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Electrophysical properties of $Cd_xHg_{1-x}Te$ C crystals at weak electric fields

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Abstract

To identify the specific features and clarify the mechanism of interaction between free charge carriers and various defects in $Cd_xHg_{1-x}Te$ crystals, the temperature dependence of electrophysical parameters (specific dark conductivity, Hall constant, and Hall mobility) was experimentally studied in n- and p-type $Cd_xHg_{1-x}Te$ crystal samples with different Cd contents (with a value of $0.30 \leq x \leq 0.80$) at weak electric fields. It is shown that in these crystals at $T \leq 120$ K, in addition to the scattering of free charge carriers on impurity ions, a significant influence of drift barriers on the process of charge carrier transfer is manifested, and at higher temperatures the influence of scattering on lattice vibrations begins to dominate.

Keywords: solid solution, electrical conductivity, Hall coefficient, Hall mobility, defects, carrier scattering.

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1. Introduction

Chalcogenide-based binary and ternary compounds have attracted considerable attention owing to their diverse and multifunctional physical and chemical properties [1–9]. These materials exhibit excellent chemical stability, high crystallographic symmetry, and the ability to accommodate rare-earth ions at relatively high concentrations, making them promising candidates for a wide range of technological applications [9–16]. Depending on their cationic composition and structural arrangement, chalcogenides can be synthesized in highly symmetric polycrystalline and single-crystalline forms, as well as in amorphous glassy states. The versatility of their structural, optical, electrical, and luminescent properties has stimulated extensive research interest and continues to drive the development of advanced functional materials [15–20].

Crystals of $Cd_xHg_{1-x}Te$ semiconductor solid solutions [21] have long been known to researchers, engineers, technologists, and designers around the world as promising materials for semiconductor physics and solid-state electronics. Although, in connection with the great potential for practical use for the production of various infrared (IR) technology devices, in many cases, the crystals of this semiconductor with a relatively low Cd content (with a value of $x \leq 0.23$) mainly attract attention, the information accumulated to date indicates that $Cd_xHg_{1-x}Te$ crystals with $x > 0.23$, with their unique physical properties, can also be quite suitable and useful materials for studying many interesting issues in the physics of semiconductors [22-27]. In particular, the small value of the effective mass and the high mobility of free current carriers, the possibility of smooth regulation of the Cd content in the solution and, accordingly, the value of the band gap and other characteristic parameters in a wide range, control of the concentration and parameters of defects, as well as surface processes in various ways [28-30] make it possible to study the interaction of charge carriers with defects under various conditions, as well as to identify the features and clarify the mechanisms of various electronic phenomena in this material in particular and in many other semiconductors with similar chemical compositions and crystal structure in general.

Based on the above, in order to identify the features of the electrophysical parameters and clarify the mechanism of interaction of free charge carriers with various defects in $Cd_xHg_{1-x}Te$ crystals, the features of the specific dark electrical conductivity, Hall coefficient and Hall mobility in samples of n- and p-type conductivity of $Cd_xHg_{1-x}Te$ crystals with $0.30 \leq x \leq 0.80$ were experimentally studied at weak electric fields.

2. Experiments

The samples were cut using spark erosion from ingots of $Cd_xHg1_{-x}Te$ single crystals with n- and p-type conductivity, grown using the Bridgman method. Crystals with different conductivity types were obtained by varying the concentration of mercury vacancies. After cutting, grinding with abrasive powders (such as M14, M10, M7, and M5) and polishing with a special diamond polishing paste ensured the desired geometric shape and plane-parallel surfaces. They were then thoroughly rinsed with running bidistilled water and etched.

After washing and etching, the samples were fitted with current contacts made of indium (for n-$Cd_xHg_{1-x}Te$) and a special contact alloy (for p-$Cd_xHg_{1-x}Te$). The resulting current contacts were ohmic within the experimental measurement conditions, as monitored using a characteristic curve tracer.

The conductivity of the samples studied was determined by the sign of the thermo-e.m.f. and (or) the Hall coefficient.

3. Results and discussion

First, the temperature dependence curves of the dark specific electrical conductivity (σ_{D0}) were recorded in samples of both types of $Cd_xHg_{1-x}Te$ crystals with $0.30 \leq x \leq 0.80$ (figures 1 and 2).

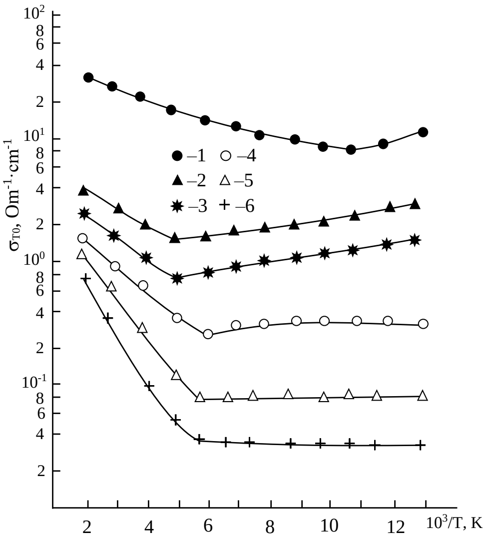

Figure 1. Temperature dependence of specific dark conductivity in n-$Cd_xHg_{1-x}Te$ crystals with different Cd contents (x values). x: 1 - 0.30; 2 - 0.40; 3 - 0.45; 4 - 0.55; 5 - 0.65; 6 - 0.80.

It was established that, according to the nature of the temperature dependence of σ_{D0}, the studied n-type samples (figure 1) are clearly divided into two groups: samples with $0.30 \leq x \leq 0.40$ (figure 1, curves 1-3) and $0.40 < x \leq 0.80$ (figure 1, curves 4-6), respectively. In the first group of samples (figure 1, curves 1-3) in the region of relatively low temperatures (T) with increasing T the value of σ_{D0} decreased somewhat, and in the region of higher temperatures (at $T>T_M$) it increased sharply. With an increase in the Cd content in the solution, the value of the temperature T_M at which the course of the curves of the dependence of σ_{D0} on T changes, i.e. both the temperature range and the absolute value of the decrease in σ_{D0} with temperature increase.

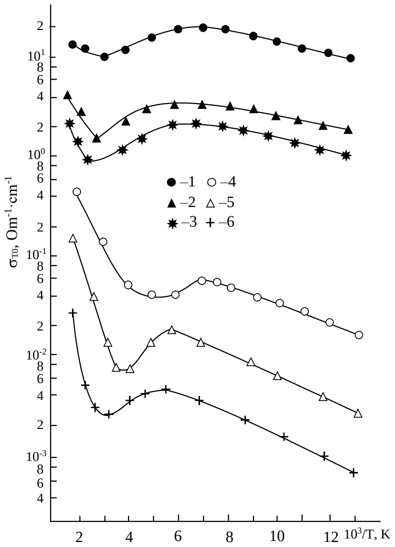

Figure 2. Temperature dependence of specific dark conductivity in p-$Cd_xHg_{1-x}Te$ crystals with different Cd contents (x values).
x: 1 - 0.30; 2 - 0.40; 3 - 0.45; 4 - 0.55; 5 - 0.65; 6 - 0.80.

In the region of relatively high T, the increase in σ_{D0} with increasing temperature has an activation character and the values of the conductivity activation energy determined from the slope of this part of the $\sigma_{D0}(T)$ curves satisfactorily coincide with the value of the band gap of the studied compositions. In $Cd_xHg_{1-x}Te$ samples with x>0.50 (figure 1, curves 4-6), the value of σ_{D0} is almost independent of T in the region of relatively low temperatures, while at higher T it increases with increasing temperature. Moreover, the values of conductivity activation energy found from the slope of the high-temperature branch of the $\sigma_{D0}(T)$ curves are in satisfactory agreement with the band gap of the studied compounds.

In samples of p-$Cd_xHg_{1-x}Te$ crystals (figure 2, curves 1-6), regardless of the composition (at $0.30 \leq x \leq 0.80$), with an increase in temperature, at first (in the region of relatively low T), the value of the dark specific electrical conductivity (σ_{D0}), although weakly, still increases, then passing through a maximum, decreases somewhat (2-3 times), and in the region of higher temperatures increases sharply. In this sharply increasing region, the temperature dependence of the specific dark electrical conductivity has an activation character.

In these (p-$Cd_xHg_{1-x}Te$) samples, the energy value determined from the slope of the high-temperature branch of the $\sigma_{D0}(T)$ dependence curves also satisfactorily coincides with the value of the band gap of the studied compositions.

When studying the temperature dependence of the Hall coefficient (R_H) (figure 3), it was found that in all the studied $Cd_xHg_{1-x}Te$ samples, regardless of the composition and type of conductivity (Figure 3, curves 1-6), at relatively low temperatures ($T<T_M$, where T_M - is the temperature below which impurity conductivity dominates), the value of R_H, and accordingly the concentration of free majority charge carriers (the concentration of free electrons n_0 and free holes p_0 in n- and p-type crystals, respectively), is almost independent of temperature, and in the region of higher temperatures with an increase in T, it increases.

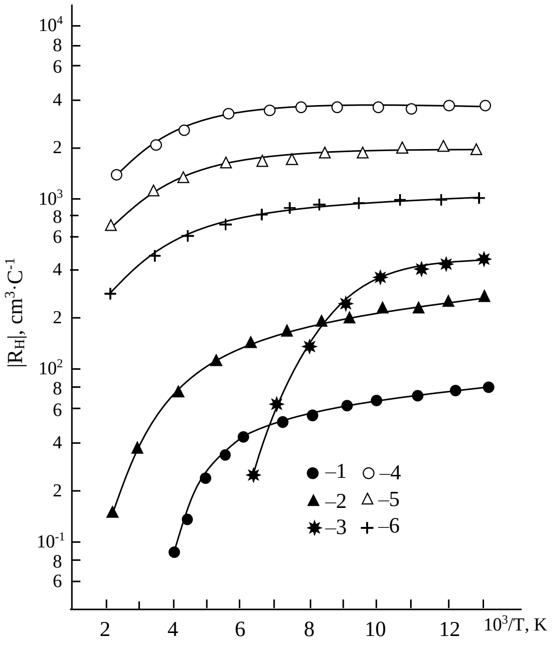

Figure 3. Temperature dependence of the Hall constant in n- (curves 1-3) and p- (curves 4-6) type $Cd_xHg_{1-x}Te$ crystals with different Cd content (x values).
x: 1, 4 - 0.30; 2, 5 - 0.55; 3, 6 - 0.80.

Based on the obtained experimental values of R_H and σ_{D0}, we estimated the values of the Hall mobility of charge carriers (μ_H) in the studied samples at different temperatures using the well-known relationship [31] (figure 4).

It was found that in the $Cd_xHg_{1-x}Te$ crystals studied, the value of μ_H and its temperature dependence depend on the composition of the samples. In samples with x>0.50, for all considered values of T, with increasing temperature, the value of μ_H decreases according to the law $\mu_H \sim T^{-3/2}$. In samples with x≤0.50, with increasing temperature in the region of relatively low T, the value of μ_H increases according to the law $\mu_H \sim T^{3/2}$, and at higher T, it decreases according to the law $\mu_H \sim T^{-3/2}$. With an increase in the Cd content in the solution, all other conditions being equal, the value of μ_H decreases noticeably.

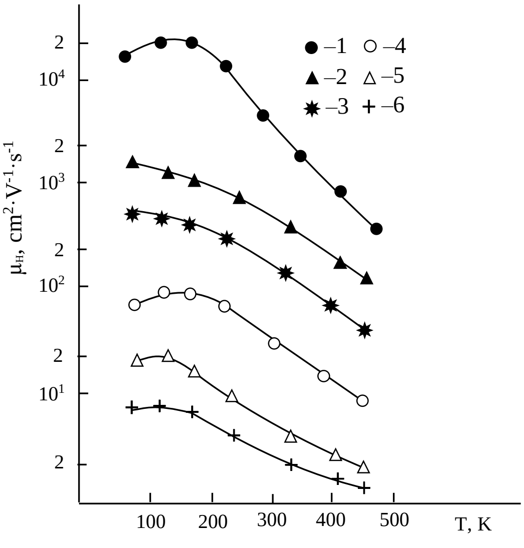

Figure 4. Temperature dependence of the Hall mobility in n-(curves 1-3) and p-(curves 4-6) type $Cd_xHg_{1-x}Te$ crystals with different Cd content (x values).
x: 1, 4 - 0.30; 2, 5 - 0.55; 3, 6 - 0.80.

Proceeding to a discussion of the experimental results obtained, it should be noted that, as follows from the work of some other authors [30, 32, 33], in this semiconductor material, regardless of the degree of improvement of the applied method and growth regime, technological defects exist that significantly affect electronic phenomena, including charge transfer. These technological defects primarily include point defects consisting of mercury vacancies, cadmium, and interstitial tellurium atoms (acceptor type), as well as interstitial cadmium and mercury atoms and tellurium vacancies (donor type). Therefore, significant self-compensation of $Cd_xHg_{1-x}Te$ crystals is possible under certain conditions. It is also known that the energy position of individual impurity levels relative to the edge of the corresponding allowed bands in this material depends on the composition (Cd content) of the sample being studied. For example, at low Cd contents (at small values of x), the acceptor-type impurity band even lies within the conduction band. With further increase in x, it enters the band gap and gradually moves away from the edge (bottom) of the conduction band. Special doping of $Cd_xHg_{1-x}Te$ crystals compensates for some of the uncontrolled (technological) levels existing in their band gap. When exposed to penetrating radiation or thermal annealing, the concentration (density) of a particular defect type changes depending on the dose and type of irradiation, the energy of the radiation particles, and the annealing mode. All these circumstances can also significantly affect the features and characteristics of individual physical, including electrophysical parameters of the material.

The possibility of accumulation of point defects in $Cd_xHg_{1-x}Te$ single crystals in the form of clusters or various inclusions (random macroscopic defects) cannot be ruled out, which can also significantly affect their electronic properties, especially their electrophysical properties [34-36].

A comparative analysis of the temperature dependence of the dark specific electrical conductivity, the Hall constant and the Hall mobility obtained in a joint experimental study in the studied $Cd_xHg_{1-x}Te$ single crystals of n- and p-type conductivity of different compositions allows us to say that in these crystals, in the region of relatively low temperatures ($T \leq T_M$), impurity conductivity dominates. Moreover, at T=77 K, depending on the composition, all impurity levels are either completely (at $x<0.50$) or partially (at $x \geq 0.50$). Therefore, in the region $T<T_M$, the Hall coefficient (and, accordingly, the concentration of free charge carriers) either does not depend on temperature or decreases slightly (the concentration of free charge carriers increases) with increasing T. The barely noticeable increase in R_H with increasing T in the region of relatively low temperatures found in some samples can be explained by the compensation of the crystal being studied [37]. In this case, like what was proposed in [38], it can be assumed that with increasing sample temperature, free charge carriers are recaptured by compensating levels through thermal pumping through the corresponding zones. At the same time, like what was proposed in [19], in some samples in the region of relatively low temperatures, the change in the value of R_H (and, accordingly, the concentration of free charge carriers) can be explained by the partial spatial inhomogeneity of the sample under study.

The weak temperature dependence of the specific dark electrical conductivity observed in the region of relatively low temperatures (where the value of R_H does not depend on T) can be explained by the temperature dependence of the mobility of free charge carriers. It should be noted that this dependence $\mu_H(T)$ occurs both because of carrier scattering on various point defects and lattice vibrations [31], and because of a decrease in the influence of drift barriers for current [39] created due to the presence of random macroscopic defects on the process of charge carrier transport.

It should be noted that the main signs of the manifestation of one or another mechanism of change in the mobility of free charge carriers is the specific course of its temperature dependence. In the case of scattering of free charge carriers on various point defects and lattice vibrations, the dependence of their mobility on temperature obeys power laws (the only exception is the case when scattering on polar optical phonons dominates) [31], and in the case of a change in the influence of drift barriers for current, the temperature dependence of the mobility of charge carriers should have an activation character [39].

A comparative analysis of the curves of the $\sigma_{D0}(T)$, $R_H(T)$, $\mu_H(T)$ dependencies allows us to say that the decrease in the σ_{D0} value with increasing T, detected in n-$Cd_xHg_{1-x}Te$ samples with $0.30 \leq x < 0.40$ in the low temperature region, is associated with the scattering of free charge carriers on acoustic vibrations of the lattice. As for the growth of σ_{D0} with increasing temperature in samples with $x \geq 0.40$ in the region $T \leq 120$ K, it is apparently due to the dominance of the scattering of free charge carriers on impurity ions [31].

In the region of relatively high temperatures (at $T > T_M$), intrinsic conductivity dominates. With increasing temperature, both the concentration of free charge carriers (correspondingly, the value of R_H decreases) and the electrical conductivity (σ_{D0}) increase sharply (exponentially). In this temperature range, the rate of temperature dependence of n_0 on temperature significantly exceeds the rate of temperature dependence of μ_H. Therefore, the $\mu_H(T)$ dependence does not appear on the curves of σ_{D0} versus T.

The negative value of R_H in the studied n-$Cd_xHg_{1-x}Te$ crystals at all the temperatures considered indicates that in these samples, under the conditions of the experimental studies, the value of σ_{D0} is always determined by electrons (the main charge carriers).

The observed behavior of the μ_H temperature dependence curves indicates that in both n- and p-type $Cd_xHg_{1-x}Te$ crystals, at higher temperatures, the dominant mechanism for free charge carrier scattering is scattered by acoustic lattice vibrations. Depending on the value of x (the Cd content in the solution), the dominance of this mechanism decreases at the lower limit of the temperature range, and in some cases even reaches 77 K.

4. Conclusion

In the temperature range $T \leq 120$, a decrease in σ_{D0} with increasing T in n-$Cd_xHg_{1-x}Te$ crystals with $0.30 \leq x < 0.40$ is associated with the scattering of free charge carriers on acoustic vibrations of the lattice, and an increase in σ_{D0} with increasing temperature in samples with $x \geq 0.40$ is due to the dominance of scattering of free charge carriers on impurity ions; At relatively high temperatures ($T > T_M$), intrinsic conductivity dominates in n-$Cd_xHg_{1-x}Te$ crystals, and the rate of temperature dependence of n_0 significantly exceeds that of μ_H. Therefore, the $\mu_H(T)$ dependence does not manifest itself in the curves of σ_{D0} versus T. In n-$Cd_xHg_{1-x}Te$ crystals, at all the temperatures and conditions of the experimental studies considered, the value of σ_{D0} is determined by the majority charge carriers. In both n- and p-type $Cd_xHg_{1-x}Te$ crystals, at higher temperatures, the dominant scattering mechanism for free charge carriers is scattered by acoustic lattice vibrations. Depending on the value of x (the Cd content in the solution), the dominance of this mechanism decreases at the lower limit of the temperature range, and in some cases even reaches 77 K. In the region of relatively low temperatures (where the value of R_H does not depend on T), the weak dependence of σ_{D0} on T is caused only by the dependence of $\mu_H(T)$, which occurs both as a result of the scattering of carriers on various point defects and lattice vibrations, and as a result of the reduction in the influence of drift barriers for current created due to the presence of random macroscopic defects on the process of charge carrier transport.

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