Recent developments with CMOS SSPM photodetectors

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CMOS highlights

- SSPM in Commercial CMOS provides:
  - Process control
  - Lower cost <1€ / mm² (eng. run)
  - Libraries for component integration

- Target Application: Scintillator readout
  - Fill Factor (FF) maximization
  - Back illumination of thinned die
  - Position sensitivity in SSPM arrays
Fill Factor FX

- Prototype array with varying pixel size and spacing

<table>
<thead>
<tr>
<th>Q</th>
<th>FF</th>
<th>Pixel Size (μm)</th>
<th># of Pixels</th>
<th>Pixel C (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>49%</td>
<td>30x30</td>
<td>961</td>
<td>0.13</td>
</tr>
<tr>
<td>Q2</td>
<td>61%</td>
<td>50x50</td>
<td>441</td>
<td>0.27</td>
</tr>
<tr>
<td>Q3</td>
<td>43%</td>
<td>50x50</td>
<td>324</td>
<td>0.33</td>
</tr>
<tr>
<td>Q4</td>
<td>29%</td>
<td>30x30</td>
<td>576</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Study increased fill factor effects:
- QE/DE
- Dark noise
- Cross talk
- Afterpulsing

DE = 0.021 * (Vx)
Fill Factor FX: dark counts

- Dark counts
  ~1Hz / V / \mu m^2
- Simulated increased dark counts with a CW LED bank.
Fill Factor FX: Cross talk

- Ratio of 1 to 2 p.e. rates for XTM
- XT Scales with pixel size, inversely with pixel spacing
- Increases with excess bias
- Small excess noise?
Resolution vs. quadrant

- $^{137}$Cs resolution: LYSO on 1.5 mm SSPM
- $\sim$11% energy resolution
- Illumination with 1.5 mm² LYSO and $^{241}$Am
- XT does not outweigh FF
- Constant Vx (est.)
- Full chip of Q2 due in June
Back-thinned CMOS devices

• Improve fill factor
• Allow improved charge collection
• 50 μm and 20 μm devices
  n on p type diodes and arrays of diodes
• Packaged for front and back illumination

10 μm
40 μm / 10 μm
800 μm

p
n
P-epilayer
Bulk Si
ITO/glass
Improved fill factor

- Surface scan with orthogonal focused illumination
- Pattern in front illumination due to hexagonal packing
- Geiger-mode dark counts are similar
• Improved QE in far red
• Small improvement in charge collection from substrate bias
• Multiplexed position sensitive readout at four nodes
• Traditional resistor network does not preserve orthogonality of X and Y signals: mixing at nodes

\[ P = \left( \begin{array}{c} V_b \\ S_1 \\ S_2 \\ S_3 \end{array} \right) \]
$X_n = \frac{1}{\sqrt{2}} \left[ \frac{A - C}{A + C} - \frac{B - D}{B + D} \right], \quad Y_n = -1 \frac{1}{\sqrt{2}} \left[ \frac{(B - D)}{B + D} + \frac{A - C}{A + C} \right]$

- PSICE model used to generate charge output at four nodes
- Preamp. input $Z=150 \, \Omega$
- Circular method improves pincushion for certain resistor values
Imaging SSPMs

• Combined Anger and circular method produces further improvements

\[ X_a = \frac{(B + C) - (A + D)}{(A + B + C + D)}, \quad Y_a = \frac{(A + B) - (C + D)}{(A + B + C + D)} \]
Conclusions

- Gains from fill factor beat losses form excess noise factors

- Back illumination:
  - Can improve spatial QE but not yet charge collection

- Imaging SSPM devices are feasible
  - Image quality can be affected by both resistor choice and calculation method
Available SSPMs

Integrated Signal Processing

Position Sensitive

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>AE208</th>
<th>AE213 Q1</th>
<th>AE213 Q2</th>
<th>AE213 Q3</th>
<th>AE213 Q4</th>
<th>AE215 Q1</th>
<th>AE215 Q2</th>
<th>AE215 Q3</th>
<th>AE215 Q4</th>
<th>(AE217) Avail. 06/08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip/quadrant size</td>
<td>mm²</td>
<td>3 x 3</td>
<td>1.5 x 1.5</td>
<td>1.5 x 1.5</td>
<td>1.5 x 1.5</td>
<td>1.5 x 1.5</td>
<td>3 x 3</td>
<td>3 x 3</td>
<td>3 x 3</td>
<td>3 x 3</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Number of pixels</td>
<td></td>
<td>708</td>
<td>1020, 700, 700, 576</td>
<td>961, 441, 324, 576</td>
<td>2068</td>
<td>708</td>
<td>1020, 700, 700, 576</td>
<td>961, 441, 324, 576</td>
<td>2068</td>
<td>708</td>
<td>1020, 700, 700, 576</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>μm²</td>
<td>707</td>
<td>346, 779, 779, 900</td>
<td>900, 2500, 2500, 900</td>
<td>2500</td>
<td>707</td>
<td>346, 779, 779, 900</td>
<td>900, 2500, 2500, 900</td>
<td>2500</td>
<td>707</td>
<td>346, 779, 779, 900</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>%</td>
<td>7</td>
<td>19, 29, 29, 29</td>
<td>49, 61, 43, 29</td>
<td>61</td>
<td>7</td>
<td>19, 29, 29, 29</td>
<td>49, 61, 43, 29</td>
<td>61</td>
<td>7</td>
<td>19, 29, 29, 29</td>
</tr>
</tbody>
</table>
Fill Factor FX: QE improvement

- Increasing fill factor corresponds directly to increased QE and Detection Efficiency (DE)

\[ \text{DE} \sim \text{QE}(\lambda) \cdot P_g(V_x) \]
PSSSPM test array

- 4 x 1.5 mm position sensitive quadrants
- Q1 33 x 33 Quench current
- Q2 30 x 30 Geiger voltage
- Q3 30 x 30 RC
- Q4 transistor gate, RC