MONOLITHIC ARRAY OF 32 SPAD PIXELS FOR SINGLE-PHOTON IMAGING AT HIGH FRAME-RATES

Simone Tisa, Fabrizio Guerrieri and Franco Zappa
Politecnico di Milano

New Developments In Photodetection 2008, Aix-les-Bains (France), June 2008
APPLICATIONS
DEMANDING ARRAYS APPLICATIONS REQUIRE

Very high sensitivity (single-photon level)

AND

High frame-rate
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Very high sensitivity (single-photon level)

AND

High frame-rate
STANDARD IMAGERS: CCDs

- High EQ (about 90%)
- High Fill-Factor (about 90% if back-illuminated)
- CCDs can be very sensitive (EM-CCDs sense single photons)
- Slow
STANDARD IMAGERS: CMOS APS

- Reduced Fill-Factor (30-40%)
- High Frame-Rate
- Low sensitivity (they are limited by electronics noise)
SPAD
Single-Photon Avalanche Diode
**WHAT’S A SPAD?**

**Avalanche PhotoDiode**
- Bias: slightly **BELOW** breakdown
- Linear-mode: it’s an **AMPLIFIER**
- Gain: limited < 1000

**Single-Photon Avalanche Diode**
- Bias: well **ABOVE** breakdown
- Geiger-mode: it’s a **TRIGGER** device!!
- Gain: meaningless... or “infinite”!!
Custom SPAD

- Big diameter (up to 100µm)
- Low DCR
- Low Afterpulsing
- Good PDE
- Excellent timing resolution
- Not suitable to be integrated in arrays
CMOS SPAD

- Diameters up to 50µm
- Moderate DCR
- High afterpulsing (it can be reduced integrating the quenching electronics)
- Good PDE
- Very good timing resolution
- Suitable to be integrated in “smart pixels” of complex arrays
SPAD ARRAYS
The SPADA array

- 60 pixels
- 4 custom SPADs with different diameters for every pixel

Many bonding pads and routing wires:
- Very difficult to increase pixels number
- High parasitics: higher afterpulsing
Other arrays

- Low number of pixels
- Shared electronics
- Event-driven...
ARRAY of CMOS SPAD

- SPAD
- Quenching circuit
- Post-processing logic
- Array managing electronics
REQs for QUENCHING CIRCUITS

1. Reduced dimensions → PQC
2. hold-off, short dead time, linearity... → AQ.
3. Reduced avalanche charge → PQC o hybrid

NO ONE FULFILLS ALL REQs

NEW QUENCHING CIRCUIT REQUIRED
VLQC: Variable-Load Quenching Circuit

1. Low number of transistors
2. Two MOS connected to the SPAD
3. Customizable hold-off time
**PIXEL architecture**

- **SPAD CMOS (20µm)**
- **VLQC**
- **Ancillary electronics**
- **Global signals**
- **Counter**
- **Latch**
- **8 Bit counter**
- **Integrated quenching circuit**
- **Internal buffer memory**
- **Bitlines**
#1: Photon absorption and SPAD quenching
#2: Count increase
#3: SPAD reset
#4: Frame STOP
#5: Frame START
ARRAY: Operation
ARRAY: Operation

Frame STOP (latch phase)
ARRAY: Operation

New Frame START (reset phase)
ARRAY: Operation

Array readout
ARRAY LAYOUT

3,64mm

843μm

100μm
EXPERIMENTAL RESULTS
AFTERPULSING

![Graph showing the relationship between Total Afterpulsing Probability and Dead Time for different overvoltages. The graph includes data for 6V, 5V, 4V, and 3V overvoltages.]
DARK-COUNTING RATE

Dead-time = 600ns

@RT 75% of pixels have DCR < 4 kcps thus we have single-photon sensitivity for frame-rate > 4 kframe/s
CROSSTALK

<table>
<thead>
<tr>
<th>Distance</th>
<th>Cross-talk Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>100µm</td>
<td>3.53 x 10^{-5}</td>
</tr>
<tr>
<td>200µm</td>
<td>4.33 x 10^{-6}</td>
</tr>
<tr>
<td>300µm</td>
<td>2.86 x 10^{-5}</td>
</tr>
<tr>
<td>400µm</td>
<td>7.15 x 10^{-7}</td>
</tr>
</tbody>
</table>

Crosstalk is much lower than those reported for other SPAD arrays, even at shorter distances.
TIMING RESOLUTION

Black: high counting-rates (1Mcps)

Blue: low counting-rates (5kcps)

FWHM=55ps

5V excess bias

FWM/100=550ps
CONCLUSIONS & PERSPECTIVES

- We design and fabricated a column of 32x1 smart pixels.
- Pixels comprise a SPAD front-end and counting electronics.
- Pixels work completely in parallel.
- Remarkable performances in photon-counting and photon-timing.
- Suitable for low-light-level and high frame-rate applications
- We are working on bidimensional arrays
THANK YOU FOR YOUR ATTENTION

Fabrizio Guerrieri
fabrizio.guerrieri@mail.polimi.it
ARRAY: Performances

Using a 100MHz clock frequency the maximum frame-rate is 98kframe/s
VLQC - Afterpulsing vs Hold-Off

Charbon 2006
SPAD 10µm
PQC
\( V_{EX} = 4V \)

\[ P_{AP} = 7\% \ @ \ T_{HO} = 150\text{ns} \]
\[ P_{AP} = 1\% \ @ \ T_{HO} = 500\text{ns} \]
Stoppa 2006
SPAD 20µm
AQC
$V_{EX} = 4V$

Dead time:
- 150ns
- 500ns
- 1us
- 8us

$P_{AP} = 67\%$
$P_{AP} = 17\%$

VLQC - Afterpulsing vs Hold-Off
PQC - Passive Quenching Circuit

Quenching is performed by a resistor in series with the SPAD.

Avalanche current generates a voltage across the resistor that quenches the avalanche
PQC - Passive Quenching Circuit

\[ I_{\text{SPAD}} \]

\[ V_{\text{EX}}/R_L \]

100\,\mu A

\[ t \]

\[ V_{\text{A}} \]

\[ V_{\text{EX}} \]

\[ T_{\text{RESET}} \]

FAST QUENCHING
PQC - Passive Quenching Circuit

\[ I_{\text{SPAD}} \quad \text{photons} \]

\[ V_{\text{EX}}/R_L \]

100\,\mu\text{A}

\[ t \]

\[ V_A \]

\[ V_{\text{EX}} \]

SLOW RESSET

\[ T_{\text{RESET}} \]
PQC - Disadvantages

With high light intensities:

1. The electronics doesn’t detect all avalanches

2. Avalanches are triggered in non-nominal conditions: since many are the SPAD parameters that depend on the bias voltage non-linearities are introduced.

3. Non monotonous relationship between the number of counts and the number of avalanches

High-afterpulsing even at low photon-rates
PQC - Disadvantages

LOW PHOTON-RATE

MODERATE PHOTON-RATE

HIGH PHOTON-RATE

\[ C_{\text{COUNT RATE}} \]

\[ P_{\text{PHOTON RATE}} \]
AQC - Active Quenching Circuit

1. Avalanche length defined by the electronics
2. Adjustable hold-off time
3. Fast quenching and reset.