

Evolution of the time and spatial photoresponse instabilities of the sensors based on CdZnTe crystals

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By comparing the $I(t)-dI/dt$ diagrams, wavelet-spectrograms of kinetics $I(t)$ and coordinate dependences $I(y)$ of photocurrent, the features of time and spatial photoresponses of CdZnTe crystals are revealed and studied. It is shown that switching of the sensor from the steady state to unsteady one is accompanied by the photoresponse signal energy redistribution from high to low frequencies and a gradual transition of the instability process to the larger scale levels.

Путем сопоставления диаграмм $I(t)-dI/dt$, вейвлет-спектрограмм кинетики $I(t)$ и зависимостей фототока от координаты $I(y)$ выявлены и исследованы особенности временного и пространственного фотооткликов кристаллов CdZnTe. Показано, что переключение сенсора из устойчивого состояния в неустойчивое сопровождается перераспределением энергии сигнала фотоотклика с высоких частот на низкие и постепенным переходом процесса неустойчивости на более крупные масштабные уровни.

The variety of structural inhomogeneities (SI) arising in piezoelectric CdZnTe crystals under substantially non-equilibrium conditions of their manufacture gives rise to inhomogeneous interdependent elastic and electric fields. Their reconfiguration caused by external and internal factors (power fields, irradiation, residual stress relaxation, radiation, temperature changes, etc.) defines the evolving "structure" of the sensor response. The character of such evolution is determined from irreversible changes in the crystals physical properties, and their origination is hardly visible, being manifested itself as the initiation of local instabilities, spectral and other artifacts [1–4]. The reversible or irreversible changes in the crystal characteristics causes transformations in the informative content of their response which we have managed to find by studying the local spectral instability via the wavelet-analysis [5]. Automation and computerizing of researches by increasing

the sampling rate and application of modern signal processing methods allow to transform physical problems into informational ones. This opens fundamentally new possibilities to reveal the origin of the crystal instability development and to study them, that was the main purpose of this work.

The photocurrent kinetics $I(t)$ under dotting-pulse photoexcitation and dependence of the stationary photocurrent I on the monochromatic optical probe coordinate y were studied for $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ ($x = 0.1$ to 0.2) crystals grown by vertical crystallization from the melt under various conditions and containing a variety of two-dimensional structural defects [6]. Gold or indium-gallium contacts were deposited onto the opposite largest faces of the samples having resistivity $\rho \sim 10^{10} \div 10^{11}$ Ohm-cm and shaped as rectangular parallelepipeds $5 \times 5 \times 2$ mm³. The monochromatic optical pulse repetition frequency was varied in the range

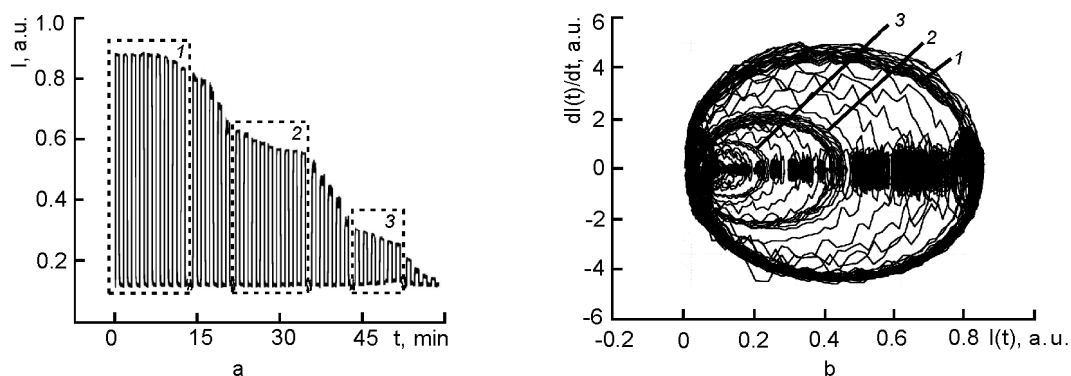


Fig. 1. The photocurrent kinetics $I(t)$ at the area-integral photoexcitation of a $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ crystal (a) and the $I(t)$ - dI/dt diagram (b) based thereon. Attractors: (a) 1 - 298–310 K; 2 - 348–356 K; 3 - 384–390 K; $\lambda = 880$ nm, $E = 10^8$ V/cm.

0.01÷1 Hz. Thus, the pulse repetition duty factor n was 2÷20. The photocurrent kinetics $I(t)$ for the samples under dotting-pulsed photoexcitation was measured in the field of $10\div 10^3$ V/cm strength using an electrometric transformer based on an AD795 operational amplifier. The signal was digitized and the data obtained were processed by computer using the wavelet-analysis in the Matlab software package. The energy distribution in the crystal response signal was estimated by the frequency dependence $A^2(f)$ of the squared wavelet-coefficient amplitude. The structural inhomogeneities were revealed using the photo-electric method by measuring the $I(y)$ dependences at the sample automated movement at a constant speed from 0.5 to 10 mm/min with respect to the 50–100 μm wide optical probe. The crystals were photoexcited by the optical probe from the 850÷910 nm wavelength range using the semiconductor and laser light emitting diodes as well as a halogen lamp with a set of infrared interference light filters. At the integral photoexcitation, the optical beam diameter was 1 to 10 nm at $0.1\div 10$ mW/cm² radiation power density. During the experiment, the time dependences of photoresponse $I(t)$ and its change rate in time $dI(t)/dt$ were measured under the sample photoexcitation by the probe or in integral mode. Therefore, it was found to be possible to describe the photoinduced state of the sensor electronic subsystem at every instant t by the pair of the measured $I(t)$, $dI(t)/dt$ values and thus to represent it graphically as a point in the phase plane $\{I(t), dI(t)/dt\}$ [7]. The curve formed in the phase plane by the $\{I(t_i), dI(t_i)/dt\}$ points corresponding to consecu-

tive time moments t_i corresponds the phase trajectory with a configuration representing integratively the photoresponse. The power of the photoinduced state subset arising under excitation of the crystal by an optical pulse is equal to the area enclosed in the phase trajectory. Thus, the sets of the $I(t)$ - dI/dt phase diagrams obtained under the simultaneous dotting-pulsed photoexcitation and monotonous heating or cooling make it possible to study the steady (attractors) and unsteady photocurrent cycles of the industrial photodetectors [8]. The heating and cooling of the samples was carried out at a constant rate in the 293÷450 K temperature range during 10 to 120 min.

Our studies have shown that unsteady electronic processes originate in the local regions and modulate the integral sensor response by forming its informative structure [9]. In contrast, addition of an external dotting modulating field promotes the development or elimination of local instability, depending on the field polarity. The instability manifests itself explicitly only under certain excitation pulse repetition frequencies and duty factors [9]. That is, the response instability exhibits features of a process with a variable informative structure [10]. To reveal and study the structure, cyclic measurements are required. Therefore, the photocurrent kinetics stability was studied in the cyclic mode followed by its transformation into a set of $I(t)$ - dI/dt diagrams [4], which are essentially signatures and represent the sequence of the crystal dynamic states.

Indeed, the $I(t)$ - dI/dt diagrams constructed basing on the crystal photocurrent kinetics (Fig. 1a, b), not only allow to separate the sequence of the states resulting in the pho-

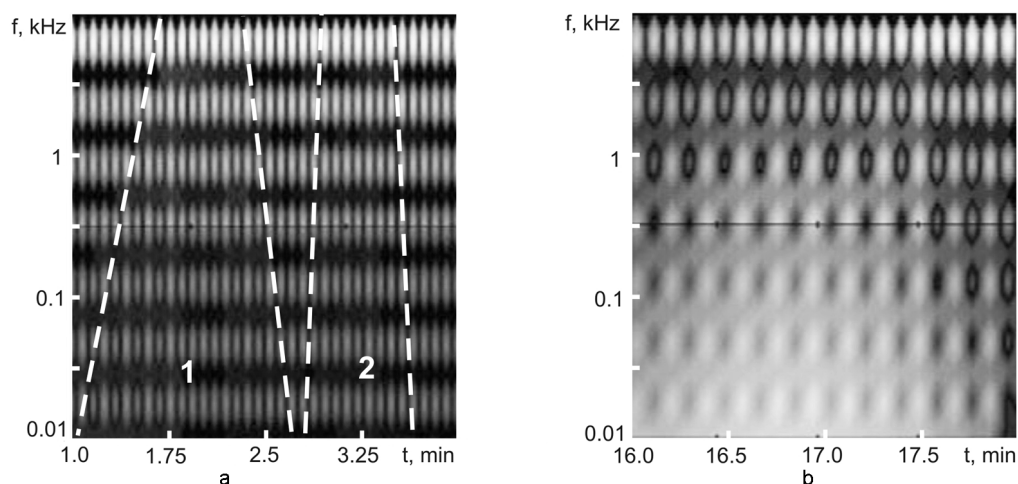


Fig. 2. Wavelet-spectrograms of the photocurrent kinetics $I(t)$ for a $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ crystal; $\lambda = 880$ nm, $E = 10^3$ V/cm. Photoresponse state: *a*, steady; *b*, unsteady.

toresponse instability, but also represents finer individual features of the informative structure transformation. It is established that the sets of limit cycles being attractors correspond to the steady photoresponse states in the $I(t)$ - dI/dt diagrams. This is experimentally confirmed by following facts: (a) certain temperature intervals ΔT where the photoresponse amplitude is essentially invariable correspond to such sets of limit cycles; (b) at the constant photoexcitation intensity, a monotonous temperature photocurrent quenching is observed in the temperature ranges corresponding to the attractors; (c) the bias field strength E increase by a factor of 2 to 3 does not result in any loss of the limit cycle stability.

The process of photoresponse transition from the steady states to unsteady ones has a pronounced stepwise character and is accompanied by changes in the $I(t)$ - dI/dt signature shapes, where the smooth phase trajectories are transformed into a sequence of similar, but nonuniformly scaled bow-shaped sections. This fact as well as another one (all the revealed photoresponse features manifest themselves only under periodic pulse photoexcitation) indicate the origination of the self organized electron processes in the crystal. Similarly to numerous processes in nature, the self-organization runs according to a certain algorithm naturally formed at growth, similar to those defining the function of computer programs [11]. Thus, the character of the self-organization dynamics integratively manifests itself in change of the response signature shapes and areas, and its finest features, in alteration of informative structure. The consideration

of the photoresponse informative content makes it possible to study qualitatively the character of the sensor switching from the steady to unsteady state and to reveal the competition between the fast and slow photoresponse constituents.

In this connection, of the most interest was the detailed analysis of origination and development processes of the photoresponse instability using the wavelet-transformation of the photoresponse kinetics. Fig. 2 shows the wavelet-spectrograms of the photoresponse kinetics corresponding to the attractor and unsteady states obtained using the Haar wavelet for one of the studied samples. The set of the localized spectral constituents (Fig. 2a), with amplitudes (and thus brightness) decreasing at the frequency reduction are seen clearly. The number of such constituents for the wavelet-spectrogram of the unsteady photocurrent kinetics is 1.5 times less, that is related to limited time frame of the response stability process quenching (Fig. 2b). The wavelet is scaled smoothly at increasing scale factors, that made it possible to analyze the changes of informative structure of time-and-frequency signal image at high spectral resolution. Thus, the power reduction of the certain wavelet-coefficient subsets was revealed at some frequencies and its increasing at other ones. So in the frequency range 10 to 750 Hz and the time intervals 1 to 2 min and 3 to 3.5 min (Fig. 2a, 1 and 2 regions), the amplitudes of some spectral constituents in the crystal response was observed accompanied by simultaneous increase thereof in neighboring frequency ranges. Such alteration of the time-and-frequency structure

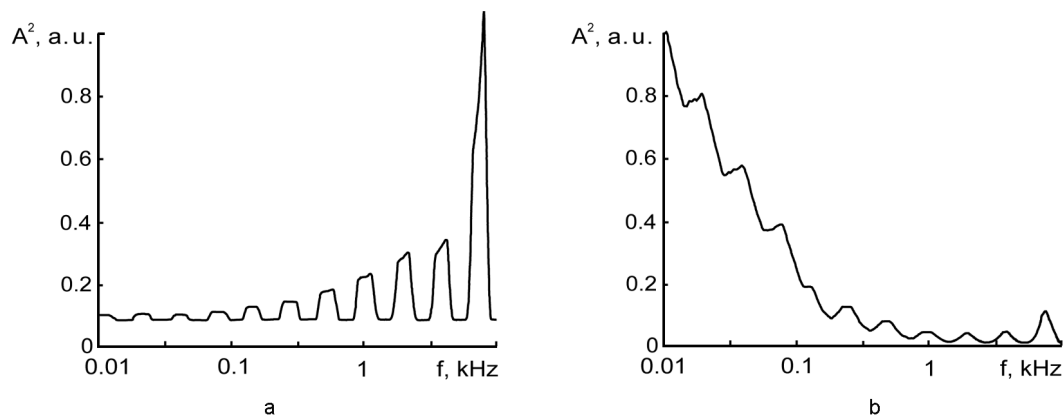


Fig. 3. Frequency distribution of the photoresponse signal energy.

image can be considered as the onset of the unsteady state formation, i.e. as the origination of the instability nuclei the evolution of which involves other scale levels. The limit cycles in the $I(t)-dI/dt$ diagram are the sequence of the bow-shaped sections being transited smoothly in each other, which include the set of the photoinductive states. Therefore, the photoresponse under such conditions is stable as a whole, and the influence of the instability nuclei thereon is insignificant. This is testified also by the discrete character of the signal energy distribution and its localization mainly at high frequencies (Fig. 3a).

As is seen in Fig. 3b, the process of photoresponse stability quenching is accompanied not only by destruction of attractors but also by transformation of the signal energy distribution from discrete to continuous one, which is besides redistributed toward low frequencies. Indeed, the greatest amplitudes have now the low-frequency constituents in the 10 to 500 Hz interval, as is indicated by the highest values of wavelet-coefficients (Fig. 2b). Thus, the character of the cycle type change in the $I(t)-dI/dt$ diagrams evidences the nonlinear crystal response. This is confirmed by (a) coverage of different phase plane regions by the trajectories; (b) fast deviation of the phase trajectories from attractor; (c) elements of chaotic behavior of trajectories at the limit cycle destruction. The outcome of phase trajectories beyond the attractor bounds for some samples testifies on the one hand that the crystal as the study object is a nonlinear dynamic system capable of the response steady state restoration by means of self-organization of the structure of interconnections, and on the other hand, points

to the local instability transition to integral one.

That is why of a particular interest was to determine the spatial coordinates of those SI sets, which are the nuclei of the photocurrent kinetics instability. However, even cyclic studies of the photocurrent dependences on the monochromatic optical probe co-ordinate $I(y)$ at high signal sampling rate and the probe position accuracy at the crystal did not provide their precise localization. Only for a small group of crystals, the $I(y)$ dependences obtained using multiple scanning, it was possible to reveal the poorly reproducible extremes and local fluctuations of the photocurrent generated by the non-uniformly scaled aggregates of structural inhomogeneities. This is confirmed by studies of spatial photocurrent in variable dotting-pulsed [9] and harmonic [12] fields.

For the majority of studied CdZnTe crystals, the unsteady states of spatial photocurrent are more hidden. The assumption that the origination and development processes of the instability states are manifested equally both in the character of photoresponse kinetics $I(t)$ and in its spatial character $I(y)$ is confirmed by the comparison of the wavelet-transformation results of the $I(t)$ and $I(y)$ dependences obtained in the same conditions. A characteristic feature of the crystal steady spatial response (Fig. 4) consists in the decomposition of the wavelet-spectrograms into a sequence of the overlapping subsets of coefficients (and, accordingly, frequencies), with distinguished spatial co-ordinates of each. Of a particular interest are those coefficients subsets (Fig. 4, 1 and 2 regions) having the areas in the informative space of wavelet-coefficients increasing most quickly even at the 3 to 5 K

temperature rise or the 5 to 10 V/cm field strength increase, that points to the transition of the instability process from one scale levels to another. At the same time, the coefficient subsets overlapping is observed in the wavelet-spectrograms of $I(t)$ and $I(y)$ dependences, that seems to be the cause of the development character similarity for the spatial and time photoresponse instabilities. Indeed, a further increase of temperature or field strength results in still greater increase of the areas covering the wavelet-coefficient subsets. When those become practically fully merged, the spatial photoresponse becomes unsteady. The revealed alteration of the wavelet-spectrograms is observed in ranges of 0.4 to 0.7 kHz (Fig. 4, region 1) and 0.3 to 0.9 kHz (Fig. 4, region 2), which correspond to the origination frequencies of the photocurrent $I(t)$ kinetics instability.

It should be noted that the possibility to reveal the co-ordinates of regions being functionally the nuclei of instability is no doubt of a practical importance. On the one hand, this provides an efficient selection of crystalline boule cuts to manufacture the detectors and spectrometers already at early technological stages and, on the other one, indicates the high potential of the selective electro-acoustic processing method [13] based on the local "healing" of the crystal instability sources.

Thus, the increase of the photoresponse signal sampling rate and its wavelet-analysis provide the reveal of the changes of time-and-frequency image setting conditions for transformation of informative structure during the instability nuclei activation in CdZnTe crystals. Comparing the wavelet-spectrograms representing photocurrent kinetics $I(t)$ and its co-ordinate $I(y)$ dependence in the informative space of the wavelet-coefficients, the overlapping of the coefficient subsets has been revealed that points to correlation between the local and integral instabilities. It is shown that a further development of the instability is accompanied by the signal energy redistribution from high to low frequencies and its gradual transition to larger scale levels. The time-and-frequency ranges of the instability process origination determined from the wavelet-spectrograms make it possible to

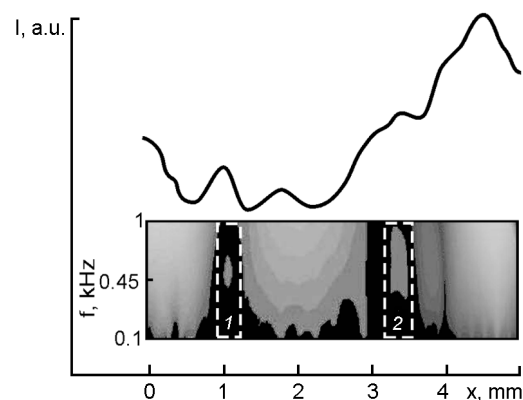


Fig. 4. The $I = f(y)$ dependence for a $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ crystal and its wavelet-spectrogram; $\lambda = 880$ nm, $T = 298$ K, $E = 10^3$ V/cm.

optimize the conditions of the electro-acoustic processing [13] and to forecast the character of photoresponse change in extreme conditions.

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Розвиток часової та просторової нестійкостей фотовідклику сенсорів на основі кристалів CdZnTe

А.В.Бут, В.П.Мигаль, О.С.Фомін

Шляхом співставлення діаграм $I(t)-dI/dt$, вейвлет-спектрограм кінетики $I(t)$ та залежностей $I(y)$ виявлено та досліджено особливості часового і просторового фотовідклику кристалів CdZnTe. Показано, що перемикання сенсора зі стійкого стану у нестійкий супроводжується перерозподілом енергії сигналу фотовідклику з високих частот на низькі та поступовим переходом процесу нестійкості на більш великі масштабні рівні.