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Multipixel geiger-mode photon detectors for ultra-weak light sources

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Abstract

Arrays of Single Photon Avalanche Detectors (SPAD) are considered today as a possible alternative to PMTs and other semiconductor devices in several applications, like physics research, bioluminescence, Positron Emission Tomography (PET) systems, etc. We have developed and characterized a first prototype array produced by STMicroelectronics in silicon planar technology and working at low voltage (30−40 V) in Geiger mode operation. The single cell structure (size down to 20 μm) and the geometrical arrangement give rise to appealing intrinsic characteristics of the device, such as photon detection efficiency, dark count map, cross-talk effects, timing and energy resolution. New prototypes are under construction with a higher number of pixels that have a common output signal to obtain a so-called SiPM (Silicon PhotoMultiplier) configuration.

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1. Introduction

Photon handling is nowadays considered an emerging issue, with so many applications covering a full branch of science and technology dedicated to it, namely photonics. High-resolution small-size photon detectors are fundamental to develop photonic systems with high performances in terms of sensitivity, precision, large-scale integration, etc. Examples of such applications are high-density charged particle trackers with position and timing capabilities, γ-ray detectors suitable for a high-resolution Positron Emission Tomography (PET), servo control systems in adaptative optics, 3-D imaging cameras, cameras for very weak light intensity, biophysical spectrometry. In this paper we propose bidimensional arrays of Single Photon Avalanche Detectors (SPADs) fabricated via a standard planar silicon production processing. We developed prototype arrays of 5 × 5 elements operating at low voltage (30–40 V) with active diameter of the single cell of 20 and 40 μm. We are going to illustrate our characterization of such arrays, in terms of bias voltage, operating temperature, dark-counting rates, photon detection efficiency, cross talk. We also describe tests we made in common output mode, thus achieving a photon-resolving operational mode called Silicon PhotoMultiplier (SiPM [1–3]) which has shown to resolve very efficiently the peaks of few-photon spectra produced by an ultra-weak light source.

2. Sensor description

The arrays of Geiger mode avalanche photodiodes we describe in this section are constituted of single pixels fabricated in silicon planar technology [4]. These pixels can

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detect very weak light fluxes, down to the single photon regime, thanks to the working principle described in the following. The single pixel is a circular highly doped n-p silicon junction biased above the breakdown voltage (the exceeding voltage is called overvoltage (OV) and with a uniform high electric field over the depletion layer. The junction is quiescent until an electron–hole pair is photogenerated, and so that an avalanche is triggered by an impact ionization mechanism. The current rises up to a macroscopic level (mA range) in few tens of picoseconds and the rise-up time of the avalanche marks the arrival time of the photon [5]. Because of the multiplication process above breakdown the avalanche presents a self-sustaining mechanism, and an external quenching circuit has to be used in order to reset the pixel and make it ready to detect another photon [6]. Microscopic views of our array are illustrated in Fig. 1. We have characterized two 5×5 sensors with five independent rows, and the diameter of the active area of the single cell 20 and 40 μm, respectively. The pitch, the distance between two adjacents pixel centres, is 200 μm for both sensors. The anode contacts are in common for each row and the single pixel cathode is separately available by means of external pads. Breakdown voltage distribution over an array has a mean value of 28 V with a standard deviation of 0.08 V. The quenching circuit we have chosen to use is passive and makes use of a ballast resistor higher than 100 kΩ in series with the cathode contact, whereas the anode is connected to 50 Ω load resistor (typically a coaxial cable or an oscilloscope input). Such a kind of circuit allows us to keep the overall circuitry very simple.

The intrinsic noise of a SPAD is due to charges thermally generated with a poissonian statistical distribution and it is called dark counting rate (s^{-1}). When a charge has a sufficiently thermal energy to reach the conduction band, an avalanche is generated and the output signal has exactly the same shape as the photo generated e–h pair. An array of SPADs, where each pixel is separately accessible, finds application in fields where the sensor is read in parallel or in imaging-like mode. In the latter the dark counting rate uniformity over many pixels is important to avoid strong off line corrections. We have measured dark counting rates for many arrays, discovering that our fabrication process gives a very narrow statistical distribution, as reported in Fig. 2 for a 20 μm diameter array with a mean value of about 400 s^{-1}. For the single pixel the timing jitter

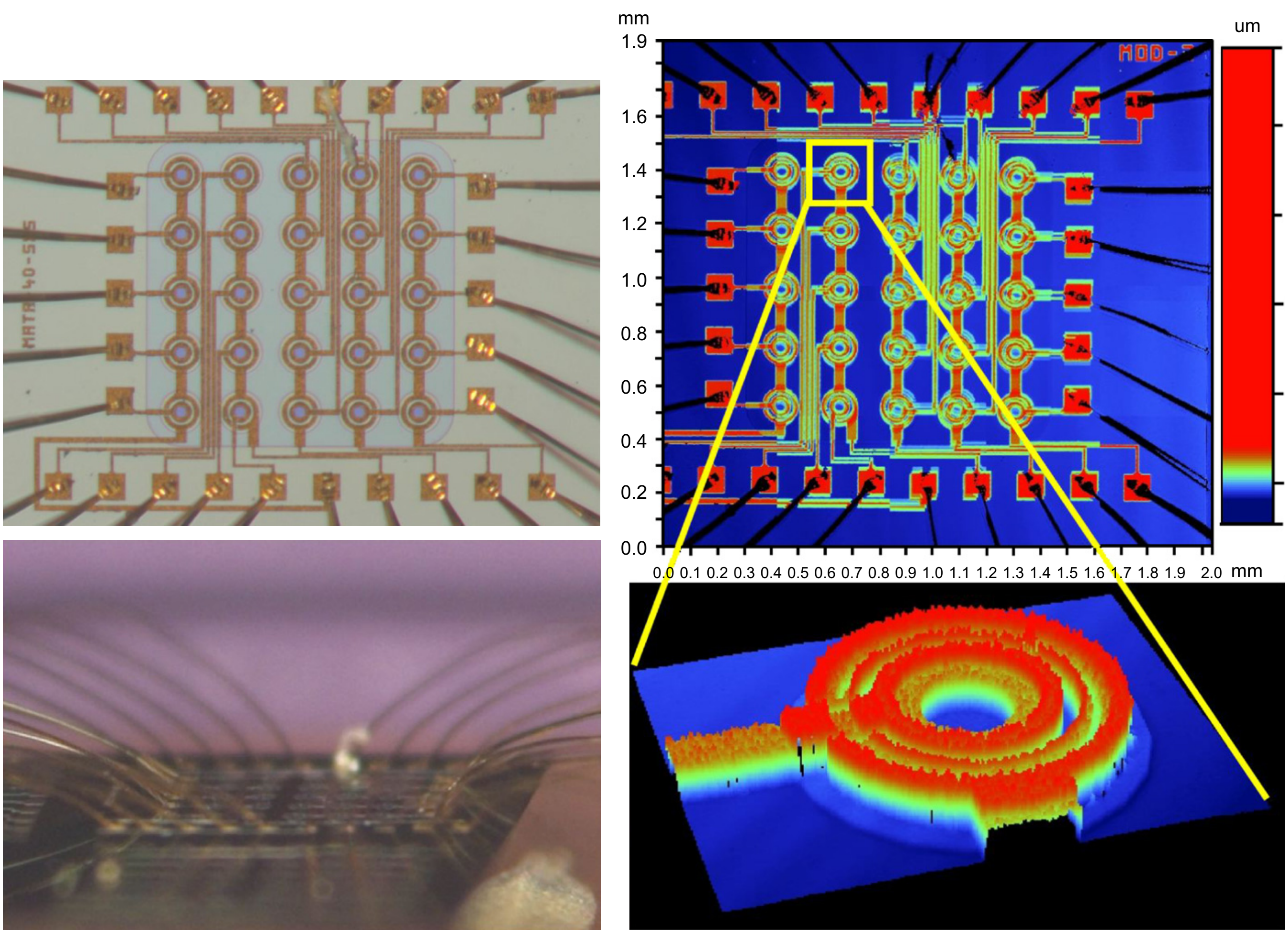

Fig. 1. Two micro-photographs of the tested 5×5 SPAD array (left side); corresponding image reconstructed by means of a non-contact profilometer (upper right); 3D profile of a cell, with exaggerated z-axis, as reconstructed using the mentioned profilometer.