Single-Photon and Photon-Number-Resolving Detectors

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Abstract: Several important advances were reported in single-photon detectors and photon-number-resolving detectors in 2011. New materials with smaller superconducting gaps were demonstrated for superconducting nanowire single-photon detectors (SNSPDs) that led to improved signal-to-noise ratios and infrared performance. Faster superconducting transition edge sensors (TESs) were demonstrated by using normal metal heat sinks. Both TESs and SNSPDs were evanescently coupled with waveguides as a step toward demonstrating quantum photonic integrated circuits. Photon-number resolution has been the goal in several demonstrations using semiconductor detectors, and recent results suggest a potential convergence of Geiger-mode and linear-mode avalanche diodes in exhibiting the high-gain, low-noise analog behavior necessary to reach this goal. There has also been progress focused on additional trends in single-photon avalanche diodes (SPADs) for high-rate counting and detector array scaling.

Index Terms: Single photon detectors, photon number resolving detectors, single photon avalanche diodes, superconducting single photon detectors, quantum optics.

Significant advances in both superconducting and semiconducting single-photon detectors have been achieved in recent years, and these devices have largely supplanted photomultiplier tubes for many applications because of their ease of use and especially their superior performance. There are many emerging applications that require single-photon detectors, including single-molecule fluorescence and detection, LIDAR, quantum key distribution, and linear optical quantum computing. The key performance metrics for single-photon detectors include detection efficiency (DE), dark-count rate (DCR), timing jitter, and reset time. We will describe recent advances in these metrics that enable emerging applications.

Until last year, superconducting nanowire single-photon detectors (SNSPDs) were typically made from NbN or NbTiN, with single-photon response from the UV to the near-infrared (IR). These devices operate at 2–4 K. They are very fast, with timing jitter of around 30–100 ps achieved [1]. Robust coupling to single-mode optical fiber and a cryogen-free refrigerator has enabled SNSPDs to be deployed in several interesting demonstration experiments, including QKD [2] and LIDAR [3]. SNSPDs are of particular interest for wavelengths longer than 1000 nm, where Si single-photon avalanche diodes (SPADs) are replaced by InGaAs SPADs.

Detection of photons with wavelengths longer than 1.5 μm using NbN or NbTiN is challenging because the hot spot that develops when a photon is absorbed is relatively small. This limits the

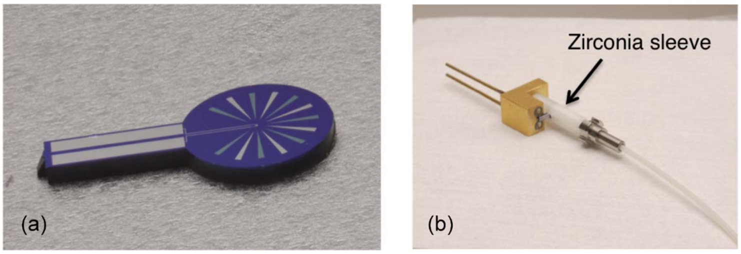

Fig. 1. (a) A completed TES chip that is freed from the wafer. The diameter of the circular part of the chip is 2.5 mm. (b) A completed assembly with a zirconia sleeve fitted over the chip and a single-mode optical fiber and ferrule.

performance of NbN SNSPDs with wire widths of ∼100 nm. However, recent papers [4], [5] have reported improved infrared performance, including some limited response at 3.5 μm, by using narrow wire widths ($\leq$ 50 nm). Two recent papers [6], [7] demonstrated new materials with smaller superconducting gaps to alleviate this problem. Amorphous NbSi, with nanowire widths of 160 nm, was demonstrated to have relatively better DE for wavelengths longer than 1550 nm when compared to NbTiN SNSPDs [7]. Amorphous tungsten silicide ($\mathrm{W_xSi_{1-x}}, \mathrm{x} \sim 0.25$), with nanowire widths of 150 nm, demonstrated 19%–40% DE from 1280–1650 nm, with a DCR of ∼1 Hz [6]. Furthermore, the WSi SNSPD demonstrated a wide plateau at the maximum DE versus bias current curve. This plateau is very significant as it is indicative of saturated internal quantum efficiency, a requirement for making 100% efficient detectors. Both NbSi and WSi are deposited by room temperature sputtering, which is significantly more forgiving than the high temperature processing typically used for NbN.

Superconducting transition edge sensors (TESs) made from tungsten have demonstrated the highest system DE (SDE), i.e., ∼95%, of any single-photon detector [8]. The W-TES is also an outstanding photon-number-resolving detector because of this high efficiency, low DCR, and linear response function. However, the weak link between the electrons and phonons in tungsten also makes the recovery time slow, i.e., ∼5 μs (the recovery time is the time it takes for the TES to be able to respond to another single photon). Experimental demonstrations showed devices with the recovery time reduced to ∼1 μs by using a normal-metal heat sink to speed up the electron cooling in the TES [9]. It is notable that this speed-up occurs without any degradation in photon-number-resolving capability. The technique has the potential to reduce the recovery time below 50 ns.

Just as researchers in conventional optoelectronics have embraced photonic integrated circuits (PICs) for the benefits of reduced size, ease of packaging, and reduced coupling losses, the nascent field of quantum information has begun investigating quantum PICs (QPICs). Until recently, single-photon detectors were the missing component from QPICs. However, both TESs [10] and SNSPDs [11] have recently been evanescently coupled to waveguides as a stepping-stone toward complete QPICs. NbN SNSPDs have been integrated on GaAs waveguides. These devices show ∼20% device efficiency (3.4% SDE, including waveguide coupling loss) at a DCR of ∼10 kHz and timing jitter of ∼60 ps. These metrics are similar to normal incidence measurements from NbN devices. Photon-number-resolving W-TESs have recently been integrated onto silica waveguides. The SDE of these devices is 7.2%, somewhat lower than the predicted value of 13.2%. This discrepancy may be due to waveguide loss or fiber splice loss. Both of these devices are promising for future implementation of QPICs.

Another significant advance in packaging of superconducting detectors was introduced by Miller *et al.* [12] Differential thermal expansion can cause large dimensional shifts in components when devices are cooled from room temperature to their cryogenic operating temperature. This can lead to misalignment problems, especially when using single-mode optical fiber (mode field diameter of ∼9 μm). The new packaging scheme is shown in Fig. 1. The superconducting detector chips are released from the silicon wafer by etching entirely through the substrate. The chips are then placed on a custom-designed mount and a (commercial off-the-shelf) zirconia alignment sleeve is slid over the detector chip. The single-mode optical fiber and ferrule are then attached to the open end of the zirconia sleeve until the fiber touches the chip. This arrangement enables reproducible assembly with low coupling loss ($< 1\%$) and makes the device robust to thermal cycling.

In addition to advances made in superconducting single-photon detectors, there were new reports of photon-number resolution in semiconductor-based single-photon detectors in 2011. One breakthrough [13] uses a scaled-down silicon-on-insulator (SOI) metal–oxide–semiconductor field-effect transistor (MOSFET) with photoconductive gain. In this device and similar devices in GaAs [14], photogenerated individual holes are trapped below the negatively biased gate and clearly modulate the current flowing in the small silicon nanowire conduction channel with steps as photons are absorbed. The size of the step is proportional to the number of photons absorbed. It remains an interesting challenge to raise the effective area to obtain DE useful for applications.

For Geiger-mode detectors to detect the photon number in a pulse of light, the challenge has actually been to *reduce* the effective gain and provide more highly consistent avalanches. A demonstration by the Toshiba group [15] in Cambridge, U.K., shows the feasibility of obtaining sufficient analog behavior with Geiger-mode operation to exhibit photon-number resolution. Using a conventional silicon SPAD with a self-differencing bias technique that was initially developed to achieve gigahertz-scale photon counting rates by use of InGaAs SPADs [15], [16], they were able to distinguish events with up to four photons absorbed by the detector. Interestingly, the self-difference technique also improved the DE, reduced the DCR, and reduced the afterpulsing rate compared to the conventional biasing technique for this SPAD.

Yet another approach to realizing photon-number resolution with avalanche photodiodes is the attempt to achieve single-photon sensitivity using linear-mode APDs, in which the detectors are operated below their avalanche breakdown voltage (in contrast to SPADs, which are designed for operation above the avalanche breakdown voltage). From the perspective of photon counting, it is interesting to note that advances in SPADs and linear-mode APDs are beginning to blur the distinctions between them. For inherently analog linear-mode APDs, the primary challenge has been to achieve much higher gain while maintaining low noise. The most promising detector materials system for reaching this goal is mercury cadmium telluride (HgCdTe), which exhibits very low excess noise (close to 1) when grown with an appropriate stoichiometry. Two groups recently reported [17], [18] HgCdTe detector performance with gains of 100 to 500 providing single-photon sensitivity and photon-number resolution. While these detectors are not as sensitive as SPADs operated in Geiger mode—e.g., using a metric such as noise equivalent power, SPADs exhibit two to three orders of magnitude better performance—the inherently analog response of linear-mode HgCeTe APDs makes photon-number resolution possible if the following amplifier circuitry is sufficiently low noise and if their lower operating temperatures can be tolerated. In achieving these results, the difficulty in designing the necessary amplifier circuitry is at least as challenging as that of the APD detector design.

A final example of significant recent progress in SPADs is the drive for scaling to larger formats for single-photon imaging. A Delft University group has reached a format of 160 × 128 pixels with 50 μm pitch by use of a deep-submicrometer (0.13 μm) CMOS process [19]. Monolithic circuit integration involving 60 million transistors on each chip provided every pixel with the ability to record photon time-of-arrival values for various medical applications employing fluorescence lifetime measurements. The trend toward even larger SPAD imaging array formats will continue as these sensors find further applications in 3-D LIDAR imaging and low-light-level imaging.

Research in single-photon detectors remains an active field with advances in both superconducting and semiconducting devices. For some performance metrics, superconducting devices exceed the performance of their semiconductor-based counterparts. However, more widespread adoption remains a challenge because of difficulties in implementation and/or integration into systems. Some of the improvements in 2011 could address these issues. Analogously, semiconducting devices continue to improve in DE and photon-number resolution, approaching the metrics achieved with superconducting devices.

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