InGaAsP/InP Single Photon Avalanche Photodetectors For 1.06 µm Free-Running Photon Counting

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Abstract: We demonstrate large area InP-based single photon avalanche diodes capable of free-running operation at 1.06 µm with dark count rates below 1000 Hz, detection efficiencies greater than 10%, and single photon count rates exceeding 1 MHz.

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The detection of single photons at 1.06 µm is of considerable importance for lidar systems designed for remote sensing and ranging [1] as well as for free-space optical communications in photon-starved applications [2]. However, silicon-based single photon avalanche diodes (SPADs) used at shorter wavelengths have very low single photon detection efficiency (~1–2%) at 1.06 µm, while InP/InGaAs SPADs designed for telecommunications wavelengths near 1.5 µm exhibit dark count rates that generally inhibit non-gated (free-running) operation. To bridge this "single photon detection gap" for operation just beyond 1 µm, we have developed large area (80 – 200 µm diameter) InP-based InGaAsP quaternary absorber SPADs optimized for operation at 1.06 µm and based on a highly reliable planar geometry avalanche photodiode structure. In this paper, we present the first demonstration of non-gated operation for an InP-based SPAD which, when operated at temperatures accessible using thermoelectric coolers, exhibits dark count rates and photon counting rates comparable to those of commercial Si SPADs while achieving detection efficiencies far surpassing those of the Si-based detectors.

When an avalanche photodetector is biased above its breakdown voltage, the creation of a single electrical carrier can induce a run-away avalanche that gives rise to a detectable macroscopic current. In this mode of operation, often referred to as Geiger mode, the detector is sensitive to the absorption of a single photon. Our SPAD device design shares similarities with InP/InGaAs SPAD designs we have employed for longer wavelength operation with a 1.65 µm cutoff [3]. Related mesa-based small-area devices have been studied by researchers at MIT-Lincoln Labs [4,5]. For the detection of photons at 1.06 µm, we employ an InGaAsP absorption layer with a 295 K cutoff wavelength of ~1200 nm. Avalanche gain occurs via impact ionization in an undoped InP multiplication layer. The absorption and multiplication layers are separated by a doped InP field control layer that maintains a high electric field in the multiplication region to induce impact ionization while maintaining low field in the absorption region to minimize tunneling-related dark carrier creation. Grading layers smooth the abrupt heterointerface that would exist between the InGaAsP absorber and the InP field control.

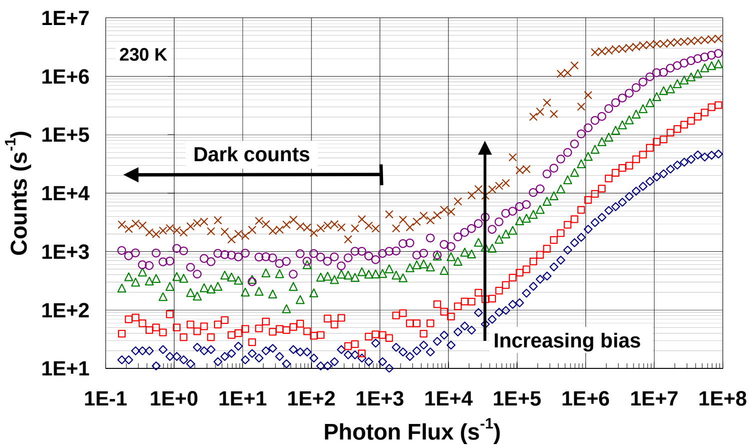

Fig. 1. Free-running counts per second as a function of photon flux at 1064 nm for an 80 µm diameter InP-based SPAD at 230 K for five different bias voltages using an active quenching circuit.

Free-running photon counting data were obtained using a Poisson source of 1.06 µm photons, the SPAD detector, and appropriate backend electronics. We used a commercially available active quenching circuit (AQC) described in [6], and photon flux was calibrated using a reference Si-based SPAD detector. The data in Fig. 1 were obtained by measuring total counts at 230 K from the SPAD-AQC detector as a function of photon flux for an 80 µm diameter active area SPAD. The constant count rate for low photon fluxes (< 10^3 s^{-1}) is due to dark counts. For flux values larger than ~10^4 s^{-1}, the count rate increases approximately linearly with photon flux, indicating single photon counting with a dynamic range of three orders of magnitude in photon flux. The effects of afterpulsing can be minimized by (i) limiting the overbias voltage and time above breakdown, (ii) restricting the application to time-of-flight uncertainty less than the de-trapping time, and (iii) developing detector arrays [4].

From the data in Fig. 1, the detection efficiency is computed using $(C_{tot} - C_d)/\Phi$, where C_{tot} is the total count rate, C_d is the dark count rate, and Φ is the photon flux. Using C_{tot} at $\Phi \sim 10^6$ s^{-1}, we calculate the 230 K dependence of DCR on detection efficiency as shown in Fig. 2. (For the highest count rate dataset, indicated by 'x', we used $\Phi \sim 10^5$ s^{-1} since data at higher fluxes were noisy.) Similar data were obtained for 295 K operation, with DCR larger by a factor of ~100.

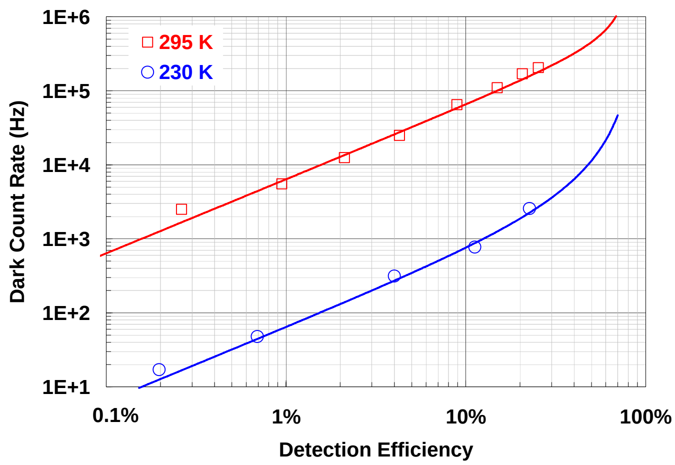

Fig. 2. Dark count rate vs. detection efficiency at 1064 nm. Experimental data at 295 K (squares) and 230 K (circles) were extracted from counts vs photon flux measurements (as presented in Fig. 1 for 230 K data). The solid lines are simulated performance using the formalism in [5].

Also presented in Fig. 2 are theoretical simulations for the expected performance of these 1.06 µm SPADs. Following the formalism of Donnelly, et al. [5], avalanche probabilities are calculated using field-dependent ionization coefficients. Non-local effects are neglected, as is valid for multiplication layer thicknesses ~ 1 µm and larger. Dark carrier generation is considered for all layers in the structure and includes temperature-dependent models for generation-recombination, band-to-band tunneling, and trap-assisted tunneling mechanisms. As seen in Fig. 2, there is close agreement between our experimental data at 230 K and 295 K and the simulated performance at these two temperatures. A comparison of the different dark carrier mechanisms shows that at 295K, generation current in the absorber and trap-assisted tunneling in the multiplication layer are both significant. At 230 K, trap-assisted tunneling in the multiplication layer dominates the DCR.

The data in Fig. 2 illustrate that at a detection efficiency of 10%, 80 µm diameter devices exhibit free-running operation with dark count rates below 1000 Hz when operated at 230 K. Under these conditions (corresponding to the dataset indicated by circles "○" in Fig. 1) photon counting rates exceeding 1 MHz have been obtained. Significantly higher detection efficiencies (>30 %) are achievable with acceptable tradeoffs in dark count rate.

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