Probabilistic Bits for Unconventional Computing Systems

Jiyong Woo, Associate Professor

School of Electronics Engineering
Kyungpook National University

Outline

- **Why Unconventional Computing?**
  - -Probabilistic Bit (p-Bit) as Key Building Block
- **p-Bit Implementation: From Material to Device**
  - -Leveraging Instability of SiO_x Oscillator
  - -Highly Controllable Probabilistic Oscillation
- **p-Bit Applications: From Optimization to Logic**
  - -Vehicle Routing Problems
  - -Invertible Probabilistic Logic Gates
- **Outlook and Summary**

Data Is Everywhere

✓ A minute on the internet in 2023

✓ Real-time data handling

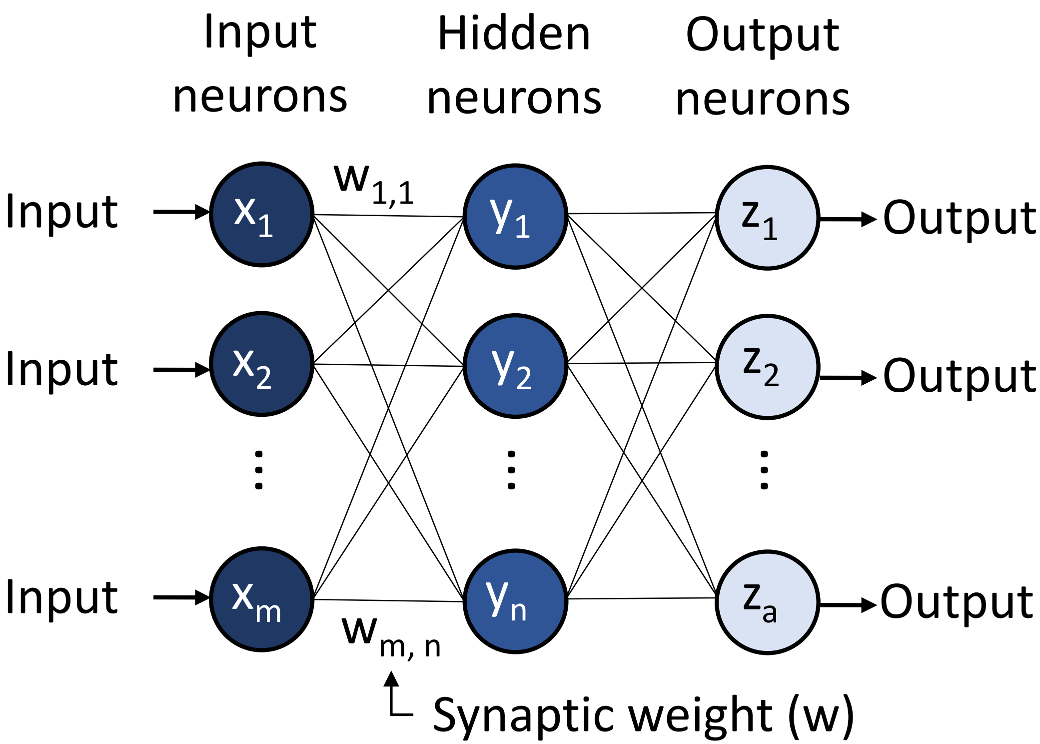
✓ 2 zettabyte (ZB=10^{21}) in 2010 → 47 ZB in 2020 → 2,142 ZB in 2035

✓ Memory-centric computing systems

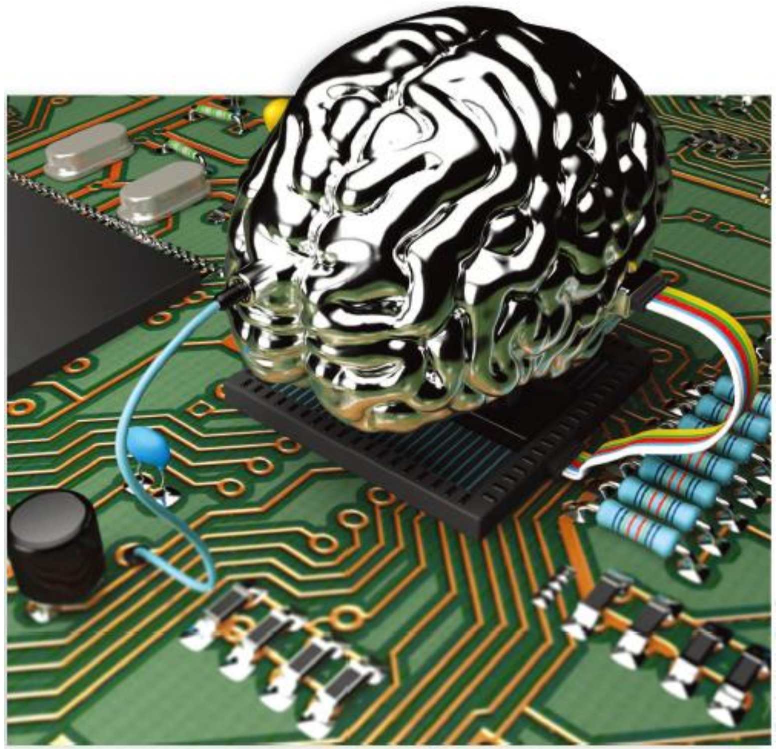
→ Data processing in an efficient manner from power and latency perspectives

Brain Inspired Neuromorphic Technology

✓ Deep neural network



✓ Neuromorphic system



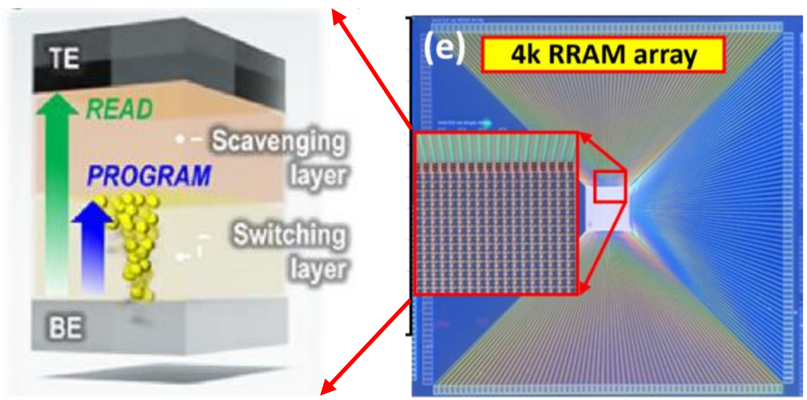
✓ Emulating the brain that processes data

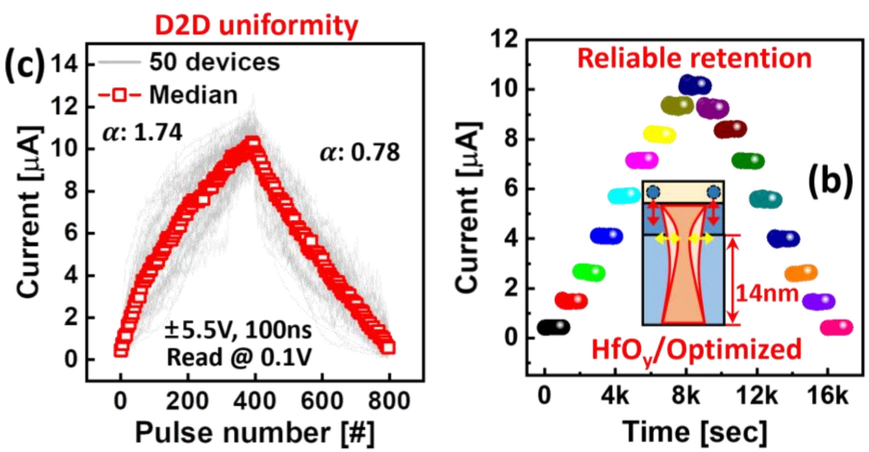
-Transfer data from one neuron to the other through synapses in parallel

✓ Analog synaptic elements speed up the computation efficiency in hardware

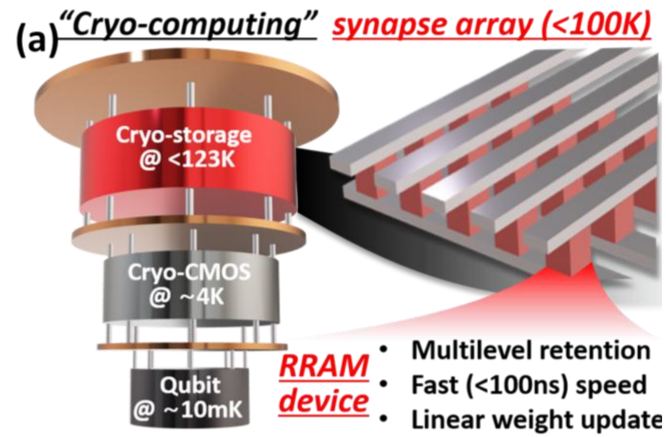
Analog and Cryogenic RRAM Synaptic Devices

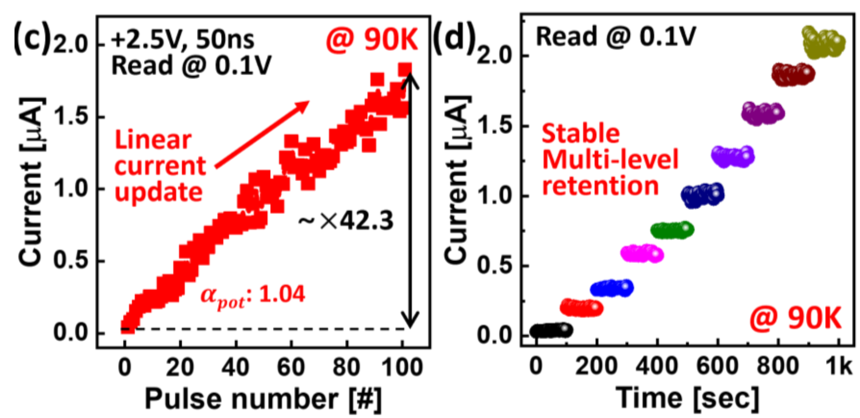
✓ Large scale 4K (64x64) RRAM





✓ Cryogenic RRAM

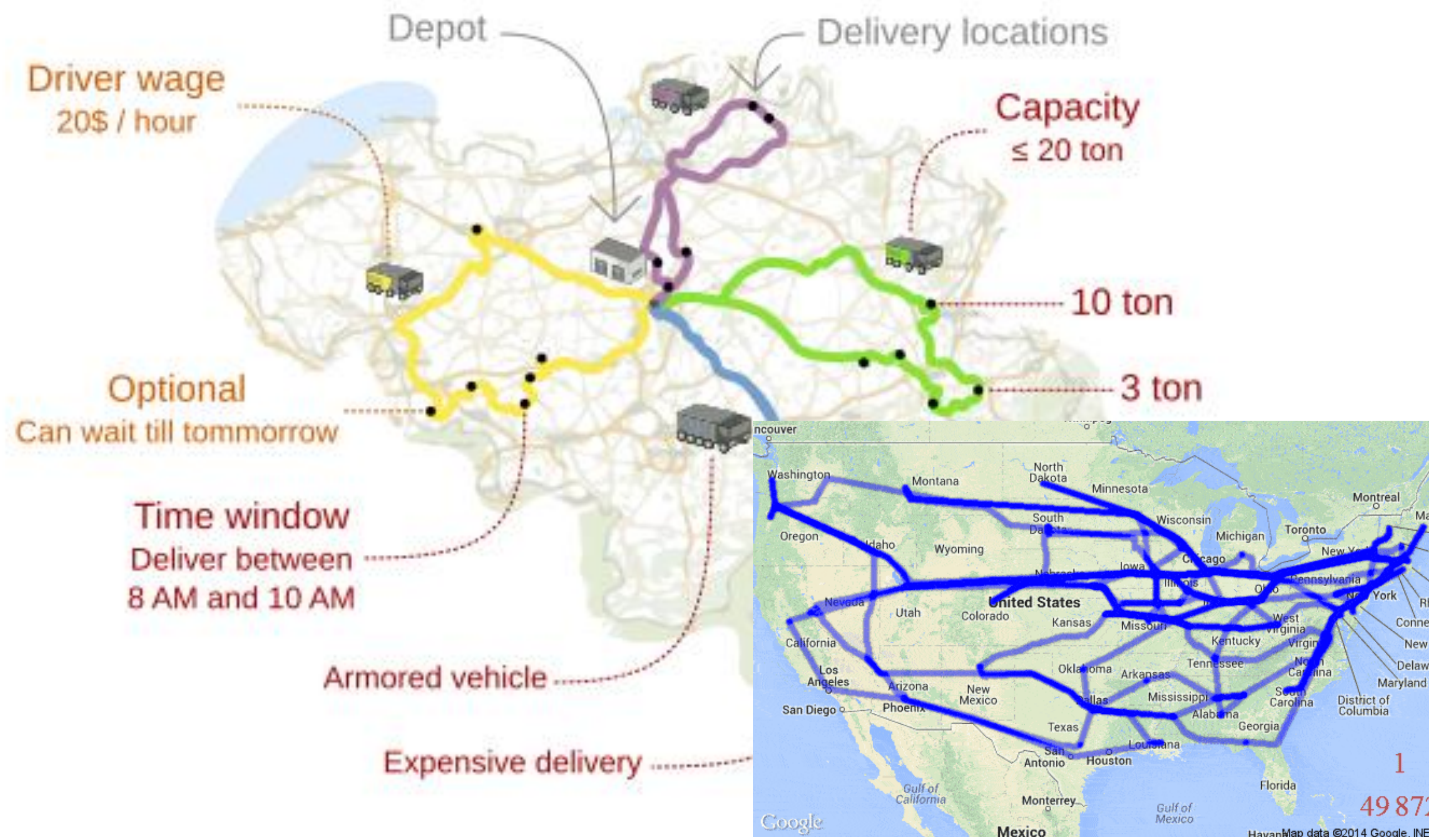




✓ Fully sputtered HfO_x RRAM for analog and cryogenic synapses

✓ Reliable analog switching with sub-100 ns speed even at 90 K

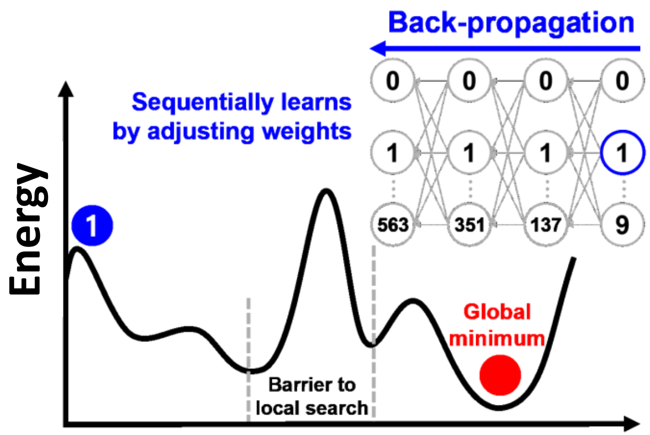
New Applications Beyond Classification



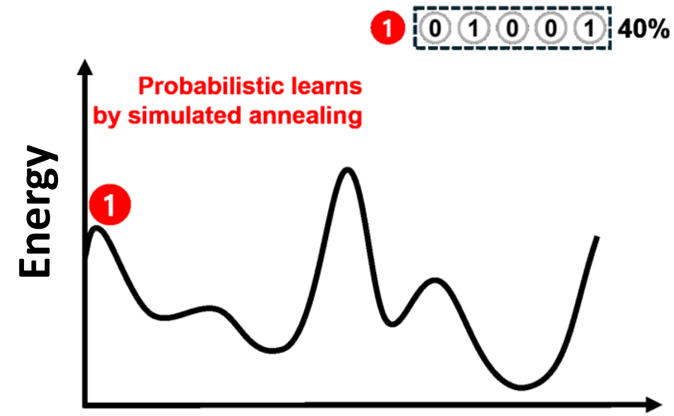
- ✓ AI technology plays an important role in future business
- ✓ Assign delivery order of vehicles more efficiently to reduce time/fuel consumption
- ✓ Demands for solving complex optimization problems

Unconventional Computing

✓ Neural network



✓ Optimization algorithms

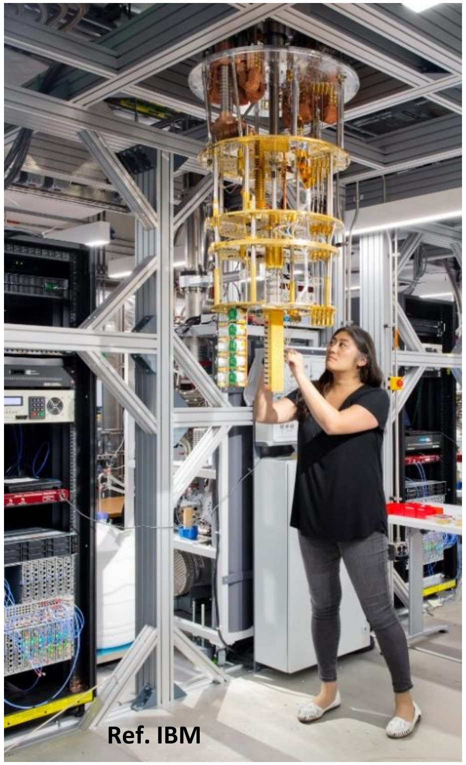


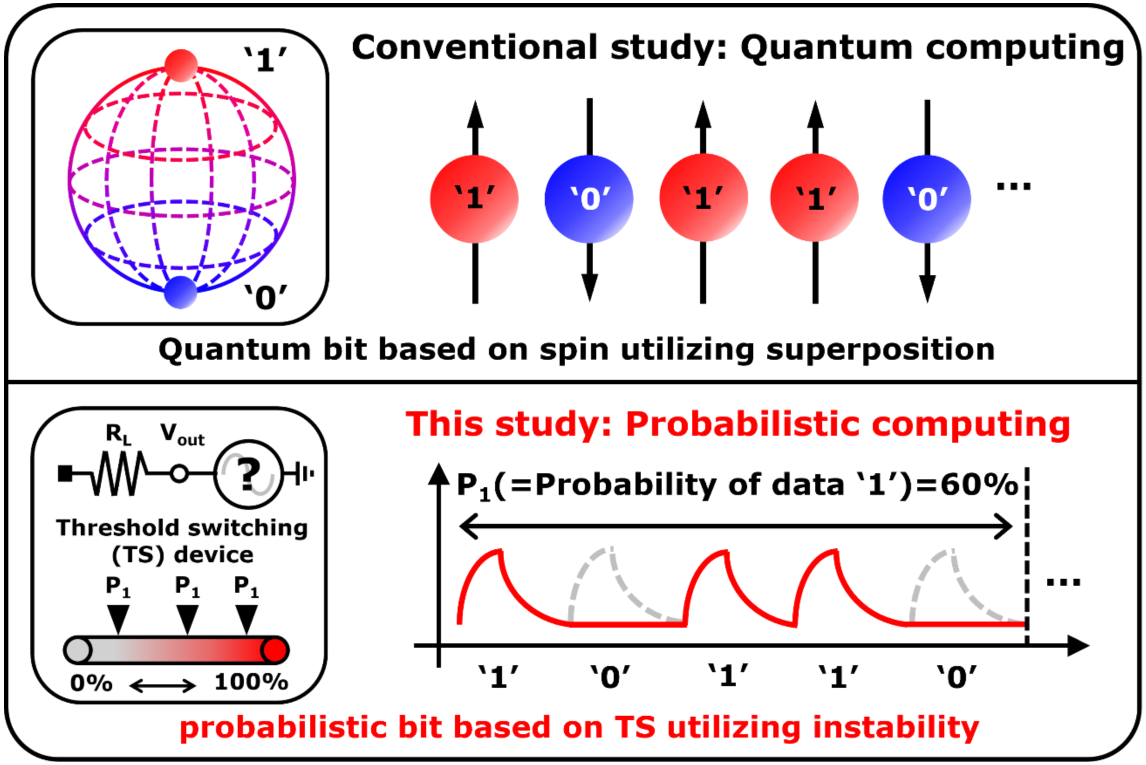
Back-propagation	Learning Algorithms	Simulated Annealing
Gradient Descent	Optimization Process	Energy Minimization
Stuck-at-local Minimum	Cost Landscape	Lack of Cost Stability
Pattern Recognition	Applications	Optimization Solver (COP)

J. Kim et al., IEEE IRPS 2025
J. Kim et al., IEEE Access, 2025

p-Bit for Probabilistic Computing

✓ p-Bit vs. qubit



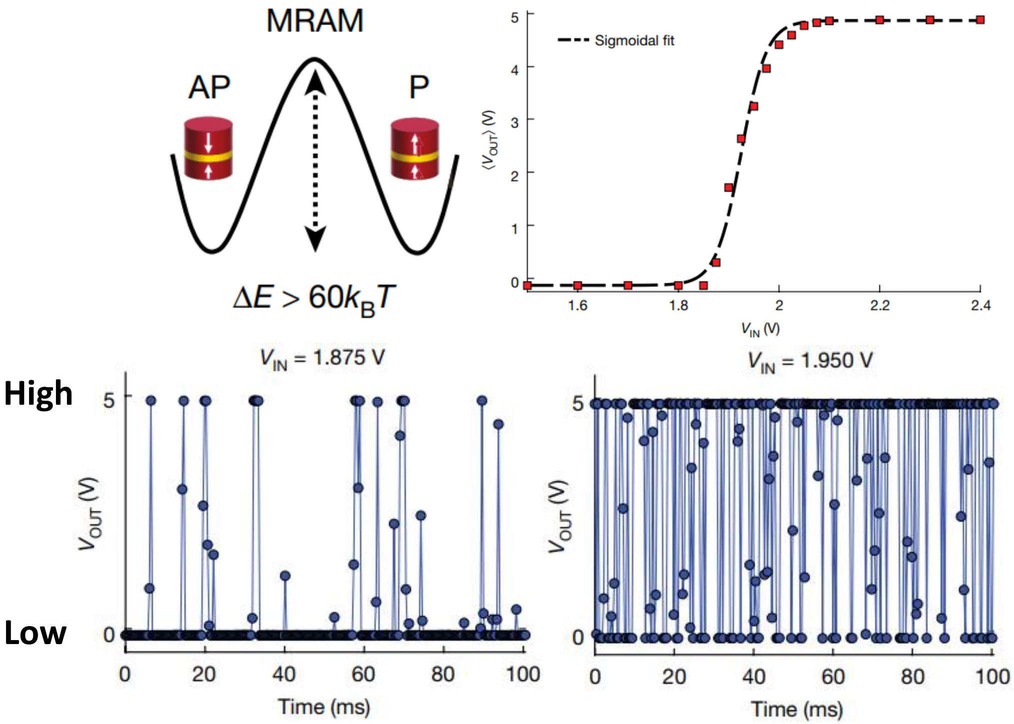


✓ What if we could use device instability to intentionally describe qubit?

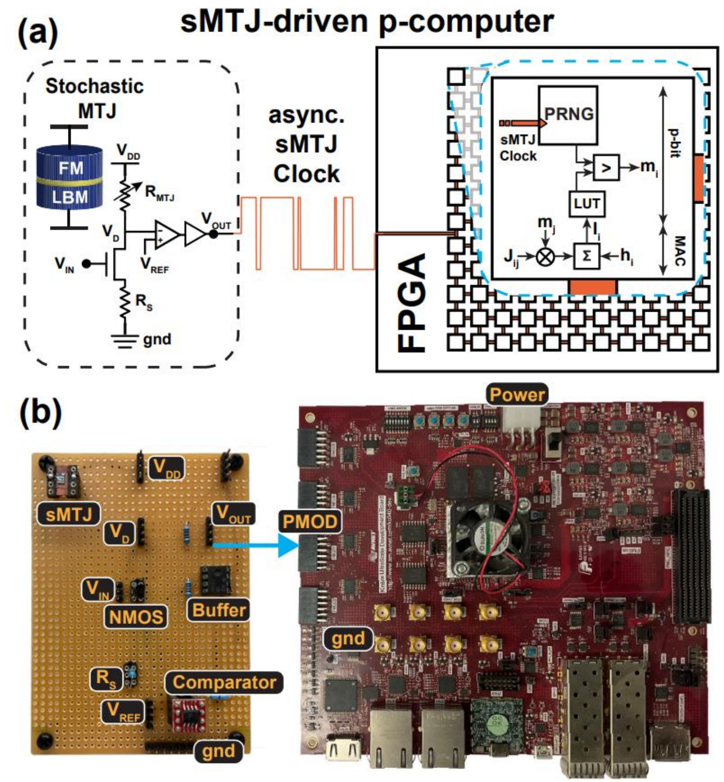
✓ Probabilistic bit (p-Bit), where the data '0' and '1' are fluctuated over time

p-Bit using Spintronics

✓ MTJ p-Bit characteristic



✓ Hardware demonstration



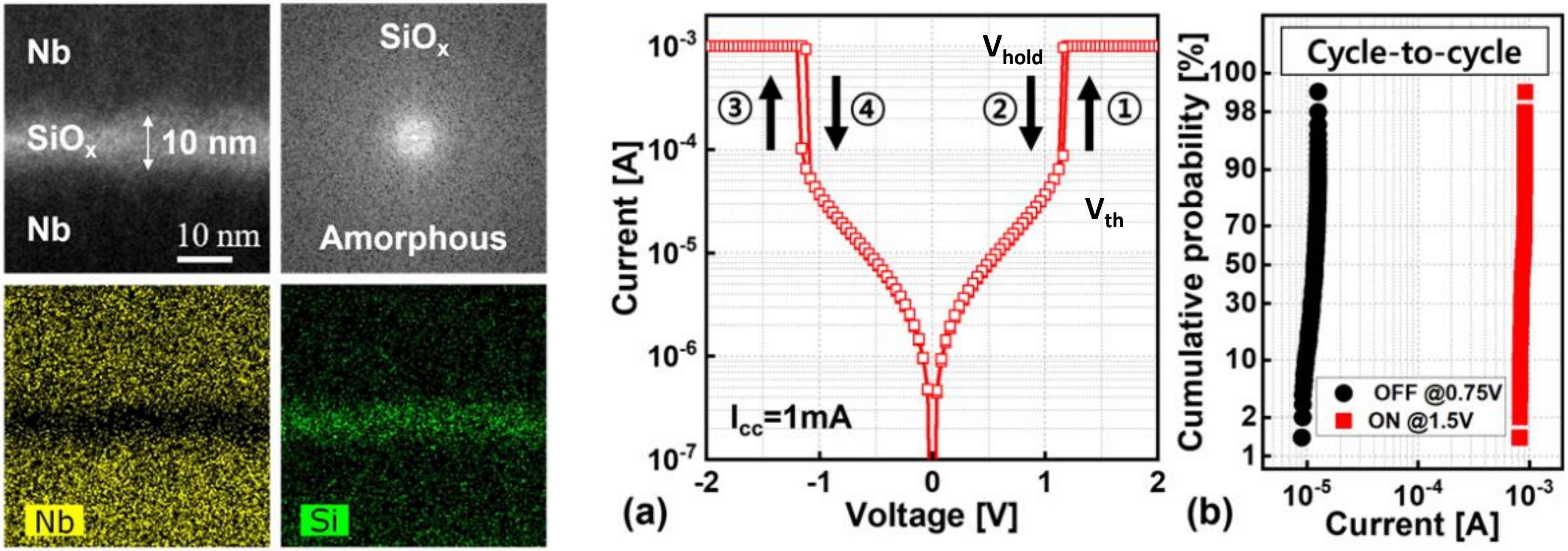
✓ MTJ-based p-Bit operates using thermal noise and bias current

✓ 100 times energy efficiency and power advantage over GPUs

✓ Narrow and limited probability control range (~0.1V)

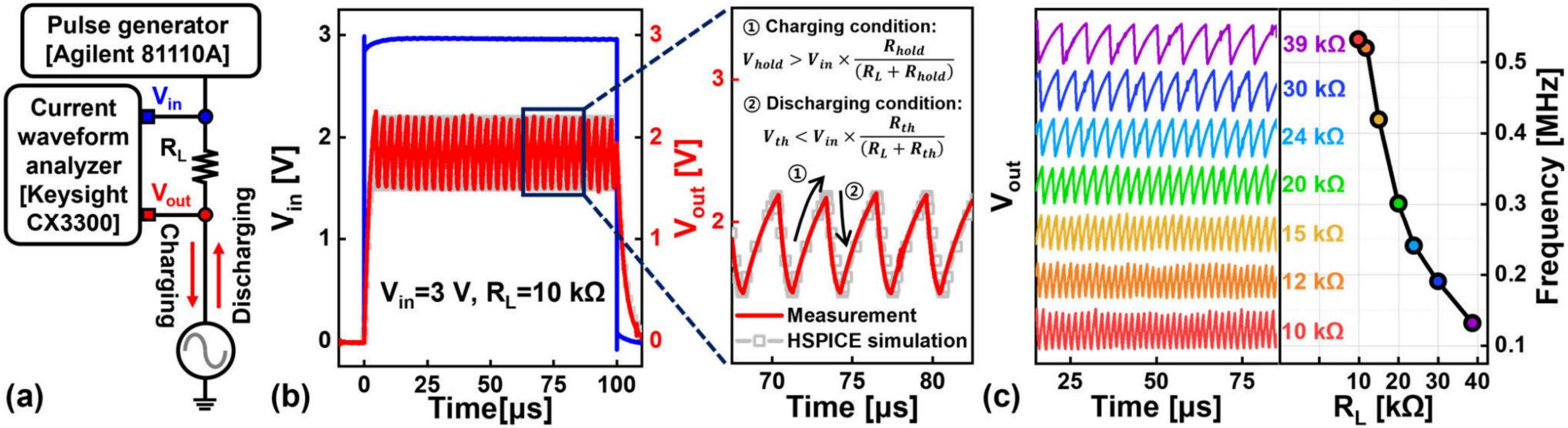
✓ Need for many transistors with comparator in configuration perspective

SiO_x Threshold Switch for Oscillator



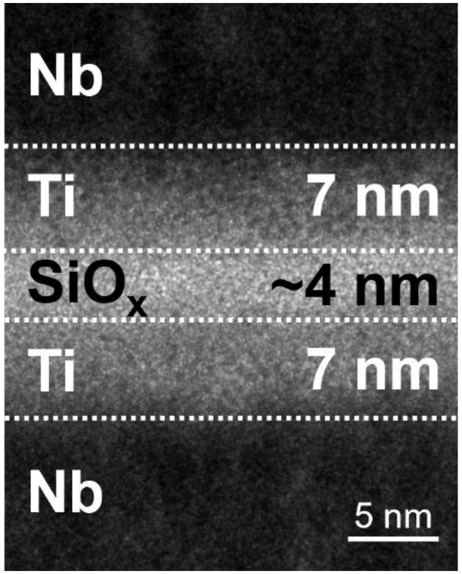
- ✓ Bidirectional and uniform threshold switching (TS) in undoped SiO_x
- ✓ Switches from off-state to on-state at threshold voltage (V_{th}) after firing
- ✓ Returns to off-state at hold voltage (V_{hold})

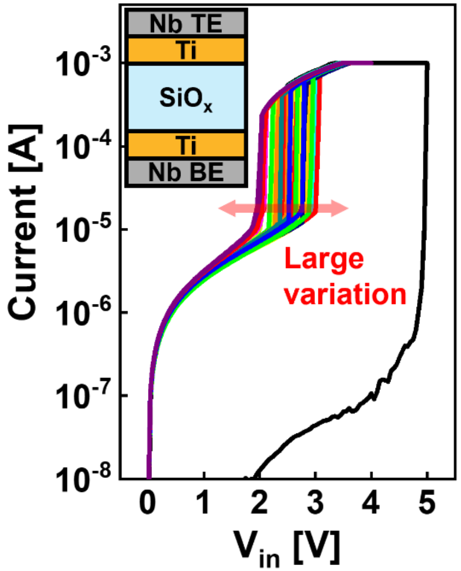
Reliable, Self-Sustained Oscillation in SiO_x TS

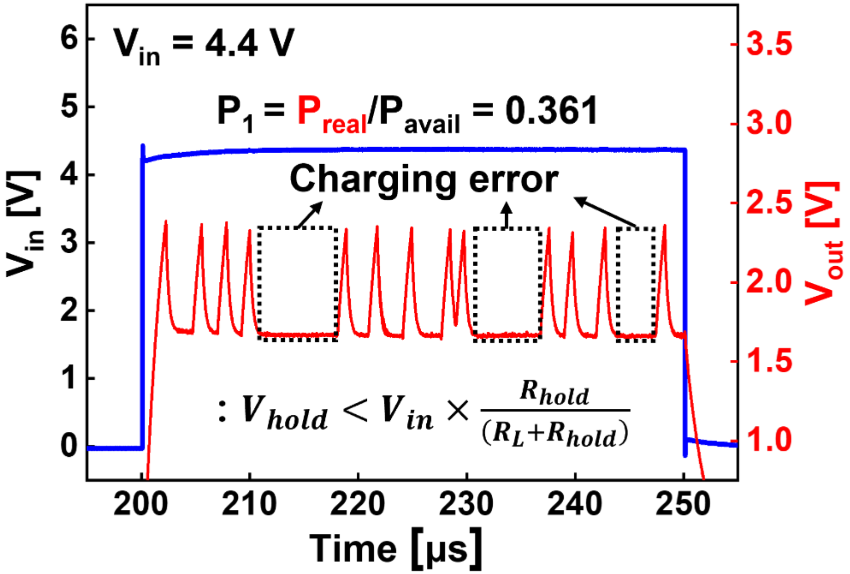


- ✓ Voltage begins to be applied to the threshold switch (TS) → Charging
- ✓ Charged voltage at V_{th} discharges → Discharging
- ✓ Back and forth of the charging and discharging → Voltage oscillation
- ✓ Only oscillation frequency modulation by varying V_{in} or external resistor

Probabilistic Oscillation in Ti/SiO$_x$/Ti TS

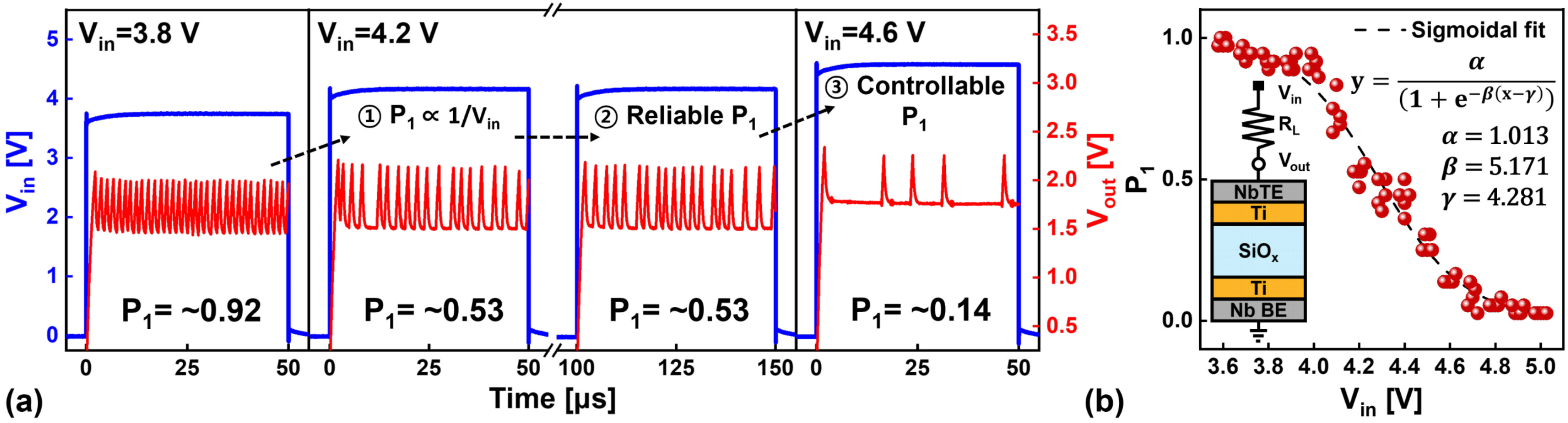






- ✓ Ti scavenging layer induces variations in the TS distribution
- ✓ Charging error generate random oscillatory behavior
- ✓ The number of spikes: probability (P_1)

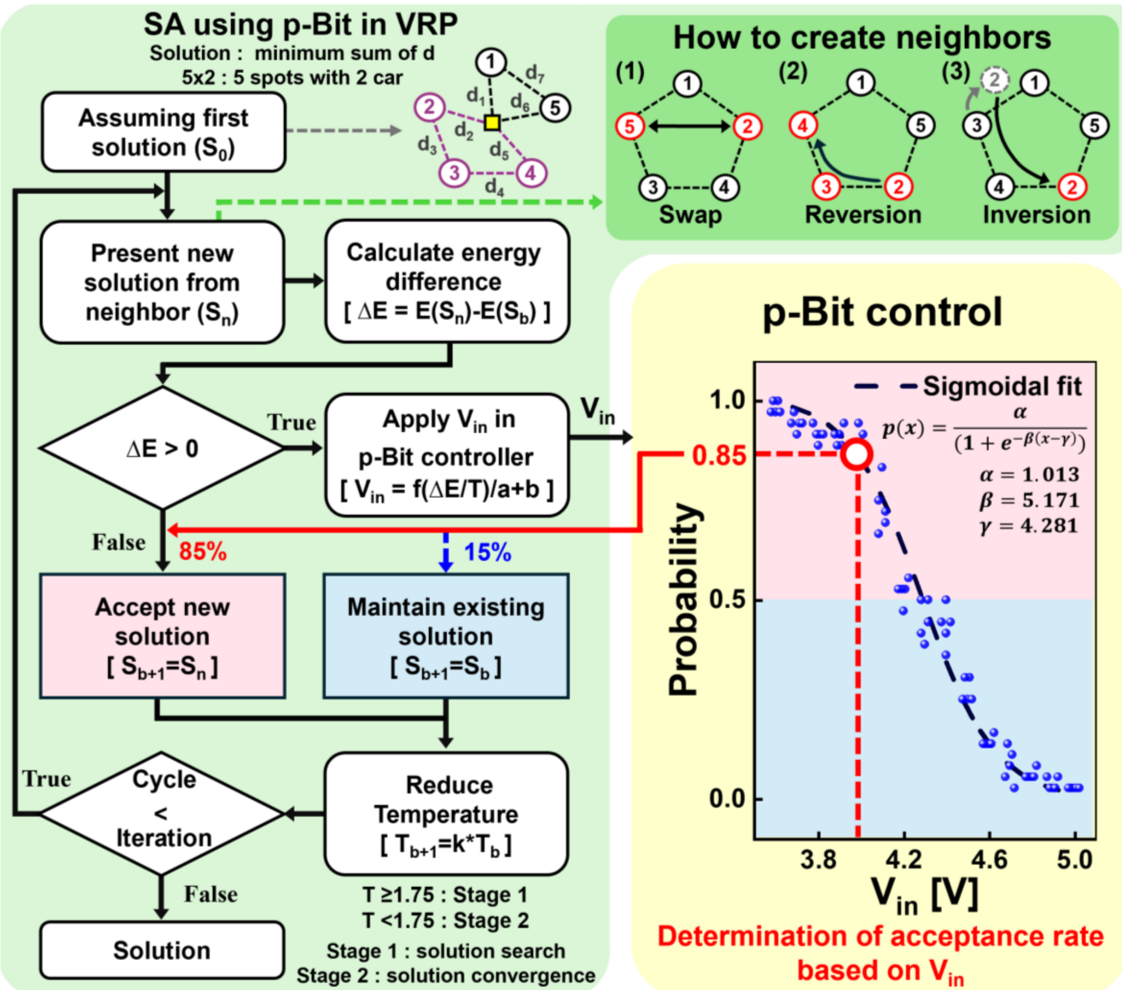
Highly Controllable Ti/SiO_x/Ti p-Bit

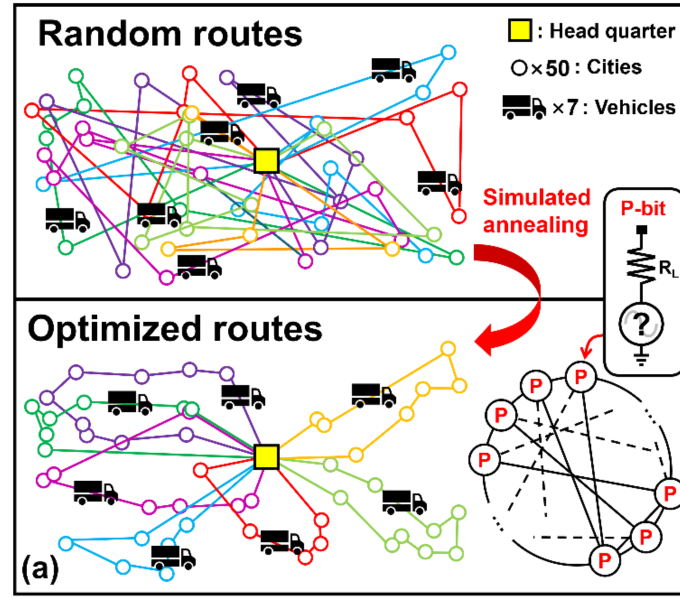


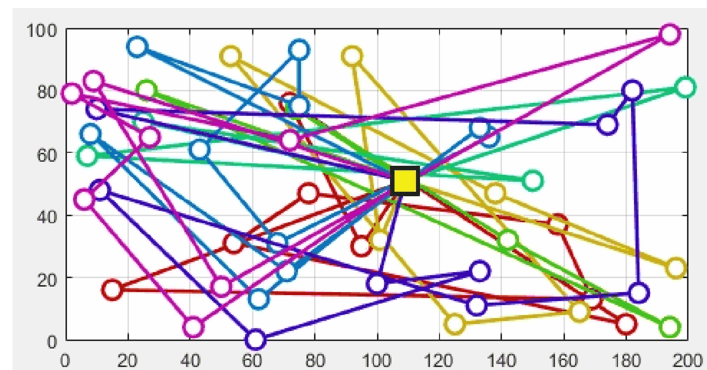
✓ Probability inversely proportional to V_{in}

✓ Sigmoid probabilistic behavior within the V_{in} range of 3.6 V to 5 V

Vehicle Routing Problems

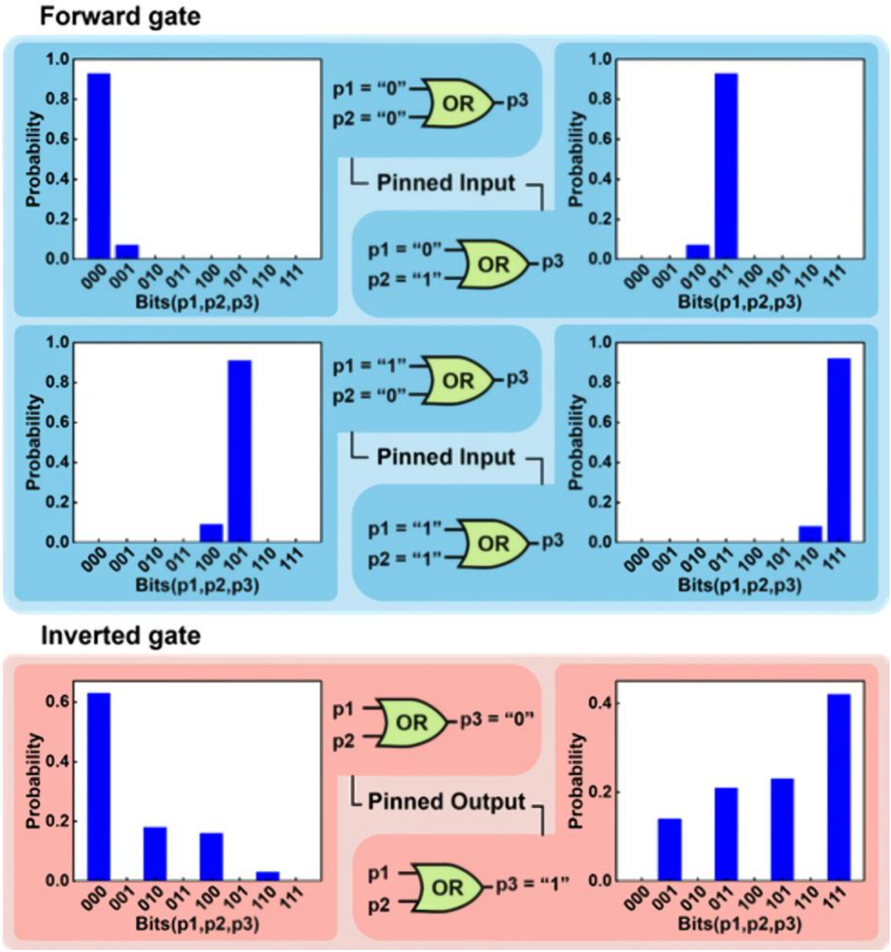


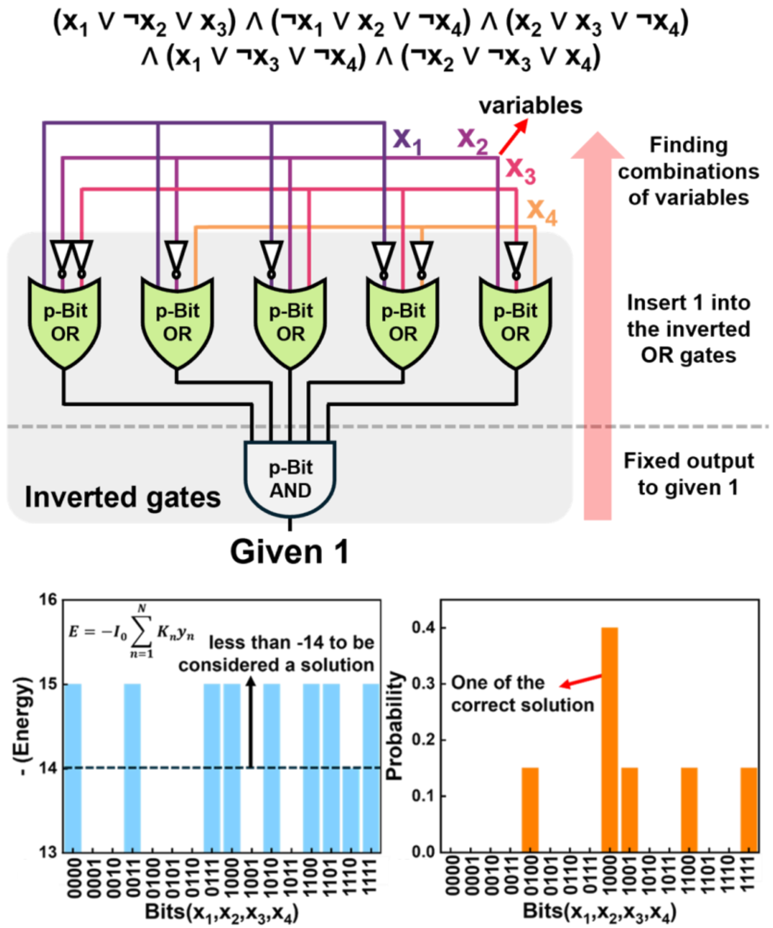




✓ Accelerate simulated annealing algorithm for finding the optimal path

p-Bit Gate for MAX-SAT

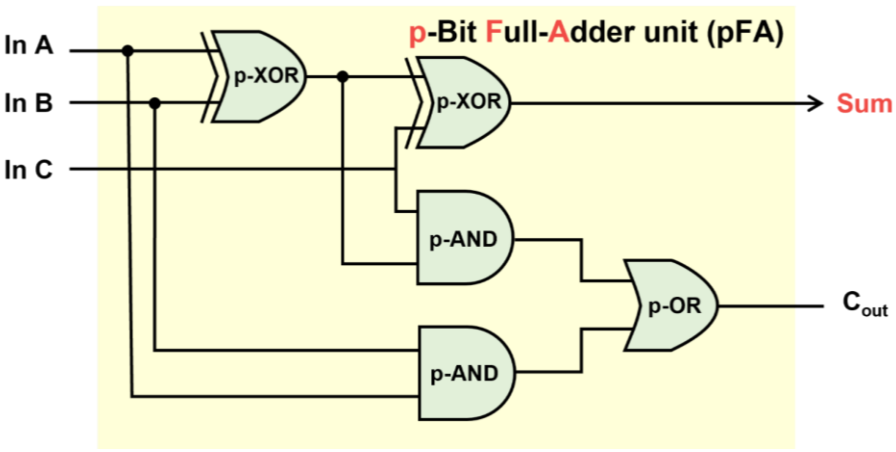


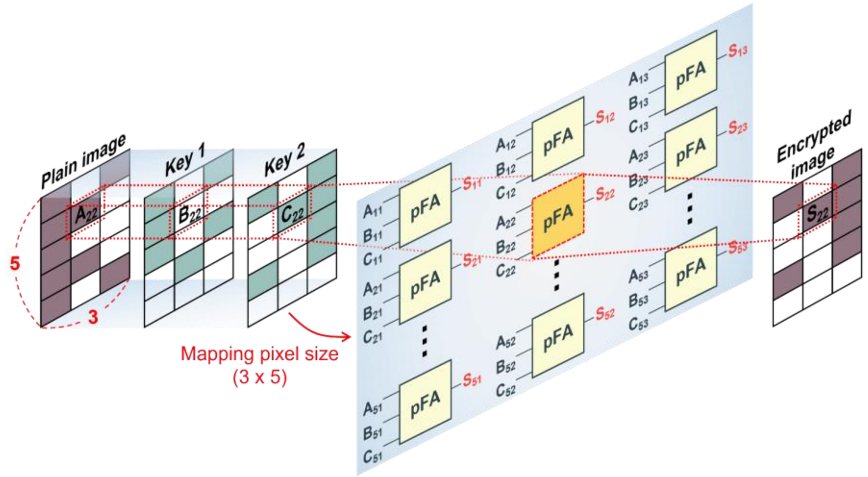


✓ Conventional deterministic CMOS logic gates only allow forward operation

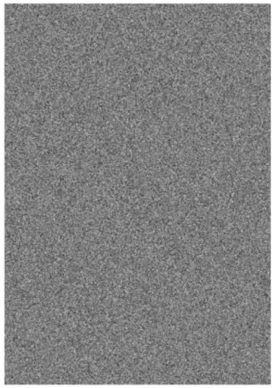
✓ Invertible p-Bit logic gate can infer input values at the given output

p-Bit Full Adder for Cryptography Accelerator





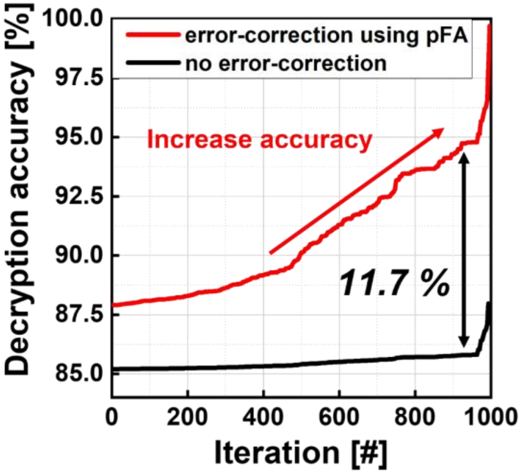
Plain image



Encrypted image

Decrypted image

Error-corrected image



✓ Newly designed full-adder unit using p-Bit gates for encryption/decryption

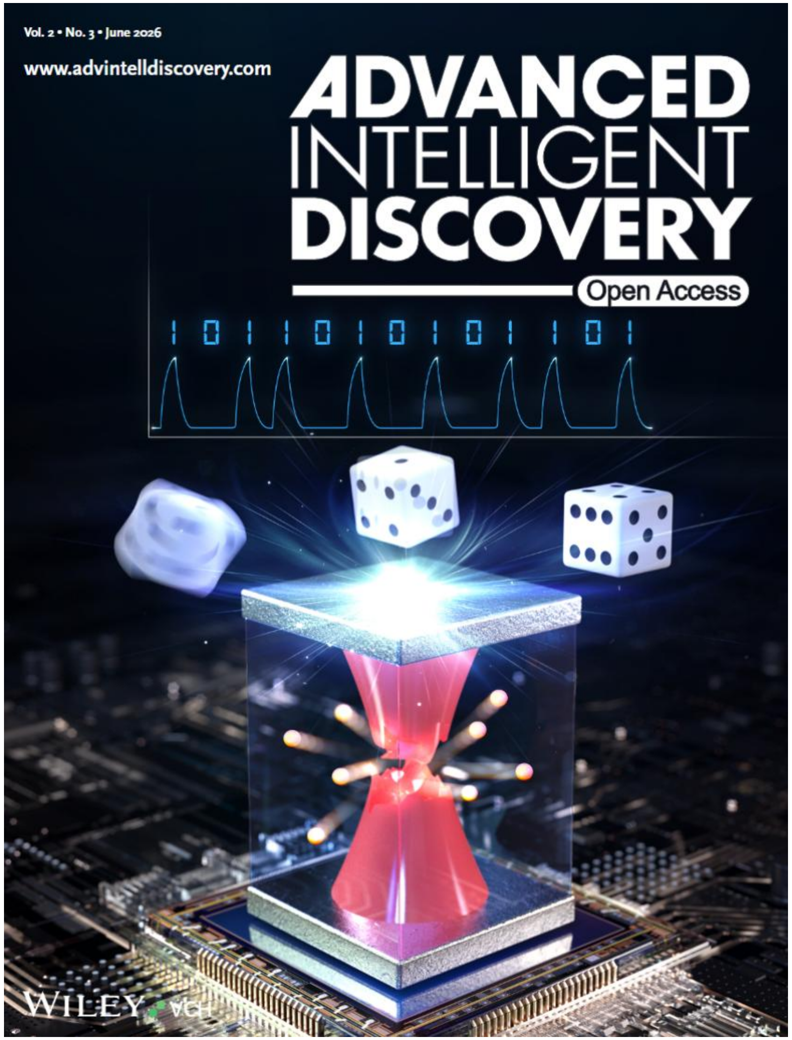
✓ 99.7% accurate decryption of 8-bit image

Summary

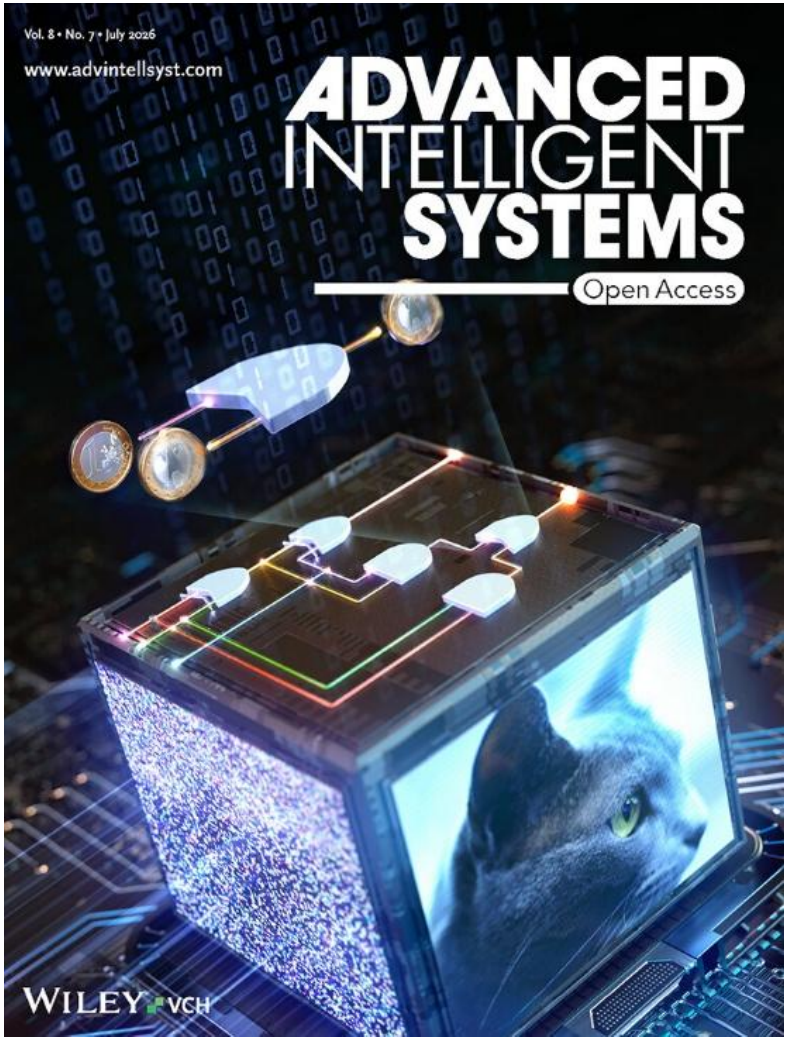
- ✓ Demonstrated p-Bits in 1K cross-point SiO_x TS oscillator arrays by intentionally leveraging intrinsic switching instability
- ✓ Achieved a sigmoidal P_1 response over a V_{in} range of >1 V in interface-engineered Ti/SiO_x/Ti p-Bits
- ✓ Developed a p-Bit module by integrating comparator and counter circuits verified via a binary-encoded LED display
- ✓ Showed the feasibility of p-Bit logic gates through simulations
- ✓ Demonstrated p-Bit applications in finding optimal routes (VRP) and solving constraint satisfaction problems

Outlook

Dice-like p-Bit leveraging randomness



Invertible logic using p-Bit gates



Thank you for your attention

NRF
National Research Foundation of Korea

차세대지능형반도체사업단

Keit 한국산업기술평가관리원
Korea Evaluation Institute of Industrial Technology

ITRC
대학정보통신연구센터협의회

ETRI
한국전자통신연구원
Electronics and Telecommunications Research Institute

KIMS 한국재료연구원
Korea Institute of Materials Science