Photoelectric Energy Conversion at a Metal-$Cd_xHg_{1-x}Te$ Contact Under Conditions of Heating of Current Carriers by a Strong Electric Field

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Abstract. The main features of photoelectric energy conversion at the contact metal (In or Sn)-$Cd_xHg_{1-x}Te$ (0.25<x<0.90 with *n*- and *p*-type conductivity) under conditions of heating of free charge carriers in the semiconductor component ($Cd_xHg_{1-x}Te$) of contacting pairs (metal-semiconductor) by a strong electric field with ultra-high frequency (with a frequency of 10^{10} Hz) with a strength from 10^2 V/cm up to 4 10^3 V/cm were experimentally investigated. The dependences of the value of the photo-emf (U_{ph}) created under the influence of monochromatic illumination on the contact under study on the intensity (I_l) and wavelength of light (λ_l), the temperature of the sample under study (T_0), time (t), the intensity (E) of the microwave electric field with a value greater than a certain critical value (E_{cr}), i.e. the value of the electric field intensity at which the heating of free charge carriers by the electric field and the effects caused by hot current carriers in the contacting semiconductor component of the contact structure under study begin to be observed were measured experimentally. It is shown that the discovered features of the photo-emf on the studied metal-$Cd_xHg_{1-x}Te$ contacts under the influence of a strong electric field are directly related to the heating of minority free charge carriers by the electric field in the contacting semiconductor component and the studied metal-$Cd_xHg_{1-x}Te$ contact structures can be used to create on their basis a new type of highly sensitive, significantly low-inertia photovoltaic energy converters compared to conventional ones.

Keywords: metal-semiconductor contact, photo-emf, charge carrier heating.

1 Introduction

Electronic processes (or photoelectric phenomena) that enable the direct conversion of light energy into electrical energy, as well as photoelectric functional elements, devices, and instruments of various types and purposes created on the basis of these electronic phenomena, are of significant interest not only to various areas of modern science, technology, and production, but also play a huge role in human everyday life. These electronic phenomena underlie the process of conversion (act) "light-electricity-light" in optoelectronics [1], as well as "light-electric energy" in photoelectric converters

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of light radiation energy, including solar radiation into electrical energy (solar renewable energy devices) [2, 3].

In most practical cases, various types of contact structures are used, one of which is metal-semiconductor contacts, both for recording and studying light signals (radiation), and for studying the properties and parameters of various physical, chemical, biological and other similar objects by exposing them to light, or by analyzing the light radiation (light signal) coming from them [4].

As a result of numerous scientific studies on the physical properties of metal-semiconductor contacts, it has been established that by selecting a semiconductor component with an appropriate band gap, it is possible to create a photoconverter (photocell) based on a metal-semiconductor contact for a different region of the optical spectrum, which allows the energy of the light flux incident on it to be converted into electrical energy [5, 6].

Our bibliographic research shows that for this purpose, one of the promising semiconductor materials may also be single crystals of the semiconductor solid solution cadmium-mercury-tellurium ($Cd_xHg_{1-x}Te$) with a cadmium content of 25-90% (with a value of x=0.25-0.90).

The possibility of smoothly regulating the width of the forbidden zone of this semiconductor material by varying the cadmium content (the x value) in the composition allows one to vary its photosensitivity accordingly in the optical spectrum range of 0.30–10.00 μm [7-10].

On the other hand, the small effective mass and the significantly high mobility of free charge carriers in these crystals make it possible, in a wide temperature range even at not very high electric field strengths, to carry out heating of free charge carriers in them (in $Cd_xHg_{1-x}Te$ single crystals with x=0.20-0.90) under the influence of a strong external electric field [11-15].

This semiconductor material (a solid solution with a single-crystal structure) is also successfully used on a large scale to create various thermoelectric and photoelectric converters of thermal and light energy into electrical energy, which, in addition to the common properties of many semiconductor materials, also possess unique features [16-19]. However, despite all of this, to date, all the potential physical properties and characteristics of this semiconductor material that have fundamental significance and applied interest have not yet been identified or have been extremely insufficiently studied.

In this aspect, attention is also drawn to the experimental study of the main features and possibilities for the practical application of electronic phenomena, including those that allow for the direct conversion of light energy into electrical energy of photovoltaic effects (photo-emf), caused by the heating of free charge carriers by an external strong electric field in $Cd_xHg_{1-x}Te$ single crystals with different compositions (different cadmium content in the alloy) and conductivity types (n- and p-type conductivity). Naturally, in this aspect, the results obtained during the implementation of experimental studies (information both about the material under study and about the physical phenomenon under consideration), in addition to identifying new features of the physical properties and possibilities for the practical application of this semiconductor, can also be useful for the development of solid-state physics and photoelectric phenomena in semiconductors, as well as for the technology of photoelectric converters of light radiation (in particular, solar light) into electrical energy, i.e. photovoltaic devices for renewable energy.

Based on the fact that the magnitude and main characteristics (spectral distribution, light or lux-ampere characteristic, time dependence, i.e. kinetics) of the photo-emf at the metal-semiconductor contact caused by the action of light, in addition to the characteristic (fundamental) parameters of the semiconductor component in contact with the metal and the temperature of the sample (T_o), also depend on the value of the effective temperature (T_e) of free charge carriers [2, 4-6], in the present work, we have experimentally investigated in a comprehensive manner, under various external and intracrystalline conditions, the main features, characteristics and parameters of the process of photoelectric energy conversion (conversion of light radiation energy into electrical energy) at the metal-$Cd_xHg_{1-x}Te$ contact under conditions of heating of free charge carriers in the contacting semiconductor component under the action of an external strong electric field (an external electric field with a strength greater than a certain critical value for the contacting semiconductor component).

2 Research Objects and Experimental Measurements

The objects of the experimental studies were samples cut from large pure (not specially alloyed) ingots of $Cd_xHg_{1-x}Te$ single crystals with $0.30<x<0.90$ of different (*n*- and *p*-) types of conductivity, grown by the Bridgman method. The samples used for the experimental measurements were cut using a widely used method for cutting semiconductor materials, electric spark cutting, from large single-crystal $Cd_xHg_{1-x}Te$ ingots with $0.30<x<0.90$ of different (*n*- and *p*-) types, and after electric spark cutting, by grinding with special abrasive powders of the M14, M10, M7, M5 brands and a special polishing paste [12], their required geometric shape, dimensions and plane-parallel surfaces were ensured. These samples were then thoroughly rinsed with running bidistilled water and dried without heating. After rinsing and drying, they were fitted with metal contacts by soldering them in open air without flux. The metal contacts were soldered to opposite ends of the samples, positioned so that during experimental measurements, the direction of the external strong electric field acting on the sample and the current flowing through it would be along its length. The contact materials were metallic indium (In) or tin (Sn). Heating of free charge carriers in the semiconductor component of the studied samples (contacts) was carried out by exposing the considered sample to rarely repeating (with a repetition frequency of no more than 5-6 Hz) pulses of an ultra-high-frequency (with a frequency of 10^{10} Hz) electric field with a strength from 10^2 to 4 10^3 V/cm.

Experimental measurements were carried out using a universal complex setup assembled based on an MDR-23 monochromator with an electronic computing complex, a magnetron generator and a special cryostat [20, 21].

The intensity of the light incident on the sample under study was regulated by using a set of special neutral glass and (or) graduated metal optical filters, and sometimes also by the diaphragms of the monochromator itself (MDR-23).

3 Experimental Results

The dependences of the value of the photo-emf (U_{ph}) created by illumination on one of the contacts (on the contact located in the region of the strong microwave electric field heating the free charge carriers) of the studied metal-$Cd_xHg_{1-x}Te$ samples on the intensity (I_l) and wavelength (λ_l) of the light incident on the studied contact, time (t), the strength of the microwave electric field (E) acting on the studied contact with a value greater than the critical one (E_{cr}), i.e. the microwave field strength at which the heating of free current carriers by the electric field in the contacting semiconductor component begins to occur [16, 18, 22, 23] were experimentally recorded (measured). These dependences were determined by different values of the above-mentioned parameters of external factors (temperature, electric field strength, intensity and wavelength of light). More precisely, experimental measurements were carried out on the contact of metal (In or Sn)-$Cd_xHg_{1-x}Te$ ($0.25<x<0.90$ with n- and p-type conductivity), at temperatures T_0=77-300 K, microwave electric field strengths of $10^2 \leq E \leq 4\cdot10^3$ V·cm^{-1}, intensities and wavelengths of the incident light on the sample under study $I_l=2\cdot10^2$ lx and λ_l=0.30-4.0 μm, respectively, according to the method (order) described in [20, 21].

In order to ensure a high degree of accuracy and reliability of the obtained experimental results of the phenomenon under study (photo-emf at the metal-$Cd_xHg_{1-x}Te$ contact under conditions of exposure to a strong electric field, i.e. under conditions of heating of free charge carriers in the region of the semiconductor component in contact with the metal), each measured characteristic was recorded both on the same sample (contact structure) 4-5 times, and on different samples with the same type of conductivity and composition of the semiconductor component.

As a result of the experimental measurements, it was established that both in the absence and under the influence of a strong microwave electric field, the photo-emf on the contact structures under study, i.e. on In (or Sn)-$Cd_xHg_{1-x}Te$ contacts with different compositions (with $0.25<x<0.90$) and conductivity types (n- and p-type conductivity), is observed in the entire spectral range of the optical spectrum, in which photoconductivity is observed in its semiconductor component. Moreover, in the considered range of intensity of light incident on the contact under study (I_l) and temperature of the sample (T_0), both in the absence of exposure and under conditions of exposure to a strong microwave electric field on the contact structure under study, the magnitude of the detected photo-emf (U_{ph}) with an increase in I_l initially (at relatively low illumination) increases linearly, and then (at higher illumination) the dependence $U_{ph}(I_l)$ gradually approaches saturation (Figure 1, curves 1-5). In both cases (both in the absence of exposure and under the influence of a strong microwave electric field on the contact structure under study), with an increase in T_0, the value of U_{ph} decreases monotonically (Figure 1, curves 6 and 7). However, when an external microwave electric field with a strength (E) greater than a certain critical value (E_{cr}) is applied to the metal-semiconductor contact under study, or rather when a change in the dark specific electrical conductivity (σ) occurs in the semiconductor component in contact with the metal due to the heating of free charge carriers by the electric field [16], a thermo-emf of hot carriers [22] or a thermo-photo-emf of hot charge carriers [23] arises; the value of the photo-emf (U_{phE}) created on the contact structure under study turns out to be significantly greater than the value of the photo-emf (U_{ph0}) created at the strengths of an external electric field with a strength of $0 \le E < E_{cr}$ acting on the contact structure under study (in the absence of heating of free charge carriers by the electric field in the contacting semiconductor component).

As a result of the experimental measurements, it was established that both in the absence and under the influence of a strong microwave electric field, the photo-emf on the contact structures under study, i.e. on In (or Sn)-$Cd_xHg_{1-x}Te$ contacts with different compositions (with $0.25<x<0.90$) and conductivity types (*n*- and *p*-type conductivity), is observed in the entire spectral range of the optical spectrum, in which photoconductivity is observed in its semiconductor component. Moreover, in the considered range of intensity of light incident on the contact under study (I_l) and temperature of the sample (T_0), both in the absence of exposure and under conditions of exposure to a strong microwave electric field on the contact structure under study, the magnitude of the detected photo-emf (U_{ph}) with an increase in I_l initially (at relatively low illumination) increases linearly, and then (at higher illumination) the dependence $U_{ph}(I_l)$ gradually approaches saturation (Figure 1, curves 1-5). In both cases (both in the absence of exposure and under the influence of a strong microwave electric field on the contact structure under study), with an increase in T_0, the value of U_{ph} decreases monotonically (Figure 1, curves 6 and 7). However, when an external microwave electric field with a strength (E) greater than a certain critical value (E_{cr}) is applied to the metal-semiconductor contact

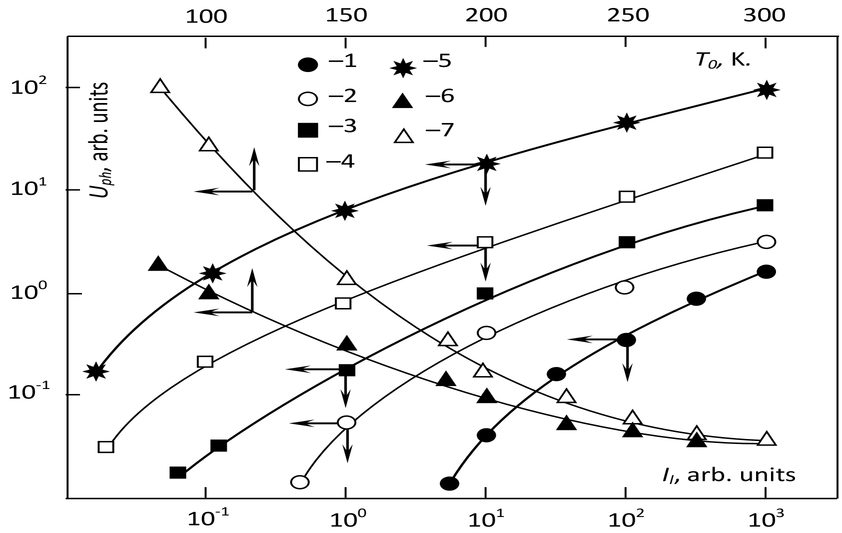

Fig. 1. Dependence of the photo-emf (U_{ph}) on the In/n-$Cd_{0.80}Hg_{0.20}Te$ contact on the light intensity (curves 1-5) and the sample temperature (curves 6 and 7) for different values of the intensity of the microwave electric field acting on the contact under study (E): for $E<E_{cr}$ (curves 1 and 6) and for $E \ge E_{cr}$ (curves 2-5 and 7).

E, V cm^{-1}: 1.6 - 0; 2 - $5 \cdot 10^2$; 3 - $8 \cdot 10^2$; 4 - 10^3; 5 - $4 \cdot 10^3$;
T_0, K: 1, 2, 3, 4, 5 - 77; I_l, rel. units: 6, 7 - 10^3.

under study, or rather when a change in the dark specific electrical conductivity (σ) occurs in the semiconductor component in contact with the metal due to the heating of free charge carriers by the electric field [16], a thermo-emf of hot carriers [22] or a thermo-photo-emf of hot charge carriers [23] arises; the value of the photo-emf (U_{phE}) created on the contact structure under study turns out to be significantly greater than the value of the photo-emf (U_{ph0}) created at the strengths of an external electric field with a strength of $0 \leq E < E_{cr}$ acting on the contact structure under study (in the absence of heating of free charge carriers by the electric field in the contacting semiconductor component).

It was established that under the considered external and intracrystalline conditions, the behavior of the main characteristics of U_{phE} (the curves of the dependences of U_{phE} on the strength of a strong microwave electric field, on the wavelength and intensity of light incident on the studied contact, on time) on contacts with different metals (In or Sn), as well as a semiconductor component ($Cd_xHg_{1-x}Te$) with different types of conductivity (*n*- or *p*-type conductivity) and (or) compositions (the percentage content of cadmium in the solid solution $Cd_xHg_{1-x}Te$) are almost identical. Depending on these listed factors, only the numerical values of individual characteristic parameters and the magnitude of the detected photovoltage differ slightly. In particular, with an increase in the cadmium content in the contacting semiconductor component, the red edge and the maximum of the spectral distribution of the detected U_{phE} shift toward shorter wavelengths. In addition, with an increase in the cadmium content in the contacting semiconductor component, all other things being equal, the excess photovoltage ($\Delta U_{ph} = U_{phE} - U_{ph0}$) decreases, and in the case of a *p*-type contacting semiconductor component (p-$Cd_xHg_{1-x}Te$), it turns out to be greater than in the case of an *n*-type contacting semiconductor component (n-$Cd_xHg_{1-x}Te$). It should be noted that, based on the above, the figures only show graphs that directly relate to the In/n-$Cd_{0.80}Hg_{0.20}Te$ contact structures under study. During the experimental measurements it was established that the value of the excess photo-emf $\Delta U_{ph} = U_{phE} - U_{ph0}$, caused by the heating of free

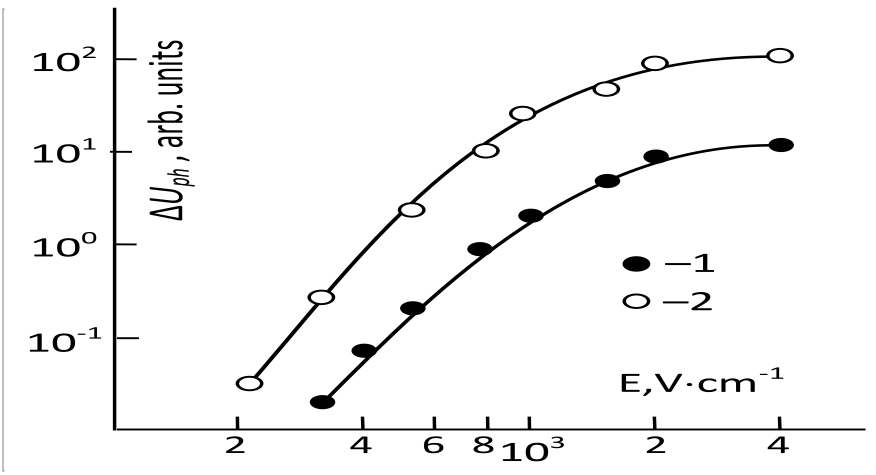

Fig. 2. Dependence of the excess photovoltage (ΔU_{ph}) on the In/n-$Cd_{0.80}Hg_{0.20}Te$ contact on the strength of the microwave electric field acting on the contact under study at T_0=77 K. I_l, rel. units: 1-10^1, 2 – 10^3.

charge carriers in the contacting semiconductor arm of the considered contact structures, where U_{phE} and U_{ph0} are the values of the photo-emf at the considered metal-semiconductor contact at $E<E_{cr}$ and $E\geq E_{cr}$, respectively, depends on the intensity of the electric field heating the free charge carriers. In particular, with an increase in the intensity of the heating free charge carriers in the semiconductor component of the metal-semiconductor contact under study, the value of ΔU_{ph} first (in the region of relatively weak heating free charge carriers at electric field intensities) increases according to a quadratic law, then (in the region of relatively strong heating free charge carriers at electric field intensities) - almost according to a linear law, and at even higher intensities of the heating free charge carriers of the electric field, the dependence of ΔU_{ph} on E gradually reaches saturation (Figure 2).

When the metal-semiconductor contact under study is exposed to an electric field with a strength of $E\geq E_{cr}$, the kinetics (the processes of establishing a steady-state value when the light is turned on and disappearing after the light is turned off) of U_{phE} also differs from the kinetics of the usual photo-emf U_{phE} (observed in the absence of a strong electric field applied to the metal-semiconductor contact under study). In particular, the kinetics (relaxation processes) of U_{phE} are significantly faster (low-inertia or instantaneous) in nature compared to the kinetics (relaxation processes) of U_{ph0} (Figure 3).

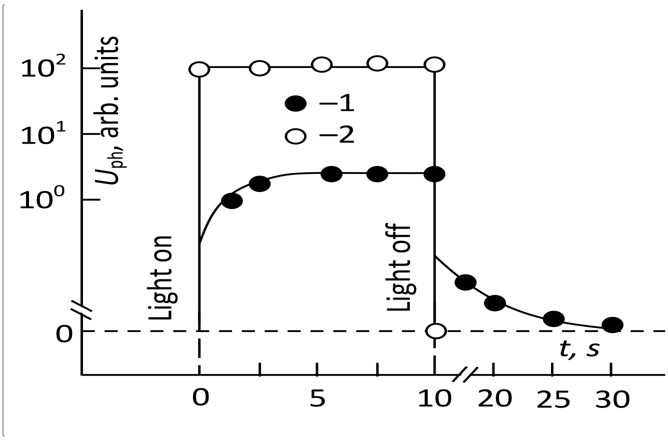

Fig. 3. Kinetics of photo-emf (U_{ph}) at the In/n-$Cd_{0.80}Hg_{0.20}Te$ contact at different values of the microwave electric field strength (E) acting on the contact under study: at $E<E_{cr}$ (curve 1) and $E\geqslant E_{cr}$ (curve 2)
T_0=77 K; I_l, rel. units: 1, 2 - 10^3.

The dependence of the increment of photo-emf (the value of excess photo-emf $\Delta U_{ph}=U_{phE}-U_{ph0}$, caused by the heating of free charge carriers in the semiconductor component of the metal-semiconductor contact under study) on the intensity of a strong microwave electric field, detected at $E>E_{cr}$, is initially quadratic (at not very high E), then (at average values of E) it becomes linear, and at higher values of E it reaches saturation. Sometimes, or rather for some contact structures created on the basis of the contacting semiconductor component $Cd_xHg_{1-x}Te$ with a higher cadmium content (at $x>0.70$) at such values of E, with its growth (the strength of the strong electric field), the value of the excess photo-emf, i.e. ΔU_{ph} even decreases somewhat.

In addition to the above, other interesting results from a scientific and practical point of view and necessary for identifying the mechanism and main features of photo-emf caused by the effect of a strong electric field on free charge carriers in a contacting semiconductor component were also obtained during the experimental measurements. In particular, it was established that, under the considered external and intracrystalline conditions, the dependences of the ΔU_{ph} value on the temperature of the contacts under study (T_0), the composition and type of conductivity of the $Cd_xHg1\text{-}xTe$ crystals used to create the contact structures under study correlate at a fairly good level with the corresponding dependences of the change in dark specific electrical conductivity (σ) due to the heating of free charge carriers by a strong electric field in these crystals.

4 Discussion of Results

Moving on to the discussion of the features of the photo-emf at the metal-Cd_xHg_{1-x} Te contact discovered during the experimental studies under conditions of exposure to a strong electric field, which differ from those existing for the usual photo-emf at the metal-semiconductor contact [5, 6], it can be said, first of all, that these features, without any exception, are caused by the heating of free charge carriers in the contacting semiconductor component. Therefore, in order to identify in detail the physical causes of these features and to clarify the mechanism of the appearance of the photo-emf itself at the metal-$Cd_xHg_{1-x}Te$ contact under conditions of heating of free charge carriers, we relied on the conclusions made in [6, 15, 21], where, on the basis of the experimental and theoretical analyses, expressions were formulated for U_{ph} under conditions of heating of free charge carriers by an electric field and the patterns of its dependence on the intensity and wavelength of light, the temperature of the sample under study, the strength of the heating of free charge carriers in the semiconductor component in contact with the metal, the coefficient and length of diffusion of free charge carriers in this semiconductor, the subordination of the $U_{ph}(E)$ dependence to quadratic and linear laws in the region of relatively low and higher values of strength, on the degree of doping of the semiconductor component, as well as the value of the coefficient and length of diffusion of free charge carriers in this material were indicated.

As a result of the conducted analyses, it was established that in all the metal-$Cd_xHg_{1-x}Te$ contact structures studied by us, under the considered external conditions, the obtained experimental results and the established photo-emf dependencies on the strength of the acting strong electric field, the temperature of the sample, the intensity and wavelength of the monochromatic light incident on the studied contact, on the time and composition of the contacting semiconductor component $Cd_xHg_{1-x}Te$, i.e. all the experimentally established dependencies $U_{ph}(E)$, $U_{ph}(T_0)$, $U_{ph}(I_l)$, $U_{ph}(\lambda)$, $U_{ph}(t)$, $U_{ph}(x)$ are in good agreement with the conclusions in the aforementioned works [6, 15, 21]. The deviation of the dependence from linearity observed in the region of higher intensities of a strong electric field (observation of sublinearity or sometimes even saturation and a decline in the dependence of U_{ph} on E), similar to the case of thermophotovoltage of hot charge carriers in these semiconductor crystals, can be explained by the possibility of free charge carriers overcoming the near-surface potential barrier at higher intensities of a strong electric field acting on the sample under study.

The dependences $U_{ph}(x)$, $U_{ph}(T_0)$ and $U_{ph}(I_l)$ obtained during experimental measurements also satisfactorily comply with the conclusions of works [6, 15, 21].

The analysis of the obtained results in the experimental studies carried out on the basis of the concepts formulated in [6, 15, 21] also allows us to say that the features of the photo-emf at the metal-$Cd_xHg_{1-x}Te$ contact discovered under the influence of a strong electric field are directly related to the stronger heating of the minority charge carriers by the electric field in the contacting semiconductor component of the $Cd_xHg_{1-x}Te$ crystals compared to the majority charge carriers and therefore, all other conditions being equal, the value of ΔU_{ph} in the metal/p-$Cd_xHg_{1-x}Te$ contact structures is greater than in the metal/n-$Cd_xHg_{1-x}Te$ contact structures.

The experimental results obtained allow us to recommend metal-$Cd_xHg_{1-x}Te$ contact structures for the creation of a new type of highly sensitive, significantly low-inertia photovoltaic energy converters on their basis.

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