leti innovation for industry

Overview on the characterization for RRAM technologies

Amal Chabli,
Vincent Jousseaume, Pierre Noé and Sylvain Maitrejean

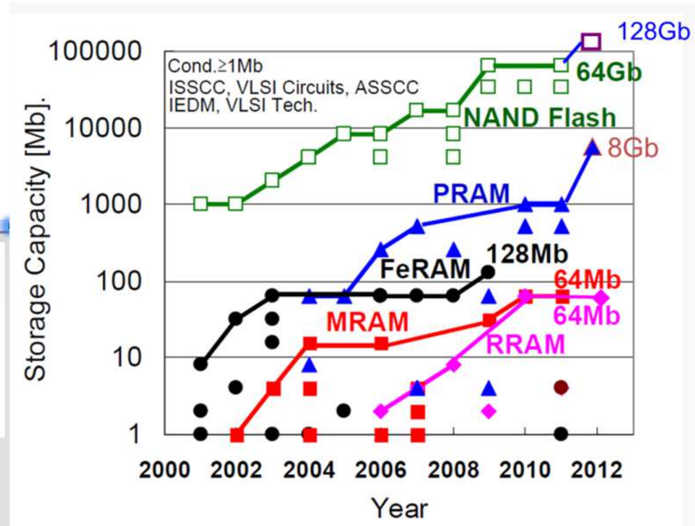
CEA, LETI, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France
amal.chabli@cea.fr
vincent.jousseaume@cea.fr

MINATEC CAMPUS

Resistive Random Access Memories (RRAM)

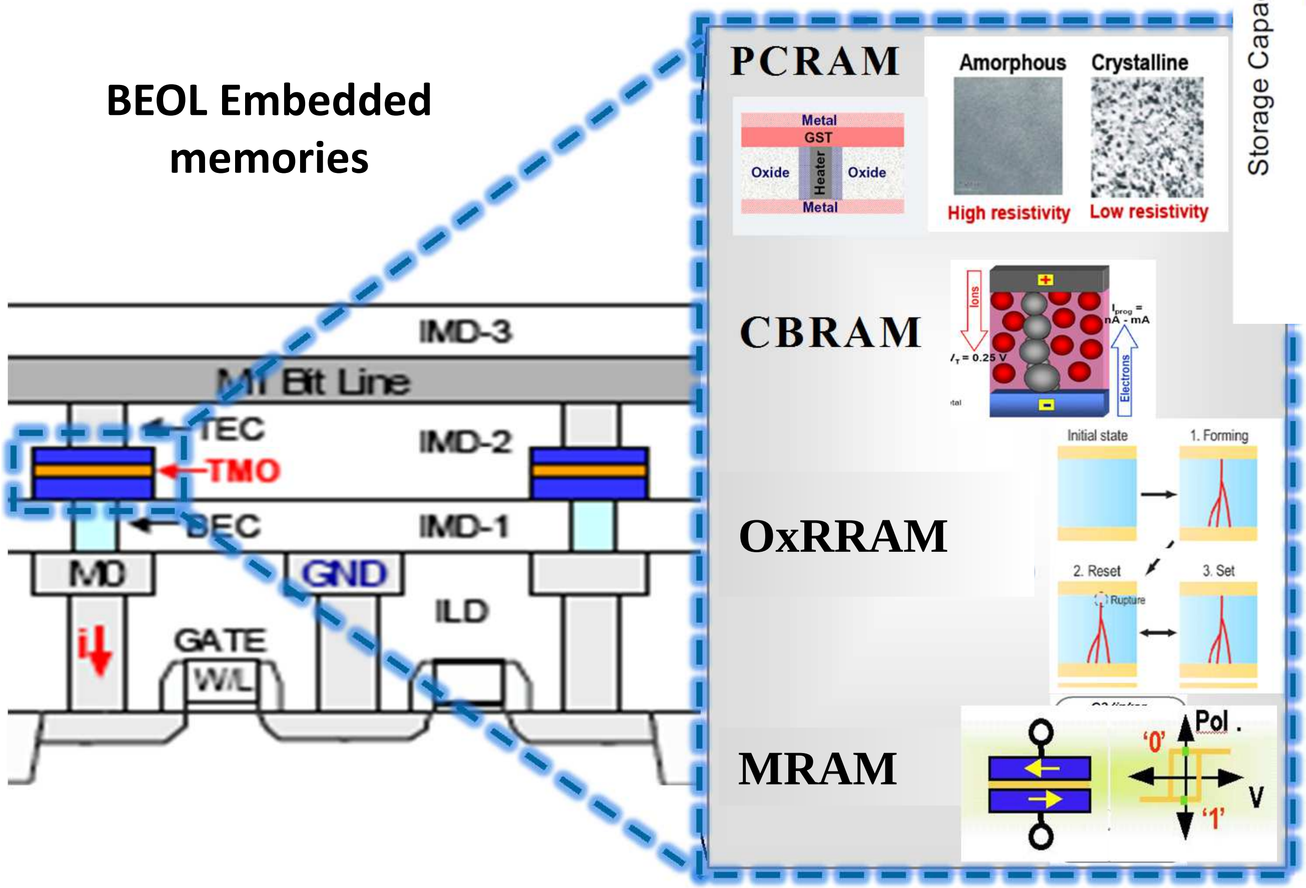
Stored information

- **RRAM: Resistivity change**
- Flash memories: Trapped charges



D. Takashima, Toshiba Corp., Keynote, NVMTS 2011, Nov7th, 2011

BEOL Embedded memories

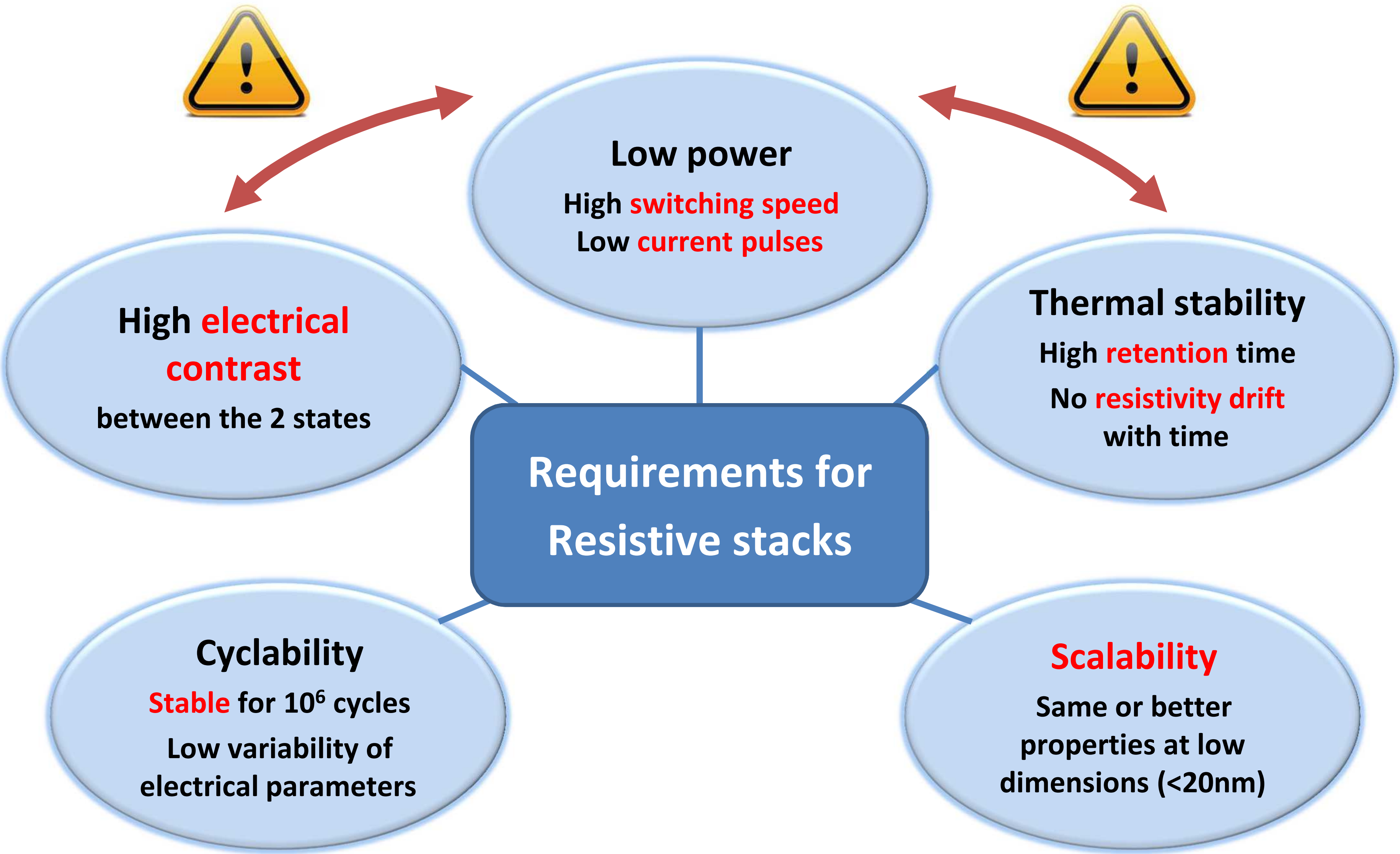


Above CMOS
Simplified integration

3D stacking
Increased storage density

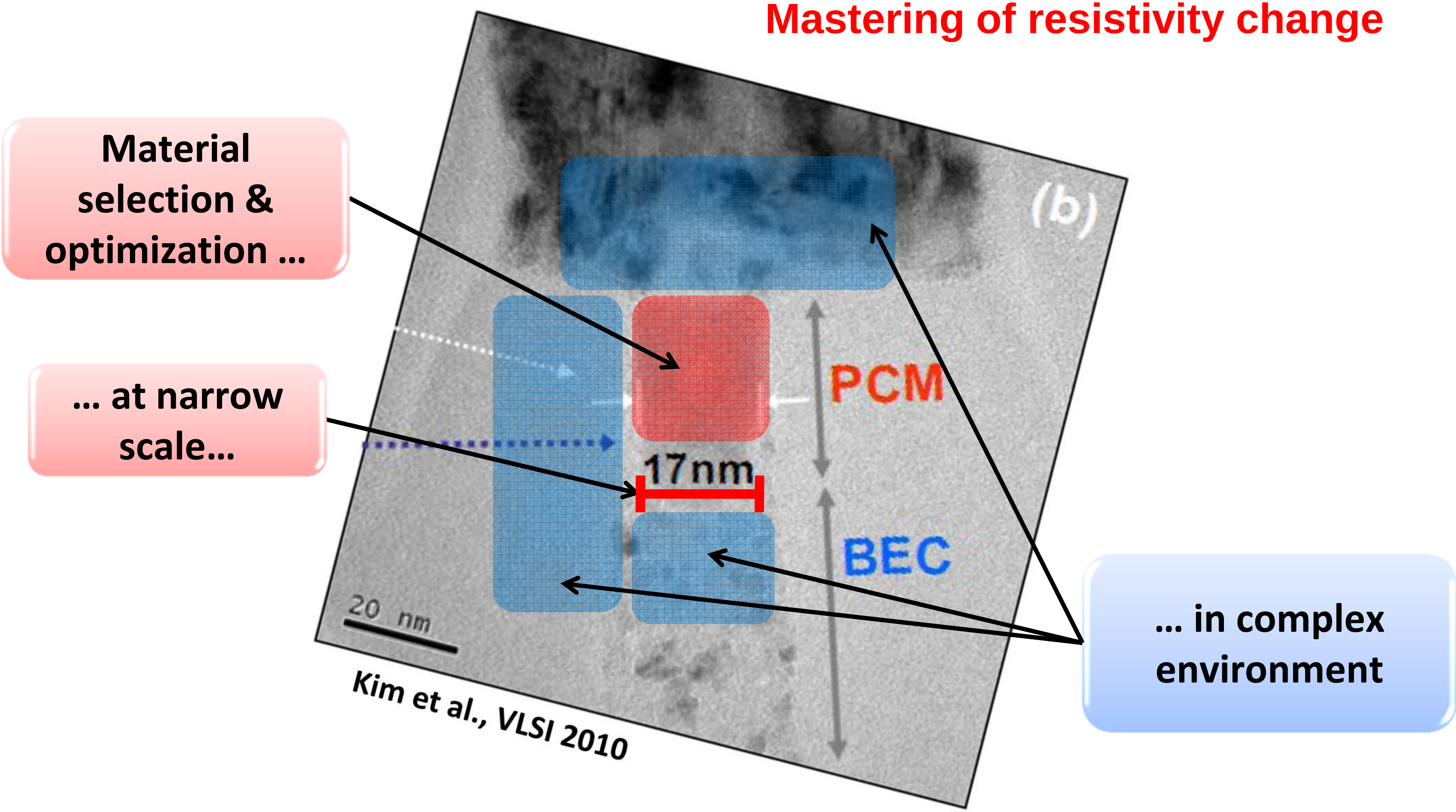
PC: Phase Change **CB**: Conductive Bridge **OxR**: Oxide Resistive

Challenges of RRAM specifications



Characterization challenges for RRAM developments

Mastering of resistivity change



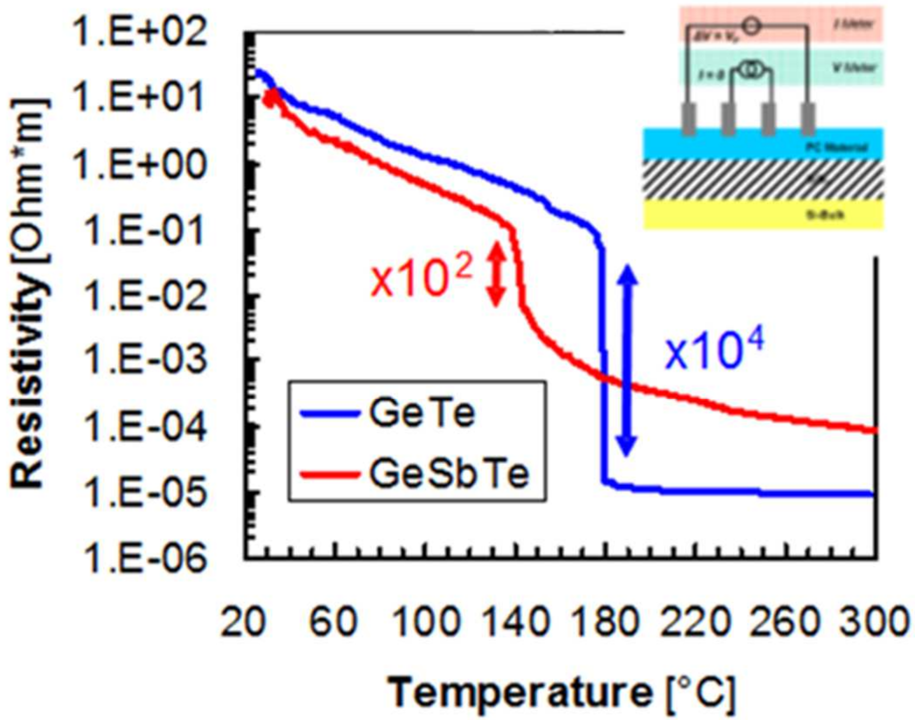
From the characterization point of view

Outline

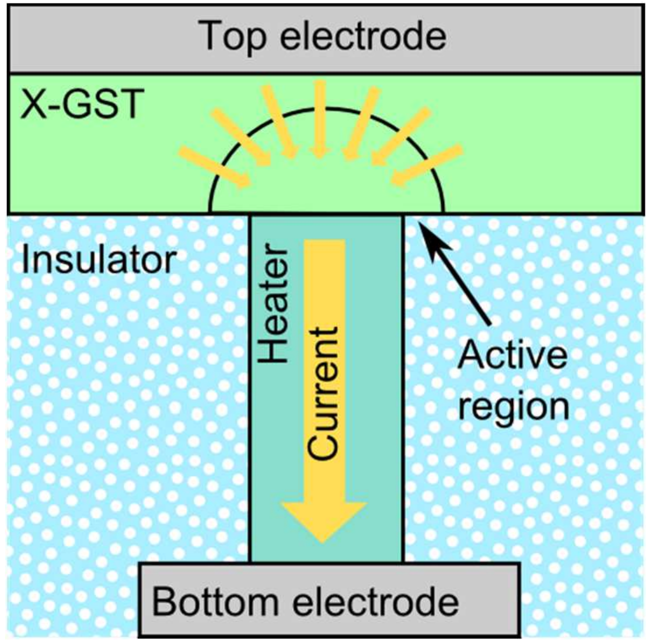
- Introduction to Resistive Random Access Memories
- Phase Change RAM
  - Selection and optimization of materials
  - Assessment of size effect on switching properties
- Conductive Bridge and Oxide Resistive RAM
  - Effect of integration environment on switching properties
  - Identification of switching mechanism
- Summary

PCRAM basic device

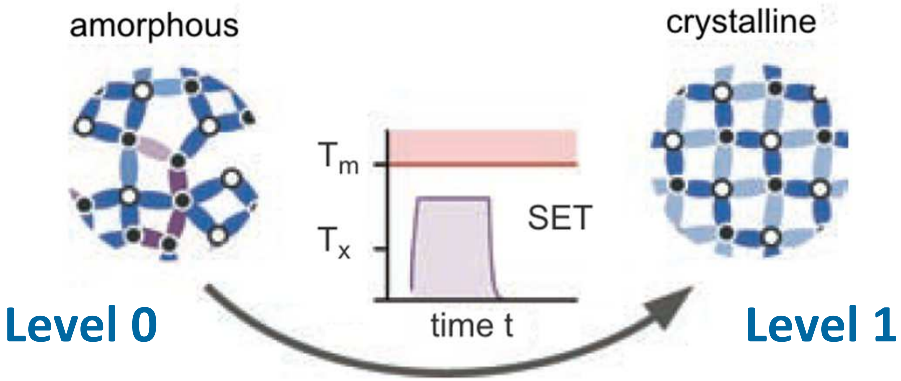
Temperature driven switching via Joule effect



Fantini et al., IMW 2009



Heater width < 100 nm



Tx: Crystallization temperature

Tm: Melting temperature of crystal

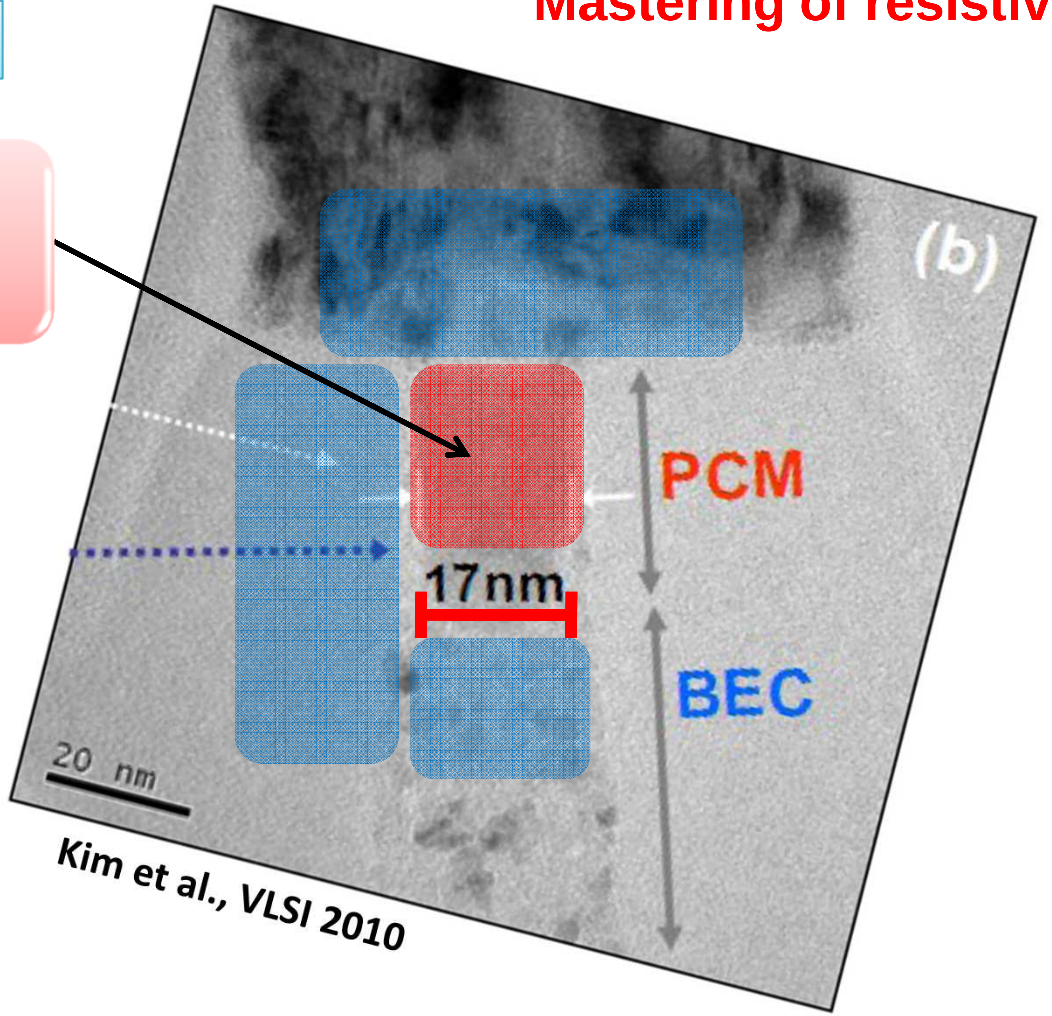
- **Data retention relies on amorphous phase stability**

Characterization challenges for RRAM developments

PCRAM example

Mastering of resistivity change

Material selection & optimization …



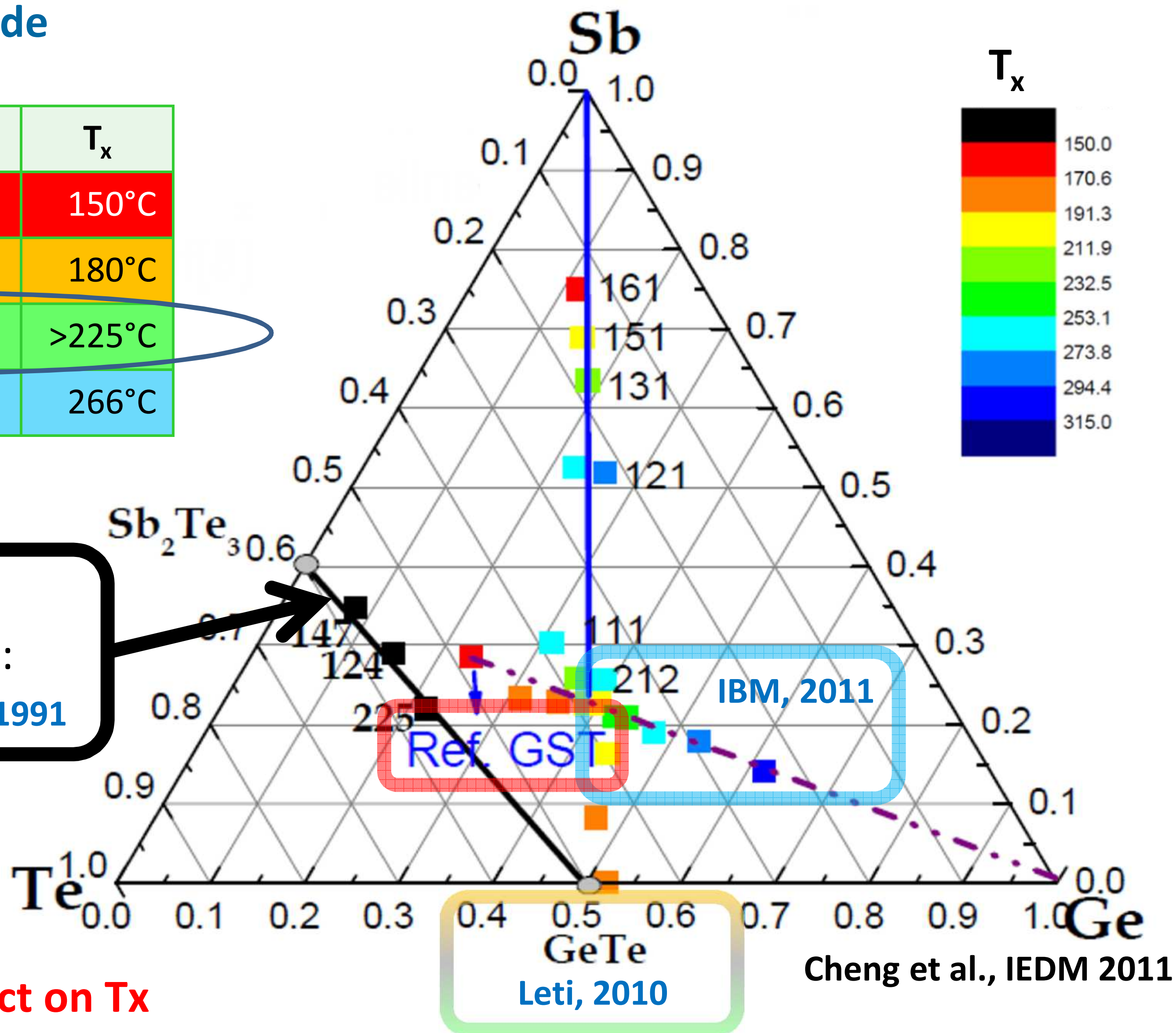
- **Tx increase** for high temperature applications (ex: automotive)

PCRAM typical materials

Chalcogenide

Material	T_x
$Ge_2Sb_2Te_5$ (GST)	150°C
GeTe	180°C
GeTeC and GeTeN	>225°C
Ge-rich $Ge_2Sb_1Te_2$	266°C

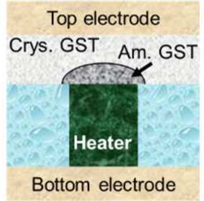
GeTe – Sb_2Te_3 pseudobinary line:
Yamada and coworkers, 1991

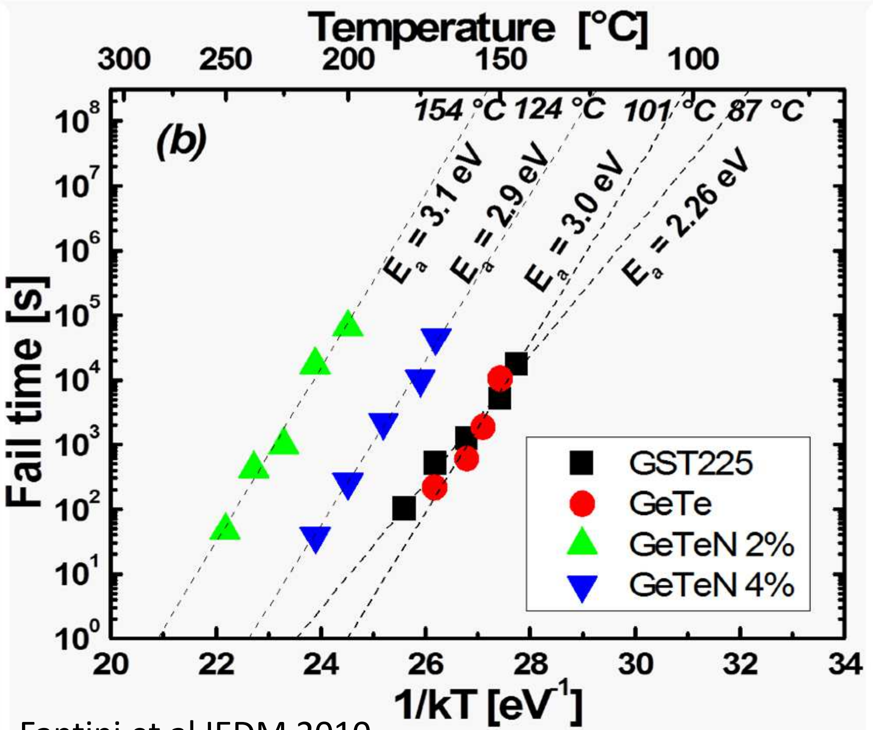


Cheng et al., IEDM 2011

Huge doping effect on Tx

PCRAM – Data retention vs doping

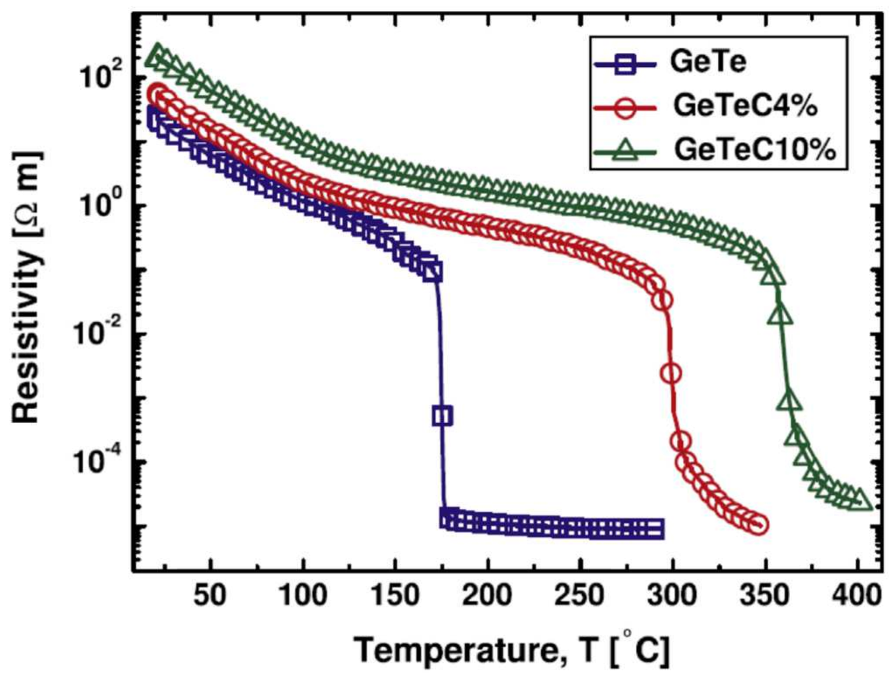




Fantini et al IEDM 2010

- O Doped GST
  - Matsuzaki et al., IEDM 2005
- In doped GeTe
  - Morikamwa et al., IEDM 2007

Betti Beneventi et al Sol. State Elec. 2011



- N doped GST, N doped GeTe
  - Horii et al. VLSI 2003
  - Fantini et al., IEDM 2010
- C doped GST, C doped GeTe
  - Czubatyj et al. EPCOS 2006
  - Betti Beneventi et al., Sol. State Elec. 2011
- …

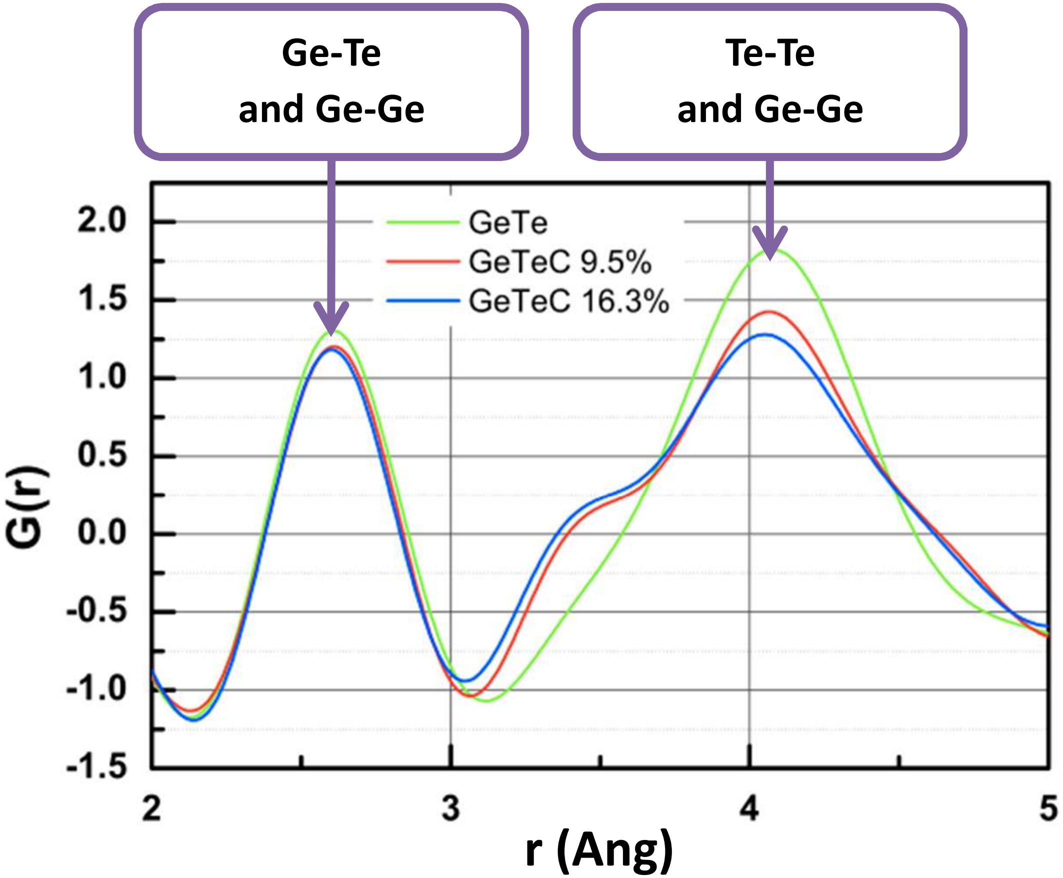
Role of C and N doping in Tx increase ?

Deal with amorphous phase characterization

Amorphous phase structural analysis

Pair Distribution Fonction (PDF) of amorphous GeTe / GeTeC

- Mean distances between atoms



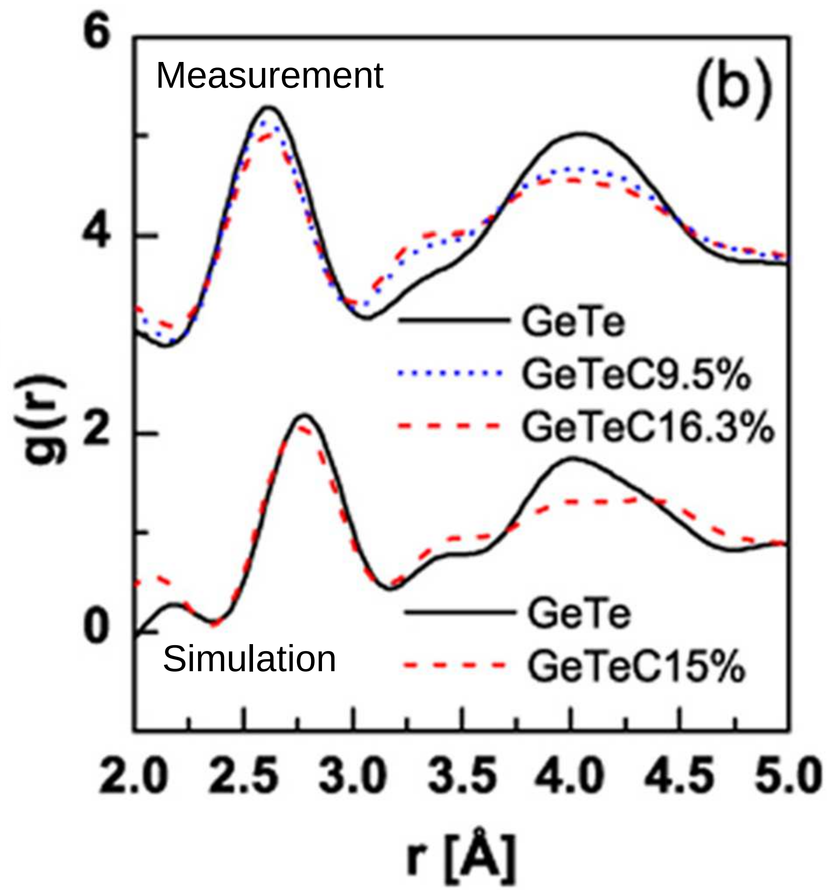
G. Ghezzi et al., APL 2011

- The first peak is unchanged
- A **new peak appears** at a distance around **3.5 Å**

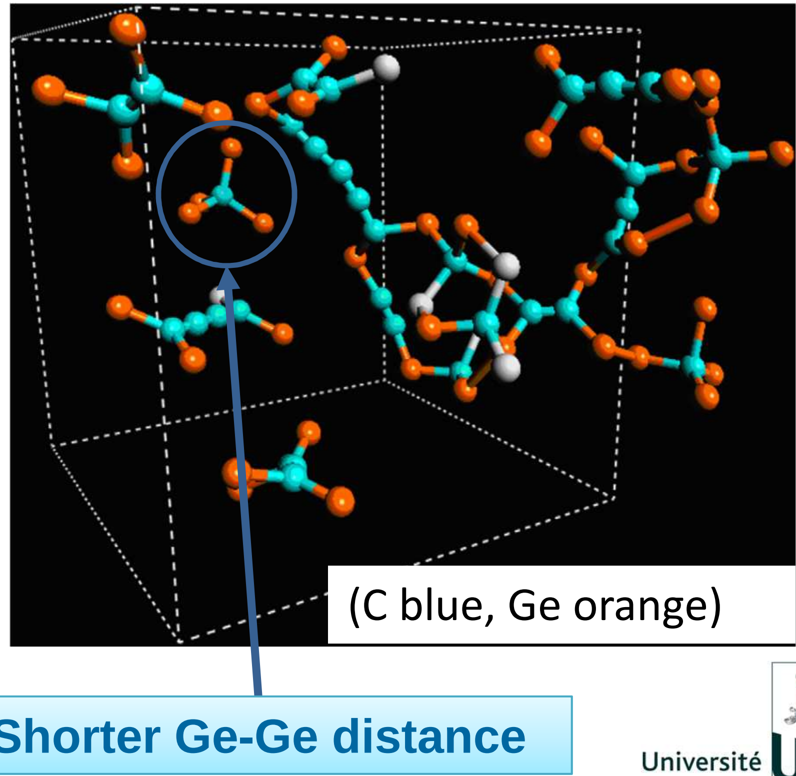
Ge – Ge
Te – Te
Ge – Te
~~C – Ge~~
~~C – Te~~
~~C – C~~

- Low scattering efficiency of C
- Need for **ab-initio simulation**

Amorphous phase structural ab-initio simulation



Instantaneous snapshot of a-GeTeC configuration at 300 K



Université de Liège

- Good agreement with experiment
- Evidence of C-C bonds
- Various C-Ge configuration

- Strengthening of local structure by C doping
- **Stabilization of amorphous phase**

G. Ghezzi et al., APL 2011

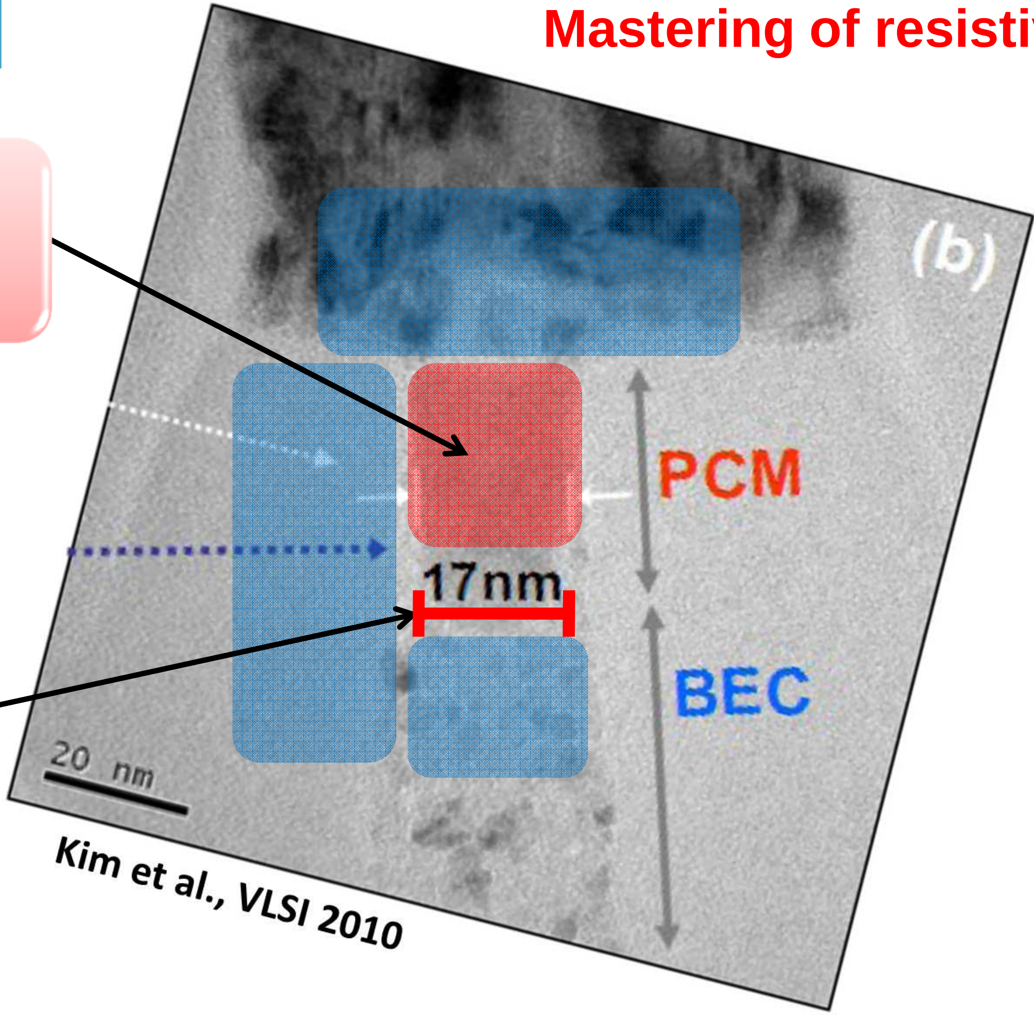
Characterization challenges for RRAM developments

PCRAM example

Mastering of resistivity change

Material selection & optimization …

… at narrow scale…

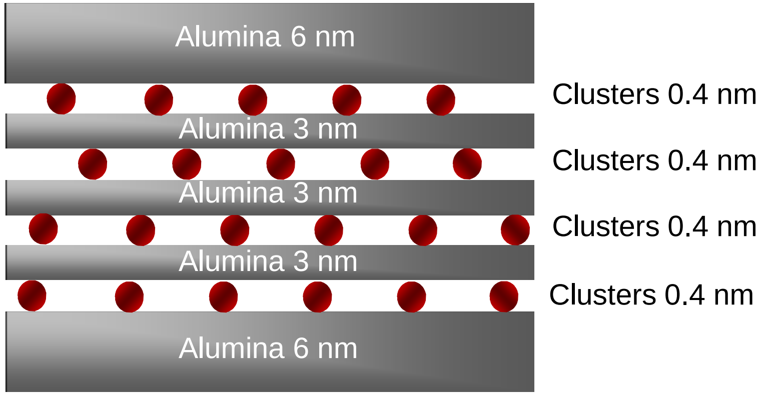


Kim et al., VLSI 2010

- **Keeping switching with size reduction** for scalability

Phase Change of nanoclusters

- GST clusters

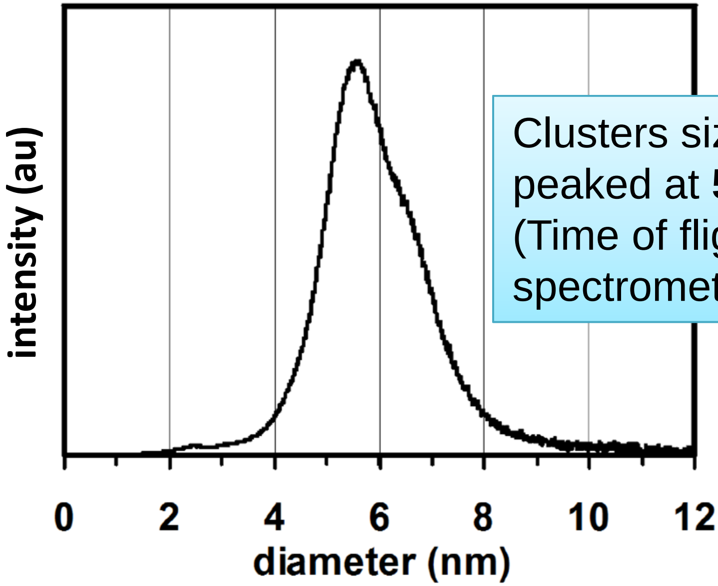


- GST thin film

Sputtering gas-phase condensation

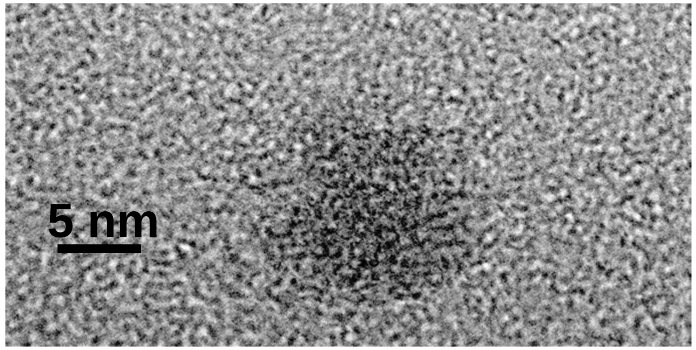
Composition by RBS-PIXE

Film	Ge:Sb:Te = 23:24:53
Clusters	Ge:Sb:Te = 28:27:45



Clusters size distribution peaked at **5.7** nm ±1 nm (Time of flight mass spectrometer)

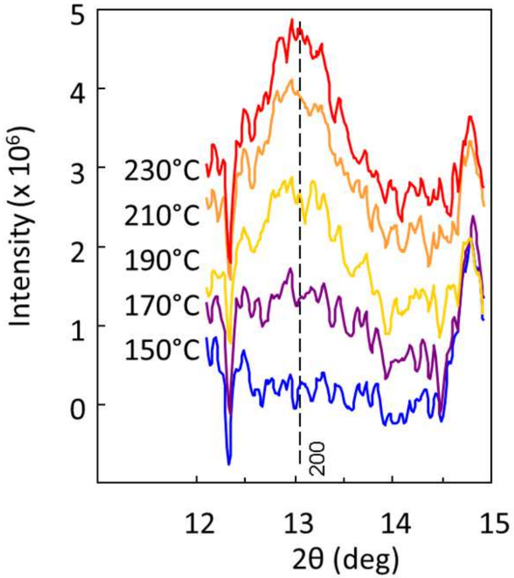
Cluster TEM images

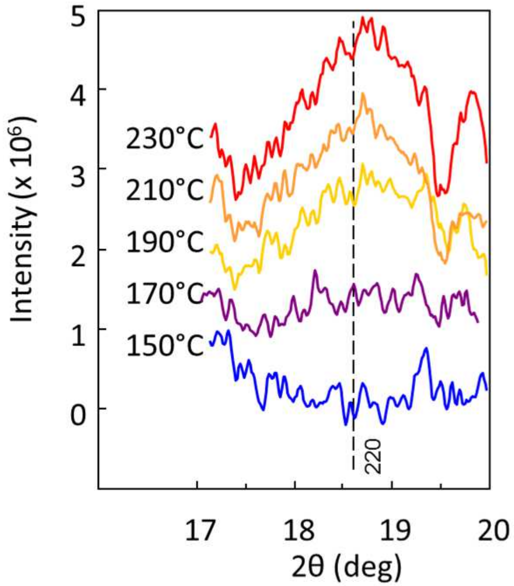


G. Ghezzi et al., APL 2012

PIXE: Proton induced X-ray Emission

Crystallization temperature of nanoclusters

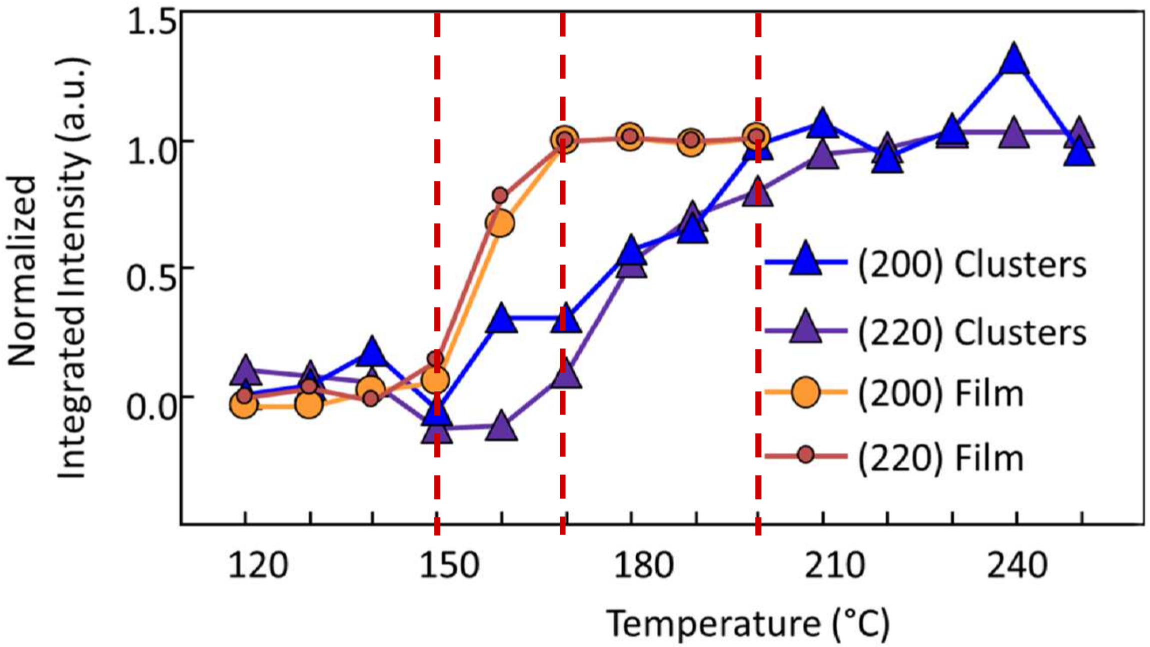




In situ XRD analysis

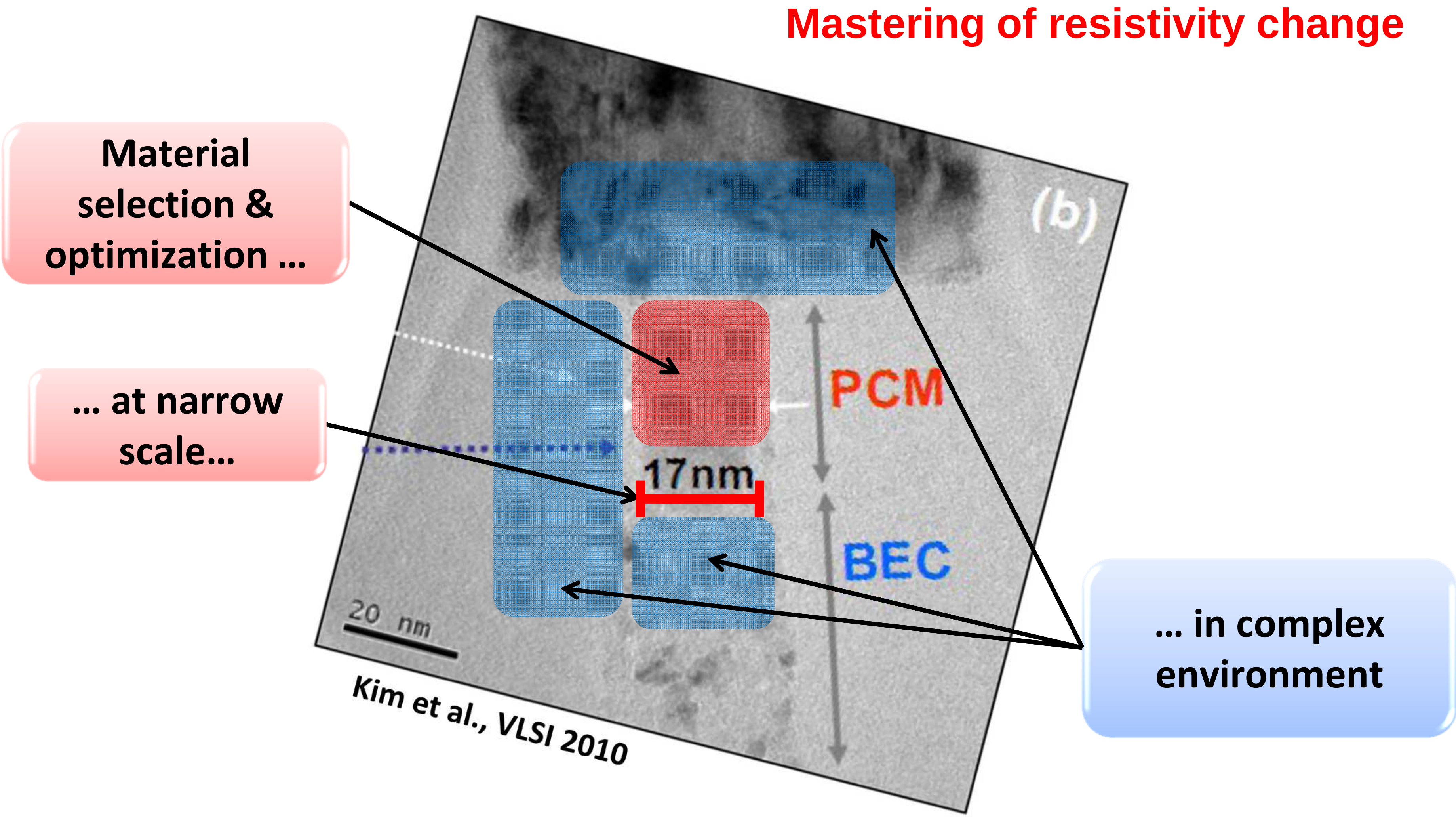
G. Ghezzi et al., APL 2012

- **No peaks appearing at temperatures lower than 170°C**
- **Crystallization of nanoclusters**
- **Crystallization is complete at around 200°C**



- **Phase transition kept @ nanosize**

Characterization challenges for RRAM developments



Example of the « Filament like » resistive RAM

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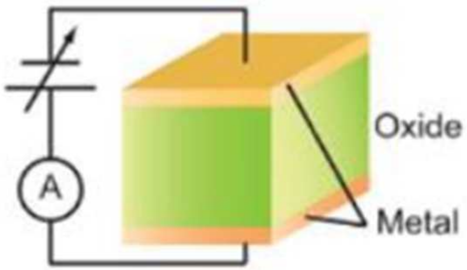
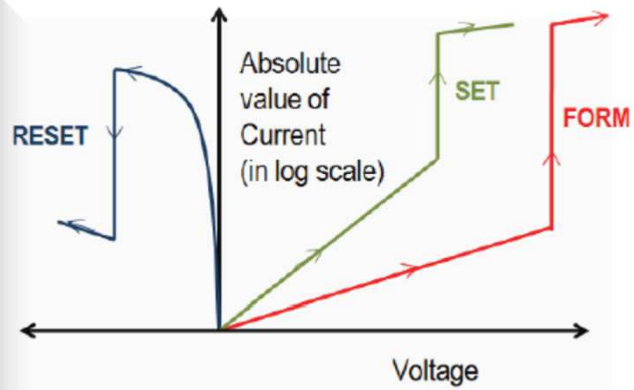
Conductive Bridging RAM and Oxide Resistive RAM

- The basic stack is a **MIM structure**



- Most of them show **bipolar switching**
- The switching is often related to **filamentary mechanisms**.



Bipolar switching
Opposite polarity for RESET/ SET,FORMING

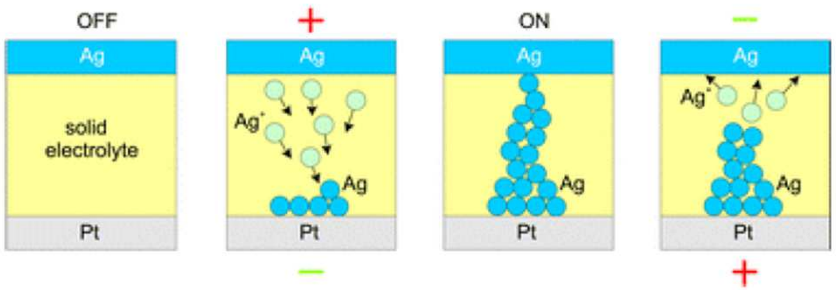
- **CBRAM**

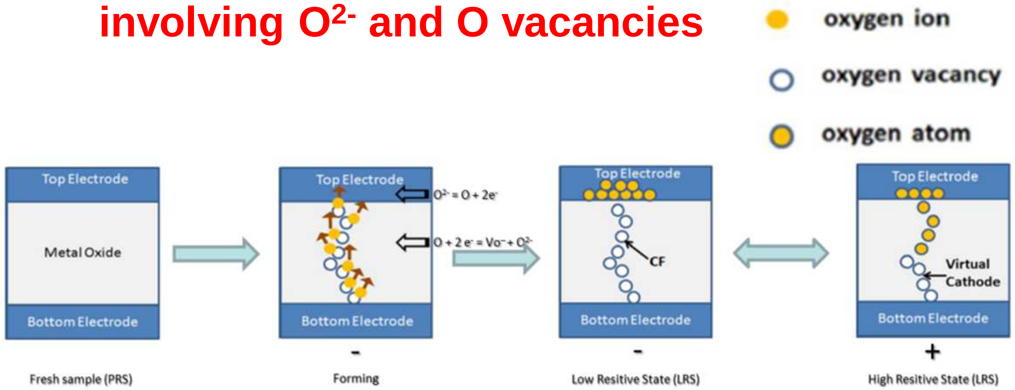
  Growth/dissolution of a **filament of metal ions** (Ag, Cu) in a solid electrolyte

- **OxRRAM**

  A high k between 2 electrodes

  Mostly invoked: **filamentary mechanisms involving O^{2-} and O vacancies**

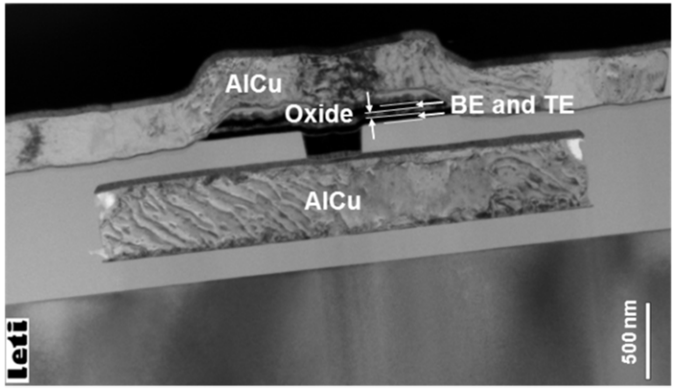


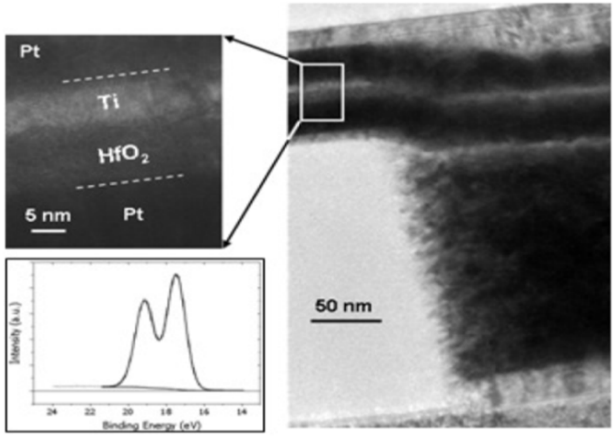


▶ **Need for pristine sample characterization**

Effect of integration environment on material

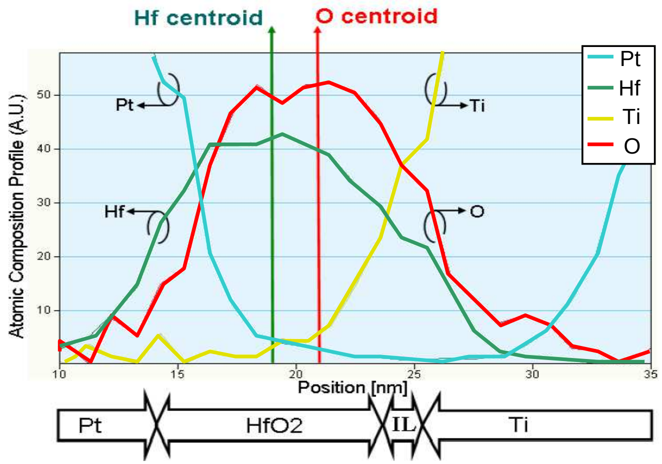
HfO_2 OxRRAM

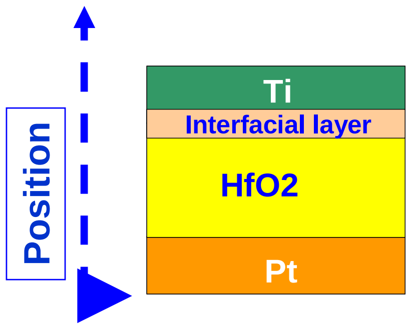




- HfO_2 capped with a top electrode
- Oxygen getter effect (ex: Ti)

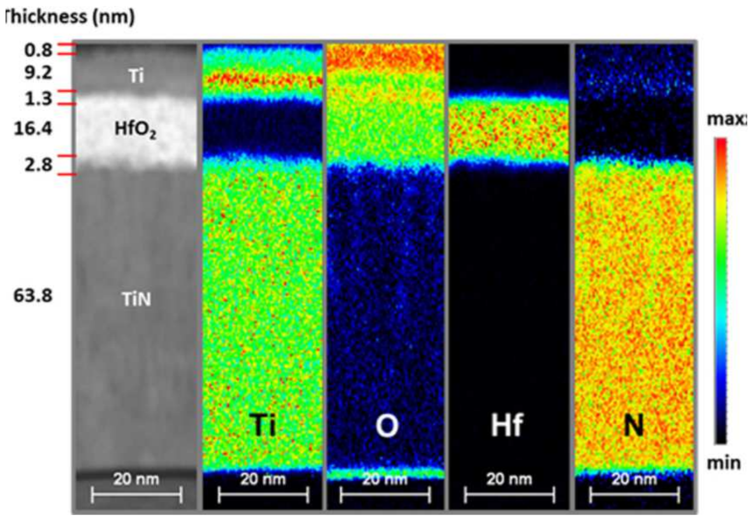
STEM-EDX





C. Cagli et al., IEDM 2011

HAADF-STEM and EDX images



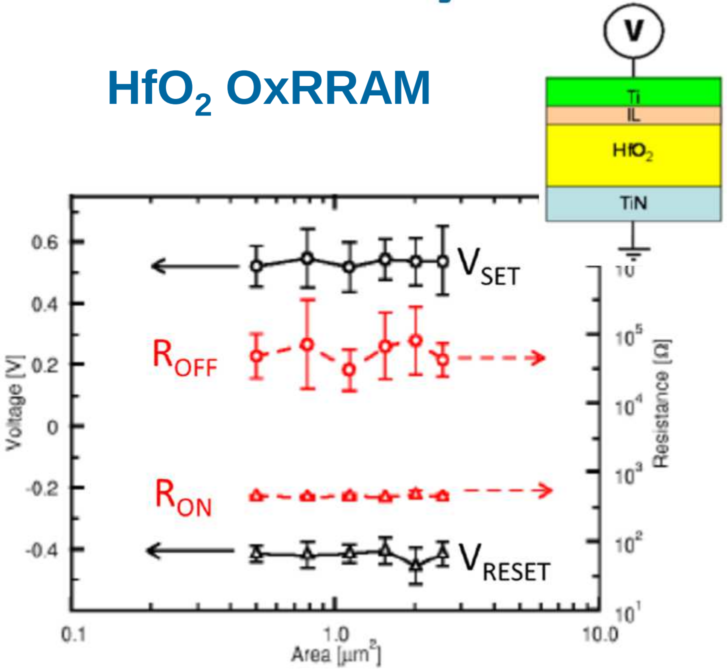
Sowinska et al., Appl. Phys. Lett. 100, 233509 (2012)

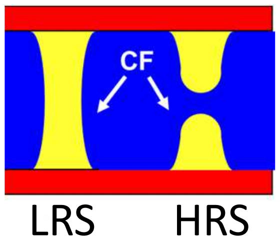
O diffusion in Ti

▸ **HfO_2 modified by integration**

Filamentary mechanism assumption

HfO_2 OxRRAM





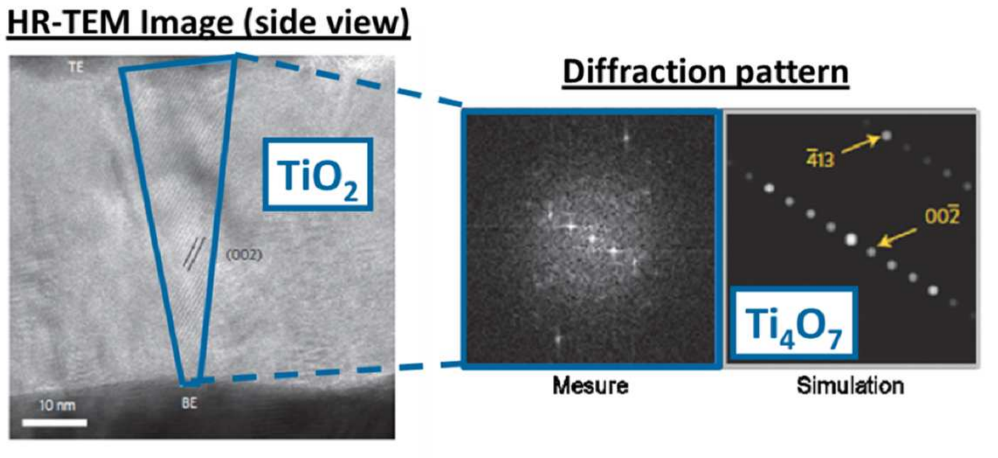
C. Cagli et al., IEDM 2011

No area scaling effect

- **Filament like conduction**

TiO_2 OxRRAM

TEM with in-situ electrical switching of the oxide



D.-H. Kwon et al., Nature Nanotech. 5, 148-153 (2010)

TiO_2 (Rutile) => Ti_4O_7 (Magneli)

- **Phase change mechanism**
- **OxRRAM or PCRAM ?**

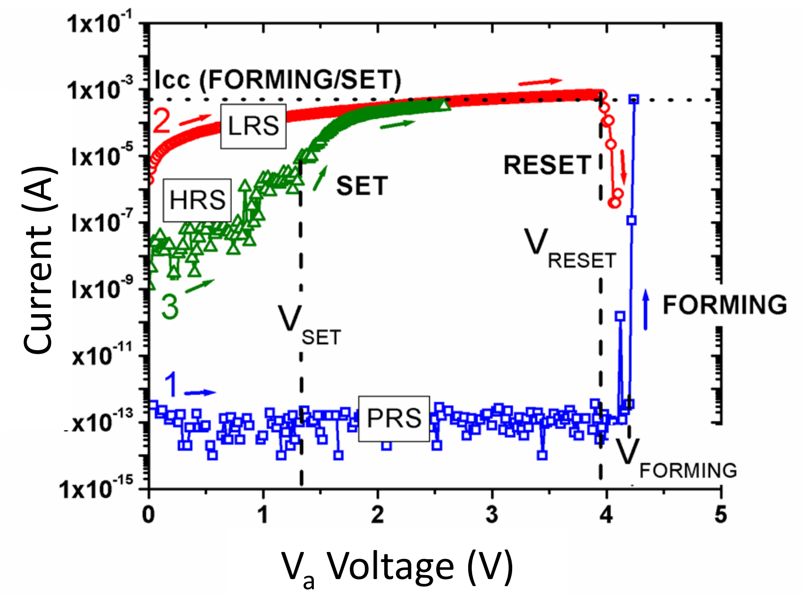
No other direct evidence of a conductive path

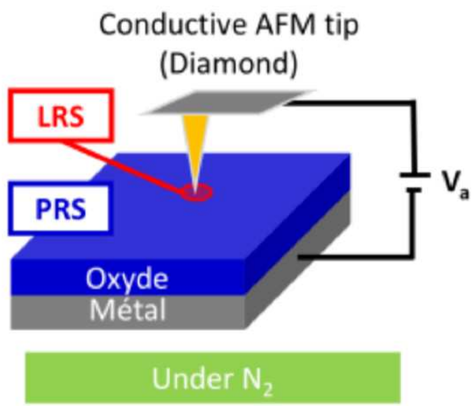
Observation of local electrical switching

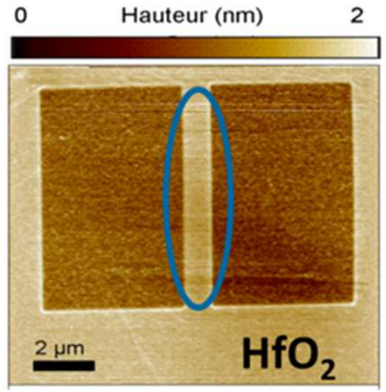
P. Calka et al., et al. Nanotechnology 24 (2013)

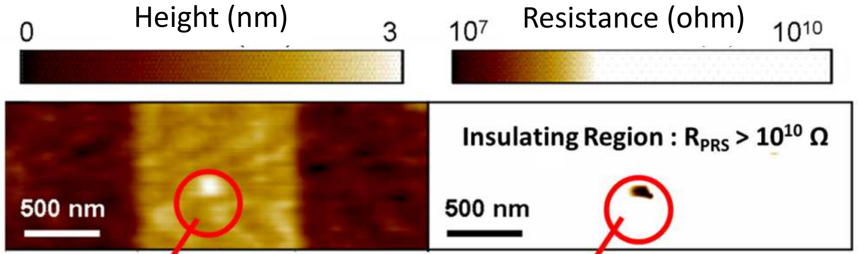
HfO_2 OxRRAM

C-AFM for local switching









Height increase: 1 nm

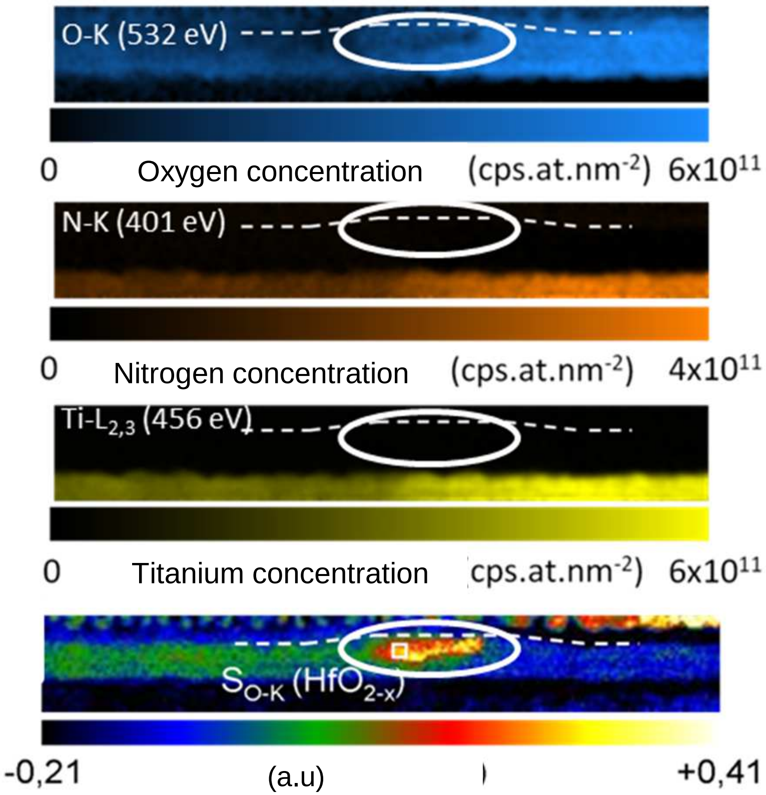
Conductive region
$R_{LRS} \sim 10^7\ \Omega$

- **Resistive switching by C-AFM**
- **Localization of a conductive path by SSRM**
- **TEM lamella preparation around the conductive path**

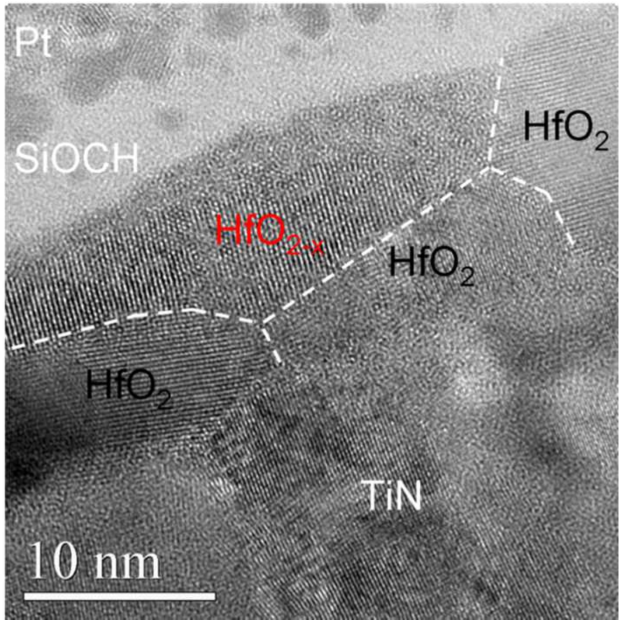
PRS: Pristine State　　LRS: Low Resistance State　　HRS: High Resistance State

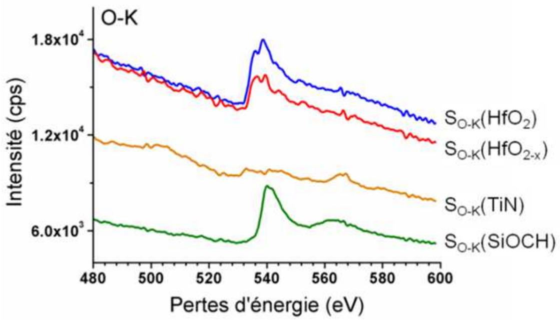
Observation of local electrical switching

STEM-EELS



HR-TEM





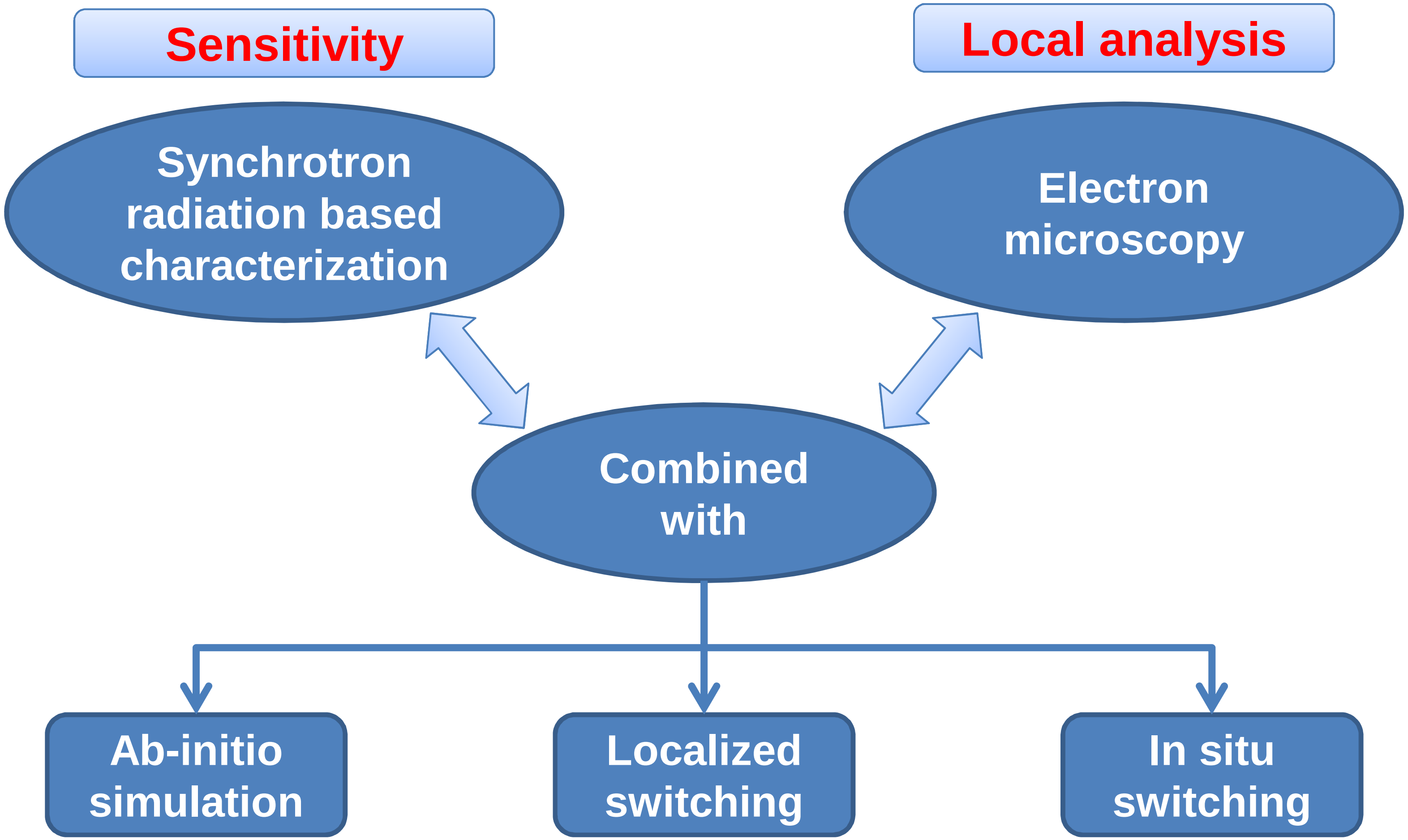
- **Oxygen depletion localized at the top of the switching area**
- **O in HfO_{2-x} main component of the O-K line**
- **What about set and reset ?**

PRS: Pristine State LRS: Low Resistance State HRS: High Resistance State

P. Calka et al., et al. Nanotechnology 24 (2013)

Summary

RRAM developments require characterization of atom displacements



Speed up the process-characterization loop

Summary

<table>
<tr><th colspan="2">RRAM Issues</th><th>Phase Change
LRS and HRS</th><th>Filament like
PRS, LRS and HRS</th></tr>
<tr><td colspan="2">Characterization challenges</td><td>Amorphous phase</td><td>Filament observation</td></tr>
<tr><td colspan="2">Sample preparation challenges</td><td>To avoid phase transition</td><td>To localize the filament</td></tr>
<tr><td rowspan="5">Sample nature</td><td>Mechanism studies</td><td>Stack of films</td><td rowspan="3">Device like</td></tr>
<tr><td>Material choice</td><td>Stack of films</td></tr>
<tr><td>Integration effect</td><td>Device like</td></tr>
<tr><td rowspan="2">Size effect</td><td>Integrated Nanomaterials</td><td rowspan="2">–</td></tr>
<tr><td>Device like</td></tr>
</table>

"In operando" characterization ?

As suggested in Sowinska et al., Appl. Phys. Lett. 100, 233509 (2012)

PRS: Pristine State LRS: Low Resistance State HRS: High Resistance State

Aknowledgements

- J.-Y. Raty
- F. Hippert
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BM08 - The GILDA Beamline

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LABORATOIRE D'ÉLECTRONIQUE
ET DE TECHNOLOGIES
DE L'INFORMATION

CEA-Leti
MINATEC Campus, 17 rue des Martyrs
38054 GRENOBLE Cedex 9
Tel. +33 4 38 78 36 25

www.leti.fr

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