



## *PCM memories: an overview*


Andrea L. Lacaita  
*Dipartimento di Elettronica e Informazione  
Politecnico di Milano & IUNET*  
Nov. 26, 2008

---



## Outline

- PCM concept and basic operation
- Modeling
  - ▶ Switching
  - ▶ Set/Reset programming
- Cell structures and scaling perspectives
- Reliability issues
  - ▶ Retention, Drift
- Conclusions



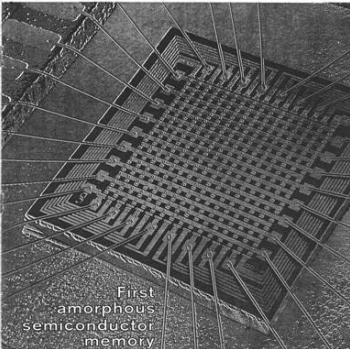
## Phase Change Memory

Dipartimento  
Elettronica  
Informazione

Amorphous semiconductors: jury still out 56  
 Designing low-noise bipolar amplifiers 82  
 The big gamble in home video recorders 89

A MICROELECTRONICS PUBLICATION  
September 28, 1971

# Electronics



First amorphous semiconductor memory


**1970**  
**Die: 122 mil X 131 mil**  
**Capacity: 256 bits**  
**Reset: <200 mA, < 25V, 5 ms**  
**Set: 5 mA, ~ 25V, 10 ms**  
**Read: 2.5 mA, < 5V**

“Nonvolatile and Reprogrammable, the Read-Mostly Memory is Here,” R. G. Neale, D. L. Nelson, and Gordon E. Moore, *Electronics* (Sept. 1970) p. 56.

DEI Politecnico di Milano

- 3 -

Andrea L. LACAITA





## Chalcogenide Alloys

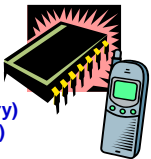
Dipartimento  
Elettronica  
Informazione

IVA	VA	VIA	VIIA	
C	N	O	F	
Si	P	S	Cl	
Ge	As	Se	Br	
Sn	Sb	Te	I	
Pb	Bi	Po	At	

↑  
**Chalcogens**

1970 → **Xerography** 

1990 → **DVD-RW  
CD-RW** 

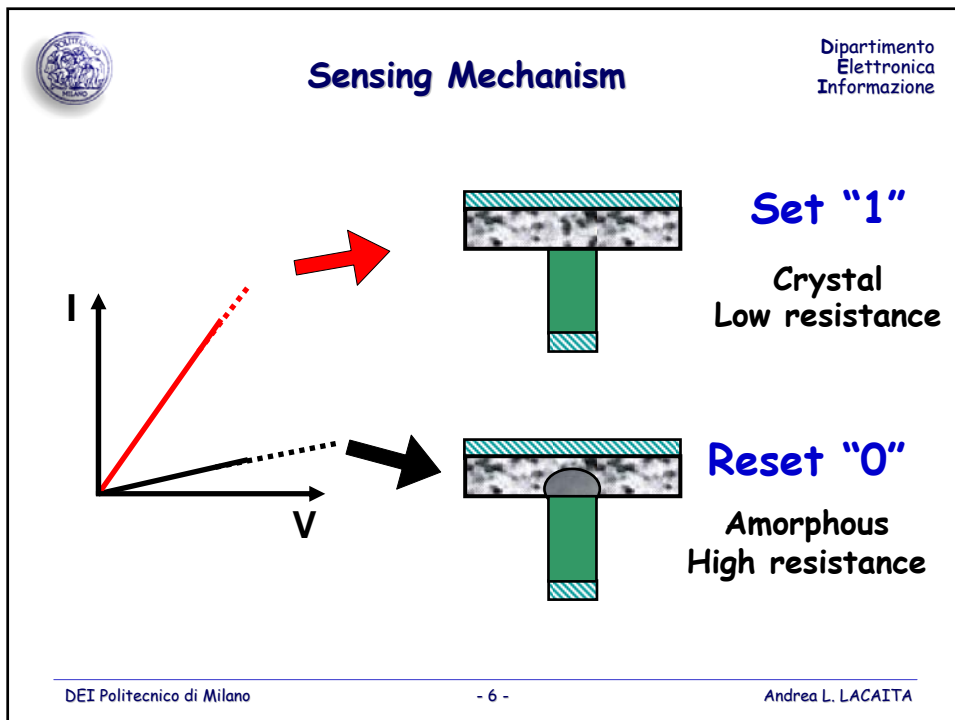
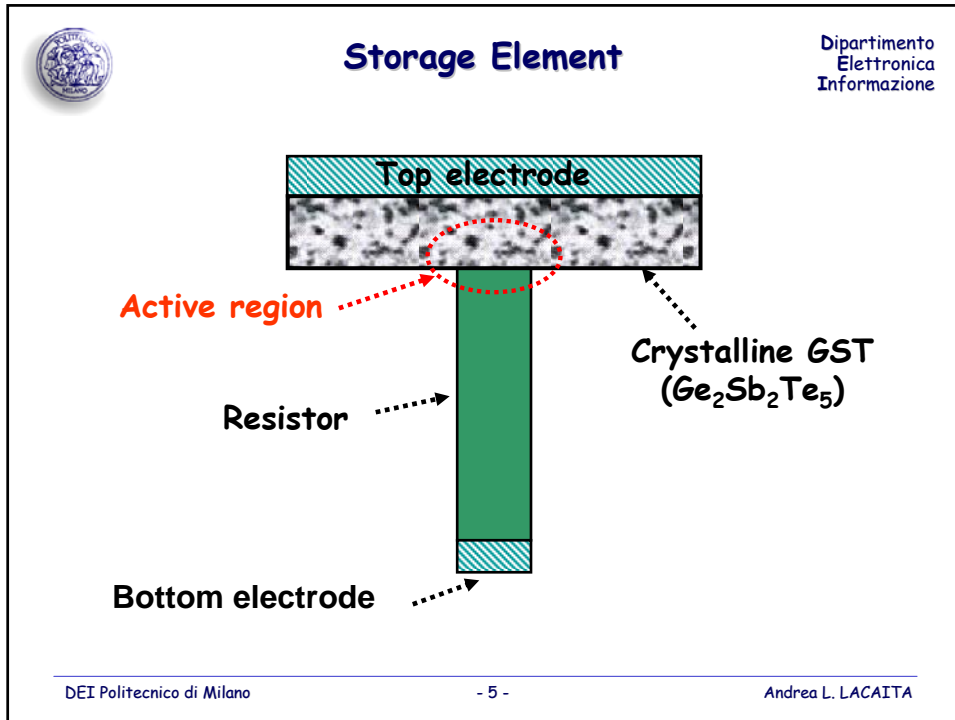
2000 → **Memories** 

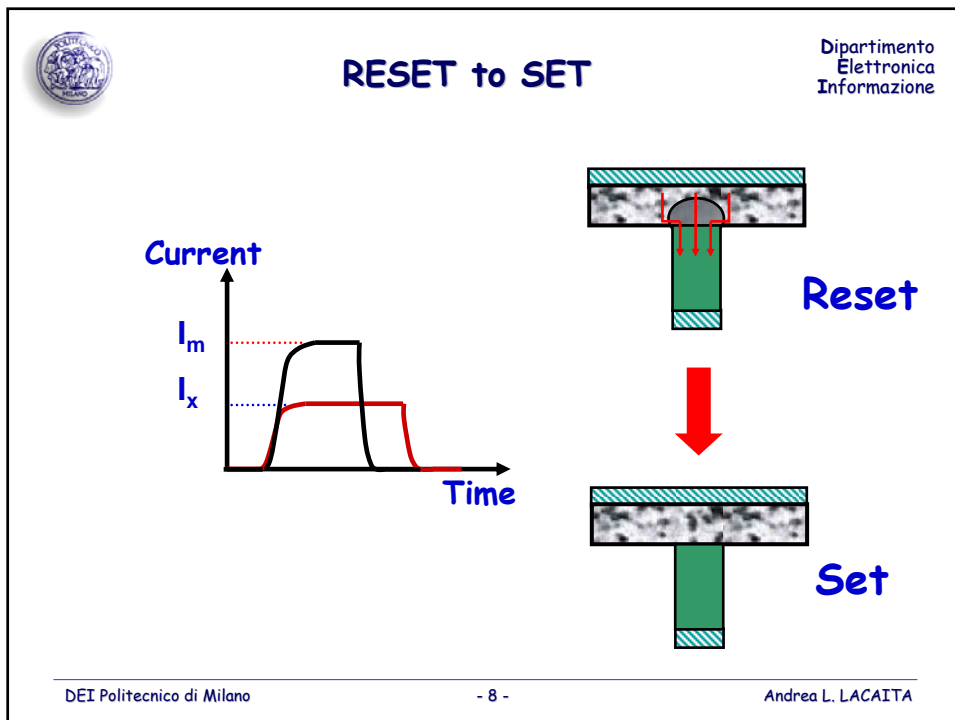
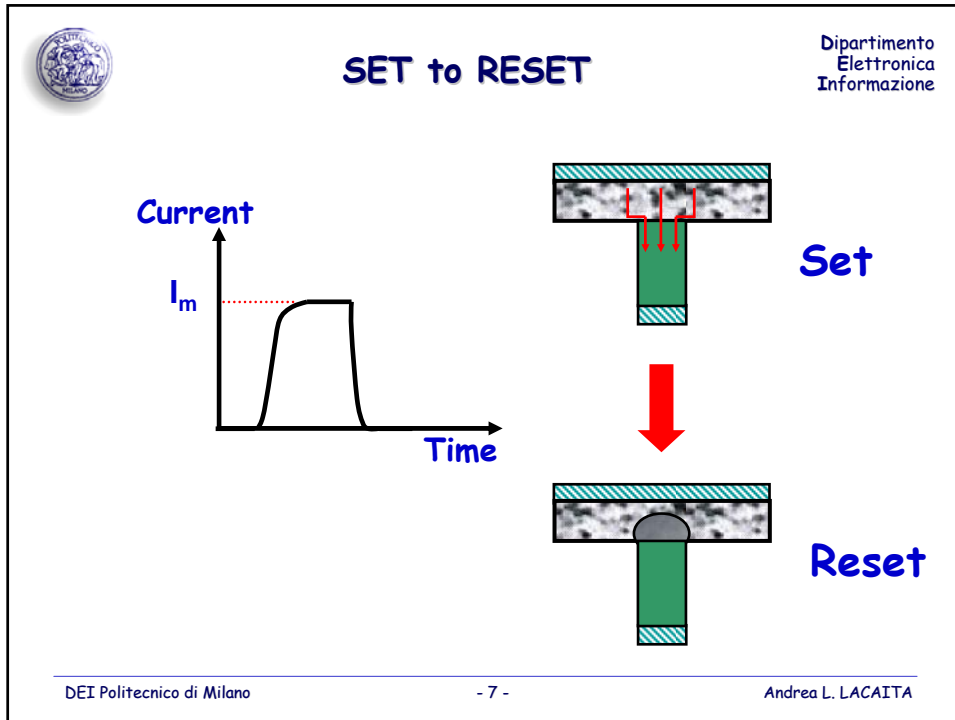
OUM (Ovonic Universal Memory)  
PCM (Phase Change Memory)  
PRAM (Phase-change RAM)

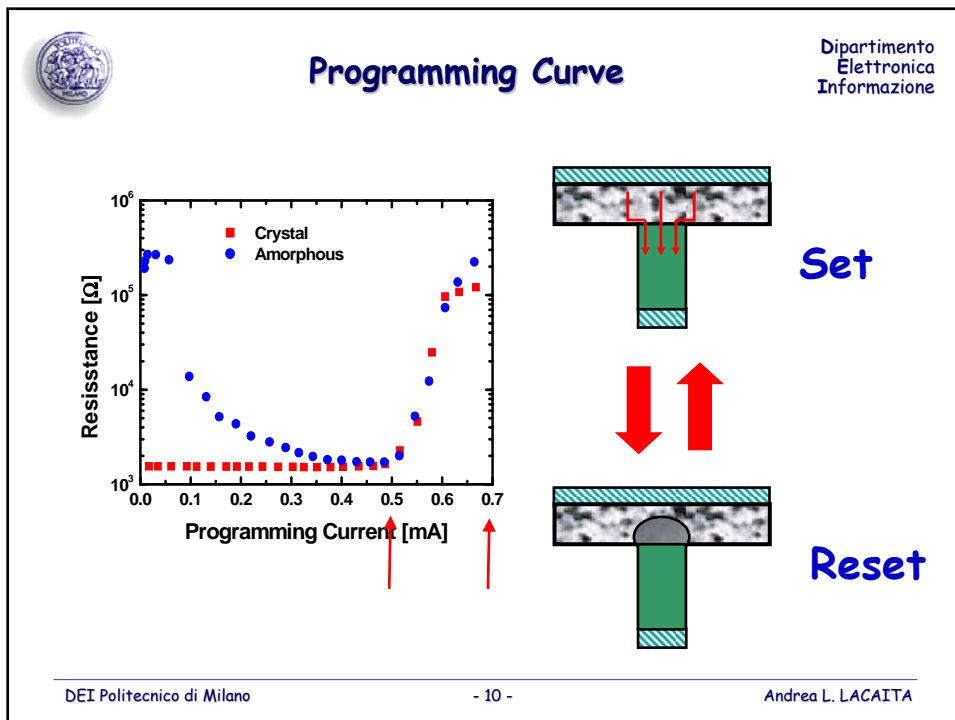
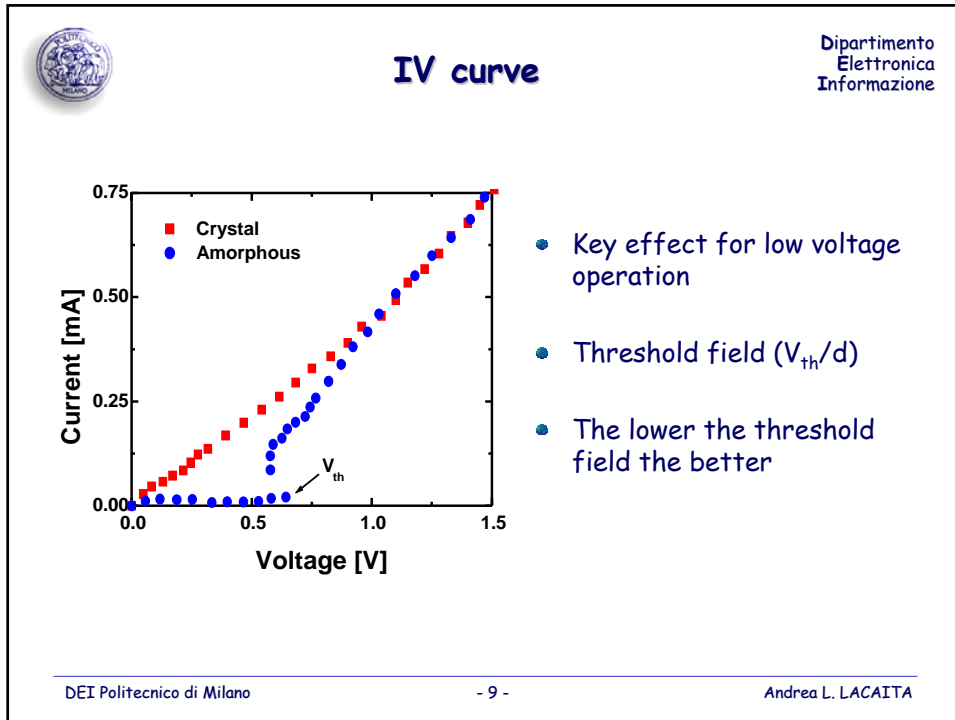
DEI Politecnico di Milano

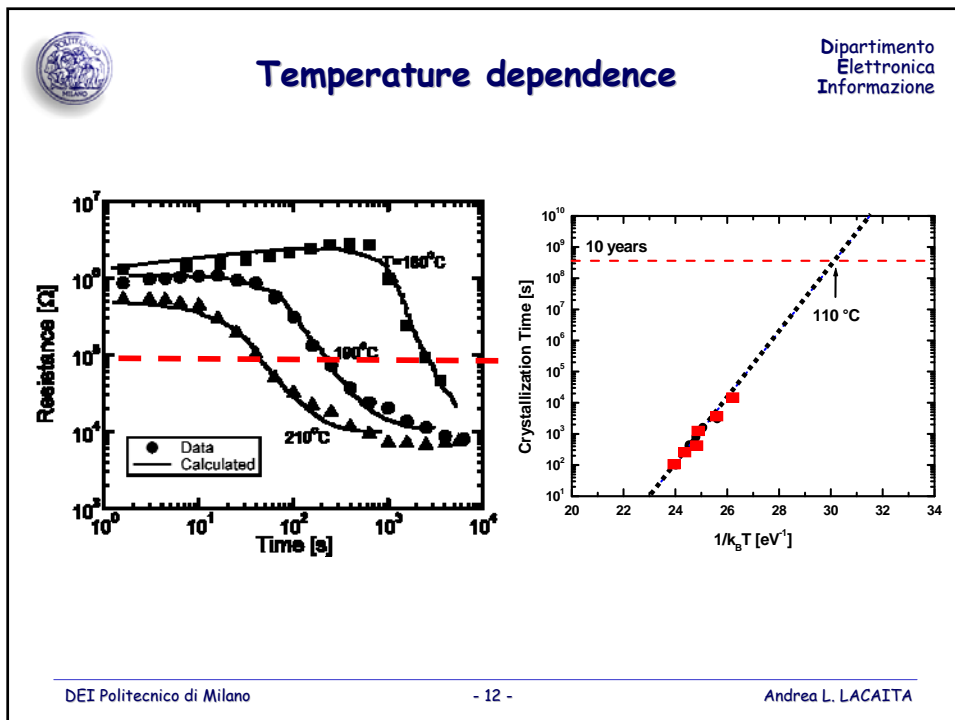
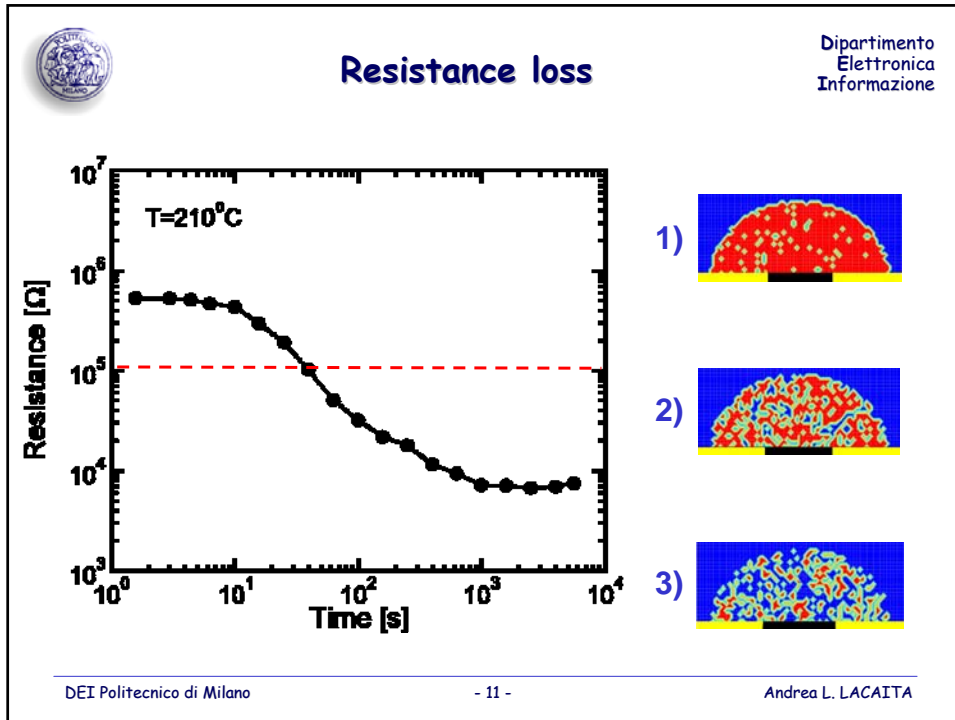
- 4 -


Andrea L. LACAITA












## Material selection rules

Dipartimento  
 Elettronica  
 Informazione

Memory window	resistivity of amorphous phase	high (0.3 MOhm.μm)
Reset Power	resistivity of crystalline phase	high (350 Ohm.μm)
	melting temperature	low (621°C)
Retention	crystallization temperature	high (155°C)
	activation energy	high (2.6-2.9eV)
Bias voltage	threshold field	low (30-40 V/μm)

DEI Politecnico di Milano
- 13 -
Andrea L. LACAITA



## Material options

Dipartimento  
 Elettronica  
 Informazione

- $Sb_2Te_3$ -GeTe GeTe-InTe
  - ▶ higher amorphous stability, better retention
  - ▶ higher maximum operating temperatures
  - ▶ slower

- O/N doped GST
  - ▶ higher resistivity
  - ▶ lower current

- Doped SbTe, GeSb
  - ▶ fast growth materials

DEI Politecnico di Milano
- 14 -
Andrea L. LACAITA



## Summary

Dipartimento  
 Elettronica  
 Informazione

- Beyond the capacitive concept
- Fast write (set/reset) and read
- Medium/low voltage write
  
- Supply (threshold field)
- Power consumption (melting temperature)
- Retention (crystallization temperature, activation energy)
- Window (resistivity change)

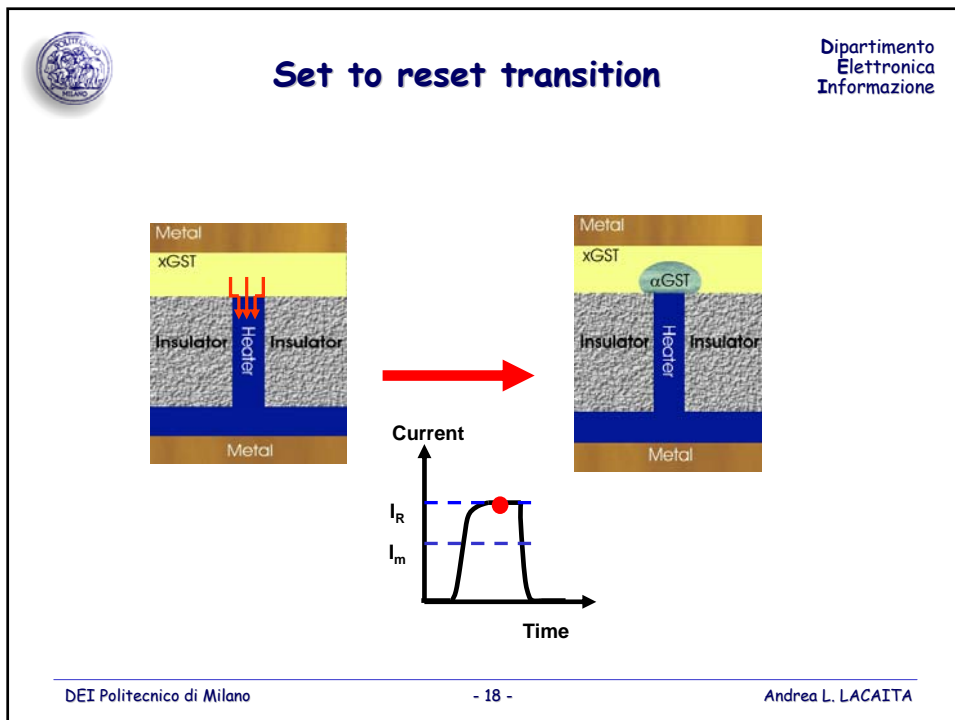
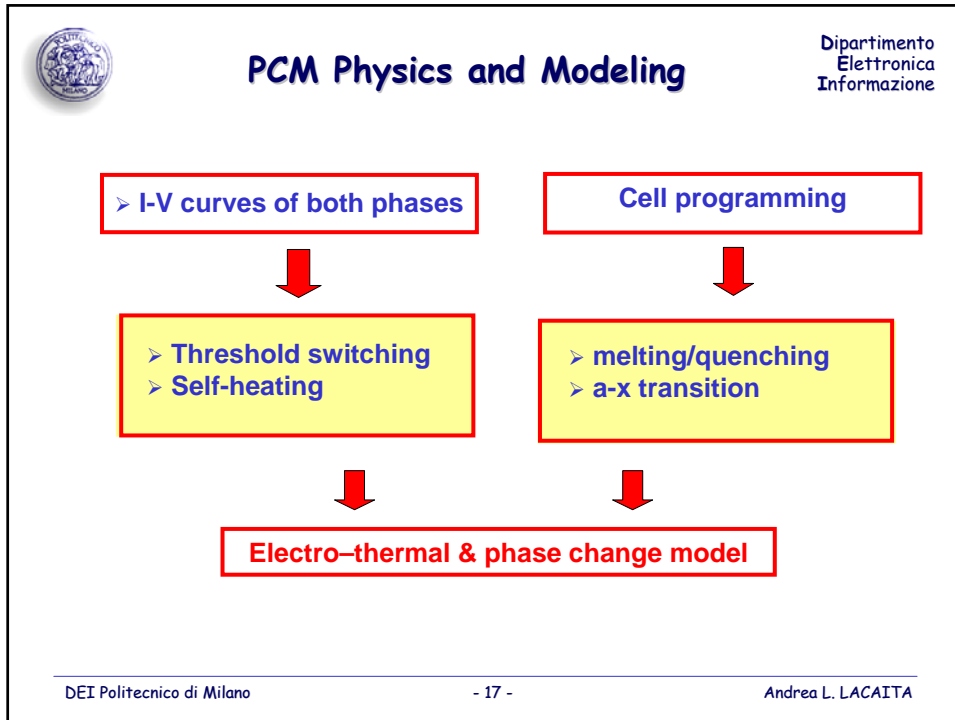


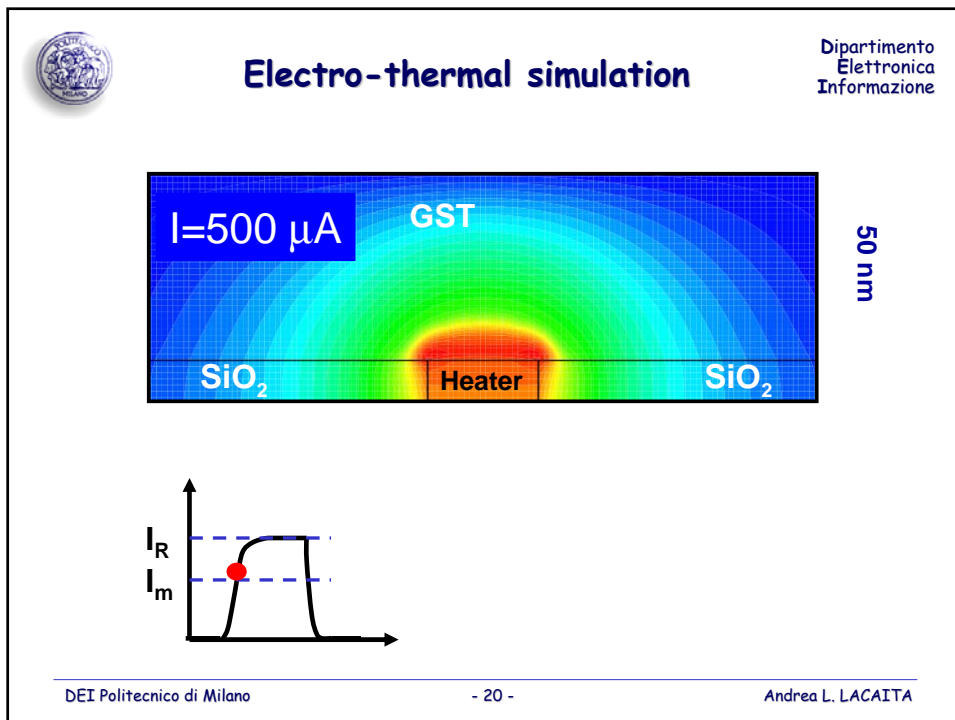
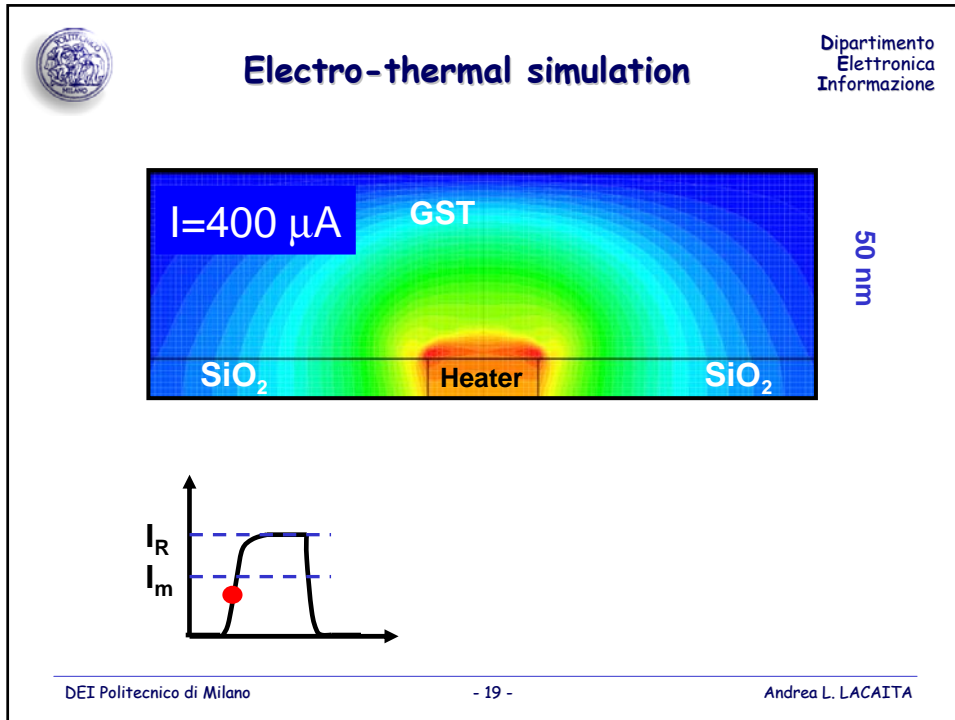
## Outline

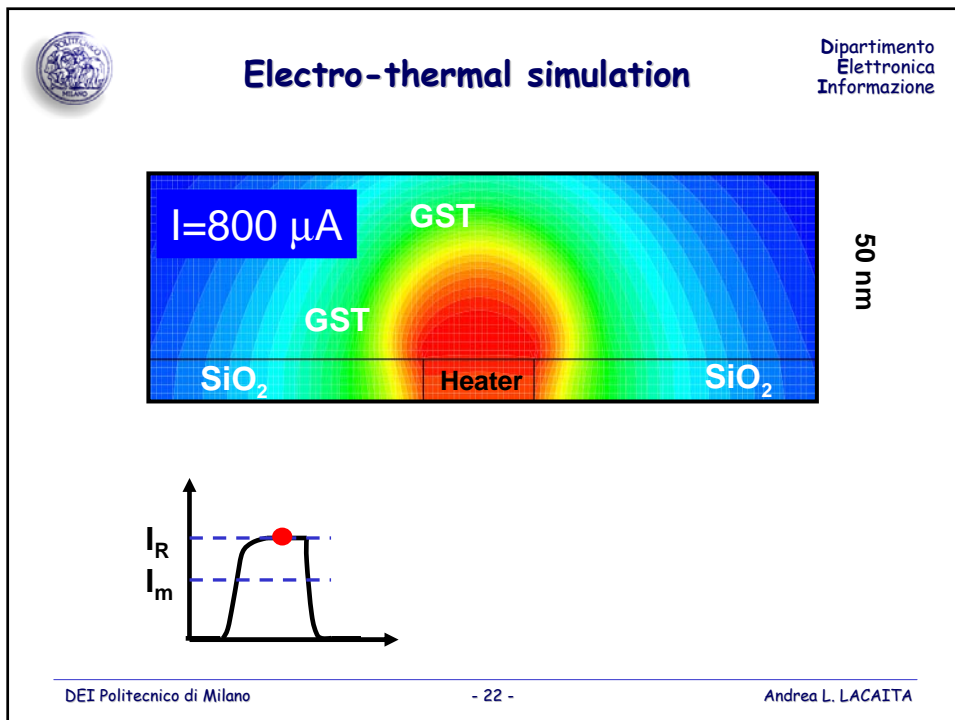
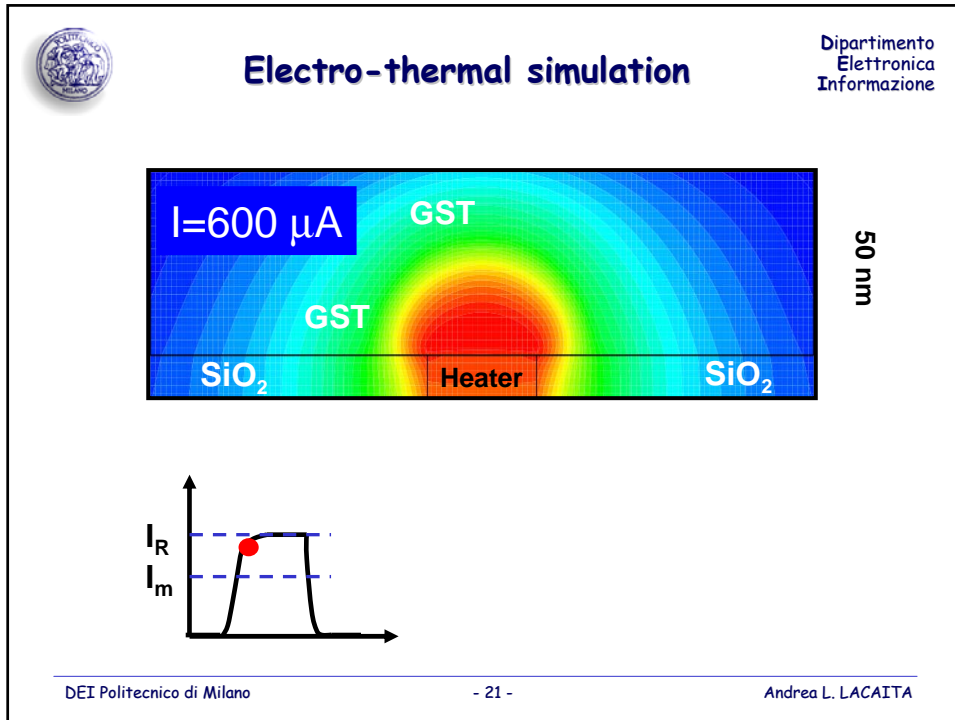
Dipartimento  
 Elettronica  
 Informazione


- PCM concept and basic operation
- Modeling
  - ▶ Switching
  - ▶ Set/Reset programming
- Cell structures and scaling perspectives
- Reliability issues
  - ▶ Retention, Drift
- Conclusions





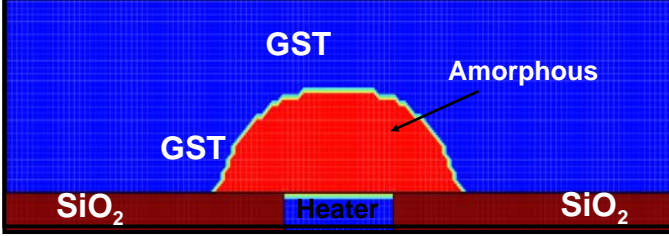


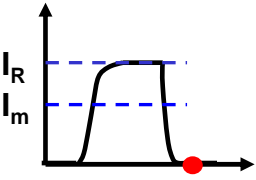




## Electro-thermal simulation

Dipartimento  
Elettronica  
Informazione






DEI Politecnico di Milano

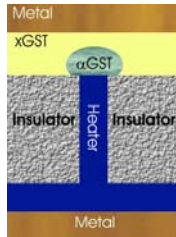
- 23 -

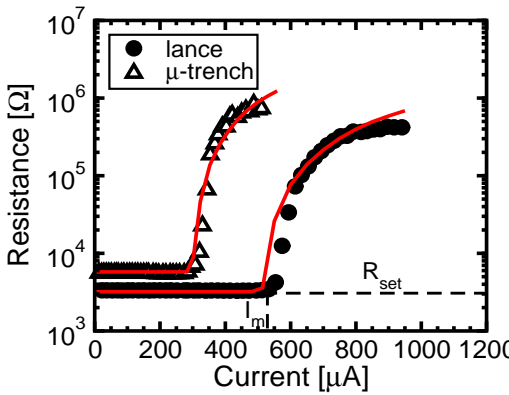
Andrea L. LACAITA

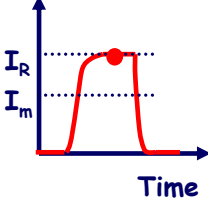


## Programming curve

Dipartimento  
Elettronica  
Informazione







DEI Politecnico di Milano

- 24 -

Andrea L. LACAITA

## Material parameters

Dipartimento  
Elettronica  
Informazione

$\rho = 17 \text{ m}\Omega\text{cm}$   
 $\kappa = 1 \text{ W/Km}$

$\rho = 25 \text{ m}\Omega\text{cm}$   
 $\kappa = 12 \text{ W/Km}$

$\rho = 50 \Omega\text{cm}$   
 $\kappa = 0.3 \text{ W/Km}$   
+ Wiedemann-Franz  
+ Thompson

$\kappa = 0.7 \text{ W/Km}$

DEI Politecnico di Milano

- 25 -

Andrea L. LACAITA

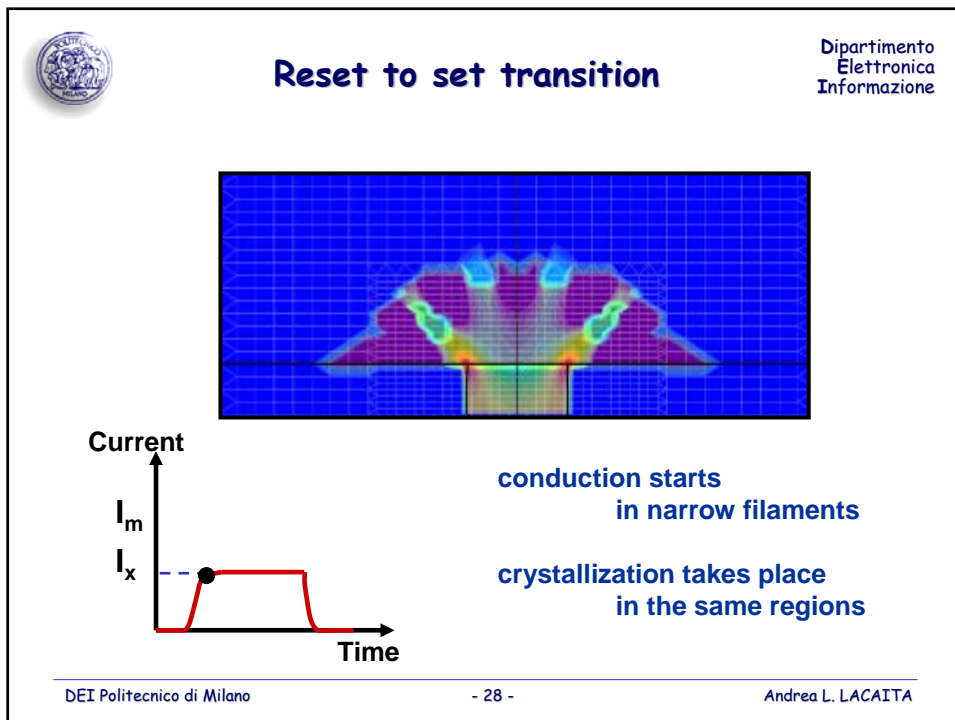
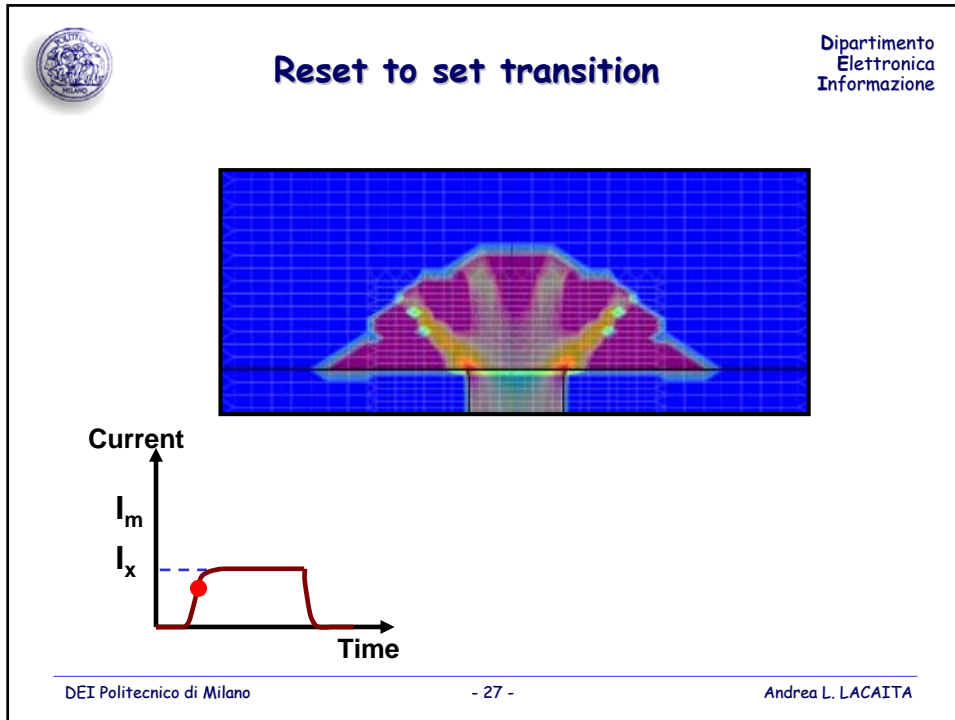
## Reset to set transition

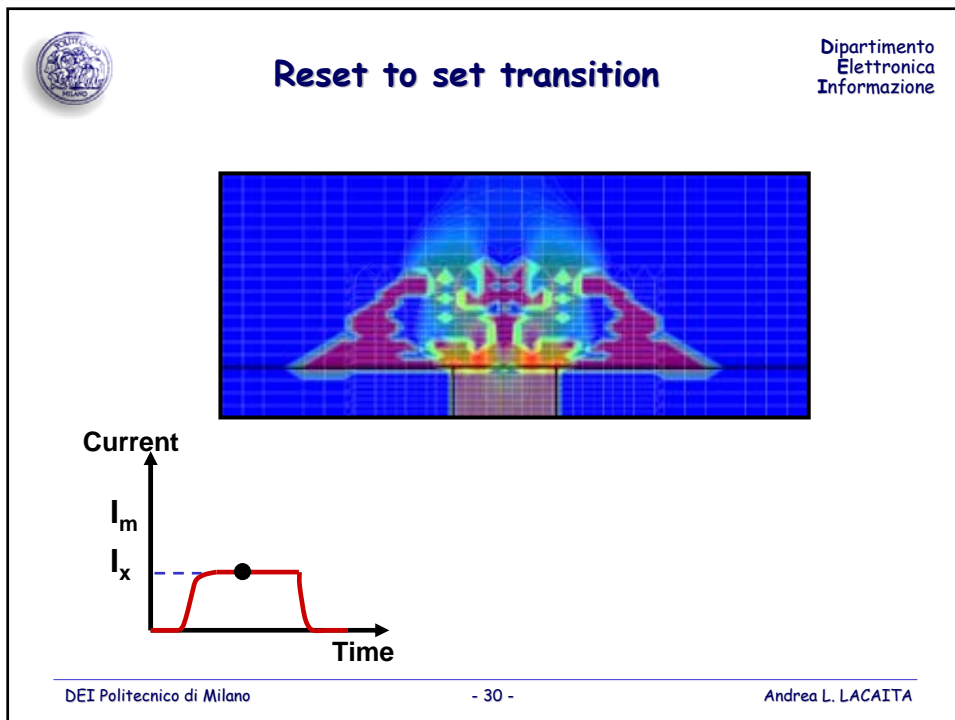
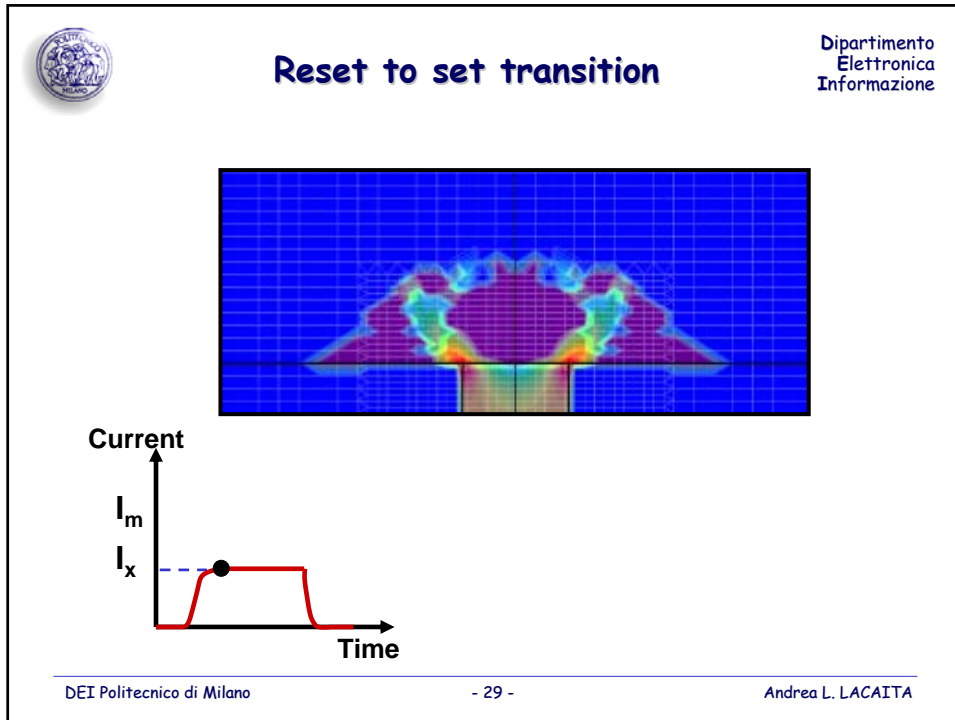
Dipartimento  
Elettronica  
Informazione

DEI Politecnico di Milano

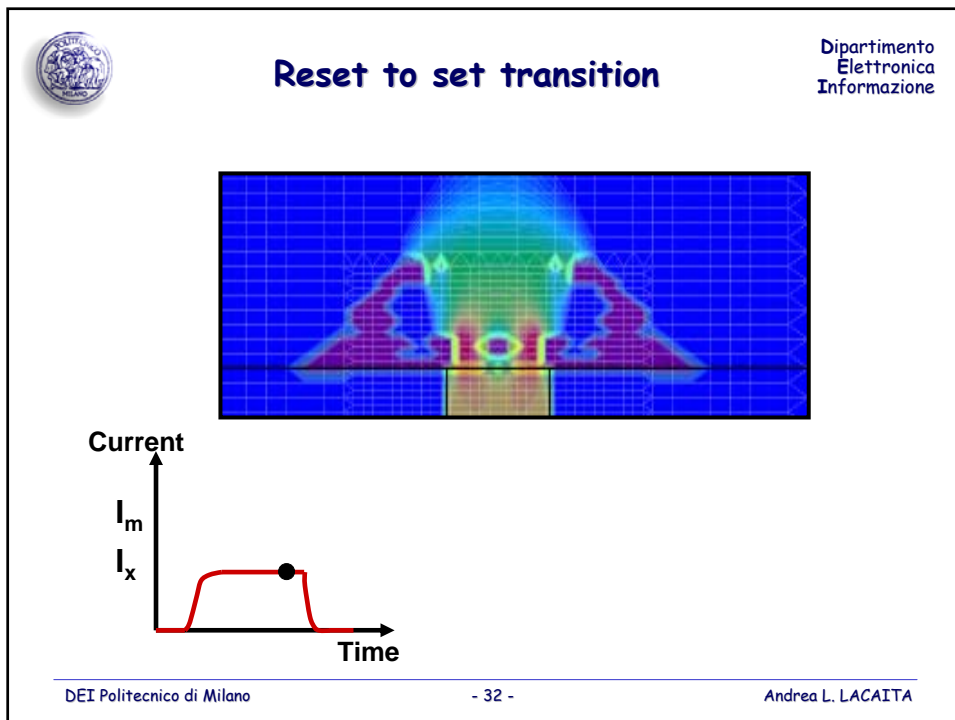
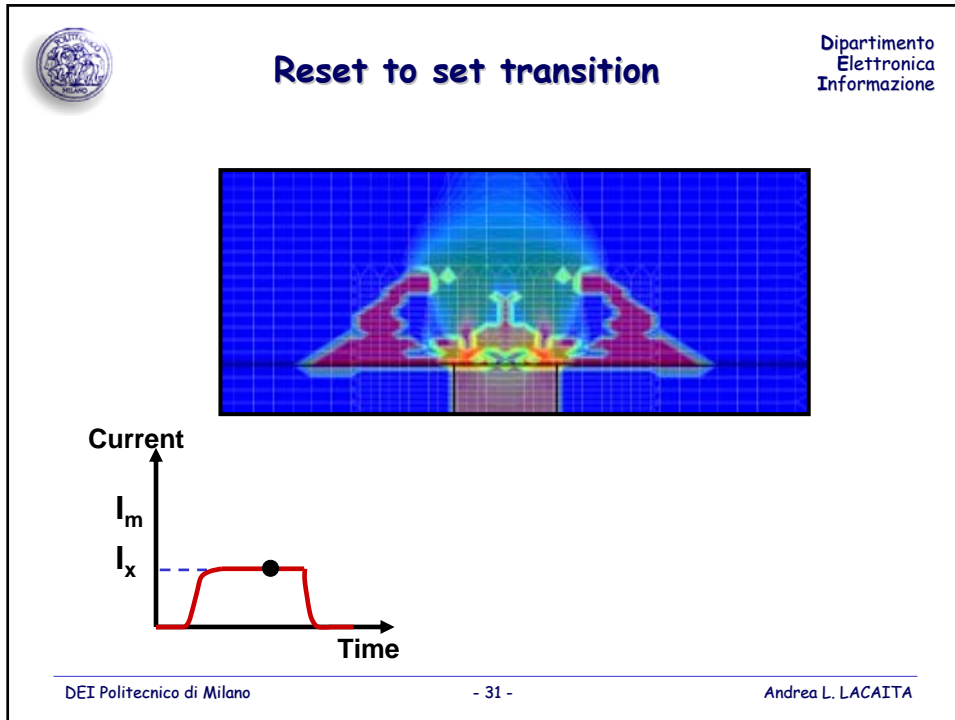
- 26 -

Andrea L. LACAITA








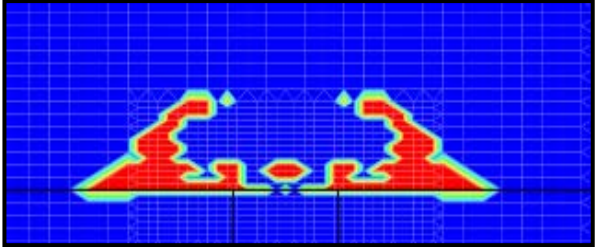




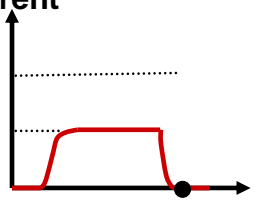


### Reset to set transition

Dipartimento  
Elettronica  
Informazione




**Current**



DEI Politecnico di Milano

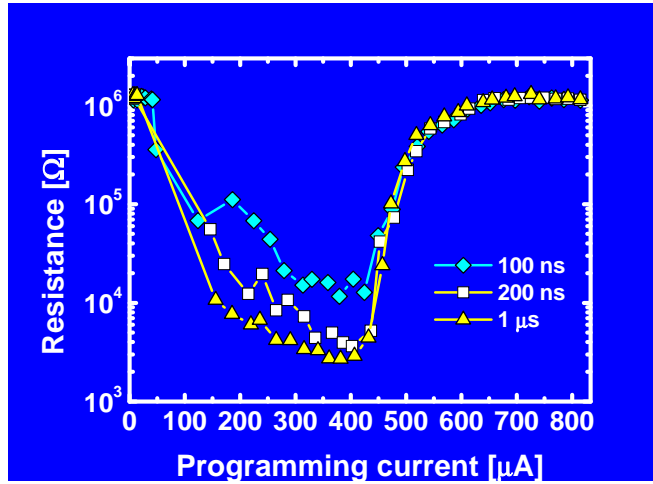
- 33 -

Andrea L. LACAITA



### Set state: set-time dependence


Dipartimento  
Elettronica  
Informazione



DEI Politecnico di Milano

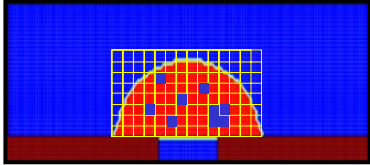
- 34 -

Andrea L. LACAITA



## Coupling with crystallization

Dipartimento  
Elettronica  
Informazione



$\Delta t$

Electro-thermal  
simulation  
 ↓  $T_i$   
 Nucleation &  
Growth  
 ↓  
 Updated phase  
distribution

Transient loop


Nucleation and Growth implemented through a Montecarlo method

---

DEI Politecnico di Milano

- 35 -

Andrea L. LACAITA



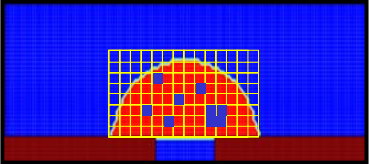
## Crystallization

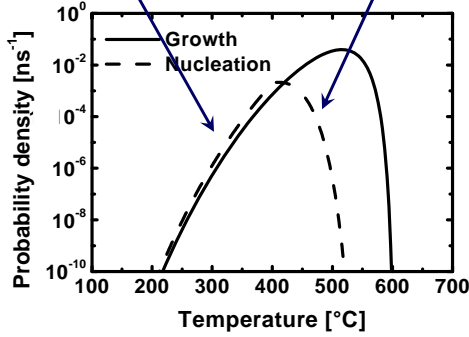
Dipartimento  
Elettronica  
Informazione

Thermal enhancement  
of atomic mobility

drop of free energy  
gain per unit volume

Nucleation - growth





The graph shows two curves: a solid line for 'Growth' and a dashed line for 'Nucleation'. The y-axis is 'Probability density [ns<sup>-1</sup>]' on a log scale from 10<sup>-10</sup> to 10<sup>0</sup>. The x-axis is 'Temperature [°C]' from 100 to 700. The 'Growth' curve peaks at approximately 500°C, while the 'Nucleation' curve peaks at approximately 450°C. Arrows point from the text 'Thermal enhancement of atomic mobility' to the growth curve and 'drop of free energy gain per unit volume' to the nucleation curve.

---

DEI Politecnico di Milano

- 36 -

Andrea L. LACAITA



## Summary

Dipartimento  
 Elettronica  
 Informazione

- Numerical tools have been developed to support the design and optimization of PCM technology
- Carrier transport and heat flow are self-consistently coupled in the frame of semiconductor device simulator
- Material parameters have been tailored to quantitatively account for experimental results
- These tools are essential to design further scaled cell architectures.



## Outline

Dipartimento  
 Elettronica  
 Informazione

- PCM concept and basic operation
- Modeling
  - ▶ Switching
  - ▶ Set/Reset programming
- Cell structures and scaling perspectives
- Reliability issues
  - ▶ Retention, Drift
- Conclusions

## PCM and Joule heating

Dipartimento  
Elettronica  
Informazione

- Endurance
- Cross talk

- Power dissipation / current consumption
  - ▶ 30mA @ 1,8V
  - ▶ Reset current 500µA/cell
  - ▶ Write cycle time 1µs
  - ▶ 16Mb/s = 2MB/s

10mA @ 5V  
 20 cells in parallel  
 1Mcycles/sec

DEI Politecnico di Milano

- 39 -

Andrea L. LACAITA

## Current reduction by scaling

Dipartimento  
Elettronica  
Informazione

1

↓

$\Delta T_M = P_d \cdot R_{TH}$

k

↓

$P_d = R \cdot I^2$

1/k


↓

1/k

DEI Politecnico di Milano

- 40 -

Andrea L. LACAITA



## PCM scaling strategies

Dipartimento  
 Elettronica  
 Informazione


<i>Parameters</i>		<i>isotropic</i>	<i>anisotropic</i>
GST/Heater contact area	$A_{\text{cell}}$	$1/k^2$	$1/k^2$
<b>Layer thickness</b>		$1/k$	<b>1</b>
Electrical/Thermal Resistances	$R$	$k$	$k^2$
Power dissipation	$P_{\text{cell}}$	$1/k$	$1/k^2$
Current	$I$	$1/k$	$1/k^2$
Voltage	$V_{\text{cell}}$	1	1
Current density	$J$	$k$	1

$$R_{\text{set}} \times I_m = \text{const}$$

---

DEI Politecnico di Milano
- 41 -
Andrea L. LACAITA



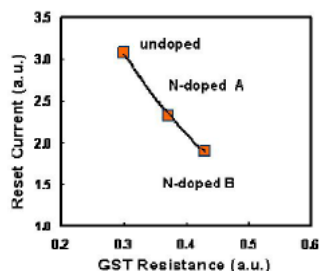
## Current reduction

Dipartimento  
 Elettronica  
 Informazione

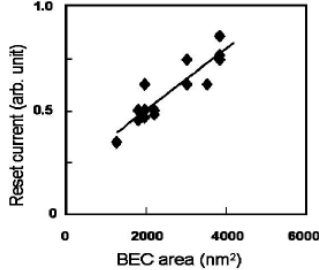
- by scaling
- by material engineering (active/heater)
- by cell architecture

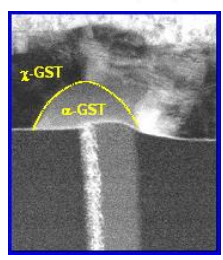


Reset Current (a.u.) vs GST Resistance (a.u.)

Legend: undoped, N-doped A, N-doped B




Reset current (arb. unit) vs BEC area (nm<sup>2</sup>)



$\chi$ -GST  
 $\alpha$ -GST

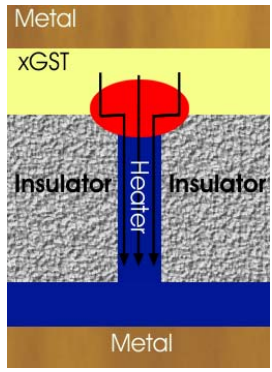
---

DEI Politecnico di Milano
- 42 -
Andrea L. LACAITA

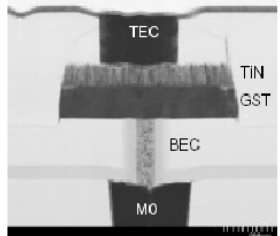


## Lance / Ring


Dipartimento  
Elettronica  
Informazione



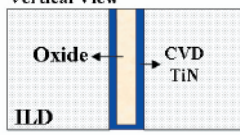
Hori et al. VLSI 2005



Top View




Vertical View



DEI Politecnico di Milano

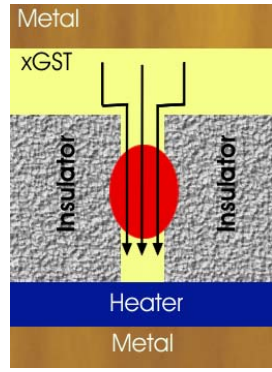
- 43 -

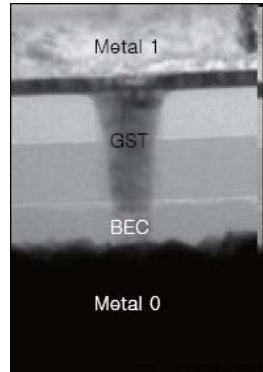
Andrea L. LACAITA



## Pillar / Pore

Dipartimento  
Elettronica  
Informazione






DEI Politecnico di Milano

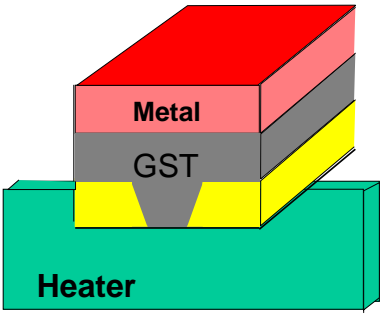
- 44 -

Andrea L. LACAITA

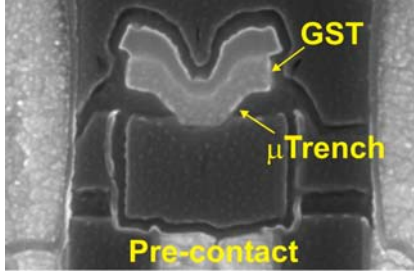


## μtrench

Dipartimento  
Elettronica  
Informazione



**Heater**



**Pre-contact**

F. Pellizzer et al, VLSI'06


- Contact area: heater thickness x sublitho

---

DEI Politecnico di Milano

- 45 -

Andrea L. LACAITA



## Technology benchmarking

Dipartimento  
Elettronica  
Informazione

	STM-Intel VLSI 06	Samsung IEDM 06	Hynix J. Sem. Sci. And Tech. 8(2), 128, 2008	Hitachi IEDM06 ISSCC06	IBM- Qimonda- Macronix VLSI 06	IBM- Qimonda- Macronix VLSI 07
F [nm]	90	90	90	130	180	180
Cell type	μtrench/ lance, bipolar,	Ring, GST N-doped, diode, 5,8F <sup>2</sup>	-	Lance, GST -Ta <sub>2</sub> O <sub>5</sub> layer, MOSFET	Pillar, GST N-doped MOSFET	Pore, GST N-doped MOSFET
Ireset [mA]	0.4/0.7	0.6	1.0	0.1	0.9	0.4
Array size [# bit]	128M	512M	512M	4M	Mini array	256k
Set time [ns]				1200	300 (MLC)	80
Endurance [#]	>10 <sup>8</sup>	10 <sup>5</sup>		10 <sup>6</sup>	10 <sup>6</sup>	10 <sup>5</sup>

---

DEI Politecnico di Milano

- 46 -

Andrea L. LACAITA

## From MOSFET's to diodes

Dipartimento  
Elettronica  
Informazione

Samsung, VLSI'04

DEI Politecnico di Milano

- 47 -

Andrea L. LACAITA

## Summary

Dipartimento  
Elettronica  
Informazione


- Among the various candidates for future NVMs, PCM technology has shown the most convincing prospects for commercial products
- High density arrays as well as embedded solutions have been successfully demonstrated
- Short-term: valuable solution for embedded applications, code storage, high performance memory systems
- Long-term: solution for data storage applications

DEI Politecnico di Milano

- 48 -

Andrea L. LACAITA






## Outline

Dipartimento  
Elettronica  
Informazione

- PCM concept and basic operation
- Modeling
  - ▶ Switching
  - ▶ Set/Reset programming
- Cell structures and scaling perspectives
- Reliability issues
  - ▶ Retention, Drift
- Conclusions

---

DEI Politecnico di Milano
- 49 -
Andrea L. LACAITA



## Data-loss statistics

Dipartimento  
Elettronica  
Informazione

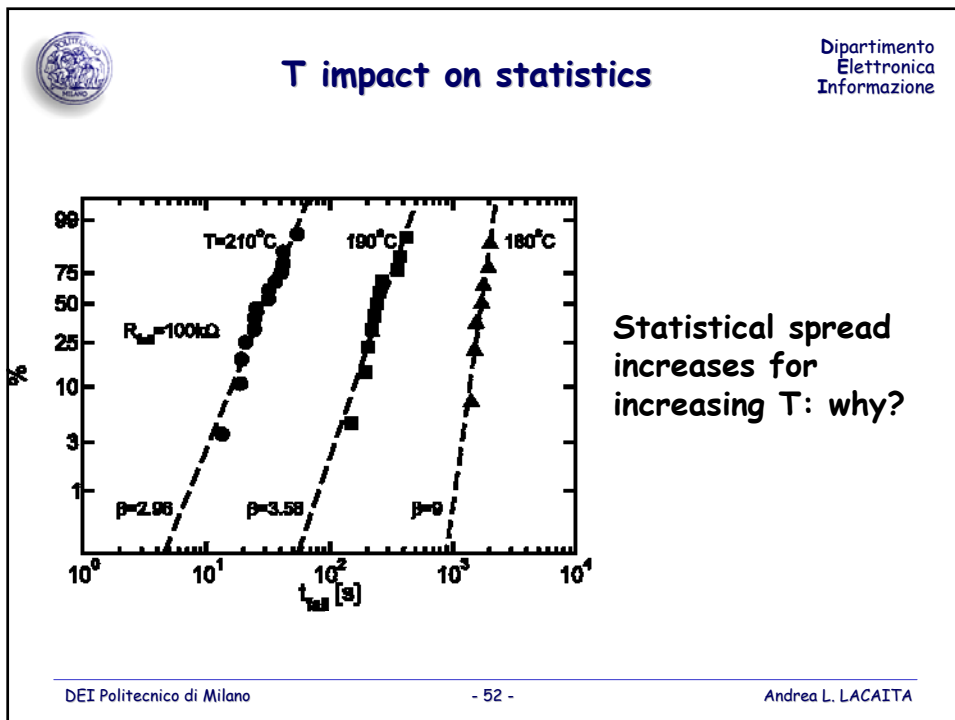
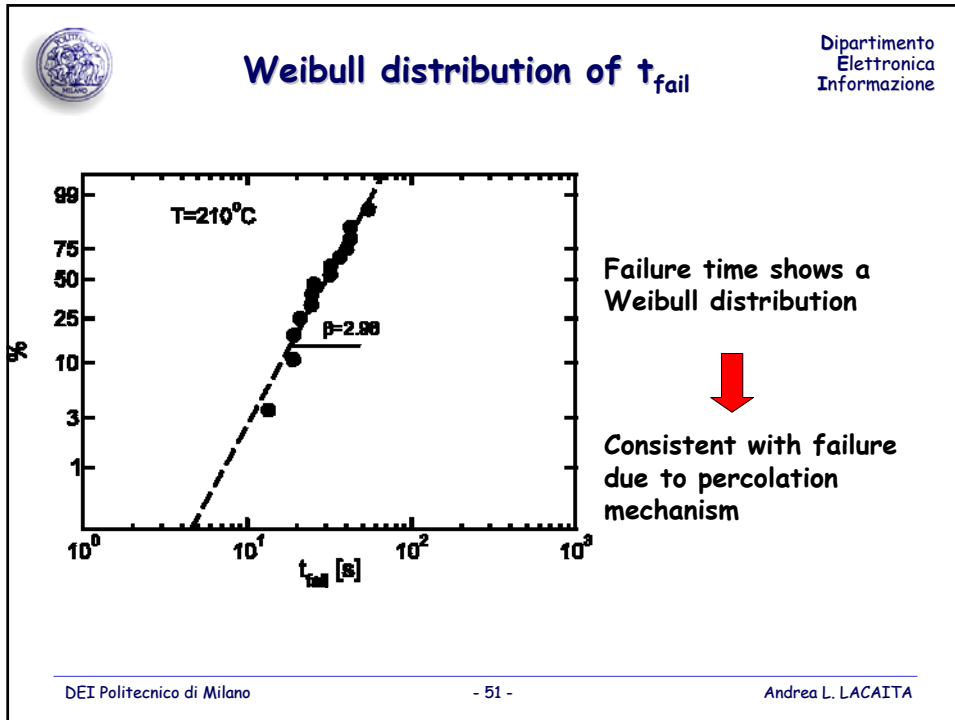
Repetitive measurements on the same cell show statistical spread

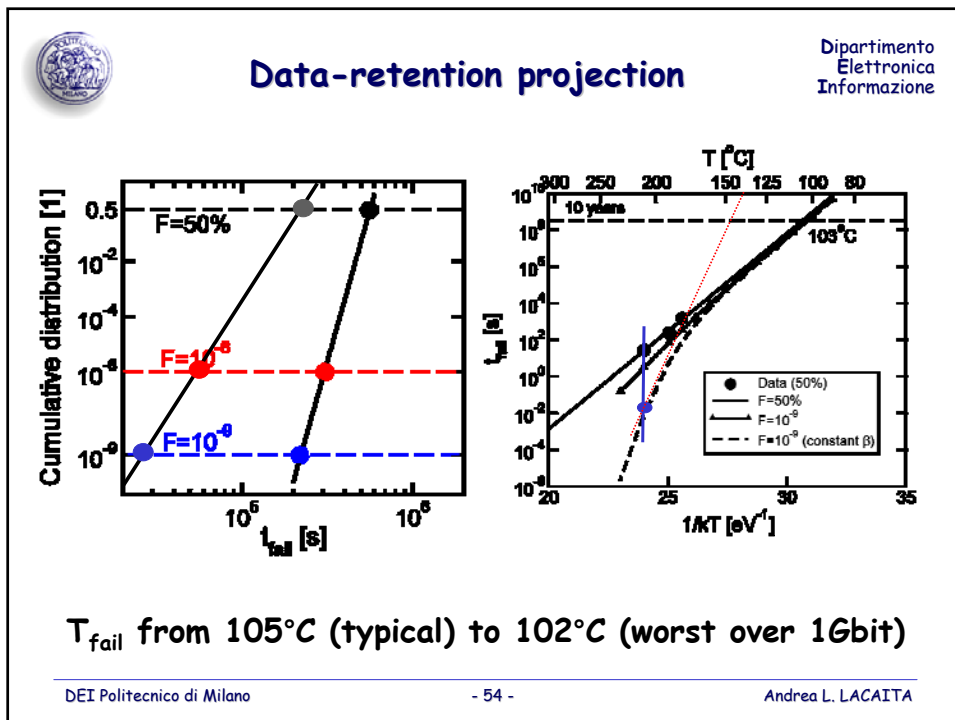
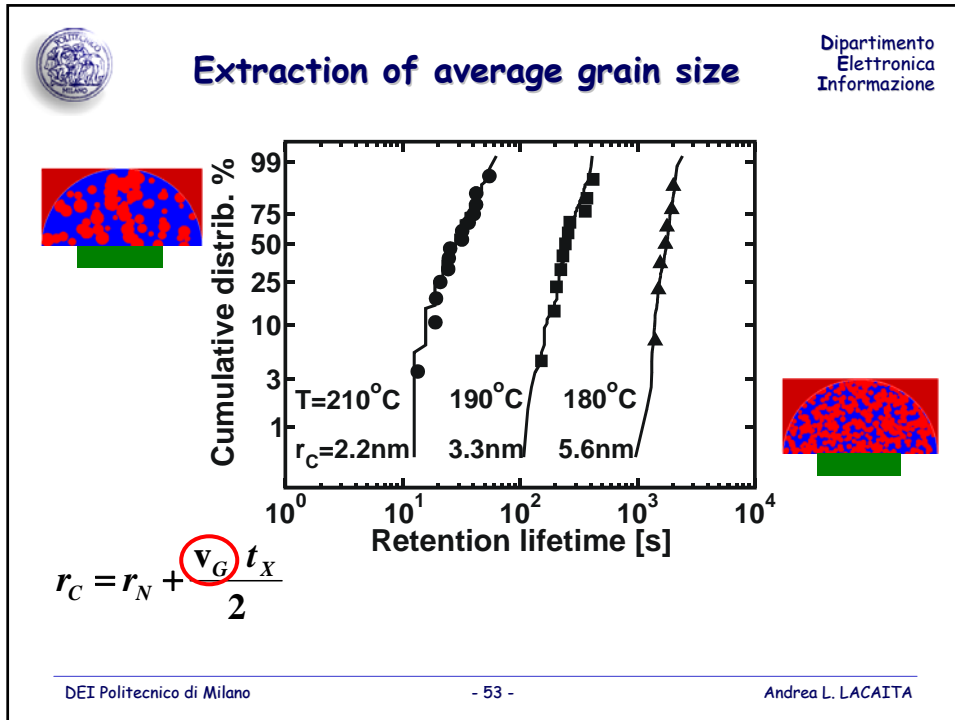
↓

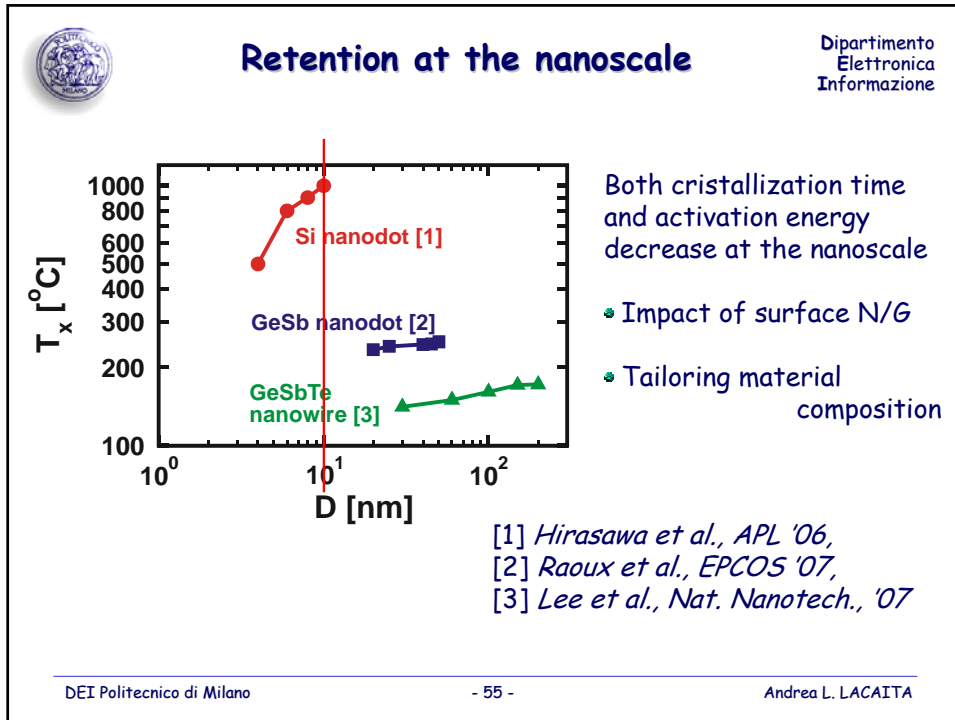
data loss is erratic

---

DEI Politecnico di Milano
- 50 -
Andrea L. LACAITA





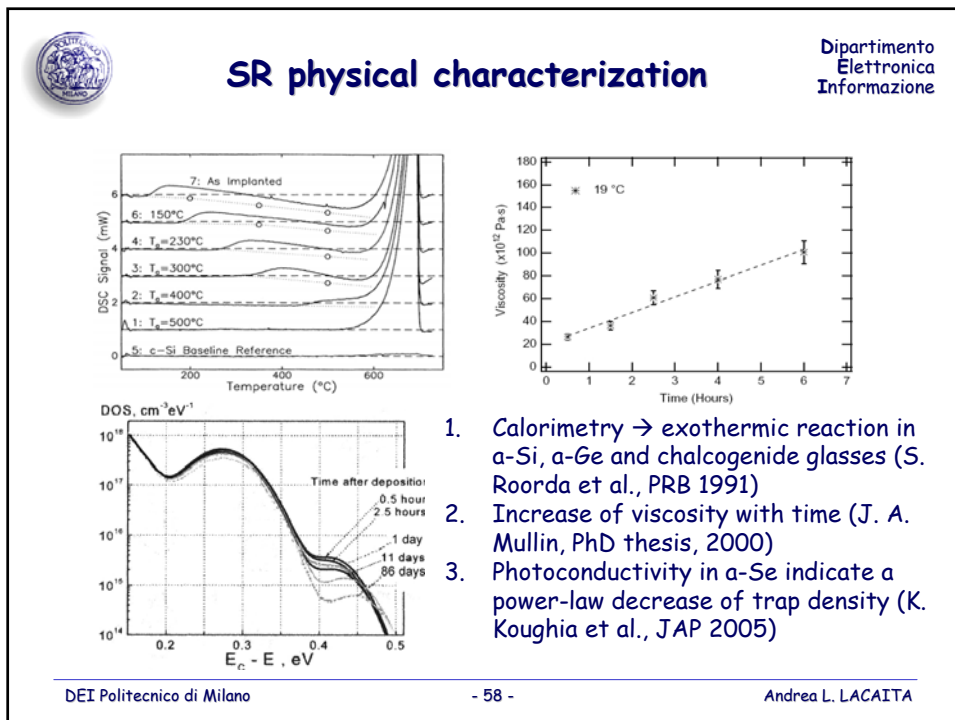
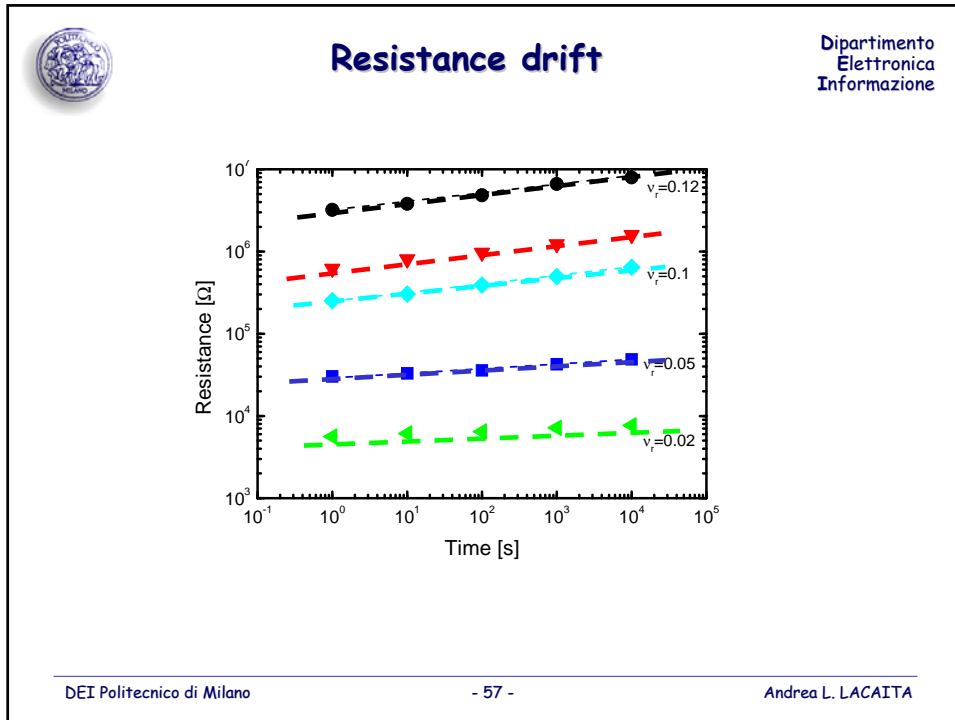



### Reliability issues

Dipartimento  
Elettronica  
Informazione

Reliability issue	Impact on Cell
Crystallization	Resistance decrease
Structural relaxation	Resistance increase
Cycling endurance	Stuck set/reset
Program disturb	Resistance decrease/increase
Read disturb	Switching and resistance decrease

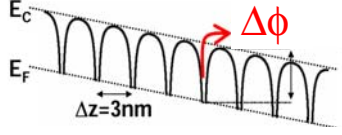
DEI Politecnico di Milano - 56 - Andrea L. LACAITA





### Poole-Frenkel conduction

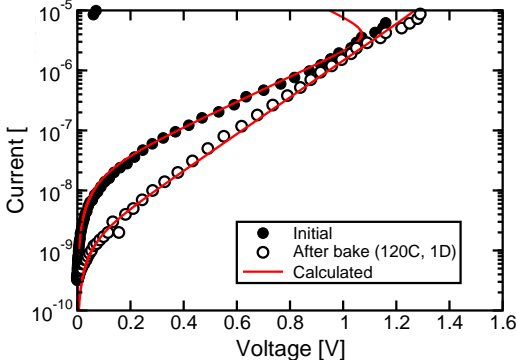
Dipartimento  
Elettronica  
Informazione



Less defects

Lower current

Higher resistance




*Ielmini et al., IEDM'07*

---

DEI Politecnico di Milano

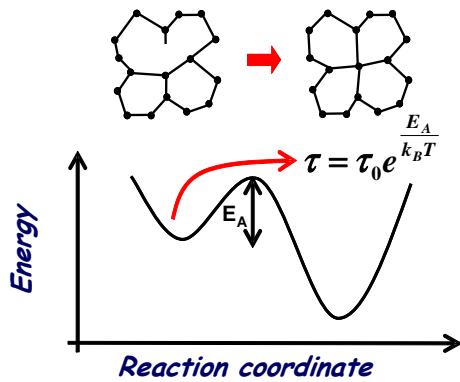
- 59 -

Andrea L. LACAITA



### Kinetic model for SR

Dipartimento  
Elettronica  
Informazione



- SR is due to atomic rearrangements in the disordered structure
- kinetic reproduced by metastable defect relaxation with broad distribution of activation energies
- Material engineering
- Programming/reading schemes to minimize the effect

---

DEI Politecnico di Milano

- 60 -

Andrea L. LACAITA



## Summary

Dipartimento  
 Elettronica  
 Informazione

- Perspectives of PCM at the nanoscale calls for optimization/engineering of material properties
- Drift and defects dynamics, intrinsically linked to the amorphous phase has to be faced and dominated to make reliable MLC.
- Great fun in the next future!



## Acknowledgments

Dipartimento  
 Elettronica  
 Informazione

- STMicroelectronics, Intel, Numonyx
- EU (CAMELS)
- D. Ielmini, A. Pirovano, A. Redaelli, D. Mantegazza, U. Russo and many other students of the Nano Lab - Politecnico di Milano