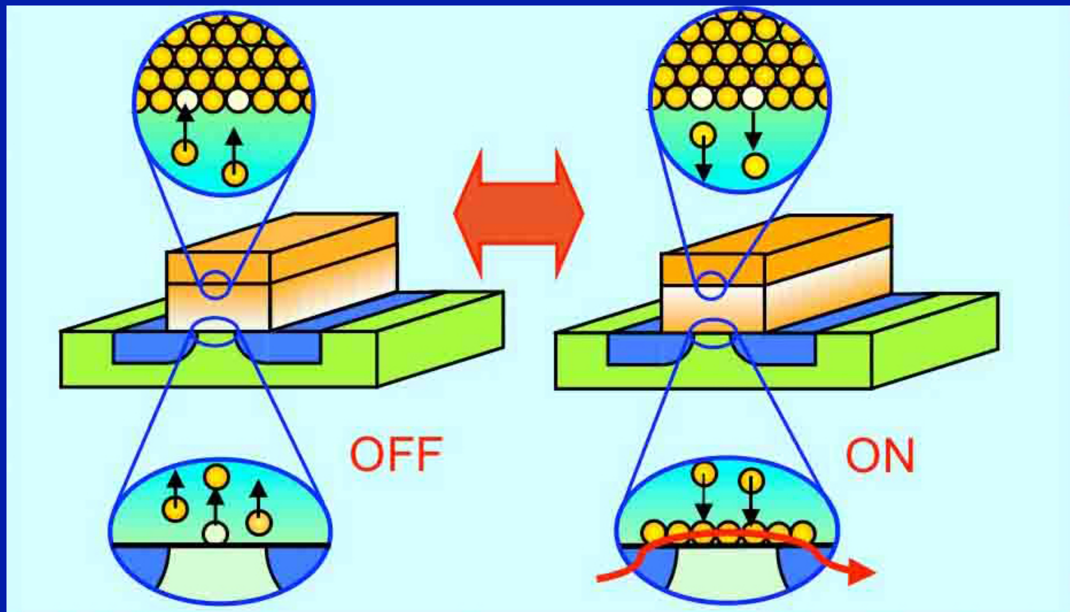
Atom/ion movement controlled three-terminal atomic switch, ‘Atom Transistor’



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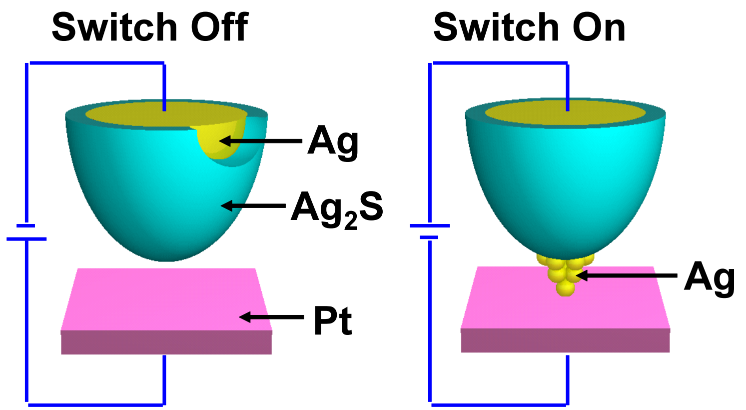
National Institute for Materials Science (NIMS)

Two-terminal atom movement controlled device: Atomic Switch

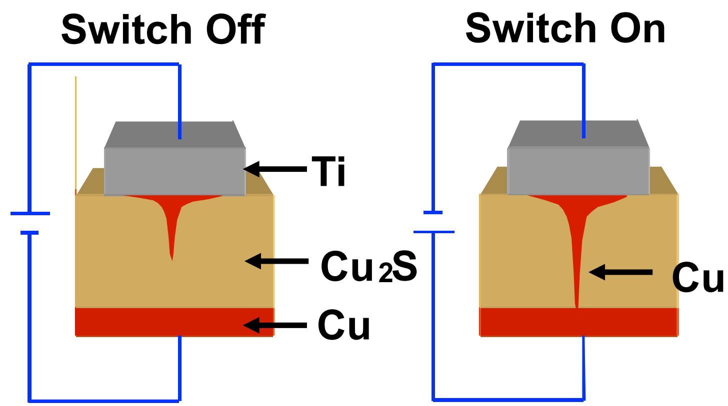
Metal filament formation and annihilation is controlled by solid-electrochemical reaction.

Metal cations are controlled.



Initial type of Atomic switch

K. Terabe et al., Riken Review *37* *(2001) 7.*

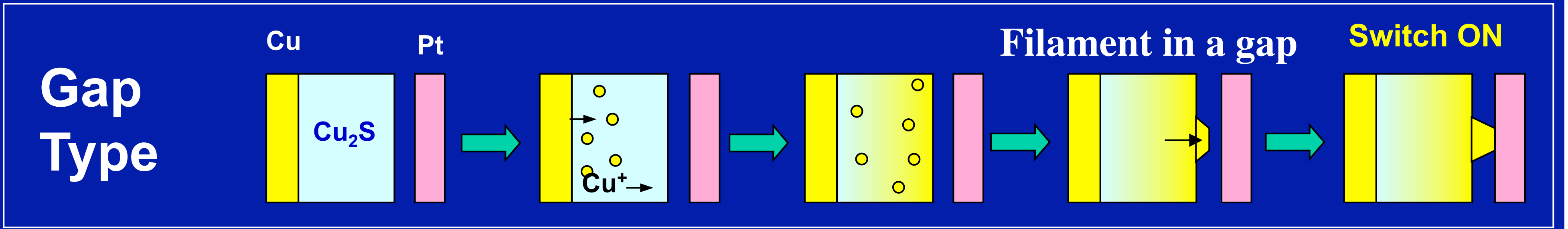


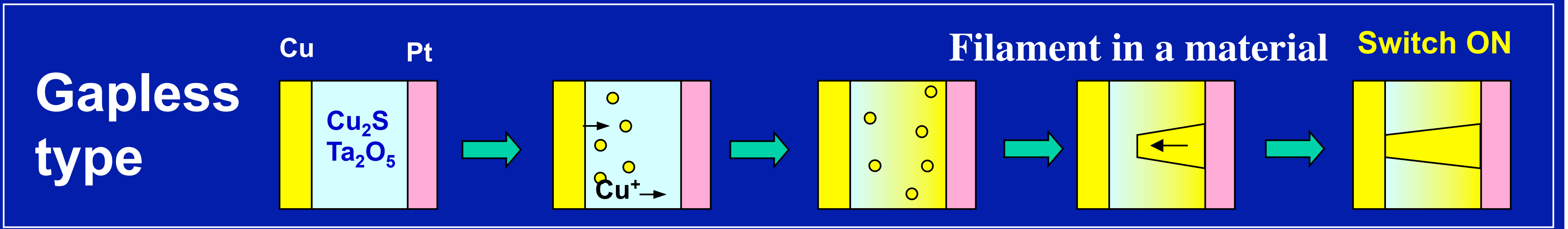
Gapless atomic switch (NanoBridge™)

T. Sakamoto et al., Appl. Phys. Lett. *82* *(2003) 3032.*

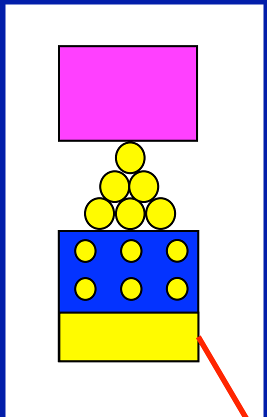
Operating mechanism of the atomic switches

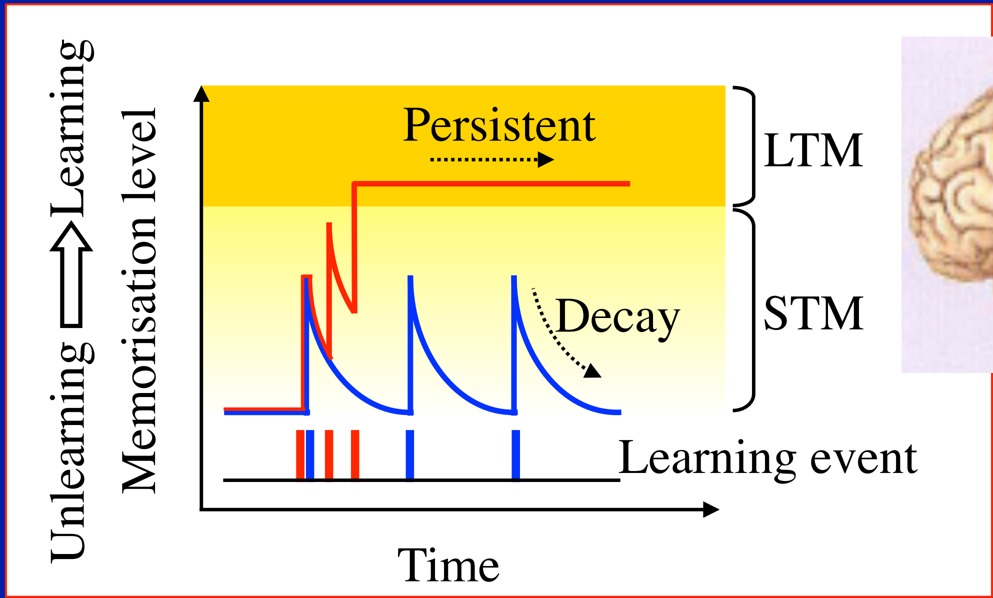
Diffusion of Metal Cations+Reduction/Oxidation
(Demonstrated by Ta_2O_5, Nb_2O_5, HfO, Ag_2S, Cu_2S, etc.)

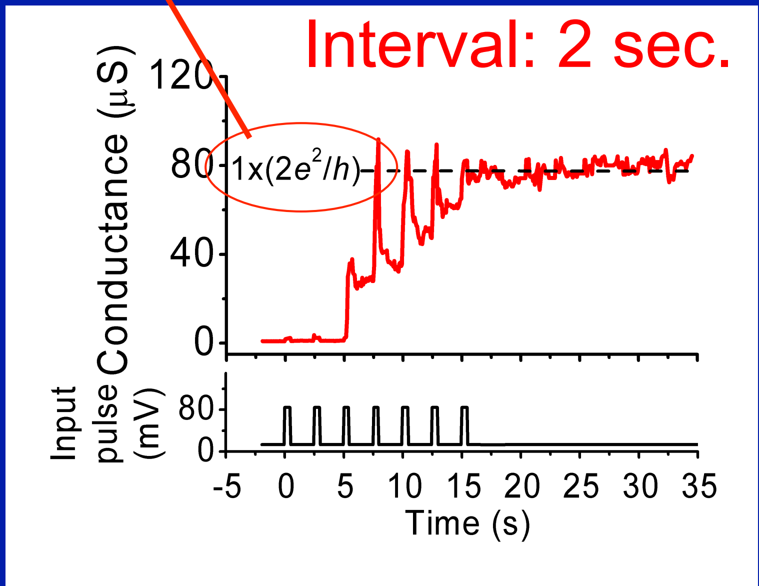


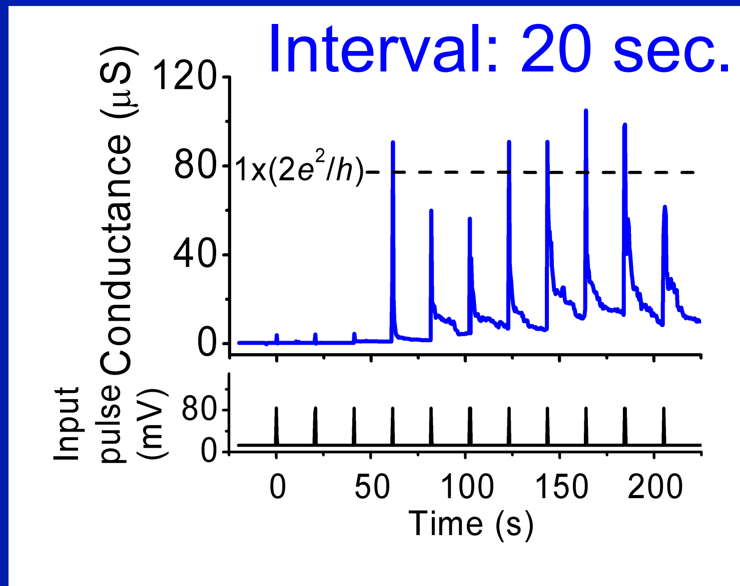


Learning Atomic Switch



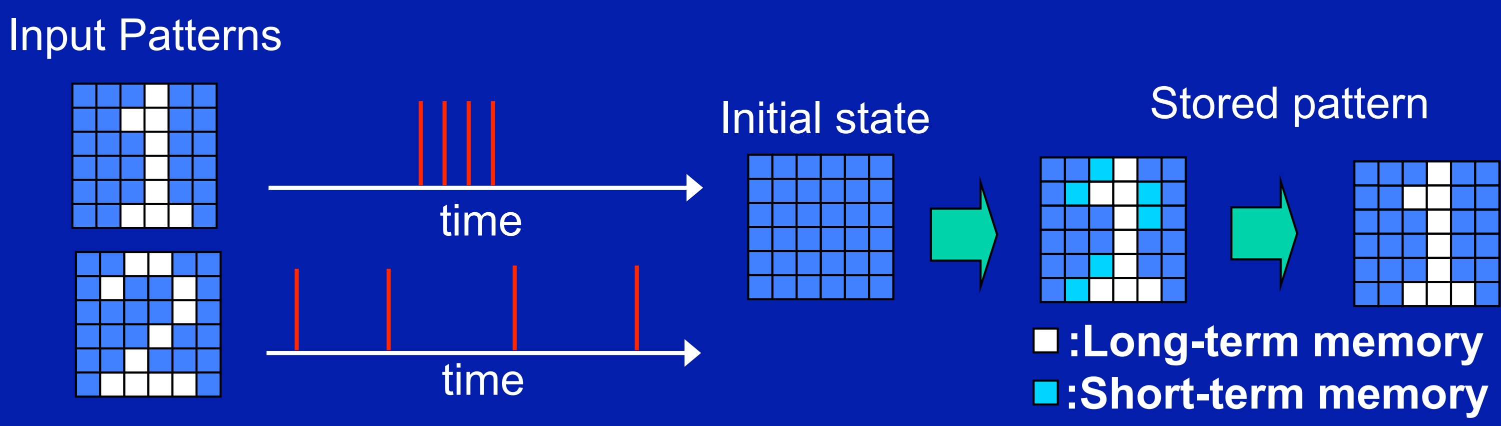


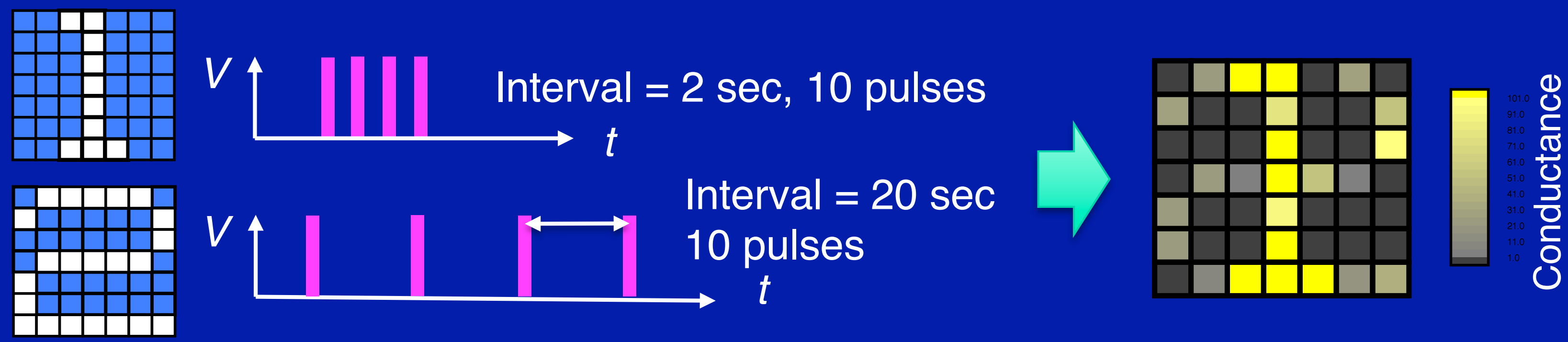




T. Ohno et al., Nature Mater., 10, 591-595 (2011).

STM-LTM based Memorization





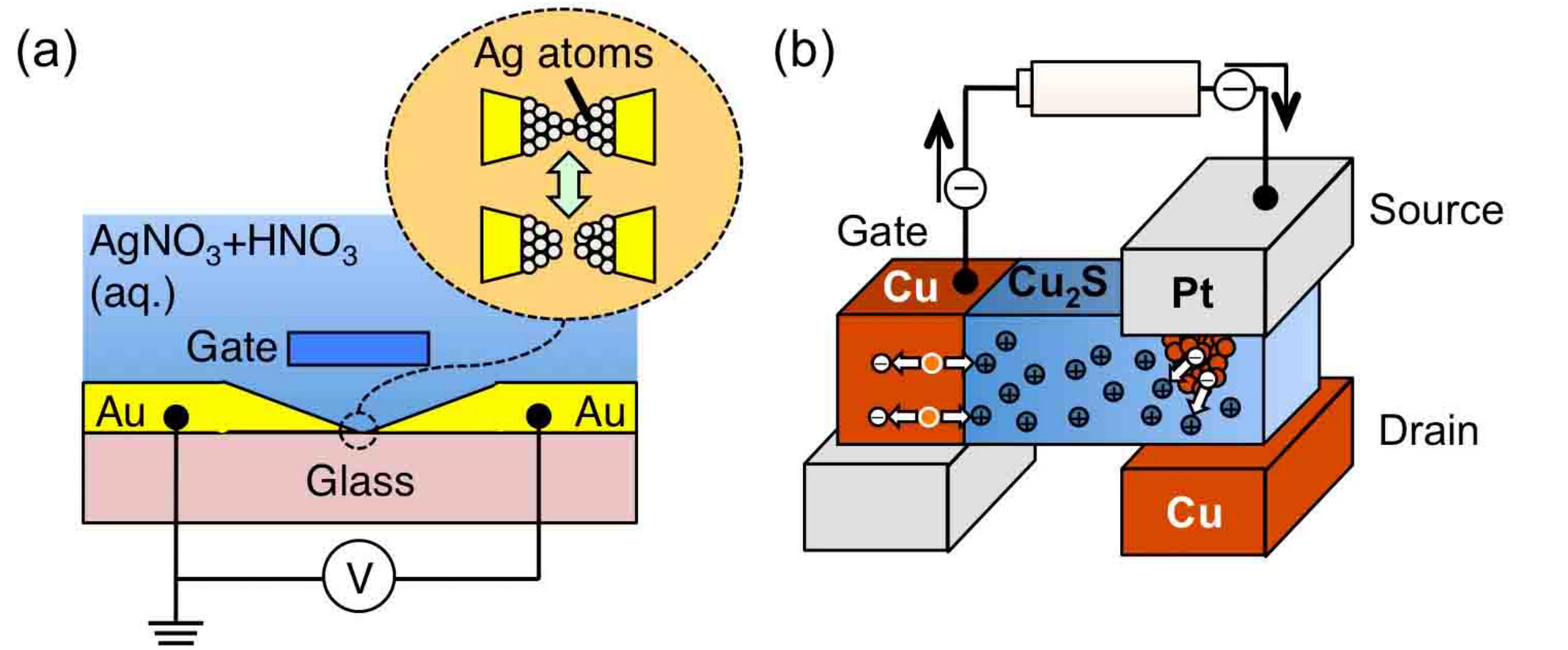
For Logic Application

Three-terminal devices are advantageous to two-terminal devices.

Nonvolatile three-terminal devices are key for low-energy computing systems.

Three-terminal switches controlling metal filament formation

Filament formation and annihilation are controlled such as in the two-terminal atomic switches

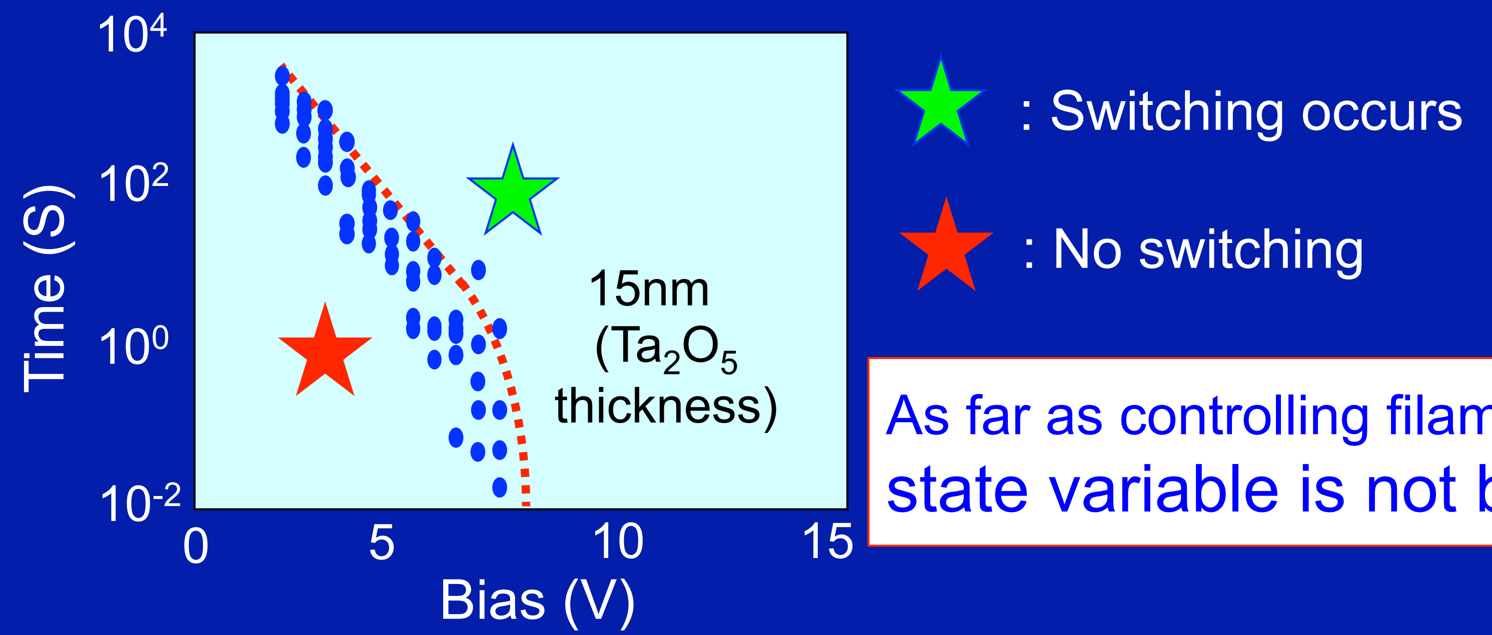


F-Q. Xie et al., Phys. Rev. lett., 93 (2004) 128303.

N. Banno et al., IEICE Trans. Electro., E89-C 11 (2006) 1492.

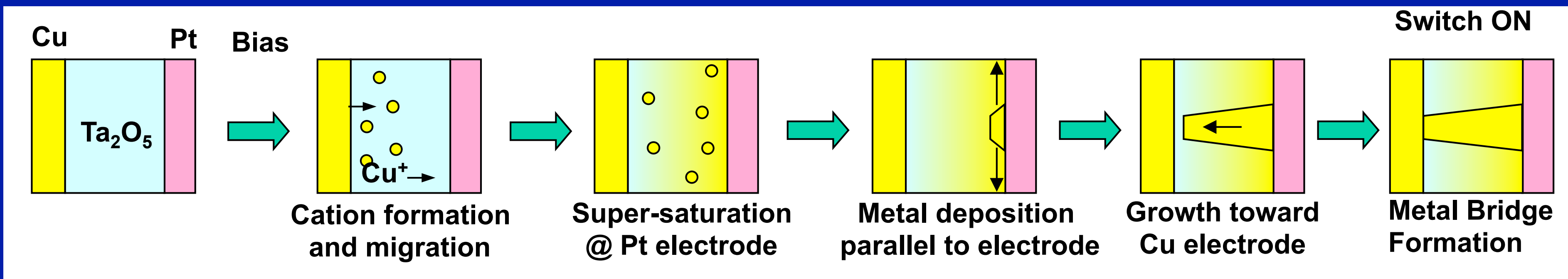
Switching time vs. Switching bias

switching time in the forming process of
$Cu/Ta_2O_5/Pt$ gapless atomic switch



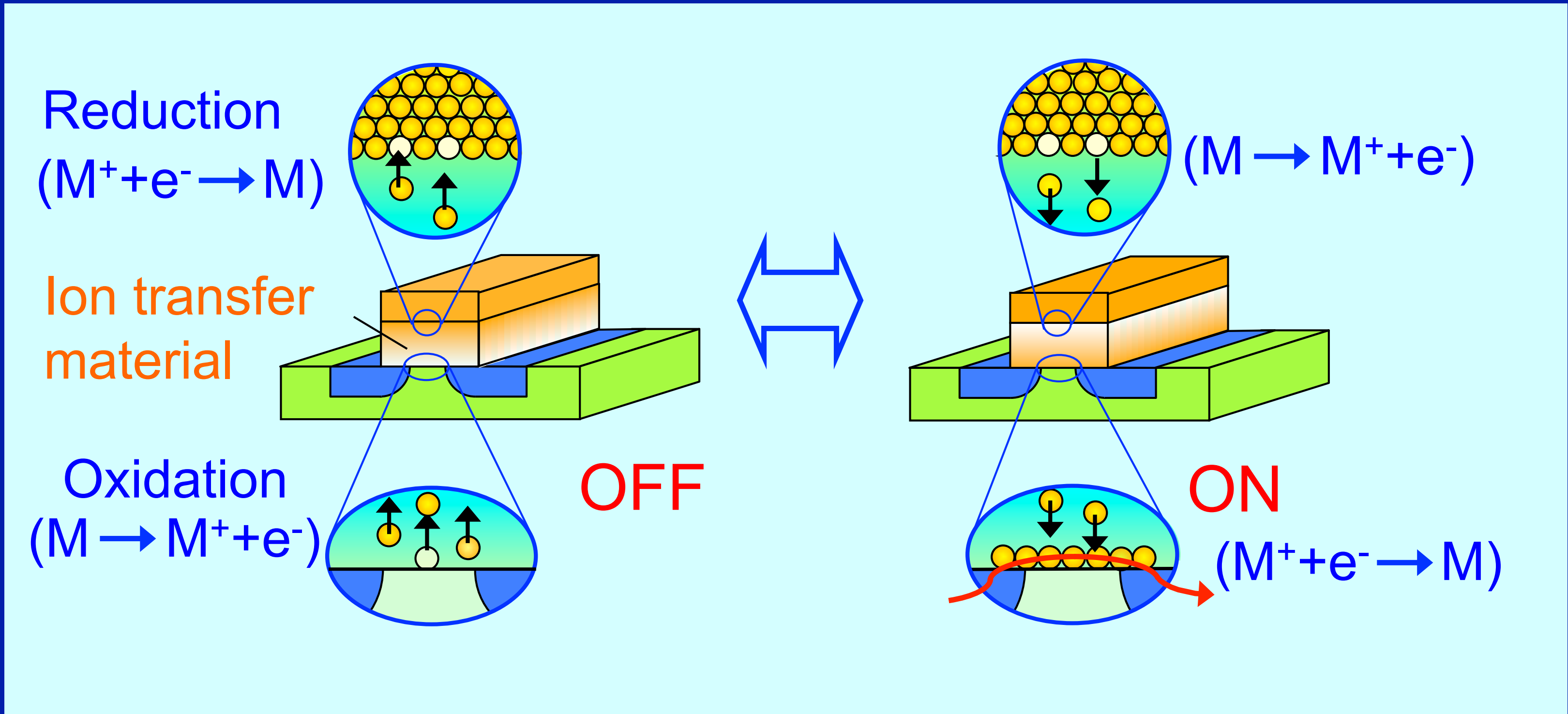
As far as controlling filament growth,
state variable is not bias voltage.

T. Tsuruoka et al., Nanotechnol., 21 (2010) 425205.



Atom Transistor

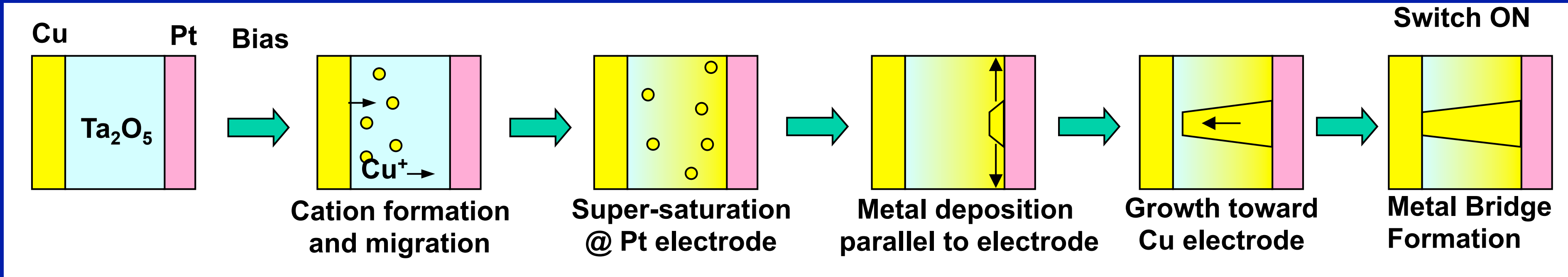
3-terminal atomic switch



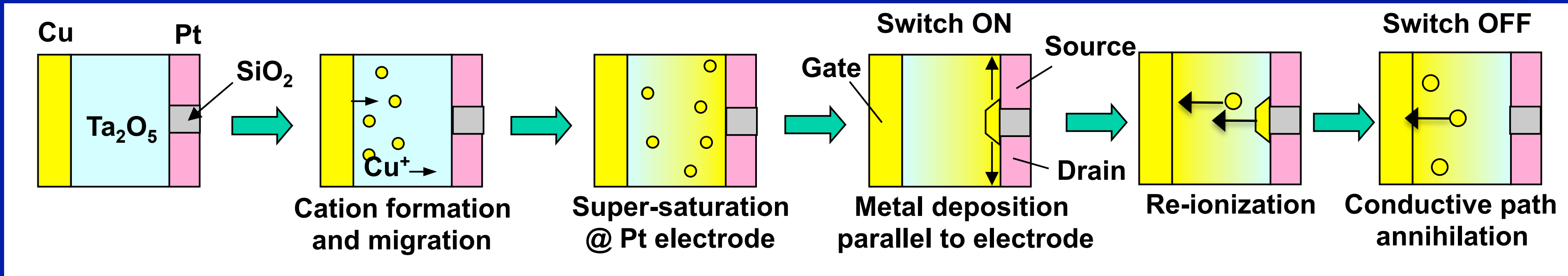
T. Hasegawa et al., APEX 4, 015204 (2011).

Metal cations brought to the channel region make a conductive path. Reduction to metal atoms is the origin for the nonvolatility.

Operating mechanism of Atom Transistor



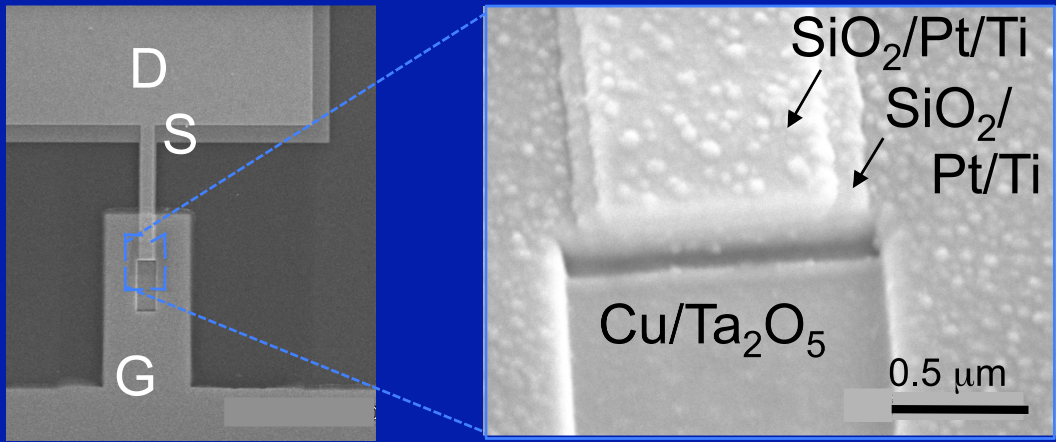
State variable can be bias



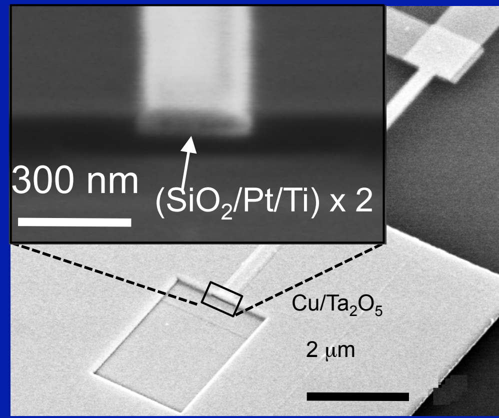
Super-saturation induced conductive path formation.

T. Hasegawa et al., APEX, 4 (2011) 015204.

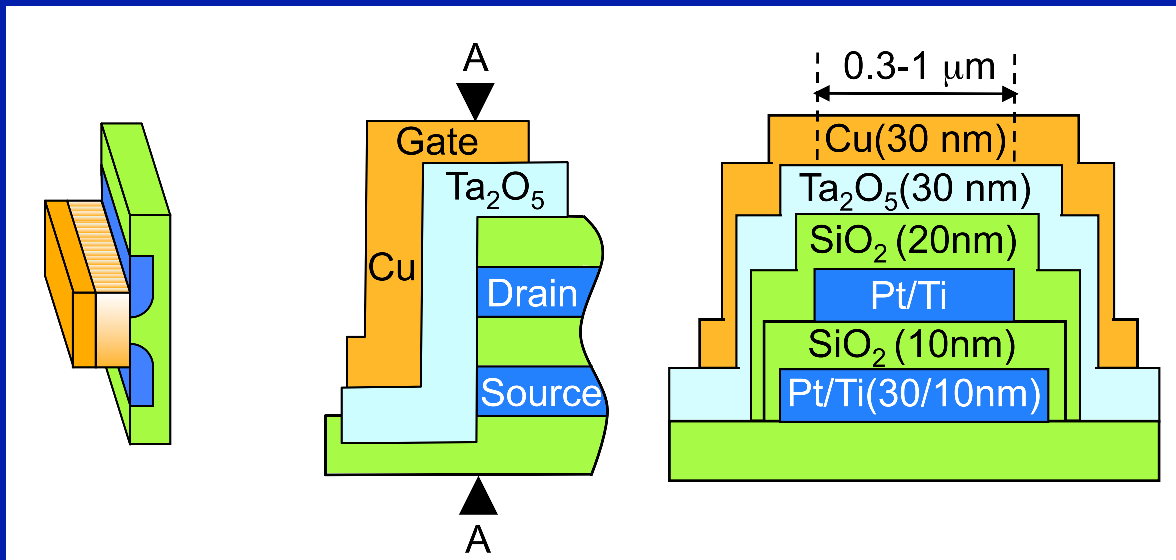
Prototype of the Atom Transistor



SEM images of the Atom Transistor

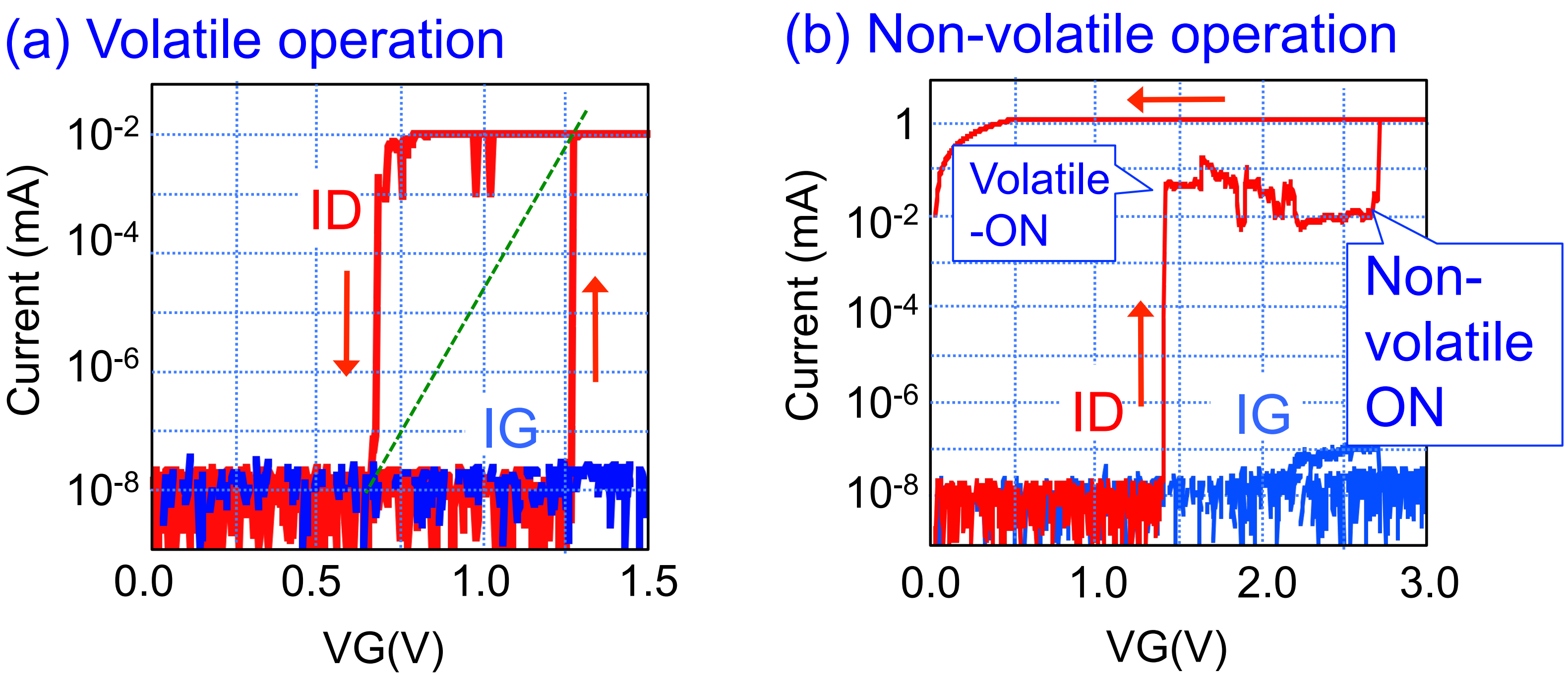


After the side-wall formation



Schematic illustration of Atom Transistor and its cross-sections.

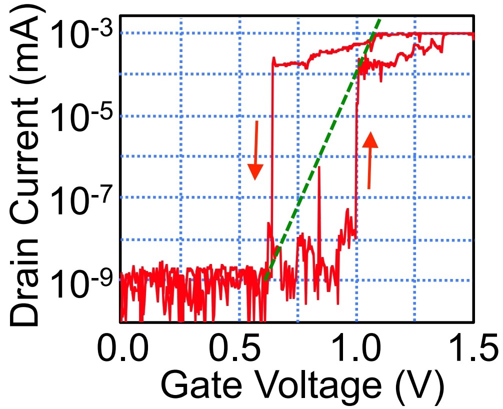
Operating results of $Cu/Ta_2O_5/Pt$,Pt Atom Transistor

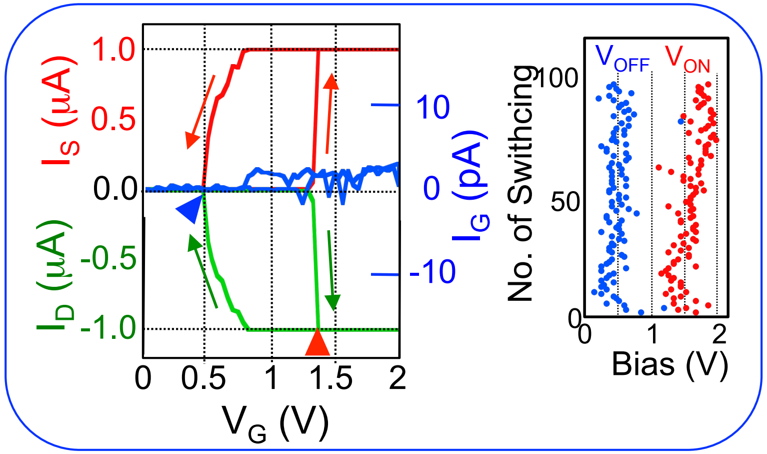


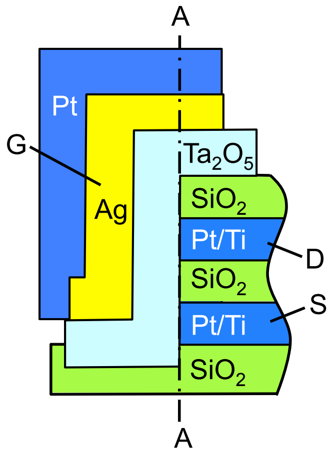
- Volatile and non-volatile operations depending on the gate bias range
- I_G remains small both in the volatile and non-volatile operations.
- High ON/OFF ratios, 10^6 for volatile and 10^8 for nonvolatile operations.

Operating results of $Ag/Ta_2O_5/Pt$,Pt Atom Transistor

Volatile operations（ON/OFF ratio：10^6)

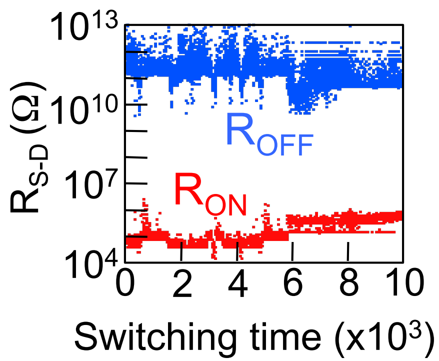




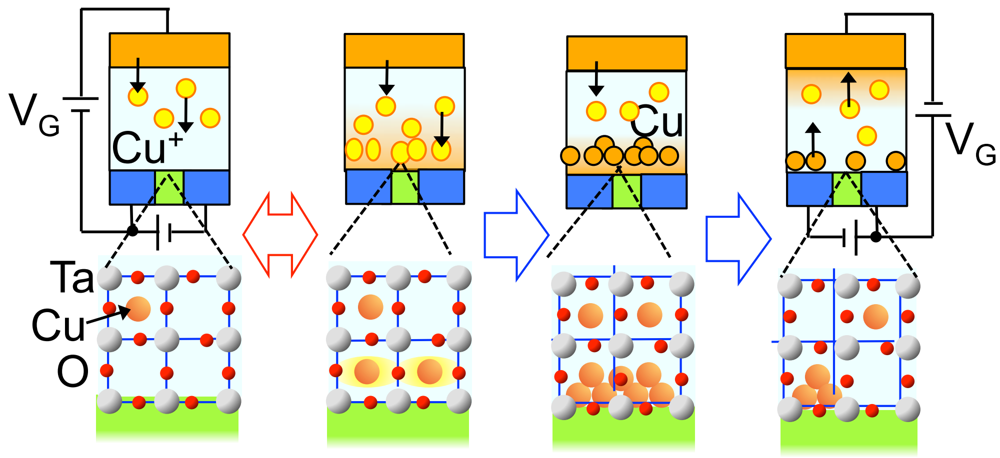


Pt(35 nm)
/Ag(2～3 nm)
/Ta_2O_5(20 nm)
/Pt(30 nm)/Ti
/SiO_2(10 nm)
/Pt(30 nm)/Ti

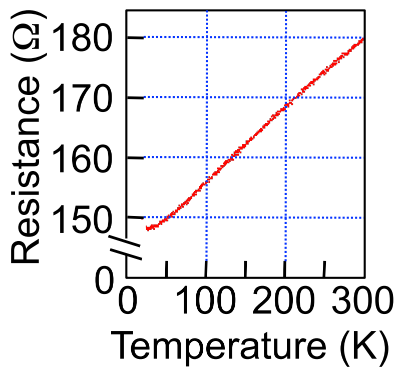
cyclic endurance test



What is the operating mechanism for the volatile and non-volatile operations?



Temp. dependence of nonvolatile R_{ON}



Measured by I/V sweeping between ±1V

Conductive path should consist of metal atoms

Reduction/ionization of metal cations/atoms at the S-D electrodes should cause the non-volatile operation.

Summary

Atom transistor is an atom movement controlled three-terminal nanodevice. It shows volatile and non-volatile operations with very low power consumption.
It may achieve the downscaling further than 11 nm technology node.