Avalanche Diodes (APD) Detectors: Introduction and Recent Advances*

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“SNIC”
SLAC, Stanford, April  2006

*Focus on Fast X-Ray Detection
A Change in Scale...

Compared to the detector effort in high-energy physics, the effort in synchrotron radiation is in its childhood,

... and the APD effort in x-ray scattering is nearly a newborn.

Small efforts: ESRF, BNL, DESY, SPring-8, KEK, (SSRL) & the recent addition of a dedicated technician at ESRF is already a major jump.
Historical

Development in the 60s & 70s
(Huth, McIntyre, Webb, Jones at GE & RCA)

Some discussion of a “Solid State Photomultiplier”
(but gain not so high...)

Main utility is high speed (large gain-bandwidth product).
Optical Communication, Laser range-finding...
& Applications where for some reason a PMT is not suitable
Positron Emission Tomography (High Magnetic Field)

Introduced to the x-ray scattering community via

Nuclear Resonant Scattering (NRS) of Synchrotron Radiation

1990’s

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Nuclear Resonant Scattering (NRS)

*Pulsed X-Ray Beam* ~ eV Wide

Resonant Nuclei ~ E~ neV, ~100 ns

Detector

Prompt Scattering up to 10 orders bigger than the Nuclear Signal

Carefully Choose the Sample (Gerdau, Rüffer)

Build the Right Optics (Faigel, Siddons, Hastings)

Use the Right Detector (Kishimoto, Baron)

Continues to provide a challenge for detectors...

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APD Research Applications

Fast photon counting: 1 MHz Easy,
                      ~100 MHz Possible
                  Diffraction, Imaging

Time resolved detection: ~1 ns Easy
                      ~0.1 ns Possible
                   NRS, XIFS

Places where a PMT is not possible...

Magnetic Fields
Size Constraints
Power Requirements

Note one large application (>10^5 devices) is for the CMS Calorimeter for scintillator readout in a 4T field (Dieters, Renker)
A Diode With Gain

Drift Region
10^2-10^4 V/cm

Avalanche Region
~10^5 V/cm

Absorption
10-200 um Si

Drift
~ 10 ps/um

Gain
10^1-10^4

x-ray

Limited Stopping Power
10 keV X-Rays → OK
20 keV → Losses

~50 Typical
Intrinsic (excess) noise due to amplification of BOTH Electrons & Holes
"McIntyre" Theory (~1970)

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**Geiger vs Linear Operation**

**Linear Operation:**
- Diode biased below breakdown.
- Well defined small-signal gain.

**Geiger Operation:**
- Diode biased above breakdown.
- Single electron leads to run-away gain until quenched.
- Noisy: $10^2$-$10^5$ cps/channel

(Also Poster/Abs 143, Renker)
Structures

“Reach Through”

“Beveled Edge”

“Reverse”

Narrow Gain Region
Medium Voltage 50-700V
Large Drift Region
Modest Gains (<200)
Also one-sided epitaxial & diffused & back entry...

Wide Gain Region
High Voltage (1-2 kV)
High Gains Possible
Larger Areas Possible
Also “Planar”

Narrow Gain Region
Medium Voltage <500V
Small Drift Region
Modest Gains (<200)

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## Some Single-Element Devices

<table>
<thead>
<tr>
<th>Company</th>
<th>Model</th>
<th>Size</th>
<th>Operating Voltage</th>
<th>Active Thickness (μm)</th>
<th>Capacitance pF/mm² (a)</th>
<th>Gain (a)</th>
<th>Time Resolution FWHM / Tail (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perkin-Elmer (PKI/EG&amp;G)</td>
<td>C30626</td>
<td>5x5 mm²</td>
<td>300-400</td>
<td>~110</td>
<td>1.2</td>
<td>50-150</td>
<td>~ 1 / 3</td>
</tr>
<tr>
<td></td>
<td>C30703</td>
<td>10x10 mm²</td>
<td>350-450</td>
<td>~110</td>
<td>1.2</td>
<td>50-150</td>
<td>~ 1 / 4</td>
</tr>
<tr>
<td>Prototype (b)</td>
<td></td>
<td>5x5 mm²</td>
<td>350-450</td>
<td>~180</td>
<td>&lt; 1</td>
<td>50-150</td>
<td>1.7 / 7</td>
</tr>
<tr>
<td>C30719 (b)</td>
<td>Reverse</td>
<td></td>
<td>350-450</td>
<td>&lt; 10</td>
<td>-</td>
<td>~50</td>
<td>0.17 / 2-3 (c)</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>SPL2625 (b)</td>
<td>φ 3 mm 3x5 mm²</td>
<td>500-700</td>
<td>~130</td>
<td>~1</td>
<td>30-50</td>
<td>1.3 / 3</td>
</tr>
<tr>
<td></td>
<td>S238X</td>
<td>φ0.2 to 5 mm</td>
<td>~150</td>
<td>~30</td>
<td>6</td>
<td>50-100</td>
<td>0.3 / 5 (c)</td>
</tr>
<tr>
<td></td>
<td>S534X</td>
<td>φ1, 35 mm</td>
<td>~150</td>
<td>~10</td>
<td>16</td>
<td>~50</td>
<td>~0.08 / &lt;2</td>
</tr>
<tr>
<td></td>
<td>S534X LC (b)</td>
<td>φ1, 3, 5 mm</td>
<td>~250</td>
<td>~20</td>
<td>5</td>
<td>~50</td>
<td>~0.15 / &lt;2</td>
</tr>
<tr>
<td></td>
<td>S8644-XXK</td>
<td>φ0.2 to 5 mm</td>
<td>~400</td>
<td>~7</td>
<td>3</td>
<td>~50</td>
<td>~0.25 / &lt;2</td>
</tr>
<tr>
<td></td>
<td>Reverse</td>
<td>&amp; 5x5 mm² &amp;10x10 mm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Photonix, Inc.</td>
<td>LAAPD</td>
<td>φ3 to 16 mm</td>
<td>~2000</td>
<td>30-50</td>
<td>~1</td>
<td>~200</td>
<td>~0.4 / &gt;5 (c)</td>
</tr>
<tr>
<td>(API)</td>
<td>Beveled Edge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Monitoring</td>
<td>S0814</td>
<td>8x8 mm²</td>
<td>~1700</td>
<td>30-50</td>
<td>~1?</td>
<td>300-2000</td>
<td>~0.4 / &gt;10 (c)</td>
</tr>
<tr>
<td>Devices (RMD)</td>
<td>S1315</td>
<td>13x13 mm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beveled Edge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
1. *Not* extremely careful conditions.
2. Device Dependence.
3. CMS expects >99% reliability (after selection) for 10 years

* As of ~1998

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Electronics

- Photon (Pulse) Counting & Timing

APD → Fast Voltage Pre-Amp (~ GHz) → Discriminator (NIM or ECL) → Logic

Counter
Or
TAC/TDC
Or
Autocorrelator

Not YET integrated... SM Technology & Modular (NIM) electronics

ASIC?
Typical Scope Traces

Leading edge (rise time) is governed by carrier transport in the device.

Trailing edge by diode capacitance and amplifier impedance.

Best case ~ 0.6 to 0.9 ns FWHM.
X-Ray Time Resolution

As x-rays penetrate and tend to uniformly illuminate a device, the FWHM of the time resolution is mostly determined by the thickness of the drift region

\[ \sim 10 \text{ ps/um near saturation} \]

Tails determined by the field profiles near the surface

Note use of leading edge discriminator.
Best Time Resolution

Best FWHM: 75 ps
~ 10 um Device, Hamamatsu

Best Tail: ~1.4 ns at 1/10^5
~30 um Device, PKI

Good Tail: < 2 ns at 1/10^5

Note: Geiger Mode operation of small area devices has shown
~20 to 30 ps nominal resolution
(Cova, Lacaita)
Fast Counting

Simplest “Non-Paralyzable” Model

\[ n = \frac{m}{1 - mT} \]

- \( n \) = True Rate, \( m \) = Measured Rate
- \( T = \) System Dead Time
  - \( T = 3 \) to 20 ns
- Source + APD + Discriminator + Counter
- \( mT = 0.1 \) (20 MHz for \( T=5 \) ns)
  - \( \rightarrow \) Can correct to \( \sim 1\% \)

For \( mT > 0.1 \) \( \rightarrow \) MUST Calibrate!

(a) 5x5 mm\(^2\) C30626

(b) \( 3\) mm SPL2625 16.5 keV

(c) 5x5 mm\(^2\) C30626 ESRF Package
Pulse Height Distribution
(X-Rays and Fast Electronics)

Contributions:
- Amplifier Noise
- APD Gain Noise
- Penetration into gain region

Typically 20-30% for thicker devices.

Base-line shift at high rates (AC-Coupling).
Better for lower capacitance devices.

Note: Slow Electronics, Low Gains,
Cooling (-20C)
-> resolution ~5% possible
(Kishimoto)
Other Points

Low T operation is possible - increased gain and T-sensitivity

- ~ 40K with API Beveled Edge (Yang)
- ~ 100K with Ham. Rev. APD (Dorokhov)

Electron Detection is possible - note radiation damage!

- Hamamatsu Devices with special surface (Kishimoto)
  - With Gain - VAPD (Kushman)

Progress toward a more realistic PMT replacement?

- Many (10^3/mm^2) Geiger mode devices to keep
dynamic range & high gain (Buzhan, Sadygov)
  (Next Talk, Otte and poster/ abs 126: Yokoyama)
# APD Arrays

<table>
<thead>
<tr>
<th>Company</th>
<th>Device Structure</th>
<th>Type</th>
<th>Array Pixels</th>
<th>Pixel Size</th>
<th>Dead Space (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perkin-Elmer (PKI/EG&amp;G)</td>
<td>C30985</td>
<td>M</td>
<td>1 x 25</td>
<td>~0.4 mm x 0.3 mm pitch</td>
<td>~0.07</td>
<td>Webb &amp; McIntyre, 1984</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a)</td>
<td>1 x 32</td>
<td>0.35 mm x 0.15 mm pitch</td>
<td>~0.05</td>
<td>Trakalo, et al., 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a)</td>
<td>1 x 128</td>
<td>2 mm x 0.15 mm pitch</td>
<td>~0.05</td>
<td>Webb &amp; Dion, 1991</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S238X</td>
<td>M</td>
<td>1 x 16</td>
<td>φ1 or 1 x 1 mm²</td>
<td>0.1</td>
<td>Hara, et al., 1996</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b)</td>
<td>1 x 32</td>
<td>3.8 x 0.5 mm²</td>
<td>Var.</td>
<td>Nonaka, et al., 1996</td>
</tr>
<tr>
<td></td>
<td>S534X LC</td>
<td>M</td>
<td>1 x 16</td>
<td>2.5 x 1 mm²</td>
<td>0.1</td>
<td>Baron, et al., 2004</td>
</tr>
<tr>
<td></td>
<td>SPL2625</td>
<td>A</td>
<td>2 x16 &amp; 2 x 4</td>
<td>3 x 5 mm²</td>
<td>1</td>
<td>Kishimoto, et al., 2004</td>
</tr>
<tr>
<td></td>
<td>50 µm (c)</td>
<td>M</td>
<td>2 x 4</td>
<td>1 x 0.5 mm²</td>
<td>0.1</td>
<td>Kishimoto, et al., 2004</td>
</tr>
<tr>
<td></td>
<td>S5343 LC</td>
<td>R</td>
<td>1 x 10</td>
<td>φ3</td>
<td>3 or 0.1</td>
<td>This work.</td>
</tr>
<tr>
<td>Advanced Photonix, Inc. (API)</td>
<td>Bev. Edge Grooved</td>
<td>M</td>
<td>8 x 8</td>
<td>1.3 x 1.3 mm²</td>
<td>0</td>
<td>Gramsch, et al., 1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 x 0.5 mm²</td>
<td>0</td>
<td>Gramsch, et al., 1994</td>
</tr>
<tr>
<td>Radiation Monitoring Devices (RMD)</td>
<td>Plan. Bev Grooved</td>
<td>M</td>
<td>4 x 4</td>
<td>2.1 x 2.1 mm²</td>
<td>0.4</td>
<td>Farrell, et al., 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 x 8</td>
<td>13 x 13 mm²</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plan. Bev Grooved. Pitch</td>
<td>M</td>
<td>14 x14</td>
<td>2 x 2 mm²</td>
<td>0.1</td>
<td>Shah, et al., 2001</td>
</tr>
<tr>
<td></td>
<td>Plan. Bev Anger. (d)</td>
<td>M</td>
<td>1</td>
<td>14 x 14 mm²</td>
<td>0</td>
<td>Levine, et al., 2004</td>
</tr>
</tbody>
</table>

M=Monolithic  A=Assembled  R=Replaceable

**Note:** Still relatively small numbers of pixels
ns Linear Array
(Webb & McIntyre, 1984 - PKI C30985)

Linear Array, 25 elements, 0.3 mm pitch
~ 100 um thick, ~1 ns resolution

Segmented cathode with bump bonding.

~1 ns resolution
Fast Linear Array

How can one keep good (200 ps) time resolution and high efficiency?

-> Grazing Incidence

16 Elements, 1.1 mm pitch
1x2.5 mm² x 20 um thick

2 Degree grazing angle -> 0.6 x 2.5 mm Acceptance, 0.6 mm Thick
Efficiency: ~1% -> 17 %

Magnetic Relaxation in Spin-Ice (Sutter et al)

Note: Device stability is an issue.
Modular Array
Now Under Construction - SPring-8 - ESRF Collaboration

Similar concept to the “Fast Array”
Grazing incidence gets you good (200 ps) time resolution
and good x-ray stopping power

But Modular: Element replacement possible.
Amplifier design simplified.

8 Elements, 3mm x 20 um, incline at 2 degrees -> ~ 0.8 x 2.0 mm² x 0.6 mm thick
The Next Step: Integration

Discussion/Collaboration:
ESRF, APS, SPring-8, DESY, KEK, &..

First Goal (?): Fast (us) framing detector.

A Properly Instrumented APD Array
Pixel Size: ~ 0.3 x 0.3 mm$^2$ x 0.2 mm thick
(Efficient and ~ 2 ns time resolution)
~10$^3$ channels (1 cm$^2$) at first -> 10$^5$

Utility: Fast imaging, Stroboscopic Measurements, XPCS
With different electronics, NRS: NSAXS, SRPAC

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Fast Framing Detector

1. The Array Device -> Not so hard.
2. Electronics -> ?

Question: On board histogramming for stroboscopic work?
Modified Electronic for NRS

APD

10^2-10^3 Chan

Fan in

TDC

TAC/ADC?

Prompt Counter

Fast Switch

Timing Adjust

Disc.

508 MHz

20 ps Res.

100 kHz

Channel Info
APD Collaborators

KEK: S. Kishimoto

ESRF: T. Deschaux, R. Rüffer

SPring-8: T. Ishikawa (& T. Kudo)
Packaged Fast Counting Systems

BNL
Kuczewski, Siddons

ESRF
Rigal, Morse, et al.