MODELING OF SEASONING EFFECTS IN PHASE CHANGE MEMORY ARRAYS

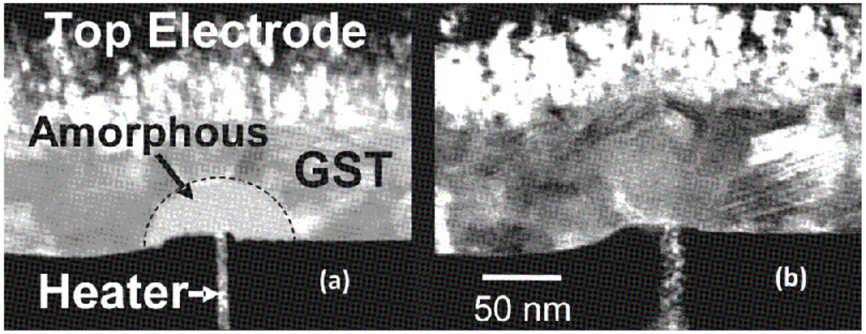
Cristian Zambelli, Andrea Chimenton and Piero Olivo
Dip. Ingegneria - ENDIF
Università degli Studi di Ferrara (Italy)

OUTLINE

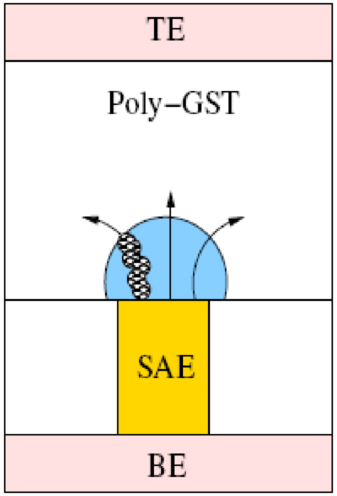
- Introduction to Phase Change Memory technology
- Experimental evidence of Seasoning effect
  - Effects on R_{RESET}/R_{SET}
  - Effects on the I-V device characteristics
- First modeling approach to Seasoning: RESET operation only
- Physical interpretation of SET Seasoning in PCM
- Modeling of SET Seasoning
  - Phase Change Memory cell Erase operation kinetics model
  - SET Seasoning model
- Conclusions

PHASE CHANGE MEMORY (PCM) TECHNOLOGY

- The PCM concept relies on the phase change transition from crystalline into amorphous and vice versa of an active chalcogenide material such as the Ge2Sb2Te5 (GST).
- The crystalline phase is associated with the SET state of the memory and it can be obtained by an erase operation (logical '1' stored).
- Dually, the amorphous phase is associated with the RESET state of the memory and can be obtained by a program operation (logical '0' stored).



RESET SET

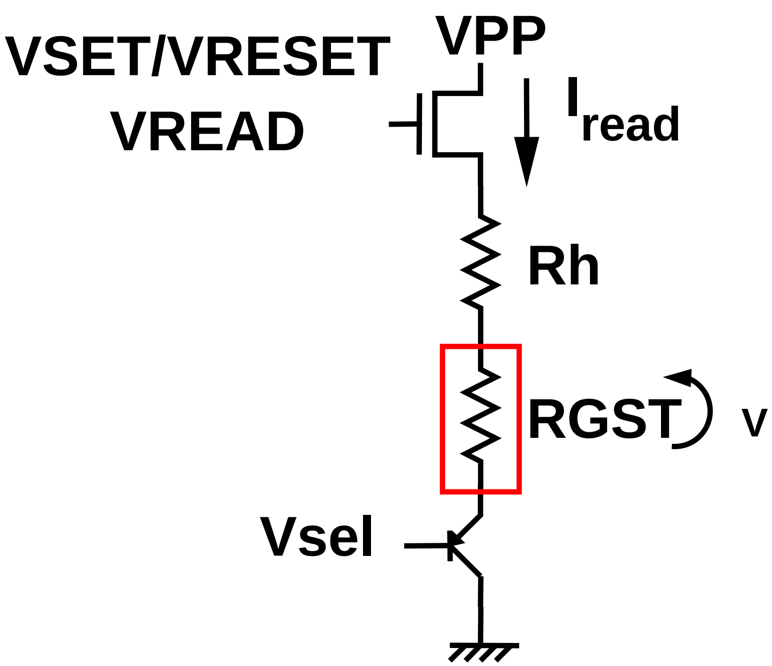


PHASE CHANGE MEMORY (PCM) OPERATION PRINCIPLES

- The active material phase change between amorphous (a-GST) and crystalline state (x-GST) relies on Joule Heating
- The transition from x-GST to a-GST (storage of a logical ‘0’) takes place by applying a long time voltage pulse (typ. 5V for 4 μs) which melts and subsequently amorphize the material
- The viceversa transition (storage of a logical ‘1’) exploits the theory for Field-Induced Nucleation on which a crystalline shunt grows into the amorphous dome until saturation by applying a shot time voltage pulse (typ. 3.75V for 100 ns)

EXPERIMENTAL SETUP

- Electrical Characterization measurements were performed on a 512kbit cells population of a PCM test chip device in 0.18 μm technology with BJT selector

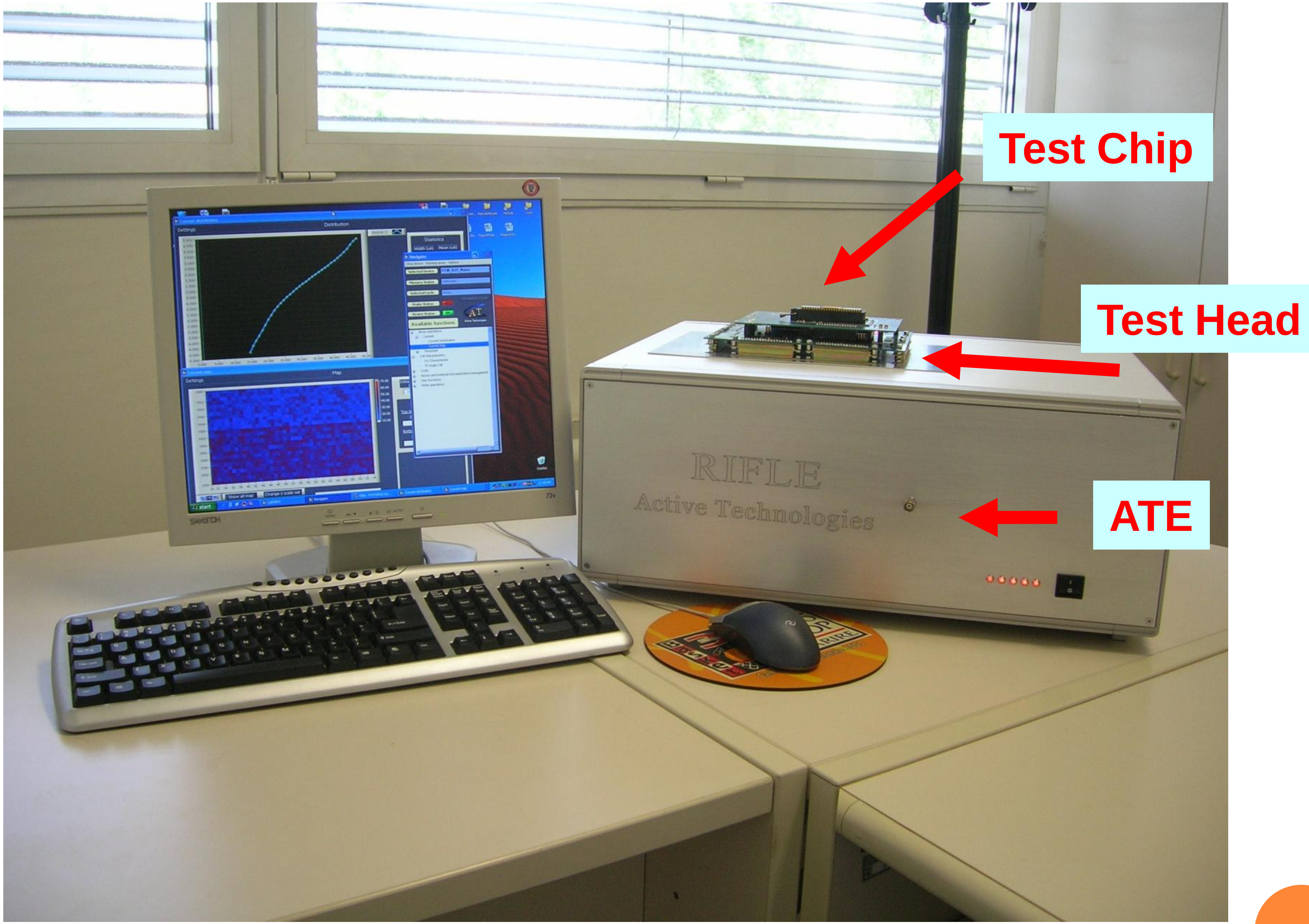


Single cell architecture

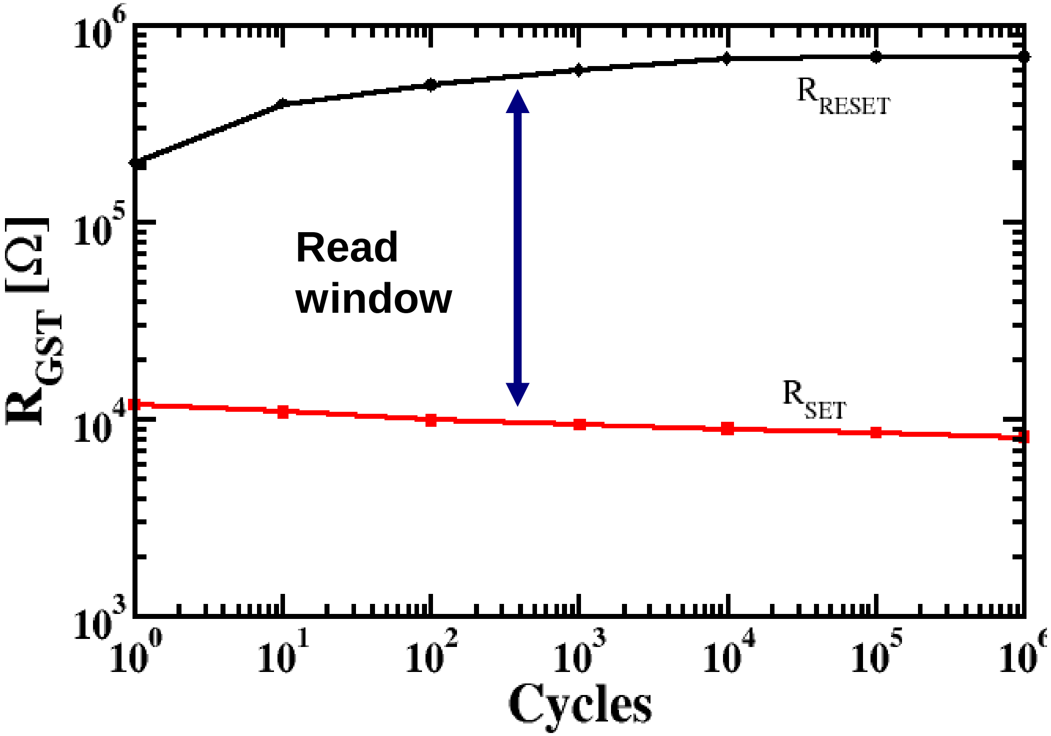
Both Writing and Reading operations have been performed with a dedicated ATE capable of applying fully arbitrary waveforms. The sensed Iread current when a read voltage VREAD is applied gets converted into RGST values by appropriately accounting the cells connections to the array.

VREAD = 1.8 V (typ.)

Iread = 4 μA (RESET) to 70 μA (SET)


Test Chip
Test Head
ATE
RIFLE
Active Technologies

EXPERIMENTAL EVIDENCE OF SEASONING IN PCM (R_{RESET}/R_{SET})

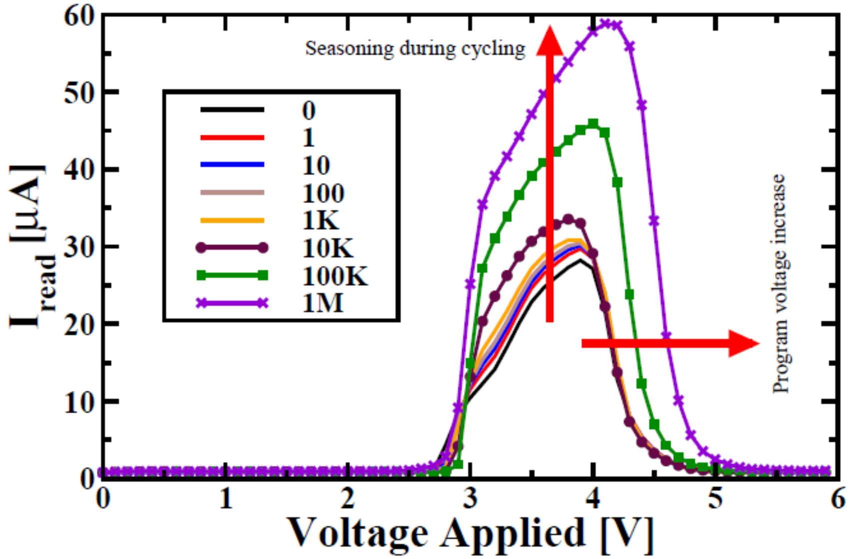


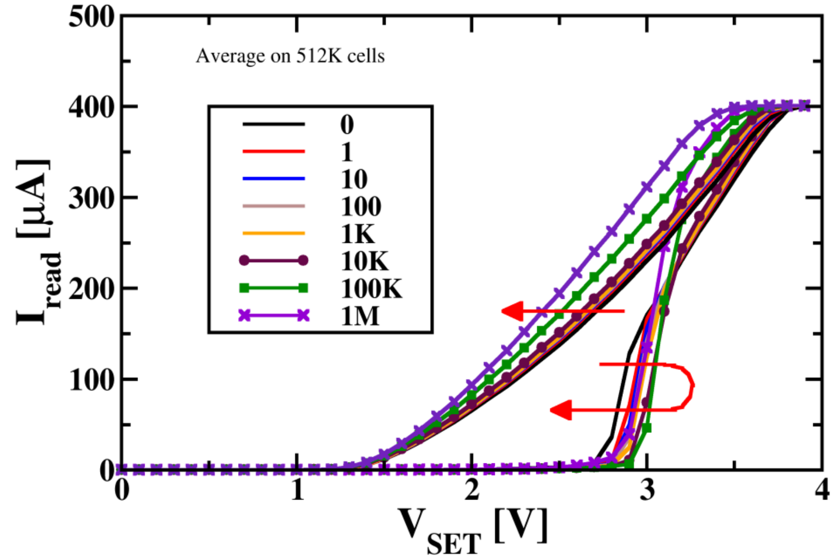
- Although the phase transition between SET and RESET conditions is always reversible an alteration of the properties of the active material during cycling conditions may occur

Appears to not threatens the overall reliability

Seasoning is evidenced as an increase of R_{RESET} and a consequent decrease of R_{SET} during cycling

EXPERIMENTAL EVIDENCE OF SEASONING IN PCM (I-V DEVICE CHARACTERISTICS)





Equivalent device I-V

SET/RESET device I-V

- In cycling a constant increase of programming voltage required is appreciable

- Increase also of Iread current

- Both SET/RESET characteristics exhibits a slope change in cycling

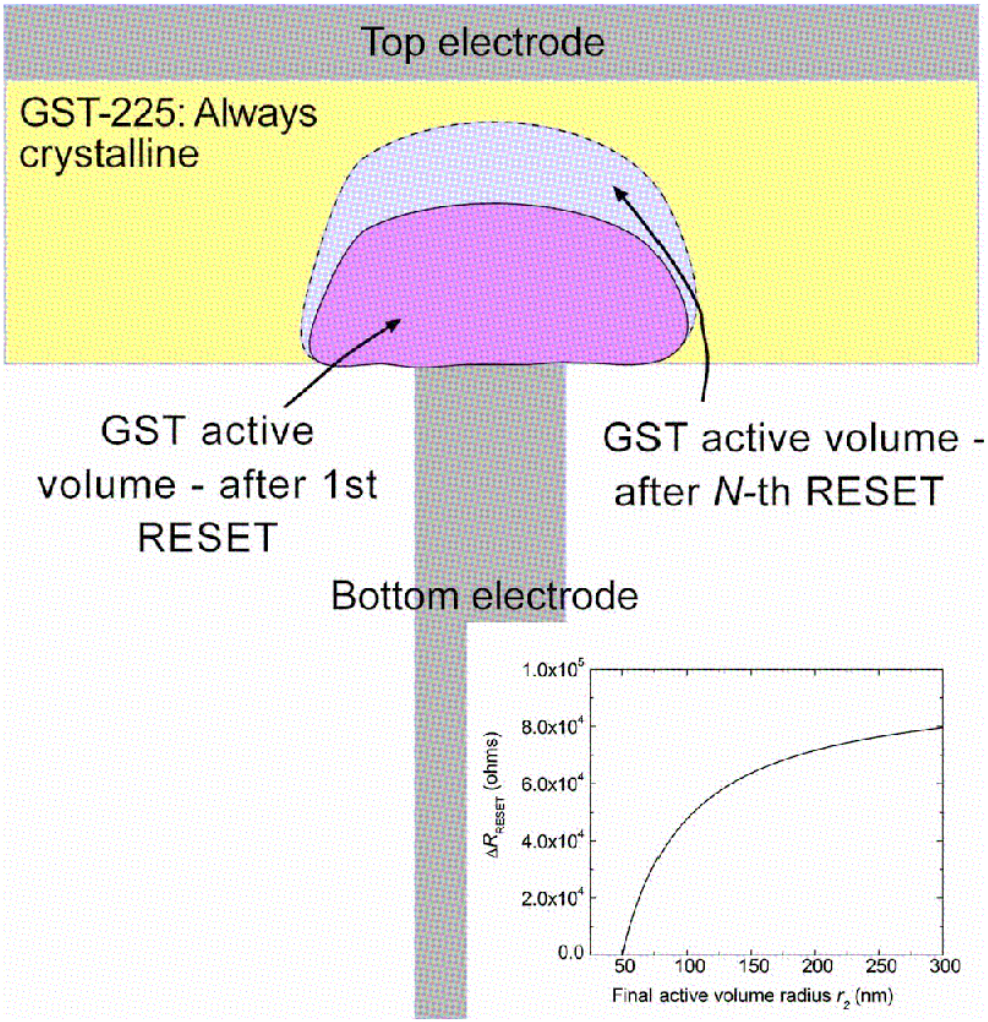
- The effect is stronger on RESET operation

FIRST MODELING APPROACH: R_{RESET} SEASONING

- A first explanation/modeling of seasoning was performed by *Sarkar et al.* which attributed the RESET seasoning to an alteration of the programmable volume due to stoichiometric modification of GST material in cycling

- The permanent change in material characteristics during the programming (RESET) operation of the memory allows to melt and amorphize more x-GST cycle after cycle (Tmelt decrease)

- This augments the amorphous hemispherical dome and therfore increase the resistance R_{RESET}



The analytical dependence of the Ohmic resistance change ΔR_{SET} of a hemispherical dome - shaped resistor with increasing radius is:

$$\Delta R_{RESET} = \frac{\rho_a}{2\pi}\left(\frac{r_2 - r_1}{r_2 r_1}\right)$$

$\rho_a = 3\ \Omega cm$
$r_1 = 50$ nm (fixed)
$50 < r_2 \leq 300$ nm

An initial steep increase of the resistance up to approximately 100% increase is then followed by an asymptotic taper in good agreement with electrical characterization data

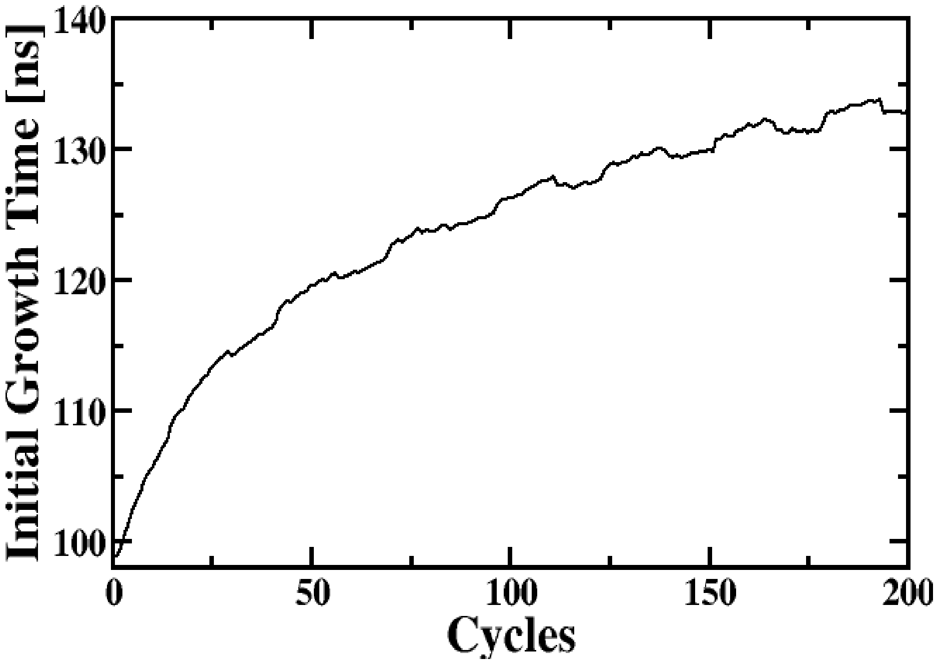
PHYSICAL INTERPRETATION OF SET SEASONING

- The picture of SET seasoning can be partially ascribed to the mechanisms depicted for RESET
- During Erase operation a crystalline shunt inclusion on the hemispherical amorphous dome must be created in order to have a current percolation path
- As the amorhphous cap thickness modify, the crystalline shunt geometry consequently morphs
- Also, as the stoichimetry of x-GST changes as the thermo-electrical parameters such as the x-state resistivity and the heat dispersion coefficent do

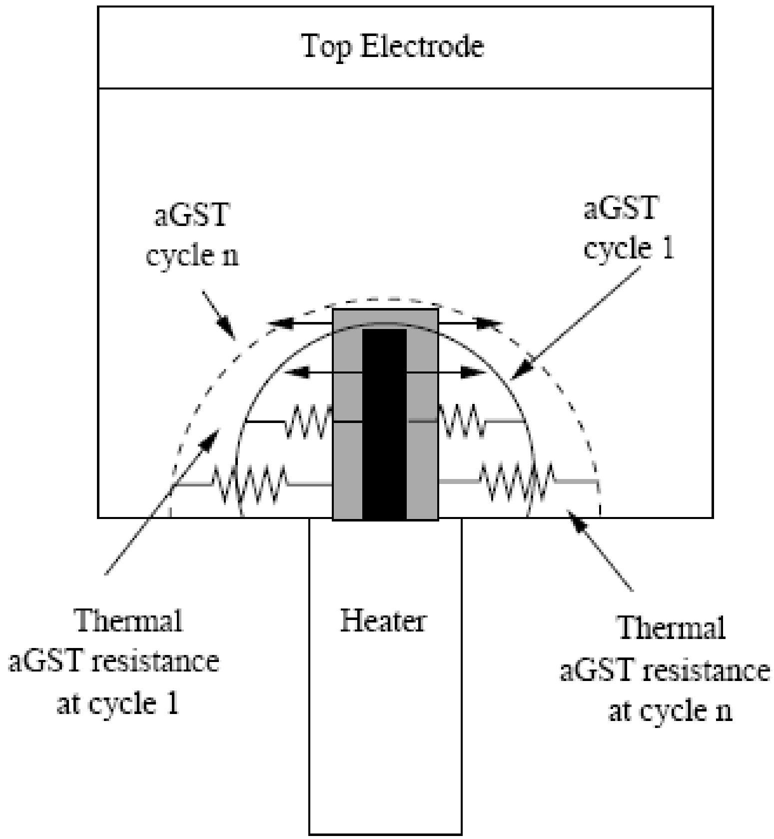
INITIAL GROWTH TIME PARAMETER EXTRACTION

- Another proof of the geometric alterations occuring on the active material volume can be found by extracting the parameter t_0 (IGT) from the R_{SET} cycling data

- The increase with cycles of the time required for creating a percolation path into the programmable region of the memory cell supports the hypothesis of a growth of the amorphous hemispherical dome and therefore an increase of the percolation path length



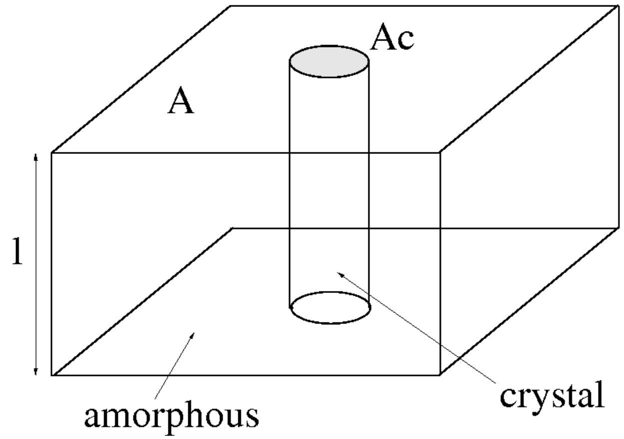
The variation of t_0 during cycling must be accounted when simulating the PCM cells



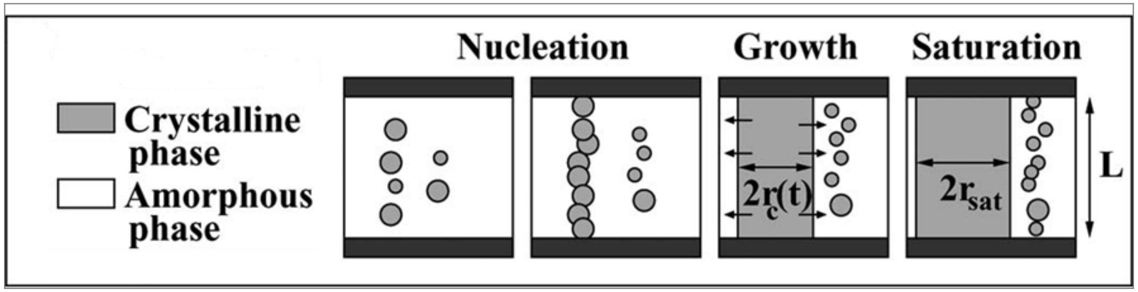
- The lateral heat flux dispersion gradually decreases during cycling, being the conductivity of the amorphous GST much smaller than that of the crystalline GST (0.19 W/mK versus about 1 W/mK respectively). As a consequence, a larger energy is used for phase change process.

Initially it was thought that ρ_C played a major role on the SET Seasoning effect → Necessity to verify it with an Erase (SET) operation model

PHASE CHANGE MEMORY ERASE KINETICS MODEL



$$A_C = \frac{\frac{l}{R_{GST}} - \frac{A}{\rho_A}}{\frac{1}{\rho_C} - \frac{1}{\rho_A}}$$



$$R_C = \sqrt{\frac{A_C}{\pi}}$$

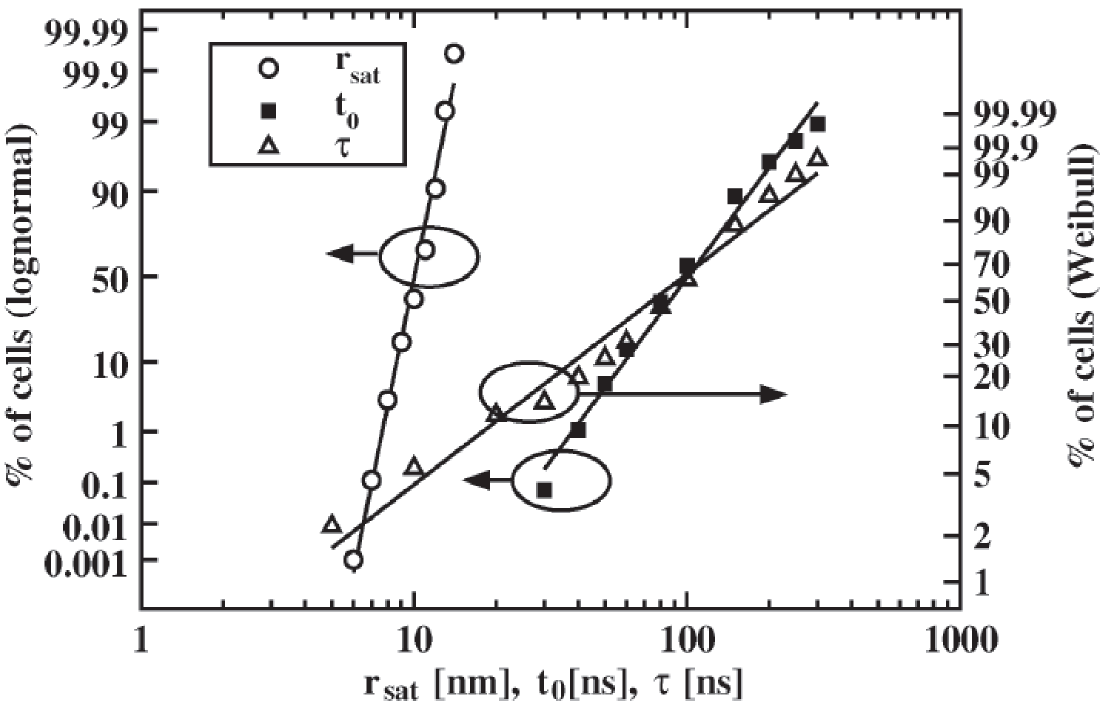
$$R_C(t) = r_{sat}(1 - e^{-\frac{(t-t_0)}{\tau}})$$

Time evolution of the crystalline shunt radius

$l = 30$ nm
$\rho_A = 50\ \Omega$cm
$\rho_C = 20$ mΩcm
$A = 800\ nm^2$

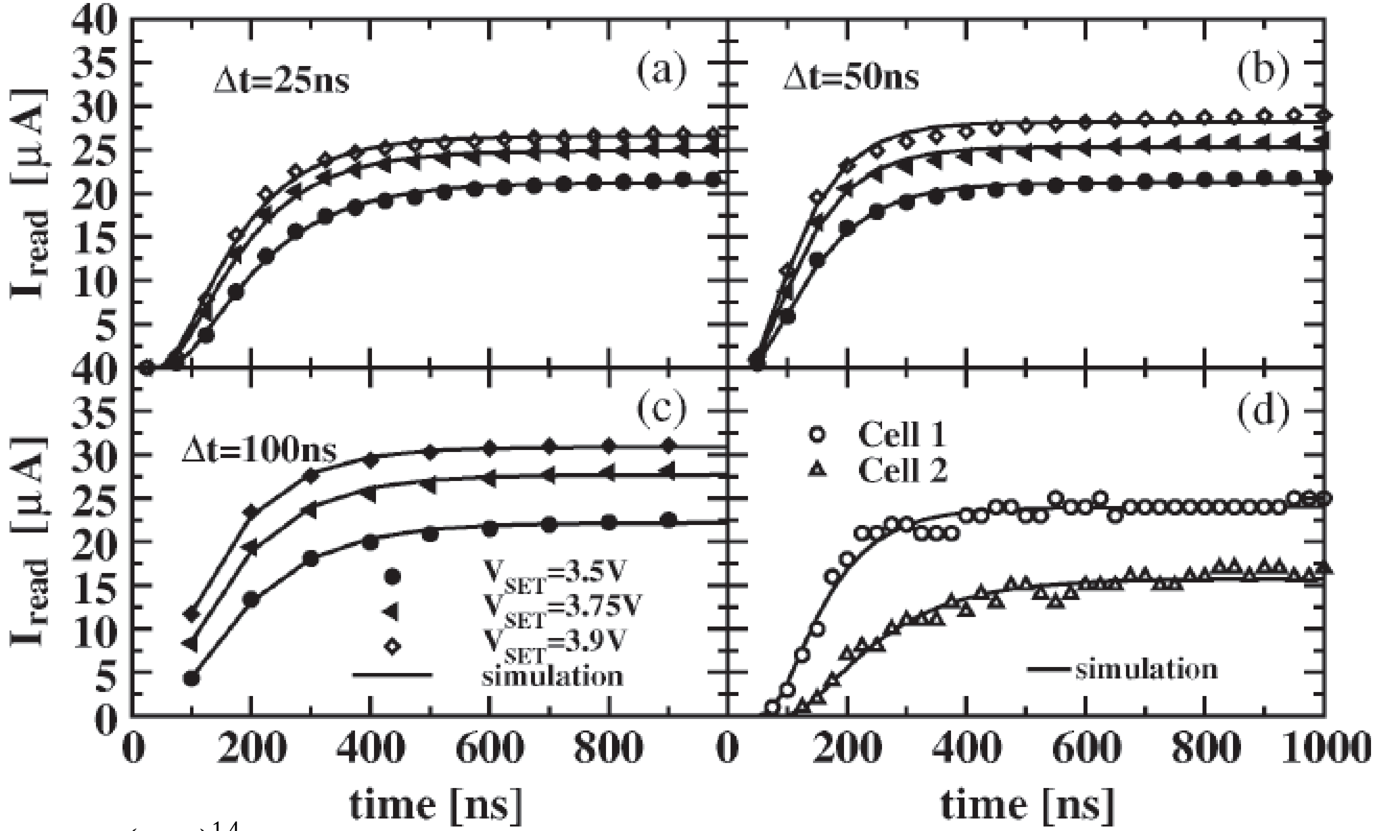
ρ_C is marginal on cycling

PARAMETERS FOR ERASE OPERATION KINETICS SIMULATION



From the collected electrical characterization data of 512kbit PCM cells we are able to model the distributions of these parameters in order to simulate the erase operation

- r_{sat} is the saturation radius of the crystalline shunt inclusion (Lognormal)
- t_0 is the initial growth time required for creating a stable conductive percolation path (Lognormal)
- τ is a constant governing the kinetics of crystal growth (Weibull)



$$F(\tau)=1-e^{-\left(\frac{\tau}{9.7n}\right)^{1.4}}$$

$$F(r_{sat})=\frac{1}{2}erfc\left[-\frac{\ln(r_{sat})-10n}{0.1\sqrt{2}}\right]$$

$$F(t_0)=\frac{1}{2}erfc\left[-\frac{\ln(t_0)-100n}{0.41\sqrt{2}}\right]$$

$$I_{read}=\frac{x*(V_{read}-V_{drop})}{1+(R_{heater}*x)}$$

$$x=\frac{1}{l}*\left[A_c*(\frac{1}{\rho_C}-\frac{1}{\rho_A})\right]+\frac{A}{\rho_A}$$

- The previous expression for I_{read} blend the crystalline component and the amophous component of R_{GST}

$$R_{GST} = \frac{L}{A}\frac{\rho_C \rho_A}{\rho_C + C(t)(\rho_A - \rho_C)} = \frac{R_{SET} R_{RESET}}{R_{SET} + C(t)*(R_{RESET} - R_{SET})}$$

$$C(t) = \frac{A_c(t)}{A}$$

↓

For crystalline fraction equal to 1 (Erase operation complete) R_{GST} tend to R_{SET}

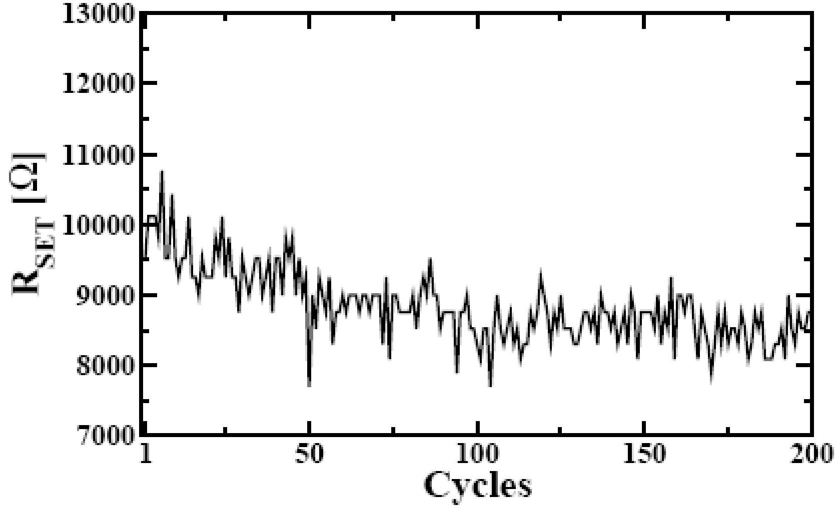
↓

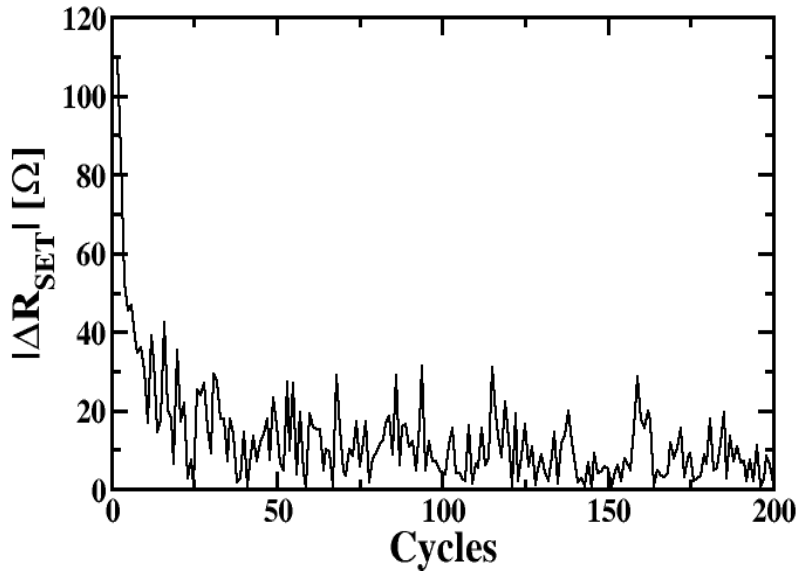
The last point of the Erase operation kinetics simulation must taken into account when simulating

CHARACTERISTICS OF SET SEASONING PHENOMENON

- The R_{SET} seasoning mechanism is quasi-linear on a logarithm scale over a large number of cycles with a saturating trend after 100K cycles. A deeper investigation shows that this effect is stronger during the very first operative cycles.

- Therefore we decided to use for sake of modeling and simulation speed a window of 200 SET/RESET operative cycles





$|\Delta R_{SET}(i)| = R_{SET}(i) - R_{SET}(i-1)$

SET Seasoning model expression

$$\Delta R_{SET} = R_{SET}(i) - R_{SET}(i-1) = \frac{l(i)\rho_C(i)}{A_C(i)} - \frac{l(i-1)\rho_C(i-1)}{A_C(i-1)}$$

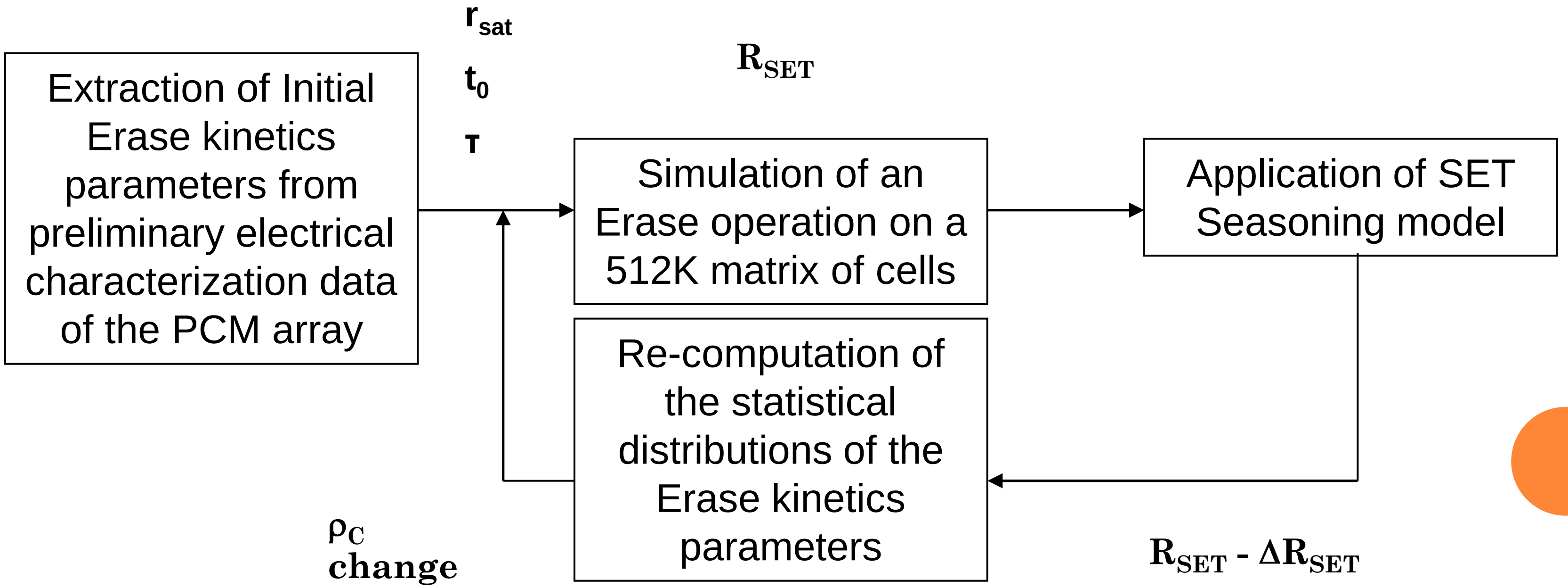
↓

The only parameter which significantly affects the R_{SET} value is the cystalline shunt area which depends on r_{sat}

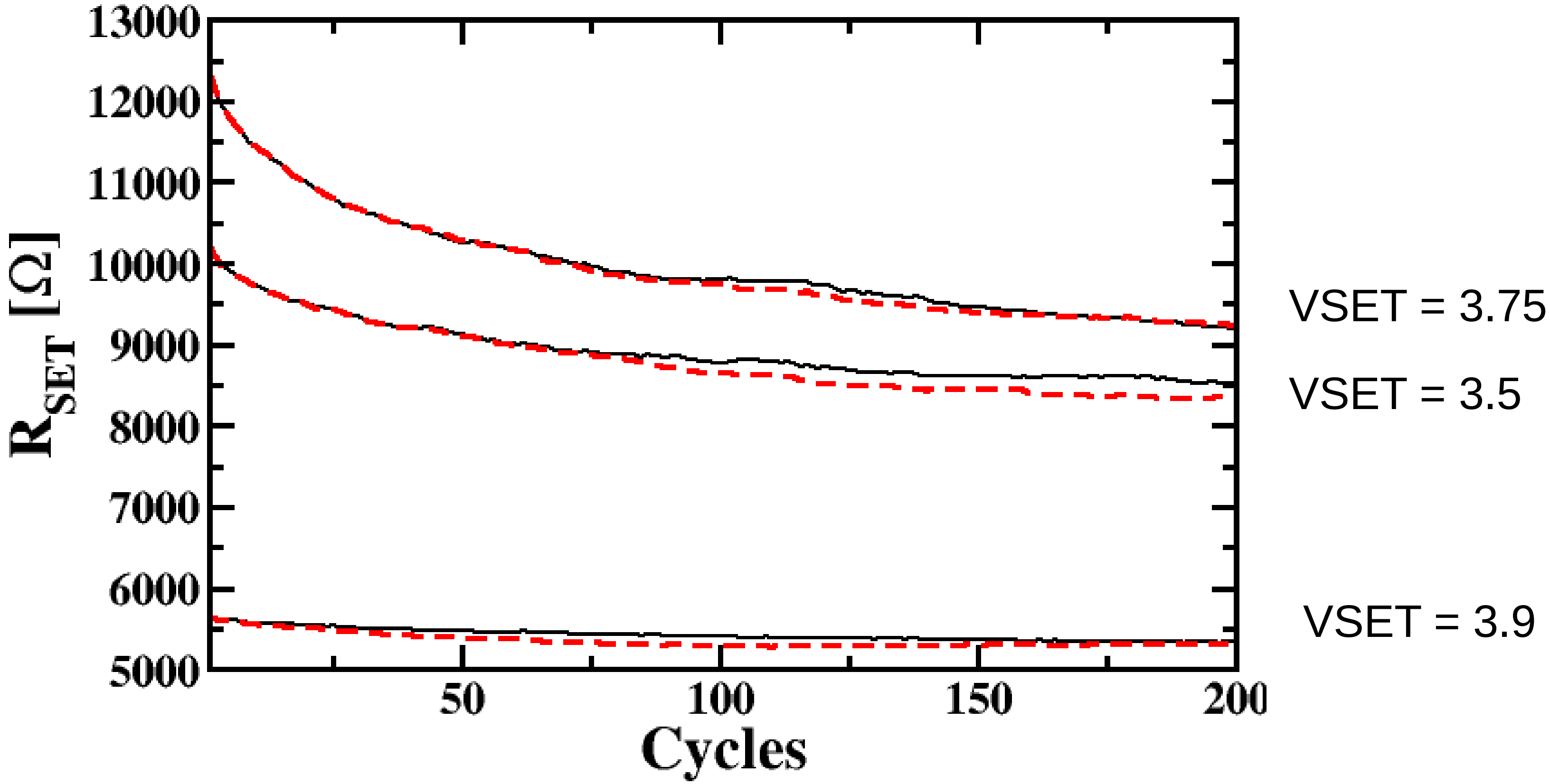
SIMULATION FRAMEWORK

- Both Erase operation kinetics and SET Seasoning effect has been implemented on a numerical analysis tool such as MATLAB

- The simulation flow has been implemented as follows in order to maximize the simulation speed (about 50 sec. on a Dual-Core machine)



SET Seasoning Model results



Good agreement between model (red dahsed lines) and measurements data (black solid lines) are evidences. Both model and measurements are based on a statistical population of 512Kbits cells.

CONCLUSIONS AND FUTURE WORKS

- The Seasoning phenomenon has been described for Phase Change Memory arrays during memory cycling
- A physical interpretation of the phenomenon was given both for RESET and SET states of the memory
- We presented a complete model for SET Seasoning in Phase Change Memory which include Erase operation kinetic modeling/simulation
- Next step is porting model to SPICE-like simulators
- …