Optical crosstalk in InGaAs/InP SPAD array: analysis and reduction with FIB-etched trenches

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***Abstract*—This paper describes the reduction of optical crosstalk by means of FIB-etched trenches in InGaAs/InP Single-Photon Avalanche Diode arrays. Platinum-filled trenches have been fabricated in a linear array in order to limit the direct optical crosstalk between neighboring pixels. Experimental measurements prove that optical crosstalk has been reduced by ~ 60% thanks to a strong suppression of direct optical paths. An optical model is introduced in order to describe the main contributions to crosstalk and to validate measurements.**

***Index Terms*— Single Photon Avalanche Diodes, crosstalk, trench, Focused Ion Beam, photon counting, InP, InGaAs.**

I. Introduction

Single-photon imagers working in the short-wavelength infrared range (SWIR, from 900 nm up to 1700 nm) have been used recently in a growing number of applications, including terrain mapping, environmental monitoring, quantum imaging, safety and security. Some of these systems are based on single-photon time-of-flight (ToF) light detection and ranging (LiDAR) [1][2] and require arrays of single-photon detectors for the SWIR. InGaAs/InP SPAD (single-photon avalanche diode) arrays are the most promising detectors for SWIR for both performance and practical implementation, but they require further development [3].

In this paper, we analyze the optical crosstalk in a linear array of InGaAs/InP SPAD designed and fabricated with the same technology of the single pixel reported in [4]. We demonstrate that the optical crosstalk can be reduced, without degrading the performance of the device, by means of metal-filled trenches fabricated with focused ion beam (FIB) technique. Our main purpose was to identify the main contributions to the overall optical crosstalk and we prove that the direct path of the optical coupling from pixel to pixel is completely suppressed by the trenches. However, the indirect path based on the reflection at the bottom substrate interface still contributes significantly to optical crosstalk. We also present a model of the optical coupling that predicts the dependence of crosstalk on the distance between the pixels.

II. Device and Crosstalk Description

A. InGaAs/InP SPAD structure

We investigated optical cross-talk in an array of InGaAs/InP SPADs based on the single devices described in Ref. [4]. Such detectors exploit the Separate Absorption, Grading, Charge and Multiplication (SAGCM) heterostructure. A low energy photon is absorbed in the InGaAs layer (E_g ~ 0.75 eV at 295 K), generating an electron-hole pair that is separated by the electric field. The hole enters into the high field region and triggers the impact ionization process within the InP multiplication layer (E_g ~ 1.35 eV), thus giving rise to a self-sustaining avalanche process, whose current pulse is easily detectable by the read-out circuitry.

B. Optical crosstalk

During an avalanche, near-infrared photons are emitted due to the relaxation of hot carriers generated in the multiplication region because of the high electric field [5][6]. These secondary photons can be detected by neighboring pixels and trigger crosstalk avalanches.

The main emission wavelength at 300 K is ~ 950 nm (near band-edge component of the InP material), plus a broadband component that fits roughly a 3000 K blackbody spectrum [7]. Some of these photons travel through the InP layer without being absorbed and can reach the InGaAs layer of neighboring pixels, thus triggering new avalanches.

C. FIB-etched trenches

In order to investigate methods for decreasing the optical crosstalk, we designed and fabricated trenches between pixels

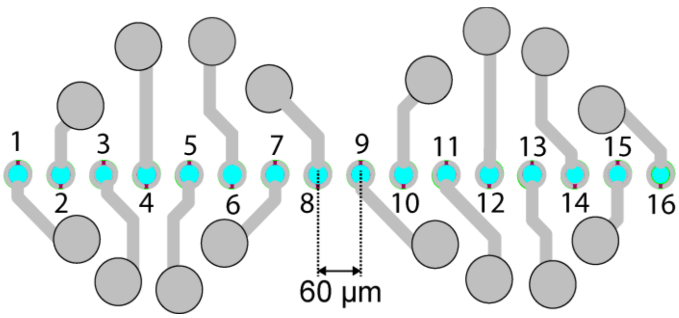

Figure 1: Layout of InGaAs/InP SPAD array under test. Pixel pitch is 60 μm and the active area of each pixel has a diameter of 25 μm.

Manuscript received ??; revised ??; accepted ??. Date of publication ??; date of current version ??.

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of a linear array composed by 16 elements (see Figure 1).

By means of a Focused Ion Beam (FIB) tool, we milled two different trenches: one empty, between pixels 10 and 11, and another one metallized with platinum, between pixels 11 and 12. Typically, FIB is employed on silicon wafers, therefore we had to set up non-standard milling recipes for milling InP and InGaAs layers. Given the diameter of the SPAD active area of 25 µm, the length of the trench it was designed to be 40 µm so as to avoid any direct path from pixel to pixel. The total thickness to mill was about 6 µm in order to go through the InGaAs layer below about 3.5 µm of InP, while the width was designed to be 5 µm in order to have a low width/depth aspect ratio for processing reliability. We used a DCG Systems P3X II, with the ions beam set at 30 keV, 1 nA, dwell time 100 ns, minimum retrace of 33 ms. Both pure physical mill and gas assisted (XeF2) one have been tested to define the best result. The InP layer melted and boiled under the beam bombardment: the beam current had been tuned to reduce it.

Figure 2 shows SEM (Scanning Electron Microscope) images of the fabricated empty and metal-filled trenches. We chose the metallization process to obtain a thin metal layer (Platinum) as a liner instead of completely filling the trench: while the Pt deposition valves were open, we refreshed several time the image. The result is to have a thin and uniform metal layer acting as a mirror for shielding photons travelling along a direct path between pixels. The drawback of this method is the risk to short all the metal structures exposed to the ion beam with a very thin metal layer. Therefore, it was necessary to add a beam cleaning of the surface near the conductive geometries to have no electrical path that can generate shorts.

III. Crosstalk measurements

Pixels from the SPAD array are biased and read out by means of a passive quenching circuit and the avalanches are

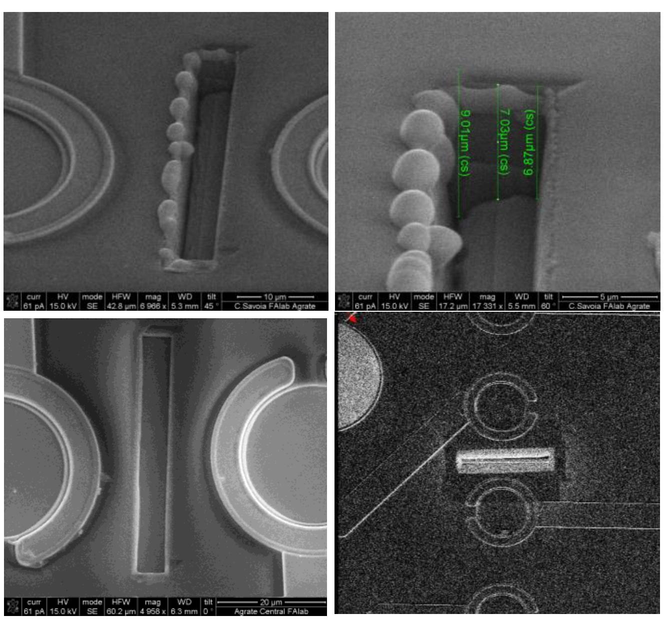

Figure 2: SEM images of: i) different results during the recipe setup, the debris of the "boiled layer" are clearly visible (above); ii) (below) the trench (left) before and after (right) metallization and metal removal to clean the die surface. In the darker regions, the metal (Platinum) has been removed in the areas surrounding the trench (right image).

detected using a comparator, whose output is fed to a counter. We measured the dark count rate of each pixel when all the other ones are kept off. Then, we measured the count rate R_V of a pixel, that is the victim V, when only one aggressor pixel A is ON. R_V results from the sum of the primary dark count rate (DCR) of the victim and the counts caused by crosstalk events, given by the aggressor dark counts multiplied by the probability to trigger an avalanche via crosstalk:

$$R_V = DCR_V + P_{CT} \cdot DCR_A$$

where subscript "A" stands for "aggressor", while subscript "V" stands for "victim", and P_{CT} is the crosstalk probability. Thus, the crosstalk probability can be calculated as:

$$P_{CT} = \frac{R_V - DCR_V}{DCR_A}$$

The dark count rates of both pixels are small enough that the probability of simultaneous counts can be neglected compared to the crosstalk probability. We repeated such characterization with and without trenches (both empty and filled ones), and at different inter-pixel distances. All the measurements were taken with the SPAD array cooled at 225 K.

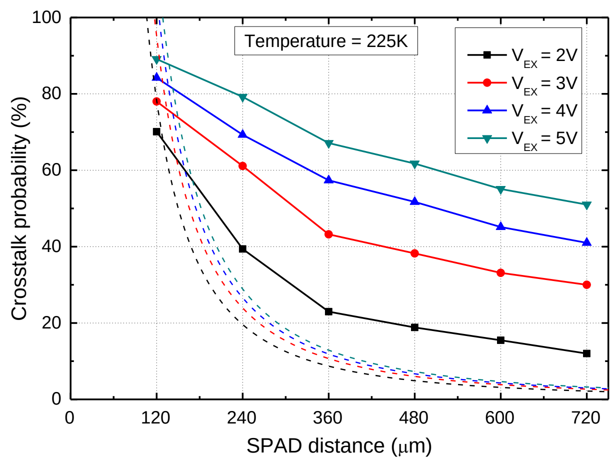

Figure 3: Measured crosstalk probability between two pixels at different distances and for different excess bias voltages when no trench is present between pixels. The dotted lines are the $1/R^2$ curves.

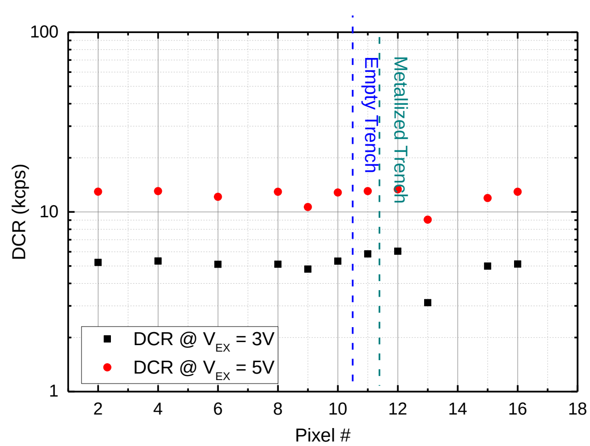

Figure 4: DCR distribution on the 16x1 InGaAs/InP SPAD array after milling trenches by means of the FIB process.

A. *No trench between pixels*

In Figure 3, we report the dependence of crosstalk probability on the distance of the aggressor A from the victim V when no trench is present. The crosstalk probability does not follow the $1/R^2$ law typical of the direct optical path. Moreover, for distances shorter than 120 µm, the crosstalk probability exceeds 80% even at the low excess bias of 3 V, thus showing a very strong optical coupling between pixels.

B. *Trenches between pixels*

First, we analyzed the impact of trenches on the performance of the SPAD by verifying that the FIB process does not damage the photodetector structure increasing the defect density in the depleted region, eventually resulting in higher DCR. In Figure 4, the dark count rate of some pixels in the array is shown and the positions of the trenches are also reported. After the FIB processing, the dark count rate for pixels in close proximity to the trenches is comparable to the ones far from it and no trend with distance from the trench is present.

We compared the measured crosstalk probabilities of the array with trenches with the ones obtained when no trench is present. Figure 5 shows that trenches effectively reduce the crosstalk: at 3 V of excess bias the crosstalk decreases from 88% to 47% for empty trenches and to 37% for trenches filled by Platinum. However, crosstalk is still high due to the indirect optical paths of the photons reflected from the back surface of the chip, as described by the model reported in the following section.

C. *Model and analysis*

Based on the experimental results and starting from what already reported in literature [8], we developed an optical model that describes the crosstalk between pixels as a function of distance. We considered only the spectral component not absorbed by the InP layer, we neglected the small differences between the refractive index of the layers of the device (n_{InP} = 3.4, n_{InGaAs} = 3.5), we supposed the aggressor as a cylindrical volume confined within the high electric field region and emitting photons isotropically. Moreover, we assumed the metal as a hybrid surface, both Lambertian and specular.

In our model, we consider two optical paths (see Figure 6):

- direct path: the photons travel in the InP layer and reach the absorption layer of a victim pixel.
- indirect path: the photons pass through the absorption layer, are reflected by the cathode metallic contact on the back of the chip and reach the victim pixel.

The results of a ray trace simulation are shown in Figure 7, where we evaluated the total amount of photons that reach a victim pixel from an aggressor one. The direct path decay follows the $1/R^2$ curve, as expected, whereas the indirect path shows a maximum at about 150 µm and longer decay due to the combination of Lambertian and specular reflection at the cathode metallization.

The direct comparison of the simulations with the experimental data reported in Figure 7 shows that our model accurately predicts the crosstalk dependence with the position of the SPADs.

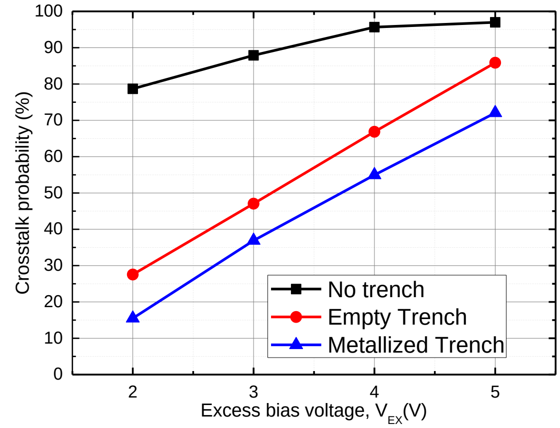

Figure 5: Measured crosstalk probability at different excess bias voltages with no trench, empty trench and Platinum-filled trench between pixels with 60 µm of pitch.

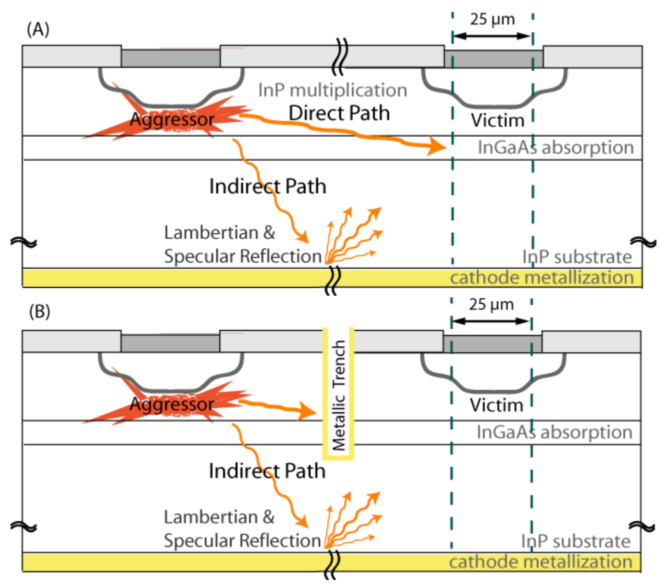

Figure 6: Schematic representation of the optical paths (direct and indirect) between two pixels without (A) and with (B) a trench in between. With the metal-filled trench, the direct path is completely obstructed.

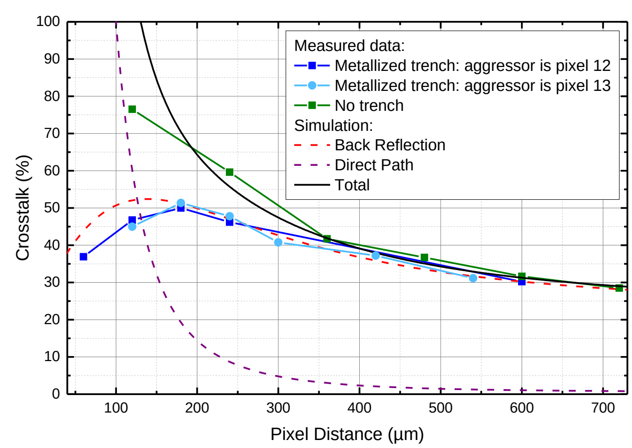

Figure 7: Crosstalk probability as a function of the pixel distance, with and without metallic trench at 3V of excess bias. Measured data are reported with filled symbols (squares when pixel 12 is the aggressor, circles when pixel 13 is the aggressor). The dotted lines are the simulated optical intensity reaching the victim.

The crosstalk decreases with the distance much slower than $1/R^2$ (a dependence that we would expect if the crosstalk were due only to direct optical paths). This effect is correctly predicted by our model and is due to indirect optical paths. When a trench is interposed between the pixels, the crosstalk is also well fitted by the simulated indirect optical intensity.

IV. Conclusion

Optical crosstalk is the main drawback in high-density InGaAs/InP SPAD arrays. In this paper, we investigated the main contributions and we proposed a model for the dependence of optical crosstalk on the position of the devices within the array. For the first time, we employed a focused ion beam (FIB) for milling trenches in InP and InGaAs, proving that there is no damage to the neighboring pixels. We identified and modeled the path of the photons from one pixel to the others, achieving a good agreement between the proposed model and the experimental data, both with and without a trench filled by Platinum. Even if the FIB-based approach is not suitable for scaling the approach to big arrays with thousands of pixels, our investigation identified the relative contributions of the direct and indirect paths in InGaAs/InP SPAD arrays, and the possible role of metallic liner of the trench.

Acknowledgements

The Authors wish to thank Salvatore Distefano for his support for the experimental activities here reported.

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