Polarity-Configurable Photodiodes for In-Pixel Computing in Neuromorphic AI Vision

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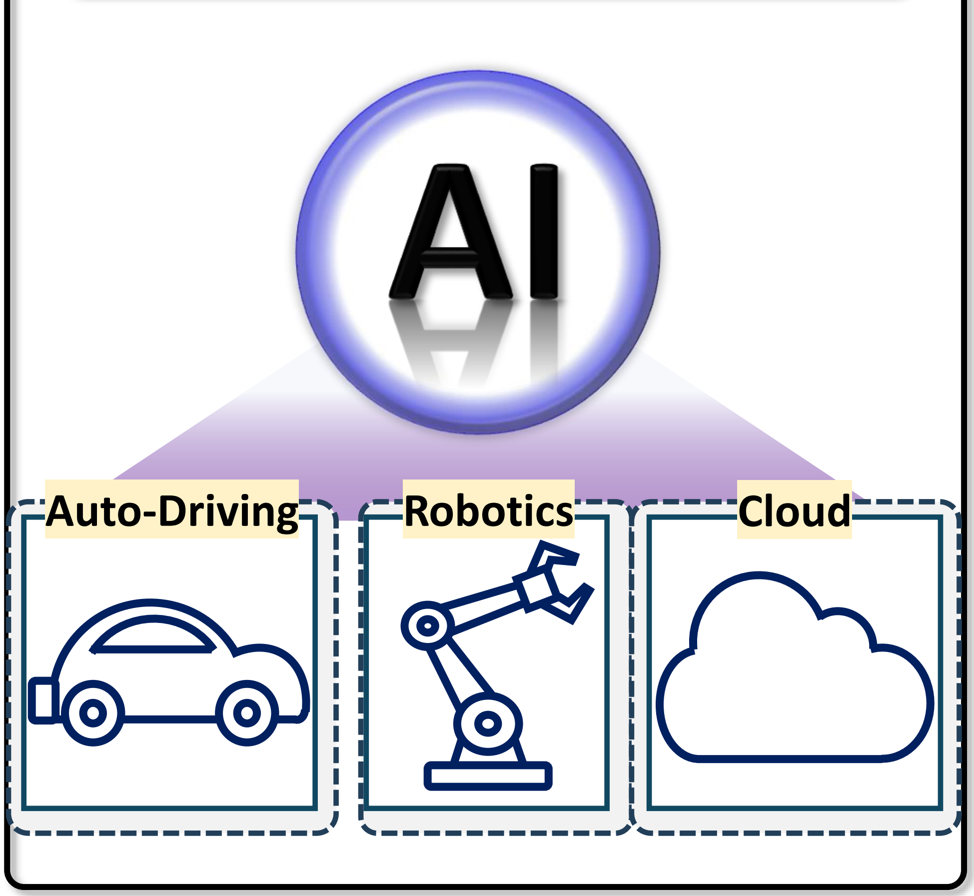
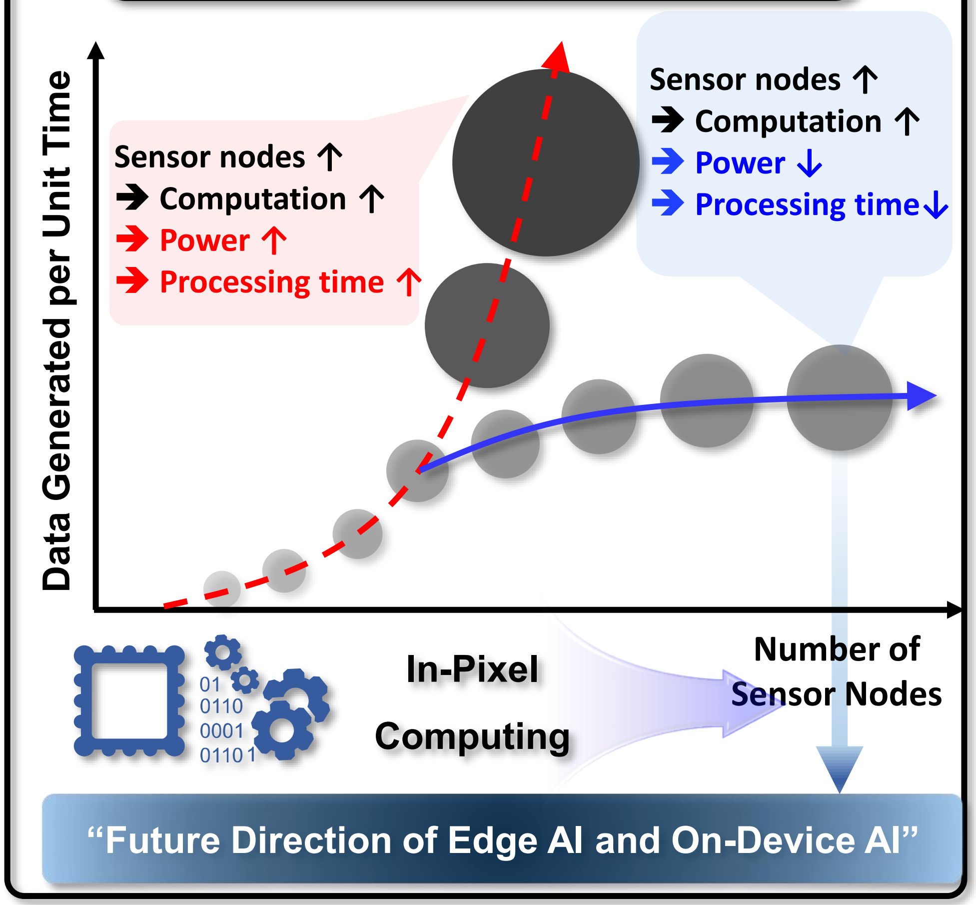
Growing Energy Demand of Edge AI Systems

- **The rapid expansion of AI applications is driving a dramatic increase in sensor-generated data and computational demand**
- **Increasing sensor density inevitably leads to higher data-processing energy unless computation is moved closer to the sensor**

Expansion of AI Applications



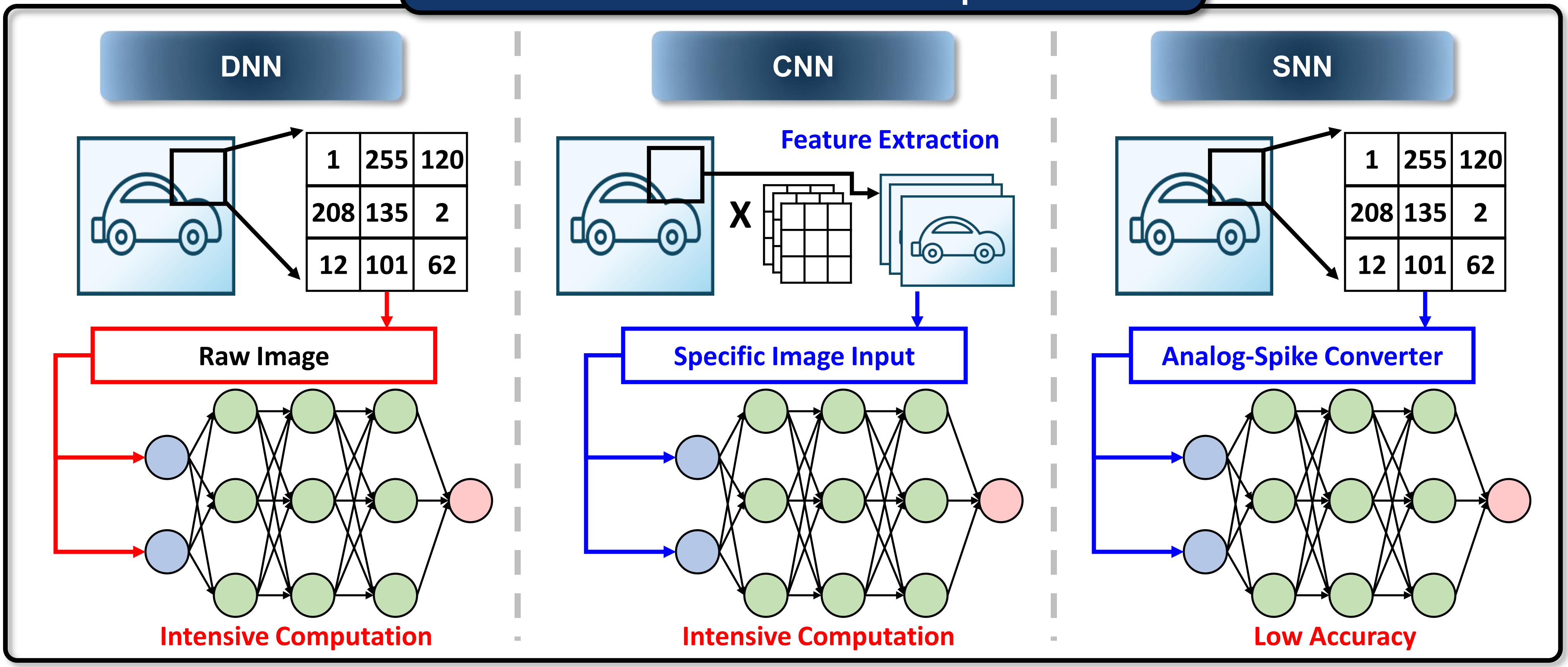
Data and Energy Scaling



Accuracy–Energy Trade-Off in Neuromorphic AI

- Conventional CNNs provide high inference accuracy but require intensive computation.
- SNNs offer high energy efficiency but often suffer from low accuracy.
- A new architecture is required to achieve both high accuracy and low energy consumption.

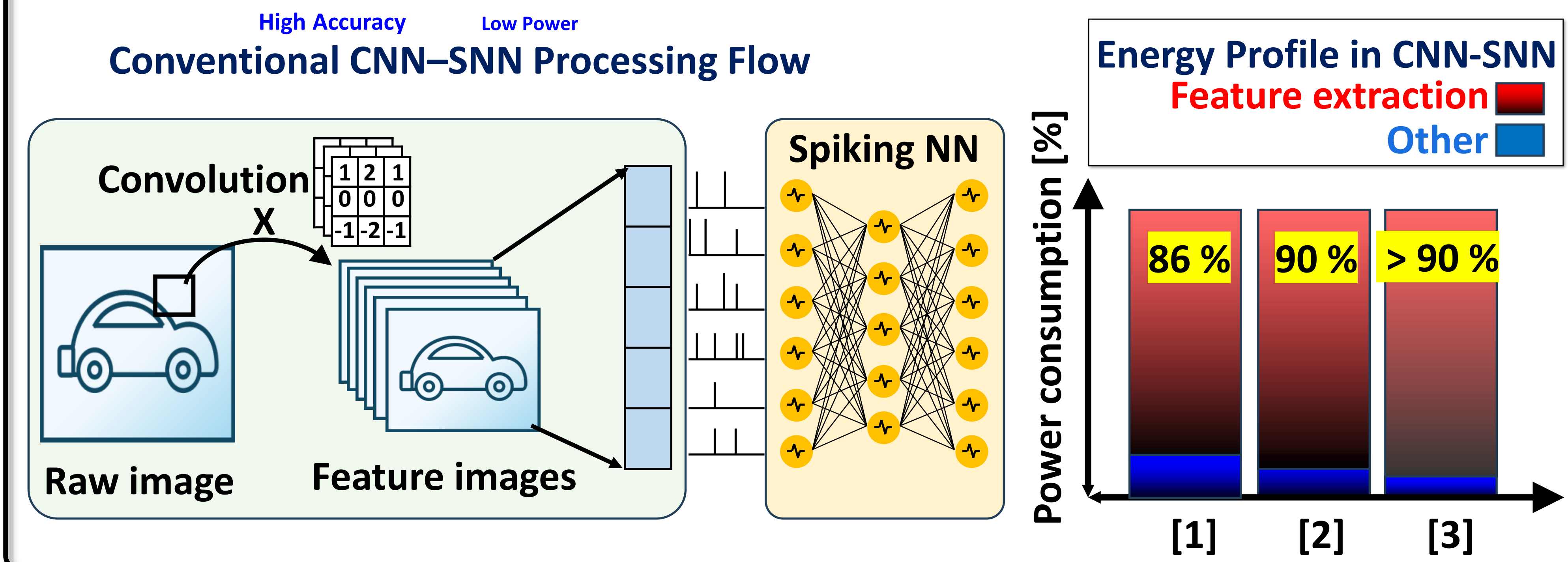
AI Model Features and Comparison



Feature Extraction: The Hidden Energy Bottleneck in CNN–SNN

- **CNN–SNN hybrid architectures combine the high accuracy of CNNs with the energy efficiency of SNNs.**
- **However, feature extraction still accounts for more than 86% of the total energy consumption.**
- **Therefore, feature extraction and spike conversion must be performed directly at the sensor level.**

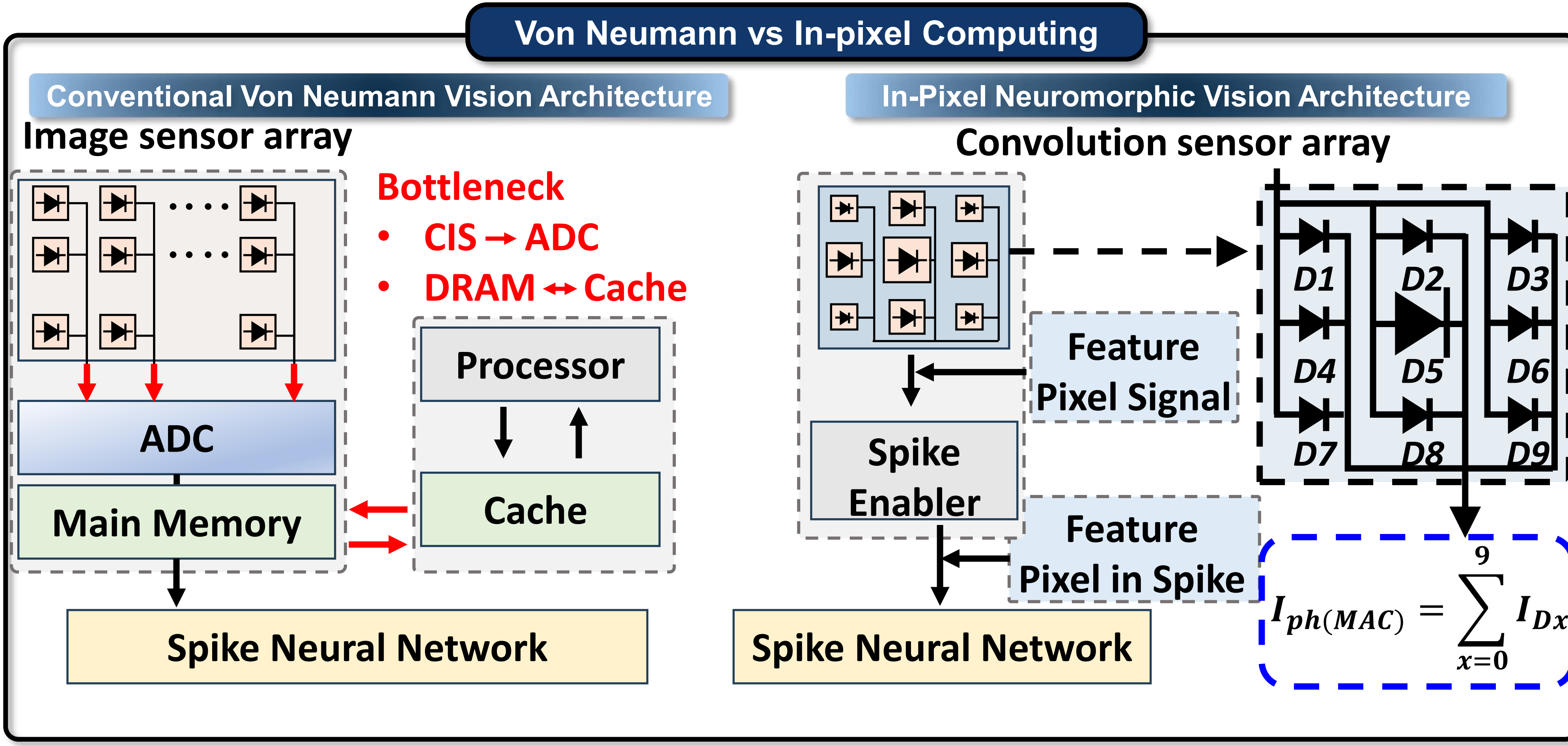
Energy distribution of a CNN-SNN system



[1] S. Kim et al., AAAI (2020)
[2] D. Wu et al., Frontiers in Neuroscience (2022)
[3] M. Sorbaro et al., IEEE T-NNLS (2019)

In-Pixel Computing: Energy-Efficient Vision Processing

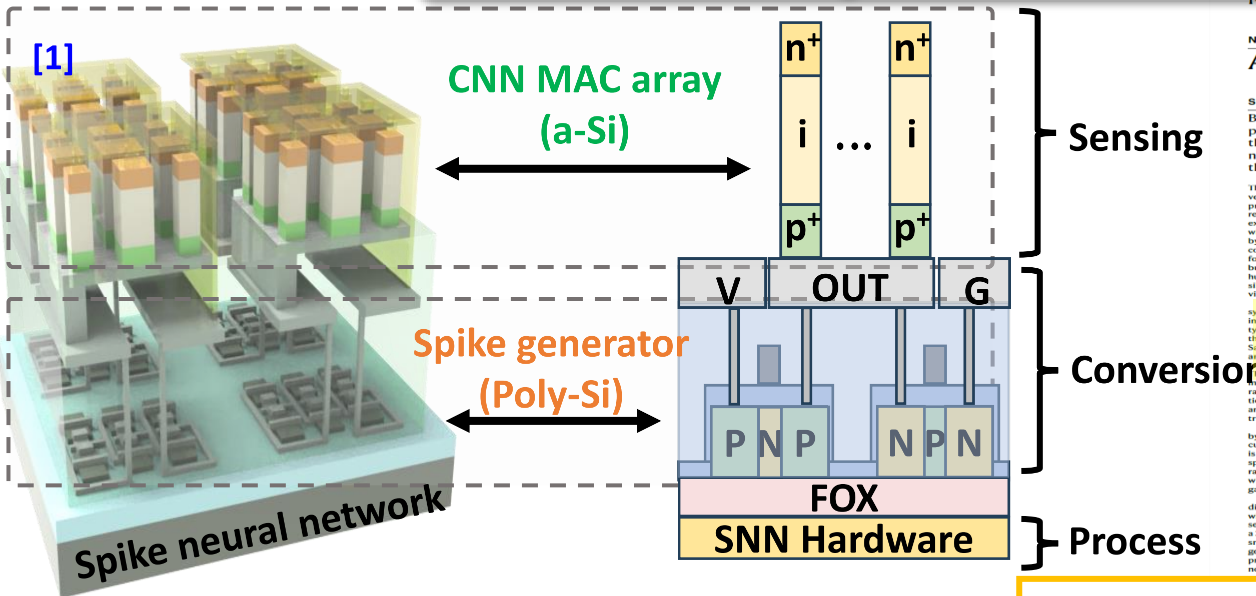
- Conventional vision systems suffer from **repeated data transfer** between the sensor, memory, and processor.
- **In-pixel computing performs feature extraction directly within the sensor array, minimizing data movement and conversion overhead.**

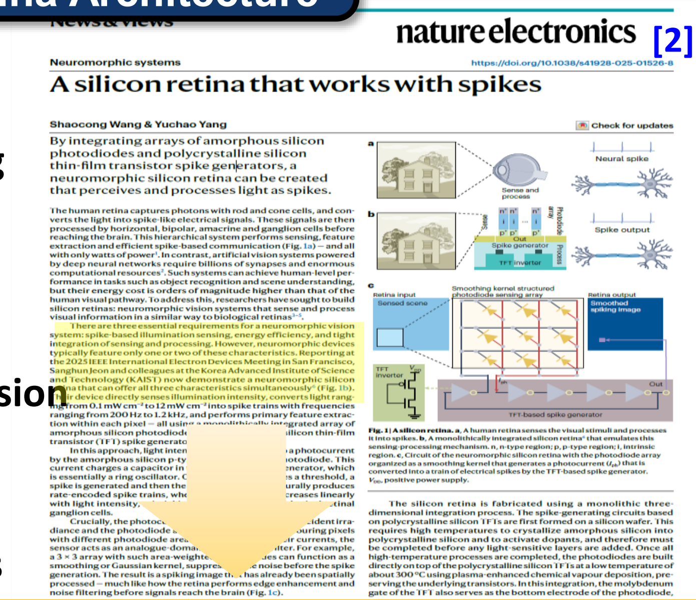


World–First Silicon Retina Architecture for Neuromorphic Vision

- ➢ World-first silicon retina architecture simultaneously achieving **light-to-spike conversion, high energy efficiency, and 3D vertical integration**
- ➢ **Selected as an IEDM 2025 Highlight Paper→ Exceptionally strong endorsement from the IEDM Program Committee**
- ➢ **Featured in a dedicated Nature Electronics News & Views article**

World-First 3D-Integrated Silicon Retina Architecture





"2025 International Electron Device Meeting (IEDM) Highlight paper"

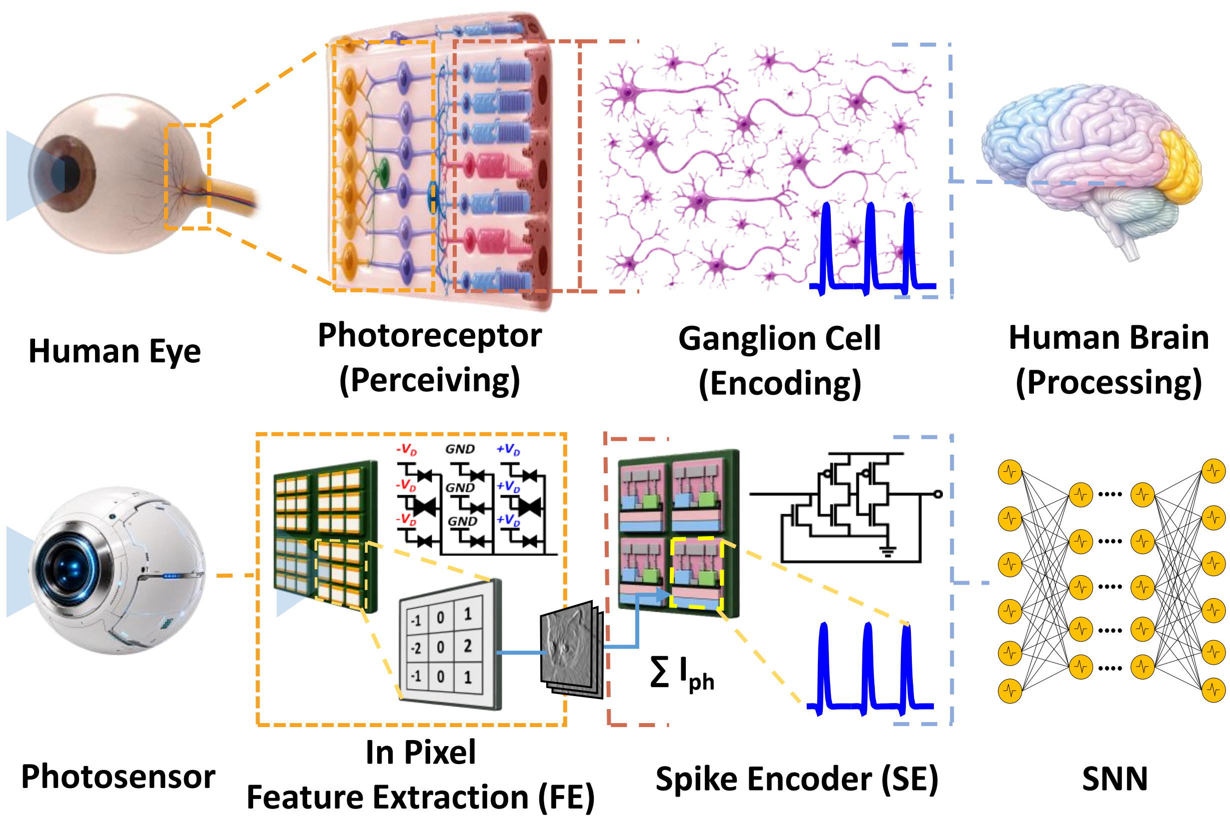
[1] Seungyeob Kim et al, 2025.12.9 IEDM
[2] Modified from Shaocong Wang et al, Nature News & views (2025)

There are three essential requirements for a neuromorphic vision system: 1.spike-based illumination sensing, 2.energy efficiency, and 3. tight integration of sensing and processing. [...] Sanghun Jeon and colleagues at KAIST now demonstrate a neuromorphic silicon retina that can offer all three characteristics simultaneously. But challenges remain. Scaling from small prototypes to megapixel-class cameras with reliability and DTCO will require further advances [...].

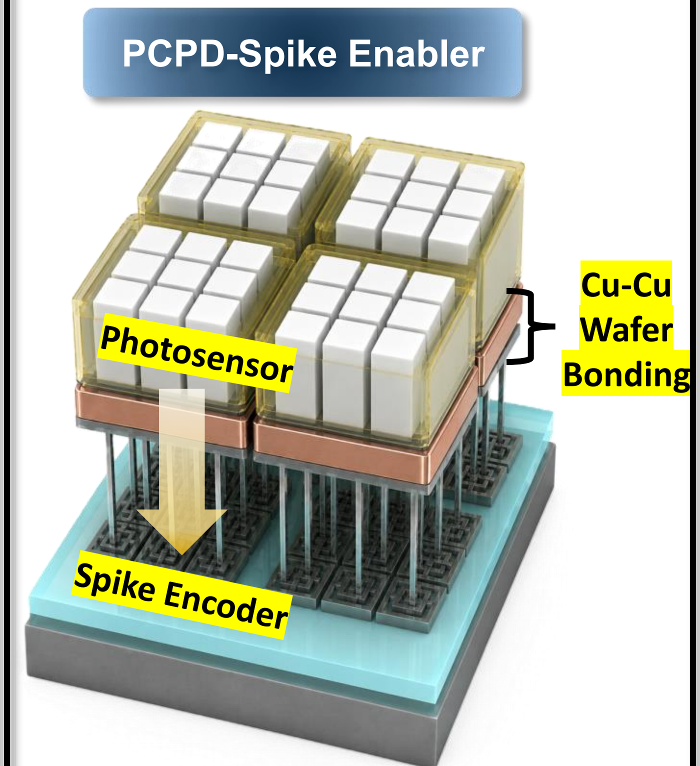
Bio-Inspired 3D-Integrated PCPD-Spike Enabler Vision Processor

- Directly mimics the biological visual pathway: Photoreceptor → Ganglion Cell → Brain
- PCPD: Direct in-pixel feature extraction from incident light
- Spike Enabler: Direct conversion of PCPD photocurrent into spike signals
- W2W bonding enables dense vertical integration of the PCPD and Spike Enabler

Bio-Inspired In-Sensor CNN–SNN Processing



W2W-Integrated



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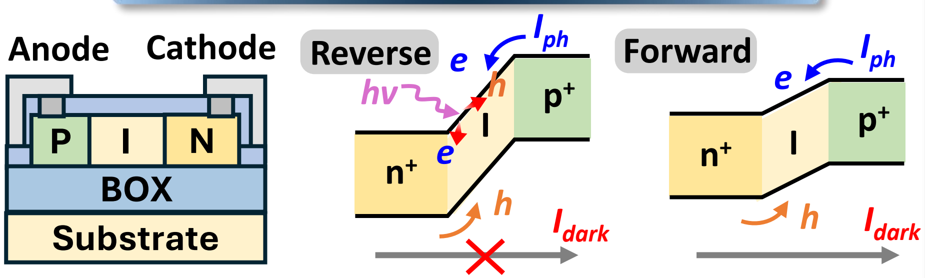
Fundamental Limitation of Conventional PIN Photodiodes

- Fixed junction polarity **prevents negative photocurrent generation**
- Critical limitation for in-pixel CNNs: **signed weights required** for edge detection cannot be implemented

Photocurrent Generation

EHP Generation



EHP Generation → Carrier Drift → Iph

Photocurrent

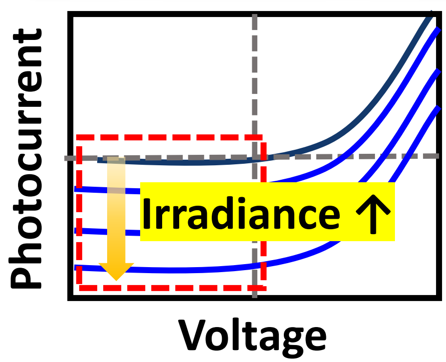
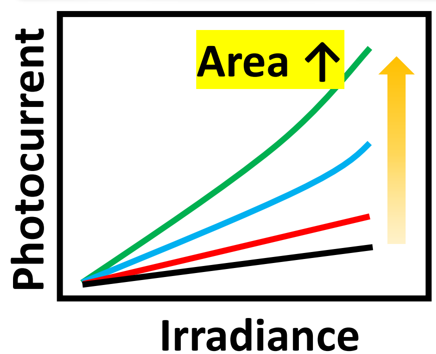


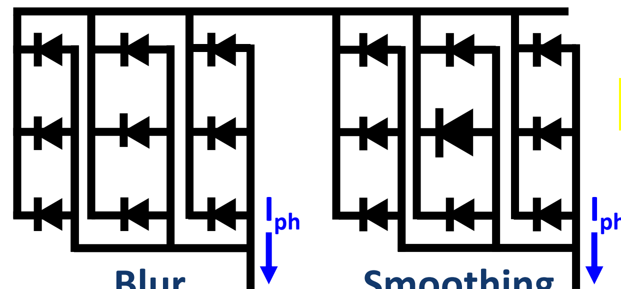
Photo responsivity



Light Intensity ↑ / Device Area ↑ → Photocurrent ↑

Limitation of Positive-Only Optical Weights

Kernel Implementation Using PIN Diodes



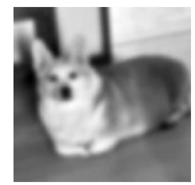
Positive Weights by Device-Area Scaling

Limitation of Unidirectional Weights

Optical Image

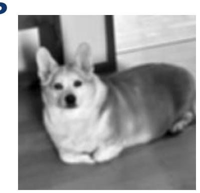
Blur

1	1	1
1	1	1
1	1	1



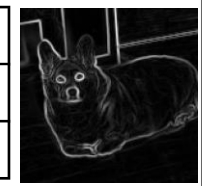
Smoothing

1	1	1
1	2	1
1	1	1



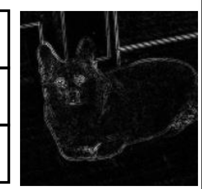
Sobel

-1	1	1
-2	1	2
-1	1	1



Laplacian

0	1	0
1	-4	1
0	1	0



No Negative Weight → No Edge Detection

Signed Weights Are Essential for Accurate In-Pixel Computing

- ➤ Unidirectional Weights → Lower Accuracy → Increased Recognition Errors → Signed Weights Required
- ➤ Existing Approaches: Photocurrent–Leakage Trade-Off + Complex Wiring

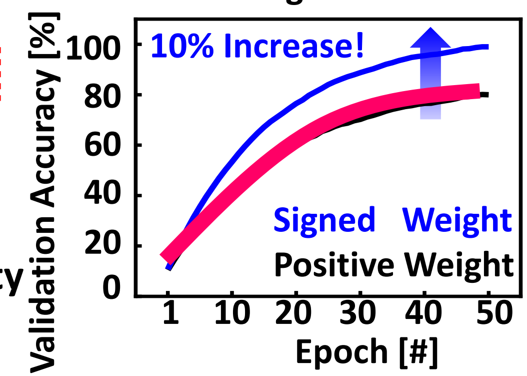
PIN Photodiode Limitation

Signed Weights in Kernel Implementation

Config.	Number
Pos.	8
Pos./Neg.	34
Total	42

Limited Kernel Diversity
→ Accuracy ↓

CIFAR Image Simulation



브런치
"테슬라 자율주행 사고, 중국 진출 불투명"
"테슬라 자율주행 사고, 중국 진출 불투명" ... 최근 미국에서 테슬라의 완전자율주행(FSD) 시스템이 연루된 보행자 사망 사고가 발생해 자율주행 시스템에...
2026. 1. 8.

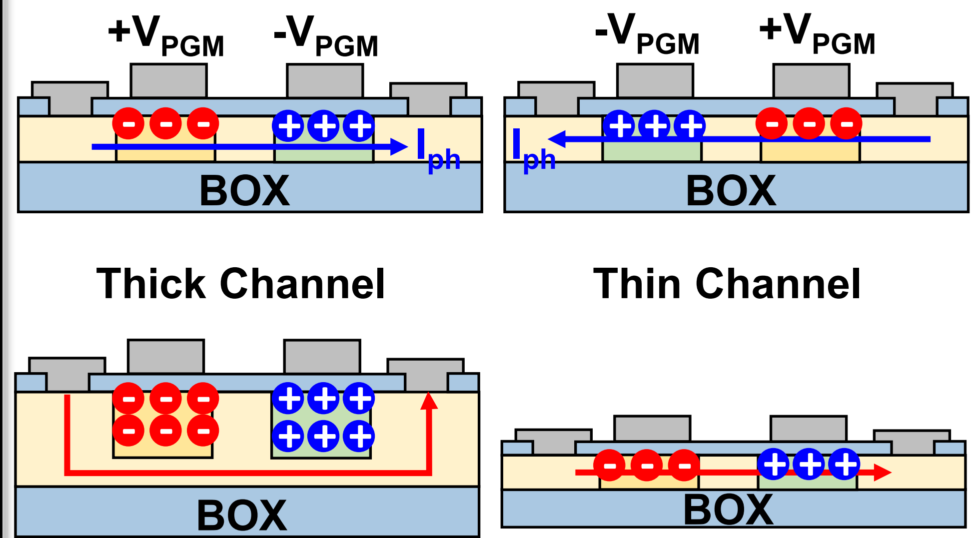
초이스스탁
[초점] 테슬라 '완전 자율주행' 또 논란...호수로 돌진 시도 영상 확산
테슬라의 '완전 자율주행(FSD)' 기능을 사용하던 차량이 운전자를 태운 채 호수로 향해 돌진하려 했다는 주장이 미국에서 제기돼 논란이 일고 있다고 전기차 전문매체...
2026. 2. 17.

중앙일보
"테슬라 3378억 배상" 판결...자율주행 비상등 켜졌다 [팩플]
미국 법원이 테슬라의 자율주행 보조시스템 '오토파일럿' 관련 사망 사고에 대해 처음으로 회사 책임을 인정하면서다. 회사 측은 항소 의사를 밝혀...
2025. 8. 3.

Difference in CNN Accuracy → Increased Object Recognition and Decision Errors in Autonomous Driving

Limitations of Reconfigurable Photodiodes

Gate-induced Photodiode



Junction Leakage

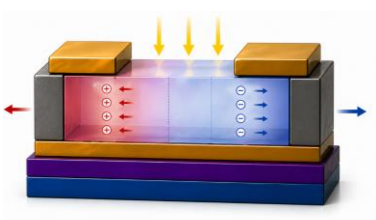
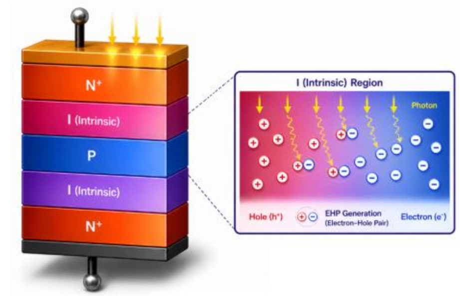
Photocurrent ↓

Channel Thickness ↑
→ Photocurrent ↑ ↔ Leakage ↑
4-Terminal Structure → Complex Wiring

[1] Z. Xiong et al., Nature Communications (2025)

Polarity-Configurable Photodiode (PCPD)

- Gate-Induced PDs → External TIA Required → Integration Density ↓ / Power Efficiency ↓
- Nonvolatile PDs → Easy Vertical Integration / Limited Signed Photocurrent & Reliability
- **PCPD → Signed Photocurrent + Vertical Scalability + High Reliability**

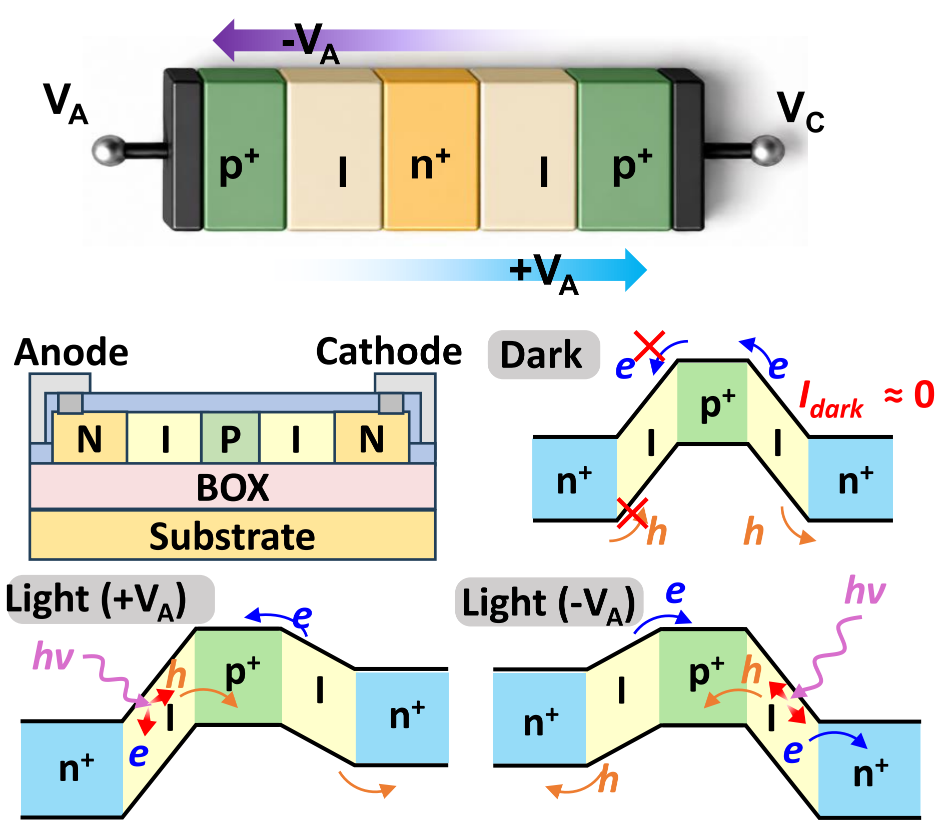
Type	Gate-Induced PD	Phototransistor	Nonvolatile PDs	PCPD
Schematic				
External Circuit	TIA	TIA	Not Required	Not Required
Vertical Scalability	Difficult	Limited	Excellent	Excellent
Signed Photocurrent	Excellent	Not Available	Limited	Excellentt
Endurance (cycles)	10^6 ~ 10^8	10^6 ~ 10^7	10^2 ~ 10^7	>10^{16}
Response Time	ns ~ μs	μs ~ ms	μs ~ ms	ns ~ μs
Number of Terminals	4	3	2	2

Operating Principle and Electrical Characteristics of the PCPD

- Dark State → Low OFF Current Regardless of Bias Polarity
- Bias Polarity Reversal → Photocurrent Polarity Reversal
- TCAD Optimization → PCPD Fabrication on SOI

Operating Principle of the PCPD

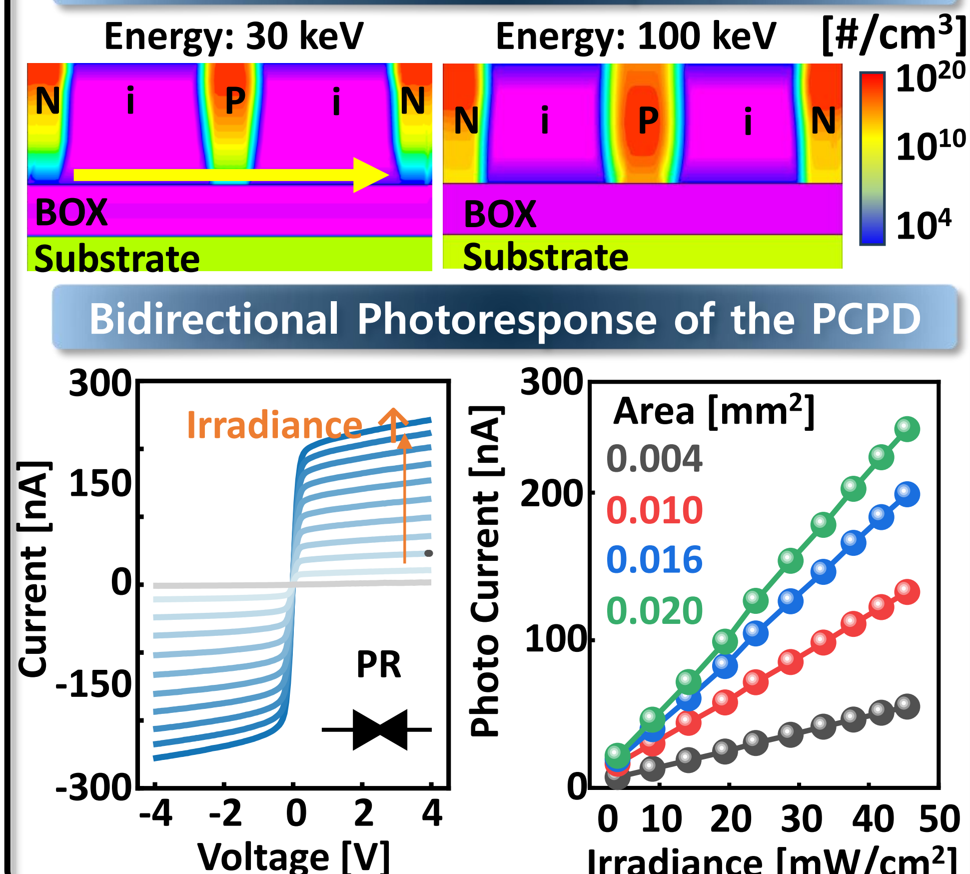
Energy-Band Diagram of the PCPD



Process Simulation and Device Characteristics

TCAD-Based Process Optimization

Bidirectional Photoresponse of the PCPD

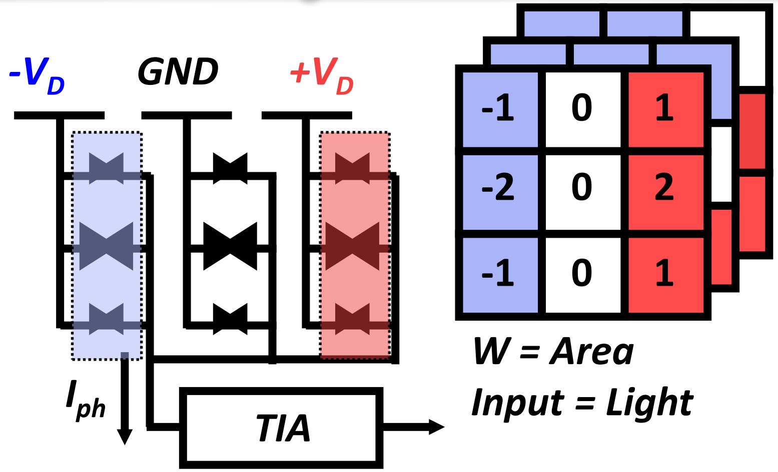


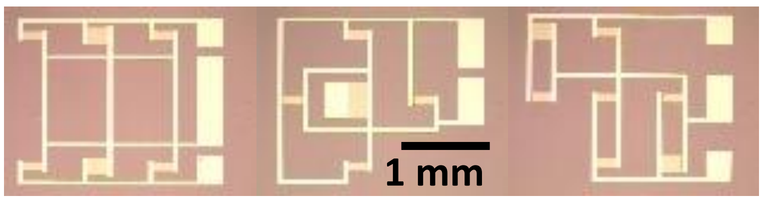
Reconfigurable Optical Kernel Operation Using PCPDs

- Bias Polarity → Positive / Negative Optical Weight
- Applied Voltage Control → Reconfigurable CNN Kernels → Edge Detection
- Moving Light Spot → Spatial Differential Response Verified

Real-Time CNN Kernel Operation with a PCPD Array

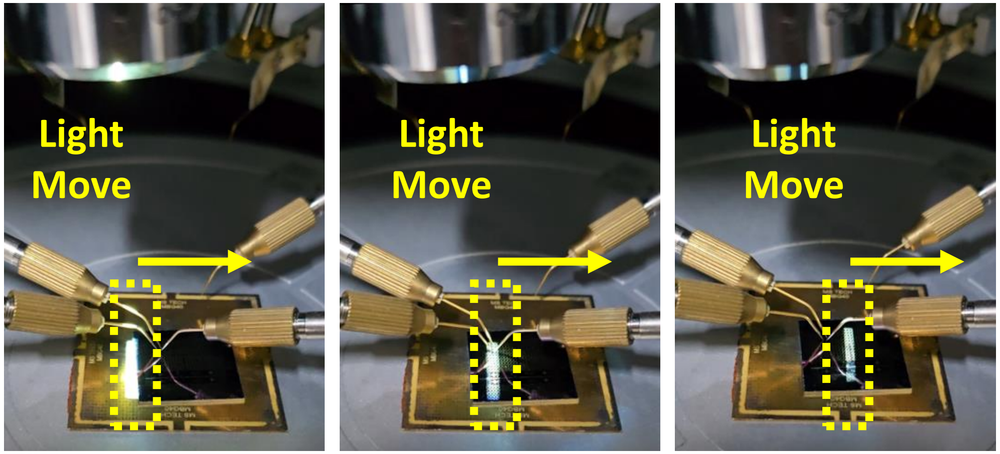
CNN Kernel Configuration with Area-Weighted PCPDs

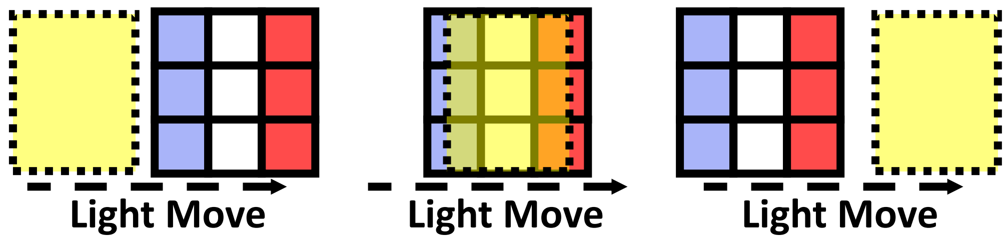




Sobel Laplacian Emboss

Moving-Light Experiment Using a Beam Projector

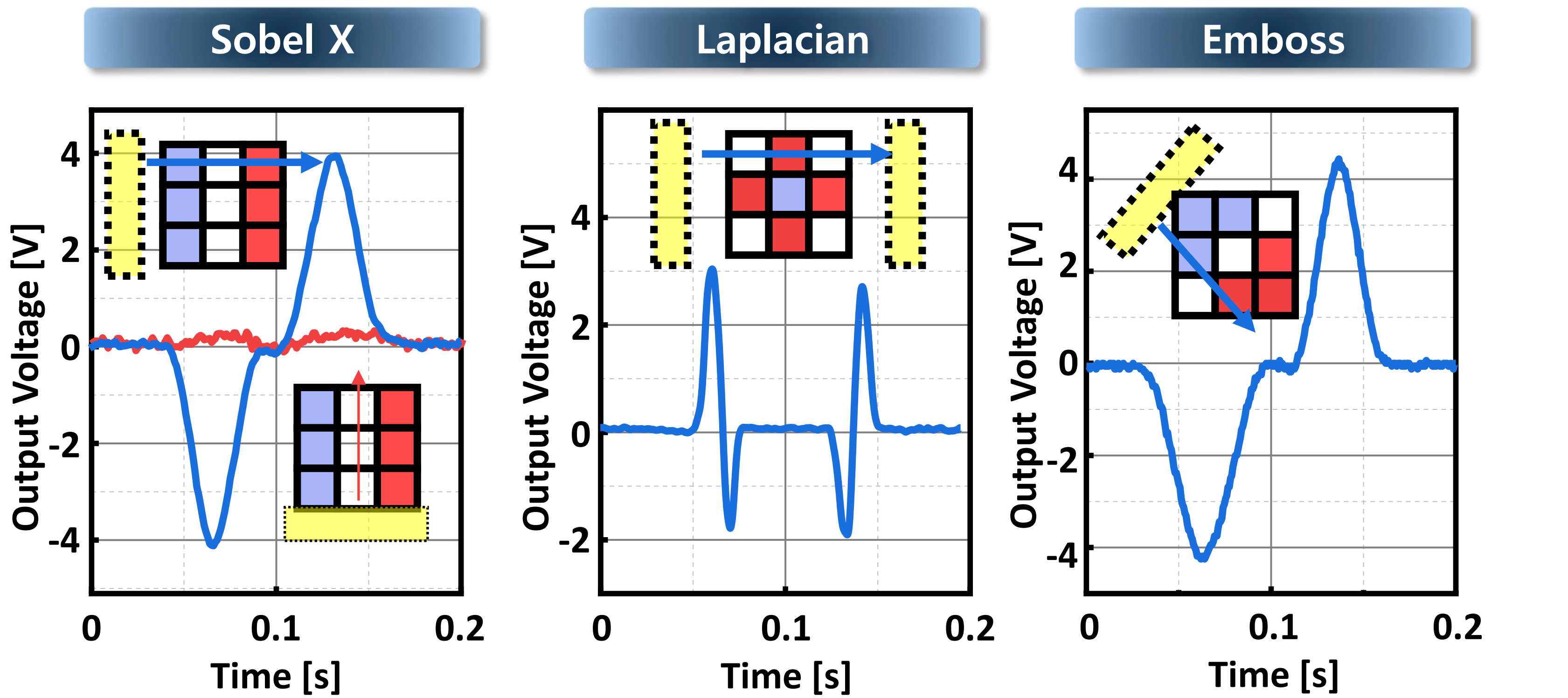




Experimental Demonstration of PCPD-Based Spatial Filtering

- Device Area + Polarity Control → Multiple Spatial Filters
- Moving Light → Kernel-Specific Output Responses
- Edge Detection + Directional Feature Extraction → Experimentally Verified

Measured Responses of PCPD Spatial Filters



Thank you

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