Phase-Change Memory Devices: Fundamentals and Applications (Part I)

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Oxford, March 18, 2019

Acknowledgements

- **Neuromorphic and in-memory computing**
  - ✓ Thomas Bohnstingl
  - ✓ Irem Boybat
  - ✓ Iason Giannopoulos
  - ✓ Riduan Khaddam-Aljameh
  - ✓ Benedikt Kersting
  - ✓ Christophe Piveteou
  - ✓ Vinay Joshi
  - ✓ S. R. Nandakumar
  - ✓ Timoleon Moraitis
  - ✓ Stanislaw Wozniak
  - ✓ Varaprasad Jonnalagadda
  - ✓ Manuel Le Gallo
  - ✓ Angeliki Pantazi
  - ✓ Giovanni Cherubini
  - ✓ Evangelos Eleftheriou
- **Foundations of cognitive solutions**
- **Cloud storage and analytics**
- **IBM TJ Watson Research Center**
- **IBM Research-Almaden**
- **NJIT, Univ. of Patras, RWTH Aachen, ETH, EPFL, Exeter, Oxford**

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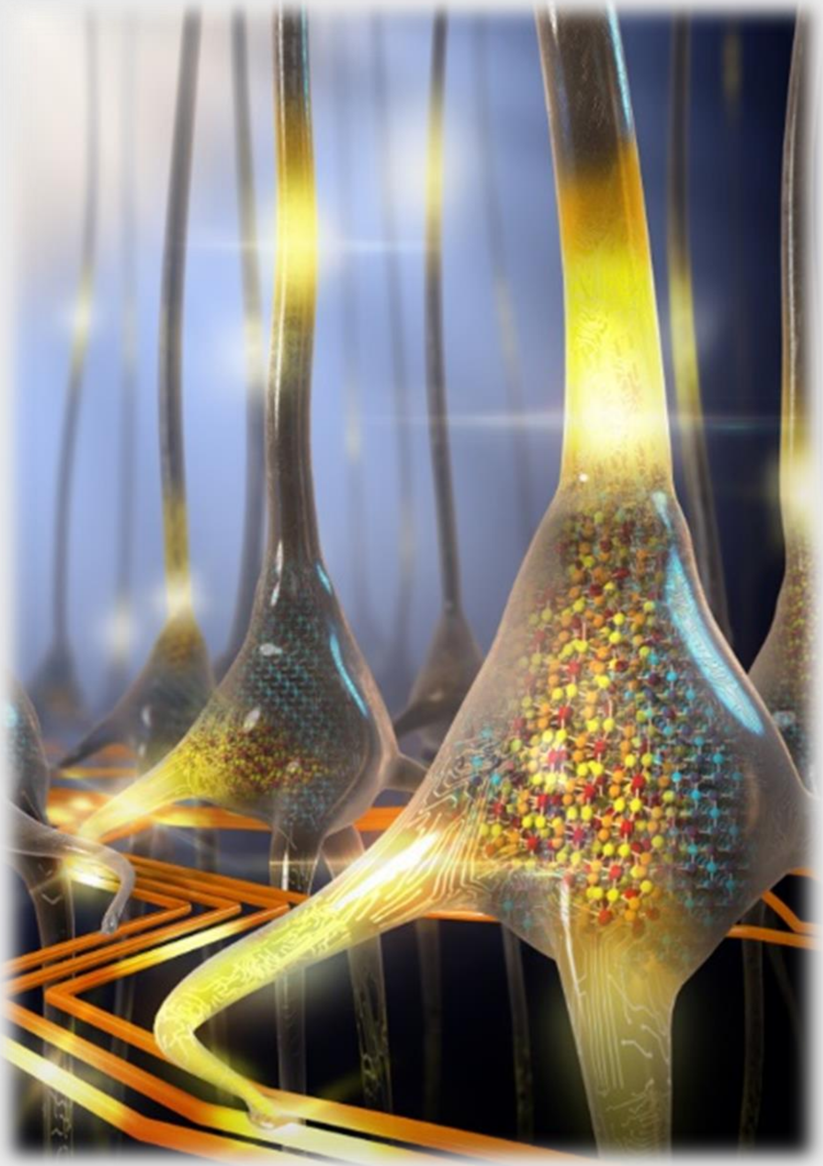
Outline: Part I

- **Introduction to PCM**
- **PCM device physics**
  - ✓ **Electrical system**
    - Subthreshold electrical transport
    - Threshold switching
  - ✓ **Thermal system**
  - ✓ **Structural dynamics**
    - Melt-quench process
    - Crystallization
    - Structural relaxation
- **Key challenges and device-level advances**
  - ✓ Projected PCM
  - ✓ Single-elemental PCM



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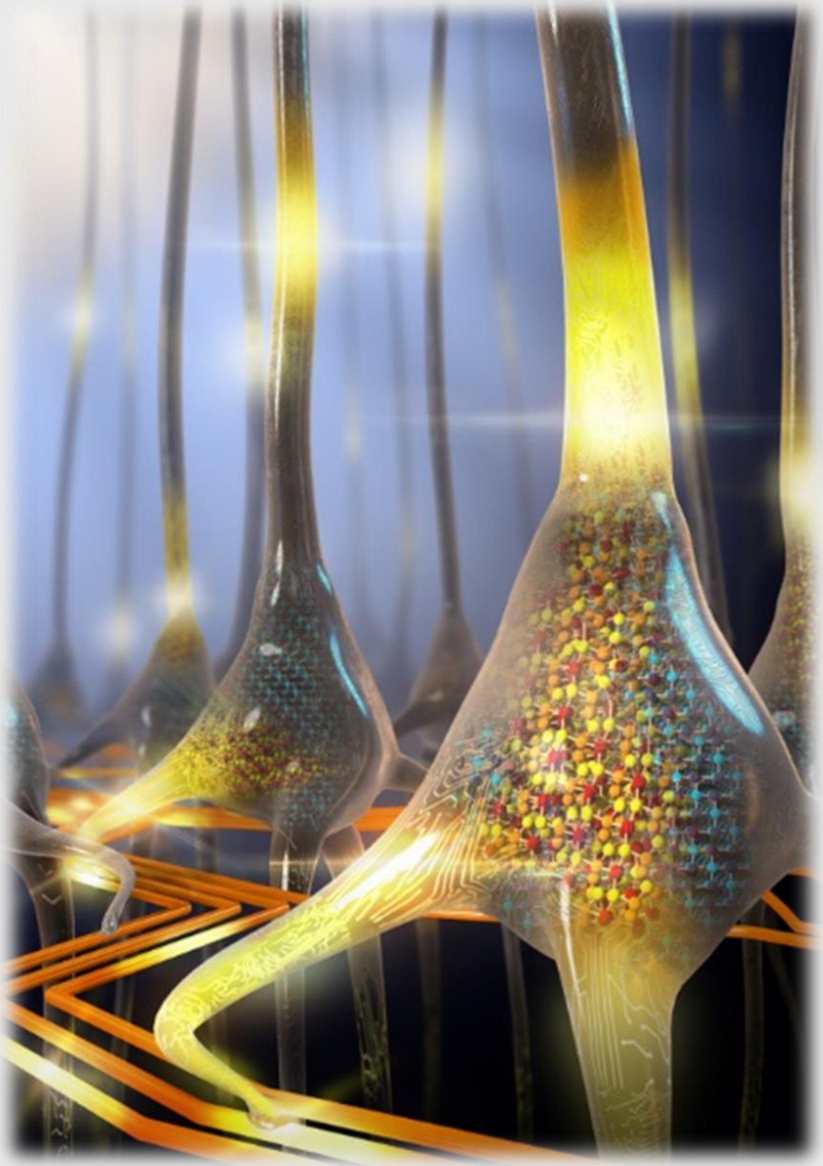
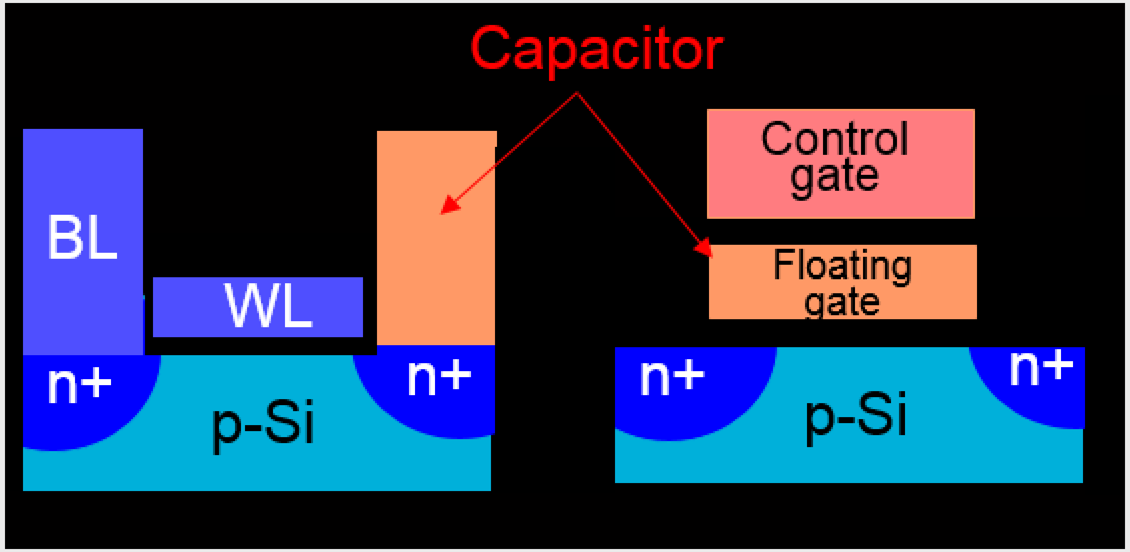
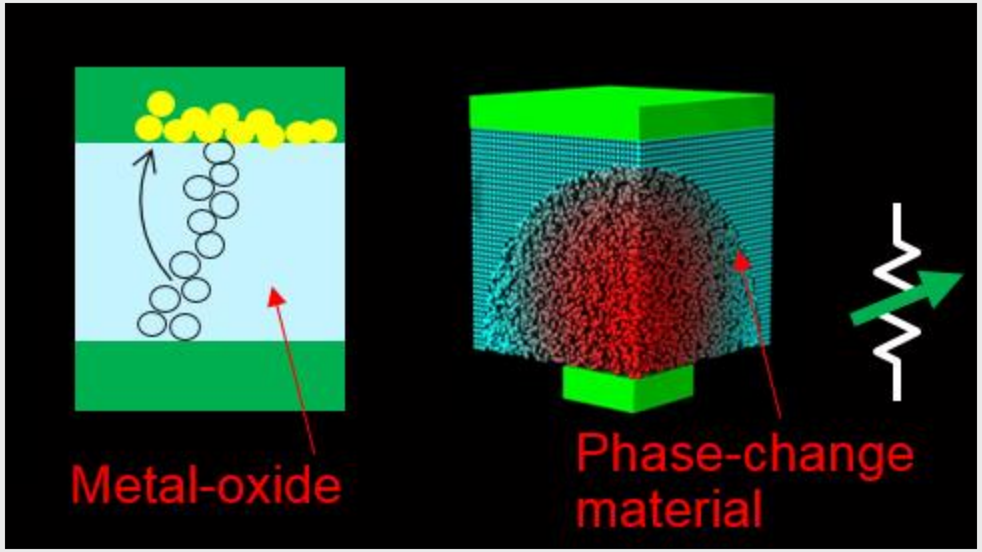


Resistive memory devices

“Charge on a capacitor”



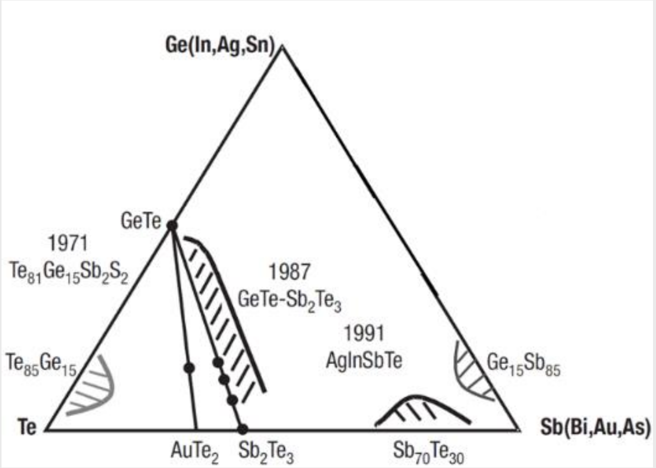
“Alternate atomic arrangements”



- Difference in atomic arrangements induced by the application of electrical pulses and measured as a difference in electrical resistance
- **Resistive memory devices** or “**memristive**” devices
- Based on physical mechanisms such as **ionic drift** and **phase transition**

Phase-change memory

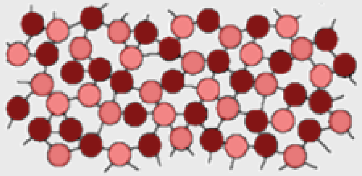
Commonly used phase change materials



Wuttig & Yamada, Nature Materials, 2007
Burr et al., JETCAS, 2016

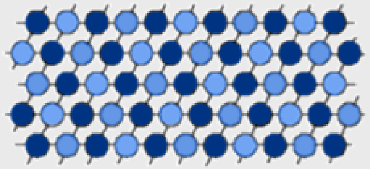
- A nanometric volume of phase change material between two electrodes
- "WRITE" Process
  - ✓ By applying a voltage pulse the material can be changed from crystalline phase (SET) to amorphous phase (RESET)
- "READ" process
  - ✓ Low-field electrical resistance

Amorphous

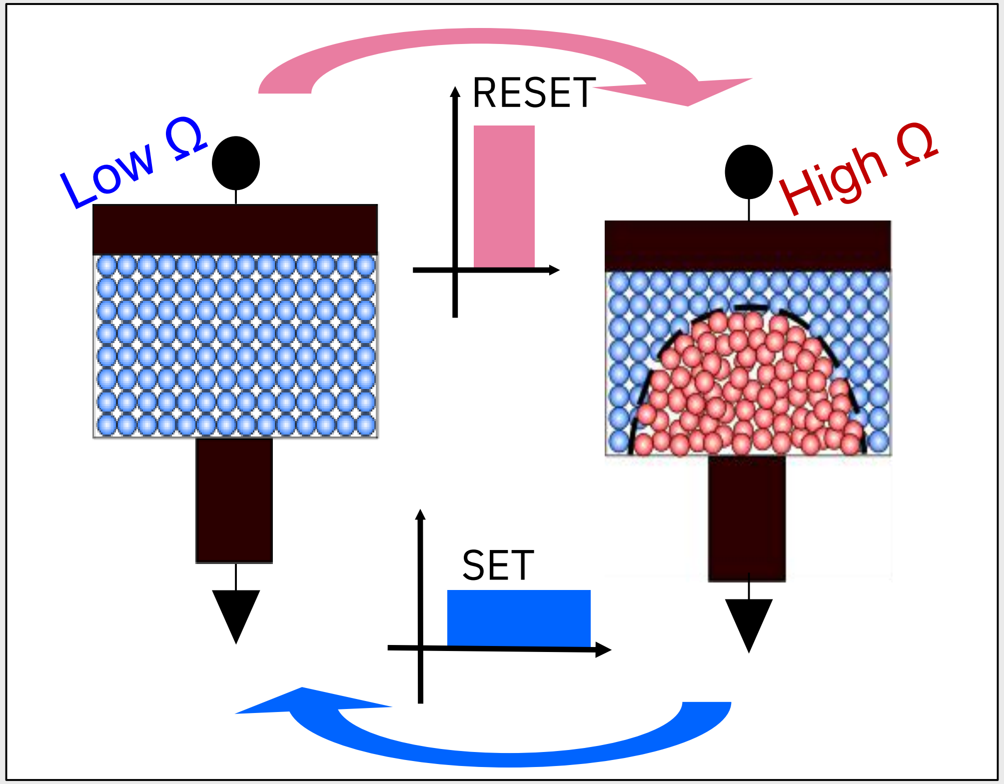


Disordered, high resistance

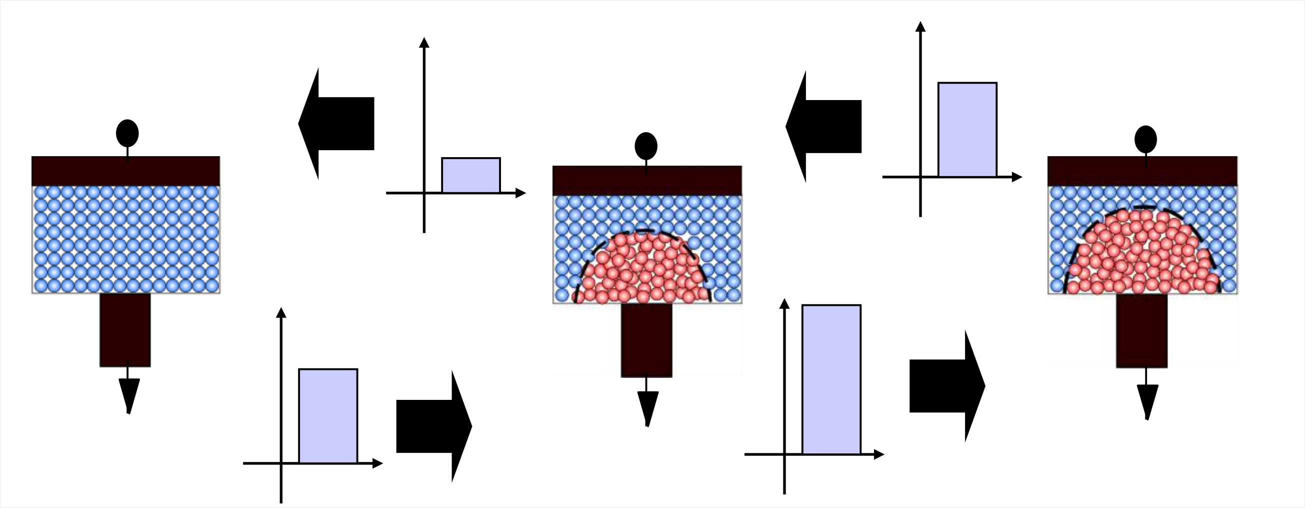
Crystalline

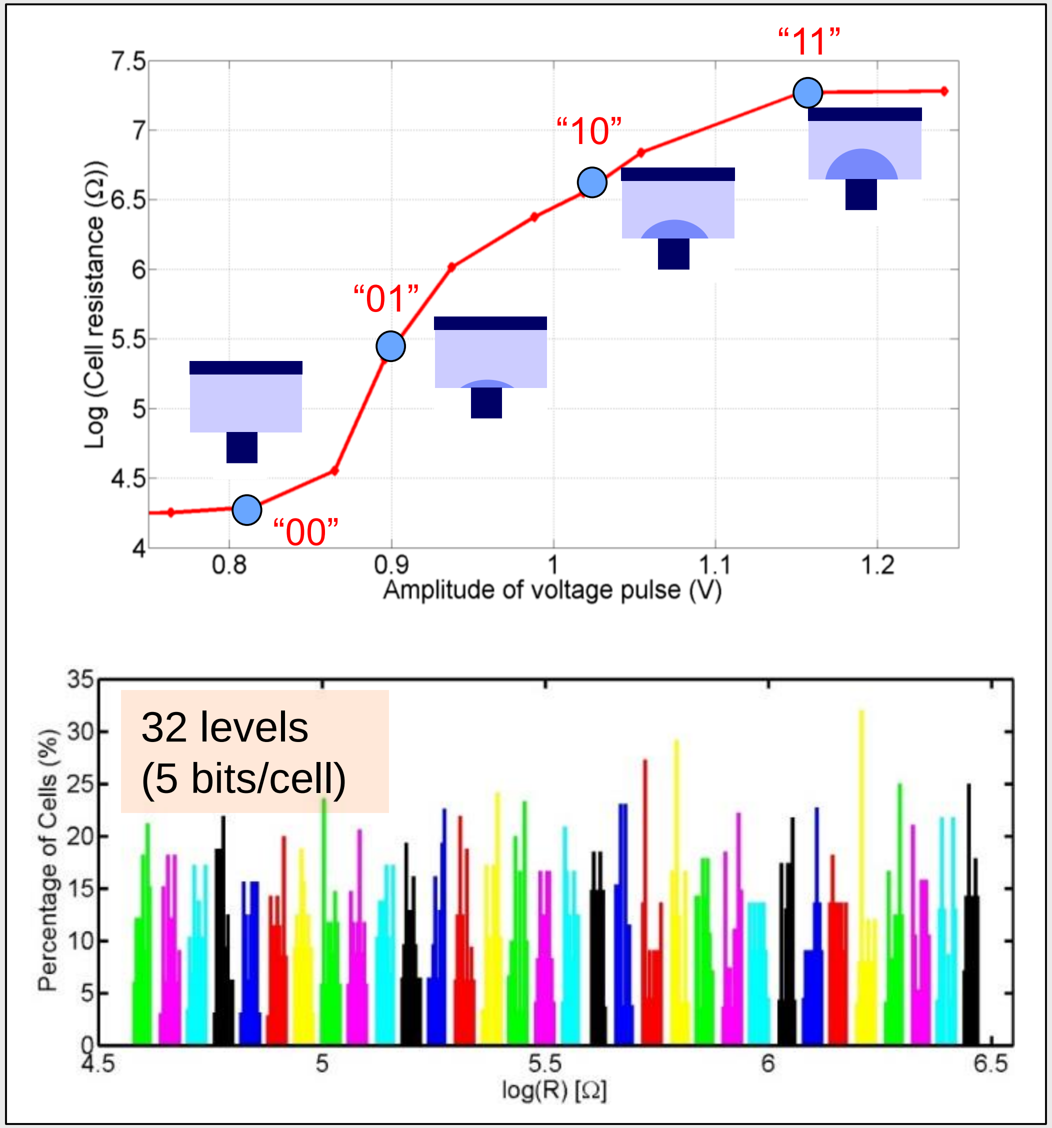


Ordered, low resistance



Multi-level storage



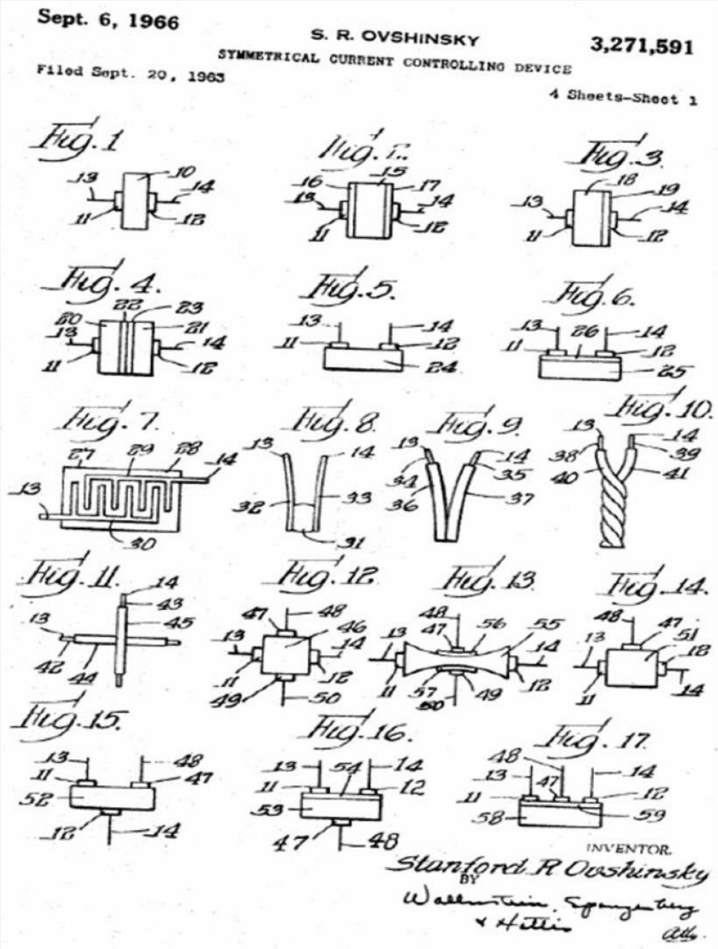


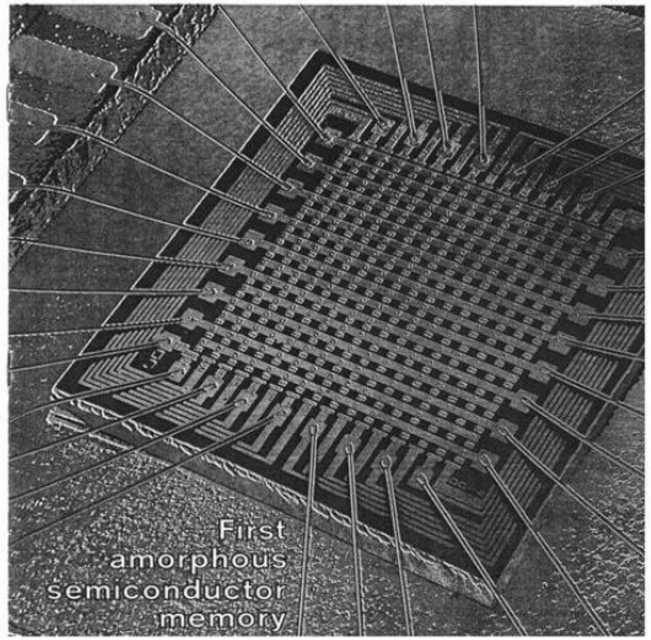
- It is possible to continuously vary the crystalline/amorphous phase configuration and hence the resulting electrical resistance
- Can store more than 1 bit of information in a cell

Papandreou et al., ISCAS, 2011

A brief history of phase change memory

Stan Ovshinsky (1960s)





R. G. Neale, D. L. Nelson and G. E. Moore., Electronics, 1970

Capacity: 256 bits
RESET: ~200mA, <25V, 5 us
SET: 5mA, ~25V, 10ms
Read: 2.5mA, <5V

A brief history of phase change memory

Commercial success of optical recording

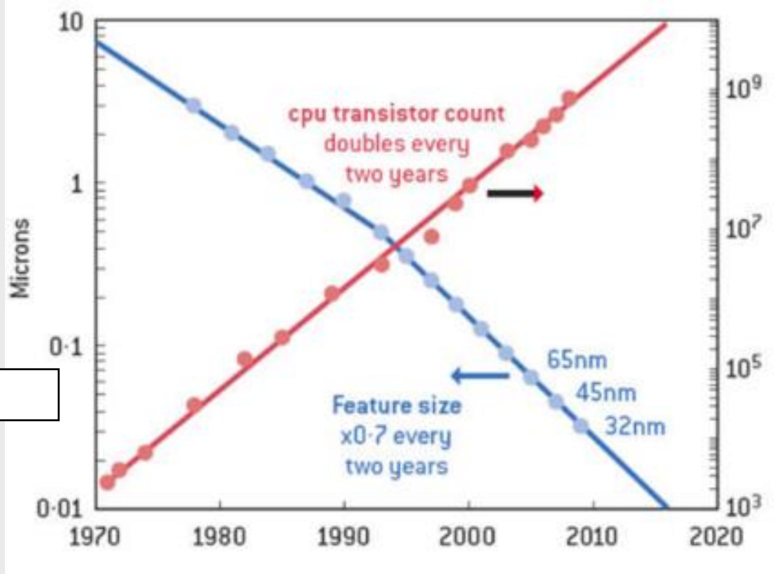
SET Speed

~10ms → ~100ns

~200mA → ~50uA

Write current

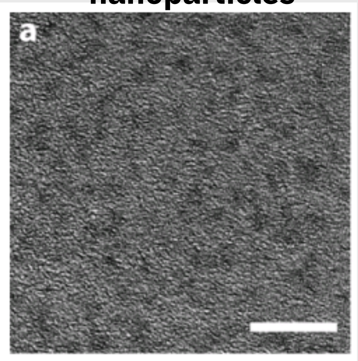
Advances in semiconductor manufacturing



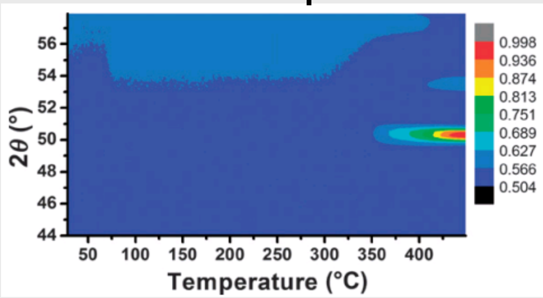
Scalability

IBM ARC/YKT & Stanford (2007-2009)
XRD studies of phase-change thin-films, nanodots, nanoparticles (1.8nm Ø)

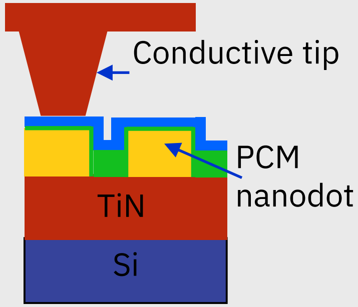
TEM picture of 1.8nm nanoparticles

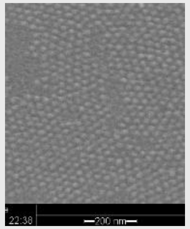


In-situ XRD pattern

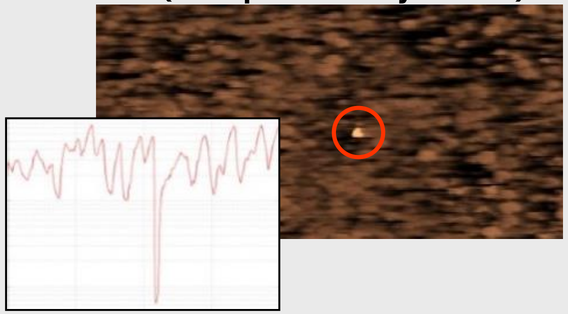


IBM-Zurich/Stanford (2009)
Joule-heating induced switching of single phase-change nanodots (~15nm Ø)

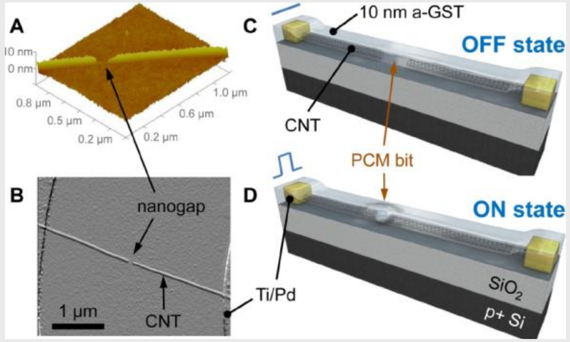


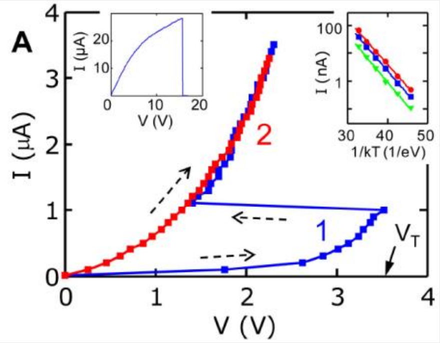


Switching of a single nanodot (amorphous → crystalline)



UIUC, Xiong et al., Science (2011)
Phase change material deposited between a carbon nanotube which has been ruptured
Nanotube diameter is ~2-3 nm

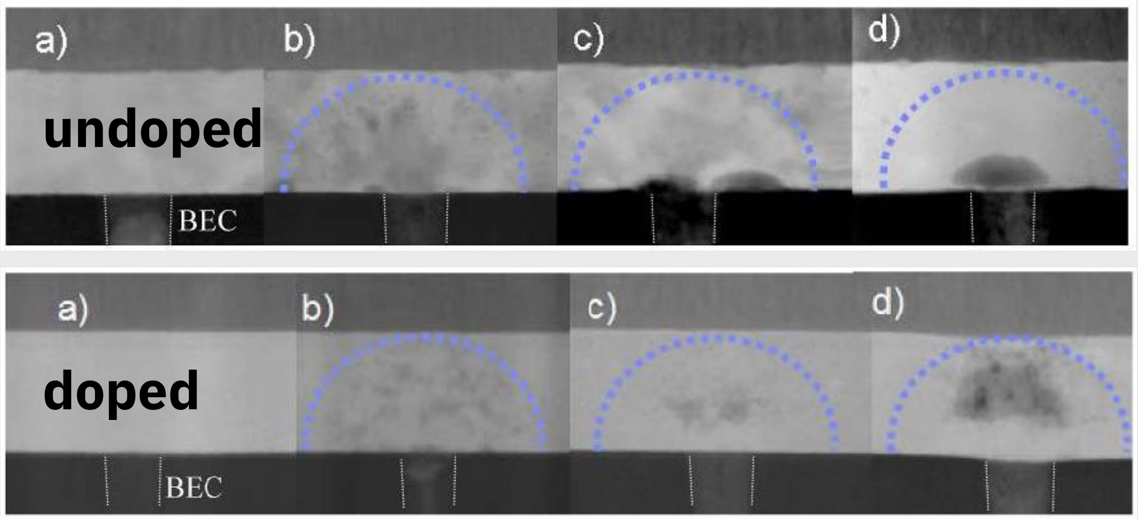




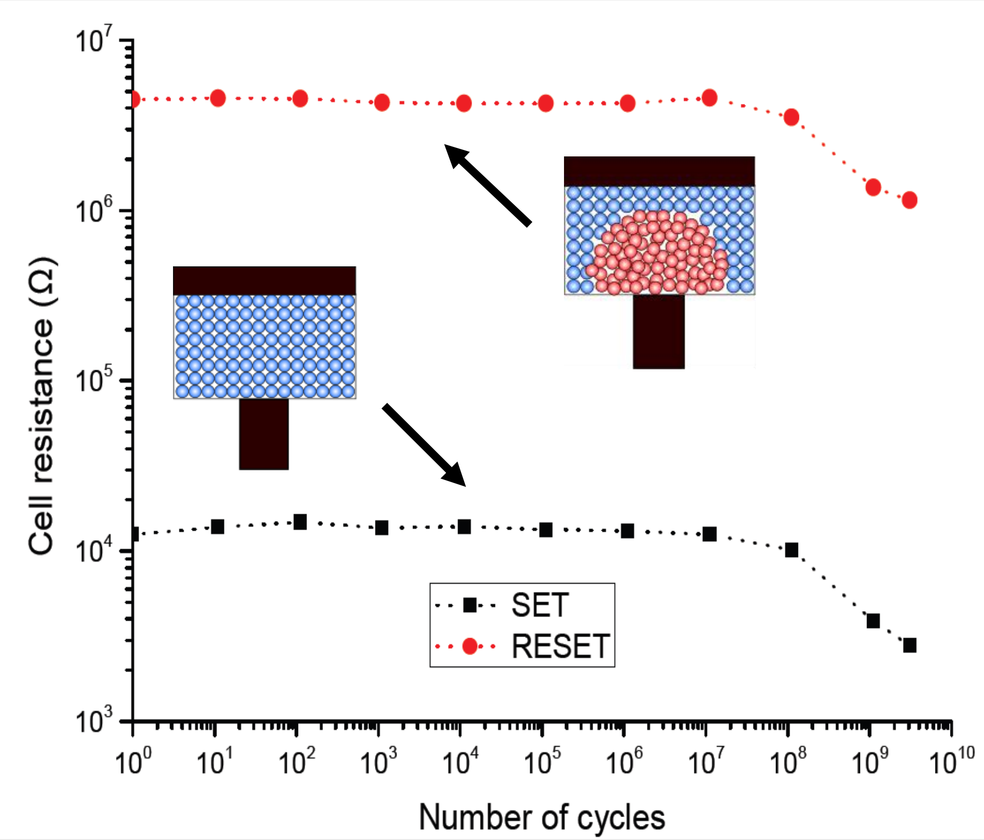
A phase change device can scale to a few nanometers

Cycling endurance

PCM cells with doped and undoped materials

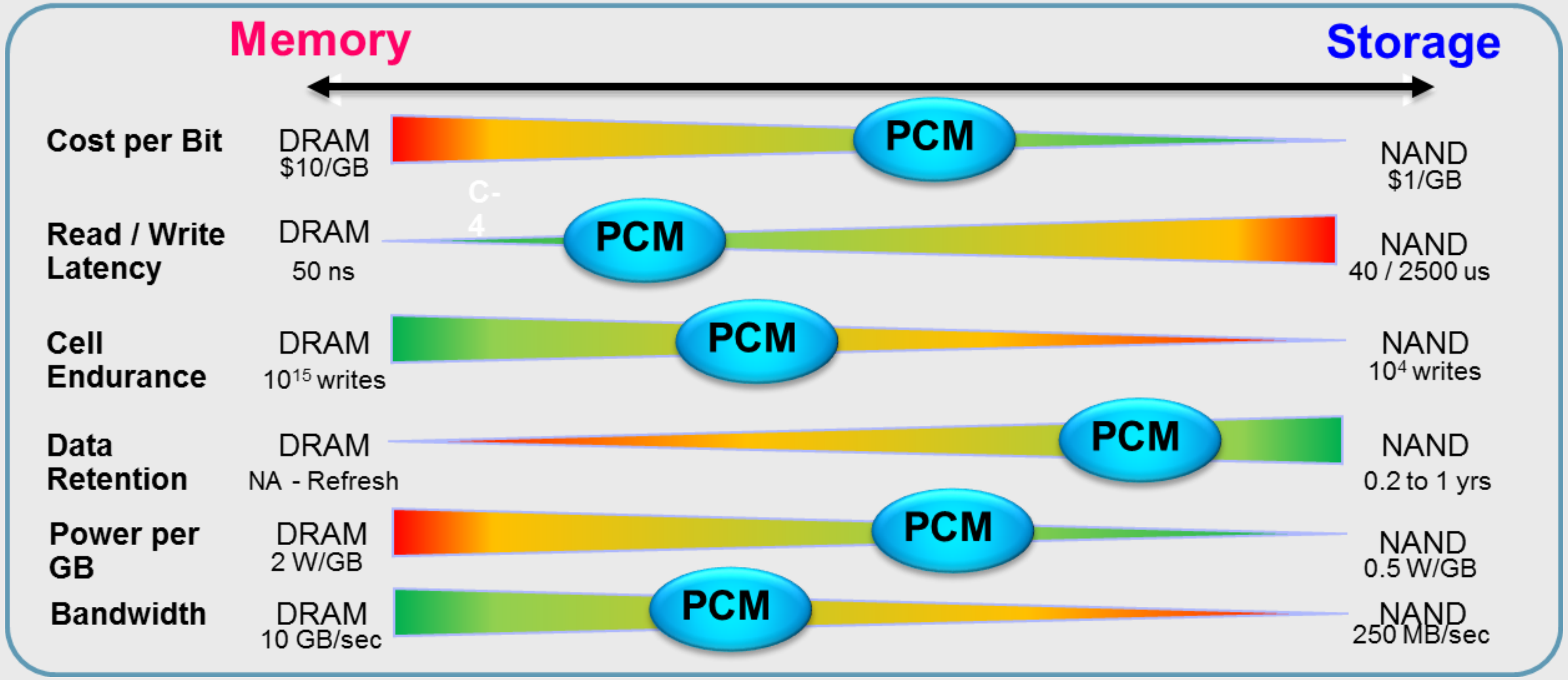


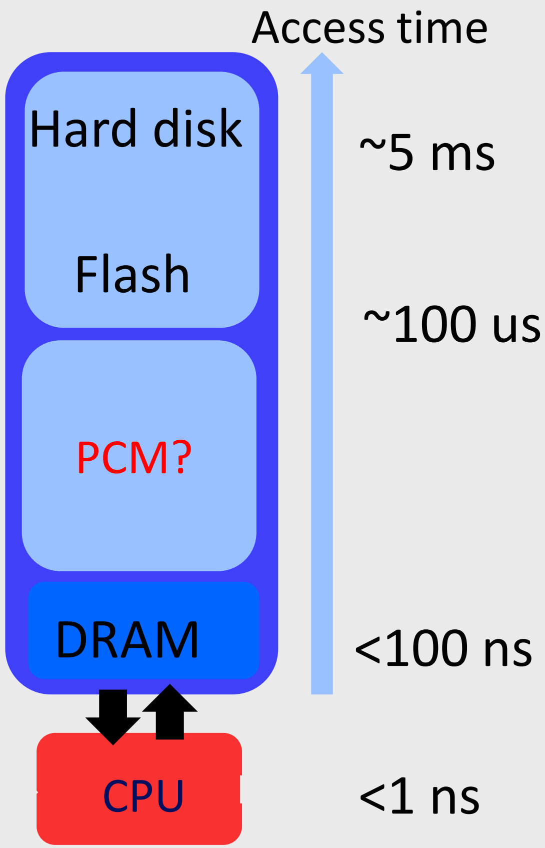
Chen et al., IMW, 2009



- Void formations and elemental segregation limit cycling endurance
- Doping/alloying the phase change material has shown to improve the endurance
- Cycling endurance of > 10^9 feasible

PCM as storage class memory





- Latency: much faster than FLASH (100's of ns vs. 100's of us)
- Write endurance: 1,000 x FLASH
- Nonvolatile, true random access capability, write in-place
- Very good scaling potential demonstrated (beyond 10nm node)
- Cost: between FLASH and DRAM (as technology matures)

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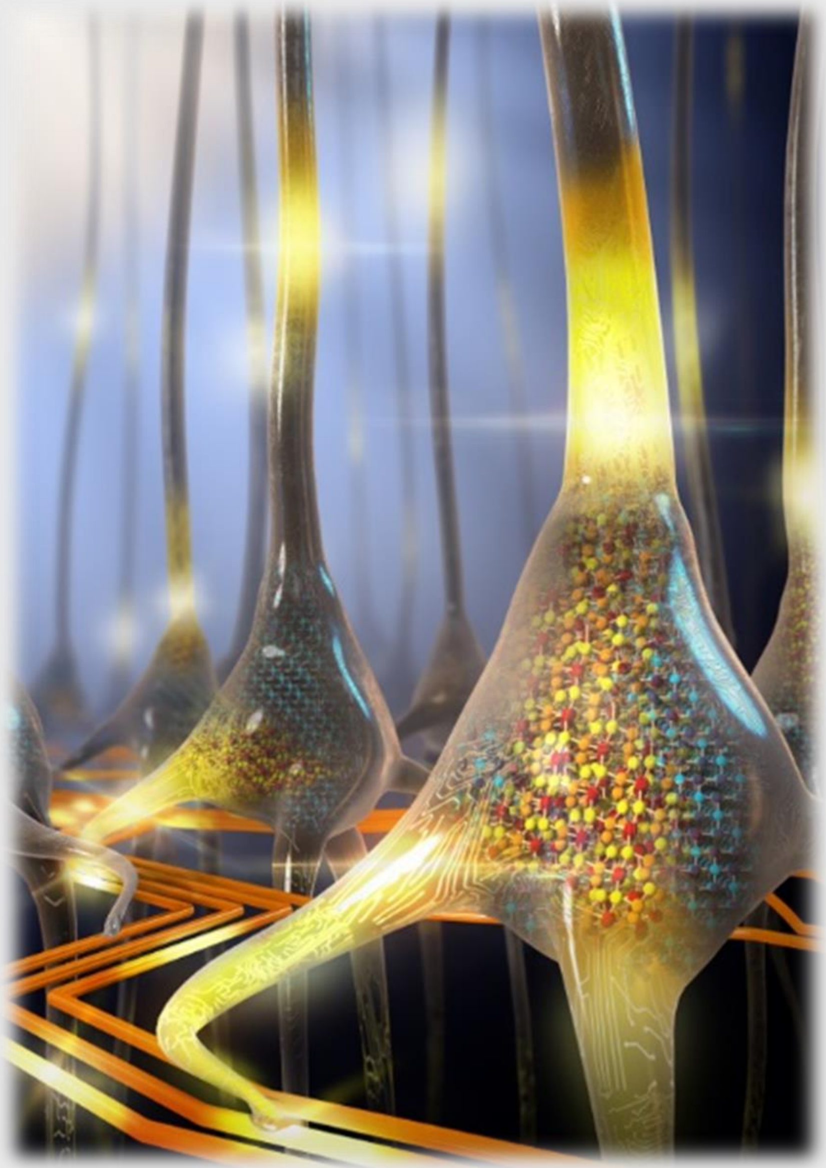
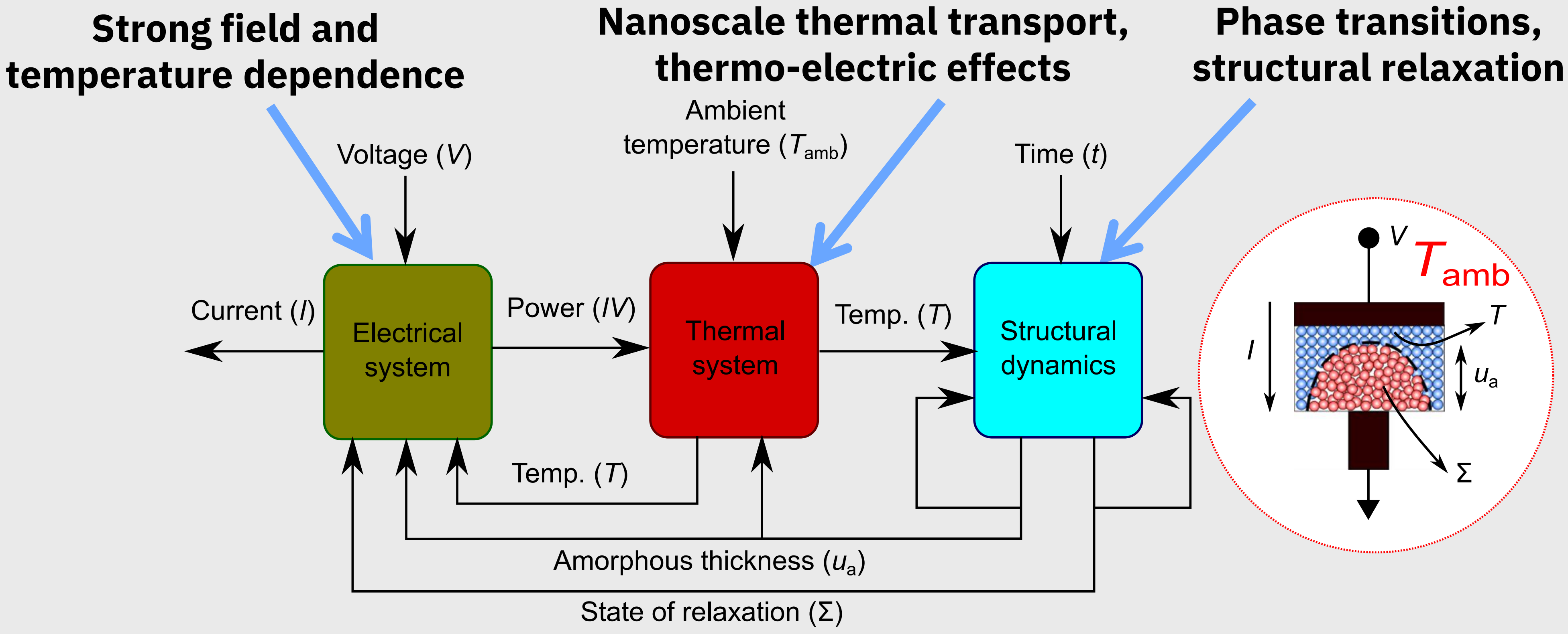


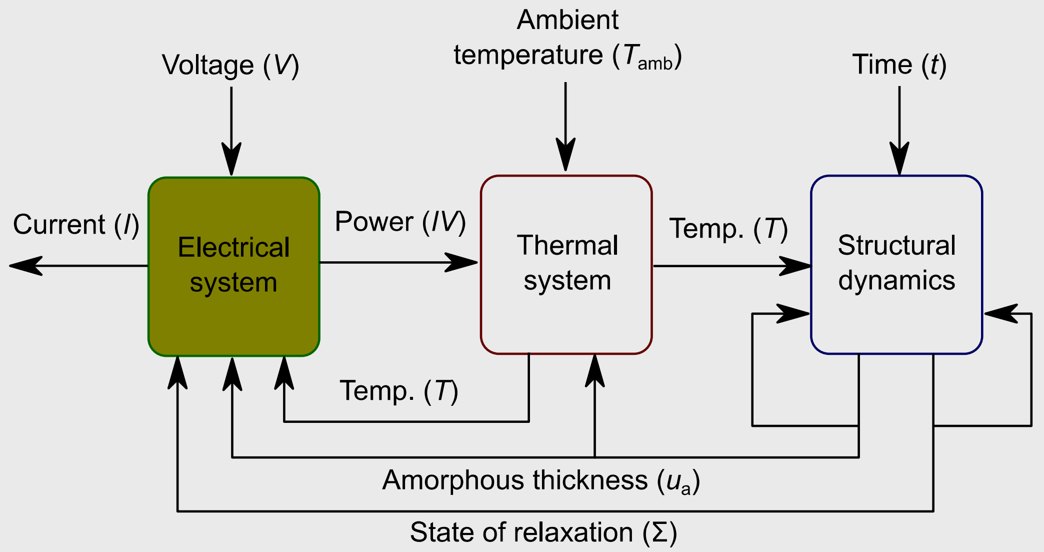
PCM device physics at a glance



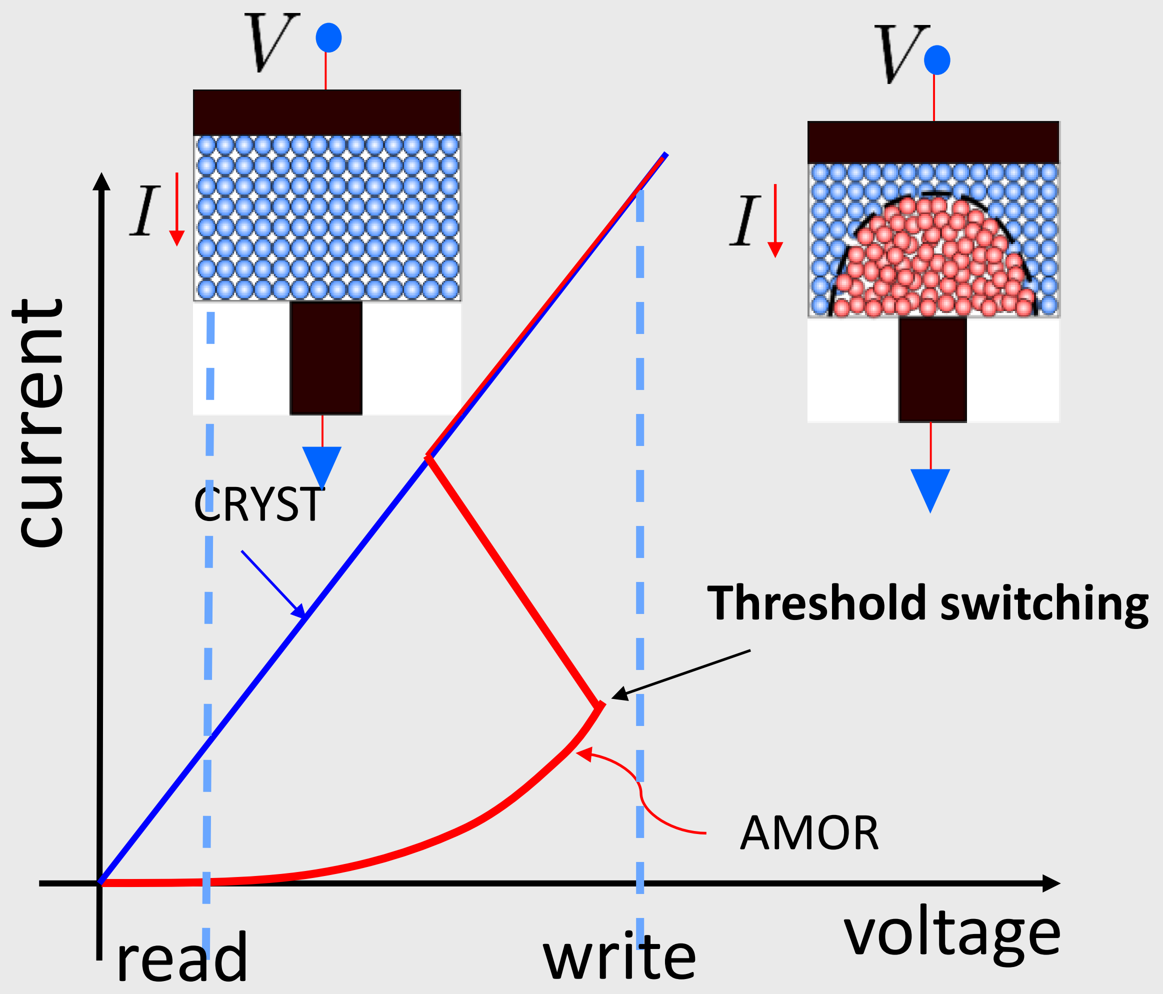
- Intricate feedback interconnection of electrical, thermal and structural dynamics
- Write operation: Alter the phase-configuration (Via Joule heating and structural dynamics)
- Read operation: Decipher the phase-configuration (Typically via reading the resistance at low field)

Sebastian et al., Nature Comm., 2014, Le Gallo et al., New J. Phys., 2015, Le Gallo et al., J. Appl. Phys., 2016, Le Gallo et al., Adv. Electr., Mat., 2018

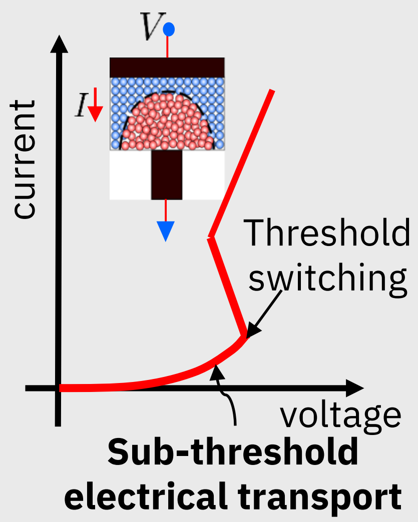
PCM: The electrical system

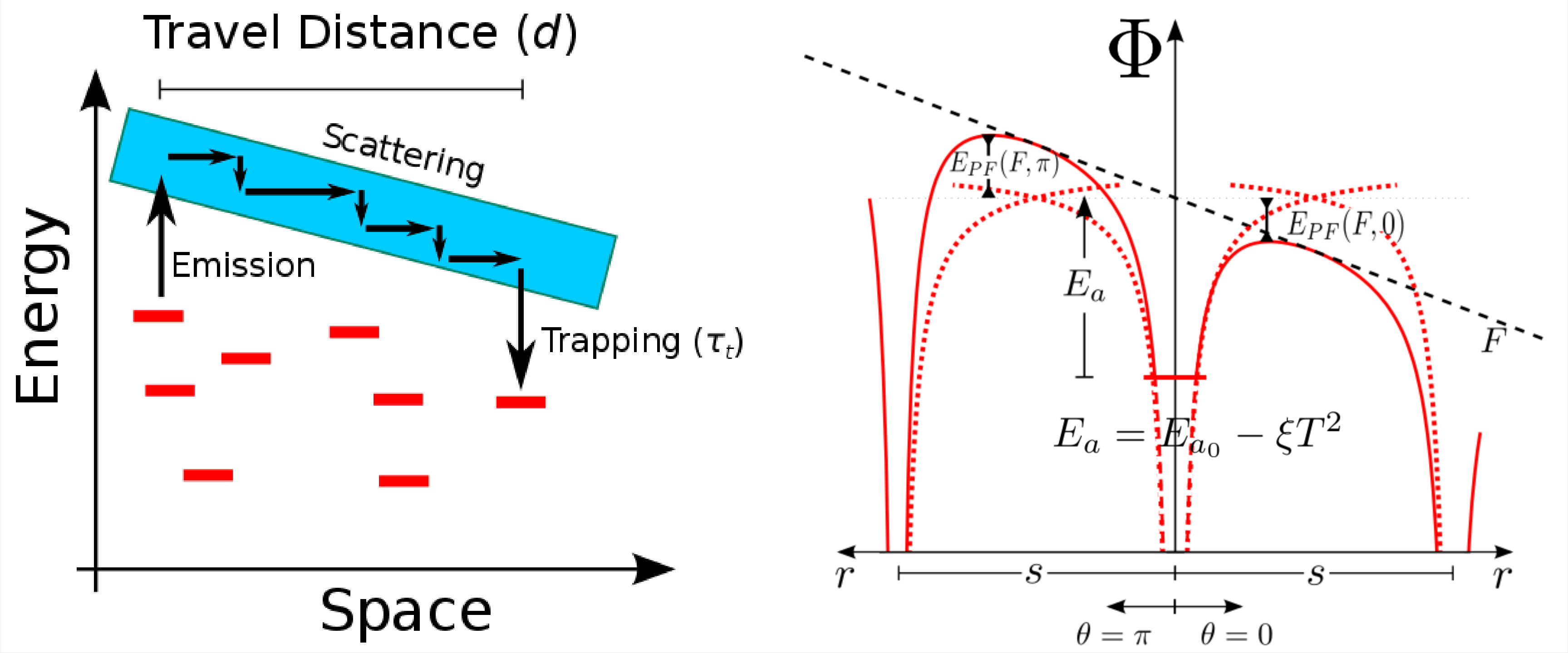


- Crystalline phase exhibits near-Ohmic transport and has minimal temperature dependence
- Electrical transport in the amorphous phase exhibits strong temperature and field dependence
  - ✓ Sub-threshold region
  - ✓ Threshold switching



Electrical transport model



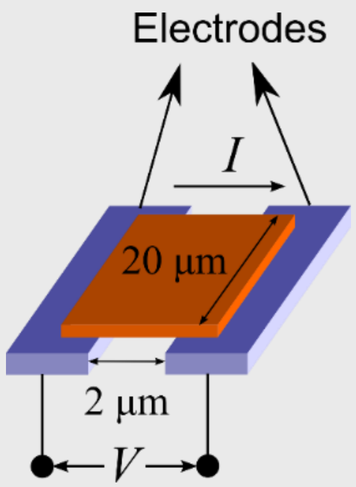


- Challenging to capture all the experimentally observed characteristics: 3 distinct regimes
  - ✓ Hill (1970), Hartke (1968), Ielmini (2007), Beneventi (2013)
- Well described by **trap limited band transport** together with **3D Poole-Frenkel emission** from a **two-center Coulomb potential**
- Two key parameters:
  - ✓ Activation energy for carrier emission: E_a
  - ✓ The distance between the two defect centers: s (mean inter-trap distance)

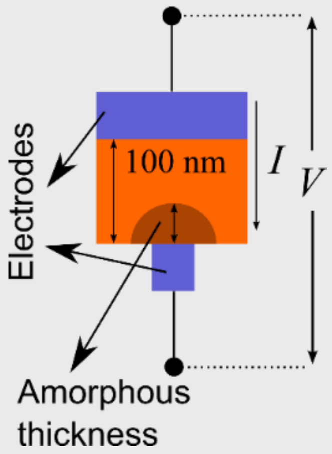
Le Gallo et al., "Subthreshold electrical transport in amorphous phase-change Materials", New J. Phys., 2015

Model validation

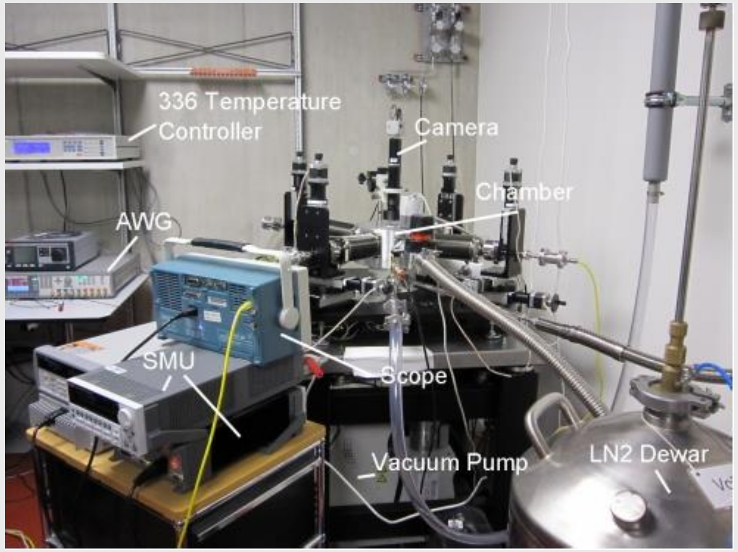
Line Cell (as-deposited)



PCM Cell (melt-quenched)

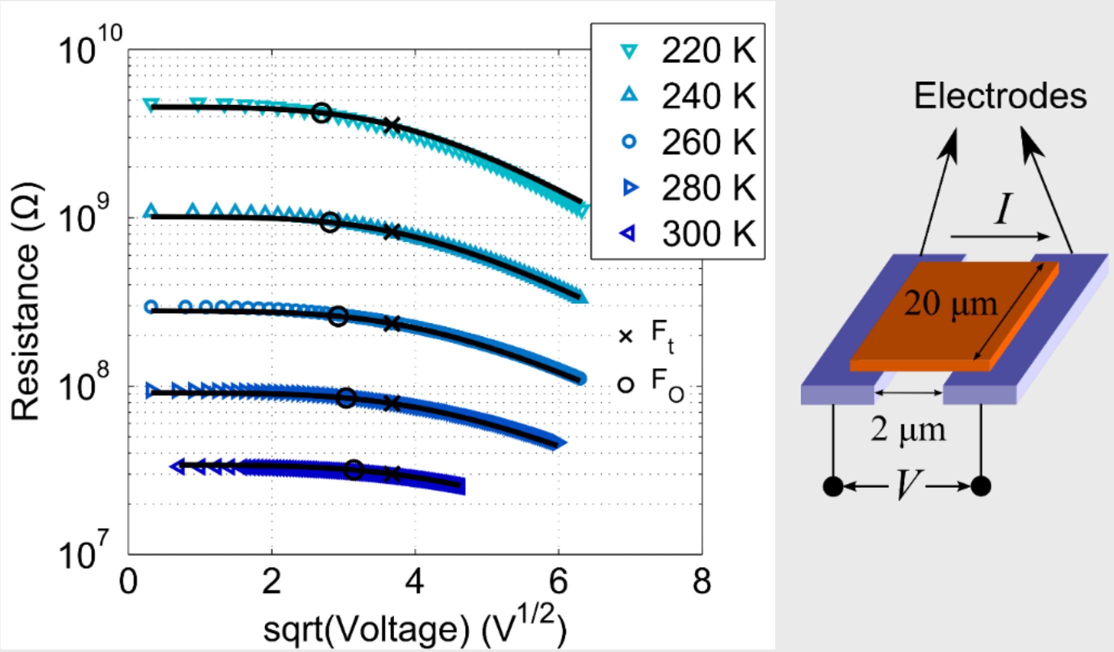


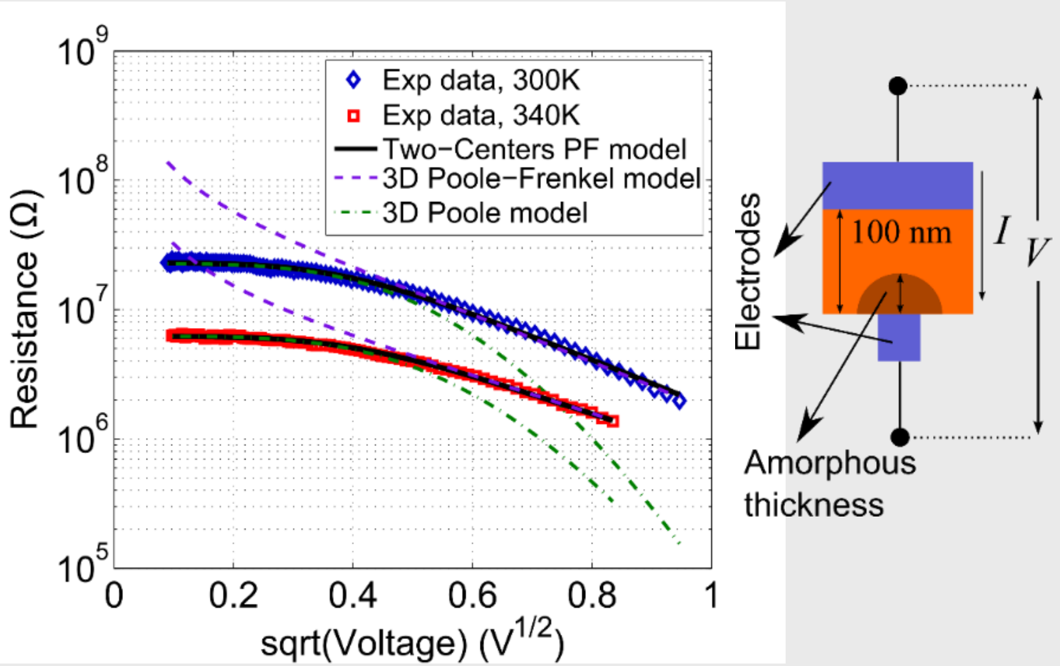
Cryogenic probe station



- IV curves measured on:
  - ✓ Line cells (uniform field distribution, large device of micrometer-scale)
  - ✓ PCM cells (non-uniform field distribution, small device of nanometer-scale)
- Cryogenic probe station used to obtain the IV characteristics over a wide temperature range

Model validation





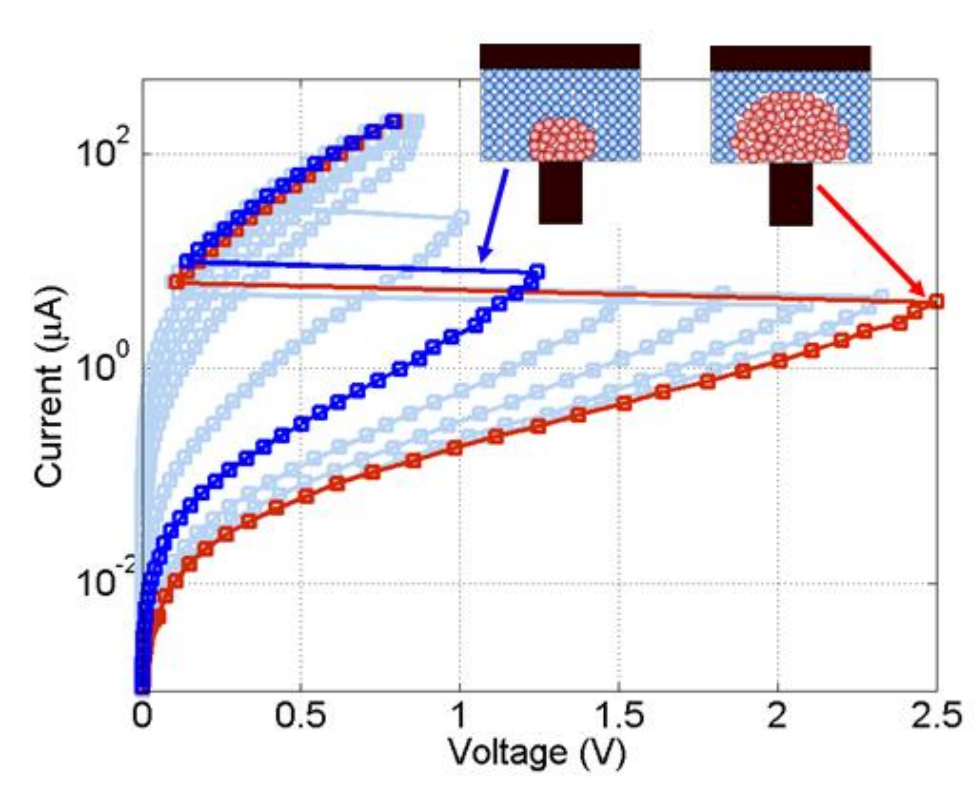
- ε_r = 13 (FTIR)
- Electrode distance = 2 µm
- E_a from R(T) data
- s = 8.1 nm (room temperature fit)

- ε_r = 13 (FTIR)
- u_{Aeff} = 15 nm
- E_a from R(T) data
- s = 8.1 nm (room temperature fit)

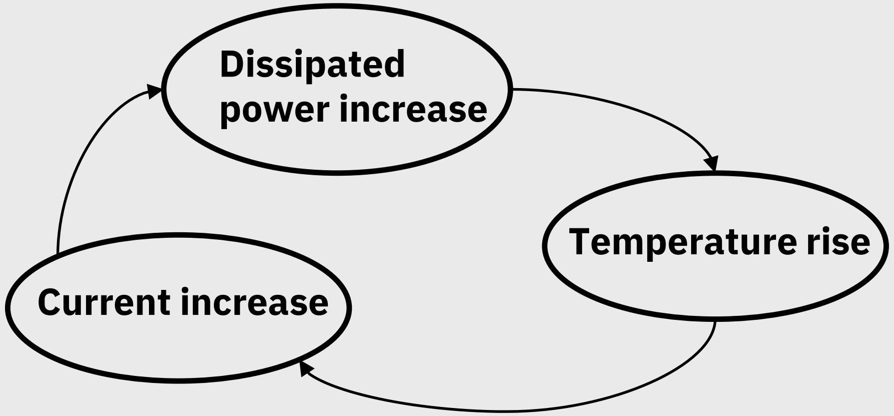
- Model captures the experimental data from 300K down to 220K without fitting across temperature
- Standard Poole and Poole-Frenkel models fail to capture the IV characteristics on the whole voltage range
- Full model captures the experimental data with similar physical parameters as for line cells

Threshold switching

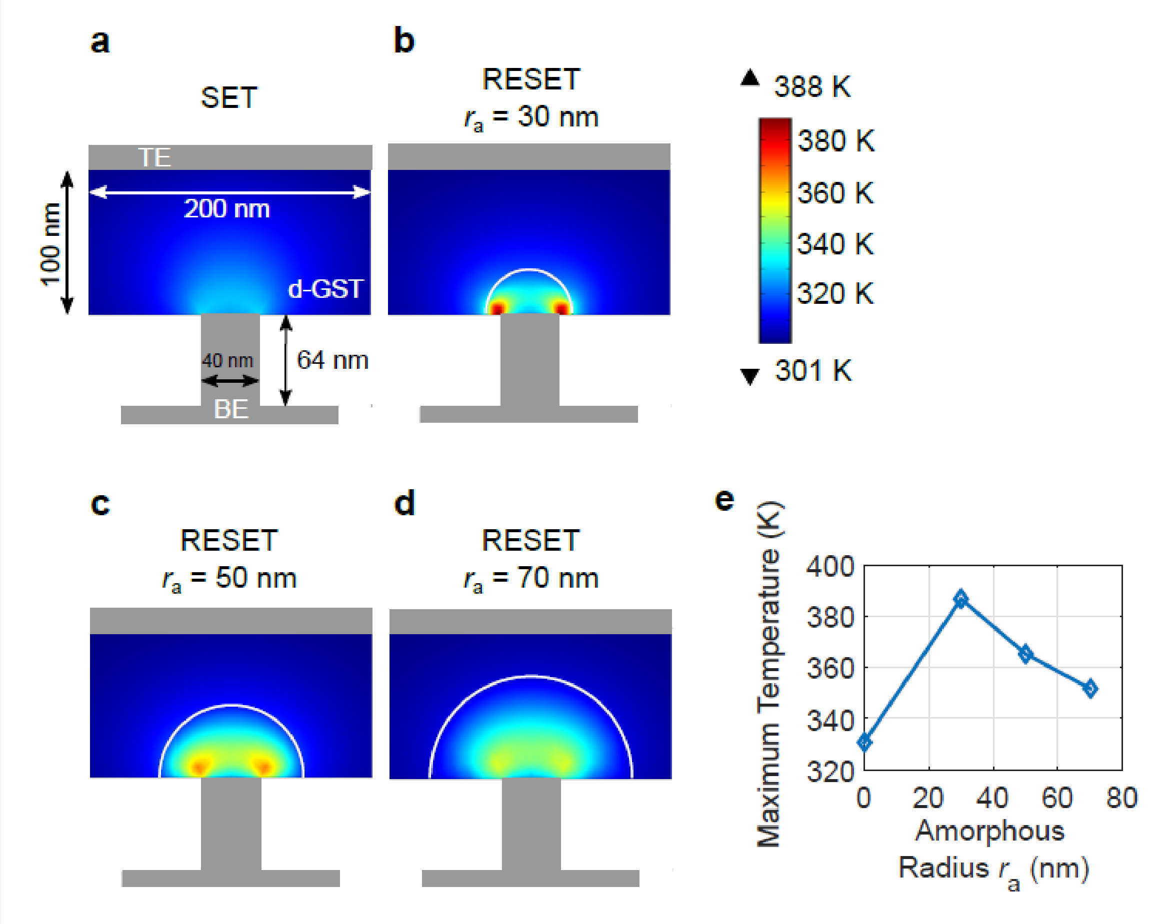
- Threshold switching enables dissipation of substantial electric power at relatively low voltages → A key enabling property
- Threshold switching voltage depends on the thickness of the amorphous region and the activation energy for electrical transport (E_a)
- After TS, the high field “ON” resistance similar for all states
- Details of the dynamics still a matter of ongoing research (after 50 years!)
  - ✓ **Thermal models** (Eaton, Boer, Tsendin etc.) vs **Purely electronic models** (Mott, Henisch, Adler, Pirovano, Lacaita etc.)
  - ✓ Others: Tunneling between trap states, energy gain via carrier temperature increase, field induced nucleation



Threshold switching in PCM devices: Thermally induced?

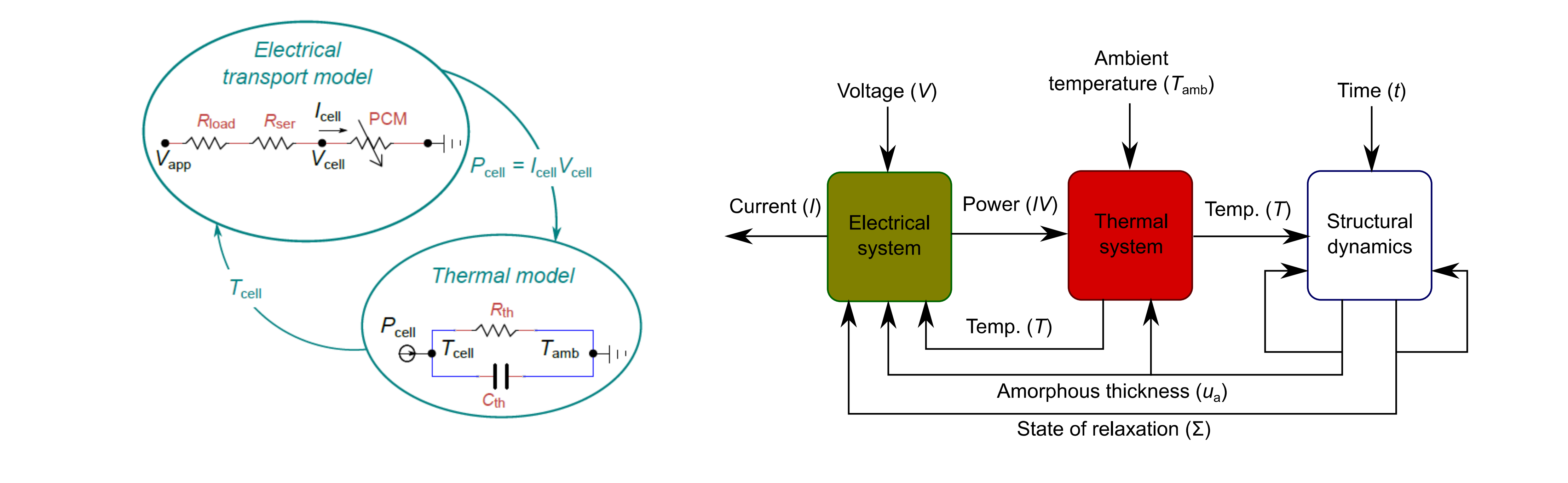


The positive feedback can trigger an onset of instability in this highly non-linear system



- High effective thermal resistance in nanoscale PCM devices (>1K/μW)
- Small thermal time constants (<10 ns)

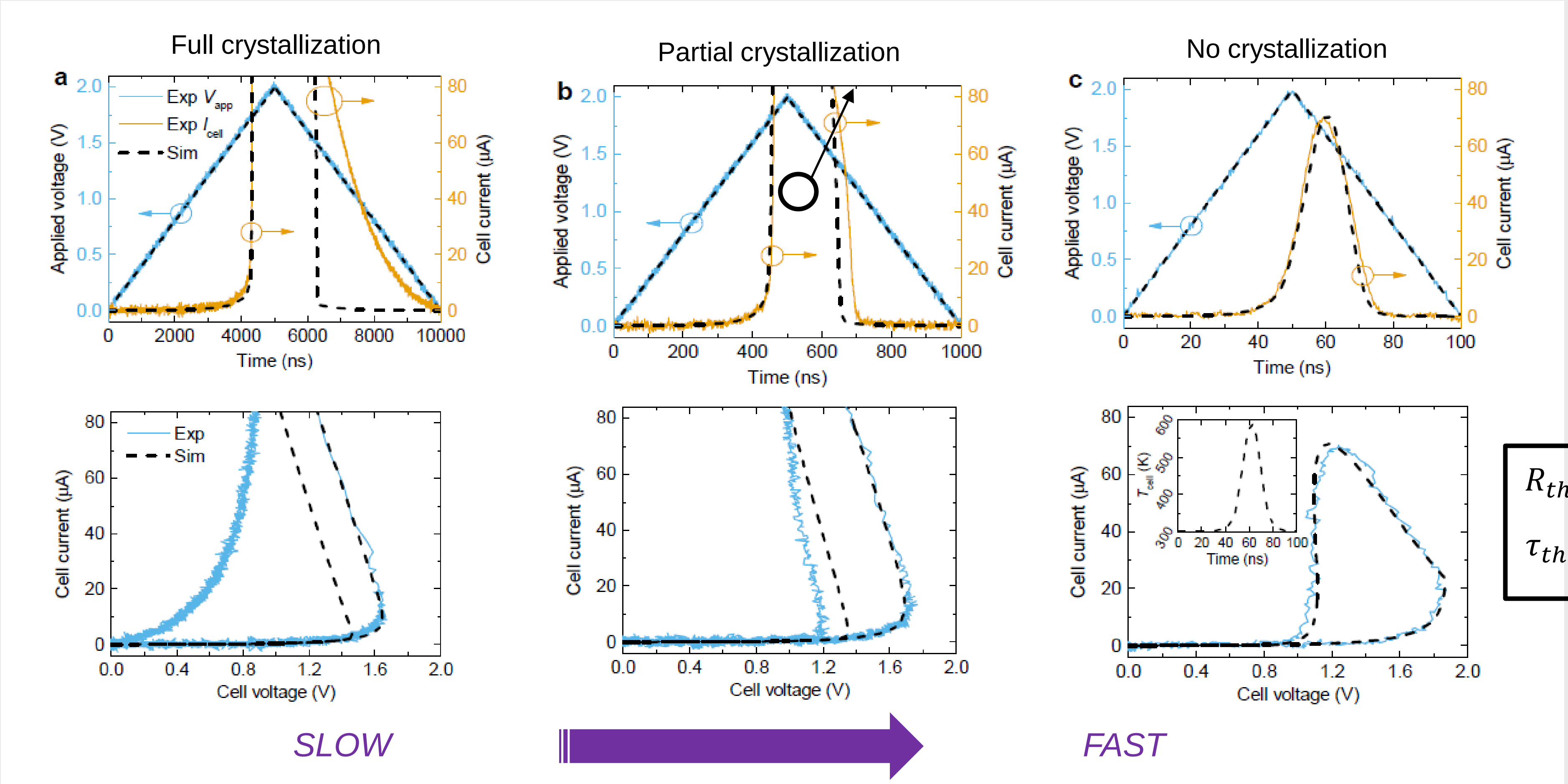
Modeling



- Electrical transport model:
  - ✓ Field and temperature dependent subthreshold conduction model for PCM amorphous phase
  - ✓ Assume no influence of crystalline phase (e.g. no crystallization included)
- Thermal model:
  - ✓ Cell temperature rise from Joule heating coming from input power
  - ✓ Heat conduction described with effective thermal resistance and capacitance

Le Gallo et. al, J. Appl. Phys., 2016

Switching at Different Voltage Ramps



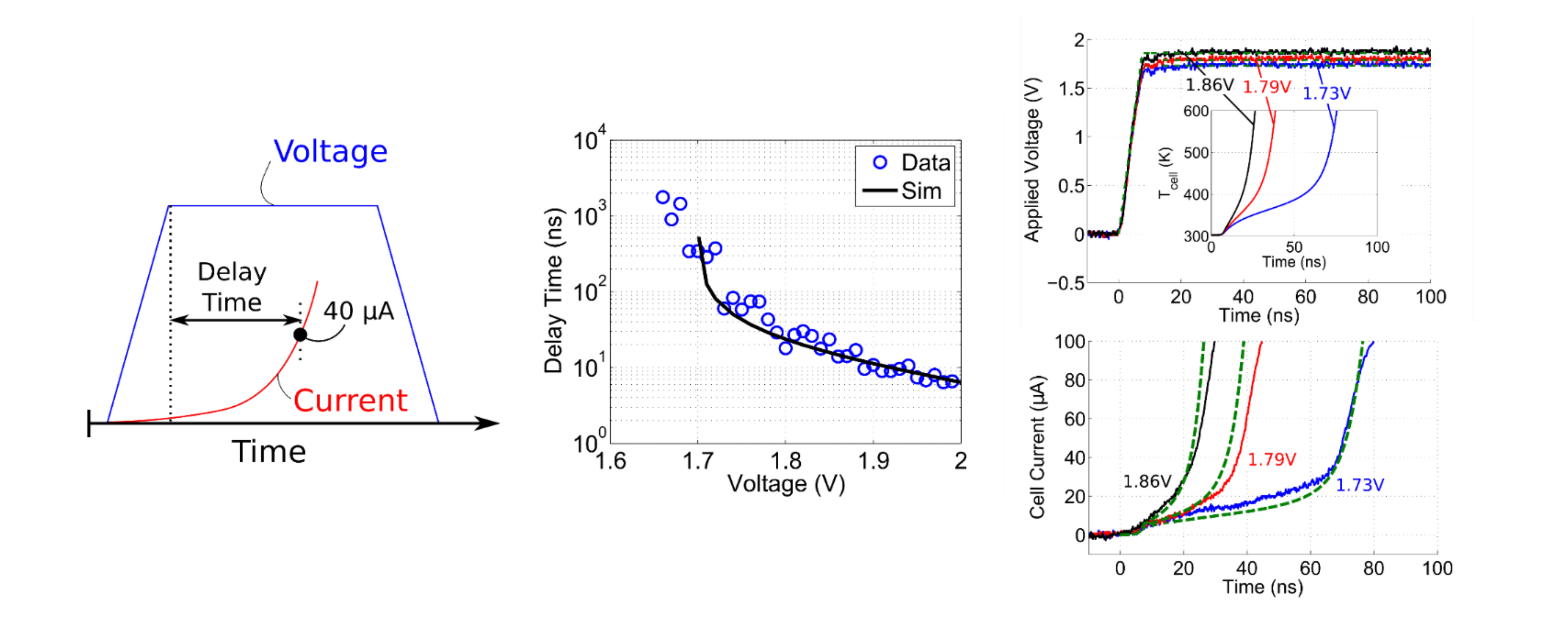
$$R_{th} = 3.71\ \mathrm{K/\mu W}$$

$$\tau_{th} = 4\ \mathrm{ns}$$

- Threshold switching dynamics are well captured by the thermally-assisted model
- Obtained values of R_{th} and τ_{th} realistic for nanoscale PCM cells.

Le Gallo et. al, J. Appl. Phys., 2016

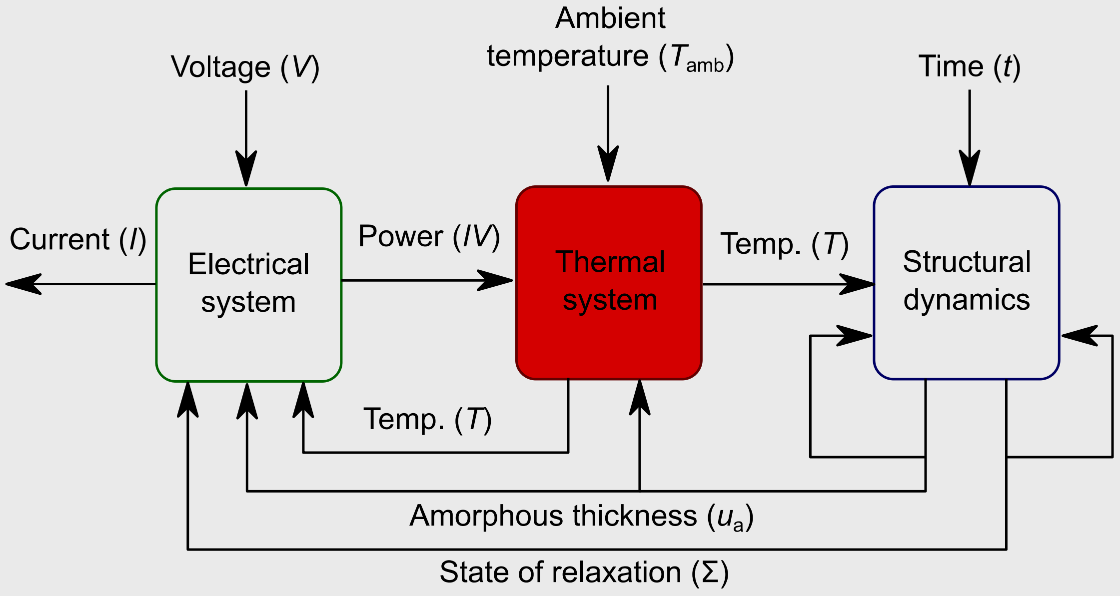
Delay Time Switching

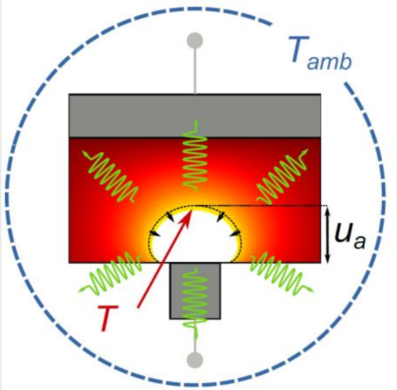


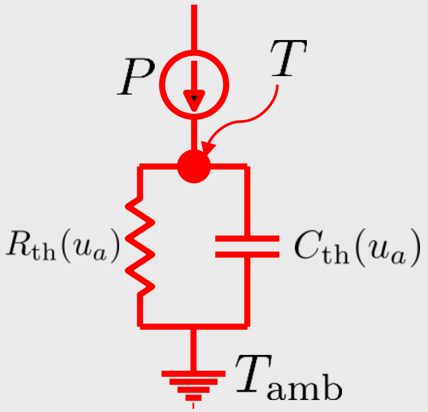
- Delay-time switching with voltage box pulse
- Short delay times (<1000 ns) well captured by thermal feedback model
- Slow current rise prior to switching explained by temperature buildup
- Manifestations of feedback instability in a highly non-linear system!

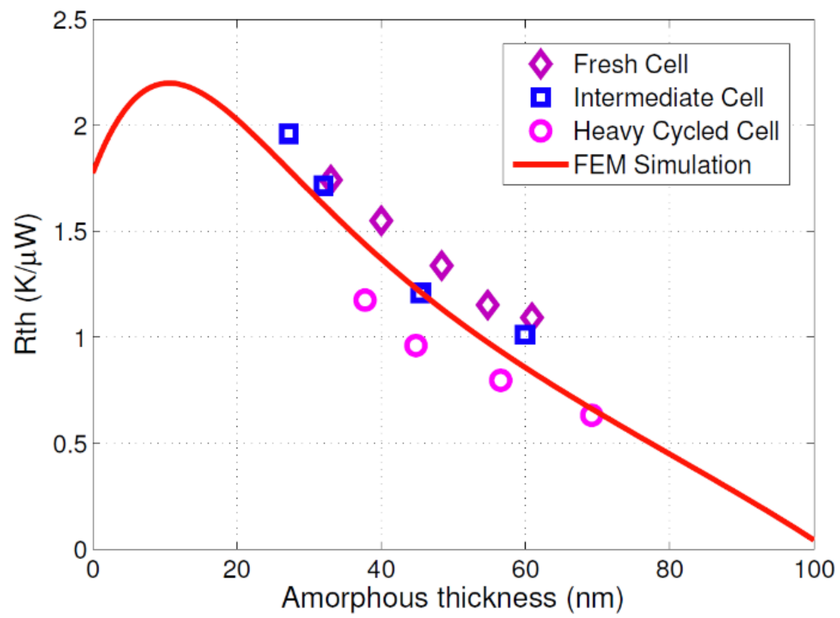
Le Gallo et. al, J. Appl. Phys., 2016

PCM: The thermal system





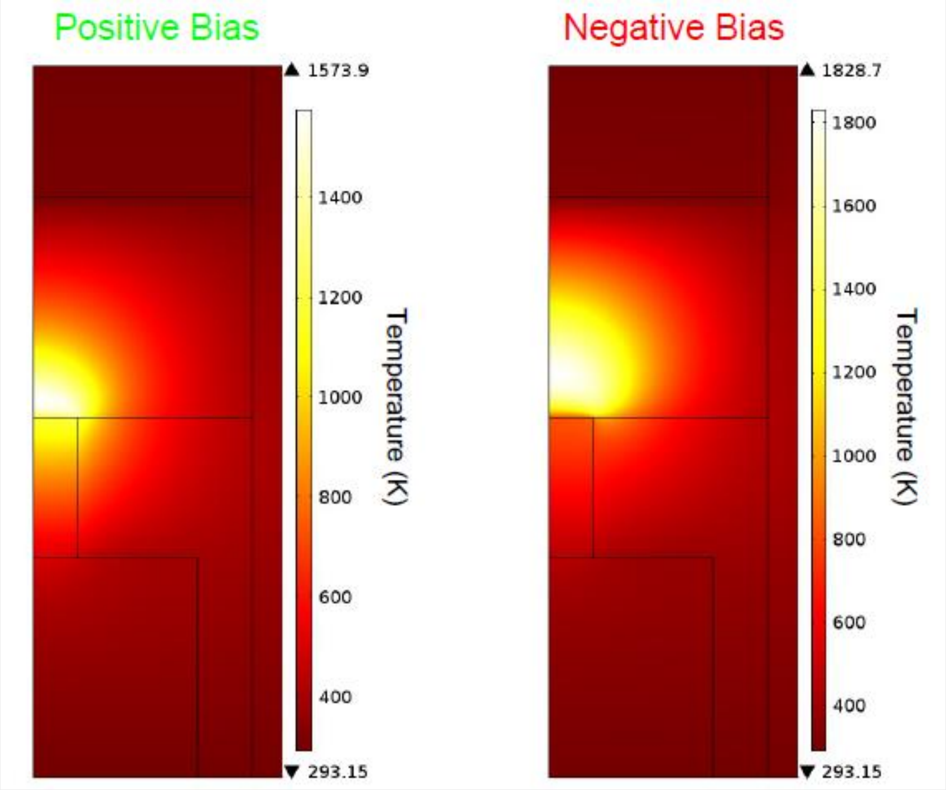


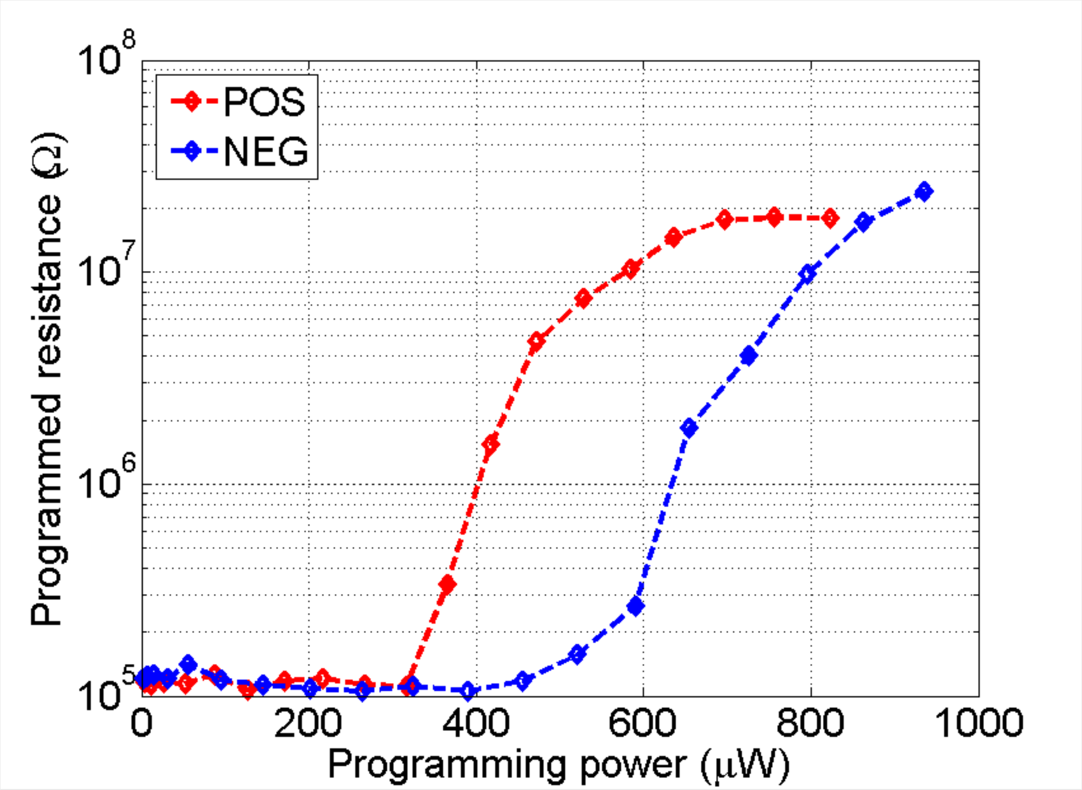


Sebastian et. al, Nature Comm., 2014

- The electrical power that is dissipated in the device results in a temperature rise within the device
- Temperature distribution with a "Hot spot" within the PCM segment
- Temperature distributions in a PCM device can be simulated and even experimentally verified!
- The "thermal" dynamics can be captured by an equivalent thermal resistance and capacitance

Thermo-electric Effects

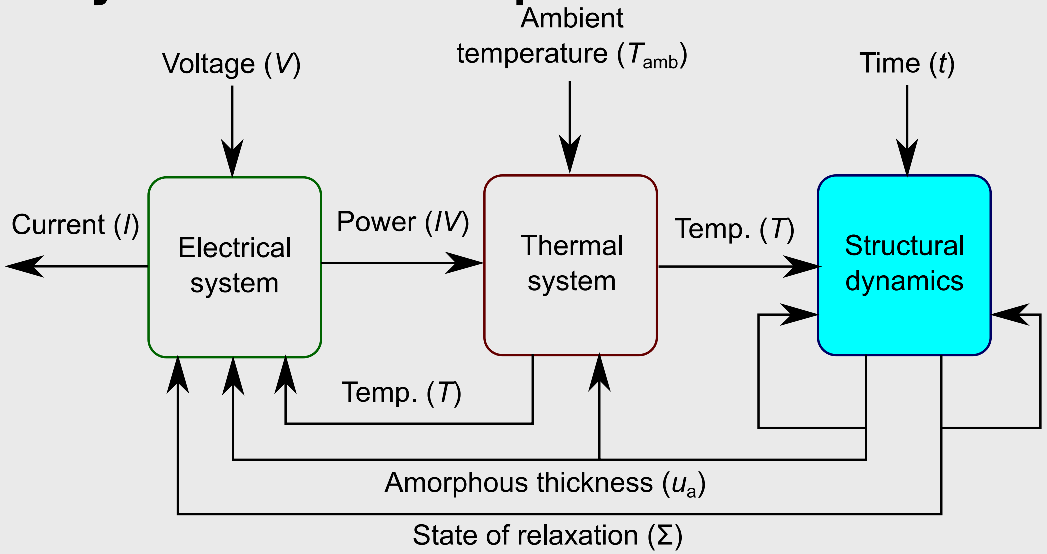




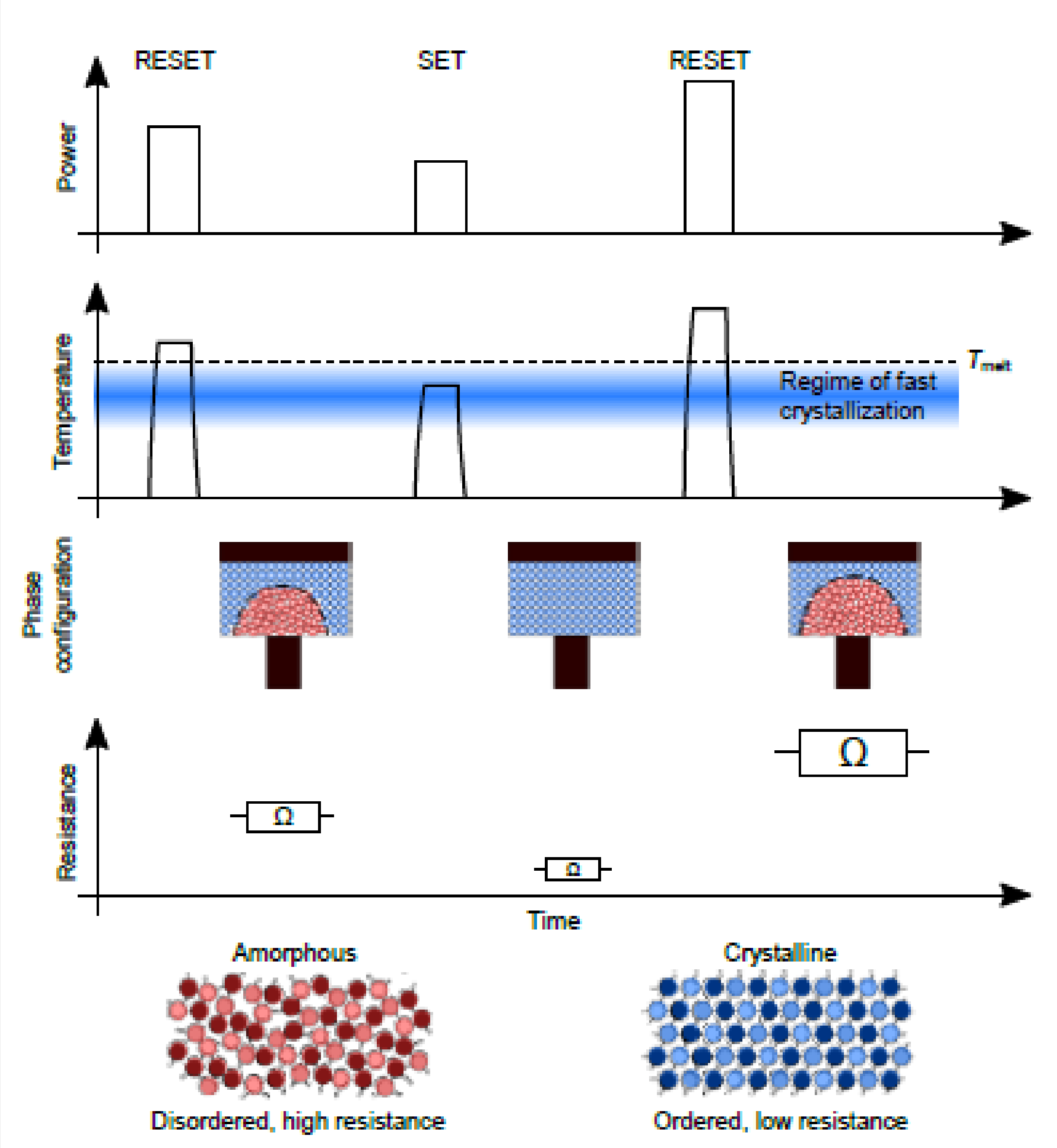
- The large temperature gradients → thermo-electric effects such as Seebeck effect and the non-Joule heating terms such as Thomson, Peltier and Bridgeman cannot be neglected
- Polarity dependence in asymmetric devices

Lee et al., Nanotechnology, 2012
Athmanathan et al., SISPAD, 2015

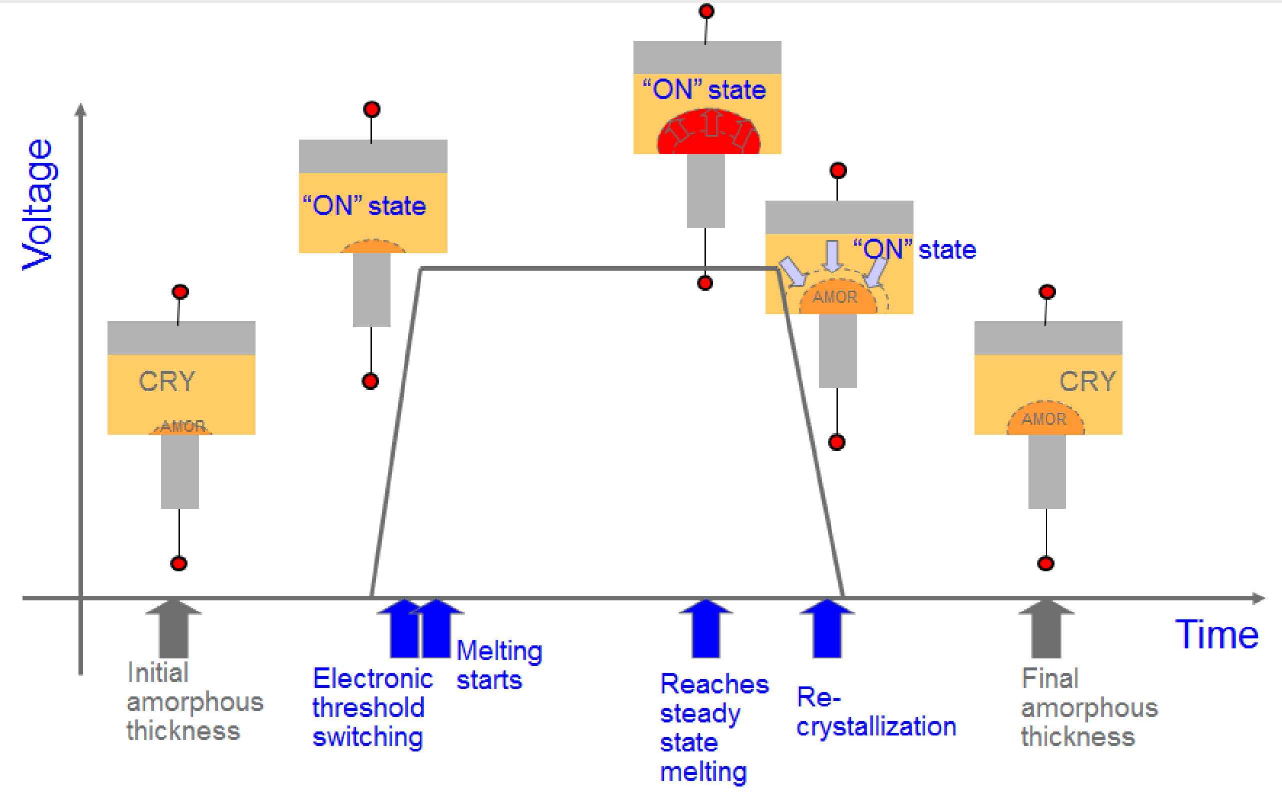
Structural changes induced by the write process

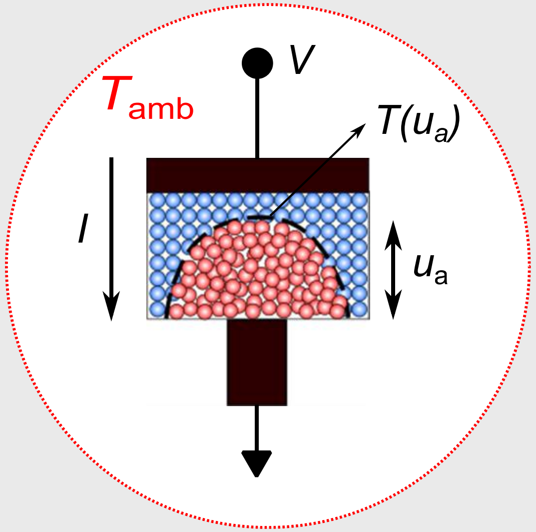


- During the write process we induce structural changes to the phase-change material
- The structural dynamics is governed mostly by the temperature distribution within the device
- **Melting and quenching** to create disordered amorphous phase
- **Crystallization** to create ordered crystalline phase



PCM structural dynamics: “Amorphization” via Melt-quench

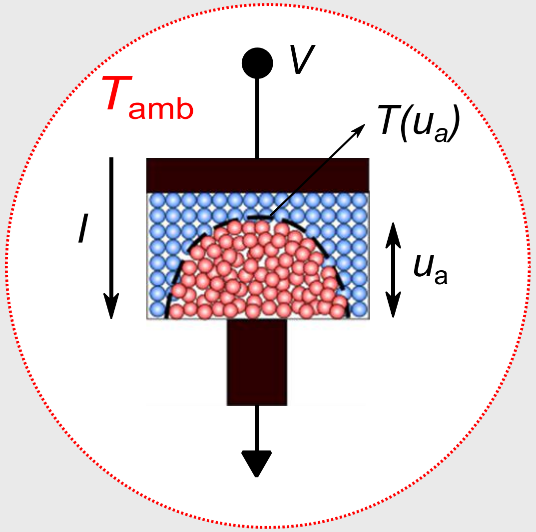


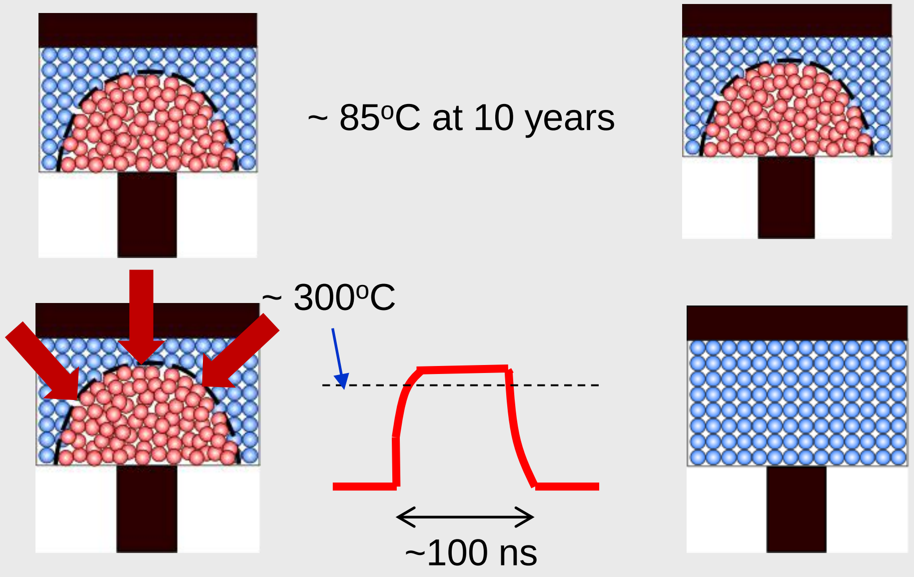


$$\frac{du_a}{dt} = \frac{1}{2\pi u_a^2}\left[\frac{T(u_a)-T_m}{R_{th}(u_a)\Delta H}\right]$$

- Melting kinetics mostly governed by the thermal resistance (R_{th}) and latent heat of fusion (ΔH)
- T_m is the melting temperature of the phase change material (approx. 890 K for $Ge_2Sb_2Te_5$)
- The melting process takes some time (in the order of tens of nanoseconds) and eventually $T(u_a)$ equals T_m where a steady state will be achieved and no further melting is possible
- The molten material is cooled down abruptly to freeze the atomic structure into a disordered state

PCM structural dynamics: Crystal growth

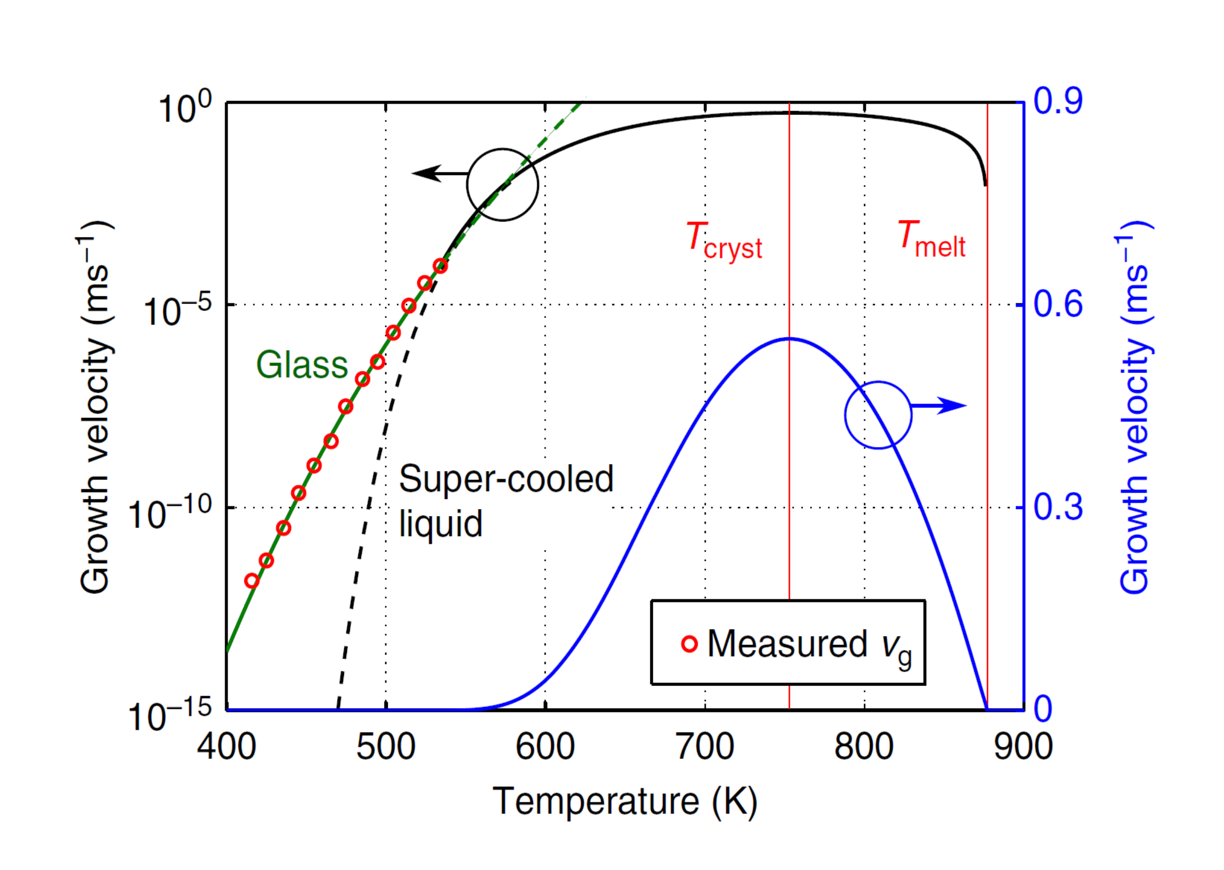




- Crystallization in nanoscale devices dominated by crystal growth
- Moreover, melt-quench phase has a significant number of built-in nuclei
- Crystal growth in phase change materials changes by 16 to 17 orders of magnitude as a function of temperature
- Single most important property that enables PCM

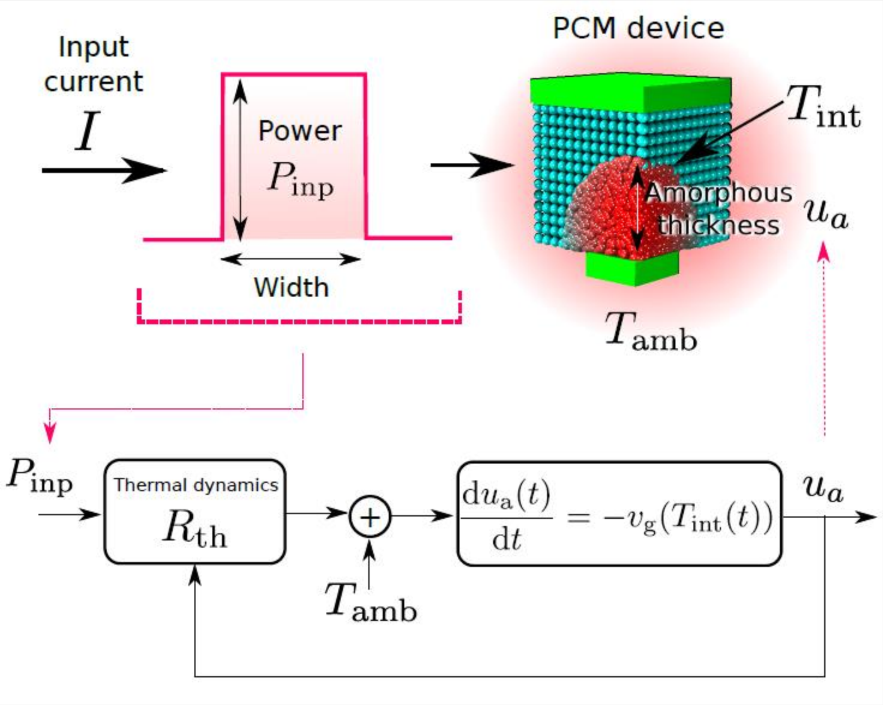
Temperature dependence of crystal growth

- First experimental measurement of T dependence of growth velocity till melting temperature
- Measurements made directly inside the PCM device!
- Arrhenius-like temperature dependence spanning over 8 orders of magnitude
  - ✓ Deviates from the super-cooled liquid behavior potentially due to the ultra-fast quench rate!

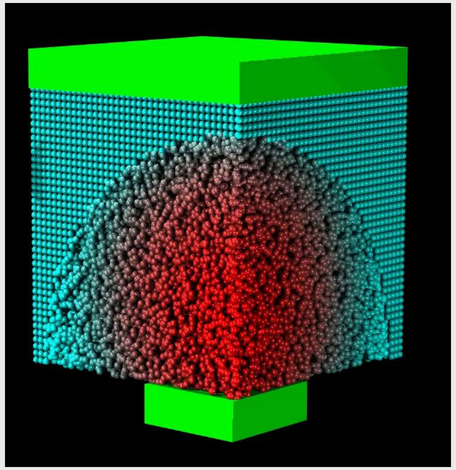


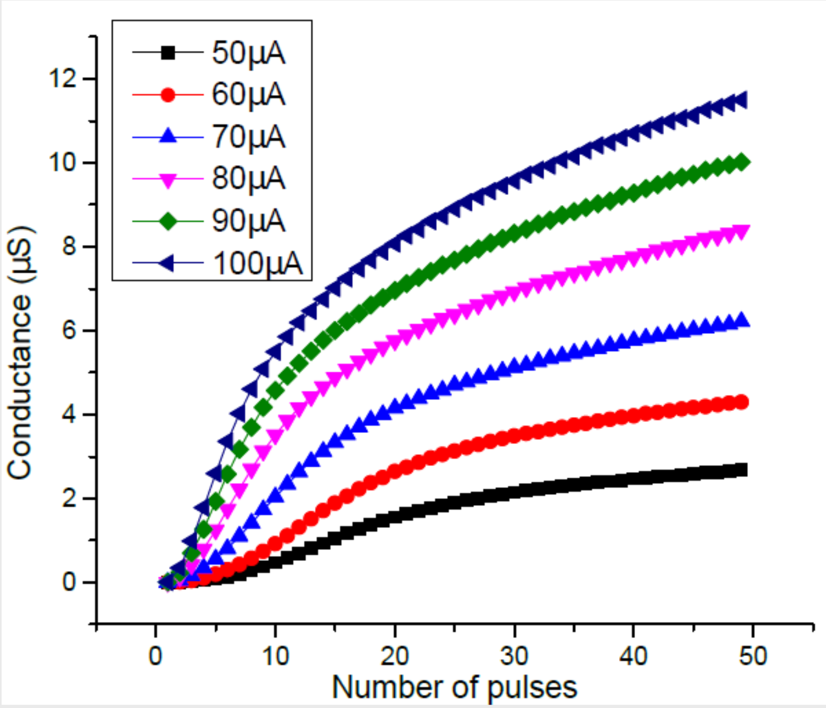
Sebastian et. al, Nature Comm., 2014

Accumulative behavior



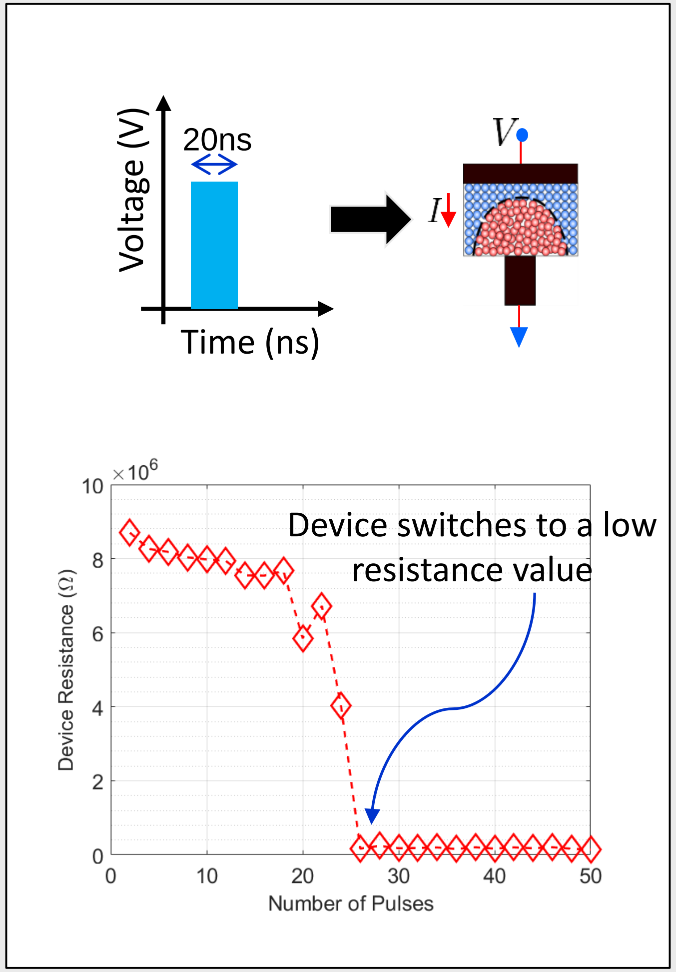
$$\frac{du_a(t)}{dt} = -v_g(T(t))$$
$$u_{a_0} = u_a(0)$$

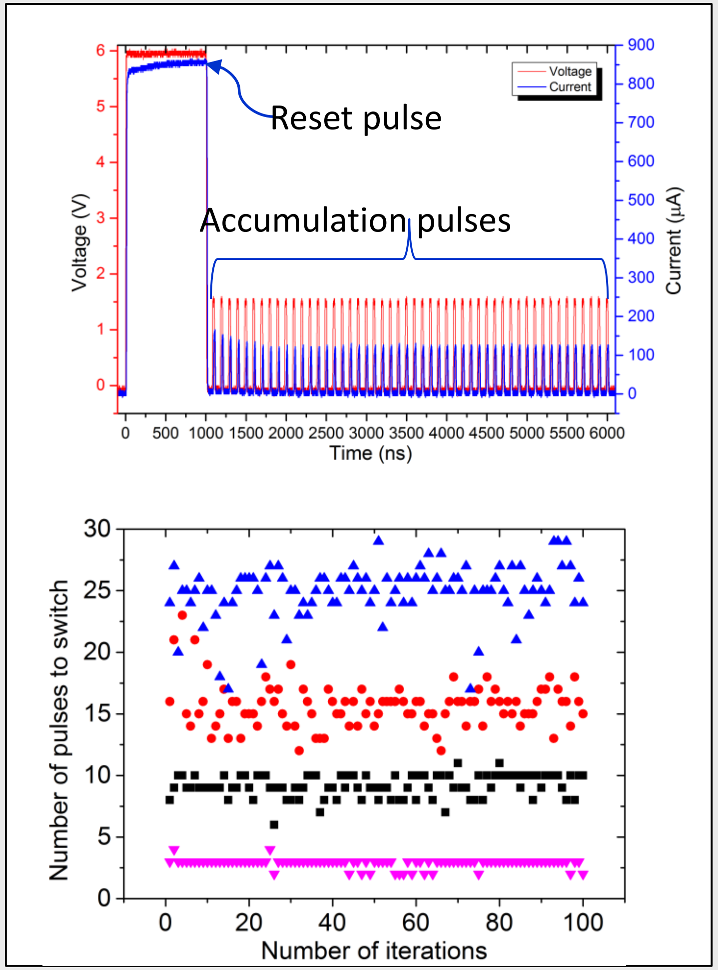


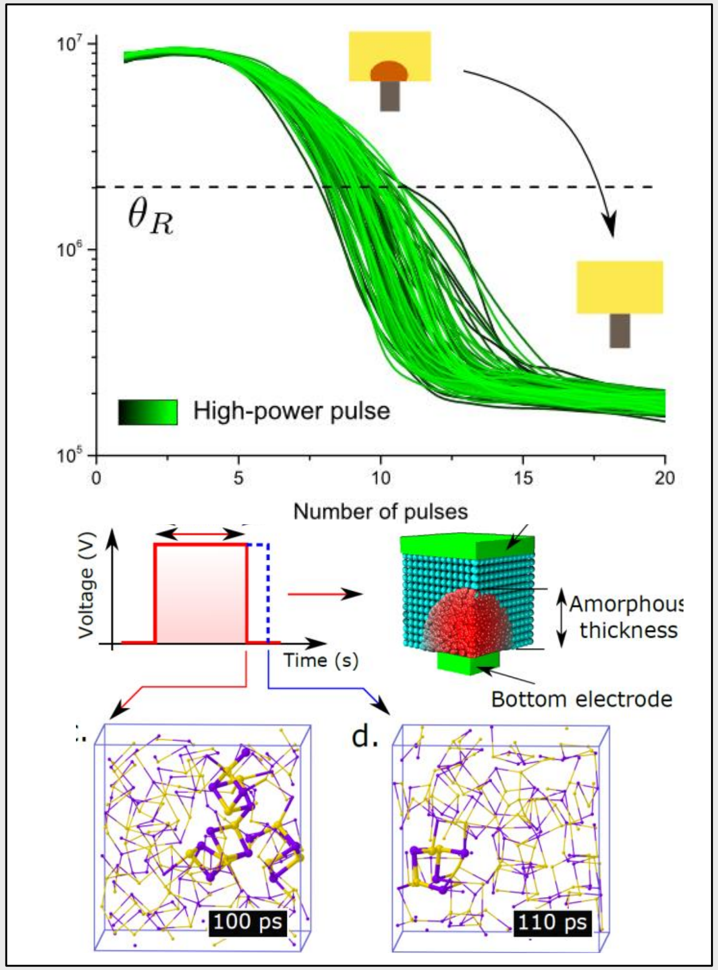


Sebastian et. al, Nature Comm., 2014

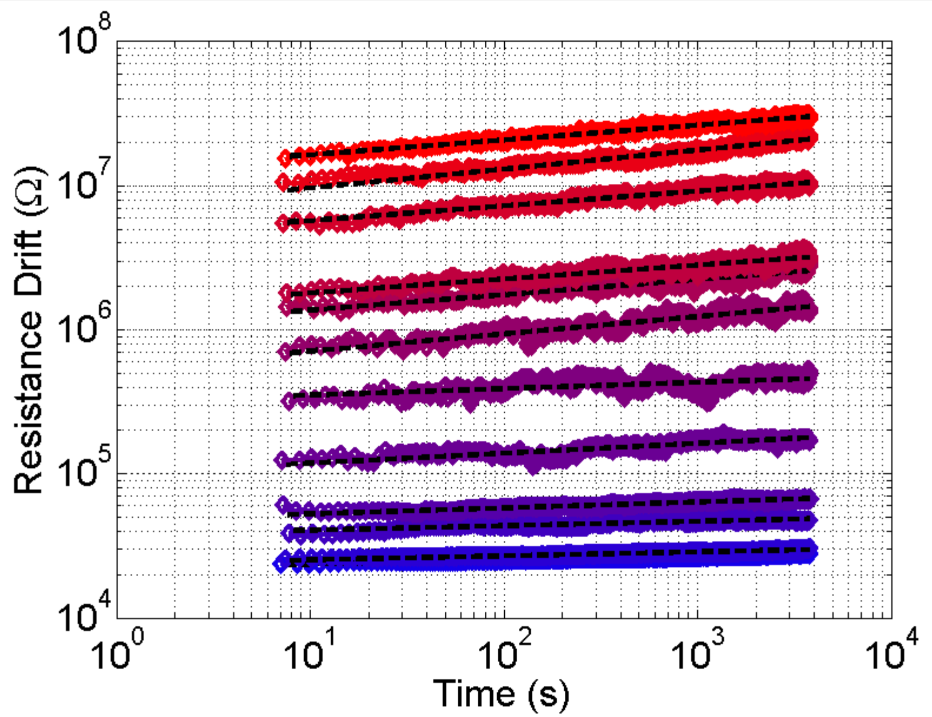
Inherent randomness

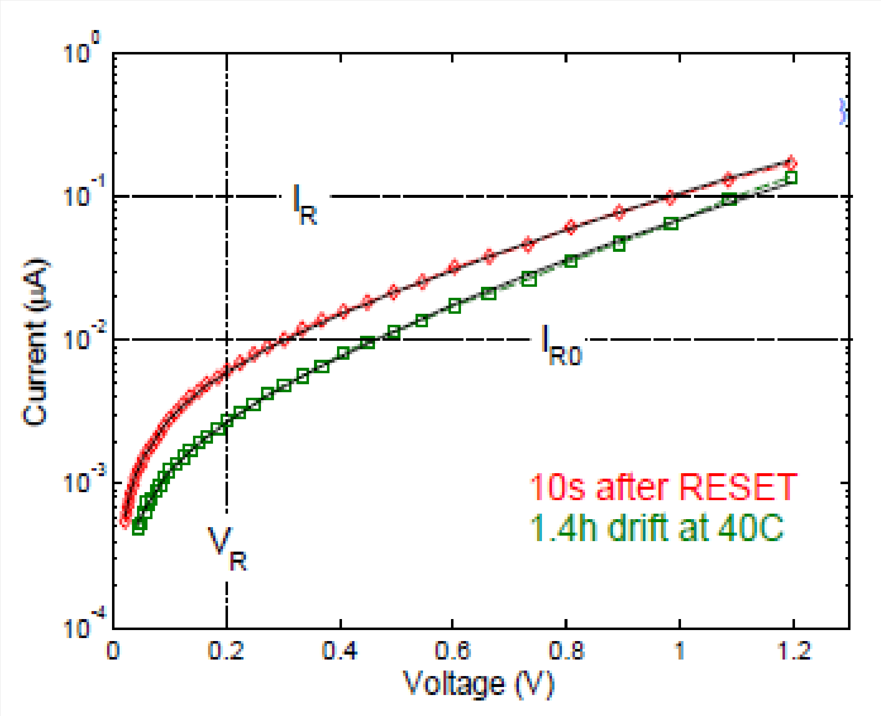






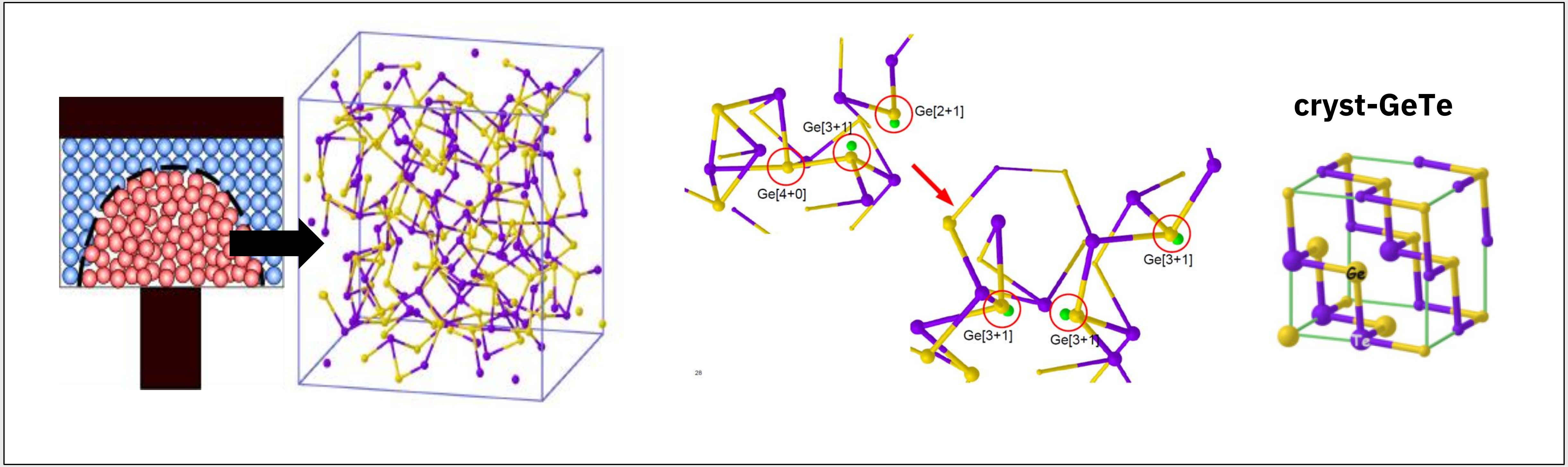
“Drift” in PCM





Ielmini et al., IEEE Trans. Elec. Dev., 2009
Rizzi et al., Appl. Phys. Lett.,2011
Fantini et al., Appl. Phys. Lett., 2012

The cause of drift: Spontaneous structural relaxation



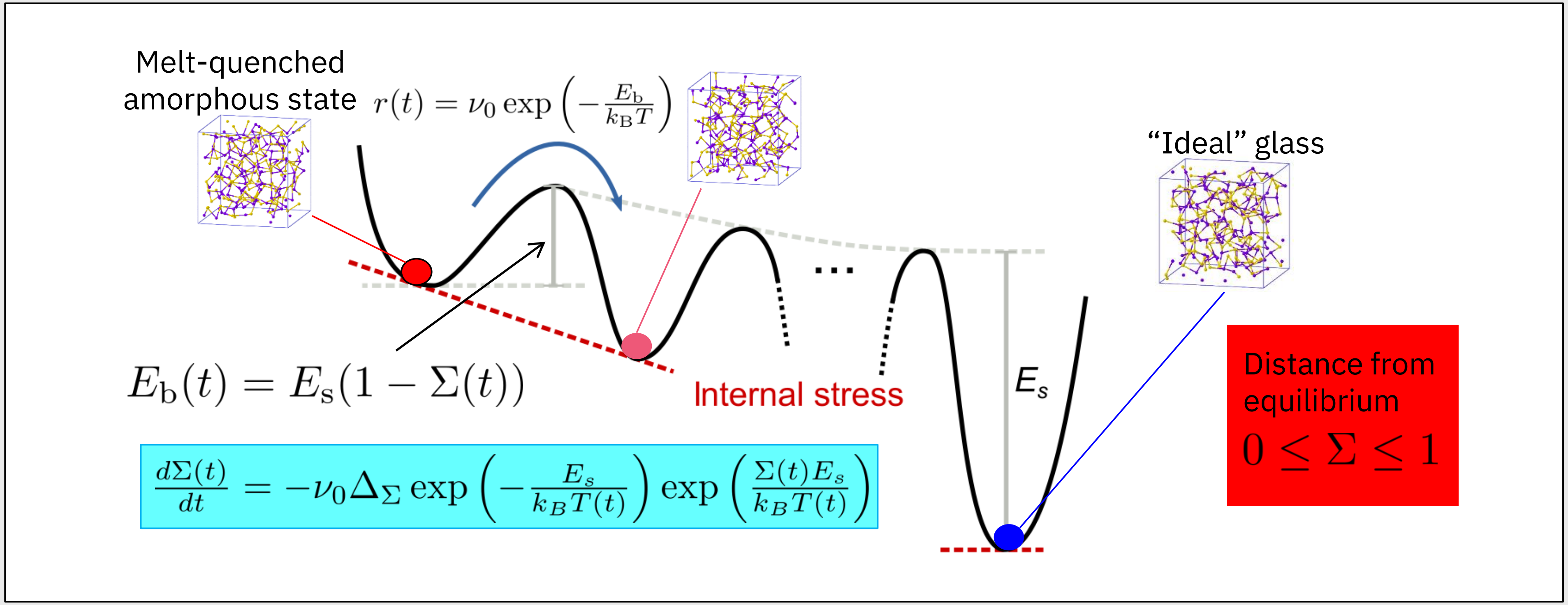
Structural relaxation of amorphous phase towards an “ideal” glass state

Recent insights into the nature of the “ideal” glass state

Ielmini et al., IEEE Trans. Elec. Dev., 2009
Rizzi et al., Appl. Phys. Lett.,2011
Fantini et al., Appl. Phys. Lett., 2012

Raty et al., Nature Comm., 2015
Gabardi et al., Phys. Rev. B, 2015
Zipoli et al., Phys. Rev. B, 2016

The collective relaxation model



- The structure collectively rearranges whereby every local configuration is changed repeatedly to achieve an overall lower energy state
- The relaxation proceeds in a sequence of transitions between neighboring states
- Closer to the equilibrium the system is → the higher the barrier for subsequent relaxation

Sebastian et al., Proc. IRPS, 2015, Le Gallo et al., Proc. IRPS, 2016
Le Gallo et al., "Collective Structural Relaxation in Phase-Change Memory Devices", Adv. Electr. Mat., 2018

The link between collective relaxation and electrical transport

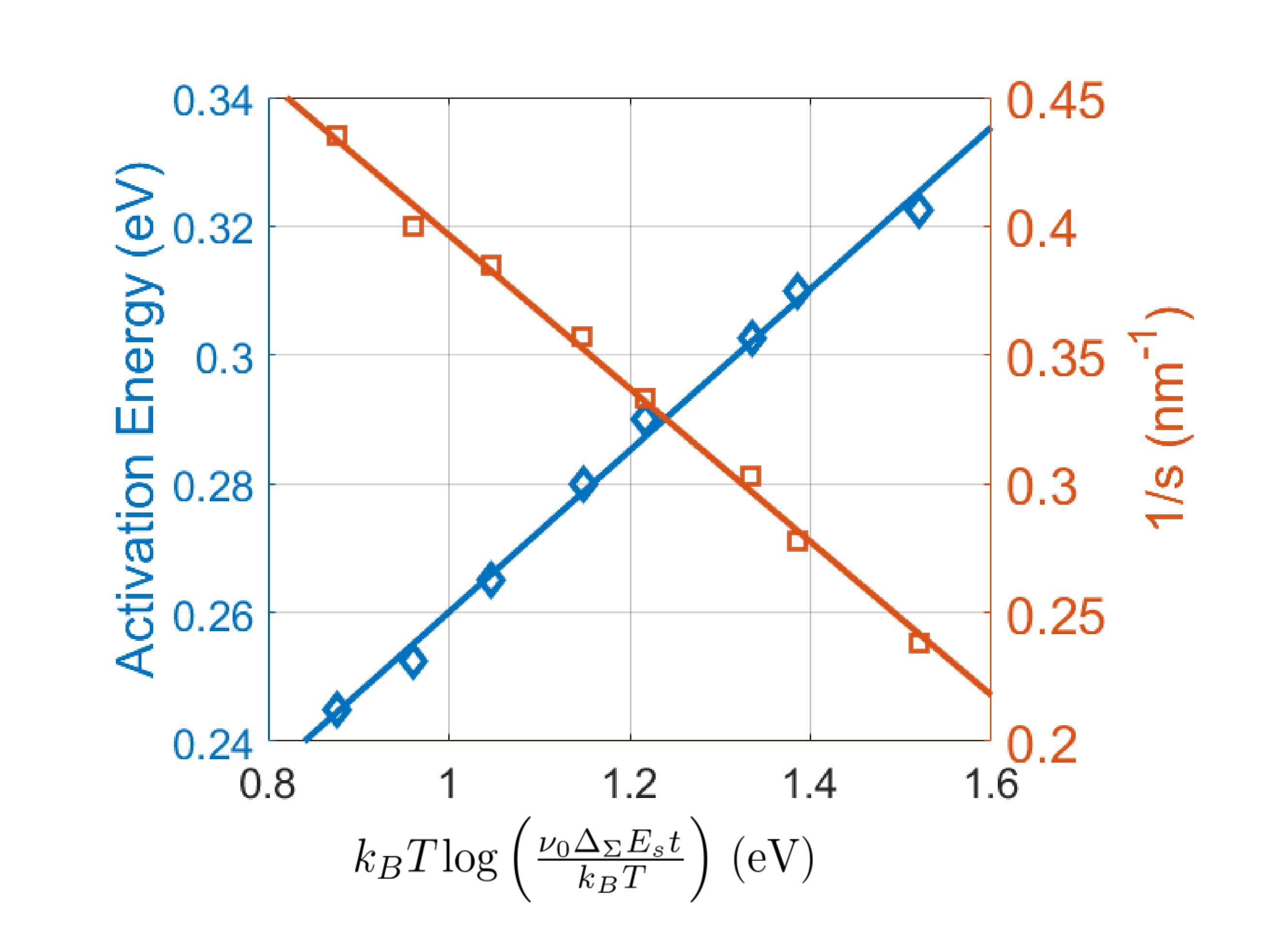
The relaxation dynamics
@ constant temperature

$$\Sigma(t) = -\frac{k_B T}{E_s} \log\left(\frac{t+\tau_0}{\tau_1}\right)$$
$$\tau_1 = (k_B T/\nu_0 \Delta_\Sigma E_s) \exp\left(\frac{E_s}{k_B T}\right)$$
$$\tau_0 = \tau_1 \exp\left(-\frac{\Sigma_0 E_s}{k_B T}\right)$$

if $t >> \tau_0$

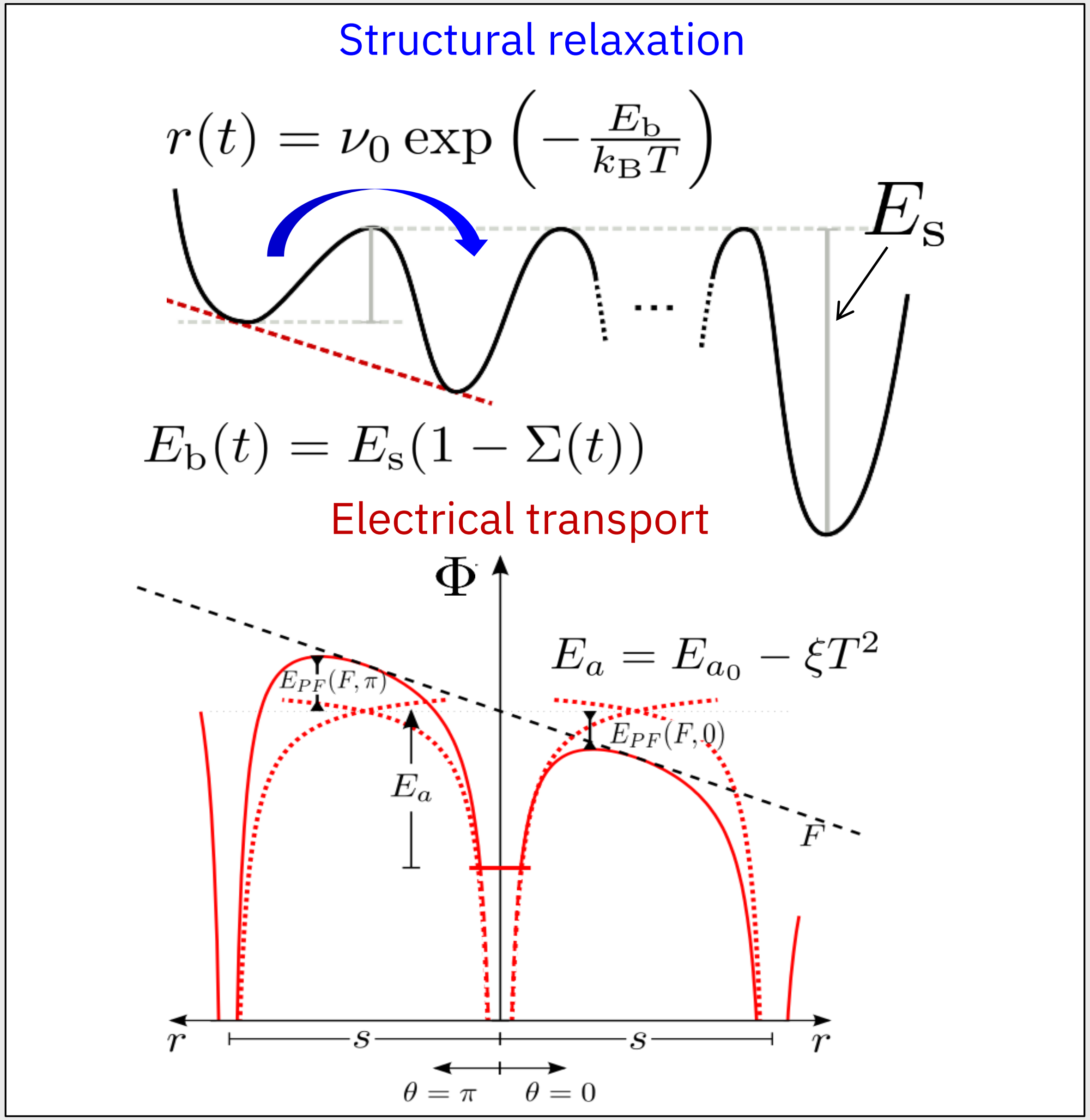
$$\Sigma(t) = 1 - \frac{k_B T}{E_s} \log\left(\frac{\nu_0 \Delta_\Sigma E_s t}{k_B T}\right)$$
$$\Delta\Sigma \propto k_B T \log\left(\frac{\nu_0 \Delta_\Sigma E_s t}{k_B T}\right)$$

"Relaxation Energy"



Remarkable linear dependence of E_a and 1/s on the relaxation energy

Collective relaxation and electrical transport: The Link



Amorphous state created with an initial distance from the "ideal glass"

$$\Sigma_0 = \Sigma(0)$$

Dynamics of structural relaxation

$$\frac{d\Sigma(t)}{dt} = -\nu_0 \Delta_\Sigma \exp\left(-\frac{E_s}{k_B T(t)}\right) \exp\left(\frac{\Sigma(t) E_s}{k_B T(t)}\right)$$

$$E_{a_0}(t) = E_{a_0}^{max} - \alpha \Sigma(t)$$

$$s(t) = s_0 / \Sigma(t)$$

Link to electrical transport

$$E_a(t) = E_{a_0}(t) - \xi T^2$$

$$\Phi(r, \theta, F) = -eFr\cos(\theta) - \frac{\beta^2}{4e}\left(\frac{1}{r} + \frac{1}{s-r}\right) + \frac{\beta^2}{es}$$

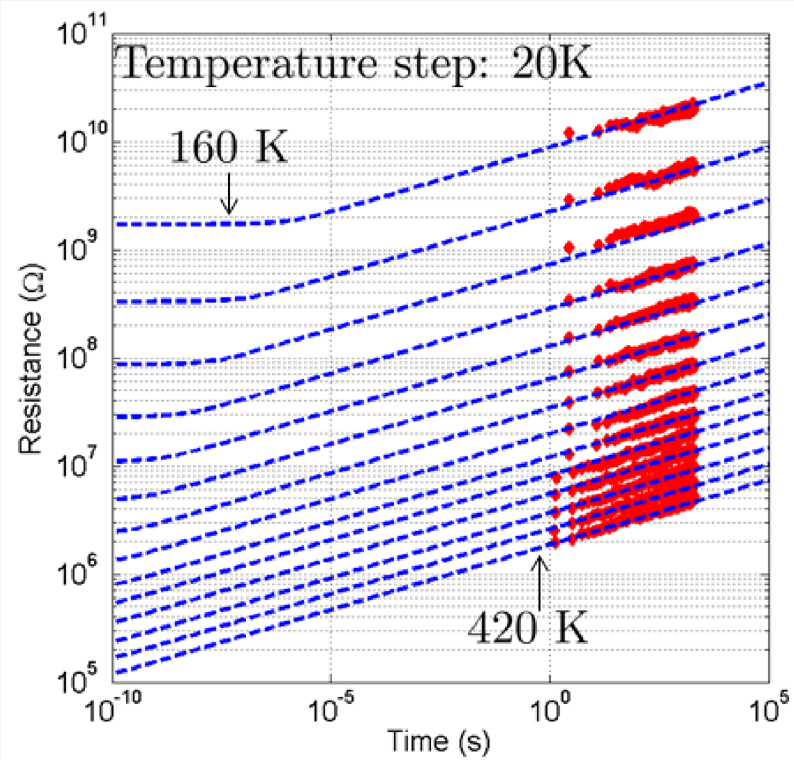
$$E_{PF}(F, \theta) = -\max_r V(r, \theta, F)$$

$$n(F) = \frac{K}{4\pi} \int_0^\pi \exp\left(-\frac{E_a - E_{PF}(F,\theta)}{k_B T}\right) 2\pi \sin(\theta) d\theta$$

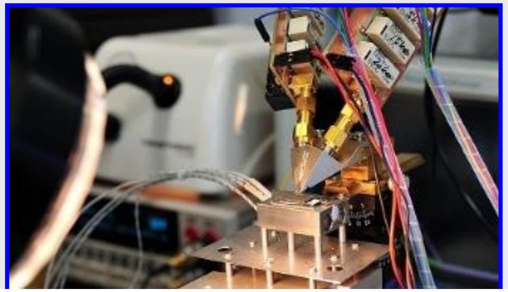
$$\sigma(F) = e\mu n(F)$$

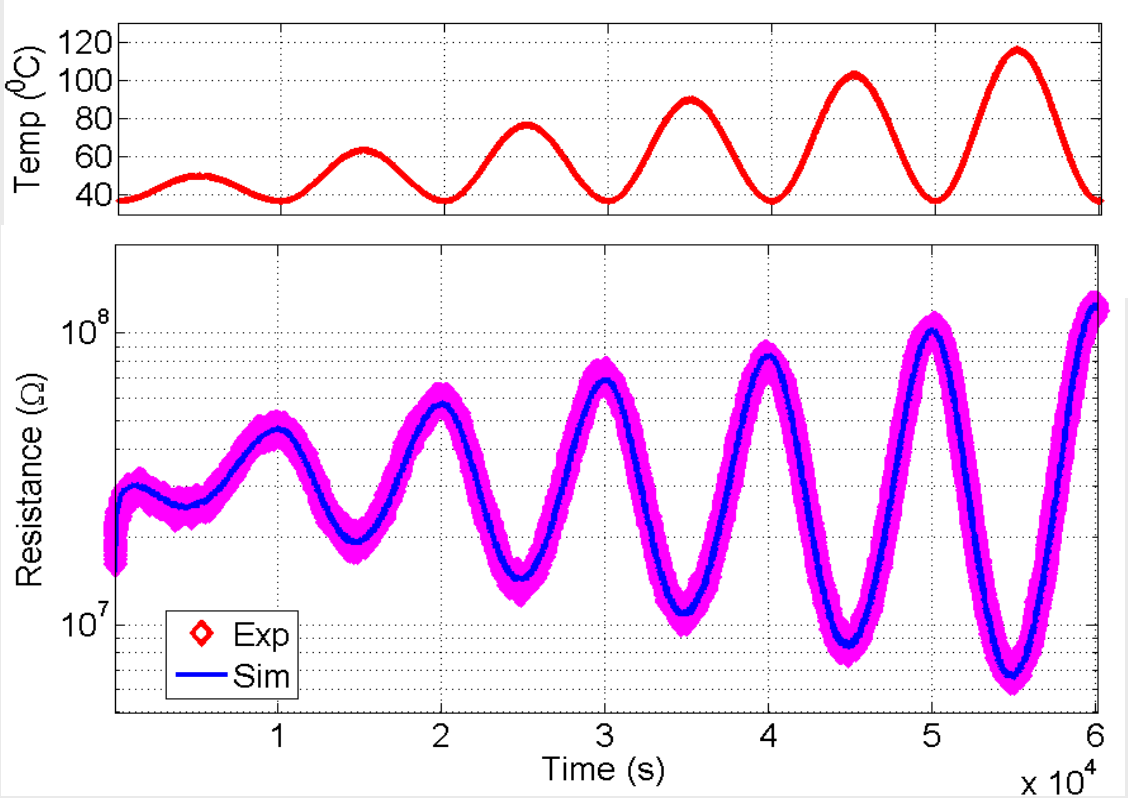
Model validation

Constant temperature over a wide range



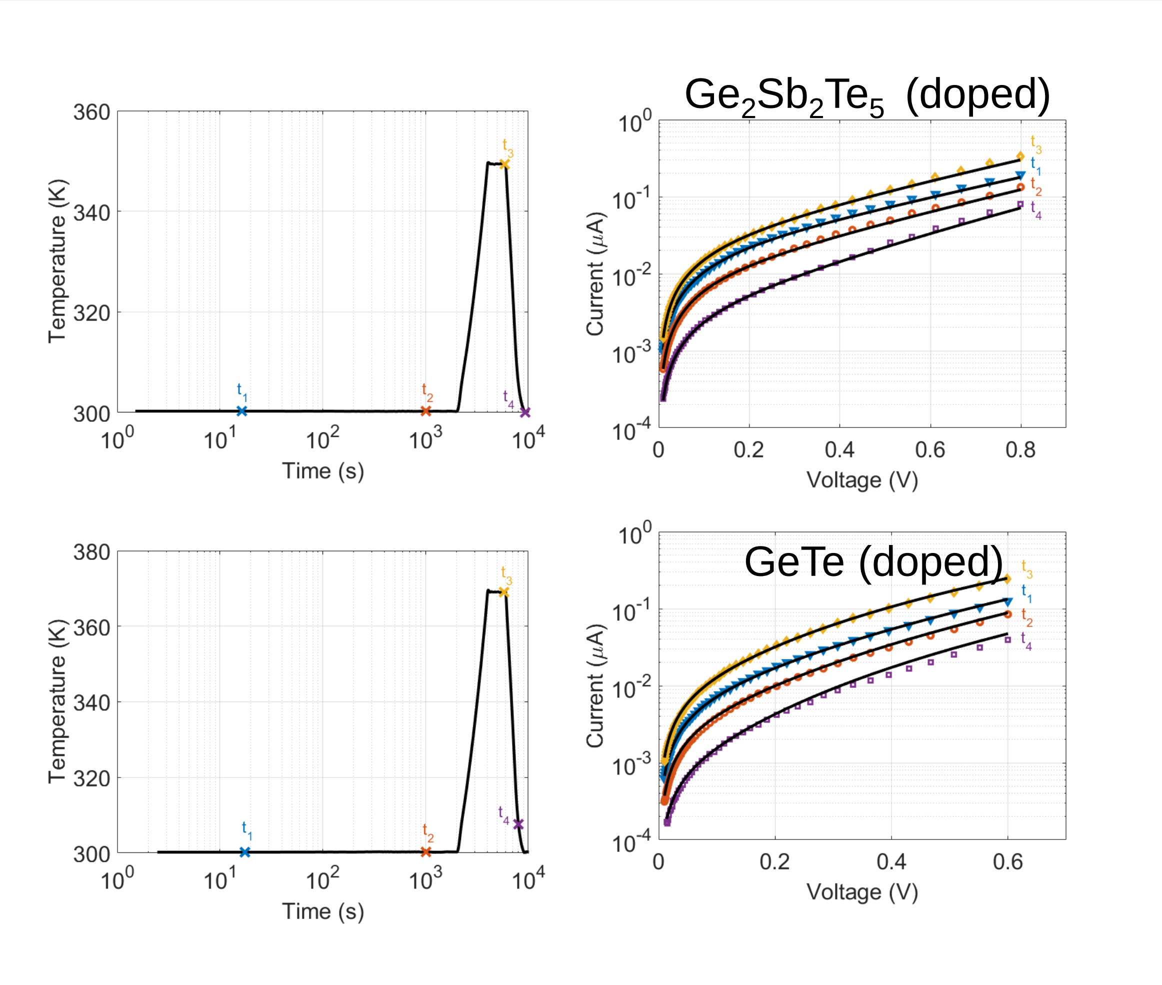
Time-varying temperature





Model validation: $Ge_2Sb_2Te_5$ and GeTe

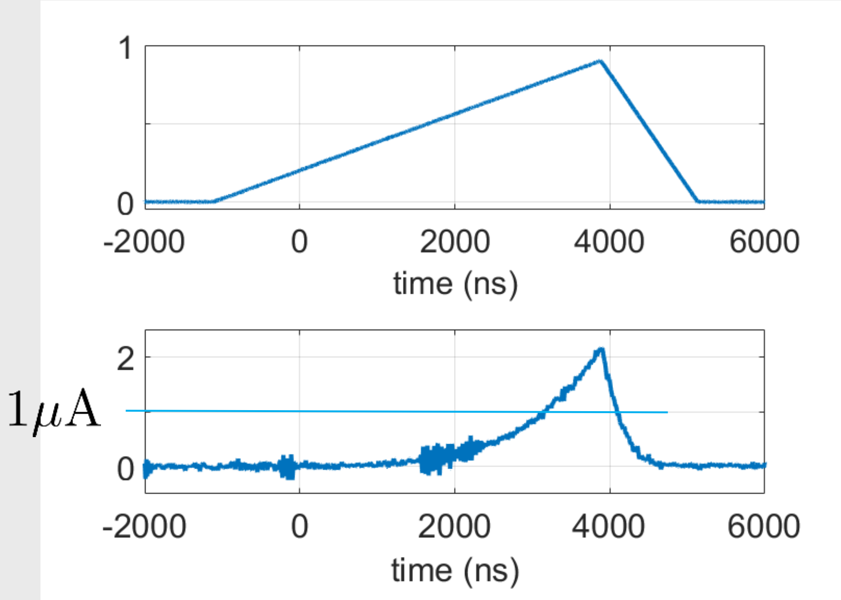
- Time-temperature profile applied to the PCM cell after RESET
- I-V curves accurately predicted by the drift model
- Clear increase of log(I) vs V slope → signature of increasing s

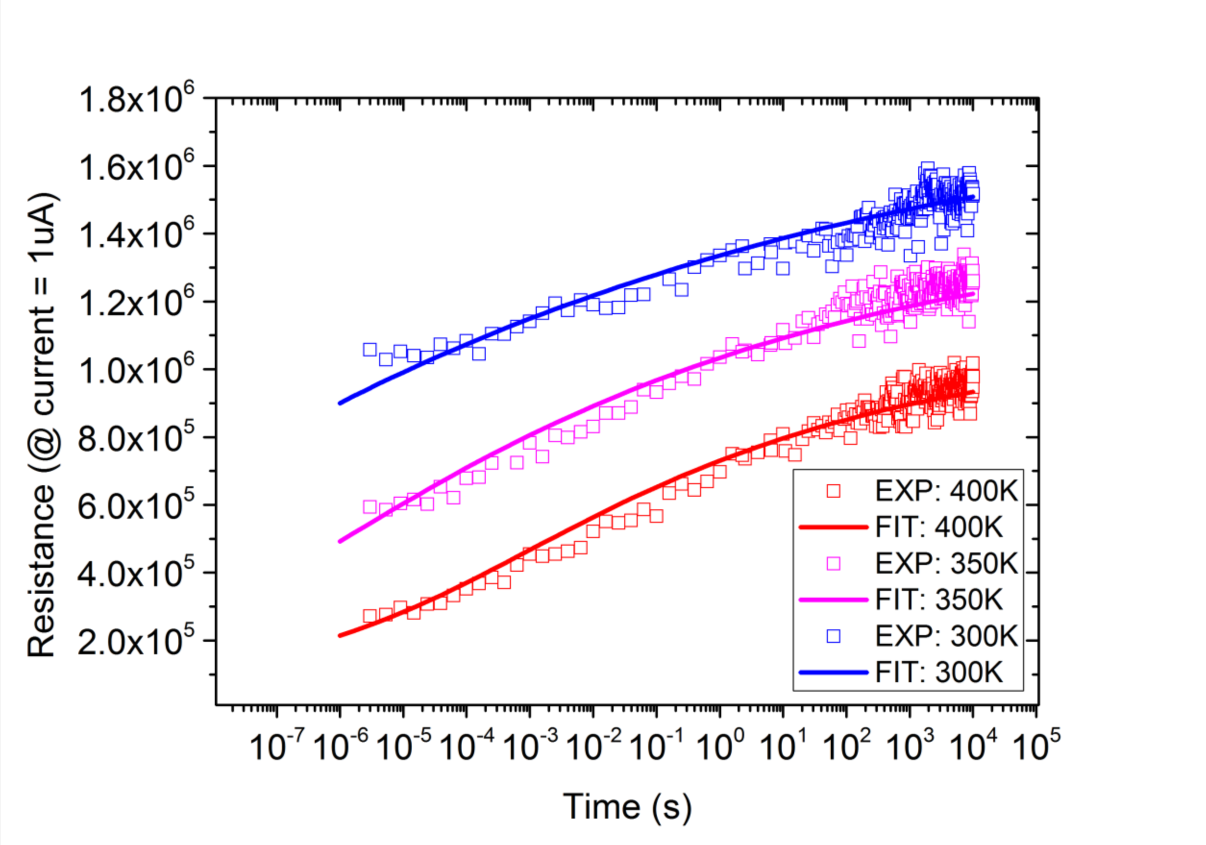


Indicative of the universality of the drift model

Model validation: High field resistance

Fast measurement of high field resistance



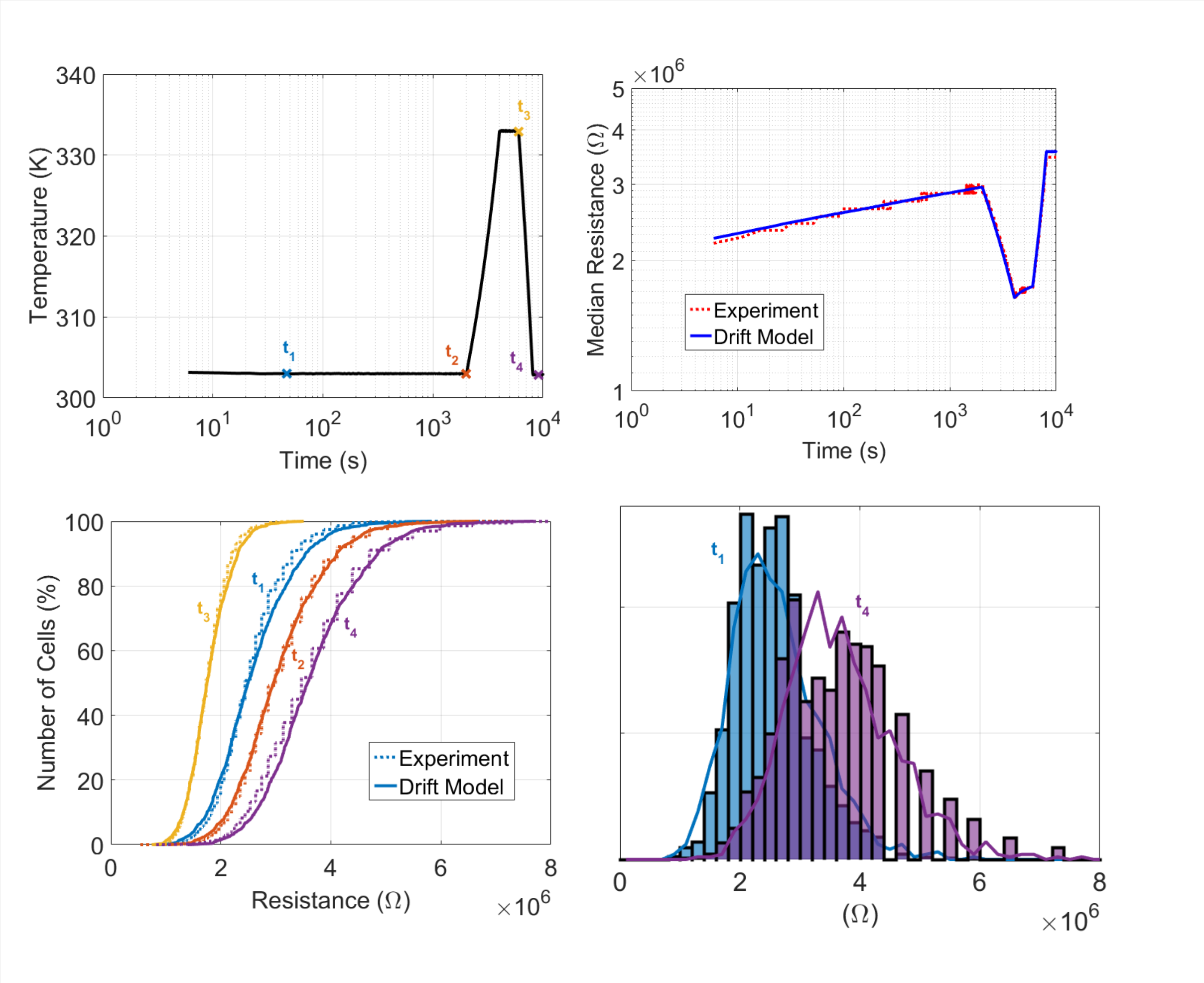


Model valid over 10 orders of magnitude in time

Model validation: Array of 4k cells

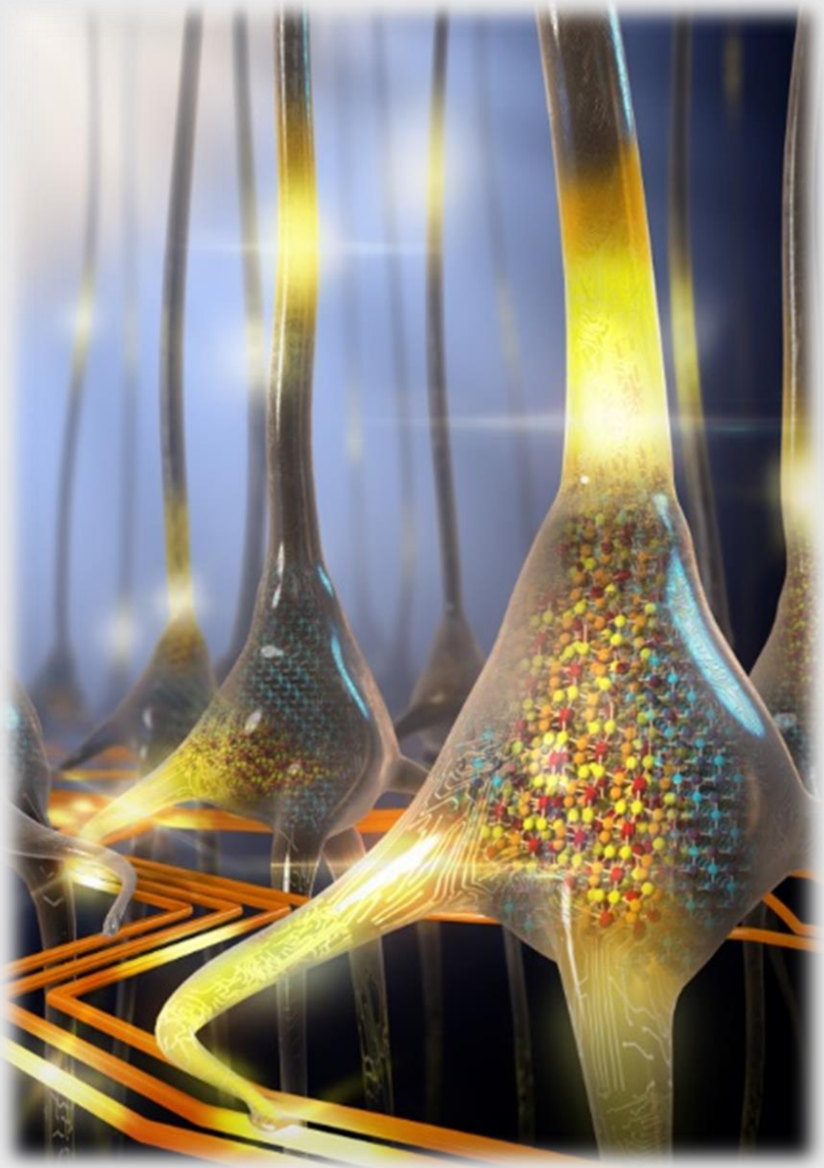
- A prototype PCM chip with addressing, readout and programming circuitry
- Measurements on a array of 4k cells undergoing changes in ambient temperature
- Model captures the evolution of the median resistance value
- Significant drift variability leads to a wide distribution of resistances even after short period of time
- Distributions broaden with increasing relaxation

Distributions and their broadening captured by the model

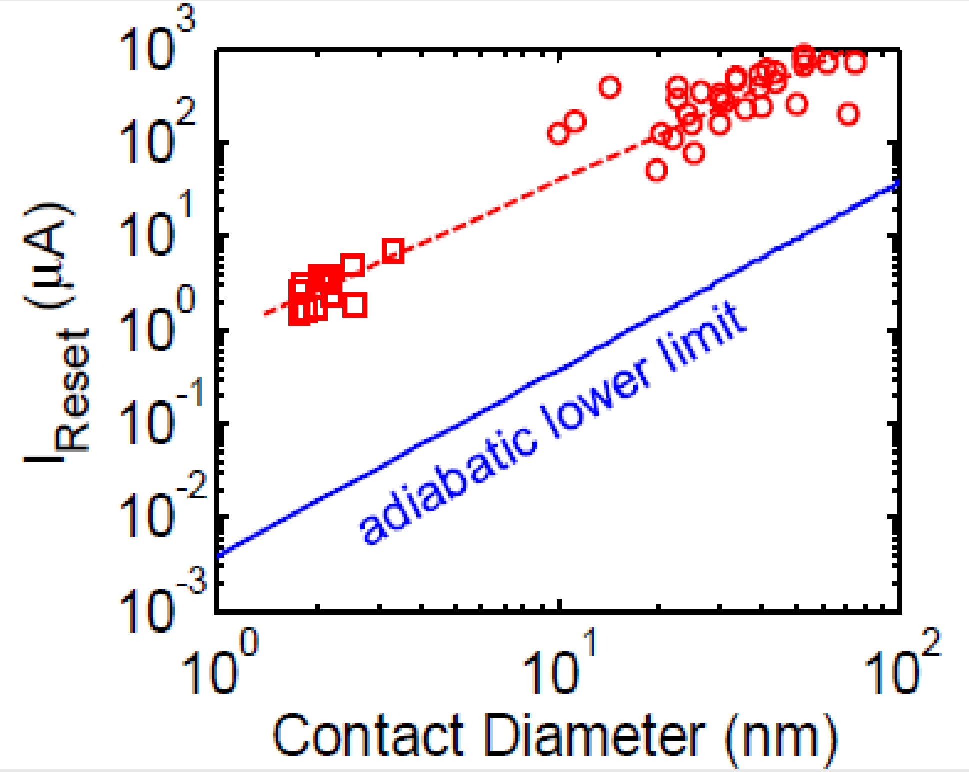


Outline: Part I

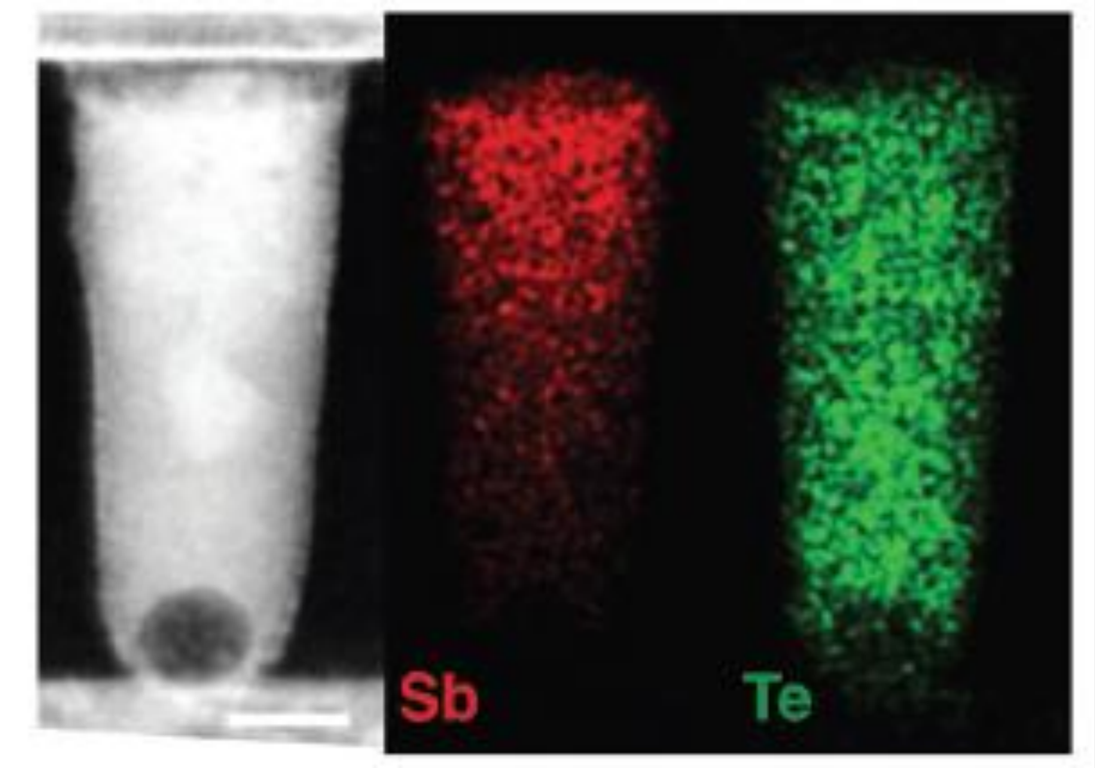
- **Introduction to PCM**
- **PCM device physics**
  - ✓ **Electrical system**
    - Subthreshold electrical transport
    - Threshold switching
  - ✓ **Thermal system**
  - ✓ **Structural dynamics**
    - Melt-quench process
    - Crystallization
    - Structural relaxation
- **Key challenges and device-level advances**
  - ✓ Projected PCM
  - ✓ Single-elemental PCM



Challenge 1: Programming energy



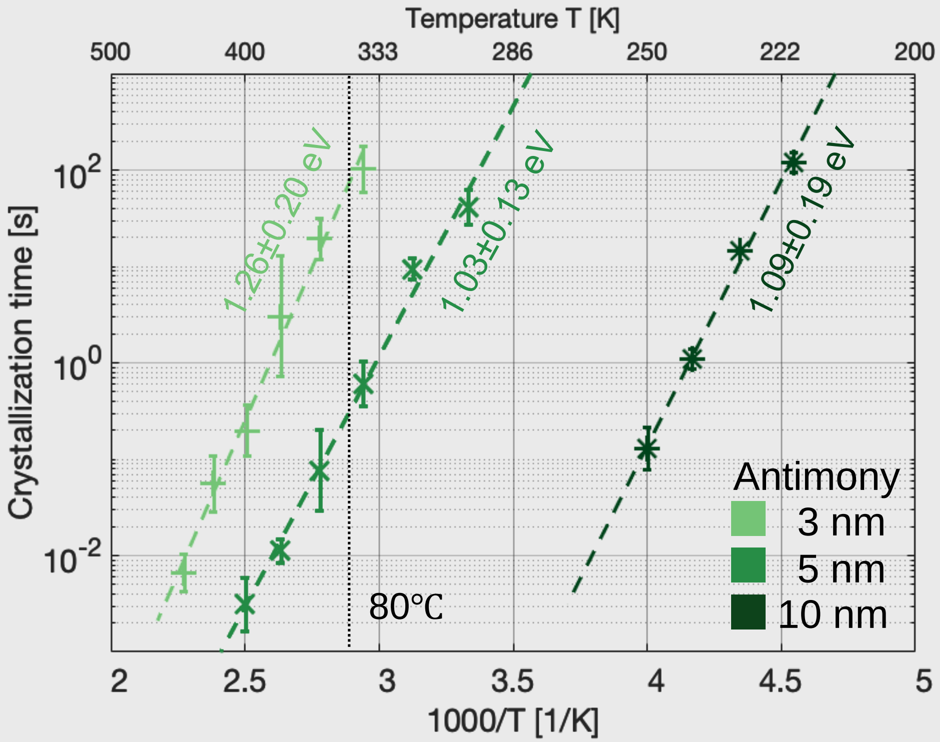
Xiong et al., IEDM, 2016

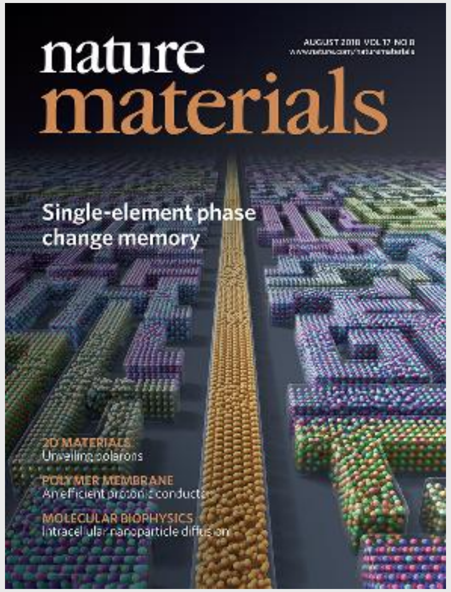


Xie et al., Adv. Mat., 2018

- Need to reduce the volume of material that needs to be melted
- Scaling to small dimensions severely hampered by fabrication challenges and elemental segregation

Single element phase-change memory

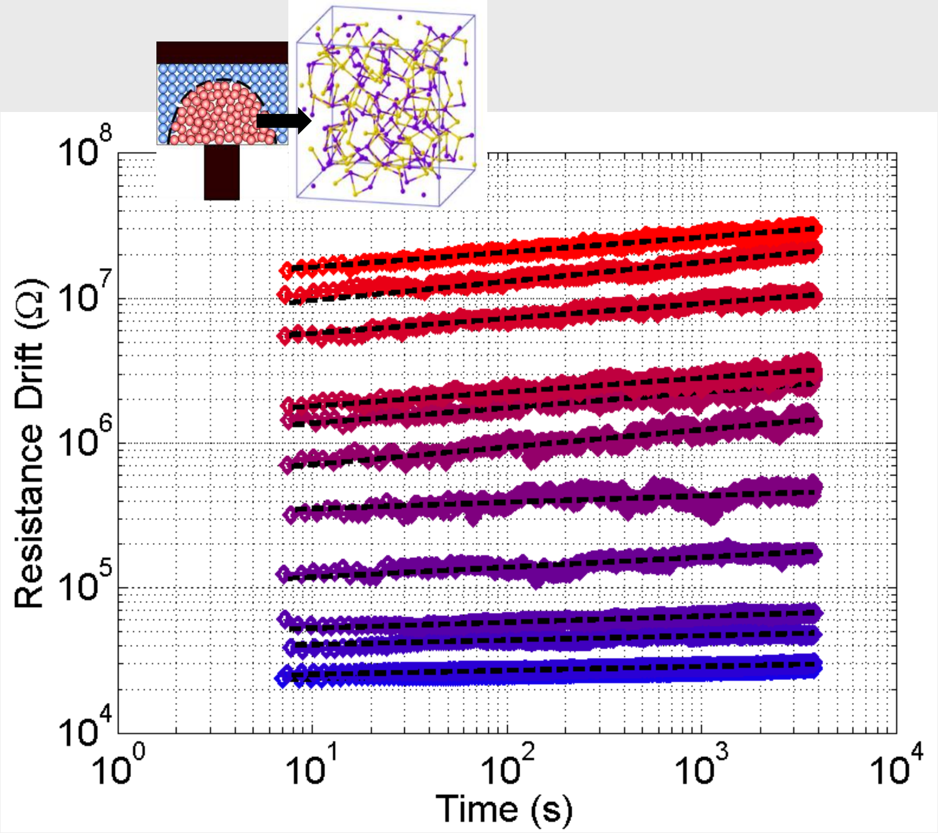


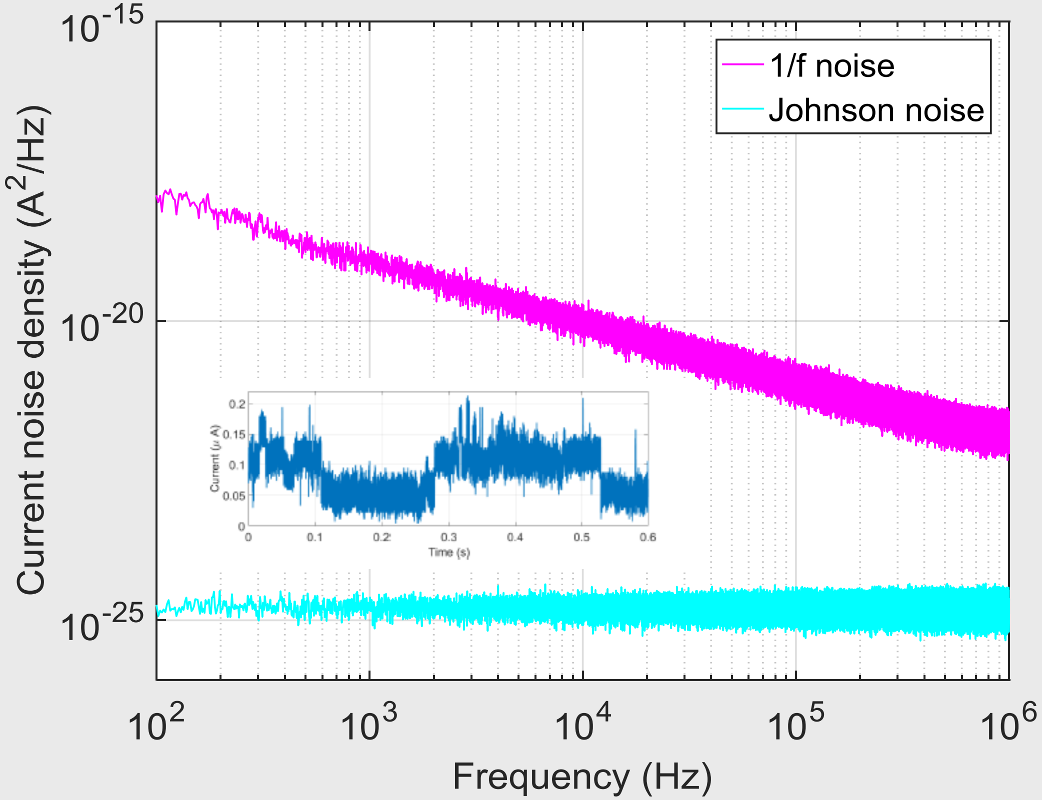


- **Single elemental Sb** can be used for PCM when confined to nanoscale dimensions!
- Directs research away from materials optimization to nanoscale confinement!

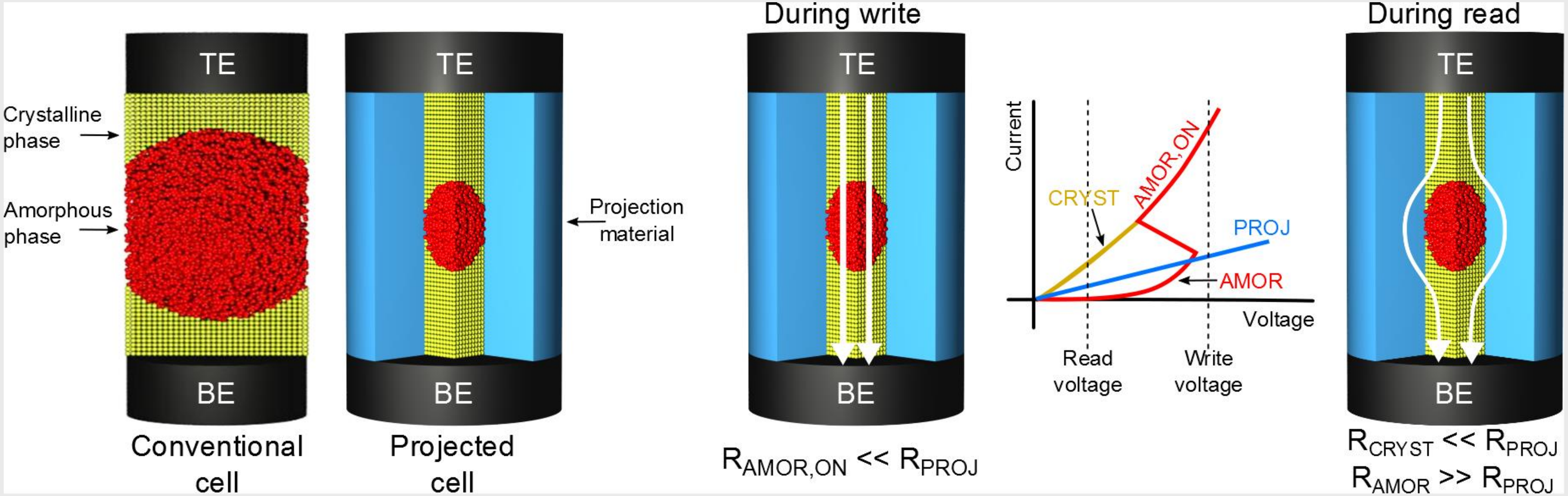
Salinga et al., Nature Materials, 2018

Challenge 2: Drift and noise





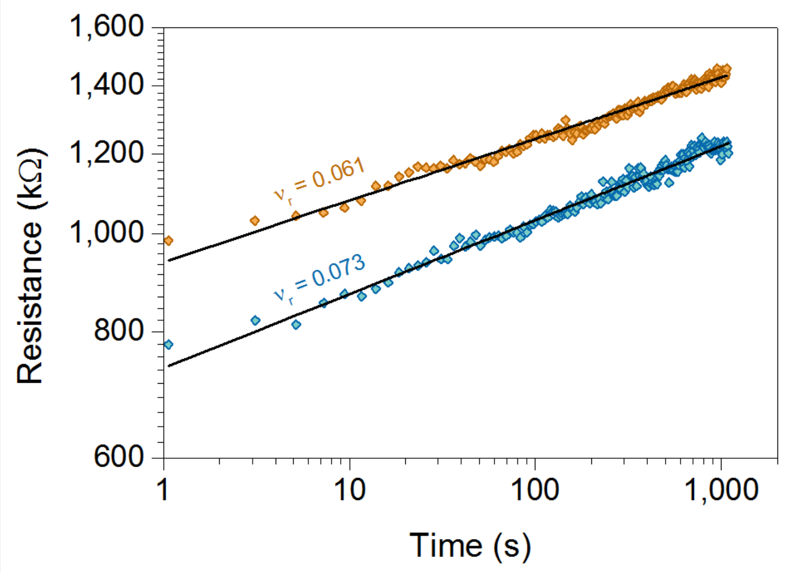
Projected phase-change memory



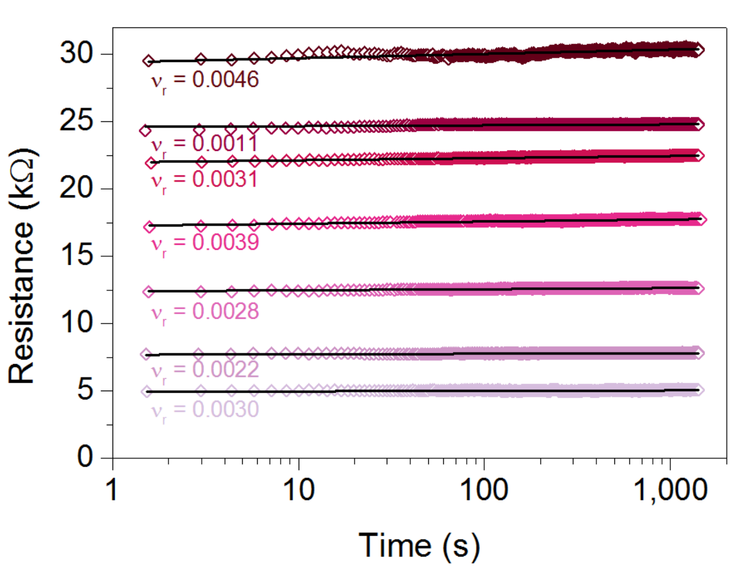
Koelmans et al., Nature Comm., 2015

Projected phase-change memory

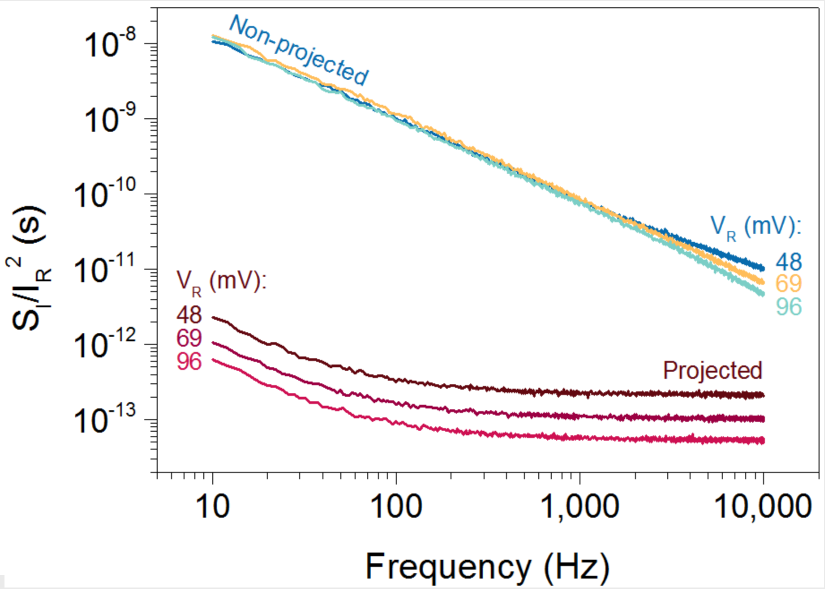
Drift in un-projected devices



Drift in projected devices



Comparison of noise characteristics



- Near elimination of drift
- Substantial reduction in noise

Summary

- **PCM is arguably the most advanced resistive memory technology**
  - ✓ The primary applications are foreseen in the domains of storage class memory and non-von Neumann computing
- **PCM device characteristics can be viewed as a intricate feedback interconnection of electrical, thermal and structural dynamics**
  - ✓ The electrical system
    - Subthreshold transport attributed to trap-limited band transport with PF emission
    - Threshold switching likely to arise from thermal feedback (at least in PCM devices)
  - ✓ Thermal system
    - Large temperature gradients within the devices → Thermoelectric effects need to be considered
  - ✓ Structural dynamics
    - Amorphization arises via melt-quench process
    - Crystal growth has a strong temperature dependence
    - Structural relaxation of the amorphous phase can be described via a collective relaxation model
- **Key challenges: The relatively large programming current and resistance fluctuations**
  - ✓ Single elemental PCM a promising avenue towards ultra-scaled PCM devices
  - ✓ Projected PCM, a device-level approach to countering resistance variations