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Investigation of Ge *p-i-n* photodetector as a part of pulsed laser rangefinder prototype

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Abstract. The process of diffusion method for production of high-speed Ge *p-i-n* photodiodes for a laser rangefinder with a maximum photosensitivity at the wavelength 1.54 µm and a new passivating layer of ZnSe is described. Theoretical modeling of the rangefinder operation in real conditions was performed to determine the requirements for the sensitivity of the photodetector. The threshold sensitivity of the split photodetector as a part of the model of laser rangefinder was experimentally investigated. The correspondence between the calculated values and the sensitivity of the photodetector was ascertained, which allowed to draw the conclusion about the possibility of its application as a part of laser rangefinder.

Keywords: Ge, *p-i-n* photodiode, pulsed laser rangefinder, range of action, threshold sensitivity of the photodetector.

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1. Introduction

It is well known that measuring a distance is an important task for many fields of science and technique. This task is usually solved using laser rangefinders. In accord with their operational principle, they can be separated by two groups: pulsed and phased. The main elements of a pulsed rangefinder are a pulsed laser and photodetector. The distance to an object is determined through the full time necessary for the light pulse to pass from the light source to the object and back to the detector. The sharper the pulse front, the more accurate the measurement of distance. The pulsed laser rangefinders provide measuring rather long distances, since the pulse might have a high power. Also, they provide high emission security owing to a very short pulse period [1].

Phased laser rangefinders operate with a short-time additional illumination of the target by using various modulated frequences. The obtained phase shift serves for measuring the necessary distance to the target. The inaccuracy in measuring with phased laser rangefinders is related with determination of only small fractions of wavelengths corresponding to the modulation frequency, therefore, the phased rangefinders are considerably accurate than the pulsed ones. Besides, they are essentially cheaper, since they need no super-precise timer. However, the necessity to use more durable additional illumination of the target causes application of a laser with lower power, which, as a consequence, shortens the operation distance down to one kilometer [2].

The main requirements to the photodetector as a part of rangefinder are its fast response and sensitivity [3]. In the case of pulsed rangefinders, the sensitivity limits the maximum operation distance, which can be compensated only by increasing the power of laser source. In its turn, the fastness of response defines the device accuracy, and it should be matched with pulsed laser parameters. Since increasing the fast response lowers the sensitivity and vice versa, which is related with the construction features of the very photodiode, then the choice of photodetector optimum parameters for a specific device is extremely important [4].

The aim of this work was to study the developed fast-acting Ge *p-i-n* photodetector from the viewpoint of its application as a part of laser rangefinder, when measuring the maximum possible distances to an object. It implied preparing and studying the performances of developed experimental samples of Ge *p-i-n* photodetectors, performing theoretical calculations and estimations of pulsed energy losses, when measuring the distance, as well as using the prototype of laser rangefinder to determine the experimental values of minimum pulse energy that can be detected with this photodetector.

2. Preparation of experimental samples

The operation wavelength of laser rangefinders is defined by the so-called “windows of transparency” for the atmosphere (*i.e.*, the ranges where the light flux is least absorbed than within others) as well as by the possibilities for creation of laser active media [2]. The rangefinders with the operation wavelength λ_{max} = 1.54 µm are promising for this aim, since they are safety for human eyes [5], the near infrared range corresponds to the window of transparency, and this relatively small wavelength is more suitable for detection of objects. Ge *p-i-n* photodiodes satisfy these operation conditions [6, 7].

Using the scientific-and-technological resources of the V. Lashkaryov Institute of Semiconductor Physics of NAS of Ukraine, the composite author designed and prepared the experimental samples of diffusion Ge *p-i-n* photodetectors for the operation wavelength λ_{max} = 1.54 µm [8]. Passivation and protection of mesastructure active region was performed using the ZnSe polycrystalline layer (transparent in the near infrared range) of the thickness 1.5 µm. The thermal treatment of contacts provided formation of heavily doped sub-contact regions of p^+- and n^+-types in *p*- and *n*-regions of the junction, respectively. The subsurface diffusion p^+-layer of the thickness close to 0.1 µm in this junction has the effective concentration of holes $p^+ = 2\cdot10^{18}\ cm^{-3}$, which is related with Zn solved in Ge under diffusion temperatures close to 800 °C [9, p. 96].

To passivate the surface of germanium structures metal–dielectric–semiconductor, Si_3N_4 layers are used most often. This material possesses considerable advantages as compared with GeO_2, if taking into account its hardness, chemical inertness and dielectrical properties. However, as a consequence of the essential difference between the values of thermal expansion coefficients for the layer Si_3N_4 and Ge substrate, the inversion layer of *p*-type can be created in the sub-surface region of the *n*-type substrate. This inversion layer is caused by generation of misfit dislocations that arise due to relaxation of mechanical stresses in the system Si_3N_4–Ge [9]. This fact can caused a negative effect on stability of operation parameters and performances of Ge photodetectors, in which passivation and protection of active region were realized using the dielectric layers Si_3N_4. Besides, the density of surface states at the hetero-interface Si_3N_4/Ge cannot be obtained less than approximately $10^{12}\ eV^{-1}\cdot cm^{-2}$, which essentially increases recombination losses of photocurrent.

The advantage of photodiodes designed and produced by us is the passivating layer of ZnSe [10] that provides considerably lower degradation of photodetectors with time due to good matching between lattice parameters of this layer and germanium. Preliminary investigations have shown that the experimental samples did not change their performances for three years.

3. Theoretical calculation of the signal extinction for the process of distance measurements

To determine the maximum distance that can be measured using a specific pulsed laser rangefinder, it is necessary to ascertain a minimum level of pulse energy, which can be reliably detected by the used photodiode. To measure the output laser energy is not difficult, however, it is necessary to take into account all possible energy losses during distance measurements. The operation medium for rangefinders is atmosphere, and energy losses in it have the predominant influence on the value of maximum measurable distance.

In the NIR spectral range, the Earth atmosphere has a rather complicated absorption spectrum (see Fig. 2, where the adduced curve of atmosphere transmission corresponds to annual conditions in mean latitudes, when the total concentration of water vapors conforms to 2 cm of deposited water [11]).

The transmission of Earth atmosphere (defined by molecular absorption and scattering) for the horizontal path of the length 1 km in the bottom layer is adduced in Table 1 for the emission wavelengths 0.355, 0.532, 1.54, and 2.09 µm [12] and under the high and mean air humidity that has its effect on the atmosphere transmission only in the NIR spectral range. The values of aerosol extinction indexes for the above wavelengths and the same path are summarized in Tables 2 and 3 for two atmosphere models.

Summarized in Table 2 are the data for continental aerosol used in the optics-location model [13] (this model corresponds to the optical condition of atmosphere with the meteorological range of visibility close to 15 km), while in Table 3 one can see the data for American model of pure standard atmosphere [14] (this model corresponds to the optical condition of atmosphere with the meteorological range of visibility close to 25 km).

Table 1. Atmosphere transmission coefficients (for the case of only molecular absorption and scattering).

λ, µm	0.355	0.532	1.54	2.09
Atmosphere transmission (humidity 90%)	0.819	0.951	0.774	0.72
Atmosphere transmission (humidity 60%)	0.819	0.951	0.831	0.76

Table 2. Indexes of aerosol extinction for the model of continental aerosol.

λ, μm	0.355	0.532	1.54	2.09
Index of scattering, km^{-1}	0.337	0.255	0.086	0.054
Atmosphere transmission	0.741	0.775	0.918	0.947

Table 3. Indexes of aerosol extinction for the model of pure standard atmosphere.

λ, μm	0.355	0.532	1.54	2.09
Index of scattering, km^{-1}	0.24	0.16	0.1	0.087
Atmosphere transmission	0.787	0.852	0.904	0.917

Thus, with account of molecular and aerosol contributions of extinction, it was possible to calculate the extinction coefficient for atmosphere per 1 km at the sea level in the horizontal plane under good climatic conditions. As an example, for the wavelength 1.54 μm and the distance 5 km the transmission coefficient of atmosphere reaches the value 0.258.

To perform a full theoretical calculation, they use the so-called “range equation”, the general form of which is represented by the formula (1) [15]:

$$L^2 = \frac{P_l \tau_1 \tau_2 \rho_s k_t k_{rt} S_{pd}}{U_{pd}} \frac{d^2}{4} \exp\left(-2\alpha_a L\right), \quad (1)$$

where L is the distance to the target, P_l – output power of the laser, τ_1 – transmission coefficient of the optical system inherent to the rangefinder transmitting channel, τ_2 – transmission coefficient of the optical system inherent to the rangefinder receiving system, ρ_s – coefficient of scattering emission by the target, k_{rt} – coefficient characterizing spatial distribution of emission reflected by the target, when departure from the Lambert law takes place (this coefficient is equal to unity, if this law is observed), k_t – coefficient characterizing the fraction of the total emission energy reaching the target, S_{pd} – sensitivity of photo-receiving facility under optimum values of the pass band (inherent to the electronic channel) and signal-to-noise ratio, U_{pd} – signal at the output of photo-receiving facility, d – diameter of the entrance pupil characterizing the objective of the receiving facility, α_a – coefficient of energy losses in atmosphere.

It is noteworthy that beside the atmosphere transmission one should take into account transmission coefficients inherent to the chosen optical systems, the diameter of entrance window, beam divergence, target sizes, and the reflection coefficient typical to the target.

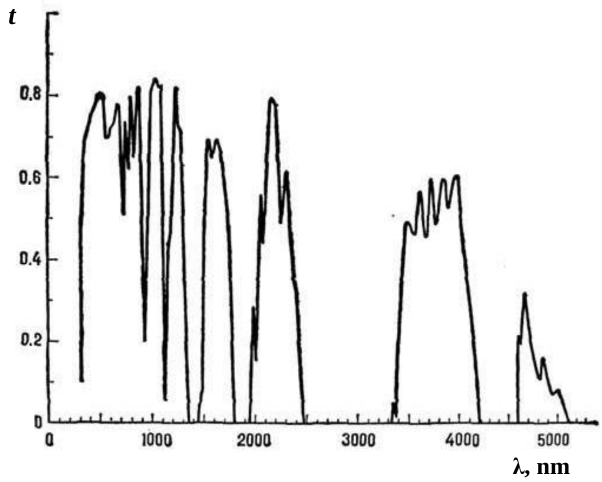

Fig. 1. Atmosphere transmission in the visible and near infrared spectral ranges [11].

In calculations, they use the following target sizes: 1×1 – small-size target, 2.3×2.3 – truck, 3×3 – bulky target exceeding the laser beam spot.

To estimate a maximum distance available for measurements, it is reasonable to use the typical values [13]. The values of transmission coefficients for transmitting and receiving optical channels of a rangefinder for λ = 1.06 μm are very close to those for λ = 1.54 μm: $\tau_1 \cong 0.547$, $\tau_2 \cong 0.48$.

The values of coefficients related to the small-size target for λ = 1.54 μm were chosen as follows: $\rho_s = 0.3$, $k_t = 0.186$.

These are the main coefficients that characterize losses independent of laser and photodetector characteristics. Thus, the coefficient of lowering the output signal in summer under fear weather in the mean latitudes at the distance 5 km can reach 0.0038.

4. Results of experiments and their discussion

Experimental investigations were performed using the prototype designed at the Institute of Single Crystals (Kharkiv, Ukraine). There the pulsed laser with passive Q-switching was used as an emission source (λ = 1.54 μm). For pumping, we used a semiconductor laser diode operating at the wavelength 940 nm. As an active medium, we used the element made of phosphate glass activated with the sensitizing ion pair Yb^{3+}–Er^{3+}. Modulation was provided with the single crystal of magnesium-aluminum spinel doped with cobalt (Co^{2+}:MALO). Also used in the facility was the double-mirror hemispherical resonator of the 45-mm length with the plane output mirror ($T_{OCM} = 30\%$). The laser source provided single pulses with the energy 0.5 mJ and duration 20 ns.

The experimental sample of diffusion germanium *p-i-n* photodiode with the active area 1 mm^2 was tested with regard to its threshold sensitivity in the photodiode regime under the reverse-bias voltage –9 V. Its connection is illustrated in Fig. 2.

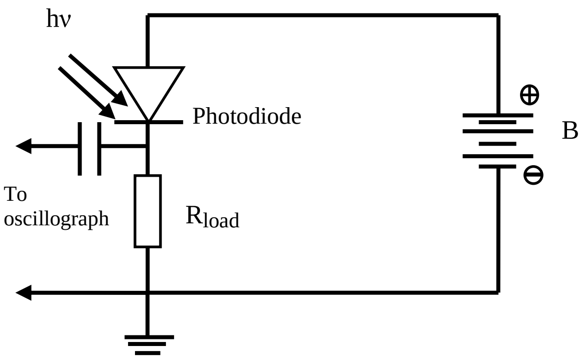

Fig. 2. Electric circuit for supplying the photodiode when measuring energetic parameters of its photoresponse. B – battery 5f22. The type of high-frequency oscillograph – GDS-3502.

Fig. 3. Oscillogram of the photodetector signal corresponding to the laser output energy 25 μJ.

The algorithm for determining the photodetector threshold sensitivity was as follows. First, the energy of laser output pulse was measured using a calorimeter. This energy was close to E_{output} = 580 μJ. Then, the light path was blocked with a light filter, and the lowered signal energy was measured. Thus, the transmission coefficient for the filter was determined as a conventional ratio of these signals.

As a result of measurements, we ascertained that the filter No 3 provided the lowest transmission: under E_{output} = 578 μJ, the signal after the filter reached only E_{f3} = 25 μJ, which corresponds to the transmission coefficient k_{f3} = 0.043. The example of reliable registrating the signal of 25 μJ is illustrated in Fig. 3. In this case, the value of voltage taken from the oscillograph load resistor is close to 1 V. The energy close to 10 μJ was the minimum one for measuring with the chosen calorimeter. Therefore, the transmission coefficients of additional filters necessary for measurements were determined using the above way. These filters were placed in sequence with the filter of the minimum transmission (along the light path).

Our experiments have shown that the threshold sensitivity of the used photodetector reaches E_{f1-4} = 253 nJ. The total transmission coefficient was in this case k_{f1-4} = 0.000437. It corresponds to lowering the output laser energy by more than three orders.

If one compares this value of transmission coefficient with the theoretical one calculated for the distance 5 km – 0.0038, he can see that this photodetector is able to operate in this rangefinder prototype up to the distance 5 km. The difference between these values exceeds one order, which provides operation under deteriorated atmospheric conditions or longer distances.

5. Conclusion

The performed theoretical calculations and experimental studies have given us the possibility to conclude that the designed and produced by us *p-i-n* photodetector with the passivating ZnSe layer satisfies all the requirements to the sensitivity of detectors used in pulsed laser rangefinders.

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Дослідження Ge *p-i-n* фотоприймача в складі макета імпульсу лазерного далекоміра

А.В. Федоренко, І.О. Ворона, В.П. Маслов

Анотація. Описано процес виготовлення дифузійним методом швидкодіючих Ge *p-i-n* фотодіодів для лазерного далекоміра з максимумом фоточутливості на довжині хвилі 1,54 мкм та новим пасивуючим шаром ZnSe. Проведено теоретичне моделювання роботи далекоміра в реальних умовах для визначення вимог до чутливості фотоприймача. Експериментально досліджено порогову чутливість розробленого фотоприймача в складі макета лазерного далекоміра. Встановлено відповідність між розрахованими значеннями та чутливістю фотоприймача, що дозволило зробити висновок про можливість його застосування в складі лазерного далекоміра.

Ключові слова: Ge, *p-i-n* фотодіод, імпульсний лазерний далекомір, дальність дії, порогова чутливість фотоприймача.