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Three advanced designs of micro-pixel avalanche photodiodes: Their present status, maximum possibilities and limitations

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Abstract

Novel types of micro-pixel avalanche photodiodes (MAPDs) and their principle of performance are analyzed. The first design contains a common silicon wafer on which a matrix of independent p–n junctions (micro-pixels) with individual surface resistors are created. The individual resistors provide a local suppression of the avalanche process and discharge each micro-pixel to a common metal grid (electrode). The second design is an avalanche photodiode with independent micro-pixels in which the local suppression of the avalanche process is carried out due to the limited conductivity of individual surface drift channels formed along the silicon–silicon oxide boundary. This design is considered as a prototype for a future super-fast avalanche CCD matrix capable to work in a single-photon detection mode. The third design contains a matrix of deep buried multilayer pixels with an individual suppression of the avalanche process in independent vertical channels.
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1. Introduction

Different versions of silicon avalanche photodiodes (APD), as well as new micro-pixel/channel avalanche photodiodes (MAPDs) have been discussed widely during the last decade as an advanced photon counter for various applications. The sensitive area of a MAPD contains a matrix of independent micro-pixels with individual passive elements, which are created on a common silicon wafer. The individual passive elements provide local suppression of the avalanche process and discharge each micro-pixel to a common conducting or metal electrode.

The advanced properties of a MAPD are connected with a local negative feedback (LNF) effect, which result in a local self-suppression of the avalanche gain due to individual passive elements with necessary resistivity and capacitance and, consequently, significantly reduces the influence of crystal non-uniformities on the characteristics of the avalanche multiplication process. The LNF effect is achieved by forming a specific matrix in the multilayer silicon structure, which ensures a localization of the avalanche processes and limits them in frames of independent micro-regions of 3–50 μm in size, depending on the MAPD design.

In principle, each micro-pixel has a non-linear photo response because of a local redistribution of bias voltage between semiconductor and individual passive element during the avalanche process. At a bias higher than the breakdown voltage, each micro-pixel becomes a binary device with approximately constant amplitude of the photo response independently of the number of incoming photons. Such a behavior of the avalanche process in micro-pixels is like the performance of the known Geiger

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counters, which have no linear response. Actually, the MAPD contains a matrix of "micro-amplifiers" working in gain saturation mode. If the incident light generates in average less than one photoelectron per pixel, then the MAPD may work as linear device with single photon detection capabilities. Thus, the micro-pixel structure in a MAPD results in a unique combination of high signal amplification and uniform avalanche multiplication over the entire sensitive area of the device [1].

The basic design of the MAPD has been initially suggested and realized for operation in the red and near-infrared regions of the spectrum [2,3]. This design contains a common semitransparent metal layer and a matrix of small independent p–n junctions ("needles") with a typical size of 3 μm and a spacing of about 5 μm. The space between the p–n junctions is coated with thermal silicon dioxide to minimize the leakage current. Each pixel has a sandwich design like a metal-resistive layer-semiconductor (MRS) structure. This device is made in a very simple technology and it may demonstrate very good parameters in the red and near-infrared regions of spectrum. However, the basic design of MAPD has two main problems: a low yield of working devices because of the short circuit problem through its thin resistive layer with thickness of about 0.1–0.2 μm, and a low sensitivity in the blue and UV range because of a significant light absorption in both, resistive layer and the p–n junctions with a thickness of about 1.5 μm. In this paper, three advanced designs of MAPDs are considered from the point of view of their advantages, restrictions and qualification for a mass production [4].

2. MAPD with individual surface resistors

The first design (Fig. 1a) contains a matrix of independent planar p–n junctions/micro-pixels with individual surface resistors separated from the silicon wafer by a buffer layer [5]. The individual surface resistors made of amorphous silicon or another high-resistive material provide suppression of the avalanche process and consequently, discharge each micro-pixel to the common metal grid (electrode). This type of a MAPD has high yield and good sensitivity in the blue and UV regions of spectrum because of, firstly: the surface resistors may have large spacing between the micro-pixel and a metal electrode. This large spacing is necessary to avoid the short circuit problem mentioned above. Secondly, the main part of the sensitive area is not covered by the resistive layer. This type of MAPD has a low noise factor ($F\sim1$) and a high level of signal gain ($G\sim10^6$), but has following problems: a low geometrical transparency (max. ~50%), a limited pixel density (max. ~1000 pixels/mm^2) and a non-standard technology for the individual surface resistors with high values (~1 MΩ).

After the information about the first advanced design of MAPDs which has been published in 1998 (priority of 1996, [5]), some other designs named silicon photomultipliers—"SiPM", APD with MRS structure—"MRS APD" or Geiger mode APD—"GAPD" have been fabricated by different institutions. In Fig. 2 pictures of three different MAPD devices from Hamamatsu [6], MEPhI [7] and CPTA [8] are presented. It can be seen that all samples contain the same distinguishing features—a matrix of p–n junctions/pixels on a common wafer, individual surface resistors and a common metal electrode—which were first suggested in 1996 and shown in Fig. 1a.

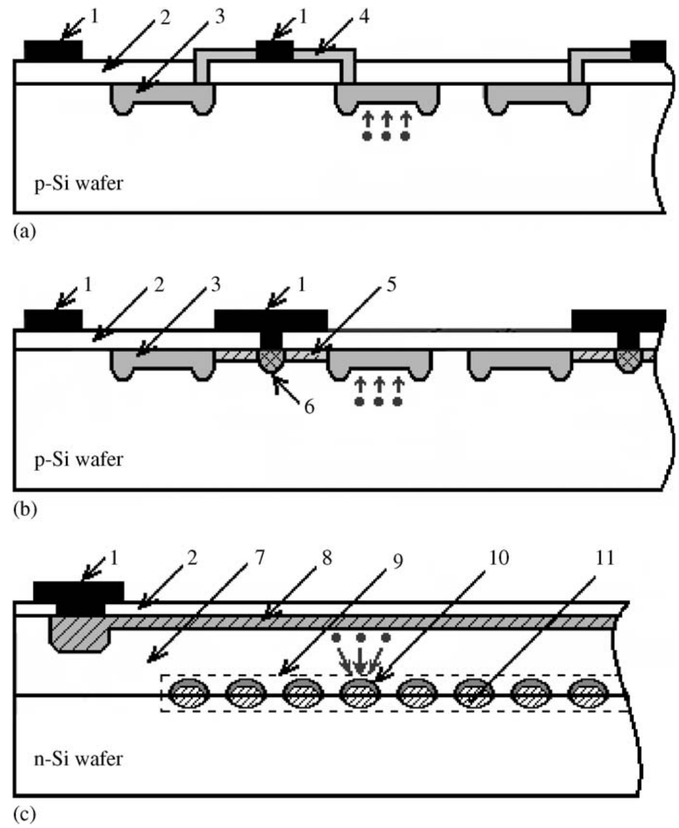

Fig. 1. Schematic views of the novel MAPD: (a) the MAPD with individual surface resistors; (b) the AMPD with surface transfer of charge carriers; (c) the MAPD with individual micro-wells. 1—Common metal electrode, 2—buffer layer of silicon oxide, 3—p–n junctions/micro-pixels, 4—individual surface resistors, 5—individual surface channels for the transfer of charge carriers, 6—drain region/contact, 7—epitaxial silicon layer of p-type conductivity, 8—a high-doped silicon layer of p-type conductivity, 9—a region with micro-wells, 10—local avalanche regions, 11—individual micro-wells.

3. MAPD with the surface transfer of charge carriers

The main feature of the second-type MAPD is the surface transfer of charge carriers along the silicon substrate (Fig. 1b) [9,10]. The operational principle of this MAPD is the following: a positive bias is applied to the field electrode, which is large enough to cause an avalanche multiplication in the matrix of p–n junctions/micro-pixels. At this bias, the space between the micro-pixels and their individual drain region is completely depleted, and a very thin (~10 nm) layer of n-type conductivity with high resistance is formed. The value of the surface resistance

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