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# How to squeeze high quantum efficiency and high time resolution out of a SPAD

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## ABSTRACT

We address the issue whether Single-Photon Avalanche Diodes (SPADs) can be suitably designed to achieve a trade-off between quantum efficiency and time resolution performance. We briefly recall the physical mechanisms setting the time resolution of avalanche photodiodes operated in single-photon counting, and we give some criteria for the design of SPADs with a quantum efficiency better than 10% at 1064nm together with a time resolution below 50ps rms.

## I. INTRODUCTION

Solid state photodetectors nowadays employed in laser ranging applications fall into two categories: reach-through avalanche photodiodes (APDs) with a depletion layer about $30 \div 200\mu m$ thick [1-3], and shallow junction APDs with a depletion layer about $1\mu m$ thick [4-6]. The former are commercially available devices designed for low noise operation in optical communications, while the latter, called Single-Photon Avalanche Diodes (SPADs), are specifically designed for timing applications.

In laser ranging measurements reach-through APDs show several advantages over ordinary Photomultiplier Tubes (PMTs): i) At the operative bias the photodiode is fully depleted and the depletion layer, tens of microns thick, leads to a quantum efficiency higher than 30% at the Nd-YAG emission wavelength. ii) A time resolution of 150ps rms has been demonstrated with RCA C30902S: this value favourably compares with the timing performance of PMTs [7]. iii) The sensitive area diameter (500$\mu$m or more) is large

enough to make possible the alignment of the telescope and the subsequent tracking of the satellite.

Indeed, high performance SPADs can attain much better time resolution (8ps rms) [4]. However, these devices have a quantum efficiency lower than 1% at 1064nm and their small active area (5μm diameter) makes impossible their use in laser ranging measurements.

In this paper we address the issue whether a silicon SPAD can be suitably designed to achieve a trade-off between quantum efficiency and time resolution performance. We briefly recall the physical mechanisms setting the time resolution of APDs operated in single-photon counting. We discuss how the performance depends on the device geometry and the junction electric field profile. We give some criteria for the design of SPADs with a quantum efficiency higher than 10% at 1064nm and a time resolution below 50ps rms. This combination of performance cannot be achieved with any commercially available single photon detector, both solid state and vacuum tube.

## II.   AVALANCHE PHYSICS AND TIME RESOLUTION

Single photon sensitivity is achieved with APDs operated biased above the junction breakdown voltage, $V_b$. At this bias a single photogenerated carrier can trigger a diverging avalanche process. The leading edge of the avalanche current marks the photon arrival time [1-6]. Any jitter in the delay between photon absorption and the crossing time of the discriminator threshold, impairs the precision in timing measurements [4-6].

The ultimate limit to the timing resolution of a SPAD comes from the thickness of the depletion layer. In fact, the distance between the point where the photon is absorbed and the junction leads to a statistical delay between the photon absorption time and the avalanche triggering. As a rule of thumb, if the photon absorption length, $L_a$, is longer than the depletion layer thickness, W, and carriers drift at the saturated velocity ($v_s = 10$ps/μm) almost everywhere in the depleted region, the ultimate rms time jitter will be of the order of $W/(3.5v_s) = 2.9$ps rms per each depleted micron. Since in silicon the absorption length, $L_a$, of a photon at 1064nm is 83μm, the choice of a 10μm depletion layer thickness guarantees a quantum efficiency higher than 10%, with an ultimate time resolution less than 30ps rms. Unfortunately, other mechanisms do not allow to reach this limit.

In the device operation the avalanche is triggered by photon absorption in a seed point, then it progressively spreads over the whole detector area. The leading edge of the diode current is affected by the spreading process. In SPADs, with thin depletion layer and small active volume, the avalanche spreads evenly from the seed point to the remaining detector area by transverse diffusion of avalanching carriers [5,6]. This mechanism makes the avalanche propagating with a transverse velocity given by [5]:

$$v_p = 2\sqrt{D/\tau} \qquad (1)$$

where D is the average transverse diffusion coefficient of the carriers and $\tau$ is the time constant of the avalanche build-up, which increases by increasing the device bias.

Fig.1 helps in understanding how the avalanche spreading impairs the timing performance. In fact, the closer the seed point is to the center of the junction area, the faster is the activation of the whole device. Therefore, in the circular device shown in

Fig.1, the current leading edge becomes steeper as the seed point moves from the periphery to the center. Since a photon can be absorbed everywhere on the detector area, this effect causes a randomness in the pulse crossing of the timing threshold. It follows that the achievable time resolution is related to the difference, $\Delta$, between the crossing times of the fastest and the slowest current pulses. This difference increases by increasing the sensitive area and/or decreasing $v_p$ (i.e. the bias).
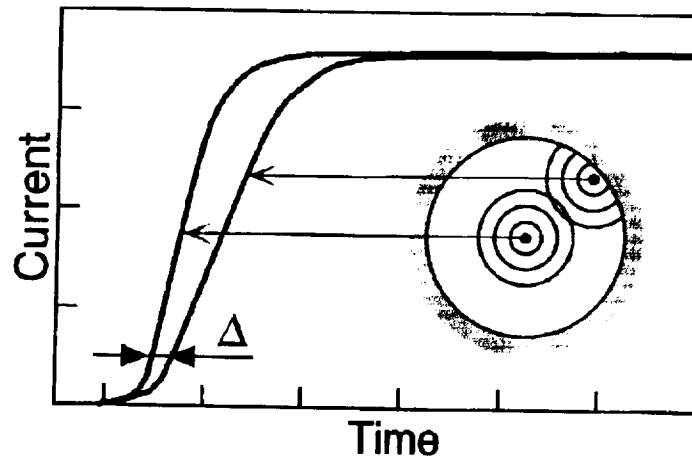


Fig.1 Avalanche dynamics in a circular device: the shift $\Delta$ between the crossing times of the fastest and the slowest leading edges sets the limit to the time resolution of the detector. The inset schematically shows the sensitive area of the detector with concentric circles representing the spreading avalanche.

As the detector volume increases, another phenomenon can play a role in the avalanche propagation. Secondary photons, emitted by hot carriers radiative relaxation processes in the avalanching region, can be absorbed in other regions, thus triggering the avalanche even there. Photons with absorption length of a few hundred microns are the most effective in sowing the avalanche. This latter process is dominant in APDs with large sensitive area and thick depletion layer [3].

We have developed a computer simulation of the avalanche dynamics. Fig.2 shows a comparison between the current leading edge of a RCA C30902S APD biased 40V above $V_b$ at room temperature and the result of the computer program. It is worth noting that, due to the intrinsic randomness of the photon-assisted process, the timing performance of the device (170ps rms) is considerably worst than the ultimate limit set by the 30$\mu$m thick depletion layer. Moreover, the time dispersion increases by increasing the level of the timing threshold.

In order to reach a reasonable trade-off between quantum efficiency and time resolution, the impairing effects of the photon-assisted spreading have to be overcome. In principle this goal can be achieved in two ways: i) by adopting a timing threshold low enough to sense the avalanche current soon after the avalanche triggering and before the emission of

the first secondary photon; ii) by designing the detector structure so that the lateral carrier diffusion becomes the steering mechanism of the avalanche spreading. The design of fast and sensitive detector circuits is under way in our laboratories. In the next section, we will give some guide-lines on the design of high quantum efficiency SPADs with the avalanche propagation steered by transverse carrier diffusion.
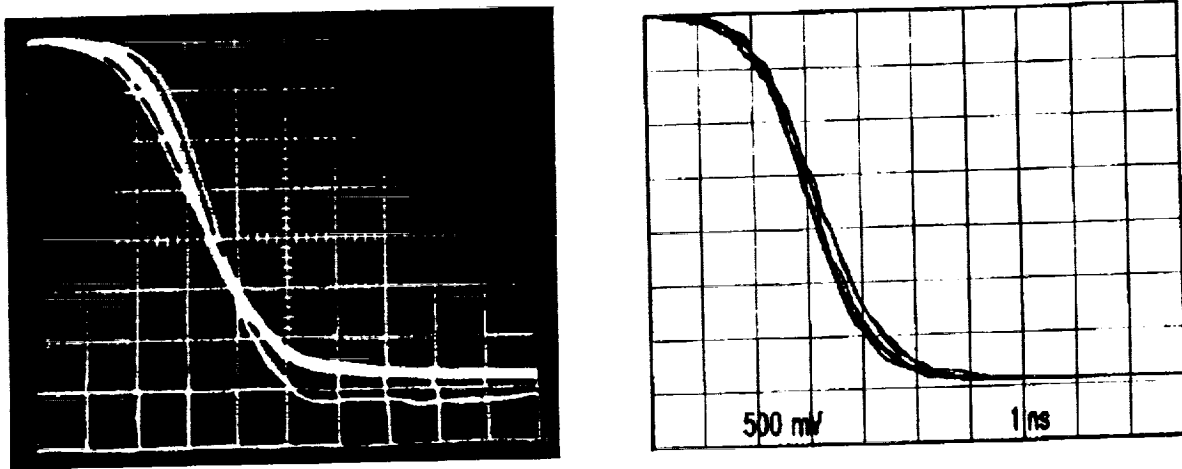


Fig.2 Comparison between the current leading edge of a RCA C30902S APD biased 40V above $V_b$ at room temperature (left) and the result of the computer simulation of the avalanche dynamics (right).

## III. DESIGN CRITERIA

In order to make it clear some fundamental design rules, let us compare the expected performance of two devices with 10% quantum efficiency at 1064nm. Therefore, both devices are supposed to have a 10$\mu$m depletion layer thickness. The inset of Fig.3 shows the electric field profile of the first device (D#1) at 169V, that is 34V above the estimated $V_b=135V$. The peak electric field is $3.3 \times 10^5$V/cm. The high field region is about 3$\mu$m thick and, in the remaining part of the depletion layer, the electric field ($6 \times 10^4$V/cm) makes the carriers drifting at saturated velocity. The second device (D#2) has a similar electric field profile (inset of Fig.3) but a high field region only 0.3$\mu$m thick and an estimated $V_b$ of 63V. Since the two devices have different $V_b$, we will compare their performance at the same relative excess bias $(V_0-V_b)/V_b$. Thus D#2 will be operated at 79V and the peak electric field will be $6 \times 10^5$V/cm.

Fig.3 shows the dependence on the device radius of both diffusion and photon assisted spreading velocities, as obtained from a computer simulation of the avalanche dynamics. The diffusion velocity was estimated from Eq.(1), while the photon assisted contribution was estimated by switching off the diffusion process in the simulation, and then computing the resulting ratio between the device radius and the current risetime. As expected, the role of the photon-assisted process increases by increasing the sensitive area radius; it becomes

eventually dominant in D#1 for a radius greater than 80μm. D#2 has a diffusion velocity more than three times larger and a photon assisted process less effective than in D#1.
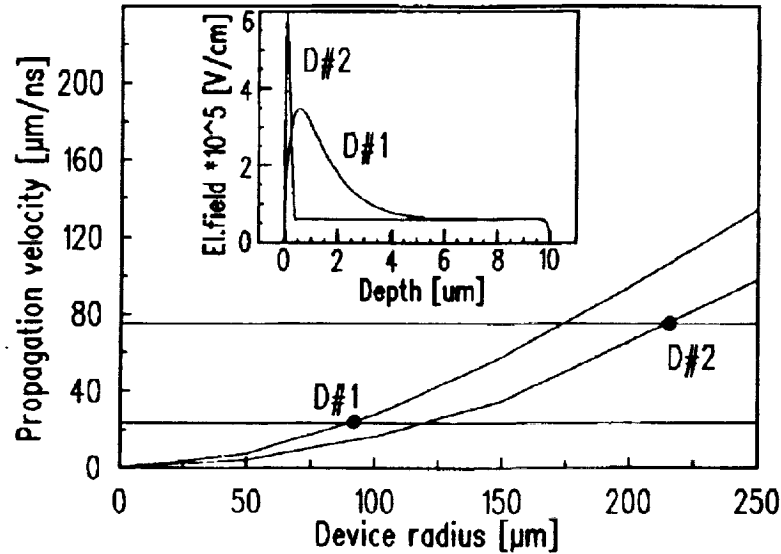


Fig.3 Dependence of the diffusion and the photon assisted spreading velocities on the device radius, as obtained from a computer simulation of the avalanche dynamics in two devices with a 10μm thick depletion layer. The inset shows the electric field profiles assumed in the calculations.

The higher diffusion velocity is due to the steeper electric field profile of D#2. In fact, the avalanche time constant, $\tau$, is proportional to the carrier transit time in the high field region and is inversely proportional to the loop gain of the avalanche feedback process (i.e. the average number of impact ionization events experienced by a carrier crossing the junction). It can be shown that two junctions with similar electric field profile have the same avalanche loop gain when biased at the same relative excess bias. Therefore, in the present comparison, the devices are operated at the same loop gain, and the thinner high field region of D#2 results in a correspondingly shorter multiplication time constant, $\tau$. From Eq.(1) it follows that D#2 is expected to have a faster diffusion-assisted avalanche propagation.

With regard to the difference in the photon-assisted process, it should be noted that D#2 is supposed to work at only 16V above $V_b$, while D#1 is operated at 34V excess voltage. Both of them have the same depletion layer thickness and therefore the same series resistance. It follows that, at the supposed operating conditions, the current flowing through D#2 is less than that of D#1. Since the photon emission rate is proportional to the current, the photon assisted propagation is less effective in D#2.

These results highlight that, by adopting a suitable steep electric field profile, the diffusion-assisted avalanche propagation can overcome the noisy photon-assisted process even in large area SPADs. We estimated the time resolution of a SPAD detector with 100μm diameter and the electric field profile of D#2 as follows. We computed the leading

edge of the avalanche pulses triggered at the center and at the edge of the detector, assuming that the avalanching area spreads evenly with a radial velocity of $75\mu m/ns$. The time resolution is expected to be proportional to the difference, $\Delta$, between the crossing times of the fastest and the slowest avalanche pulses. By using a timing threshold at 0.3mA, we forecast $\Delta = 87ps$. Therefore the time resolution of such a device, defined as the rms value of the timing curve, should be better than 50ps.

## IV. CONCLUSIONS

We have discussed the physical mechanisms setting the timing resolution of Single-Photon APDs. In present devices, the timing resolution is limited by the mechanisms involved in the avalanche spreading from the seed point to the entire sensitive area. The best time resolution is obtained when the steering mechanism is the multiplication-assisted diffusion. We have shown that, with a proper design of the electric field profile, the diffusion-assisted process can overcome the photon-assisted spreading also in APDs with a large sensitive area. Therefore, SPAD devices with time resolution better than 50ps rms and a quantum efficiency better than 10% at 1064nm could be obtained. In such devices, the timing resolution would be ultimately limited by the transit time in the thick depleted region.

## ACKNOWLEDGEMENTS

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