Characterisation of arrays of avalanche photodiodes for small animal positron emission tomography

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- "reverse" type structure
- 2 matrices of $2 \times 8$ pixels
- $1.6 \times 1.6 \text{ mm}^2$ sensitive area
- 1 common cathode per matrix
- 32 independent anodes per matrix
- 1 mm thick ceramic package
- 0.5 mm thick epoxy window
• deep-diffusion type structure
• 4 × 4 “bevelled-edge” pixels
• 2 × 2 mm² sensitive area
• common anode
• 16 independent cathodes
• no window
Tuneable Light Pulse Generator (TLPG)

- 200 - 700 nm range
- 13 nm FWHM resolution
- Xe short arc lamp
- low-pressure Hg calibration lamp
- H10 Yvon Jobin monochromator
- rotating UV mirror
- fused silica lenses
- movable filters
- calibrated light trap
- computer controlled
Tuneable Light Pulse Generator (TLPG)

- monochromator
- filters
- device under test (DUT)
- lenses
- calibrated light trap used as reference detector (RED)
- mirror
Temperature Controlled Measurement Board

- same board used for:
  - capacitance
  - gain
  - dark current
  - quantum efficiency

- 0.1 °C temperature accuracy
- 1 PT100 temperature sensor
- 2 Peltier elements
- OMRON PID regulator
- anodes connected either to:
  - ammeter
  - ground
  - left floating
Capacitance versus Bias Voltage

- 0.5 pF accuracy
- GenRad 1689 RLC digital capacitance bridge

A1604
- working bias voltage: 1600 V
- capacitance: (4.0 ± 0.4) pF
- sensitive area: 4.00 mm²

S8550 (matrix a, array 15)
- working bias voltage: 360 - 385 V
- capacitance: (9.5 ± 0.5) pF
- sensitive area: 2.56 mm²
Doping profiles

\[ d \equiv \sqrt{\frac{2\varepsilon V}{eN}} \Rightarrow \frac{dV}{d\left(\frac{1}{C^2}\right)} \propto N \]

- \( d \) depletion depth
- \( N \) dopant concentration
- \( e \) electron charge
- \( \varepsilon \) permittivity
- \( V \) bias voltage
- \( C \) capacitance

A1604
- deep-diffusion structure
- wide multiplication region

S8550 (matrix a, array 15)
- “reverse” type structure
- full depletion above 200 V
Transconductance versus Bias Voltage

- p-channel J-FET characteristic
- transconductance $\propto$ pixel contact surface
- APD pixels isolated above 200 V

S8550 (matrix a, array 13)
**Dark Current dependence on Temperature**

\[ i_d(T) = i_d(T_0) \times 2.3^{(T-T_0)/10} \]

\[ i_d(T) = i_d(T_0) \times 2.2^{(T-T_0)/10} \]
Hypothesis: $M = 1$

Gain $\times$ Quantum Efficiency versus Bias Voltage

$\lambda = 450$ nm
$T = 22$ °C
Quantum Efficiency versus Wavelength

$$QE_{DUT}(\lambda) = QE_{RED}(\lambda) \frac{i_{DUT}(\lambda)}{i_{RED}(\lambda)M_{DUT}}$$

- **APDs S8550**
  - bias voltage 30 V ($M = 1$)
  - temperature 22 °C
  - $QE = (59.6 \pm 0.5)\%$ at 370 nm
  - $QE = (80.6 \pm 0.3)\%$ at 450 nm

- **APD A1604**
  - bias voltage 500 V
  - temperature 22 °C
  - $QE = (27 \pm 2)\%$ at 370 nm
  - $QE = (49 \pm 3)\%$ at 450 nm
Gain dependence on Temperature

A1604 (pixel 6)

\[ M(U) = \frac{i_{\text{DUT}}(U)}{i_{\text{DUT}}(500)} \]

\[
\left( \frac{1}{M} \right) \frac{dM}{dT} = \begin{cases} 
-2.6\%/^\circ\text{C at } U = 1650\text{ V} \\
-5.0\%/^\circ\text{C at } U = 1670\text{ V}
\end{cases}
\]

S8550 (pixel 28, array 15)

\[ M(U) = \frac{i_{\text{DUT}}(U)}{i_{\text{DUT}}(30)} \]

\[
\left( \frac{1}{M} \right) \frac{dM}{dT} = \begin{cases} 
-2.1\%/^\circ\text{C at } U = 360\text{ V} \\
-2.4\%/^\circ\text{C at } U = 370\text{ V}
\end{cases}
\]
Gain dependence on Temperature

\[
\frac{dU}{dT} = 0.73 \text{ V/°C}
\]

S8550 (pixel 23, array 13)
Dark Current versus Gain

\[ i_d = i_{db} M + i_{ds} \]

- **internal line**
  - matrix a
    \[ i_{ds} = (0.576 \pm 0.063) \text{ nA} \]
    \[ i_{db} = (0.027 \pm 0.003) \text{ nA} \]
  - matrix b
    \[ i_{ds} = (0.646 \pm 0.070) \text{ nA} \]
    \[ i_{db} = (0.031 \pm 0.002) \text{ nA} \]

- **external line**
  - matrix a
    \[ i_{ds} = (0.174 \pm 0.009) \text{ nA} \]
    \[ i_{db} = (0.016 \pm 0.004) \text{ nA} \]
  - matrix b
    \[ i_{ds} = (0.174 \pm 0.008) \text{ nA} \]
    \[ i_{db} = (0.020 \pm 0.001) \text{ nA} \]

\[ T = 22 \degree \text{C} \]
Dark Current versus Gain

A1604 (pixel 6)

\[ i_{ds} = (21.7 \pm 0.5) \text{ nA} \]
\[ i_{db} = (0.053 \pm 0.001) \text{ nA} \]

\( T = 22 ^\circ \text{C} \)

S8550 (pixel 1, array 15)

\[ i_{ds} = (0.166 \pm 0.020) \text{ nA} \]
\[ i_{db} = (0.019 \pm 0.001) \text{ nA} \]
Gain versus Wavelength

A1604

- deep-diffusion structure
- wide multiplication region

\( T = 22 \, ^\circ\mathrm{C} \)

S8550

- “reverse” type structure
- limited multiplication region
## Conclusion

We would like to thank the members of the CERN Crystal Clear Collaboration for fruitful discussions. This work is supported by the Swiss National Foundation for Research under Grant No. 21-63870.00

<table>
<thead>
<tr>
<th></th>
<th>A1604</th>
<th>S8550</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE at 370 nm (LuAP)</td>
<td>(27 ± 2)%</td>
<td>(59.6 ± 0.5)%</td>
</tr>
<tr>
<td>QE at 420 nm (LSO)</td>
<td>(44 ± 3)%</td>
<td>(75.7 ± 0.3)%</td>
</tr>
<tr>
<td>QE at 450 nm (GSO)</td>
<td>(49 ± 3)%</td>
<td>(80.6 ± 0.3)%</td>
</tr>
<tr>
<td>bias voltage</td>
<td>1690 V</td>
<td>370 V</td>
</tr>
<tr>
<td>gain</td>
<td>858</td>
<td>55 - 87</td>
</tr>
<tr>
<td>capacitance</td>
<td>&lt; 1 pF/mm²</td>
<td>&lt; 3.7 pF/mm²</td>
</tr>
<tr>
<td>bulk current</td>
<td>0.05 nA</td>
<td>0.01 - 0.03 nA</td>
</tr>
<tr>
<td>surface current</td>
<td>21.9 nA</td>
<td>0.2 - 0.6 nA</td>
</tr>
<tr>
<td>temperature</td>
<td>22 °C</td>
<td>22 °C</td>
</tr>
<tr>
<td>(1/M)(dM/dT)</td>
<td>&lt; –5%/°C</td>
<td>–2.4%/°C</td>
</tr>
<tr>
<td>(1/M)(dM/dU)</td>
<td>3.9%/V</td>
<td>3.4%/V</td>
</tr>
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