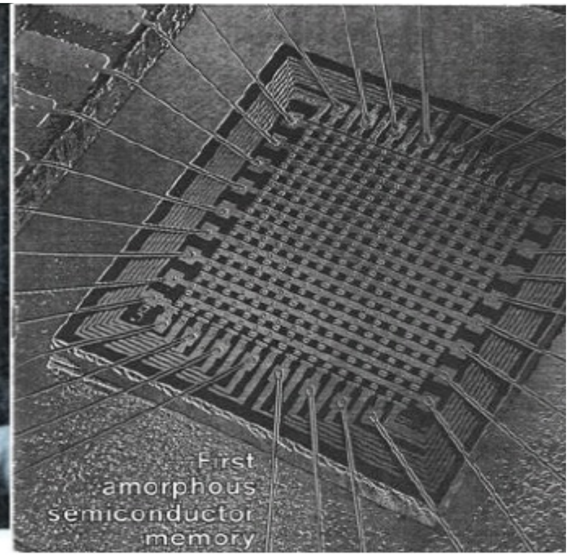
Phase Change Memory

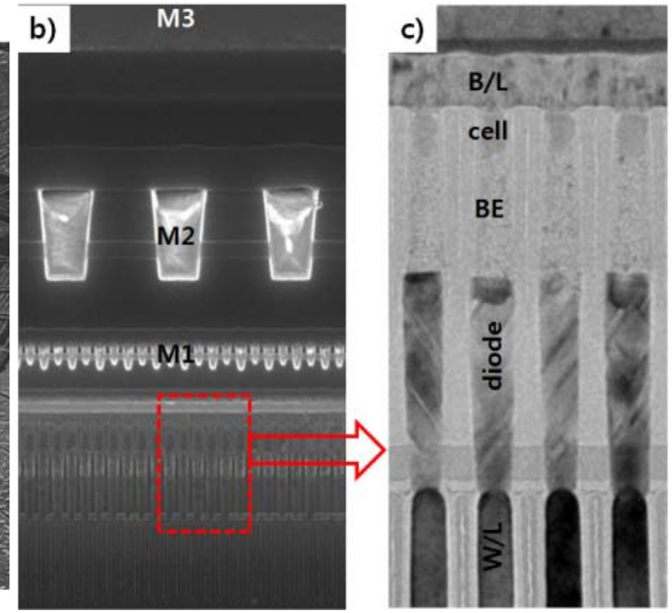


- **Resistance change achieved by controlling the size of the amorphous region**
- **Amorphous volume ∝ Programming power**

History of Phase Change Memory







N. Carlisle, "The Ovshinsky invention," Science & Mechanics, Feb. 1970

R. G. Neale, D. L. Nelson and G. E. Moore, "Nonvolatile and Reprogrammable, the Read Mostly Memory is Here," Electronics, Sep. 1970

M. Kanga *et al*., *IEDM* 2011

F ≈ 2mm
1 bit

F ≈ 350μm
256 bit

F ≈ 20nm
8 Gbit

PCM Status

- **90 nm, 128Mb NOR replacement on market**
- **45 nm, 1Gb (IEDM 09, ISSCC 10), 58 nm 1Gb (ISSCC 11)**
- **20 nm cell (IEDM 11), 42 nm half pitch 1Gb chip (IEDM 11), 20 nm 8Gb chip (ISSCC 12)**
- **Will keep researchers busy for a long time**
  - Physics of threshold switching
  - Threshold switching voltage and resistance drift
  - Device size scaling
  - Partial set and reset (multi-bit operation)
  - Thermal engineering (programming energy reduction)
  - Materials engineering for target applications (speed, temperature, reliability)
  - Reliability (thermal expansion, alloy composition)
  - …

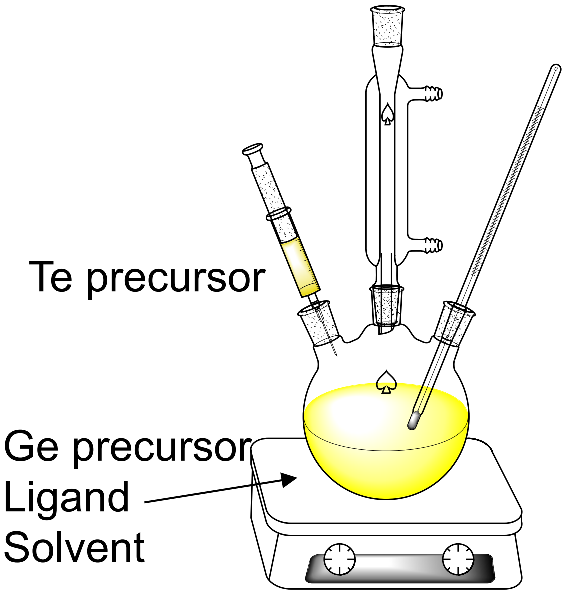
PCM Status

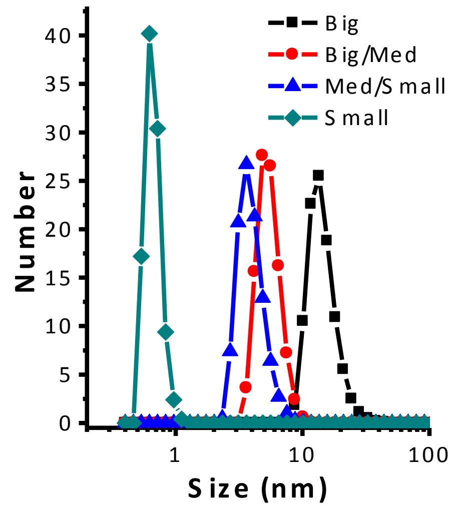
- **90 nm, 128Mb NOR replacement on market**
- **45 nm, 1Gb (IEDM 09, ISSCC 10), 58 nm 1Gb (ISSCC 11)**
- **20 nm cell (IEDM 11), 42 nm half pitch 1Gb chip (IEDM 11), 20 nm 8Gb chip (ISSCC 12)**
- **Will keep researchers busy for a long time**
  - Physics of threshold switching
  - Threshold switching voltage and resistance drift
  - Device size scaling
  - Partial set and reset (multi-bit operation)
  - Thermal engineering (programming energy reduction)
  - Materials engineering for target applications (speed, temperature, reliability)
  - Reliability (thermal expansion, alloy composition)
  - …

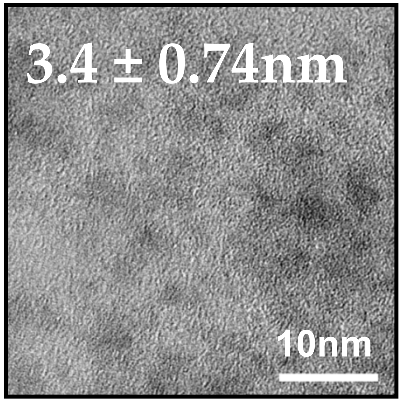
Outline

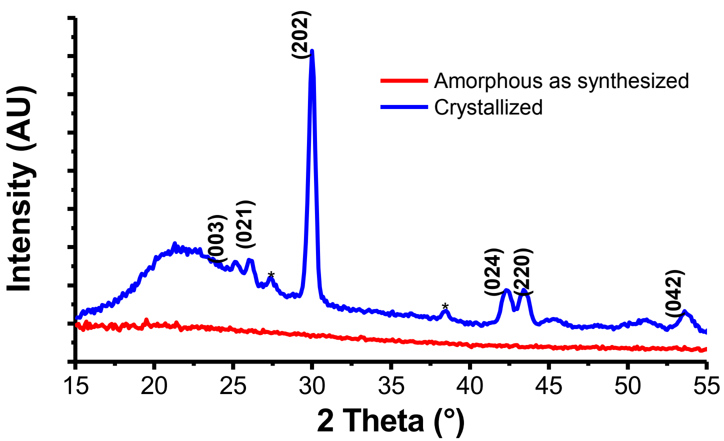
- Phase Change Memory (PCM) Basics
- **Phase Change Material Scaling using GeTe Nanoparticles**
- 1D Thickness Scaling Studies using Additional Top Electrode (ATE) Devices
- Programming Current (Electrode) Scaling using CNTs
- Micro Thermal Stage (MTS) - An On-Chip Heater and Thermometer to Study PCM Physics
- Conclusion

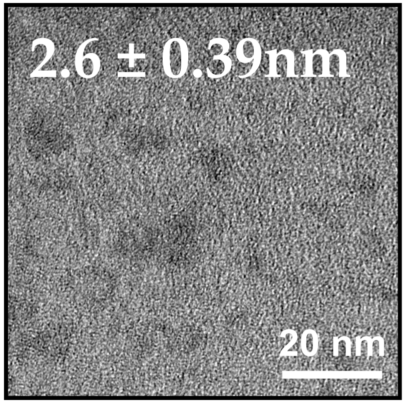
Synthesis of Amorphous GeTe Nanoparticles

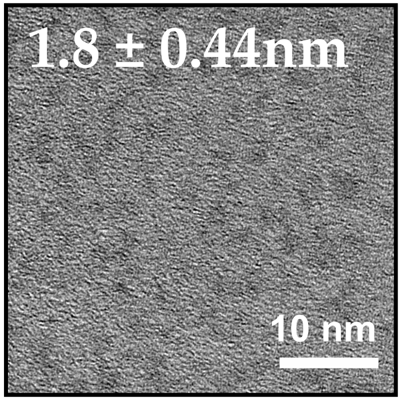








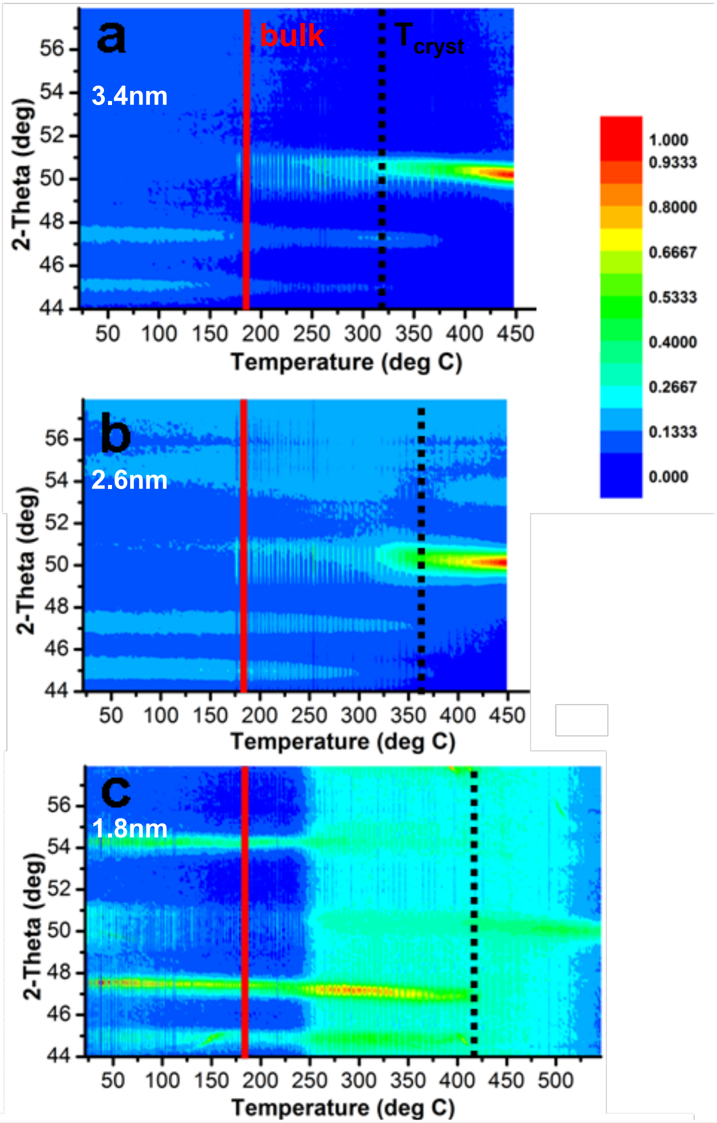


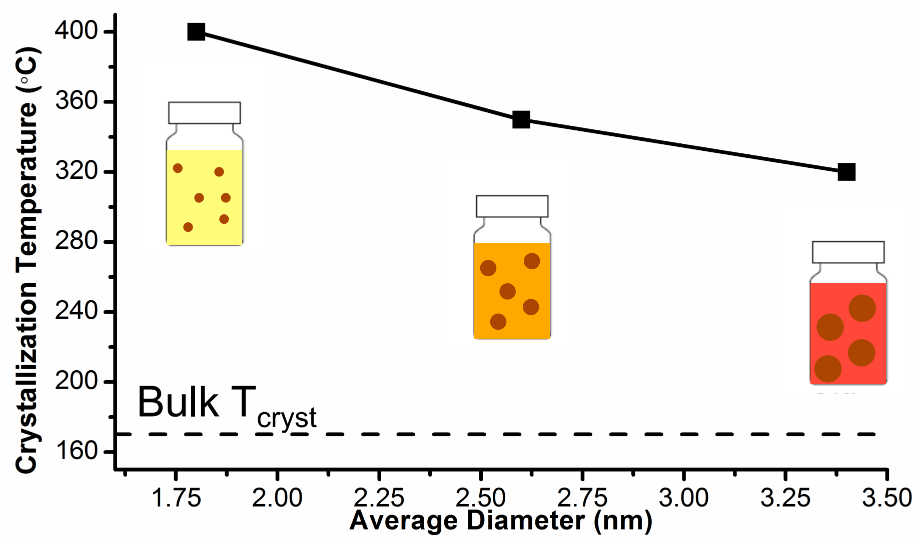


Caldwell, M. et al. *J. Mater. Chem.* **20.** (2010) 1285.

Work completed with Delia Milliron at the Molecular Foundry.

Size Dependence of Crystallization Temperature





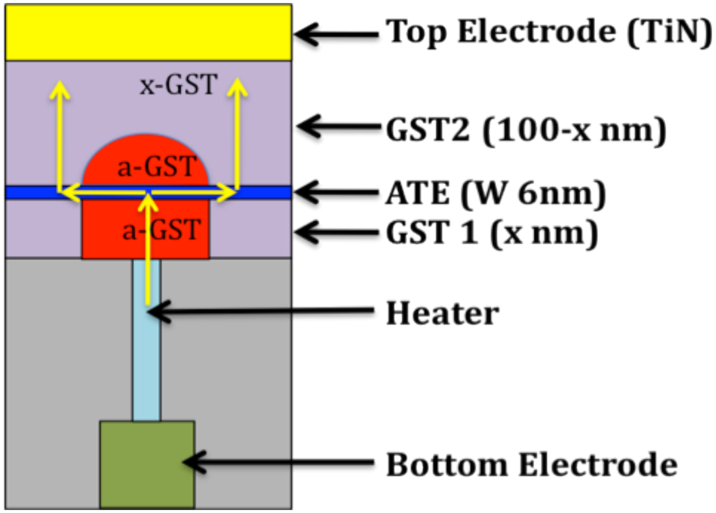
- Higher crystallization temperature ↔ Greater amorphous phase stability ↔ Data Retention

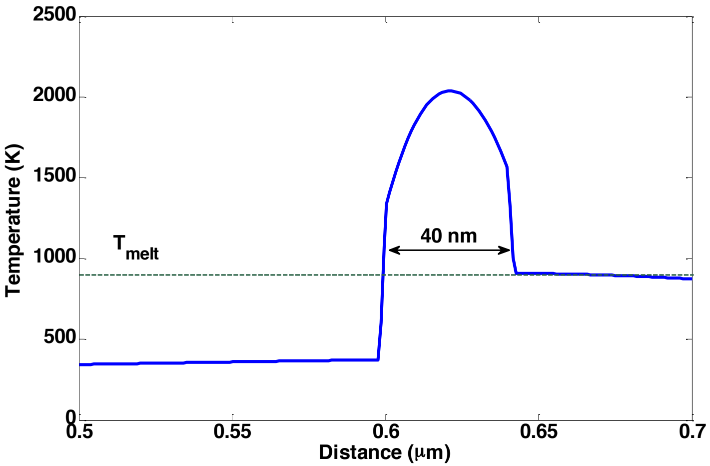
Collected at Brookhaven National Laboratory by Simone Raoux (IBM) and completed with Delia Milliron at the Molecular Foundry.

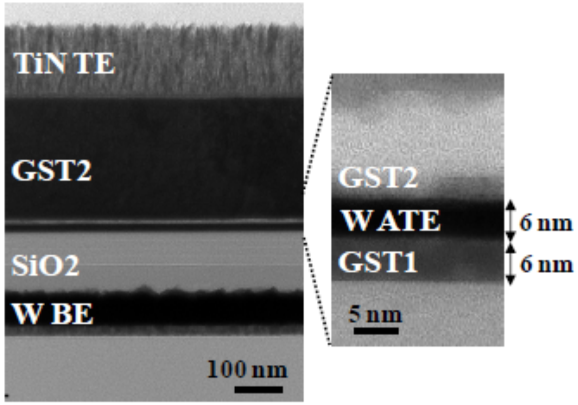
Outline

- Phase Change Memory (PCM) Basics
- Phase Change Material Scaling using GeTe Nanoparticles
- **1D Thickness Scaling Studies using Additional Top Electrode (ATE) Devices**
- Programming Current (Electrode) Scaling using CNTs
- Micro Thermal Stage (MTS) - An On-Chip Heater and Thermometer to Study PCM Physics
- Conclusion

Additional Top Electrode (ATE) Structure

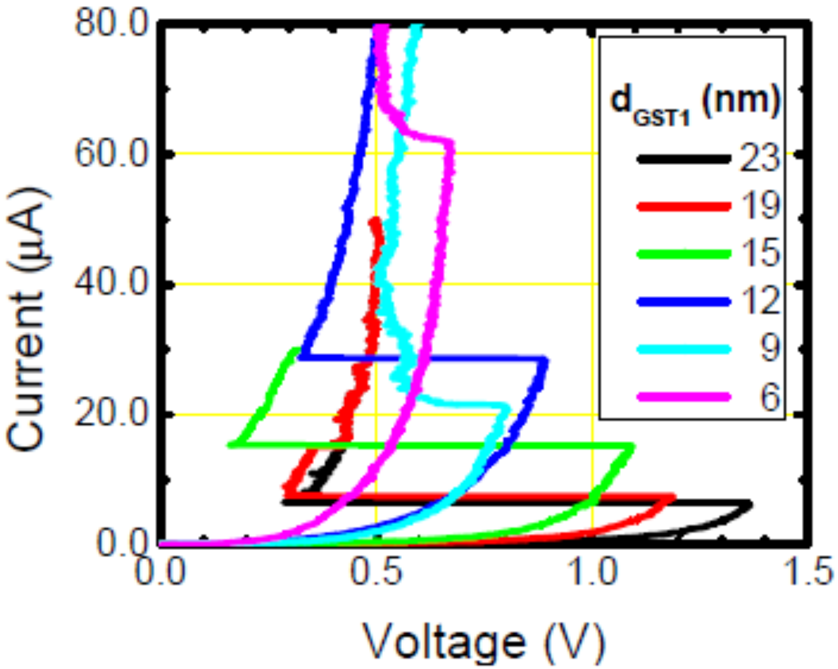


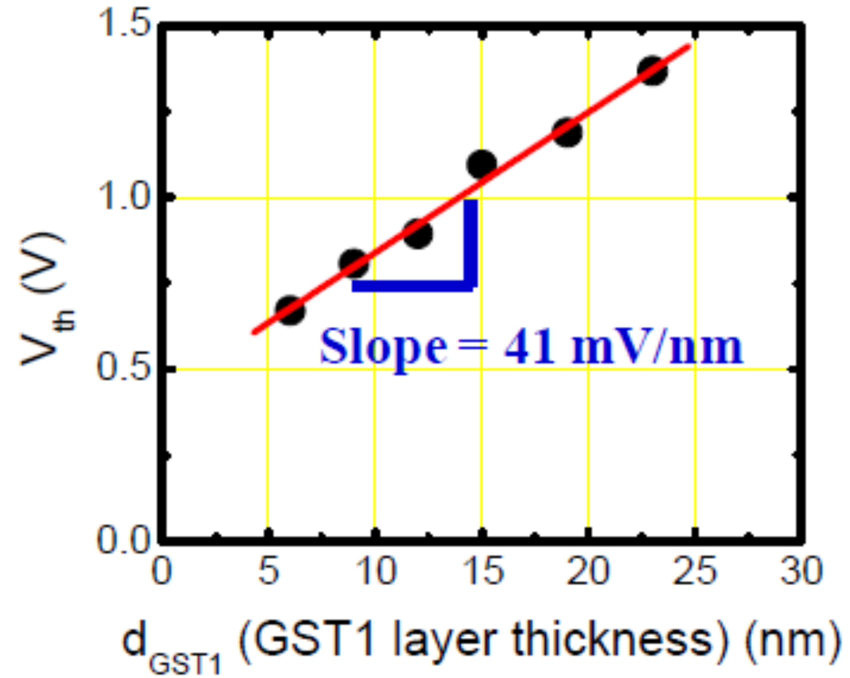




- **ATE layer acts as an electrical conductor**
  – Confines probed amorphous region to a known thickness

Thickness Dependence of V_{th}

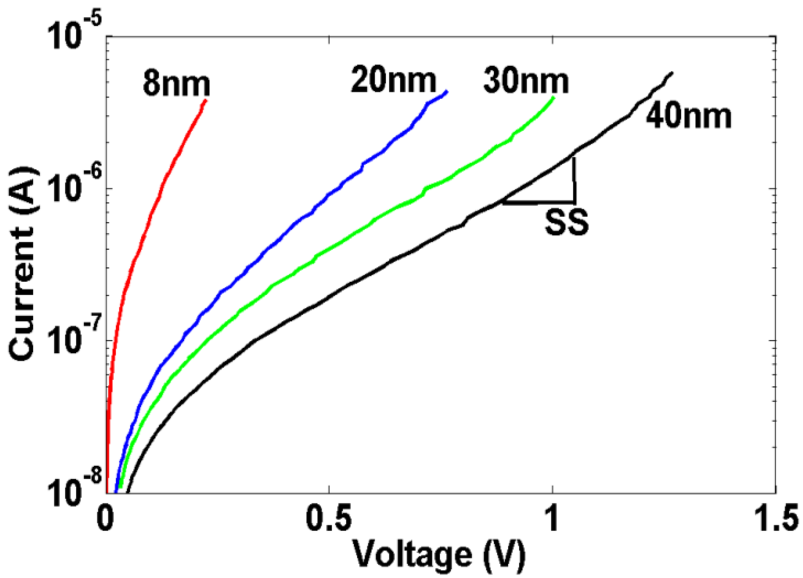


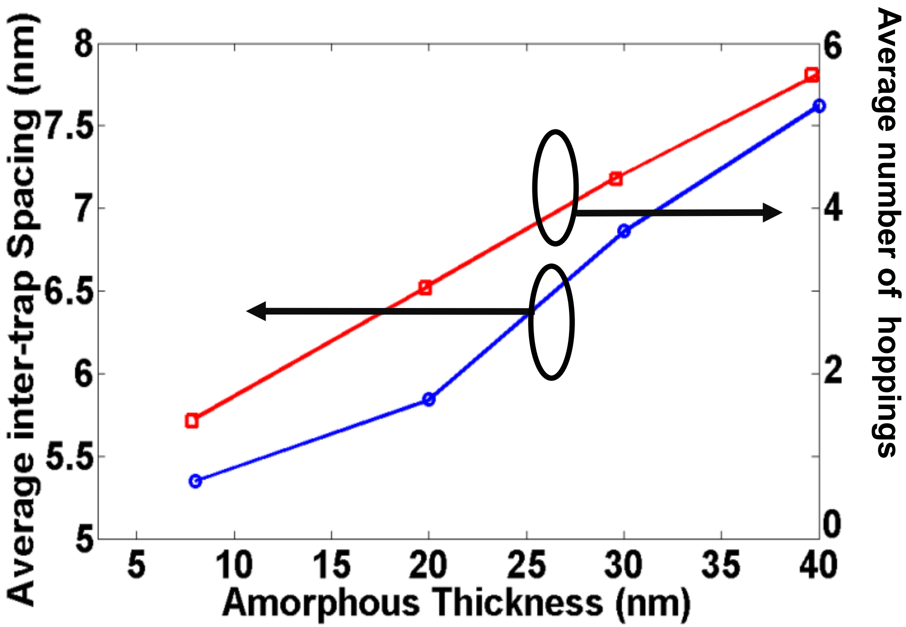


- **V_{th} scales linearly with GST1 thickness**
  - Both E_{th} (41mV/nm) and V_{th0} match well with previously reported values

S.Kim et al., *IEEE Trans. Elec. Dev.*, vol.58, no.5, 2011

Direct Measurement of Trap Spacing using ATE Devices





$$\mathrm{STS} = \frac{\partial \log I}{\partial V_A} = \frac{q}{2kT}\frac{\Delta z}{u_a}$$

Thickness (nm)	Average Trap Spacing (nm)	Average Number of Hoppings	Trap Density (cm^{-3})
8	5.3	1.5	6.7×10^{18}
20	6	3.3	4.6×10^{18}
30	6.8	4.4	3.2×10^{18}
40	7.6	5.3	2.3×10^{18}

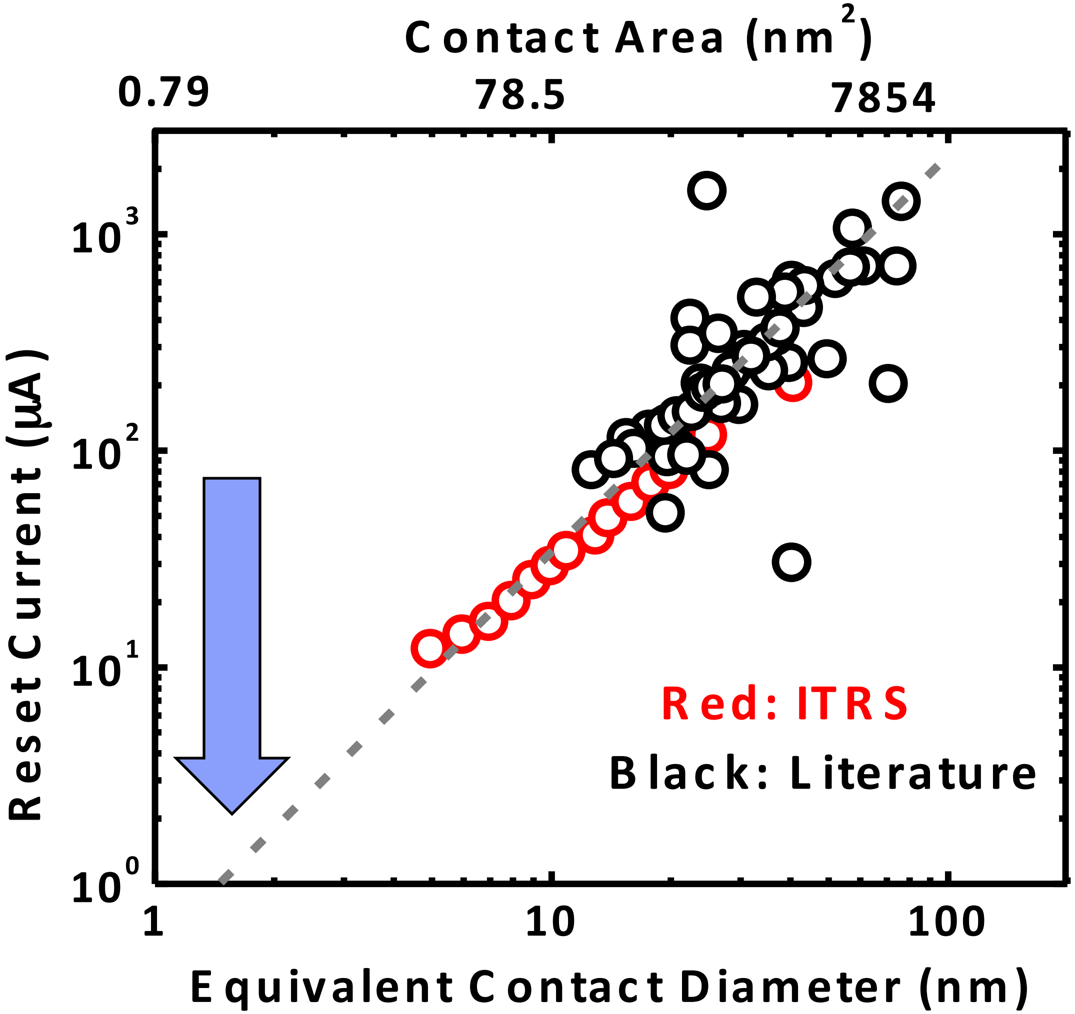
R. Jeyasingh et al., *IEEE Trans. Elec. Dev.*, vol. 58, no. 12, 2011

Trap spacing changes with thickness and reset voltage

Outline

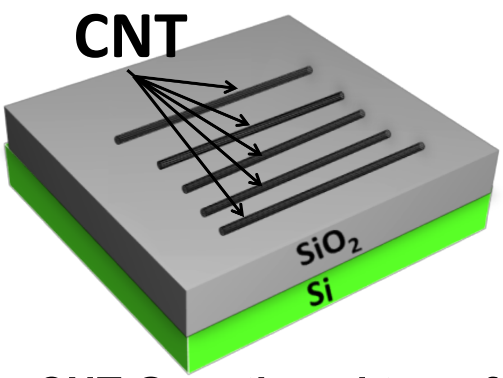
- Phase Change Memory (PCM) Basics
- Phase Change Material Scaling using GeTe Nanoparticles
- 1D Thickness Scaling Studies using Additional Top Electrode (ATE) Devices
- **Programming Current (Electrode) Scaling using CNTs**
- Micro Thermal Stage (MTS) - An On-Chip Heater and Thermometer to Study PCM Physics
- Conclusion

Phase Change Memory Scaling to ~1µA Prog. Current

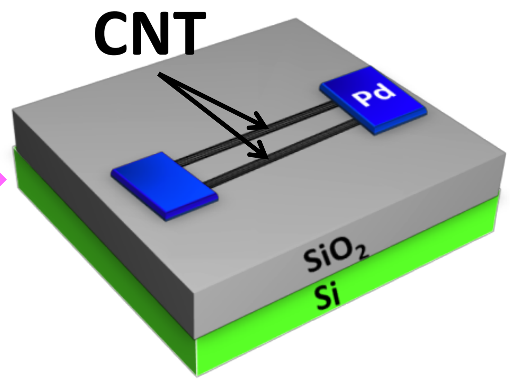


J. Liang et al., *Symp. VLSI Tech.*, paper 5B-4, 2011 (best paper award); *T-ED* p. 1155 (2012)

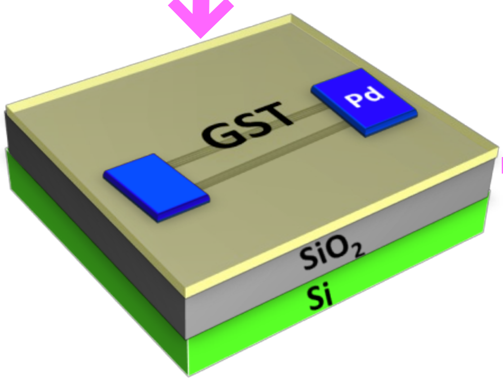
Phase Change Memory w/ Carbon Nanotube Electrode



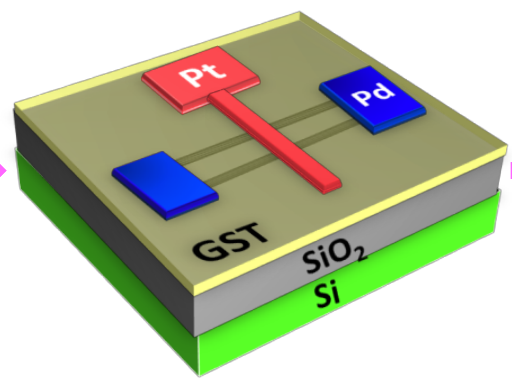
CNT Growth and transfer on SiO_2/Si substrate



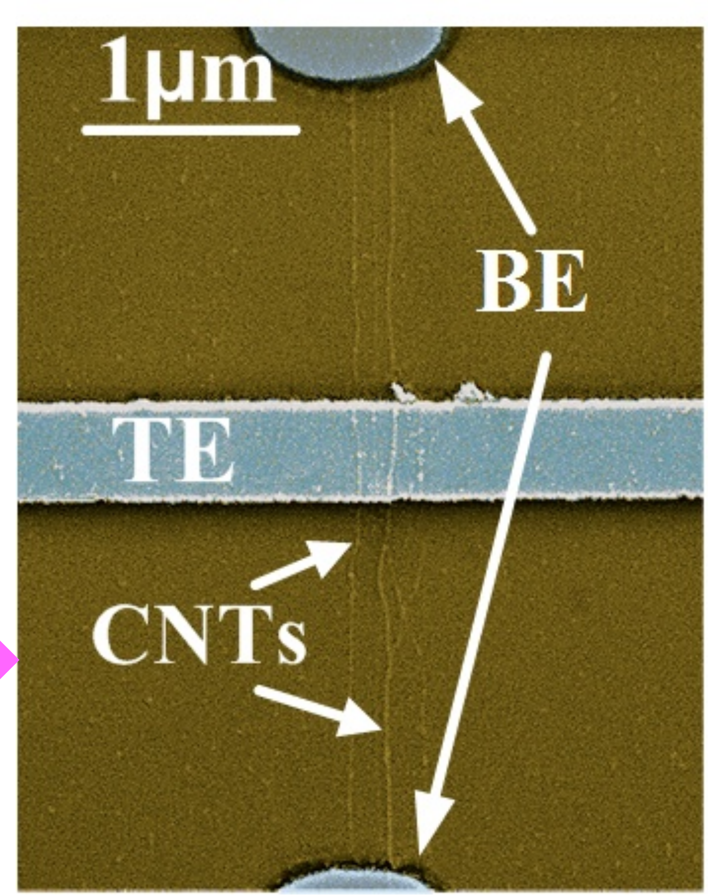
Pd metal pad evaporation and O_2 plasma etch to remove unwanted CNTs



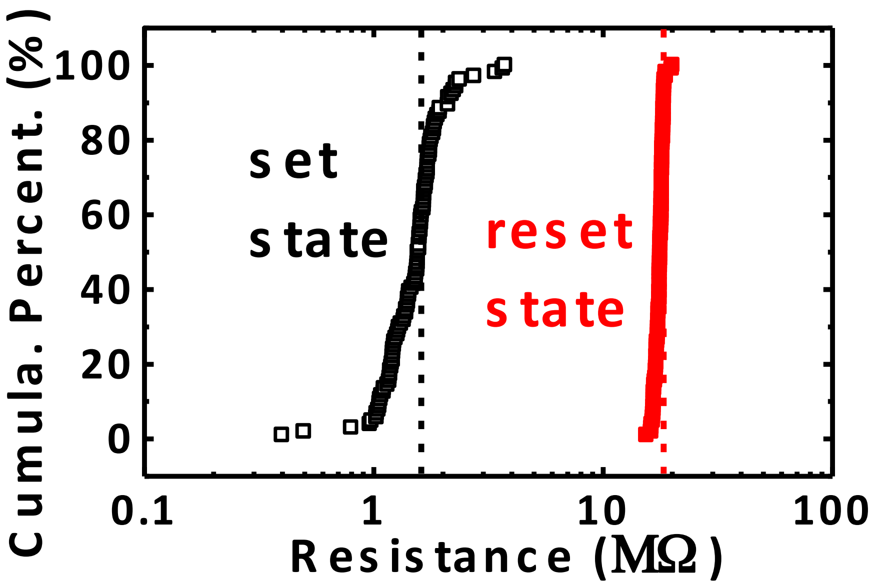
10nm GST deposition



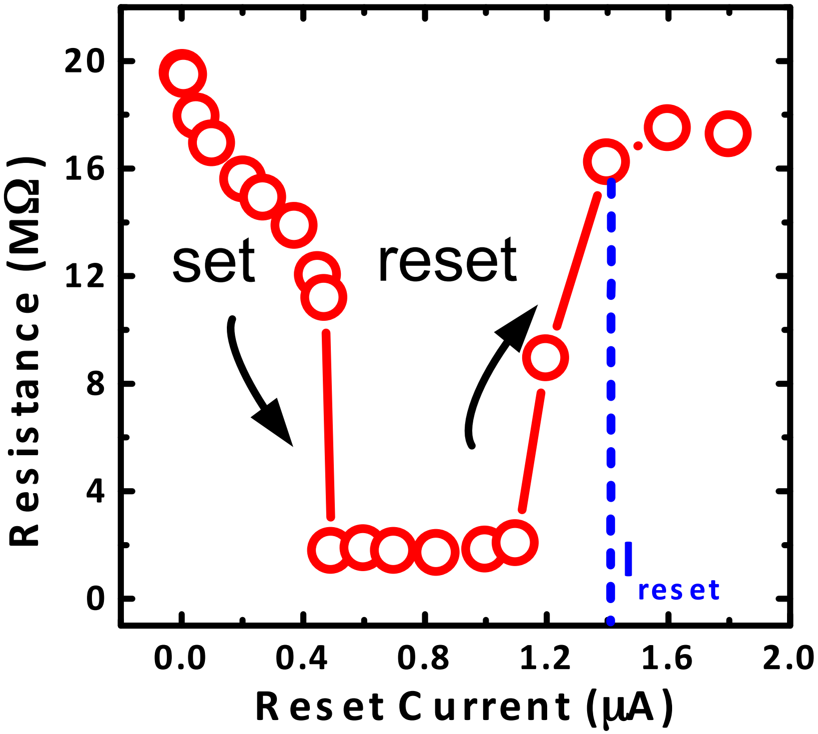
Pt/Ti metal pad evaporation and Al_2O_3 passivation



PCM with CNT Electrode



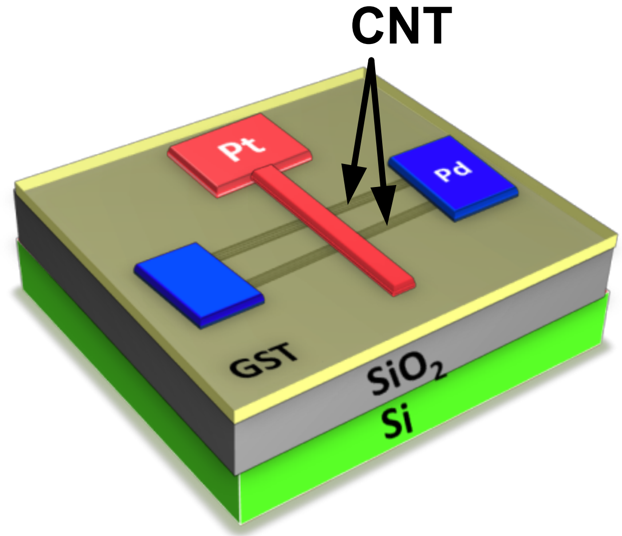
50 ns reset pulse



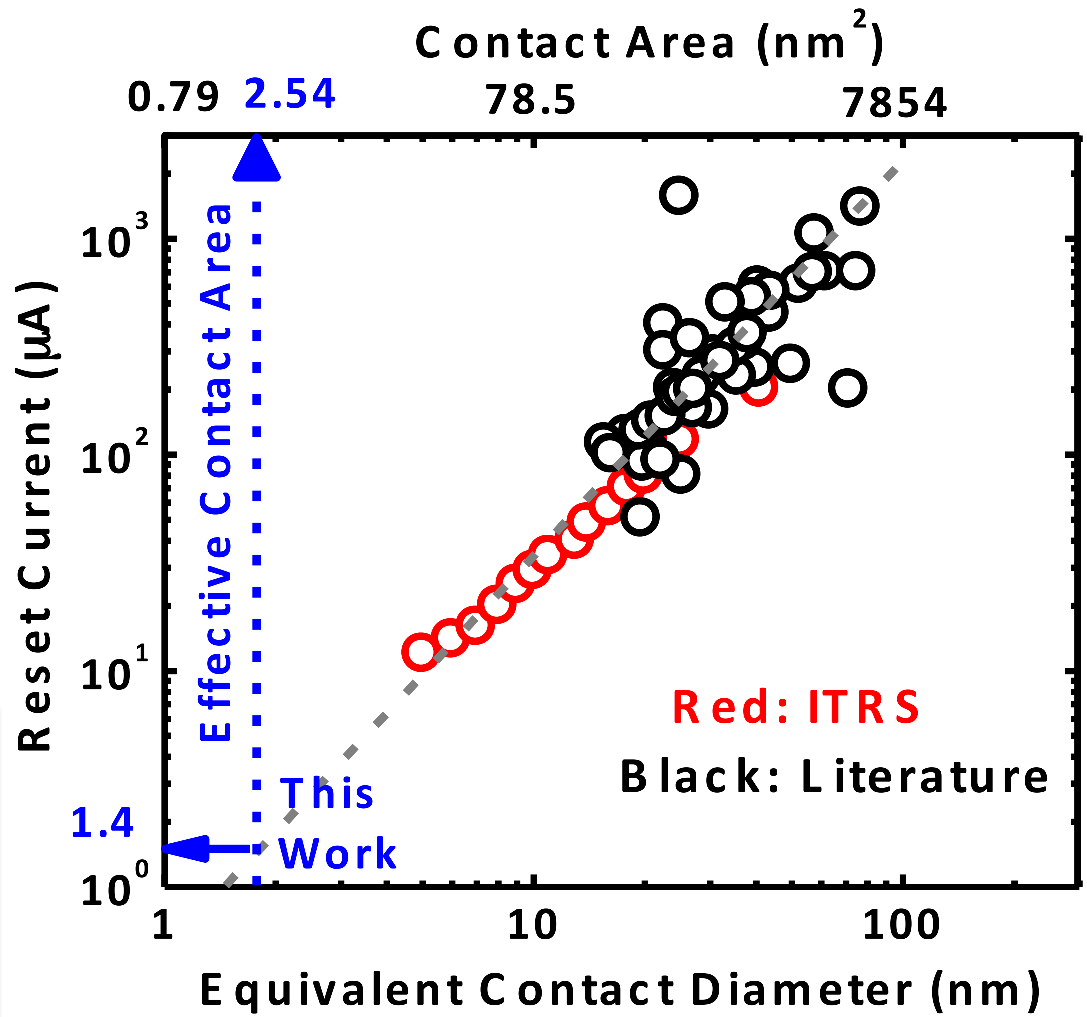
Reset current = 1.4 μA
100X lower than state-of-the-art

J. Liang *et al.*, *Symp. VLSI Tech*. 2011

Phase Change Memory Scaling to 1.8 nm Node



Reset current: 1.4 μA,
Energy: 210 fJ/bit
→100X lower than state-of-the-art



J. Liang et al., *Symp. VLSI Tech.*, paper 5B-4, 2011 (best paper award); *T-ED* p. 1155 (2012)

Scaling Studies - Summary

- **Scaling is a complex question**
- **GeTe Nanoparticles offer a route to investigate size dependent properties**
  - Ability to solution process PCM opens options for device geometries
- **ATE devices allow scaling studies in a more practical device design**
  - Study threshold voltage scaling
  - Trap spacings can be directly measured
  - Aids in developing accurate models for sub-threshold conduction
- **CNTs have been shown to be an effective way to probe electrode scaling**
  - Extremely low RESET current and programming energy

Scaling of Phase Change Memory – Strong prospects of scaling down to few nm both at the materials and the device level

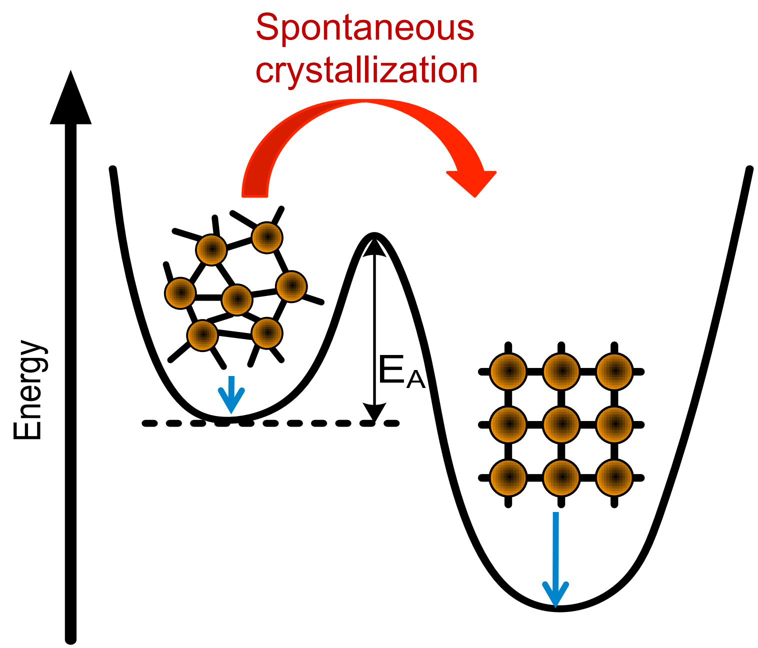
Outline

- Phase Change Memory (PCM) Basics
- Phase Change Material Scaling using GeTe Nanoparticles
- 1D Thickness Scaling Studies using Additional Top Electrode (ATE) Devices
- Programming Current (Electrode) Scaling using CNTs
- **Micro Thermal Stage (MTS) - An On-Chip Heater and Thermometer to Study PCM Physics**
- Conclusion

Memory Loss Mechanism in PCM

1. Spontaneous crystallization

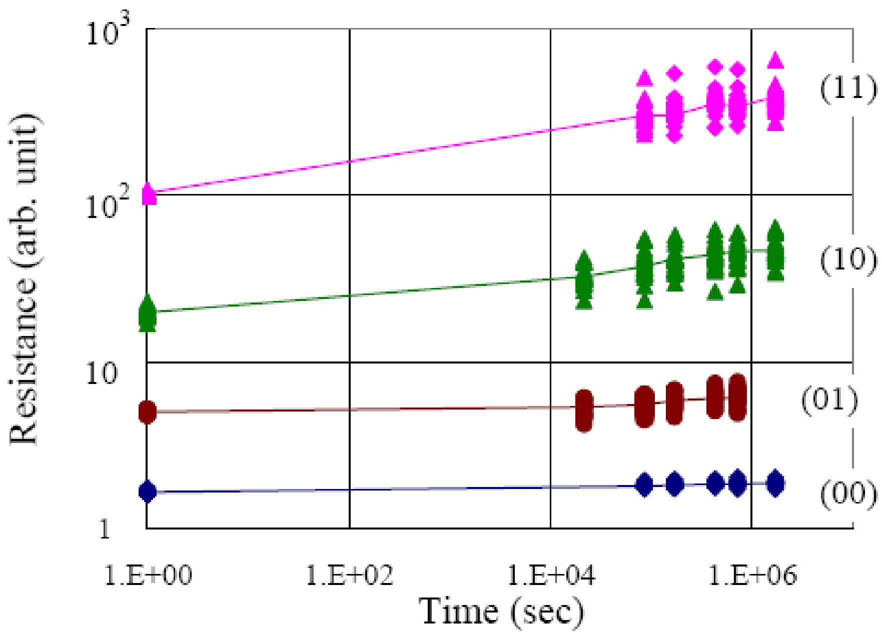
- **Crystalline phase is more stable.**



2. Multi-bit cell & drift

- **Resistance drift**

→ Smaller margin



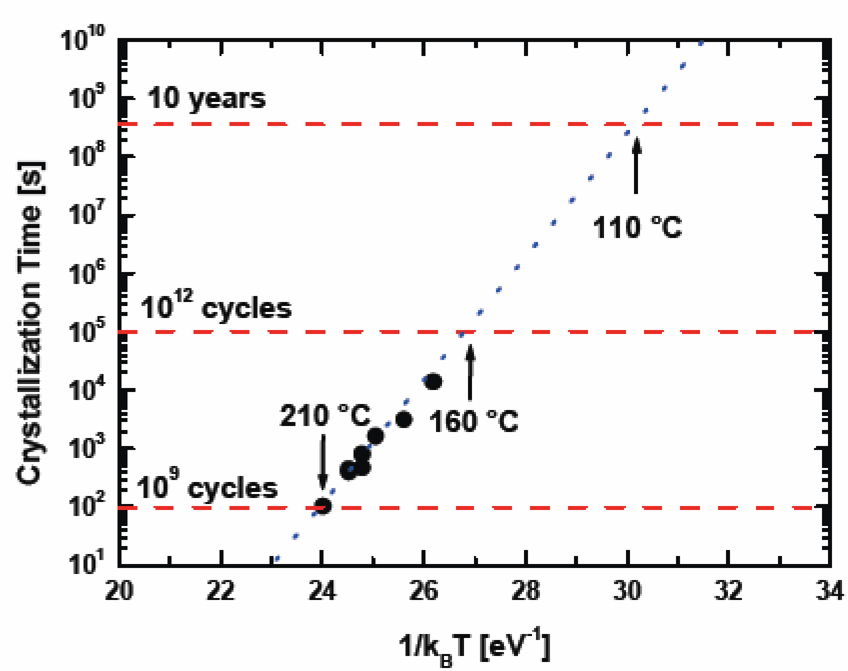
D.-H. Kang et al., *Symp. VLSI. Tech.*, 2008.

Temperature Dependence of Reliability Issues

Spontaneous crystallization

- **Higher temperature**

→ Faster crystallization.

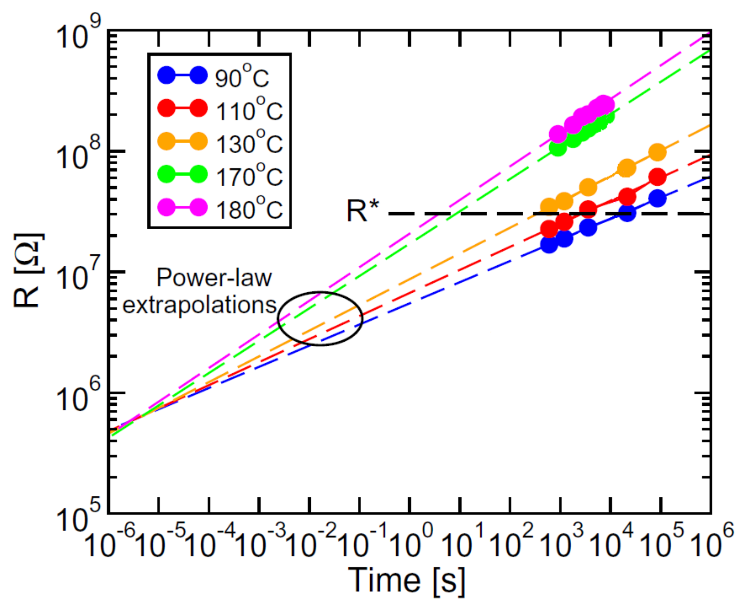


A. Pirovano et al., *IEDM*, 2003.

Drift (R_{RESET} + V_{th})

- **Higher temperature**

→ Faster drift



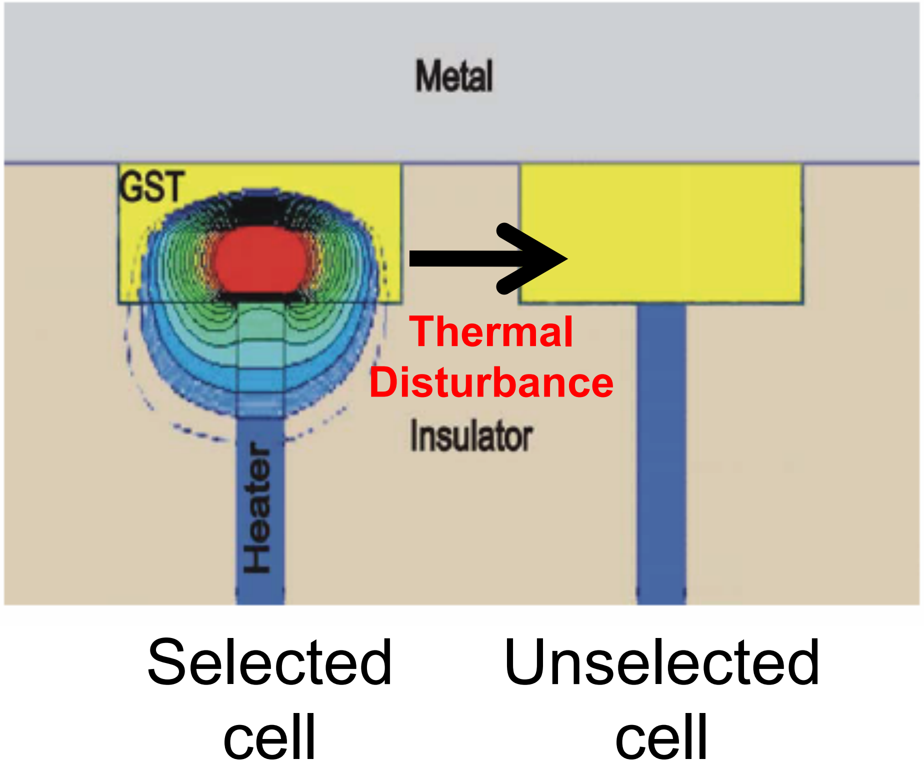
D. Ielmini et al., *Microelectronic Engineering*, v. 86, p.1942, 2009.

Thermal (program) Disturbance in PCM

- **PCM uses heat for programming.**

→Thermal disturbance in PCM.

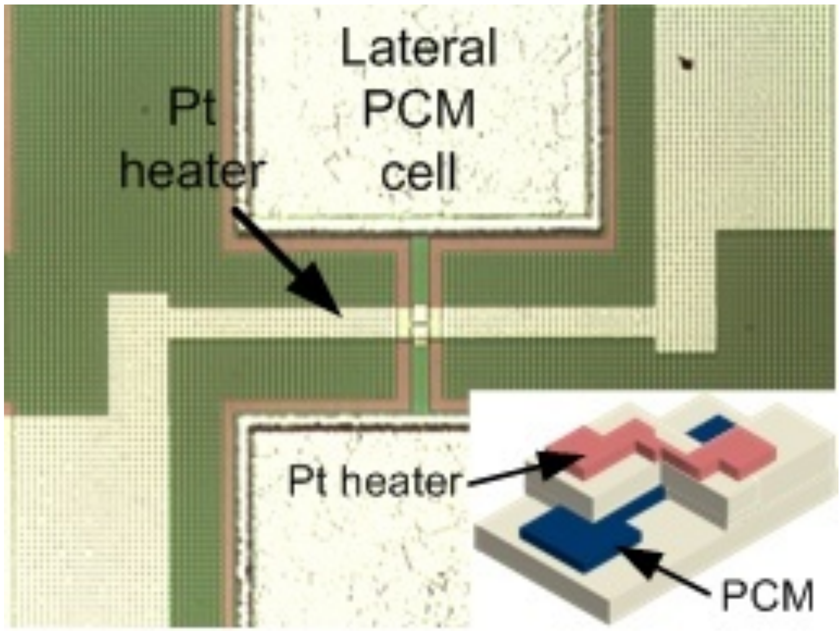
- **Thermal disturbance makes reliability issues worse – especially for scaled devices**



A.Pirovano et al., *IEDM*, 2003.

Micro-thermal stage (MTS)

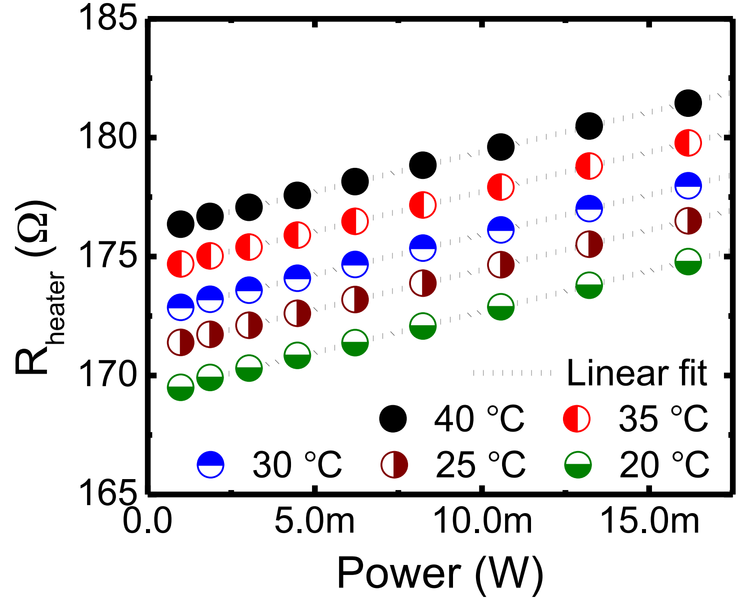
An external heater integrated with the PCM cell



- **Lateral PCM cell + Pt heater on top**
- **Thermal time constant: ~1.5 μs**

S. Kim et al., IEEE Tran. Elec. Dev. Vol. 58, pp. 584, 2011

Temperature calibration on the external heater

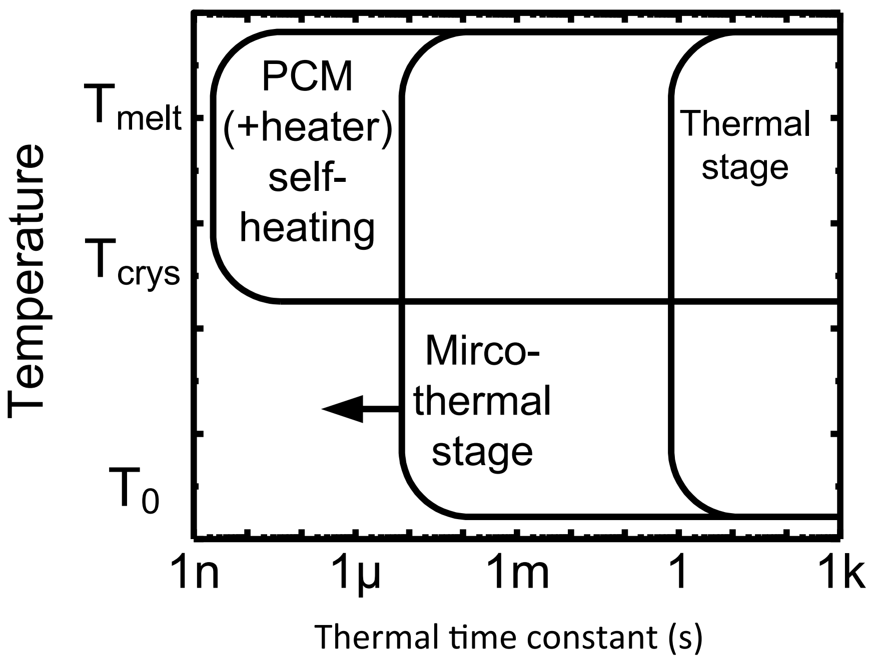


$$R_{heater} = R(T_0) + \beta\Delta T$$

$$\Delta T_{heater} \propto Power$$

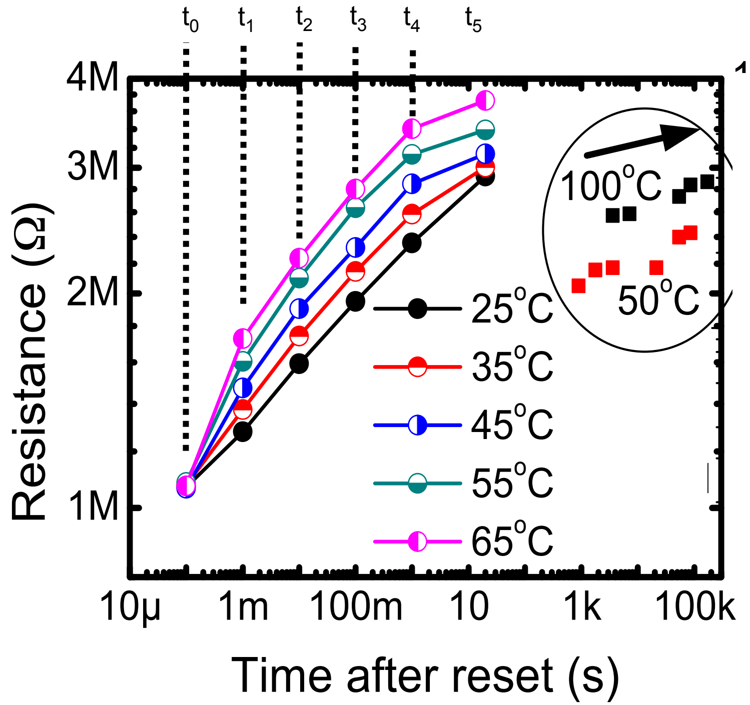
- **Pt bridge: Heater + thermometer**

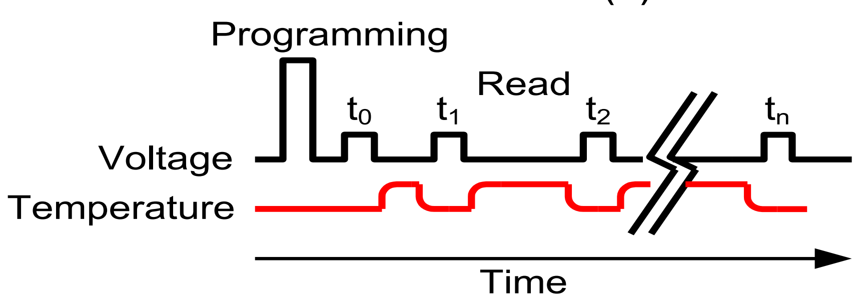
Need for a Micro – Thermal Stage (MTS)

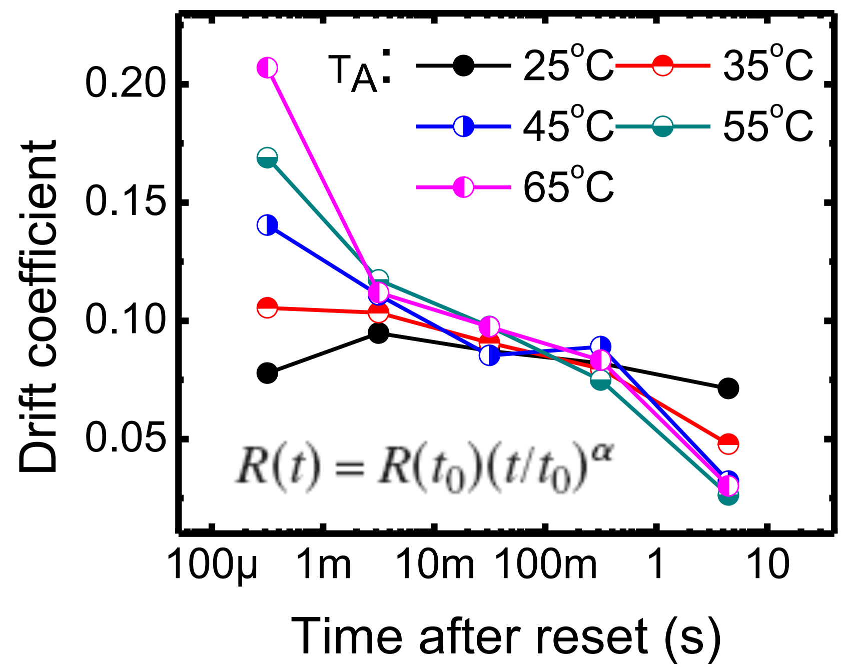


- Enables temperature measurements closer to real device operating conditions
- MTS – allows fast measurements of drift and crystallization on real PCM devices
- Measurements on technologically relevant melt-quenched amorphous phase
- Study the effect of electronic and thermal effects in isolation

R_{RESET} Drift Measurement



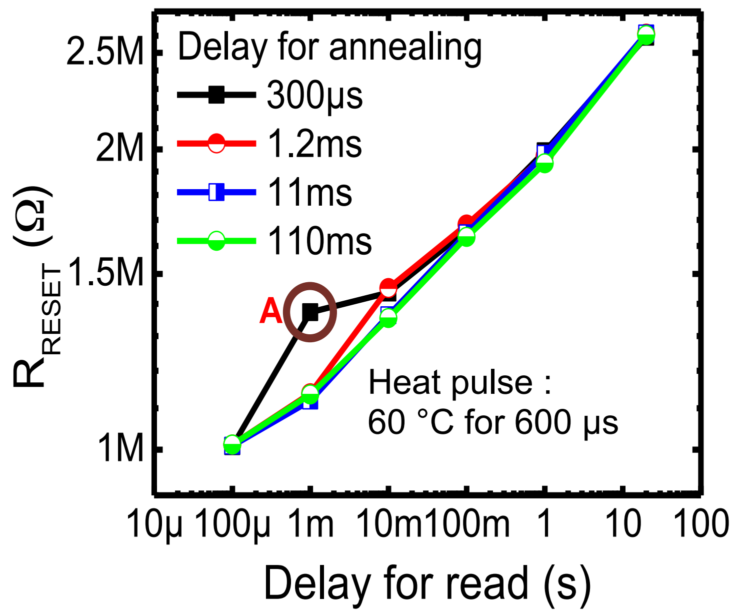


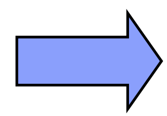


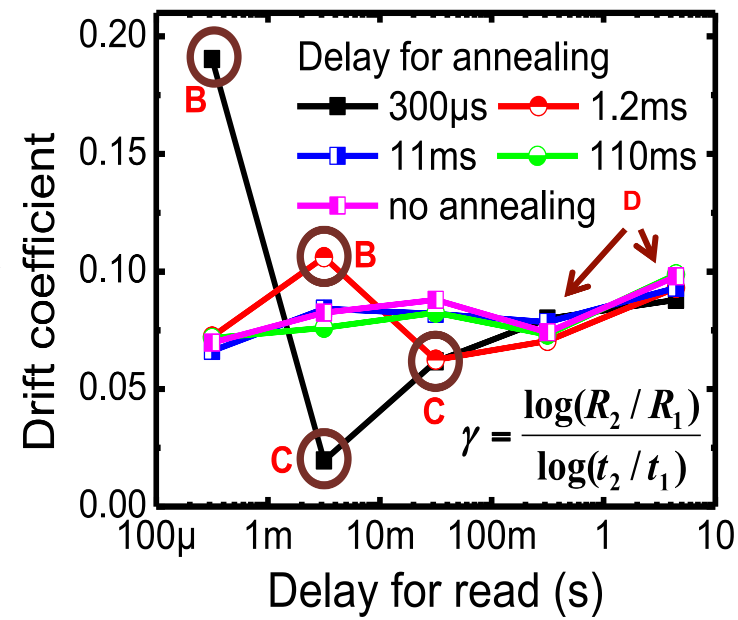
- **Faster drift at higher T_A.**
- **3 times larger drift coefficient between 100 μs and 1 ms at 65 °C**

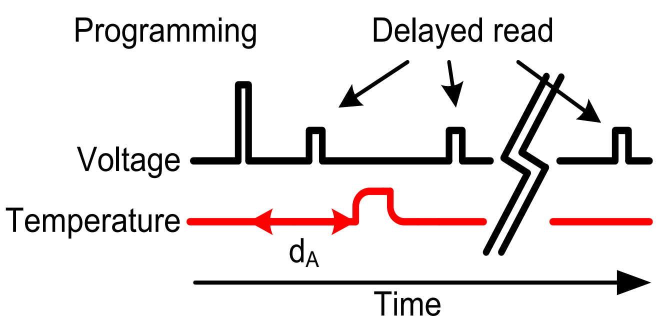
S. Kim et al., IEEE Tran. Elec. Dev. Vol. 58, pp. 584, 2011

R_{RESET} Drift Impacted by Thermal Disturbances





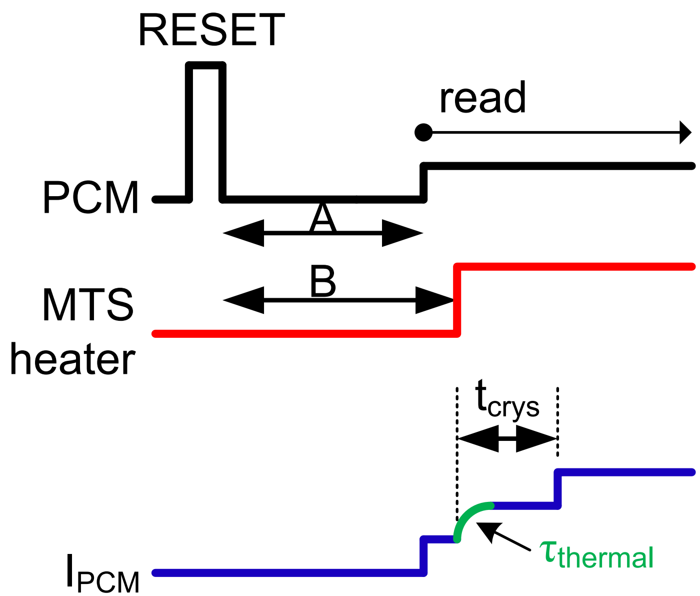




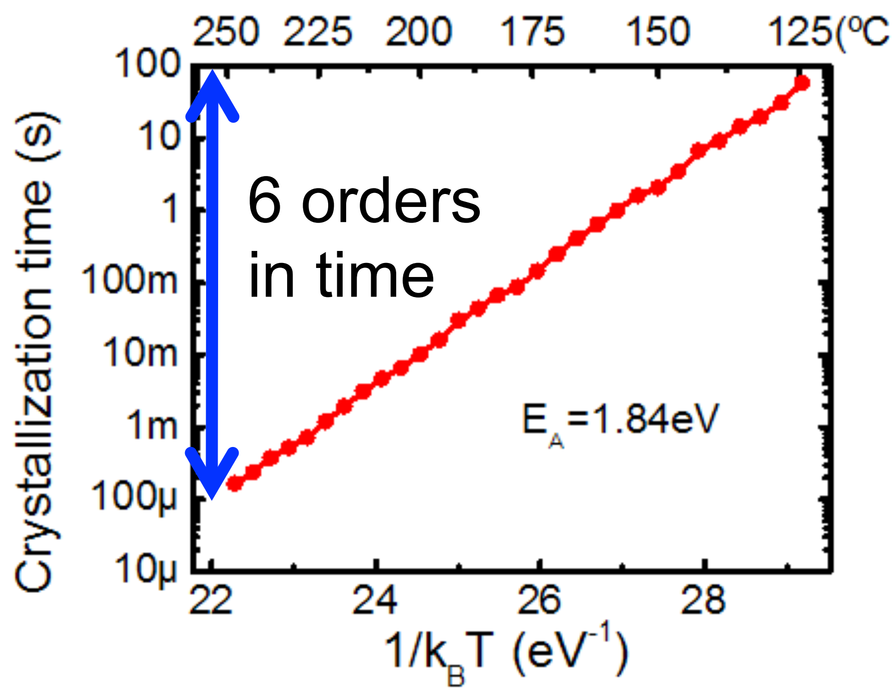
d_A: Delay for annealing (TD)

- Important features
  - A: ~25% variation on resistance.
  - B: Drift is faster
  - C: Drift is slower
  - D: No change (>100ms)

Crystallization Time (t_{crys}) Vs Temperature (T)

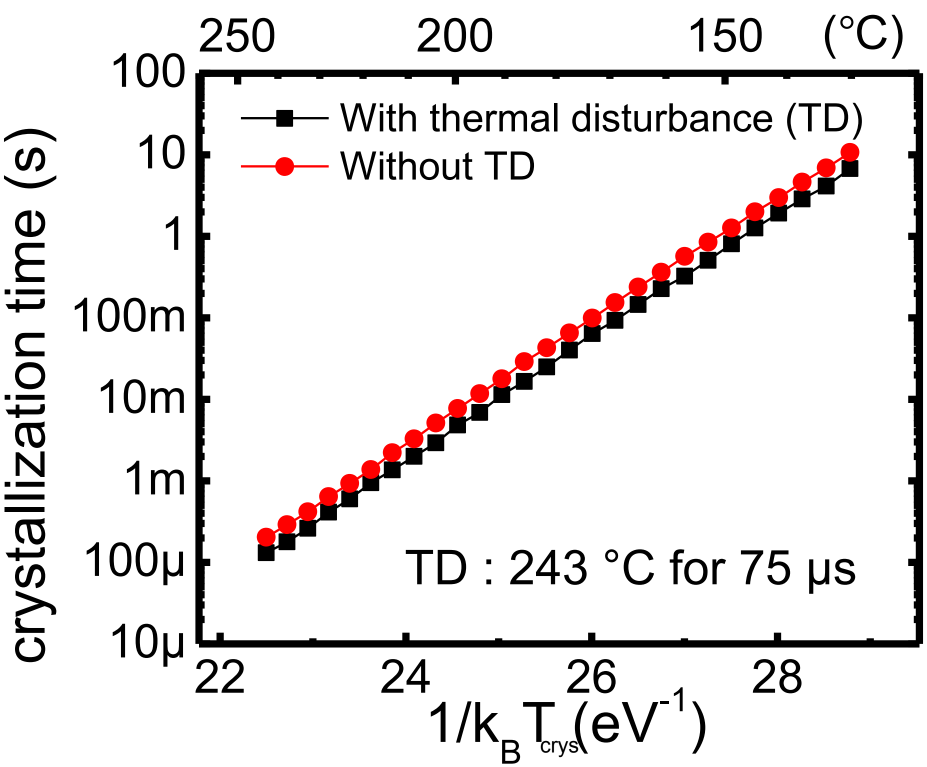


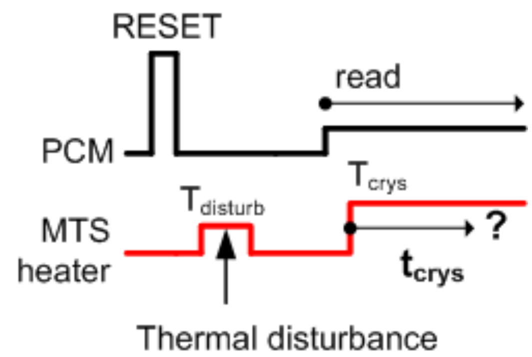
A : Delay for read
B : Delay for annealing



- **Current MTS enables t_{crys} measurement down to ~100μs.**
- **Arrhenius behavior with constant activation energy (E_A)**

Crystallization Time (t_{crys}) with Thermal Disturbance





$$v_{crys}(T) = \frac{1}{t_{crys}(T)}$$

$$r_{crys} = \int v_{crys}(T(t))dt$$

v_{crys}: Crystallization speed
r_{crys}: degree of crystallization

- **Constant shift in log(t_{crys})**
  → The t_{crys} ratio is constant.

S. Kim et al., IRPS 2010

Effects of Temperature on PCM Reliability - Summary

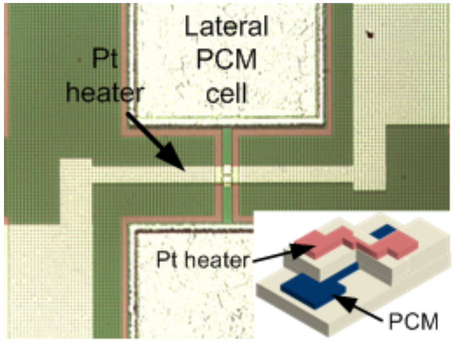
- Spontaneous crystallization and Resistance drift – major reliability issues of PCM
- Significantly impacted by short thermal disturbances – variability in the retention and drift behavior
- Use of Micro Thermal Stage – fast heater and thermometer to study the reliability physics in short time scales

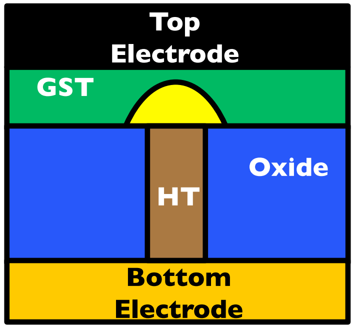
Non-Volatile Memory Technology Research Initiative (NMTRI) at Stanford University

Technical Collaborators on Memory

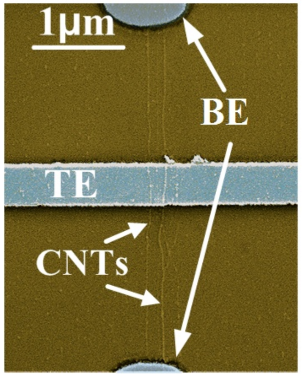
Methodologies to Study Scalability and Physics of PCM

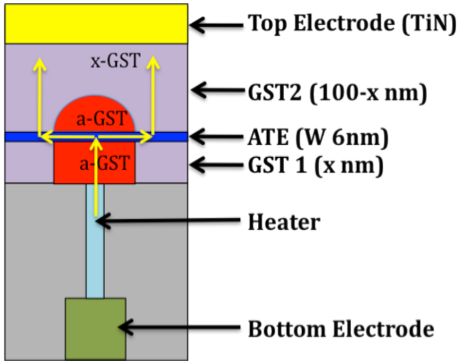
Understanding Physics & Reliability





Device Scaling





Material Scaling