

# Influence of hot-carrier luminescence from avalanche photodiodes on time-correlated photon detection

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We present the results of our time-resolved measurements of hot-carrier luminescence from passively quenched Geiger-mode avalanche photodiodes. In time-correlated photon-counting (TCPC) experiments, hot-carrier luminescence interferes overwhelmingly with the coincidence spectrum, which results in artifacts. This potential problem should be taken into account in setting up TCPC experiments. © 2000 Optical Society of America

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Single-photon avalanche photodiodes (APD's) have been established as a strong alternative to photomultiplier tubes in photon-counting applications because they provide comparable performance, are small and rugged, and require simpler and less-expensive electronics.<sup>1</sup> Single-photon sensitivity is achieved by reverse biasing of the diode above breakdown. The absorption of a photon triggers an avalanche of hot carriers, which results in a large-current pulse. Hot-carrier luminescence in reverse-biased  $p-n$  junctions is a known concept in the literature.<sup>2,3</sup> We observed the invasive effects of hot-carrier luminescence from avalanche photodiodes (APD's) in a time-correlated photon-counting experiment. We operated commercially available silicon APD's (EG&G, C30902S-TC) in Geiger mode to record coincidences between entangled photons.<sup>4</sup> Extraneous peaks were recorded in the coincidence spectrum, overwhelming the data of interest. In this Letter we report a preliminary examination of the nature of this observation and its influence on time-correlated photon-counting experiments that utilize APD's.

The essence of the experiment (the setup is shown in Fig. 1) is to observe quantum correlation between entangled photon pairs produced from the laser pump by parametric downconversion process in a nonlinear crystal ( $\text{LiIO}_3$ ). The detectors are reach-through APD's with active diameters of 0.5 mm and are cooled by double Peltier stages. They are connected to the start and stop inputs of a standard time-correlated photon registration setup via simple passive-quenching circuits.<sup>1</sup> During the experiments, we encounter coincidence spectra such as that plotted in Fig. 2. The peaks extend over a temporal region of  $\sim 100$  ns. The spectrum persists with the pump source turned off and with a mirror replacing the crystal facet, excluding the possibility of a peculiar phenomenon in the crystal or of stray light owing to the pump. These symptoms indicate the likely origin of this artifactual spectrum to be the avalanche emission from each APD detected by the other. This claim is consistent with the already existing literature on hot-carrier

visible-IR luminescence in reverse-biased  $p-n$  junctions. The peaks on the left and the right are due to the emission events from the stop and the start detectors, respectively. The avalanches in the detectors can occur as a result of the detection of any photon in the surroundings or of generation of a random carrier in the absorption region (dark noise). Each coincidence event is a result of registering the time difference between the occurrence of the current pulse that is due to the avalanche in one of the detectors and the detection of a photon, emitted during that avalanche, by the other detector. On the left peak, associated with the stop detector, the decay appears at earlier times because the detection of the emitted photons initiates the coincidence event, whereas, for the right peak, the avalanche current pulse triggers the coincidence circuit.

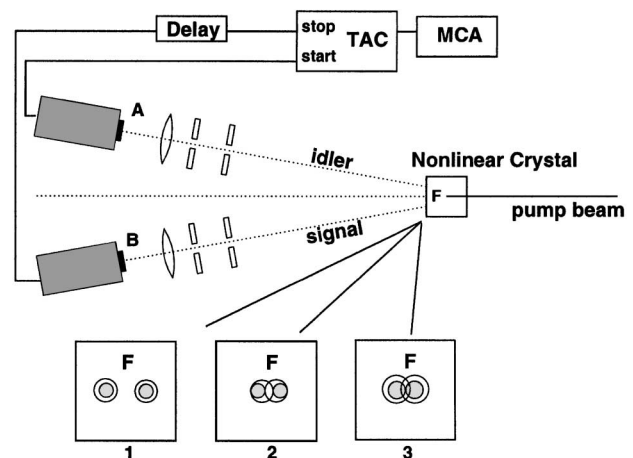


Fig. 1. Setup for time-correlated measurement of entangled photons. The squares show different possibilities for overlap of APD imaging paths. The shaded circles are the entangled photon streams, and the larger circles are regions imaged by the APD's: 1, no overlap; 2, overlap owing to misalignment; 3, inevitable overlap at optimum alignment. TAC, time-to-amplitude converter; MCA, multichannel analyzer.

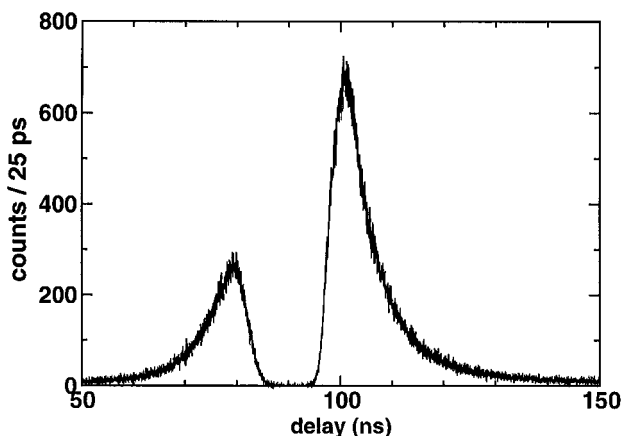


Fig. 2. Sample luminescence decay spectrum. We turn off the main experiment by shutting down the pump to emphasize the interfering phenomenon.

An explanation of our observations requires careful consideration of the optical configuration of the setup. The entangled photons, conventionally named the signal and the idler, emerge from the crystal at angles given by phase-matching conditions according to their frequency. The detectors and the optical components that are placed in the path of signal and idler photon streams image two regions on the crystal exit surface. When both signal and idler branches are at small and nearly equal angles to the facet normal, optimum alignment may lead to the existence of an optical path between detectors A (start) and B (stop). The path starts from the window of one detector, passes through the components in one branch, reflects off the crystal facet (region F), and, passing through the other branch, ends on the other detector. We have observed that the existence of the coincidence spectrum depends on the existence of this optical path, A–F–B. The strength of the optical coupling between the two detectors depends on the overlap of the imaging volumes of the APD's on the crystal surface either required by the optimal positional settings of the optical components or as a result of their misalignment. Because the detection is at single-photon-counting level, even weak optical coupling will cause luminescence interference in the experiments. Its amount and temporal range make luminescence a prohibitive problem, especially when the signal of interest is weak. The optical path between the detectors cannot be spatially isolated merely by alignment in experiments in which photon pairs are created collinearly.

We also studied the bias voltage and temperature dependence of the time-resolved luminescence. Several mechanisms have been proposed for describing light emission from reverse-biased Si  $p$ - $n$  junctions based on spectral observations.<sup>3,5,6</sup> Lacaíta *et al.*<sup>7</sup> reported that photon emissions are responsible for spreading the avalanche in large area reach-through APD's such as the ones used here. They pointed out that photon-assisted avalanche growth sets the ultimate limit to the timing performance of the APD's. Preliminary examination indicates that the most of the observed luminescence energy lies in the range 1.1–2.0 eV (650–1100 nm), which is consistent with indirect interband

transitions. The number of photons detected by the stop detector is 1–10 photons per avalanche event on the start detector. Taking into account the transmission of the optical elements and apertures and the detection efficiency of the stop detector, we estimate that the number of photons emitted per avalanche into  $2\pi$  sr is of the order of  $10^3$ – $10^4$ . A typical avalanche current pulse lasts approximately 10–20 ns, with a peak at a few milliamperes, resulting in  $10^7$ – $10^8$  carriers crossing the junction. Therefore the estimated efficiency of the hot-carrier emission is approximately  $10^{-5}$ , which is consistent with previous reports.<sup>7</sup>

The luminescence events observed in the coincidence data are not simple optical pump-decay processes. The temporal behavior of emissions is expected to be a convolution of the avalanche process, which is the major driving mechanism of the hot-carrier population, with optical relaxation mechanisms. Because these mechanisms are much faster than the multiplication process, the observed spectrum is approximately the time evolution of the charge population during the avalanche. The inset in Fig. 3 shows the time-resolved emission peak when all wavelengths are collected. The data are fitted to a biexponential with time constants  $t_1$  and  $t_2$ . Although the temporal response of the receiving (stop) detector is not deconvolved from the data, it remained constant throughout the measurements. As shown in Fig. 3,  $t_1$  and  $t_2$  decrease when the bias voltage is increased. The decay side of the peak is similar to the oscilloscope trace of the output pulse of the APD and shows the same dependence on bias as  $t_1$  and  $t_2$ . However,  $t_1$  and  $t_2$  remain fairly constant, with an ambient chip temperature that varies from  $-25$  to  $-5$  °C. The coincidence spectrum persists in a large time interval for any practical combination of bias voltage and temperature.

The obvious solution to the problem of reducing the influence of APD emissions is to make sure by design that no direct optical path exists between the two detectors as a result of specular reflection off an intermediate surface such as the nonlinear crystal in our experimental case. So we chose the cut angle ( $\theta$ ) of our thick nonlinear crystal such that the entangled photon streams of interest exit the surface through well-separated sections. The cut angle for thin crystals

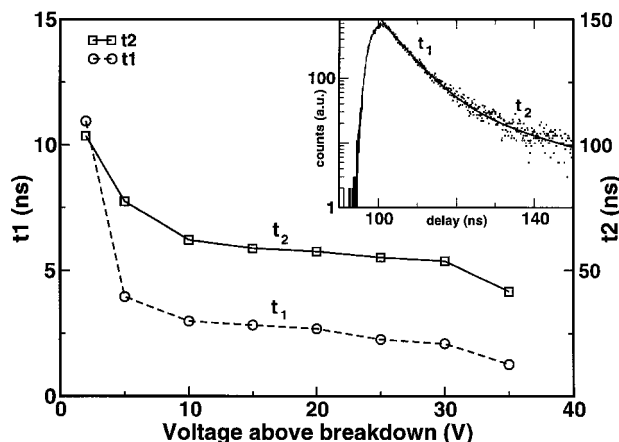


Fig. 3. Voltage dependence of the luminescence decay constants.

can be chosen appropriately to work with the pump at off-normal incidence so the normal of the crystal surface does not coincide with the bisector of the entangled photon streams. Additionally, one can utilize bandpass filters if the optical spectrum of the signal of interest and the APD emission do not overlap. Another solution arises when we note that the APD's were passively quenched: In several other similar experimental configurations with actively quenched APD's, no luminescence-related artifacts were noticed, even though the photon pairs were collinear and the optomechanical alignment required full overlap of optical paths leading to the APD's. In active quenching, the avalanche is suppressed by an active circuit. Shortly after the onset of the avalanche, the circuit lowers the bias voltage rapidly below breakdown and halts the growth of the avalanche process long before it can reach its passively quenched limit. However, depending on the settings, the avalanche proceeds passively for 5–15 ns. For the same detector, actively quenched operation will produce a smaller population of hot electrons than passively quenched operation if the timing parameters of the circuit are shorter than the stray and junction capacitance-charging times of the detector.<sup>1</sup>

Another possible side effect of luminescence is an interesting external afterpulsing effect. The photons emitted by the avalanche of a registered photon may reflect off a normal surface in the imaging path back onto the detector itself. The reflected photons will keep the timing circuit busy blocking the detection of the events of interest. Advanced active-quenching circuits provide a hold-off time during which the diode is kept quiescent. The hold-off feature serves to minimize afterpulsing that is due to charge trapping.

It can actually be extended to cover the external afterpulsing as long as the major surface of reflection is known and localized and its distance to the detector is of reasonable length. In general, it is advisable to minimize reflective surfaces by using antireflective coatings where possible.

In conclusion, we have presented a report of the effects of hot-carrier luminescence in APD's on time-correlated photon-counting experiments. The artifacts observed have a direct influence on the timing performance of individual APD's as well as on the applicability of single and multiple APD's in certain configurations.

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