Artificial Neuron Devices Fully Compatible with CMOS Technology for Neural Processing and Sensing in Neuromorphic Hardware

The 1st ROK-EU Semiconductor Researchers Forum

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- Artificial neuron device based on a single MOSFET
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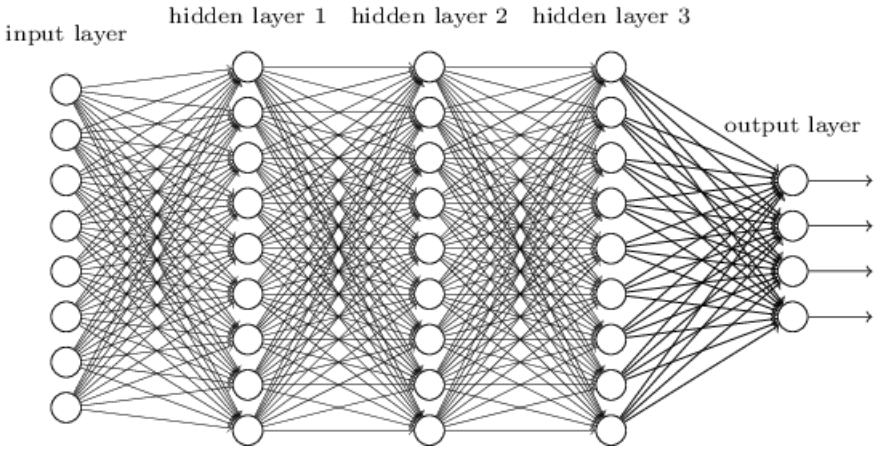
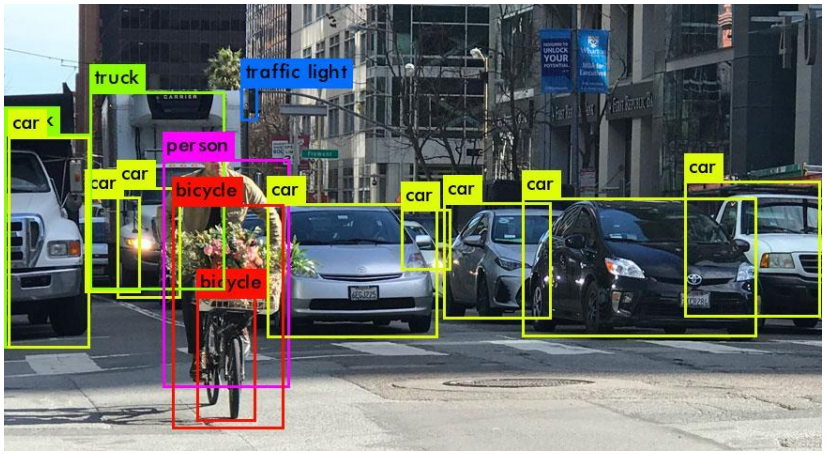
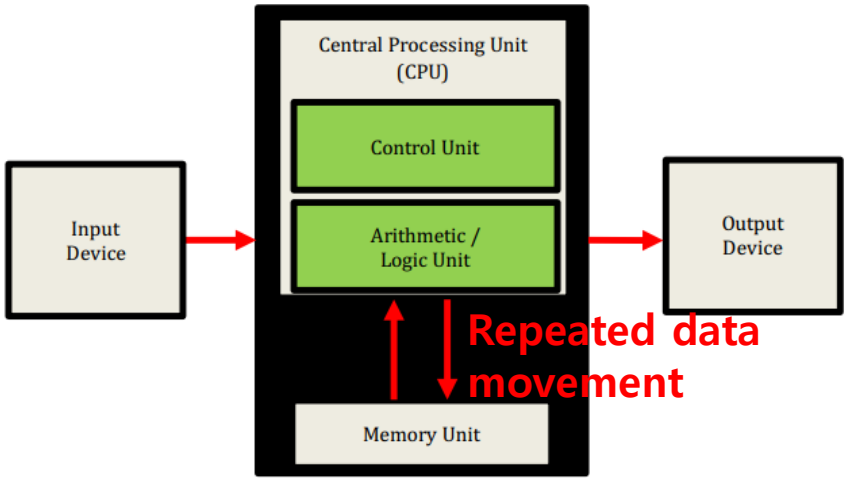
Introduction
Software based deep learning





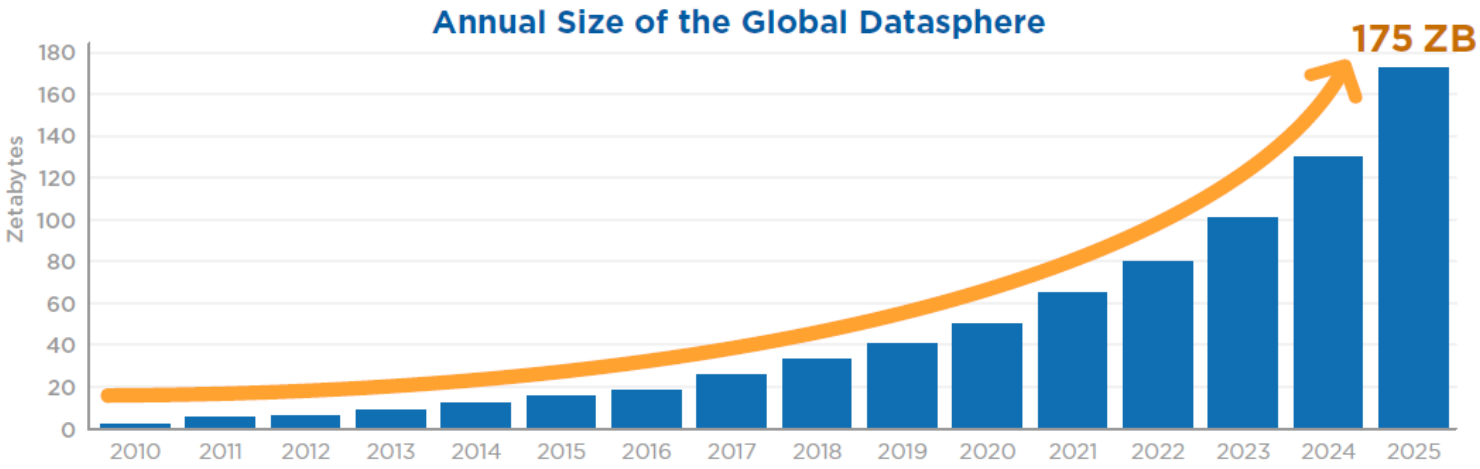
von Neumann architecture



von Neumann bottleneck

- **memory wall problem**
- **high energy consumption**
  (62.7 % of total energy is consumed by data movement)

Introduction
Explosion of data



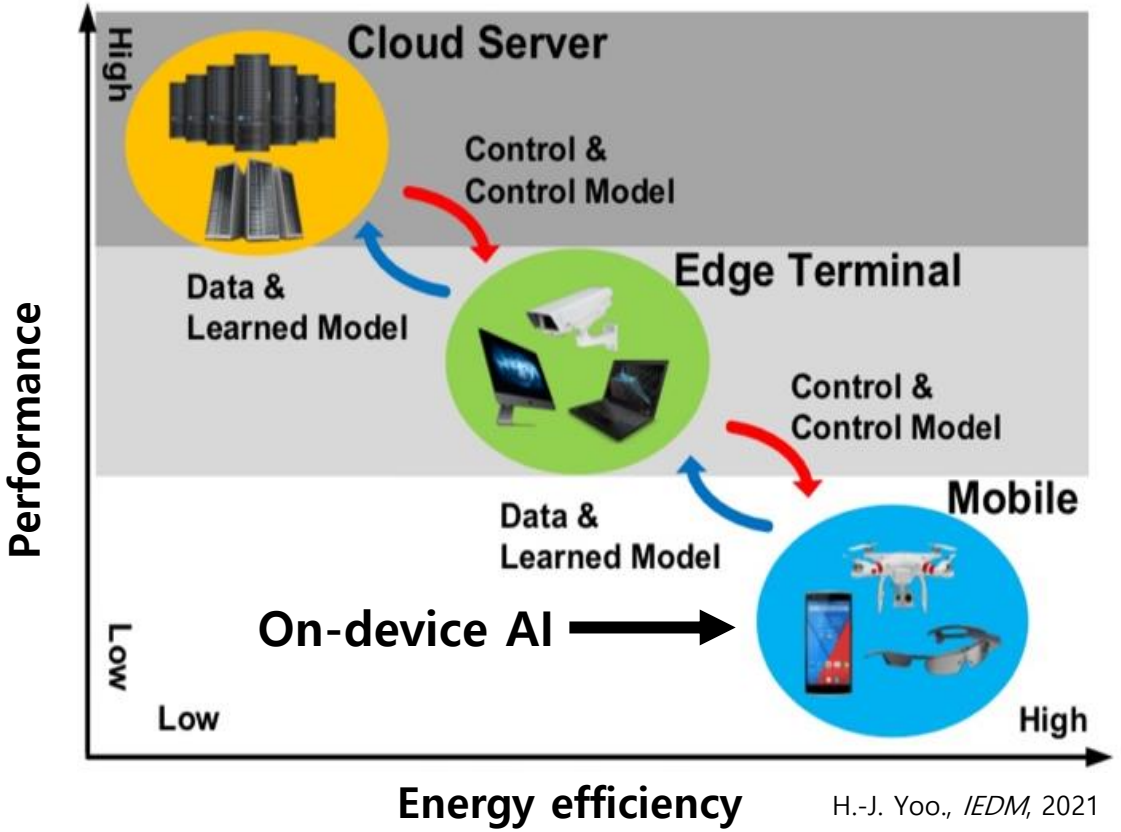
Data Age 2025, sponsored by Seagate with data from IDC Global DataSphere, 2018

ChatGPT (Hyper-scale AI)
: 570 GB data &
175 billion parameters

Introduction
Importance of energy efficiency

Mobile data
: 77.5 billion GB per month
(10 GB/month/person)

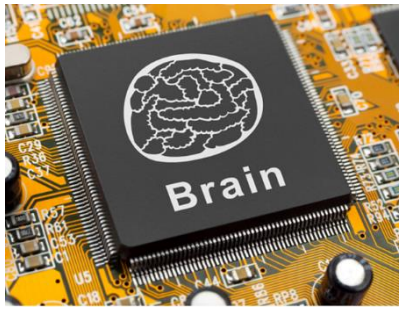
Connected IoT devices
: 3.6 per person
(13.6 for North America)



H.-J. Yoo., *IEDM*, 2021

- **New computing architecture is needed for mobile & edge devices**

Introduction
Hardware based neuromorphic computing

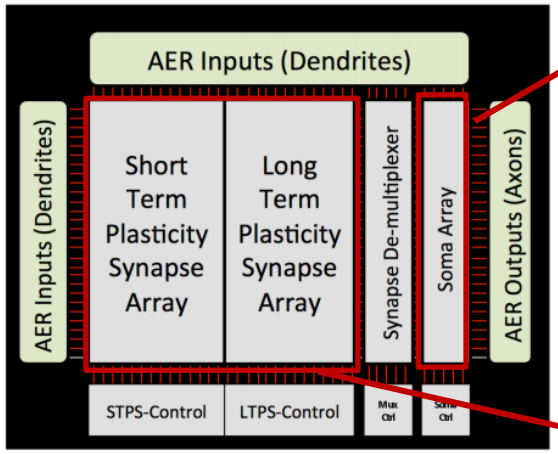


	Human brain	Software based deep learning	Hardware based neuromorphic computing
Target	Biology	Deep neural network (DNN)	Spiking neural network (SNN)
Components	Neuron array	Von Neumann architecture	Neuron array
	Synapse array		Synaptic device array
Learning algorithm	STDP[1], SRDP[2]	Back-propagation	STDP[1], SRDP[2]
Power consumption	**Extremely low**	**High (212 J/image)**	**Low (0.0004 J/image)**
Maturity	**Extremely high**	**High**	**Low**

[1]STDP: spike-timing-dependent plasticity
[2]SRDP: spike-rate-dependent plasticity

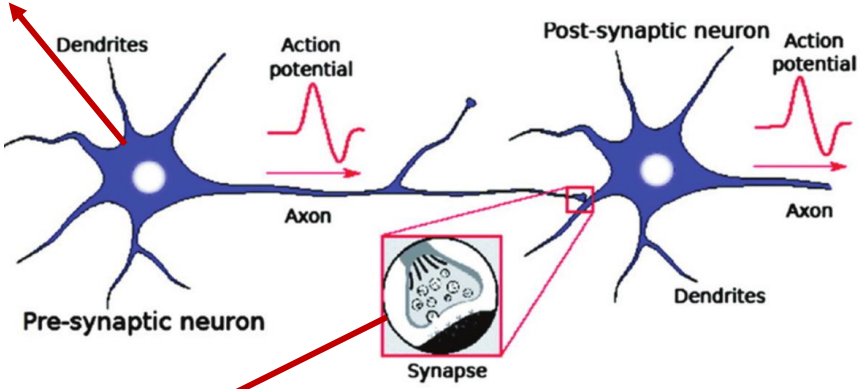
Introduction
Hardware based neuromorphic computing

Neuromorphic architecture



U.S. Department of Energy, 2015

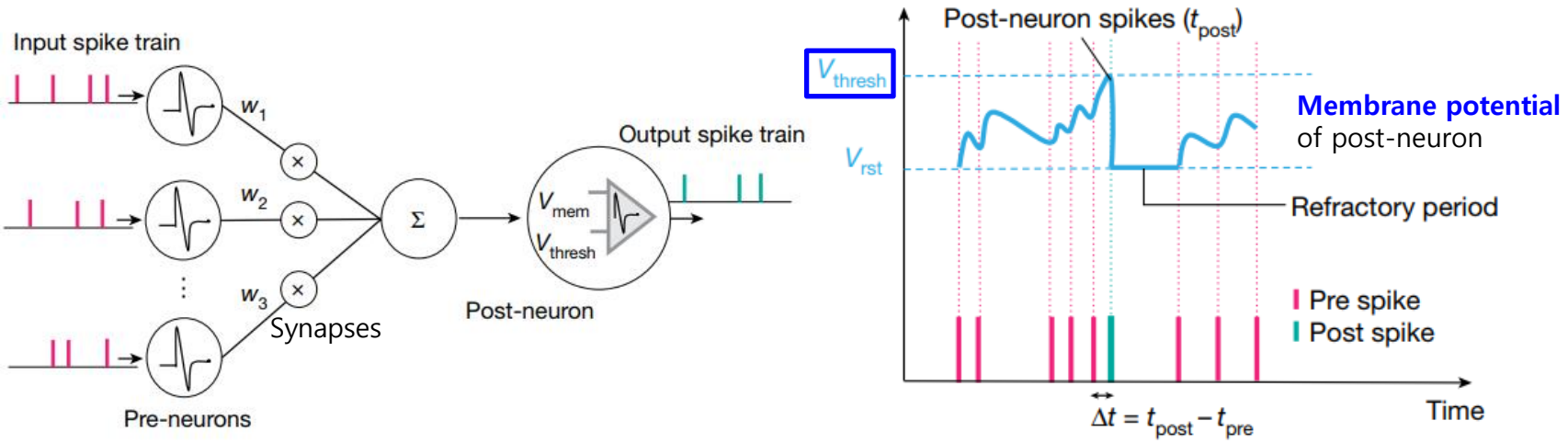
Neuron (~10^{11})



Synapse (~10^{15})

- **Neuron: Leaky integrate & fire (LIF)**
- **Synapse: Potentiation & depression**

Introduction
Neuron in neuromorphic hardware



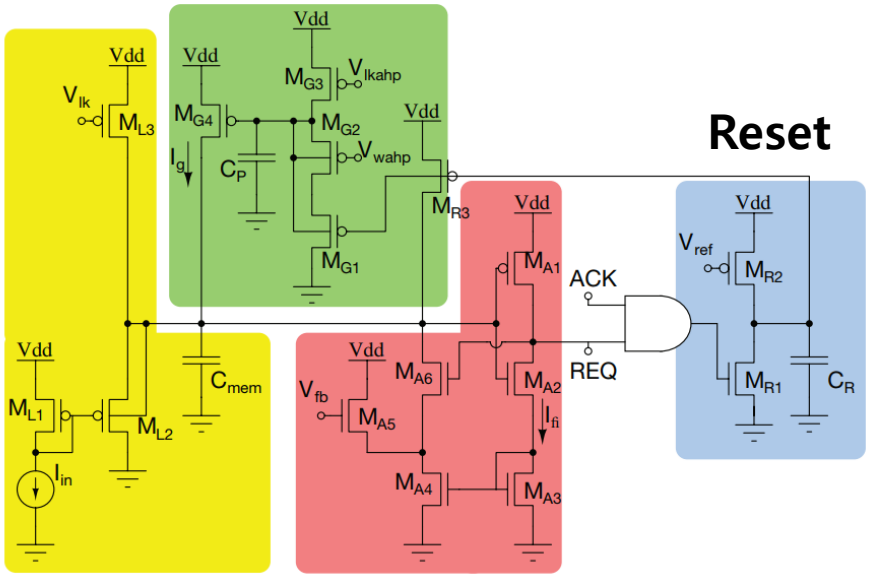
K. Roy *et al.*, *Nature*, 2020

- **Neuron receives signals from previous synapses and produces an output spike when the membrane potential reaches a threshold**

Introduction
Neuron in neuromorphic hardware

Circuit-based neuron

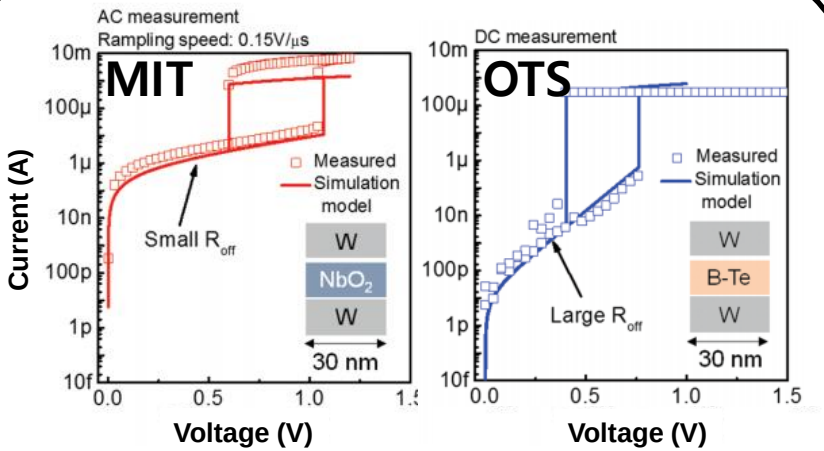
G. Indiveri *et al.*, *Frontiers in Neuroscience*, 2011



Integrate **Comparator**

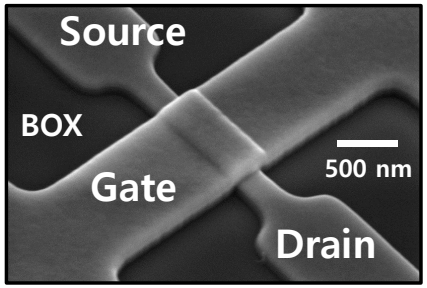
→ large area and hardware cost

Device-based neuron



D. Lee *et al.*, *Advanced Electronic Materials*, 2020

MOSFET



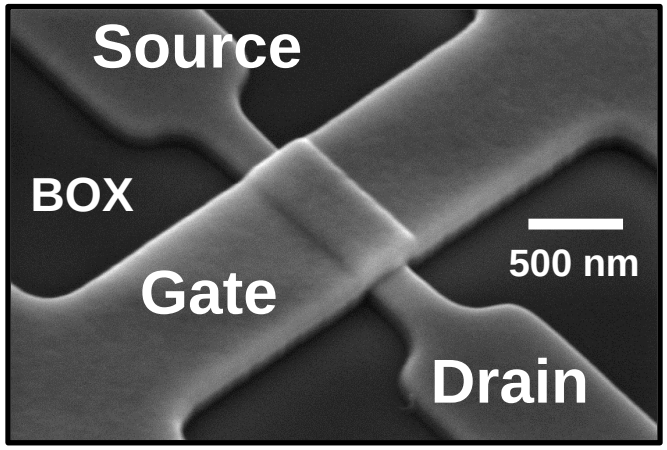
→ 100% compatible with CMOS

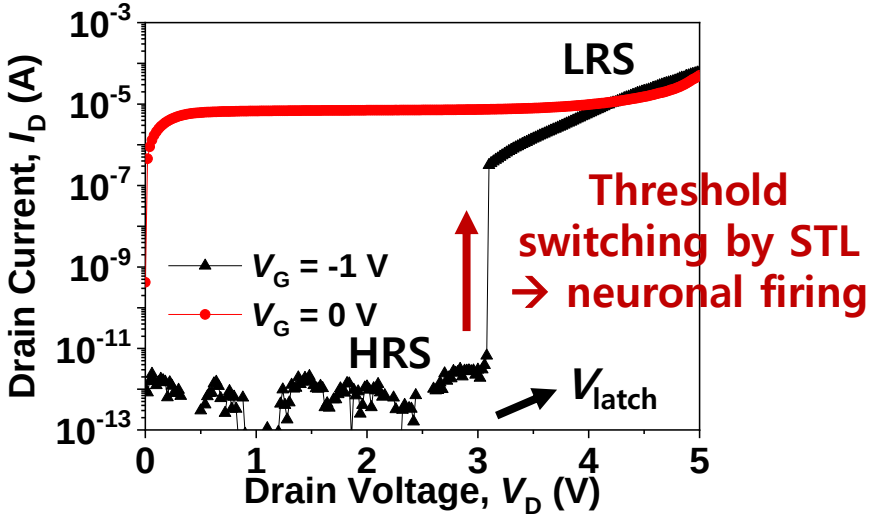
J.-K. Han *et al.*, *IEEE Electron Device Letters*, 2020

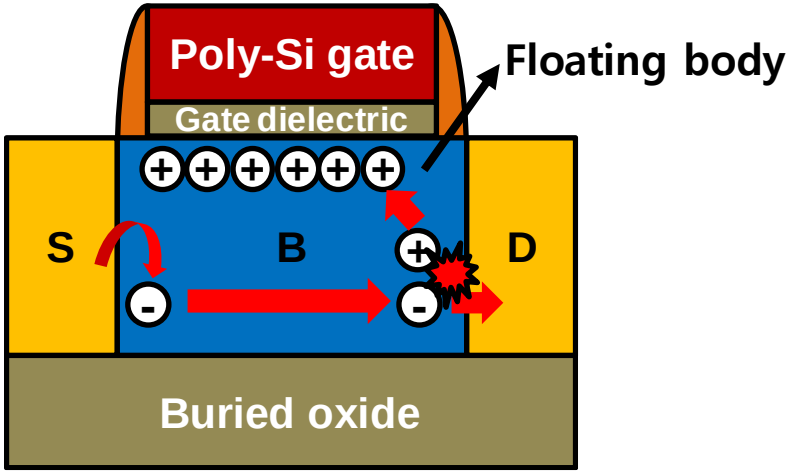
*MIT: Metal to Insulator Transition
*OTS: Ovonic Threshold Switch
*MOSFET: Metal-oxide-semiconductor field-effect transistor

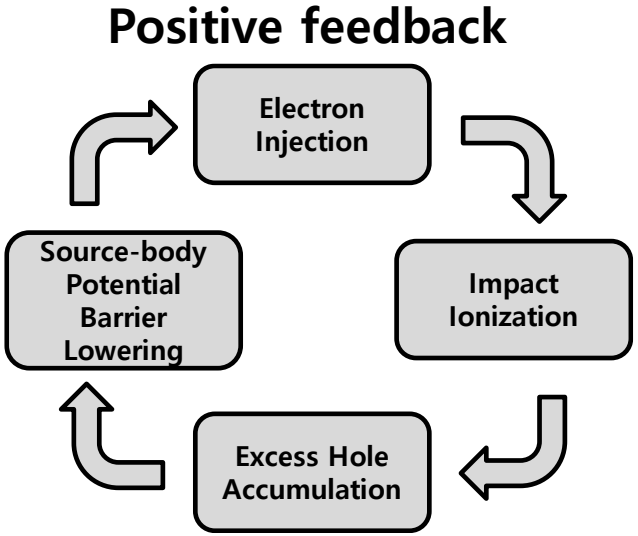
Contents

Artificial neuron based on a single MOSFET
Single transistor latch (STL) phenomenon



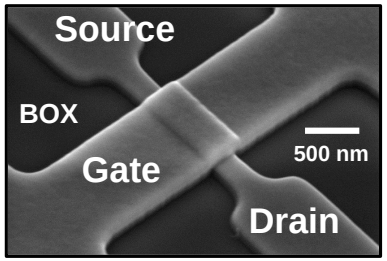


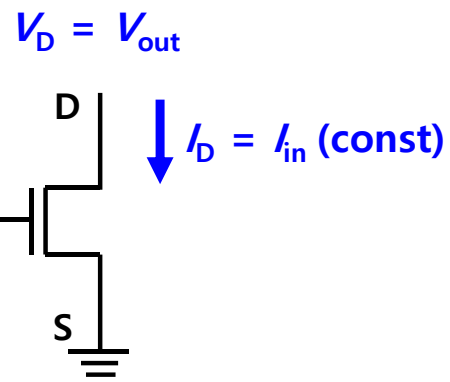


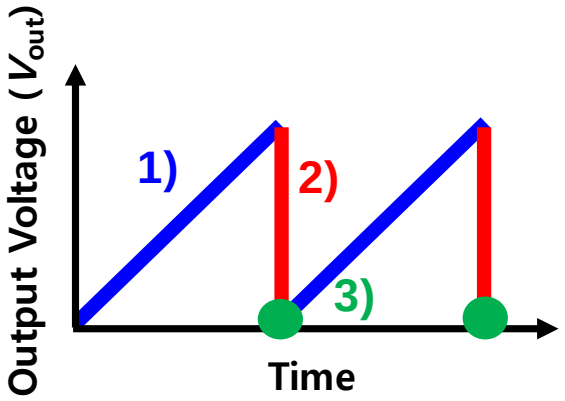


*HRS: high resistance state, LRS: low resistance state, V_{latch}: latch-up voltage

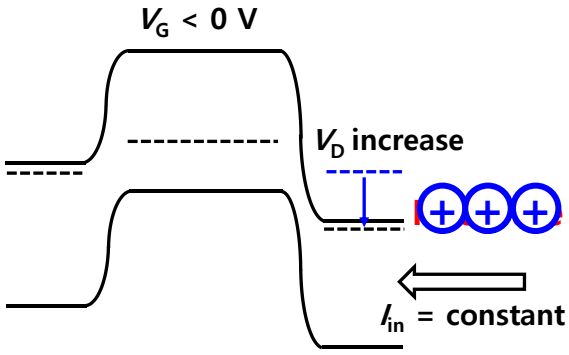
Artificial neuron based on a single MOSFET
Mechanism of neuron operation



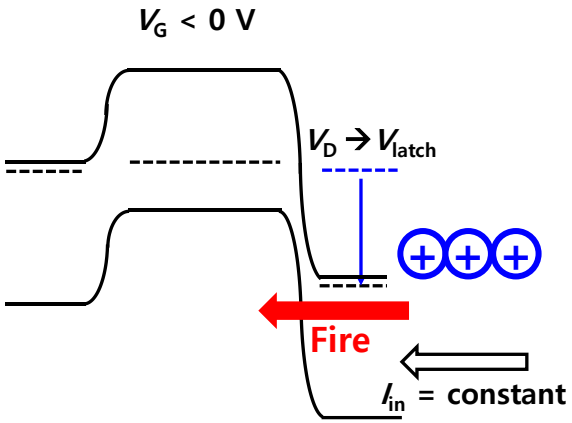




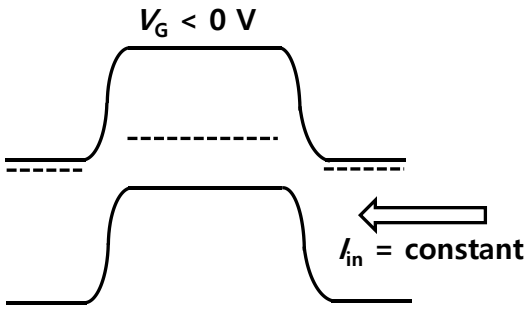
1) Charge integration



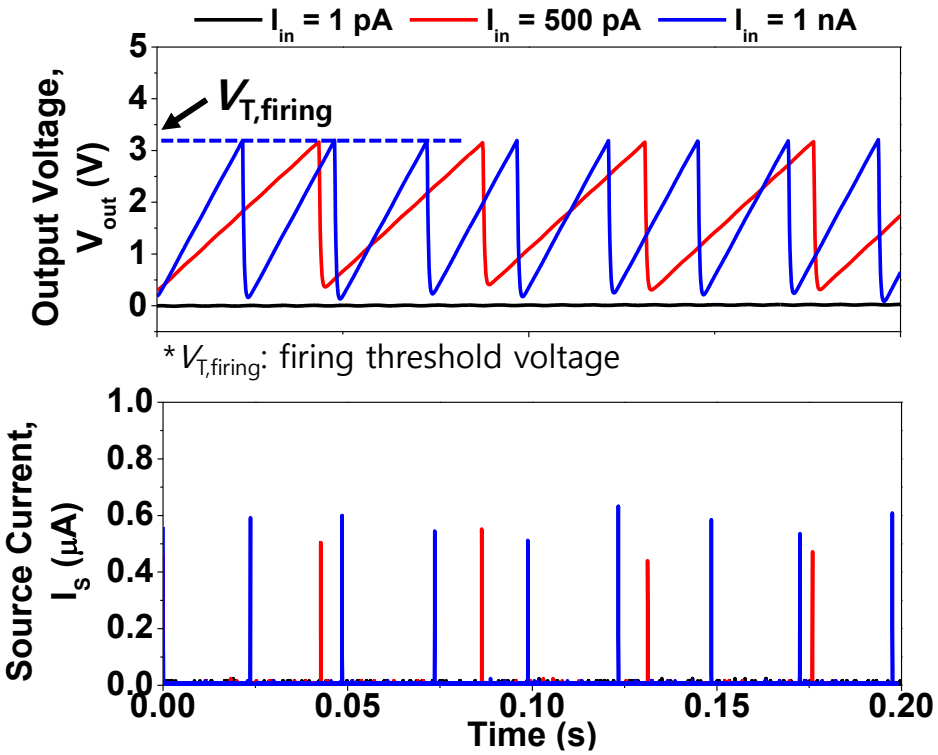
2) Firing by single transistor latch

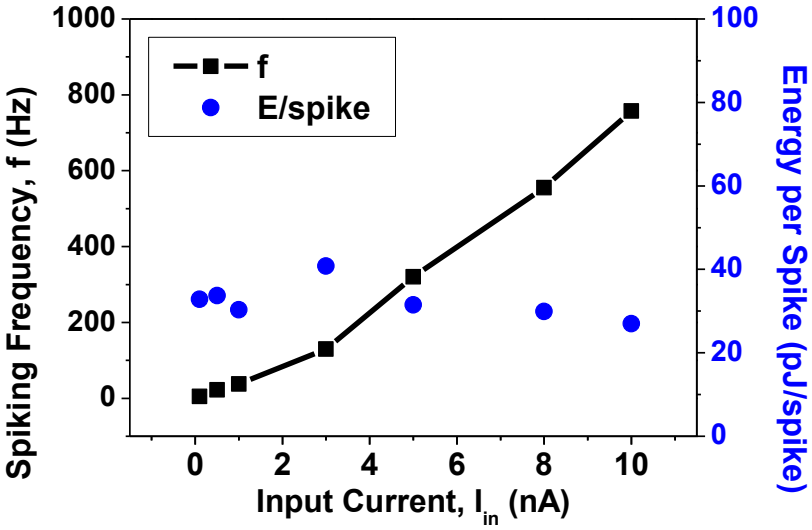


3) Resting state



Artificial neuron based on a single MOSFET
Neuron operation

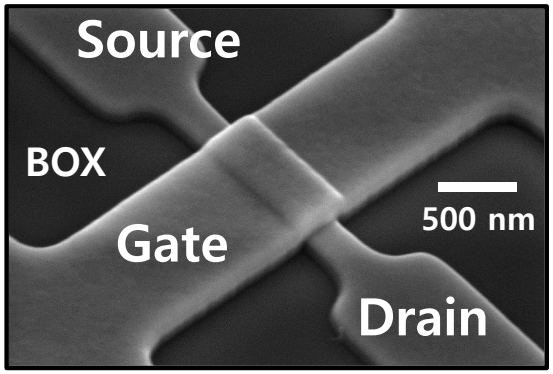




J.-K. Han *et al.*, *IEEE Electron Device Letters*, 2020

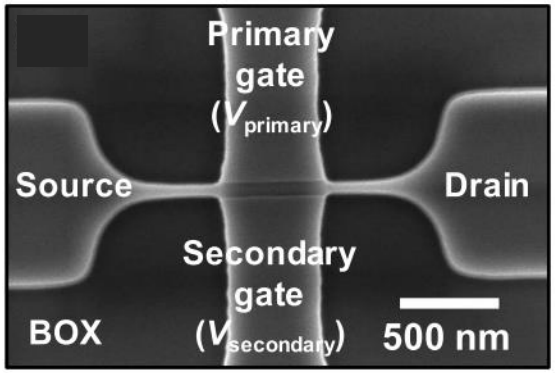
- **Neuron operation was achieved with a single MOSFET**

Artificial neuron based on a single MOSFET
Various structures



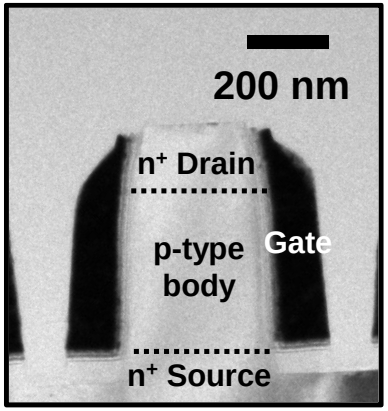
J.-K. Han *et al.*, *IEEE Electron Device Letters*, 2020

Planar MOSFET (single gate)



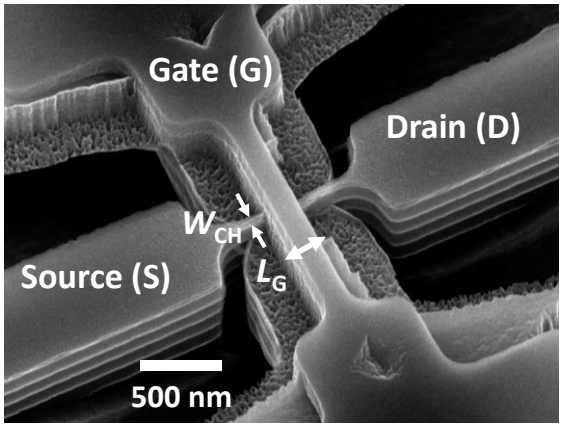
J.-K. Han *et al.*, *IEEE Electron Device Letters*, 2021

Planar MOSFET (double gate)



J.-K. Han *et al.*, *Small*, 2021

Vertical MOSFET

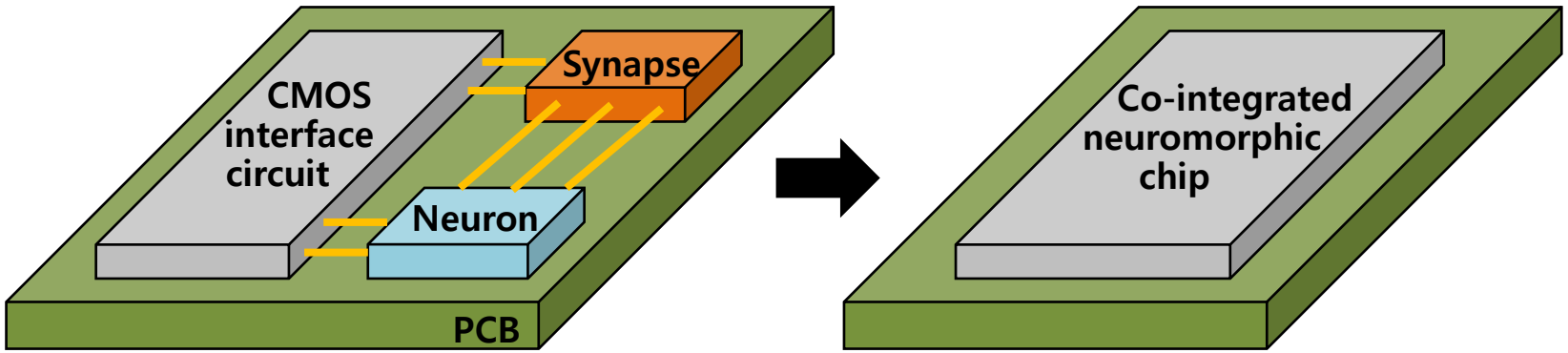


J.-K. Han *et al.*, *IEEE Transactions on Electron Devices*, 2021

Multi-bridge-channel MOSFET

Contents

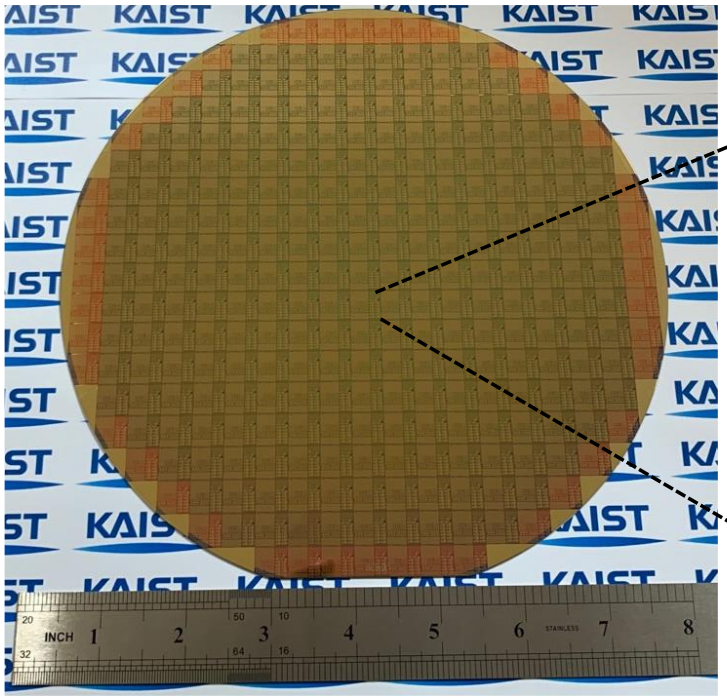
Co-integration of neuron device and synaptic device
Research concept



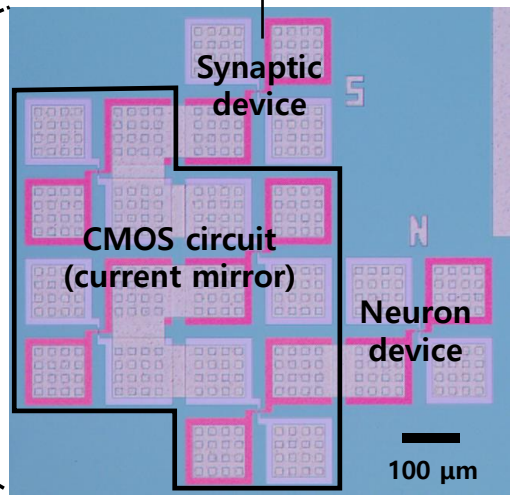
- **Enhance packing density, reduce chip cost, simplify fabrication, reduce energy consumption & delay at interfaces**

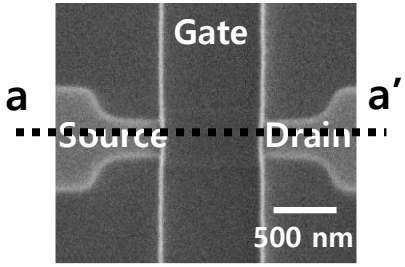
Co-integration of neuron device and synaptic device
2D integration

8-inch

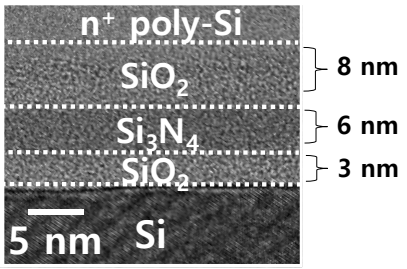


charge trap flash memory





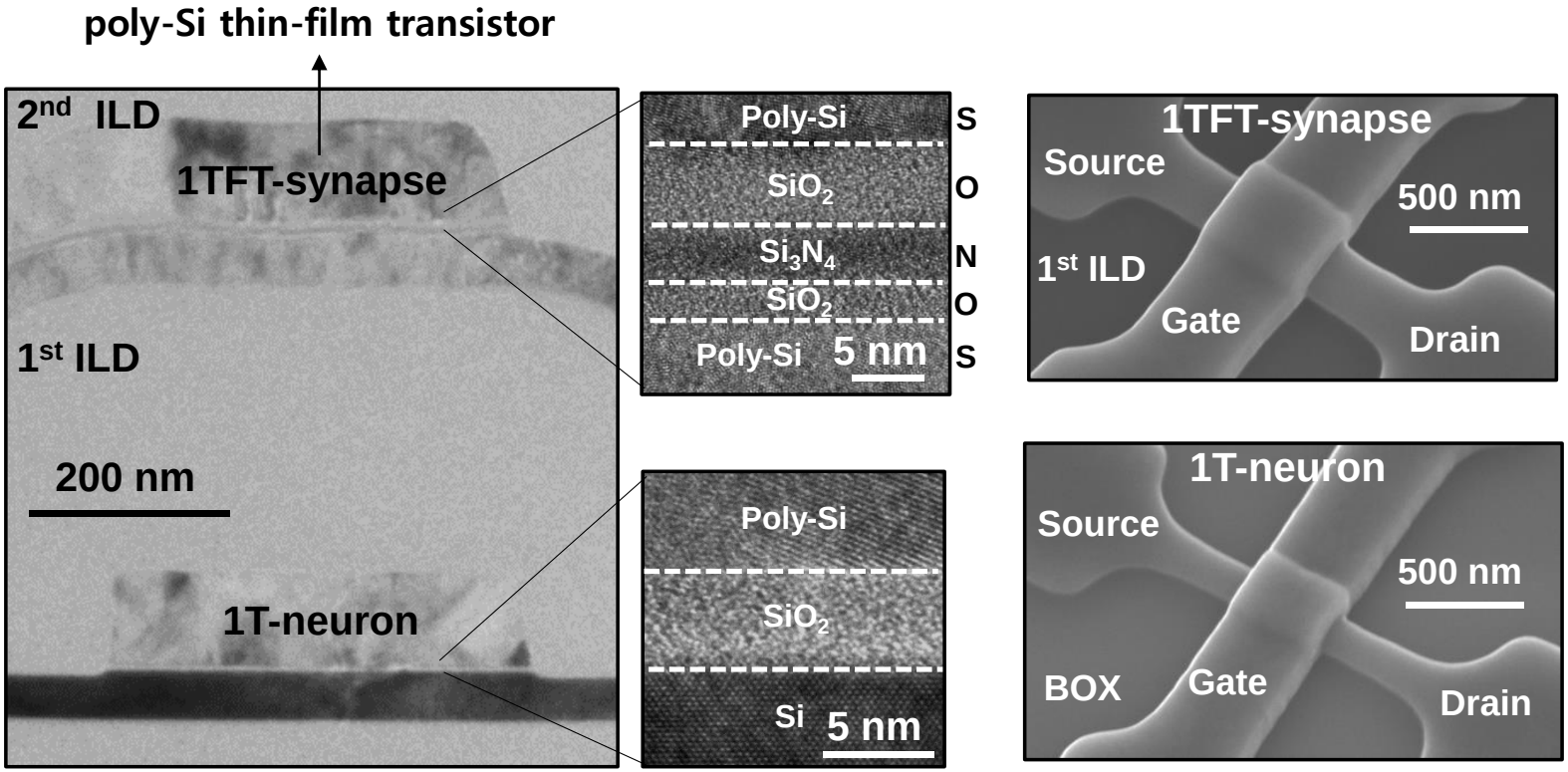
Cross section of a-a'



J.-K. Han *et al.*, *Science Advances*, 2021

- **Neuron, synapse, and CMOS interface circuit can be co-integrated in a 2D plane with the same process**

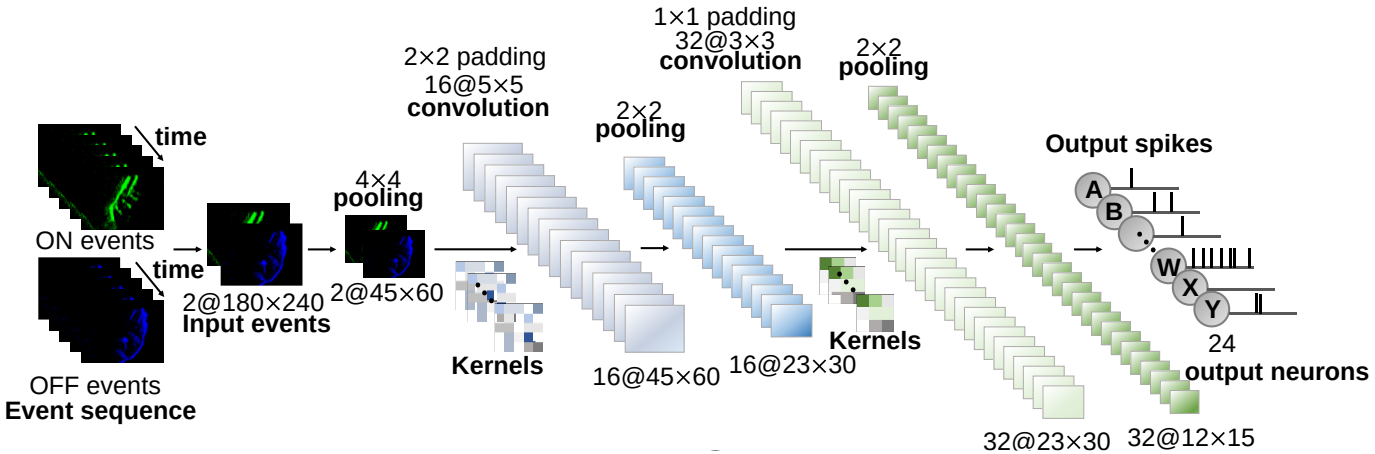
Co-integration of neuron device and synaptic device
3D integration



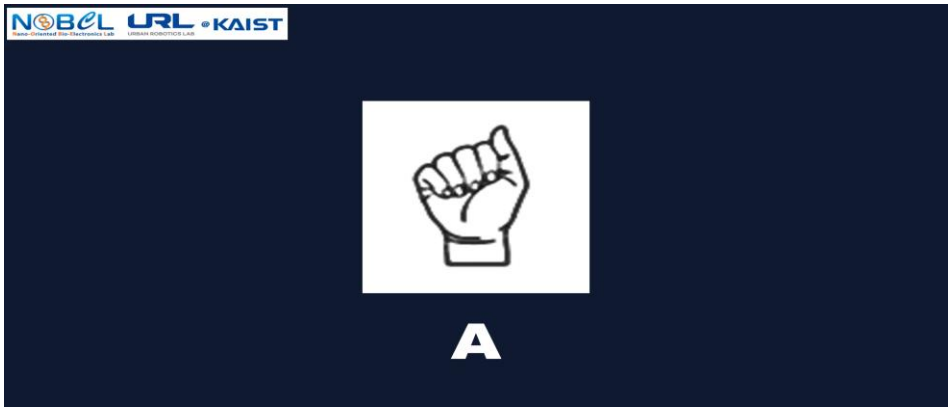
J.-K. Han *et al.*, *Advanced Science*, 2023

- **Neuron and synapse can be 3D integrated with higher density**

Co-integration of neuron device and synaptic device
Applications



Face recognition



Sign language recognition

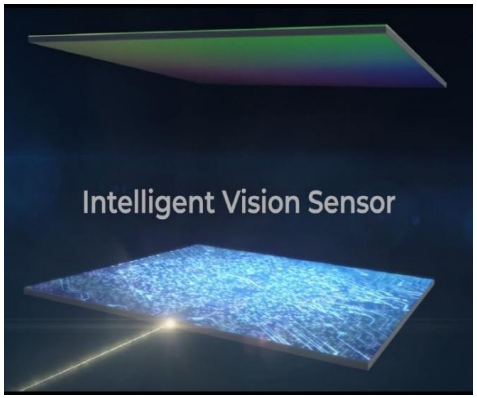
Contents

Artificial sensory neuron for in-sensor computing
Smart sensors

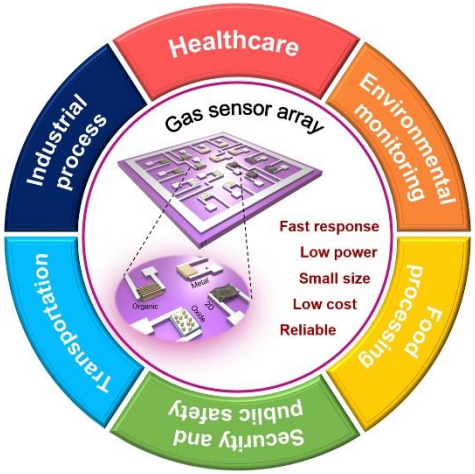
Sensor

Analog-to-digital conversion

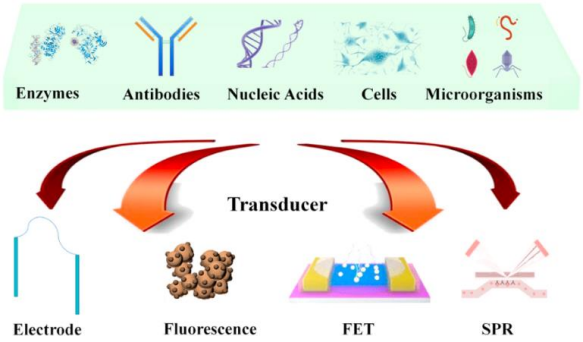
Machine learning (AI)



Image



Gas



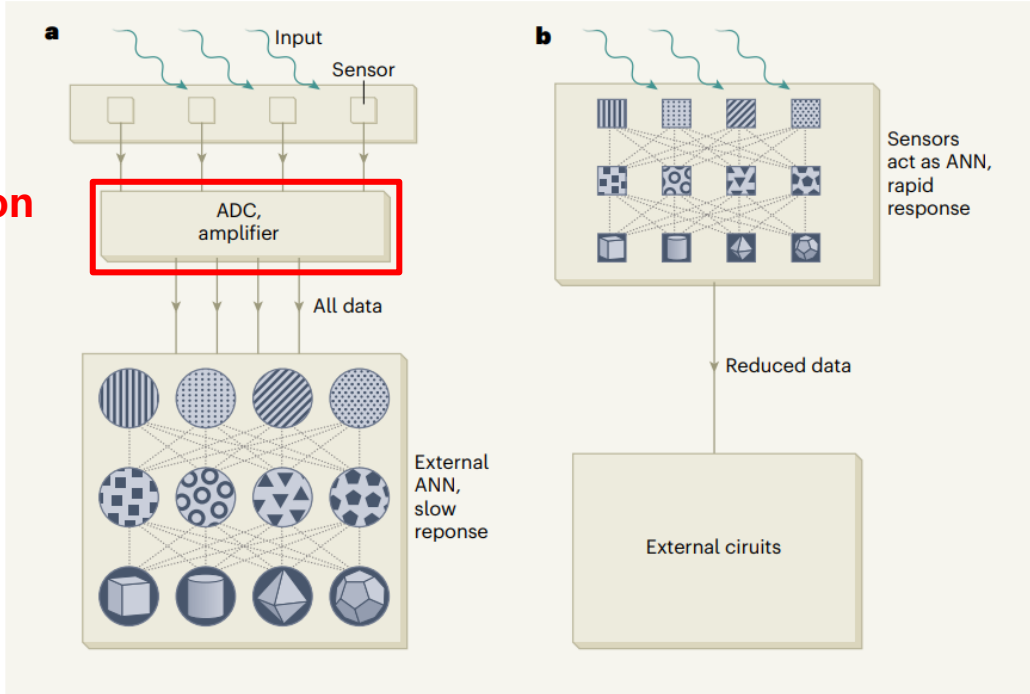
Biochemical

- Smart sensors can recognize/classify images, gases, chemicals, etc. with high accuracy by AI

Artificial sensory neuron for in-sensor computing

In-sensor computing

Bottleneck
(energy consumption
& signal latency
& hardware cost)

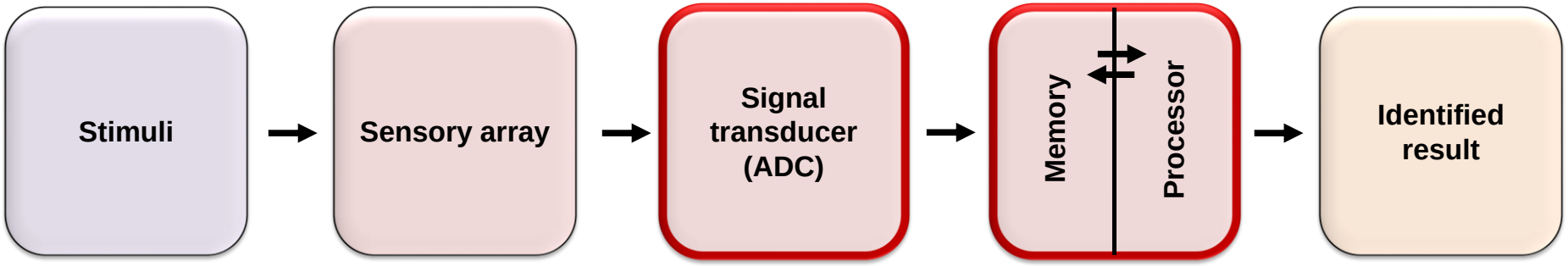


Y. Chai, *Nature Electronics*, 2020

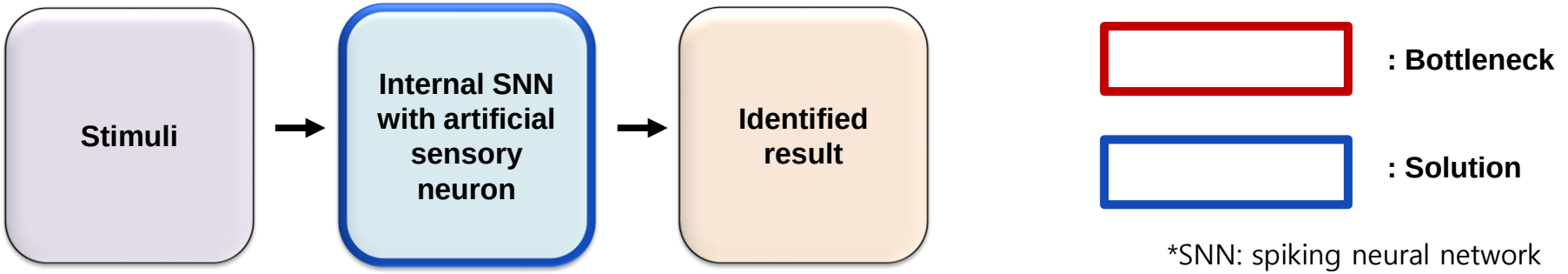
- **Bottleneck exists between the sensor and external neural network**
- **In-sensor computing can remove bottlenecks**

Artificial sensory neuron for in-sensor computing
Neuromorphic sensory system

Conventional sensory system with a conventional von Neumann processor



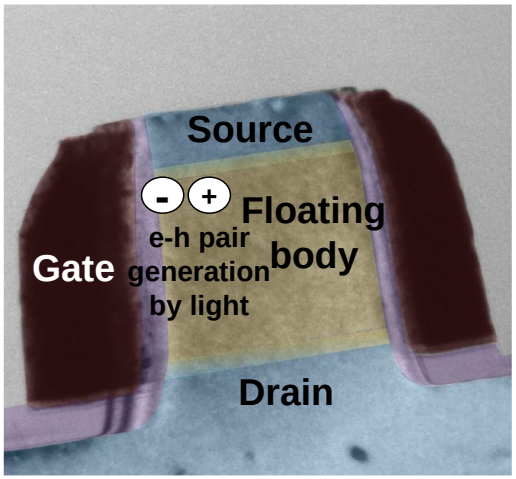
Neuromorphic sensory system with an in-sensor computing



*SNN: spiking neural network

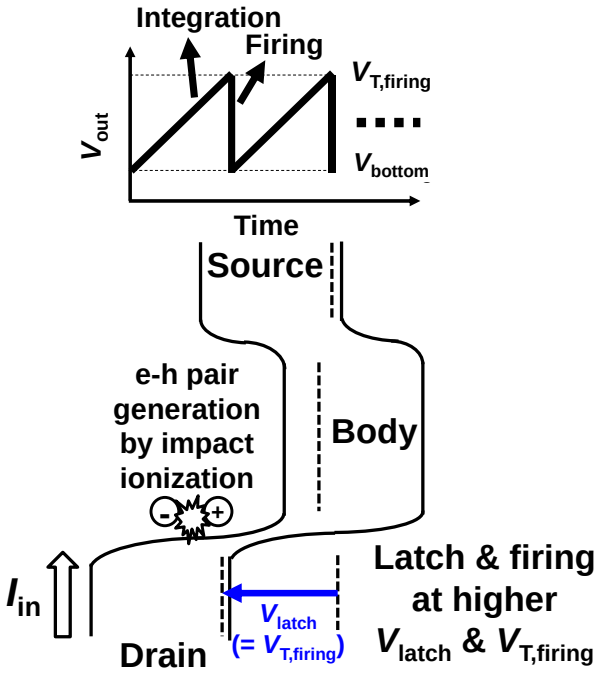
- **Various stimuli (light, gas, chemical, pressure, etc.) should be encoded into electrical spike signals**
  → Mimicry of biological sensory neuron

Artificial sensory neuron for in-sensor computing
Artificial visual sensory neuron

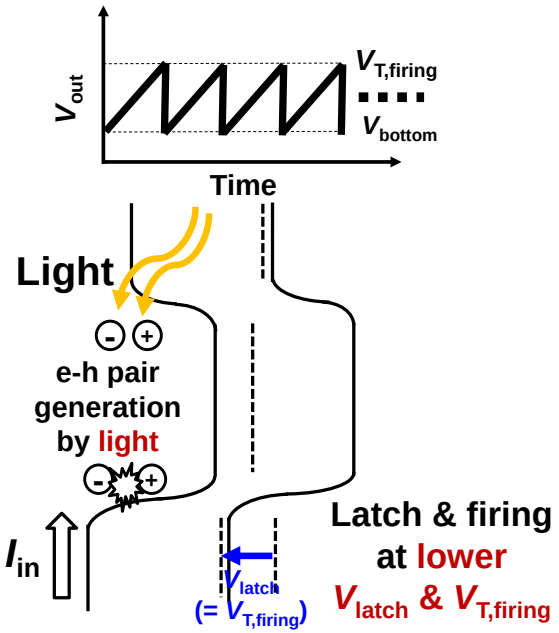


J.-K. Han *et al.*, *Nano Letters*, 2020
J.-K. Han *et al.*, *IEDM*, 2021

Without light illumination



With light illumination

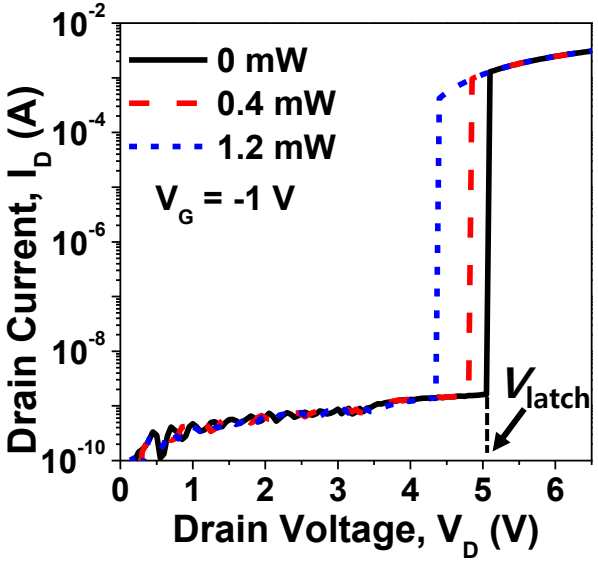


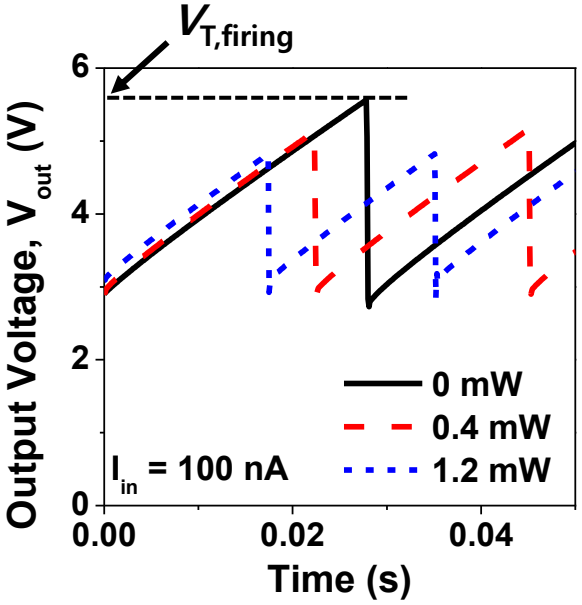
* V_{latch}: latch-up voltage, $V_{T,firing}$: firing threshold voltage

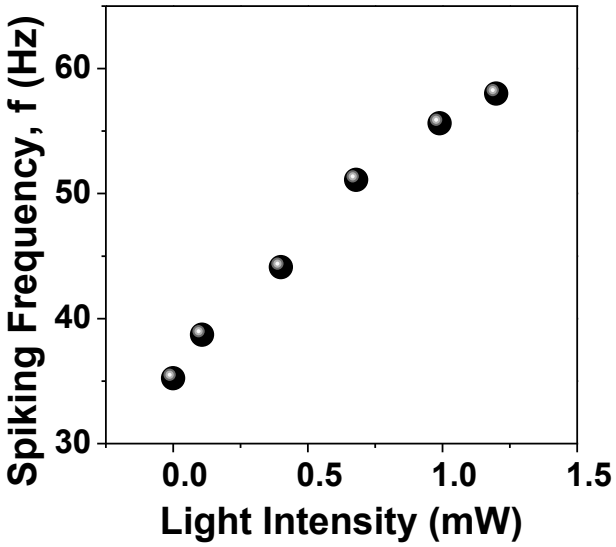
- V_{latch} & $V_{T,firing}$ can be reduced by light illumination
  → spiking frequency increases

Artificial sensory neuron for in-sensor computing

Artificial visual sensory neuron







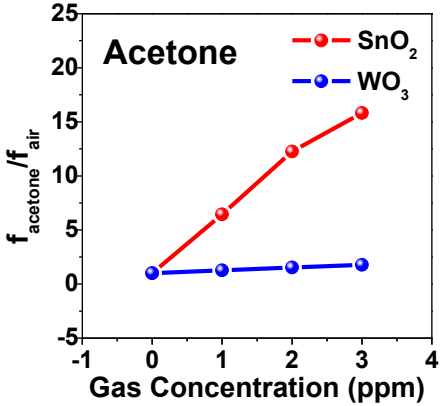
* V_{latch}: latch-up voltage
* $V_{T,firing}$: firing threshold voltage

- **The operation of an artificial visual sensory neuron was achieved with a single MOSFET**

Artificial sensory neuron for in-sensor computing

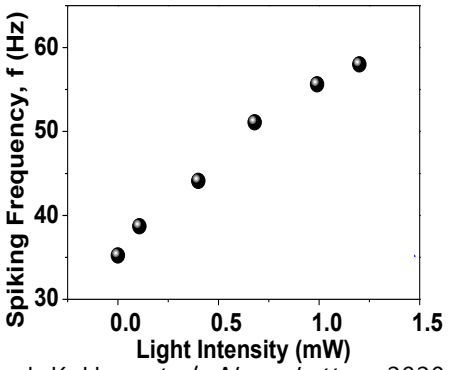
Artificial sensory neuron for five senses

Gas sensing
→ Electronic-nose (E-nose)



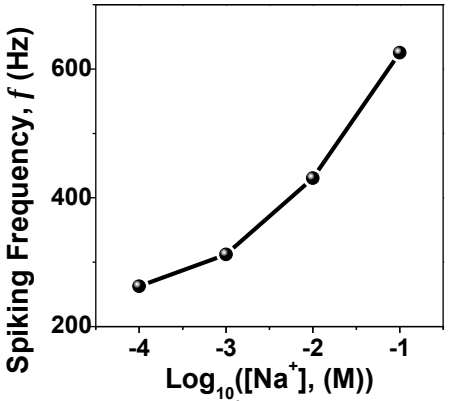
J.-K. Han et al., *Advanced Science*, 2022

Optical sensing
→ Artificial vision system



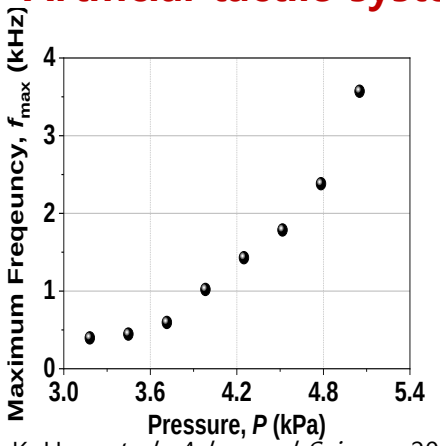
J.-K. Han *et al.*, *Nano Letters*, 2020
J.-K. Han *et al.*, *IEDM*, 2021

Chemical sensing
→ Electronic tongue (E-tongue)

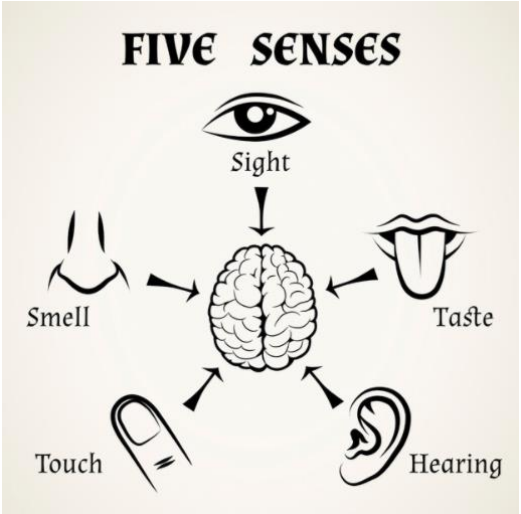


J.-K. Han *et al.*, *Nano Letters*, 2022

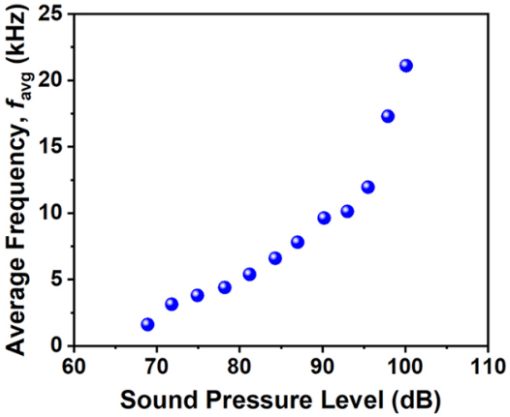
Pressure sensing
→ Artificial tactile system



J.-K. Han *et al.*, *Advanced Science*, 2022



Sound sensing
→ Artificial acoustic system



S.-Y. Yun, J.-K. Han *et al.*, *Nano Energy*, 2023

Contents

Conclusion
Summary of research

- Neuromorphic hardware can greatly reduce the energy consumption for AI
- Highly scalable neuron device based on a single MOSFET was demonstrated
- 2D & 3D co-integration of neuron device and synaptic device were demonstrated
- Artificial sensory neuron devices that can act as an input neuron for in-sensor computing were developed
- High packing density and reduction of energy consumption can be achieved

Thank you very much for your attention