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MICROCHANNEL AVALANCHE PHOTODIODE (VARIANTS)

Description of the Invention

The invention relates to semiconductor photosensitive devices and specifically to semiconductor avalanche photodiodes with internal amplification of the signal. The proposed microchannel avalanche photodiode can be used for registration of super feeble light pulses, including up to individual photons, and also gamma quants and charged particles in devices for medical gamma tomography, radiation monitoring, and nuclear physics experiments.

A device [1] is known, which includes a semiconductor substrate, [and] a matrix of semiconductor areas that have conductivity type opposite that of the substrate and that are separated from the translucent field electrode by a buffer resistive layer with specific conductivity. Avalanche amplification of the photoelectrons takes place on the boundaries between the substrate and the semiconductor areas. The avalanche current then flows to the translucent electrode through the resistive layer situated above these areas. A shortcoming of this device is the low quantum output in the visible and ultraviolet areas of the spectrum due to the poor transparency of both the buffer layer and the highly doped semiconductor areas. In addition, there is no possibility that the photoelectrons formed between the semiconductor areas can be amplified, which leads to a reduction in the sensitivity of the device.

A device [2] is known, which includes a semiconductor substrate with n-type conductivity and an epitaxial layer with p-type conductivity separated from the substrate by a resistive layer and a dielectric layer. Separate semiconductor areas with n-type conductivity are formed inside the dielectric layer and exit on the one side at the resistive layer and on the other at the epitaxial layer. Highly doped areas with n-type conductivity ensure localization of the avalanche process in the p-n junctions separated one from the other by areas of the dielectric layer. The photosensitive layer where the photoelectrons are formed is actually the epitaxial layer grown on the surface of heterogeneous materials—dielectric and resistive layers. That is why the main shortcomings of the device are the complexity of the technology of preparing such epitaxial layers and the high level of dark current, which leads to deterioration of the sensitivity, and the signal-to-noise ratio of the device.

A device [3] is also known, which has been taken as a prototype and which includes a semiconductor substrate and a semiconductor layer forming a p-n junction with the substrate. The surface of the substrate contains a matrix of separate semiconductor areas with enhanced conductivity compared to that of the substrate. In the prototype, the semiconductor areas are used with the purpose of creating separate avalanche areas (micro-channels) that ensure amplification of the signal. A shortcoming of the device is the presence and also the formation in the process of operation of uncontrollable local micro-sparkovers in the interface regions where amplification of the photoelectrons is taking place. The problem here is that the semiconductor areas are located immediately on the pn junction interface formed on the substrate–semiconductor layer interface. That is why the semiconductor areas have a charge and current connection

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between them or through the electrically neutral part of the semiconductor layer or through the substrate depending on the conductivity type. In other words, the device does not have implemented local limitation of the current in the separate areas where the avalanche process is taking place. The one or several areas with decreased sparkover potential do not permit an increase in the device voltage in order to attain a high level of the avalanche process over the whole area of the device. In this way, the device has a limited factor of amplification of the avalanche process, which is an indicator of the sensitivity level of the avalanche photodiode.

The proposed invention is aimed at improving the stability of the signal amplitude and increasing the sensitivity of the avalanche photodiode in the visible and ultraviolet regions of the spectrum. In order to achieve these technical results, at least one matrix consisting of separate solid-state areas with enhanced conductivity surrounded on all sides by semiconductor material with one type of conductivity is formed in the avalanche photodiode that includes a semiconductor substrate and semiconductor layers with various electrophysical parameters. The solid-state areas are located between two additional semiconductor layers, which have enhanced conductivity in comparison to the semiconductor layers with which they have a common interface. Moreover, at least one of the additional semiconductor layers with enhanced conductivity does not have a common interface with the solid-state areas. The semiconductor areas are located along the common interface of the semiconductor layers.

Depending on the variant of implementation of the device, the solid-state areas with enhanced conductivity are formed of material, which is the same as that of one of the semiconductor layers but with a different type of conductivity, of narrow zone semiconductor with regard to the material of the semiconductor layers, and also of metal material. This leads to the formation in the device of either alternating p-n junctions, or heterojunctions, or metal-semiconductor junctions in a direction perpendicular to the substrate plane.

As a result, at least one two-dimensional matrix of separate potential holes located between the additional semiconductor layers with enhanced conductivity is formed in the device. The formation of two and more matrices of solid-state areas with enhanced conductivity leads to great improvement of the sensitivity and stability of the signal amplitude of the device.

The invention is illustrated with a drawing (Figure 1) where the cross sections of the micro-channel avalanche photodiode with one (A) and two (C) matrices of the solid states areas located between the additional semiconductor layers with enhanced conductivity are shown. The device is manufactured on a base of a semiconductor substrate 1, for example silicon with n-type conductivity and a resistivity of 1 Ohm*cm. At the beginning, the first additional semiconductor layer 2 with n-type conductivity and a resistivity of 0.1 Ohm*cm is formed in the work area of the semiconductor substrate by means of local diffusion doping with phosphorus. Then a silicon semiconductor layer 3 with p-type conductivity and resistivity in the range of 1-100 Ohm*cm forming a p-n junction with the first additional semiconductor layer is grown on the surface of the substrate by means of molecular epitaxy. The solid-state areas with enhanced conductivity 4 are formed by means of ion-doping of the semiconductor layer with phosphorus atoms. The doping dose is selected in the 5-100 $\mu Ci/cm^2$ range. After annealing the defects at a temperature of 900°C, areas or islets with n-type conductivity and a resistivity of about 0.01 Ohm*cm surrounded on all sides by semiconductor material with p-type conductivity and resistivity in the 1-100 Ohm*cm range are formed in the semiconductor

layer. Then a second additional semiconductor layer 5 with a resistivity of about 0.01 Ohm*cm is formed on the surface of the semiconductor layer 3 by means of ion-doping with boron. This leads to the formation in the volume of the device of alternating p-n junctions in direction 6 perpendicular to the substrate plane, whereby the alternating p-n junctions are located between the two additional semiconductor layers with enhanced conductivity.

Depending on the variant of implementation of the device, the solid-state areas with enhanced conductivity are formed also of germanium or titanium clusters surrounded by silicon material. In order that germanium or titanium clusters cab be formed in the volume of the silicon semiconductor layer, the dose of doping with germanium or titanium is selected to be above 1000 $\mu Ci/cm^2$. Then either alternating p-n junctions or metal—semiconductor junctions in a direction perpendicular to the substrate plane are formed in the device.

The cross-section dimensions of the solid-state areas and the clearance between them are determined by a special photo-template by means of which windows are opened in a photo-resist or in a special mask for local doping of the semiconductor layer. The energy of the ions in the process of doping is selected depending on the necessary depth of imbedding of the implanted atoms. Then the known components of the device as the protecting rings or the deep grooves around the work area as well as the contact electrodes are prepared.

Unlike the prototype, the avalanche amplification of the photocurrent in the proposed device takes place only in the boundaries of the solid-state areas with semiconductor layers, which represent by themselves independent channels of amplification of the charge carriers coinciding with direction 6. This occurs thanks to the fact that the areas with alternating potential barriers in direction 6 are surrounded by p-n junction areas located in direction 7. In operating mode, a voltage with polarity corresponding to the depletion of the semiconductor substrate from the main carriers of the charge is added to the top electrode of the semiconductor layer. When this happens, the middle junction in the multiplication channel becomes displaced in the forward direction and the two outside junctions—in the opposite direction. The p-n junction areas located between the multiplication channels also become displaced in the opposite direction. Moreover, the first additional semiconductor layer with enhanced conductivity limits spreading of the electric field in the substrate and in this way it ensures a decrease in the dark generation current and spreading of the avalanche process only in the work area of the device. The second additional semiconductor layer with enhanced conductivity limits the electric field from the external side and ensures homogeneity of the potential along the photosensitive surface of the device. As a result, a form of distribution of the potential inside the device is attained such that the gathering of the photoelectrons formed in the upper photosensitive semiconductor layer towards the potential micro-holes is stimulated. The amplification of the photoelectrons takes place in the first channel of multiplication from top to bottom, and the next junction displaced in the forward direction plays the role of a potential hole with a depth of about 0.5-1 V where the multiplied electrons gather. The accumulation of electrons in the above-mentioned potential hole for a time of several nanoseconds leads to a sharp decrease in the electric field in the avalanche area (i.e., in the boundary area of the first junction) and as a result of this the avalanche process in the given multiplication channel stops. Afterwards, for a time of several tens of nanoseconds after the discontinuation of the avalanche process, the accumulated electrons

go into the substrate thanks to sufficient leakage of the third junction. In this way, avalanche amplification of the photoelectrons takes place in independent multiplication channels, which do not have a charge connection between themselves. Thanks to that, the stability of operation is improved and the sensitivity of the avalanche photodiode increases.

Sources of Information.

1. Gasanov A. G. et al. Patent of the Russian Federation No. 1702831 from June 27, 1997. Application 4747595/25 from October 11, 1989 (analog).
2. Antich P.P., et al. US Patent No. 5844291 from December 1, 1998, Class: H 01L 31/107; H 01 L 31/06. Application No. 771207 from December 10, 1996 (analog).
3. Sadygov Z. Y., Patent of Russia No. 2102821 from January 20, 1998, Class: H 01 L 31/06. Application No. 96119670 from October 10, 1996 (prototype).

FORMULA OF THE INVENTION

1. Avalanche photodiode containing a substrate and semiconductor layers with various electro-physical properties having common interfaces both between themselves and with the substrate, characterized by the presence in the device of at least one matrix consisting of separate solid-state areas with enhanced conductivity surrounded by semiconductor material with one and the same type of conductivity, whereby the solid state areas are located between two additional semiconductor layers, which have higher conductivity in comparison to the semiconductor layers with which they have common interfaces.
2. Avalanche photodiode in accordance with Claim 1, distinguished by the following: the solid-state areas are made of the same material as the semiconductor layers surrounding them but with conductivity type that is opposite with respect to them.
3. Avalanche photodiode in accordance with Claim 1, distinguished by the following: the solid-state areas are made of a semiconductor with a narrow forbidden zone with respect to the semiconductor layers with which they have common interfaces.
4. Avalanche photodiode in accordance with Claim 1, distinguished by the following: the solid-state areas are made of a metal material.