BEGN 216
Neuromorphic Integrated Bioelectronics

Week 2: Silicon Retina

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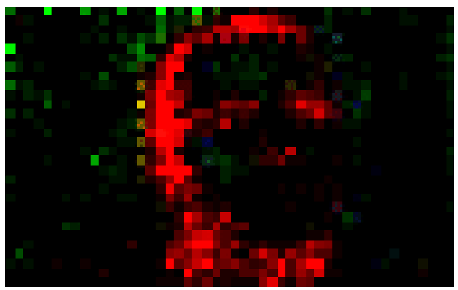
http://isn.ucsd.edu/courses/beng216

BENG 216 Neuromorphic Integrated Bioelectronics

Date	Topic
9/30, 10/2	Biophysical foundations of natural intelligence in neural systems. Subthreshold MOS silicon models of membrane excitability. Silicon neurons. Hodgkin-Huxley and integrate-and-fire models of spiking neuronal dynamics. Action potentials as address events.
10/7, 10/9	Silicon retina. Low-noise, high-dynamic range photoreceptors. Focal-plane array signal processing. Spatial and temporal contrast sensitivity and adaptation. Dynamic vision sensors.
10/14, 10/16	Silicon cochlea. Low-noise acoustic sensing and automatic gain control. Continuous wavelet filter banks. Interaural time difference and level difference auditory localization. Blind source separation and independent component analysis.
10/21, 10/23	Silicon cortex. Neural and synaptic compute-in-memory arrays. Address-event decoders and arbiters, and integrate-and-fire array transceivers. Hierarchical address-event routing for locally dense, globally sparse long-range connectivity across vast spatial scales.
10/28, 10/30	Midterm review. Modular and scalable design for neuromorphic and bioelectronic integrated circuits and systems. Design for full testability and controllability.
11/4, 11/6	Low-noise, low-power design. Fundamental limits of noise-energy efficiency, and metrics of performance. Biopotential and electrochemical recording and stimulation, lab-on-a-chip electrophysiology, and neural interface systems-on-chip.
11/13	Learning and adaptation to compensate for external and internal variability over extended time scales. Background blind calibration of device mismatch. Correlated double sampling and chopping for offset drift and low-frequency noise cancellation.
11/18, 11/20	Adaptive offset cancelation and autoranging in dynamic vision sensing. Tobi Delbruck's lecture on silicon retina history with a live demo of event-based dynamic vision systems.
11/25, 11/27	Energy conservation. Resonant inductive power delivery and data telemetry. Ultra-high efficiency neuromorphic computing. Resonant adiabatic energy-recovery charge-conserving synapse arrays.
12/2 - 12/6	Project final presentations. All are welcome!

Silicon Retina

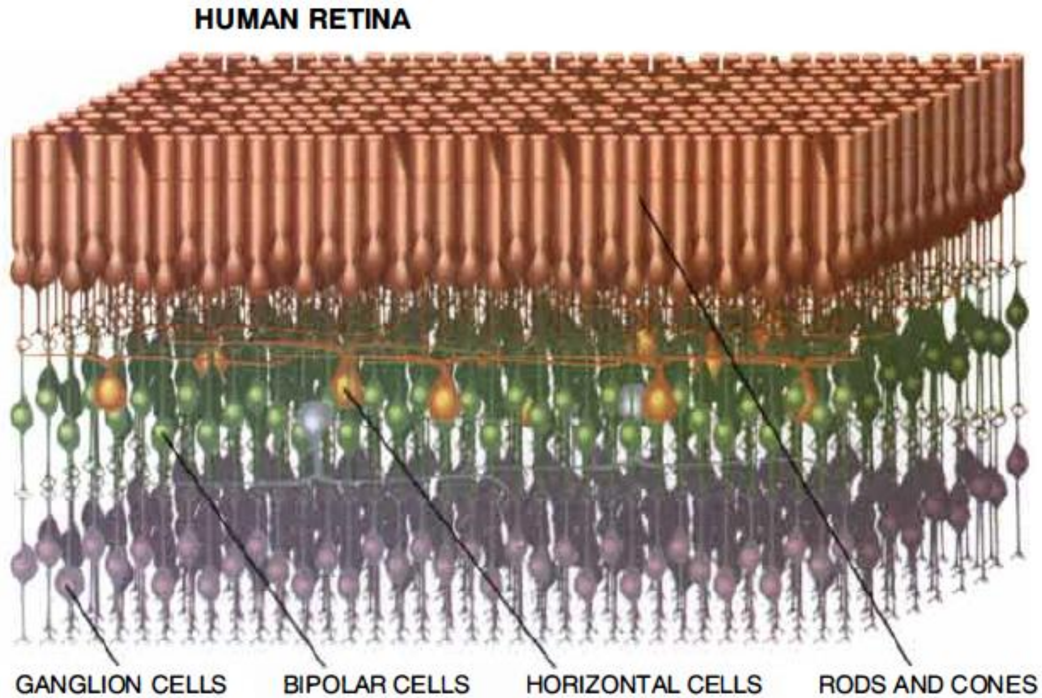


- Mimics retinal processing in a silicon chip
  - *Neuromorphic*
    - *imitating form and function of neurobiology*
  - *Integrated photosensors (rods)*

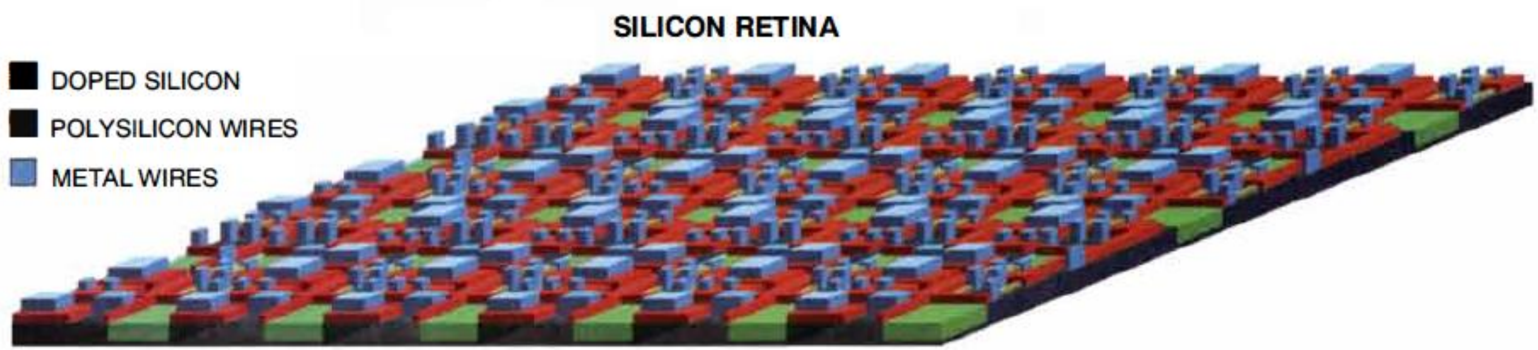
Boahen, "Neuromorphic Chips", Scientific American, May 2005

Silicon Retina

Mahowald and Mead, 1991



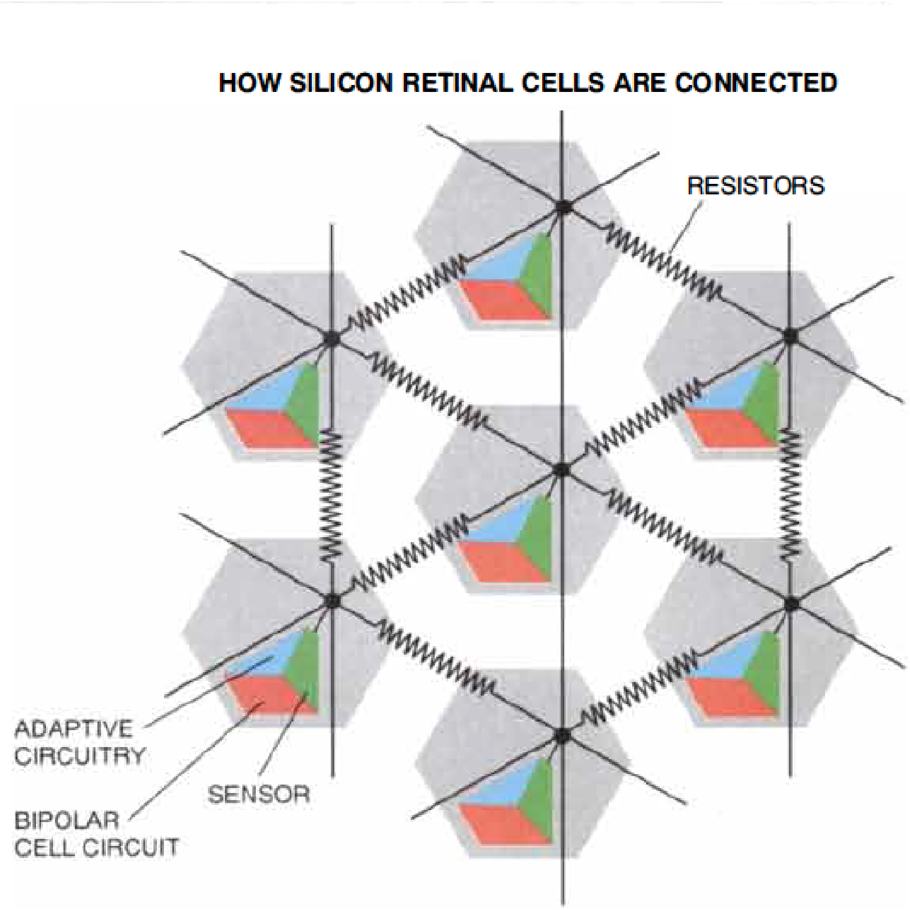
The human retina consists of cells that conduct neural signals both within layers and from one layer to another. The silicon retina models the functions of the outermost three layers—photoreceptors (rods and cones), horizontal cells and bipolar cells. The rods and cones transform light into electrical signals; the horizontal cells, meanwhile, respond to the average light intensity in their neighborhood. Bipolar cells transmit a signal corresponding to the ratio of the signals from rods and horizontal cells through the ganglion cells, where it is further processed before being delivered to the brain.



Mahowald and Mead, Scientific American, 1991

Silicon Retina

Mahowald and Mead, 1991

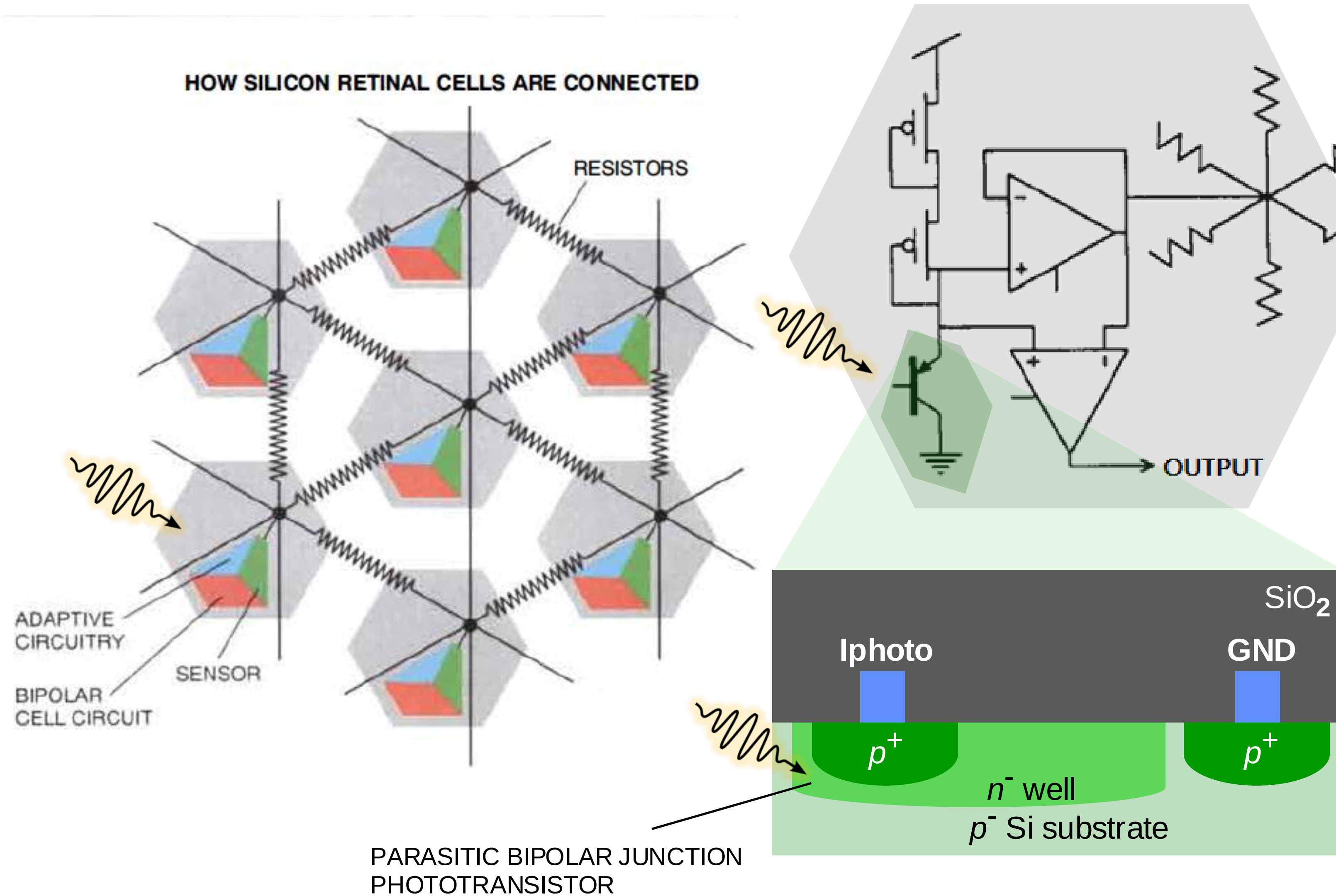


Each silicon photoreceptor mimics a cone cell. It contains both a photosensor and adaptive circuitry that adjusts its response to cope with changing light levels. A network of variable resistors mimics the horizontal cell layer, supplying feedback based on the average amount of light striking nearby photoreceptors. And bipolar cell circuitry amplifies the difference between the signal from the photoreceptor and the local average. The physical layout of the chip (*above*) contains circuitry in staggered blocks. Silicon areas doped with impurities (*green*) are the basis for transistors and photosensors, polysilicon (*red*) forms wires and resistors, and metal lines (*blue*) act as low-resistance wires. The functional diagram at the left shows the arrangement of receptor circuitry and the hexagonal grid of variable resistors that makes up the horizontal cell network. The response of the retinal circuit closely approximates the behavior of the human retina.

Mahowald and Mead, Scientific American, 1991

Silicon Retina

Mahowald and Mead, 1991



Mahowald and Mead, Scientific American, 1991

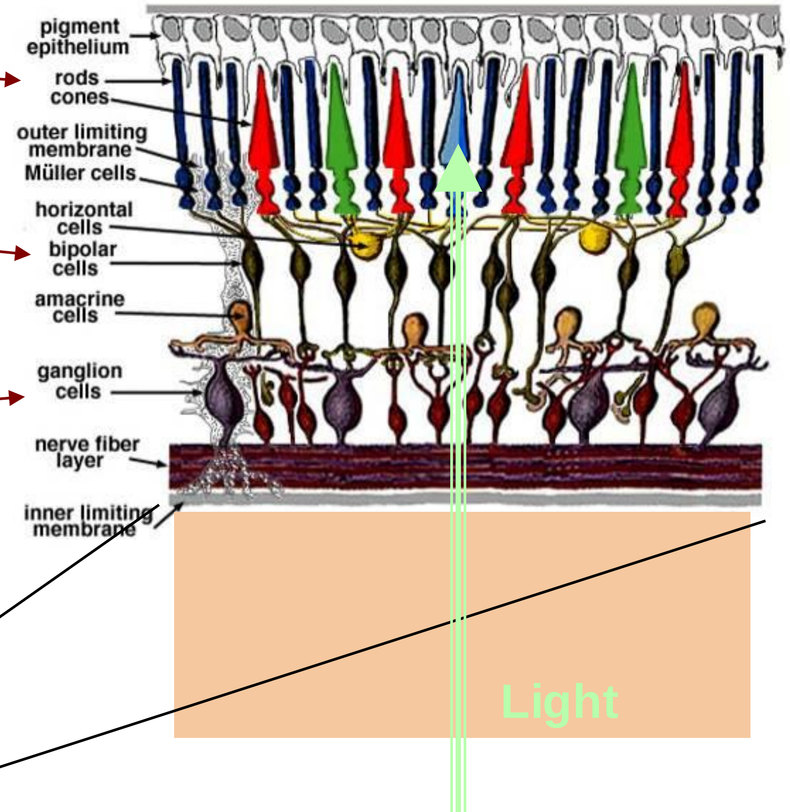
Silicon Retina

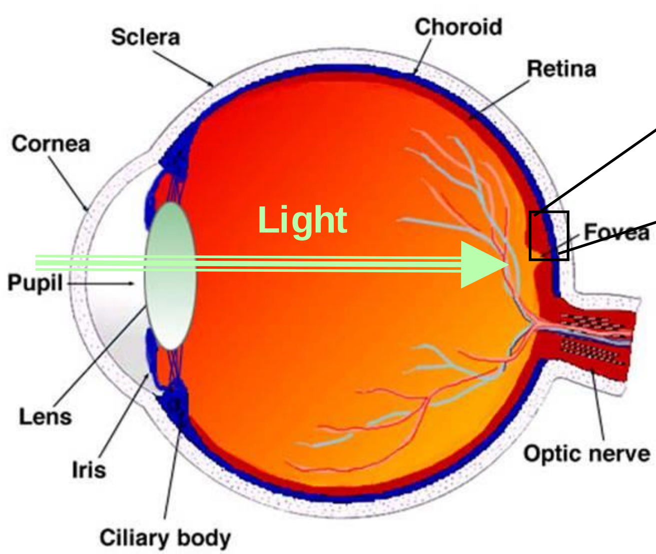
Mahowald and Mead, 1991

Mahowald and Mead, Scientific American, 1991

Retina and Visual System

- **Photoreception**
  - Cones are color sensitive (red, green, blue)
  - Rods are sensitive to low light for dark vision
- **Retinal processing**
  - Horizontal and bipolar cells: spatial highpass filtering
  - Amacrine cells: temporal highpass filtering
- **Optic nerve neural encoding**
  - Retinal ganglion cells: spike rate and temporal event encoding

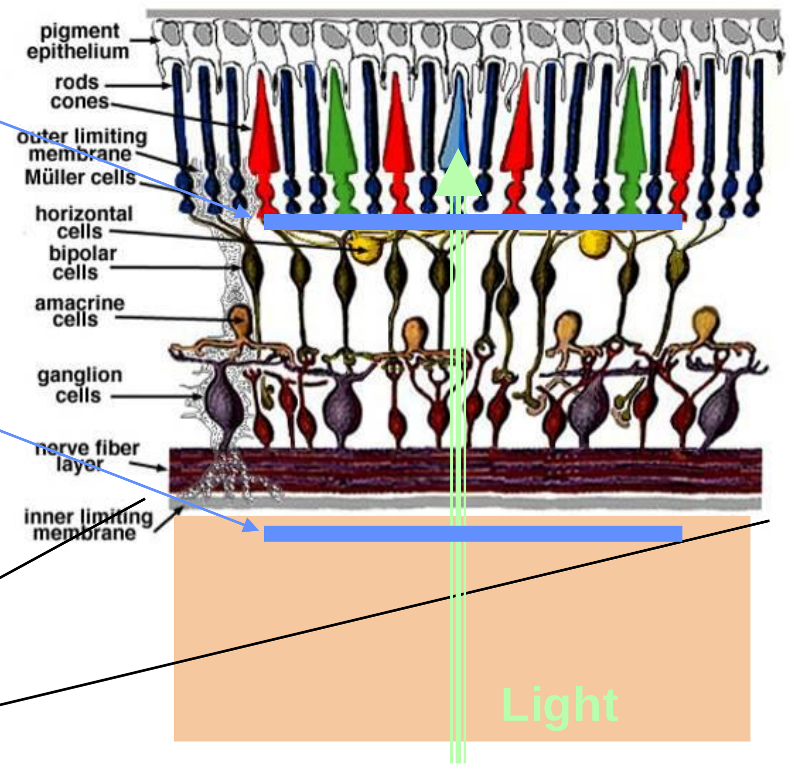


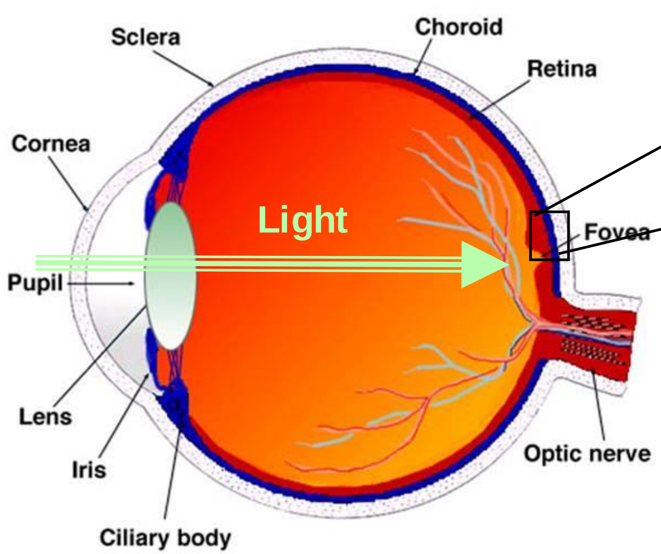


J.D. Weiland and M.S. Humayun, IEEE EMB Mag., Sept/Oct 2006.

Retinal Prostheses

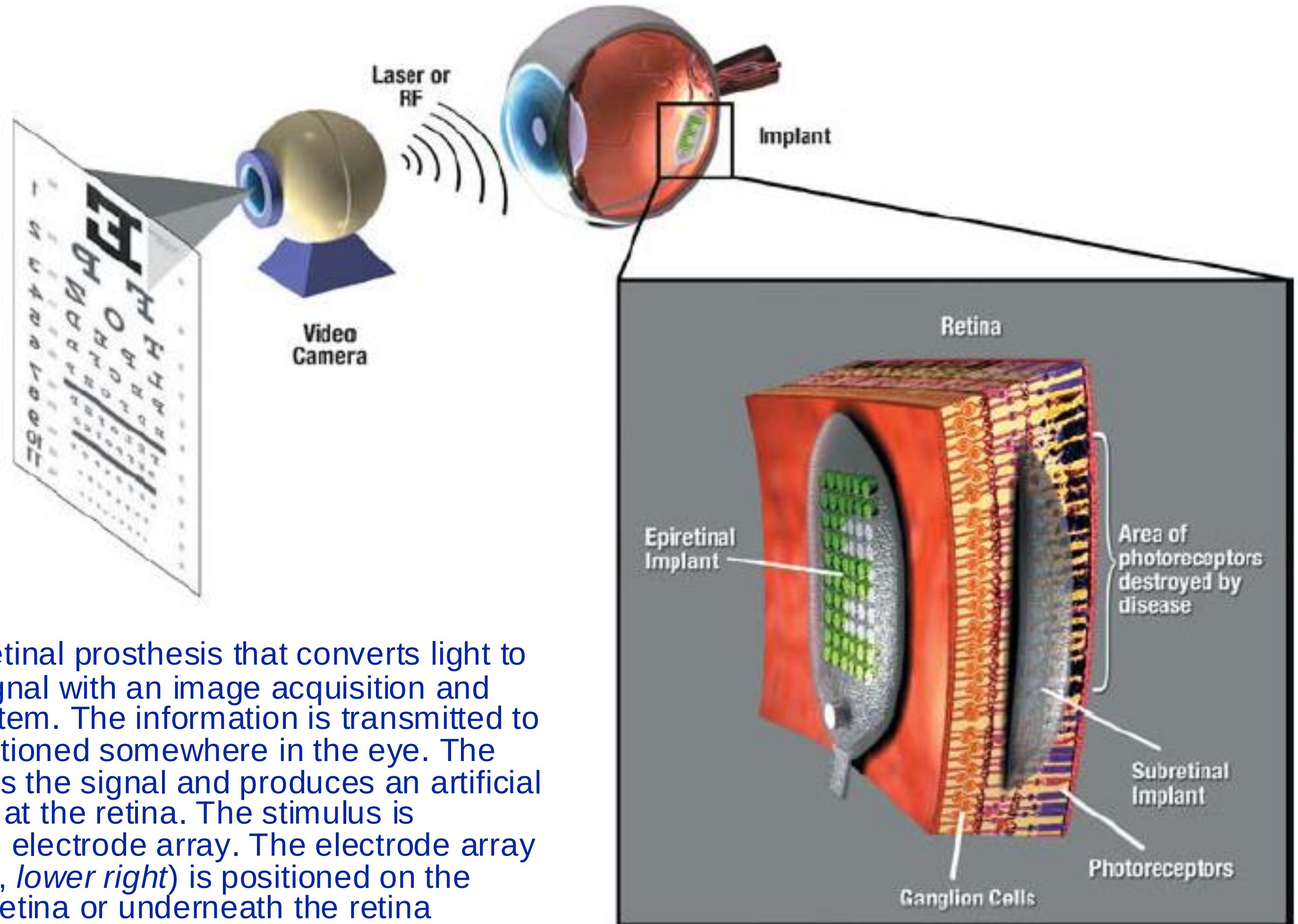
- **Subretinal implant**
  - uses intact retinal processing, accessing bipolar cells
  - surgically more involved, constraining device sizing
- **Epiretinal implant**
  - uses silicon retina to emulate retinal processing
  - easier to integrate and interface





J.D. Weiland and M.S. Humayun, IEEE EMB Mag., Sept/Oct 2006.

Retinal Implant

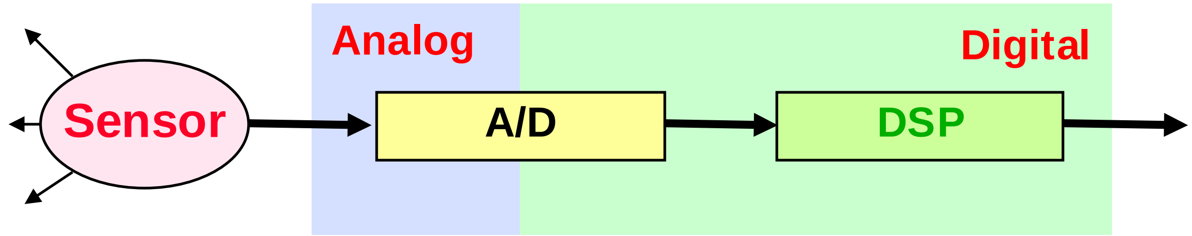


Concept of a retinal prosthesis that converts light to an electrical signal with an image acquisition and processing system. The information is transmitted to an implant positioned somewhere in the eye. The implant receives the signal and produces an artificial stimulus signal at the retina. The stimulus is delivered by an electrode array. The electrode array (*shown in inset*, *lower right*) is positioned on the surface of the retina or underneath the retina (electrode array not shown for subretinal implant).

J.D. Weiland, W. Liu, M.S. Humayun, Ann. Rev. Biom. Eng., vol. 7, 2005

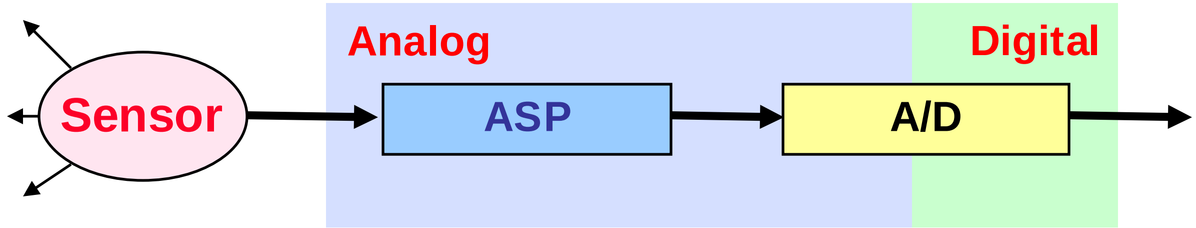
Why Neuromorphic Sensory Processing?

- **Conventional Digital Sensory Processing:**



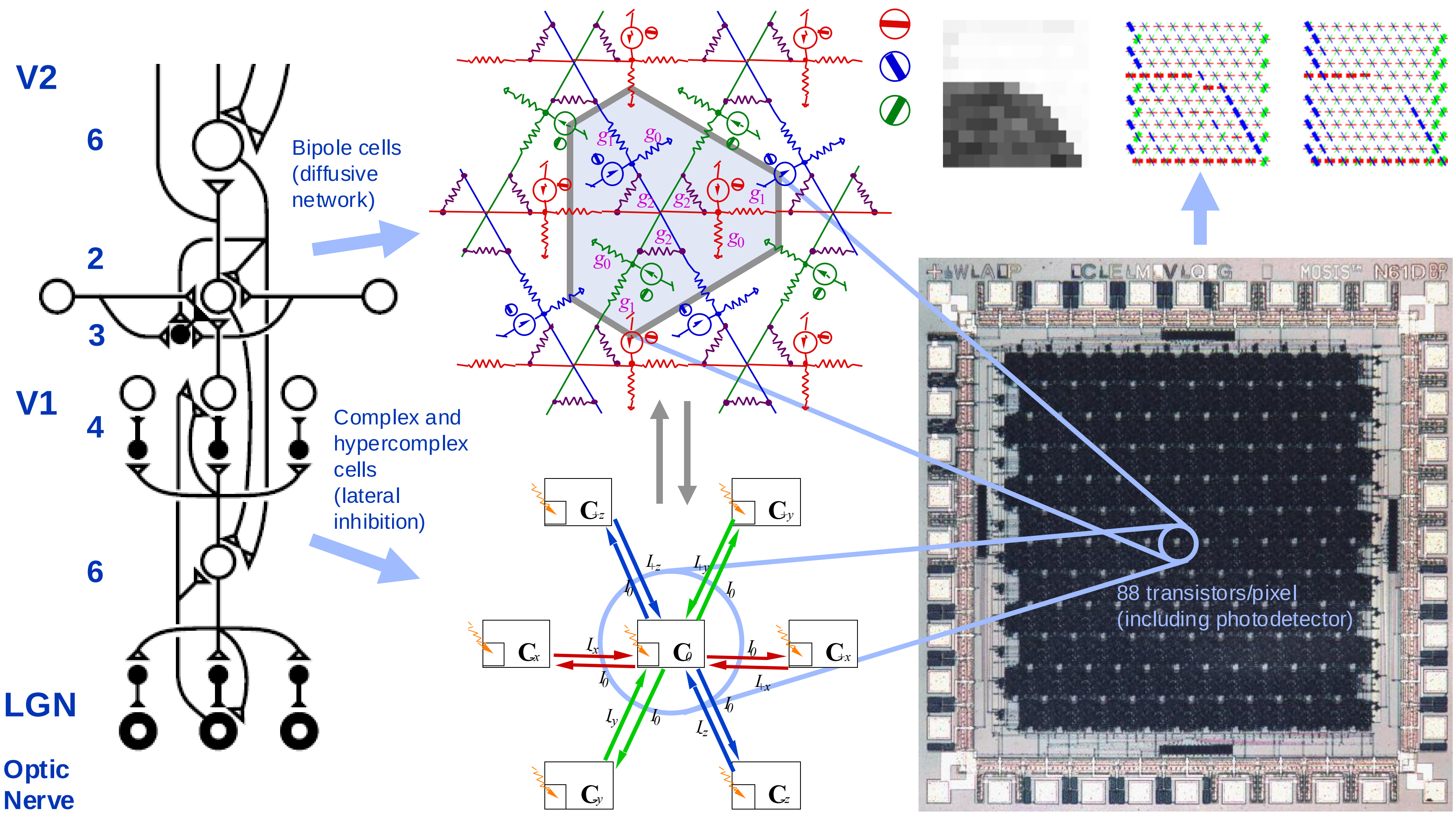
  - General-purpose
  - High precision (limited by A/D)

- **Neuromorphic Analog/Mixed-Signal Sensory Processing:**



  - “Smart” A/D
  - Low power

Silicon Model of Visual Cortical Processing

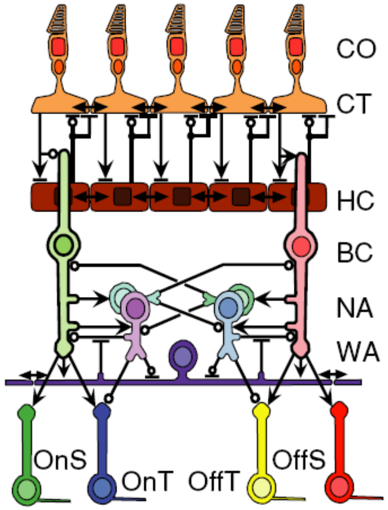


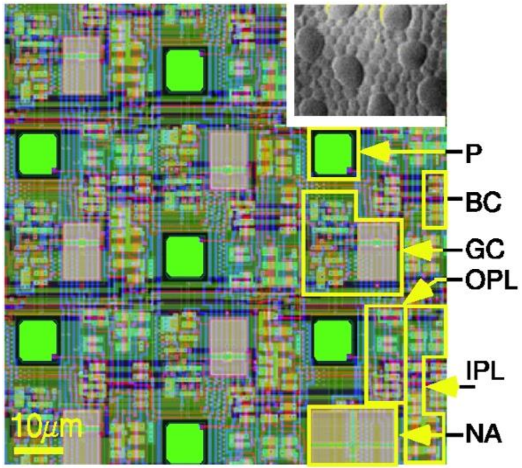
Neural model of boundary contour representation in V1, one orientation shown (Grossberg, Mingolla, and Williamson, 1997)

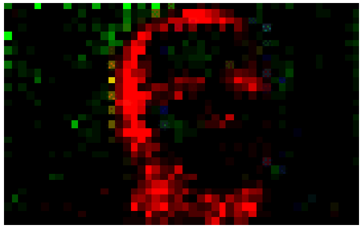
Single-chip focal-plane implementation (Cauwenberghs and Waskiewicz, 1999)

Event-Coding Silicon Retina

Zaghloul and Boahen, 2006



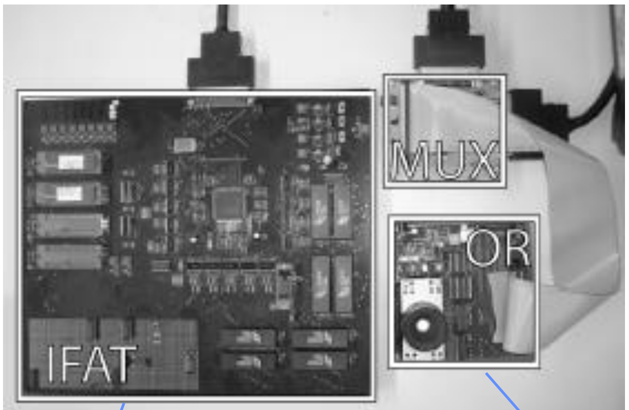




- Models coding and communication of visual events in the mammalian retina and optic nerve
  - *Integrated photosensors (rods)*
  - *On and off transient and sustained ganglia cell outputs*
    - *Spatiotemporal compressed coding and communication in optic nerve*
    - *Address-event coding of spikes*

Hierarchical Vision and Saliency-Based Acuity Modulation

Vogelstein, Mallik, Culurciello, Cauwenberghs, and Etienne-Cummings, NECO 2007

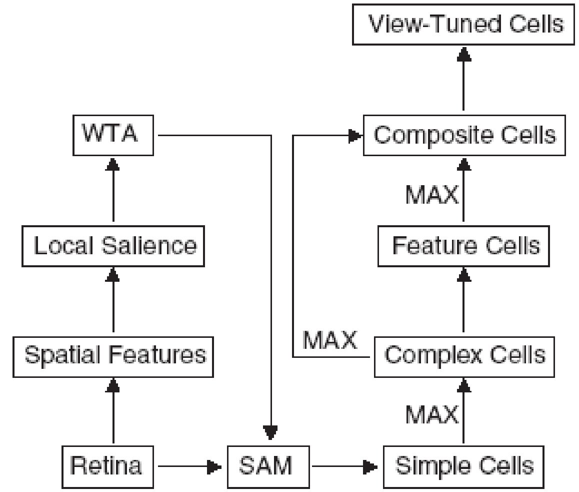


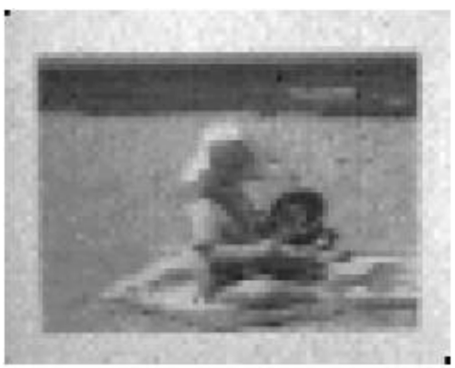
IFAT **Cortical Model**

4800 silicon neurons
4,194,304 synapses

Octopus **Silicon Retina**

80 x 60 pixels
AER spiking output





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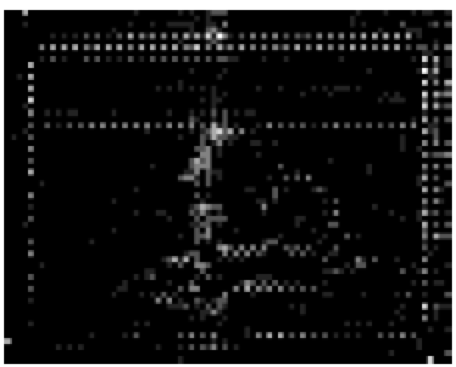
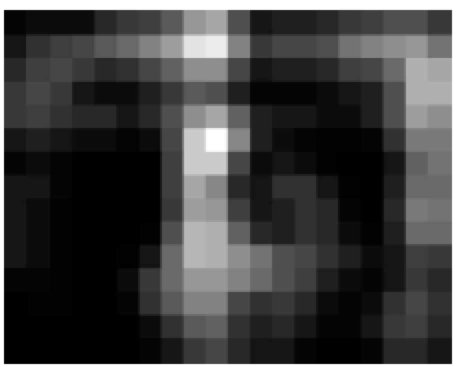


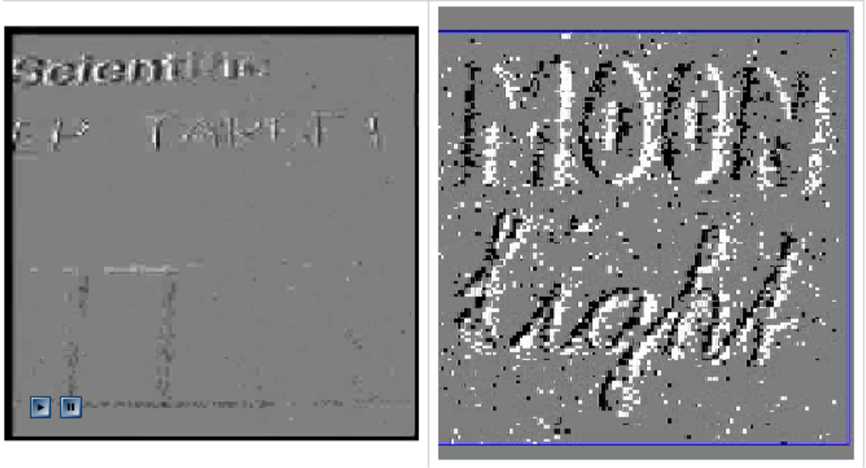
Simple cell response



Saliency map

Dynamic Vision Sensors (DVS)

- Visual event detection on the focal plane.
- High dynamic range, high temporal resolution.
- Power scales with activity.



http://siliconretina.ini.uzh.ch/wiki/index.php

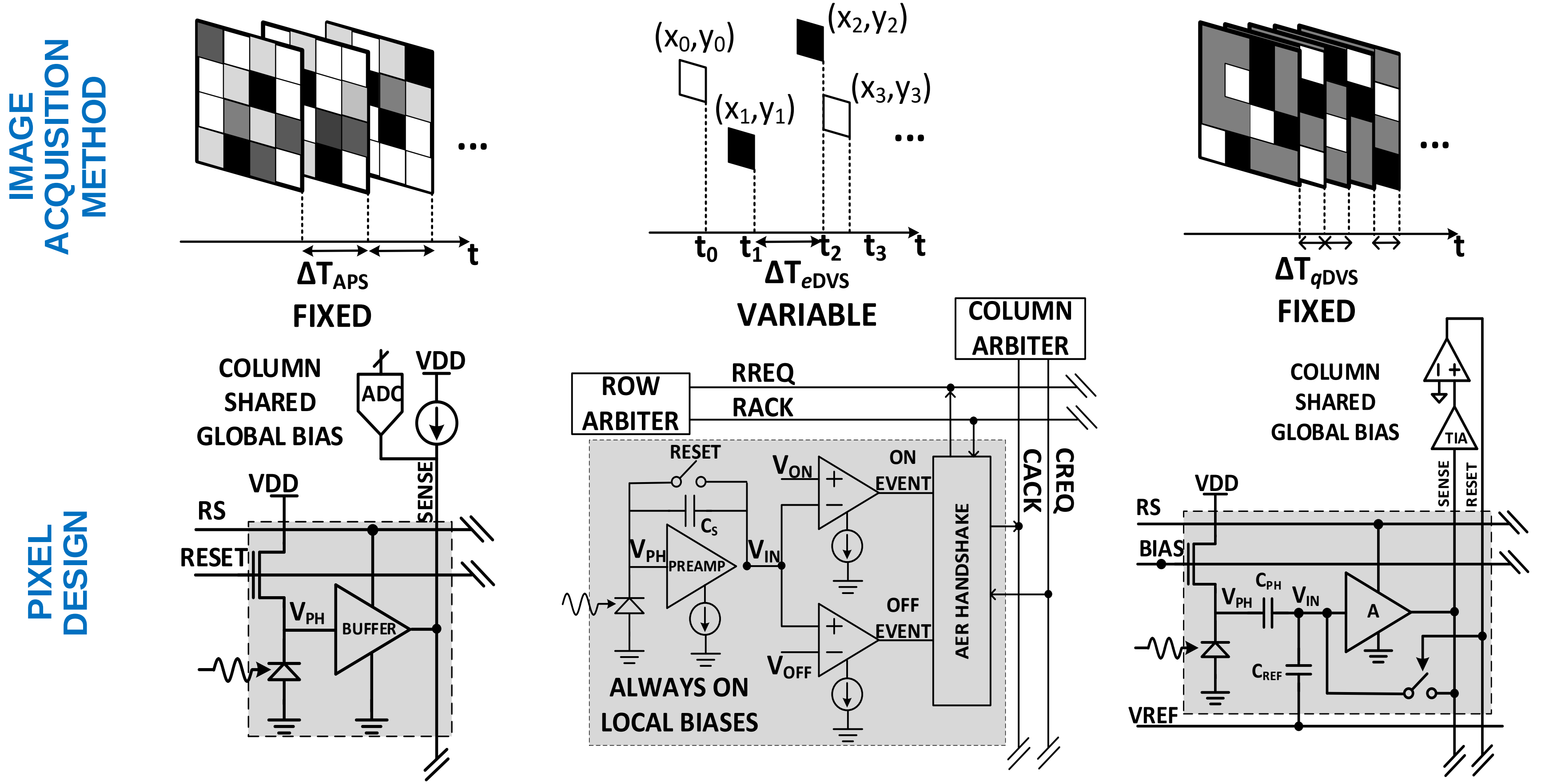
DVS Applications

- **The compactness, lower system complexity, low power consumption can benefit the areas of:**
  - High-speed/high temporal-resolution dynamic machine vision systems that need access to real-time visual information (robotics, roving robot ad-hoc networks, autonomous navigation, industrial robotics).
  - Motion detection and analysis applications (e.g. gesture recognition, contact-less device control, 3D touch screen, game controller)
  - Low-data rate video for e.g. wireless sensor networks or TCP-based applications (smart buildings, ambient intelligence, …)
  - High Dynamic Range, high quality, high-temporal resolution imaging and video e.g. for scientific applications. (x-ray crystallography, fluidics, particle physics, fluorescence imaging, medical imaging)

http://www.institut-vision.org/index.php?option=com_content&id=283%3Aequipe-de-r-benosman&Itemid=15&lang=en

Active Pixel vs. Dynamic Vision Sensors

ACTIVE PIXEL SENSOR (APS) | **EVENT DRIVEN DYNAMIC VISION SENSOR (*e*DVS)** | **QUERY DRIVEN DYNAMIC VISION SENSOR (*q*DVS)**



Kubendran, Paul and Cauwenberghs, "A 256x256 6.3pJ/pixel-event Query-driven Dynamic Vision Sensor with Energy-conserving Row-Parallel Event Scanning," IEEE CICC 2021.

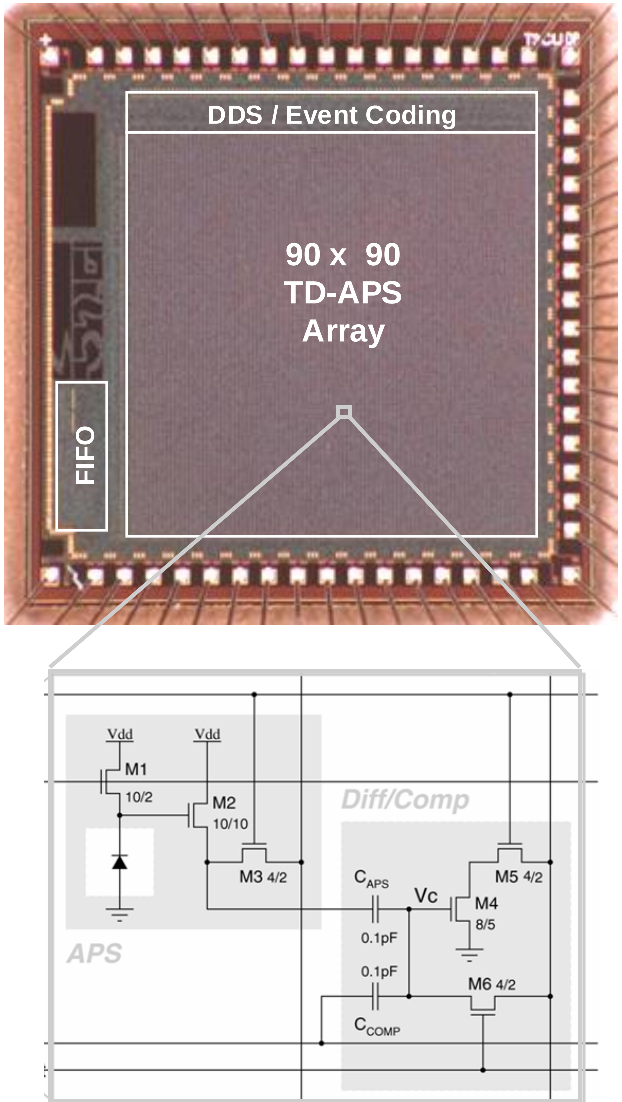
Active Pixel vs. Dynamic Vision Sensors

PARAMETER	APS	*e*DVS	*q*DVS
LATENCY	HIGHEST (upto ~100fps ≈ 10ms)	LOWEST (frameless ≈ 10μs)	MEDIUM AND VARIABLE (upto ~1000fps ≈ 1ms)
BANDWIDTH UTILIZATION	HIGHEST Activity independent (High resolution, high speed ADC)	MEDIUM Activity dependent (Pixel address + 2 bit event + REQ/ACK)	LOWEST Activity dependent (2 bit event)
DENSITY	HIGHEST (3T-5T/pixel)	LOWEST (>10T/pixel)	HIGH (7T-10T/pixel)
POWER	HIGH DYNAMIC MEDIUM STATIC (100-500 nW per pixel)	MEDIUM DYNAMIC HIGH STATIC (80-500 nW per pixel)	LOW DYNAMIC LOW STATIC (<10 nW per pixel)

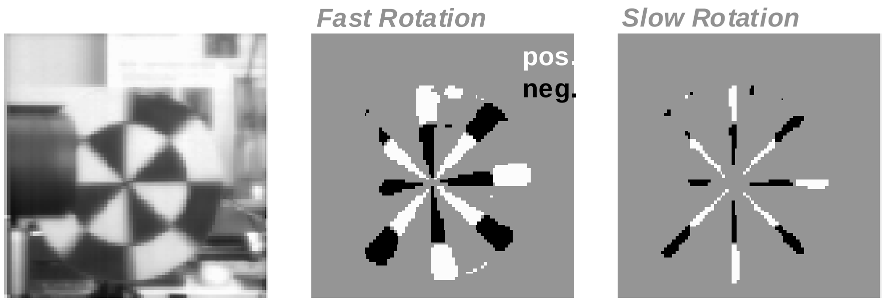
Kubendran, Paul and Cauwenberghs, "A 256x256 6.3pJ/pixel-event Query-driven Dynamic Vision Sensor with Energy-conserving Row-Parallel Event Scanning," IEEE CICC 2021.

Change Threshold Detection APS CMOS Imager

Chi, Mallik, Clapp, Choi, Cauwenberghs and Etienne-Cummings (2007)

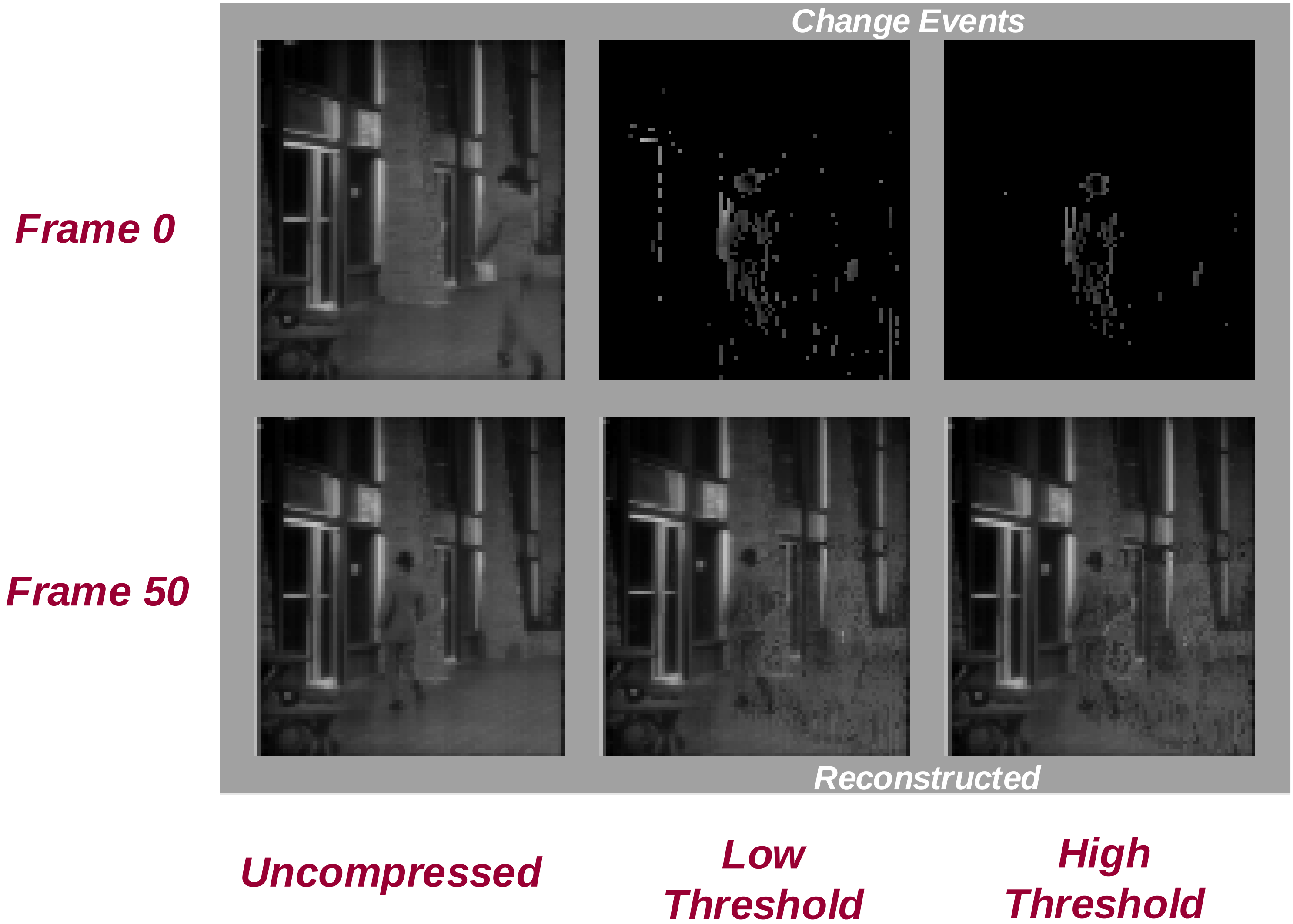


- Event-driven video compression
  - *Change detection and threshold encoding on the focal plane*
- 6T pixel combines APS and change event coding
- 4.3mW power at 3V and 30fps



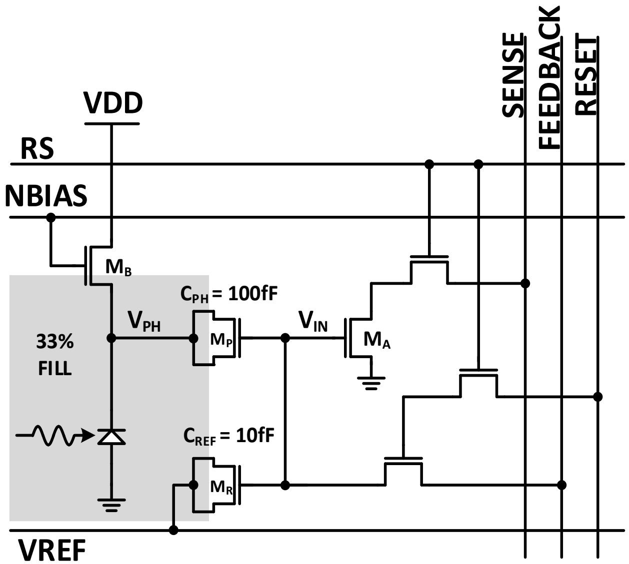
Video Out ***Change Events Out***

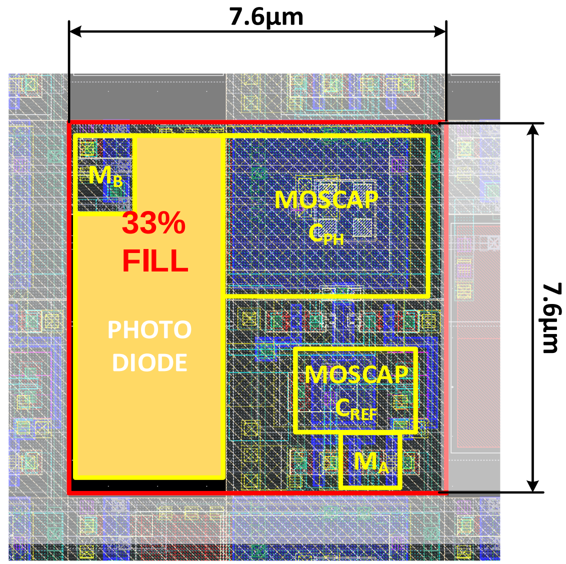
Change Detection APS: Compression and Reconstruction

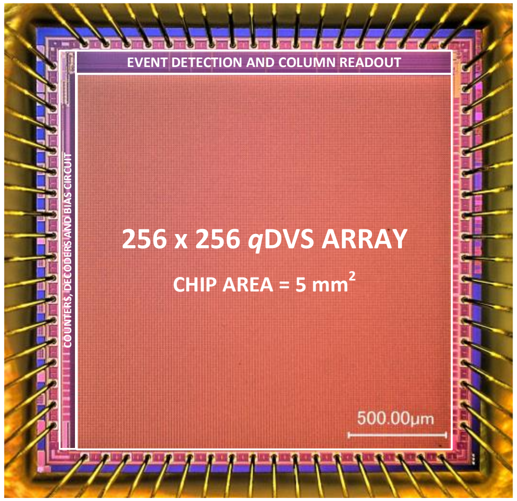


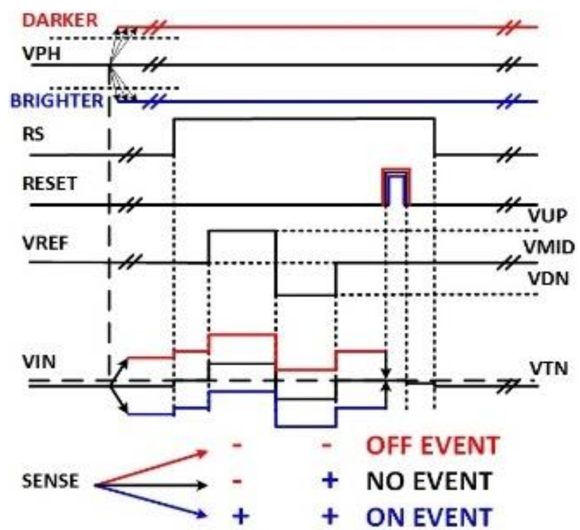
Query-Driven Dynamic Vision Sensor (*q*DVS)

Kubendran, Paul, and Cauwenberghs, 2021







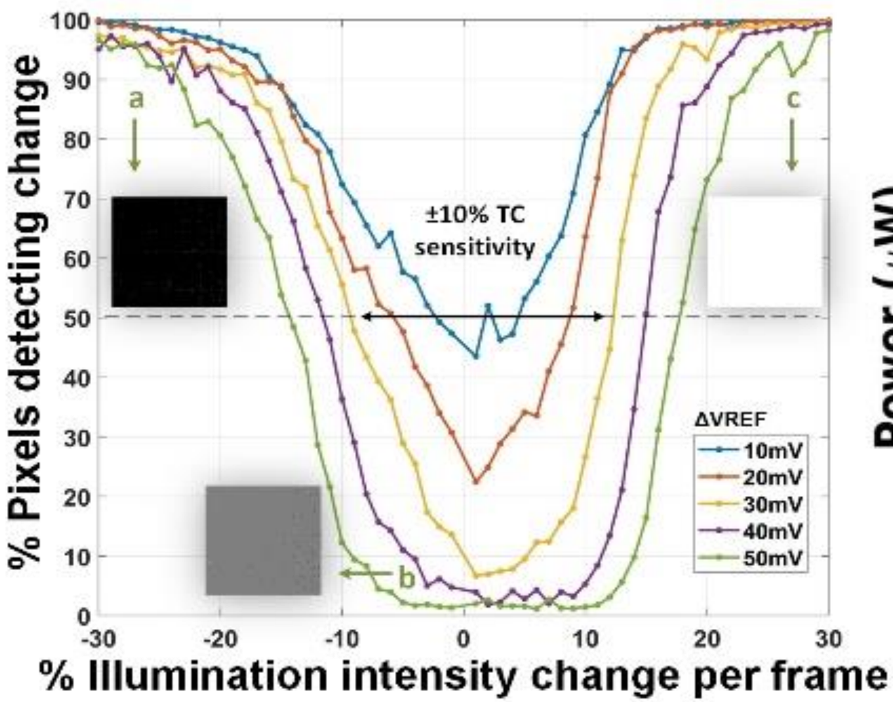


- The qDVS active pixel combines functions of phototransduction, temporal differencing, threshold detection, and reference reset, using as few as five MOS transistors and two MOS capacitors.
- Custom photodiode nwell/psub in 180nm CMOS
- 10:1 ratio of C_{PH} / C_{REF} for high contrast sensitivity
- No source follower – no static bias current
- Voltage clamp sense line for zero CV^2 readout energy

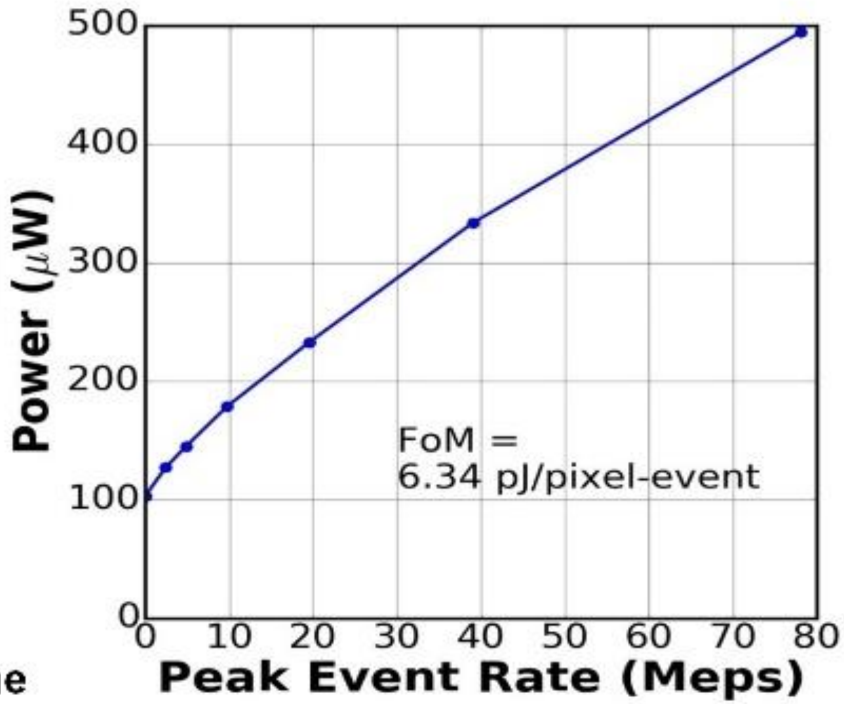
Kubendran, Paul and Cauwenberghs, "A 256x256 6.3pJ/pixel-event Query-driven Dynamic Vision Sensor with Energy-conserving Row-Parallel Event Scanning," IEEE CICC 2021.

*q*DVS Performance

Temporal Contrast Sensitivity

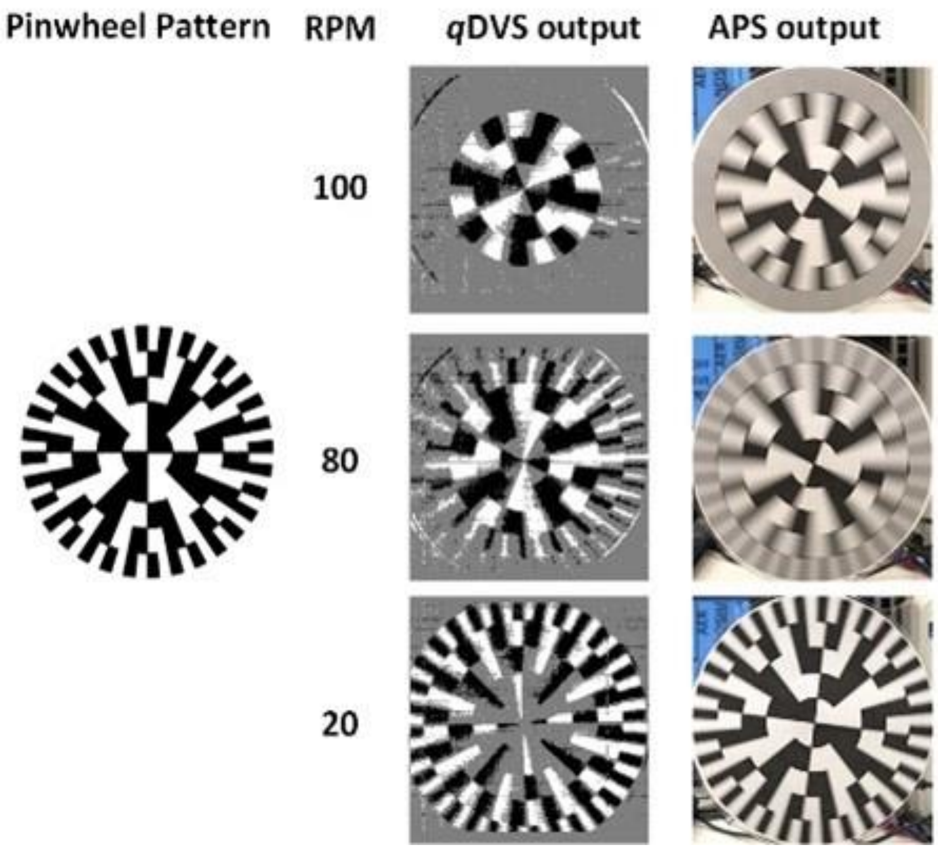


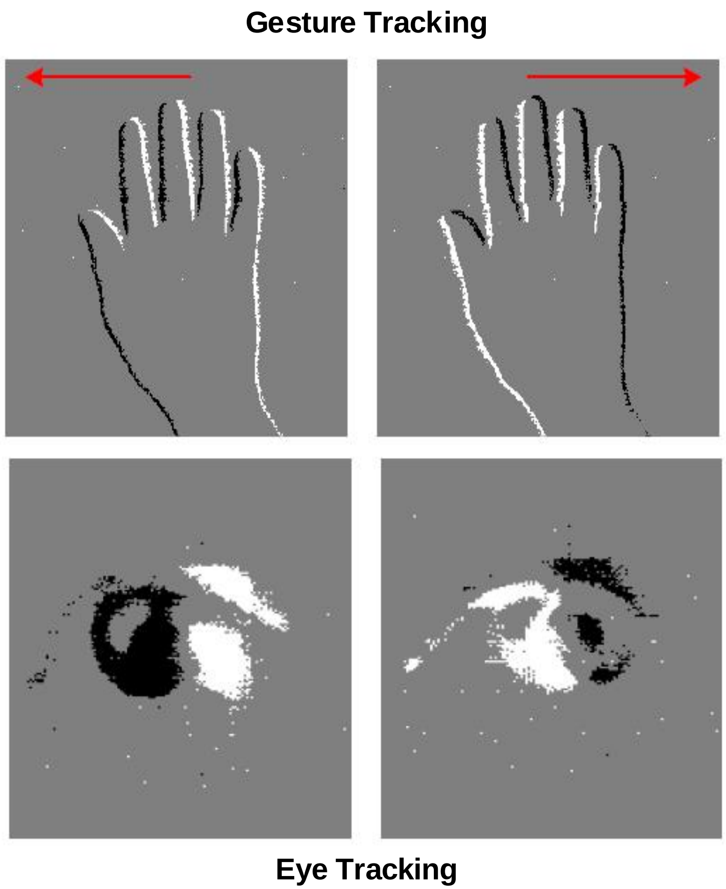
Energy Efficiency



Kubendran, Paul and Cauwenberghs, "A 256x256 6.3pJ/pixel-event Query-driven Dynamic Vision Sensor with Energy-conserving Row-Parallel Event Scanning," IEEE CICC 2021.

*q*DVS Movement Tracking





Kubendran, Paul and Cauwenberghs, "A 256x256 6.3pJ/pixel-event Query-driven Dynamic Vision Sensor with Energy-conserving Row-Parallel Event Scanning," IEEE CICC 2021.

*q*DVS Performance Comparison

	Prophesee ISSCC'20 [2]	CelePixel CVPR'19 [3]	Samsung ISSCC'17 [4]	iniLabs JSSC'15 [5]	DDS JSSC'07 [6]	*q*DVS This Work
Technology	90nm BI CIS + 40nm CMOS	65nm CIS	90nm 1P5M	0.18µm 1P6M	0.5 µm 2P4M	**0.18 µm 1P6M**
Resolution	1280x720	1280x800	640x480	60x30	90x90	**256x256**
Chip Area (mm^2)	6.22x3.5	14.3x11.6	8x5.8	3.2x1.6	3x3	**2.236x2.236**
Pixel Size (μm^2)	4.86x4.86	9.8x9.8	9x9	31.2x31.2	25.2x25.2	**7.6x7.6**
Fill Factor (%)	77	8	11	10.3	17	**33.2**
Supply Voltage (V)	1.1/2.5	1.2/2.5	1.2/2.8	1.8	3	**1.2/1.2**
Power (mW) (at 100Keps)	32	NA	27	0.72	4.2	**0.103**
Power (mW) (at 100Meps)	73	400	34	-	-	**0.465**
Energy Efficiency (pJ/pixel-event)	137	7200	340	7200	42000	**6.34**
Min. Contrast Sensitivity (%)	11	10	9	1	2.1	**10**
Dynamic Range (dB)	124	120	90	130	51	**68**
Latency (µs)	1.2	8	65-410	NA	366-33000	**5.2 - 1331**

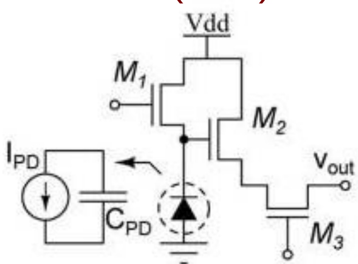
Kubendran, Paul and Cauwenberghs, "A 256x256 6.3pJ/pixel-event Query-driven Dynamic Vision Sensor with Energy-conserving Row-Parallel Event Scanning," IEEE CICC 2021.

Photodiode Low-Noise Photoreceptors

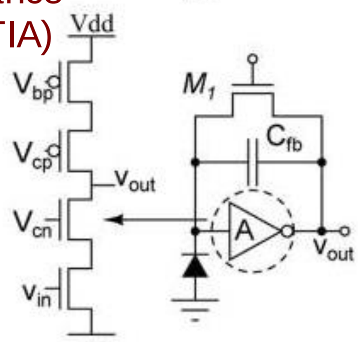
Photodiode Structure: n^+ / p-sub | n-well / p-sub | p^+ / n-well / p-sub

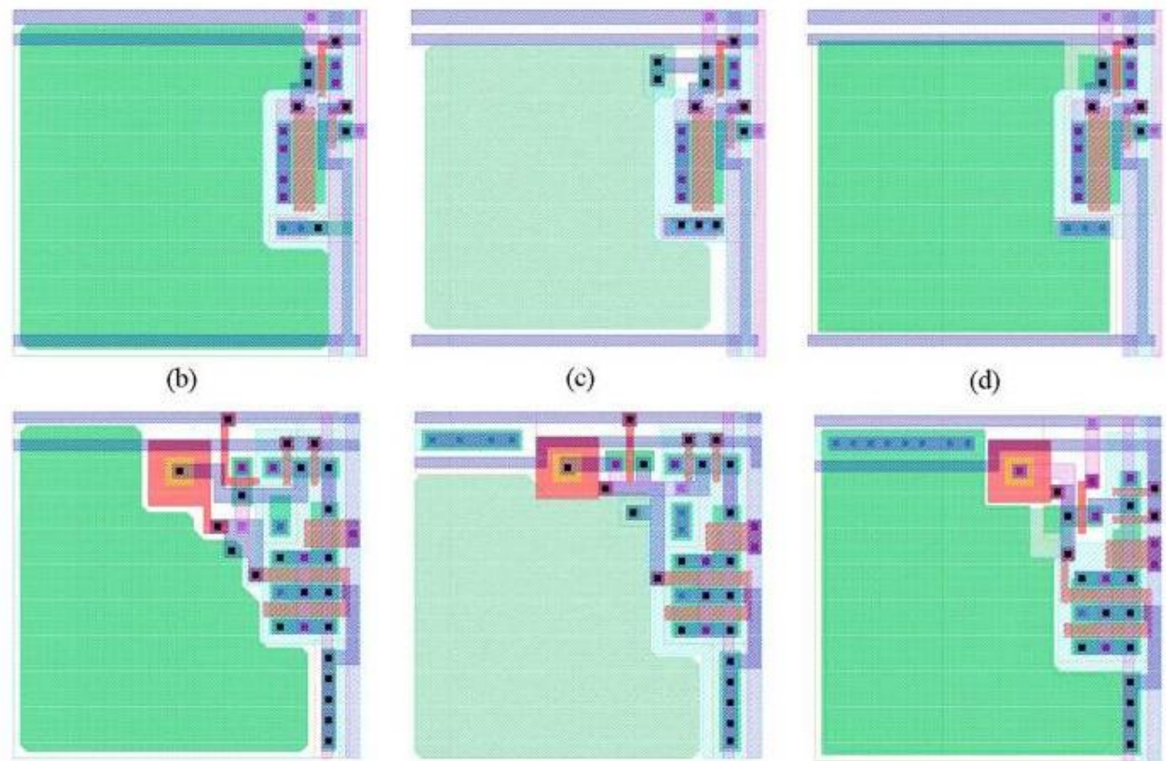
Interface Circuit:

3T Active Pixel Sensor (APS)



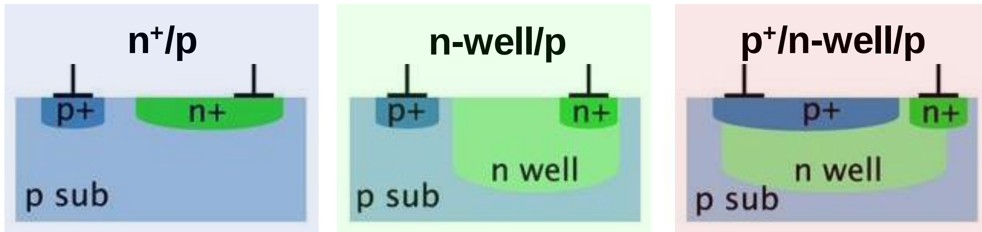
Capacitive Transimpedance Amplifier (CTIA) APS

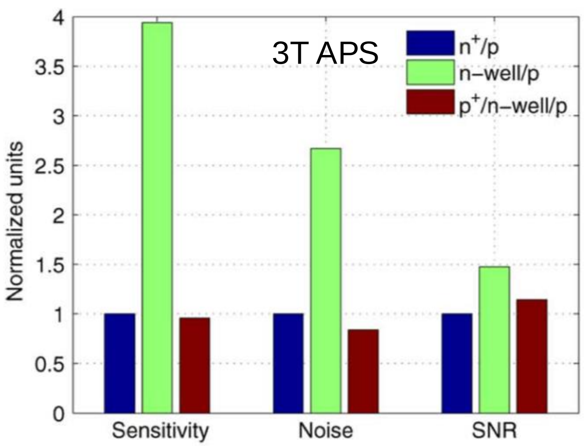


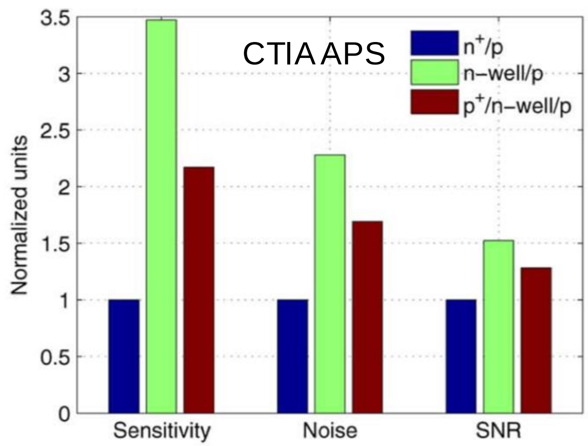


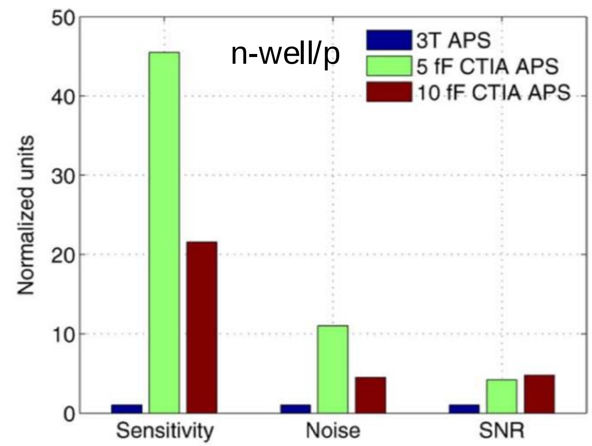
Murari, K., Etienne-Cummings, R., Thakor, N., & Cauwenberghs, G, "Which Photodiode to Use: A Comparison of CMOS-Compatible Structures," IEEE Sensors Journal, 9(7), 752–760, 2009.

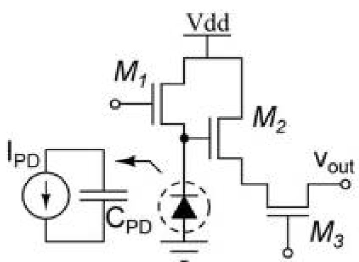
Photodiode Low-Noise Photoreceptors



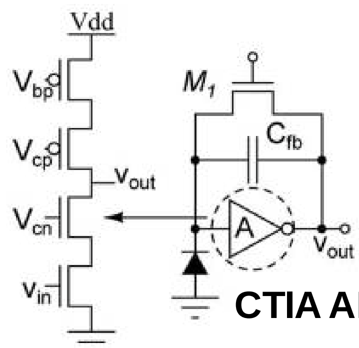








3T APS



CTIA APS

Photodiode type	Dark current (nA/cm^2)	DTOP (nW/cm^2)
n^+/p-sub	96.2	0.14
n-well/p-sub	363.4	0.15
p^+/n-well/p-sub	90.3	0.05

Murari, K., Etienne-Cummings, R., Thakor, N., & Cauwenberghs, G, "Which Photodiode to Use: A Comparison of CMOS-Compatible Structures," IEEE Sensors Journal, 9(7), 752–760, 2009.

BENG 216 Neuromorphic Integrated Bioelectronics

Date	Topic
9/30, 10/2	Biophysical foundations of natural intelligence in neural systems. Subthreshold MOS silicon models of membrane excitability. Silicon neurons. Hodgkin-Huxley and integrate-and-fire models of spiking neuronal dynamics. Action potentials as address events.
10/7, 10/9	Silicon retina. Low-noise, high-dynamic range photoreceptors. Focal-plane array signal processing. Spatial and temporal contrast sensitivity and adaptation. Dynamic vision sensors.
10/14, 10/16	Silicon cochlea. Low-noise acoustic sensing and automatic gain control. Continuous wavelet filter banks. Interaural time difference and level difference auditory localization. Blind source separation and independent component analysis.
10/21, 10/23	Silicon cortex. Neural and synaptic compute-in-memory arrays. Address-event decoders and arbiters, and integrate-and-fire array transceivers. Hierarchical address-event routing for locally dense, globally sparse long-range connectivity across vast spatial scales.
10/28, 10/30	Midterm review. Modular and scalable design for neuromorphic and bioelectronic integrated circuits and systems. Design for full testability and controllability.
11/4, 11/6	Low-noise, low-power design. Fundamental limits of noise-energy efficiency, and metrics of performance. Biopotential and electrochemical recording and stimulation, lab-on-a-chip electrophysiology, and neural interface systems-on-chip.
11/13	Learning and adaptation to compensate for external and internal variability over extended time scales. Background blind calibration of device mismatch. Correlated double sampling and chopping for offset drift and low-frequency noise cancellation.
11/18, 11/20	Adaptive offset cancelation and autoranging in dynamic vision sensing. Tobi Delbruck's lecture on silicon retina history with a live demo of event-based dynamic vision systems.
11/25, 11/27	Energy conservation. Resonant inductive power delivery and data telemetry. Ultra-high efficiency neuromorphic computing. Resonant adiabatic energy-recovery charge-conserving synapse arrays.
12/2 - 12/6	Project final presentations. All are welcome!