Silicon Single-Photon Detector with 5 Hz Dark Counts

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Abstract: We report operation of a passively quenched silicon single-photon avalanche photodiode (SPAD) at extremely low dark count rate of 5 Hz. This was achieved by lowering the temperature of a PerkinElmer C30921S SPAD down to -77 °C. We found that the quantum efficiency at 780 nm remained constant over a wide range of cooling temperatures from -32 °C down to -77 °C. The after-pulsing characteristics, however, depended on the cooling temperature.

OCIS codes: (040.1345) Avalanche photodiodes (APDs), (270.5570) Quantum detectors

Single-photon counting detectors are widely used for measuring extremely weak light and they are one of the most basic tools used in precision metrology, biophysics, astrophysics, and quantum optics/information. Presently there exist a number of competing technologies for single-photon detection, e.g., photomultipliers, superconducting single-photon detectors, visible light photon counters, single-photon avalanche photodiodes (SPADs). When it comes to real world applications which require detecting single photons in the visible wavelengths and in the fiber-optic communication bands, however, SPAD is the most practical choice due to its superior characteristics and relatively lower costs.

For detecting single-photons in the visible wavelength region, silicon SPADs are most often used [1]. Although Si SPADs cost less than other single-photon detectors, complete detectors are not inexpensive: commercial actively quenched SPAD modules that exhibit dark count rate around 400 Hz cost around $5000 each (much more for dark count rates less than 50 Hz) [2]. Modules with extremely low dark count rate of less than 1 Hz also exist, but they have very small photosensitive area (20 μm) and low quantum efficiency at longer wavelengths (about 10% at 780 nm) [3].

In this paper, we report an inexpensive (under $1000 in components) home-made single-photon detector which exhibits dark count rate of 5 Hz. The detector is based on a passively quenched PerkinElmer C30921S SPAD [2]. This SPAD has large input aperture (250 μm) and high quantum efficiency (above 50% at 780 nm). Low dark count rate has been achieved by lowering the temperature of the APD down to -77 °C. Our tests show that the quantum efficiency at 780 nm remained constant in the temperature range from -32 °C down to -77 °C.

Let us first describe the SPAD package shown in Fig. 1(a). The SPAD is mounted on a 4-stage thermoelectric cooler (TEC; Kryotherm TB-4-(83-18-4-1)-1.3). The TEC-SPAD assembly is placed in an aluminum alloy housing with an anti-reflection coated window through which the light enters. The housing is sealed with o-rings to keep it air-tight. All the electronics remains outside the housing. To minimize heat flow to the cold plate, electrical connections to the SPAD are made with 25 μm gold wires. To reduce convection, the SPAD and upper stages of the TEC are surrounded with cut-to-shape styrofoam (of ordinary type commonly found in, e.g., shipping packaging for consumer electronics). Finally, to prevent ice formation at the SPAD aperture, we have placed desiccant in the detector housing (down to at least -60 °C, we've had good results with Drierite; for lower temperatures we've tried P_2O_5 with mixed success).

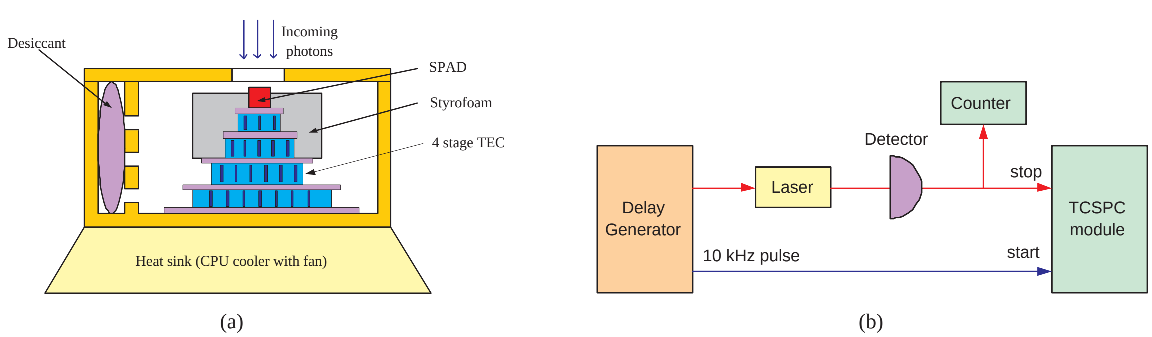
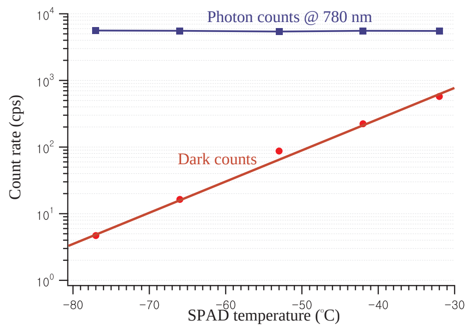
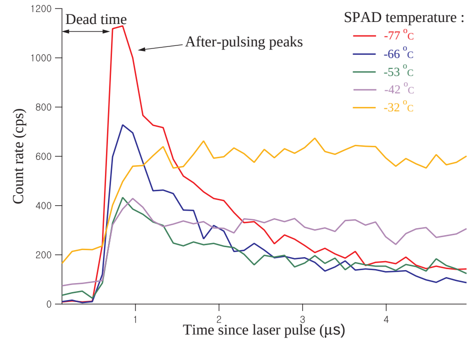


Fig. 1: (a) Diagram of the complete SPAD package. (b) Experimental setup to measure the after-pulsing probabilities.



(a)



(b)

Fig. 2: (a) Relative quantum efficiency and dark count rate of the detector depending on the SPAD temperature. (b) The after-pulsing characteristics of SPAD as a function of its temperature.

The electronics consist of a high-speed comparator for sensing the onset of avalanche, NIM and TTL output buffers, a high-voltage bias power supply for the SPAD, and a TEC controller. The electronics has originally been designed by C. Kurtsiefer and his coworkers, and modified by us. We used 390 kohm bias resistor in the passively quenching scheme, and set SPAD bias voltage 11 V above the threshold voltage at which the detector started producing counts.

The operating characteristics of our detector were tested including the quantum efficiency, dark count rate, threshold voltages, and after-pulsing probabilities. The dark count rate as a function of the SPAD temperature is shown in Fig. 2 (a). The data show that the dark count rate drops exponentially as the temperature is lowered. The dark count rate of 600 Hz per second at -32 °C drops down to less than 5 Hz at -77 °C.

The quantum efficiency as a function of the SPAD temperature was measured as follows. A CW laser beam at 780 nm was attenuated and directed to the SPAD. The count rate was measured while varying the SPAD temperature. Although this measurement does not give absolute quantum efficiency, it provides relative quantum efficiency as a function of the operating temperature. The plot in Fig. 2(a) shows that the quantum efficiency is insensitive to the temperature down to -77 °C. Based on calibrated quantum efficiency measurements of this SPAD model reported in the literature, we expect our detector to have at least 50% quantum efficiency even when its dark counts rate is $<$5 Hz. This is several times higher quantum efficiency than other commercially available low dark count SPADs.

The after-pulsing characteristics of the SPAD were measured using the experimental setup shown in Fig. 1(b). A pulsed laser triggered with an electrical signal emits a 20 ns laser pulse which is subsequently attenuated and directed to our detector. The triggering electrical signal and the TTL output signal of the detector are used as the start and the stop, respectively, for the time-correlated single-photon counting (TCSPC) module. The TCSPC histogram then displays the photo-count distribution in time. The count probability as a function of time elapsed since the laser pulse is shown for several SPAD temperatures in Fig. 2(b). The experimental data at -32 °C show that a short period of dead-time follows the main photo-detection event (not shown in the figure) and then the count probability rises to the dark-count level. There are no apparent after-pulsing effects at this temperature. At lower temperatures, however, we see a clear signature of increased after-pulsing probability, as evidenced in the increased counts (above the dark count level) right after the dead time. The after-pulsing probabilities and the decay times increase as the APD temperature is lowered. For full characterization of afterpulsing at low temperatures, a TCSPC measurement over a longer time scale is needed. The optimum operating temperature for the SPAD would depend on the application and on the expected photon count rate; however the data in Fig. 2(b) already hints it lays below -32 °C for the passively quenching scheme.

In summary, we have described a home-made detector based on passively-quenched Si SPAD which exhibits an extremely low dark count rate of 5 Hz and simultaneously has relatively large sensitive area and high quantum efficiency. All the data in this summary are from only one SPAD sample, however we will take improved measurements on several samples and report them in the talk. Other performance characteristics as well as optimal operating parameters, limitations, and potential improvements will be also presented.

References

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