CMOS Quantum Imagers for Picosecond Sensing Applications

Edoardo Charbon

Ecole Polytechnique Fédérale, Lausanne (EPFL)
Emerging Imaging Needs

• \textit{ultra-fast, time-correlated}, molecular processes in physics and the life-sciences

• \textit{quantitative} bio-chemistry and molecular biology

• New class of problems addressed by \textit{precision imaging} techniques
Precision Imaging

- Quantum sensitivity *single photon resolution*
- Picosecond *timing accuracy*
- Over 100,000 *frames per second*
- Over 5 decades of *dynamic range*

All of the above: *in massive pixel arrays!*
Applications

• Vision
  – Nightvision
  – 3D vision, HCIs
  – Security, automotive

• Engineering
  – Fluid-dynamics
  – Energy
  – Bioimaging

• Medical / Research
  – Molecular imaging
  – Functional neuro-scanning
  – Microscopy, spectroscopy
Human-Computer Interfaces
3D Vision: Biometrics & Gaming

© A3Vision
Fluid-dynamics

[Ancey/Charbon 2006]

[Fritz 2000]
Combustion Engine Dynamics

[Injection A]
320 μs
350 μs
380 μs
410 μs

[Injection B]

[Text credit: Eisenberg 2005]
Functional Neuro-scanning

[Grinvald et al., 2001]
Molecular Imaging

- Fluorescence Correlation Spectroscopy (FCS)

[Gösch, et al., 2003]
In Vivo Bioimaging

- Salivary glands of Drosophila larvae with giant chromosomes
- Two-photon fluorescence lifetime imaging (FLIM) enables avoiding to break nuclei for “2D spreading”

[Jie Yao, *Nature* 2006]
Outline

• Single Photon Detection
• Single Photon Imagers
• Some Applications
• Next Generation Systems
• Conclusions
Single Photon Detection
Silicon Avalanche Photodiodes

- **Review:**
  - Photon to electron - Secondary electron - Multiplication
  - Multiplication in depletion region by *impact ionization*
Silicon Avalanche Photodiodes

High variability of gain
From bias
Operating in Geiger Mode

- In avalanche mode:
  \[ <G> \approx 1000 \]
- In Geiger mode:
  \[ <G> \rightarrow \infty \]
  \( \rightarrow \) avalanche must be stopped
Quenching the Avalanche

Passive quenching:

- One photon $\Rightarrow$ one cycle (dead time definition)
- Thermally generated carriers $\Rightarrow$ dark counts
Other quenching techniques exist: e.g. active FB
[Cova et al., Rochas et al., etc.]
Fabrication Issues

- p- guard ring for electric field reduction in edges
- Prevention of premature edge discharge
- Creation of zone with constant electric field

Original idea proposed in the 1960s by Haitz and others
SEM Micrograph

[Niclass and Charbon, ISSCC05]
SPAD Salient Parameters

- **Dark counts**
  - Spurious pulses unrelated to photons

- **Photon detection probability (PDP)**
  - Probability of a photon triggering an avalanche

- **Timing resolution**
  - Uncertainty between photon arrival and pulse generation

- **Cross-talk**
  - Optical & electrical cross-pixel interference

- **Afterpulsing**
  - Spurious pulses related to photons

- **Dead time**
Dark Counts

Traps capture photocharges and release them randomly → avalanche is triggered → spurious pulses

Mechanisms:
- Tunneling generation
- Trap-assisted thermal generation
- Trap/tunneling assisted generation
Photon Detection Probability

- Peak: 26% @ 460nm
- 12% @ 635nm

Wavelength [nm]

Photon Detection Probability [1]

- $10^{-3}$
- $10^{-2}$
- $10^{-1}$

400 500 600 700 800 900 1000

Multiplication region

n-well

p-sub

p+
Time Resolution

115ps FWHM

Counts

Time Delay [ns]
Crosstalk

- Electrical cross-talk reduced by potential barrier
- Optical cross-talk alleviated by reduced number of carriers in avalanche

[ Niclass, Charbon et al., JSSC 2005 ]
Effects of Miniaturization

• Single photon counting can be performed on a small surface

• Reduced parasitic capacitance
  – Reduced **dead time**
  – Smaller photoemission due to avalanche, thus reduced probability of secondary avalanches
  – Reduced probability of **afterpulses** and **optical cross-talk**
Technology Migration

0.8µm CMOS

0.35µm CMOS (shallower multiplication region)

Photon Detection Probability [%]

Wavelength [nm]

0.8µm CMOS

0.35µm CMOS
Single Photon Imagers
Challenges of Large Arrays

SPADs are digital, dynamical devices, they must be treated as such in designing the sensor architecture.
Architectures

• Complexity in pixel
  – Fast (full parallelism)
  – Large pixels, small arrays
  – In general, low post-layout flexibility

• Complexity in readout
  – Small pixels, large arrays
  – Slower processing
  – More post-layout flexibility

Architectures depend on implementation
Readout Mechanisms

• Random access (sequential) readout
  – Column parallel
  – Pixel based
• Event-driven readout
• Pipelined readout
Random Access Readout

Pixel based readout (no parallelism)

Column parallel readout (limtd parallelism)
First Massive SPAD Pixel Array

Single-Photon Counters Get a Second Wind

[Niclass, Charbon, ISSCC 05]
Event-Driven Readout

- Principle
  - Column becomes a timing preserving bus
  - A pixel hit by a photon transmits its ID
  - Timing pulse travels through the bus and is measured outside array
CMOS 64x48 Pixel Array

[Niclass, Sergio, Charbon, Esscirc 06]
Digital Pixel vs. Digital Readout

- VHDL
  - Auto-routed

- Custom pixels
Pipelined Readout

- Principle
  - Column becomes a timing preserving bus
  - A pixel hit by a photon transmits the pulse in TDMA
  - Timing pulse travels through the bus and is measured outside array
CMOS 128x2 Pixel Array

Fabrication:
0.35\(\mu\)m CMOS technology
4.1 \(\times\) 1.1mm\(^2\)

[Sergio, Niclass, Charbon, ISSCC 07]
Dark Count Rate (DCR)
DCR Distribution

![Bar chart showing DCR distribution at different frequencies.](Image)
Some Applications

⇒ 3D Vision
⇒ LLL/Ultrafast cameras
⇒ Room/T chemiluminescence detection
⇒ Multi-photon fluorescence
⇒ *In situ* single-photon counting
3D Vision: Time-of-Flight

- pulsed light source
- TOF measurement
- 3D image reconstruction
- optical sensor
- target

\[ d = \left( \frac{c}{2} \right) \text{ TOF} \]
Depth Map Example

- Lateral resolution:
  - 64x64 pixels
- Depth resolution:
  - 1.3mm (wc)
- Range:
  - 3.75m

Example: face recognition
© A3vision

[Niclass and Charbon, ISSCC 2005]
High Speed

Features

– No measurable thermal noise (Poisson noise dominates)
– No measurable cross-talk, blooming, smearing

[4μs 10μs 25μs 100μs 1ms]

[Niclass, Rochas, Besse, Popovic, and Charbon, Transducers 2005]
Chemiluminescence Reactor

[Chemiluminescence Diagram]

Peroxidase-Linxed Secondary Antibody (Anti-Mouse IgG)

ECL Plus Western Blotting Detection Reagents

Chemiluminescence

Pump

Outlet

Inlet

Ink

Water

Laminar flow

[Gersbach, Maruyama, Sawada, Charbon, μTAS'06]
Calcium Signaling / Patch Clamp

- Monitor ion channels in sensory cortex
- Stimulation via patch clamp

[Nagasawa et al., Transducers 2005]
Confocal FLIM Optical Setup

Mode-locked Ti:Sapphire Laser (740~920nm)

Dichroic Beam Splitter

Attenuator

Filter (λ=488nm)

Detector

TDC

Fluorescent sample On x/y table

Histogram processing
Integrated Two-Photon FLIM

Ca²⁺ Concentration

- X Wavelength: 800nm
- Response: 400~430nm
- Rep. Rate: 80MHz
- Output Freq.: 19kHz
- Avg. power output: 0.5W
- Eff. Avg. power: 35mW

Fluorophore: Oregon Green Bapta-1

[Fluorophore: Oregon Green Bapta-1]

[Fluorophore: Oregon Green Bapta-1]

[Gersbach, Charbon, et al., CLEO-Europe, 2007]
New Results

• Thanks to an IRF FWHM of 79ps, we observed a triple-exponential fit for OGB-1 as predicted by Wilms
• Increased dynamic range of Ca$^{2+}$ Signaling
New Results (Cont.)

7 decades for Ca^{2+} concentration detection

** [Wilms 2006]
* [Agronskaia 2004]
EPFL Single Photon Sensor Family

World’s largest CMOS single photon sensor
Deep Submicron Detectors

[Image of a microchip with a scale bar of 3µm]

CMOS 130nm

[Niclass, Gersbach, Henderson, Grant, and Charbon, JSTQE’07]
Conclusions

- Picosecond time resolution (1~100 ps)
- High number of pixels (64x64 ~ 1M pixels)
- High frame rates (1 Mfps in continuous mode)
- High intensity saturation levels (10x improvement)
- High sensitivity (single photon)
- Low power
The AQUA Group was started in June 2003. It is funded by the Swiss National Science Foundation, the European Commission, and the European Space Agency.
http://aqua.epfl.ch/