Calibration of silicon single-photon avalanche diode detectors using a narrow-bandwidth quantum emitter

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A narrow-bandwidth, traceable single-photon source is used to improve the calibration of single-photon avalanche diode (SPAD) detectors. The near-infrared emission of a single InGaAs quantum dot under non-resonant pulsed excitation is detected simultaneously by two SPAD detectors of the same type, and the ratio of their detection efficiencies has been determined to be 1.059 with a relative standard uncertainty of 0.7 %. This result is validated by a comparison with a standard calibration using an attenuated laser.

INTRODUCTION

Standard calibration methods for SPAD detectors use attenuated laser light, which follows the Poisson statistics. Therefore, even at very low photon fluxes, there is still a nonzero probability for a multiphoton event, which cannot be resolved by an avalanche photodiode operating in the Geiger mode. To circumvent this problem imposed by the photon statistics, it is favourable to use a non-classical light source, a single quantum emitter with a high single-photon purity. Additionally, this new source should simultaneously fulfil the requirement of a directed monochromatic emission, needed for calibration purposes. The narrow emission bandwidth of semiconductor quantum dots makes them perfect candidates for this task.

SINGLE-PHOTON SOURCE

We aim for a high photon flux reaching the detection area of a SPAD detector by means of an efficient quantum emitter combined with a low-loss optical setup. A single InGaAs quantum dot (QD) is embedded into a monolithic microlens, which directs the emitted light into a small solid angle, thus increasing the extraction efficiency into the first lens of the setup (Figure 1.a). The sample is cooled down to 10 K and is non-resonantly excited at 850 nm at a repetition frequency of 80 MHz (see Figure 1.b). Figure 2.a shows a micro-photoluminescence scan of the QD layer, obtained by confocal imaging. One of the quantum dots, marked by a white circle, is placed in focus for spectral analysis.

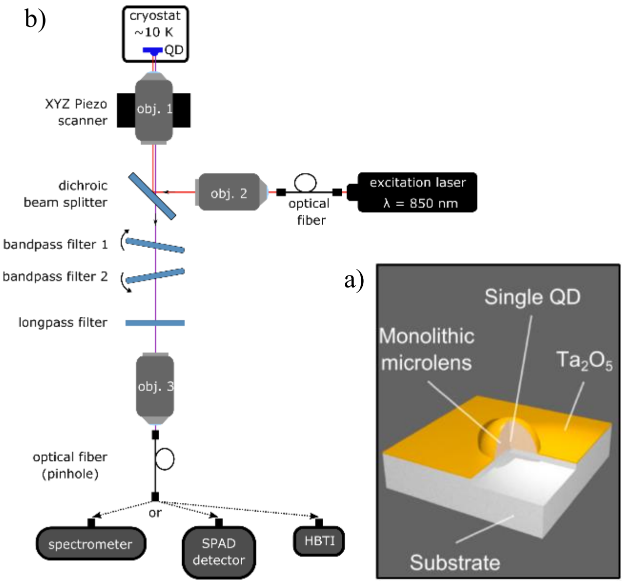

Figure 1. a) Scheme of a deterministic quantum dot microlens [1]. b) Confocal setup.

To minimize the optical losses, we are using two ultra-narrow bandpass filters for the spectral filtering instead of a monochromator. Each filter transmits about 90% of the incoming near-infrared emission. The exciton recombination line with highest intensity is selected by shifting the transmission window through filter rotation. Figure 2.b shows the presence of a single spectral peak having a full width of half maximum of only 0.04 nm. The emission wavelength is determined to be (922.37 ± 0.02) nm. Finally, the single-photon purity of the emission has been verified with a Hanbury-Brown and Twiss interferometer (Figure 2.c). The histogram of normalized coincidences yields a $g^{(2)}(\tau = 0)$ value of 0.25.

CALIBRATION METHOD

Simultaneous measurement of the photon flux with two SPAD detectors of the same type (SPCM-AQRH-13-FC, Perkin Elmer) employing the fiber exchange

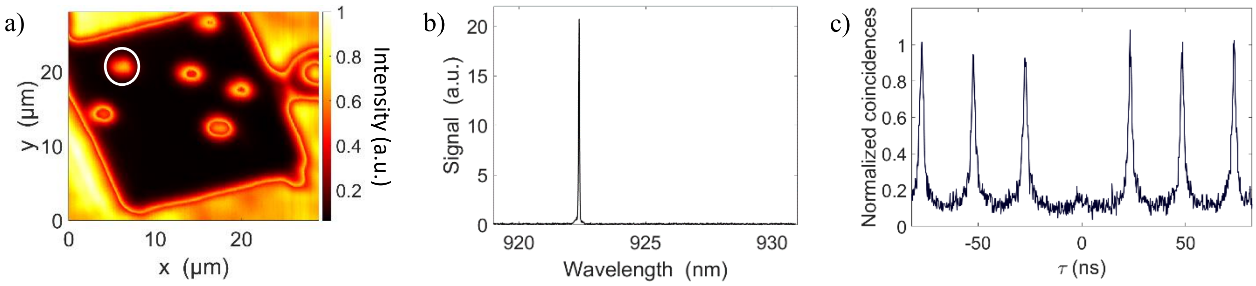

Figure 2. a) Micro-photoluminescence scan of the quantum dot layer at 10 K. b) Spectrum of the spectrally filtered quantum dot emission under non-resonant excitation. c) Corresponding second-order correlation measurement for pulsed excitation.

calibration technique [2] enables us to determine the ratio of detection efficiencies *r* according to:

$$r = \frac{\eta_{\mathrm{SPAD1}}}{\eta_{\mathrm{SPAD2}}} = \sqrt{\frac{\dot{N}_{\mathrm{A}}^{I}}{\dot{N}_{\mathrm{B}}^{I}} \cdot \frac{\dot{N}_{\mathrm{B}}^{II}}{\dot{N}_{\mathrm{A}}^{II}}} \cdot f_{\mathrm{cr}}, \qquad (2)$$

where $\dot{N}_{\mathrm{A,B}}^{I,II}$ denotes the measured detector counts per second. The intrinsic dark counts have been subtracted from the measured values. The single-photon emission of the quantum dot is split into two optical fibres A and B, which are connected to detectors 1 and 2 correspondingly. For the second (*II*) measurement, the positions of the detectors are switched, so that equation 2 becomes independent of the coupling ratio of the beam splitter.

An additional correction factor f_{cr} takes into account the temporal stability of the light source, as well as the reproducibility deduced from repeating the measurement ten times. An Allan deviation analysis was conducted to determine the optimal averaging time. The influence of after-pulse probability and dead time can be neglected due to the very low mean photon number (below 0.002) used for the calibration.

RESULTS

The SPAD calibration is conducted with a photon flux of approx. 120 kHz, originating from a single spectral line of the quantum dot emission spectrum. This photon flux corresponds to an optical power of 26 fW and falls into the linear regime of the silicon SPAD detectors, so that no attenuation is needed and a lower overall uncertainty can be reached. The detection efficiency ratio was determined to be $r_{\mathrm{QD}} = 1.059 \pm 0.008$. As expected, the value for r_{QD} is very close to unity since we are comparing two detectors of the same type with very similar properties. Additionally, both detectors were calibrated against a reference analogue detector by means of the double attenuator technique [3]: $\eta_{\mathrm{SPAD1}} = 0.324$, $\eta_{\mathrm{SPAD2}} = 0.305$ with a relative standard uncertainty of 1%. This yields a ratio of $r_{\mathrm{laser}} = 1.063 \pm 0.015$. The results from both independent methods are in a very good agreement.

In conclusion, the presented light source fulfils the criteria of an efficient, directed, monochromatic single-photon emission. Moreover, we have demonstrated its usefulness for detector calibrations in the near infrared in the field of quantum radiometry. Next steps will be to increase the photon flux of the single-photon source by using more sophisticated structures allowing for a higher collection efficiency.

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