07

On the determination of the diffusion length of charge carriers in the absorber material of 2D mercury-cadmium-tellurium-based focal-plane-array detectors from spot-scan profiles

© V.A. Stuchinsky, A.V. Vishnyakov, V.V. Vasiliev

Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia
e-mail: stuchin@isp.nsc.ru

Received April 12, 2023
Revised November 7, 2023
Accepted November 10, 2023

Using the Monte Carlo method, we studied the influence of the lateral transport of photogenerated charge carriers along diodes on the result of determining, from measured spot-scan profiles, the bulk length of charge-carrier diffusion in the absorber material of focal-plane diode arrays. An estimate of the corresponding inaccuracy in determining this length is given. The numerical simulation was carried out using the example of focal-plane diode arrays with $30\,\mu$m pitch, 14×14-μm diode size, and 6-μm thick absorber layer. The range of examined values of the bulk diffusion length of charge carriers in the absorber material was from 5 to $30\,\mu$m. It is shown that the analysis performed makes it possible to describe the fine structure of spot-scan profiles at both high and low levels of diode photocurrents. It was found that the method used yields the values of the bulk diffusion length of charge carriers increased compared to the true ones by approximately 20−25%.

Keywords: 2D IR focal-plane-array detector, photodiode, diode photoresponse, spot-scan profile, illumination spot, charge-carrier diffusion length, mercury-cadmium-tellurium material, Monte Carlo simulation.

DOI: 10.61011/JTF.2024.01.56911.87-23

Introduction

The diffusion length of photogenerated charge carriers (PCCs) in the absorber layer of focal-plane-array (FPA) detectors based on mercury-cadmium-tellurium (MCT) material is a parameter that determines many important characteristics of the corresponding photodetector devices (PDD), such as the inter-pixel photoelectric crosstalk, the spatial and temperature resolution, etc. [1]. When designing and manufacturing focal plane arrays, one has to be able to predict and characterize the quality of such arrays for ensuring a high spatial resolution of the IR camera as a whole [2–5]. The electrophysical parameters of MCT epitaxial layers can vary since various technological processes are involved in the production of MCT-based FPAs (chemical etching, ion implantation, heat treatment, etc.) [6–8]. Therefore, it is necessary to develop efficient tools and methods for characterizing MCT layers and determining the diffusion length of PCCs in already manufactured MCT FPAs.

Several methods are presently available for experimental determination of the diffusion length of PCCs in MCT films and in photodetector arrays based on this material. Such methods employ specially prepared structures with a varied width of the shading zone around diodes [9,10] and measurements of electron- or laser-beam-induced currents [11–14], etc.

Some time ago we proposed a new method for determining the bulk diffusion length l_d of PCCs in the absorber material of IR FPAs based on MCT layers with graded-gap passivated boundaries [15]. The method is based on measuring the spatial photo-response profiles $S(x)$ of an array diode used to scan a linear illumination spot under conditions of low resultant diode photocurrents j_{ph}. Under the resulting photodiode current, here we understand the difference between the diode photocurrent carried over by PCCs collected from the absorber and the injection counter-current of the forward-biased diode, those currents also being referred to below respectively as „the photocurrent incident onto the diode“ and „the current reflected from the diode“. Low photocurrent level j_{ph} is achieved in this case via reducing the gate voltage of input field-effect transistors of the photovoltaic cells of FPAs, as a result of which the FPA diodes get biased forward with a decrease of diode junction barrier. The effective (depending on the level of j_{ph}) diffusion length of PCCs $l_d^{\rm eff}$ (j_{ph}) can be determined based on the maximum gradient of S on the semi-logarithmic plot of the diode photo-response in each profile $S(x)$ measured on the consecutive increase of the input-transistor-channel resistance and, accordingly, on a decrease of current j_{ph}. For $j_{ph}\to0$, the sequence of the obtained values $l_d^{\rm eff}$ was expected to give the sought value of the bulk diffusion length of PCCs in the absorber material of FPA at.

It should be noted that the dependence $l_d^{\rm eff}$ $(j_{ph}\to0)$ was analyzed earlier using the quasi-two-dimensional diffusion model [15], which circumstance did not allow us to give an adequate analysis of the impact of all acting factors on the result of application of the method. The effective (additional to diffusion) transport of PCCs along FPA diodes away from the illumination spot caused by the „rereflection" of the photocurrent from FPA diodes is analyzed in this paper as an additional factor affecting the result of using the method [15] for estimation of the length l_d (see below).

1. Problem formulation

When analyzing the distributions $S(x)$ formed at a low level of diode photocurrents, it is necessary to take into account the fact that a small resultant photodiode current occurs in MCT-based *n*-on-*p*FPAs as the difference between the significant current due to photoelectrons collected from the absorber layer by the *n*-regions of diodes, and a comparable counter-current of the forward-biased photodiode, formed by the electrons which, overcoming the built-in barrier of the *p-n* junction, penetrate from the mentioned *n*-regions into the *p*-absorber. When the resultant current across the diode is low, the latter current makes up a significant fraction of the former current; we will call this current the „reflected" photocurrent. In the context of the present analysis of profiles $S(x)$, it is important that the electron photocurrent that flows into the *n*-region of the diode and the „reflected" electron current caused by the tendency of diodes when illuminated to become biased in forward direction have different coordinate dependencies. Indeed, the reflected photocurrent is emitted into the absorber rather uniformly over the *p-n* junction area. On the contrary, the photoelectrons that carry the former current are distributed over the junction area according to the solution of the diffusion problem for PCCs in the absorder layer. The latter takes place because of the rapid equalization of the electron concentration inside the *n*-region of the diode compared to the characteristic rate of the penetration of the electrons through the built-in barrier of the *p-n* junction into the *p*-absorber. As a result, in the case of a low net current across the photodiode there occurs an additional (to diffusion) transport of PCCs along the absorber layer from the illumination spot; that transport proceeds with the participation of array diodes. Indeed, the PCCs that flow into the *n*-region of the diode are mainly concentrated at the diode edge closest to the illumination spot, whereas the „center of gravity" of the „reflected" PCCs is located at the center of the diode. That is why the transport described above should contribute to a more distant lateral spreading of PCCs from the illumination spot and thereby lead to slightly overestimated values of length l_d determined based on the experimental data obtained at low diode photocurrents.

With the aim of evaluating the inaccuracy induced by the additional lateral transport of PCCs along diodes when determining the length l_d, we performed a numerical modeling of spot-scan profiles formed when scanning with an FPA diode a narrow illumination spot at different levels of diode photocurrents (normal and extremely low ones). Subsequent differentiation of such profiles yielded the profiles of the local effective diffusion length $l_d^{\text{eff}}(x)$ of PCCs in the array. In this way, the application of the method [15] was simulated in the numerical modeling for determining the length l_d. The shape of the profiles $l_d^{\text{eff}}(x)$ formed at different levels of diode photocurrents was additionally analyzed for verification of the numerical model and comparison of the results obtained for different problem statements. The comparison of the average local diffusion length of PCCs in the calculated profiles $l_d^{\text{eff}}(x)$ for an extremely low level of PCC withdrawal from the absorber with the „true" values of the bulk diffusion length l_d of charge carriers found in the calculation allowed judging on the magnitude of the analyzed inaccuracy in determining this length.

2. Monte Carlo simulation of PCC diffusion and measurement of spot-scan profiles

As noted above,in the present study for estimating the inaccuracy of method [15] in determining the length l_d, the Monte Carlo method was used to calculate the diode photoresponse profiles obtained when scanning a narrow illumination spot with one of the FPA diodes at a normal and at a low level of diode photocurrents j_{ph}. The diffusion of PCCs from the illumination spot was simulated using an earlier developed approach described in [16]. The simulated situation basically matched the one implemented in the experiments of [15].

A photodiode array with $6\,\mu$m thick absorber layer, $30\,\mu$m array pitch and $14\times14\,\mu$m diode size was considered. The calculation domain (Fig. 1) was a series of photosensitive elements (PSEs) arranged in a PSE array stretching perpendicularly to the illumination spot (9 PSEs in total). The calculation grid had $0.25\,\mu$m pitch, and the optical absorption length in the absorber was assumed to be $1\,\mu$m. The spatial profiles of the photo signal $S(x)$ of an array diode were calculated. This diode scanned the illumination spot in the form of an illuminated strip with a width of $5\,\mu$m. The scanning pitch was $5\,\mu$m. In schematic

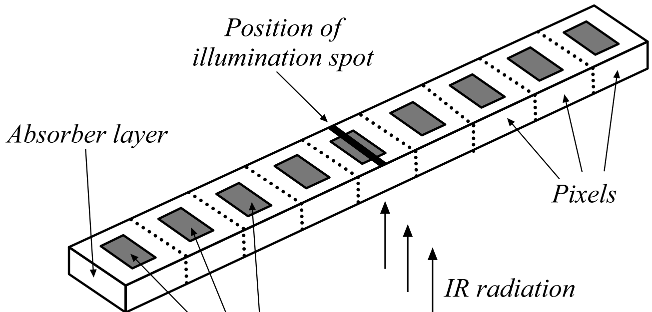

Figure 1. The calculation domain, including 9 backside-illuminated FPA pixels.

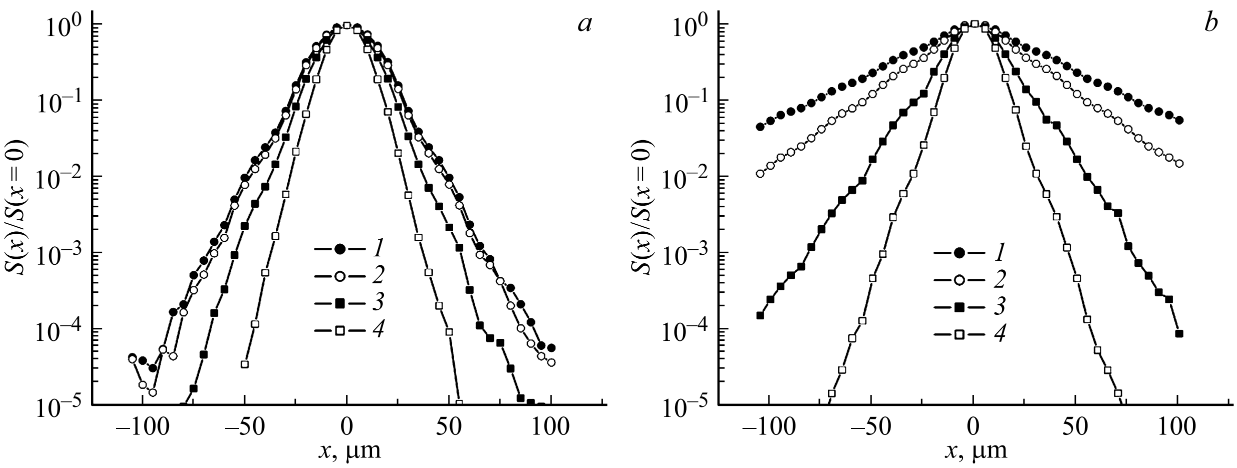

Figure 2. Calculated normalized spatial distributions of the photosignal obtained by scanning a linear illumination spot with 5 μm width by a selected array diode in the FPAs with back- (a) and forward-biased (b) photodiodes. The values of the bulk diffusion length l_d of charge carriers in the absorber material used in the calculation: *1* — 30, *2* — 20, *3* — 10, *4* — 5 μm.

calculations, the magnitude of photodiode deepening into the film was assumed to be zero, and the distribution of radiation intensity in the illumination spot was assumed uniform with sharp edges, i.e., situation under consideration was not complicated by the spot edge blurring due to light diffraction. In each calculation case, the spot area was seeded with two million particles.

The results of the Monte Carlo simulation were verified by their comparison with the scanning profiles measured using a photodetector with a similar FPA with basically the same characteristics as the FPA for which the calculations were made, namely with the same values of the array pitch, diode size and absorber layer thickness. The experimental facility used and the details of the spot-scan measurement procedure are described in [15].

3. Results of modelling and their discussion

3.1. Fine structure of diode photo-response profiles: numerical modeling

The process of PCC diffusion over the absorber layer from the illumination spot was modeled using the Monte Carlo method. First, the values of the photocurrents of all diodes were calculated for different positions of the illumination spot in a situation in which all photoelectrons generated in the spot were fully absorbed by the *n*-regions of back-biased FPA photodiodes. Then, the problem of the magnitude of photodiode currents was solved when electrons were emitted into the absorber layer from the *n*-region of one selected FPA diode (uniformly over its area). Further, the data obtained were employed to calculate the diode photo-responces occurring in the system as a result of multiple „absorptions" and „reflections" of photocurrents in the photodiode array (a total of 100 iterations were made, after which the pattern of diode currents no longer changed noticeably). Fig. 2 shows the photo-response profiles calculated the FPAs with the „absorbing" (i.e. back-biased) and „reflecting" diodes (i.e., forward-biased diodes with a reduced height of the built-in junction barrier) $S(x)$. The results of the simulation, calculated for different values of the PCC bulk diffusion length l_d, are shown in Fig. 3 in the form of distributions of the „local effective diffusion length" $l_d^{\text{eff}}(x)$ obtained by differentiation of $S(x)$-profiles, $l_d^{\text{eff}}(x) = \left| dx/d[\ln S(x)] \right|$.

Oscillations with the FPA period obviously reflecting the discrete diode structure of the array are distinctly observed in the dependences $l_d^{\text{eff}}(x)$. Interestingly, the minima of the distributions $l_d^{\text{eff}}(x)$ calculated for the FPA with the „reflecting" diodes appear as substitutes to the maxima observed in the profiles $l_d^{\text{eff}}(x)$ calculated from the profiles $S(x)$ for the „absorbing" diodes (with a negligibly small „reflected" current) (Fig. 2, a) (the comparison is given in Fig. 3, b). It seems that the observed oscillations of l_d^{eff} appear as a result of the occurrence, during the scanning procedure, of an „absorbing" or a „reflecting" diode at the position opposite to the illumination spot. The occurrence of an absorbing diode at the location of the illumination spot modulates (namely, reduces) the number of PCCs reaching the „farthest" (along the absorber) FPA photodiodes (including the scanning diode), and the oscillations in the dependences $l_d^{\text{eff}}(x)$ with the different position of maxima and minima occur as a result of the effective transport of PCCs along the reflecting diodes proceeding as described above.

3.2. Fine structure of diode photo-response profiles as revealed in spot-scan measurements

The adequacy of the obtained simulation results was qualitatively confirmed by the comparison of the calculated

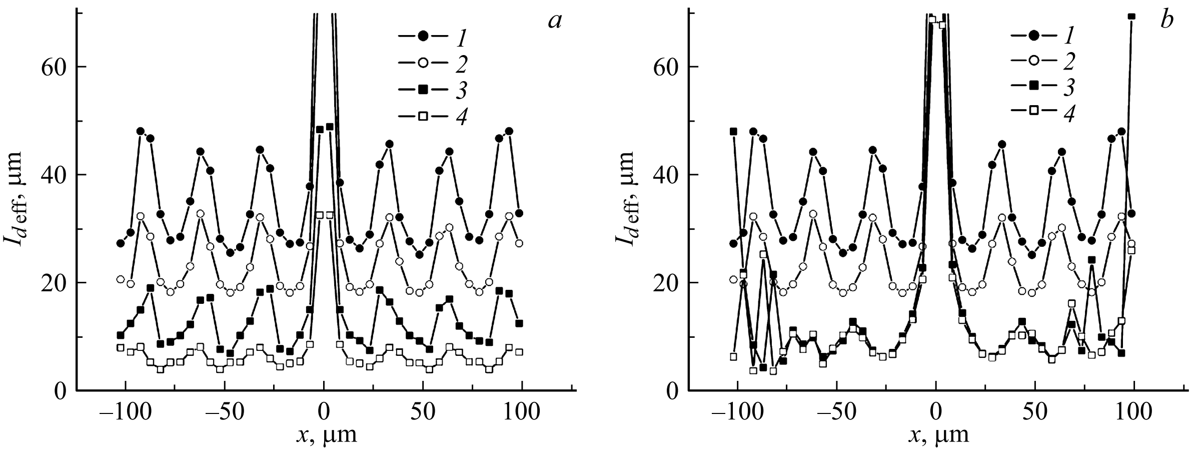

Figure 3. *a* — profiles of „effective local diffusion length“ $l_d^{\mathrm{eff}}(x)$ obtained by differentiation of the profile of Fig. 2, *b* for the case of „reflecting“ FPA diodes. The values of the bulk diffusion length l_d of PCCs in the absorber material used in the calculation: *1* — 30, it 2 — 20, *3* — 10, *4* — 5 μm. *b* — comparison of the profiles of „effective local diffusion length“ l_d^{eff} shown in Fig. 2, *a* for the cases of $l_d = 30\,\mu$m (curve *1*) and $l_d = 20\,\mu$m (curve *2*), with the profiles $l_d^{\mathrm{eff}}(x)$ calculated for the same values of l_d (curves *3* and *4*, respectively), but for the case of back-biased FPA diodes, when all photoelectrons that reach the *n*-regions of the diodes get absorbed by these regions, with the counter component of the electron current being equal to zero.

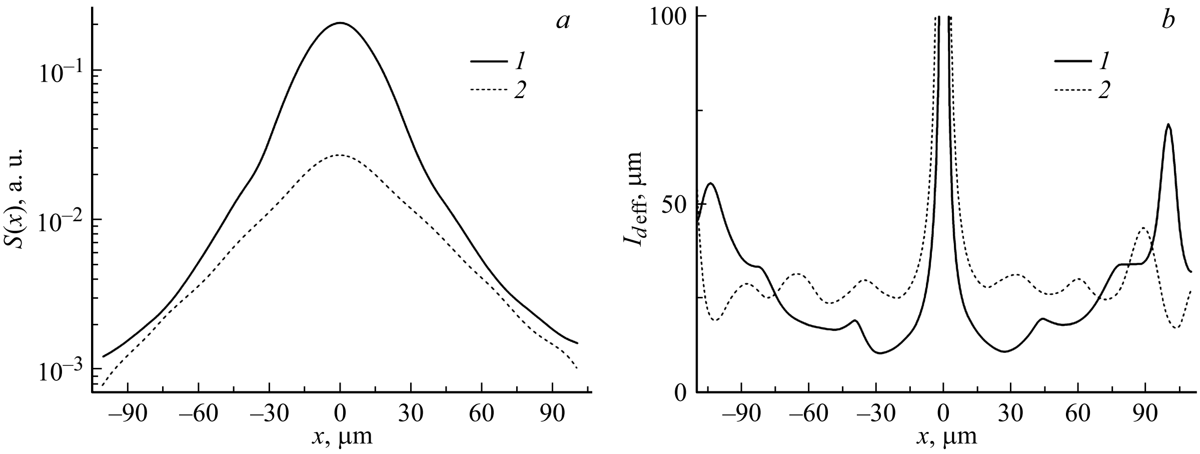

Figure 4. *a* — spot-scan profiles for a linear illumination spot measured using FPAs with back-biased and forward-biased pixel diodes (gate voltage of input pixel transistors $V_g = 1$ and 0.72 V, curves *1* and *2* respectively); *b* — distributions of the effective local diffusion length l_d^{eff} of PCCs calculated by differentiation of profiles *1* and *2* in Fig. 4, *a* (curves *1* and *2*, respectively). Before differentiation, the measured diode photo-response profiles $S(x)$ were smoothed with a cubic spline.

distributions of the local effective diffusion length $l_d^{\mathrm{eff}}(x)$ with similar distributions measured in an experiment performed using an FPA with similar values of geometric parameters (Fig. 4). Measurements were performed at wavelength $\lambda = 4\,\mu$m using an illumination spot in the form of $\approx 8\,\mu$m wide illuminated strip. The mentioned comparison is called here qualitative because of the difference in the distribution of radiation intensity in the model and experimental illumination spots, because of the disregard of the modulation transfer function (MTF) of the used IR lens [17] in the analysis of measured data (Fig. 4), and because of the small difference between the geometries of the model and real FPAs (namely, the magnitude of the diodes' deepening into the absorber layer). However, a comparison of the data in Figs. 3, *b* and 4, *b* reveals the same pattern noted above in the position of maxima and minima in the profiles $l_d^{\mathrm{eff}}(x)$, in which the minima of the distributions $l_d^{\mathrm{eff}}(x)$ calculated for the arrays with „absorbing“ diodes are observed approximately at the location of the maxima of the distributions $l_d^{\mathrm{eff}}(x)$ calculated for the arrays with diodes which „weakly absorb“ PCCs. A closer examination of the data provided Figs. 3, *b* and 4, *b* shows that the minima in the profiles $l_d^{\mathrm{eff}}(x)$ calculated for the highly absorbing diodes are positioned slightly closer to the illumination spot than the maxima in the profiles $l_d^{\mathrm{eff}}(x)$ for the reflective diodes. The latter circumstance is quite consistent with the above interpretation of the fine structure of the $S(x)$-profiles. Indeed, the number of photoelectrons entering the tails of PCC concentration distributions in the case of absorbing diodes is minimal when the illumination spot scanned by the array diode assumes a position opposite the middle of another FPA diode in the row of pixels perpendicular to the spot. This circumstance explains the occurrence of minima in the dependences $l_d^{\rm eff}(x)$ for absorbing diodes near the points $x = n \cdot 30\,\mu$m ($n = 0$, ± 1, ± 2, ...). At the same time, the occurrence of maxima in the dependences $l_d^{\rm eff}(x)$ for an FPA with reflecting diodes should be expected when the rear edges of the next diodes occurring near the illumination spot reach this spot. The latter circumstance results in the occurrence of local maxima in the profiles $l_d^{\rm eff}(x)$ for FPAs with reflecting diodes located slightly farther than the minima described above. This is what is observed both in calculations and in the experiment.

3.3. Estimation of the PCC bulk diffusion length in the absorber material

We assume that proper deconvolution of data can be performed after measurement of spot-scan profiles for the linear illumination spot in order to account for the lens MTF; as a result, the optical distortions will be removed from measured data, and data similar to the calculated data described above will be obtained. Comparing the average values of the diffusion length in the profiles $l_d^{\rm eff}(x)$ calculated for small resulting diode currents with the „true" values of the bulk diffusion length used in the calculations, we conclude that the inaccuracy in determining the length l_d due to the disregard of the additional transport of PCCs along diodes proves to be not too large for photodetector arrays with the adopted parameter values. After averaging the data in Fig. 3, *a* over the two oscillations of the dependence $l_d^{\rm eff}(x)$ in the range of $x = 25 - 70\,\mu$m we find that for the „actual" (i.e. used in the calculation) values $l_d = 5$, 10, 20 and $30\,\mu$m, as a result of the experiment, the researcher will obtain the values ~ 6, ~ 13, ~ 25 and $\sim 36\,\mu$m, i.e. the discussed inaccuracy for these cases will not be greater than $\sim 20 - 25\%$.

Conclusions

1. Modeling imitating the application of method [15] to MCT diode arrays with $30\,\mu$m pitch, $14 \times 14\,\mu$m diode size and $6\,\mu$m thick absorber layer was performed for studying the effect of the effective (additional to diffusion) transport of PCCs along diodes occurring due to the reflection of photocurrents from FPA diodes on the inaccuracy in determining the bulk diffusion length l_d of PCCs in the absorber layer of MCT-based FPAs using this method. It was found that the typical inaccuracy in determining the bulk diffusion length of PCCs in the absorder material due to their lateral transport of PCCs induced by their reflection from diodes is equal to $\sim 20 - 25\%$ for the studied arrays.

2. The „fine structure" of diode photo-response profiles observed during scanning of illumination spots was studied for verification of the calculation model and comparison of the results for the focal plane arrays with reflecting and absorbing diodes. The analysis shows that the formation of this structure revealed during numerical modeling is caused by the modification of boundary conditions of the diffusion problem for PCCs by back-biased or forward-biased diodes located on the diode side of the focal plane and realizing the „absorption" or „reflection with additional lateral transport" of PCCs at the corresponding boundary when passing by the light spot. The results of calculation are qualitatively confirmed by the obtained experimental data.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A. Rogalski. *Infrared Detectors, Second Edition* (CRC Press, Boca Raton, 2010)

[2] W. Cabanski, R. Breiter, K-H. Mauk, W. Rode, J. Ziegler, L. Ennenga, H. Lipinski, T. Wehrhahn. Proc. SPIE, **4028** (2000). DOI: 10.1117/12.391734

[3] P.S. Lazarev, M.G. Mazin, A.V. Sidorin, V.N. Solyakov, E.O. Trenina, K.A. Hamidullin, A.D. Yudovskaya. Prikladnaya fizika, **4**, 107 (2012) (in Russian).

[4] O. Schreer, M. López Sáenz, Ch. Peppermüller, U. Schmidt. Proc. SPIE, **6542**, 65421C (2007). DOI: 10.1117/12.725273

[5] W. Userell. in: *Design of Optical Systems*, ed. by R. Shannon, J. Vyant (Mir, Moscow, 1983)

[6] A. Rogalski. in: *Mid-infrared Optoelectronics. Materials, Devices and Applications*, ed. by E. Tournie, L. Cerutti (Elsevier Ltd., 2020), DOI: 10.1016/B978-0-08-102709-7.00007-3

[7] V. Srivastav, R. Pal, H.P. Vyas. Opto-Electron. Rev., **13** (3), 197 (2005).

[8] E. Belas, R. Grill, J. Franc, A. Toth, P. Höschl, H. Sitter, P. Moravec. J. Cryst. Growth, **159** (1), 1117 (1996). DOI: 10.1016/0022-0248(95)00696-6

[9] H. Jung, H.C. Lee, C.-K. Kim. J. Electron. Mater., **25** (8), 1266 (1996).

[10] H. Jung, H.C. Lee, C.-K. Kim. Jpn. J. Appl. Phys., **35** (10B), L1321 (1996).

[11] B.E. Artz. J. Appl. Phys., **57** (8), 2886 (1985).

[12] A. Yéche, F. Boulard, C. Cervera, J.P. Perez, J.B. Rodriguez, P. Christol, O. Gravrand. Infrared Phys. Technol., **95**, 170 (2018). DOI: 10.1016/j.infrared.2018.10.005

[13] D.A. Redfern, J.A. Thomas, C.A. Musca, J.M. Dell, L. Faraone. J. Electron. Mater., **30** (6), 696 (2001).

[14] M. Liu, S. Wang, J.C. Campbell, J.D. Beck, C.-F. Wan, M.A. Kinch. J. Appl. Phys., **98**, 074509 (2005). DOI: 10.1063/1.2060948

[15] A.V. Vishnyakov, V.A. Stuchinsky, D.V. Brunev, A.V. Zverev, S.A. Dvoretsky. Appl. Phys. Lett., **104**, 092112 (2014). DOI: 10.1063/1.4867349

[16] V.A. Stuchinsky, A.V. Vishnyakov. *Trudy XXV Mezhd. nauchno-tekhnicheskoj konferencii i shkoly po fotoelektronike i priboram nochnogo videniya v dvukh tomakh*, vol. 2, (AO „NPO„Orion", publishing house „OFSET MOSKVA", MOSCOW, 2018), p. 430–433 (in Russian).

[17] G.D. Boreman, *Modulation Transfer Function in Optical and Electro-Optical Systems*, Second Edition, V. TT121, ISBN: 9781510639379 (2021). DOI: 10.1117/3.419857

Translated by A.Akhtyamov