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In memory of I.T. Serenkov

Silicon avalanche photodiode with photoresponse rise time less than 350 ps at wavelength 1064 nm

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Received October 19, 2023
Revised December 4, 2023
Accepted December 5, 2023

The optical, electrical and dynamic characteristics of the developed silicon avalanche photodiode with an active area diameter of 350 μm were studied. It is shown that the developed avalanche photodiode has the following set of characteristics: external quantum output is 215 electrons/photon at a wavelength of 1064 nm, dark current is 0.77 nA, multiplication factor is 2353, rise time is less than 350 ps at a reverse bias voltage of 274 V.

Keywords: silicon, avalanche photodiode, near-infrared, lidar.

DOI: 10.21883/0000000000

Detectors operating in the near infrared range with a rise time below 1 ns have several applications in scientific, commercial, industrial, and aerospace instrumentation engineering. The spectral range around 1064 nm is one of the promising ones for such systems: first, laser emitters and photodetectors designed for these wavelengths are readily available; second, the level of interference from solar radiation here is several times lower than the corresponding level in the visible region. The determination of orbit altitude of navigation satellites with a laser ranging device (satellite laser ranging, SLR) [1,2] is one example of the applications mentioned above. Unfortunately, the distribution of detailed scientific and technical information on devices of this kind is restricted deliberately; it is also important that such detector parameters as area, capacitance, response time, and packaging type need to be optimized for a specific practical task. Silicon detectors are the optimum choice in the range in question, since detectors based on materials with a smaller band gap feature higher levels of excess noise [3]. Two types of detectors are practically available: avalanche detectors and single-photon ones. The latter devices are used at pulse repetition rates lower than 100 kHz and have a several orders of magnitude smaller area [4]. No commercial silicon avalanche photodiodes (APDs) designed for wavelength $\lambda = 1064$ nm with a response time below 400 ps are currently produced in Russia. The aim of the present study is to examine the electrical, spectral, and dynamic characteristics of a silicon APD that was designed at the Ioffe Institute for operation at $\lambda = 1064$ nm.

We have already reported [5] on the fabrication of a silicon APD with an active area diameter of 1500 μm, an active area thickness of $\sim 100\,\mu$m, and a rise time of 1500 ps at a wavelength of 1060 nm. In the present study, which was aimed at reducing the photoresponse rise time, a silicon APD with an active area diameter of 350 μm and an active area thickness of $\sim 20\,\mu$m was designed, fabricated, and examined. The structure of this reach-through APD is of a front-illuminated type (Fig. 1, *a*). The term „reach-through“ implies that the APD operates under total substrate depletion. A photographic image of the examined APD is shown in Fig. 1, *b*.

Its characteristics were measured in a laboratory environment at a temperature of 22−23°C. The absolute values of responsivity (**R**) and external quantum yield (EQY) of the APD were determined in accordance with the procedure outlined in [5]. Spectral dependences of **R** and EQY at a reverse bias voltage of 230 V are presented in Fig. 2, *a*. A Keithley 6487 picoammeter with a built-in power supply was used to examine the reverse branch of the current–voltage curve. The capacitance–voltage curve was measured with Keithley 2400. The results are presented in Fig. 2, *b*.

Subsequent measurements were performed for $\lambda = 1064$ nm. The dependence of EQY on the reverse bias voltage (Fig. 3, *a*) was determined in DC measurements with the use of a setup including a spectrophotometer (see [3] for details). The dependence of the APD rise time on the reverse voltage (Fig. 3, *a*) was determined using a digital oscilloscope, a picosecond laser diode [6], the power supply of a Keithley 6487 picoammeter, and a transimpedance amplifier with a bandwidth of 2.8 GHz and a gain of 1500 V/A. The inset of Fig. 3, *a* presents an oscilloscope record of the APD response to a laser pulse at a reverse bias voltage of 240 V. The response of the calibrated photodiode with a response time of 20 ps to a laser pulse is shown in Fig. 3, *b*.

Let us examine the spectral dependence of EQY in Fig. 2, *a* (curve *1*). It follows from the presented data that the APD EQY for $\lambda = 800$ nm is at the level of 25

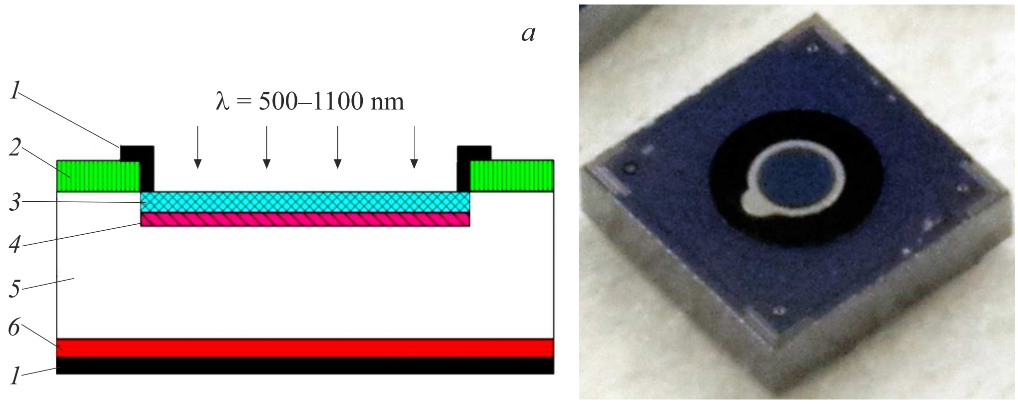

Figure 1. *a* — APD structure. *1* — Metallic contacts, *2* — silicon dioxide, *3* — silicon n^{++} layer, *4* — *p*-type avalanche multiplication region, *5* — *p*-type silicon, and *6* — silicon p^{++} layer. *b* — Photographic image of the APD crystal.

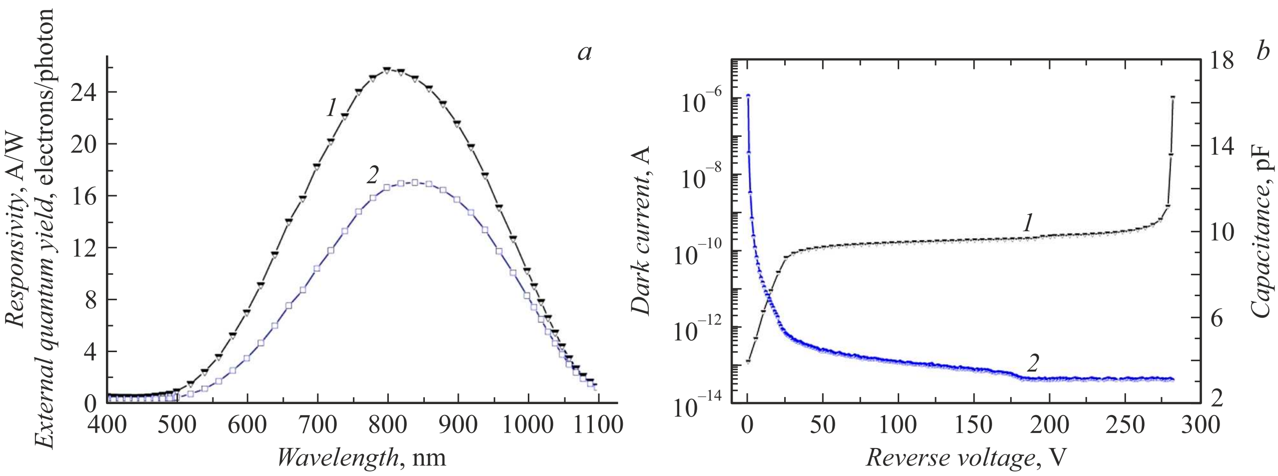

Figure 2. APD parameters. *a* — Spectral dependences of the external quantum yield (*1*) and the responsivity (*2*). *b* — Dependences of the dark current (*1*) and the capacitance (*2*) on the reverse bias voltage.

electrons/photon at a reverse bias voltage of 230 V. Since the APD active area has no anti-reflective coating, it is assumed that reflection losses are at the level of $\sim 33\%$, which is set by the optical properties of silicon [7]. Losses in the n^{++}- layer may be neglected, since its thickness is $\sim 0.5\,\mu$m, while the absorption depth of radiation with $\lambda = 800$ nm in silicon is $\sim 10\,\mu$m. We assume that 67% of incident radiation with this wavelength are absorbed completely in the active area of the APD with a thickness of $20\,\mu$m. The following expression is used to determine the APD multiplication factor at a reverse bias voltage of 230 V (M_{230}):

$$M_{230} = \mathrm{EQY}(800)_{230}/0.67, \quad (1)$$

where EQY_{230} is the external quantum yield of the APD for $\lambda = 800$ nm at a reverse bias voltage of 230 V and 0.67 is a coefficient needed to factor in the reflection losses and the assumed complete absorption of radiation with $\lambda = 800$ nm in the APD active area. The M_{230} value is then ~ 37.

The data for dependence *1* in Fig. 3, *a* and the following expression are used to determine the APD multiplication factor at a reverse bias voltage of 274 V (M_{274}):

$$M_{274} = M_{230}\mathrm{EQY}(1064)_{274}/\mathrm{EQY}(1064)_{230}, \quad (2)$$

where $\mathrm{EQY}(1064)_{274}$ is the external quantum yield of the APD for $\lambda = 1064$ nm at a reverse bias voltage of 274 V (215 electrons/photon) and $\mathrm{EQY}(1064)_{230}$ is the external quantum yield of the APD for $\lambda = 1064$ nm at a reverse bias voltage of 230 V (3.38 electrons/photon). Thus, the value of M_{274} for the examined APD is ~ 2353.

Comparing the characteristics of the proposed APD with the parameters of similar commercially available diodes produced in Russia, one should consider the SPD-031P photodiode [8] with an active area $500\,\mu$m in diameter, the sensitivity maximum around 830 nm, a capacitance of 1 pF, and a rise time of 500 ps (the radiation wavelength is not indicated). Compared to SPD-031P, the presented APD has a two times smaller active area and a three times higher capacitance, but its rise time at $\lambda = 1064$ nm is 1.4 times shorter. This is likely attributable to the fact that this APD has a thinner active area than SPD-031P. Unfortunately, a

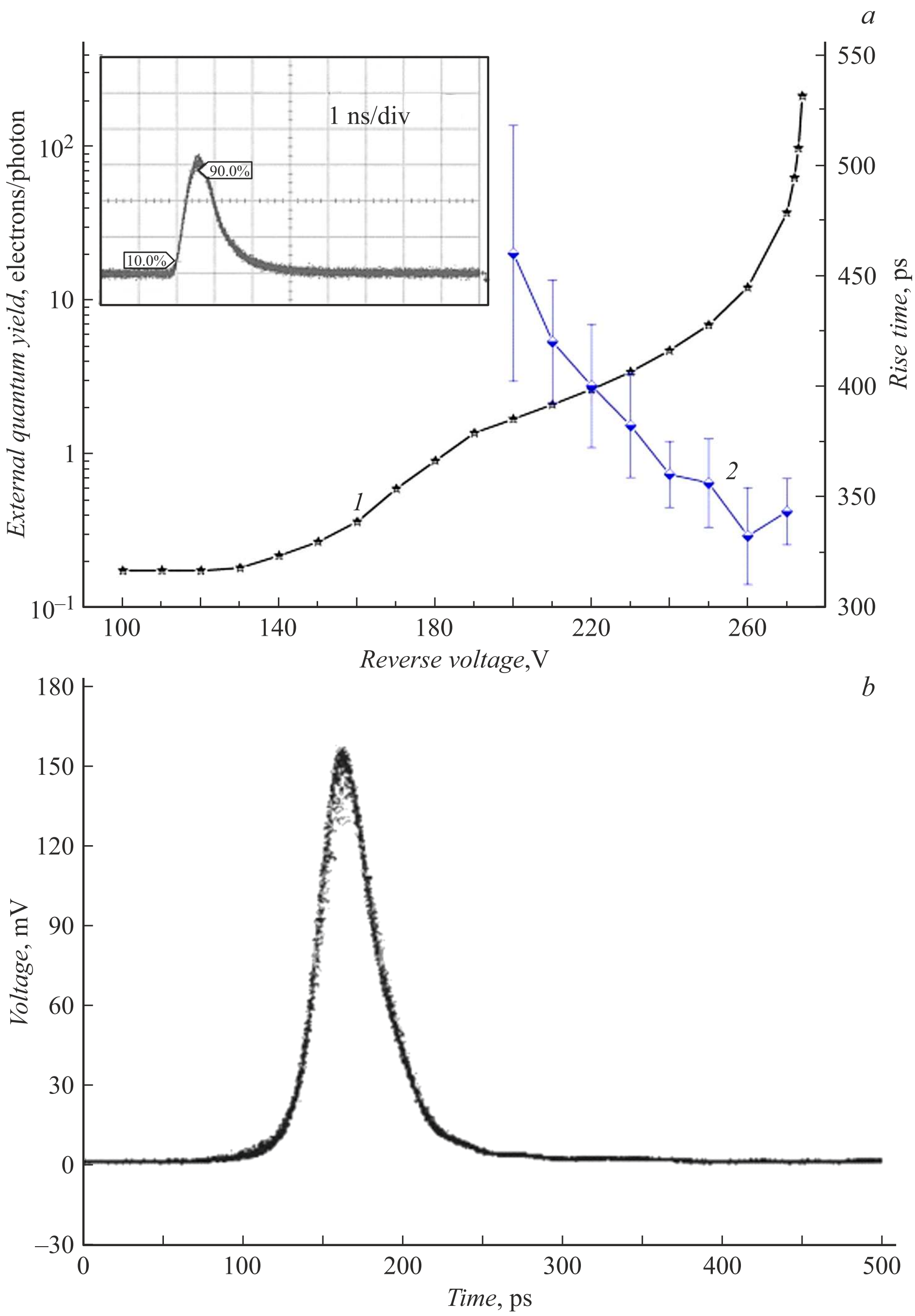

Figure 3. *a* — Dependences of the external quantum yield (*1*) and the rise time (*2*) of the APD on the reverse bias voltage. *b* — Response of the calibrated photodiode to a laser pulse.

fully correct comparison cannot be made, since the data for SPD-031P at $\lambda = 1064$ nm are lacking.

Thus, the results of examination of optical, electrical, and dynamic characteristics of the designed silicon APD with an active area $350\,\mu$m in diameter were presented. It was demonstrated that this APD has the following set of characteristics at a temperature of 22–23°C and a reverse bias voltage of 260–274 V: an external quantum yield of 12–215 electrons/photon for $\lambda = 1064$ nm, a dark current of 0.34–0.77 nA, a capacitance of 3 pF, and a rise time below 350 ps. It follows that the presented APD may be regarded as a promising candidate for LIDAR applications (e.g., in the SLR region [1,2]).

Acknowledgments

The authors wish to thank their colleagues N.V. Zabrodskaya, M.S. Lazeeva, M.V. Drozdova, L.F. Antonova, and V.V. Vasil'eva from the Ioffe Institute for their help in fabrication of photodiodes.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin