Biologically Inspired Vision Systems in Standard CMOS

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INSTITUTE FOR SYSTEMS RESEARCH
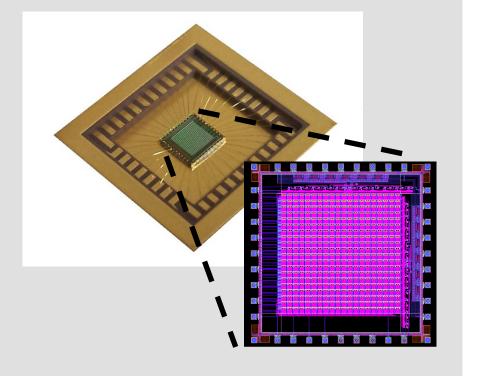A. JAMES CLARK SCHOOL OF ENGINEERING

Core Expertise: CMOS Imagers

Our lab develops custom CMOS imagers with a focus on:

- biosystems applications such as lab-on-CMOS systems
- flight stabilization for unmanned aerial vehicles
- image plane processors
- medical diagnostics

Commercial CMOS imagers are ubiquitous in every day devices. They are cheap, achieve high sensor densities, and easily integrate with other electronics. This highly successful technology is based on the standard sensing system paradigm of front-end analog sensing, then conversion to digital, followed by digital processing. This approach does not fully utilize the capabilities that CMOS integrated circuits offer – namely, single chip integration of circuits, sensors, and signal processing.

In order to fully realize the potential of CMOS imagers, a systems-level design approach must be utilized, taking into consideration of both the sensing measurement and the systems-level functionality.

Current Research: Single Chip CMOS Image Processors

Ongoing work focuses on the development of fully integrated, single chip solutions to vision problems that reduce size, weight, and power requirements to meet the needs of current and future microsystems. These vision systems will offer high performance, low-power consumption, and high functionality.

We are addressing these needs through innovative instrumentation techniques, adaptive circuits for high fidelity sensing and computation, and compact implementations of sophisticated image and video processing techniques.

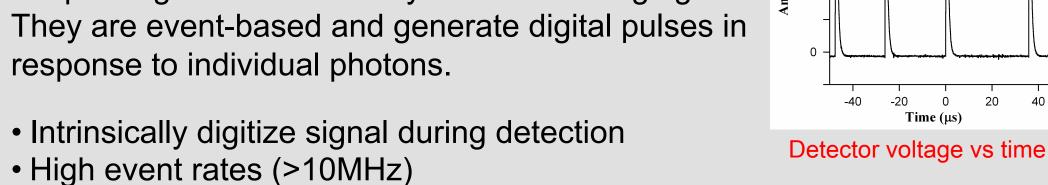Applications for such vision systems include:

- Advanced imagers for lab-on-CMOS applications
- Vision-based navigation and stabilization for autonomous robotic platforms
- High dynamic range imagers for day/night operation
- Computational imagers for computer vision systems
- Time-resolved fluorescence spectroscopy
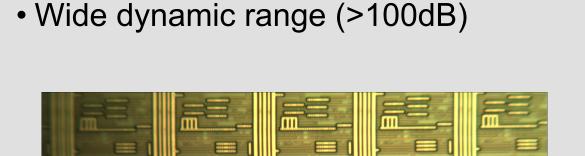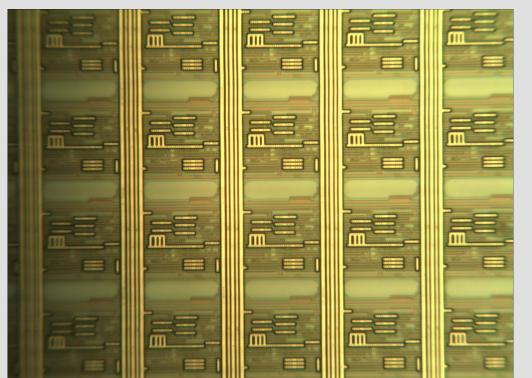
Picture of Crazyflie, Source: www.geek.com

Single Photon Avalanche Diodes

- Traditional CMOS imagers use long integration times to overcome weak optical signals and noise
- Time-correlated imaging requires single photon sensitivity with sub-nanosecond temporal resolution … traditional techniques can't do this!
- Strategy: high sensor gain improves temporal dynamics and sensitivity

- Single photon avalanche diodes (SPADs) are PN junction diodes reverse biased above breakdown
- High gain (>10^6) through avalanche breakdown
- Custom physical design allows fabrication in standard CMOS
- Single photon sensitivity
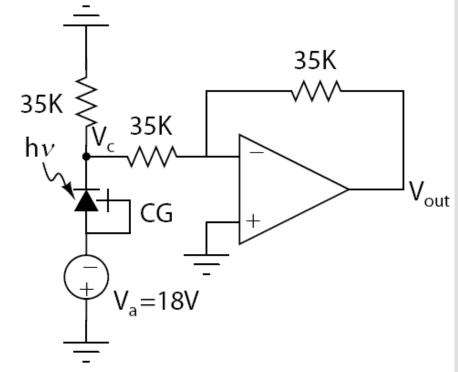- Sub nanosecond timing resolution

Like biological photoreceptors, SPADs do not follow the paradigm of traditional synchronous imaging. They are event-based and generate digital pulses in response to individual photons.

- Intrinsically digitize signal during detection
- High event rates (>10MHz)
- Wide dynamic range (>100dB)

Detector voltage vs time

V_a=18V

Photomicrograph

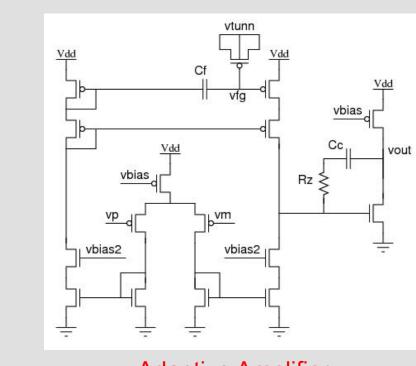Readout circuit w/ passive quenching

Adaptive Integrated Circuits

Analog circuits are often required to sense phenomena in the analog world. They offer a small footprint and low power consumption but are susceptible to interference and mismatch, motivating the need to trim their parameters.
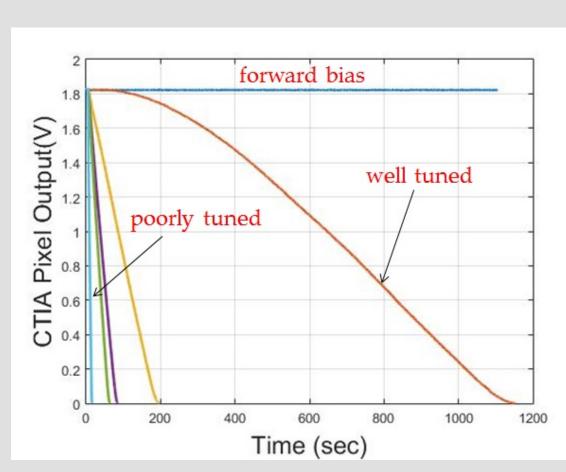
- Matched analog devices are large and expensive
- Currently, most sensors are calibrated post-fabrication and post-sensing using digital signal processing techniques
- Alternative strategies for parameter matching include adaptive analog circuits

- CMOS photodetectors are cheap, small but … noisy
- Strategy: suppress photodiode dark current by collecting carriers at zero bias voltage with capacitive trans-impedance amplifier (CTIA)
- BUT … input offset of integration amplifier limits ability to reduce dark current (must be <1 mV)
- Solution: use adaptation!

Adaptive Amplifier
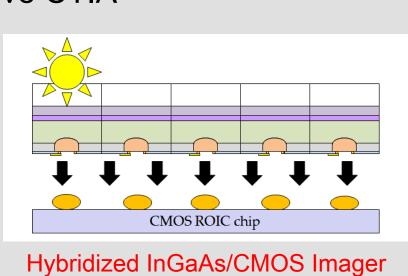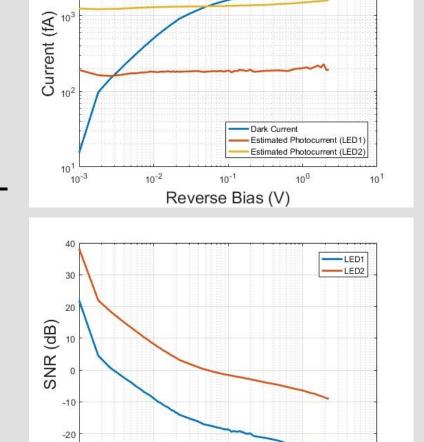
VP

CTIA Photocircuit

10pF cap   Op-Amp
79um   61um

Photomicrograph

Room Temperature SWIR Sensing

- IR detectors suffer from high dark currents (10-100x higher than Si)
- SWIR detectors are cooled to decrease noise…large cost in SWaP
- Strategy: suppress photodiode dark current with adaptive CTIA photocircuit
- Performance improves by >30dB over non-adaptive CTIA

CMOS ROIC chip

Hybridized InGaAs/CMOS Imager

Low-Light Optic Flow Detection

- VLSI-friendly, non-directional optic flow algorithms and spatial filtering for autonomous navigation
- Spatial pattern of optical motion provides information about self motion and environmental cues
- Can be used for visual navigation and stability
- >2-bit resolution in velocity estimation with <100 photons/photoreceptor/frame

Integrated Biomorphic Information Systems Lab