PHYSICAL SCIENCES

THE INFLUENCE OF SURFACE RECOMBINATION VELOCITY ON THE EXCLUSION OF MINORITY CHARGE CARRIERS IN CDXHG1-XTE MONOCRYSTALS

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Abstract

This study experimentally investigates the effect of surface recombination velocity on the parameters of photoconductors based on CdxHg1-xTe with $0.18 \leq X \leq 0.30$ under conditions of carrier extraction due to a longitudinal electric field. The analysis of the obtained experimental results established that for samples with a ground surface, the specific detectivity D*λmax is almost independent of U_bias, whereas for samples with a polished surface, D*λmax decreases with increasing U_bias. It was determined that the surface recombination velocity significantly affects the exclusion effect and its mechanism in CdxHg1-xTe monocrystals.

The obtained dependencies indicate a significant influence of surface recombination on the parameters of photodetectors operating in the mode of minority carrier extraction in CdxHg1-xTe-based devices.

Keywords: recombination, exclusion, minority carriers, voltage sensitivity, specific detectivity, bias voltage.

Introduction

One of the specific non-uniform electronic phenomena in semiconductors is the exclusion of minority charge carriers. The physical essence of this effect is as follows. In semiconductors, minority charge carriers play a significant role in conductivity. If the externally applied electric field to the sample is sufficiently high, specifically when the condition $L/\mu E \leq \tau$ is met (where L is the sample length, E is the electric field intensity, and μ is the mobility of minority charge carriers), the minority charge carriers are extracted from the sample through the contacts during the transit time $t\_tr = L/\mu E$, leading to a decrease in conductivity.

There have been relatively few studies on the exclusion effect in various semiconductors to date [1-5]. However, prior to our research, information on this phenomenon in CdxHg1-xTe was almost nonexistent, despite the fact that CdxHg1-xTe monocrystals, due to the significantly high mobility of minority charge carriers (electrons), could be among the most suitable materials for studying this effect.

Theoretical Section

Semiconductor solid solutions with a variable bandgap width attract the attention of physicists and engineers worldwide as promising materials for semiconductor optoelectronics and as interesting objects for fundamental research in solid-state physics.

One of the unique representatives of this class of semiconductors is the material CdxHg1-xTe, whose bandgap width increases from -0.3 eV to 1.6 eV as x (the CdTe content in the solid solution) increases from zero to one. Today, CdxHg1-xTe monocrystals have already found widespread application in various fields of technology, primarily in the production of infrared radiation detectors operating over a wide spectral range based on intrinsic photoconductivity. The results obtained from a comprehensive study of the electronic properties of CdxHg1-xTe with different compositions and the influence of various external factors on them are valuable not only from a practical standpoint but also for understanding the mechanisms of physical phenomena in this material, discovering new properties, and identifying its unique characteristics. These studies may also help resolve many controversial issues in the physics of complex semiconductor compounds. Based on the results obtained, there is a possibility of developing fundamentally new devices and improving the parameters and characteristics of existing ones.

In strong pulling electric fields, the transit time of excess minority charge carriers (t_tr) through the sample may become shorter than their lifetime in the studied material. Under such conditions, these carriers can be extracted from the sample by the field before they have time to recombine. As a result, a nonuniform charge carrier distribution is established along the sample.

To clarify the mechanism of this process, let us consider a p-type semiconductor sample in the form of a parallelepiped with length L and cross-sectional area S (Figure 1a). Assume that the generation of non-equilibrium charge carriers by light occurs uniformly throughout the entire volume of the sample, the carrier concentration varies only in one direction parallel to the

excitation surface, and the electric field E is directed along the "x" axis. Then, in the case of a low excitation level, i.e., when $\Delta\sigma << \sigma_0$ (where $\Delta\sigma$ is the photoconductivity and σ_0 is the dark conductivity), the expression for the photocurrent at any point in the sample can be written as follows [1,5]:

$$\Delta J = \frac{e(1+b)\mu_P ES}{L}\int_O^\infty \Delta n(x)\,dx \qquad (1)$$

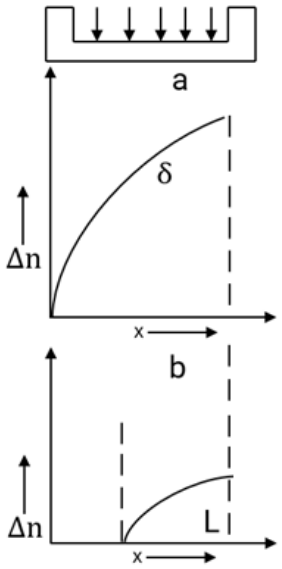

Figure 1. *Sample schematic (a) and distribution of nonequilibrium charge carrier concentration along the sample in a strong electric field (b and c).* ***(b)*** *At the initial moment* ***(c)*** *After a time interval Δt following illumination*

Where **Δn(x)** represents the concentration of excess minority charge carriers in the studied sample.

The distribution of the minority carrier concentration **Δn(x)** in general form is determined by solving the continuity equation.

$$\frac{d\Delta n}{dt} = g_s - \frac{\Delta n}{\tau} + \mu_0 E\frac{\nu\Delta n}{\nu x} + Д_a\frac{\nu^2\Delta n}{\nu x^2} \qquad (2)$$

where **g_s** is the carrier generation rate per unit time, **τ** is the carrier lifetime, **D_a** is the ambipolar diffusion coefficient, and $\mu_a = \frac{(p-n)\mu_n\mu_p}{n\mu_n+p\mu_p}$ is the ambipolar drift mobility, which characterizes the drift velocity of the induced perturbation.

First, we determine the charge carrier distribution **Δn(x)** along the sample length under steady-state conditions. In the case of a sufficiently strong electric field (where diffusion effects can be neglected), equation (2) can be rewritten as:

$$\frac{d\Delta n}{dx} = \frac{g_s}{\mu_a E} - \frac{\Delta n}{\mu_a E\tau} \qquad (3)$$

The solution of this equation under the boundary condition **Δn(0) = 0** has the following form:

$$\Delta n(x) = g_s\tau\left[1 - exp\left(-\frac{x}{\mu_a E\tau}\right)\right] \qquad (4)$$

If expression (4) for **Δn(x)** is substituted into equation (3) and integrated, we obtain:

$$\Delta J_a = e(1+b)\frac{\mu_P\tau}{L}E\eta\Phi_s\{1 - \frac{\mu_a E\tau}{L}\left[1 - exp\left(-\frac{x}{\mu_a E\tau}\right)\right]\} \qquad (5)$$

where **η** is the quantum yield of the internal coefficient, and Φ_s is the photon flux of the signal. The resulting formula is: $g_s = \frac{\eta\Phi_s}{SL}$.

Formula (5) defines the stationary photocurrent in a semiconductor under exclusion conditions.

In the case of weak fields, when $\mu_0 E\tau << L$, expression (5) simplifies to:

$$\Delta J_{см} = \eta\Phi_s e(1+b)\frac{\mu_P\tau}{L^2}И_{ст} \qquad (6)$$

Where = **E** · **L** is the voltage applied to the sample.

The distribution of minority carriers **Δn** after a time interval **t** following the cessation of excitation is shown in Figure 1(b).

As can be seen from equation (6), in this case, the stationary photocurrent increases proportionally to the applied bias voltage and depends on the carrier lifetime.

In the other limiting case, when the field is strong, i.e., $E >> L/\mu_a\tau$, the transit time of charge carriers (**t_tr**) becomes shorter than their lifetime (flight mode). The stationary photocurrent reaches saturation and does not depend on the bias voltage [6]. Under the condition $\mu_a E\tau >> L$, from equation (5) we obtain:

$$\Delta J_{max} = \frac{1}{2}\eta\Phi_s e(1+b)\frac{\mu_P}{\mu_a} \qquad (7)$$

The dependence of the stationary photocurrent on the bias voltage, plotted based on expression (5), is shown in Figure 2. Thus, the photocurrent increases proportionally to the applied voltage at low biases and, at sufficiently strong electric fields, reaches saturation, which is determined by formula (7).

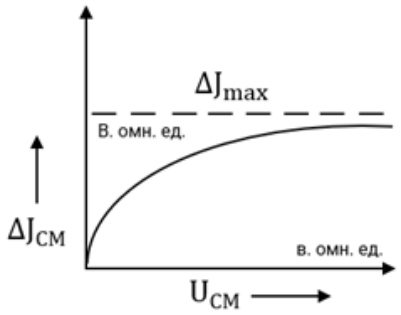

Figure 2. *Dependence of the stationary photocurrent on the bias voltage.*

This operating mode of the sample is called the flight mode. The bias voltage **U₀**, at which the flight mode occurs, can be conditionally defined as the bias at which the length of the bipolar drift equals the distance between the electrodes. From there, we have:

$$И_0 = L^2/ \mu_a\tau \quad (8)$$

Now, let us consider the dynamic characteristics of the semiconductor sample. To determine the transient photocurrent from equation (1), it is necessary to know the distribution **Δn(x, t)**, which takes the following form (considering the recombination of charge carriers) [7-10]:

$$\Delta n(x,t) = \begin{cases} 0, 0 \le x \le x_1 \\ g_s\tau\left[1 - exp\left(-\frac{x-x_1}{\mu_a E\tau}\right)\exp(-\frac{t}{\tau})\right], x_1 < x < L \end{cases} \quad (9)$$

Where $x_1 = \mu_a E\tau$ is the distance by which the charge carrier is pulled away from the negative contact.

The total photocurrent decay time under exclusion conditions is determined by the transit time in weak fields (when $\mu_a E\tau << L$). In this case, equation (9) takes the form:

$$\Delta J(t) = \eta\Phi_s e(1+b)\frac{\mu_a\tau}{L^2}И_{ст}\exp\left(-\frac{t}{\tau}\right) = \Delta J_{см}\exp\left(-\frac{t}{\tau}\right)$$

In this case, the relaxation of the photocurrent is determined solely by the recombination of charge carriers and follows an exponential decay law.

In the other limiting case of a strong field (in the flight mode), the photocurrent relaxation is influenced by different factors.

$$\Delta J(t) = f(x) = \begin{cases} \frac{1}{2}\eta\Phi_s e(1+b)\frac{\mu_n}{\mu_a}(1-\frac{\mu_n E}{L}t)^2, 0 \le t \le \frac{L}{\mu_a E} \\ 0, t \ge \frac{L}{\mu_a E} \end{cases} \quad (10)$$

In the flight mode, the transit time $t_{пр}=L^2/\mu_a E$,, as mentioned earlier, determines the total decay time of the photocurrent. This allows for estimating the ambipolar drift mobility μ_a based on the measured value of $t_{пр}$. As shown by the corresponding calculations, the photocurrent curves are symmetric with respect to the decay curves.

It should be noted that the expressions derived above for the transient photocurrent (9) and (10) describe the relaxation process when the sample is excited by a long rectangular excitation pulse, i.e., it is assumed that the duration **Δt** of the light pulse is much greater than the time required to reach the steady-state photoresponse. In this case, during the action of the light pulse, a certain distribution of the concentration of minority carriers is established in the semiconductor, as described by equation (4).

Now, let's briefly consider the processes when the sample is excited by a short radiation pulse (**Δt << τ**). In this case, the concentration of nonequilibrium carriers does not have time to change significantly during the light pulse. In weak fields (when $\mu_a E\tau << L$), the concentration of nonequilibrium carriers decreases due to their recombination according to the law:

$$\Delta n = \Delta n0 \exp(-t/\tau)$$

In this case, both **Δn** and **Δn₀** do not depend on **x**. Then, from equation (10) for the transient photocurrent, we obtain:

$$\Delta J(t) = \frac{e(1+b)\mu_P ES}{L}\int_0^L \Delta n\, e^{-t/\tau}\, dx = \delta I_{max} e^{-t/\tau} \quad (11)$$

The photocurrent, as in the case of long rectangular pulses, decays according to an exponential law. In the case of strong fields (in the flight mode, i.e., when **t_tr < τ**), the photoresponse time becomes equal to the transit time:

$$\tau_0 = t_{пр} = L^2 / \mu_a \cdot U_{sm}$$

Neglecting the decrease of **Δn** due to recombination, we obtain the following expression for the transient photocurrent:

$$\Delta J(t) = \frac{e(1+b)\mu_P S}{L}\int_{x_1(t)}^{L}\Delta n\,(x)dx \quad (12)$$

The lower limit of integration **$x_1(t)$** represents the distance by which the charge carrier is pulled away from the negative contact.

$$X_1(t) = \mu_n E t = \mu_n t / L \cdot U_{sm}$$

By performing the integration in equation (12), we obtain:

$$\Delta J(t) = \frac{e(1+b)}{L^2}\mu_P S \cdot И_{ст}\,\Delta n_0[L - x_1(t)]$$

или

$$\Delta J(t) = \delta I_{max}(1 - \frac{\mu_a \cdot И_{ст}}{L^2}t) \quad (13)$$

где

$$\delta I_{max} = \frac{e(1+b)\mu_a \Delta n_0 S}{L^2} \cdot И_{ст} \quad (14)$$

From equations (13) and (14), it follows that in the case of short light pulses, i.e., when $\Delta t < \tau_0$, the decay of the photocurrent in the flight mode follows a linear law, and the amplitude of the photocurrent I_max does not reach saturation or offset. However, with an increase in the bias voltage, τ_0 decreases, violating the above condition, leading to saturation of the photocurrent amplitude.

Experimental Part

In previous measurements, it was assumed that the generation of nonequilibrium charge carriers in the studied samples is homogeneous, and that they do not recombine at the surface, i.e., the role of generation-recombination processes of charge carriers at the crystal edges could be neglected, and the influence of the sample's transverse dimensions was not considered.

However, our studies, as well as those by other authors, show that this assumption is not correct. In real samples, the generation of minority nonequilibrium carriers is inhomogeneous, and recombination at the surfaces cannot be neglected. These effects can significantly alter photodetector parameters, such as voltage sensitivity and detectivity under exclusion conditions. Since the mode of extracting nonequilibrium charge carriers provides the maximum value of the photomultiplier coefficient, it is of interest to conduct a detailed study of the influence of surface recombination rates on the parameters of photodetectors operating in this mode.

To this end, we experimentally investigated the impact of surface recombination rates on the parameters of photodetectors made of $CdxHg_{1-x}Te$ with $0.18 \leq x \leq 0.30$ under conditions of charge carrier extraction by a longitudinal electric field. To achieve different surface recombination rates, the surfaces of the studied photodetectors were subjected to various types of processing. We investigated samples whose surfaces were subjected to mechanical polishing with fine-grained powder, diamond paste polishing, and mechanical processing followed by chemical etching. In the first two cases, the samples were then rinsed only in a boiling HCl_4 solution, and induced current contacts were applied to them.

It should be noted that in the samples subjected to different surface treatments, the surface recombination rate varied within the range of 10^5 – 10^2 cm/s. After each operation, the photoelectric parameters of the fabricated photodetectors were measured.

Experimental results obtained during the study of relative spectral characteristics of the studied photodetectors (Figure 3 for x = 0.19 and x = 0.30) after three types of surface treatment showed that, unlike the conventional photoresistive mode (where additional peaks were observed in the wavelength range corresponding to surface absorption), in the extraction mode, the photo-sensitivity in the short-wavelength region of the spectrum stabilizes. That is, at high electric field values, the "peaks" in the short-wavelength region of the spectrum seem to be absent. The photo-sensitivity increases at high **E** compared to the values at low **E**.

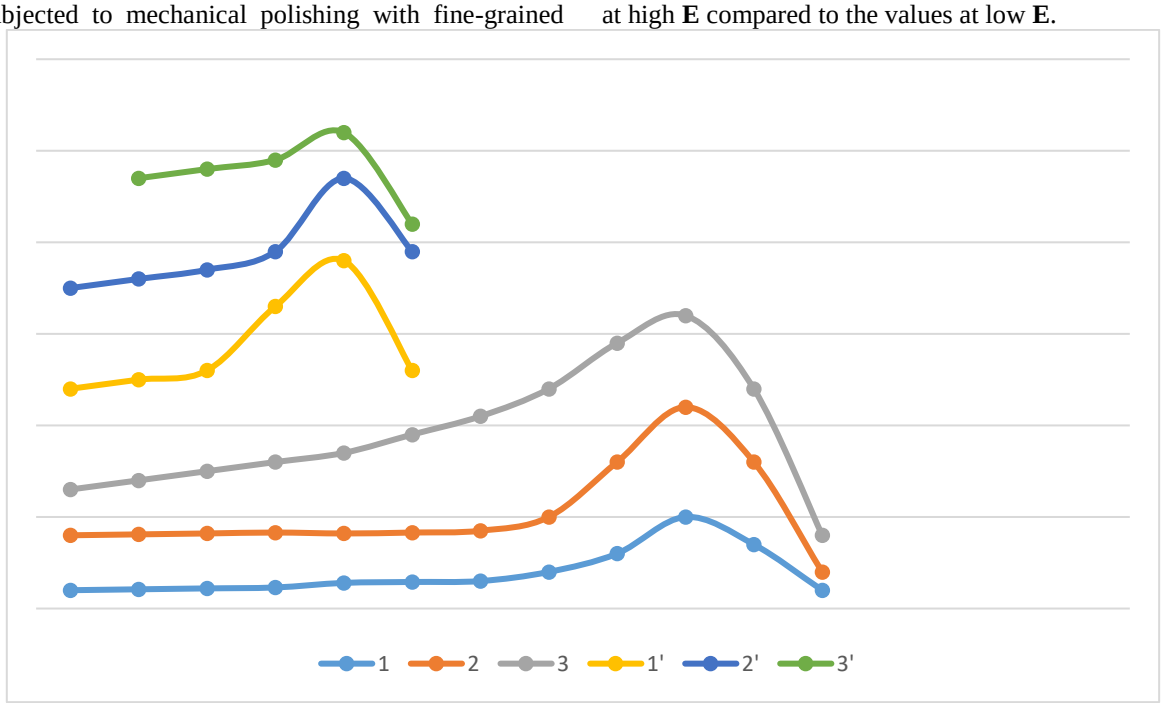

Figure 3. *Spectral dependence of the photosensitivity of P-$CdxHg_{1-x}Te$ samples with* ***x = 0.19*** *and* ***x = 0.30*** *under exclusion conditions.*
1 – after grinding, 2 – after polishing, 3 – after etching. T = 80 K, $U_{sm} \geq 3.0$ *V.*

It should be noted that the increase in photosensitivity with the field strength does not follow a linear law.

In the setup based on an ABS (absolute black body) at **T = 300 K**, the dependence of the photocurrent signal U_s on the type of surface treatment of the samples was studied. The results showed that with an increase in $\mathbf{U_{sm}}$, the photocurrent signal initially (at low $\mathbf{U_{sm}}$) increases linearly, and then (at higher $\mathbf{U_{sm}}$) reaches saturation. It was found that the bias voltage corresponding to the beginning of the saturation region of the photocurrent signal differs in samples subjected to different surface treatments, even under otherwise identical conditions [11, 12, 13].

These obtained dependencies again demonstrate the significant impact of surface recombination on the parameters of photodetectors operating in the mode of extracting minority charge carriers based on $Cd_xHg_{1-x}Te$.

The joint study of the dependencies of the photocurrent signal and noise in photodetectors on the type of surface treatment of the semiconductor allowed us to determine key parameters such as voltage sensitivity and specific detectivity. In order to investigate the impact of these factors on the inertia of the photodetector, measurements were conducted on samples with various surface treatments (Figures 4 and 5).

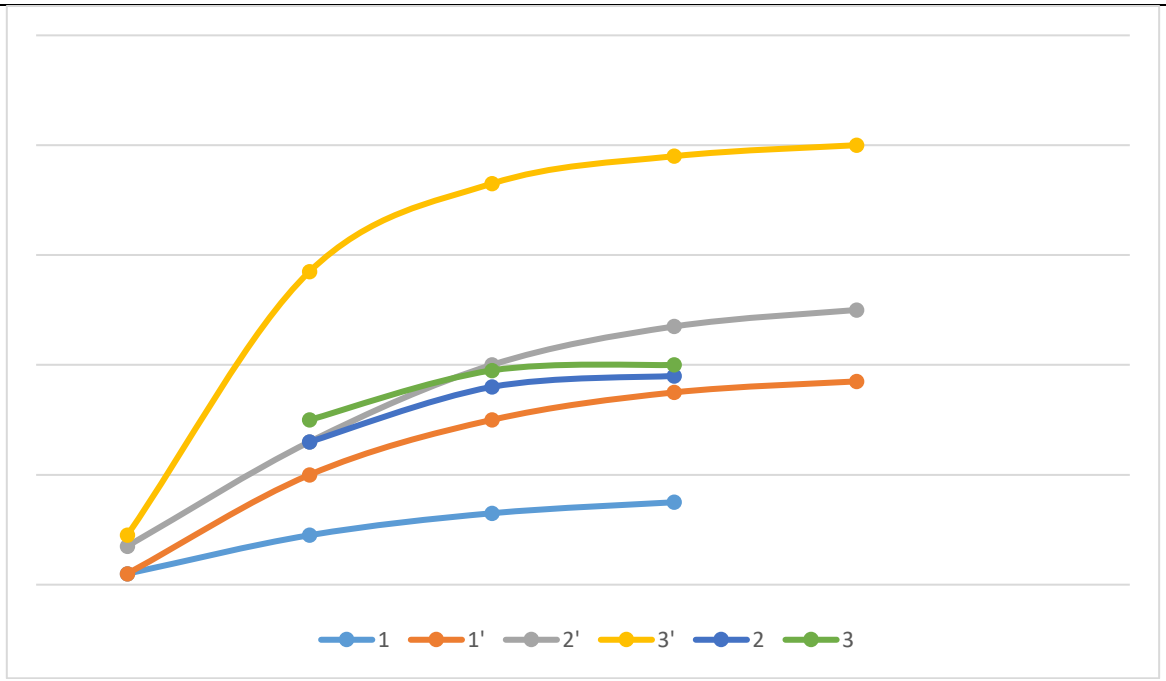

Figure 4. *Dependence of $S_{\lambda max}$ U_{sm} in P-$Cd_xHg_{1-x}Te$ crystals with* ***x = 0.19*** *(curves 1-3) and* ***x = 0.25*** *(curves 1'-3') after grinding (curves 1, 1'), polishing (curves 2, 2'), and etching (curves 3, 3') of the surface.*

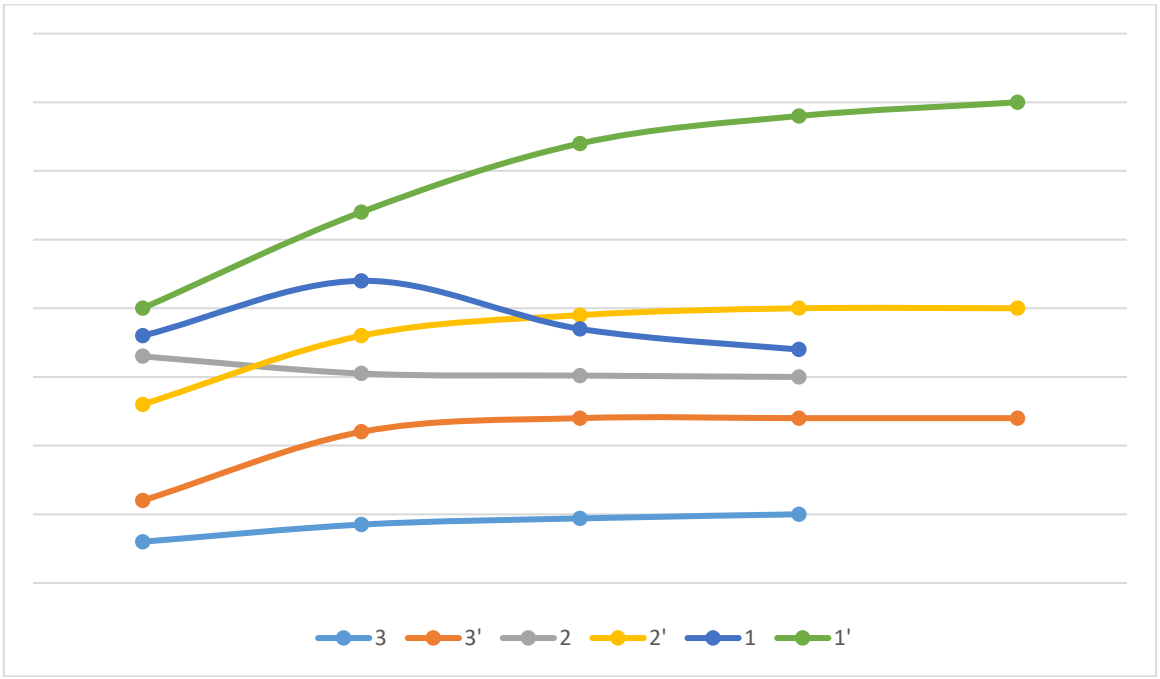

Figure 5. *Dependence of* ***Δλ_max*** *on* ***U_sm*** *in P-CdxHg$_{1-x}$Te crystals with* ***x = 0.19*** *(curves 1-3) and* ***x = 0.25*** *(curves 1'-3') after grinding (curves 1, 1'), polishing (curves 2, 2'), and etching (curves 3, 3') of the surface.* ***T = 80 K.***

Analysis of the experimental results revealed that for samples with a ground surface, $Д_{\lambda max}$ almost does not depend on U_{sm}, while for samples with a polished surface, $Д^*_{\lambda max}$ decreases with increasing U_{sm}. For samples with an etched surface, the $Д^*_{\lambda max}$ (U_{sm}) dependence behaves similarly to the $U_s(U_{sм})$ dependence – initially, with an increase in the bias voltage, $Д^*_{\lambda max}$ decreases, and then it reaches saturation. This behavior can be explained by the fact that for samples with ground and polished surfaces, with increasing bias voltage in the range **U_sm = 0.05 – 0.15 V**, the noise increases sharply. After further increasing $U_{sм}$, the noise level passes through a minimum and then grows again. For samples with an etched surface, a slow increase in noise was observed with increasing bias voltage.

To explain the experimental results obtained in this article, let's consider the continuity equation for the total disturbance **Δn + Δp** in the two-dimensional case, which, according to [13], is expressed as:

$$\mu_a E \frac{d\Delta n(x,y)}{dx} = P_a \frac{d^2\Delta n(x,y)}{dy^2} - \frac{\Delta n(x,y)}{\tau} + g_ф S(y) \quad (15)$$

The boundary conditions for this are:

$$j(x,0) = -S\Delta n(x,0);\ j(x,t) = S\Delta n(x,t);$$
$$\Delta n(0,y) = 0 \quad (16)$$

The first two equations correspond to the usual boundary conditions for surface recombination velocity

S [14], and the third corresponds to the ohmic contact. The solution of equation (15) with the boundary conditions (16) can be analytically solved for **S = 0** and **S =** ∞. In the latter case, the boundary conditions (16) take the form:

$\Delta n(x,0) = 0;$

$\Delta n(x,t) = 0;$

$\Delta n(0,y) = 0.$

The total number of nonequilibrium electron-hole pairs (Δn) in the sample in this case is equal to [13]:

$$\Delta n = \frac{4\eta K_\lambda \Phi \tau W}{t}(k^{-K_\lambda t} + 1)\left\{\sum_{h=0}^{\infty} \frac{1}{K_\lambda^2 + [\frac{n(2n+1)}{t}]^2}\left[\frac{L}{1+Д_a\tau[\frac{n(2n+1)}{t}]^2} + \frac{\exp\left(-\frac{L}{\mu_a E\tau}\right)}{1+Д_a\tau[\frac{n(2n+1)}{t}]^2}\right]\frac{\frac{Д_a}{\mu_a E}[\frac{n(2n+1)}{t}]^2 L - \frac{1}{\mu_a E\tau}}{1+Д_a\tau[\frac{n(2n+1)}{t}]^2}\right\}$$

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