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*In memoriam of E.M. Kruglov and V.V. Filimonov*

# Quantum yield of an avalanche silicon photodiode in the 114−170 and 210−1100 nm wavelength ranges

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*Received September 17, 2021*
*Revised November 19, 2021*
*Accepted November 29, 2021*

An avalanche silicon photodiode has been developed for the near IR, visible, UV and VUV light ranges. The external quantum efficiency has been studied in the 114−170 and 210−1100 nm ranges. It has been demonstrated that the avalanche photodiode reaches the quantum yield of 29 to 9300 electrons/photon at the 160 nm wavelength and bias voltage of 190−303 V, respectively.

**Keywords:** avalanche photodiode, vacuum ultraviolet, visible light range, near IR, silicon

DOI: 10.21883/TPL.2022.03.52871.19026

Earlier we have represented an $n^{++}-p-\pi-p^{++}$-avalanche silicon photodiode (ASPD) with the external quantum yield $\eta_{\mathrm{ASPD}} = 24-150$ electrons/photon in the 120−170 nm spectral range [1]. To increase $\eta_{\mathrm{ASPD}}$ in the vacuum ultraviolet range, we have developed and studied photodiode ASPD of a relevantly optimized structure.

As shown in [1], conventional antireflection coatings based on dielectrics ($SiO_2$, $MgF_2$, LiF, $Si_3N_4$) are inadmissible at wavelengths $\lambda < 130$ nm because of a drastic decrease in the photon absorption depth (down to $\sim 10$ nm). This absorption depth of VUV photons makes any dielectric antireflection coating nontransparent for radiation of $20 < \lambda < 130$ nm [2]. As an alternative to the antireflection coatings, the known method of texturing the active region surface [3] was applied in constructing the new ASPD. This was done in order to reduce the loss associated with the VUV reflection. In addition, the temperature of boron diffusion during formation of the isotype $p^{++}$-layer on the textured surface was reduced. This was done to increase the VUV detection efficiency due to decreasing the depth of the isotype $p^{++}-\pi$-junction. Moreover, the photodiode active region thickness was reduced by reactive ion etching to 150 $\mu$m in order to reduce the dark current. In other respects, the structure of ASPD optimized so as to ensure VUV detection was similar to that of ASPD described in [1].

The optimized ASPD in the „front illuminated" and „back illuminated" modes is schematically depicted in Fig. 1. In this work, ASPD in the „front illuminated" mode was irradiated with a photon beam in the $\lambda = 600-1100$ nm spectral range from the side of the $n^{++}$-layer coated with silicon nitride (Fig. 1, *a*). In the „back illuminated" mode, ASPD was irradiated with a photon beam in the $\lambda = 114-170$ and 210−1100 nm spectral ranges from the side of the $p^{++}$-layer (Fig. 1, *b*). The ASPD irradiation modes were changed over by overturning the sub-crystal board and fixing it by soldering to the TO-5 package terminals (Fig. 1, *c*).

Spectral dependences of $\eta_{\mathrm{ASPD}}$ for the „front illuminated" and „back illuminated" operating modes were studied using the metrological base from [1] at the back bias voltage of 280 V and temperature of 22°C. For the $\lambda = 114-170$ nm range, the vacuum monochromator exit slit was narrowed from $0.3 \times 0.3$ to $0.15 \times 0.15$ mm. This was done to guarantee the entering of the entire VUV beam into the ASPD active region 1 mm in diameter. This condition is necessary for measuring spectral characteristics by the comparison method. Parameter $\eta_{\mathrm{ASPD}}$ was defined as

$$\eta_{\mathrm{ASPD}} = \eta_{\mathrm{SPD}}(I_{\mathrm{ASPD}}/I_{\mathrm{SPD}}), \qquad (1)$$

where $\eta_{\mathrm{SPD}}$ is the external quantum yield of the calibrated photodiode, $I_{\mathrm{ASPD}}$ is the ASPD photocurrent, $I_{\mathrm{SPD}}$ is the calibrated photodiode photocurrent. As the calibrated diode, photodiode SPD free of internal amplification [4] was used. The results are presented in Fig. 2.

Methodologically, this study differs from that in [1] in determining the ASPD multiplication factor ($M_{\mathrm{ASPD}}$). Factor $M_{\mathrm{ASPD}}$ was determined via spectral dependence of $\eta_{\mathrm{ASPD}}$ in the „front illuminated" mode (Fig. 2). In this mode, ASPD was irradiated from the side of the $n^{++}$-layer coated with silicon nitride 0.12 $\mu$m thick. Since the thickness of the silicon nitride layer on the $n^{++}$-layer surface is known from the manufacturing procedure accurately to at least 2%, it appears from the Fresnel transform [5] that reflection loss for $\lambda = 940$ nm is below 1% and, hence, may be ignored. This assumption allows later on proceeding from the premise that 100% of radiation will be absorbed in the ASPD active

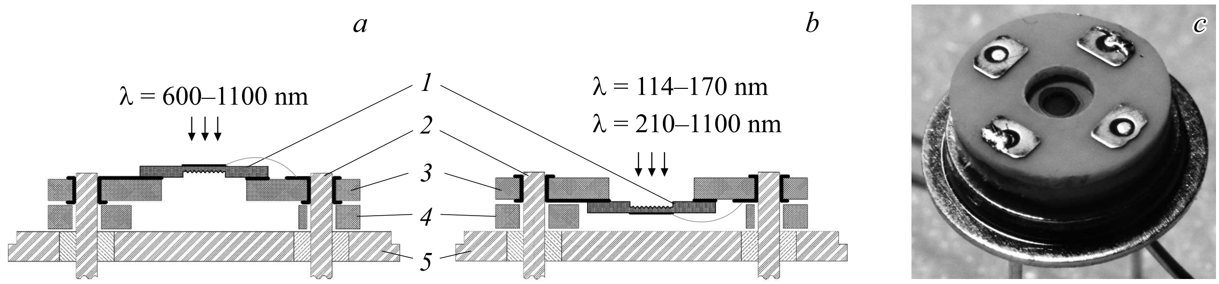


**Figure 1.** ASPD in the TO-5 package. *a* — „front illuminated“mode, *b* — „back illuminated“ mode (*1* — ASPD crystal, *2* — electrically isolated package terminals, *3* — metallized sub-crystal dielectric board, *4* — dielectric board, *5* — TO-5 metal–glass package header), *c* — a photograph of ASPD in the TO-5 package in the „back illuminated“mode.

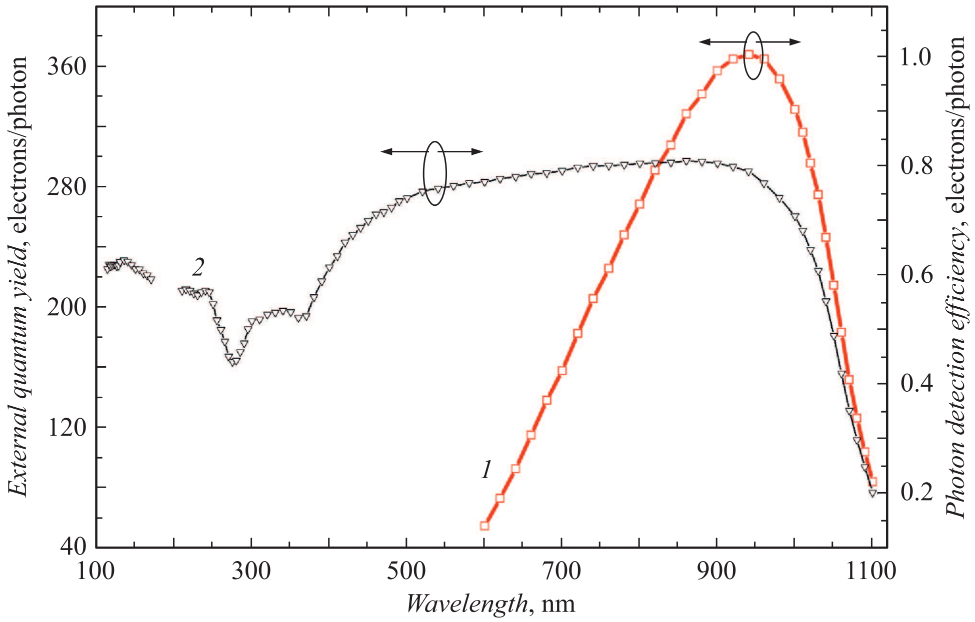


**Figure 2.** Spectral dependences of the ASPD external quantum yield and efficiency of the ASPD photon detection in the „front illuminated“ (*1*) and „back illuminated“ (*2*) modes.

region (for $\lambda = 940$ nm in the „front illuminated“mode). From the ASPD manufacturing procedure it is known that the $n^{++}$-layer thickness is $\sim 0.5\,\mu$m, total thickness of the $p$- and $\pi$-regions is $\sim 150\,\mu$m, thickness of the $p^{++}$-layer is $\sim 0.03\,\mu$m. Since absorption depth of the $\lambda = 940$ nm radiation in silicon is $\sim 40\,\mu$m [2], no less than 99% of this radiation will be absorbed in the $p$- and $\pi$-regions. This is because the loss of this radiation in the $n^{++}$-layer will be about tenths of percent, and even less amount of the radiation will reach the $p^{++}$-layer. Above it was shown that at $\lambda = 940$ nm the reflection loss is close to zero; taking into account the distribution of radiation with this wavelength in the ASPD structure, it is possible to affirm that $M_{\text{ASPD}}$ at $\lambda = 940$ nm in the „front illuminated“ mode coincides with $\eta_{\text{ASPD}}$ by 99%:

$$M_{\text{ASPD}} = \eta_{\text{ASPD}}, \qquad (2)$$

where $\eta_{\text{ASPD}}$ is the ASPD external quantum yield calculated via (1). In this work, $M_{\text{ASPD}}$ was equal to 366 (Fig. 2) in the „front illuminated“ mode at $\lambda = 940$ nm. In calculations for the „back illuminated“ mode, value $M_{\text{ASPD}} = 366$ obtained for the „front illuminated“ mode at $\lambda = 940$ nm was used, since we regard $M_{\text{ASPD}}$ as a characteristic of the $n^{++}-p$-junction and, hence, as a function of the junction temperature and back bias voltage that were almost equal in the „front illuminated“ and „back illuminated“modes. Based on the known values of $\eta_{\text{ASPD}}$ and $M_{\text{ASPD}}$, spectral dependences of the ASPD photon detection efficiency ($\varepsilon_{\text{ASPD}}$) were calculated for the „front illuminated“ and „back illuminated“irradiation modes. Quantity $\varepsilon_{\text{ASPD}}$ was defined as

$$\varepsilon_{\text{ASPD}}(\lambda) = \eta_{\text{ASPD}}(\lambda)/M_{\text{ASPD}}. \qquad (3)$$

Fig. 2 presents also the $\varepsilon_{\text{ASPD}}$ values in the „front illuminated“ and „back illuminated“modes.

To estimate the available range of $\eta_{\text{ASPD}}$ values in the „back illuminated“ mode in the vacuum ultraviolet spectral range, the wavelength of 160 nm was chosen. Radiation

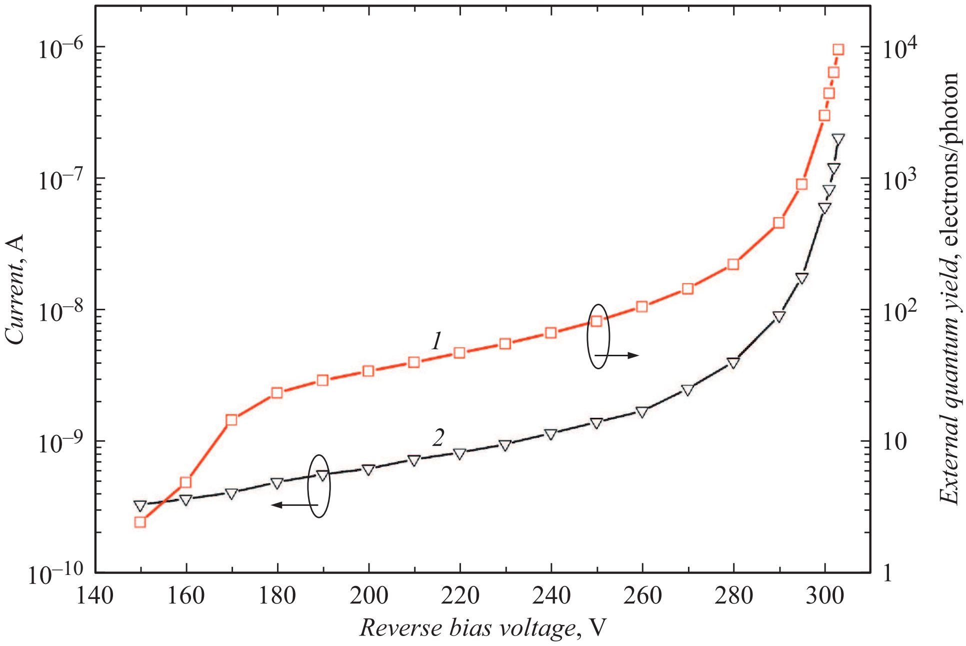


**Figure 3.** ASPD characteristics in the „back illuminated" mode versus the back bias voltage. *1* — external quantum yield ($\lambda = 160$ nm), *2* — dark current.

density of a gas–discharge lamp was maximal at this wavelength, which is convenient from the metrological viewpoint. The $\eta_{\text{ASPD}}$ value was calculated via relation (1). Fig. 3 presents the APSD $\eta_{\text{ASPD}}$ and dark current versus the back bias voltage.

Experimental data show that the isotype $p^{++}-\pi$-junction on the textured surface of the avalanche photodiode active region ensures the external quantum yield of 29 to 9300 electrons/photon at the wavelength of 160 nm. The optimized ASPD exhibits in the „back illuminated" mode the photon detection efficiency of 0.59–0.63 electrons/photon in the wavelength range of 114–170 nm and 0.44–0.81 electrons/photon in the wavelength range of 210–1050 nm. The photon detection efficiency of the studied ASPD in the wavelength ranges of 114–130 and 275–1050 nm exceeds that of the photodiode described in [6].

Thus, in this work an ASPD optimized so as to ensure detection of the VUV radiation was studied. It has been shown that, due to reduction of the reflection loss by texturing the active region and decrease in the isotype $p^{++}-\pi$-junction depth, the external quantum yield and VUV photon detection efficiency were increased by more than 4.5 times relative to the same characteristics reported in our earlier paper [1].


### Acknowledgements

The authors are grateful to their Ioffe Institute colleagues N.V. Zabrodskaya, M.S. Lazeeva, M.V. Drozdova and V.I. Marshalova for the assistance in fabricating the photodiodes.


### Conflict of interests

The authors declare that they have no conflict of interests.

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