# Tracking capabilities of SPADs for laser ranging

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## ABSTRACT

The spatial sensitivity of Single-Photon Avalanche Diodes (SPADs) can be exploited in laser ranging measurements to finely tune the laser spot in the center of the detector sensitive area. We report the performance of a SPAD with $100\mu m$ diameter. It features a time resolution better than 80ps rms when operated 4V above $V_b$ at -30C, and a spatial sensitivity better than $20\mu m$ to radial displacements of the laser spot. New SPAD structures with auxiliary delay detectors are proposed. These improved devices could allow a two dimensional sensitivity, that could be employed for the design of pointing servos.

## I.   INTRODUCTION

Due to their high quantum efficiency and picosecond time resolution, Single-Photon Avalanche Diodes (SPADs) are gaining acceptance as detectors for laser ranging experiments. In SPADs the onset of the avalanche current, triggered by a photogenerated carrier, marks the photon arrival time. We have recently demonstrated that not only the timing information, but also the position of the photon absorption can be extracted from the avalanche current rising edge, by exploiting the physical mechanisms involved in the device operation [1]. Measurements previously performed on a position-sensitive SPAD with $14\mu m \times 140\mu m$ rectangular sensitive area showed that these structures are capable of time resolution better than 30ps rms and spatial resolution better than $5\mu m$ rms [1].

In this paper we suggest to exploit the position-sensitive capability of SPADs to keep the echo signal from the satellite always in the center of the detector sensitive area. First, we briefly recall the operation of these novel detectors. Then, we discuss the performance of a circular device ($100\mu m$ diameter) large enough to make possible the first alignment of the telescope and the subsequent tracking of the satellite. Auxiliary electrodes could be used to obtain position sensitive detectors with angular measurement capability.

## II.   OPERATION OF SPAD POSITION SENSITIVE DETECTORS

Recently, the avalanche dynamics in silicon SPADs has been investigated; high performance detectors have been designed and fabricated [2-4]. To the purpose of our discussion, here we briefly recall the basic operation of SPADs with a depletion layer only a few microns thick [5]. The avalanche photodiode is operated biased above the breakdown voltage, $V_b$, but no current flows until the first carrier triggers the avalanche in a seed point. Then, the free carrier concentration swiftly rises by impact ionization around the seed point and, in a few tens of picoseconds, the free carrier space charge lowers the local multiplication rate to a self-sustaining level. The carrier density around the seed point cannot increase further, unless the avalanche is triggered in the surroundings by lateral diffusion of avalanching carriers. As the activated area increases, the diode current rises. At the end, when the multiplication process occurs over the whole active area, the avalanche current reaches the final steady state value given by the ratio of the excess bias above $V_b$ and the diode series resistance.
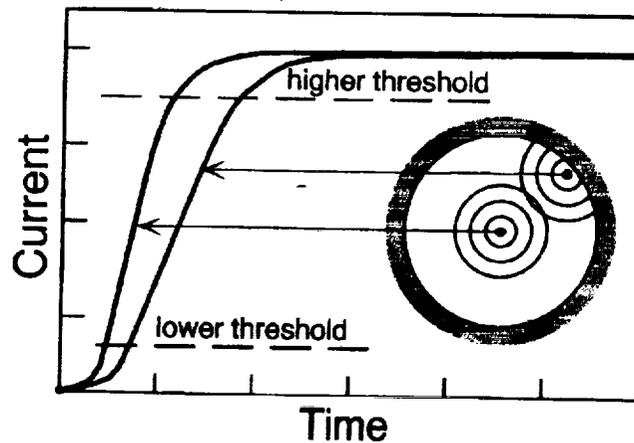


*Fig. 1 Avalanche dynamics in a circular device: the curves qualitatively show the dependence of the current rise on the point where the avalanche is triggered. The circle schematically represents the sensitive area of the detector with spreading avalanches. The delay between the crossing times of the two thresholds is proportional to the current rise-time.*

The pulse crossing of a discriminator threshold gives the timing information. However, this peculiar dynamics causes the avalanche pulse leading edge to depend on the position where the avalanche is triggered. Fig.1 schematically shows the rise of the diode current in a circular device. The closer is the seed point to the center, the faster is the activation of the whole sensitive area. Therefore, the current leading edge becomes steeper as the seed point moves from the periphery to the detector center. This effect sets a limit to the timing performance of the detector [2,3], but it can also be exploited to get the position

information: the shape of the avalanche leading edge carries the spatial information on the point where the photon was absorbed [1].


## III.  EXPERIMENTAL DATA

Fig.2 shows the cross section of the tested devices. The avalanching region is the $n^+p^+$ junction: the depleted region is about $1\mu m$ thick. The electric field at the edge is tailored by the $n^+p$ junction with the epilayer. A complete discussion of the structure is carried out in Ref.6. The detector has a $100\mu m$ diameter and a $V_b$ of 14.3V.

The rise time of the avalanche current pulses was accurately measured by an Active Quenching (AQ) circuit [7] with two discriminators having different thresholds. The purposes of the AQ circuit are: i) to sense the onset of the avalanche current; ii) to lower the bias of the photodiode below the breakdown voltage, thus quenching the avalanche; and iii) to rapidly restore the bias after a suitable dead time to enable the detection of another photon. The first discriminator is set to sense the avalanche when the current is still low (0.4mA), while the second is triggered when the avalanche is almost saturated. The delay between the output pulses of the discriminators gives the rise time of the avalanche pulse.
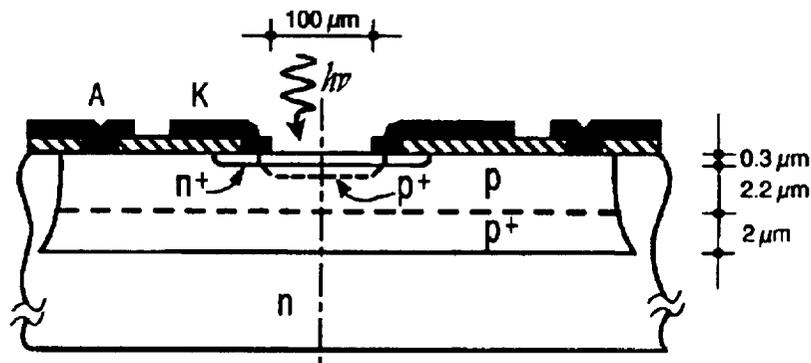


Fig.2 Cross section of the double epitaxial devices tested in the experiments.
The active $n^+p^+$ junction is built in a 10 $\Omega cm$ p epistrate. The buried $p^+$ epilayer is 0.3 $\Omega cm$.


In order to reduce the dark count rate, the detector was cooled by a Peltier stage at -30C and operated in gated mode: in stand-by the diode was reverse biased below $V_b$, and a waveform generator provided pulses at 10 kHz, raising the bias 4V above $V_b$ for 500ns. A 850nm laser diode synchronously emitted a 20ps rms optical pulse, focused to a $10\mu m$ spot with a microscope. A Time to Pulse Height Converter measured the delay between the triggering times of the two discriminators. A histogram of the measurements was collected with a MultiChannel Analyzer.

We carried out various measurements by changing the radial position of the light spot. Fig.3 shows the histograms of the delay between the threshold crossing times. The peak shifts 130ps when the laser spot moves from the center to the edge of the detector. The

inset of Fig.3 shows the complete dependence of the peak shift on the spot position. As the laser spot shifts more than 20μm from the device center, the histogram peak moves considerably and a suitable feedback system can react to restore the original centered position.

The time resolution of the device was measured just by recording the delay between the laser shot and the crossing time of the low threshold discriminator. The observed resolution changed somewhat with focusing and with the position of the spot. With the light focused to a 10μm spot size in the center of the sensitive area, the time resolution was 80ps rms.
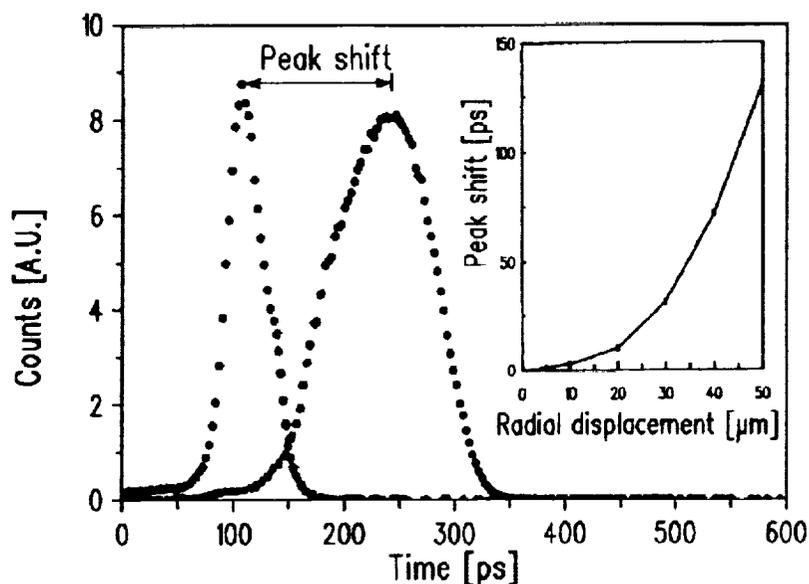


Fig.3 Avalanche pulse rise-time, measured as the delay between the crossing times of the low and the high thresholds of Fig.1. The two histograms correspond to the measurements performed by focusing the laser spot in the center (first histogram to the left) and at the edge of the detector of Fig.2 (histogram to the right). The peak shifts 130ps when the laser spot moves to the periphery of the detector. The inset shows the complete dependence of the peak shift on the spot position.

It is worth noting that photons absorbed at the same distance from the device center generate avalanche pulses with the same risetime. Therefore, these devices cannot give the information on how to operate in order to position the light spot in the detector center, in a single measurement. A trial and error method should be adopted to keep centered the echo light signal.

Fig.4 describes a possible improvement of the technique in order to achieve a complete angular sensitivity. Four SPAD sensors are placed along two perpendicular axes of the main detector, close enough to its boundary to be triggered when the avalanche reaches the corresponding edge. Since the avalanche spreads evenly from the seed point, by measuring the time delay between the current pulses of the sensors one can get the position of the laser

spot over the main sensitive area. Pointing servos could be implemented to correct for misalignement, thus keeping the laser spot always in the center of the main photodetector. It is worth noting that the design of such a device is expected to be critical in the coupling between the delay detectors and the central SPAD. Projects are under way in our laboratories to study suitable stuctures and the most effective coupling arrangements.
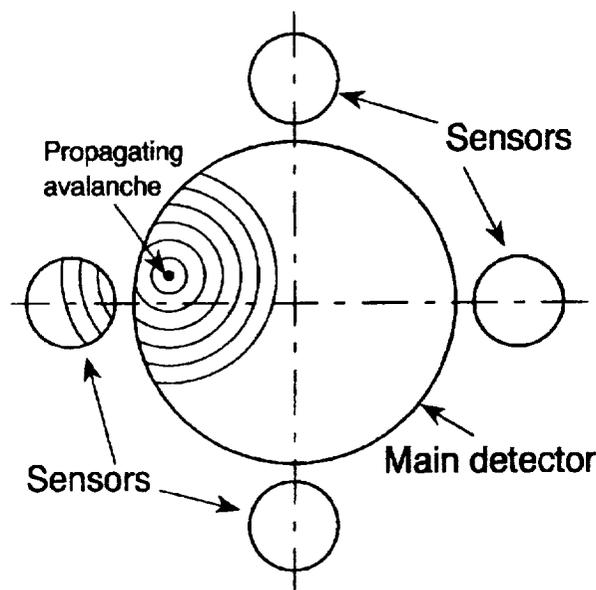


*Fig.4 Proposed improvement of the position sensitive detector in order to achieve a complete angular sensitivity. Four SPADs can sense when the avalanche reaches the edge of the central device. By measuring the time delay between the current pulses of the sensors, one can obtain the position of the laser spot over the main sensitive area.*

## IV.    CONCLUSIONS

A position-sensitive single-photon detector with $100\mu$m diameter has been demonstrated. It features a time resolution better than 80ps rms when operated 4V above $V_b$ at -30C, and a spatial sensitivity better than $20\mu$m to radial displacements of the laser spot. The detector provides a continuous sensitive area, free from dead zones, and can be exploited in laser ranging measurements to keep the laser signal always centered into the sensitive area. We have also proposed a more complex SPAD structure, where the introduction of auxiliary delay detectors could allow a complete angular sensitivity of the device. These structures are investigated to overcome the trial and errors method used in pointing with simple position-sensitive SPADs.

## ACKNOWLEDGEMENTS

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