

A Ta₂O₅ Solid-Electrolyte Switch with Improved Reliability

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■ Introduction

- Background
- FPGA with high performance (programmable CBIC)
- Switching mechanism (Cu₂S-NanoBridge)
- Issues: **low switching voltage & poor reliability**

■ Switching voltage

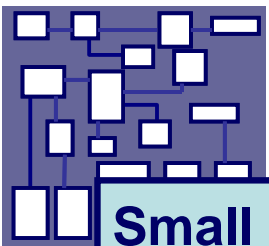
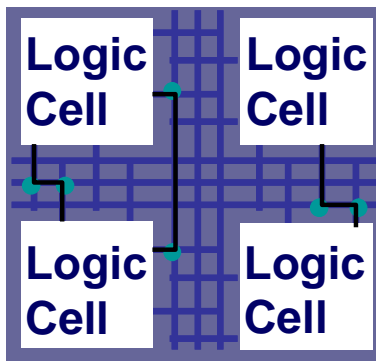
- Concept to increase switching voltage
- Ta₂O₅-NanoBridge
- Observation of conducting path

■ ON-state reliability

- Improved reliability by using Ta₂O₅
- Formula for ON state reliability
- Trade-off between Reliability & Switching current

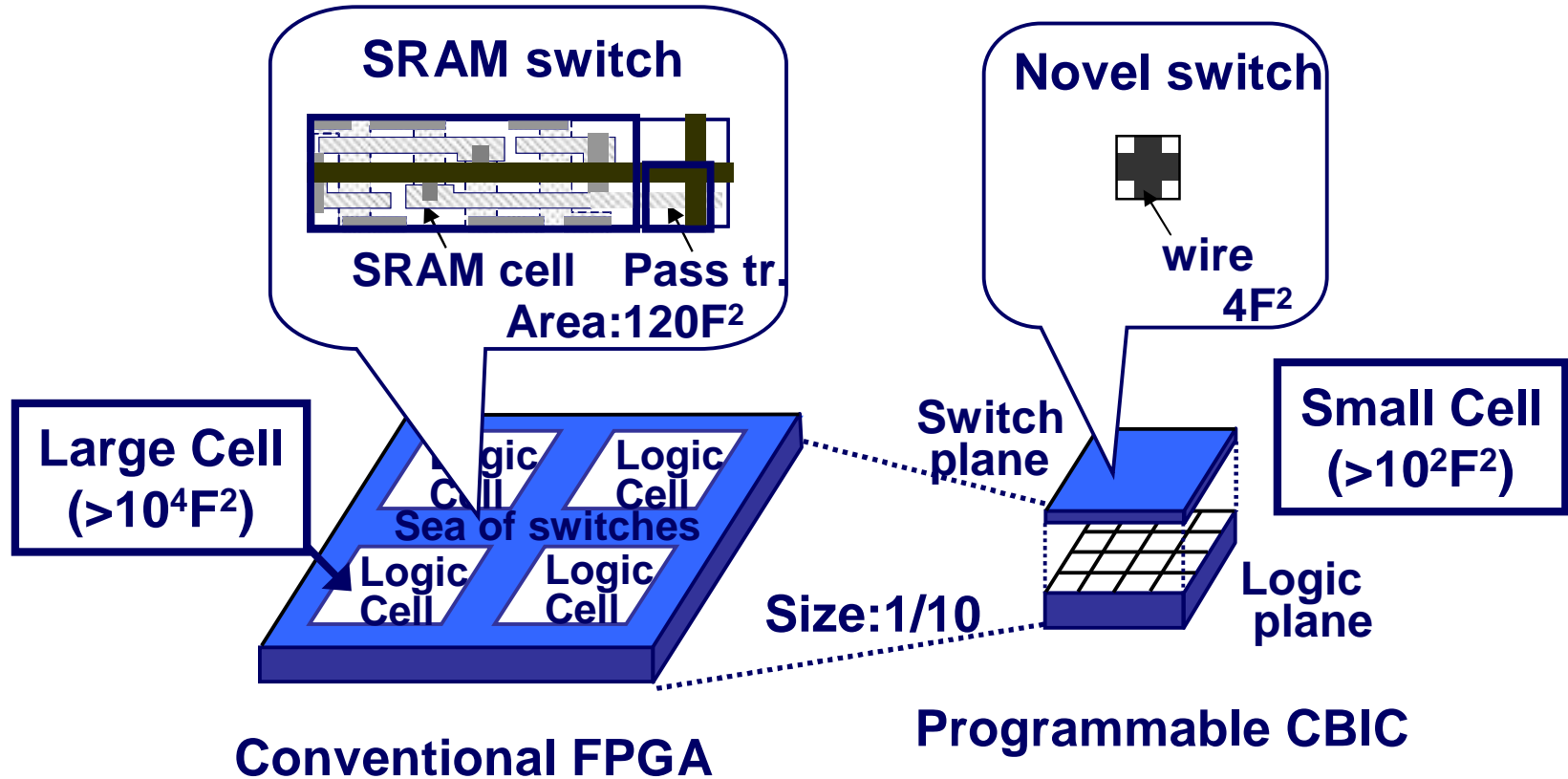
■ Conclusion

Background: two ASIC platforms

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

Breakthrough in programmable switch

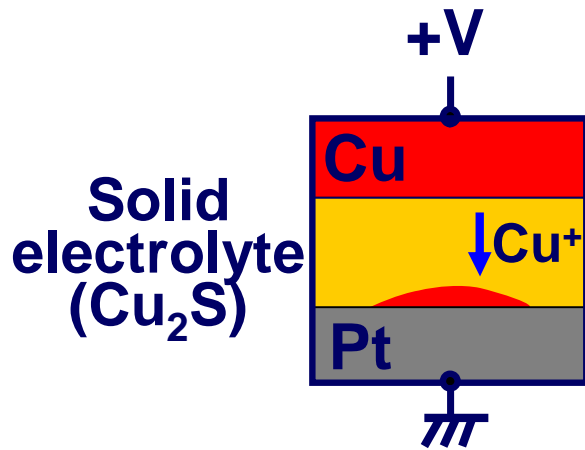
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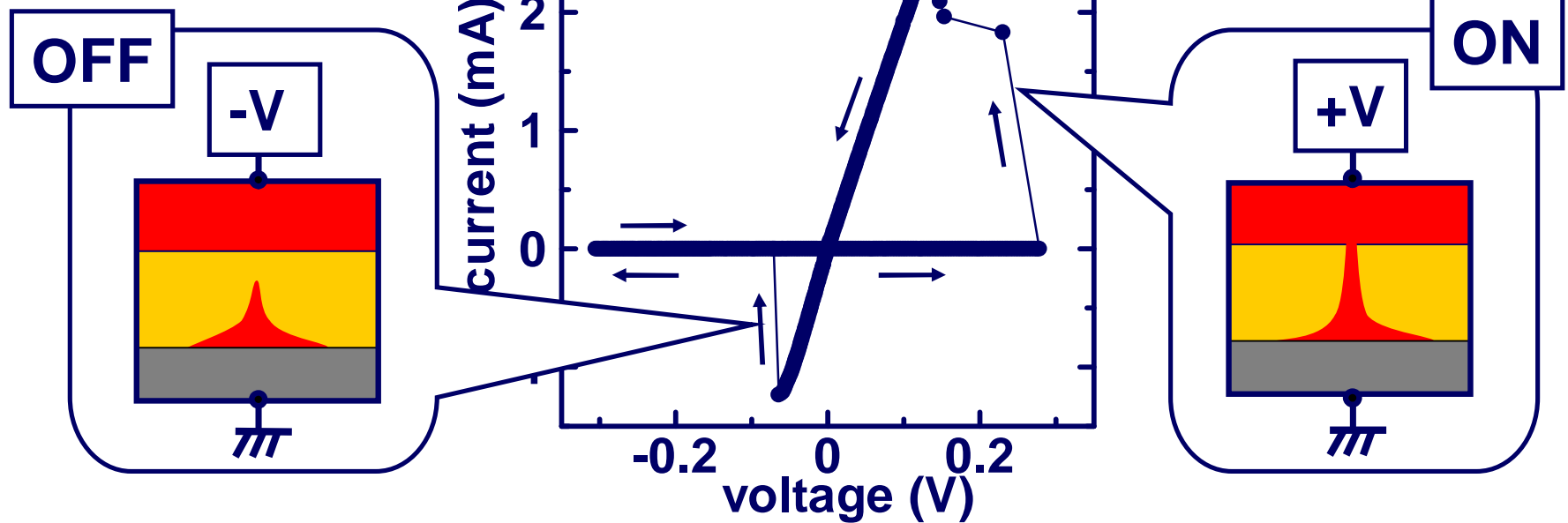
- Negligible switch area & small logic cell
- Low chip cost, high performance

Solid electrolyte switch ("NanoBridge")

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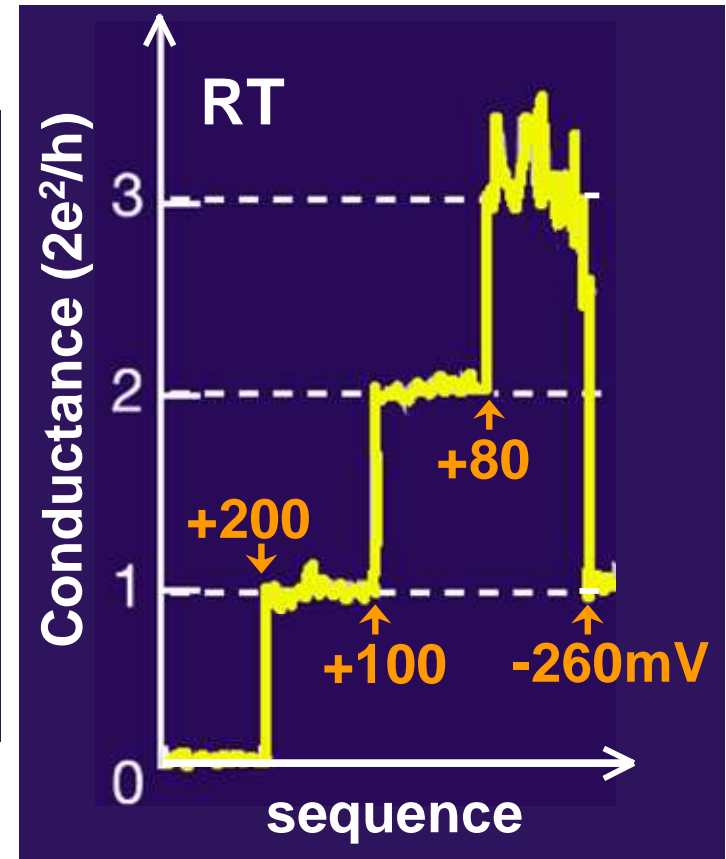
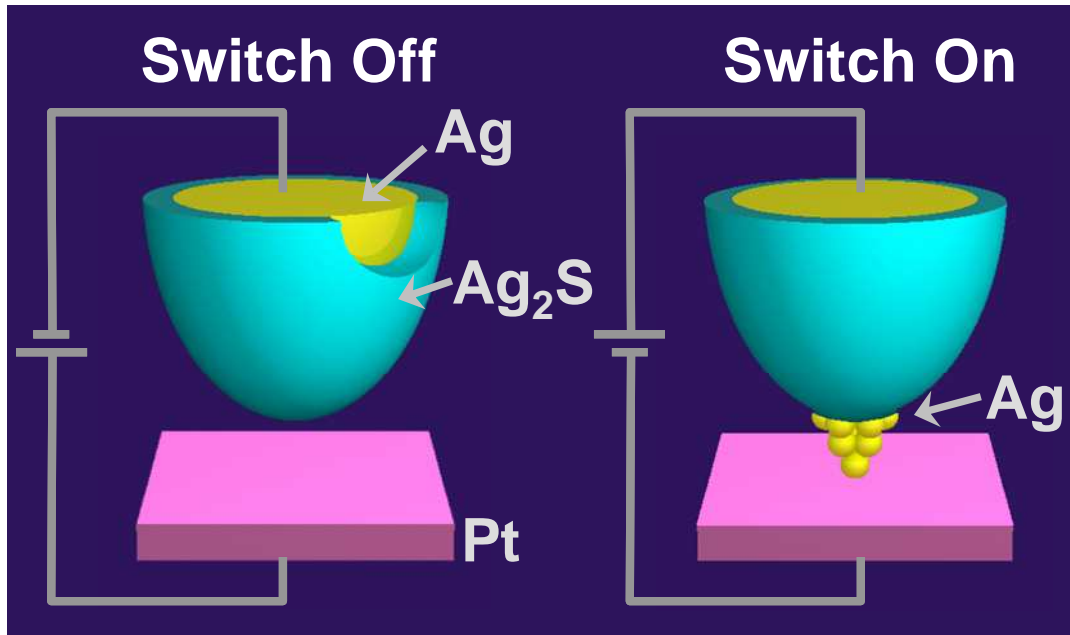


Solid electrolyte: Ionic conductor
ex. Cu_2S , Ag_2S , AgGeSe , ...



...based on Atomic Switch (NIMS)

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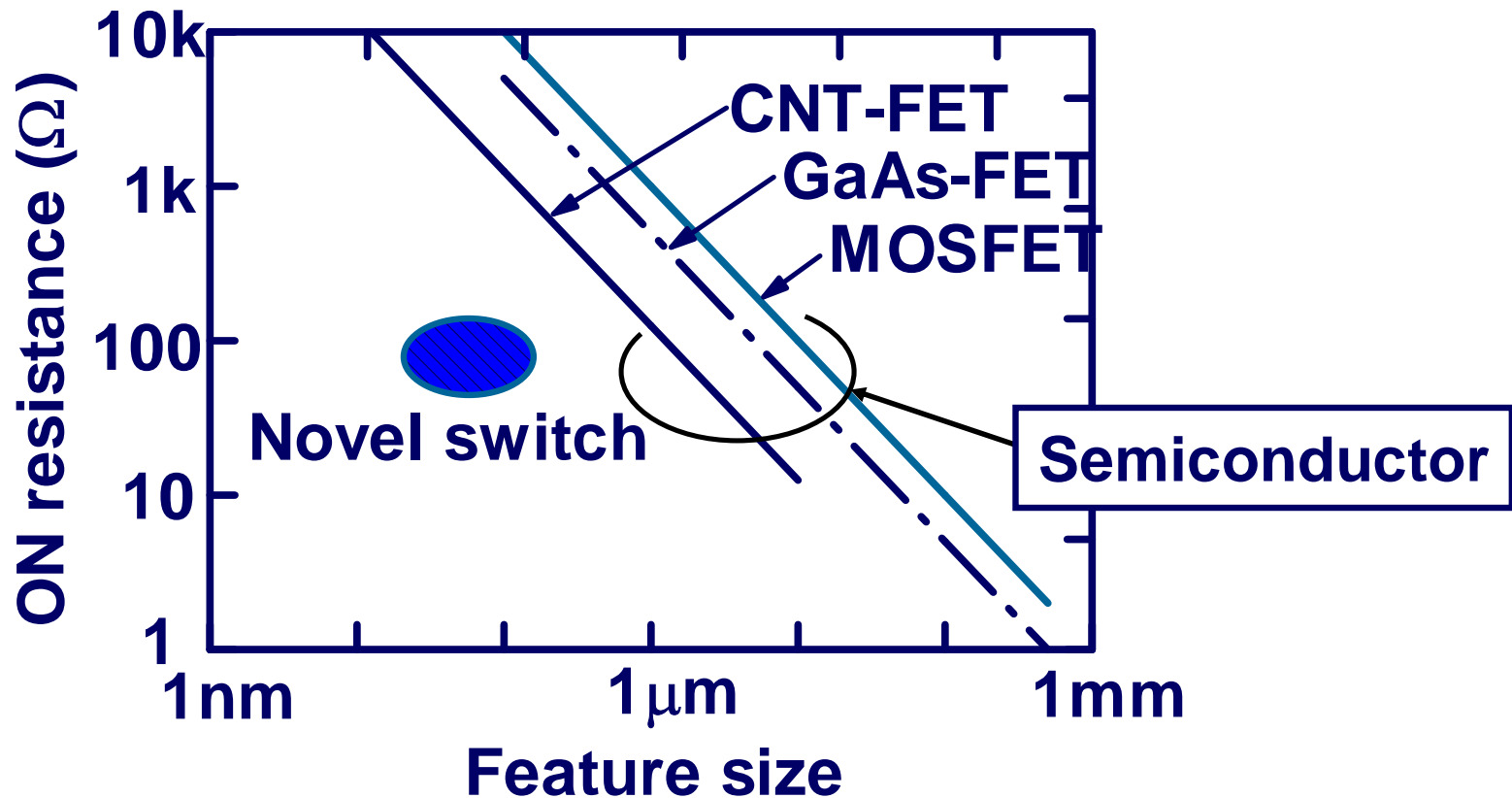
- Ag atom precipitates when positive voltage is biased on Ag.
- Formation and annihilation of atomic bridge changes conductance in units of $2e^2/h$.

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

Features of solid-electrolyte switch

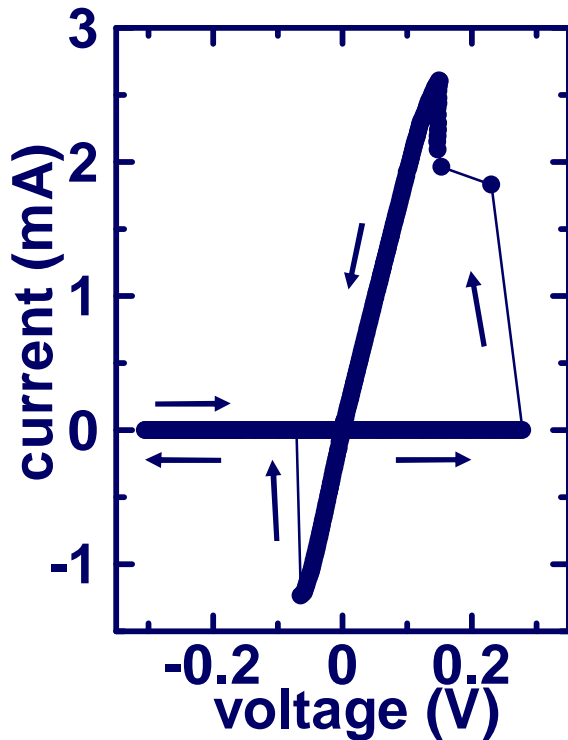
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- Low ON resistance : metallic bridge
- Small : thin bridge (<30nm)
- Simple structure ($4F^2$)



Features of Cu_2S solid-electrolyte switch

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Meet the demand for programmable logic?

Parameter	Cu_2S NanoBridge
ON resistance	OK ($<100\Omega$)
Switch size	OK ($4F^2$)
Switching speed	OK ($<10\mu\text{sec}$)
Cycling endurance	OK (10^3-10^5)
Turn-on voltage	NG ($\sim 0.2\text{V}$)
Retention	NG ($<3\text{month}$)
Process compatible	NG
Switching current	NG ($>3\text{mA}$)

Breakthrough
in Material (Ta_2O_5)

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■ ON-state reliability

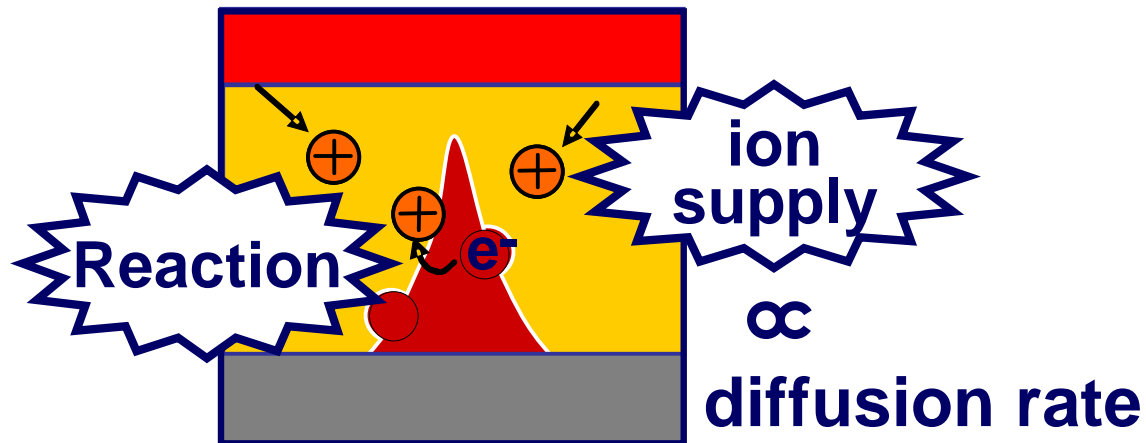
- Improved reliability by using Ta₂O₅
- Formula for ON state reliability
- Trade-off between Reliability & Switching current

■ Conclusion

What determines switching voltage?

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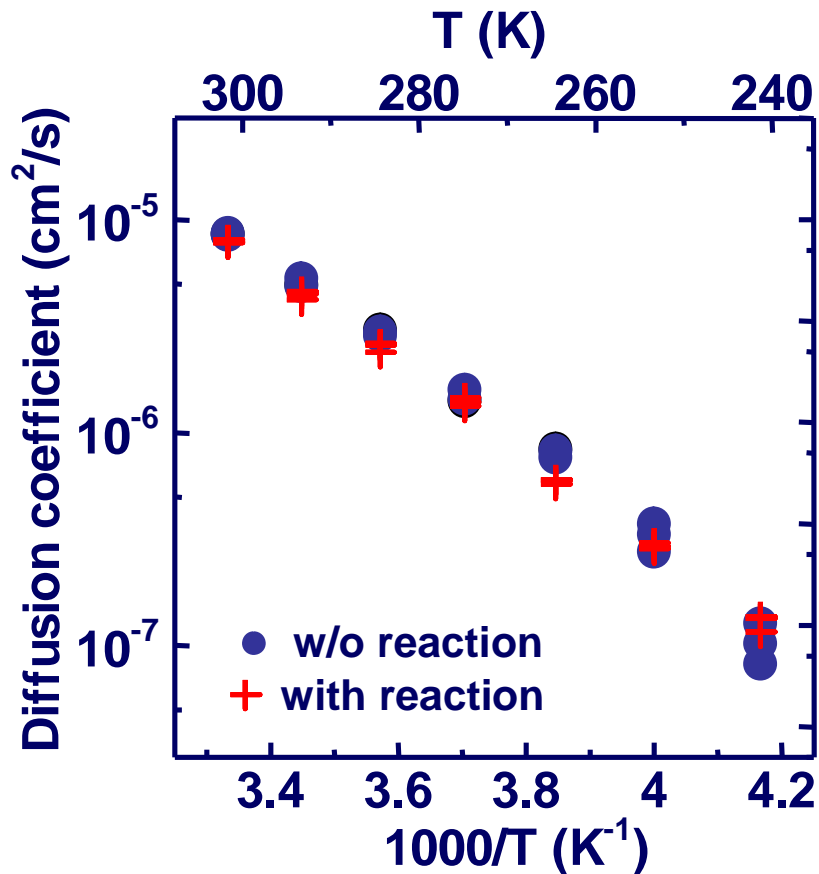
Cu⁺ supply and chemical reaction are involved. Which determines switching voltage?



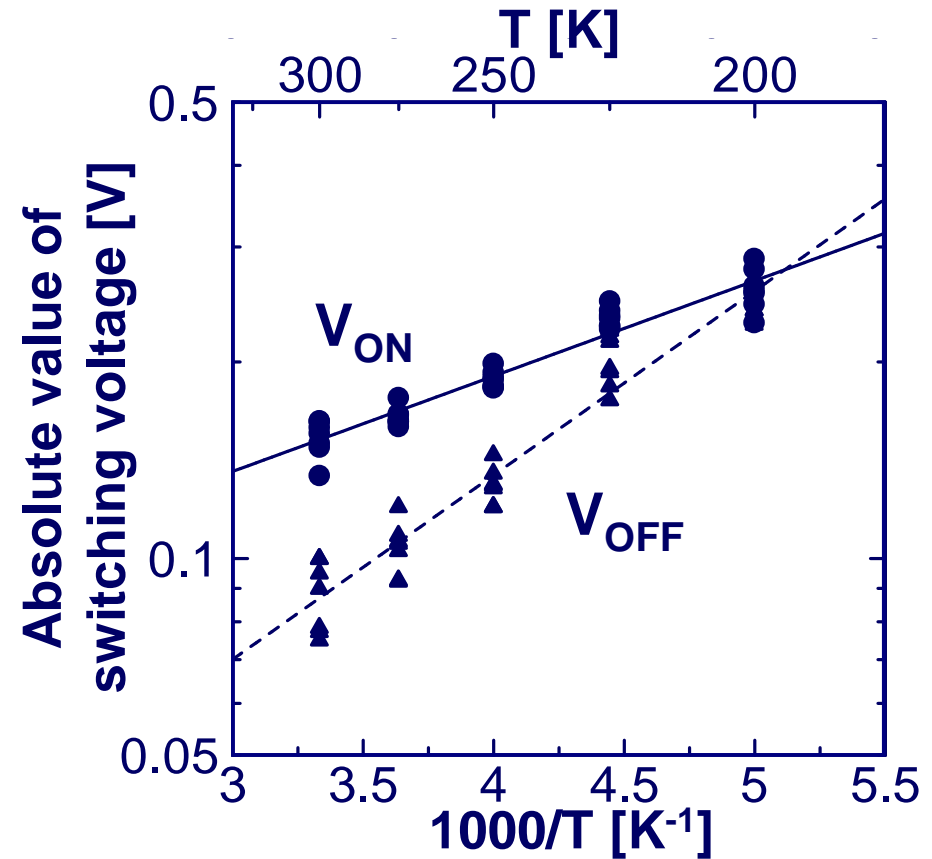
Cu-ion diffusion rate with chemical reaction vs. the rate without reaction.

T dep. of diffusion coefficient & switching voltage ¹¹

Diffusion vs. Temp.



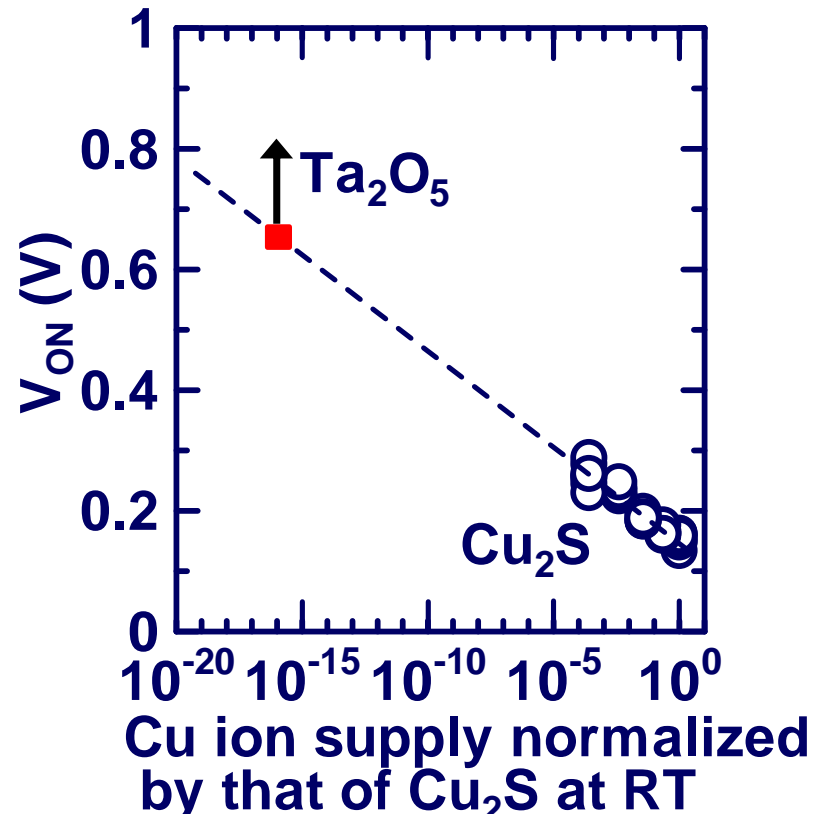
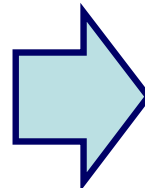
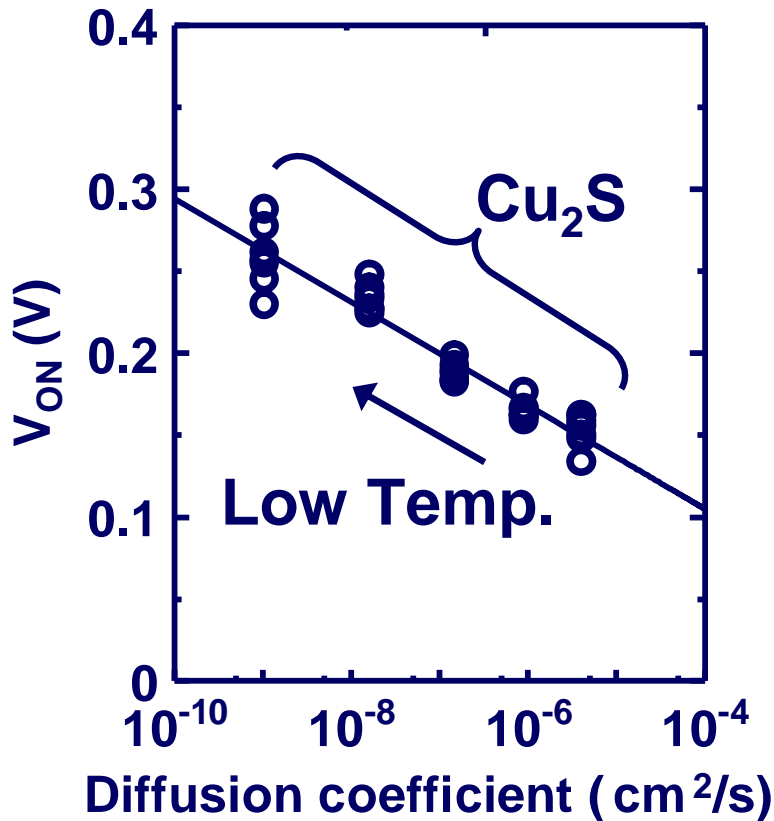
Switching voltage vs. Temp.



■ Diffusion rate determines switching voltage.

Concept to increase switching voltage

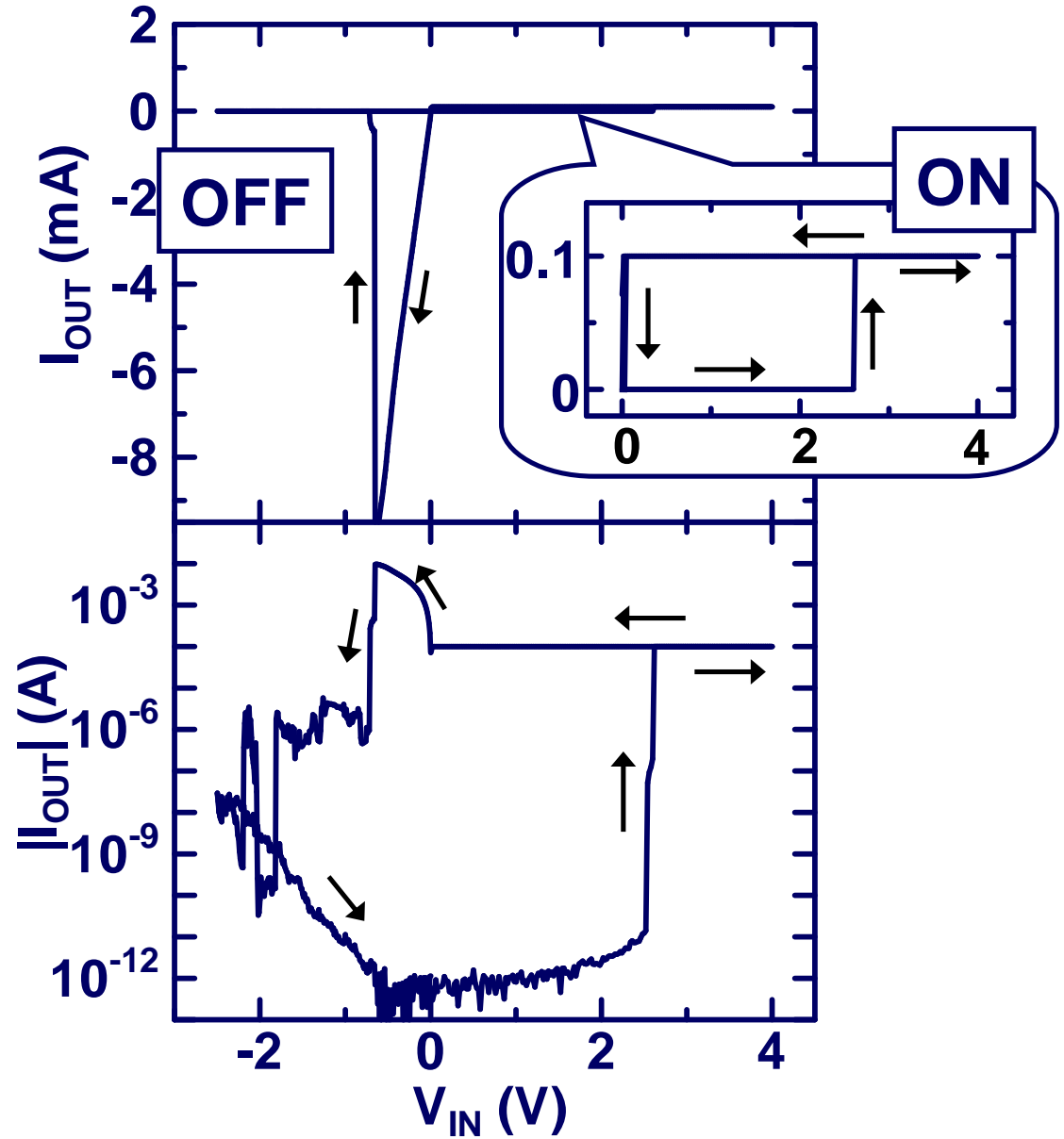
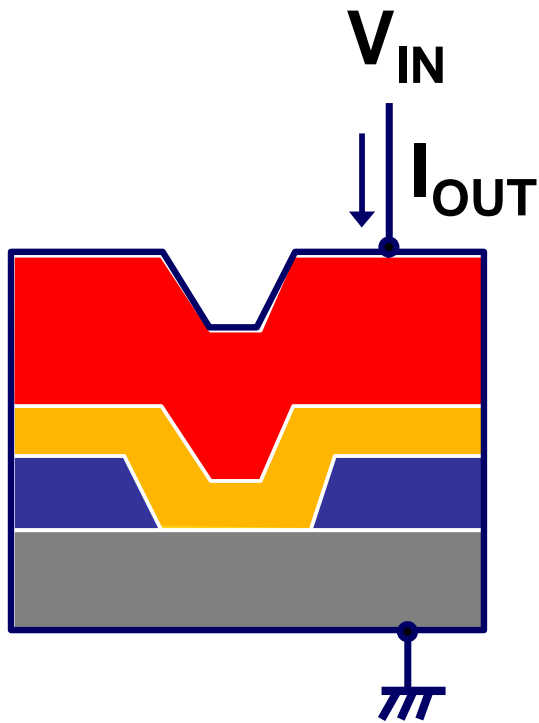
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Cu^+ supply \propto Cu^+ concentration \times diffusion rate.

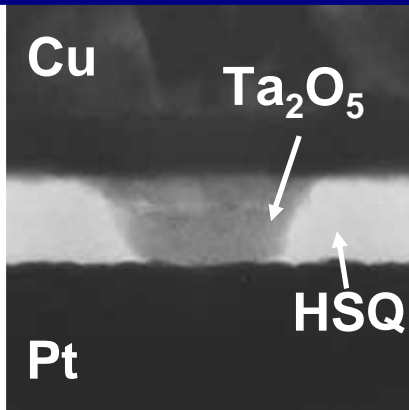
- Material with very low diffusion rate is needed.
- Ta_2O_5 : good compatibility with LSI process
- 0.65V or larger is expected for Ta_2O_5 .

IV characteristics

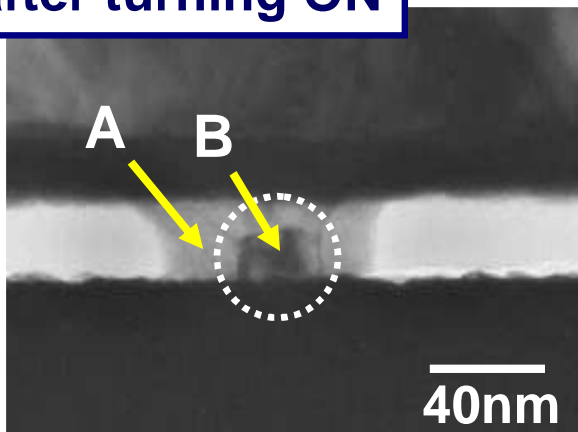


Origin of current path

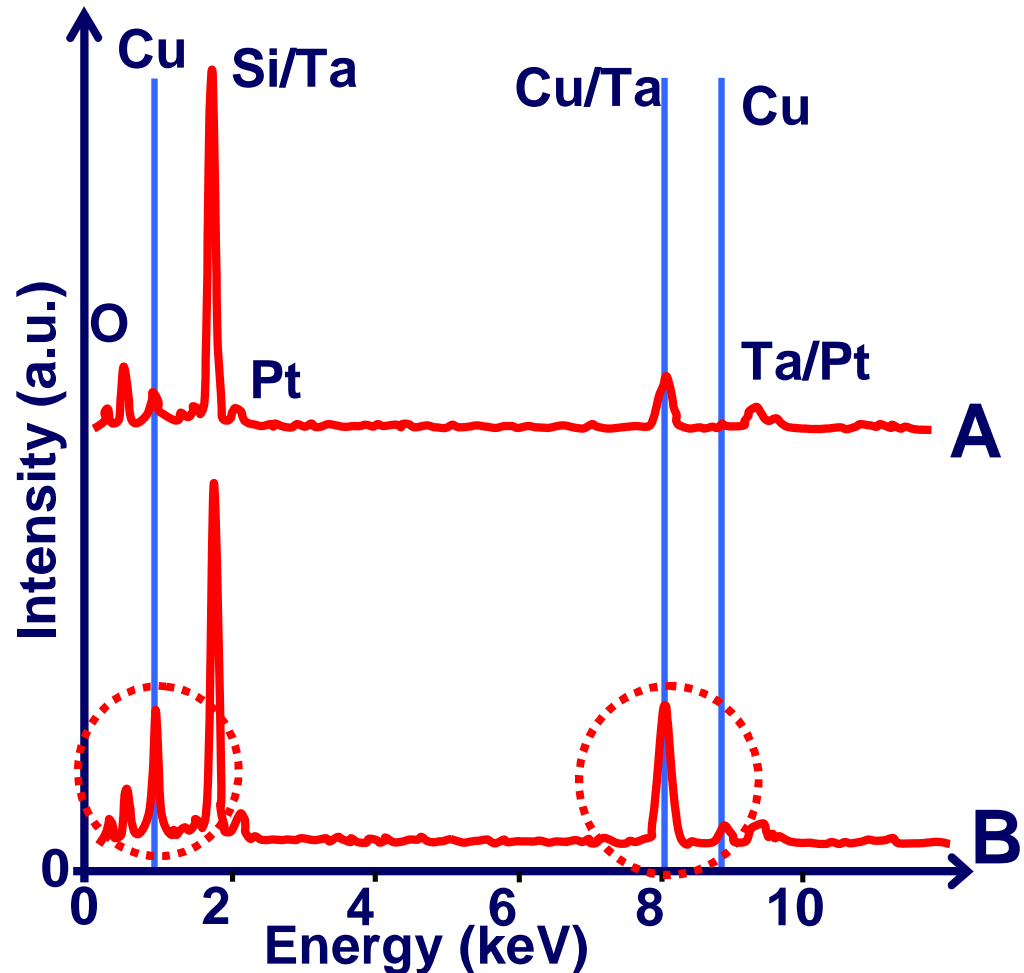
before turning ON



after turning ON



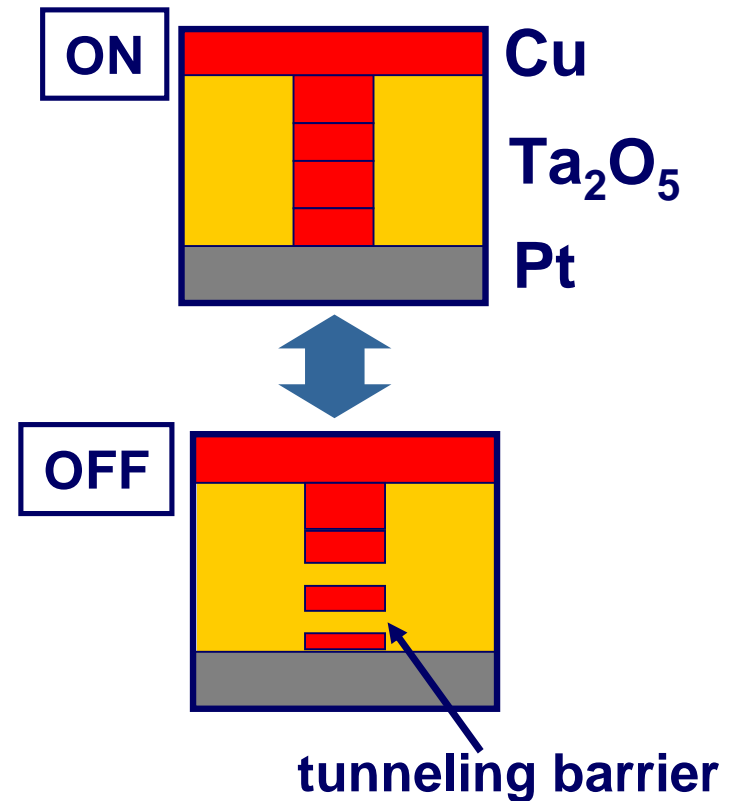
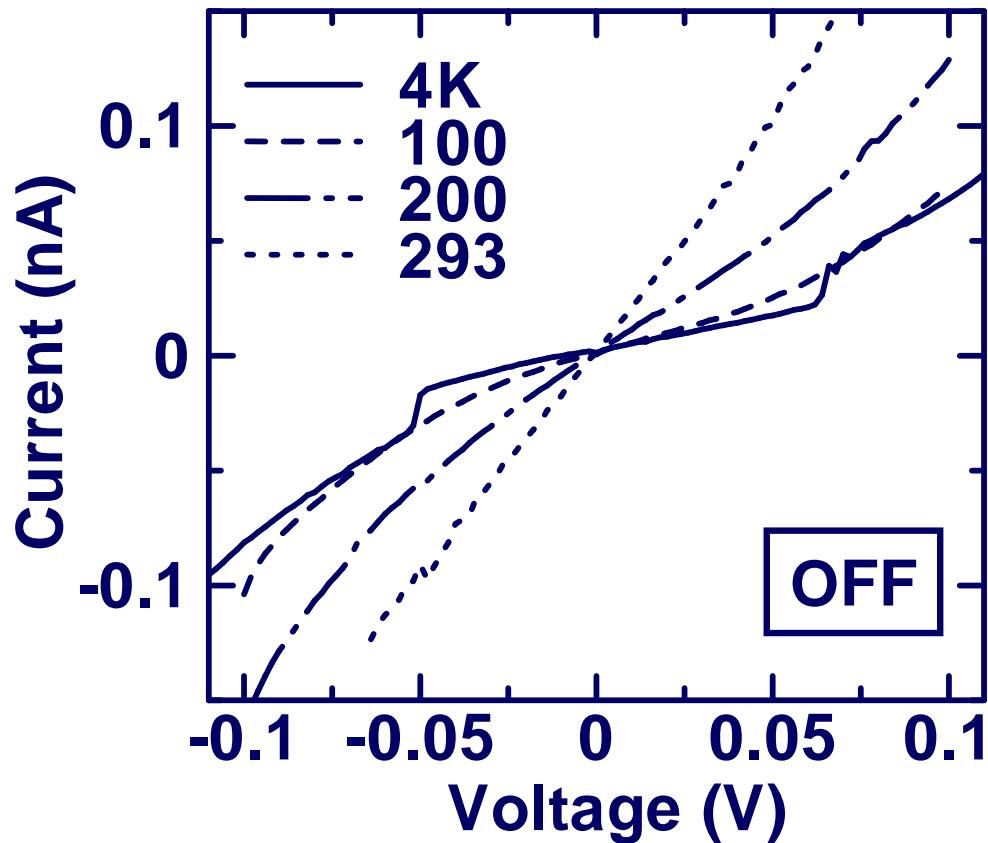
Element analysis by EDX



■ Resistive switching is attributed to formation of Cu bridge.

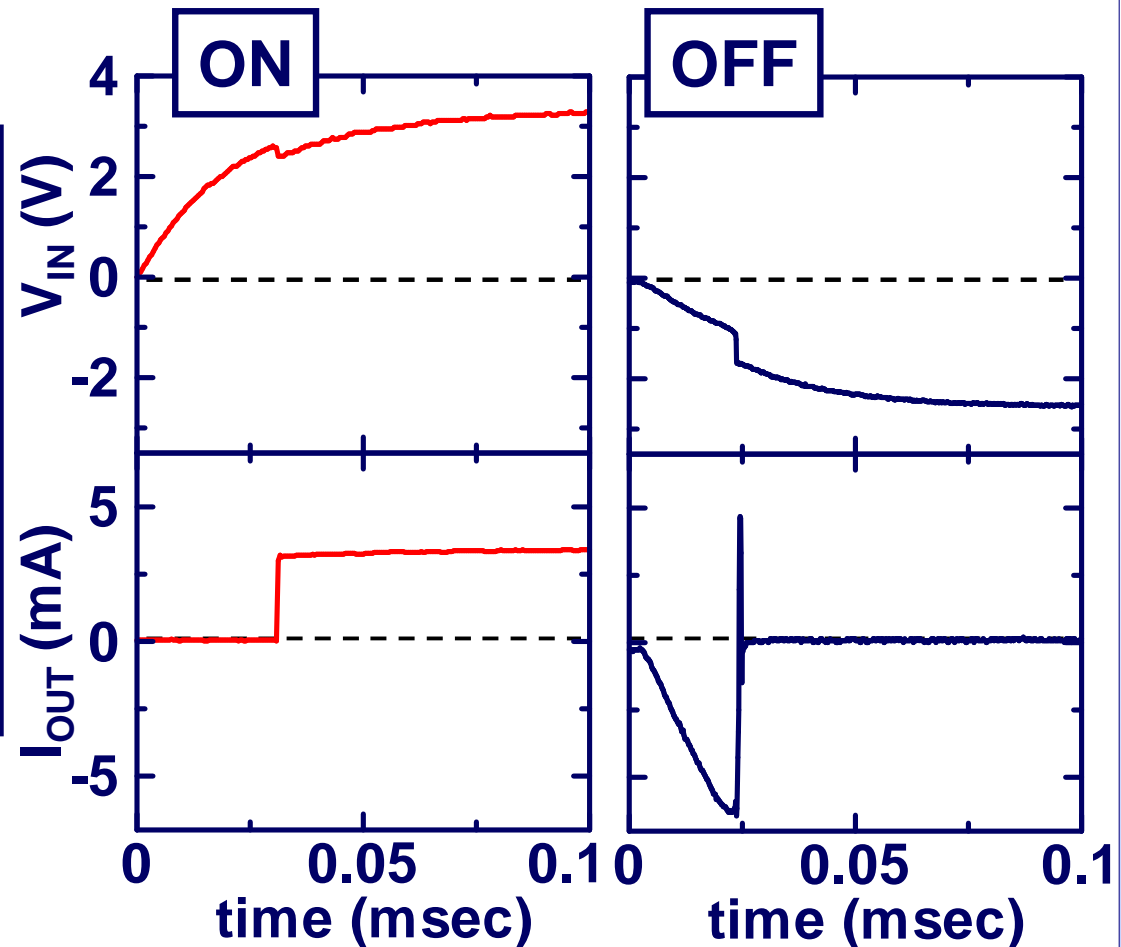
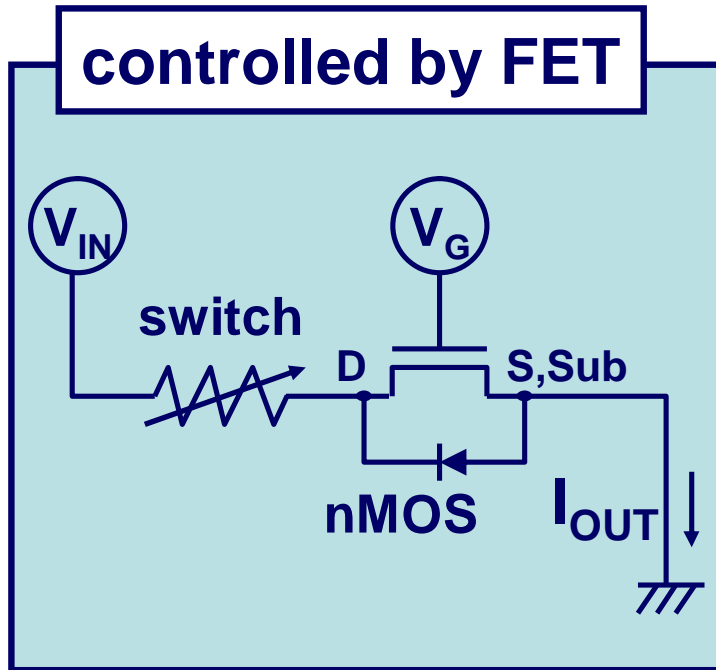
Temperature dependence of OFF resistance

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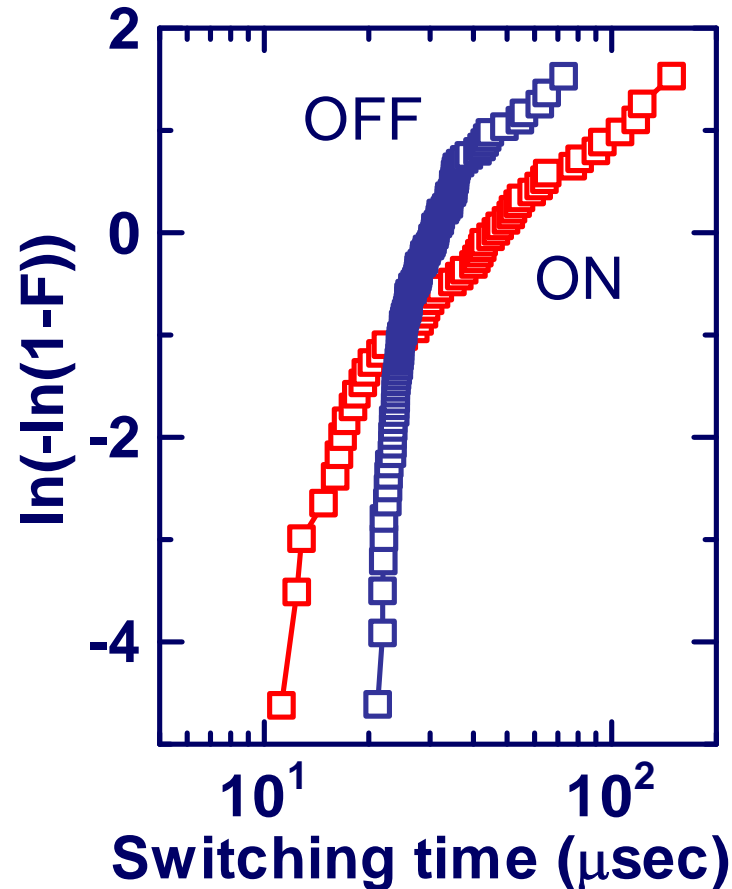


- Before p/e, R_{OFF} exponentially increases with T (not shown).
- After p/e, R_{OFF} weakly depends on T .
- Single-electron charging effect is observed.

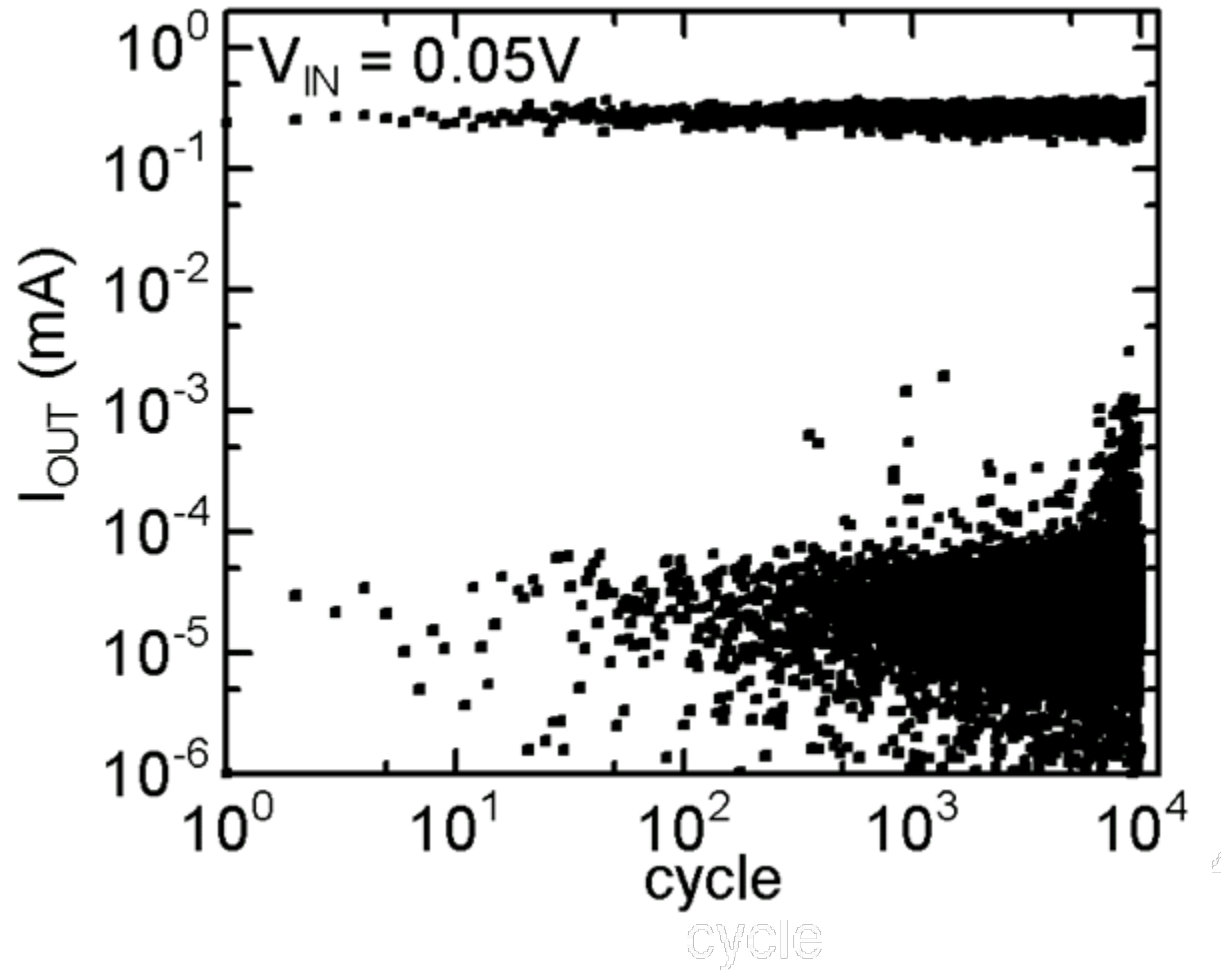
Current controlled by nMOSFET



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



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



■ Cycling endurance $> 10^4$

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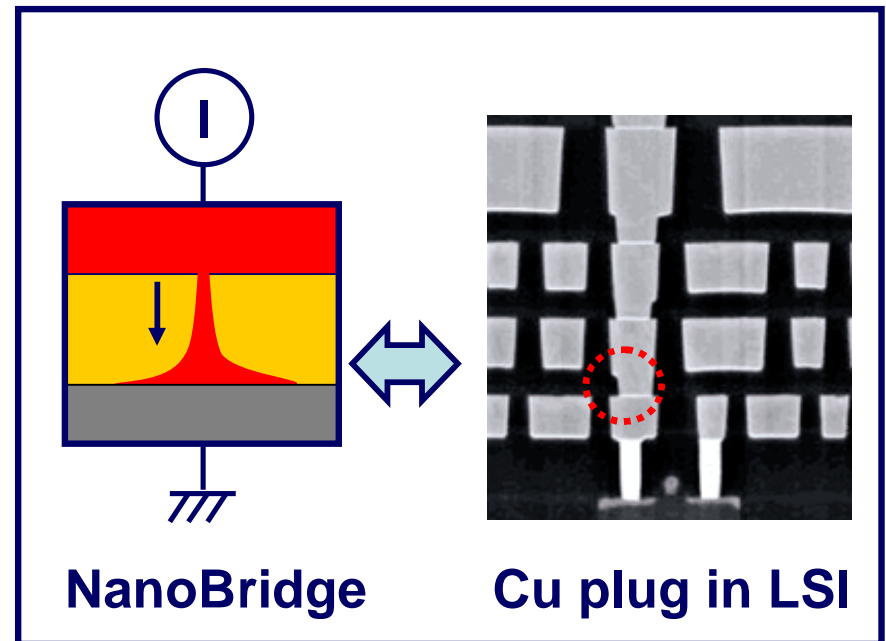
- Improved reliability by using Ta_2O_5
- Formula for ON state reliability
- Trade-off between Reliability & Switching current

■ Conclusion

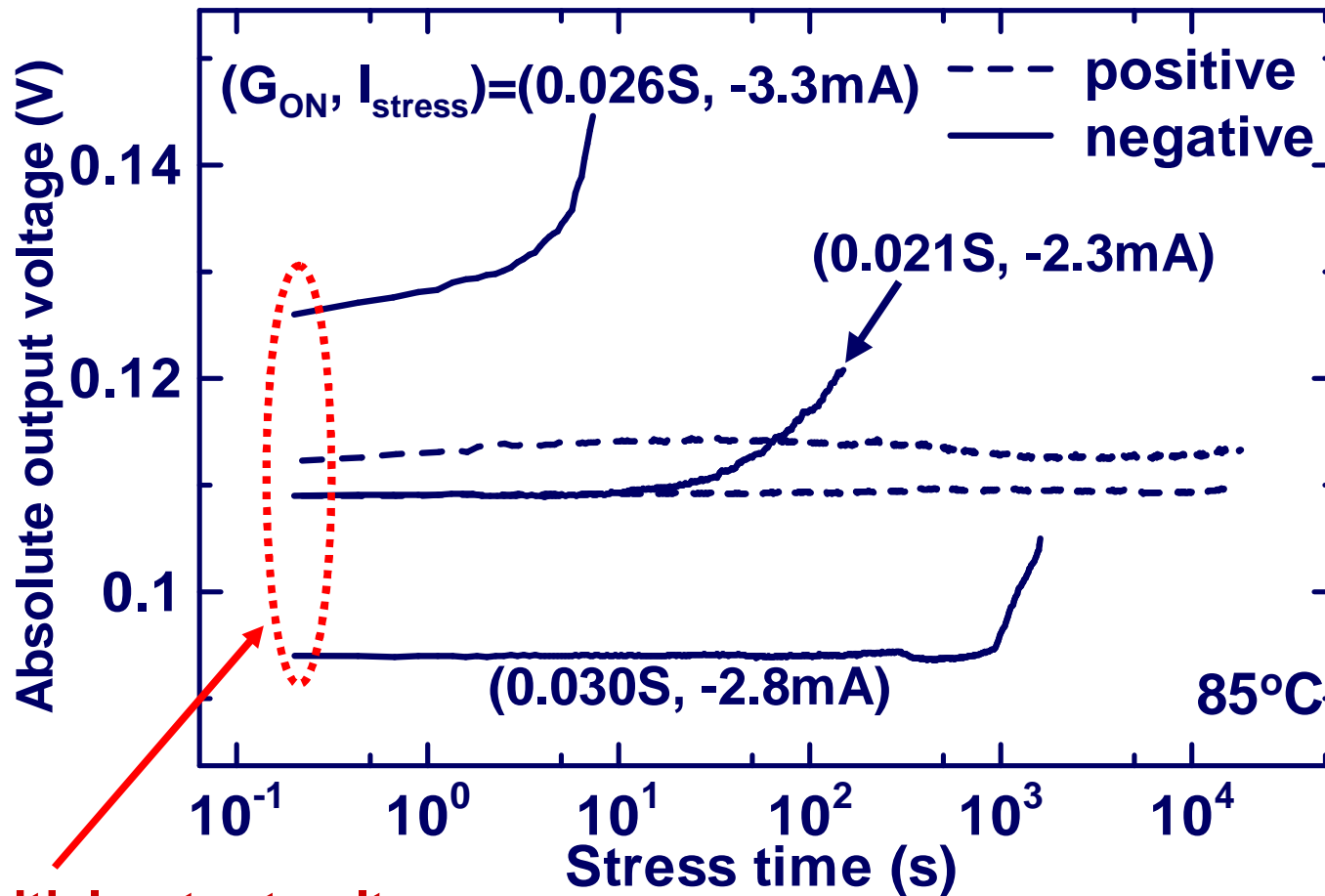
- ON state reliability of NanoBridge should be comparable to Cu plug in LSI interconnection.
- ON state reliability could depend on :
 - ON conductance (thickness of Cu bridge)
 - Bias current or voltage
 - Biasing polarity
 - Ambient temperature.



**Formulate ON-state duration
& Check it out!**

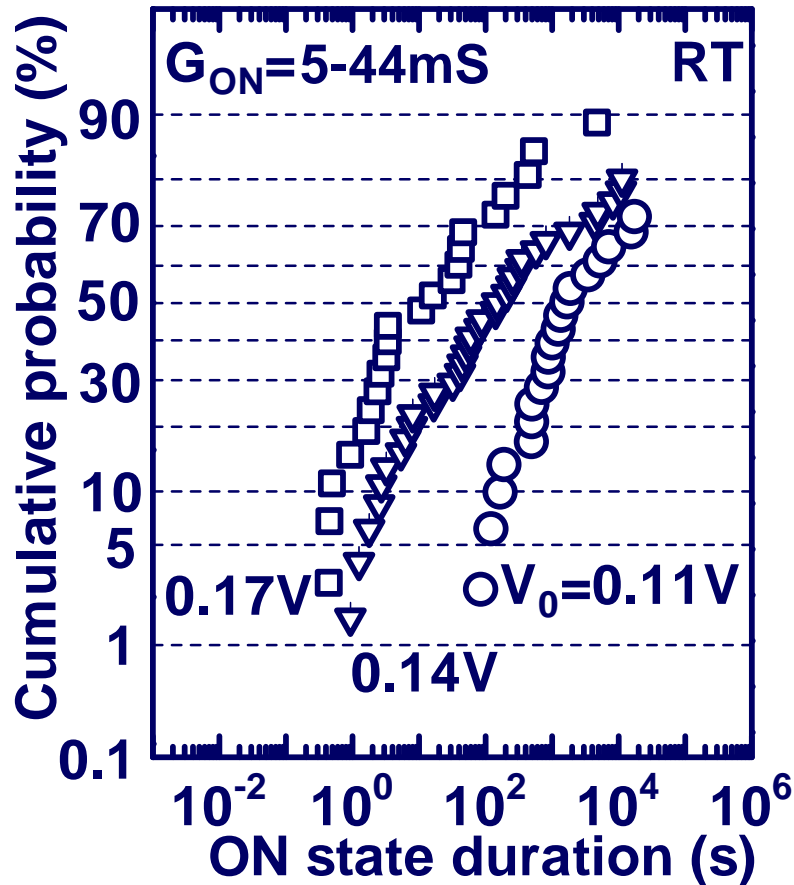


ON-state duration for various G_{ON} , I_{STRESS} , polarity

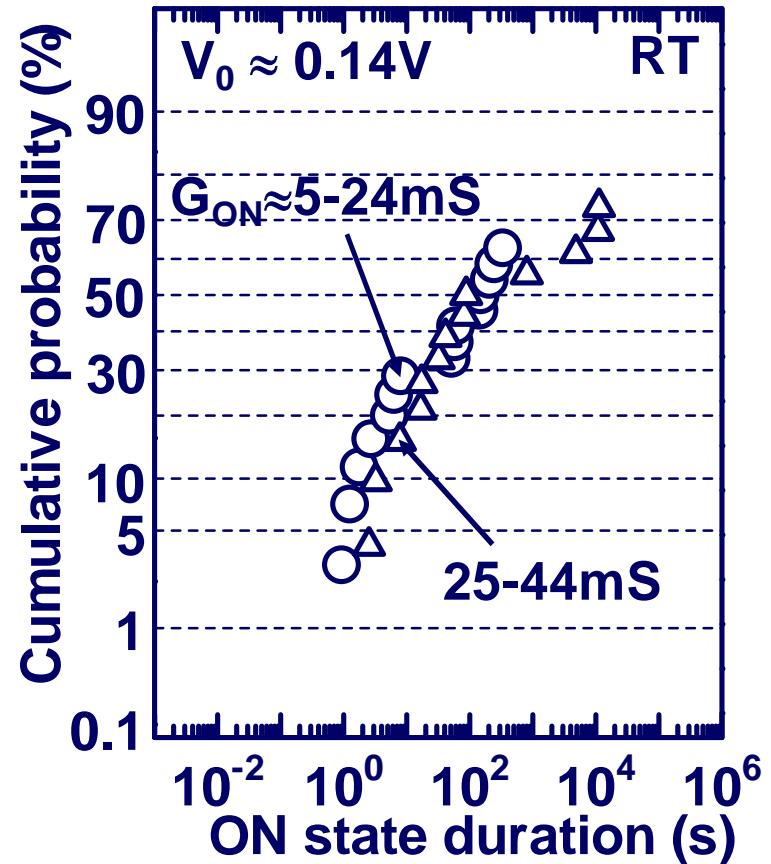


V_0 : initial output voltage

Dependence on V_0



Dependence on G_{ON}
for $V_0 \approx 0.14\text{V}$



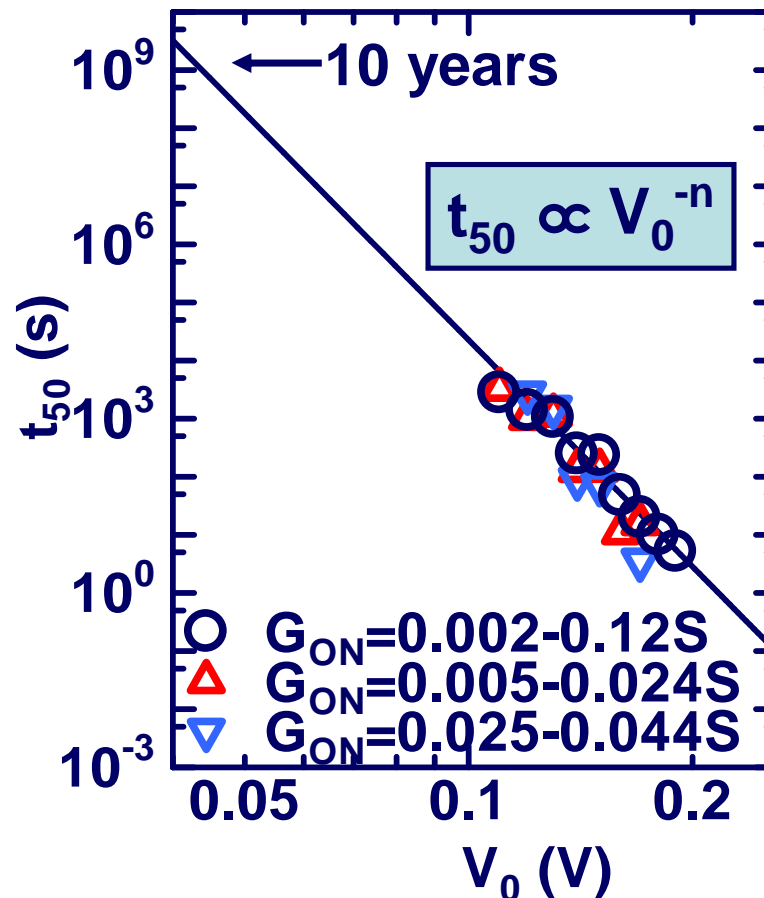
■ ON-state duration depends on V_0 ($=I_{\text{STRESS}}/G_{ON}$).

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

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

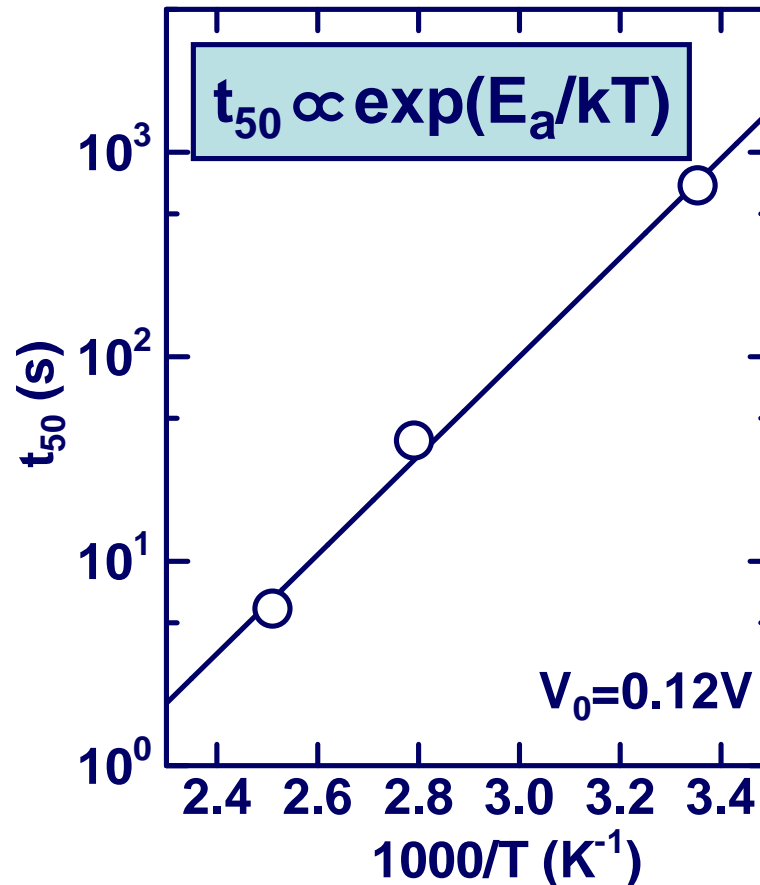
- ON-state duration depends on V_0 ($=I_{STRESS}/G_{ON}$).

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



■ ON state persists for 10years when $V_0 < 50\text{mV}$.

Temperature dependence of
median of duration



- Activation energy (E_a) is about 0.48 eV.

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

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

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

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

$$\left[\begin{array}{l} A : \text{Constant} \\ n = 12 \text{ (voltage exponent)} \\ E_a = 0.48\text{eV} \end{array} \right]$$

- 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)

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

$$\left\{ \begin{array}{l} \text{ON state duration} : t_{ON} > 10\text{years} \\ \text{Temperature} : T = 105^{\circ}\text{C} \\ \text{Maximum current} : I_{STRESS} > 0.2\text{mA.} \end{array} \right.$$

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

$$t_{ON} = 2.8 \times 10^{-21} \cdot (I_{STRESS}/G_{ON})^{-12} \cdot \exp(0.48/kT).$$

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

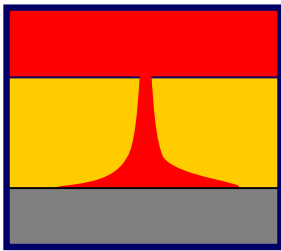
$$I_{STRESS} = 1.4 \times 10^{-2} \cdot G_{ON} > 0.2\text{mA}$$

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

Trade-off between reliability and switching current 28

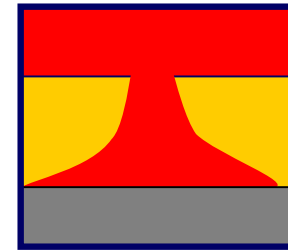
ON state reliability improves with G_{ON} .
.. But, switching current increases.

Thin Cu bridge (Low G_{ON})



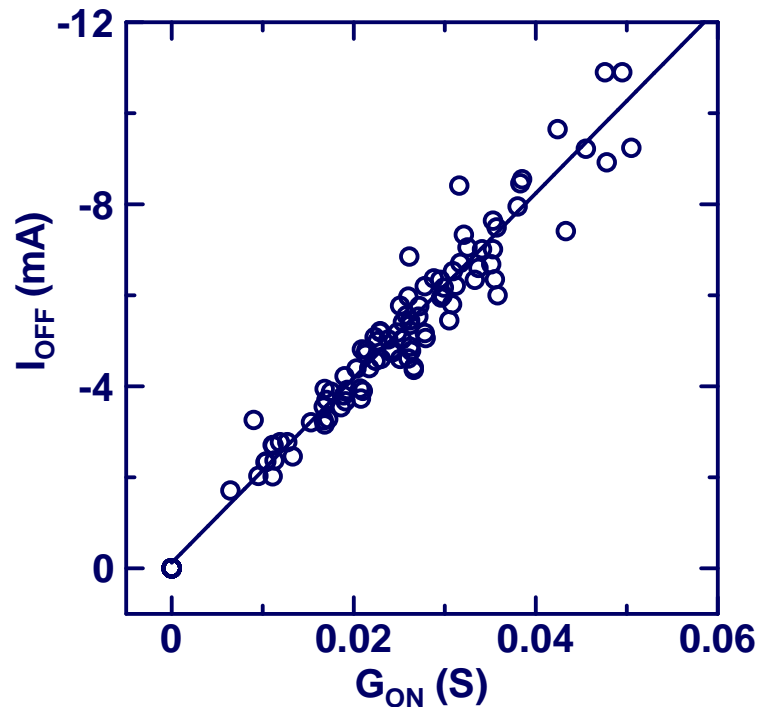
- Poorly reliable
- Low switching current

Thick Cu bridge (High G_{ON})



- Highly reliable
- Large switching current



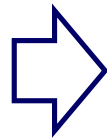


$$I_{OFF} = 0.2 \times G_{ON} < 5\text{mA}$$

(Minimum current for antifuse)

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

$$\left\{ \begin{array}{l} I_{OFF} = 0.2 \times G_{ON} < 5\text{mA} \\ I_{max} = 1.4 \times 10^{-2} \cdot G_{ON} > 0.2\text{mA} \end{array} \right.$$



$$G_{ON}: 14 - 28\text{mS}$$

$$R_{ON}: 41.7 - 71.4\Omega$$

Summary of properties

Parameter Name	Cu ₂ S switch ¹⁾	Ta ₂ O ₅ switch
ON resistance	OK (<100)	OK (<100)
Switch size	OK (4F ²)	OK (4-8F 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

- 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.

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- Nano Electronics Res. Labs., NEC

Noriyuki Iguchi, Shinji Fujieda

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