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FEATURES OF STATIONARY PHOTOCONDUCTIVITY OF HIGH-OHMIC SEMICONDUCTORS UNDER LOCAL ILLUMINATION

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Photoconductivity has been thoroughly studied for a long time. However, most researchers have examined photoconductivity of semiconductors while illuminating the entire surface of samples. The present paper examines the effect of local exposure that ensures a high level of injection of free charge carriers upon the conductivity of high-ohmic cadmium telluride and semi-insulating gallium arsenide samples and upon the properties of ohmic contacts to samples. The authors found that regardless of the exposure area the value of transition resistance of ohmic contacts decreases and the concentration of the main charge carriers increases in the sample in proportion to radiation intensity. This research uncovered a number of previously unknown effects that are interesting from the physical point of view. This paper focuses on discussing these effects.

Keywords: high-ohmic semiconductor, photoconductivity, ohmic contact, local illumination.

INTRODUCTION

When working with high-ohmic semiconductors, such as for instance detector cadmium telluride, semi-insulating gallium arsenide etc., one faces the problem of reliable identification of their electrophysical parameters (electric resistivity, ρ, concentration of the main charge carriers and their mobility). The problem is that practically all methods for identification of these parameters require creating ohmic contacts to the examined samples. Unfortunately, real ohmic contacts have transition resistance, the value of which depends on the large number of factors, the main being the concentration of free charge carriers in the examined sample [1–3]. For high-ohmic semiconductors this transition resistance can reach very large values (up to 5–6 GOhm), so the standard methods for measurement of electrophysical parameters (probe methods, Hall effect, and van der Pauw method) [4] become problematic.

The authors of [5] suggested a novel method to reduce the transition resistance of the contact by creating excess (non-equilibrium) charge carriers in the contact area. As a source of non-equilibrium charge carriers one can use any stimulating radiation capable of generating electron-hole pairs when interacting with the sample substance. They also undertook measures so that the share of exposed part of the sample would be insignificant and would not affect conductivity of the sample as a whole. However, studies [6–11] aimed at modernizing the metrics of high-ohmic semiconductors demonstrated that even local exposure of the sample leads to significant conductivity change of the crystal as a whole. These studies revealed a number of previously unknown effects that are interesting from the physical point of view and that this paper is focusing on.

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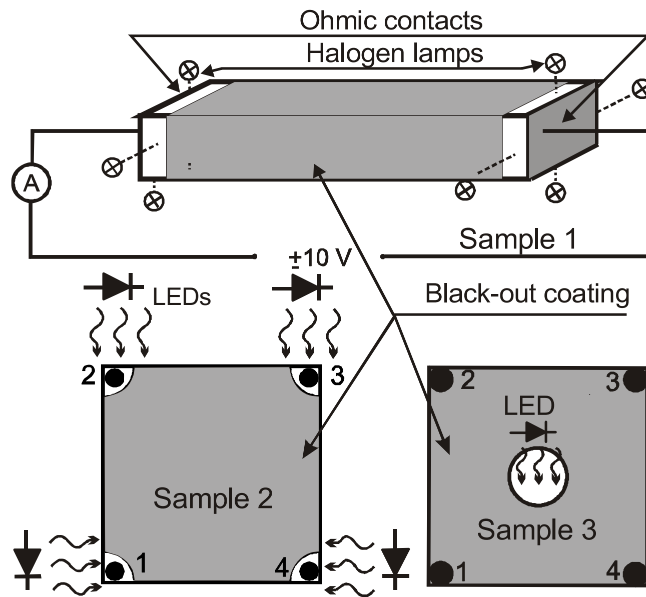

Fig. 1. Shape of samples used in experiments.

EXPERIMENT METHODOLOGY AND DISCUSSION OF RESULTS

The paper examined the samples of semi-insulating gallium arsenide and high-ohmic cadmium telluride. GaAs ingots were produced by the Czochralski process and doped with chromium that creates deep acceptor centers in GaAs that have an energy level located near the middle of band gap (for instance, see [12]). Cadmium telluride ingots were produced by the travelling heater method (THM) and doped with chlorine – a shallow donor impurity with ionization energy near 7 meV.

It is known that electric properties of undoped cadmium telluride are determined by an 'assembly' of electrically active intrinsic point defects (primarily doubly ionized cadmium vacancies), so CdTe ingot, intentionally left undoped, has *p*-type electric conductivity with hole concentration of $\sim 10^{16}$ cm^{-3}. When doping with chlorine ($CdCl_2$ is added into the batch), during the ingot growth chlorine enters it suddenly and non-uniformly. So we have *p*-type material on one end of the ingot (where there is little chlorine and intrinsic defects prevail) and low-ohmic material with *n*-type electric conductivity – on the other end. And only in the small central part of the ingot, where intrinsic defects are compensated by donor impurity (chlorine), there is an area of material with high specific resistance, from where the examined samples were cut out.

Fig. 1 presents the shapes of samples used for research.

In primary studies [6] researchers used a sample of semi-insulating cadmium telluride with *p*-type electric conductivity and electric resistivity $\rho \geq 10^7$ Ohm·cm at room temperature. The sample had a shape of rectangular parallelepiped with dimensions 3×3×23 mm (No. 1 in Fig. 1). Indium was deposited onto the butt ends of the sample to create ohmic contacts. Linearity of volt-ampere characteristic (VAC) of the two-pole network was ensured in the voltage range of ±10 V.

In order for the light to affect only the near-contact area of the sample that is ~ 1 mm wide, lightproof coating was deposited onto the crystal surface. Open areas were illuminated by halogen lamps (four from the side of each contact and from the side of each plane). After having been placed on the holder, the sample was kept in the dark for several hours, in order to eliminate the impact of background illumination.

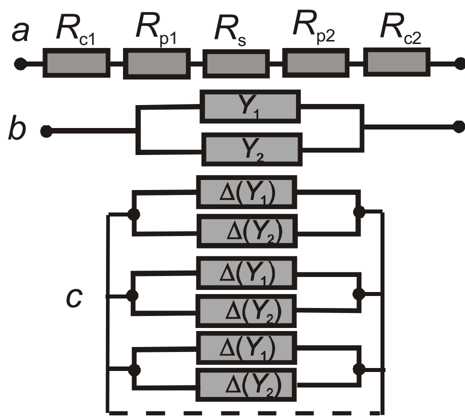

Fig. 2

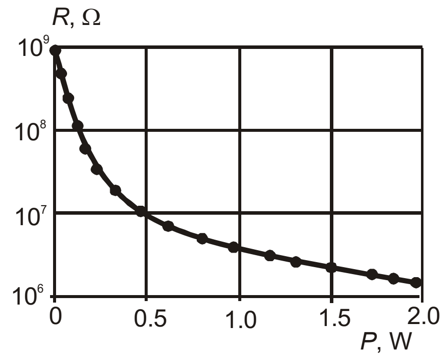

Fig. 3

Fig. 2. Evolution of ideas about the equivalent experimental circuit: *a* – initially envisaged equivalent sample circuit, *b* – equivalent sample circuit that allows explaining the results of experiments shown in Fig. 3 and 4, *c* – equivalent sample circuit that also allows explaining the results of experiment presented in the table.

Fig. 3. Dependence of sample resistance on the power consumed by the lamps (per 1 lamp).

Due to the very high resistance of samples, time of stationary signal detection was tens of seconds and measurements were performed in the stationary state only.

As experimental information was accumulated and analyzed, our ideas about equivalent sample circuit changed. Evolution of these ideas is presented in Fig. 2. It seemed natural to present the equivalent sample circuit as five series-connected resistances (Fig. 2*a*): resistances of contacts R_{c1} and R_{c2}, resistances of illuminated segments R_{p1} and R_{p2} and resistance of the sample volume R_s. We assumed that illuminated areas of the sample were to play the role of ordinary photoresistances. The sample was specifically made that long, in order for the share of illuminated surface not to exceed 10% of the sample surface. We expected that with the rise in illumination intensity, resistances R_{c1}, R_{c2}, R_{p1}, R_{p2} would decrease and, correspondingly, total resistance of the sample would reach saturation.

Fig. 3 presents the dependence of sample 1 resistance on the power consumed by the lamps. As one can see from Fig. 3, resistance of the sample decreases almost by three orders of magnitude with the increase in light intensity, however, contrary to our expectation, it does not reach saturation. This means that either maximal illumination created by these lamps is not sufficient, or additional factors play a role. In order to check for other effects, we performed analogous research using a more well studied material, namely *n*-type semi-insulating gallium arsenide (sample 2) with initial equilibrium concentration of electrons ~10^7 cm^{-3} at room temperature [5, 6]. The sample was cut out of the square 1.7 mm thick plate, with dimensions 10×10 mm. Round indium contacts with ~0.8 mm diameter were deposited onto the sample corners. The sample shape was selected to allow for future Hall measurements. Illumination of the near-contact areas was performed using EDEF-1LS3 light emitting diodes (wavelength in the radiation maximum – 740 nm), which ensured the inter-band generation.

Fig. 4 presents the lux-ampere characteristics (LAC) – dependences of current through contacts 1 and 3 at constant voltage 90 V on the current through LEDs (only contacts 1 and 3 were illuminated, individually and jointly).

As far as LED radiation intensity is proportional to current, illuminance of the sample was evaluated based on the value of direct current through LEDs. When several LEDs were used, they were connected consecutively.

It was found out that dependences of current through the sample on illuminance level (LAC), starting from a certain value of light intensity, become a straight line, the angular coefficient of which depends on whether both contacts are illuminated or one. Furthermore, it turned out that such an effect is caused not only by illumination of current contacts 1 or 3, but also potential contacts 2 or 4. In the latter case, photocurrent is noticeably smaller.

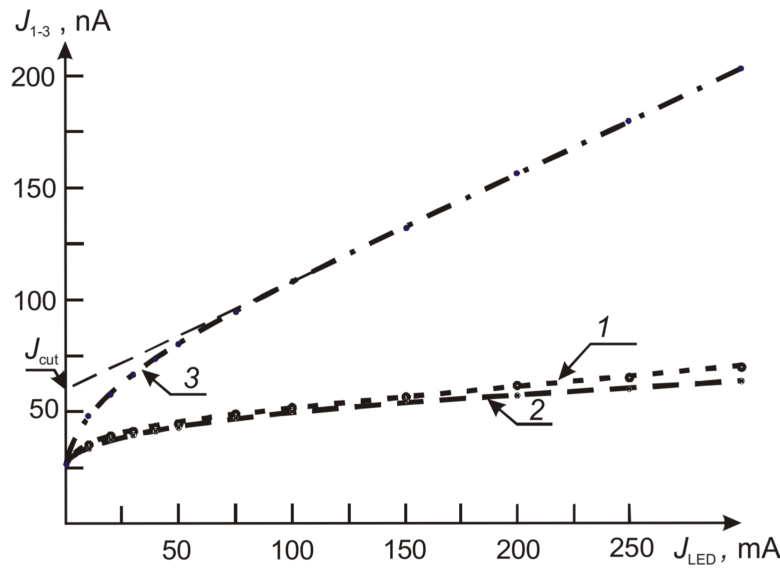

Fig. 4. Dependence of current through contacts 1 and 3 of sample 2 under different illumination conditions: curve *1* – only contact 1 was illuminated, curve *2* – only contact 3 was illuminated, curve *3* – both contacts 1 and 3 were illuminated.

On the linear section LAC is described by equation

$$J_{1-3} = kJ_{\text{LED}} + J_{\text{cut}}, \tag{1}$$

where k is the angular coefficient, J_{LED} is the current through the LEDs, and J_{cut} is the cutoff current.

Using contacts 2–4 as potential ones, one can measure the Hall EMF and determine the concentration of electrons inside the crystal and its dependence on illumination level of contacts 1–3 in different combinations. These dependences are given in Fig. 5. One can see that starting from a certain illuminance level the concentration has a linear dependence on current through LEDs and hence on radiation intensity.

Therefore, experiments confirm the surprising fact that illumination of a small area of the sample near any contact leads to the increase in concentration of the main charge carriers in the entire sample, including at a distance from the illuminated contact that is much larger than diffusion length. Furthermore, the result does not depend on the contact with which potential (positive or negative) is illuminated.

In order to explain this fact, a model was suggested [8], clarified using Fig. 6. In the case when one illuminates the area of crystal near the contact with positive potential (Fig. 6*a*), electron-hole pairs produced by the light are separated by the sweeping field. Generated electrons go to the contact, while holes get drawn by the field into the depth of the sample at the stretched diffusion length. What happens is a kind of injection of holes into the material with extremely low initial concentration of the main charge carriers (in our case $n_{n0} \sim 1.5 \cdot 10^7$ cm^{-3}). In other words, practically in any illumination conditions a high level of injection emerges, at which the same number of the main charge carriers flows from the external circuit to compensate for the charge of injected minority charge carriers. In the stationary state, the holes recombine with electrons within the diffusion length limits, thus closing the current streamline. In order to ensure the stationary process, the required number of electrons must constantly enter the recombination area. Thus, despite the fact that non-equilibrium charge carriers are created near the illuminated contact, concentration of the main charge carriers increases in the entire sample. This fact is confirmed by Hall measurements.

Events proceed in a somewhat different way, when the contact with negative potential is illuminated (Fig. 6*b*). Light-generated minority charge carriers (holes) are drawn by the field into the contact, while electrons are forced to

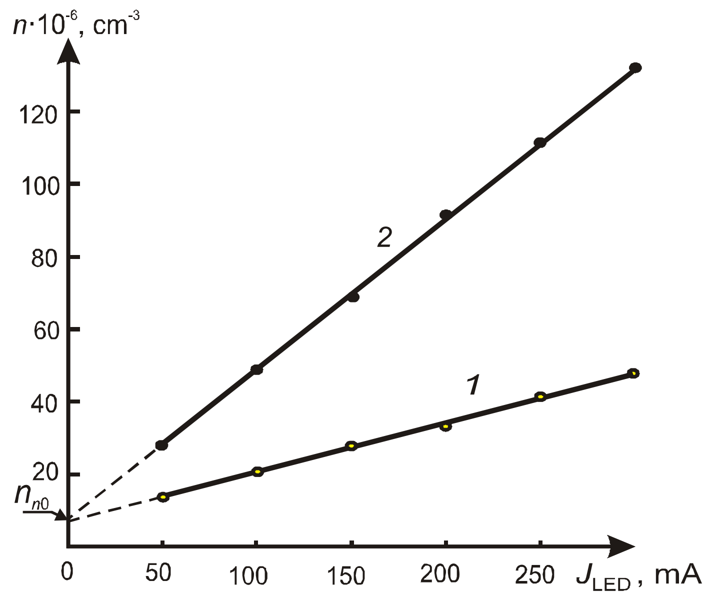

Fig. 5. Dependence of electron concentration in sample 2 under different illumination conditions: curve *1* – only contact 1 or 3 was illuminated, curve *2* – both contacts 1 and 3 were illuminated.

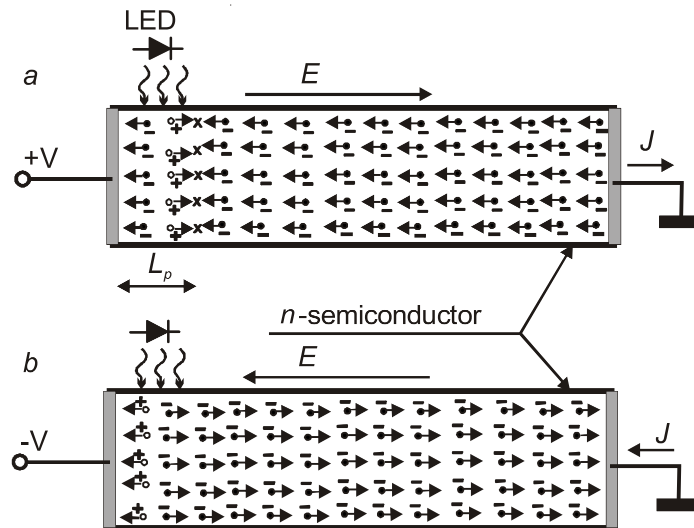

Fig. 6. Behavior model of free charge carriers in a sample of semi-insulating *n*-type semiconductor when illuminating one of the contacts: *a* – contact with positive potential, *b* – contact with negative potential.

flow to the positive electrode across the entire sample, thus increasing the concentration of the main charge carriers in it. That is why the result turns out to not to depend on which contact we illuminate.

Equivalent circuit corresponding to this model is presented in Fig. 2*b*. Conductivity $Y_1 = \frac{1}{R_s}$ represents the initial system (see Fig. 2*a*), where due to exposure of the near-contact areas one can neglect the resistances of contacts

TABLE 1. Experimental Results

Diameter of diaphragm opening, mm	Angular coefficient k, nA/mA	Cutoff current J_{cut}, nA
0.5	0.022	8.2
1.0	0.053	9.5
1.5	0.12	11.9
2.0	0.15	13.3
2.5	0.27	17.8
3.0	0.46	25.8
4.0	0.53	31.0

and illuminated segments. Conductivity Y_2 is associated with charge carriers produced by light that increase the conductivity of the sample volume. In this case, that conductivity must have a linear dependence on the number of non-equilibrium electron-hole pairs separated by the field per time unit. The number of these pairs must be proportional to the absorbed light quanta, i.e. proportional to the intensity of radiation falling onto the sample. Correspondingly, LAC of conductivity Y_2 must be a linear function.

Therefore, it was experimentally established that illumination of contacts in any combination leads to practically the same outcome – increase in concentration of the main charge carriers in the sample. At the same time, however, it is necessary that electric field (it does not matter, whether it is external or internal) be present in the exposure area [9, 10].

The fact that change in resistance of the sample volume occurs even when one illuminates the contacts, through which current does not pass, suggests that we ought to observe a similar effect when illuminating any local area of a crystal.

In order to confirm this hypothesis, we studied sample 3 (Fig. 1), also produced from n-GaAs, where the central part of the sample was illuminated through the diaphragm in the lightproof screen [11]. Diameter of the diaphragm varied from 0.5 to 4 mm, in order to check the size factor. One could suggest that photocurrent of the sample (on the linear section of LAC) would depend, first, on the number of electron-hole pairs separated by the field per time unit, and, second, on the value of electric field intensity in the area where separation of electron-hole pairs takes place. In view of this, it was expected that, first, in the case of diaphragm diameter change the angular coefficient of straight-line section $\left(k = \dfrac{dJ_{1-3}}{dJ_{\text{LED}}}\right)$ of LAC registered at constant external voltage will change proportionally to the illuminated area ($k \sim D^2$). Second, that regardless of the diaphragm diameter, extrapolation of linear sections of dependences $J_{1-3} = f(J_{\text{LED}})$ will provide the same cutoff current value equal to $J_{\text{cut}} = \dfrac{V}{R_{\text{vol}}}$ [6]. However, none of these assumptions was confirmed in the experiment (see Table 1).

Dependence of the angular coefficient of LAC on the diaphragm diameter D turned out to be a degree function $k \sim D^n$, where $2 > n > 1$. This means that angular coefficient is proportional to neither the square of the illuminated spot, nor its perimeter. One can explain the result as follows. As far as the concentration of equilibrium charge carriers in the initial material is very small, even relatively weak intensity of irradiation creates an area with high level of injection in a sample. And as far as absorption depth of the applied light is also small, an area with high conductivity emerges in the thin layer under illuminated surface. The electric field picture is significantly distorted [11]. As a result, only a very small part of external bias will fall on illuminated area with high concentration of non-equilibrium charge carriers. That is why any noticeable field is absent in this area. Hence, non-equilibrium electron-hole pairs in this area are practically not separated and their excess concentration is determined by processes of generation, recombination and diffusion. Only those of electron-hole pairs that diffuse from this area to the non-illuminated part of the crystal find themselves in the operating area of electric field, are separated by it and create the photocurrent that we observe. If the sample thickness did not exceed absorption depth, then, according to the described model, photocurrent would be proportional

to the perimeter length of the illuminated spot, i.e. proportional to the diaphragm diameter. Meanwhile, in our case, the sample thickness is much larger than absorption depth, and field force lines approach the illuminated area not only over the surface, but also underneath. As a result, photocurrent must be proportional to the number of field force lines closing on the illuminated area.

Obviously, in such a model the number of non-equilibrium charge carriers separated by the field and participating in the current will be significantly lower than the overall number of generated charge carriers.

As for the intensity of electric field, where separation of electron-hole pairs takes place, it to a large extent depends on the length of field force line closing on the illuminated area. And as far as the lengths of these force lines are different [8], one would naturally expect that the resultant contribution from different illuminated area segments to the photocurrent will be different too. This model of current spreading changes our idea about the equivalent sample circuit (Fig. 2*c*), where there is a conductivity chain corresponding to each electric field force line. This circuit helps understand the dependence of cutoff currents on the diaphragm diameter.

Current element ΔJ_i along the *i*-th force line, in a manner similar to expression (1), can be written as

$$\Delta J_i = k_i \cdot J_{\mathrm{LED}} + \Delta J_{\mathrm{cut}\,i}, \tag{2}$$

where k_i is the proportionality coefficient that depends on the number of light-generated electron-hole pairs per time unit in the vicinity of this (*i*-th) field force line and on the electric field intensity in the area where pair separation takes place, and

$$\Delta J_{\mathrm{cut}\,i} = \frac{V}{\Delta R_{\mathrm{vol}\ i}}. \tag{3}$$

If z force lines are illuminated, then the resultant current through the structure in the first approximation will be

$$J_{\mathrm{res}} = \sum_{i=1}^{z} \Delta J_i = \left(\sum_{i=1}^{z} k_i \right) J_{\mathrm{LED}} + \sum_{i=1}^{z} \Delta J_{\mathrm{cut}\,i} = k \cdot J_{\mathrm{LED}} + J_{\mathrm{cut}}. \tag{4}$$

The resultant angular coefficient and the resultant cutoff current will depend on the number of field force lines approaching the boundary of the illuminated part of the sample.

That is why, the more field force lines are illuminated, the bigger is the total conductivity (Y_1+Y_2) and hence the value of cutoff current, which in this case is equal to

$$J_{\mathrm{cut}} = V \cdot \sum_{i=1}^{z} \Delta Y_{2i}. \tag{5}$$

Stemming from the above, it is hard to escape drawing an analogy between the examined samples and a vacuum diode, with a crystal performing the role of vacuum and illuminated area – that of a cathode. According to this analogy, one would expect that when all the light-generated electron-hole pairs will be separated by the field, photocurrent through the sample will stop changing when the voltage increases. Hence, VAC of the sample ought to be sublinear. However, we see no hint of deviation from linearity in the experiment (Fig. 7).

There can be two explanations for this. Either the model suggested above is not correct, or the electric field used in the experiment is not sufficiently large and separates only a small share of light-generated electron-hole pairs. The second supposition is indirectly confirmed by comparison of current of the photodiode placed instead of the sample under diaphragm and photocurrent through the sample, under the same illumination conditions. Photodiode current in the photodiode mode turned out to be by three orders of magnitude larger. It means that in our case the field separates one thousandth of the generated electron-hole pairs. That is why there is no photocurrent saturation with the voltage increase.

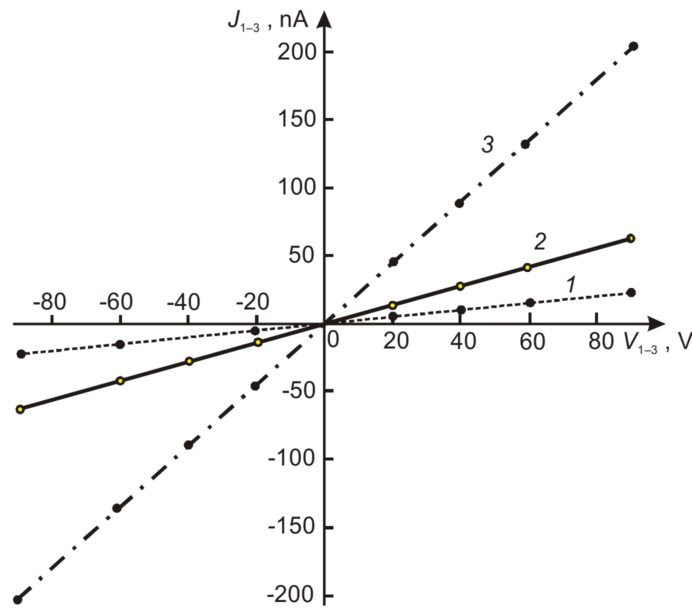

Fig. 7. Volt-ampere characteristics of sample 2 under different illumination conditions: curve *1* – dark VAC, curve *2* – only contact 1 or 3 was illuminated, curve *3* – both contacts 1 and 3 were illuminated.

Finally, there is one experimental fact that at first glance does not fit the examined model of photoconductivity. Namely, that the photocurrent through the sample in the case of simultaneous illumination of current contacts turns out to be significantly larger (by around 30%) than the sum of currents when contacts 1 and 3 are illuminated individually (Fig. 3 and 7). However, this can also be explained, taking into account that the spreading resistance of the square sample in the case of diagonal switching is determined by the expression produced in [7]:

$$R_{1-3} = \frac{\rho}{2d} \ln\left(\frac{a\sqrt{2}}{2D_k}\right), \tag{6}$$

where ρ is the resistivity of initial material of the sample, d is the thickness of the sample plate, a is the side length of square sample, D_k is the diameter of the ohmic contact. Noticeable decrease in specific resistance occurs in the illuminated part of the semiconductor, which is equivalent to the ohmic contact diameter increase and thus the sample spreading resistance decrease. This explains the observed difference between situations when each contact is illuminated individually and when two contacts are illuminated at the same time.

CONCLUSIONS

1. Volt-ampere and lux-ampere characteristics of high-ohmic gallium arsenide and cadmium telluride samples have been measured under conditions of local illumination of near-contact areas of the sample or its central part with radiation from LEDs with energy of quanta exceeding the band gap of semiconductor.

2. It was experimentally established that concentration of the main charge carriers in the semiconductor increases in a linear manner with the increase in intensity of LED radiation regardless of the place of local exposure.

3. It was also established that lux-ampere characteristics of the examined samples in the case of currents through LED exceeding 50 mA are linear functions.

4. It was shown that volt-ampere characteristics of *n*-GaAs samples in the voltage range of ± 90 V at all levels of illumination intensity are straight lines.

5. A qualitative model explaining the experimental data obtained has been suggested. The model has been illustrated using *p*-CdTe and *n*-GaAs samples as examples.

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