A $512 \times 512$ SPAD Image Sensor with Built-In Gating for Phasor Based Real-Time siFLIM

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Objectives of This Work

• Time-resolved SPAD image sensor with
  – Large pixel array (512×512)
  – Time gating
    (5 ns min. gate length, 10 ps gate step)
  – High frame rate (195 kfps)
  – Low noise (< 0.1 Hz/µm²)
  – User friendly

• Target Applications
  – High resolution, widefield FLIM
  – Real time FLIM-FRET analysis
  – siFLIM
  – Localization based super-resolution microscopy
  – 3D time-of-flight imaging
Device Architecture

1- Sensor architecture

- Row decoder (256x)
- Row address register (256x)

- 512×256 SPAD pixels

- Output pads (128x)
- Output 4:1 multiplexer (128x)
- Output register (512x)
- Column pullup (512x)
- Balanced gating signal trees (3x)

2- Sensor micrograph

- 512 x 512 Pixel Array
- Balanced signal trees (3x), Column Pullup, Output Register / Multiplexer
- Row Address Register, Row Decoder, Reset Generator

Dimensions:
- 9.6 mm x 9.5 mm
- 16.38 μm x 16.38 μm
- 6 μm
Pixel Architecture

Pixel Features:
- Passive quenching
- Cascode transistor: Excess bias up to 6.6 V
  Higher PDP
- Active recharge
- Time gating
- 1-bit DRAM
- Memory reset
- Row selection
Pixel Operation

Avalanche
Gate
Memory
Readout
Reset
Out
1- SPAD cross section

2- Photon detection probability (PDP)

3- Dark count rate (DCR)

Active Area: 113.1 μm²
## Performance Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Pixels</td>
<td>512×512</td>
</tr>
<tr>
<td>Process</td>
<td>0.18 µm CMOS</td>
</tr>
<tr>
<td>Chip Size</td>
<td>9.5×9.6 mm</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>16.38 µm</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>10.5%</td>
</tr>
<tr>
<td>Max. Frame Rate (1 bit)</td>
<td>97.7 kfps</td>
</tr>
<tr>
<td>Max. PDP</td>
<td>55% (V\textsubscript{ex} = 11 V, \lambda = 520 nm)</td>
</tr>
<tr>
<td>Dark Count Rate</td>
<td>0.18 Hz/µm² (V\textsubscript{ex} = 3 V)</td>
</tr>
<tr>
<td></td>
<td>1.67 Hz/µm² (V\textsubscript{ex} = 11 V)</td>
</tr>
<tr>
<td>Gate Jitter</td>
<td>110 ps</td>
</tr>
</tbody>
</table>
Conclusions

<table>
<thead>
<tr>
<th></th>
<th>Burri et al.</th>
<th>Dutton et al.</th>
<th>Gasparini et al.</th>
<th>Perenzoni et al.</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>0.35 µm</td>
<td>0.13 µm</td>
<td>0.35 µm</td>
<td>0.35 µm</td>
<td>0.18 µm</td>
</tr>
<tr>
<td>Array Size</td>
<td>512×128</td>
<td>320×240</td>
<td>100×100</td>
<td>160×120</td>
<td>512×512</td>
</tr>
<tr>
<td>Transistors Per Pixel</td>
<td>12</td>
<td>9</td>
<td>7 + 1 METALCAP</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>24 µm</td>
<td>8 µm</td>
<td>25 µm</td>
<td>15 µm</td>
<td>16.38 µm</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>5%</td>
<td>26.8%</td>
<td>22%</td>
<td>21%</td>
<td>10.5%</td>
</tr>
</tbody>
</table>

- Largest SPAD imager to date (to the best of our knowledge)
- The first array of p-i-n SPADs, which have exceptionally low noise, wide spectrum, and high PDP
- Novel quenching based on cascode transistor for higher-than-technology-allowed excess bias voltage
- The largest continuous frame rate in a SPAD camera to date
Fluorescence lifetime contains a wealth of information regarding e.g. neural activity, metabolism at the sub-cellular level.

1 - Jablonski diagram showing the electronic states and transitions in a molecule

2 - Fluorescence emission decay
Time Gated FLIM

\[ g = \cos(2\pi ft_j) \quad s = \sin(2\pi ft_j) \]

\[ g_{avg} = \frac{1}{N} \sum_{i=1}^{N} g_i \quad s_{avg} = \frac{1}{N} \sum_{i=1}^{N} s_i \]

\[ g_{avg} = \frac{1}{1 + (2\pi f \tau)^2} \quad s_{avg} = \frac{2\pi f \tau}{1 + (2\pi f \tau)^2} \]

g, s: phasor coordinates

T_j: ToA of the bin number j

N: total photon count

\( f(t) = A \exp(-t/\tau) \)

\( t_{j+1} - t_j = h \)

N_j: photon count of gate number j

GL: gate length

N_0, N_1, N_2, N_{M-1}

t_0, t_1, t_2, t_{M-1}

Non-overlapping gates

Overlapping gates
Future Work

- Gate sensitivity test
- Minimum gate length measurement
- Adding microlenses
- Characterization of square SPAD (13% fill factor)
- Implementation of phasor based time gated FLIM
- Demonstrations in target applications
- Investigation of suitability for additional potential applications, such as quanta image sensors (QIS)
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