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Avalanche current read-out circuit for low jitter parallel photon timing

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Abstract

We propose a novel circuit for single photon avalanche diode (SPAD) current read-out, for photon timing applications. The circuit consists of a single transistor trans-impedance amplifier with a GHz bandwidth: the feedback loop fixes the SPAD anode voltage and allows us to obtain a high time resolution with a very high equivalent current threshold (almost 700 μA). The trans-impedance stage is followed by a low pass filter that reduces the crosstalk of other on-chip detectors and makes the designed structure suitable for multi-detector systems. The discrete components prototype presented in this letter achieves a state-of-art resolution of 34.4 ps FWHM, presents negligible crosstalk between the different pixels and opens the way for the development of an integrated structure with a large number of channels.

Introduction

Nowadays, the applications exploiting photon timing techniques, such as time-correlated single photon counting (TCSPC) [1] and time-of-flight (TOF) measurements [2], require the development of new systems, with several parallel single photon detectors followed by multi-channel acquisition chains. This way multi-dimensional analysis can be easily performed, thanks to the maximum counting rate improvement, and to the reduction of the measurement acquisition time.

Until now, the development of multi-pixel detectors and of a multi-channel electronics for TCSPC systems is still incomplete. Available solutions are based on multi-anode photo multiplier tubes (PMTs) [3], which present some intrinsic drawbacks, and on single photon avalanche diodes (SPAD) arrays fabricated in standard CMOS technologies and with performance far from the state-of-art [4]. On the contrary, the best-in-literature results have been obtained exploiting custom technologies for SPAD fabrication, although these structures are limited to a low number of parallel detectors [5].

One of the most important requirement in a multi-detector system is a low crosstalk between the different channels. However, In the custom SPAD structures, such request is typically conflicting with the need of a high resolution, in fact the classical AC coupled pick-up circuit [6], used in single detector systems to obtain a low timing jitter, cannot be used in multi-SPAD arrays because of the too high current sensitivity, while the integrated MOS structure presented in [7] and used in multi-detector systems leads to a worse time resolution, to a higher power dissipation and to a lower fill factor of the detectors. Therefore we developed a new current pick-up structure, suitable for custom SPAD arrays, achieving high time resolution in conjunction with low crosstalk.

Designed structure

Until now, the avalanche detection circuits were based on the detection of voltage variations of the SPAD anode or cathode. On the contrary, the structure represented in Fig. 1, directly senses the SPAD avalanche current. The read-out circuit consists of a trans-impedance stage: the SPAD anode voltage, connected to the bipolar transistor base, is kept at a fixed voltage thanks to the feedback effect and all the SPAD avalanche current flows in the feedback resistance R_1 . The pick-up circuit output voltage, after a low pass filter, is compared to a threshold voltage (V_{TH}), to detect the avalanche. Therefore, the equivalent SPAD current threshold is:

$$I_{TH} = \frac{V_{out,pick-up} - V_{TH}}{R_1} \quad (1)$$

where $V_{out,pick-up}$ is the quiescent value of the read-out circuit output voltage. Since no current flows in the parasitic capacitance between the SPAD anode and substrate, it is possible to obtain a very good timing resolution even at a high threshold (up to 1 mA), opposite to the AC coupling case, where a very low threshold is necessary to obtain a good timing resolution [8].

The 600 MHz low pass filter of Fig. 1 is useful to reduce the circuit sensitivity from the external crosstalk. To better analyze this aspect, we can consider the structure shown in Fig. 2, reporting a 2 SPAD structure and the equivalent circuit useful when evaluating the interference between different detectors. When the interfering SPAD detects a photon, the active quenching circuit (AQC_a) [9] brings the voltage across the SPAD below the breakdown; since the cathode (C_a) voltage is quickly modified a current flows through the parasitic capacitance between cathode and substrate (C_{cs}). If the substrate voltage were fixed, all this current would be collected by the substrate contact, however, because of the parasitic impedance of the substrate supply line (R_{ss} and L_{ss}), part of the current flows through the anode-substrate capacitance (C_{as}) of the observed SPAD and can be detected as an avalanche. Since the crosstalk current is connected to the AQC output node edges and these edges are as fast as possible, it is possible to reduce the effect of this current by filtering the output voltage of the trans-impedance stage, as in the designed circuit, without having a relevant influence on the actual SPAD signal.

Moreover, to improve both the time resolution and the crosstalk performance, it is necessary to minimize the substrate supply voltage line impedance, to keep constant the voltage across the C_{as} capacitance.

Experimental results

Fig. 3 reports the time jitter measured with the circuit of Fig. 2 coupled to a custom technology SPAD. The two curves show the results obtained with two different BJTs (BFR93A and BFS17A by NXP), having the same features except for the transition frequency, equal to 6 GHz and 3 GHz. The measurements have been carried out using a femtosecond laser (80 MHz repetition rate, 780 nm wavelength) and a Becker & Hickl SPC-130 module; the equivalent current threshold is fixed at a very high level, equal to 666 μ A. A 34.4 ps time resolution, comparable with the state-of-art results, has been obtained with the 6 GHz BJT, while with the slower transistor the resolution noticeably decrease to 68.9 ps.

This behavior can be understood by reminding that a good time resolution can be obtained only providing that the C_{as} capacitance is not charged. The anode voltage is fixed by the feedback loop as long as the loop gain is much higher than 1; since the SPAD current has a

rising edge of about 500ps [10], its maximum frequency is around 1GHz, hence the pick-up circuit must have a unity loop gain frequency higher than this value. Considering the designed circuit, a simplified expression of the loop gain is:

$$G(j\omega) = \frac{-\beta \cdot R_C}{R_C + R_F + \beta/g_m} \cdot \frac{1}{1 + j\omega \cdot \frac{\beta}{2\pi f_T} \cdot \frac{R_C + R_F}{R_C + R_F + \beta/g_m}} \quad (2)$$

where β is the BJT current gain and f_T is its transition frequency. Since $\beta=90$, by substituting the actual values in (2), using the 3 GHz BJT the unity gain frequency is equal to 1 GHz, while with the fast BJT is equal to 2 GHz. Therefore only using the fast BJT the parasitic capacitance does not have any effect and therefore a good time resolution can be obtained also using a high threshold.

Fig. 4 reports the disturbances on the output voltage of the pick-up circuit when another SPAD detects a photon. The effectiveness of the low pass filter is clearly visible: while the disturbance measured on the BJT collector terminal has a peak-peak value of almost 0.5 V, after the filter the disturbance is reduced to less than 0.1 V. Moreover the time resolution of the single channel is not influenced by the other on-chip detectors: the 34 ps resolution has been obtained also with 3 SPAD operated simultaneously.

Finally, the output disturbance is independent from the distance between the two SPADs and therefore it cannot be due to a parasitic coupling between the anodes and the cathodes. On the contrary, since the measured substrate resistance between opposite sides of the chip is 1Ω , the substrate coupling is geometry independent. The same output disturbance has been measured also using two SPADs on different chips, which substrate were connected by a copper plane. Hence, the main crosstalk reason is the substrate voltage fluctuation.

Conclusion

We presented a new current pick-up circuit, suitable for SPAD detector arrays. The discrete components prototype achieves good performance in terms of time resolution and crosstalk between the different channels; moreover, it has allowed to obtain the guidelines for a future development of an integrated structure featuring the same performance. Considering the integrated circuit level, the trans-impedance amplifier must present a loop gain larger than 1 at a 1 GHz frequency to obtain a good temporal resolution and it has to be followed by a low pass filter to reject the external disturbances. At a board level, the parasitic impedance of the substrate bias voltage has to be minimized to reduce the crosstalk between the detectors.

Acknowledgments

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References

1. Becker, W. 'Advanced time-correlated single photon counting techniques'. Springer; Berlin, Germany: 2005.
2. Amann MC, Bosch T, Lescure M, Myllyla R, Rioux M. 'Laser ranging: a critical review of usual techniques for distance measurement'. Opt. Eng. 2001; 40(1):10–19.
3. Becker; Hickl, GmbH. 'Multi-wavelength FLIM data sheet'. <http://www.becker-hickl.de/spectral.htm#multi>
4. Niclass C, Gersbach M, Henderson R, Grant L, Charbon E. 'A single photon avalanche diode implemented in 130-nm CMOS technology'. IEEE J. Sel. Top. Quant. 2007; 13(4):863–869.

5. Ghioni M, Gulinatti A, Rech I, Zappa F, Cova S. 'Progress in silicon single photon avalanche diodes'. *IEEE J. Sel. Top. Quant.* 2007; 13(4):852–862.
6. Gulinatti A, Maccagnani P, Rech I, Ghioni M, Cova S. '35 ps time resolution at room temperature with large area single photon avalanche diodes'. *Electron. Lett.* 2005; 41(5):272–274.
7. Cammi C, Gulinatti A, Rech I, Panzeri F, Ghioni M. 'Spad array module for multi-dimensional photon timing applications'. *J. Mod. Optic.* 2012; 59(2):131–139.
8. Assanelli M, Ingargiola A, Rech I, Gulinatti A, Ghioni M. 'Photon-timing jitter dependence on injection position in single-photon avalanche diodes'. *IEEE J. Quantum Elect.* 2011; 47(2):151–159.
9. Gallivanoni A, Rech I, Ghioni M. 'Progress in quenching circuits for single photon avalanche diodes'. *IEEE T. Nucl. Sci.* 2010; 57(6):3815–3826.
10. Ingargiola A, Assanelli M, Rech I, Gulinatti A, Ghioni M. 'Avalanche current measurements in SPADs by means of hot-carrier luminescence'. *IEEE Photonics Tech. L.* 2011; 23(18):1319–1321.

Fig. 1. Schematic of the current pick-up structure, including the readout circuit, the low pass filter and a comparator

Fig. 2. Structure of a 2 SPAD array, including the aggressor SPAD (denoted by a), the victim SPAD (v) and the parasitic components involved in crosstalk

Fig. 3.
Time response of the designed system with a custom SPAD detector

Fig. 4. Output voltage of the designed circuit when another on-chip SPAD detects a photon. The first disturbance corresponds to the AQC quench edge, the second one to the AQC reset