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

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Abstract:

The rapid expansion of AI applications across autonomous driving, robotics, and cloud computing has driven a steep rise in computational load and energy consumption. In hybrid CNN–SNN vision architectures, the feature-extraction stage dominates the power budget, consuming over 86% of total energy due to the conventional von-Neumann bottleneck between sensor, memory, and processor. Realizing spike-based, in-pixel feature extraction therefore requires a reconfigurable photodiode capable of generating optical convolution kernels directly at the sensor plane. Conventional PIN photodiodes, however, are limited to unidirectional (positive) photocurrent, making the signed-weight kernels required for edge detection physically unrealizable.

In this work, we propose a Polarity-Configurable Photodiode (PCPD) that electrically reconfigures the photocurrent polarity through a vertical N-I-P-I-N junction on an SOI substrate. The device shows near-zero dark current regardless of bias polarity and a linear, symmetric bipolar photoresponse under forward and reverse bias, enabling both positive and negative kernel weights within a single two-terminal pixel. A 3×3 PCPD array was used to implement Sobel, Laplacian, and Emboss spatial filters directly at the optical input stage, and edge features were experimentally extracted without digital post-processing. The PCPD was further monolithically integrated with a CMOS-compatible, poly-Si complementary-TFT Spike Enabler, converting the convolution photocurrent into a frequency-encoded spike train that scales linearly with illumination intensity. This CMOS-Compatible Spike-Embedded Neuromorphic Sensor (C-SENS) performs in-sensor blurring, smoothing, and noise suppression that improve the classification accuracy and noise robustness of a downstream spiking neural network. This work was selected as a 2025 IEDM Highlight Paper and separately featured in Nature Electronics' News and Views [1].

As future work, the PCPD will be extended toward megapixel-scale arrays through wafer-to-wafer (W2W) hybrid bonding, enabling further scaling of the reconfigurable in-pixel neuromorphic vision platform beyond the thermal-budget limitations of monolithic-3D integration.

References

1. S. Jeon et al.,, IEEE International Electron Devices Meeting (IEDM), Highlight Paper (2025).