

SURFACES, INTERFACES, AND THIN FILMS

Effect of Surface Scattering of Carriers in the Photoconductivity Spectra of CdS

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Abstract—The effect caused by electron scattering at a semiconductor surface is revealed in the low-temperature (77 K) photoconductivity spectra of second-group CdS crystals subjected to the influence of an external enriching transverse electric field.

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1. INTRODUCTION

In [1–4], the influence of a transverse electric field (TEF), or an external electric field applied to a semiconductor by the field-effect method (on the field-effect method, see, e.g., [5]), on the low-temperature ($T = 77$ K) edge photoconductivity (PC) spectra of CdS crystals is studied. It is shown that the effect of an external TEF on a semiconductor surface leads to characteristic quantitative and qualitative changes in these spectra, which are caused by the dependence of the surface recombination rate and, consequently, the lifetime of nonequilibrium carriers near the semiconductor surface on the near-surface bending of electron bands. The authors of [6] revealed the “anomalous” character of variations in the edge PC spectra in the depletion TEF associated with the screening effects of electron–hole interaction in the surface layer with a cadmium excess of the technological origin [7, 8].

In this publication, we report data on anomalous variations with increasing external enriching TEF in the edge PC spectra of some CdS crystals. We assume their relation to the scattering of nonequilibrium electrons by the semiconductor surface during their motion in the near-surface potential well formed by the external TEF. Preliminary results of these studies were reported in [9].

2. EXPERIMENTAL METHODS AND TECHNIQUE

We studied the influence of a TEF on the spectra of the low-temperature ($T = 77$ K) PC of second-group

CdS crystals.¹ The crystals used in the experiments were single-crystal CdS wafers several tens microns thick whose hexagonal axis C lies in the plane of the sample surface grown from the gas phase by Frerichs’ method, as well as by the resublimation method in an inert-gas flow. The samples under investigation were mounted into a field-effect capacitor with an original design as one of the plates. The other (field or controlling) capacitor plate was a thin, almost transparent, conductive layer of tin dioxide (SnO_2). As an insulator, a mica (muscovite) film with a thickness of ≤ 10 μm was used in the field-effect capacitor. Electric contacts to the samples were formed by the deposition of an indium–gallium paste onto their surface. The voltage to the field plate of the field-effect capacitor U_T was varied using a high-stability constant voltage source with a controllable output voltage in the range 0–2500 V. The magnitude of the drawing (measuring) voltage U_M did not exceed 50 V as a rule. The sample was photoexcited by continuous illumination of the field-plate side of the field-effect capacitor. The PC spectra were detected with a spectral resolution no worse than 8 Å in the $\mathbf{E} \perp \mathbf{C}$, $\mathbf{k} \perp \mathbf{C}$ geometry (\mathbf{E} and \mathbf{k}

¹ Here and below, we follow the commonly accepted classification [10, 11] of semiconductor crystals and their PC spectra by the type of observable in the PC spectra fine structure (FS), caused by excitons. According to such a spectroscopic classification of the first-type (second-type) FS (lines of exciton absorption correspond to the maxima (minima) of the photocurrent) determines the first type (second type) of the PC spectrum; in this case, the first-type (second-type) FS in the spectrum of the steady-state excitation of PC measured at $T = 77$ indicates that the crystal belongs to the first (second) group.

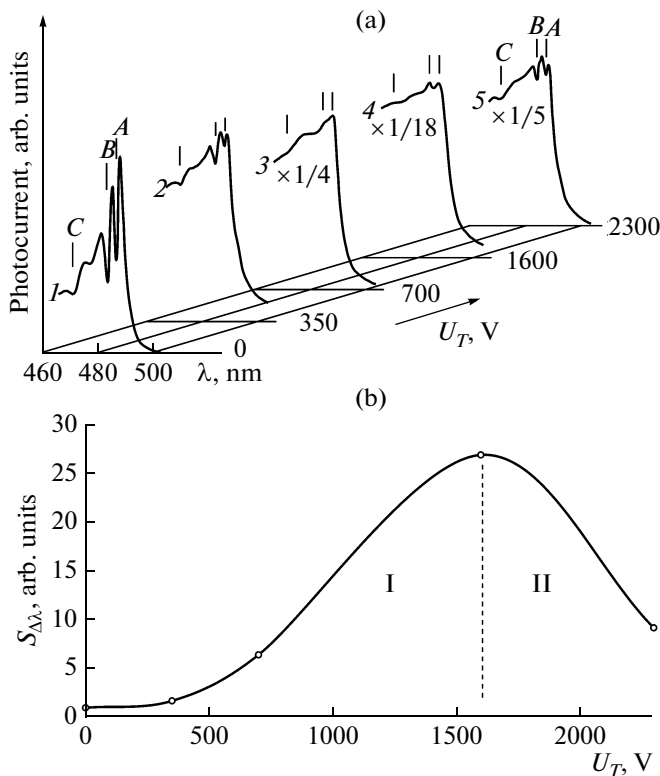


Fig. 1. (a) Photoconductivity spectra of the BK-95 CdS crystal sample at various enriching voltages U_T to the field plate of the field-effect capacitor. $T = 77$ K, $\mathbf{E} \perp \mathbf{C}$, and $\mathbf{k} \perp \mathbf{C}$. A, B, and C are the structure conditioned by excitons. (b) Dependence of the integrated photosensitivity $S_{\Delta\lambda}$ of the sample on the enriching voltage.

are the electric and wave vectors of the wave of light) using an experimental setup based on an MDR-3 monochromator. The detecting part of the experimental setup involved a V7-30 or a U5-9 electrometric amplifier and a KSP-4 recording potentiometer.

3. EXPERIMENTAL RESULTS

The edge PC spectra of the second-group crystal sample (see curve 1) at $T = 77$ K for various positive values of U_T (values of U_T are noted to the right of the λ scales) are shown in Fig. 1a. Figure 1b represents the dependence of the integrated photosensitivity (PS) $S_{\Delta\lambda}$ on U_T for the same sample, obtained via calculation of the areas under the spectral curves presented in Fig. 1a (enumeration is performed allowing for the scale multipliers of the curves, multiplier $\times 1$ of curves 1 and 2 is omitted).

It is seen from Fig. 1a that, as the enriching TEF increases, a spectrally nonuniform increase in the sample PS occurs with prevalence of the effect in the exciton photocurrent minima and, as a consequence, the spectral PC curve gradually loses its structure (curves 2, 3), and then the first-type FS appears in it

(curve 4). A further increase in the enriching TEF causes a PS drop over the spectrum again with the prevalence of the effect in the region of exciton resonances, which leads as a result to the inverse transformation of the FS of the PC spectrum into the second type (curve 5).

Thus, in the studied samples of second-group CdS crystals, an increase in the enriching TEF leads during the first stage to the transformation of the second-type spectral PC curve into that of the first type (curves 1–4 in Fig. 1a) and to a rise in the integrated PS (portion I of the curve in Fig. 1b), and during the second stage it leads to the transformation of the first-type type PC curve into that of the second type (curves 4, 5 in Fig. 1a) and to a drop in the integrated PS (portion II of the curve in Fig. 1b). To complete the picture, let us note that the effect of the enriching TEF under study led to an increase in the dark conductivity of the sample. As the enriching TEF is increased, the dark conductivity initially increases and then decreases, and the dark-conductivity drop correlated with that of the integrated PS of the semiconductor in this case.

4. DISCUSSION OF EXPERIMENTAL RESULTS

Let us discuss the obtained results.

It is known (see, e.g., [12, 13]) that the characteristic feature of semiconductor crystals is the presence of a near-surface layer of space charge, which screens the semiconductor bulk against field penetration. This layer is formed by a charge localized at the surface states. The role of the electric field of this layer in the formation of the PC spectral curves of CdS crystals at low temperatures was studied in [1–4] using the field-effect method [5, 12]. It is shown that band bending, which emerges in the nonuniform near-surface electric field of the space-charge layer, can determine the type of spectral curve of low-temperature PC of the semiconductor due to its influence on the surface recombination rate and, consequently, on the carrier lifetime near the surface. The depletion (enriching) bending of electron bands near the surface leads to a shortening (an increase) of the free-carrier lifetime on the surface relative to its value in the semiconductor bulk and, as a consequence, to the formation of the second-type (first-type) PC spectral curve. It follows that the effect of an increased-magnitude enriching (depletion) TEF on the semiconductor surface can lead to an increase (drop) in the PS and transformation of the second-type (first-type) PC spectral curve into that of the first-type (second-type). This has been fully confirmed experimentally [1–4] through studying the influence of the external TEF on the magnitude and spectral distribution of the low-temperature edge PC of CdS. This allowed the authors of [4] to consider the variations in the near-surface band bending as the main factor determining the observed variety of PC spectral curves for CdS and to draw a conclusion as to the decisive role of the near-surface bending of

electron bands in the formation of the edge PC spectrum of a semiconductor due to its influence on the electron lifetime near the surface.

This conclusion does not contradict variations in $S_{\Delta\lambda}$ and the PC spectral curves of the second-group CdS crystals that we studied, which are observed in the first stage of the effect of the enriching TEF (Fig. 1b, portion I of the curve and Fig. 1a, curves 1–4). However, the variations in $S_{\Delta\lambda}$ and the PC spectral curves for these crystals in the second stage of the effect of the enriching TEF (Fig. 1b, portion II of the curve; Fig. 1a, curves 4, 5) do not fit into the framework of notions on the formation of the edge PC spectra of CdS developed in [4], according to which, variations in the integrated PS and FS of the PC spectrum of a semiconductor under the effect of TEF are determined by the variation in the near-surface band bending and by the variation in the electron lifetime near the surface caused by it. In other words, from the viewpoint of these notions, the effects of decreasing the PS and transformation of the PC spectral curve of the first type into the second type with increasing enriching TEF are anomalous. Let us discuss the nature of these anomalies.

We assume that these anomalies are caused by the scattering of nonequilibrium electrons at the semiconductor surface, which leads to a decrease in their effective mobility [5, 14, 15].

Indeed, in unipolar semiconductors of the CdS type, PC $\Delta\sigma$ is proportional to the product of electron mobility μ_n by their lifetime τ_n : $\Delta\sigma \propto \mu_n \tau_n$ (see, e.g., [16]). By virtue of the large light absorption coefficients in CdS in the region of exciton and interband transitions ($\sim 10^5 \text{ cm}^{-1}$ [17]), photocarriers are generated in the thin surface layer of the semiconductor with a thickness of about 10^{-5} cm . The special role of this layer and values of the parameters μ_n and τ_n in it in the formation of the edge PC spectrum of the semiconductor should be noted. By varying μ_n and τ_n in this layer via the external effect, we can radically vary the spectral distribution of the edge PC [1–4, 6, 17, 18].

The external TEF greatly affects parameter τ_n in the surface layer and, consequently, the edge PC spectrum. According to the aforesaid (see also [1–4, 6, 11]), the effect on the surface of the second-group CdS crystal by the increasing enriching TEF leads to transformation of the depletion band bending near the surface into the enriching type and to an increase in τ_n near the surface to values exceeding those of the bulk. As a result, the PS of the semiconductor crystal increases, while its spectral PC curve transforms from the second-type curve into that of the first type (Fig. 1b, portion I of the curve; Fig. 1a, curves 1–4). With a further increase in the enriching TEF, a potential well with a width comparable with the free electron path length emerges near the semiconductor surface. As a result, additional electron scattering at the surface appears, which leads to a decrease in the electron

mobility and, correspondingly, to a drop in the integrated PS of the semiconductor and a change in the type of its PC spectral curve from the first type to the second (Fig. 1b, portion II of the curve; Fig. 1a, curves 4, 5). We note that the change of type of the PC spectral curve is caused by the large absorption-coefficient values at resonant exciton excitation frequencies, which greatly (by a factor of several times!) exceed its values at nonresonant frequencies in the vicinity of the absorption edge [17], as a result of which, the carriers created through the exciton states are scattered most strongly.

These results indicate that, in the region of large enriching near-surface band bending, the drop in μ_n due to surface scattering (rather than an increase in τ_n due to the suppression of recombination processes on the surface [4]) can become the determining factor in the formation of the PC spectral curve of the semiconductor.

A significant drop in the dark conductivity in the region of positive values of U_T close to the values determined by the electric strength of the dielectric of the field-effect capacitor observed for some second-group CdS samples also indicates in favor of the suggested interpretation of the discussed spectral anomaly.

5. CONCLUSIONS

Thus, the manifestation of the surface scattering of charge carriers (electrons) in the PC spectra of CdS crystals is for the first time observed in this study. Further detailed investigations of this effect can yield valuable information on the state and properties of the semiconductor surface.

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