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Resistive Switching of AlN Films Grown by PEALD

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Outline

ALD for ReRAM

Resistive switching of PEALD-AlN

Summary

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ALD for ReRAM

Resistive switching of PEALD-AlN

Summary

Surging needs for high density memory

Paradigm shift: compute-centric → data-centric era

	Compute-centric	**Data-centric**
Devices	5.6M disk	**21M disk**
Space	26,292 ft^2	98,568 ft^2
Power	25 MW	93 MW

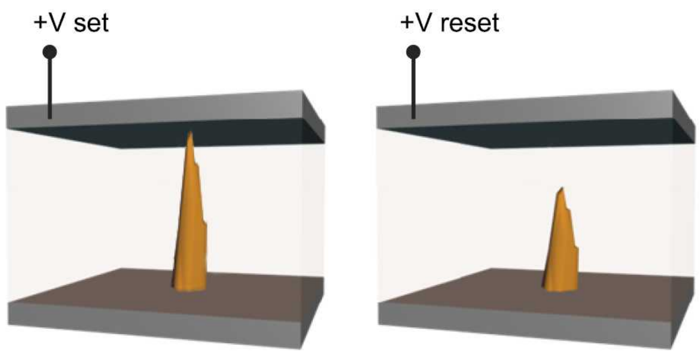
Storage system 2020 for server computer

Ever increasing demand for high density memory!

R. F. Freitas and W. W. Wilcke, IBM J. Res. Dev. 52, 439 (2008)

Strong candidate: ReRAM

- ❑ Resistive Random Access Memory (ReRAM)



Connect
(Low R)
"1"

Disconnect
(High R)
"0"

- **Materials: Metal oxides, Chalcogenides**
- **Switching:**

  Low R ↔ High R
- **Emerging technology**
- **High potential, but unclear**

R. Waser et al. *Adv. Mater.* **21**, 2632 (2009)
K. M. Kim et al. *Nanotechnology* **22**, 254002 (2011)

ALD for ReRAM

- ALD enabled crossbar-type ReRAM

Switching : Switching materials in 3-D structure, materials engineering (alloying, multiple layers, etc)

Electrode : Conducting nitride and oxide electrode

Functional : Tunnel barrier as a selector device, switching interface control

B. J. Choi et al. *J. Appl. Phys.* **98**, 033715 (2005)
K. M. Kim et al. *Electrochem. Solid-State Lett.* **9**, G343 (2006)
W. Lee et al. *ACS Nano* **6**, 8166 (2012)
S. K. Kim et al. *Appl. Phys. Lett.* **102**, 082903 (2013)

Materials selection: TiN/AlN

Why TiN/AlN?

Process

- Fab preferred materials
- Simple ALD process available

Device

- Phase stability
- High durability expected

Mechanism

- Analogue to oxide switching
- N ion movement?

B. J. Choi et al. *Appl. Phys. A*, **109**, 1 (2012) (invited paper)

Outline

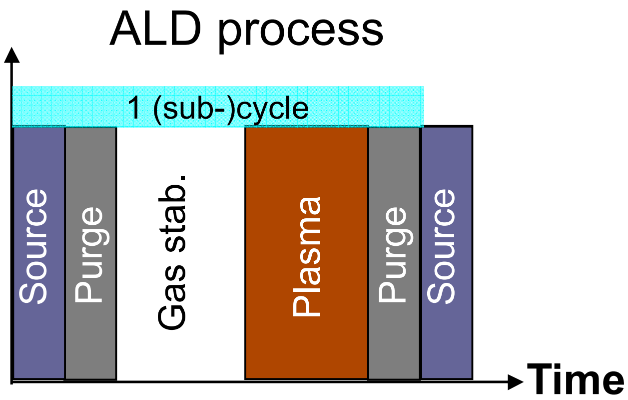
ALD for ReRAM

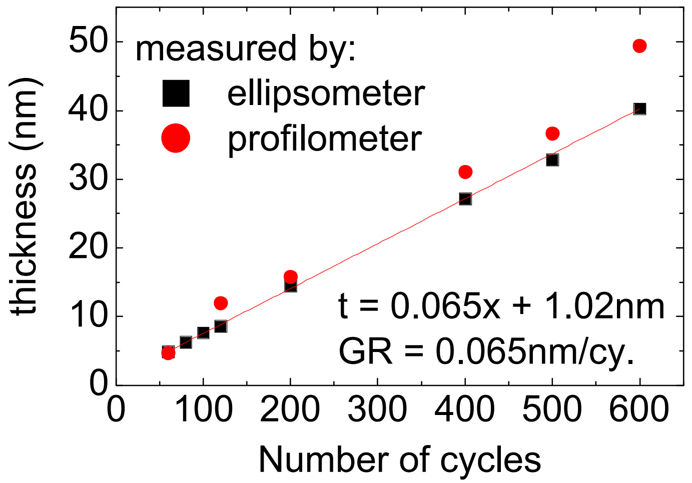
Resistive switching of PEALD-AlN

- ALD process and device performance

Summary

PEALD process: AlN switching materials

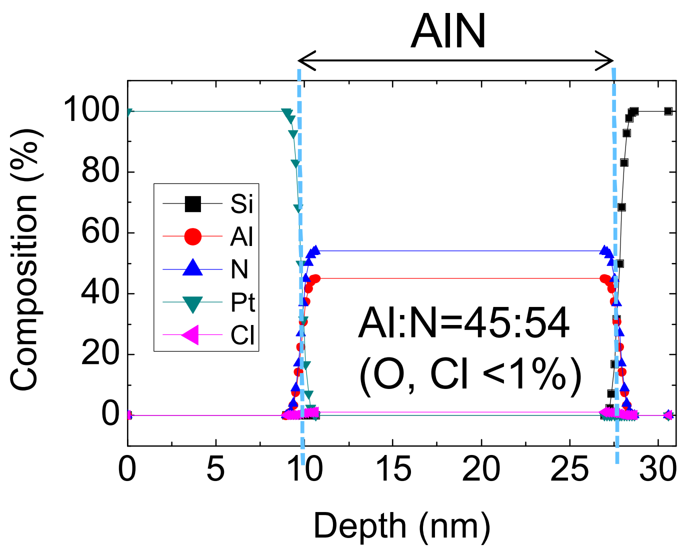




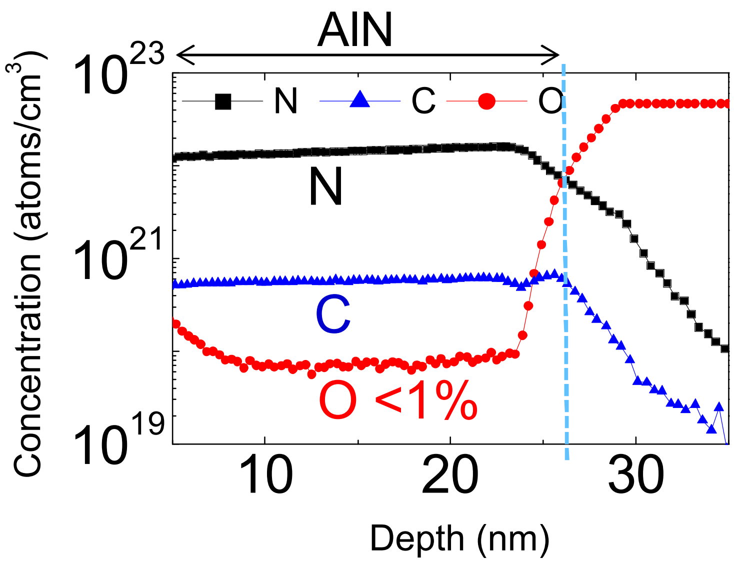
- Growth temperature: 150 – 400 ^{o}C (350 ^{o}C preferred)
- Source: TMA, N_2+H_2 or NH_3 w/ remote plasma (400W)

B. J. Choi et al. *Appl. Phys. A*, **109**, 1 (2012) (invited paper)

PEALD process: Film composition



RBS



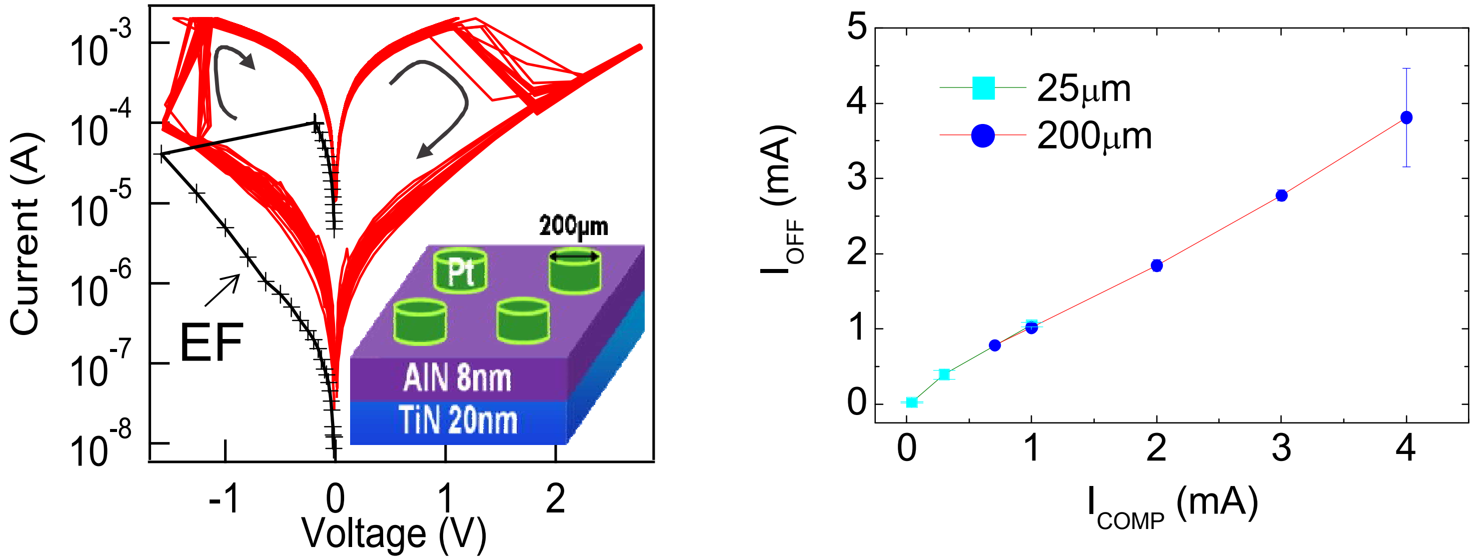
SIMS

- N-rich AlN with negligible impurities
- Uniform depth profiles with O < 1%

<u>B. J. Choi</u> et al. *Appl. Phys. A*, **109**, 1 (2012) (invited paper)

Device performance: Reproducibility

100 consecutive cycles

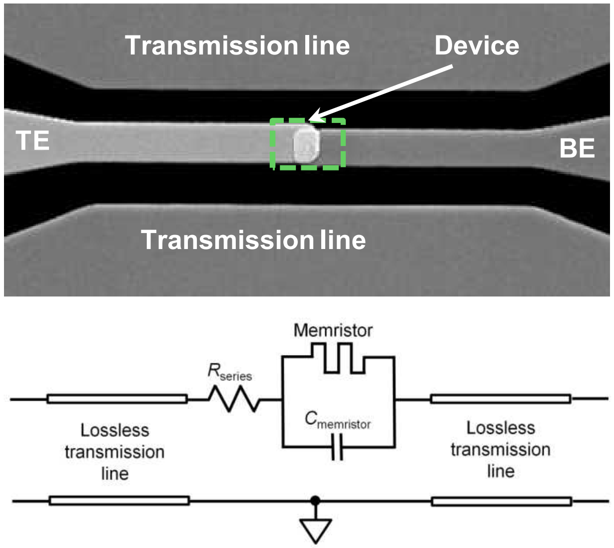


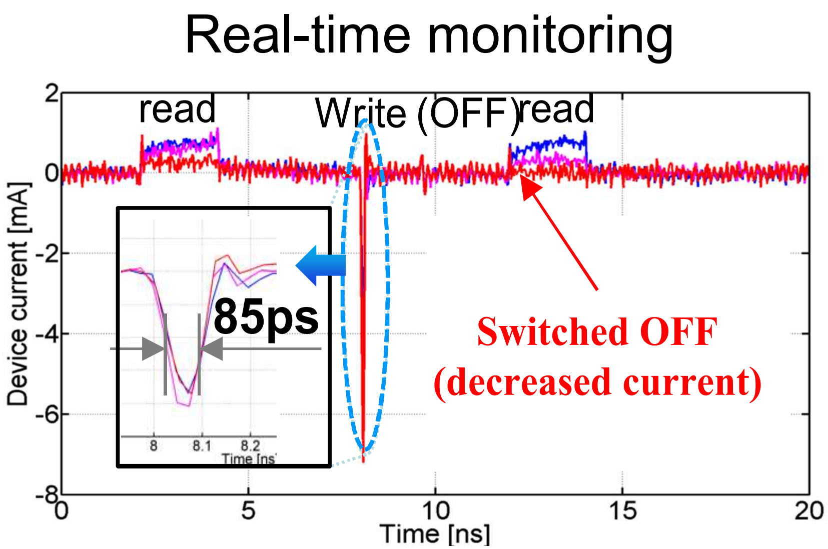
- First switching in nitride materials

- Compliance current (I_{comp}) defines device resistance and I_{OFF}

B. J. Choi et al. *Appl. Phys. A*, **109**, 1 (2012) (invited paper)

Device performance: Ultra-fast switching

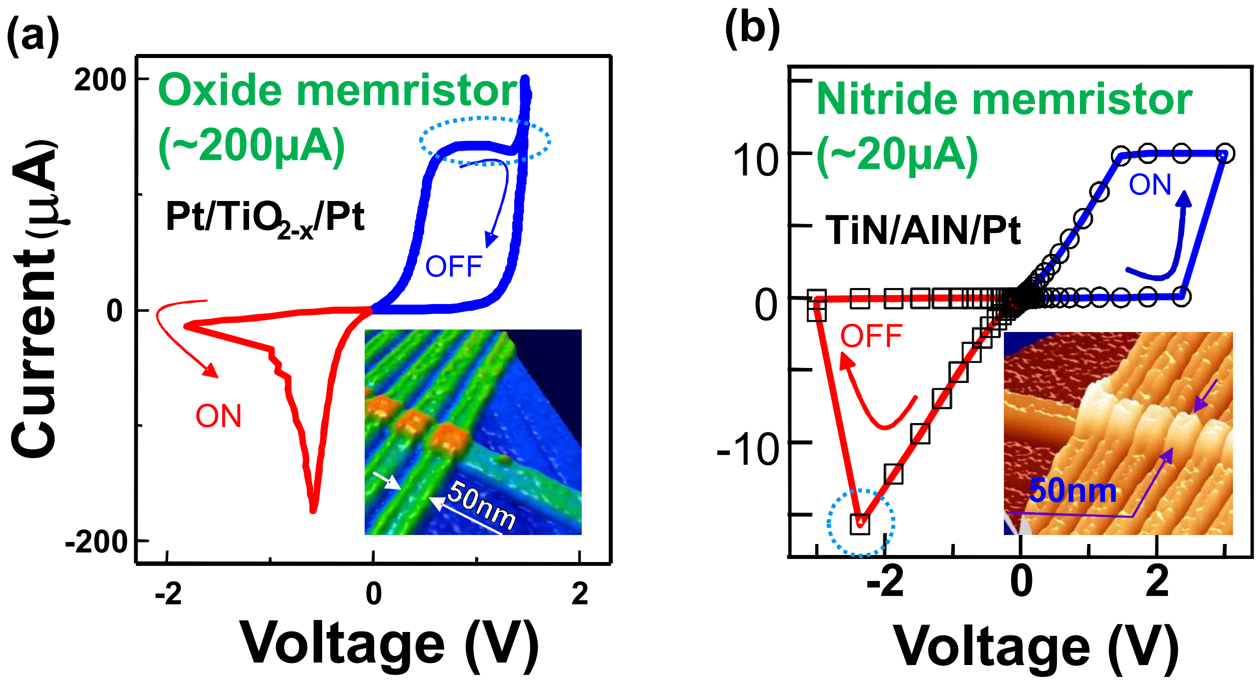




- **100ps** switching speed
- Nonlinear switching dynamics → **Ionic switching** mechanism

<u>B. J. Choi</u> et al. "Sub-100ps ultra-fast and energy-conservative nitride memristors", to be submitted

Device performance: Scalability and energy



- Nano-device (50nm x 50nm) with crossbar structure
- Low energy device; lower than oxides device

B. J. Choi et al. "Sub-100ps ultra-fast and energy-conservative nitride memristors", to be submitted

Outline

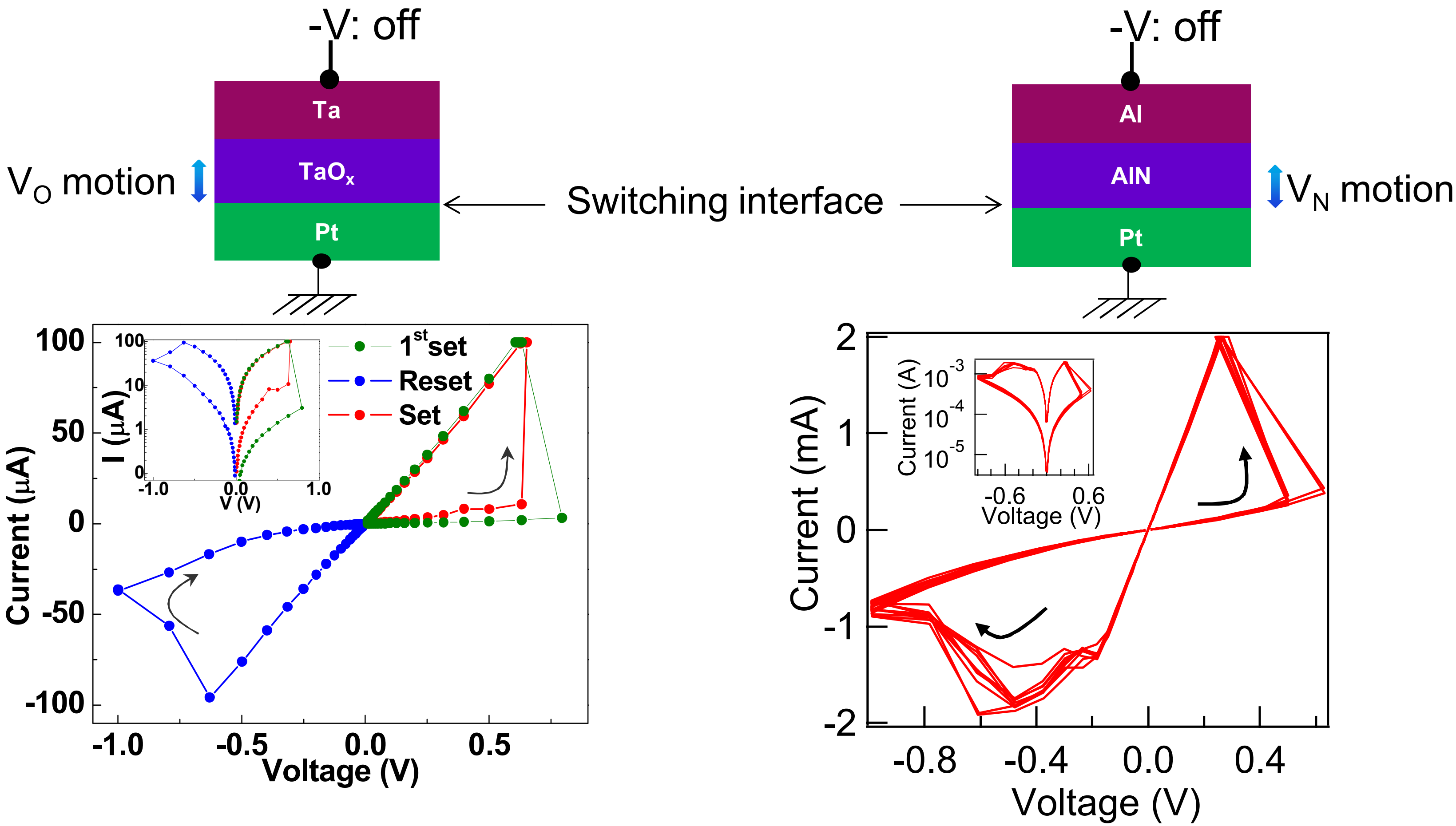
ALD for RRAM

Resistive switching of PEALD-AlN

- Switching mechanism

Summary

Mechanism: Analogous to oxide

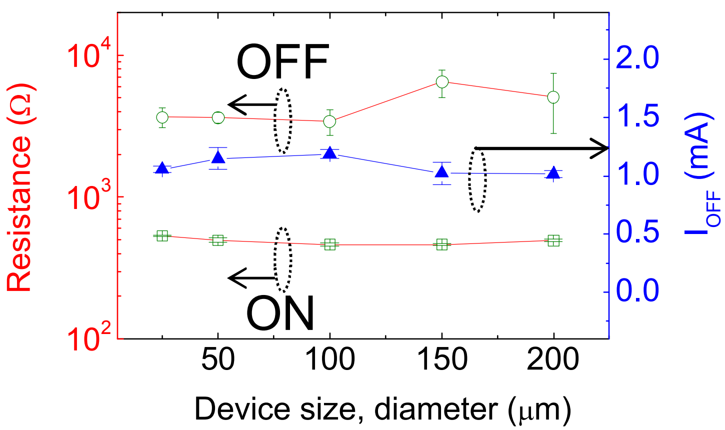


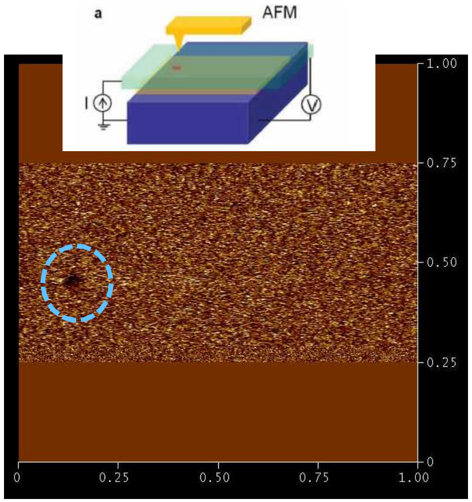
Inert interface favorable!

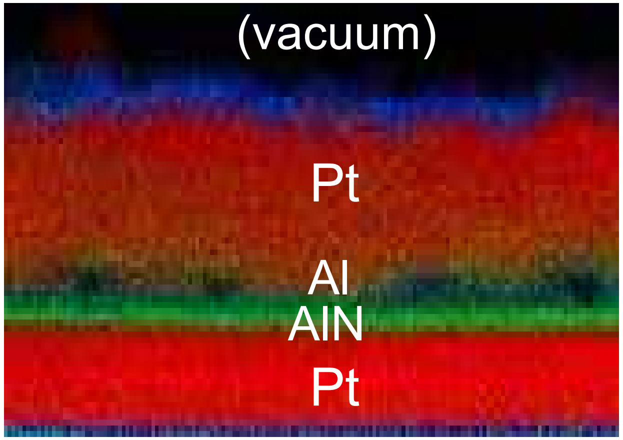
Yang *et al*. Appl. Phys. Lett. 97, 232102 (2010)
Miao *et al*. Adv. Mater. 23, 5633 (2012)

Mechanism: Localized channels

Various evidences







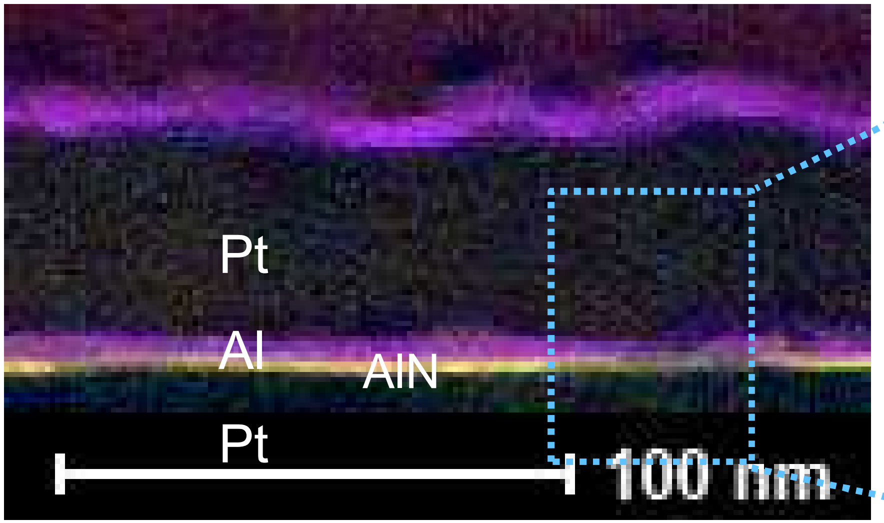
Irrelevance to area (Electrical test)

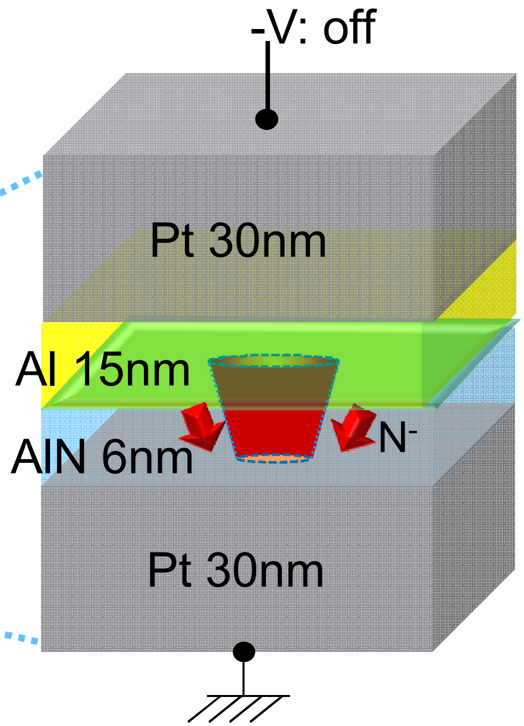
Localized conducting region detected (PMCM)

Chemical change (TEM-EDS)

Strachan *et al*. Adv. Mater. 22, 3573 (2010)
Miao *et al*. Adv. Mater. 23, 5633 (2012)

Mechanism: Al(N) channels





- Strongly localized heating
- Formation of N-deficient Al(N) → Localized channel

B. J. Choi et al. "Sub-100ps ultra-fast and energy-conservative nitride memristors", to be submitted

Summary

Process	• AlN grown by PEALD • Low impurity level
Device	• Reproducible switching • High speed and low energy
Mechanism	• Analogue to oxide switching • Al(N) channel formed

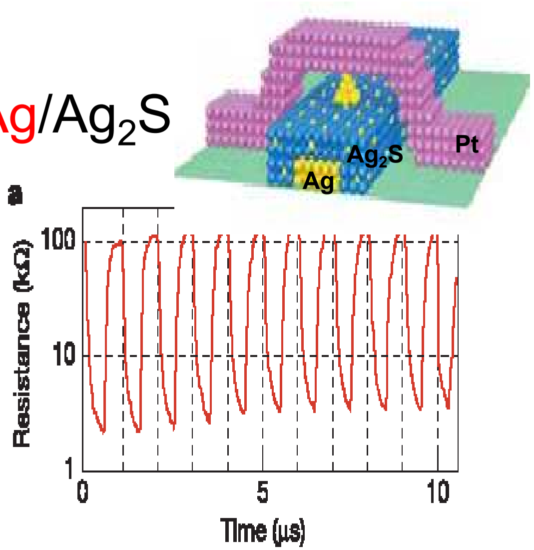
Acknowledgements

HP Labs / Sandia Labs / UC Santa Cruz

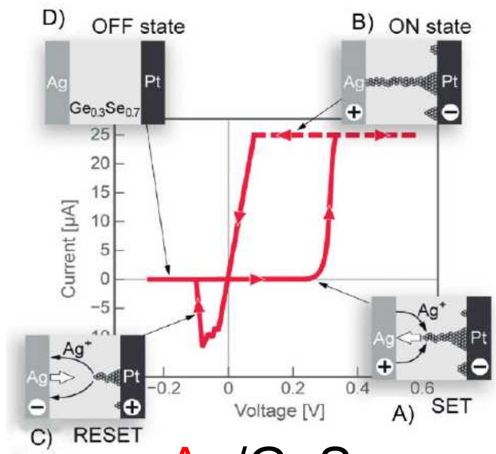
THANK YOU

Resistive switching materials

Ag/Ag_2S



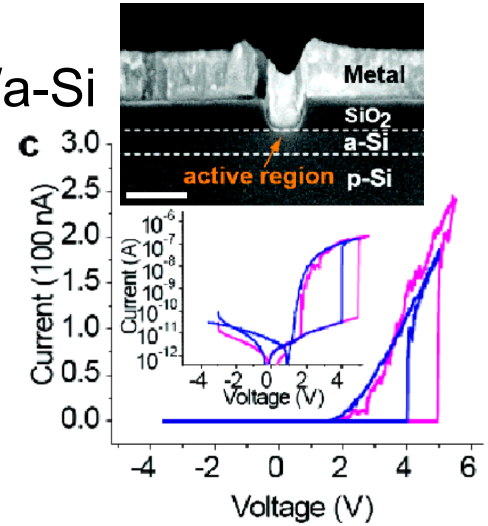
Terabe *et al*. Nature 433,47 (2005)



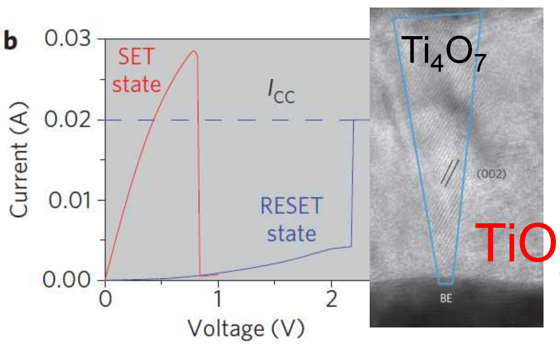
Ag/GeSe

Waser *et al*. Adv. Mat. 21, 2632 (2009)

Ag/a-Si

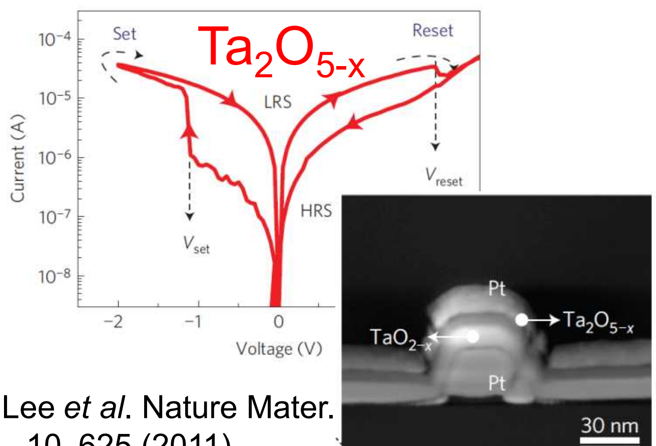


Jo & Lu, Nano Lett. 8, 392 (2008)



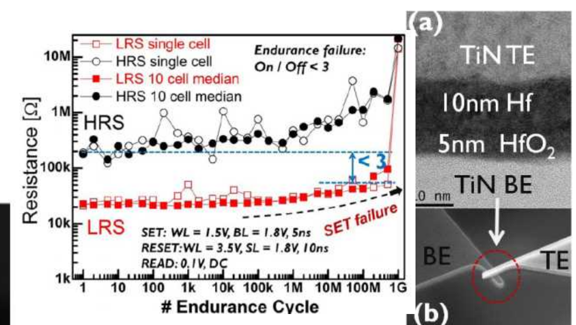
TiO_2

Kwon *et al*. Nature Nanotechnol. 5, 148 (2010)



Ta_2O_{5-x}

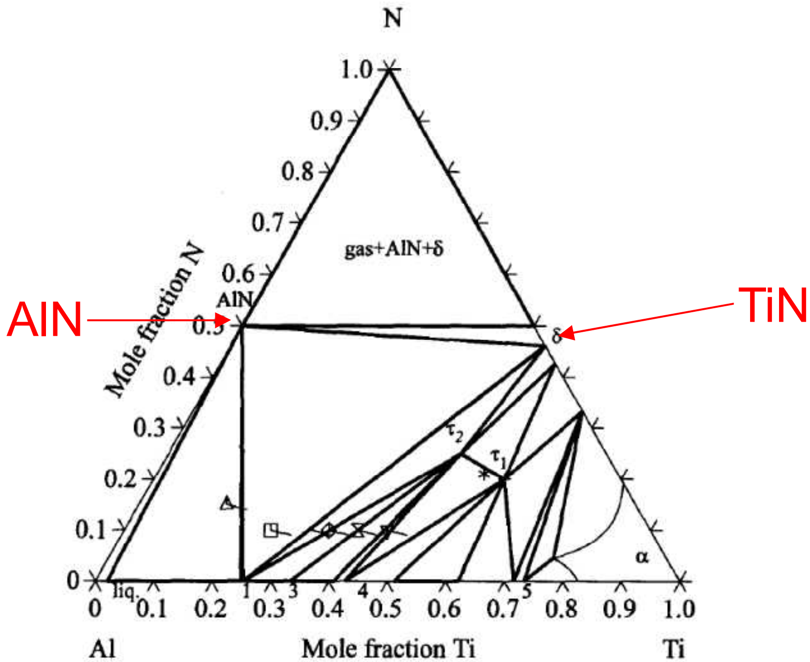
Lee *et al*. Nature Mater. 10, 625 (2011)

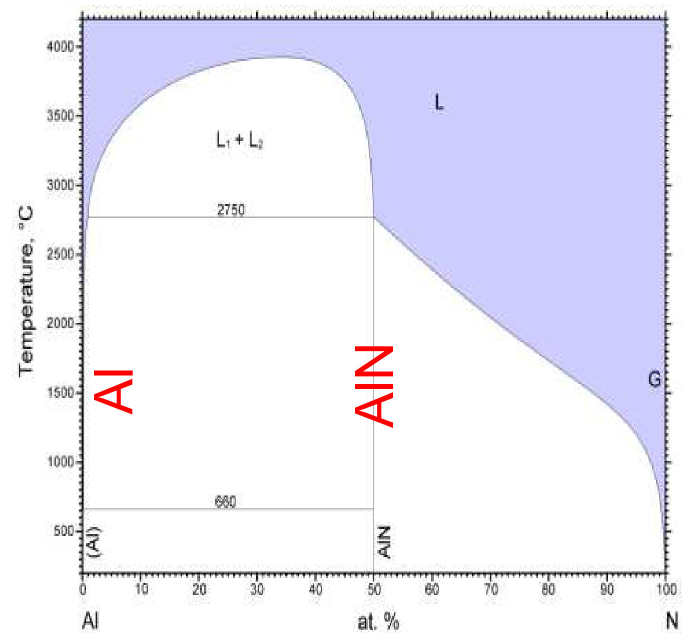


HfO_2

Chen *et al*. '2012 IEDM

Full - nitride memristor





TiN/AlN structure

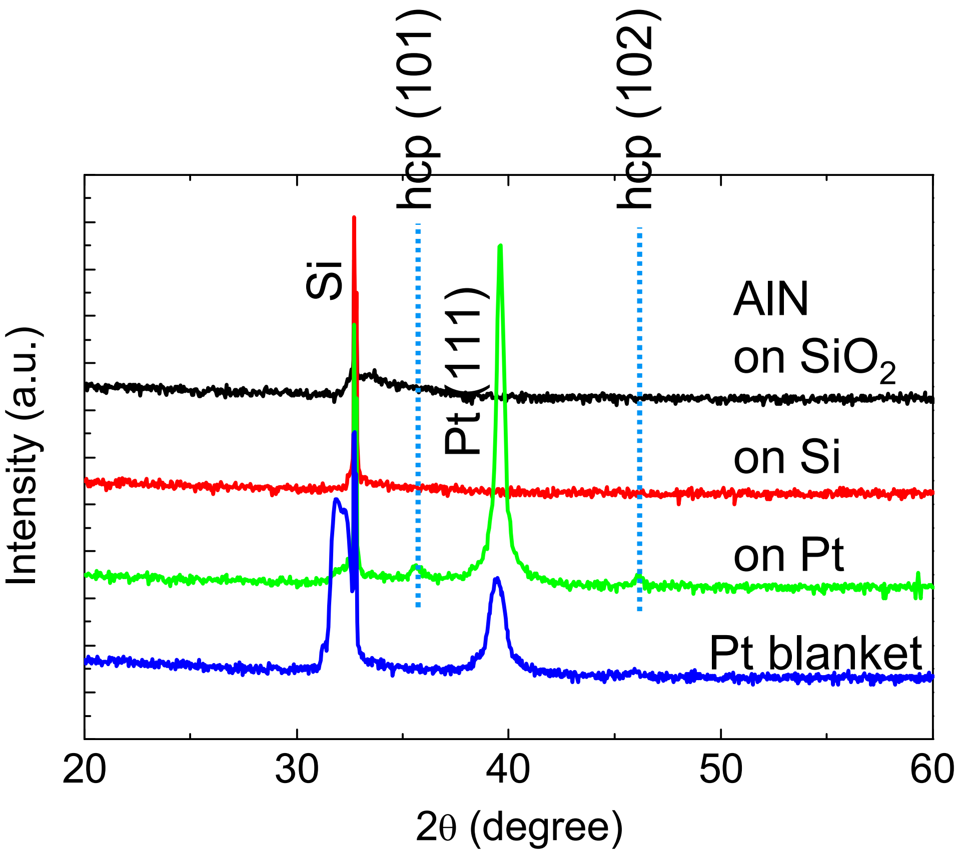
1) TiN: fab preferred material

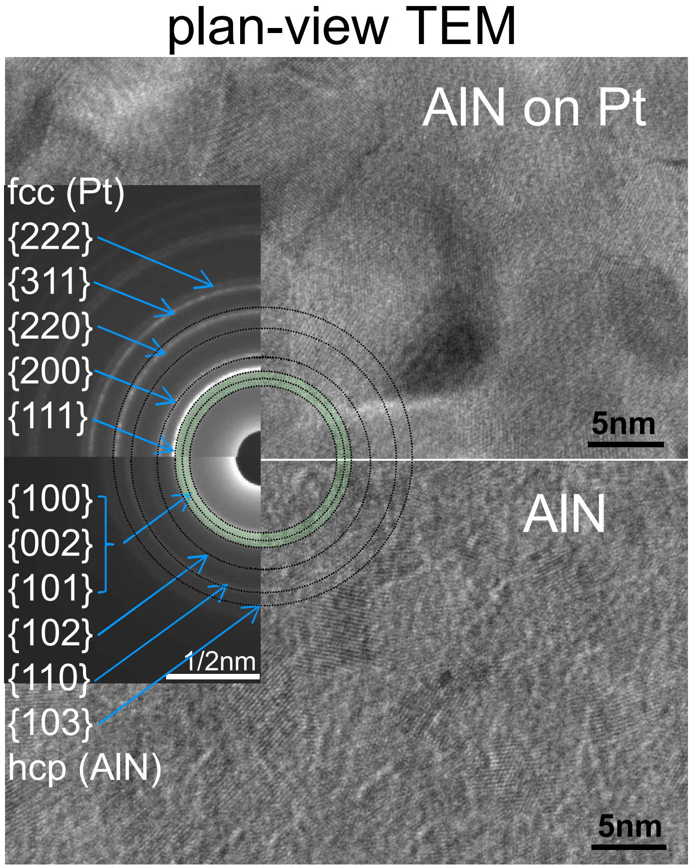
2) AlN and TiN: thermodynamic equilibrium between AlN and TiN

3) TiN: a large solubility of N → perfect electrode (serving as N reservoir)

4) AlN: only two stable solid phases →perfect switching material (a conducting phase + an insulting phase, same as Ta-O)

AlN film structure

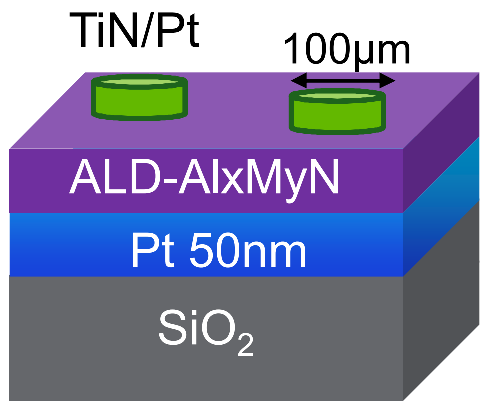


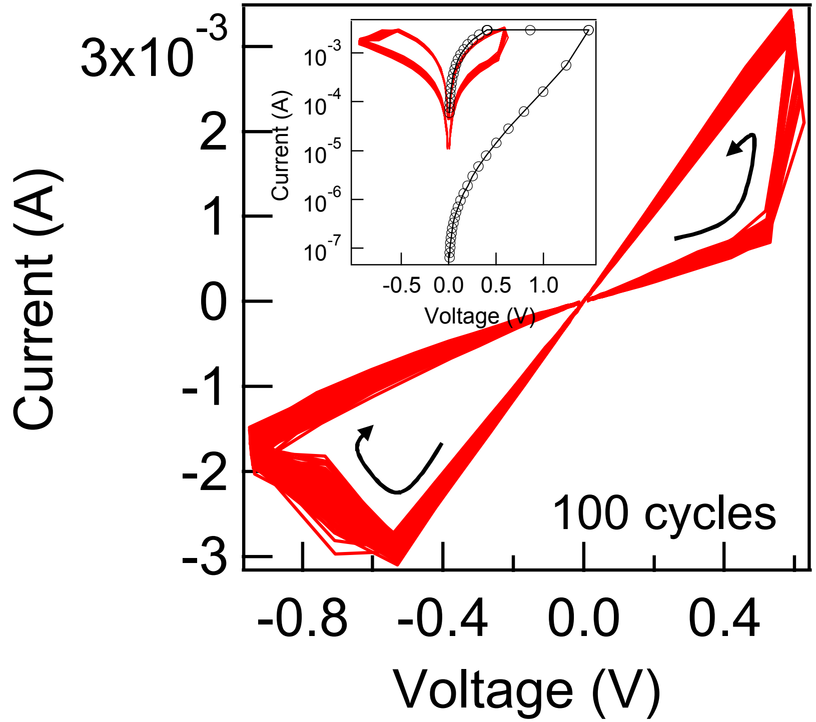


- XRD amorphous matrix
- Fine nano-crystalline (hexagonal AlN) phases

Application (1); alloying materials by ALD

AlxMyN

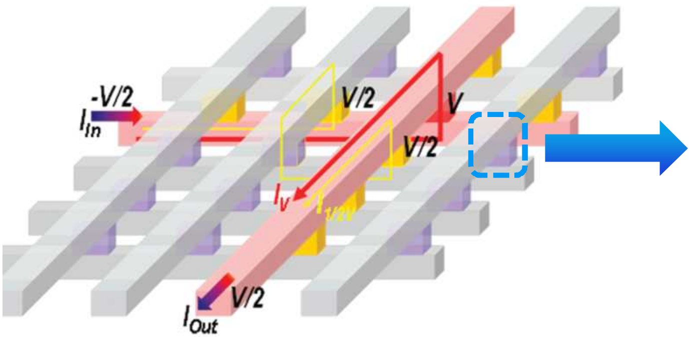


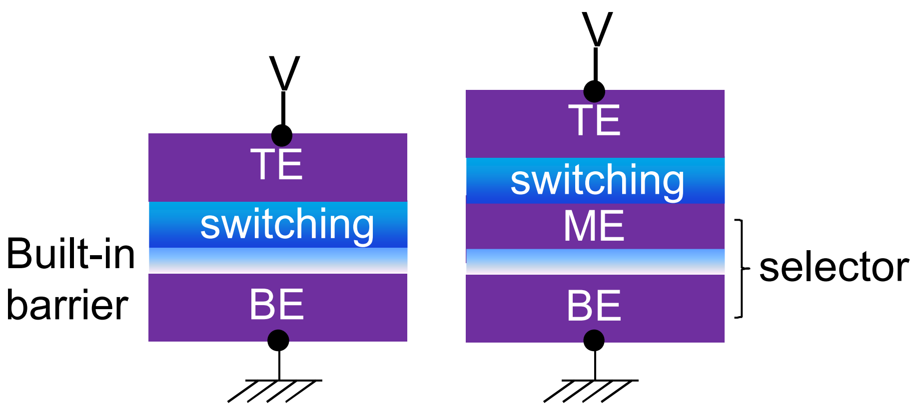


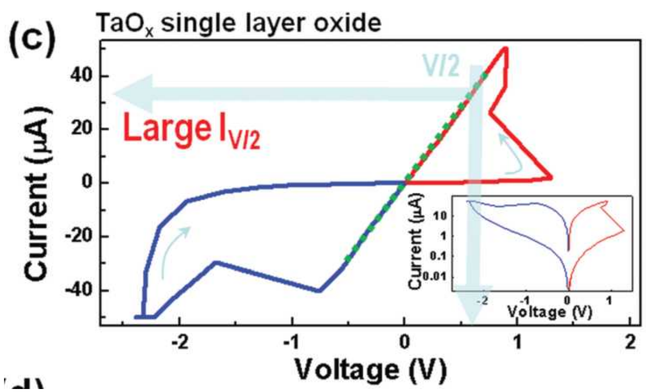
- Ternary nitride memristors implemented
- Low forming voltage and uniform switching

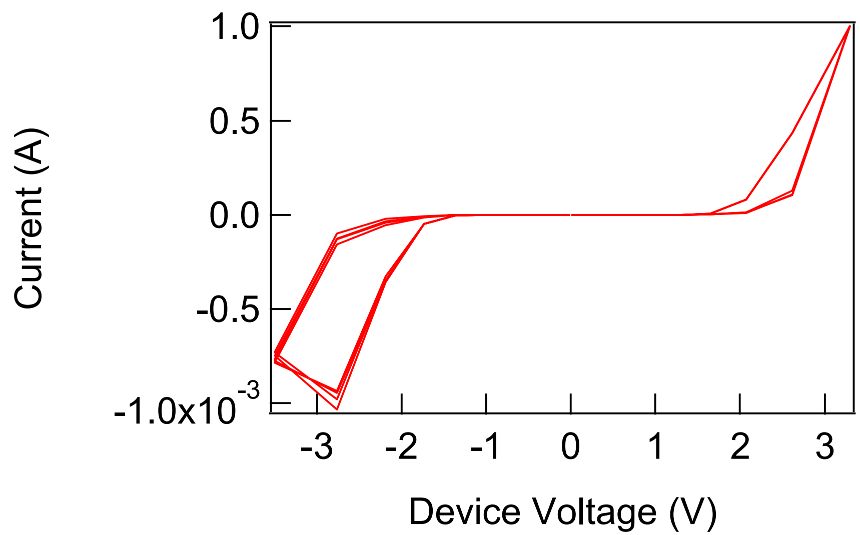
Application (2); tunnel barrier by ALD

Stacking of tunneling barrier and switching materials





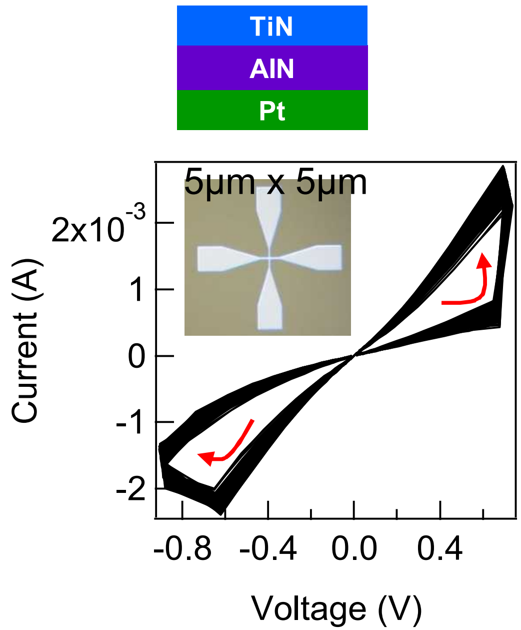


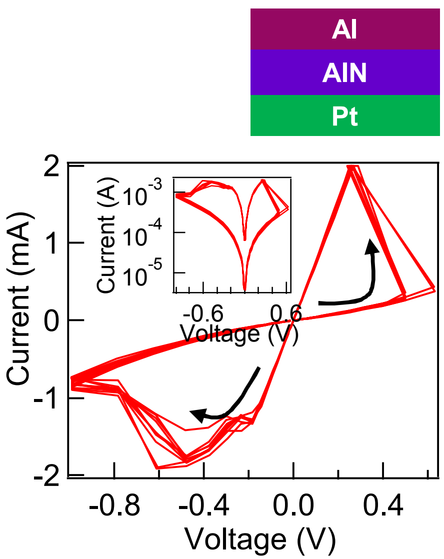


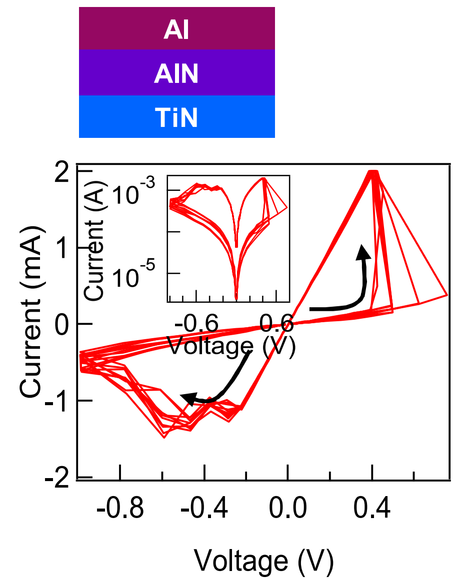
Yang *et al*. Appl. Phys. Lett. 100, 113501 (2012)

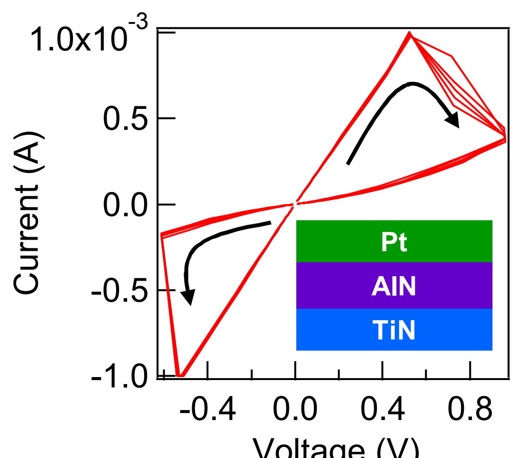
Switching mechanism: Switching polarity

Switchable interface?



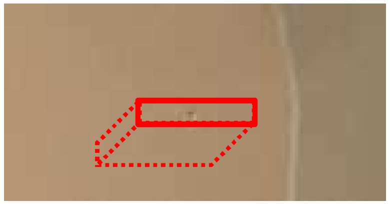


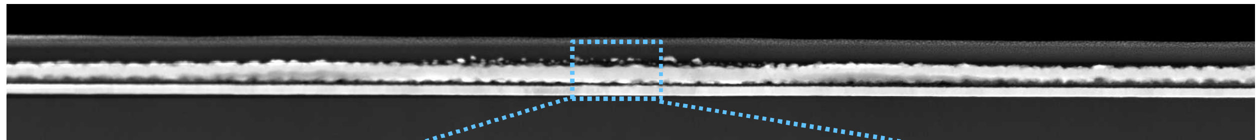




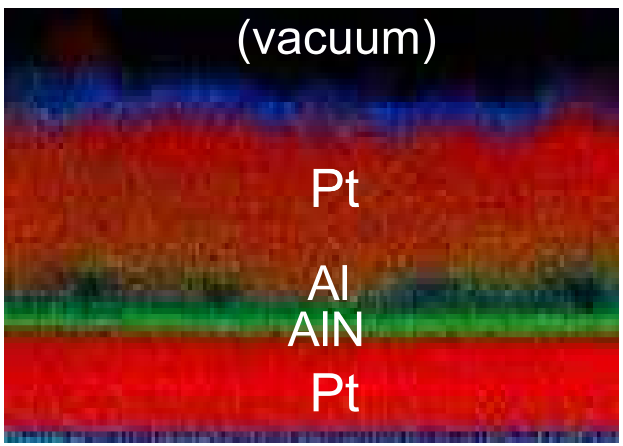
Questions:
Another oxide switch
or real nitride switch?!

Mechanism: Anatomy of conducting channel

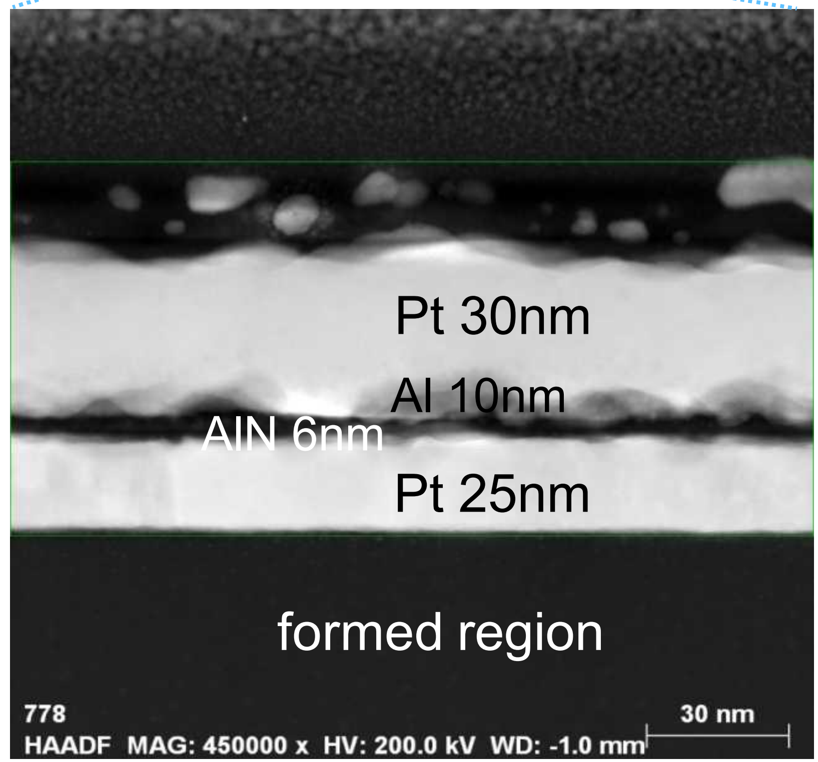




EDS analysis



- Effort for elucidating conducting filament



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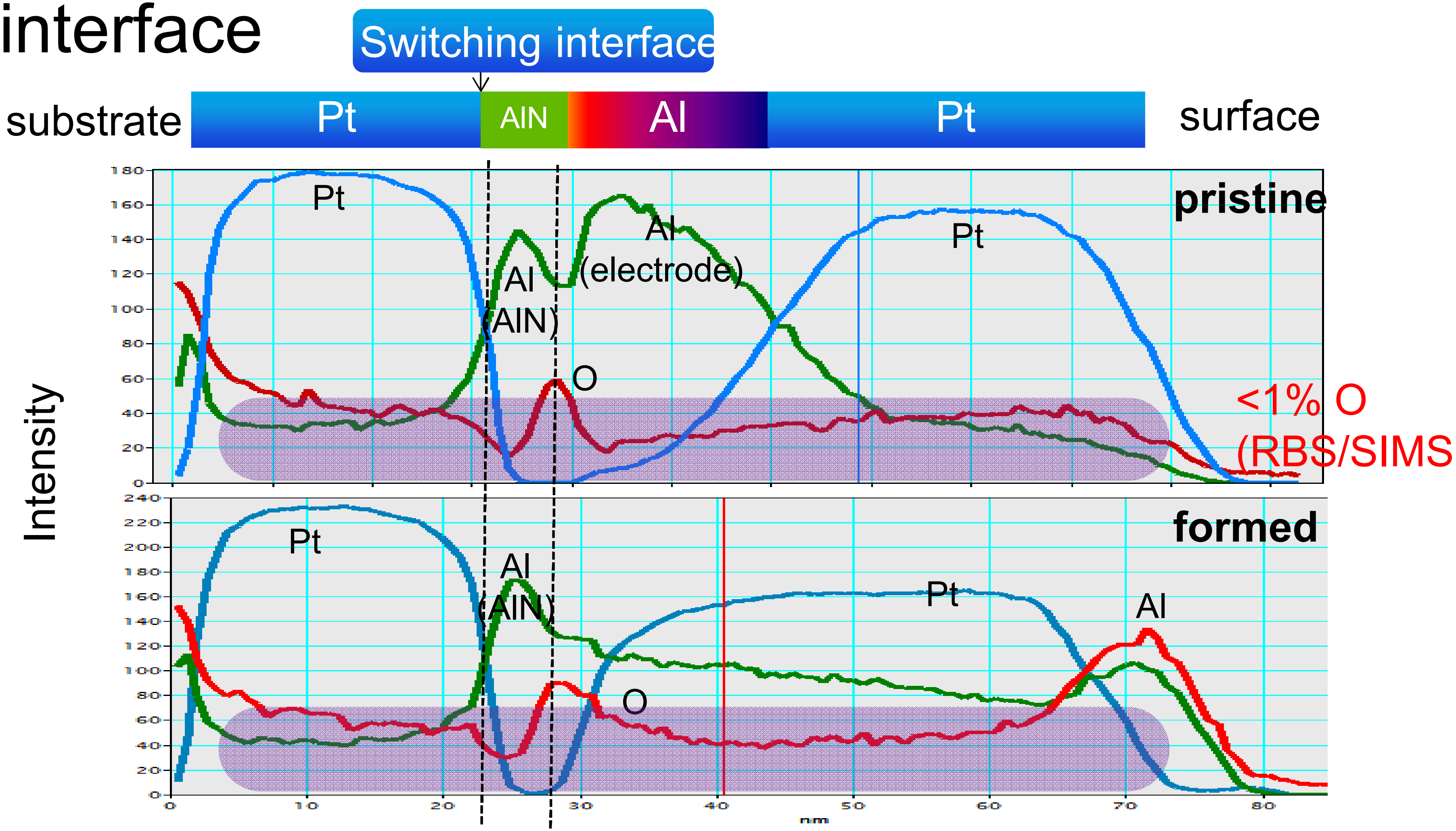
Switching mechanism: O-free switching interface



Red = Oxygen, Green = Al, Blue = Pt

- Strong heating
- The switching interface (Pt/AlN) remains O-free!
- Chemical changes? (Al(N) channel?) – on going