Overview of Single Photon Detection Technologies

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Single photon detectors are one of the essential tools connecting the photonic and electronic domains at the quantum level. A plethora of single photon detector technologies and their acronyms available today – PMT, IPD, SPAD, SNSPD, MKID, RULLE, NFAD, TCB, DAPD, TES, and many others – primarily because all have significant gaps to "ideal" performance and practical usability. Some do approach ideal performance in a specific metric such as detection efficiency or dark count rate, and there is promising new progress in new material systems and new understandings of the semiconductor avalanche gain process.

The ideal single photon detector would detect every photon (100 % efficiency) with no false detections (zero dark count rate and zero after-pulsing) with photon energy limited ($\Delta E \Delta t$) timing resolution (zero timing jitter and zero recovery time) and infinite dynamic range. The ability to resolve photon number and energy too is desirable for some applications.

Fundamental to all single photon detector technologies is an optical absorption mechanism to convert the photon to a displaced charge (electron) and an electronic gain mechanism to amplify the signal over electronic Johnson (thermal) noise. In most cases the electronic gain mechanism requires a recovery time to restore the detector to an initial state. Single photon detector technologies may be categorized by their optical absorber, gain mechanism, and recovery mechanism. Table I groups single photon detector technologies by these mechanisms.

At the present time, superconducting nanowire single photon detectors (SNSPD) offer the best combination of high detection efficiency (>70%), low false detections (< 100 Hz), and high timing resolution. (~50 ps). However, they require bulky cryogenic refrigeration to 4.2 K or lower, have small absorber areas best measured in square microns, and arrays sizes have been limited to a few pixels (<10) due to low yield and the difficulties of running many signals from a few Kelvin up to room temperature. For large absorber areas, photomultiplier tubes (PMT) can offer single photon detection performance with absorber areas from square millimeters up to large fractions of a square meter. However, they require kilovolt bias supplies and vacuum photocathode performance limits detection efficiency and timing resolution. Operational lifetimes may be only a few thousand hours. PMT's sensitive to infrared wavelengths can suffer from dark count rates can in the megaHertz range even with cooling to -60 C or lower.

For the last fifty years, extensive efforts have been placed into development of semiconductor single photon detectors using either "avalanche" impact ionization or photoconductive gain mechanisms. Most popular are semiconductor avalanche photodiodes operated in Geiger mode, where the detector is biased above breakdown, then triggered into continuous avalanche by absorption of an incident photon or an internal "dark" event, followed by a reset of the avalanche by an external electrical circuit. In the visible spectral region silicon detectors can achieve detection efficiencies over 50% with dark rates less than a kiloHertz. InGaAs is a popular absorber in the near infrared. However, because of the high rate of dark carrier generation in InGaAs, and because of after-pulsing caused by the thermal release of trapped avalanche carriers after the initial avalanche pulse, device areas are typically limited to less than 1000 square microns and a minimum recovery (dead) time on the order of 1 microsecond is required between photon detections. Device cooling reduces the dark carrier generation rate, but increases the lifetime of trapped carriers, which results in increased dead time before the detector can be re-biased above breakdown. For example, an InGaAs Geiger-mode avalanche photodiode with a 20 micron diameter might typically have a 100 KHz false count rate at -50 C with a 3 microsecond dead time, resulting in a maximum count rate of less than 300 KHz.

Progress in single photon detector development has been, and will continue to be slow. It can easily take a $5M investment to bring a new detector technology variant to market at a useful level of performance. But progress will continue and single photon detectors are "essential" for quantum future technologies. In the near term (1-5 years) there will be rapid maturation of SNSPD arrays and faster transition edge sensor (TES) detectors. In the semiconductor domain, resonate-cavity enhanced arrays will meet niche application and increasing levels of integration will lead to innovations such as hybrid semiconductor APD / FET pixels. In the longer term (5-10 years) after-pulsing reduction in InGaAs avalanche photodiodes will remain a focus, and wavelength ranges will be extended with single photon detection in new material systems and device variants such as semiconductor nanowire single photon detectors. Finally, there is still much room for blue-sky concepts such as nanotube photocathodes, miniaturized vacuum device arrays, and specialty detectors, such as direct detection of orbital angular momentum.

	Superconductor		Semiconductor						Photocathode	
ABSORBER	W, Ti, …	Nb(Ti)N, $W_{(1-x)}$, Si_x, VaN, …	Si, SiC, InGaAs(P), InSb, GaN, …						metallic / semi-metallic	
			Extrinsic As, B, …	Intrinsic						
GAIN	Broken Cooper Pairs		Non-Markovian Impact Ionization			Photo-conductive		Markovian Impact Ionization	Dynode Chain / Micro-channels	Kinetic Ionization
RECOVERY	Weak Thermal Link	Fast Phonon + Kinetic Inductance	Tunneling and / or Carrier Diffusion						Electron Diffusion	
	Transition Edge Sensor TES	Superconducting Nanowire SSPD, SNSPD, SNA, SNDA	Si:As Photon Counter SSPM, VLPC, NIPC	Heavy hole / electron APD HgCdTe,	Negative Avalanche Feedback DAPD, TCB, NFAD	Semiconductor Nanowire	Quantum-dot FET QDOFET	Geiger-Mode Avalanche Photodiode (GM-APD, SPAD, SPM, SSPM, MPPC, …)	Photo-multiplier (PMT, MCP, RULLI)	Intensified Photodiode (IPD, HPD, HPMT)

Table I. Summary of Single Photon Detector Technologies