Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications

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Canon Inc.
Kazuhiro Morimoto
Outline

- Background & Motivation
- Proposal & Simulation
- Experimental Results
- Summary & Future Perspectives
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Scaling of SPAD Arrays

- 2003: 8x4
- 2006: 112x4
- 2009: 32x32
- 2012: 128x128
- 2015: 160x128
- 2020: 512x512
- 2025: 1024x1000
- 2030: 1024x1000

- 3D IC SPAD
- 1Mpixel SPAD

- Pixel sizes: 32x32, 64x48, 128x128, 256x256, 512x512, 1024x1024
- CMOS technologies: 0.35µm, 0.8µm, 90nm, 130nm, 180nm, 40nm
- Timeline: 2003 to 2030
Frontside-illuminated (FSI) SPAD Pixels

SPAD and pixel circuit share a limited pixel area

Megaframe (2009)
- 32 × 32 pixels
- Pixel pitch = 50 µm
- Fill factor = 1.2%
- 580 Transistors / pix

J. Richardson et al., CICC (2009),
M. Gersbach et al., ESSCIRC (2009),
D. Stoppa et al., ESSCIRC (2009)
Technology Trend: 3D Stacking

Academy and industry are striving for BSI 3D-stacked SPAD arrays


SPAD Pixel Miniaturization

Benefits:
• Compact system, reduced cost
• High spatial resolution
• High dynamic range
• Low DCR, afterpulsing, timing jitter
• Low power consumption

Challenges:
• Limited fill factor
• Limited PDP, PDE
• High crosstalk
Challenge in SPAD Pixel Miniaturization

Pixel miniaturization degrades fill factor (FF)

Pixel pitch = $D_a + L$

Unscalable!

FF = 33%

FF = 18%

FF = 7%

Multiplication
region

Insensitive
region
Challenge in SPAD Pixel Miniaturization

Pixel miniaturization degrades fill factor (FF)

Theoretical fill factor (%) vs. Pixel pitch (μm)
Well Sharing

Sharing isolation well to enhance FF

N. A. W. Dutton et al., TED, 63(1) (2016)

M. Perenzoni et al., Sensors, 16(5), 745 (2016)
Guard-Ring (GR) Sharing

Eliminating isolation well and sharing GR to achieve 2.2 \( \mu \text{m} \)-pitch pixel

K. Morimoto et al., Opt. Express, 28(9), 13068 (2020)
"Sharing" improves FF, but still far from ideal trend
On-Chip Microlens (EPFL / USZ)

Optically focusing light to virtually enhance the active area

- **Advantage**
  - Enhanced effective fill factor (>10 × )

- **Issues**
  - Less effective for too small active area; small f-number lenses; tilted light

J. M. Pavia et al., Opt. Express 22(4) (2014)
Current-Assisted SPAD (Vrije Universiteit Brussel)

Photocharges focused to multiplication region assisted by current biasing

- **Advantage**
  - Large photo-conversion volume (potentially higher PDE)

- **Issues**
  - Constant current (>10 µA/pix)
  - Large DCR (>1 Mcps/pix)
  - Not scalable (currently 40 µm-pitch)

G. Jegannathan et al., Appl. Sci. 10(6), 2155 (2020)
Objective

To propose and verify next-gen. SPAD concept to achieve:

- Scalability (pixel pitch ≤ 6 µm)
- High FF (up to 100%)
- Low noise (DCR, afterpulsing, crosstalk)
- Flexible choice of optics
Conventional SPAD Devices

- Only vertical photo-charge collection
- Multiplication area = Photo-sensitive area
- Trade-off between DCR and PDE
Proposal of Charge-Focusing SPAD

- Conventional SPADs
  - Only vertical photo-charge collection
  - Multiplication area = Photo-sensitive area
  - Trade-off between DCR and PDE

- Charge-Focusing SPAD
  - Vertical + horizontal photo-charge collection
  - Multiplication area << Photo-sensitive area
  - Low DCR & high PDE
Advantages of Our Technology

1. High PDE for miniaturized pixel array

- Conventional SPAD

- Poor fill factor & PDP for small pixels

- Charge-Focusing SPAD

- Near-100% fill factor for small pixels
Advantages of Our Technology

1. High PDE for miniaturized pixel array

![Theoretical fill factor vs. pixel pitch graph](image)

- Charge-focusing
- GR sharing
- Well sharing
- No sharing

![Diagram showing theoretical fill factor (%) vs. pixel pitch (µm)](image)
Advantages of Our Technology

2. Miniaturized multiplication area
   - Low DCR (DCR density*<0.02 cps/μm²)
   - Low hot pixel population (<1%)

3. Extended photo-sensitive area
   - High PDP (>60% for visible light)
   - High fill factor (Near-100%)

4. Small p-n junction capacitance
   - Low afterpulsing probability
   - Low light emission crosstalk
   - Low power consumption
   - Short dead time

*Room temperature DCR per unit photo-sensitive area
Proof-of-Concept SPAD Image Sensor

- 180 nm CMOS (FSI)
- 16-bit digital output
SPAD Pixel Design

Electrostatic potential sim.  Electric field sim.

Cross-sectional SEM image

Color Filter

Single SPAD
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Dark Count Rate (DCR)

Hot pixel population < 1%, DCR = 3 cps, DCR density = 0.015 cps/µm² (at RT)

**Hot pixel population**

- Conventional SPAD
- Charge-focusing SPAD

**T dependence of median DCR**

- Sensitive area = 200.96 µm²
- $V_{ex} = 2.5$ V
- $E_a = 1$ eV
- $T = 60°C$
Input referred noise = 0.16 e^{-\text{rms}} at video frame rate

Exposure time dependence

\[ V_{\text{ex}} = 2.5 \text{ V, Room temp.} \]

Temperature dependence

\[ V_{\text{ex}} = 2.5 \text{ V, Exposure = 1/120 s} \]

Single photon level

0.16 e^{-\text{rms}}

1/120 s
**PDP and Sensitivity**

Max. PDP=40%, no sensitivity degradation up to 6 µm pixel

### Wavelength dependence

![Wavelength dependence graph](image)

- Photon detection probability (%) vs. Wavelength (nm)
- \( V_{ex} = 2.5 \text{ V} \)

### Pixel pitch dependence

![Pixel pitch dependence graph](image)

- Normalized sensitivity (a.u.) vs. Pixel pitch (µm)
- 2850K lamp
- Charge-focusing SPAD
- Conventional SPAD
Rolling / Global Shutter Imaging

Operation confirmed in rolling and global shutter modes

Rolling shutter mode

Global shutter mode
Photon-Counting RGB Imaging

Single-photon-sensitive color imaging is demonstrated

RGB Color SPAD

Temporal noise
= 0.16 $e^{-}_{\text{rms}}$

CMOS imager

Temporal noise
= 2.1 $e^{-}_{\text{rms}}$

Highlight

Signal = 1 photon

Signal = 0.5 photon
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<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>SPAD</td>
<td>SPAD</td>
<td>VAPD</td>
<td>CMOS</td>
<td>CMOS</td>
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<tr>
<td><strong>Process technology</strong></td>
<td>180 nm FSI</td>
<td>180 nm FSI</td>
<td>65 nm FSI</td>
<td>45/60 nm BSI</td>
<td>110 nm FSI</td>
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<td><strong>Pixel pitch (µm)</strong></td>
<td>84</td>
<td>16.38</td>
<td>6.0</td>
<td>1.1</td>
<td>11.2×5.6</td>
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<tr>
<td><strong>Pixel array size (H×V)</strong></td>
<td>128×128</td>
<td>512×512</td>
<td>400×400</td>
<td>1024×1024</td>
<td>312×512</td>
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<td><strong>Pixel output (bit)</strong></td>
<td>16</td>
<td>1</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td><strong>Operation voltage (V)</strong></td>
<td>3.3/-26.5</td>
<td>-</td>
<td>3.3/-29</td>
<td>-</td>
<td>3/25</td>
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<tr>
<td><strong>Photodiode area (µm²)</strong></td>
<td>200.96</td>
<td>28.2</td>
<td>25.2</td>
<td>1.21</td>
<td>-</td>
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<tr>
<td><strong>Max. PDP (%)</strong></td>
<td>40</td>
<td>50</td>
<td>-</td>
<td>80</td>
<td>-</td>
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<tr>
<td><em><em>DCR density</em> (cps/µm²)</em>*</td>
<td><strong>0.015</strong></td>
<td>0.26</td>
<td>2.77</td>
<td>&lt;0.16</td>
<td>-</td>
</tr>
<tr>
<td><em><em>Temporal noise</em> (e⁻ rms)</em>*</td>
<td><strong>0.16</strong></td>
<td>-</td>
<td>-</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>DSNU (e⁻ rms)</strong></td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>PRNU (%)</strong></td>
<td>1.7</td>
<td>-</td>
<td>-</td>
<td>&gt;2.6</td>
<td>-</td>
</tr>
<tr>
<td><strong>Electronic shutter</strong></td>
<td><strong>GS/RS</strong></td>
<td>GS/RS</td>
<td>RS</td>
<td>RS</td>
<td>RS</td>
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<tr>
<td><strong>On-chip color filter</strong></td>
<td><strong>w/</strong></td>
<td>w/o</td>
<td>w/o</td>
<td>w/o</td>
<td>w/o</td>
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*At room temperature
Summary

We proposed next-gen. SPAD concept to achieve:

• Scalability (pixel pitch ≤ 6 µm)
• High FF (up to 100%)
• Low noise (DCR, afterpulsing, crosstalk)
• Flexible choice of optics

Proof-of-concept SPAD sensor demonstrated:

• DCR density = 0.015 cps/µm² (lowest ever reported)
• Temporal noise = 0.16 e⁻rms (at 120 fps)
• Max. PDP = 40% (up to 6 µm)
• Single-photon-sensitive RS/GS and RGB color imaging
3D-BSI Charge-Focusing SPAD Array

Light

Top-tier (SPAD-only)

Bottom-tier (circuit-only)

Pixel Circuit

Pixel Circuit

Pixel Circuit
## Target Specifications

<table>
<thead>
<tr>
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<th>This work (FSI)</th>
<th>Target Specs (BSI)</th>
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<td>3D-BSI</td>
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<td>84</td>
<td>≤ 7</td>
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<tr>
<td><strong>Pixel array size (H×V)</strong></td>
<td>128×128</td>
<td>≥ 1Mpix</td>
</tr>
<tr>
<td><strong>Pixel output (bit)</strong></td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td><strong>Operation voltage (V)</strong></td>
<td>3.3/-26.5</td>
<td>3.3/-26.5</td>
</tr>
<tr>
<td><strong>Photodiode area (µm²)</strong></td>
<td>200.96</td>
<td>≤ 50</td>
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<tr>
<td><strong>Max. PDP (%)</strong></td>
<td>40</td>
<td>≥ 70</td>
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<tr>
<td><strong>DCR density (cps/µm²)</strong></td>
<td>0.015</td>
<td>0.015</td>
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<tr>
<td><strong>Temporal noise (e⁻rms)</strong></td>
<td>0.16</td>
<td>≤ 0.08</td>
</tr>
<tr>
<td><strong>DSNU (e⁻rms)</strong></td>
<td>0.2</td>
<td>&lt; 0.2</td>
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<td><strong>PRNU (%)</strong></td>
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### Broad spectrum for wider apps

- **RGB Imaging**
- **PET**
- **FLIM**
- **ToF / LiDAR**

![Graph showing PDE vs. Wavelength](image)

- 3D-BSI (Estimated)
  - ≥ 70% (550nm)
  - ≥ 55% (425nm)
  - ≥ 25% (850nm)
  - ≥ 10% (940nm)

- FSI (Measured)
- IEDM’16
- JSSC’19
Supplementary Materials
Electrical Microlens (TU Delft)

Using lateral avalanche propagation to virtually enhance the active area

- **Advantage**
  - Electrically tunable active area

- **Issues**
  - Large DCR (>0.1 Mcps/pix)
  - FF still limited by guard-ring / isolation

C. Veerappan *et al.*, IISW2013 (2013)