PHOTOELECTROMAGNETIC EFFECT IN $\mathbf{Hg_{1-x}Cd_xTe}$ EPITAXIAL LAYERS

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A generalized model of the photoelectromagnetic effect (PME) in epitaxial layers (EL) is formulated that takes into account a presence of the space charge region (SCR) on the free surface and the graded gap region (GGP) at the interface with a substrate. It is shown that the diffusion currents of excess minority carriers, on the one hand, and their drift currents in SCR and GGP, on the other one, may flow in alternative directions and, when the latter currents dominate, the sign of photoelectromagnetic current $J_{\rm PME}$ can take an opposite value thus allowilng observation of the anomalous PME. Dependences of this phenomenon on the exciting radiation frequency, degree of the gap bending Y_s, and illumination direction (through the free surface or substrate) are analyzed. The model-predicted results are in good agreement with the experimental data obtained for $\rm Cd_xHg_{1-x}Te$ samples ($x \approx 0.20$). These can be used for the determination of EL parameters.

Epitaxial layers formed on the basis of the narrow-gap semiconductor compound $\rm Cd_xHg_{1-x}Te$ (CMT) are widely used in the IR photoelectronics for creation of photodetectors operating in the spectral regions from 3 to 5 μm and 8 to 14 μm (see, for example, [1, 2]). Successful employment of EL CMTs as high-sensitive IR devices rises up a question of exact determination of the charge carriers' electric parameters. Usually, these parameters of equilibrium charge carriers are calculated from the dependence of the Hall coefficient and electric conductivity on magnetic field and temperature. However, some important parameters, such as the carrier life or surface recombination velocity, as well as the distribution of these parameters over the layer depth, can be obtained from the photoelectric and photoelectromagnetic measurements only. But a complexity of the real structure of ELs makes it difficult to give a theoretic description of the photoconductivity (PC) and PME phenomena in these structures and to interpret related experimental results.

First of all, the thickness of ELs (10 to 25 μm) turns out to be of the same order of magnitude as the diffusion length L_d of charge carriers. Because of this, the charge carriers' lifetime is determined by a state of both the illuminated surface and the EL/substrate interface. A specific feature of the CMT ELs is also the presence of positive charge on the anode-oxide free surface (the corresponding gaps' bending can be straightened by means of a short-time UV irradiation [1]). Besides, an EL may include the GGRs. In ELs grown, for example, by means of the liquid-phase epitaxy technique, the GGRs are formed due to a Cd molecules diffusion out off the substrate or buffer layer which are formed, in general, of a wide-gap CdTe crystal. In ELs grown by the molecular-beam epitaxy (MBE) with a purpose of suppression of the surface recombination [3], in some cases, graded-gap areas are formed whose energy gap increases towards their outer boundaries.

The mentioned peculiarities of the EL structure cause essential anomalies in the PME manifestation. These lead to the PME signal amplitude to depend largely on a wavelength of the irradiating light and, for certain parameters of the epitaxial structure, a multiple PME sign alternation can occur.

We have constructed a generalized model of PME in ELs that accounts for both the space-charge region (SCR) on a free surface and a presence of GGR on the EL/substrate interface. A typical general scheme of such n-type EL grown by the liquid-phase epitaxy is shown in Fig. 1,*a*. In this case we believe, basing on the experimental data [1], that there exist donor states of energy $_t$ and surface concentration N_t on the oxide layer adjacent to the free surface. A positive charge of ionized donors causes a bending of gaps, which usually is written in arbitrary units: $Y_s = (q/kT)[\psi_s - \psi_0]$ (q is electron charge, ψ_0 — middle band-gap potential in the quasi-neutral region, and ψ_s — surface value of the latter potential). Later on, a $l_{\rm SCR}$-thick layer enriched by the majority carriers is formed near the surface. Instead, a GGR region is located near the interface between $x = l_{\rm GGR}$ and $x = d$, whose band gap increases towards the substrate.

By applying a standard procedure of PME consideration [4], we can show easily that the short-circuit current flowing through a d-thick n-type EL illuminated from the free surface side equals

$$J_{\rm PME} = qh(\theta_n + \theta_p)D_{pH}[\Delta p(0) - \Delta p(d) +$$

$$+\frac{1}{kT}\int\limits_0^d \nabla E_g(x)\Delta p(x)dx]. \tag{1}$$

Here, h is the plate width, $\theta_{n,p} = (H/c)\mu_{n,p}(E)$ — Hall's angles for electrons and holes ($\mu_{n,p}(E)$ are the corresponding mobility values which, generally speaking, are dependent of the carriers' energy E), $D_{p,nH} = \langle[D_{p,n}/(1+\theta^2_{p,n})]\rangle$, $D_{n,p} = (kT/q)\mu_{n,p}(E)$ — diffusion coefficients of electrons and holes, $\langle\ldots\rangle$ is the energy-averaging symbol. Excessive carriers' concentration $\Delta p(x)$ is found as a resolution of the continuity equation with boundary-value conditions accounting for both the generation and recombination on the free surface and interface.

The first two summands enclosed in square brackets (1) describe the usual case of PME in a thin plate [4], whereas the third one determines the influence of the graded-gap feature [5] (it is obvious that in the EL model we have chosen and presented in Fig. 1,*a*, the third summand should be integrated from $x = l_{\rm GGR}$ to $x = d$). In this arrangement, influence of the SCR is taken into account within the model of the effective surface recombination rate s_0 that depends on the bands' bending value Y_s and possesses a physical sense of the "supply" rate of carriers from the bulk to the plane $x = l_{\rm SCR}$. Such a simplified model allows, in many (but not in all!) cases, exclusion of the processes of movement and recombination in the SCR from the consideration, which are rather complicated to be analyzed since these are determined not only by a diffusion, but also by a drift in the SCR-caused field.

Limits of applicability of this model are discussed, for example, in [6]. These limits are fixed to meet the requirement of keeping the quasi-equilibrium of charge carriers in a space of the SCR's boundary and on the surface independently of a generation manner of non-equilibrium carriers. In particular, relationship $L_d >> l_{\rm SCR}$ should be valid in these circumstances, i.e., the diffusion length has to be much longer than the SCR size.

A specific feature of EL analysis (1) is the fact of insufficiency of application, when solving the continuity equation, of the boundary-value conditions in the form of on-surface generation, since the d layer's thickness is small (for CMT, this may be of the same order of magnitude as the reciprocal absorption coefficient α^{-1}). Instead, the in-bulk generation of carriers should be exactly accounted for. This fact makes the general-case determination of the PME current to be computationally cumbersome and depending on a chosen model and specific EL parameters.

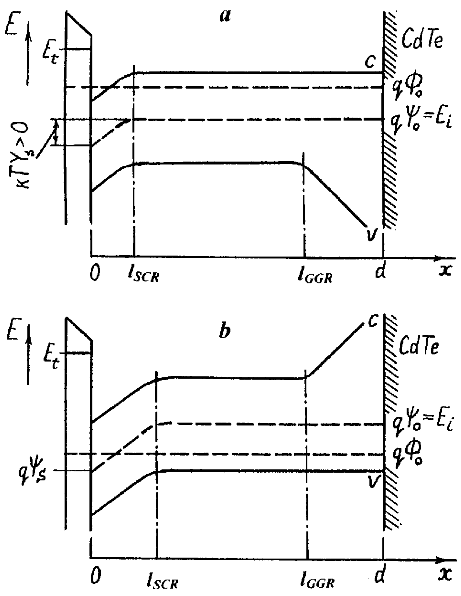

Fig. 1. Schemes of the CMT EL of n-type (a) and p-type (b). Φ_0 is the level of chemical potential

In some cases, however, one can obtain rather important analytical solutions, as was shown in [7]. Thus, for the case of a small graded-gap slope (i.e., $\nabla E_g/kT << 1$, and the last summand in square brackets in (1) can be neglected as compared with the two initial ones), the PME-current expression can be written analytically.

For the case of in-surface light absorption in a thin EL, for which $L_d > d$, the relationship $\alpha d >> l$ is valid, and, taking into account the relationship $s_0 >> s_d$ (that is, the interface recombination is slowed-down because of the presence of the GGR), we have

$$J_{\rm PME} = qh(\theta_n + \theta_p)D_{pH}I\frac{1}{s_d + D_{pH}/d}. \tag{2}$$

Here, I is the intensity of the incident light (for simplification, the quantum yield is considered to equal unity). If the interface recombination rate is low, that means $s_d << D_{pH}/d$ (this relationship is, as a rule, met, in particular, for CMT ELs investigated in [1]), then expression (2) radically simplifies: the PME current is not dependent of recombination on the surfaces at all, and is fully determined by the Hall mobility of carriers. Under such conditions, the dependence of $J_{\rm PME}(H)$ can be employed for a handy and reliable determination of these mobility values.

Instead, if the following conditions are met: i) the reverse relationship $\alpha d << 1$ is true, ii) the carriers are absorbed almost uniformly throughout the whole EL thickness (in the CMT, this takes place in the vicinity of the intrinsic absorption edge), iii) $s_0 >> s_d$, and iv) additional conditions s_0, $s_d >> D_{pH}/L_d$ and $\mathrm{ch}(d/L_d)e^{-\alpha d} > 1$ are valid, then we can obtain [7]

$$J_{\rm PME} = -qh(\theta_n + \theta_p)D_{pH} I \frac{L_d \alpha(\mathrm{ch}(\frac{d}{L_d})e^{-\alpha d} - 1)}{s_d\,\mathrm{sh}(\frac{d}{L_d})}. \quad (3)$$

As is seen from (3), the PME current alters its direction and takes a negative value. Physically, this is explained by the fact of excess of the current of carriers flowing to the illuminated surface, over the diffusion current flowing from the illuminated surface to the EL/substrate interface (the latter current is of minor significance since the light is absorbed almost uniformly throughout the whole EL thickness). Note that within the frame of the above inequalities the anomalous PME current increases in proportion as the absorption coefficient does grow up.

Now, let us consider qualitatively the opposite case of a high-graded gap, $\nabla E_g/kT >> 1$, in which we already cannot neglect the third square-brackets-enclosed summand of Eq. (1). Under the condition of a constant graded-gap gradient in GGR, we can rewrite the square-brackets-enclosed expression as

$$\Delta p(0) - \Delta p(d) + \frac{\nabla E_g}{kT} \int\limits_{l_{\rm GGR}}^{d} \Delta p(x) dx. \quad (4)$$

As can be easily seen, expression (4) can also change its sign due to the factor $\nabla E_g/kT$, provided that the absorption is quite constant throughout the whole sample's depth up to a plane inside the GGR for which E_g equals the energy of an incident quantum, and excessive concentrations of holes on both the illuminated surface and the plane $x = l_{\rm GGR}$ do differ not very much, but yet considerably larger than in the plane $x = d$ (this is the case if a CMT material on the CMT/substrate interface is already a sufficiently wide-band one). Physically, this implies that the drift current of minority holes in the GGR, which is directed from the interface to the illuminated surface, exceeds their diffusion current flowing from the illuminated surface to the interface (which also includes the diffusion current flowing to a GGR, for which $h\varpi < E_g(x)$ and generation does not occur).

Expression for PME current in an EL illuminated through the interface can be written analogously to Eq. (1). But in this case, directions of the holes' diffusion current and their drift current in a GGR do coincide. An anomalous sign of the PME current may be caused solely by an in-SCR drift current of holes directed towards the interface and by a reverse diffusion current flowing into the wide-gap zone of GGR, where a generation does not occur (see Fig. 1,*a*). But this effect may occur, as estimations show, only in the vicinity of the intrinsic absorption edge (IAE), where the concentration of excessive carriers is almost constant in the quasi-neutral region of the EL.

Therefore, in *n*-type EL illuminated from the free-surface side, the anomalous PME can be realized for two causes: i) because of a high rate of recombination on the illuminated surface and ii) because of the influence of GGR in which the minority carriers' drift current is directed oppositely to the illumination-induced diffusion current. In the case of the through-interface illumination, the anomalous PME may take place due to i) the drift current of holes in SCR, which flows oppositely to the illumination-induced diffusion current, and ii) the inverse-directed diffusion current flowing into the "wide-gap" zone of GGR. However, in all cases, validity of certain relationships between the EL parameters must be kept and, first of all, the condition of approximately uniform absorption of light throughout the EL thickness that can be realized only in the vicinity of the IAE.

As was already mentioned, the state of the free surface and, hence, the recombination rate on it can be controlled with a short-time UV irradiation of a sample. This leads to recharging of deep electron states and straightening of the energy bands, whose bending approaches zero ($Y_s = 0$). It is important that, under sufficiently low temperatures ($T < 100$ K), the recharging can be conserved practically for an arbitrary time interval. Let us consider in what way the zones' straightening can influence the above-described effects.

In a general case, the coefficient of free-surface recombination, which goes under equilibrium conditions through donors with concentration N_t and energy E_t, equals [6]

$$s_0 = \frac{c_p c_n N_t (p_0 + n_0)}{c_n(n_0 e^{Y_s} + \sqrt{n_0 p_0}\exp((E_t - E_i)/kT)) + c_p(p_0 e^{-Y_s} + \sqrt{n_0 p_0}\exp(-(E_t - E_i)/kT))}. \quad (5)$$

Here, n_0, p_0 are the coefficients of equilibrium carriers in the quasi-neutral region of EL, $c_{n,p}$ — the coefficients of capture of electrons and holes by a donor, and $E_i = q\psi_0$ — the middle energy of band-gap (see Fig. 1). For n-type material, $n_0 >> p_0$, and, with taking into account the asymmetry of capture by the donor center, $c_n >> c_p$, expression (5) essentially simplifies:

$$s_0 = c_p N_t e^{-Y_s}. \tag{6}$$

This equation shows that the free-surface recombination rate essentially boosts when there is applied the UV straightening of energy zones to achieve the condition of $Y_s = 0$. Because of this, illumination from the free surface provides relationship (3) to become valid more easily, and the anomalous-sign PME is observed in the whole spectral region. Instead, the through-interface illumination executed under the zones' straightening conditions leads to the disappearance of the main factor of a possible emergence of the anomalous sign of PME, and, hence, the PME current flows in the normal direction in the whole spectral region.

In a similar way, we consider the problem of PME in a p-type EL (Fig. 1,b). In this case, the short-circuit expression is written in form (1) with an obvious replacement $D_{pH} \to D_{nH}$ (provided that the quasi-neutrality condition $\Delta n(x) = \Delta p(x)$ is kept). Similarly, for this case, expressions (2) and (3) can be easily rewritten to describe the PME current under the condition of a weakly-varying gap, and to analyze Eq. (4) in the case of a highly-varied one.

Because of this, we dwell only on the essential differences. In contrast with the n-type ELs, in the p-type ones, a conductivity inversion is formed (the SCR conductivity is electronic here) near the illuminated surface due to surface donors. If a sample is illuminated through the free surface, the electrons' drift currents flow towards the illuminated surface in both the SCR and GGR and, as estimations show, they dominate in typical CMT ELs over the diffusion current flowing towards the interface. Furthermore, this is true even for the surface absorption, since movable electrons from SCR make the main contribution. In [8], we have considered a similar effect in thick CMT layers. (Note that the criteria of introduction of the surface recombination parameter turn out to be inapplicable in this case, and the drift and recombination of carriers in SCR should be considered immediately.) Therefore, here we have the anomalous PME sign in the whole spectral region.

In contrary to the above, under the through-interface illumination of a sample, both the diffusion current and the drift ones in both SCR and GGR are flowing in one direction. Because of this, the only cause of the PME manifestation is the diffusion into the wide-gap region of SCR. But its intensity is low for the typical parameters of CMT EL and the PME sign should be normal in the whole spectral region.

The UV-induced straightening of band gaps in a p-type material eliminates the drift current of electrons in the SCR and, thus, the anomalous PME in a sample illuminated through the free surface can occur only in a narrow spectral window due to the causes discussed above when considering an n-type material: i) high rate of the surface recombination, $s_0 >> s_d$ and ii) influence of GGR. Let us note separately that, if the conductivity inversion is eliminated in the sub-surface layer of SCR by the band-gap straightening, we can employ the s_0 parameter anew in the form (5). At the same time, since the surface center is a donor, the relation $c_n >> c_p$ is valid hereinafter, but, in this case, the relation $n_0 << p_0$ is met for concentrations of majority carriers. Therefore, expression (5), with taking into account the adduced relationships, is again essentially simplified:

$$s_0 = c_p \frac{p_0}{n_0} N_t e^{-Y_s}. \tag{7}$$

As numerical estimations show, s_0 value achieved after the band gaps are straightened ($Y_s = 0$), may turn out to be sufficient for realization of conditions of relationship (3) and manifestation of the anomalous PME (which, however, is not so perceptible as in the case of availability of the electron-conduction SCR layer). Instead, if the sample is illuminated through the interface side, a weak anomalous PME may occur near the IAE. This PME manifestation is caused by a contrary diffusion current of electrons flowing towards the plane $x = d$ from the plane $x = l_{\mathrm{GGR}}$ in which the electrons begin to be generated (at that, the excessive carriers are not generated in the GGR itself).

The spectral dependences of PME current were measured in Els of $\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$ ($x = 0.20$) of n- and p-type grown by the liquid-phase epitaxy technique [1]. In these experiments, the concentration $|N_a - N_d|$ of active dopants constituted $(0.5 \div 10) \cdot 10^{15}$ cm^{-2}, and an immobile high-density (10^{11} to 10^{12} cm^{-2}) positive charge was available on the free surface before its irradiation. Presence of the graded-gap region was checked by profiling a distribution of hard solution components throughout an EL by means of the electron probe technique. The probe scanning was carried out over a chip surface along a line perpendicular to the plane of the $\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$/CdTe hetero-border. The PME measurements have been accomplished for two

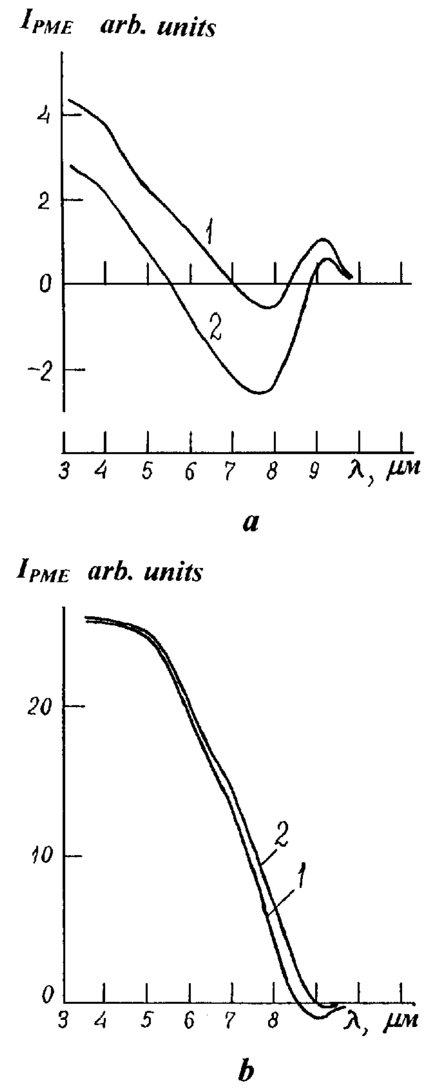

Fig. 2. Spectral dependences of the short-circuit current of PME in 17-μm-thick n-CMT EL illuminated from the free-surface side (a) and through the substrate (b) before (curve *1*) and after (curve *2*) irradiation at $T = 80$ K

illumination directions: from the free surface of EL and through its substrate.

Spectral dependences of PME current obtained at $T = 80$ K are presented in Fig. 2 (n-type material) and Fig. 3 (p-type). As is seen from the curves adduced, in the n-type material, in the vicinity of IAE, the PME current is of the normal sign. This is explained by a lack of the carriers generated in GGR under such values of λ, and there always exists an intense diffusion current that flows towards the interface and exceeds the current directed towards the illuminated surface even for large values of s_0 (Such an effect was considered in [9]). For slightly shorter values of λ, the anomalous PME is realized because of the above-considered causes. Finally, far from IAE, PME always possesses normal sign, thus confirming our preliminary conclusions. Moreover, the straightening of band-gaps leads, due to an augmentation of s_0, to a sharp increasing of the anomalous component of PME that was observed in the experiment as well.

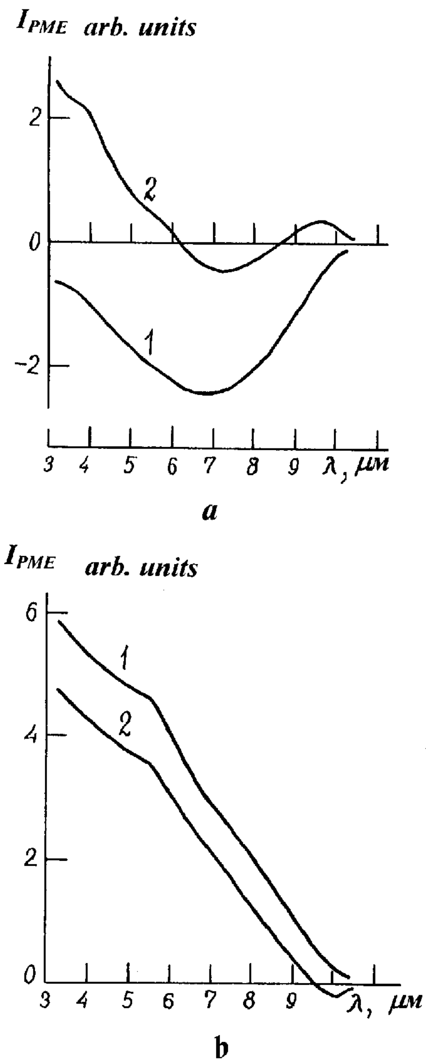

Fig. 3. The same as in Fig. 2, but for 25-μm-thick p-CMT

When an electronic material was illuminated through the interface, an "image" was observed that also agrees with the above-described model: a weak anomalous PME is manifested near IAE, but it practically disappears after being subjected to UV irradiation. Because of this,

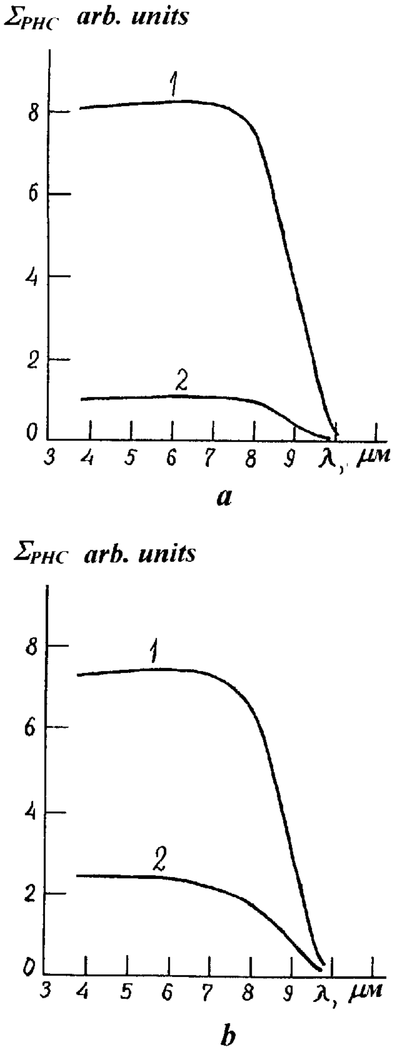

Fig. 4. Spectral dependences of photoconductivity in n-CMT EL (the same sample and conditions as in Fig. 2)

it can be connected, certainly, with the above-described drift movement of holes in the SCR.

In a p-type material irradiated from the free-surface side, the anomalous PME, as the model predicts, is realized in the EL of n-type material. Instead, under the through-interface irradiation, a weak anomaly is observed near IAE that is caused by a diffusion stream in the SCR and emerges only after the UV straightening of the energy bands.

For comparison, in Fig. 4, the spectral dependences of photoconductivity in a n-type EL are shown. As is seen, the UV straightening of bands leads to the essential reduction of photoconductivity because of boosting the surface recombination rate in accordance with expression (6). However, as is seen from the presented curves, the photoconductivity, as being a function of the recombination parameters of surface and bulk of the EL, is a less sensitive characteristic of structural inhomogeneities of the layer, in particular, as to the presence of the SCR. Therefore, these are the spectral characteristics of PME that allow obtaining, through their investigation, a more detailed information on the structure and properties of CMT ELs.

So, the analysis of PME in CMT ELs of n- and p-type of conductivity shows that the diffusion currents of excessive minority carriers in the quasi-neutral region, on the one hand, and their diffusion currents in the carriers-non-generating parts of the SCR, on the other one, can flow in opposite directions. As a result, under a domination of the latter currents, the J_{PME} current's sign may alter to the negative one, and the anomalous photoelectromagnetic effect is manifested. Dependences of this phenomenon on the excitation radiation frequency, Y_s value, and the direction of irradiation (from the free surface or through the substrate) are analyzed. The results obtained on base of this model are in good agreement with experimental data. These can be employed for determination of the EL parameters.

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ФОТОЕЛЕКТРОМАГНІТНИЙ ЕФЕКТ В ЕПІТАКСІЙНИХ ШАРАХ $\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$

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Резюме

Побудовано узагальнену модель фотоелектромагнітного ефекту (ФМЕ) в епітаксійних шарах (ЕШ) з урахуванням як області просторового заряду (ОПЗ) поблизу вільної поверхні, так і наявності області варизонності (ОВЗ) на межі з підкладкою. Показано, що дифузійні струми неосновних надлишкових носіїв, з одного боку, та їхні дрейфові струми в ОПЗ та ОВЗ — з іншого, можуть мати різний напрямок. За домінування останніх знак струму $J_{\text{ФМЕ}}$ може змінитися на протилежний, в результаті чого спостерігатиметься явище аномального ФМЕ. Проаналізовано залежність цього явища від частоти збуджуючого випромінювання, від величини вигину зон Y_s та від способу освітлення (з боку вільної поверхні, чи з боку підкладки). Результати розгляду моделі добре узгоджуються з даними експерименту, отриманими на ЕШ $\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$ ($x \approx 0.20$). Отже, їх можна буде застосовувати для визначення параметрів ЕШ.