Multi-channel LuAG-APD Pixel Array with ToT Readout System for PET application

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Outline

* Introduction (Pixel detector in PET)
* LuAG-APD-Pixel module
* Some Results
* Conclusions
Modern High resolution PET system requires a large number of granulated gamma detectors (100,000, < 2mm). Degradation in Analog Sum Circuit, Pixel gamma detector & multi-channel front-end ASIC. A large number of interconnections cause a wiring problem in PET.
ToT based Digital PET

Conventional PET

• Anger Logic (degrade spatial resolution)
• Timing Circuit and Pulse Height (low integration)
• Analog Readout and Multiplex

→

ToT (Time over Threshold) based PET

• Individual Readout / Leading Edge
• Energy information with a binary line
• Digital Readout and Multiplex
• Low power and a small number of transmission Line
• Compact
### Pr:LuAG Pixel Array

**Pixel gamma detector**

<table>
<thead>
<tr>
<th>Scintillators</th>
<th>Pr:LuAG (Lu₅Al₅O₁₂)</th>
<th>Ce:GSO (Gd₂SiO₅)</th>
<th>Ce:LSO (Lu₂SiO₅)</th>
<th>BGO (Bi₄Ge₃O₁₂)</th>
<th>Tl:Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>6.7</td>
<td>6.7</td>
<td>7.39</td>
<td>7.13</td>
<td>3.67</td>
</tr>
<tr>
<td>Light Yield (BGO=100)</td>
<td>330</td>
<td>200</td>
<td>400-500</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Decay Time (ns)</td>
<td>&lt; 25</td>
<td>60</td>
<td>40</td>
<td>300</td>
<td>230</td>
</tr>
<tr>
<td>Peak emission (nm)</td>
<td>310</td>
<td>430</td>
<td>420</td>
<td>400</td>
<td>415</td>
</tr>
<tr>
<td>Energy Resolution (%@662keV)</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>5.6</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cleavage</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>1970</td>
<td>1950</td>
<td>2150</td>
<td>1050</td>
<td>651</td>
</tr>
</tbody>
</table>

#### Specifications

- **Pixel size:** 2 × 2 × 10mm
- **Reflector:** BaSO₄
- **Total size:** 31.8 × 31.8mm
- **Channel number:** 144 (12 × 12)
- **Pixel gap:** 0.25mm

Product from Furukawa corporation
## LuAG-APD Pixel array

**UV-enhanced Pixel APD**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>2 × 2mm</td>
</tr>
<tr>
<td>Readout Scheme</td>
<td>Individual readout</td>
</tr>
<tr>
<td>Total size</td>
<td>31.8 × 31.8mm</td>
</tr>
<tr>
<td>Channel number</td>
<td>144 (12 × 12)</td>
</tr>
<tr>
<td>Pixel gap</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Fill factor</td>
<td>80%</td>
</tr>
<tr>
<td>Type</td>
<td>UV-enhanced</td>
</tr>
<tr>
<td>QE</td>
<td>5% → 55% @310nm</td>
</tr>
<tr>
<td>Dark current</td>
<td>0.1~0.7nA @gain = 50</td>
</tr>
<tr>
<td>Difference of the gain</td>
<td>±15% @gain = 50</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>380V @gain ~ 100</td>
</tr>
</tbody>
</table>
Time over Threshold based ASIC

ToT ASIC and Board

- TSMC 0.25um CMOS process
- Supply voltage: 3.3V
- Charge Sensitive Preamplifier
  and Time over Threshold circuit
- channel No.: 48channel
- Die size: 2mm × 5mm
- Board size: 3cm × 6cm
- The use of bare chip and wire bonding
- External DAC for individual threshold settings
Assembled Pixel Detector module
* Preamp ENC = 510 electrons
* Preamp rise time = 12ns
* Typical ToT pulse width = 100ns - 400ns (sampling with 250MHz clock - 7bit)
* Power consumption (-200mW) for ASIC board (ASIC,DAC)
* External threshold control pitch = 0.8mV
Linearity of Typical Channel

Linearity Curve matches with the HSPICE simulation
The actual energy is reconstructed with look-up table
DAC=12bits DAC
Threshold Adjustment pitch = 0.8mV
Optimized for 10fC-60fC which is the range of interest
Threshold variation

Scanned thresholds in one ASIC
The variation is within ±90mV
Energy Spectrum (\(^{22}\text{Na}\))

- 511keV
- 1.28MeV
- 10\% @ 511keV (FWHM)
- 4ns sampling with FPGA (6-7 bits)
144 channel (12 x 12) energy spectrum 22Na >95% is working
Timing Resolution (Coincidence)

Coincidence modules
High voltage = 390V
Timing resolution = 6ns (FWHM) (with no energy window)
4.2ns for a single module
Pulse width Measurement System

DAC control, Pulse Width Spectrum
Multiplex readout scheme

Pulse train (ToT, X, Y address)
Wired-OR Multiplexing
Transmission lines (144 -> 1)

<table>
<thead>
<tr>
<th>X (T=20ns)</th>
<th>Y (T=20ns)</th>
<th>CH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1T</td>
<td>1T</td>
<td>1</td>
</tr>
<tr>
<td>1T</td>
<td>2T</td>
<td>2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>12T</td>
<td>11T</td>
<td>143</td>
</tr>
<tr>
<td>12T</td>
<td>12T</td>
<td>144</td>
</tr>
</tbody>
</table>
Reconstructed Transmission image

1MBq 22Na source

Mask
8 module PET system

8 LuAG APD Pixel module
Ring diameter = 72.5mm (FOV=diameter 34.5mm x axial 25mm)
Reconstructed Image (point source)

- APD PET with 8 pixel detector module is assembled
- 1.76mm spatial resolution is observed with 0.5φx5mm $^{22}$Na columnar source
- Matches with the simulated resolution

1.76 mm FWHM
3.20 mm FWTM

$^{22}$Na columnar
Φ0.5mm
5mmL

0.5φx5mmのNa22円柱状線源を用いた、PET画像
Conclusion

* 144 channel LuAG-APD Pixel detector is developed with ToT based individual readout
* Successfully working as PET detector with 4.2ns time resolution and 10% energy resolution
* Spatial resolution 1.76mm (matches with simulation)
* MRI compatible-PET with digital readout technique

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Thank you for your attention