Evolution and Prospect of Single-Photon Avalanche Diodes and Quenching Circuits

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Outline

• Introduction
• From Device Physics to Detector Performance
• Technology and Device Design
• Quenching Circuit: Role and Evolution
• Conclusions
The Origin

@ Shockley Laboratory in early 60’s :

Avalanche Physics Investigation

• Basic insight
• Model of behavior above Breakdown
• Single-Photon pulses observed, but …
• application limited by device and circuit features

Avalanche PhotoDiode

- Bias: slightly **BELLOW** breakdown
- Linear-mode: it’s an **AMPLIFIER**
- Gain: limited < 1000

Single-Photon Avalanche Diode

- Bias: well **ABOVE** breakdown
- Geiger-mode: it’s a **TRIGGER** device!!
- Gain: meaningless ... or “infinite”!!
for SPAD operation anyway

mandatory

to avoid local Breakdown, i.e.

• edge breakdown $\rightarrow$ guard-ring feature

• microplasmas $\rightarrow$ uniform area, no precipitates etc.

but for good SPAD performance.....

further requirements!!
Earlier Diode Structures

Haitz’s planar diode

McIntyre’s reach-through diode

“Thin” SPAD

“Thick” SPAD
Quantum Detection Efficiency (QE)

Carrier Photogeneration

AND

Avalanche Triggering!!

→ high excess bias voltage

**Dark-Counting Rate (primary noise)**

Free Carrier Generation

**Generation - Recombination Centers**

**Field-Assisted Generation**
Carrier Trapping and Delayed Release → Afterpulsing
Trapping and Afterpulsing

in operation @ low temperature

→ slower trap release

primary dark-counting rate is reduced

but afterpulsing is enhanced!

Photon Timing

![Graph of Photon Timing]

- Main peak
- Diffusion tail

![Schematic of Photon Detector]

- n⁺
- n⁻
- oxide
- guard ring
- metal

**Workshop on Single Photon Detectors**

S. Cova et al

**POLIMI - Politecnico di Milano, DEI**

**NIST, Gaithersburg, MD, March 31 - April 1, 2003**
Photon Timing: Diffusion Tail

carrier diffusion in neutral layer

→ delay to avalanche triggering

Photon Timing: main peak width

Statistical Fluctuations in the Avalanche

- **Vertical Build-up** *(minor contribution)*

- **Lateral Propagation** *(major contribution)*
  - via Multiplication-assisted diffusion
    
    *A. Lacaita, M. Mastrapasqua et al, APL and El. Lett. (1990)*

  - via Photon-assisted propagation
    
Avalanche Lateral Propagation

Multiplication-assisted

Photon-assisted

higher excess bias voltage \rightarrow \text{improved time-resolution}

A. Spinelli, A. Lacaita, IEEE TED (1997)
Arrays and optical crosstalk

Hot-Carrier Luminescence
\[ 10^5 \text{ avalanche carriers} \rightarrow 1 \text{ emitted photon} \]


Counteract:
- Optical isolation between pixels
- Avalanche charge minimization

F.Zappa et al, ESSDERC (1997)
Low Detector Noise

• For low dark-counting rate
  → Reduce GR center concentration
  → Reduce Field-assisted generation

• For low afterpulsing probability
  → Reduce deep level concentration (minority carrier traps)

Technology issue:
for wide sensitive area very efficient gettering is required!!
Thin Si SPAD

Planar structure

- typical active region:
  - 20 \( \mu \text{m} \) diameter
  - 1 \( \mu \text{m} \) thick

Thick Si SPAD

Reach-Trough structure

- typical active region:
  - 200 \( \mu \text{m} \) diameter
  - 30 \( \mu \text{m} \) thick
<table>
<thead>
<tr>
<th>Thin Si SPAD’s</th>
<th>Thick Si SPAD’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good QE and low noise</td>
<td>Very good QE and low noise</td>
</tr>
<tr>
<td>Picosecond timing</td>
<td>Sub-nanosecond timing</td>
</tr>
<tr>
<td>Low voltage : 15 to 40V</td>
<td>High voltage : 300 to 400V</td>
</tr>
<tr>
<td>Low power : cooling not necessary</td>
<td>High dissipation : Peltier cooler required</td>
</tr>
<tr>
<td>Standard Si substrate</td>
<td>Ultra-pure high-resistivity Si substrate</td>
</tr>
<tr>
<td>Planar fabrication process</td>
<td>Dedicated fabrication process</td>
</tr>
<tr>
<td>COMPATIBLE with array detector and IC’s (integrated circuits)</td>
<td>NOT COMPATIBLE with array detector and IC’s</td>
</tr>
<tr>
<td>Robust and rugged</td>
<td>Delicate and degradable</td>
</tr>
<tr>
<td>Low-cost</td>
<td>Very expensive</td>
</tr>
<tr>
<td>NO COMMERCIAL SOURCE TODAY</td>
<td>SINGLE COMMERCIAL SOURCE</td>
</tr>
</tbody>
</table>
Photon Timing: SLIK™ reach-trough structure

Photon Timing: planar epitaxial structure

neutral p layer thickness $w$

tail lifetime $\tau = \frac{w^2}{\pi^2 D_n}$

Photon Timing: diffusion-tail-free structure

FWHM = 35ps
FW(1/100)M = 125ps
FW(1/1000)M = 214ps

Photon Timing: diffusion-tail-free structure

IR spectral range : Ge devices

Similar to silicon devices, but

• deep cooling mandatory
• absorption edge below 1500nm @ low temperature
• very strong trapping effects
• strong field-assisted generation effects

IR spectral range: InGaAs-InP devices

- very strong trapping
- fast-gated operation only!

Passive quenching is simple...

... but suffers from

- long, not well defined deadtime
- low max counting rate < 100kc/s
- photon timing spread
- et al
Active quenching....

...provides:

• short, well-defined deadtime
• high counting rate $> 1$ Mc/s
• good photon timing
• standard logic output

Output Pulses

P. Antognetti, S. Cova, A. Longoni
IEEE Ispra Nucl. El. Symp. (1975)
Euratom Publ. EUR 537e
AQC evolution

Earlier modules in the 80’s

Compact modules in the 90’s

Integrated AQC today
iAQC - Integrated Active Quenching Circuit

Input sensing and quenching stage

- F. Zappa et al, ESSCIRC 2002
iAQC - Integrated Active Quenching Circuit

CMOS design
iAQC - Integrated Active Quenching Circuit

Practical advantages

• Miniaturization → mini-module detectors
• Low-Power Consumption → portable modules
• Ruggedness and Reliability

Plus improved performance

• Reduced Capacitance
• Improved Photon Timing
• Reduced Avalanche charge
• Reduced Afterpulsing
• Reduced Photoemission → reduced crosstalk in arrays
Can Photon-Timing be improved for existing AQC's?

...in this way it does not work properly
Can Photon-Timing be improved for existing AQCs?

S. Cova, M. Ghioni, F. Zappa, US patent No. 6,384,663 B2,
date May 7, 2002 (priority date Mar 9, 2000)
Photon-Timing with PerkinElmer SLIK™ diode

with discrete-component AQC alone… …and with additional timing circuit

![Graph 1](image1.png)

- FWHM = 350 ps

![Graph 2](image2.png)

- FWHM = 145 ps
Conclusions and Outlook

• Silicon SPAD technology
  is fairly advanced and can be further improved
• Low-cost highly efficient Si-SPADs
  appear now to be feasible
• Monolithic iAQC
  make possible miniaturized (and even monolithic) detector modules
• SPAD Array detectors
  are a realistic prospect
• Ge, III-V and II-VI SPAD detector technologies
  require further progress, but may open remarkable new perspectives
QE comparison

[Diagram showing QE comparison between different photodetectors, including Hamamatsu CCD C4880-21, Mepsicron PMT (super S25), PerkinElmer SPAD, and µP10 SPAD. The graph plots detection efficiency (η) against wavelength (λ) in micrometers.]
Photon Timing comparison

PerkinElmer SPCM (SLIK™ diode)

Planar thin Si-SPAD

FWHM = 350 ps

FWHM = 27 ps