A Ta_2O_5 Solid-Electrolyte Switch with Improved Reliability

TOSHI-TSUGU SAKAMOTO

Device Platforms Res. Labs.
& Nano Electronics Res. Labs., NEC Corp.

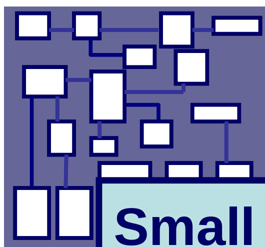
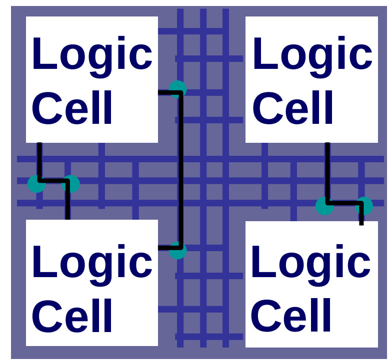
Trend of Nanotechnology 2008, Oviedo, Spain
3rd Sept, 2008

NEC

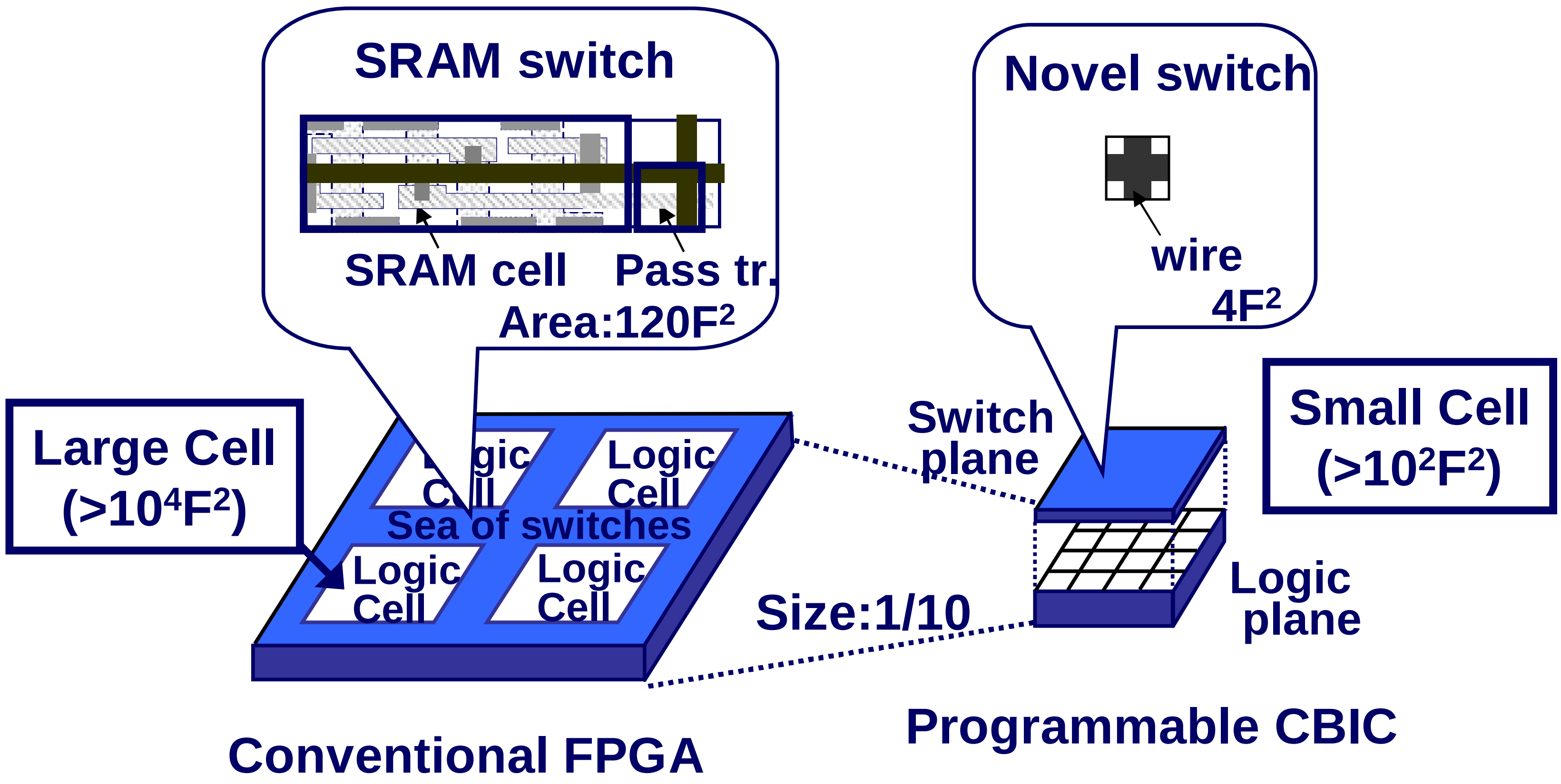
Outline

- **Introduction**
  - Background
  - FPGA with high performance (programmable CBIC)
  - Switching mechanism (Cu_2S-NanoBridge)
  - Issues: low switching voltage & poor reliability
- **Switching voltage**
  - Concept to increase switching voltage
  - Ta_2O_5-NanoBridge
  - Observation of conducting path
- **ON-state reliability**
  - Improved reliability by using Ta_2O_5
  - Formula for ON state reliability
  - Trade-off between Reliability & Switching current
- **Conclusion**

Background: two ASIC platforms

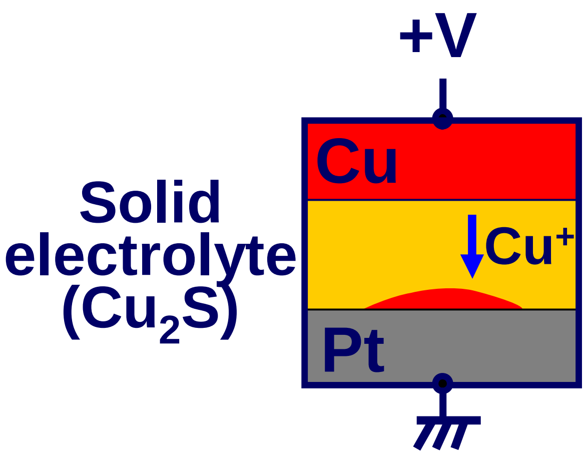
	CBIC **(Cell-based ASIC)**	**FPGA** **(Field Programmable Gate Array)**
Structure	**Fixed logic cells** **& interconnection**  **Small chip** **High performance**	**Reconfigurable logic cells** **& interconnection**  **Large chip** **Fair performance**
Production flow	**Circuit design (HDL)** **Layout (CAD)** **Mask production** **Si chip production**	**Circuit design (HDL)** **Buy FPGA and Program it!** **Short lead time** **Low initial cost**

Breakthrough in programmable switch



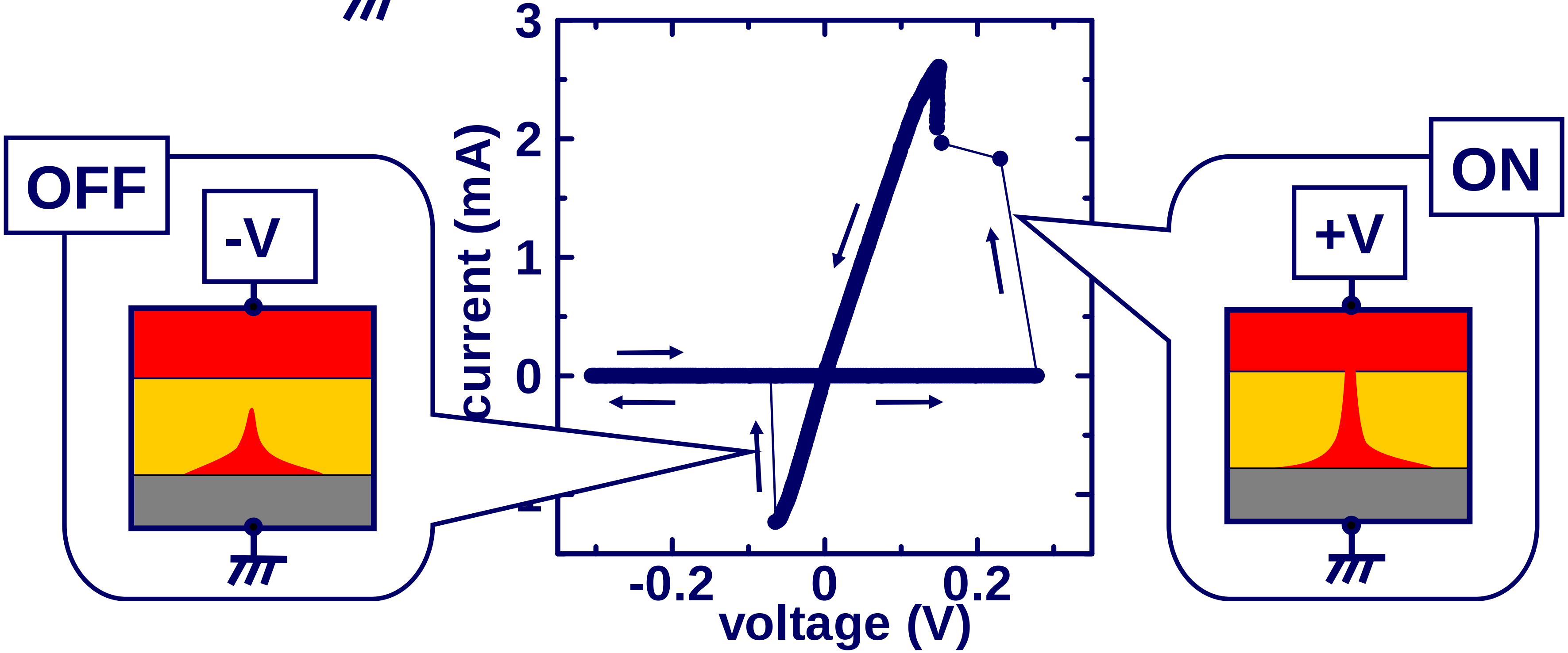
- Negligible switch area & small logic cell
- Low chip cost, high performance

Solid electrolyte switch (“NanoBridge”)

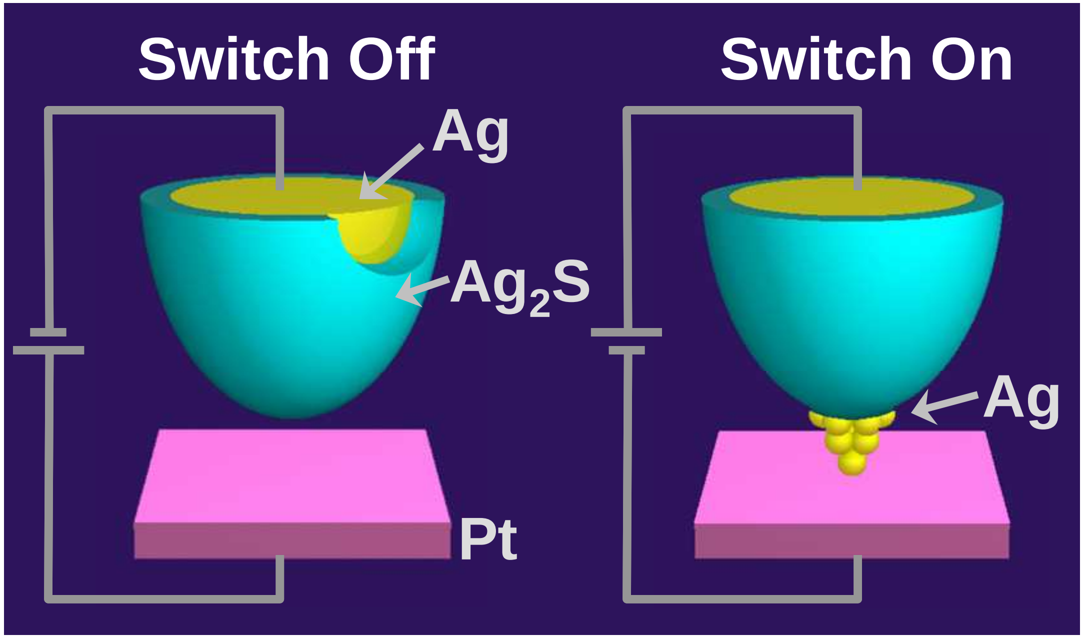


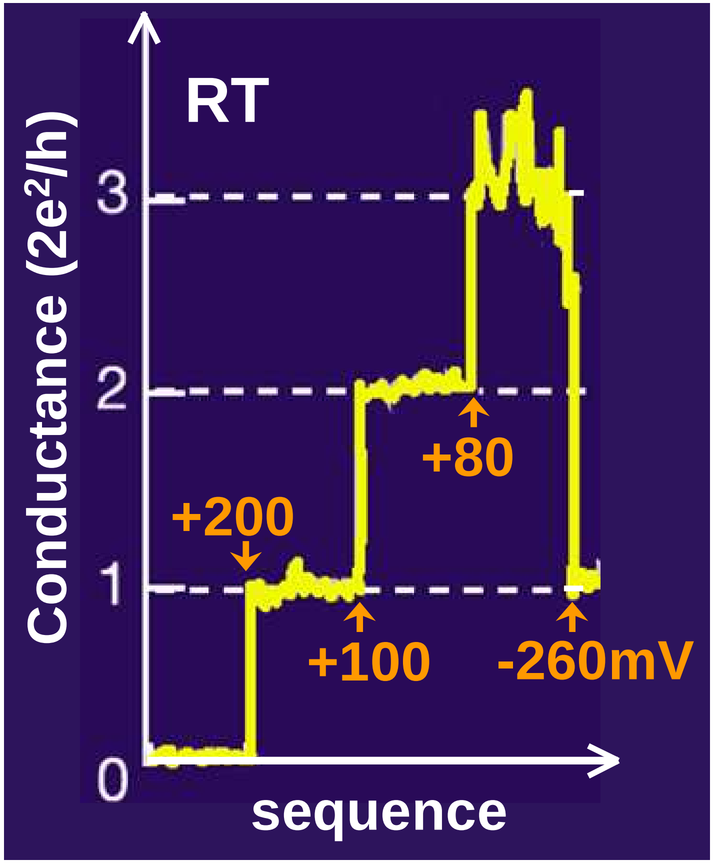
Solid electrolyte: Ionic conductor

ex. Cu_2S, Ag_2S, AgGeSe, …



…based on Atomic Switch (NIMS)



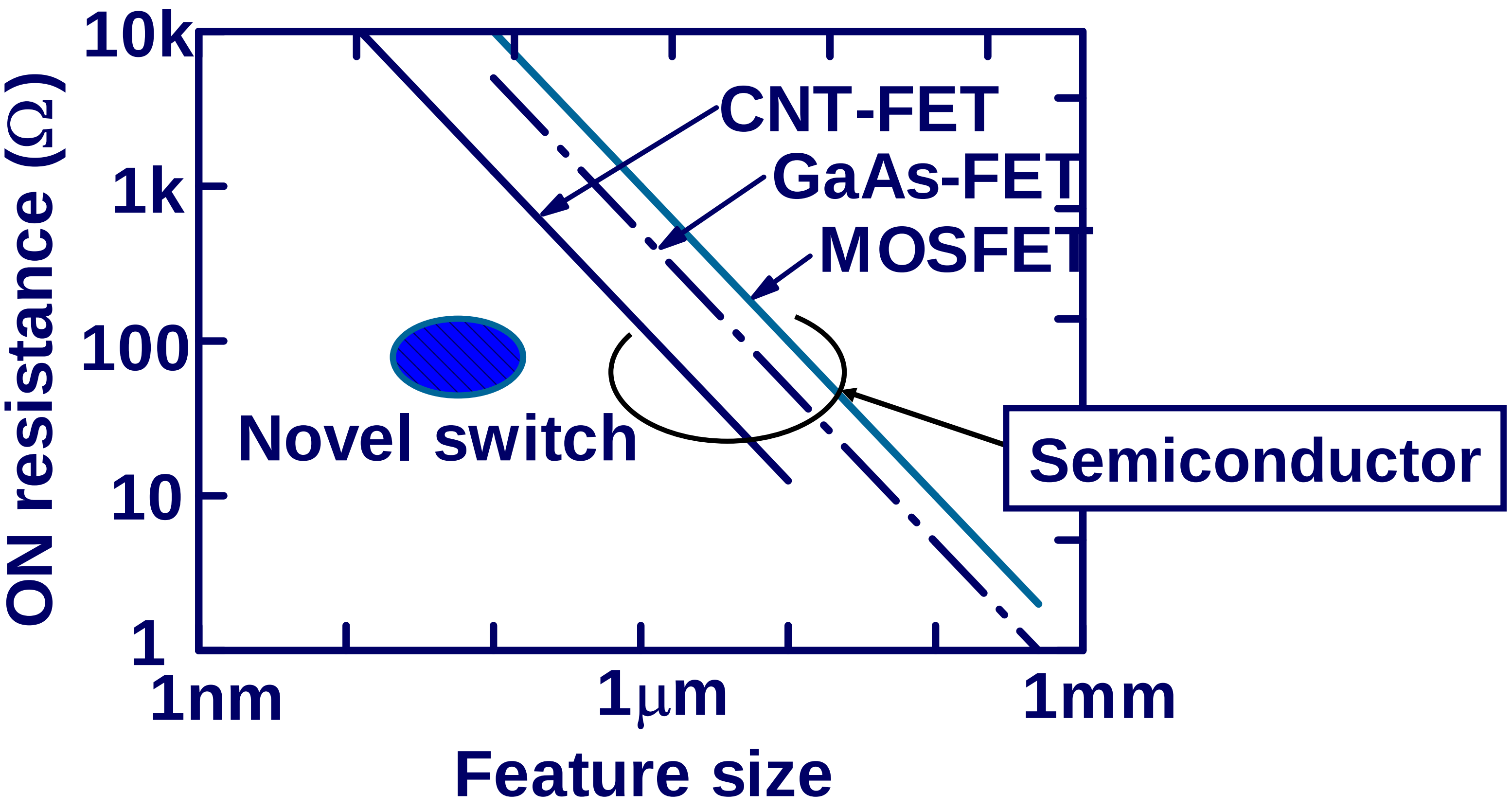


- Ag atom precipitates when positive voltage is biased on Ag.
- Formation and annihilation of atomic bridge changes conductance in units of $2e^2/h$.

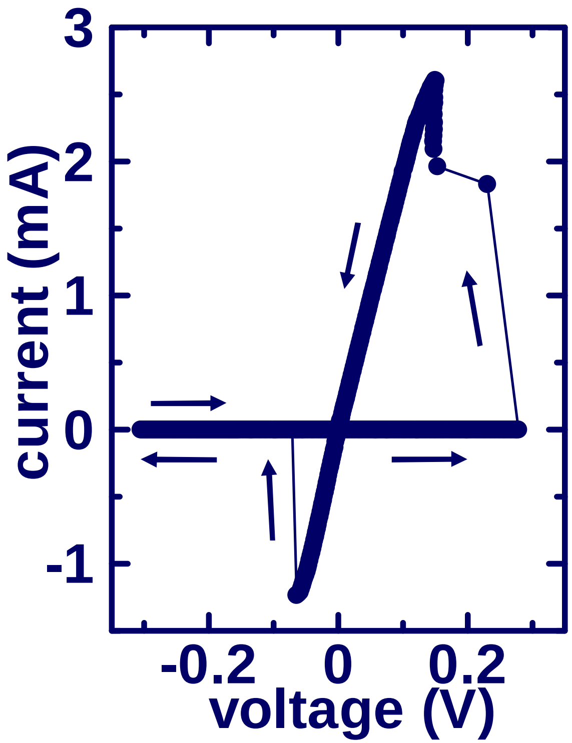
K.Terabe, et al., Nature 433, 47 (2005)

Features of solid-electrolyte switch

- Low ON resistance : metallic bridge
- Small : thin bridge (<30nm)
- Simple structure ($4F^2$)



Features of Cu_2S solid-electrolyte switch



Meet the demand for programmable logic?

Parameter	Cu_2S NanoBridge
ON resistance	OK (<100Ω)
Switch size	OK ($4F^2$)
Switching speed	OK (<10μsec)
Cycling endurance	OK (10^3–10^5)
Turn-on voltage	NG (~0.2V)
Retention	NG (<3month)
Process compatible	NG
Switching current	NG (>3mA)

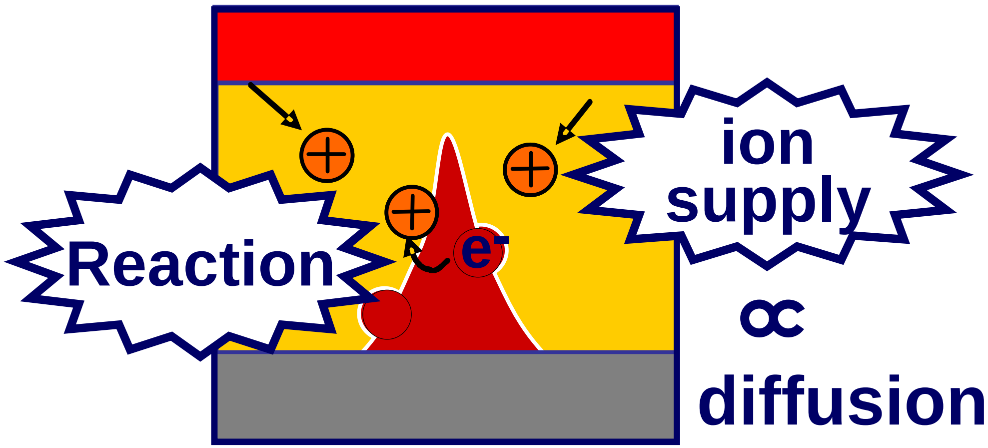
Breakthrough in Material (Ta_2O_5)

Outline

- **Introduction**
  - Background
  - FPGA with high performance (programmable CBIC)
  - Switching mechanism (Cu_2S-NanoBridge)
  - Issues: low switching voltage & poor reliability
- **Switching voltage**
  - Concept to increase switching voltage
  - Ta_2O_5-NanoBridge
  - Observation of conducting path
- **ON-state reliability**
  - Improved reliability by using Ta_2O_5
  - Formula for ON state reliability
  - Trade-off between Reliability & Switching current
- **Conclusion**

What determines switching voltage?

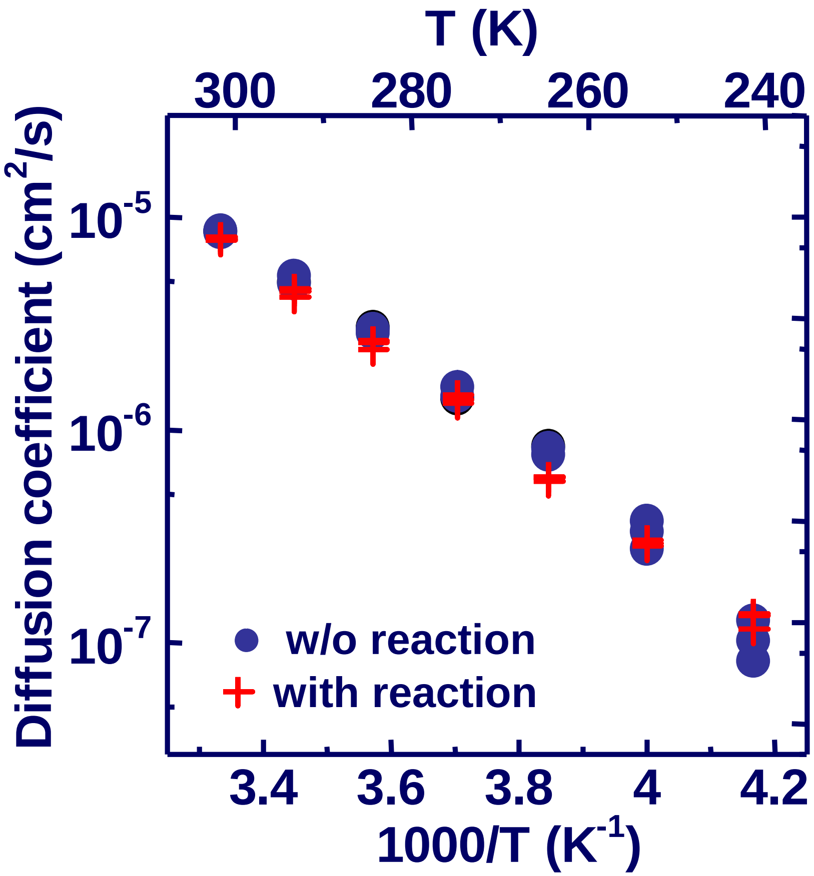
Cu^+ supply and chemical reaction are involved. Which determines switching voltage?



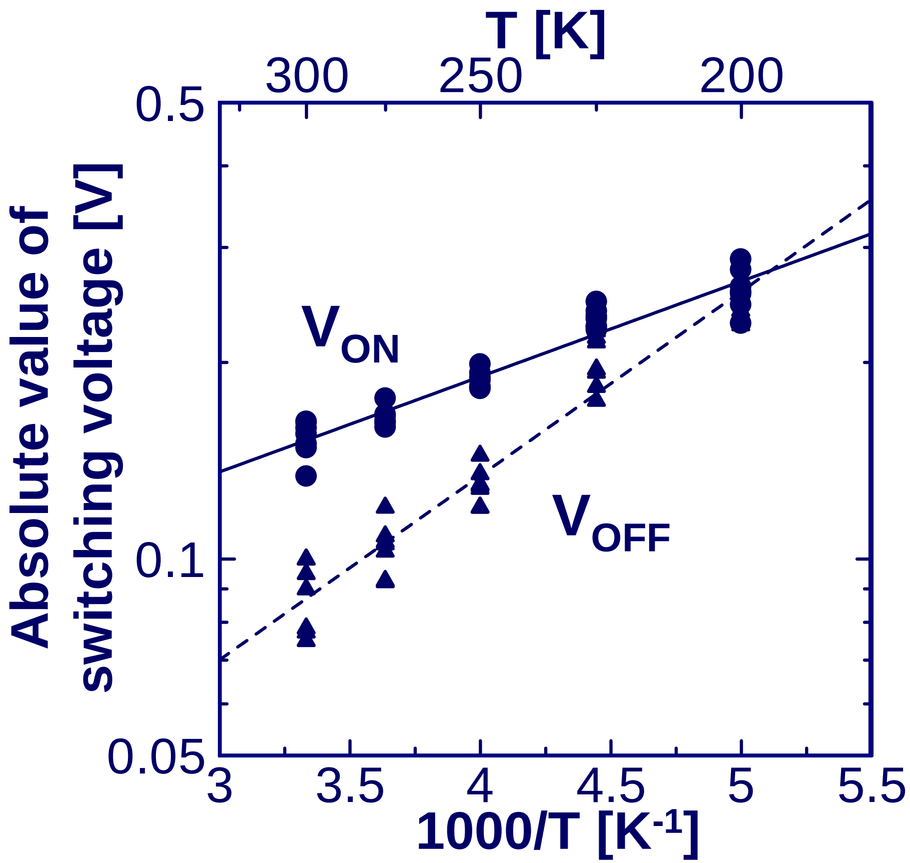
Cu-ion diffusion rate with chemical reaction vs. the rate without reaction.

T dep. of diffusion coefficient & switching voltage

Diffusion vs. Temp.

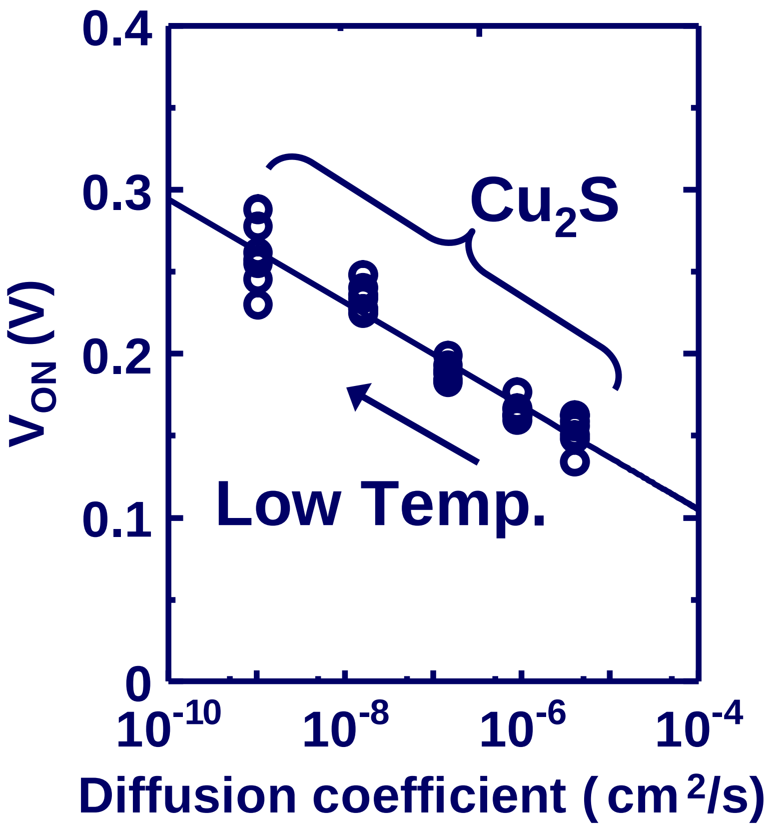


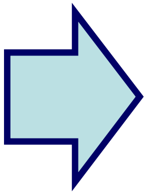
Switching voltage vs. Temp.

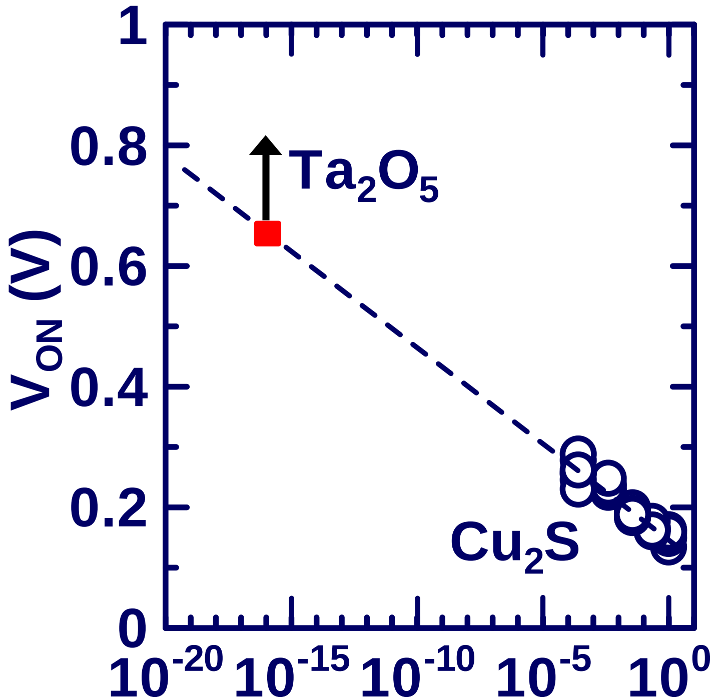


■ **Diffusion rate determines switching voltage.**

Concept to increase switching voltage



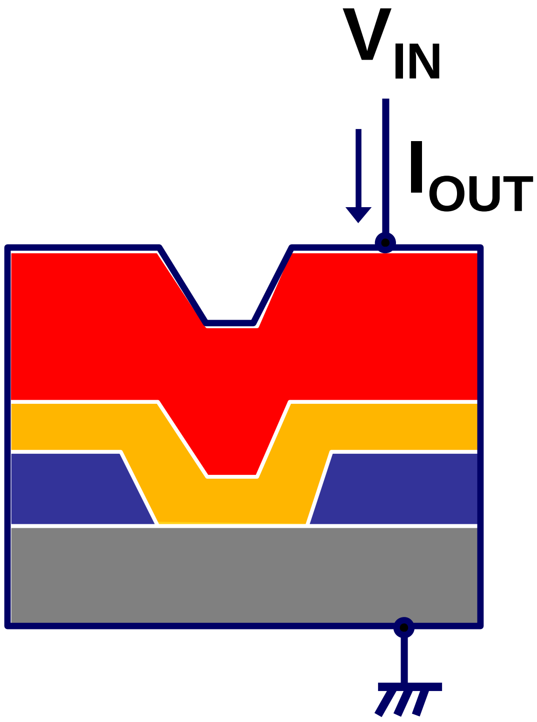


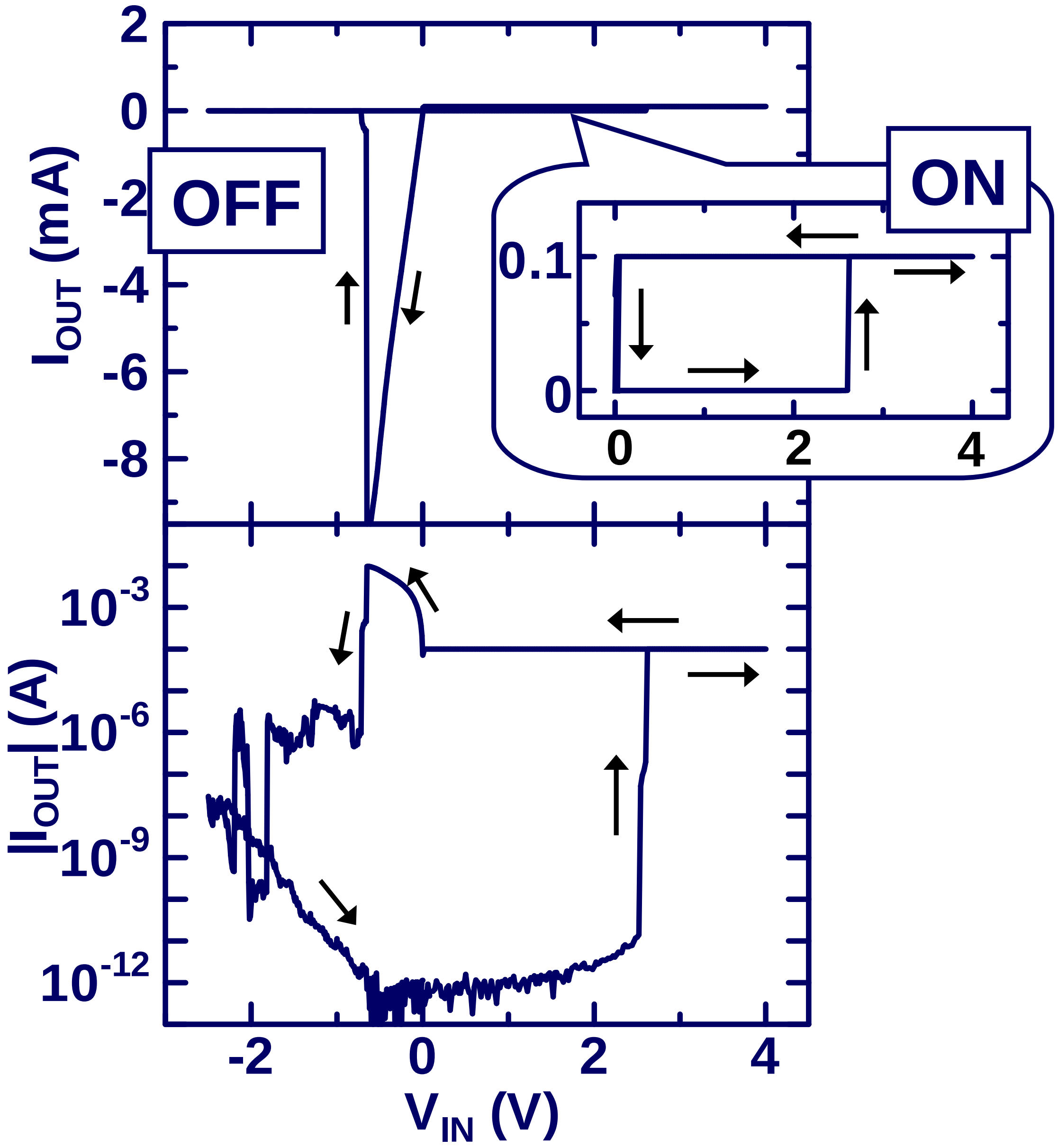


Cu^+ supply $\propto$ Cu^+ concentration X diffusion rate.

- Material with very low diffusion rate is needed.
- Ta_2O_5 : good compatibility with LSI process
- 0.65V or larger is expected for Ta_2O_5.

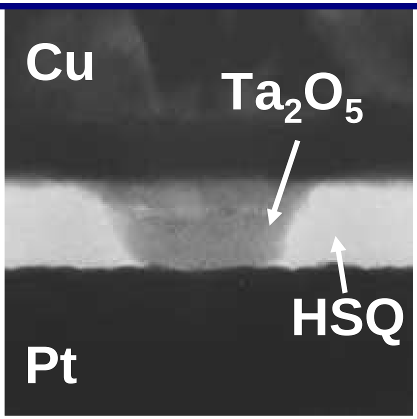
IV characteristics



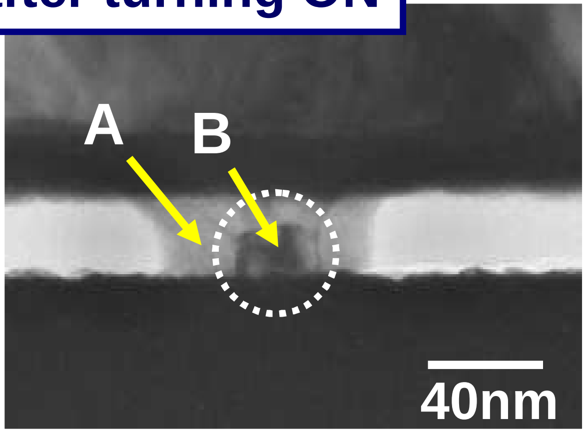


Origin of current path

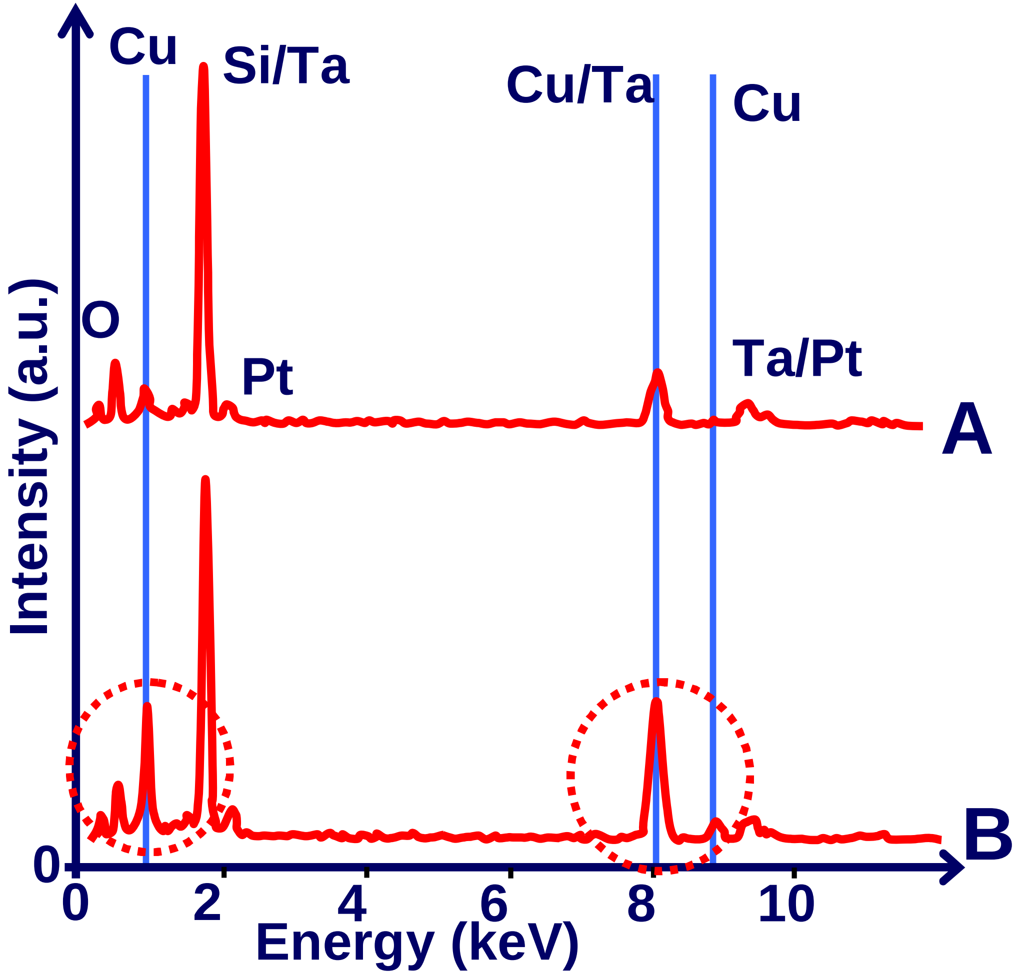
before turning ON



after turning ON

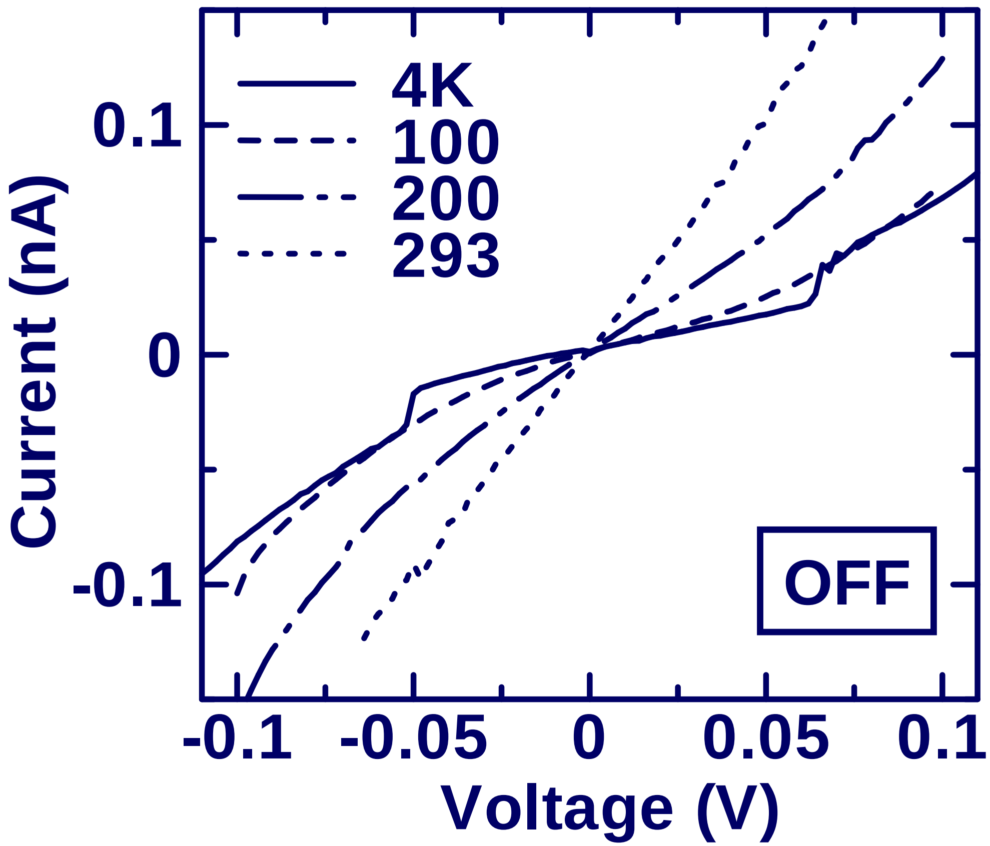


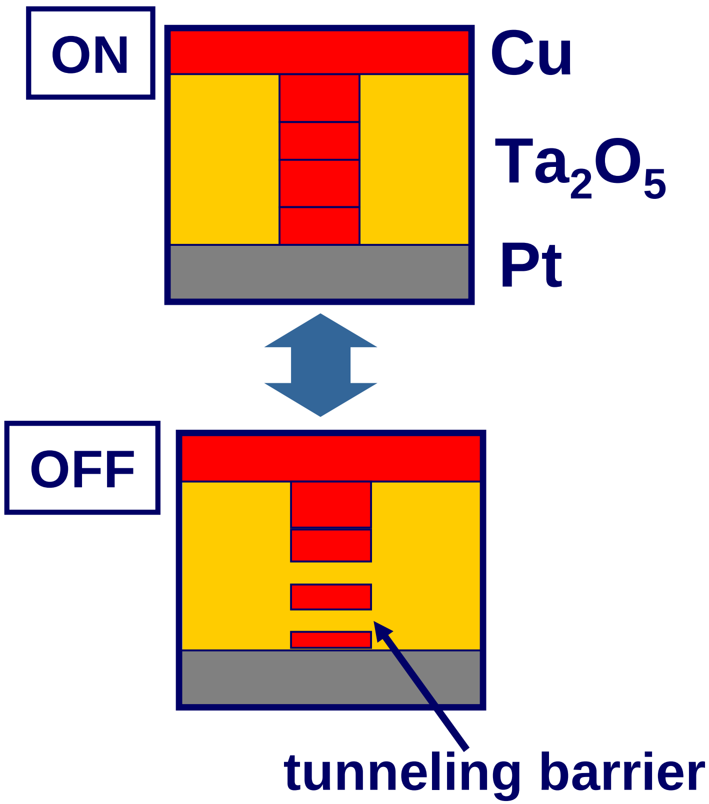
Element analysis by EDX



■ **Resistive switching is attributed to formation of Cu bridge.**

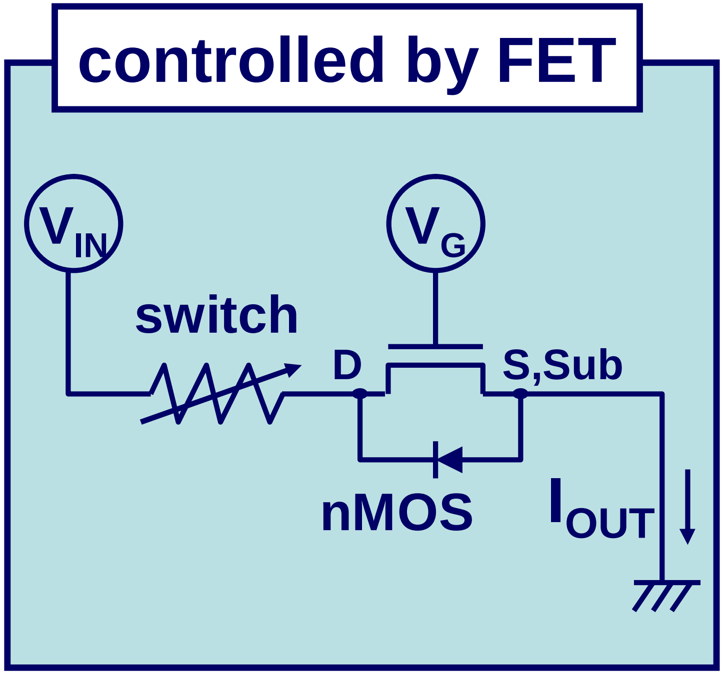
Temperature dependence of OFF resistance

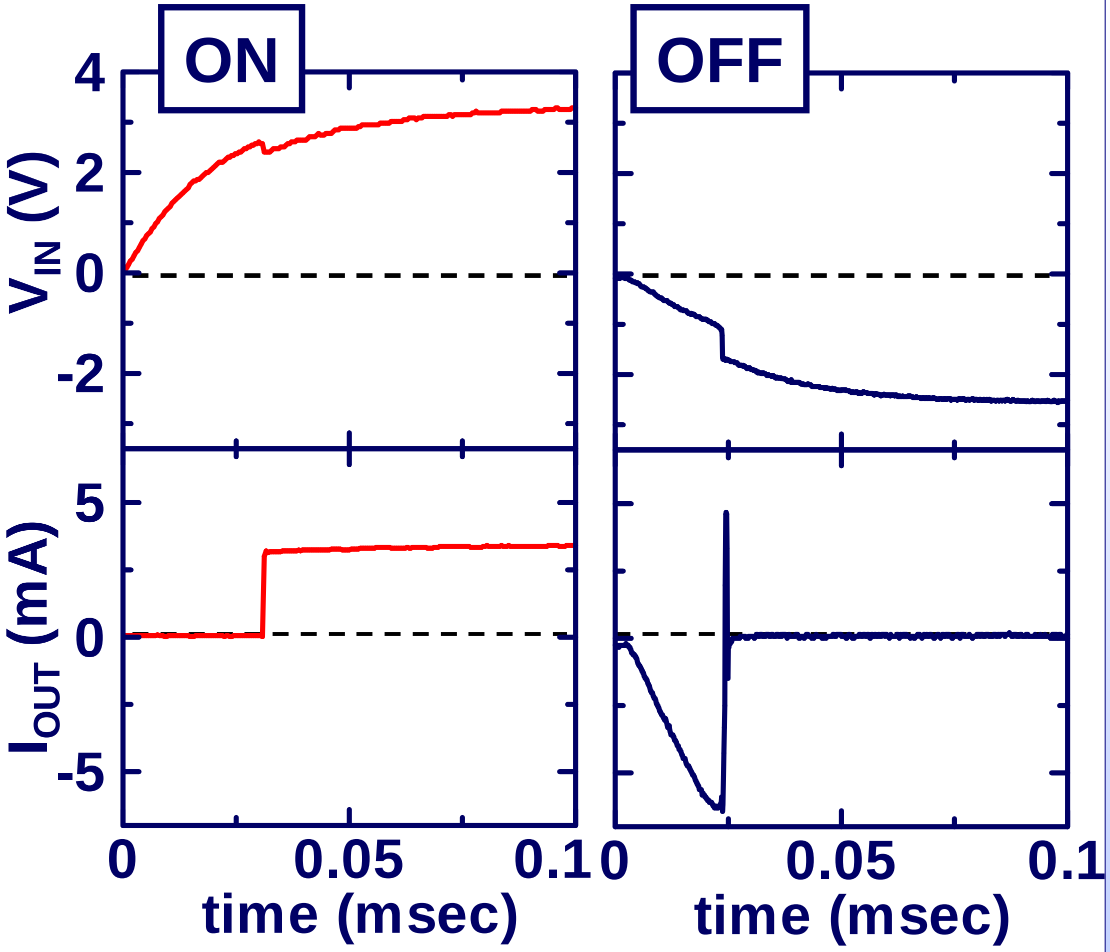




- Before p/e, R_{OFF} exponentially increases with T (not shown).
- After p/e, R_{OFF} weakly depends on T.
- Single-electron charging effect is observed.

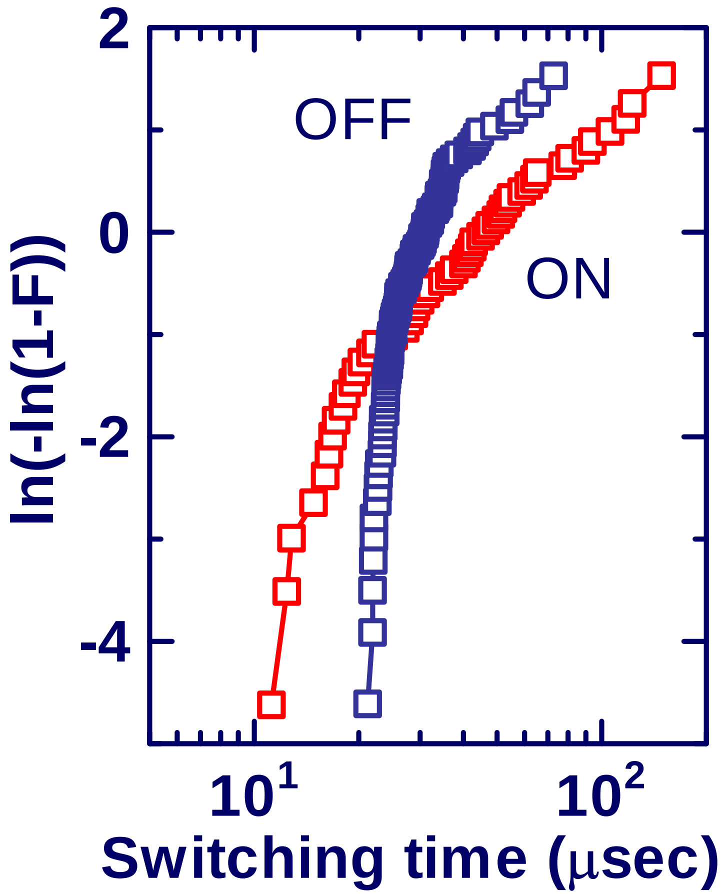
Current controlled by nMOSFET





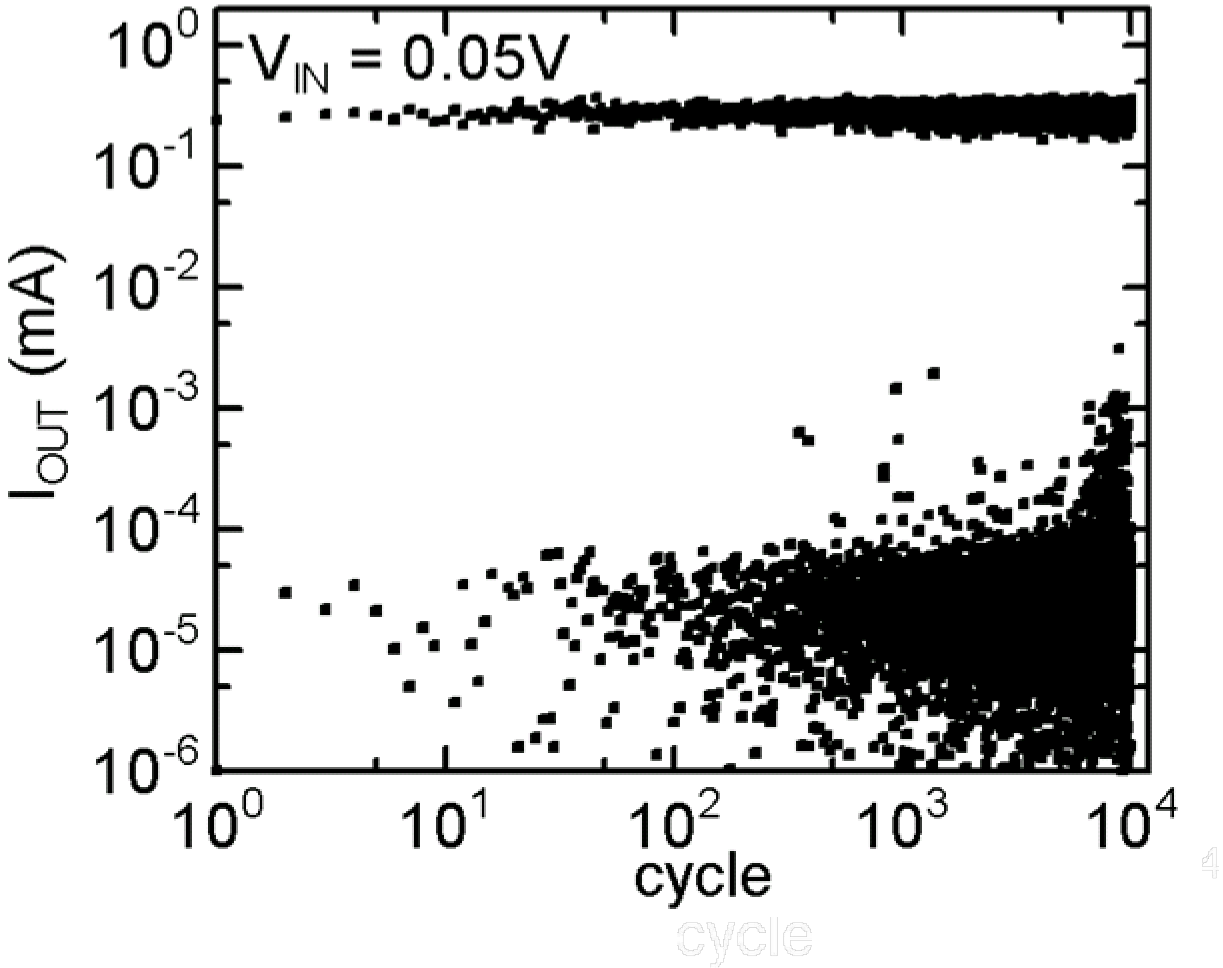
- V_{IN}>0 : Current is controlled by nMOSFET.
- Switching time

Switching time distribution



■ **Switching time depends on input voltage and distributes between 10 to 100μsec for V_{ON}=4, V_{OFF}=-2.5V.**

Cycling endurance



- Cycling endurance > 10^4

Outline

- Introduction
  - Background
  - FPGA with high performance (programmable CBIC)
  - Switching mechanism (Cu_2S-NanoBridge)
  - Issues: low switching voltage & poor reliability
- Switching voltage
  - Concept to increase switching voltage
  - Ta_2O_5-NanoBridge
  - Observation of conducting path
- ON-state reliability
  - Improved reliability by using Ta_2O_5
  - Formula for ON state reliability
  - Trade-off between Reliability & Switching current
- Conclusion

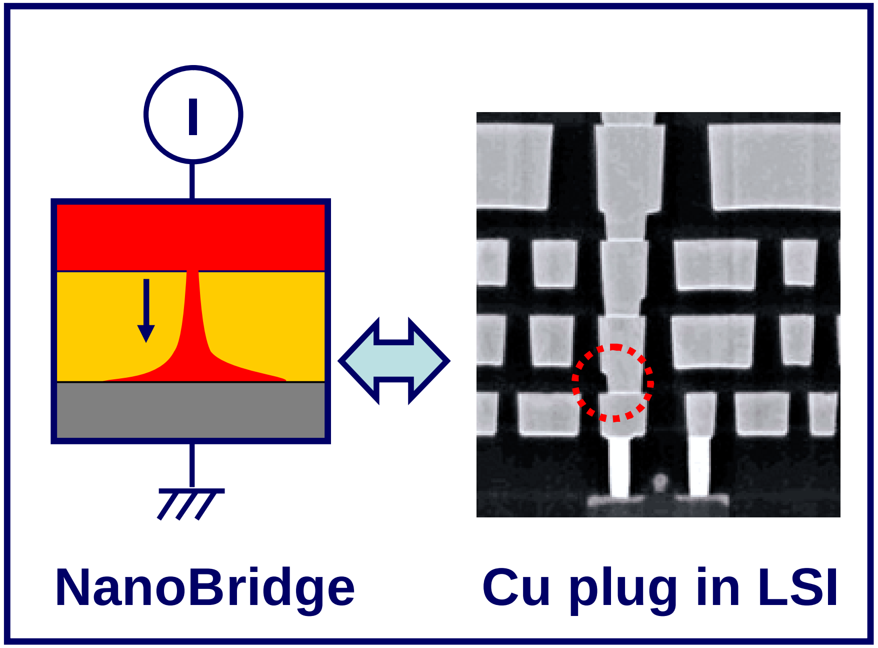
ON-state reliability

■ ON state reliability of NanoBridge should be comparable to Cu plug in LSI interconnection.

■ ON state reliability could depend on :

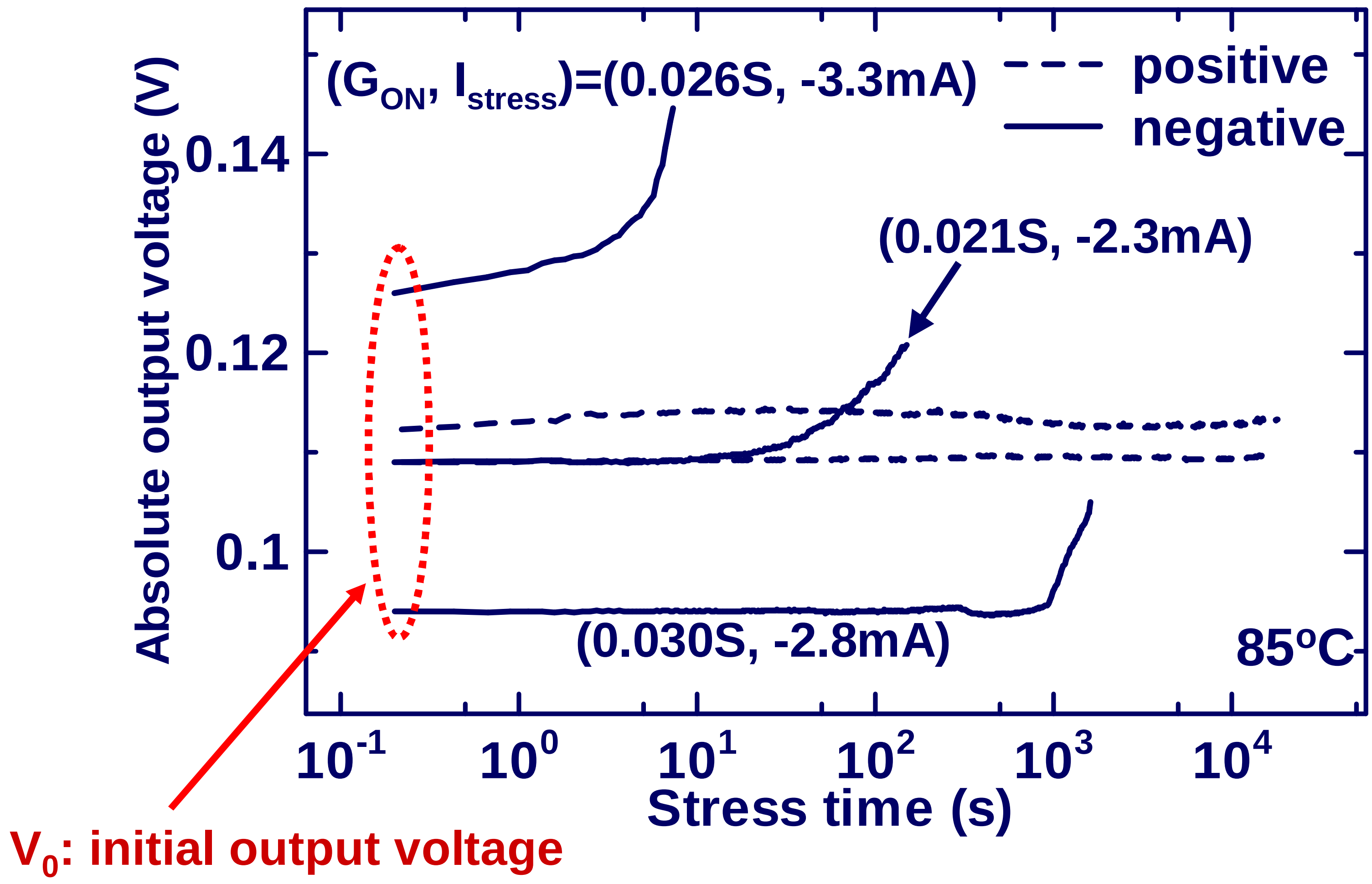
- ON conductance (thickness of Cu bridge)
- Bias current or voltage
- Biasing polarity
- Ambient temperature.

Formulate ON-state duration & Check it out!

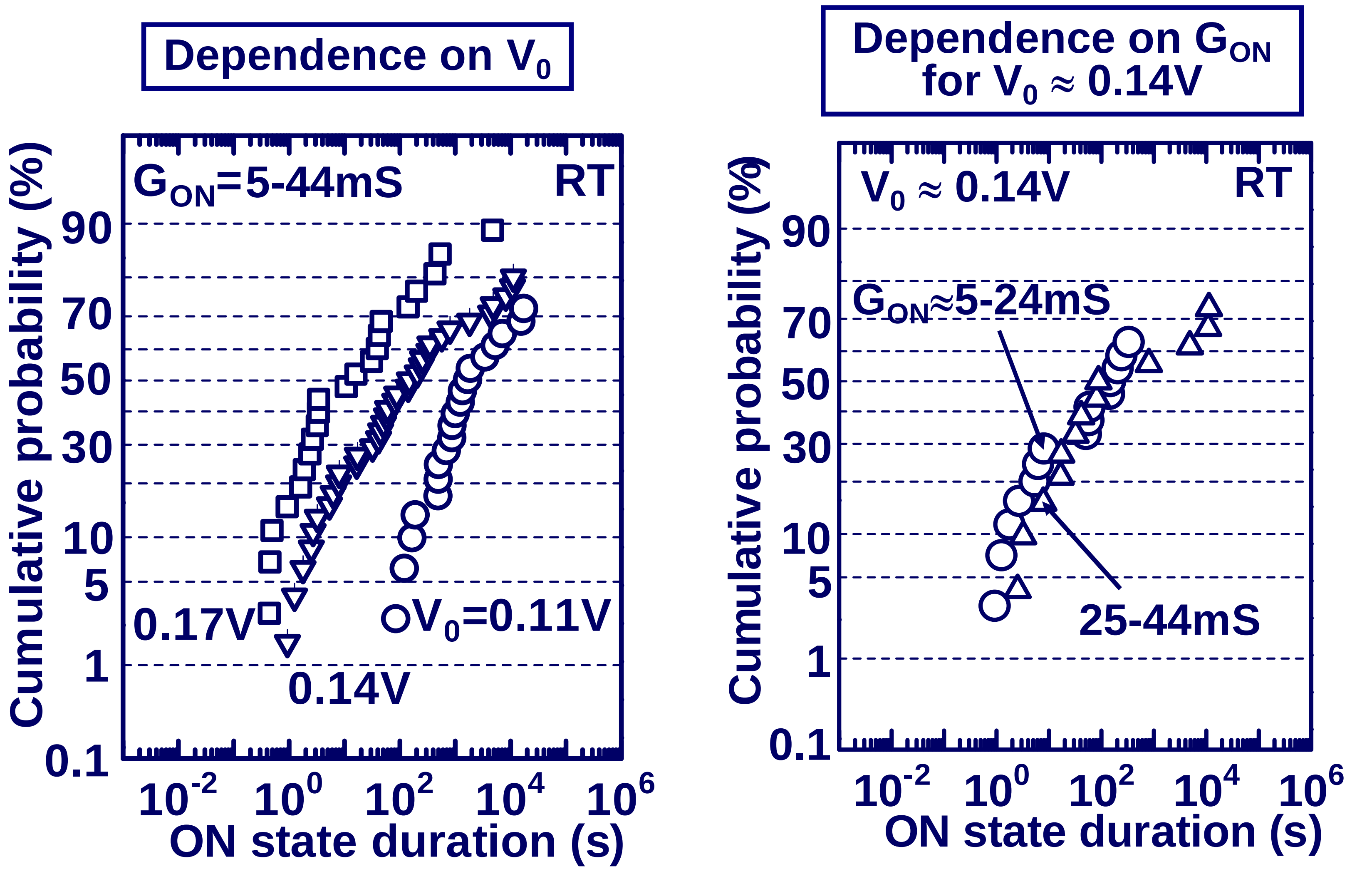


ON-state duration (t_{ON}) under DC current stress

ON-state duration for various G_{ON}, I_{STRESS}, polarity



Dependence on V_0 or G_{ON}



■ ON-state duration depends on V_0 (=I_{STRESS}/G_{ON}).

Dependence on V_0 or G_{ON} (summary)

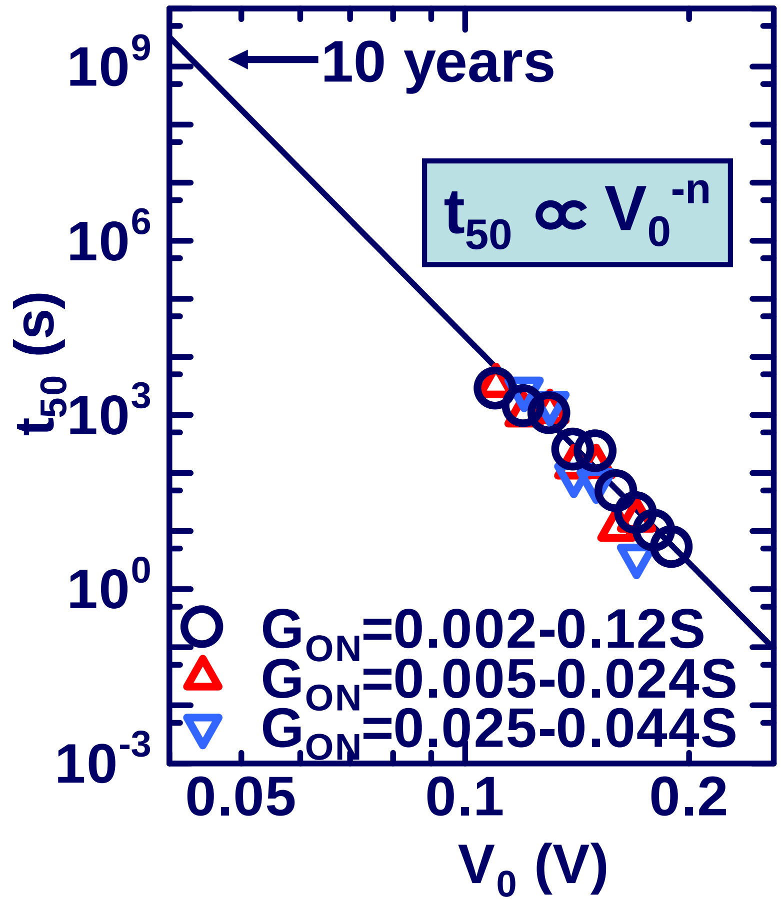
Dose t_{ON} change with varying G_{ON} or V_0?

G_{ON} \ V_0	Varied	fixed
fixed	YES	NO
Varied	YES	NO

- **ON-state duration depends on V_0 (=I_{STRESS}/G_{ON}).**

V_0 for 10years duration

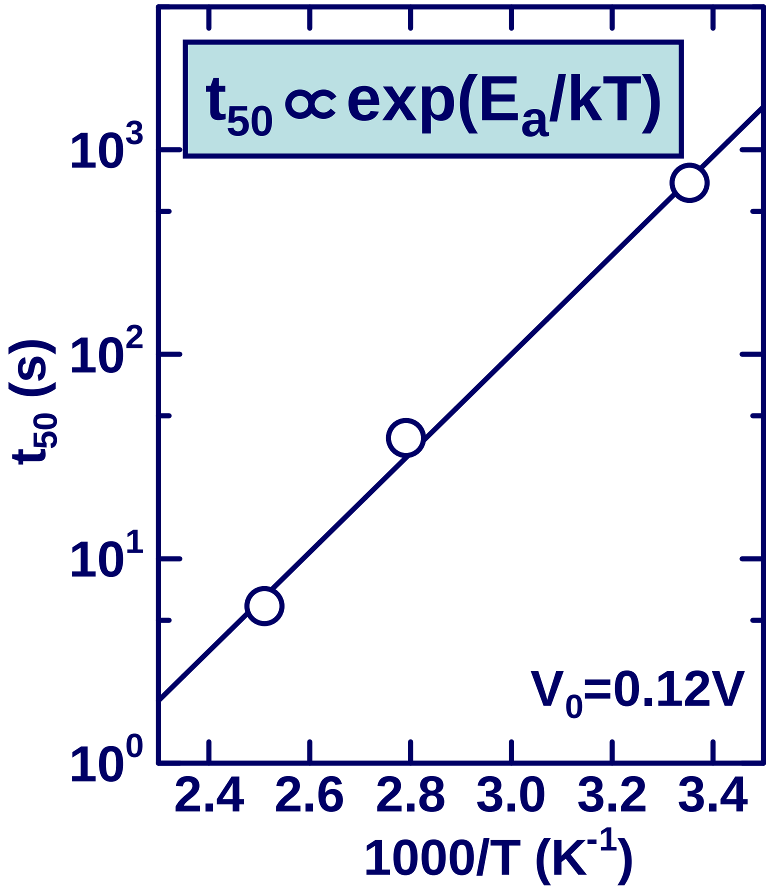
Median of ON-state duration (t_{50}) vs. V_0 for different G_{ON}



■ ON state persists for 10years when V_0<50mV.

Dependence on Temperature

Temperature dependence of median of duration



■ **Activation energy (E_a) is about 0.48 eV.**

Formula of ON-state duration

- **ON-state duration's formula derived from $t_{ON}(V_0)$ & $t_{ON}(T)$**

$$t_{ON} \propto V_0^{-n} \quad \& \quad \exp(E_a/kT)$$

$$t_{ON} = A \cdot V_0^{-n} \cdot \exp(E_a/kT)$$

$$= A \cdot (I_{STRESS}/G_{ON})^{-n} \cdot \exp(E_a/kT)$$

A :Constant
n = 12 (voltage exponent)
E_a =0.48eV

- **Comparison with formula for Cu interconnection in LSI**

$$\text{TTF (Time to Failure)} = B \cdot I_{STRESS}^{-n} \cdot \exp(E_a/kT)$$

(Black's law)

Relationship between maximum current and G_{ON}

- Consider the requirements of reliability of Cu plug in LSI;

  - ON state duration : t_{ON} > 10years
  - Temperature : $T = 105^{o}C$
  - Maximum current : I_{STRESS} > 0.2mA.

- Substitute values for A, N, and E_a of t_{ON} (99.9% of devices)

$$t_{ON} = 2.8\times10^{-21}\cdot(I_{STRESS}/G_{ON})^{-12}\cdot\exp(0.48/kT).$$

$$t_{ON} = 7.0\times10^{-15}\cdot (I_{STRESS}/G_{ON})^{-12} > 10\text{years}$$

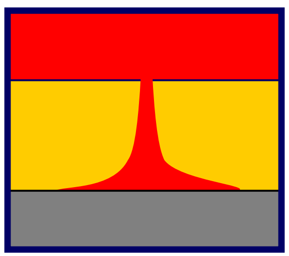
$$I_{STRESS} = 1.4\times10^{-2}\cdot G_{ON} > 0.2\text{mA}$$

$$G_{ON} > 14\text{mS}\ (R_{ON} < 71.4\Omega)$$

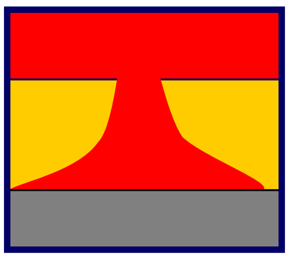
Trade-off between reliability and switching current

ON state reliability improves with G_{ON}.
.. But, switching current increases.

Thin Cu bridge (Low G_{ON})



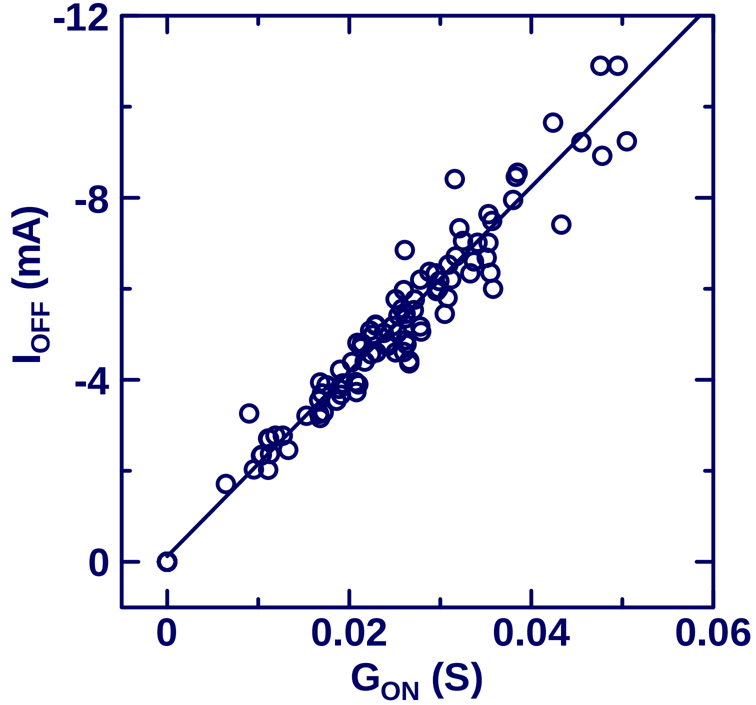
Thick Cu bridge (High G_{ON})



- **Poorly reliable**
- **Low switching current**

- **Highly reliable**
- **Large switching current**

Turn-off current versus ON conductance



$I_{OFF} = 0.2 \times G_{ON} < 5mA$

(Minimum current for antifuse)

$G_{ON} < 28mS$ ($R_{ON} > 41.7\Omega$)

Suitable G_{ON} for FPGA

$$\begin{cases} I_{OFF} = 0.2 \times G_{ON} < 5mA \\ I_{max} = 1.4\times10^{-2}\cdot G_{ON} > 0.2mA \end{cases}$$

⇨

G_{ON}: 14 – 28mS

R_{ON}: 41.7 - 71.4Ω

Summary of properties

Parameter Name	Cu_2S switch[1)]	Ta_2O_5 switch
ON resistance	OK (<100Ω)	OK (<100Ω)
Switch size	OK ($4F^2$)	OK ($4\text{-}8F^2$)
Switching speed	OK (<10μsec)	OK (<100μsec)
Cycling endurance	OK (10^3–10^5)	OK (10^4)
Switching voltage	NG (~0.2V)	OK (>1V)
ON-state duration	NG (<3month)	OK (>10years)
Turn-off current	NG (>3mA)	Allowable (~5mA)
Process Compatibility	NG	OK

Conclusions

- We propose a compact and low resistive switch which utilizes ionic conduction.
- Enhancement in switching voltage can be achieved by ionic conductor with low diffusion rate.
- On-state reliability has been improved and its formula is obtained.

Novel switch improves performances of reconfigurable LSI without scaling down.

Acknowledgement

- **National institute of materials science, NIMS**
  Tsuyoshi Hasegawa, Kazuya Terabe, Masakazu Aono

- **Dep. of Materials Eng., Tokyo Univ.**
  Prof. Shu Yamaguchi, Prof. Satoshi Watanabe

- **Device Platforms Res. Labs., NEC**
  Naoki Banno, Hiromitsu Hada, Naoki Kasai

- **Nano Electronics Res. Labs., NEC**
  Noriyuki Iguchi, Shinji Fujieda

A part of this work was supported by JST via "Nanoscale quantum conductor array project".