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Indirect optical crosstalk reduction by highly-doped backside layer in PureB single-photon avalanche diode arrays

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Abstract— **A method of reducing indirect optical crosstalk in a PureB single-photon avalanche diode (SPAD) array is investigated by TCAD simulations. The reduction is accomplished by taking advantage of the enhanced optical absorption of a highly-doped Si layer (p-type, 3×10^{20} cm^{-3}) on the backside of the wafer. The simulation environment is developed to give information about optical crosstalk by incorporating the experimental optical constants of the materials constituting the crosstalk reduction layer. It is shown that the indirect optical crosstalk is greatly reduced by increasing the thickness of the highly-doped Si layer. A crosstalk reduction of two orders of magnitude is gained with addition of the PureB/a-Si stack.**

I. INTRODUCTION

SINGLE-PHOTON avalanche-diode (SPAD) arrays are optical imagers that can register processes in nature that emit very weak optical signals and they often also have the capability to precisely determine the arrival time of the photon [1]. The performance of the array heavily depends on the number of false detections caused by unwanted carrier generation in the depletion region and on any optical crosstalk between the elements of the array. While the former is a property of the material, thus being the same for all the diodes in the array, the latter is a result of the light radiated from the avalanche multiplication process [2] causing false detections in neighboring diodes. Both are the source of noise measured as a dark count rate (DCR). The optical crosstalk is both direct from the interaction between neighboring diodes and indirect from the light reflected from the backside of the substrate [3]. Recently, SPADs with anodes fabricated by deposition of pure amorphous boron (PureB) layers achieved DCRs as low as 5 Hz at room temperature [4]. PureB SPADs are CMOS compatible, and of particular interest for applications that profit from having high responsivity in the (vacuum) ultraviolet spectral range.

In this paper, the suppression of indirect optical crosstalk of PureB SPAD arrays is investigated by means of Sentaurus Device [5] simulations. Highly-doped Si layers and PureB/a-Si stacks on the backside of the substrate are utilized for their enhanced optical absorption. The measured optical constants of PureB, a-Si and boron-doped Si layer with a concentration of 3×10^{20} cm^{-3} are implemented in the simulator along with the avalanche-multiplication radiation spectrum.

II. SIMULATION SETUP

Indirect optical crosstalk is pronounced in SPAD arrays with thin substrate where the substrate acts as a waveguide [6]. The cross-section of the simulated structure as shown in Fig. 1a is based on the SPAD fabricated in [4]. Two SPADs are defined in the 50-µm-thick p-type substrate and separated by a highly-doped p^{++} region for electrical isolation. The optical crosstalk between neighboring SPADs strongly depends on the distance d between the SPAD which emits the radiation due to an avalanche (SPAD1 - emitter) and the SPAD detecting this radiation (SPAD2 - detector). In order to simulate the optical crosstalk, the light emission of SPAD1 needed to be modeled. The spectrum emitted during the impact ionization process has a peak at a wavelength of around 650 nm, as shown in Fig. 1b [2]. This spectrum is used in the simulation as the light source defined at a single point in the middle of the anode of SPAD1, as shown in Fig. 1c. The raytracing model of the Sentaurus Device with 700 rays is defined, propagating in all directions to cover the entire 180° angle. The amount of light that can reach the detector SPAD by indirect optical crosstalk is determined from the integrated optical generation in the whole depletion region of the detector SPAD. Besides providing the electric isolation between the two SPADs, in our simulations the p^{++} region is also used to completely block the direct optical crosstalk, as in [3].

Similar to the direct optical crosstalk elimination using p^{++} region, the same highly-doped layer can be used at the backside of the substrate to absorb the light that would otherwise be reflected to detector SPAD, as shown in Fig. 1a. The efficiency of this crosstalk reduction layer depends on complex refractive index and the thickness of the materials that constitute the layer.

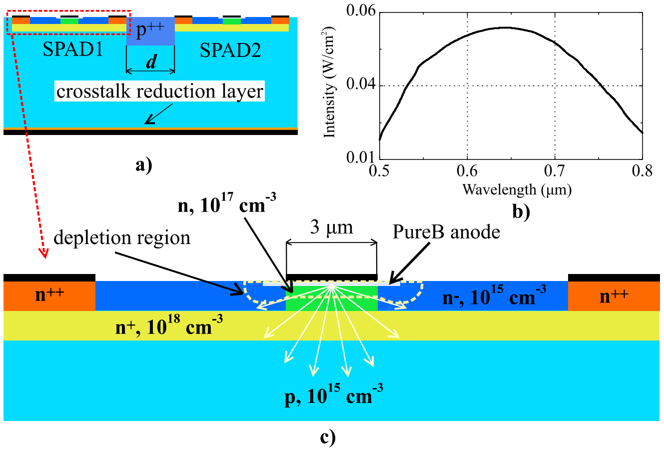

Fig. 1. (a) The simulated structure with two SPADs. The backside of the substrate is covered by the crosstalk reduction layer. (b) The intensity of the avalanche multiplication radiation. It is scaled to give a noticeable indirect optical crosstalk for the 50-µm-thick Si substrate without the crosstalk reduction layer. (c) The light rays coming out of the anode. They propagate unimpeded through the 10^{18} cm^{-3} doped buried layer.

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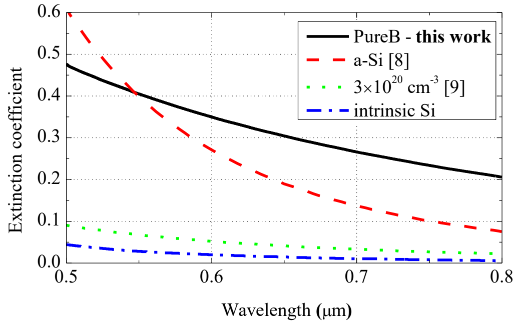

Fig. 2. Measured extinction coefficient of the PureB layer. Values for intrinsic Si, amorphous Si (a-Si) and Si doped with 3×10^{20} cm^{-3} are shown for reference.

III. RESULTS

The PureB layer can be used as an abundant source of boron diffusion to achieve high doping in the crosstalk reduction layer [7], while the optical properties of this layer are not yet reported. To that end, we measured the extinction coefficient of the PureB layer using VASE ellipsometer from Woollam. The sample is measured in the wavelength range between 240 nm and 2 μm at incident angles of 65°, 70° and 75°. This data is used to construct an optical model from which the thickness of the layer and the optical constants are derived. The measured extinction coefficient of the PureB layer is depicted in Fig. 2. This data is compared to the extinction coefficient of a-Si [8] and boron-doped Si with concentration of 3×10^{20} cm^{-3} [9]. At 650 nm, the extinction coefficient of PureB layer is 0.3 which is significantly higher than the values for intrinsic silicon and boron-doped silicon equaling 0.016 and 0.04, respectively. This value is more comparable to the value for a-Si of 0.18.

To assess the magnitude of the crosstalk, the integrated optical generation due to indirect optical crosstalk is normalized to the thermal generation of carriers in the depletion region of SPAD2. The reverse bias of 15 V creates a 500-nm-thick depletion region beneath the anode causing a thermal generation modeled as Shockley-Read-Hall generation with electron and hole recombination lifetime of 10^{-3} s. As shown in Fig. 3, the crosstalk has a maximum value for $d \approx 11$ μm, which is a result of the critical angle of reflection occurring at the Si/air interface [3]. Increasing the thickness of the B-doped layer increases the absorption of light in that layer thus reducing optical generation in the SPAD2. The indirect optical crosstalk at 11 μm for the 1-μm-thick B-doped layer is reduced 10 times. However, such a high doping might be a fabrication challenge. The PureB/a-Si stack is proposed as a way of mitigating this constraint and reducing the crosstalk even more (Fig. 4). The PureB/a-Si stack consists of a number of PureB and a-Si deposited layers. The PureB layer is simulated as a 10-nm-thick layer with the measured optical constant implemented in the simulator. Similarly, the a-Si layer is defined as 100-nm-thick layer with optical constant taken from [8]. The PureB layer is 10 nm thick, and therefore it absorbs much less amount of light compared to the 100-nm-thick a-Si layer. The indirect optical crosstalk can be reduced by more than two orders of magnitude using 100-nm-thick B-doped layer (3×10^{20} cm^{-3}) and 8-layer PureB/a-Si stack resulting in the crosstalk reduction layer thickness of 980 nm.

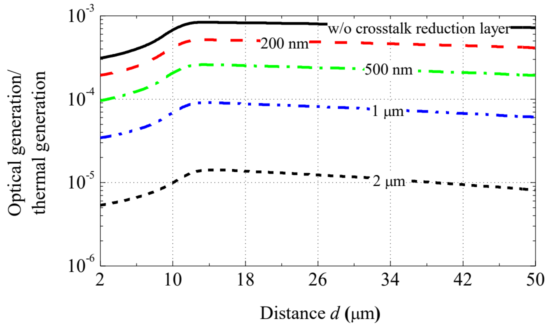

Fig. 3. Normalized optical generation in the depletion region of SPAD2 for the B-doped layer with doping concentration 3×10^{20} cm^{-3}.

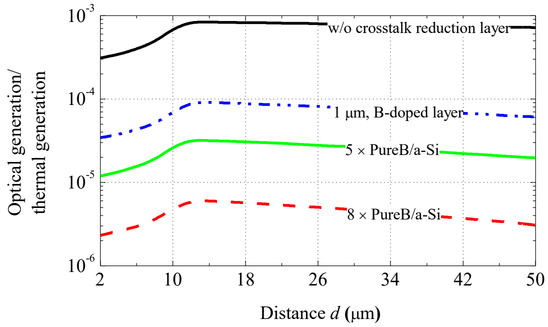

Fig. 4. Normalized optical generation for the structure with the p+/PureB/a-Si stack on the backside of the substrate.

IV. CONCLUSION

The reduction of indirect optical crosstalk in PureB SPAD array is utilized by engineering the layer at the bottom of the substrate. The avalanche radiation spectrum and complex refractive index models of PureB, a-Si and boron-doped Si for doping concentration of 3×10^{20} cm^{-3} are implemented in the simulator. The suppression of indirect optical crosstalk by two orders of magnitude can be obtained with p$^+$/PureB/a-Si stack at the bottom of the substrate.

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