

Photoionization of Trapped Carriers in Avalanche Photodiodes to Reduce Afterpulsing During Geiger-Mode Photon Counting

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Abstract: We reduced the afterpulsing probability by a factor of five in a Geiger-mode photon-counting InGaAs avalanche photodiode by using sub-band-gap ($\lambda = 1.95 \mu\text{m}$) laser diode illumination, which we believe photoionizes the trapped carriers.

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1. Introduction

There is great interest in developing a photon-counting detector usable in the 1.0 - 2.0 μm wavelength region that is comparable to silicon avalanche photodiode (APD) based devices (for the 0.4 - 1.0 μm region). Such high-efficiency, high-speed, low-dark count and low-afterpulsing devices will find use in quantum cryptography, lidar, imaging, optical time domain reflectometers, free-space optical communications and in fundamental quantum physics experiments. There have been a number of recent developments [1, 2], for devices that are sensitive at the 1.0 μm wavelength for use with Nd and Yb laser based instrument. Telecommunications and "eye-safe" laser applications require a device sensitive near 1.5 μm . A strong candidate is the InGaAs avalanche photodiode operating in Geiger mode. Good single photon detection efficiencies have been achieved by hand-selecting low-dark-current commercial InGaAs APD devices. Higher efficiencies have been achieved with resonant cavity devices.

State-of-the-art epitaxial growth still results in APDs with impurity and lattice defects. These defect sites are commonly held as responsible for trapping carriers during the avalanche process. The trapped charges are believed to be the major source of afterpulses. This has plagued Geiger-mode InGaAs APDs with a fundamental trade-off with regard to the device operating temperature. With decreasing temperature, the APD dark counts decrease, but unfortunately the afterpulsing time increases due to the lower thermal energy. Several techniques have been used to avoid or mitigate this afterpulsing effect including 1) operating at a compromise temperature to achieve both moderate dark counts and afterpulsing effects, 2) operating in gated mode with actively gating the bias voltage above breakdown for very short (ns) time periods [3], 3) correlating the counts from two detectors [4], and 4) discarding pulses during the prominent afterpulse period [5].

2. Method description

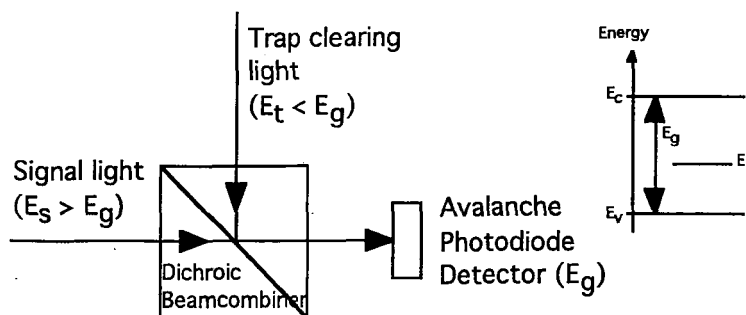


Fig. 1. Method for reducing afterpulsing in Geiger-mode APDs. [For example, InGaAs: $E_g = 0.73 \text{ eV}$, $E_s (\lambda = 1.55 \mu\text{m}) = 0.8 \text{ eV}$]

In this paper, we introduce a method to reduce afterpulsing at any operating temperature, namely, photoionization of the trapped carriers with sub-band-gap energy illumination. Our method borrows from the optical technique of photoionization spectroscopy[6], where sub-band-gap light is used to probe, identify and quantify trapping levels (most notably in nitride-based field-effect transistors). Our method for reducing the afterpulsing effect (Fig. 1) is to simultaneously illuminate continuously an APD with sub-band-gap light (to depopulate the traps) while the signal light (with photon energy greater than the detector material band-gap) is being detected. The APD current response is a function of the illumination time, intensity and wavelength and the initial amount of charge trapped after each avalanche. For the sub-band-gap illumination, we choose a wavelength that is long enough to avoid "conventional" detection (i.e. promoting carriers from the valence band), but is short enough to depopulate the significant trapping levels. The intensity of the sub-band-gap energy laser illumination is chosen high enough to depopulate the trapped charges in a short time (typically less than 100 ns) but low enough to permit practical optical (edge) filtering of the spontaneous emission within the device absorption band.

This method is general and can be used on a wide range of devices in various material systems. Most importantly, it provides a means of improving the performance of available commercial-grade APDs. We anticipate that this method will lead to full non-gated Geiger-mode InGaAs APD single photon counting detectors and arrays to expand the range of applications. Furthermore, the method may be useful on other materials with different band-gaps as long as the photoionization photon energy to release the trapped carriers is smaller than the bandgap.

3. Experiment description

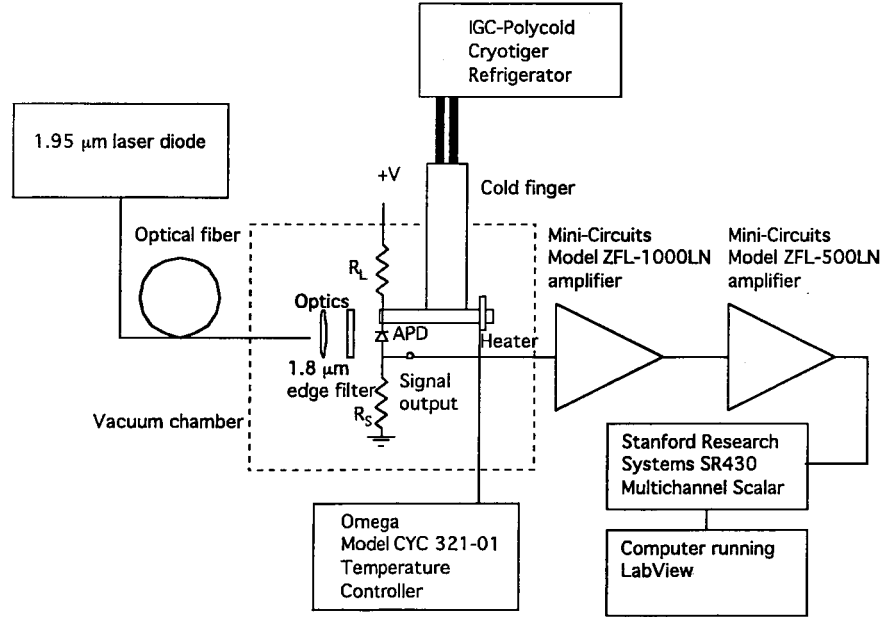


Fig. 2. Photoionization to reduce afterpulsing experiment diagram

An experiment diagram is shown in Fig. 2. Light from a room-temperature 1.95 μm wavelength fiber pigtailed laser diode (Applied Optonics Model AO-1950-100-HHLF200) travels through a 200 μm diameter core multimode optical fiber feedthrough into a vacuum chamber where it is collimated using a lens and directed through a 1.8 μm wavelength optical edge filter (Omega Filters) to the APD (Adtech Model AP1050B InGaAs/InP with 55 μm diameter). The optical edge filter is used to eliminate spontaneous emission (from the 1.95 μm wavelength laser diode) below the 1.8 μm wavelength. We use a simple passive-quench circuit arrangement. The APD was biased near breakdown (34.4 V) through a ballast resistor, ($R_L = 25$ k ohms) and the output was coupled directly to 50 ohm input-impedance low-noise RF amplifiers (Mini-Circuits Models ZFL-500LN and ZFL-1000LN). Low temperature operation was achieved using a cryogenic refrigerator (IGC-Polycold Cryotiger). A heater and temperature controller (Omega Model CYC 321-01) allows for operation between 120 $^\circ\text{K}$ and 240 $^\circ\text{K}$.

The afterpulsing probability per sample time, $p_T^{ap}(\tau)$, was computed from the autocorrelation function,

$g^{(2)}(\tau)$, of the experimental photon count record from the Stanford Research SR 420 Multichannel Scalar using [7]:

$$p_T^{ap}(\tau) = \langle n_T \rangle [g^{(2)}(\tau) - 1] \quad (1)$$

where $\langle n_T \rangle$, is the average count rate per sample time (under the condition that $\langle n_T \rangle \ll 1$). The Multichannel Scalar sample (bin) time, T , was set to 160 ns and was triggered on the count signal itself. Fig. 3 shows the experimental results. This clearly shows that the 1.95 μm wavelength illumination decreases the afterpulsing probability per sample time as a function of delay time and light intensity. The total afterpulsing probability, found by integrating Eq. (1) over time, with 100 mW/cm^2 1.95 μm wavelength illumination decreased by more than a factor of five.

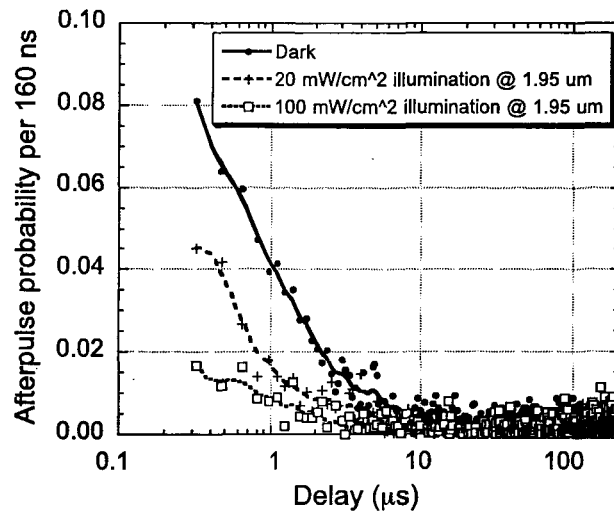


Fig. 3. Measured afterpulse probability (per 160 ns time bins) under conditions noted.

3. References

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