# Semiconductor Avalanche Diode Detectors for Quantum Cryptography

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## Abstract

Advances in semiconductor single photon avalanche diode detectors have enabled an expansion in photon-counting application areas in the near-infrared. Of particular relevance is the application area of quantum key distribution in which secure encryption keys can be shared between users using information derived from streams of encoded single-photons. We report progress towards the objective of a practical, high efficiency detector at the strategically important 1550nm wavelength band.


## I. Introduction

Single-photon counting and single-photon timing in the infrared spectral range, and in particular at the 1550nm wavelength band, have become increasingly important in a number of applications such as time-resolved photoluminescence [1], optical time-domain reflectometry (OTDR) [2], eye-safe time-of-flight laser ranging [3], and imaging. More recently they have been employed in quantum key distribution (QKD) [4][5], and non-invasive testing of VLSI circuits [6]. Commercially available InGaAs/InP avalanche photodiodes (APDs) designed for use in linear multiplication mode have been experimented and investigated in photon-counting mode [7][8], in order to extend the spectral range of single-photon detection beyond the limit (approximately $\lambda \sim 1000$nm) of Si single-photon avalanche diode (SPAD) detectors. These devices exhibit good single-photon detection efficiency (SPDE) of > 10% and fast timing, with sub-nanosecond jitter, but they are plagued by strong afterpulsing phenomena, which severely restrict the maximum counting rate. In the present work, InGaAs/InP avalanche diode with planar geometry have been specifically designed and fabricated for developing single-photon detectors operating in Geiger-mode. This study represents a fabrication program for planar InGaAs/InP SPADs and highlights some important issues in device design.

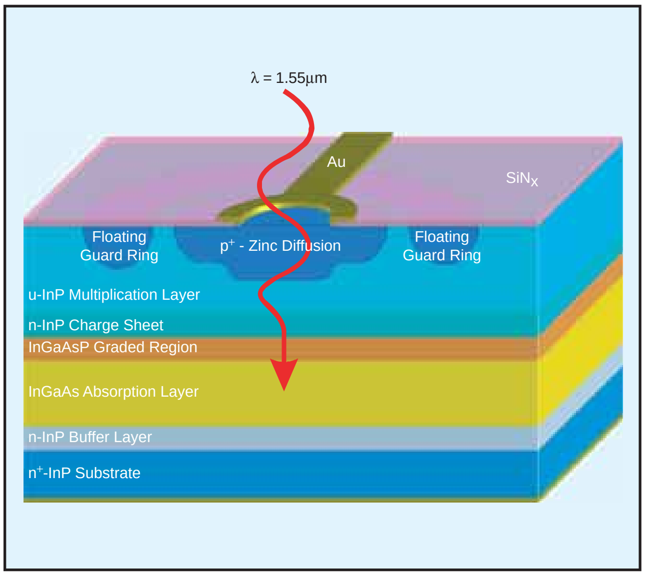


*Figure 1. SPAD cross-section*


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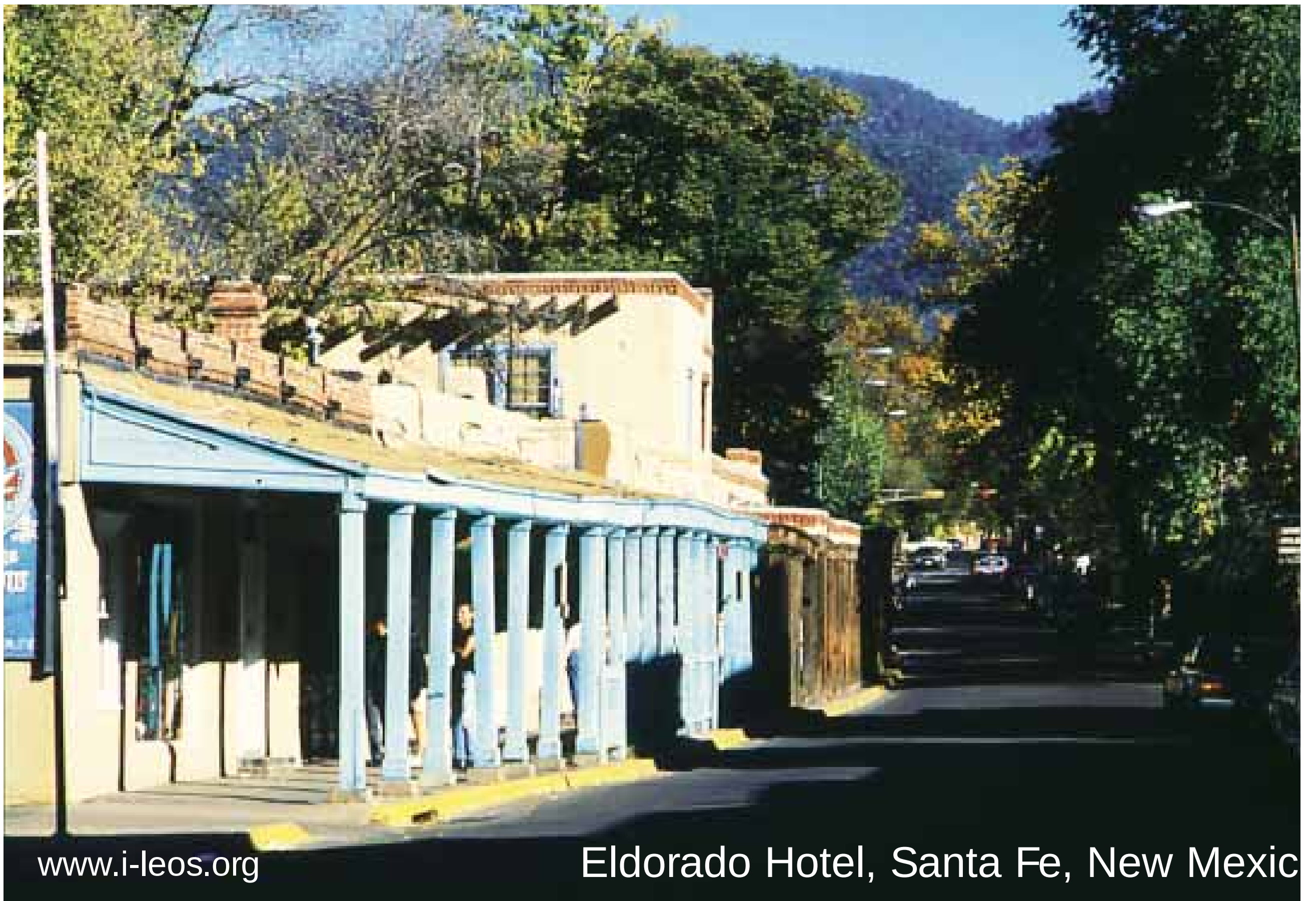
## II. InGaAs/InP Device Structure and Characterization

The SPAD design is based on a planar structure of the type originally devised for APD devices operating in linear amplification mode with separate regions of absorption grading and multiplication (SAGM) [9][10], shown in Figure 1. The schematic one-dimensional band-structure for this structure is shown in Figure 2. This structure is designed so that photo-generated holes created in the narrow-gap InGaAs layer efficiently drift into the wider-gap InP multiplication region. A thin quaternary layer is used to smooth the large valence band discontinuity between the InGaAs and InP. It is necessary to design a device in such a manner since the narrow-gap InGaAs region cannot be used for multiplication due to the high probability of tunneling in this material at the electric fields required for multiplication.

The epitaxial layer structures were grown by metal-organic chemical vapour deposition (MOCVD), and the p-n junction was formed by diffusing the p-type dopant Zn into the top InP layer. Two separate Zn diffusion steps were used in order to shape the active area and form multiple guard rings to avoid the effects of avalanche breakdown occurring preferentially at the edges of the device rather than in the central, optically addressed region. Several device issues were examined [11], for example the use of different quaternary layer structures. For one example we used a device structure with a single quaternary layer of an exactly intermediate bandgap between InGaAs and InP – which we shall denote SPAD-1Q – and a second device which was identical in all respects except that the quaternary was composed of three sub-layers which represented equal steps in bandgap – which we will denote SPAD-3Q.

To characterize these detectors, the devices were cooled to reduce the effects of thermally-generated carriers causing dark counts – the lower the temperature the lower the

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dark count rate within the devices. It was also necessary to electrically gate the detectors, so that they operated above the avalanche breakdown point – the so-called Geiger mode – only for a short period around the expected photon arrival time.

Figure 3 shows the single-photon detection efficiency and dark count rates of these detectors as a function of temperature for similar detector overbias levels. It is particularly evident that there is a large improvement in detection efficiency with the "stepped" quaternary layer. Figure 4 illustrates the jitter as a function of overbias, described in terms of a full-width at half maximum, for the SPAD 3Q device fabricated in different device diameters. It is also evident that the detectors have the potential of timing at a level consistent with GHz clocking in a quantum key distribution application. The expected device diameter dependence of the jitter is due to the lateral spreading of the avalanche during build-up across the full device diameter.

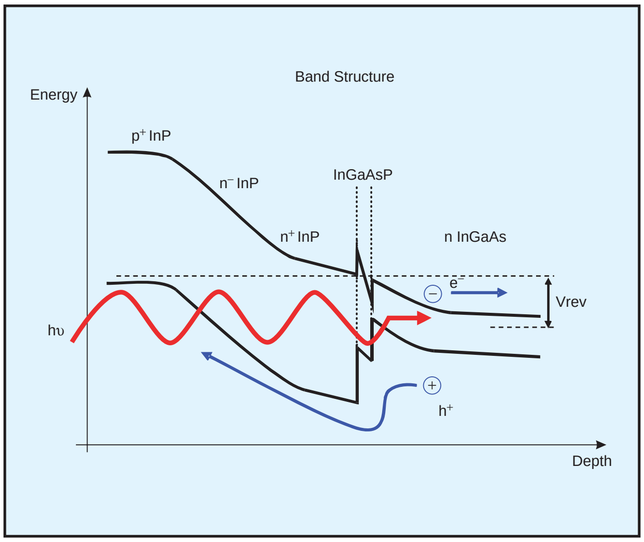


*Figure 2. Schematic energy band-structure of InGaAs/InP SPAD*

In terms of device sensitivity, one figure of merit is noise equivalent power, which takes into account the single-photon detection efficiency and the dark count rate. Figure 5 illustrates the NEP spectra of selected single-photon detectors. It is clear that in terms of single-photon counting performance, the InGaAs device shows poor NEP performance in comparison with the equivalent room temperature Si device operating at wavelengths less of than 1000nm.

## III. After-pulsing Analysis

One of the major issues in the use of InGaAs/InP photon-counting avalanche diode detectors has been the deleterious effects of afterpulsing. In these detectors, carriers are trapped during the avalanche process and are released some time later, triggering further avalanches and consequently increasing the dark count rate, and reducing the detector sensitivity. The results in Figure 6 are from a two-gate variable delay experiment which measures afterpulsing probability as a function of time after the initial avalanche event. This approach, when used with varying device temperature, helps highlight the type of traps from which the afterpulsing phenomenon originates. Arrhenius-type plots of the afterpulsing times indicate activation energies in the region of 300-400meV. As part of this ongoing study, we are examining the afterpulsing decay times of several test structures to indicate more closely the origin of the trapping phenomenon. Figure 7 illustrates the afterpulsing behaviour of an InGaAs/SPAD device and the comparison with two similar test structures, under similar experimental conditions. The first test structure was identical to the SPAD device but

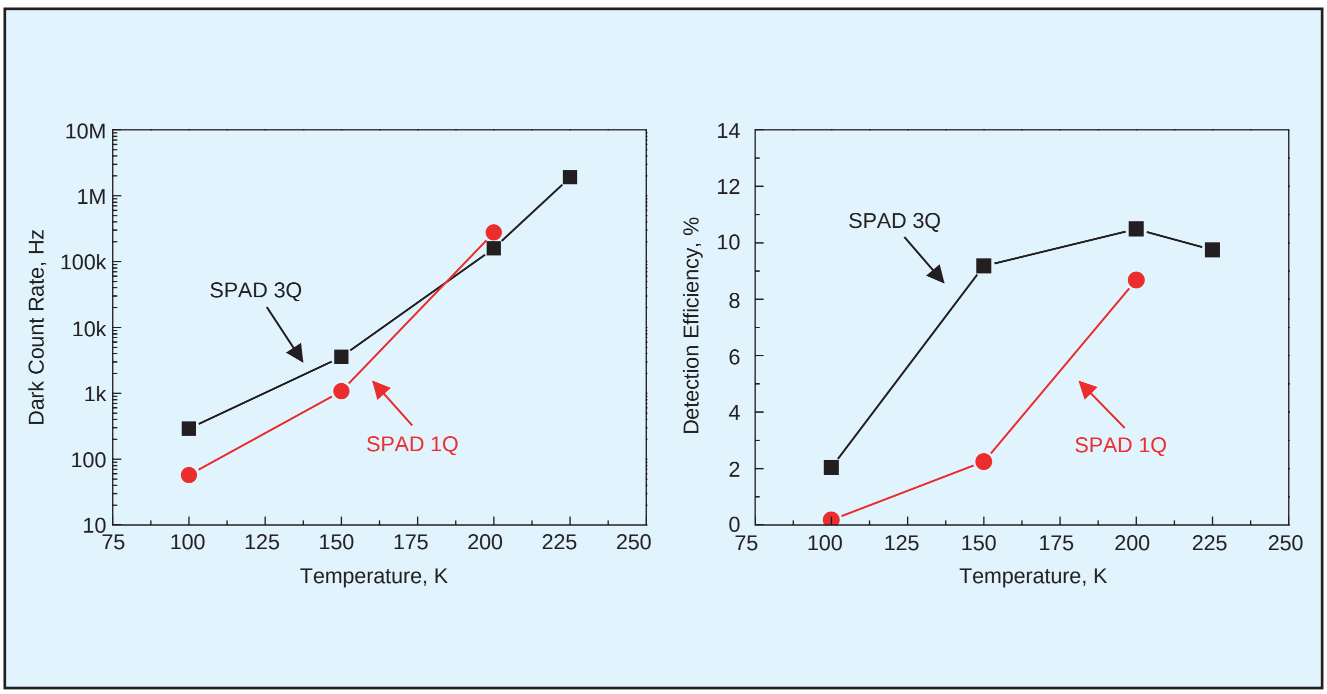


*Figure 3. Dark count rate and single-photon detection efficiency as a function of temperature for SPAD-1Q and SPAD-3Q.*

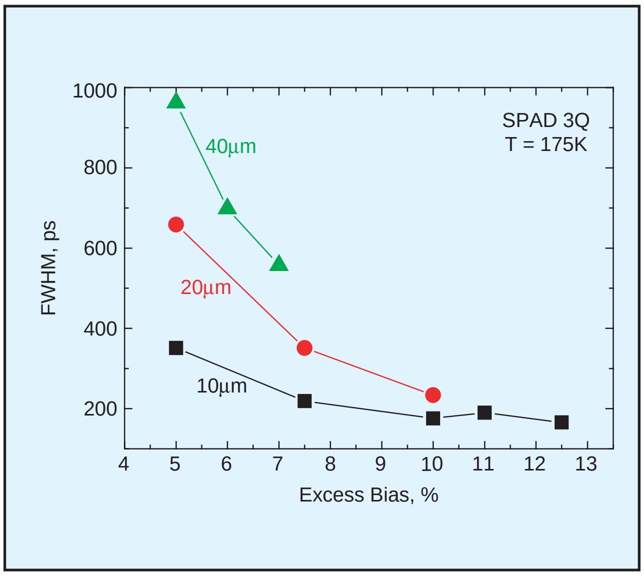


*Figure 4. Device jitter (full-width-at-half-maximum) of SPAD-3Q with device diameters of 10, 20 and 40 µm.*

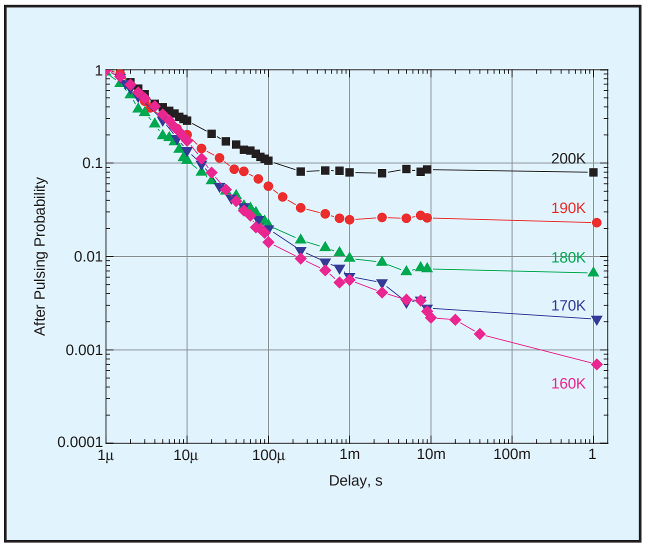


*Figure 6. Afterpulsing probability versus time after avalanche for SPAD-3Q at operating temperatures of 160K, 170K, 180K, 190K and 200K.*

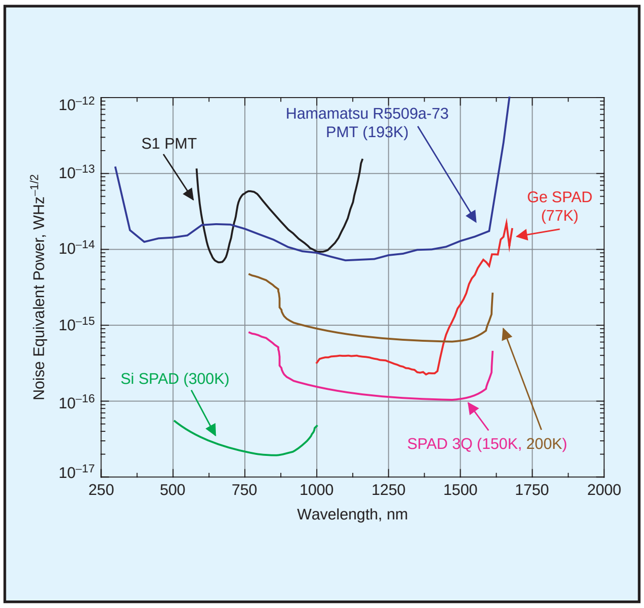


*Figure 5. Noise equivalent power spectra of several selected single-photon detectors*

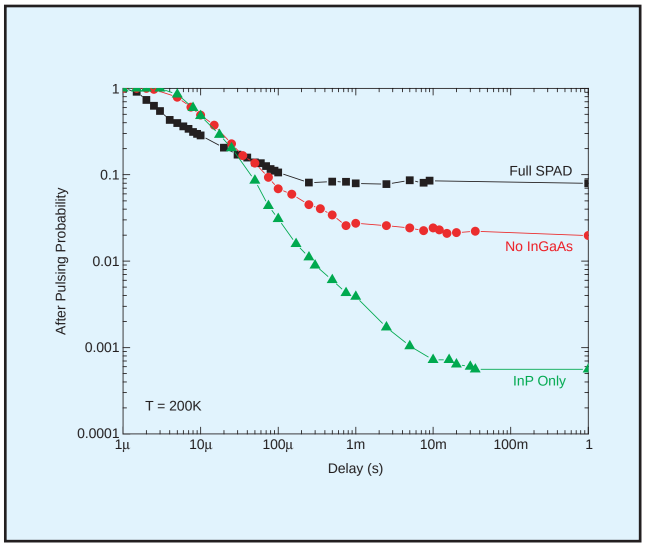


*Figure 7. Afterpulsing probability versus time after avalanche at operating temperature of 200K for (1) SPAD-3Q; (2) similar structure without InGaAs layer; (3) similar design without InGaAs and InGaAsP*

with the InGaAs layer removed and the second was with both the InGaAs and InGaAsP layers removed. Whilst these measurements are ongoing at the time of writing, it appears that similar lifetimes and activation energies are observed – leading to the likelihood of the afterpulsing behaviour being dominated by the InP layer.

Of particular relevance to the application of quantum key distribution is the count rate limitation imposed by the deleterious effects of afterpulsing in these SPADs – effects which have reduced QKD clock rates to, typically, MHz rates, far less than the potential rates afforded by consideration alone of the subnanosecond jitter in these devices, which, in the absence of afterpulsing, should permit GHz clock rates as previously demonstrated with Si-based SPADs [4][5].

## IV. Infrared Single-Photon Detectors in Quantum Key Distribution

The application of quantum key distribution places particular requirements on the performance of infrared photon-counting detectors. In quantum key distribution systems, a figure of merit used is the quantum bit error rate (QBER), which can be simply described [12] as:

$$QBER = \frac{N_{WRONG}}{N_{WRONG} + N_{RIGHT}}$$

where $N_{WRONG}$ is the rate of spurious counts and $N_{RIGHT}$ is the rate of correct counts in the time slot of expected photon arrival. The spurious counts can result from a number of factors external to the detector, for example light leakage into the system, or non-ideal passive optical components in the transmission channel. However spurious counts can also be generated by detector dark counts, including dark counts caused by afterpulsing. Also, the rate of correct counts is likely to depend linearly on the detector single-photon detection efficiency.

For improved QKD system performance in terms of reduced quantum bit error rate, the single-photon detection efficiency should be maximized and the dark count rate minimized to reduce the probability of spurious counts within a photon arrival time window, which is usually set by the detector gate width. However, in addition, the detector jitter should be kept well below the gate width. Generally there is a trade-off between reducing the timing window which will improve the QBER by decreasing the probability of a random dark event occurring within that period, and reducing the gate width such that detector jitter and electrical gate rise-times will reduce the effective detection efficiency, thus increasing the QBER.

Furthermore, the use of, for example, the "one-time pad approach" to data encryption places particular emphasis on encryption key length and, as a consequence of this, on the key distribution rate. Currently, the limitation on the key distribution rate in QKD systems utilizing InGaAs/InP SPADs is the effect of the afterpulsing phenomenon. It is clear that much research remains to be performed to enable the materials improvement necessary to reduce this issue to a significantly more manageable level. Whilst Si SPADs remain the outstanding detector of choice for QKD applications at wavelengths less than 1000nm, some work has been performed on longer-wavelength Ge-containing Si structures [13] for SPADs, although it remains unclear whether they will prove more suitable than InGaAs/InP single-photon detectors at the strategically important 1550nm wavelength band.

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