EU-South Korea Joint Researchers Forum on Semiconductors

Mott switch-based future computing

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KAIST

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Table of Contents

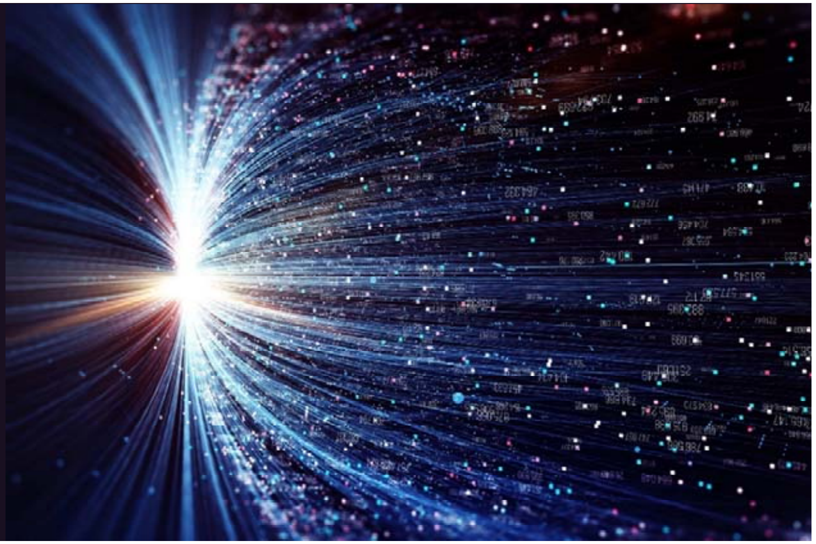
01

Introduction

Data curation in modern society

Data explosion (big data)

AI technologies promote the global data creation, and the data is multiplied by restructuring.



Internet of Things (IoT)

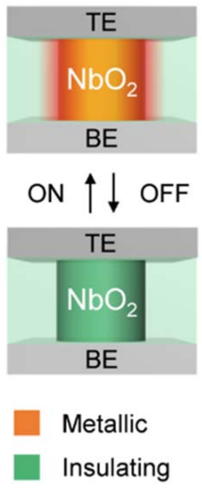
Strong Security

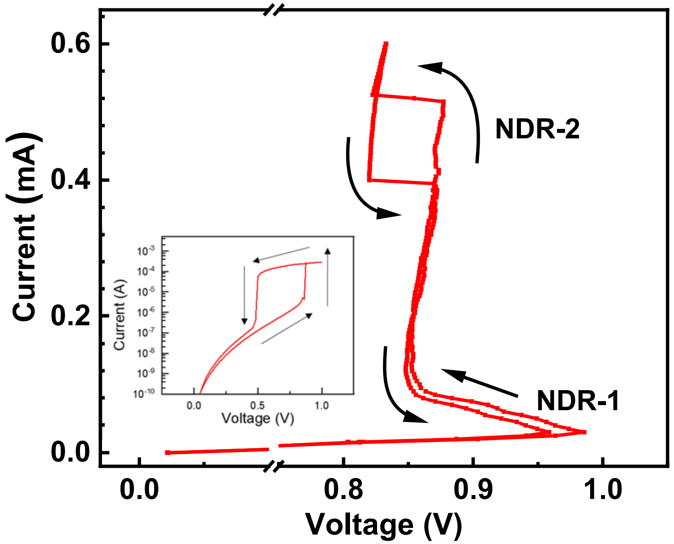
Data processing

Efficient computing

NbO_2 Mott switch memristor

- **General characteristics of Mott memristor**

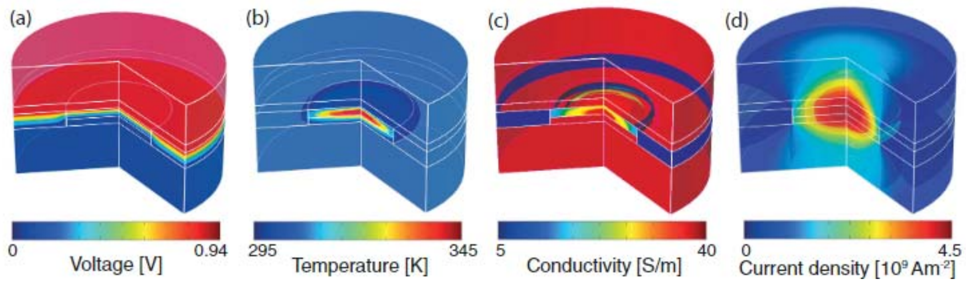




Current-controlled I-V characteristic of NbO_x based memristor device

A two-terminal switch, potentially applicable in emerging computing

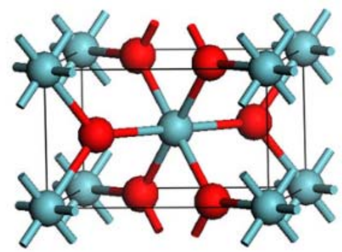
NDR-1 :
Field Triggered Thermal Runaway (FTTR)



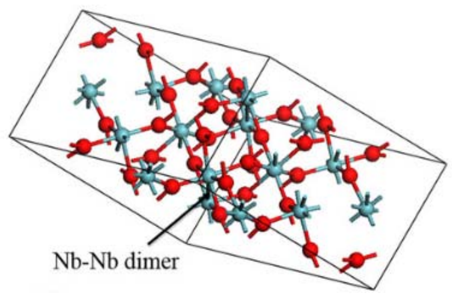
Transparent 3D view for FTTR-model

NDR-2 : Metal-insulator transition

Electric field-induced thermal runaway



High-T Rutile NbO_2 (Metallic)

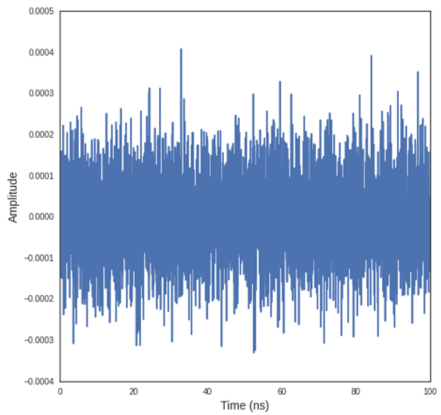


Low-T bc-tetragonal NbO_2 (Insulating)

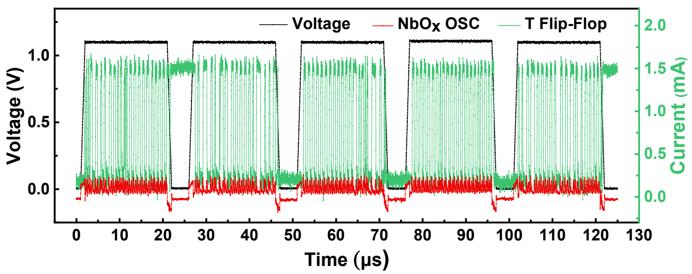
Mott memristor for future computing

- **Key features of Heat Mott memristor for future computing**

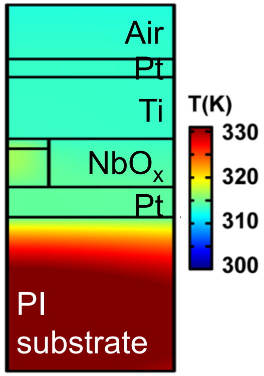
Thermal noise (stochastic)



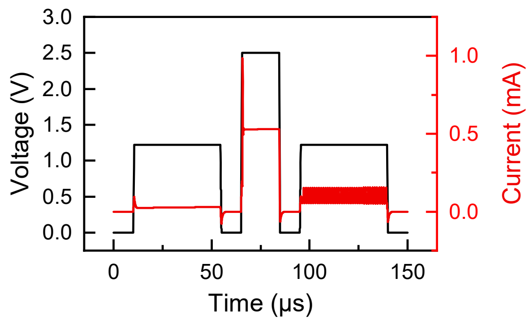
TRNG



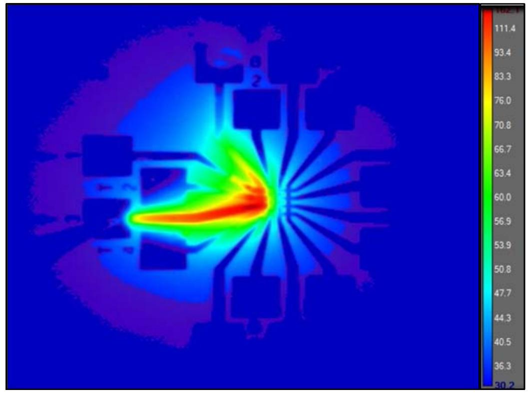
Heat accumulation (temporal dynamics)



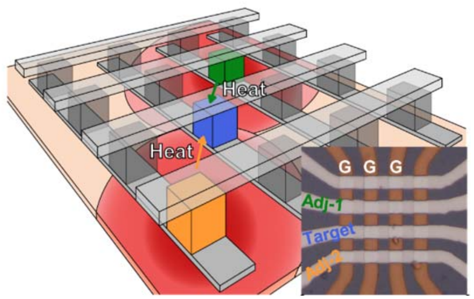
Mott Neuron



Heat diffusion (spatial transfer)



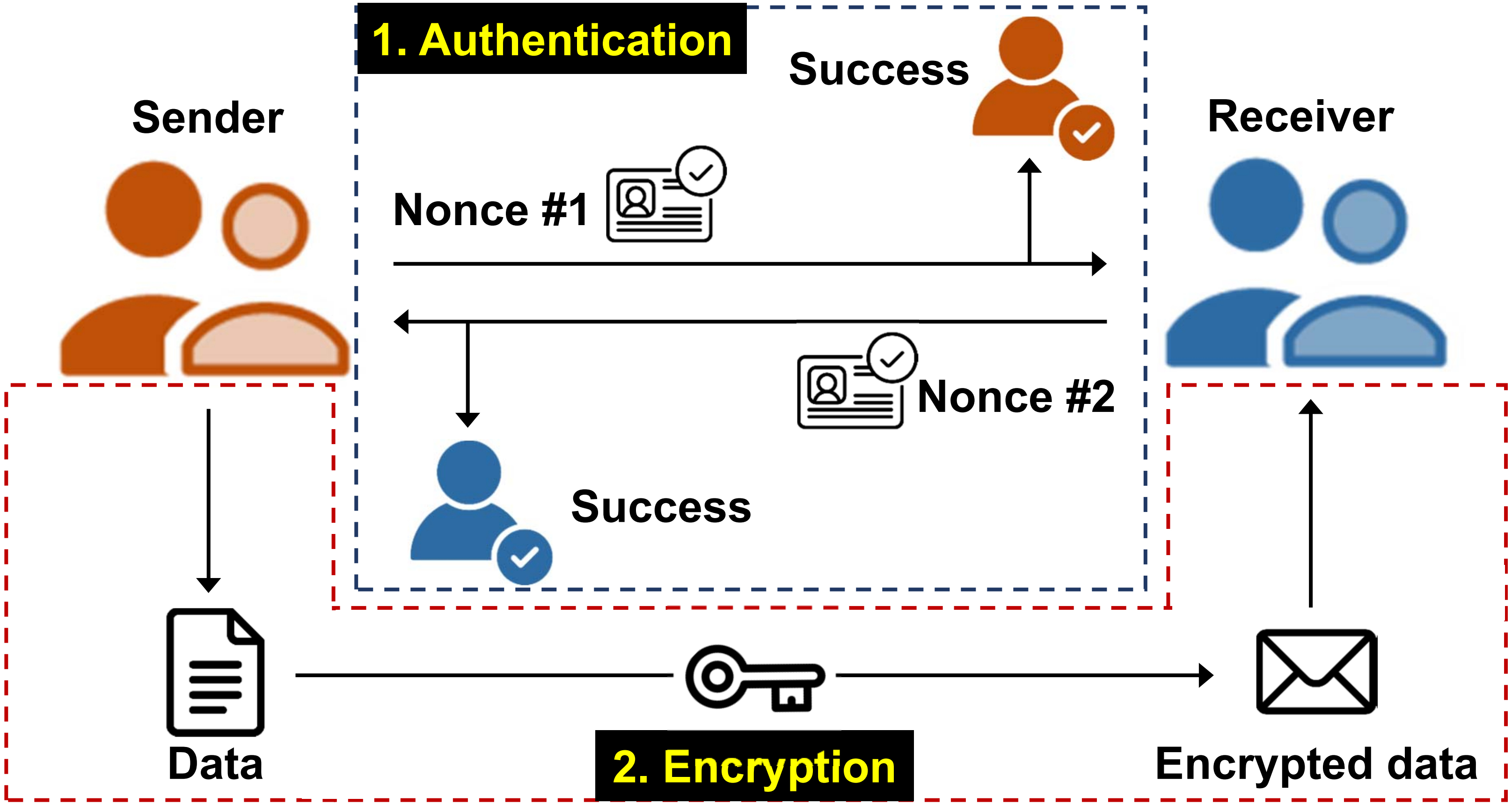
Thermal computing



02

Using thermal noise for True Random Number Generator

Secure communication using random numbers



- Number used once (nonce) is a set of random numbers for authentication.
- For each communication, two nonces are required.
- If authentication was successful, then encrypted data is transmitted.

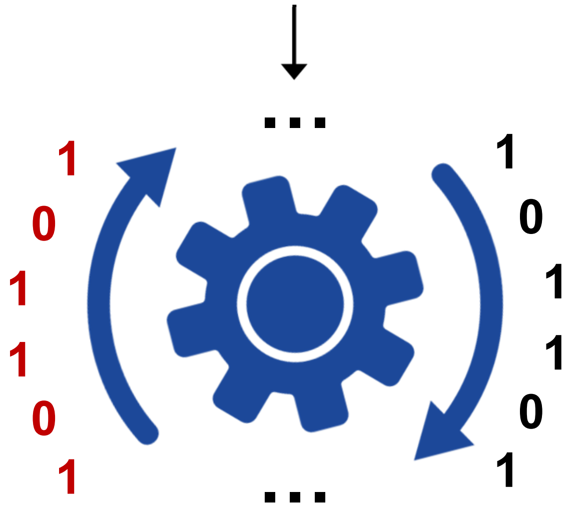
Random numbers are constantly demanded for security

Unpredictable true random number

- **Pseudo random number (PRN)**

Seed number

1001



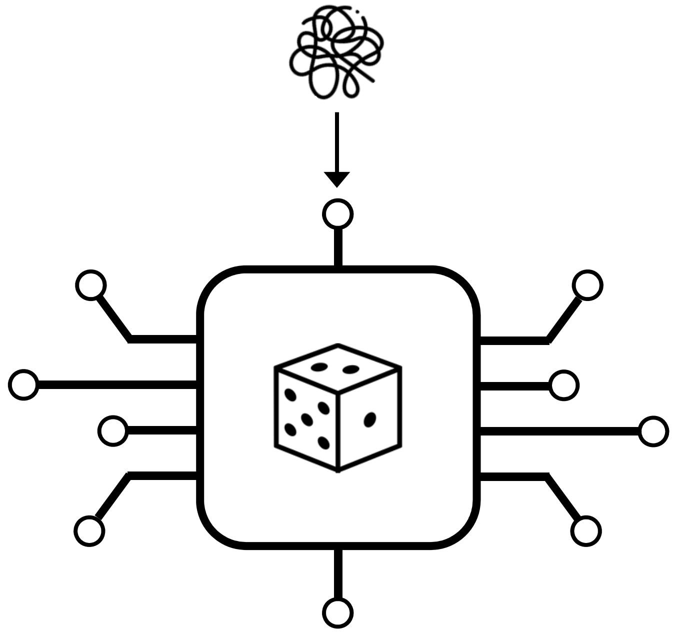
Patterned numbers
Periodic numbers

Predictable

VS

- **True random number (TRN)**

Random noise



1 or 0
Stochastic numbers

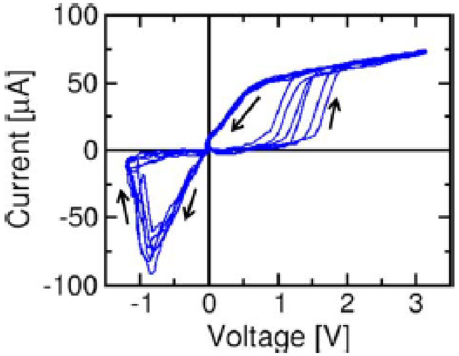
Unpredictable

TRNG exploits random noise to generate True Random Number

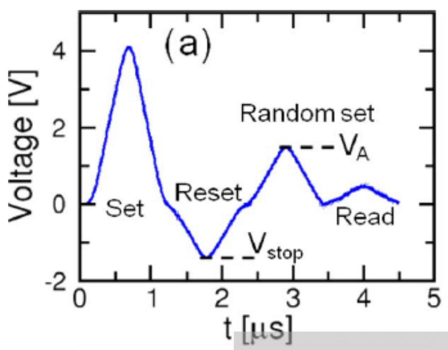
Previous memristive TRNG researches

- **Non-volatile memristor-based[1]**

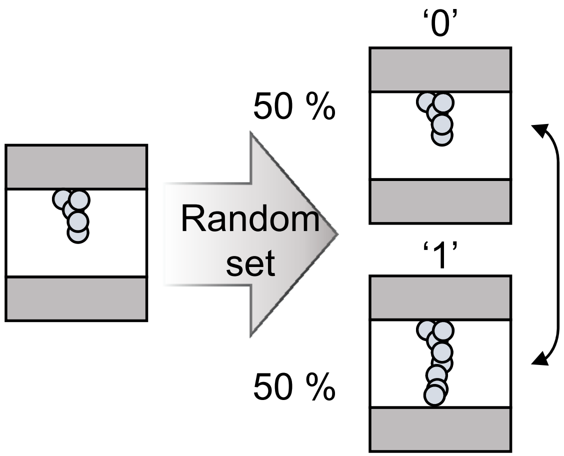
I-V



Generation process



RN generation process



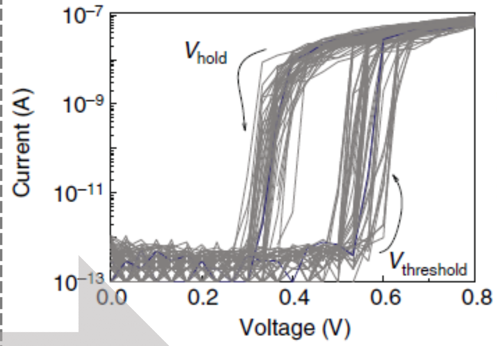
Correlation exists

- RN generation is fast, but **unreliable** because of **correlation** of switching.

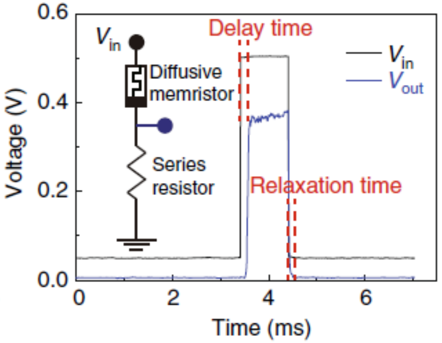
For stable RN generation

- **Volatile memristor-based[2]**

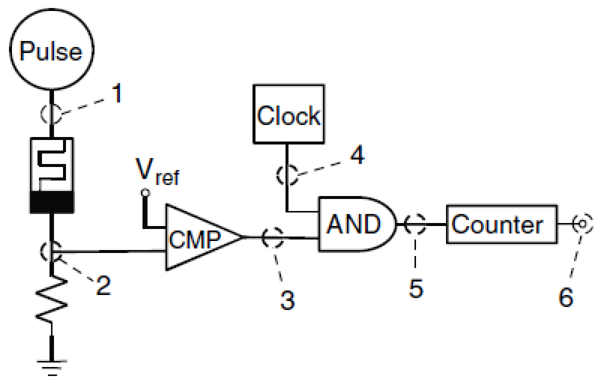
I-V



Stochastic switching



TRNG circuit

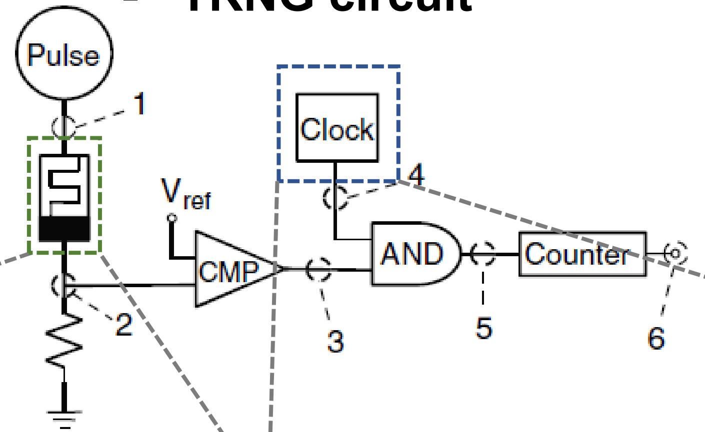


- **No correlation** between switching, so RN generation is **stable**.

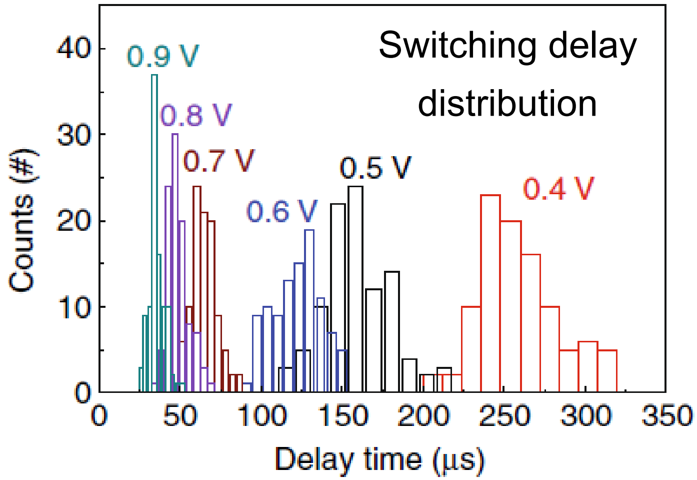
[1] S. Balatti et al., *IEEE Journal on Emerging and Selected Topics in Circuits and Systems* **5**, 2 (2015)
[2] H. Jiang et al., *Nat. Commun.* **8**, 882 (2017).

Limitations of previous volatile memristive TRNG

- **TRNG circuit**

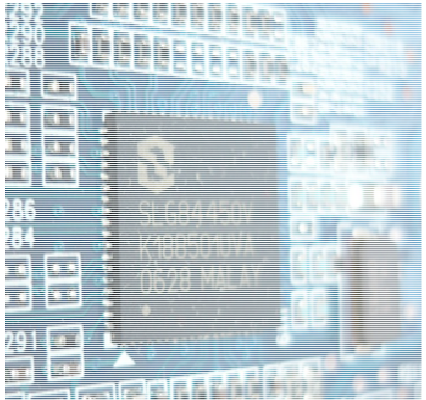


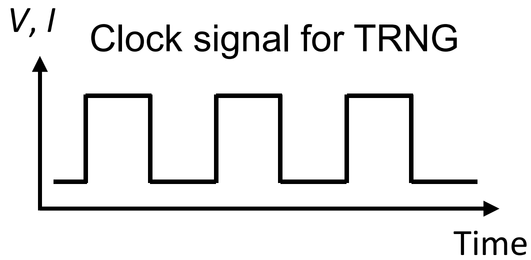
1. Slow TRNG speed



- It takes **hundreds of μs for switching**, and **TRNG speed is limited at slow.**

2. High energy consumption



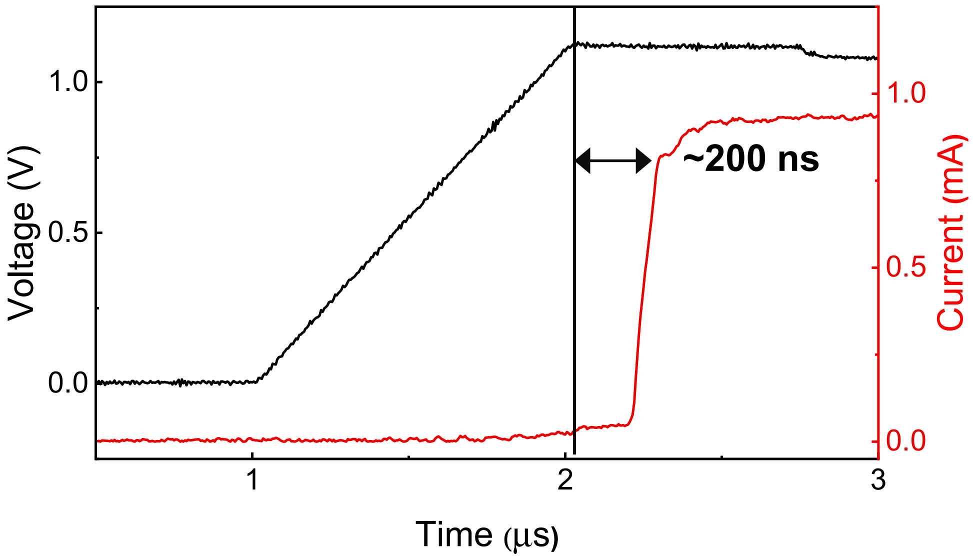


- The TRNG utilizes an **external clock generator**, and the **TRNG consumes much energy.**

H. Jiang et al., *Nat. Commun.* **8**, 882 (2017).

Fast and self-clocking capability of Mott mem.

- **Fast switching of Mott memristor**

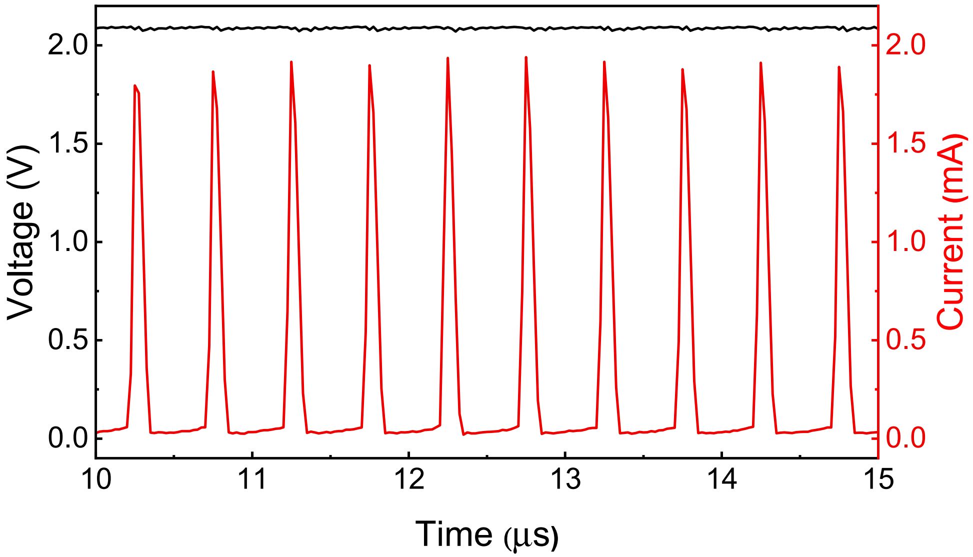


- The thermal dynamic of Mott memristor is rapid.
- Mott memristor shows **much faster switching speed** of hundreds of ns.

↓

Faster TRNG

- **Self-clocking capability of Mott memristor**



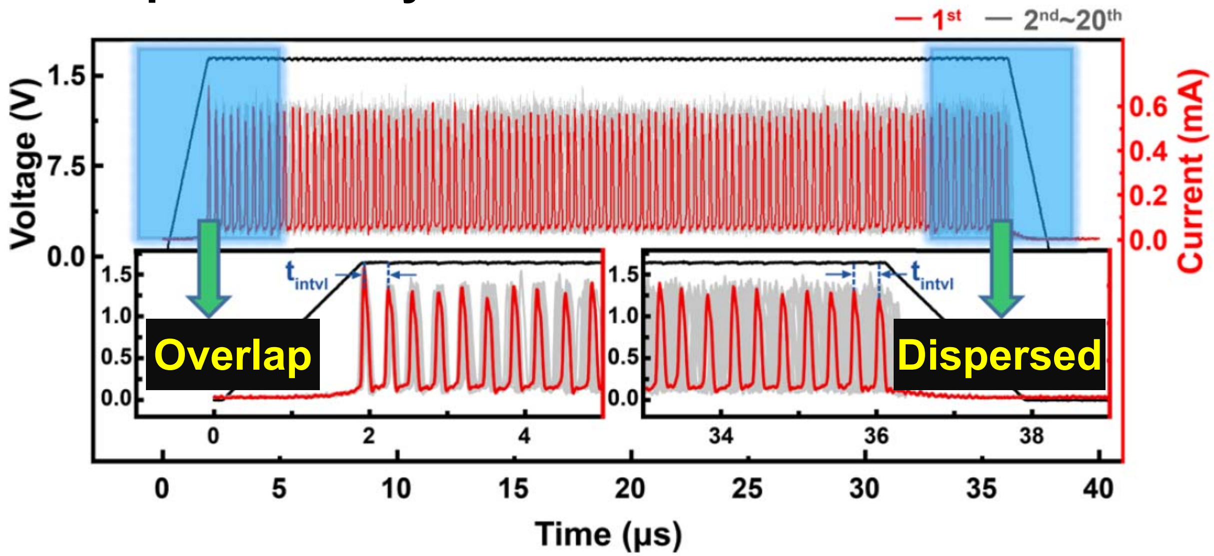
- The Mott memristor can generate **oscillations** at a static bias.
- The oscillation signal can be utilized as a **clock signal**.

↓

Energy-efficient TRNG

Thermal noise induced stochastic osc. behavior

- **Experimentally observed stochastic oscillation**



Stochastic oscillation

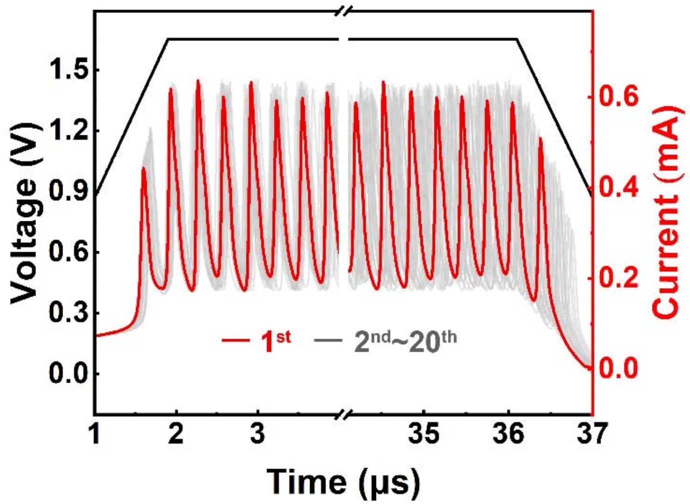
The oscillations overlap at the beginning, but **dispersed after certain time (stochastic)**

- **Numerical simulation of stochastic oscillation**

Newton's cooling law | **Thermal noise**

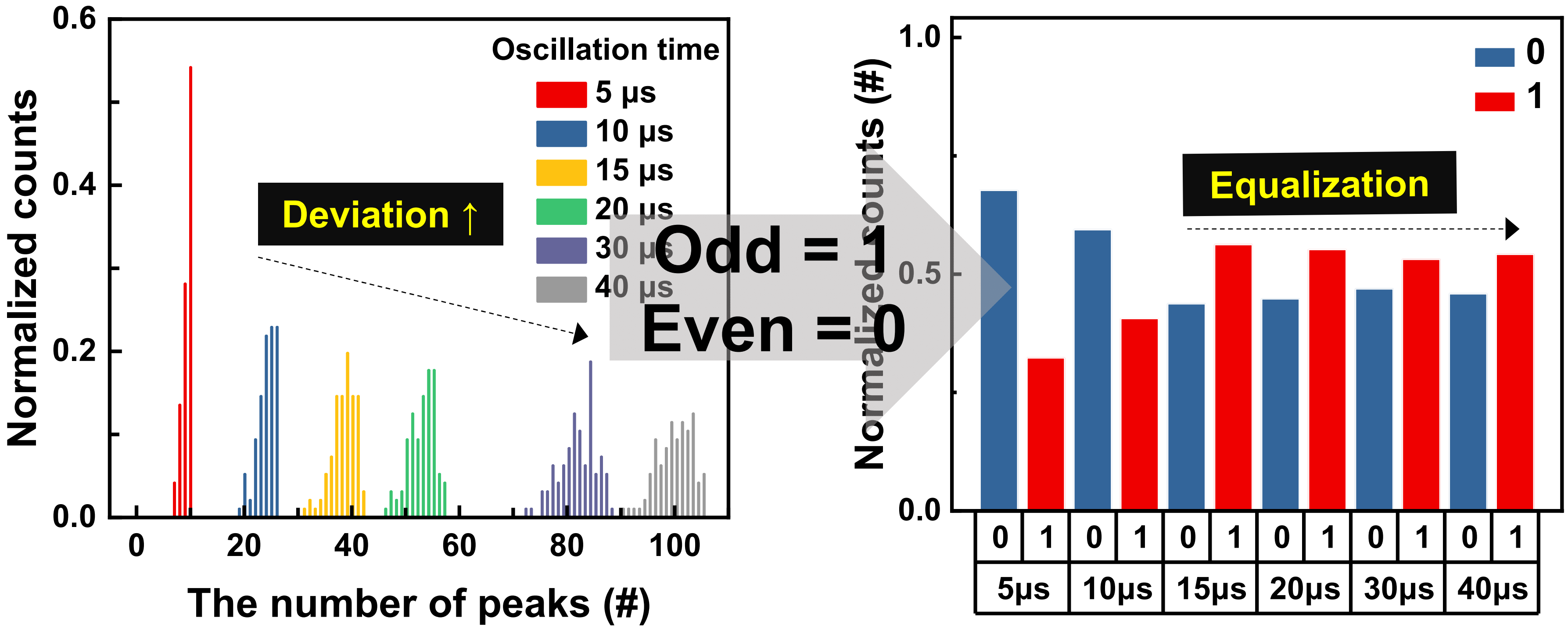
$$\frac{dT}{dt} = \frac{i_m v_m}{C_{th,m}} - \frac{T - T_{amb}}{R_{th,m} C_{th,m}} + T\left(\frac{k_b}{C_{th,m}}\right)^{\frac{1}{2}} \frac{4\pi}{R_{th,m} C_{th,m}} \cos \frac{2\pi t}{R_{th,m} C_{th,m}}$$

- **Thermal noise makes the oscillation stochastic.**
- The small variations are accumulated, and the oscillation becomes unpredictable with time.



Thermally accumulated peak number deviation

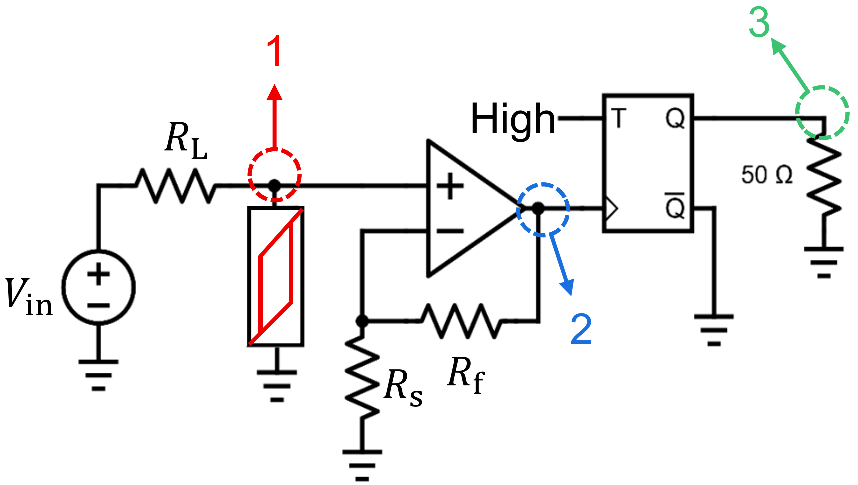
- **Time varying peak number deviation**
- **Digitalization of peak numbers**



- The peak numbers within certain time gets more deviated with time.
- Thermal noise is accumulated, making the oscillation more stochastic.

- '0' if the number is even number, '1' if it is odd number.
- After certain time, the ratio between '0' and '1' becomes almost equal.

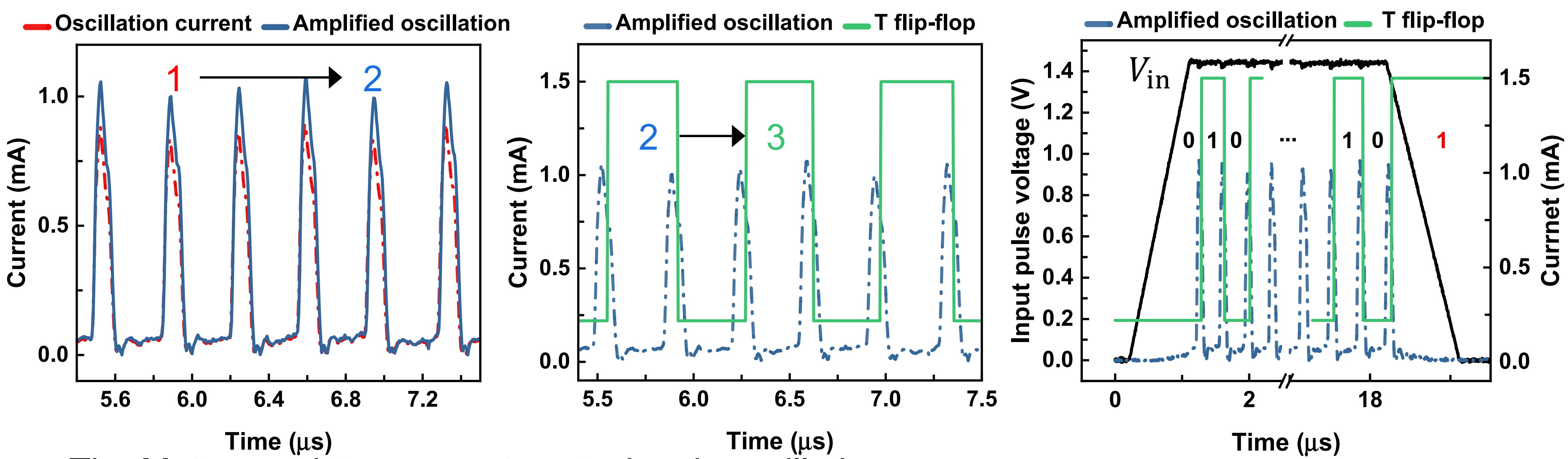
Mott True Random Number Generator (TRNG)



Self-clocking Mott TRNG

Mott memristor based TRNG utilizing the thermal noise induced **stochastic oscillation as clocking signal of T flip-flop**

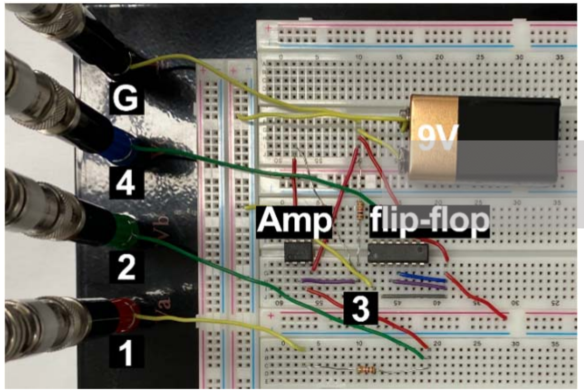
- **Mott TRNG operation principle**

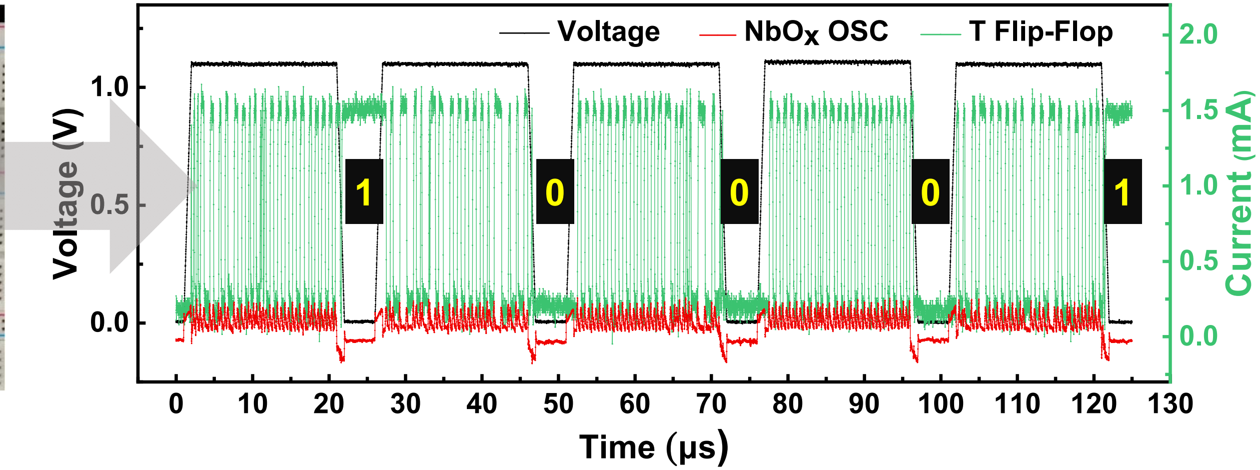


- The Mott memristor generates stochastic oscillation.
- The op-amp amplifies the oscillation signal and the signal is used for T flip-flop clock signal.
- The T flip-flop digitalizes the oscillation clock signal to ‘0’ or ‘1’.

Mott TRNG demonstration

- **Experimental five TRN generation by Mott TRNG**





- **15 Statistical NIST 800-22 randomness test (All Passed)**

	P-value	PASS (if p-value > 0.0001)	Pass rate (minimum pass rate = 125/130)
1. Monobit	0.010751	PASS	130 / 130
2. Frequency	0.451595	PASS	128 / 130
...	...	PASS	...
15. Random excursions variant	0.001527	PASS	130 / 130

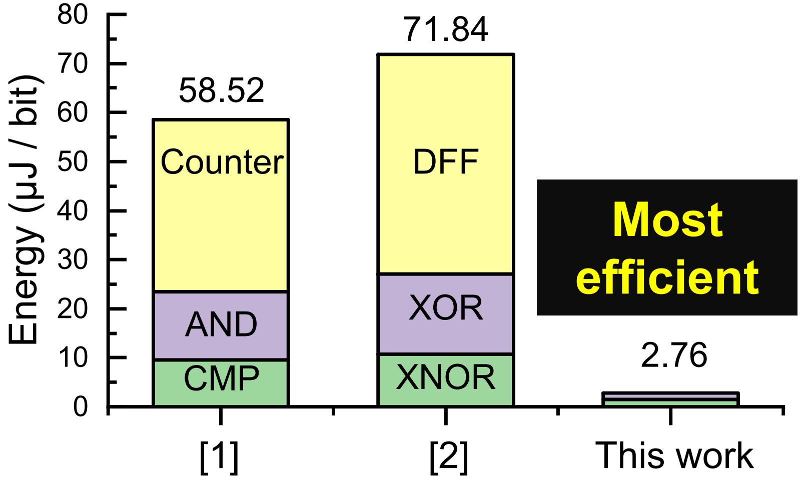
- 15 tests in National Institute for Standards and Technology (NIST) 800-22 check whether the numbers are true random number.
- 130 sets of random numbers (**1set = 10^6 bits**) are experimentally extracted and tested, proving its true randomness (**P-value > 0.0001**).

Performance of Mott TRNG

- **Comparison to other studies**

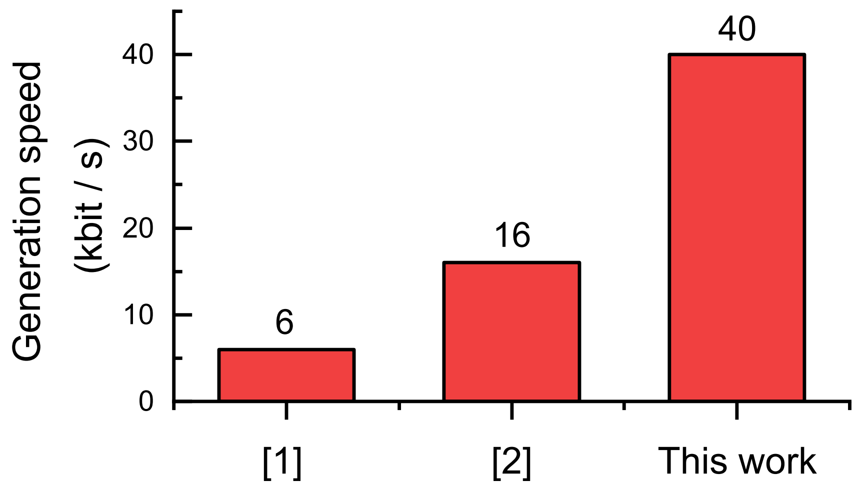
	Bit generation speed (kbit / s)	Energy consumption (nJ / bit)		Circuit complexity (#)
		Memristor	Clock generator	Electronic components
Jiang, H. et al.[1]	6	0.8×10^{-3}	2.5×10^{4}	4
Woo, K. S. et al.[2]	16	3.15×10^{-3}	9.4×10^{3}	6
This work[3]	40	5.22	Self-clocking	2

- **Energy consumption**



- **TRNG speed**

The fastest



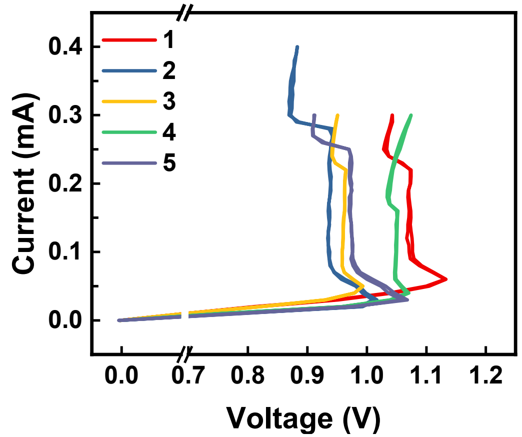
- Simple circuit with self-clocking ability enabled the energy-efficient TRNG operation.
- Thermal noise accumulation by fast oscillation enabled fast TRNG operation.

[1] H. Jiang et al., *Nat. Commun.* **8**, 882 (2017). [2] K.S. Woo et al., *Adv. Electron. Mater.* 1901117 (2020). [3] *Nat. Commun.* **12**, 2906 (2021).

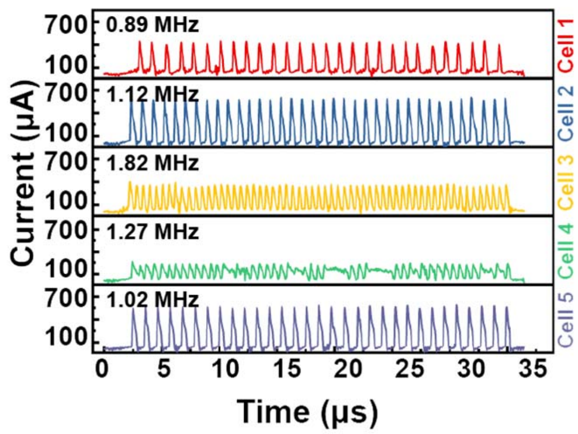
High tolerance by dimensionless thermal noise

- **Device characteristic variation tolerance**

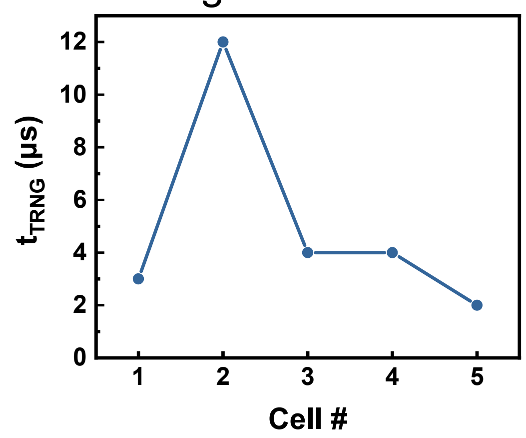
Cell variation



Oscillations

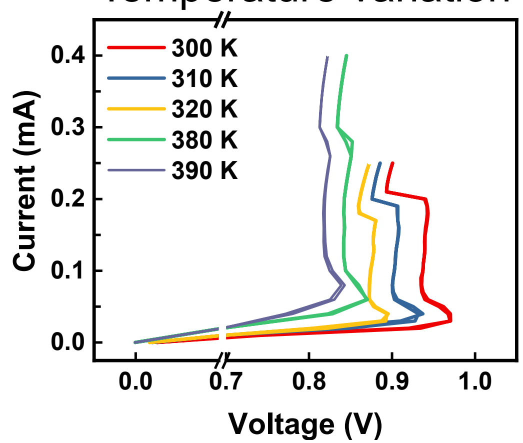


TRN generation time

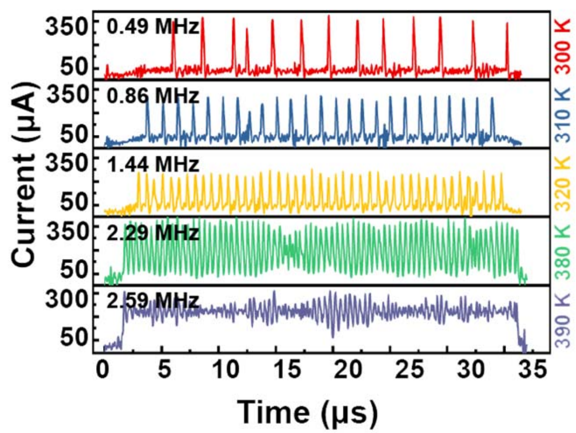


- **Device temperature variation tolerance**

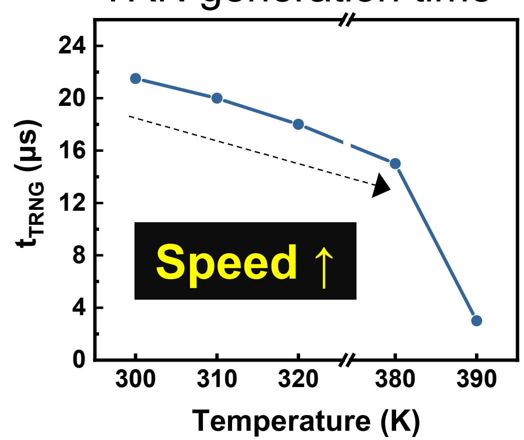
Temperature variation



Oscillations



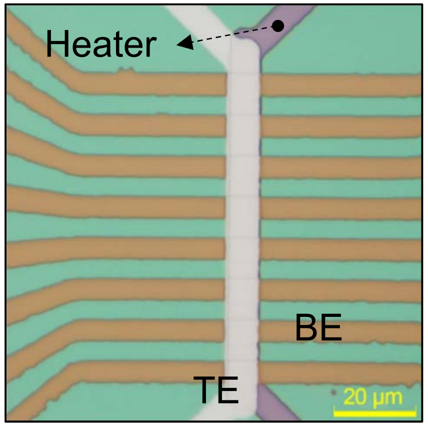
TRN generation time

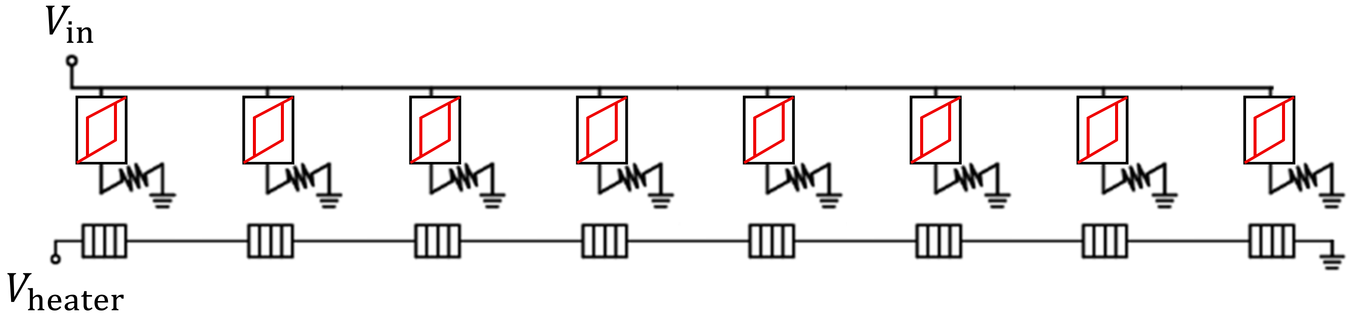


Mott TRNG exploits dimensionless thermal noise during oscillation, this enables high variation tolerance of Mott TRNG

Fast and efficient TRNG array using heat

- **Mott TRNG array scheme**





- A heater can heat up multiple Mott memristors.
- Overall TRNG speed can be ***N* × single TRNG speed**.

- **Energy consumption of Mott TRNG array**

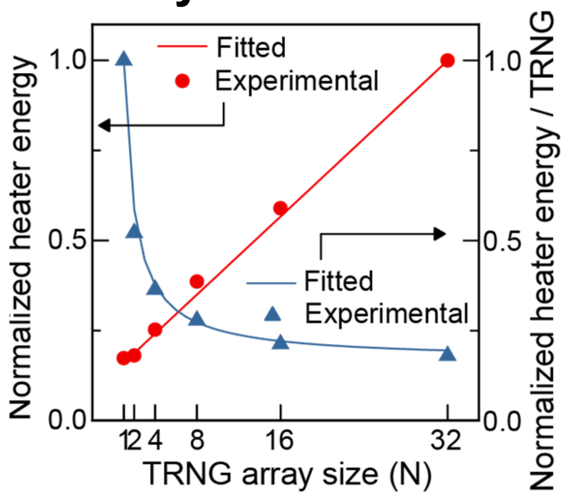
$$E_{\text{heater}}(N) = N \times E_{\Delta} + E_{\text{initial}} - E_{\Delta}$$

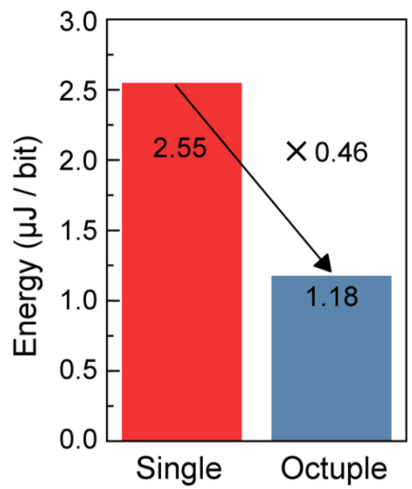
$$E_{\text{heater}}(N)/N = E_{\Delta} + \frac{E_{\text{initial}} - E_{\Delta}}{N}$$

$N\uparrow$

$*\ E_{\Delta}$: unit heater energy by N

- The heater energy per bit decreases and becomes saturated.





The speed and energy-efficiency can be thermally improved in array

03

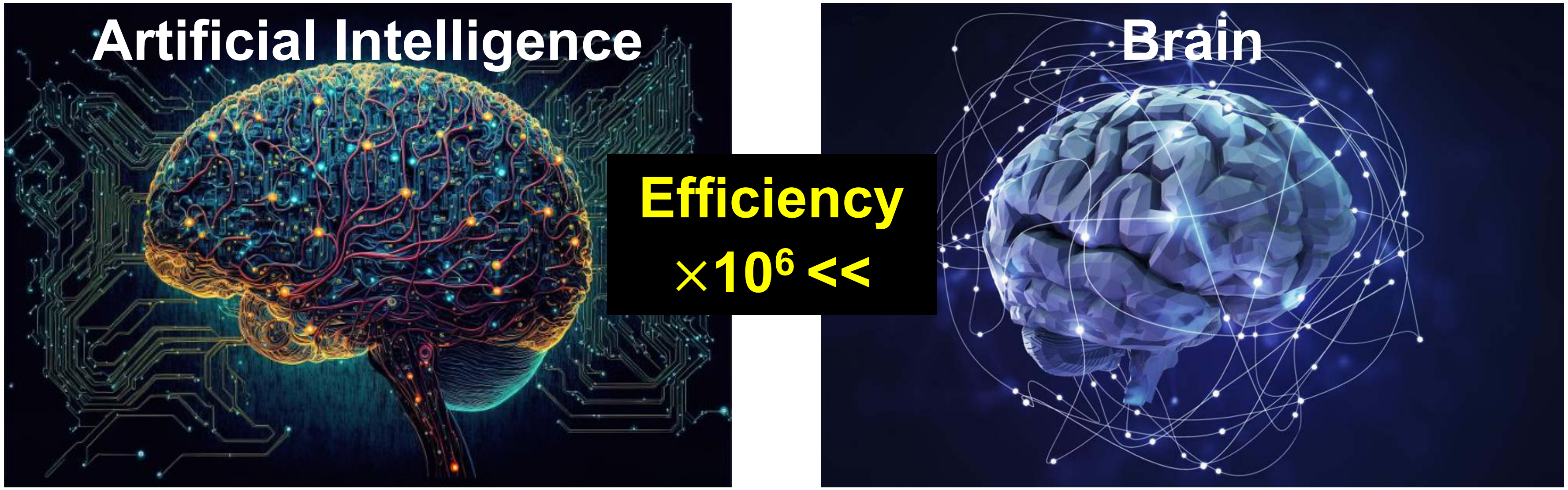
Using heat capacity for Neuron

Complex tasks in demand

- **Optimization task**

- **Creative task**

- **Neuromorphic computing to perform the complex tasks**



High-order device for efficient computing

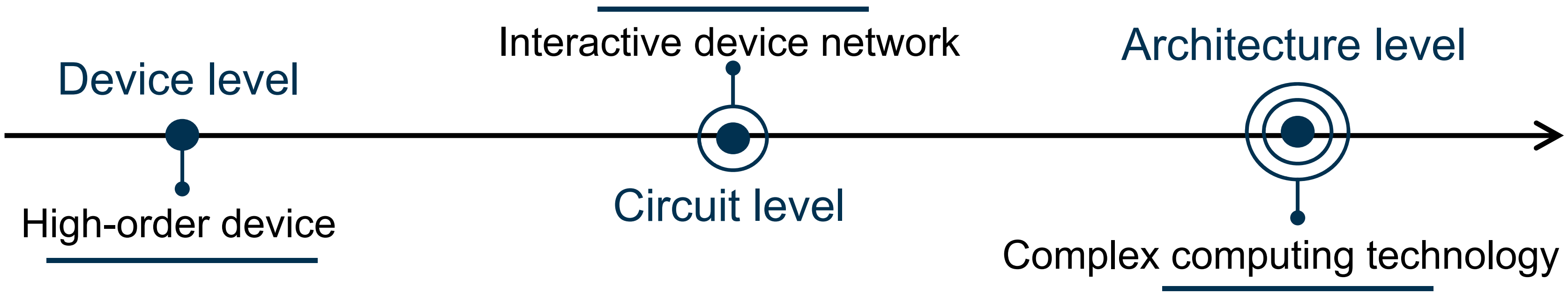
REVIEWS

Dynamical memristors for higher-complexity neuromorphic computing

Suhas Kumar[1], Xinxin Wang[2], John Paul Strachan[3,4], Yuchao Yang[5,6] and Wei D. Lu[2]

S. Kumar et al.,
Nature Reviews Materials
7, 575-591 (2022)
Cite : 144

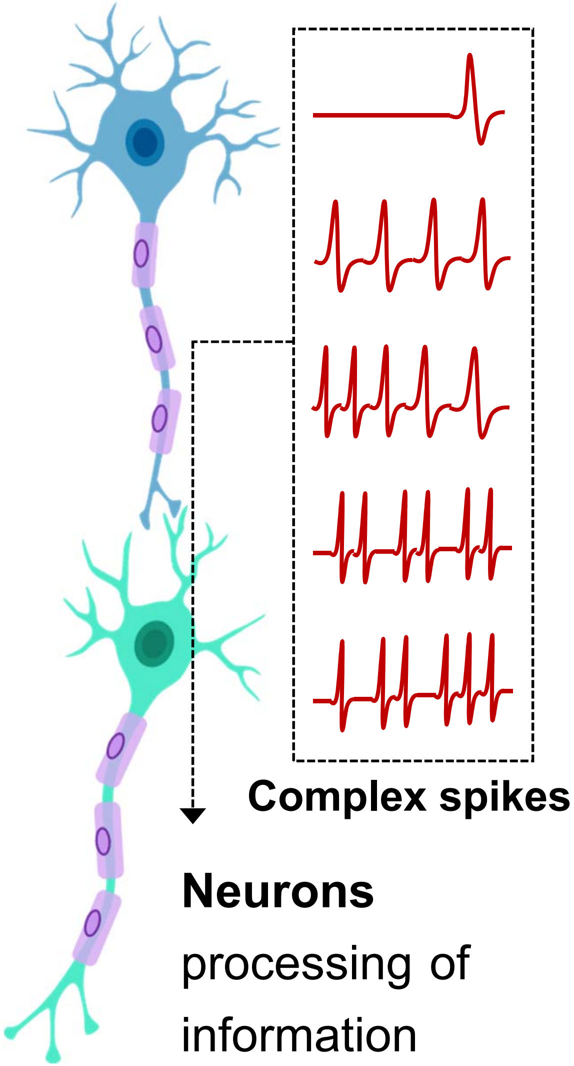
“ A single device with **such complex behaviours can functionally replace hundreds or thousands of transistors**, and interactions among such devices can lead to **higher-level capabilities and energy efficiency.**



Developing high-order device and networking the devices for efficient computing

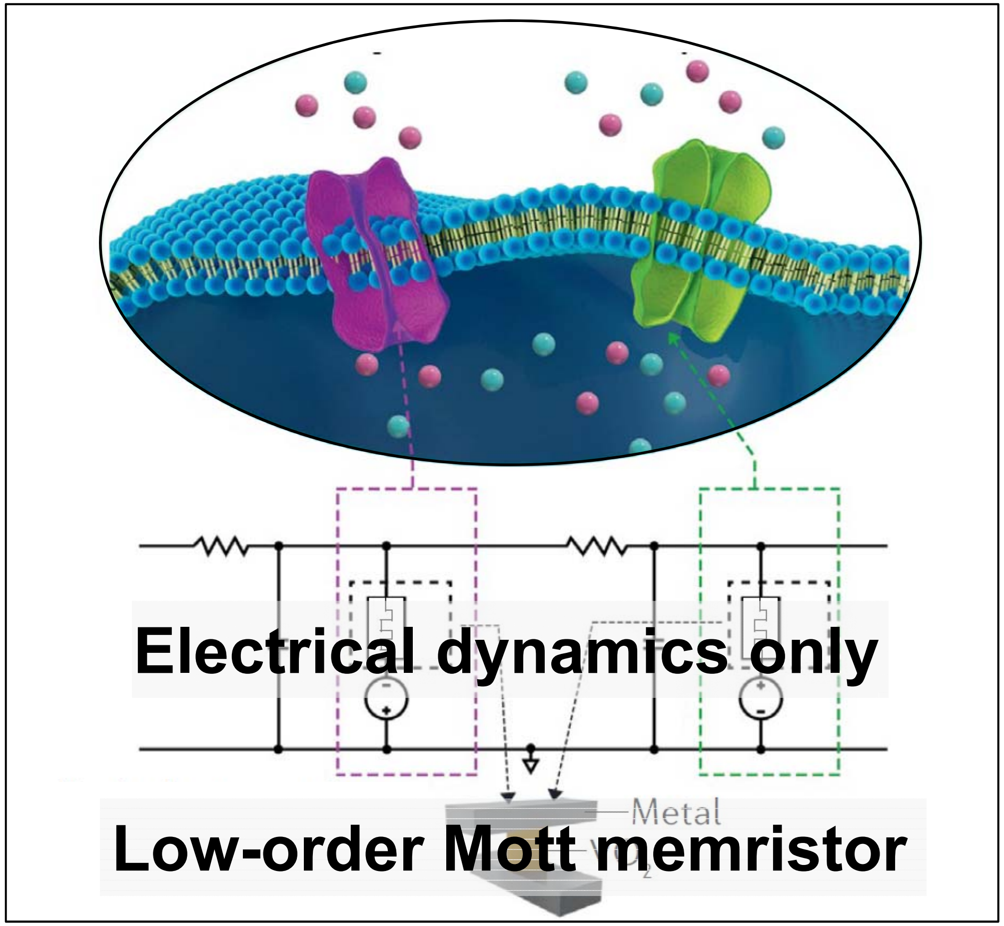
Mott memristor in Neuromorphic computing

- **Biological neuron**



Neurons
processing of information

- **Limitation of previous Mott memristive neuron**



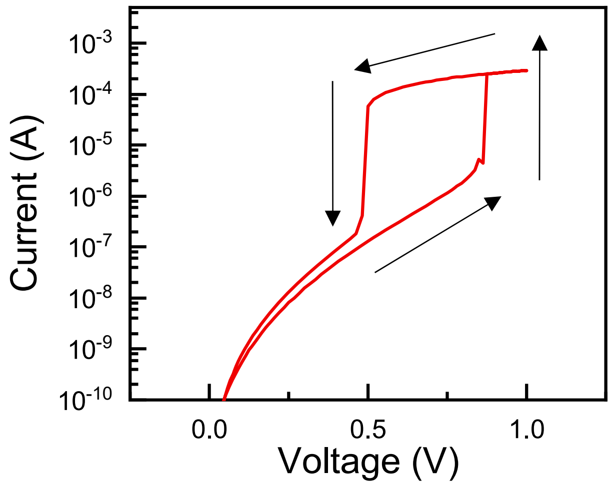
- **Low-order Mott memristors** need to be combined **complexly** to realize high-order artificial neuron by **electric**.

W. Yi et al., *Nat. Commun.* **9**, 4661 (2018). S. Kumar et al., *Nat. Rev. Mater.* **7**, 575-591 (2022)

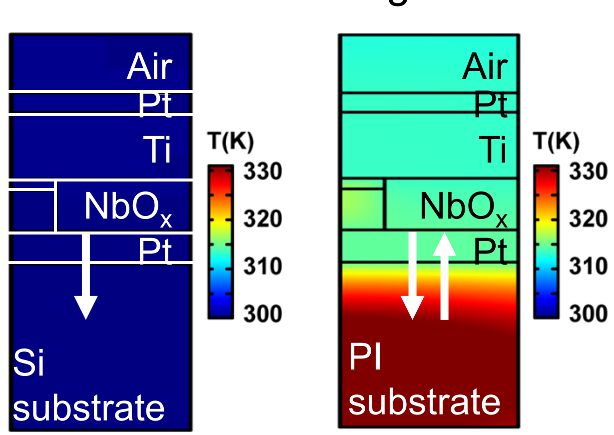
Second-order thermal Mott memristor

- **Heat storage in PI substrate confirmed by COMSOL simulation**

Switching curve



After switching



Substrate:
Thermal conductivity

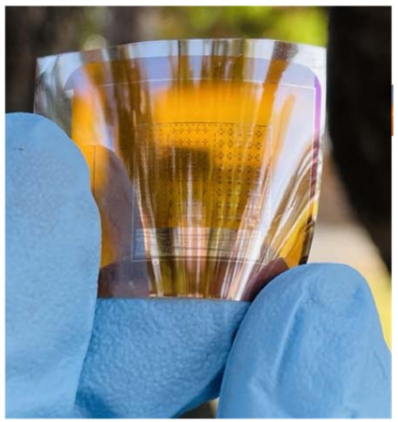
Si: 130 W/mK

Polyimide (PI):
0.12 W/mK

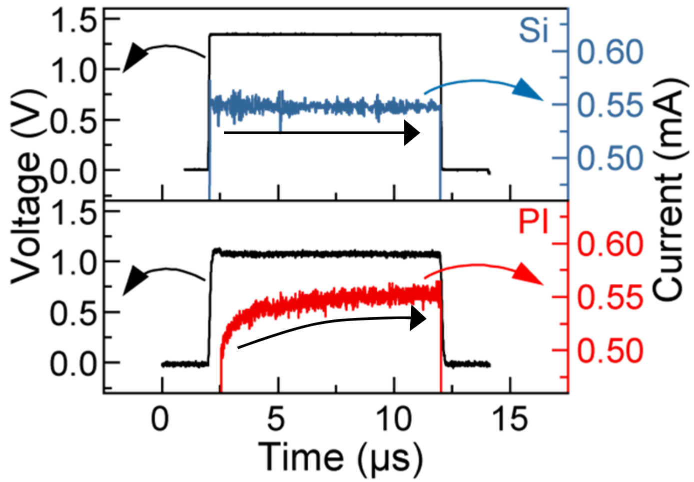
- Heat can be stored in the PI substrate, and Mott memristor can reuse the heat.

- **Second-order Mott memristor fabricated on Polyimide (PI) substrate**

Device image

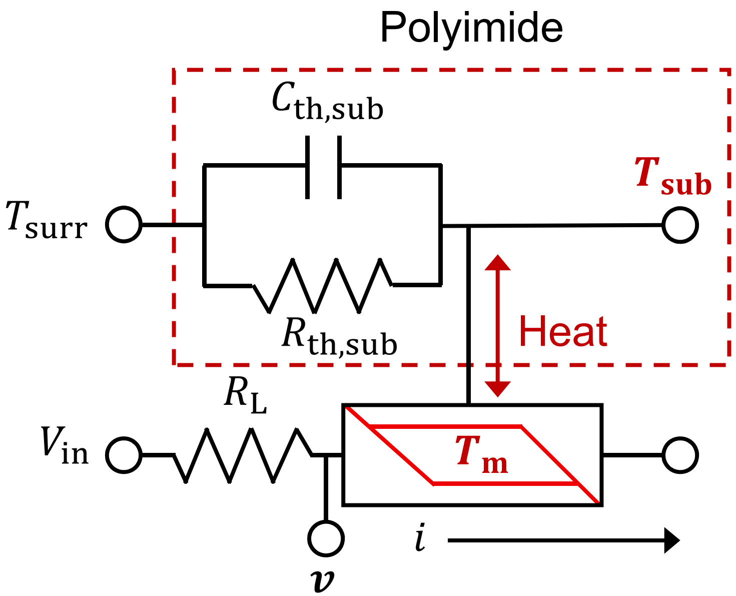


Transient switching curve



- On Si substrate, the on-current is constant.
- However, on PI substrate, the current is increased and becomes saturated.
- This attributes to the **second thermal dynamic**.

Third-order dynamical Mott neuron



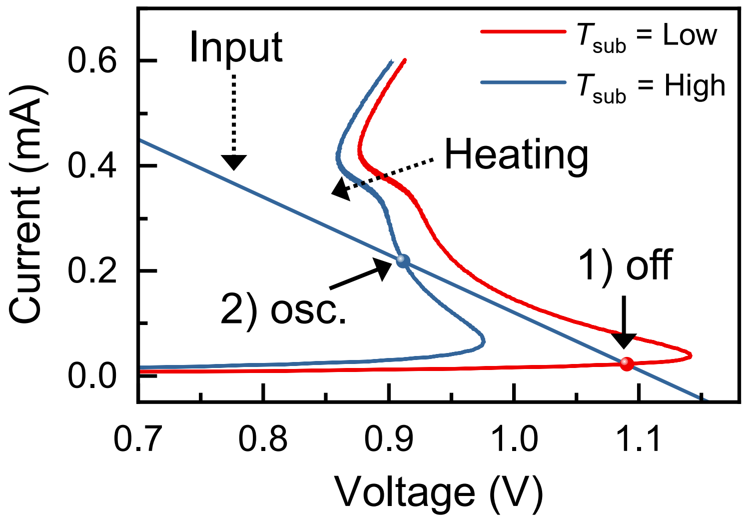
Third-order dynamics

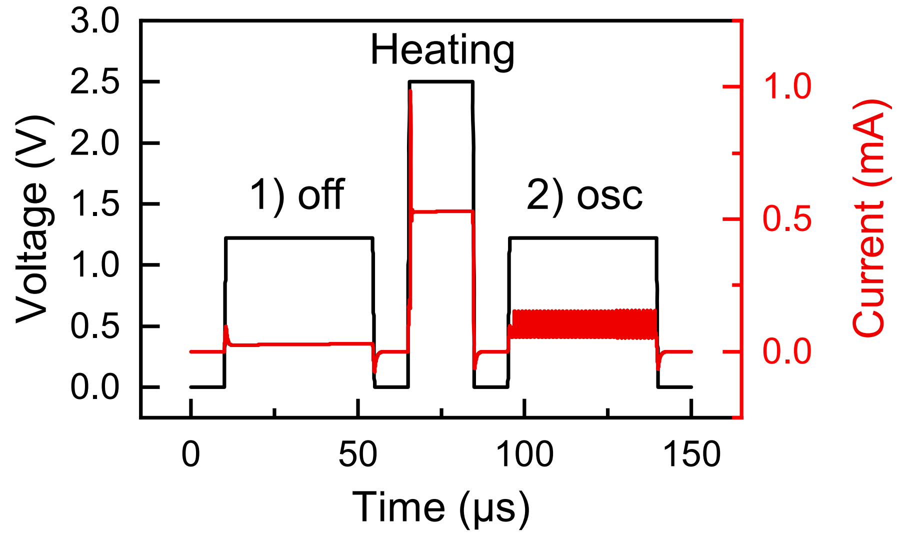
$$C\frac{dv}{dt} = \frac{1}{R_L}(V_{in} - v) - i$$ **Circuit dynamics**

$$\frac{dT_m}{dt} = \frac{1}{C_{th,m}(T_m)}\left(iv - \frac{T_m - T_{sub}}{R_{th,m}(T_m)}\right)$$ **Mem. Thermal Dynamics (Joule heating)**

$$\frac{dT_{sub}}{dt} = \frac{T_m - T_{sub}}{R_{th,m}C_{th,m}} - \frac{T_{sub} - T_{surr}}{R_{th,sub}C_{th,sub}}$$ **Subs. Thermal dynamics (Heat)**

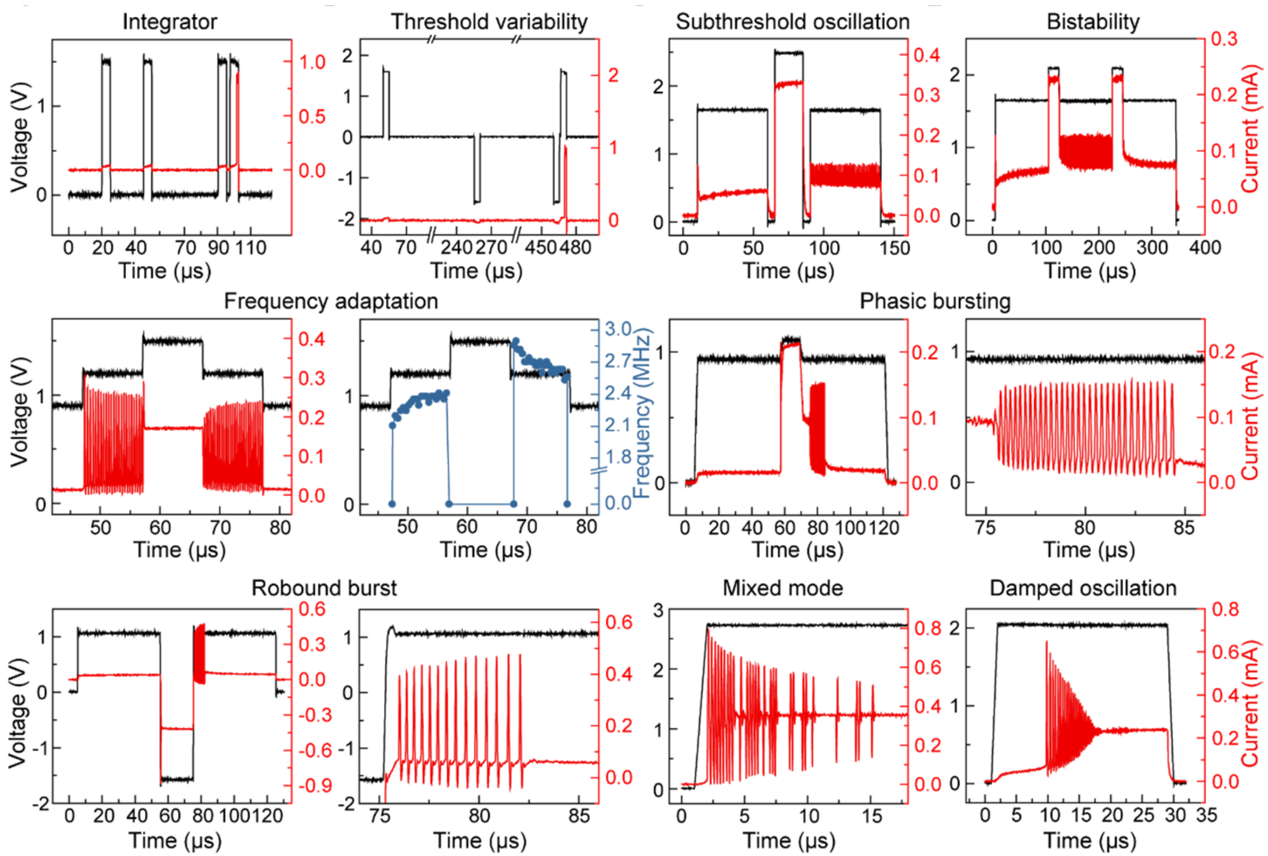
- **NDR modulation by substrate temperature for subthreshold oscillation**





Complex neuronal behaviors by Mott neuron

- **9 second-order neuronal behaviors**
  - All or nothing
  - Tonic spikes
  - Inhibition-induced spiking
  - Spike latency
  - Depolarization after potential
  - Phasic spike
  - Rebound spike
  - Excitability
  - Accomodation
- **9 third-order neuronal behaviors**

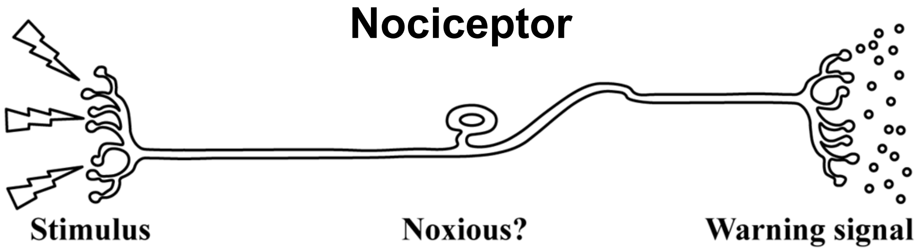


- Integrator
- Threshold variability
- Subthreshold oscillation
- Bistability
- Frequency adaptation
- Phasic bursting
- Rebound burst
- Mixed mode
- Damped oscillation

A single Mott memristor can mimic 18 neuronal behaviors

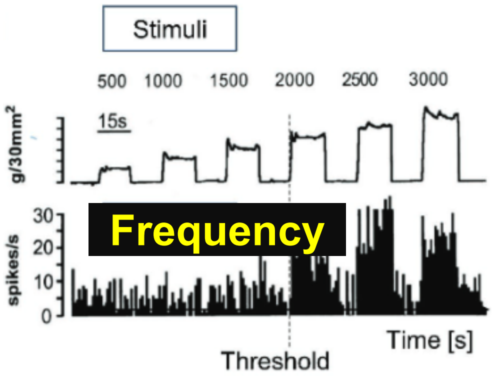
E.M. Izhikevich, *IEEE TRANSACTIONS ON NEURAL NETWORKS.* **15**, 5, SEPTEMBER 2004.

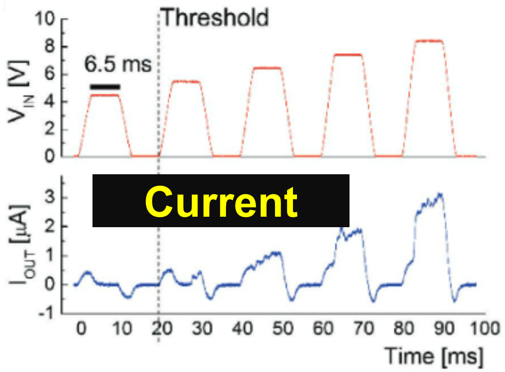
Limitations of previous memristive nociceptor



1. Interpretation of response to current amplitude[1]

Biological nociceptor　　Memristive nociceptor

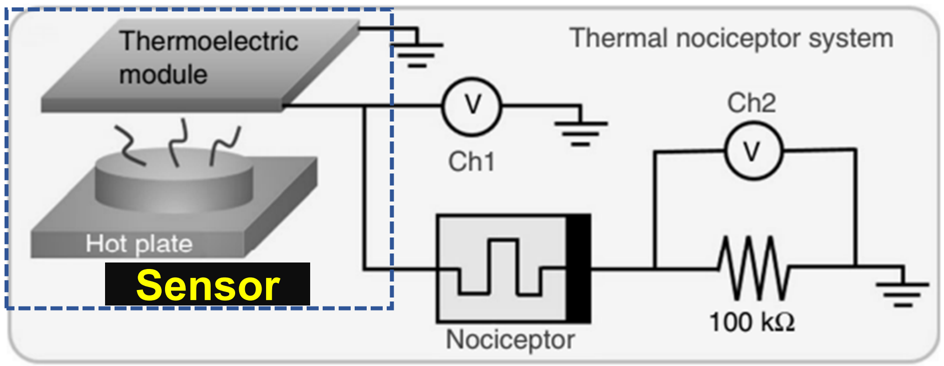




- Biological nociceptor process the signal to spike frequency.
- Memristive nociceptor process the signal to current amplitude.
- **Second-order dynamics are absent**

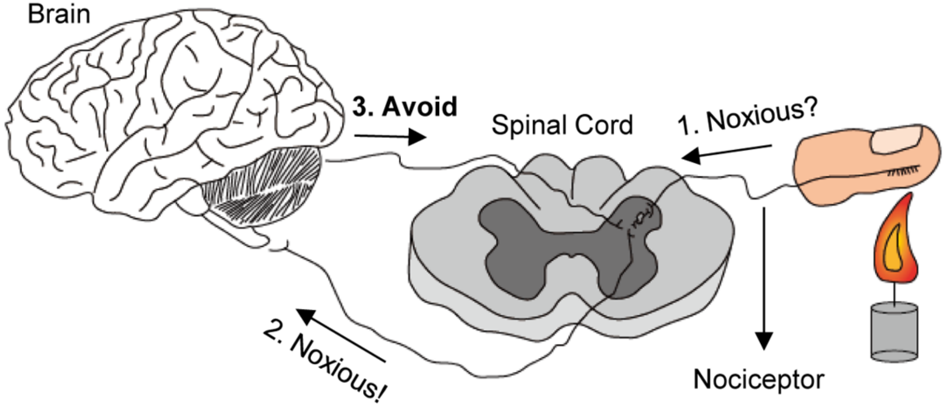
2. Conversion of signal to electrics by sensor[2]

- Utilizing an external sensor to convert the harmful signal to electrics.
- **Sensing dynamic is absent.**



[1] Y. Kim et al., *Adv. Mater.* **30**, 1704320 (2018). [2] J. H. Yoon et al., *Nat. Commun.* **9**, 417 (2018).

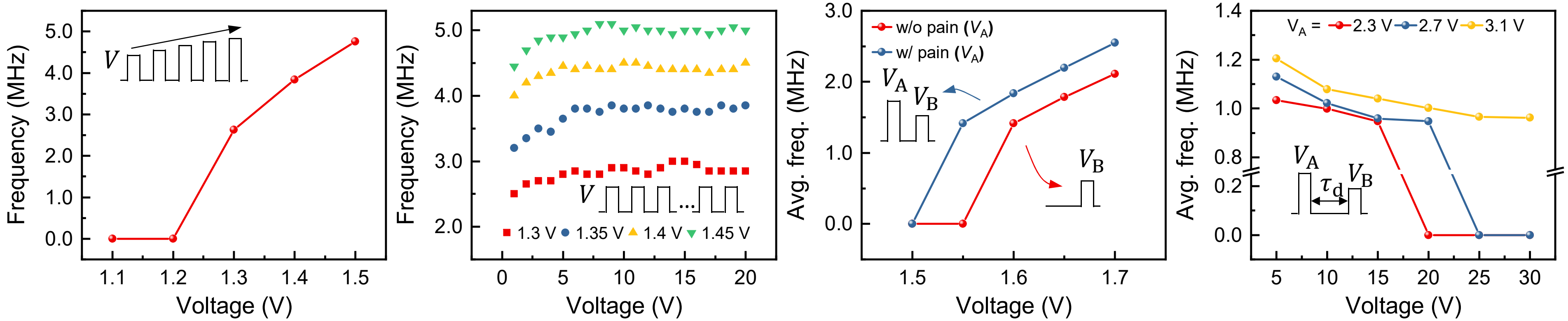
Spiking nociceptor without sensor by Mott neuron



Spiking Nociceptor

Nociceptor responds to potentially damaging stimuli by sending "possible threat" signals by spikes

- **Full spiking nociceptive behaviors using thermal dynamics without sensor**



The third-order Mott neuron performs spiking nociceptor in full

04

Using heat diffusion for Computing

Physicochemical process in neural network

- **Electronic computer**

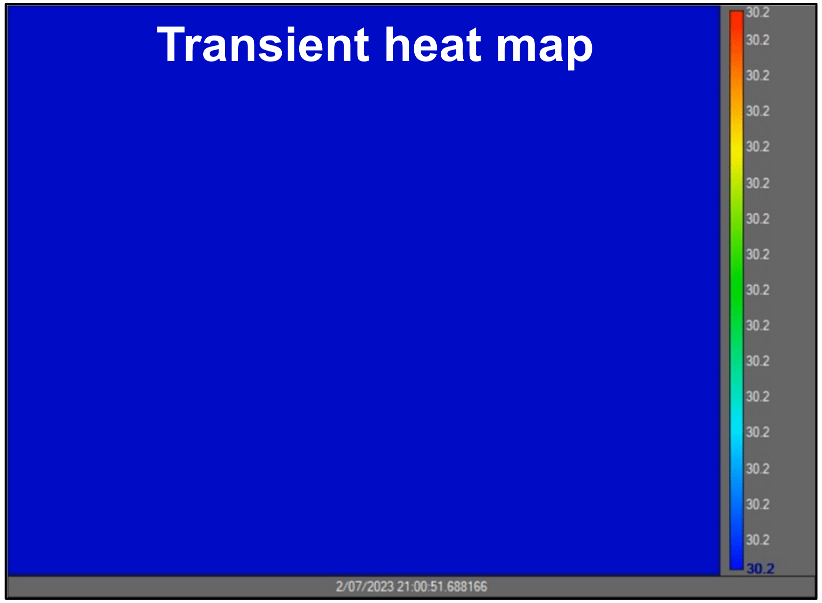
- Electronic computer employs a single thermodynamic state; **electrical bits**.
- Inter-device communications requires **conversions to precise electrical bits**, then computed step by step by clock.

- **Neural network**

- Neurons employ multiple **non-digital physicochemical process** such as ion transport, electrical energy, heat, etc.
- **Natural dynamics** within neurons are used for **inter-neuron communication**.

Beyond electrical process to achieve functionally dense computing

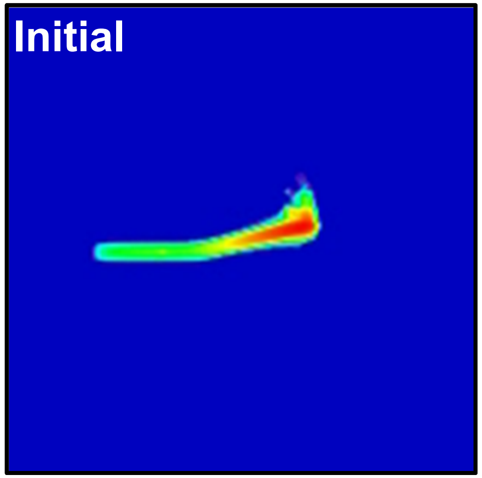
Spatiotemporal heat transfer of Mott neurons

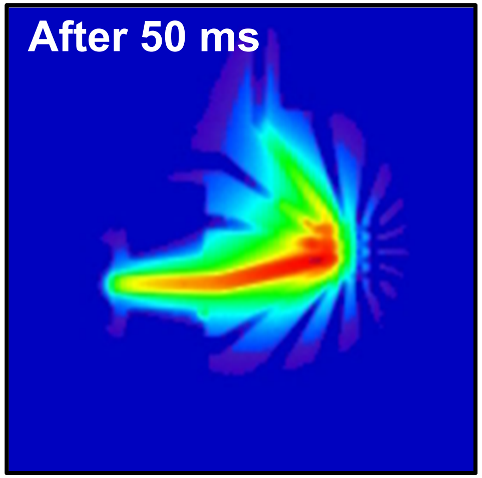


Spatiotemporal heat transfer of Mott neurons

The heat from Mott neurons can be transferred to the neighboring Mott neurons spatially and temporally.

- **Spatiotemporal heat transfer in the crossbar array**

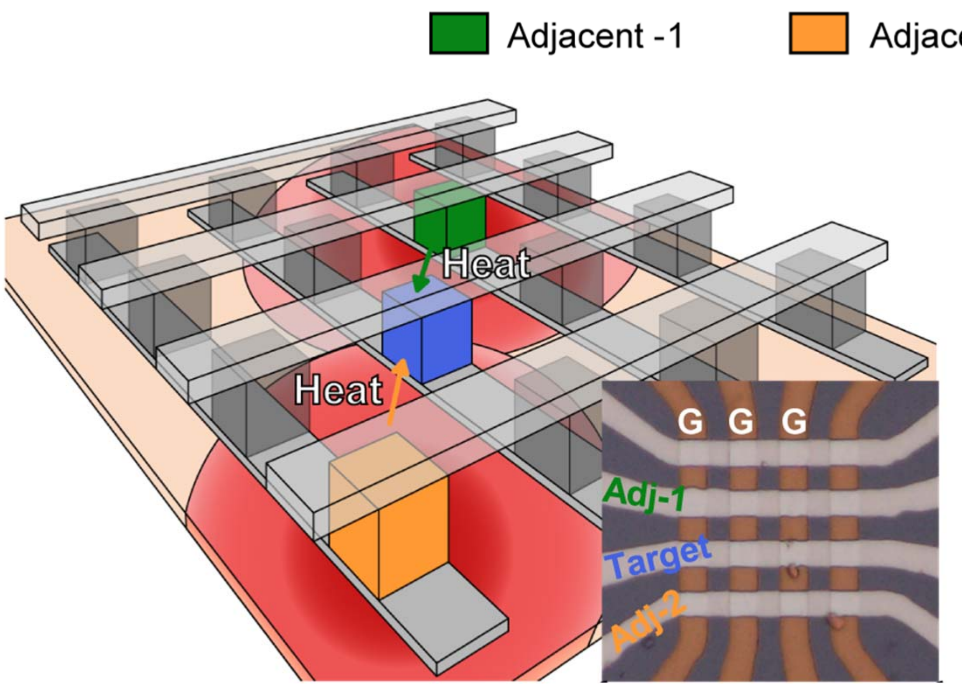


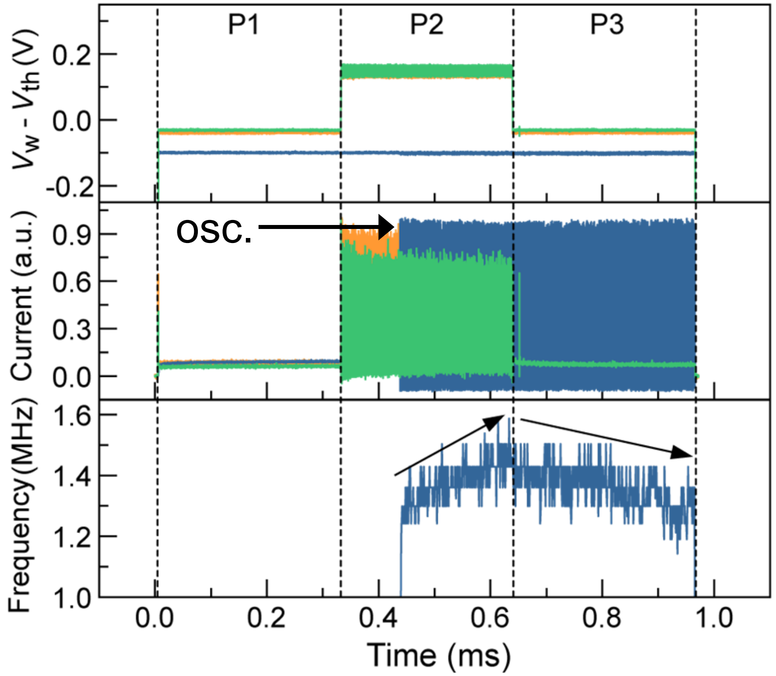


- Heat transfer is spatiotemporal behavior.
- Initially, heat is generated along current path.
- Then, heat is transferred to the neighboring Mott neurons
- **Mott neurons communicate via heat.**

Oscillation frequency modulation by heat transfer

- **3-Mott neuron in crossbar array**
- **Temporal frequency modulation**



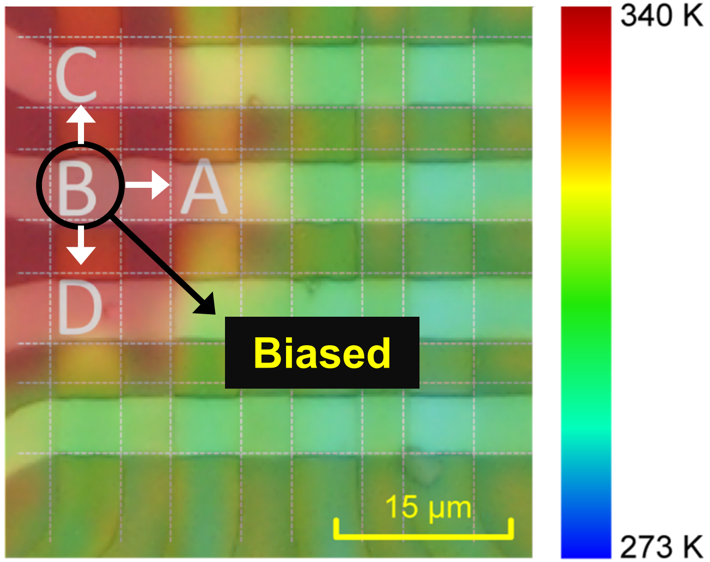


- 3-Mott neuron in diagonal were selected, and the rest are left at insulating pristine state.
- The target device in the middle was biased at subthreshold voltage, and the adjacent devices were biased at oscillation voltage.

- The heat from adjacent devices were transferred to the target device.
- The heat induced the subthreshold oscillation of the target device and the oscillation frequency modulated.

Mott neurons communicate via heat affecting oscillation frequency

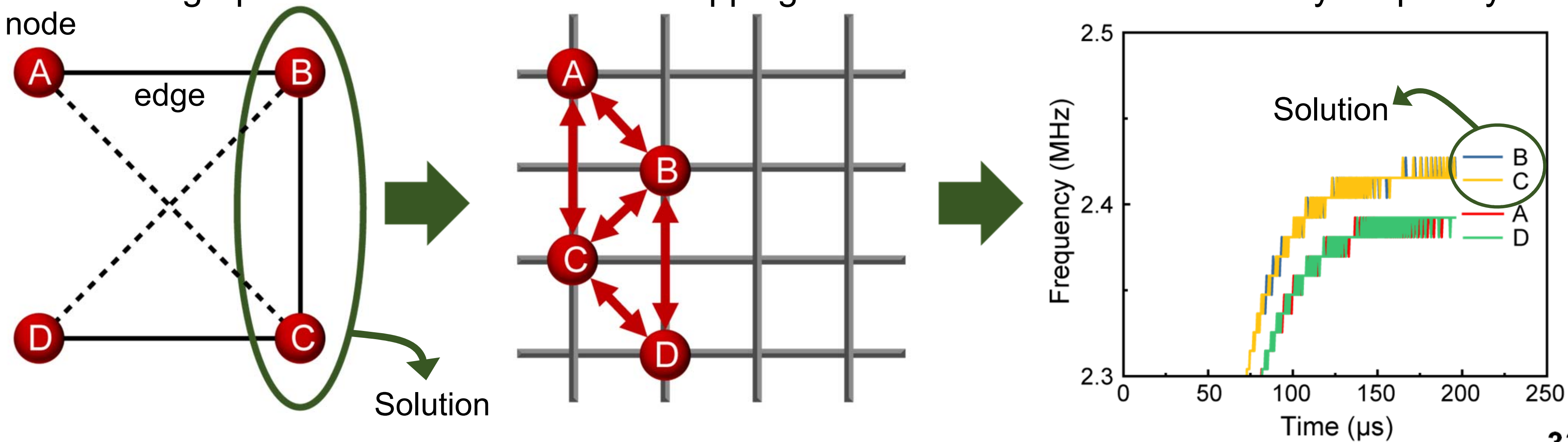
Graph problem solving in local thermal network



Local thermal network in crossbar array

The heat from a Mott neuron can be transferred to the neighboring Mott neurons constructing a thermal network where devices locally communicate via heat

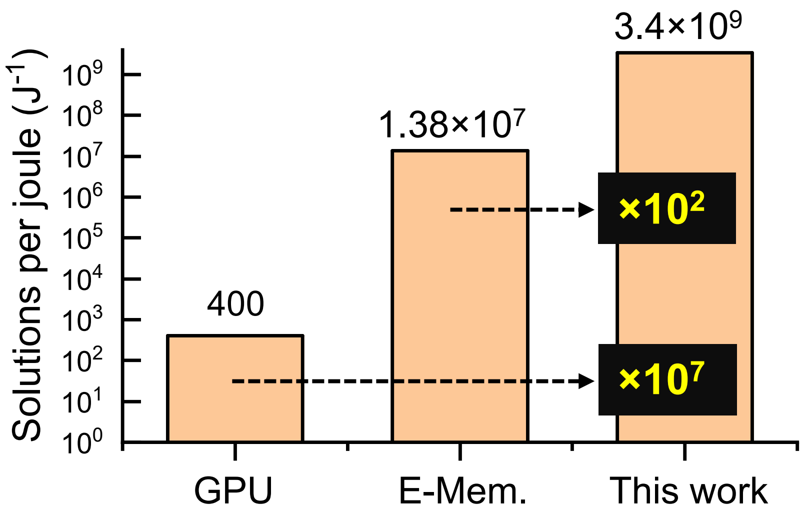
- **Max-cut problem solving through local thermal network of Mott neurons**

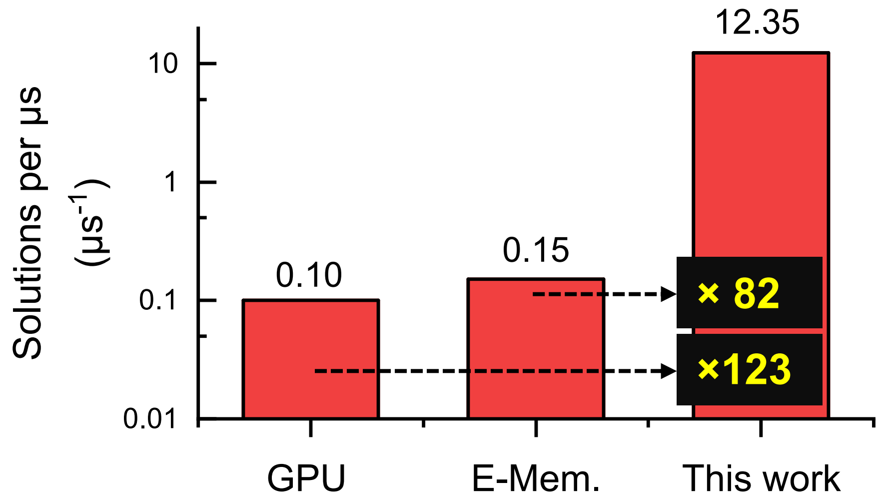


Performance of prototypical thermal computing

- **Comparison to other computing system for 60-nodes max-cut problem solving**

	Thermal (5 μm, exp.)	Thermal (16 nm, est.)	Electronic Memristor (16 nm, est.)	GPU	CPU	Quantum (D-Wave)
Time (μs)	1,800	0.081	6.6	10	223.6	10,000
Power (W)	0.0036	0.0036	0.011	250	20	25,000
Energy (nJ)	6,480	0.293	72	2.5×10^6	4×10^6	250×10^{15}
Solutions per joule (J^{-1})	1.5×10^5	3.4×10^9	1.38×10^7	>400	250	4×10^{-9}



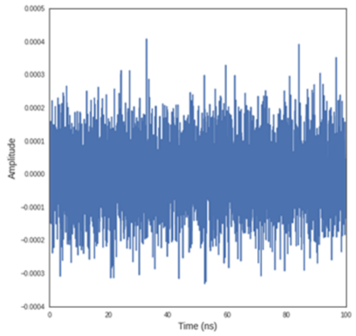


F. Cai et al., *Nat. Electron.* **3**, 409 (2020)

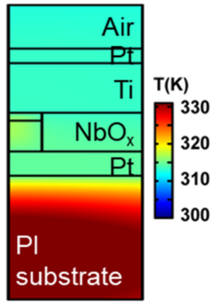
04 Summary

Mott memristor for future computing

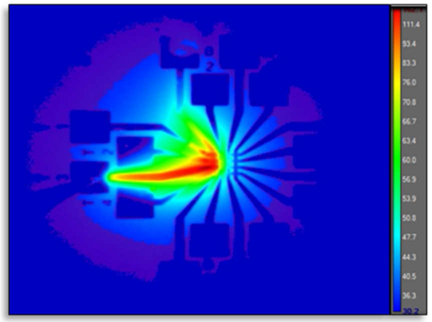
Thermal noise (stochastic)



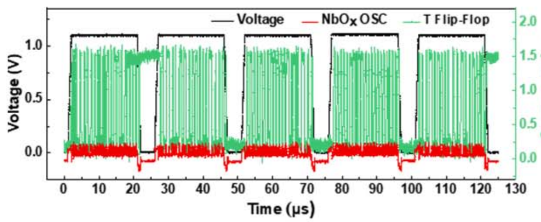
Heat accumulation (temporal dynamics)



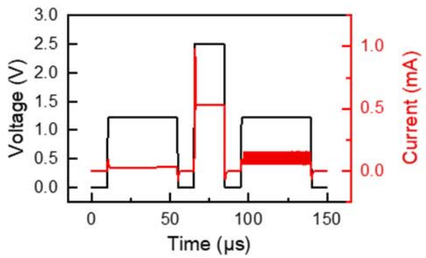
Heat diffusion (spatial transfer)



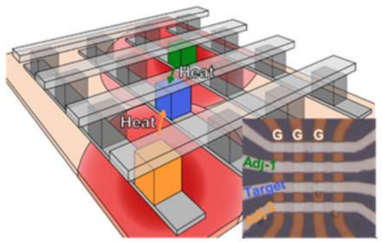
TRNG



Mott Neuron



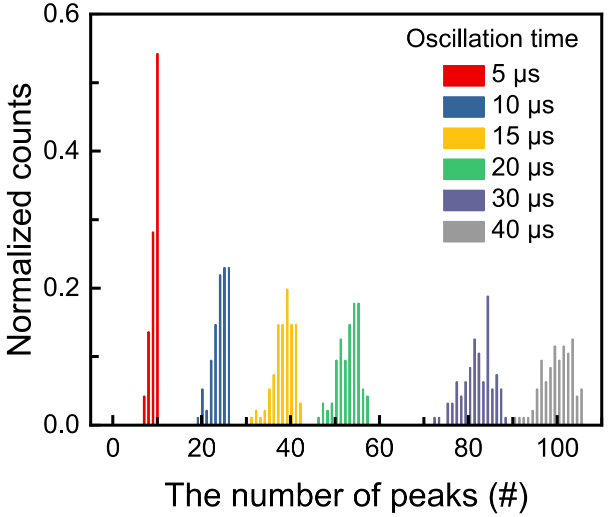
Thermal computing

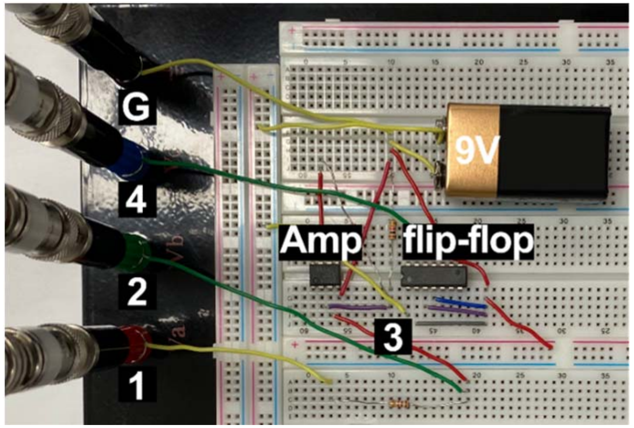


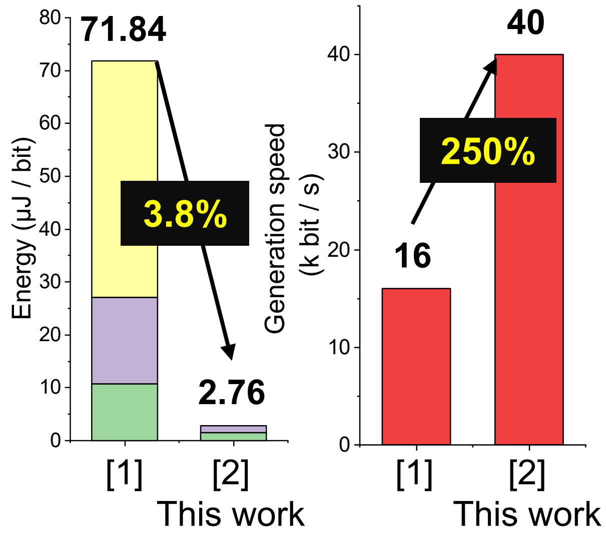
- **Mott switch may open a new paradigm of computing thanks to its electro-thermal dynamics.**

Summary

- **Stochastic oscillation**
- **TRNG fabrication**
- **Performance**







<u>Mott TRNG development utilizing thermal noise induced stochastic oscillation</u>

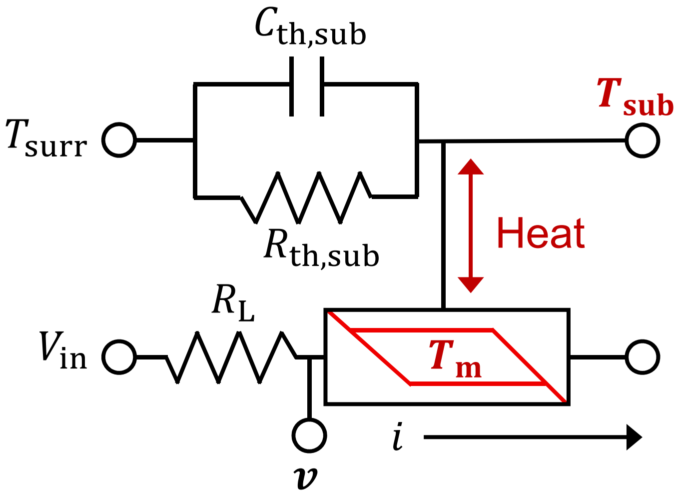
- The oscillation of Mott memristor is **stochastic by thermal noise**.
- The **oscillation is fast**, and **self-clocking capable** leading **to the most energy efficient and fast TRNG.**
- The **thermal noise is dimensionless**, making the **TRNG possible at variable situations** which allows the TRNG for **IoT application**.

10 representative researches of KAIST (2021)
Published: *Nat. Commun.* **12**, 2906 (2021)

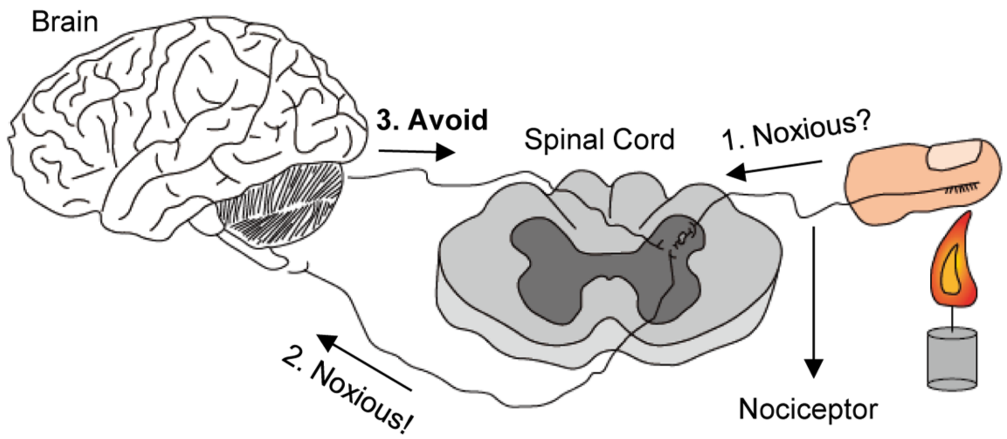
[1] K.S. Woo et al., *Adv. Electron. Mater.* 1901117 (2020). [2] *Nat. Commun.* **12**, 2906 (2021).

Summary

- **High-order Mott neuron**



- **Complex neuronal functions**

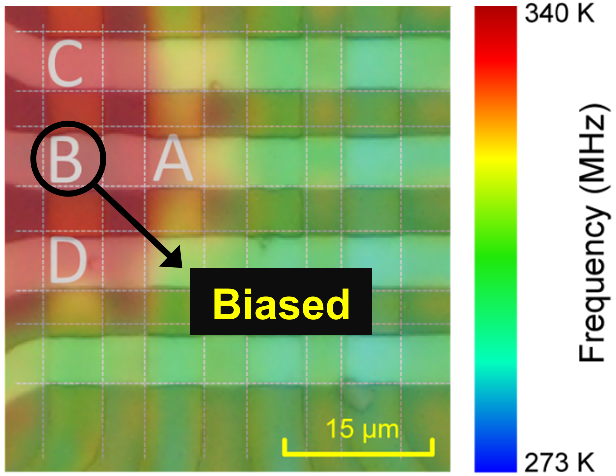


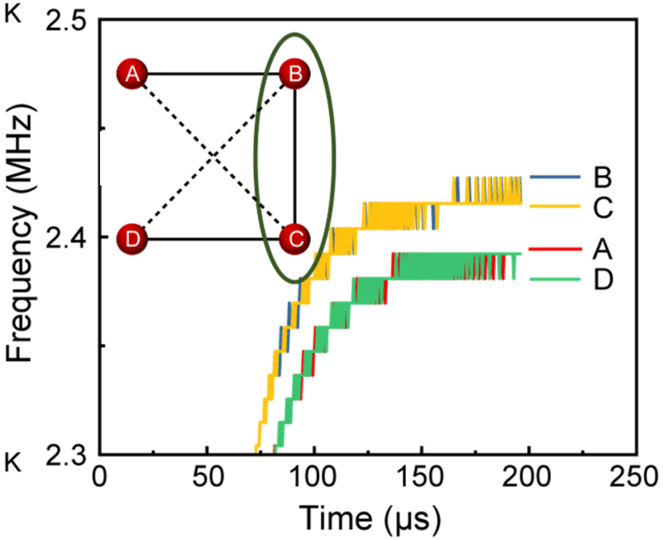
High-order Mott neuron exploiting substrate thermal dynamic

- **A single Mott memristor** performs **third-order dynamics** (Mott neuron).
- The high-order Mott neuron has **simple circuit** by utilizing thermal dynamic.
- The high-order Mott neuron mimics **18 complex neuronal behaviors**, and **spiking nociceptor** from a single Mott memristor by **thermal dynamics**.

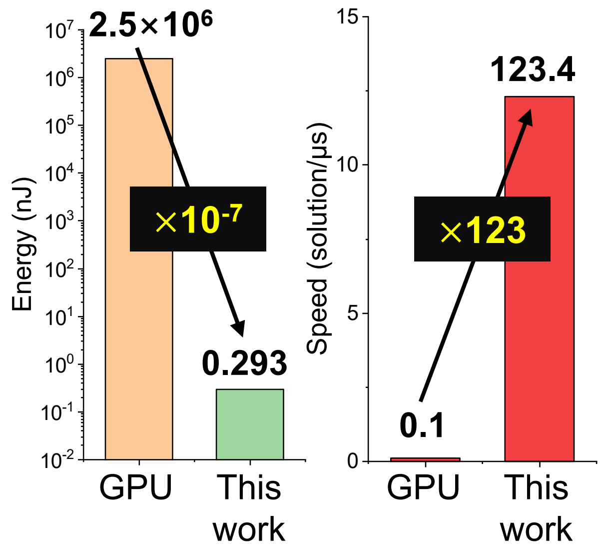
Summary

- **Mott neural thermal network for problem solving**





- **Performance**



<u>Spatiotemporal heat transfer of Mott neurons for optimization problem solving</u>

- Mott neurons can **spatiotemporally communicate via heat** modulating their oscillation frequency.
- The natural heat transfer constructs thermal network which can solve problem.
- The Mott neuron based thermal computing system outperforms the existing digital computers like GPU.

28th SAMSUNG Humantech paper award, participation prize (2022)
Nature Materials under revision

Thank you for your attention!