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ELECTRONIC AND OPTICAL PROPERTIES OF SEMICONDUCTORS

Photocurrent Spectra in Parametrical Form and their Discrete Wavelet Decomposition for CdZnTe Alloys

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Abstract—It is shown that the photocurrent spectrum $I(\lambda)$ of the $Cd_{1-x}Zn_xTe$ ($x = 0.1$–0.2) alloys can be transformed into individual subsets of the approximation C_a and detailing C_d coefficients by means of the discrete wavelet decomposition, and the distribution of these coefficients is very sensitive to the local photoresponse perturbations at different scale levels. The representation of these subsets in the form of parametrical wavelet signatures $C_d = f(C_a)$ made it possible to pass from the information wavelet coefficient space to the dynamic space of photoinduced states. The analysis of the modifications of the $C_d = f(C_a)$ configurations and areas, which they cover at each scale level of the measurements of the cyclic photocurrent spectrum, made it possible to reveal the latent reversible and irreversible local changes in them.

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1. INTRODUCTION

The substantially nonequilibrium conditions of growth of large-size boule crystals of the II–VI group result in the occurrence of a variety of structure defects of various types and scales and also in their natural self-organization [1]. The consequence of it is a number of interrelated problems (stability, steadiness, memory, etc.) of the sensors based on CdZnTe crystals, and also spectral and other artifacts, which manifest themselves, as a rule, under a certain combination of external and internal factors or under extreme conditions. They indicate that a crystal as an object of investigation is a nonlinear dynamic system for which stability of characteristics as well as the reversibility and reproducibility of properties and parameters prove to be unsolved problems. Under conventional conditions of investigation, the individual features of such processes as transport, or accumulation and recombination of nonequilibrium charge carriers manifest themselves in fine, sometimes imperceptible changes in various parameters and characteristics of crystals. In this case, their revealing and analysis are very difficult and ambiguous. In particular, the analysis of spectral dependences of the photocurrent $I = f(\lambda)$ gives no possibility of revealing fine local features of the characteristics under investigation. On the other hand, the automation and computerization of investigations made it possible to transform the photocurrent spectra $I = f(\lambda)$ of CdZnTe into the $I(\lambda) - dI/d\lambda$ diagrams, which represent the spectra in the parametrical form [2]. They display reasonably well the individual features of the photocurrent spectrum of crystals related to the defect formation during the growth, technological processing, or due to the photoactive history. In this case, an increase in the frequency of the signal sampling by an order of magnitude or more made it possible to carry out the wavelet analysis of the photocurrent spectra of CdZnTe crystals, in order to reveal the multiscale nature of the photoresponse, and to obtain qualitatively new information, the unambiguous physical interpretation of which, however, is complicated [3]. It, in turn, made it impossible to solve the interrelated problems of optimization of the crystal growth, their post-crystallization treatments, stability of characteristics under extreme conditions, and the revealing of statistically significant reversible and irreversible modifications of properties of II–VI crystals. We see the possibility of solving them in the further development of the information approach to the investigation of functional materials based on revealing and analyzing more fine features of photocurrent spectra, the resolution of which is possible by means of the discrete wavelet transform, which was precisely the main purpose of this study.

2. SAMPLES AND INVESTIGATION METHODS

The $Cd_{1-x}Zn_xTe$ ($x = 0.1$–0.2) crystals grown from melt under various conditions by the modified vertical Bridgman method [4] were investigated. The resistivity of the samples under investigation shaped as rectangular parallelepipeds with the sizes of 5 × 5 × 2 and 11 × 11 × 2 mm was within $\rho \approx 10^{10}$–10^{11} Ω cm. We deposited gold contacts on the opposite of the largest sides of the samples. The photocurrent spectra $I = f(\lambda)$ of crystals were cyclically measured in the wavelengths range

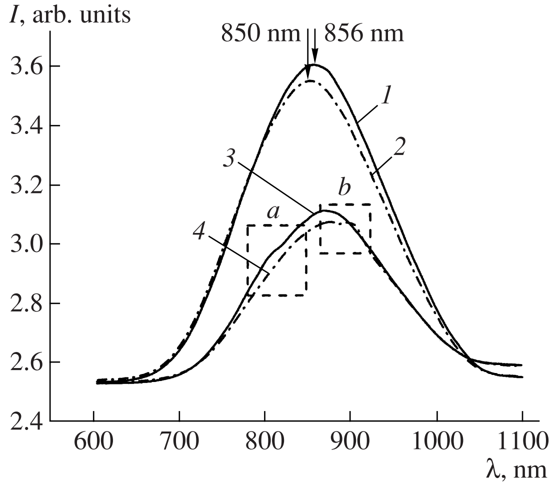

Fig. 1. Spectral dependences $I = f(\lambda)$ of the photocurrent for the samples of the first and second group for the first and tenth scans; see curves *1*, *2*, and *3*, *4*, respectively.

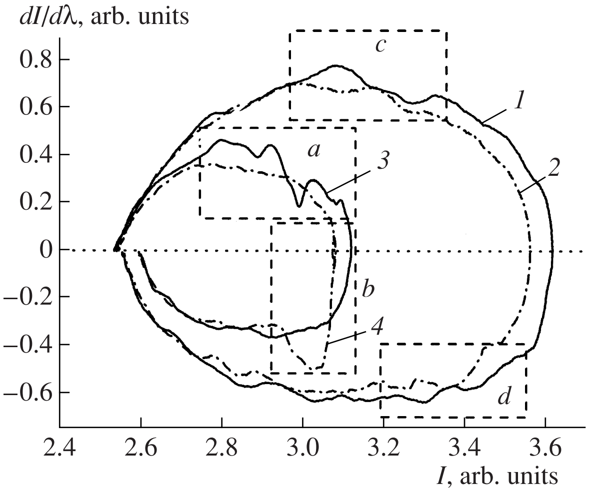

Fig. 2. Photocurrent spectra $I = f(\lambda)$ for the samples of the first and second group in the parametrical form $I(\lambda) - dI/d\lambda$ for the first and tenth scans; see curves *1*, *2*, and *3*, *4*, respectively.

of 600–1100 nm in the field with a strength of 10–2 × 10^2 V/cm using the electrometric transformer based on an AD795 operational amplifier (Analog Devices). The signal was digitized with the sampling frequency of 10^3–10^5 Hz by the commercial system of data collection ADVANTECH PCI-1711L with further processing by a personal computer. Various structural defects in type and scale were revealed by etching, infrared, optical polarization microscopy, and by the modified shadow method [4].

For revealing reversible and irreversible changes in the photoelectric properties and individual features of the photocurrent spectra for all CdZnTe crystals under investigation, 8–12 cycles of measurements under identical conditions proved to be sufficient

3. RESULTS AND DISCUSSION

According to the character of individual modifications of the photocurrent spectra, all samples were conditionally divided into two groups. For the samples of the first group, a decrease in the photocurrent value, which was accomplished through 8–10 cycles of measurements, was observed after each scan of the spectrum. No shape modifications in the spectrum $I = f(\lambda)$ with increasing the intensity of the bias electric field in samples of this group were revealed. However, for a number of samples, the multiple scanning of the spectrum under identical conditions was accompanied by an insignificant shift of the photocurrent peak to shorter wavelengths. As a rule, it is less than 3–6 nm (Fig. 1; curves *1*, *2*) and, obviously, is related to a decrease in the contribution of a highly lagging photocurrent component from cycle to cycle. It indicates a decrease in the shift with increasing the time of the spectrum scan, and also the full restoration of photocurrent spectral characteristics after the long (more than 12 h) stay of samples in darkness. We note that samples of this group proved to be mostly structurally perfect and optically homogeneous.

The prominent feature of the $I = f(\lambda)$ spectra of the samples of the second group is their gradual and sometimes steplike reconstruction (Fig. 1, areas *a* and *b*). For example, in certain wavelength ranges, the gradual disappearance of some local perturbations in PC spectra (Fig. 1a, curve *3*, area *a*) and the occurrence of others (Fig. 1, curve *4*, area *b*) was revealed. In this case, the residual conductivity, which relaxed within 5–30 min, appeared after each cycle of measurements.

In addition, the following properties are characteristic of the samples of the second group: (*a*) dependence of the $I = f(\lambda)$ spectra shape on scanning time and intensity of the bias field; (*b*) the individual number of measurement cycles necessary for accomplishing the reconstruction of the spectrum; and (*c*) an incomplete reconstruction of photocurrent spectral dependences after the long (more than 12 h) stay in darkness. All this indicates that there is the simultaneous effect of the set of various factors and processes (the composition fluctuations, the reconstruction of elastic and electric fields generated by defects in a piezoelectric crystal, the charge exchange of complicated photosensitivity centers, the photopolarization processes, etc.) instead of only their relation to the defects of various types and scales. This interpretation is, in particular, supported by both the photocurrent spectra $I(\lambda) - dI/d\lambda$ in the parametrical form containing the individual sequences of arched portions with various curvatures (Fig. 2), and the character of their modification during the cyclic measurements in the spectrum. In fact, a decrease in the number of arched portions in the $I(\lambda) - dI/d\lambda$ diagrams in the area which they cover, is indicative of the gradual completion of the spectrum-reconstruction processes and the establishment of steadier crystal characteristics.

For all samples, the $I(\lambda) - dI/d\lambda$ diagrams represent the individual graphic images of the photocurrent spectra in the space of photoinduced states. In essence, they are parametrical signatures, which integratively represent the variety of the interrelated photoinduced states. Therefore, for revealing the individual features of the $I(\lambda) - dI/d\lambda$ signatures, various techniques of the signature analysis, the application of which in various fields of the science and engineering extends [5], are suitable.

For the $I(\lambda) - dI/d\lambda$ parametrical signatures of the photocurrent spectra for the samples of the first group (Fig. 1; curves *1*, *2*), the arched portions with small curvature, whose number varies only slightly from cycle to cycle, are characteristic. A relatively small decrease in the signature area is also observed within the existing limits to which the shift of certain arched portions (Fig. 2, areas *c* and *d*) is related. At the same time, the considerable modification of the configuration of the $I(\lambda) - dI/d\lambda$ signatures (Fig. 2, areas *a* and *b*) from cycle to cycle is characteristic of the samples of the second group (Fig. 1, curves *3* and *4*). It manifests itself as a decrease in the number of arched portions and their curvature, as well as the occurrence of new portions, which exceed the bounds of the previous $I(\lambda) - dI/d\lambda$ signature. The character of modifications of the photocurrent spectrum indicates that the photoresponse of CdZnTe alloys has not only a rough but also a finer structure. We used the discrete transform of the photocurrent-spectrum wavelet on the Haar-wavelet basis, the elements of which are well located, and the mobile frequency–time window enables us to “scan” the signal simultaneously in frequency and time regions [3, 6].

In fact, transforming the signal under investigation with the use of a set of digital filters with the characteristic variable pulse, we can carry out the spectral analysis of local perturbations of the photoresponse signal with retaining the high resolution both in wavelength (scan time) and in scale (frequency) [6]. In this case, each scale level of the wavelet decomposition of the photocurrent spectrum is correspondingly characterized by individual subsets of approximation coefficients C_a and detailing coefficients C_d.

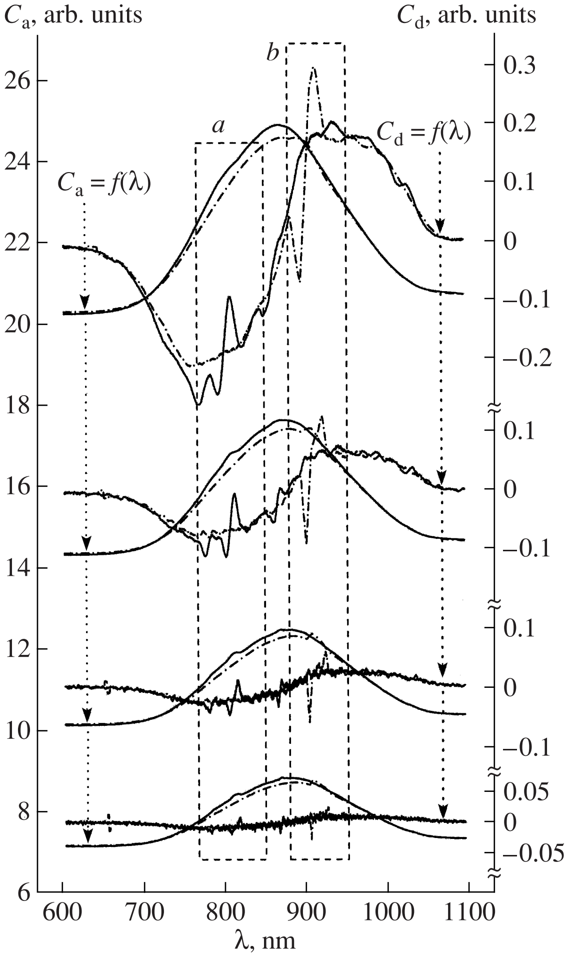

Fig. 3. Dependences of the coefficients C_a and C_d on the photoexcitation wavelength λ at the first four levels of the wavelet decomposition of photocurrent spectra for the sample of the second group. The level number *i* increases from below upwards.

The decomposition of the photocurrent spectra under investigation over various scale levels into approximation coefficients C_a with the help of the discrete Haar wavelet transform is similar to their numerical integration with various steps. At the same time, the decomposition into detailing coefficients C_d is similar to their differentiation (Fig. 3). It is well seen in the dependences C_a and C_d on wavelength λ at four levels of the wavelet decomposition of photocurrent spectra in the areas *a* and *b* (Fig. 3), that the local perturbations are transformed with an increase in the decomposition level. It enables us to reveal and qualitatively analyze the changes in the response components at each scale level. For the passage to quantitative characteristics, the algorithm of the parametrical representation of PC spectra in the form of nonuniformly scaled sets of C_a and C_d; i.e., $C_d = f(C_a)$(Fig. 4), was developed. The $C_d = f(C_a)$ diagrams represent the sequences of arched portions of various curvatures, which cover certain areas. The similarity of the $C_d = f(C_a)$ diagrams at the fourth level of decomposition (Fig. 4) and the $I(\lambda) - dI/d\lambda$ diagrams (Fig. 2) enables us to consider them as the wavelet signature of the photocurrent spectra. Their configuration for the samples of the first group does not vary at cyclic measurements, and the covered area is reconstructed at all levels of decomposition after the stay of samples in darkness; i.e., the modifications of characteristics at all scale levels are reversible.

For the samples of the second group, the reconstruction of the signature configuration both at each scale level and when passing from one level to another is

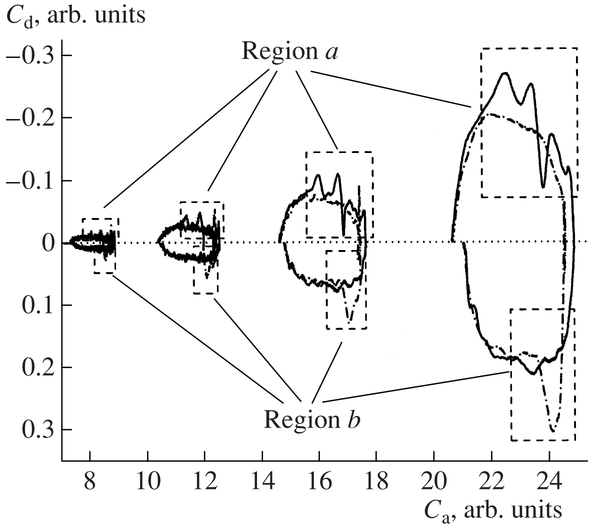

Fig. 4. Wavelet signatures $C_d = f(C_a)$ of the photocurrent spectra for the sample of the second group at the first four decomposition levels in the Haar-wavelet basis. The level number i increases from left to right.

characteristic. With increasing the decomposition level i, the curvature and length of arched portions (Fig. 4, areas *a* and *b*) change as well as the signatures area S_i (see table). Because the area of signatures can be considered as the power of subsets of photoinduced states [7], it is possible to assert that the irreversible changes, which can be estimated and interpreted within the context of different models, take place in the samples of the second group.

For example, from the analysis of the ratio S_i/S_{i-1} between the areas (see table) of the neighboring wavelet signatures, it is seen that there is a redistribution of powers of photoinduced states between various scale levels, which, obviously, just causes the irreversible changes in properties during the cyclic measurements. It confirms the similar changes in the wavelet signatures after the thermal and acoustic treatments.

Ratio between the wavelet-signature areas at the four decomposition levels

Ratio between the wavelet-signature areas	Decomposition level i	Value of S_i/S_{i-1}
First scanning cycle	2	3.8
	3	3.92
	4	3.948
Tenth scanning cycle	2	3.629
	3	3.828
	4	3.878

We note that it is possible to transform the wavelet signatures into not only spectral but also temporal, spatial, and other crystal characteristics and, thus, to carry out their comparative analysis by comparing the configurations and the ratios of areas. In addition, not only the subset of photoinduced states, but also the operations with them and their ratios enable us to carry out the comparative quantitative analysis of irreversible changes in the photoelectric properties of crystals during treatment or operation.

4. CONCLUSIONS

The use of the discrete wavelet transform of photocurrent spectra and their subsequent transformation into the wavelet signatures enable us to pass to individual subsets of approximating C_a and detailing C_d coefficients, whose configuration “is sensitive” to local perturbations of the photocurrent spectra at various scale levels. In this case, the physical problems become informative [8]. Indeed, the crystal as the object of investigation is a complicated dynamic system for which it is equally important for both dynamic (i.e., reasonably rough) and informative (i.e., finer) features of its behavior at an external action [3, 8–10]. The representation of subsets of the wavelet coefficients C_a and C_d as the parametrical wavelet signatures $C_d = f(C_a)$ (Fig. 4), which are characterized by an individual configuration, an area, and other parameters at each scale level, are similar to the parametrical signatures of the PC spectrum (Fig. 2).

Thus, for the first time, we show the possibility of the realization of “inverse transition” from the information space of wavelet coefficients to the dynamic space of photoinduced states. The power of subsets of these states, the operations with them and their ratios make it possible to analyze the changes in spectral and other characteristics of the crystal during the processing within the framework of various physical models. In particular, the proposed technique was successfully adapted to the temperature, dielectric, coordinate, and other characteristics of the photoresponse, which is the subject of the next study.

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REFERENCES

1. Yu. D. Tret’yakov, N. N. Oleinikov, E. A. Gudilin, A. A. Vertgel, and A. N. Baranov, Neorg. Mater. **30**, 29 (1994).
2. V. K. Komar’, V. P. Migal’, S. V. Sulima, and A. S. Fomin, Fiz. Tekh. Poluprovodn. **40**, 133 (2006) [Semiconductors **40**, 128 (2006)].

3. V. P. Migal' and A. S. Fomin, Pis'ma Zh. Tekh. Fiz. **32** (11), 44 (2006) [Tech. Phys. Lett. **32**, 484 (2006)].
4. V. Komar, A. Gektin, D. Nalivaiko, I. Klimenko, V. Mygal, O. Panchuk, and A. Rybka, Nucl. Instrum. Meth. Phys. Res. **458** (1–2), 113 (2001).
5. S. Bergmann, J. Ihmels, and N. Barkai, Phys. Rev. E **67**, 031902 (2003).
6. I. N. Dremin, O. V. Ivanov, and V. A, Nechitailo, Usp. Fiz. Nauk **171**, 465 (2001) [Phys. Usp. **44**, 447 (2001)].
7. V. P, Migal'. Fiz. Tekh. Poluprovodn. **35**, 1188 (2001) [Semiconductors **35**, 1135 (2001)].
8. B. B. Kadomtsev, Usp. Fiz. Nauk **169**, 507 (1999) [Phys. Usp. **42**, 435 (1999)].
9. V. P. Migal' and A. S. Fomin, Neorg. Mater. **43**, 1316 (2007).
10. V. P. Migal', and A. S. Fomin, Fiz. Tekh. Poluprovodn. **40**, 408 (2006) [Semiconductors **40**, 403 (2006)].

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