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Recombination and long-term relaxation of photoconductivity in p^+–p–p^- structures of $Cd_xHg_{1-x}Te$ ($0.24 \le x \le 0.29$)

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The paper presents the results of a study of the photoconductivity of p^+–p–p^- structures of $Cd_xHg_{1-x}Te$ ($0.24 \le x \le 0.29$) single crystals obtained by thermal diffusion of copper at T = 130°C. The long-term relaxation (LR) of photoconductivity with a duration of up to 10 ms in the presence of a thermal background of intensity $\Phi = 10^{16}$–10^{17} cm^{-2}·s^{-1} is observed for the first time in narrow-gap materials in the T = 77–150 K range. Recombination, diffusion-drift processes in the sample are analyzed, which cause LR and spectral features of photoconductivity. The obtained structures are promising for the development of various highly sensitive IR detectors with an elevated operating temperature.

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72.40.+w Photoconduction and photovoltaic effects;
73.50.–h Electronic transport phenomena in thin films;
78.30.–j Infrared and Raman spectra;
84.60.Jt Photoelectric conversion.

Keywords: HgCdTe, thermal diffusion of copper, p^+–p–p^- structures, long-term relaxation, photoconductivity, recombination.

1. Introduction

HgCdTe is the preferred material for fabrication of high-performance infrared (IR) detectors in the midwave (MW) (3–5 μm) and long-wave (LW) (8–14 μm) IR bands due to a number of superior fundamental properties [1]. Increasing the operating temperature of IR detectors without their detectivity deterioration has become a nearly universal goal in recent years [2]. The dark current and noise current that determine the required operating temperature for high performance IR HgCdTe detectors are limited by the generation of free carriers by Auger processes. Device structures with combinations of exclusion (p^+/π or n^+/ν) and extraction (n^+/π or p^+/ν) junctions in $p^+/\nu/n^+$ and $p^+/\pi/n^+$ configurations are widely used for suppression of the Auger mechanisms at elevated temperatures [3,4]. The key issue in the fabrication of such nonequilibrium photodiodes consists of a controllable p-type doping at low concentration level with long minority carrier lifetime [5].

In the present paper a series of experiments is conducted to examine copper (Cu) deep diffusion in $Cd_xHg_{1-x}Te$ ($0.24 \le x \le 0.29$) with the goal of achieving controllable low p-type doping in the absorber layer and reducing the Shockley–Read–Hall and Auger GR processes by built-in field caused by impurity concentration gradient. Recombination and diffusion-drift processes in a specimen with p^+–p–p^- junction have been investigated by photoconductivity method. In this structure one of the most interesting effects in semiconductors, so-called long-term relaxation (LR) of photoconduction, has been discovered outwardly manifesting itself as abnormally long times of photoresponse relaxation when the light is switched on or off [6]. The low

probability of the phenomenon of LR in narrow-band semiconductors, such as $Cd_xHg_{1-x}Te$, InSb, is due to the fact that photodetectors based on these semiconductors work, as a rule, at very low temperatures, and the rate of generation of excess carriers by a thermal background is much greater than the rate of their thermal generation. Under these conditions, as shown in [7], the height of the barrier of the p–n junction in the near-surface region of the narrow-band $Cd_xHg_{1-x}Te$ can decrease so much that the relaxation time becomes even less than the bulk lifetime of the charge carriers.

2. Experiment and discussion

Experimental samples were prepared from $Cd_xHg_{1-x}Te$ ($0.24 \le x \le 0.29$) single crystals of indium-doped n-type conductivity with $N_d = 2\cdot10^{13}$–$3\cdot10^{14}$ cm^{-3} of 0.8–0.9 mm in thickness. To obtain p^+–p–p^- junction the copper as acceptor was used since it is fast diffuser and haves doping level over a large range. Immediately after etching in bromine-containing etchant the copper layers of 20–50 nm in thickness were deposited by the thermal vacuum evaporation onto one side of plates. Then the process of diffusion to a depth of 0.14–0.45 mm was carried out at T = 130 °C. For each composition and diffusion deep the time of annealing was chosen from 10 to 120 min. Mechanical polishing and subsequent chemical etching were used to remove n-layer. The type of conductivity was determined due to thermo-probe. For performing measurements of photoconductivity kinetics a light-emitting diode with radiation wavelength of λ = 0.9 μm and intensity of light $\Phi = 10^{14}$–10^{15} cm$^{-2}\cdot$s^{-1} was used. The remaining details of the test are given in [7]. Figure 1 shows the characteristic pattern of photocurrent relaxation at pulse photoexcitation with pulse duration of t_u = 1 ms. The shape of photocurrent pulse consists of the initial area with τ_f = 0.1–1.5 μs and the subsequent portion with $\tau_r >> \tau_f$ and it should be said that with increasing or decreasing the constant τ_r goes up and may reach a value exceeding 40 ms. When background radiation was limited with the use of cooled diaphragm for this purpose, signal value and duration of τ_r grew and in case of additional lighting performed by an incandescent lamp photocurrent component with τ_r was gradually disappearing as lighting intensity increased. With temperature increasing from 77 to 140–150 K a component with τ_r, also was gradually falling and disappearing.

The observed peculiarities which are characteristic for LR phenomena based on spatial separation of excess carriers by electric field of inhomogeneous of impurity concentration. Since recombination is coupled with the need to overcome the potential barrier φ_r, the lifetime of excess carriers, as given in [4], is expressed by the formula

$$\tau_r = \tau_0 \exp(\varphi_r / kT) \qquad (1)$$

and their steady-state concentration

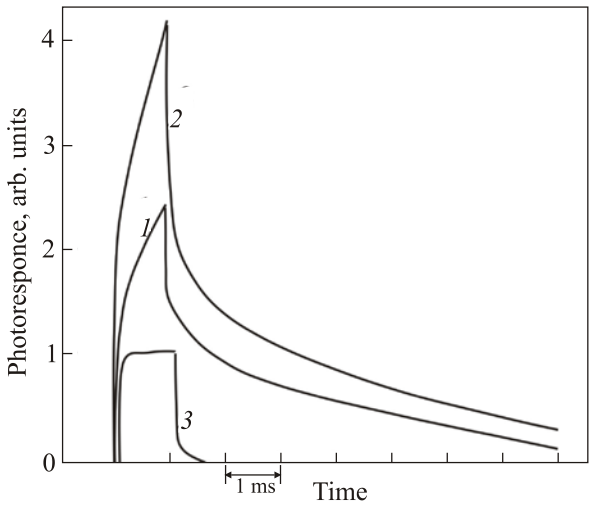

Fig. 1. Relaxation curves of photoconductivity of p^+–p–p^- structures of $Cd_{0.24}Hg_{0.76}Te$ at T = 78 K and in the presence of thermal background with intensity of Φ, cm^{-2}s^{-1}: ~ 10^{17} (*1*), ~ 10^{16} (*2*), ~ 10^{18} (*3*).

$$\Delta n = \alpha\beta\Phi\tau_0 \exp(\varphi_r(\Delta n)/kT). \qquad (2)$$

Here τ_0 is the recombination time in the absence of spatial separation of carriers, α is the absorption coefficient, β is the quantum yield, Φ is the intensity of light. The value of φ_r associated with the gradient of the impurity concentration $N_a(x)$ can be determined from the formula $\varphi_r = kT\ln(p^+/p^-)$, where it is assumed that $p(x) \approx N_a(x)$, since copper atoms that create small acceptor levels, completely ionized. The estimated value of φ_r by formula (1) is ≈ 50–70 mV, respectively, the ratio of the acceptor concentrations on the surfaces $p^+/p^- \ge 10^4$, and the value of the internal field is ~ 5–10 V/cm. The value of τ_f can be identified with the lifetime of excess carriers, caused by recombination on the surface and in the volume of the semiconductor or with the time of separation of the charge carriers by an internal electric field in the volume, depending on which of these mechanisms dominates.

It can also be seen from Fig. 1 that the components of the fast and slow components of the photocurrent are comparable. Since $\tau_r >> \tau_f$, this means that only an insignificant part of the excess carriers generated by light is separated by an internal field and participates in the formation of photoconductivity with LR. Consequently, the lifetime of a significant part of the carriers generated by background radiation in the absorption layer ~ 10 μm is determined by τ_f, and their steady-state concentration $\Delta n \approx \alpha\beta\Phi\tau_f$. It should be noted that the component with LR was present in the relaxation curve when the sample was illuminated both from the p^+ side and from the p^- side. There are several reasons that lead to this result. First of all, one must take into account that the parameters of the semiconductor, such as τ_r, μ_n, μ_p, the diffusion length of holes L_p and electrons L_n, depend substantially on the concentration of acceptors. For

example, at the initial concentration $N_a = 5\cdot10^{17}$–10^{18} cm^{-3} at the p^+ surface, because of the small values of $\tau_r \le 10^{-9}$ s and $L_n \le 5$ μm due to the Auger and radiative recombination mechanisms, the photosignal was almost not recorded. Further, it must be taken into account that the internal field to a large extent lowers surface recombination on the p^+ side, repelling the minority carriers from the surface. Therefore, we can assume that the recombination of excess carriers in the absorption region is due to Auger recombination. As the surface high-doped layer was layer-by-layer removed by chemical etching, an increase in the photosignal was observed, which is explained by the increase in τ_r and L_n. At the same time, the amplitude of the component with the LR decreased after a certain increase in the initial value and disappeared at a thickness of 180–190 μm, which is associated with a significant decrease in the height of the recombination barrier φ_r.

It should also be taken into account that, in the presence of an internal field E, the packet of excess carriers moves with a drift velocity $v_{dr} = \mu_a E$, where $\mu_a = (n - p)/(n/\mu_h + p/\mu_e)$ is ambipolar drift mobility. When the sample is illuminated from the side of p^-, where the lifetime of the carriers is greatest, the concentration of excess electrons can be comparable with the concentration of the main carriers, p_0. In this case, μ_a, μ_e and the electric field do not act on the packet of excess carriers, and therefore the component with LR is small. Considering also that the internal field increases the surface recombination by tightening the minority carriers to the surface, we can assume that the concentration of excess carriers on the p^- side is determined by surface recombination. As the p layer was removed layer-by-layer, the magnitude of the photosignal increased, which can be explained by the increase in μ_a due to the increase in the difference $(n–p)$. This facilitates the separation of some of the excess carriers by an internal field and an increase in the component with LR. We note that after some increase in the photosignal, the component with LR also in this case decreased as the sample attenuated and disappeared at a thickness of 180–190 μm, which is also associated with a decrease in the height of the recombination barrier φ_r. Disappearance of LR with increasing temperature to 140–150 K and with additional strong illumination, indicates the activation character of the phenomenon.

The presence of an internal electric field also affects the spectral characteristic of photoconductivity. Figure 2 shows the spectral characteristics of the photoconductivity of a sample of $Cd_{0.24}Hg_{0.76}Te$ with a thickness of 190 μm when the radiation falls on its p^+ and p^- sides at $T = 78$ K.

As can be seen from Fig. 2, when the p^+ side is illuminated, the longwave wing of the characteristic is very steep, and in the region of strong absorption there is no decrease in the spectral characteristic. When illuminated from the side of p^-, the long-wavelength edge of the characteristic is more gentle, and in the region of strong absorption a certain decrease in the characteristic is observed.

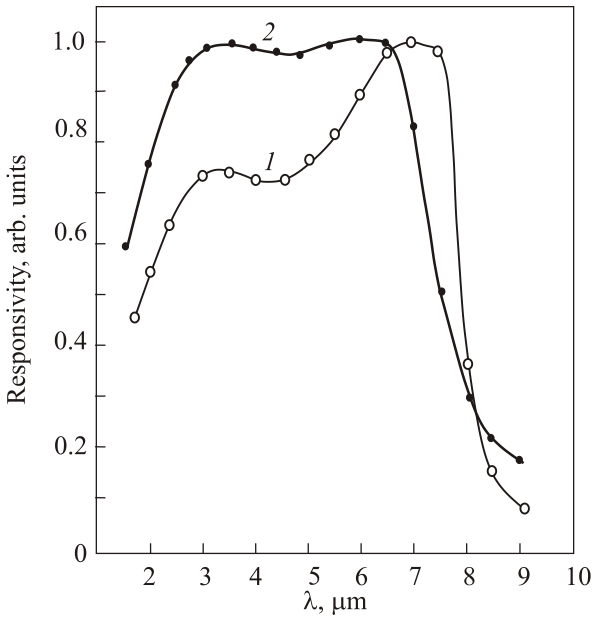

Fig. 2. Spectral characteristic of photosensitivity of p^+–p–p^- structures of $Cd_{0.24}Hg_{0.76}Te$ in case of illumination from the p^+ (*1*) and the p^- (*2*) sides.

These features are explained by the influence of the internal electric field which, depending on the direction, inhibits or accelerates the motion of a package of excess carriers. As is well known, in this case the distribution of excess carriers is determined not by the diffusion length L_n, but by the characteristic lengths [8]

$$l_1, l_2 = \frac{2L_n^2}{\sqrt{4L_n^2 + L_E^2} \mp L_E^2},$$

where $L_E = \mu_n \tau_r E$ is drift length.

Since the spectral dependence of the photoresistors is proportional to $\sim kL/(1 + kL)$, substituting l_1 or l_2 for L, depending on the direction of the field, one can obtain an experimentally observed, respectively, slope of the characteristic. The internal electric field, as indicated, suppresses surface recombination, which explains the absence of a decrease in the region of strong absorption under illumination from the p^+ side. When illuminated from the p^- side, the internal field increases the influence of surface recombination, which causes a certain decrease in the characteristic in the region of strong absorption. All the considered features of the photoconductivity of p^+–p–p^- structures of $Cd_{0.24}Hg_{0.76}Te$ have a more pronounced character for compositions $x > 0.24$.

It is important to note that the observed large values of τ_r indicate a very small probability of recombination of spatially separated charge carriers. The internal field separating the charge carriers suppresses all types of recombination-surface, Auger and Shockley–Read. Consequently, the obtained p^+–p–p^- structures are very promising for manufacturing highly sensitive IR detectors with an elevated operating temperature.

3. Conclusion

Thus, the observed long-term relaxation of the photoconductivity of p^+–p–p^- structures of $Cd_xHg_{1-x}Te$ ($0.24 \le x \le 0.29$) is due to the recombination barrier $\varphi_r \approx$ $\approx$ 50–70 mV, created by the gradient of the impurity concentration along the radiation direction. Despite the high level of background radiation, the lowering of the barrier is insignificant. This is due to the fact that a significant part of photogenerated carriers recombine in the near-surface absorption region and only a small part of them is separated by an internal field with the formation of photoconductivity with LR. The observed large values of τ_r = 10–40 ms indicate a very small probability of recombination of spatially separated charge carriers due to the suppression of all types of recombination by an internal electric field. The obtained results of the research can be applied in the development of various high-sensitivity IR detectors with increased operating temperature.

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Рекомбінація та тривала релаксація фотопровідності в p^+–p–p^- структурах $Cd_xHg_{1-x}Te$ ($0{,}24 \le x \le 0{,}29$)

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Представлено результати дослідження фотопровідності p^+–p–p^- структур монокристалів $Cd_xHg_{1-x}Te$ ($0{,}24 \le x \le 0{,}29$), отриманих термічною дифузією міді при T = 130 °C. Довгострокова релаксація (ДР) фотопровідності з тривалістю до 10 мс при наявності теплового фону інтенсивності $\Phi = 10^{16}$–10^{17} см$^{-2}$·s^{-1} вперше спостерігається в вузькощілинних матеріалах в діапазоні T = 77–150 К. Проаналізовано рекомбінацію, дифузійно-дрейфові процеси в зразку, які викликають ДР та спектральні особливості фотопровідності. Отримані структури є перспективними для розробки різних високочутливих ІК-детекторів з підвищеною робочою температурою.

Ключові слова: HgCdTe, термічна дифузія міді, p^+–p–p^- структури, довготривала релаксація, фотопровідність, рекомбінація.