Timing Enhanced Silicon SPAD design

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Abstract—**Nowadays a growing number of applications require arrays of SPAD detectors with high photon-timing jitter performance. In order to attain this result without impairing the other device characteristics a clear understanding of the avalanche dynamics and statistics is mandatory. In this work we describe the argument, supported by simulations and experimental results, that led us to suggest a timing enhanced SPAD. We state that a P-i-N device with intrinsic layer thicker than 1.5μm not only should have better timing performance but also good noise if compared to traditional SPAD devices.**

I. INTRODUCTION

Traditionally Photo Multipliers Tubes (PMT) had been the privileged technology employed in detecting ultra-low and ultra-fast optical signals. Nowadays Single Photon Avalanche Diodes (SPAD) have gained wide acceptance as solid state alternatives to PMTs. SPADs are now the winning technology because not only they provide the typical advantages of solid state devices, but they also offer inherently higher photon detection efficiency, particularly in the red and near infrared spectral regions.

The basic structure of a SPAD is a p-n junction that is reverse biased above the breakdown voltage. In this operating regime the electric field inside the depletion region is so high that a single injected carrier can start a diverging avalanche multiplication process due to impact ionization. If the injected carrier is photo-generated, the onset of the avalanche current reveals the absorption of a photon. This exponentially growing avalanche current can be detected by a suitable sensing circuit employing a discriminating threshold. The time instant at which the current is detected sets the arrival time of the photon with a resolution that can be as low as 20 ps FWHM.

SPADs have been successfully employed in various fields ranging from biology to astronomy as single-pixel devices. In the last years we observed a growing interest toward SPAD arrays for a variety of applications that require good photon-timing resolutions, ranging from parallel fluorescence correlation spectroscopy [1] to spectrally resolved FLIMs and LIDARs for 3-D imaging with sub-centimeter depth resolution [2].

In multi-pixel applications a trade-off between electrical crosstalk and photon-timing jitter emerges. Indeed, in SPAD arrays the avalanche discriminating threshold must be chosen as high as to avoid electrical crosstalk between contiguous pixels. At the same time all the available devices, some more than others, show a photon-timing jitter that deteriorates as the threshold is increased. From this, the importance of understanding the statistical phenomena involved in the avalanche current growth in order to be able to design *timing enhanced devices* with good timing performance at high threshold levels.

II. DISCUSSION

The dynamics of the avalanche current growth can be roughly divided in two phases: the former is the *buildup* of the first filament of current around its seed point and the latter consists of the *lateral spread* of the avalanche current, until it fills the whole device active area.

During the buildup, the first carrier starts the process that gives rise to the first filament of current. In this phase, the current exhibits an exponential growth as the number of free carriers in the space charge region is still relatively small. No current-limiting mechanism is present yet, since the space charge density is still too small to affect the electric field.

While the number of carriers keeps increasing, the space charge becomes sufficiently large to locally depress the electric field, thus reducing the multiplication rate. Eventually, the electric field is locally reduced to the breakdown value and the current density saturates. At the same time, as the current filament becomes stronger, the avalanche spreads through the device's active area. There are two possible spread mechanisms: the first is a multiplication-assisted diffusion in which carriers laterally diffuse and give rise to an avalanche current in the nearby regions [3]; the second is a photon-assisted diffusion and it is caused by the re-triggering of an avalanche current far from the seed point, due to hot carriers luminescence [4]. Eventually, the avalanche current spreads through the whole active area of the device. It is worth noting that, during propagation, the specific resistance and in particular the space charge effect limits the maximum current density, and so the current growth velocity [5].

As reported in [6], it is clear that the buildup contribution to photon-timing jitter is almost negligible in particular at high threshold levels. Concerning to the lateral spread of the avalanche, as reported in previous works [7] the statistical contribution was associated to the photon injection position. In fact, an avalanche triggered at the center of the active area grows faster than one triggered near the border (because of the different length of the effective diffusion fronts). As tackled extensively in our recent work [5], it is now clear that this contribution, alone, is not able to justify the strong dependence of the photon timing jitter on the threshold value. On the other hand it is not clear which is the missing statistical contribution.

In order to clarify this issue a 2D simulator of the avalanche propagation has been developed that includes both the prop-

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agation phenomena: the multiplication- and photon-assisted diffusion. In this simulator the SPAD space charge region is considered as 2-D circle corresponding to the active area. The domain is discretized with a uniform 100x100 µm mesh. A pair of carriers is statistically injected into the active area and the carrier density evolution is followed with temporal steps of 1 ps. At each time step the carrier density is increased according to the growth time constant τ that depends on the local-voltage. The local-voltage is calculated taking into account the space charge phenomena and the reduction of the voltage across the p-n junction due to the external circuit. At each time step, the diffusion of the avalanche carriers is considered and the chance of a re-injection in a quiescent zone of the device by hot-carrier luminescence is statistically treated. The obtained results identify the photon-assisted diffusion as the likely missing statistical contribution. For a comprehensive answer to this issue a further work for a careful experimental characterization of the hot-carrier luminescence rate is compulsory.

Even if the cause of the photon-timing jitter is not completely clear, the solution is quite straightforward: to make the current grow faster. The statistical phenomena can be considered as a noise superimposed to a deterministically growing current. This noise causes a spread in the avalanche rising edge. It is therefore evident that a current growing faster is less sensitive to the statistical phenomena. In our previous work [5] we experimentally verified that this assumption is correct, in fact devices with a faster growing current have always better performance than the slower ones.

So, designing timing enhanced SPADs means designing devices with currents growing faster. The main phenomenon affecting the device current growth velocity is the space charge resistance, so we focused our attention on the possible ways to reduce it. With the aid of the ISE DESSIS device simulator we explored two simple ways to reduce the space charge effect: the reduction of the space charge thickness and the polarity swap of dopants. Both these solutions cause a reduction of the *Photon Detection Efficiency* (PDE). The PDE can be accommodated with the increase in the voltage applied, but at the expense of the dark counts [8]. The dark count rate is related to the value of the electric field peak, the higher is the electric peak the higher is the dark count rate. In order to investigate this trade-off we evaluated the relation between the PDE and the electric field peak. We concluded that these simple solutions are feasible but the space charge resistance can be reduced only by a small factor without impairing the other device characteristics.

As reported in [9], a P-i-N device (with flat electric field) exhibits negative space charge resistance. We suggest, for the first time, to use this kind of device as a SPAD in order to avoid the current density limitation due to the space charge effect during the propagation and obtain, in this way, a current rise dramatically faster. We analyzed the above mentioned trade-off between the electric field and the PDE for P-i-N devices with different thicknesses. As reported in figure 1 the P-i-N devices with thickness bigger than 1.5 µm are characterized by a more favorable trade-off with respect to traditional devices (S44 and S62). That means the same PDE level with lower electric field.

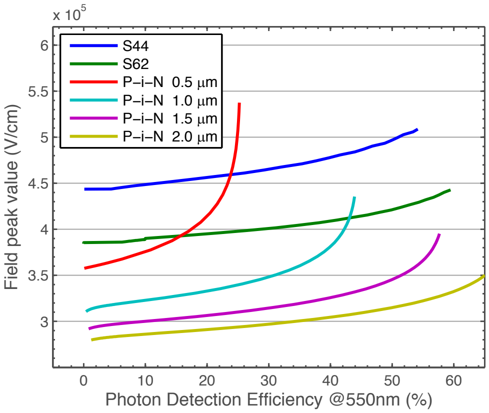

Fig. 1. Here reported the trade-off between the electric field and the efficiency for different devices: two classical devices (S44 and S62) and P-i-N device with various thicknesses of the intrinsic layer.

III. CONCLUSION

In this work we investigated the statistical phenomena involved in the current rise in a SPAD, we concluded that further experimental efforts are needed in order to confirm the photon-assisted diffusion as a key element in determining the photon-timing jitter of a device. Beside this we suggest a novel concept of SPAD device based on a P-i-N structure. This device should have better temporal resolution than the classical ones and should also maintain good dark count rates.

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