Single-photon Detector Overview

• Key metrics
• PMTs
• APDs
• Superconducting
  • TES
  • Nanowire
Key Metrics

- efficiency – how likely to detect a photon
- dark counts – how much noise in the absence of light
- deadtime – how long after detection before ready
- afterpulsing – how often is there a secondary signal
- jitter – what time resolution does a detection have
- latency – how long to get a signal out
- photon-number resolving?
- operating temperature
- $$$
Invited Review Article: Single-photon sources and detectors

M. D. Eisaman, a) J. Fan, A. Migdall, and S. V. Polyakov
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
and Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA

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We review the current status of single-photon-source and single-photon-detector technologies operating at wavelengths from the ultraviolet to the infrared. We discuss applications of these technologies to quantum communication, a field currently driving much of the development of single-photon sources and detectors. © 2011 American Institute of Physics. [doi:10.1063/1.3610677]
Photomultiplier Tube

Figure 1

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
<th>Detection efficiency, wavelength λ (nm)</th>
<th>Timing jitter, δt (ns) (FWHM)</th>
<th>Dark-count rate, D (ungated) (1/s)</th>
<th>Max. count rate (10^6/s)</th>
<th>PNR capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (visible–near-infrared)</td>
<td>300</td>
<td>40 @ 500</td>
<td>0.3</td>
<td>100</td>
<td>10</td>
<td>Some</td>
</tr>
<tr>
<td>PMT (infrared)</td>
<td>200</td>
<td>2 @ 1550</td>
<td>0.3</td>
<td>200 000</td>
<td>10</td>
<td>Some</td>
</tr>
</tbody>
</table>
Avalanche Photodiode

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
<th>Detection efficiency, wavelength (η(%), λ (nm))</th>
<th>Timing jitter, Δt(ns) (FWHM)</th>
<th>Dark-count rate, D (1/s) (ungated)</th>
<th>Max. count rate (10⁶/s)</th>
<th>PNR capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si SPAD (thick junction)</td>
<td>250</td>
<td>65 @ 650</td>
<td>0.4</td>
<td>25</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>Si SPAD (shallow junction)</td>
<td>250</td>
<td>49 @ 550</td>
<td>0.035</td>
<td>25</td>
<td>10</td>
<td>None</td>
</tr>
<tr>
<td>InGaAs SPAD (gated)</td>
<td>200</td>
<td>10 @ 1550</td>
<td>0.370</td>
<td>91</td>
<td>0.01</td>
<td>None</td>
</tr>
<tr>
<td>InGaAs SPAD (self-differencing)</td>
<td>240</td>
<td>10 @ 1550</td>
<td>0.055</td>
<td>16000</td>
<td>100</td>
<td>None</td>
</tr>
</tbody>
</table>
Superconducting Transition Edge Sensor (TES)

Calorimetric detection of UV/optical/IR photons

![Image of TES sensor](image)

**Fiber coupled self-aligned TES**

< 1% coupling loss

![Graph of pulse height vs. counts](image)


### Optical stack

- SiN$_x$/SiO$_2$
- a Si
- W (TES)
- SiN$_x$/SiO$_2$
- Ag/Au mirror
- Si substrate

### TES Simulated Absorption

![Graph of absorption fraction vs. wavelength](image)

### Detector type

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<th>Max. count rate ($10^6$/s)</th>
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Superconducting Nanowire Single-photon Detectors (SNSPDs)

![SEM Image of a detector](image)

**Figure 2.1:** Scanning Electron Microscope (SEM) image of a detector. The highlighted region is what we expect to be the active area for photon detection. The image was supplied by K. Ilin from the Institut für Mikro- und Nanoelektronische Systeme.

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<tr>
<td>SNSPD</td>
<td>3</td>
<td>$0.7 \text{ @ } 1550$</td>
<td>0.06</td>
<td>10</td>
<td>100</td>
<td>None</td>
</tr>
<tr>
<td>SNSPD (in cavity)</td>
<td>1.5</td>
<td>$57 \text{ @ } 1550$</td>
<td>0.03</td>
<td>...</td>
<td>1000</td>
<td>None</td>
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<tr>
<td>SNSPD</td>
<td>3</td>
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<td>57 @ 1550</td>
<td>0.03</td>
<td>...</td>
<td>1000</td>
<td>None</td>
</tr>
<tr>
<td>Parallel SNSPD</td>
<td>2</td>
<td>2 @ 1300</td>
<td>0.05</td>
<td>0.15</td>
<td>1000</td>
<td>Some</td>
</tr>
</tbody>
</table>
Single-photon Vision

• Can you SEE single photons?
• At this moment you are detecting $\sim 10^{16}$ photons every second. But could you see just one?
• No one knows. Past experiments suggested a minimum threshold as high as 8, as low as 1 or 2.
• Now we can give a definitive answer…

PGK, Anthony Leggett
Ranxiao Frances Wang (UIUC Psychology)

Rebecca Holmes (GS)
Yangyuxin “Amy” Zou (UGS)
Figure 2: (a) A single rod photoreceptor cell from a toad, in a suction pipette. Viewing is with infrared light, and the bright bar is a stimulus of 500 nm light. (b) Equivalent electrical circuit for recording the current across the cell membrane. (c) Mean current in response to light flashes of varying intensity. Smallest response is to flashes that deliver a mean ~ 4 photons, successive flashes are brighter by factors of 4. (d) Current responses to repeated dim light flashes at times indicated by the tick marks. Note the distinct classes of responses to zero, one or two photons. From [Rieke & Baylor 1998a].
"Heralded" Single-Photon Source

Spontaneous Parametric Downconversion:

\[ \omega_p \rightarrow \omega_s, \quad k_p \rightarrow k_s, \quad \omega_i \rightarrow \omega_s \]

- **Herald count:** 001
- **Computer control:** "Right"
- **Observer viewing station**

**Diagram Components:**
- **266 nm LED**
- **505-nm LED**
- **BBO**
- **562 nm**
- **505 nm**
- **AND**
- **PD**
- **PC**
- **25-m SMF** for optical delay
- **PBS**
- **HWP**
- **Telecom fiber**

**Wavefunction Representation:**

\[ P(n) = \begin{cases} 0.99999999... & \text{for } n = 1 \\ 0.00000001... & \text{for } n = 2 \end{cases} \]
700-nm fixation light

505-nm targets

40°

30 cm

10-µm diameter spots at 20°
on the nasal and temporal retina of the left eye
Single-Photon Vision Experiment

Researcher area

Subject area

Single-photon source

Computer

Observer presses a key to indicate on which side the photon appeared, with 3 confidence levels.
Current Status:
Weak LED and N-photon trials show SOME subjects can reliably detect <30 incident photons (~3 at the retina)

Temporal integration time of the eye longer than expected (~800 ms)

New single-photon trials underway

Can YOU see single photons?
http://research.physics.illinois.edu/QI/Photonics/vision/
“Each photon then interferes only with itself. Interference between two different photons never occurs.”

-P.A.M. * Dirac

On Hanbury-Brown Twiss correlations: “…if such a positive correlation did exist, it would call for a major revision of some fundamental concepts in quantum mechanics.”

-Brannen and Ferguson

*Paul Adrien Maurice
Hanbury Brown and Twiss ‘56

Pound and Rebka ‘57

Coincidence rate vs. Delay time
Hanbury-Brown and Twiss

“Michelson Stellar Interferometry” -- Measure field-field correlations

“HBT Interferometry” -- Measure intensity-intensity correlations
Evaporatively cooled metastable He (which one??)
Observation of Hanbury Brown-Twiss anticorrelations for free electrons

Harald Kiesel, Andreas Renz & Franz Hasselbach

Amplifier 1.3 GHz
Constant fraction trigger stop signal
Fluorescent screen +4 kV
Fast coincidence
Time-to-amplitude converter
Multi-channel analyser
Delay

Tungsten tip ~2.7 kV
Anode ~1.8 kV
Magnifying quadrupole doublet
Microchannel plate entrance ~1.8 kV
Microchannel plate exit (earth)
Collectors (earth)

Coincidences

electron_correlation_time ~10^{-14}s
Detector_resolution_time ~10^{-11}s
→ reduce effect by 1000
Unpolarized electrons → reduce effect by 2
Comparison of the Hanbury Brown–Twiss effect for bosons and fermions

T. Jeltes¹, J. M. McNamara¹, W. Hogervorst¹, W. Vassen¹, V. Krachmalnicoff², M. Schellekens², A. Perrin², H. Chang², D. Boiron², A. Aspect² & C. I. Westbrook²

Figure 2 | Normalized correlation functions for $^4\text{He}^+$ (bosons) in the upper plot, and $^3\text{He}^+$ (fermions) in the lower plot. Both functions are measured at the same cloud temperature (0.5 μK), and with identical trap parameters. Error bars correspond to the square root of the number of pairs in each bin.