Weibull Analysis of the Kinetics of Resistive Switches based on Tantalum Oxide Thin Films

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Outline

- Introduction
- Experimental
  - Samples and Basic Characteristics
  - Pulse Measurement
- Results and Discussion
  - Weibull Distribution of SET Time
  - Discussion about Joule Heating
- Conclusion

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Bipolar Resistive Switching Effects

- Observed in various metal oxides
  - TiO_x, TaO_x, HfO_x, $SrTiO_x$, …

R. Waser et al., Adv. Mater. 21, 2632 (2009)

- Potential application to devices of next generation
  - High density nonvolatile memory (ReRAM)
  - Stateful logic operation J. Borghetti, et al., Nature 464, 873 (2010)
  - Neuromorphic computing, etc.

S. Yu, et al., IEDM 2012, S. Park, et al., IEDM 2012

- Mechanisms
  - Migration of oxygen vacancies or oxygen ions (Valence change memory , VCM)
  - Formation and rupture of a conductive path

R. Waser et al., Adv. Mater. 21, 2632 (2009)

  - Detailed mechanisms are not fully understood yet

Motivation and Objective

- Tantalum oxide (TaO_x) : one of the promising candidates for industrial application.
  - Stable operations over 10^{11} cycles
  - Complementary resistive switch operation

M.-J. Lee, et al., Nat. Materials 10, 625 (2011)

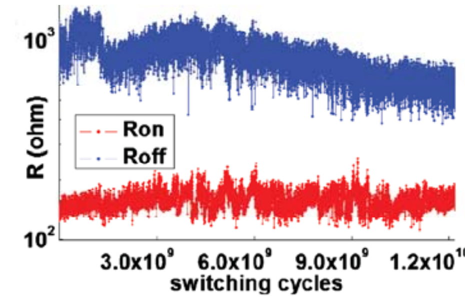
- Previous studies to understand the basic physics
  - A conductive path and its composition detected by means of physical analysis techniques.

F. Miao, et al., Adv. Mater. 23, 5633 (2011)

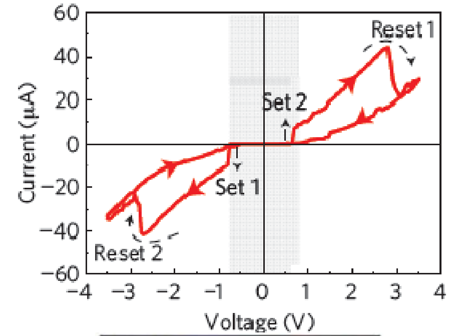
  - *Dynamic features* are yet unrevealed.

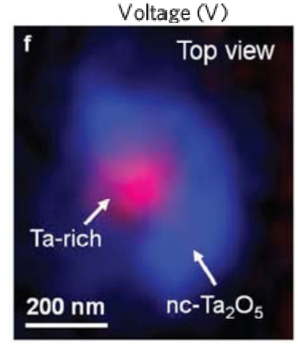
In this work…

The kinetics of the resistive switch phenomena in TaOx thin films are investigated.



J. J. Yang, et al., APL 97, 232102 (2010)





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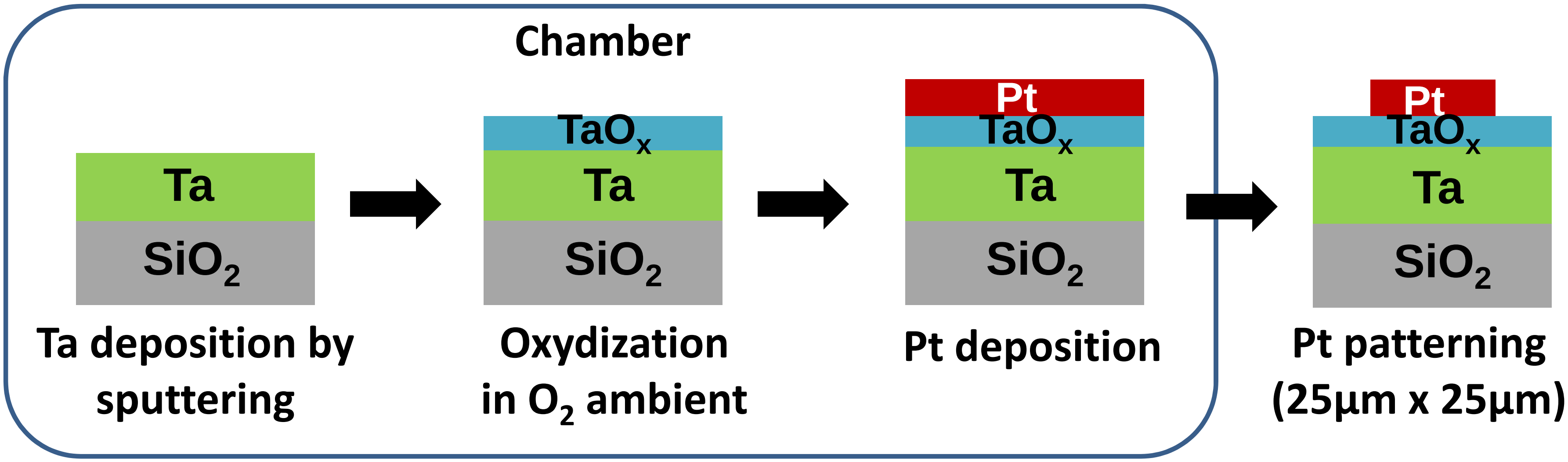
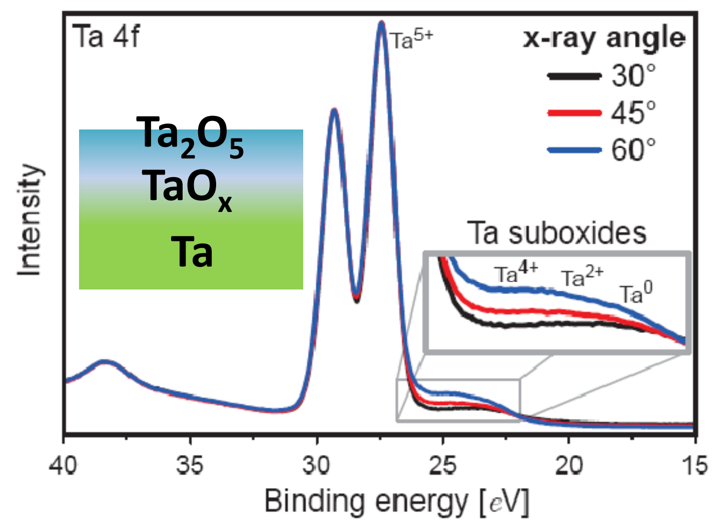
Sample Preparation

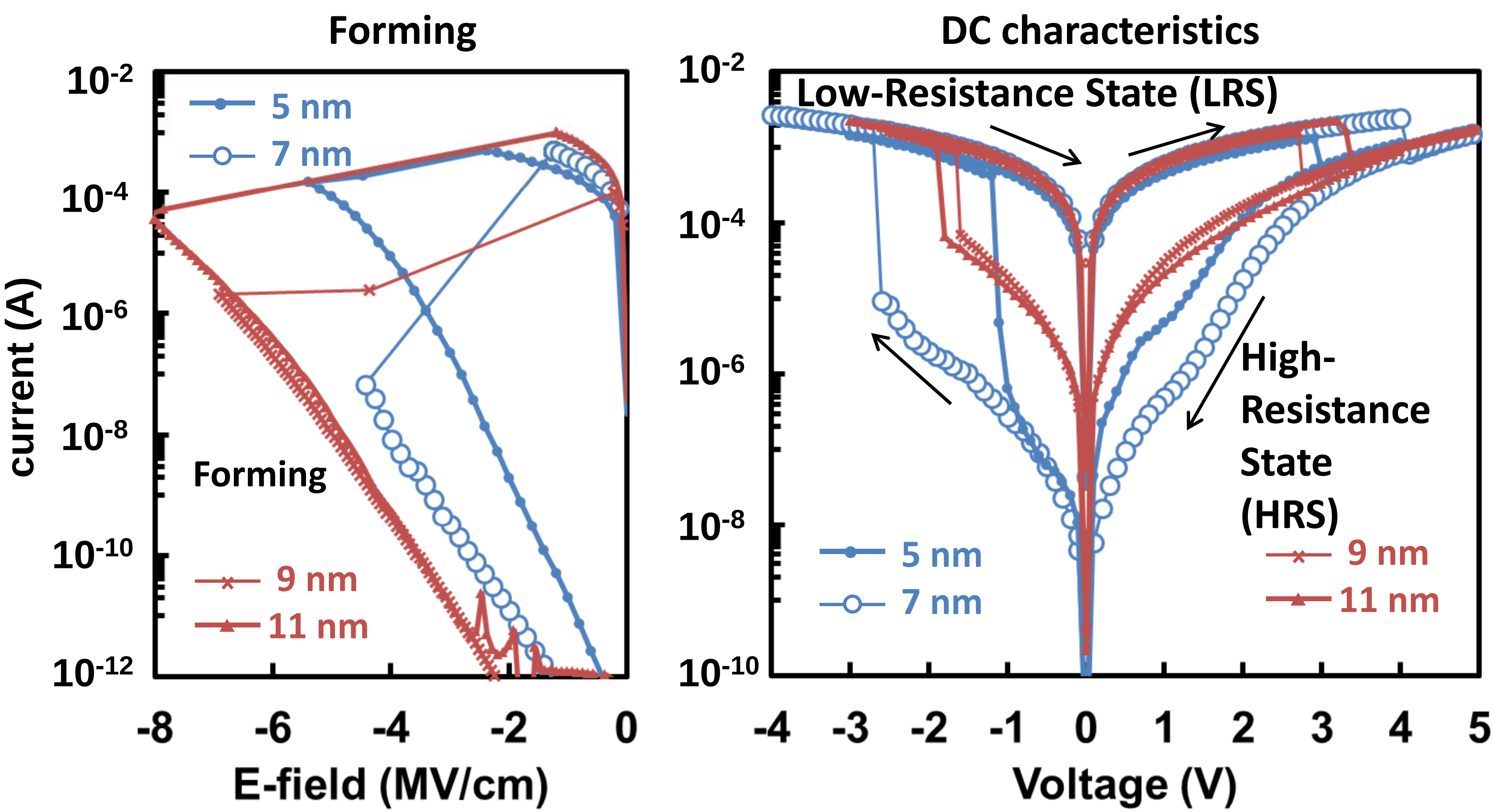


pressure (Pa)	100			
temperature (°C)	270	300	330	360
time (min)	5			
thickness (nm) *	5	7	9	11

* measured by XRR



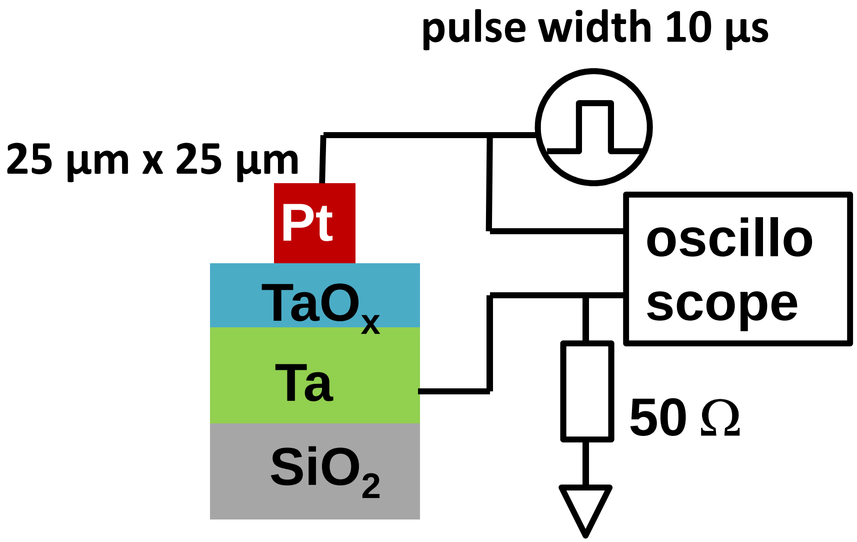
Forming and DC Characteristics

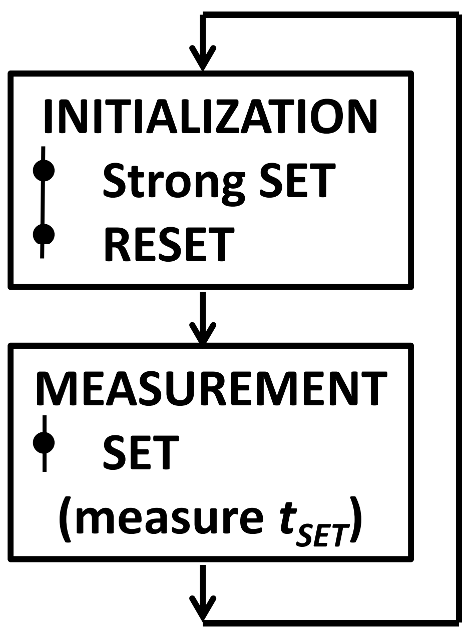


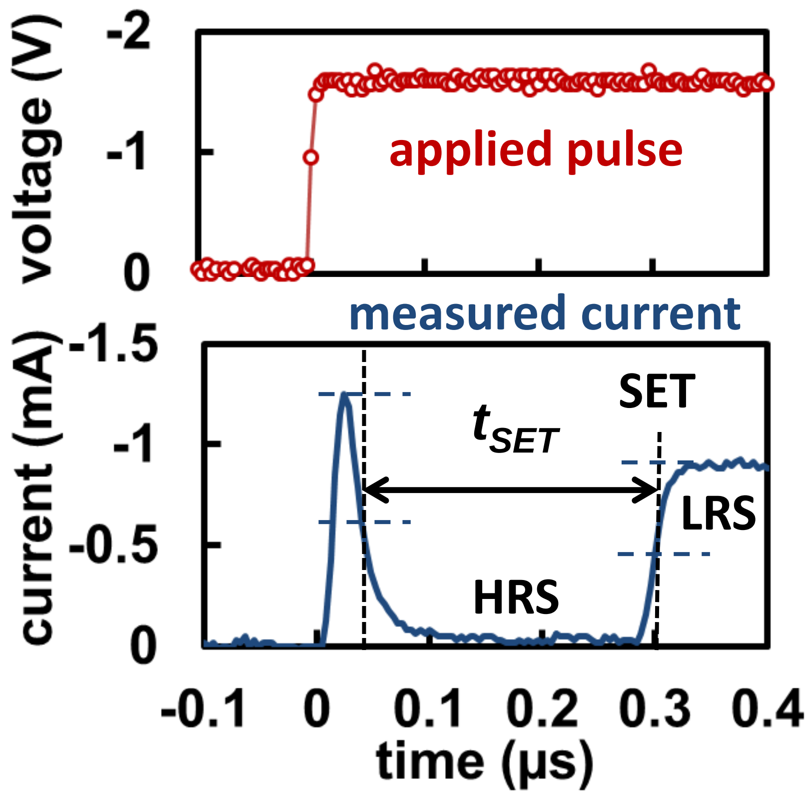
Thin (5, 7 nm) and thick (9, 11 nm) films are expected to have different switching mechanisms.

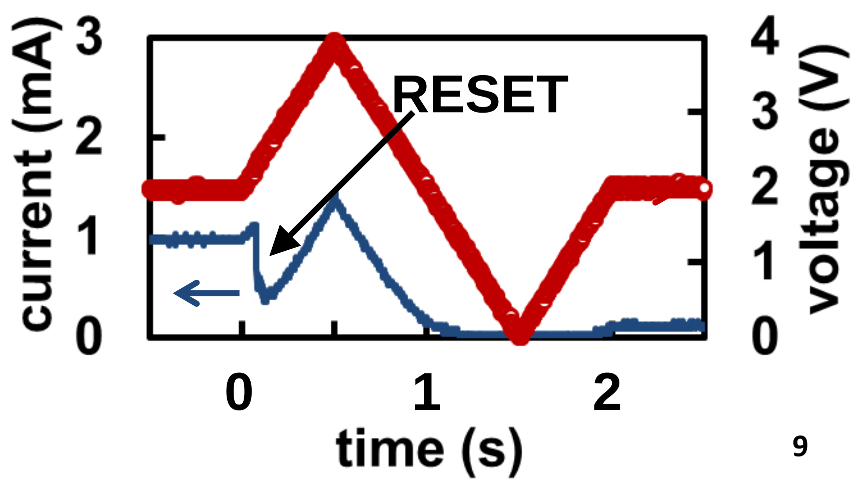
In this work, we focus on and compare two cases, 5 and 11 nm.

Pulse Measurement









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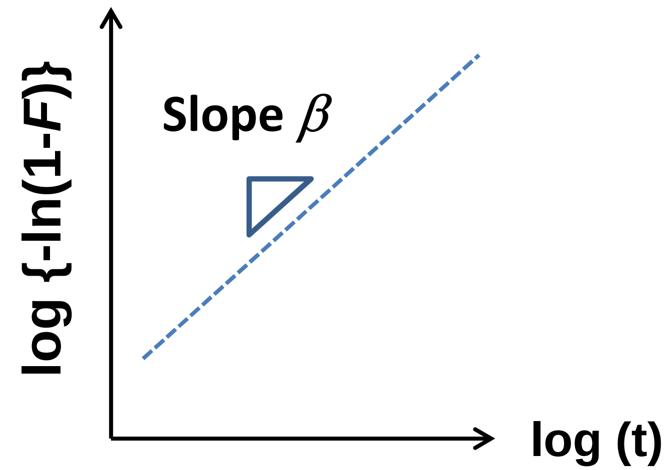
Weibull Distribution

Cumulative probability of time to SET *F*(*t*)

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

$$-\ln(1-F) \propto t^{\beta}$$



Switching rate *R*(*t*) at time *t*

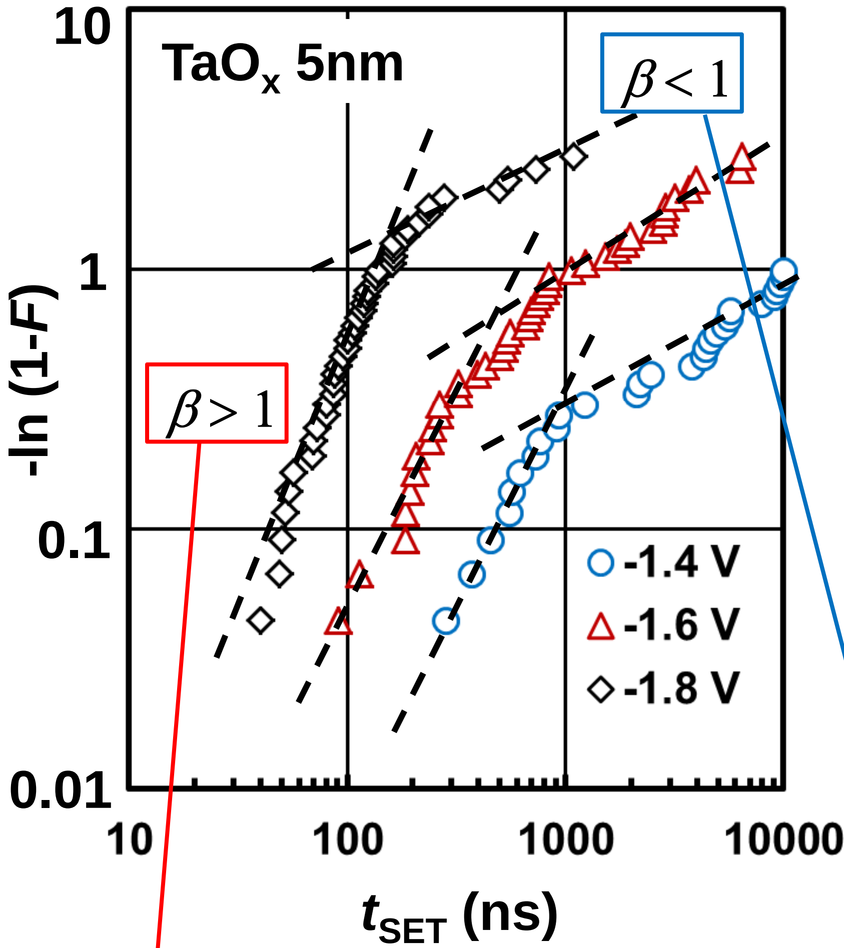
$$R(t) = \frac{dF}{dt}\Big/(1-F) \propto t^{\beta-1}$$

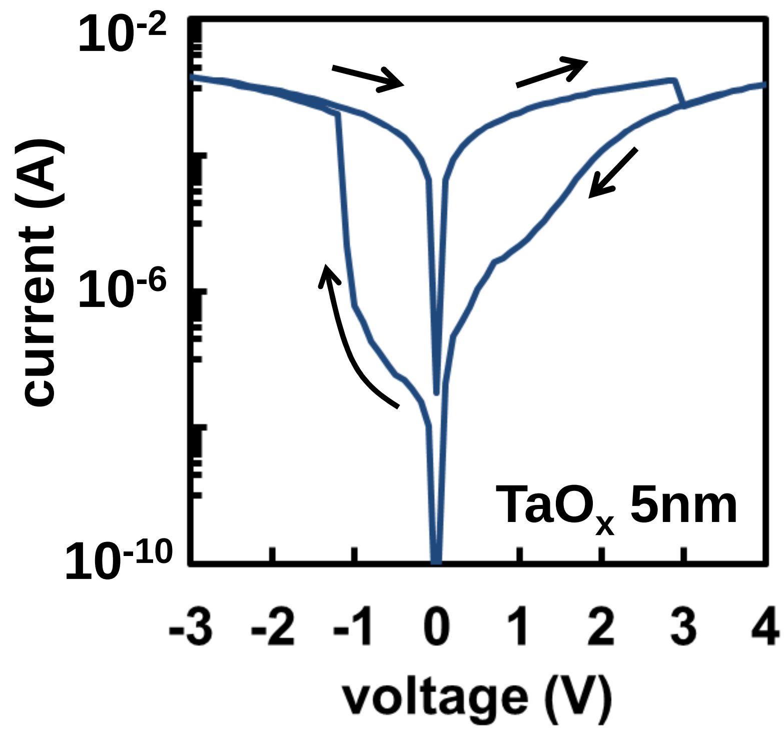
increases / **decreases** **with time for** $\beta > 1$ / $\beta < 1$

$\beta > 1$ → **SET is induced by an aging process that is accelerated with time ; progressive phenomenon.**

$\beta < 1$ → **SET is a failure event induced by the stress through the already-existing defects ; passive phenomenon.**

Weibull Plots of the SET Time (5 nm)

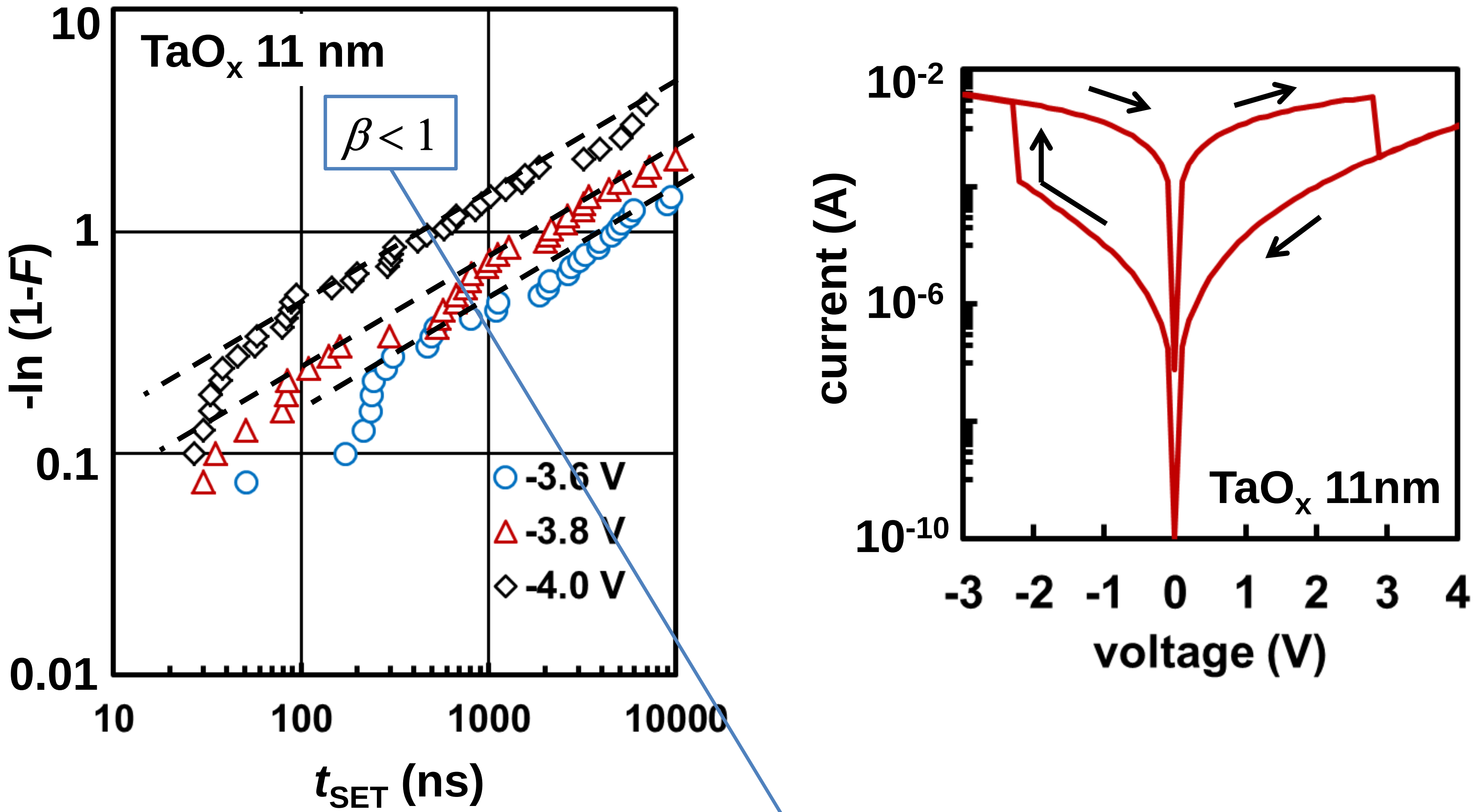




SET is accelerated with time:
SET is a progressive phenomenon

SET rate decreases with time:
SET is a failure event

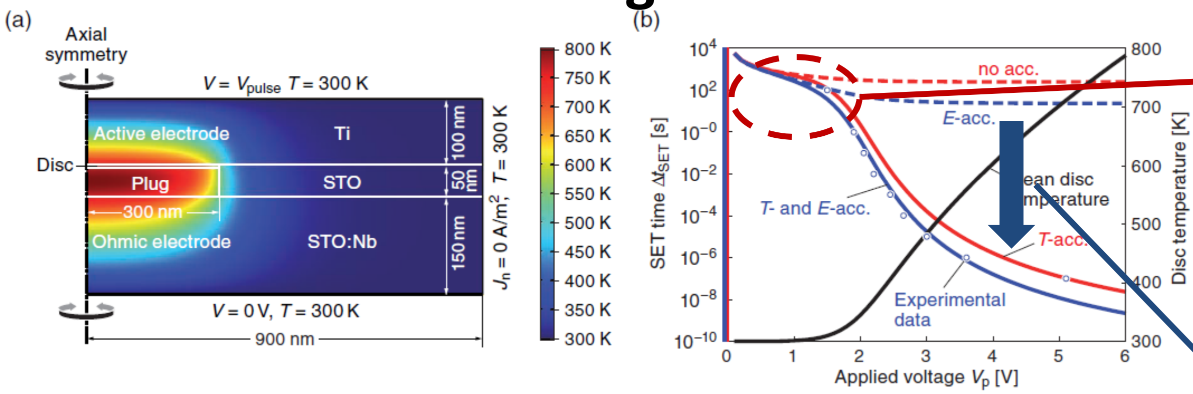
Weibull Plots of the SET Time (11 nm)



SET rate decreases with time:
SET is a failure event

What is the Driving Force in the $\beta > 1$ Region?

- **In STO: Joule heating accelerate the SET**

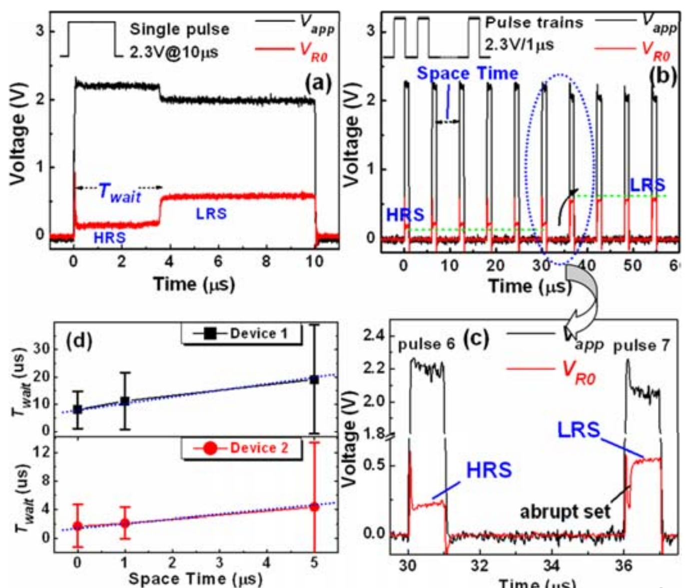


Slow SET is induced by electric field

Fast SET is accelerated by Joule heating

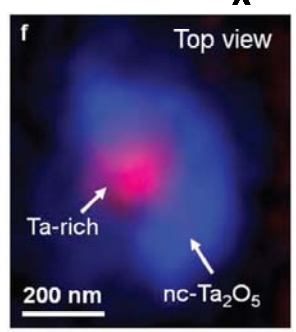
S. Menzel, et al., Adv. Func. Mater. 21, 4487 (2011)

- **In HfO_x : Pulse intervals affect the SET speed.**



M.G. Cao, et al., APL 101, 203502 (2012)

- **In TaO_x …**

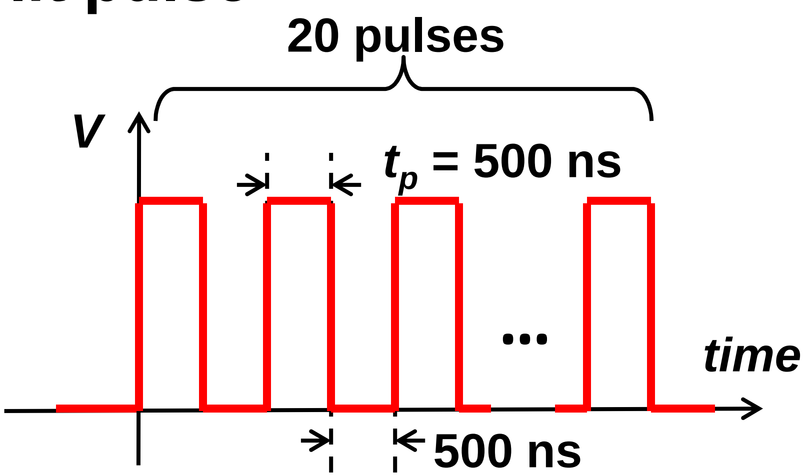


Formation of a nano-crystalline Ta_2O_5 around the conductive path : relevance of resistive switch to Joule heat.

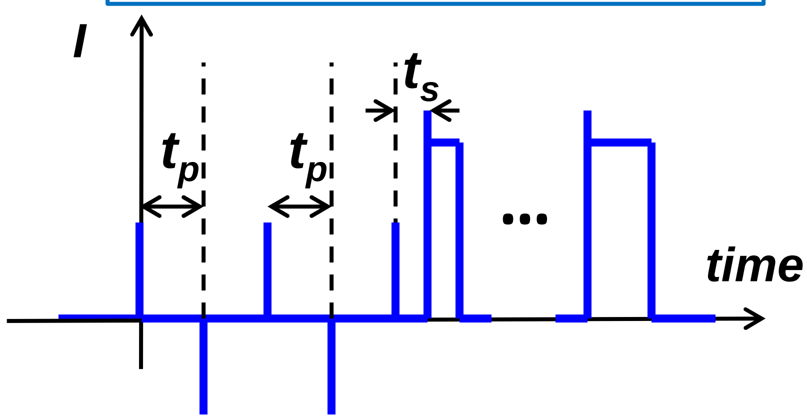
F. Miao, et al., Adv. Mater. 23, 5633 (2011)

Split pulse measurement

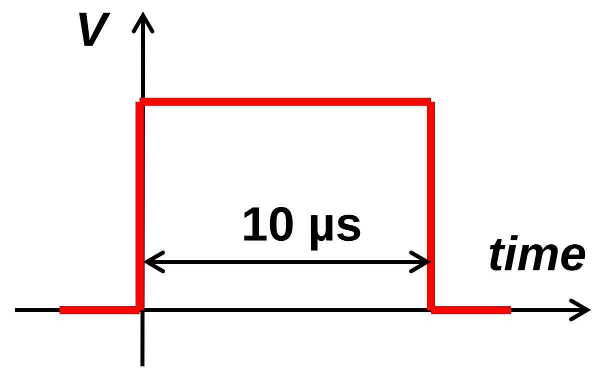
split pulse



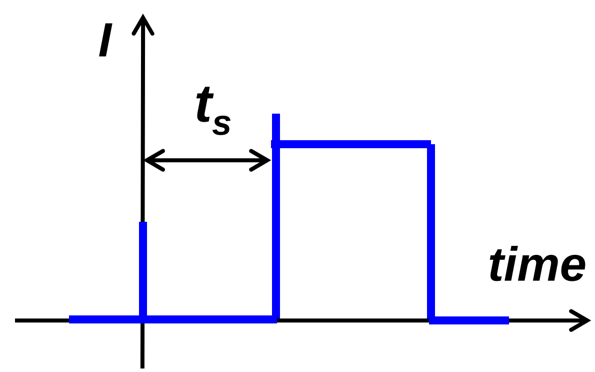
$t_{SET} = t_p + t_p + \ldots + t_s$
Accumulated time of the voltage stress until the SET.



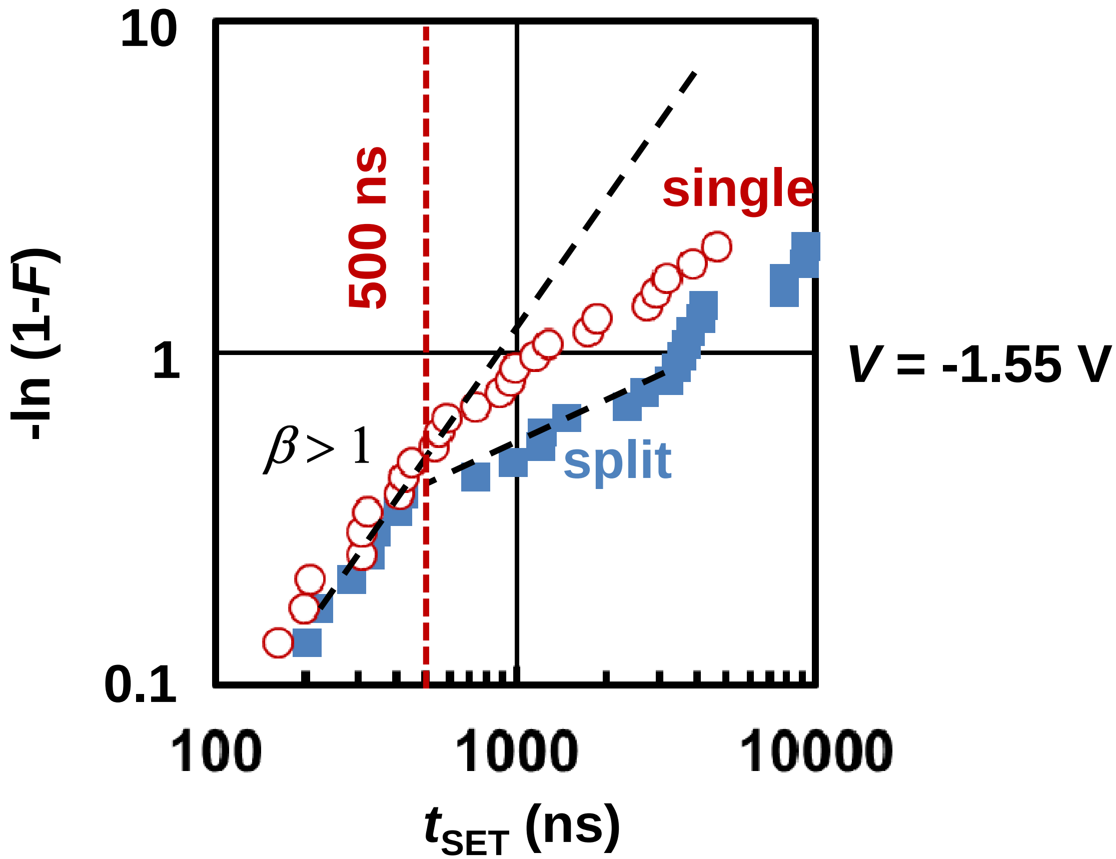
single pulse



$t_{SET} = t_s$



Split pulse measurement (5 nm, $\beta > 1$)

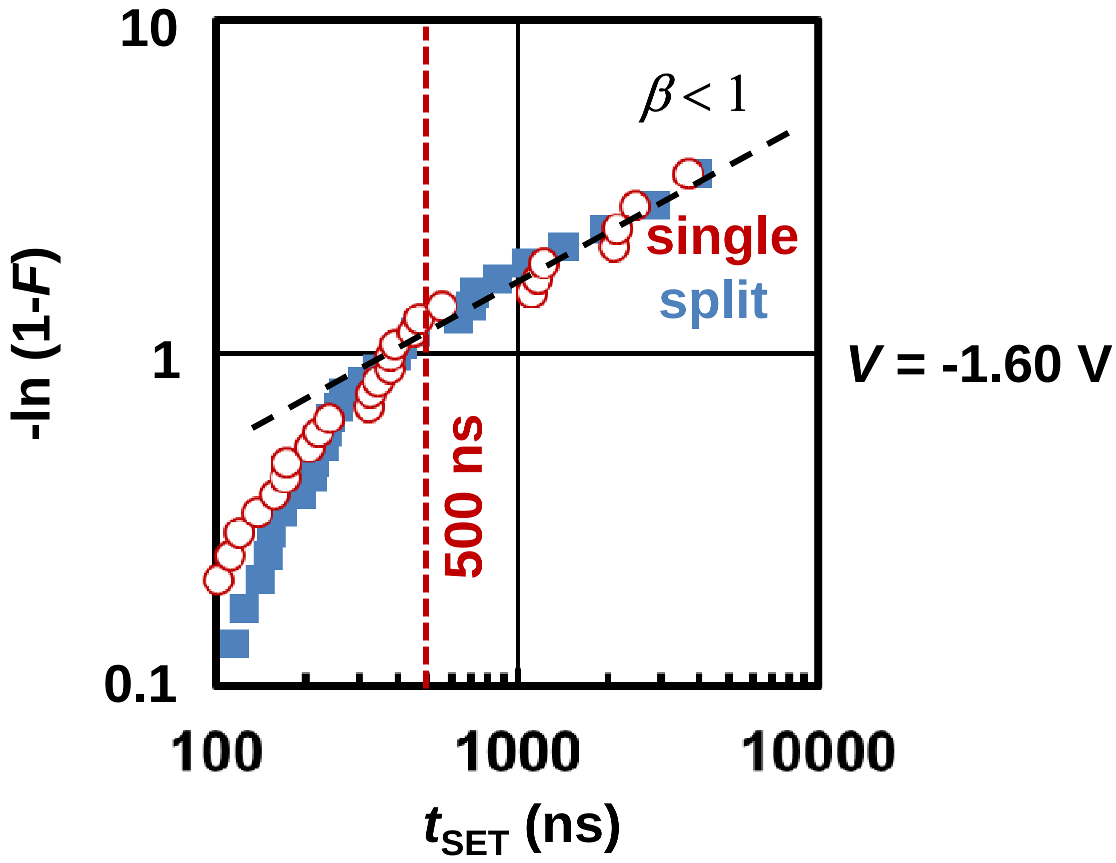


"Split" distribution deviates from that of "single" in $\beta > 1$ region.

- **$\beta > 1$: Pulse intervals (i.e. heat dissipation) affect the distributions.**

→ Joule heating contribute to SET mechanism.

Split pulse measurement (5 nm, β< 1)

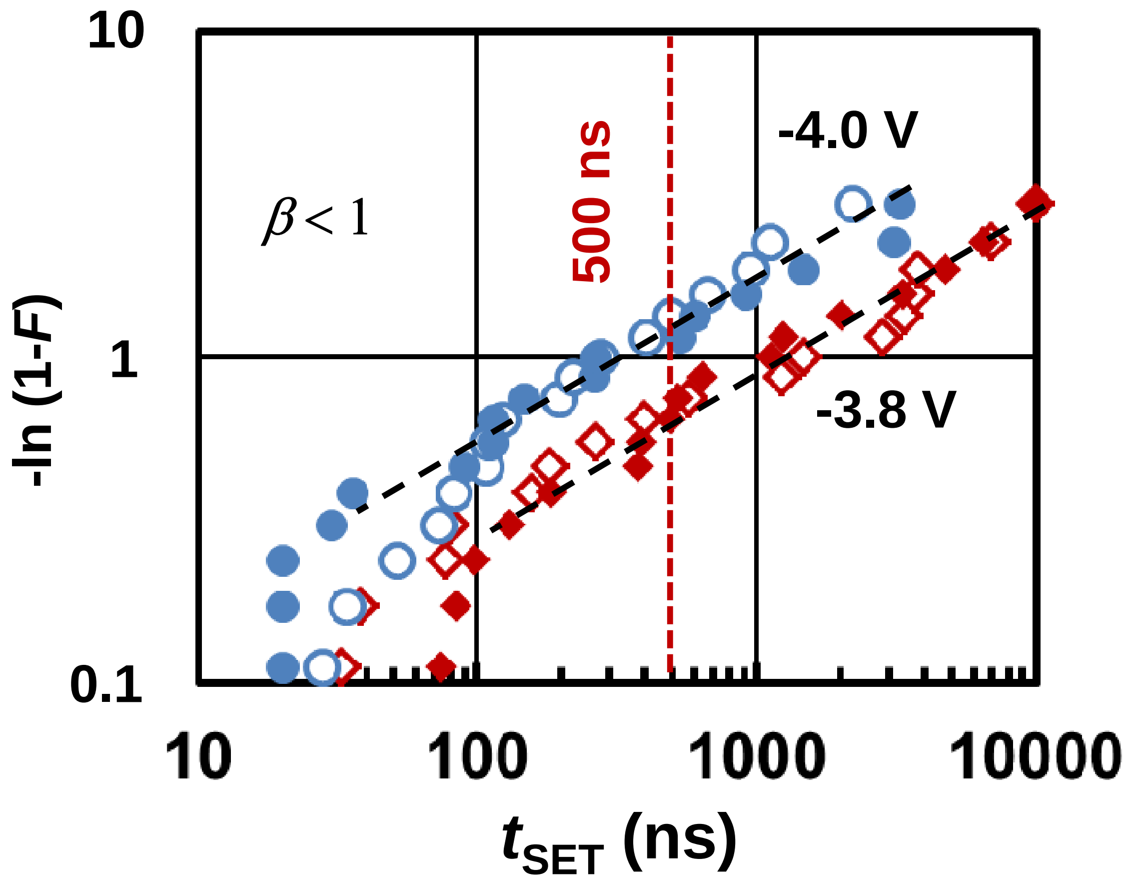


"Split" and "single" distributions overlap in β< 1 region.

- **β< 1 : Heat dissipation has no effect on the distributions**

→ SET is induced by the applied electric field only.

Split pulse measurement (11 nm)

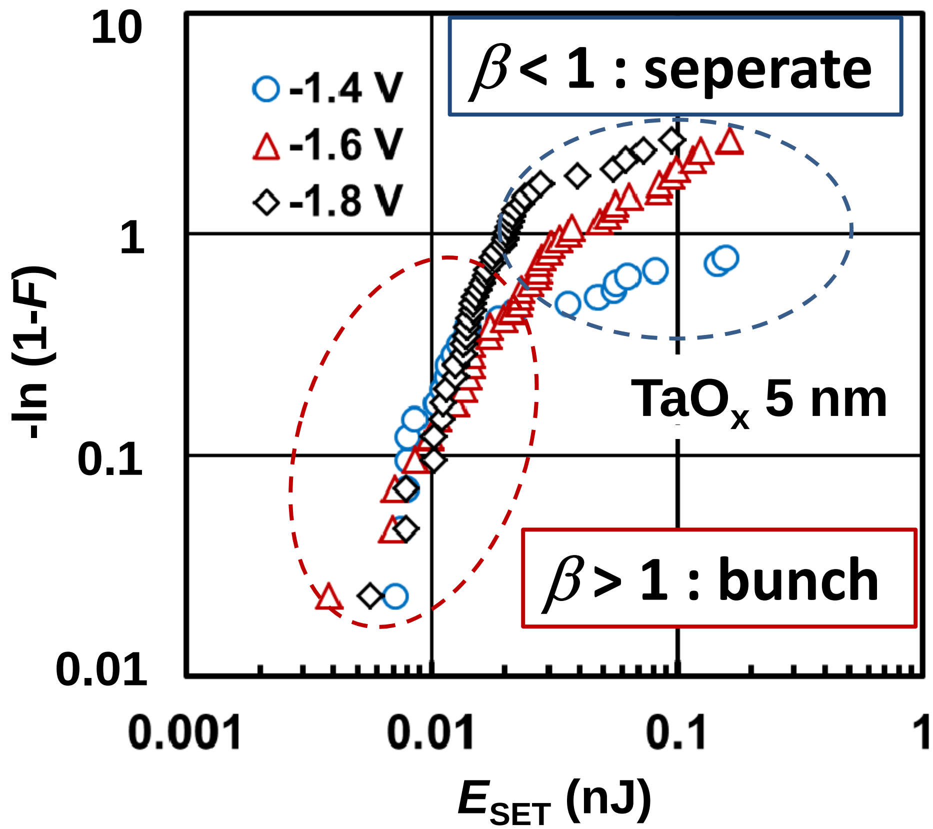


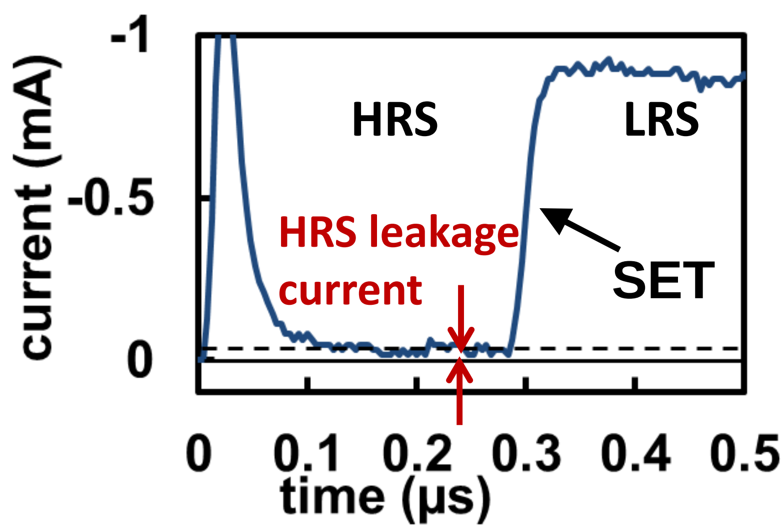
Filled : split pulse
Open : single pulse

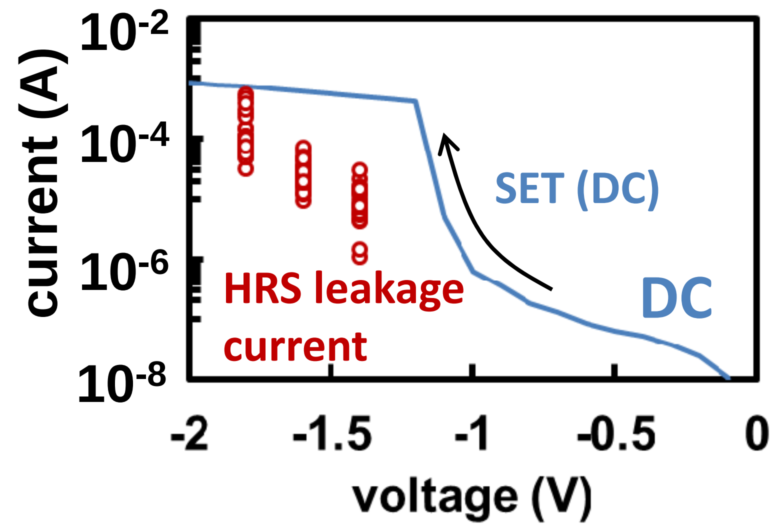
Distributions of “split pulse” and “single pulse” overlap;
Heat dissipation does not influence the distributions.
→ Effect of the electric field to SET is more dominant than that of the Joule heating.

Distributions of Energy for SET (5 nm)

E_{SET}: energy consumed before SET
$= V_{pulse} \times I_{HRS} \times t_{SET}$



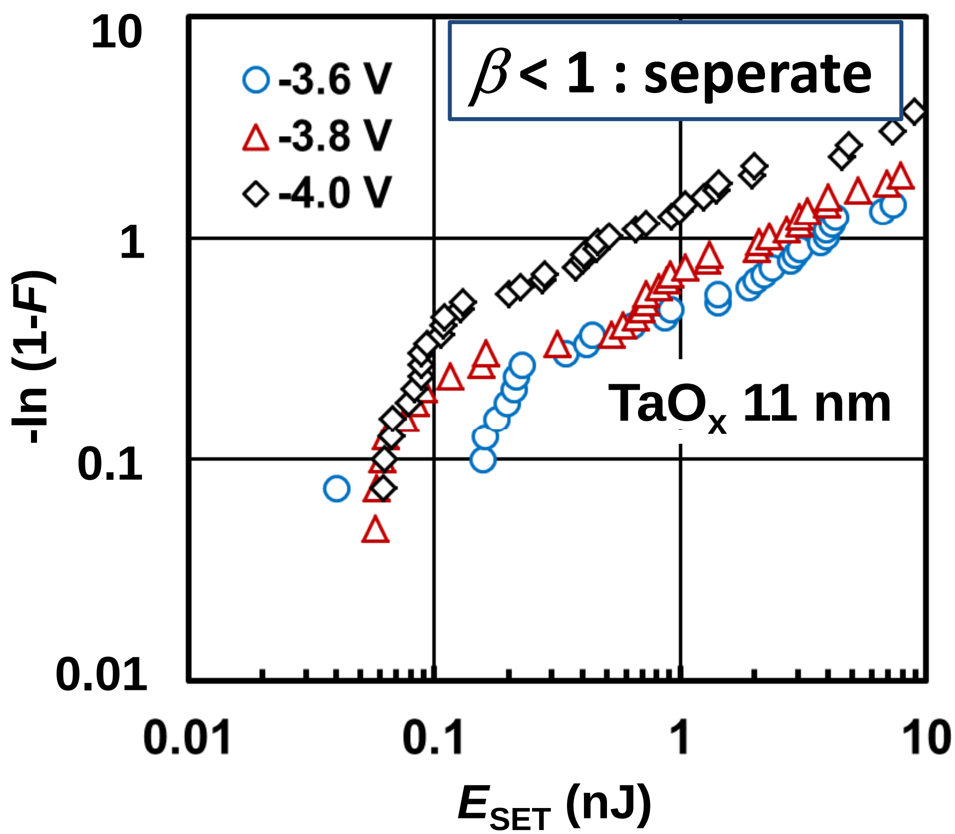


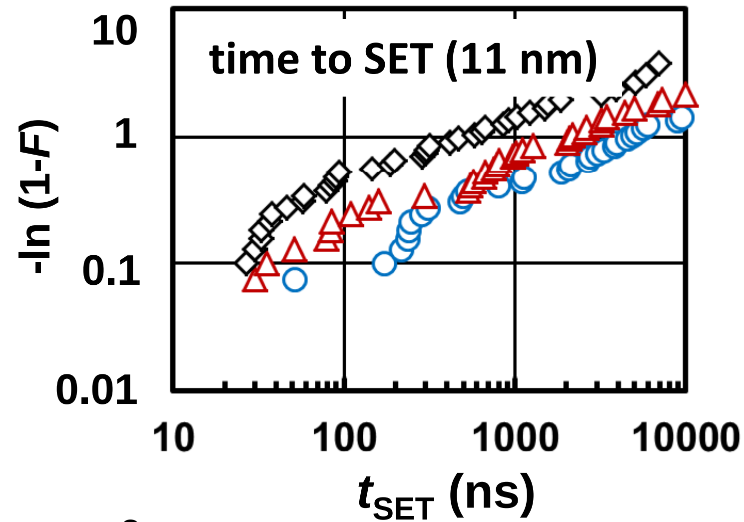


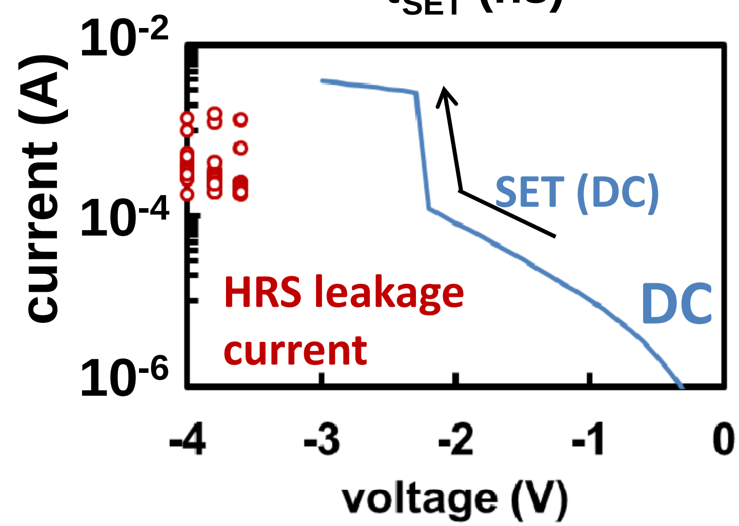
Distributions of E_{SET} in $\beta > 1$ mode indicate that the heat generated by HRS current is a key factor in the SET mechanism.

Distributions of Energy for SET (11 nm)

E_{SET}: energy consumed before SET
$= V_{pulse} \times I_{HRS} \times t_{SET}$







Distributions of E_{SET} look similar to those of t_{SET}.

Conclusion

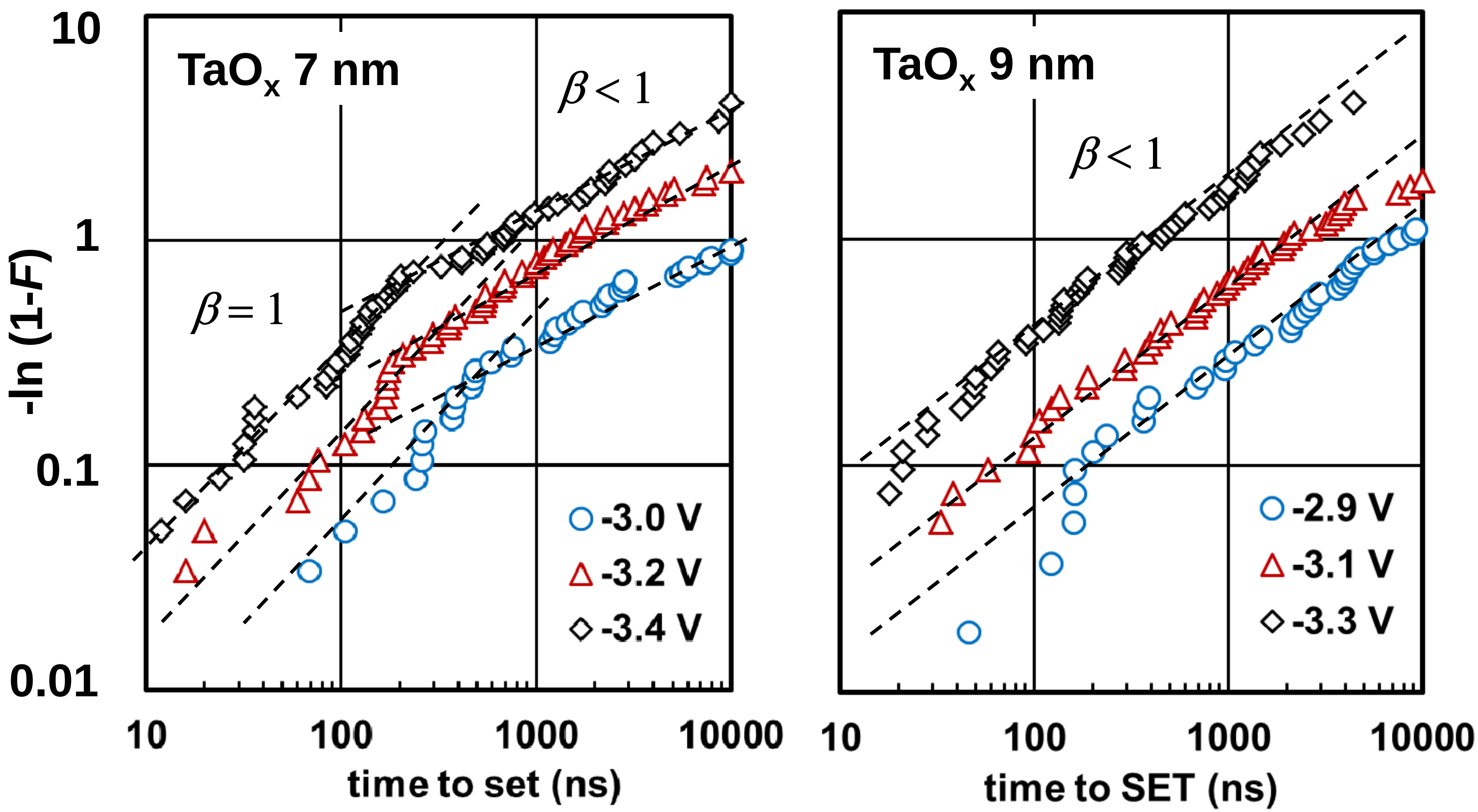
- **Statistics of the time to SET in TaO_x thin films are well explained in terms of Weibull distribution.**
  - **Both $\beta > 1$ and $\beta < 1$ distributions appear in 5 nm film.**
  - **$\beta < 1$ distribution is dominant in 11 nm film.**

- **Split pulse measurement indicates the difference in the SET mechanisms between $\beta > 1$ and $\beta < 1$ distributions.**
  - **$\beta > 1$ distribution is affected → Joule heating is relevant to the SET mechanism.**
  - **$\beta < 1$ distribution is not affected → Joule heating is less relevant in this case.**

- **Weibull plots of the total energy for SET support the hypothesis of the Joule heating in $\beta > 1$ mode.**

Thank you for your attention.

Weibull Plots of the SET Time (7, 9 nm)



Size dependence of the HRS current