Single Photon Detectors – from A to B (from Astronomy to Bio, and beyond)

D. Prober, Yale Univ. Depts. Applied Physics and Physics

with thanks for collaborators and Yale colleagues
Acknowledgements

• Spectroscopy demo – soon
Outline

• Types of sensors
  – Transition Edge Sensor
  – Superconducting Tunnel Junction; MKID
  – SC Nanowire, Avalanche Photodiode

• Applications
  – X-ray – astronomy, spectroscopy
  – Near IR - Quantum Key Distribution
  – Bio fluorescence
Why single photon?

- Weak sources; *spectroscopy*; $E_{\text{ph}} = hf = hc/\lambda$
- Encode information, entangle
- Timing, coincidence
- Measure *particle* energy
- Speed is important = challenge in cold env.
- **Arrays** = key enabler for most future applications

- **Energy scales**
  - $1 \text{ eV} = 1.2 \ \mu\text{m} = 250 \ \text{THz} \ \ T = 10^{12}
  - $1 \text{ meV} = 1.2 \ \text{mm} = 0.25 \ \text{THz}$
  - (visible: $\approx 1.6 - 3 \text{ eV}; \ 0.4 - 0.7 \ \mu\text{m}$)
Why single photon?

- *Spectroscopy demo – dispersive spectroscopy*
Why single photon?

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- Encode information, entangle
- Timing, coincidence
- Measure particle energy
- Speed is important = challenge in cold env.
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Bolometer Detector – Thermal $\rightarrow$ cold + small

Thermometer

Thermal Mass
Heat Capacity $C$

Absorber

Thermal Link
Conductance $G$

Thermal Reservoir

Single photon

$\Delta T = \frac{E_{ph}}{C}$

$\tau_{th} = \frac{C}{G}$

$R$ vs. $T$

$R$ vs. time

$R$ vs. time

$R_0$

$R_0$

$T_c$

power on

power off

$t_0$
Basic Transition Edge Sensor Operation

Superconducting wire (the TES) is used as a thermometer – read out changes of resistance electrically.

- Typical SC transition $T_c < 1K$
- Voltage bias $\rightarrow$ faster response, more sensitive
- SQUIDs essential for low T multiplexing, low noise
- Low count rates for astro x-ray applications $\approx 100/\text{sec}$; SQUID mux ‘easy’

Kilbourne, TIPP09
• A collaboration of the UK, Canada, Raytheon, and NIST
• SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 µm, half at 850 µm) on the James Clerk Maxwell Telescope.
• TES = transition edge sensor = thermometer in bolometer
• First large-array demo of TES POWER detectors (not single photon)
Techniques of semiconductor industry; special materials.
X-Ray TES structure

Robust array construction

Thick Au/Bi absorber, weakly attach Mo/Au bilayer TES

TES is thermometer only

Kilbourne, TIPP09
Au/Bi Absorbers (~1 μm Au, 4 μm Bi) on SiN membrane; msec response

Si diode – 120 eV FWHM

Kilbourne, TIPP09
Application to Laboratory Astrophysics

• Electron-Beam Ion Trap at LLNL
  – Astrophysically relevant plasmas in the laboratory

• Currently:
  – EBIT Calorimeter Spectrometer uses silicon thermistor array for broad-band coverage
  – Dispersive spectrometers for high energy resolution below 1 keV

• Next generation: TES spectrometer
  – Match (exceed) ΔE of upcoming missions
  – Reduce the need for the dispersive spectrometer
Microcalorimeter alpha particle detectors

- environmental monitoring
- nuclear safeguards
- medical assay
‘Scaled up x-ray TES’

superconducting Sn absorber

complete detector with absorber

J. Ullom, LTD13
Technology dissemination

- 4 channel alpha spectrometer installed at LANL
- SQUIDs, SQUID electronics, wiring from STAR Cryoelectronics
- TESs originally from NIST, now from STAR Cryoelectronics
- High quality spectra routine
- Phase II SBIR awarded for commercial system
STJ (excitation) detector

Photon breaks Cooper pairs ➔
2 quasiparticles/photon initially,
multiply by cascade until
\( n_{\text{avg}} \approx \frac{E_{\text{ph}}}{E_{\text{g}}}; \) this qp charge then
tunnels thru oxide barrier

➔ statistical variation \( \delta n \approx n_{\text{avg}}^{1/2} \)
this gives the energy resolution of
the STJ detector

\( T << T_{\text{c}} \)

STJ – high impedance ➔
semicond. amplifier

P. Verhoeve, LTD 13
Soft X-Ray Spectrometer Using 100-Pixel STJ Detectors for Synchrotron Radiation

X-ray Absorption Fine Structures
Non-destructive measurement of charge states and bond length

Advantages of STJ-XAFS
• Separation of light elements due to good energy resolution (< 30 eV)
• High sensitivity in soft X-ray (< 1 keV)
• Large solid angle coverage of $10^{-2}$ sr
• Fast response, $>10^6$ cps @ 100-pixel
• Automated operation (Pulse tube + $^3$He)
• Energy resolution – fine control from monochromator, not STJ

Shigetomo Shiki, (AIST)-LTD13
Beam Line use of STJs – need count rate
(does not need TES energy resolution)

Natl. Inst. of Advanced Industrial
Science and Technology (AIST), Japan
0.2 – 2 keV

Stanford SSRL - 112 pixels
LBL-ALS - 9 pixels
– S. Friedrich, LLNL
First Results On The Imaging Capabilities Of A DROID Array In The UV/Visible

R.A. Hijmering, et al., ESA LTD13

DROID = Distributed ReadOut Imaging Detector

- 3x20 DROID array 33.5x 360μm² → 120 amplifiers
- Photons from back side
- Ta DROIDs, Ta/Al STJ; 11 ‘pixels’ per DROID
- Measured in S-Cam3 system (single STJs)
- Offline coincident events determination
- Testing, development in progress
**Microwave Kinetic Inductance Detector**

Absorb photon in supercond. quarter-wavelength resonator.

Inductance = magnetic + kinetic

Kinetic inductance increases and resonant freq. decreases, due to reduced number of pairs

-the hometown candidate!
First demo – mm-wave camera at CSO

Detects power.
Nb microstrip to couple mm-wavelength photons from antenna to a lossy Al strip; creates qps in Al.

Array concepts – strong, demonstrated; capitalizes on existing microwave digital sig. processing; open source collaboration (Ben Mazin, UCSB).

Collaboration in many areas of device development.
Optical TES - Structures to Enhance Detection Efficiency for Visible/IR

- 95% ± 2% system detection efficiency for 1550 nm
- Microsecond response

Superconducting Nanowire Single Photon Detectors

Meander pattern - Yale Nb device;
Performance shown below for MIT/LL devices made from NbN films

- This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.
Detection System Performance

• 2 fibers coupled to detectors in a single cryocooler
  – Each fiber is integrated with a long-working-distance focuser
  – Focuser is nano-positioned over the detector
  – Light is coupled into a semicircular detector
  – < 2 dB coupling loss

• System detection efficiency = 31%

• Timing jitter < 40 ps

• Recovery time
  – < 9 ns to 50% of initial DE
  – < 20 ns to 90% of initial DE

Slides from E. Dauler, Lincoln Lab

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Quantum Key Distribution QKD Basics

- Key idea: send quantum states such that eavesdropping must affect the state in a measurable way

- Requirements – transmit between fiber ‘terminals’ that are up to 100 km apart; use conventional fiber networks, either 1550 nm or 1300 nm (to avoid 1550 traffic)
New QKD Secure Key Rate Record

- Previous record (100+km): Stanford / NTT / NIST groups demonstrated 17 kbit/s over 105 km and 10 bit/s over 200 km fiber
- New record (100+km): 1.85 Mbit/s secure key rate over 101 km of fiber
  - Utilizes higher-efficiency superconducting detectors & better DPSK technology – E. Dauler; K. Berggren talk
NIST Fiber QKD with LANL


S. Nam, NIST Boulder
QKD secures Elections in Geneva

Press release of Geneva State Chancellery
Geneva, October 11th 2007

**Geneva is counting on Quantum Cryptography as it counts its Votes**

The Swiss national elections on October 21 will mark a world first for Geneva as the canton employs quantum cryptography to protect the dedicated line used for counting its ballots. This unbreakable data code was conceived by the University of Geneva and developed industrially by its spin-off, *id Quantique*. With this

- First Deployment: September 2006 – October 2007, with election day on October 21st
  - Installation time: 30 minutes
  - Continuous operation during more than 7 weeks
  - Encryption of a Gigabit Ethernet link

- As of 2008, used to secure all elections in the Geneva Canton
  - Used in Oct. 08, Oct. 09 and Nov. 09

Gregoire Ribordy, *id Quantique*
Bio Applications – Single Molecule

- FRET – Fluorescence Resonance Energy Transfer
- Single molecules only emit 100s to 1000s of photons (typically)
- Want to know spectrum, timing, everything
- Visible, NIR; ≈ all commercial
- SPAD (like photomultiplier)  
  ([www.labaautopedia](http://www.labaautopedia))

FRET = higher Ca concentration
FRET – if binding and unbinding
(measure cts/sec)
Bio Applications – Single Molecule; binding

- C,T,G,A – cytosine, thymine, guanine, adenine (A--T,C--G)
- Black dot is ‘quencher’, green is absorber, red = fluor
- Cancer diagnostic? NIR
- Pathology during operation – less removal
- Molecules delivered by FedEx

Nd-YAG laser, 1064 nm

GLAS immediately following integration with ICESat in June 2002 at Ball Aerospace
In Boulder, Colorado
Pictures courtesy of Ball Aerospace
Nov. 3, 2009

- Single Photon Work
- Boulder, CO

ICESat1/GLAS Detectors on orbit

Single Photon Counting Modules (SPCMs) @ 532 nm

Linear-mode near IR enhanced silicon APD @ 1064 nm

M. Kraniak, GSFC

SPCMs for aerosols

An ICESat first day track (2/20/03) across Antarctica showing ice sheet elevations in red above the reference ellipsoid. Atmospheric phenomena are shown in varying colors from light blue for thin clouds to white for opaque layers.

Vertical exaggeration 50x, 1064 nm data only shown here, RADARSAT mosaic image from CSA, visualization courtesy of GSFC SVS
FIR Single Photon Det.- Astro Motivation

- photon counting > 1 THz (\( \lambda = 300 \, \mu m \)); Quantum-dot detector demonstrated; but only 1% detection efficiency, narrow range of \( E_{ph} \).
Antenna-coupled nano-TES testing with fauxtons

(faux photon) – a new “quanta” for single photon testing; real photons = very hard
- see Karasik – has just seen real photons; Santavicca

Fast microwave (20 GHz) pulse; absorbed pulse energy (fauxton) = energy of single higher-freq. photon. Measure the reflection coefficient (due to change of R) at 1 GHz.

Leads (rf, dc) are not shown

Based on measured performance, predict for smaller TES - single 1 THz (4 meV) photons can be counted!

D. Santavicca, Yale
Future sensitivity challenges in space

Future spectroscopic space missions featuring cryocooled (4-5 K) primary mirrors (e.g., SPICA, SAFIR, CALISTO, SPECS) will require a ~ 3-order of magnitude detector sensitivity improvement.

- Photon integration below 1 THz
- Photon counting above 1 THz

END
From the following article

**Single-photon detectors for optical quantum information applications**

Robert H. Hadfield


doi:10.1038/n photon.2009.230

**Table 1. Comparison of single-photon detectors.**

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
<th>Detection efficiency, $\eta$</th>
<th>Jitter time, $\Delta t$ (FWHM)</th>
<th>Dark count rate, $D$ (ungated)</th>
<th>Figure of merit</th>
<th>Max. count rate</th>
<th>Resolves photon number?</th>
<th>Class of report</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (visible–near-infrared)$^{31}$</td>
<td>300</td>
<td>40% @500 nm</td>
<td>300 ps</td>
<td>100 Hz</td>
<td>$1.33 \times 10^7$</td>
<td>10 MHz</td>
<td>Yes</td>
<td>▲</td>
</tr>
<tr>
<td>PMT (infrared)$^{32}$</td>
<td>200</td>
<td>2% @1,550 nm</td>
<td>300 ps</td>
<td>200 kHz</td>
<td>$3.33 \times 10^2$</td>
<td>10 MHz</td>
<td>Yes</td>
<td>▲</td>
</tr>
<tr>
<td>Si SPAD (thick junction)$^{38}$</td>
<td>250</td>
<td>65% @650 nm</td>
<td>400 ps</td>
<td>25 Hz</td>
<td>$6.5 \times 10^7$</td>
<td>10 MHz</td>
<td>No</td>
<td>▲</td>
</tr>
<tr>
<td>Si SPAD (shallow junction)$^{41}$</td>
<td>250</td>
<td>49% @550 nm</td>
<td>35 ps</td>
<td>25 Hz</td>
<td>$5.6 \times 10^8$</td>
<td>10 MHz</td>
<td>No</td>
<td>▲</td>
</tr>
</tbody>
</table>

The class of report indicates the conditions under which the detector characteristics were measured;

▲ represents a commercial product specification,

▲ represents the use of the detector in a practical experiment and
<table>
<thead>
<tr>
<th>Detector type</th>
<th>Operation temperature (K)</th>
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<th>Dark count rate, ( D ) (ungated)</th>
<th>Figure of merit</th>
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<tbody>
<tr>
<td>InGaAs SPAD (gated)\textsuperscript{55}</td>
<td>200</td>
<td>10% @1,550 nm</td>
<td>370 ps</td>
<td>91 Hz</td>
<td>( 2.97 \times 10^5 )</td>
<td>10 kHz</td>
<td>No</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>InGaAs SPAD (self-differencing)\textsuperscript{57}</td>
<td>240</td>
<td>10% @1,550 nm</td>
<td>55 ps</td>
<td>16 kHz</td>
<td>( 1.14 \times 10^5 )</td>
<td>100 MHz</td>
<td>Yes</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>Frequency up-conversion\textsuperscript{65}</td>
<td>300</td>
<td>9% @1,550 nm</td>
<td>400 ps</td>
<td>13 kHz</td>
<td>( 1.7 \times 10^4 )</td>
<td>10 MHz</td>
<td>No</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>Frequency up-conversion\textsuperscript{65}</td>
<td>300</td>
<td>2% @1,550 nm</td>
<td>40 ps</td>
<td>20 kHz</td>
<td>( 2.5 \times 10^4 )</td>
<td>10 MHz</td>
<td>No</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>VLPC\textsuperscript{69}</td>
<td>6</td>
<td>88% @694 nm</td>
<td>—</td>
<td>20 kHz</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>VLPC\textsuperscript{*}</td>
<td>6</td>
<td>34% @633 nm</td>
<td>270 ps</td>
<td>7 kHz</td>
<td>( 1.83 \times 10^5 )</td>
<td>—</td>
<td>Yes</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>TES\textsuperscript{76}</td>
<td>0.1</td>
<td>50% @1,550 nm</td>
<td>100 ns</td>
<td>3 Hz</td>
<td>( 1.67 \times 10^6 )</td>
<td>100 kHz</td>
<td>Yes</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>TES\textsuperscript{20}</td>
<td>0.1</td>
<td>95% @1,550 nm</td>
<td>100 ns</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>SNSPD (meander)\textsuperscript{90}</td>
<td>3</td>
<td>0.7% @1,550 nm</td>
<td>60 ps</td>
<td>10 Hz</td>
<td>( 1.16 \times 10^7 )</td>
<td>100 MHz</td>
<td>No</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>SNSPD (new)\textsuperscript{82}</td>
<td>1.5</td>
<td>57% @1,550 nm</td>
<td>30 ps</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>No</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>QD (resonant tunnel diode)\textsuperscript{96}</td>
<td>4</td>
<td>12% @550 nm</td>
<td>150 ns</td>
<td>( 2 \times 10^{-3} ) Hz</td>
<td>( 4 \times 10^9 )</td>
<td>250 kHz</td>
<td>No</td>
<td>$\dagger$</td>
</tr>
<tr>
<td>QD (field-effect transistor)\textsuperscript{93}</td>
<td>4</td>
<td>68% @805 nm</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
<td>$\dagger$</td>
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Antenna-coupled nano-TES - testing with Fauxtons

fauxton (faux photon) – a new “quanta” for single photon testing

Fast microwave (20 GHz) pulse;
absorbed pulse energy (fauxton) = energy of single higher-freq. photon

Readout by measuring the reflection coefficient at 1 GHz with low noise cryogenic microwave amplifier

- Testing in a dark environment; no stray photons \( P << 1 \text{fW} \)
- Arbitrary tunability of fauxton energy
- Can “sneak up” on hardest problems; optimize device fabrication, performance, and signal processing while a THz single-photon test system is developed

D. Santavicca, Yale
Testing with Fauxtons

Experimental schematic for fauxton testing
Trigger signal used
Quantum Dot Detector

Transistor stays ‘on’ for a short time = counted photo eff. 2%

FIR: FET Results

Current due to 15 µm photons increases during illumination, in steps of 3 pA (if you are charitable); note 360 µA initial current. *This is a VERY challenging detection goal!*

FIR excitation – $n_{\text{photon}}$ controls current of FET

alpha spectroscopy is a powerful tool for trace actinide measurements
- environmental monitoring
- nuclear safeguards
- medical assay

alpha branching ratios higher than $\gamma$ used for smaller samples (ug-pg)

$\sim 8$ keV resolution limit of Si detectors has consequences:
- elemental overlaps  
  slow and expensive wet chemistry to separate elements
- can’t split $^{239}$Pu/$^{240}$Pu  
  slow and expensive mass spectrometry

Typical Pu Alpha Spectrum

Typical alpha spectrum
Device Characteristics

Single-photon output pulses

- L=415 nH, \( \tau = 8.3 \) ns
- L=110 nH, \( \tau = 2.2 \) ns
- L=44.5 nH, \( \tau = 0.89 \) ns

Typical detection efficiency: 40-60% at 1550 nm; T – 2-4 K

Measured timing jitter of device at T=1.8K
~1 photon/pulse

FWHM 29.7 ps

Full width at 1% 96 ps

MIT LL data
QKD – Quantum Key Distribution

• Presently use InGaAs detectors over standard fiber = demo
• Tested in Swiss network (id Quantique) – also used single photon random number generator in voting authentication for Geneva
• Goal of QKD is to create a shared secret key that is then used to encrypt data.
• Transmission rates limited by detection efficiency, fiber losses over $L \approx 100$ km, and (for fastest NbN nanowire detectors) standard electronics (electronics might not utilize the very small timing jitter of NbN detector)
• Nanowire – fast, good detection efficiency; good for QKD
• TES – higher DE, but too slow for QKD; good for other QI apps.

Ref - J.Kerman, E. Dauler
Bio Applications – Single Molecule

Yildiz Lab, UCB

- Uses 5 ns pulses from a diode pumped Q-switched Nd:YAG laser operating in the near infrared (1064 nanometers), used for the measurement of surface topography.
- Backscattered light in the green (532 nanometers) for aerosols and other atmospheric characteristics.
- Return photons collected in a 1 meter diameter telescope and the laser transmits 40 pulses/s to the surface.
- The spots produced on the Earth's surface will have a 70 meter diameter and the spacing between spots will be 175 meters, caused by the orbital motion of the spacecraft.
- $\Rightarrow$ Low power single-photon communication, distant.

M. Kraniak,
GSFC
**FIR Single-photon Detectors**

energies in solids, molecules. 1. Quantum Dot

- SET – Quantum dot in center, use Landau levels to define hf
  - Needs large B field, 50 mK; small range of $E_{ph}$
  - Very cold, and small
  - Low Det. Eff. 2%

Recent work - FIR excitation $\rightarrow$ $n_{photon}$ controls current of FET