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SILICON PHOTODIODE FOR VISIBLE SPECTRAL REGION

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We consider the design and spectral characteristics of a photodiode with a graded n-i-p junction made by implantation of As and P into silicon with resistivity 1 kiloohm·cm. The quantum efficiency of the photodiode is higher than 90% in the spectral range 530–700 nm.

Keywords: *silicon photodiode, graded n-i-p junction, spectral sensitivity.*

Photodiodes with high sensitivity in the short-wavelength portion of the visible region of the spectrum, fabricated based on high-ohmic silicon, are widely used in scintillation devices for visualization of gamma radiation and x-radiation in nuclear physics and medicine [1]. The following have been used to improve collection of minority charge carriers generated by short-wavelength photons in the immediate vicinity of the silicon surface: a shallow *p-n* junction with a vertical [2] or a horizontal [3, 4] structure, a graded *p-n* junction formed by diffusion of boron through the lattice of a thin layer of silicon oxide on the substrate surface [5], and an inversion layer photodiode [6]. The use of an inversion layer photodiode is limited by the narrow range of linearity typical of the spectral responsivity. A general disadvantage of photodiodes formed by boron diffusion into *n*-type silicon is the presence in the near-surface layer of silicon of a barrier layer under the oxide, preventing electrons generated by light in the *p*-region of the silicon from crossing into the *p-n* junction [7]. Photodiodes based on *n-p* junctions formed by diffusion of phosphorus or arsenic are more stable in the short-wavelength portion of the visible region of the spectrum [8, 9]. Their sensitivity at $\lambda < 500$ nm is higher than the sensitivity of photodiodes formed by boron doping in *n*-type substrates [10].

In this paper, we propose a design for a silicon photodiode with a graded *n-i-p* junction [11], and we study its spectral sensitivity.

The photodiode design is shown in Fig. 1. The resistivity of the *p*-type substrate is 1 kilohm·cm. The region with *n*-type conductivity consists of two combined regions. First, by implantation of phosphorus followed by annealing, a grid of local regions of n^+-type silicon of depth 1.2 μm is created on the silicon surface. The local n^+ regions increase collection of electrons by the junction which have been generated by short-wavelength photons. Then by implantation of arsenic into the silicon surface, a continuous *n*-type region is formed. In order to reduce the number of defects in the *n*-type region and to obtain an abrupt concentration profile when creating the junction, arsenic implantation is carried out through a thin layer of SiO_2 on the silicon surface.

The arsenic and phosphorus segregation coefficient in silicon is >1 [12]. This allows us to ensure the minimum depth for the non-photoactive zone on the silicon surface. Arsenic is selected because of the following considerations. Its low diffusion coefficient makes it possible to form shallow junctions. The depth of the arsenic-doped *n*-region in our case is 0.2 μm. Due to the relatively low atomic weight and the similar size of the ionic radii for silicon and arsenic, mechanical strains arising when doping with arsenic are relatively small, which lets us decrease the number of defects in the *n*-region and reduce the effect of recombination processes compared with the phosphorus-doped n^+-regions [13].

The ohmic contact to the *n*-region is formed on the periphery of the arsenic-doped *n*-region. A guard ring reduces the surface component of the dark current. It is designed to be combined with the ohmic contact to the substrate. The dimensions of the photosensitive region of the photodiode are 5 × 5 mm. A two-layer SiO_2/Si_3N_4 antireflective coating is formed on the photosensitive surface of the *n-i-p* junction.

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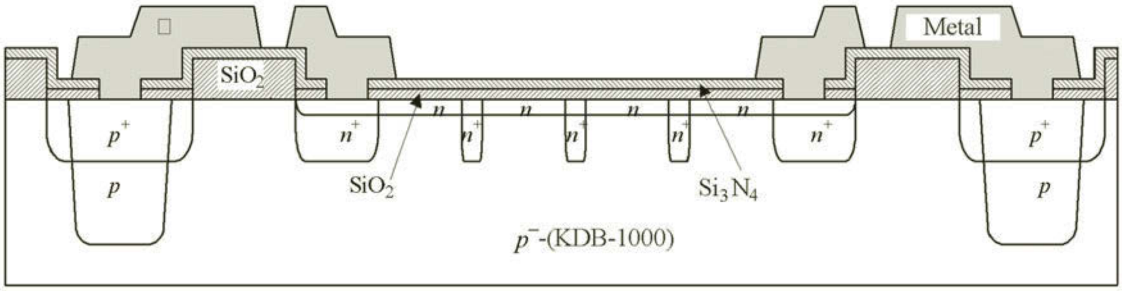

Fig. 1. Design of photodiode with graded *n-i-p* junction.

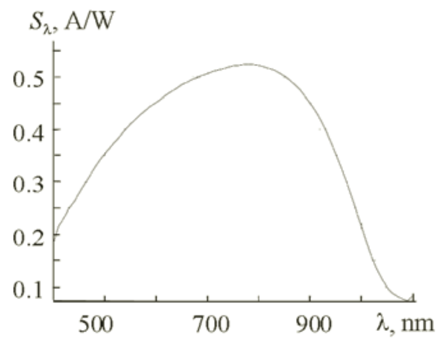

Fig. 2. Spectral characteristics of photodiode with graded *n-i-p* junction.

The spectral characteristic of the *n-i-p* photodiode with graded junction is shown in Fig. 2. In contrast to conventional silicon *p-i-n* photodiodes, for which a position of the maximum spectral sensitivity at $\lambda > 900$ nm is typical [14, 15], in the photodiode under consideration the maximum is located in the long-wavelength limit of the visible range. In the range 530–700 nm, the quantum efficiency of the photodiode is >90%. For green light with $\lambda = 550$ nm, the spectral sensitivity is $S_\lambda = 0.41$ A/W.

The short diffusion length of electrons in the substrate determines the position of the spectral sensitivity maximum of the photodiode and its comparatively low (relative to standard photodiodes) sensitivity in the IR region. According to [16], the absorption depth for light with $\lambda = 560$ nm in silicon is 1.61 μm, which is slightly greater than the depth of the phosphorus-doped n^+ region. We can assume that the short-wavelength limit of the high quantum efficiency range (530 nm) corresponds to light for which the absorption depth is no greater than the depth of the phosphorus-doped n^+ region but is greater than the depth of the arsenic-doped *n* region. The absorption depth for violet light with wavelength $\lambda = 400$ nm in silicon is <0.1 μm [3]. Accordingly, it is mainly absorbed in the arsenic-doped near-surface silicon layer. Its number of defects, distribution profile, and the effect of surface recombination at the Si–SiO_2 interface are responsible for the decrease in spectral sensitivity of the photodiode at the short-wavelength limit of the visible range of the spectrum.

The maximum spectral sensitivity in the short-wavelength region was observed for implantation of As at a dose of 1–10 μC/cm^2. Further increase in the As dose leads to an increase in the number of defects in the *n* layer, in which a significant proportion of the short-wavelength photons are absorbed, along with a decrease in the sensitivity. The dark current of the photodiode was no greater than 0.1 nA (for $U = 10$ mV). The capacitance of the photodiode was 70 pF ($f = 1$ MHz, $U = 10$ mV). The planar structure of the photodiode makes it possible to use it to make hybrid linear and two-dimensional photodiode arrays.

Thus combined doping of silicon with arsenic and phosphorus when making a graded *n-i-p* junction lets us make photodiodes with quantum efficiency >90% in the range 530–700 nm. The high spectral sensitivity for green light, the low dark current and capacitance with a large photosensitive area for the photodiode allow us to use it in CsI scintillation detectors for ionizing radiation.

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