(Challenges in) Time Correlated Single Photon Counting Imagers

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SIGNAL 2016
June 26 - 30, 2016 - Lisbon, Portugal
Outline

1. *(Time Correlated) Single-photon Counting & Single-photon Imaging*
2. SPAD basics & SPAD imagers
3. Key SPAD Parameters, pros/cons
4. SPAD Sensor Architectures
   1. Applications & related challenges
   2. Signal processing implications, HW vs FW vs SW, embedded aspects, data management
5. Roadmap
1. (Time Correlated) Photon Counting & Single-Photon Imaging
(Time correlated)
Photon Counting Camera

*Simple definition*: A camera where every pixel delivers a photon count and/or timestamp

(emphasis on CMOS developments over other time-resolved approaches, e.g. MCP-PMT, ICCD, scanning systems, ...)

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Areas of application

- Quantum Security
- 3D Vision
- Near Infrared Imaging (NIRI)
- Fluorescence Lifetime Imaging Microscopy (FLIM) and super-resolution microscopy (STED, STORM, GSDIM, PALM, etc.)
- Time-of-Flight Positron Emission Tomography (TOF PET)
- Time-resolved Raman Spectroscopy
Potentially:

single-photon granularity

-» photon-counting imaging

picosecond granularity

-» time-resolved imaging

(CMOS) low-cost, with on-chip processing capabilities
Main Challenge:
Pixel → Imager → System → «Image»
2. SPAD Basics & SPAD Imagers

(SPAD: Single-Photon Avalanche Diode)
SPAD imager overview

Advantages:
- Early digitalization
- Very fast
- No readout noise

Disadvantages:
- Lower fill factor
- Lower sensitivity

Fill factor = \frac{\text{active area}}{\text{pixel area}}

I.M. Antolovic, FOM 2015

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Avalanche photodiode (APD)

• Suppose one can perform **impact ionization** in a solid, thereby achieving **very large gain** in an area of a **few tens of μm²** (thus at pixel level)

• This can be achieved in an abrupt one-sided junction
One can achieve a virtually infinite gain biasing above breakdown...

Thus gain variability is meaningless

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Quenching

Passive quenching:

Operation cycle:

$$V_{bd}$$

$$V_{op}$$

$$V_{op}$$

$$R_q$$

$$I_A$$

photon arrival

DEAD TIME

SPAD recharge

avalanche quenching

Dead time
Quenching (and gating) a SPAD in CMOS

• The SPAD becomes like any other digital device but it is triggered by a photon!

• With two more switches one can gate sensitivity
3. Key SPAD Parameters
Characterizing SPADs for imaging

- **Dead time** (10-100ns)
- **Dark counts** (Hz-kHz)
- **Sensitivity**
  - Photon Detection Probability (PDP) (1-50%)
  - Fill-factor (1-50%)
- **Timing resolution** (~10-100ps)
- **Afterpulsing** (0.1-10%)
Sensitivity: Photon Detection Efficiency (PDE)

C. Veerappan and E. Charbon, JSTQE 2014
Dark Counts: Dark Count Rate (DCR)

- State-of-the-art SPADs in dedicated technology:
  0.04~1Hz/μm²
- State-of-the-art CMOS SPADs:
  0.1~10Hz/μm²

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DCR vs. Applications

Random Number Generators

Nuclear Medicine

Molecular Imaging – microscopy

LIDARs

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Timing resolution

FWHM = 93ps

Red Enhanced SPAD
- 50µm diameter
- 20V overvoltage
- 780nm wavelength
- Unfocused light

Counts per Channel

Time (s)

10^5
10^4
10^3
10^2
0
0.5
1
1.5
2
2.5
3
3.5
4

x 10^{-9}

Diffusion Tail

Courtesy: Sergio Cova

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Crosstalk

- Optical and electrical interference
- Measured by avalanche cross-inter-arrival
- Similar to afterpulsing acting between pixels
Take-Home Message – Uniformity:

Uniformity of sensitivity
Uniformity of noise
Uniformity of xtalk, afterpulsing (~0)
Take-Home Message – Tradeoffs:

- PDE vs. DCR
- Wavelength vs. Timing
- Dead Time vs. Dynamic Range
...For imaging...

Uniformity, Uniformity, Uniformity, Uniformity
4. SPAD Sensor Architectures & Applications
Generic pixel

COUNTING

QUENCHING CIRCUIT

GATING CIRCUIT

TDC

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4.1 MEGAFRAME – 32×32 & 128×160 Fully Integrated TCSPC Matrix
2D array

Fully parallel

Column-Parallel

3D Integration

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MEGAFRAME: Massive Integration in DSM

I/O pads

Serializer

32x16 Array

32x16 Array

Serializer

SPAD → TDC

Controls → Register

Principle of TDC

PLL clock

START

Fine interpolator

STOP

Coarse interpolator

Implemented on 130nm CMOS

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MEGAFRAME
Pixel Layout

Over 500 transistors
In 50 x 50 µm²

Pitch: 50um
Max. Resolution: 119ps
Bandwidth: 1MS/s
Accuracy: 1.2LSB (INL)
Timing jitter: 128ps (FWHM)
Timing uniformity: < 2LSB

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The MTEGRAME128 Chip

50um pitch

160x128 pixel Array

I/O Serializer

12.3mm

11.0mm

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MEGAFRAME Summary

- Format: 160x128 pixels
- Timing resolution: 55ps
- Impulse resp. fun.: 140ps
- DCR (median): 50Hz
- R/O speed: 250kfps
- Size: 11.0 x 12.3 mm²
4.1 MEGAFRAME - Applications
Fluorescence Intensity vs Lifetime Images

- Intensity images: the pixel measures the intensity in the gated window: $f(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2) + \ldots$

- Lifetime images: the pixel time-tags all photons and calculates parameters $\tau_1$, $\tau_2$, $A_1$, $A_2$, etc.

$\text{Gated camera}$

$\text{TCSPC}$

$I(t) \propto \int_w f(t) \, dt$, $f(t)$ is the fluorescence density.

Courtesy David Li, Strathclyde Univ., 2016
Video-rate FLIM (> 100fps)

Li et al., 2011, 2012
Arlt et al., 2013

Fast FLIM:

\[ \tau = \frac{\sum_{i=1}^{N_C} t_i}{N_C}, N_C = \sum_{j=1}^{M} N_j \]

Raw TCSPC data: 640Mb/s
FLIM data: 20Mb/s, No FLIM software.
4.2 SwissSPAD - 512×128 single-bit time-gated matrix
SwissSPAD

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak PDE</td>
<td>~20% at 450 nm</td>
</tr>
<tr>
<td>Min. frame time</td>
<td>6.4 μs, 512×128 pixels, 1 bit</td>
</tr>
<tr>
<td>Readout noise</td>
<td>0 counts</td>
</tr>
<tr>
<td>Dark counts</td>
<td>~200 cps at 25 °C</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>24 μm</td>
</tr>
<tr>
<td>Imager size</td>
<td>12.3×3.1 mm²</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Afterpulsing</td>
<td>&lt;0.3%</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>&lt;0.3%</td>
</tr>
<tr>
<td>PRNU</td>
<td>&lt;1.8%</td>
</tr>
</tbody>
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SwissSPAD Gate accuracy and uniformity

- 4ns gating (138ps FWHM)
- 156kfps frame rate
4.2 SwissSPAD - Applications
SwissSPAD Frame rate vs. data rate

156kfps, 1 bit
39kfps, 2 bit
10kfps, 4 bit
600fps, 8 bit
152fps, 16 bit

Frames per second and datarate depending on bits per pixel

Burri et al., Optics Express 2014

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Slice of plant root stained with a mixture of dyes

Intensity per area ratio is found to be **12%**

I.M. Antolovic et al., *Sensors*, 2016
SwissSPAD: Superresolution

• First super resolution images with a SPAD imager – 30 nm localization uncertainty, 100 nm resolution
• SPAD imagers don’t change their performance when changing the frame rate 1 bit frame time of 6.4 μs
• Optimal frame time depends on the blinking parameter, emission and background intensity
• On and off lifetimes could be used for fluorophore separation – multichannel imaging
SwissSPAD FLIM

532nm, 8ps pulse, 68MHz

<table>
<thead>
<tr>
<th>Fluorophore</th>
<th>Fit (ns)</th>
<th>Reference (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodamine 6G</td>
<td>3.8</td>
<td>4.08</td>
</tr>
<tr>
<td>CY3B</td>
<td>2.4-2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Alexa Fluor 546</td>
<td>4.2-4.4</td>
<td>4.1</td>
</tr>
<tr>
<td>QD 625</td>
<td>12.7</td>
<td>N/A</td>
</tr>
</tbody>
</table>

IRF convoluted with fluorescence decay

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4.3 LinoSPAD – 256×1 Linear Reconfigurable Array

(SPAD array & FPGA-based TCSPC)
The LinoSPAD Project: Reconfigurable Pixel

• Only SPAD integrated, fully parallel TDC array
• TDCs can use the best technology (e.g. 28nm)
• Medium fill factor (43%)
• Resolution on-demand (e.g. 9ps)
• Readout on-demand

FPGA (Xilinx Spartan or Virtex architecture)
4.4 SPADnet – 16x8 (x720) event-driven for Positron Emission Tomography (PET)
PET Imaging Background

- MRI/CT:
  - Provide *structural* information

- PET:
  - Provides *functional* information
  - Patient administered with radiotracer
  - Areas of high metabolic activity visible: applications in oncology & neurology etc.

- Goal:
  - Enabler for multi-modal imaging

R. Walker, IISW 2013
SPADnet photonic module
Sensor networks enables distributed parallel processing realizing a flexible and a scalable data acquisition system for multi-ring based PET systems.

DPCU: Data Processing and Communication Unit
DPU : Data Processing Unit
CU : Communication Unit

C. Veerappan, RTS 2014
5. Roadmap
Acknowledgements

- AQUA groups in NL (cas.et.tudelft.nl) and CH (aqua.epfl.ch), Swiss National Science Foundation, NCCR-MICS (CH), STW (NL)
- European Space Agency
- European: FP6 (MEGAFRAME-www.megaframe.eu) and FP7 (SPADnet-www.spadnet.eu) & respective partners
- Robert Henderson (University of Edinburgh)
- David Li (Strathclyde University)
- Jörg Langowski (DKFZ Heidelberg)
- Paulien Stegehuis, Jouke Dijkstra, Boudewijn Lelieveldt (Leiden University Medical Centre - LUMC)
- Fastree3D SA (CH)
- Many, many others…