Vol. 88 (1995) *ACTA PHYSICA POLONICA A* No. 4

Proceedings of the XXIV International School of Semiconducting Compounds, Jaszowiec 1995

MAGNETIC SUSCEPTIBILITY OF HgTe⟨Mn,Fe,Cr⟩[§]

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The results of the investigations of magnetic susceptibility (χ) of HgTe⟨Mn, Fe, Cr⟩ with $N_{3d} < 10^{21}$ cm^{-3} in temperature range of 80–290 K and for magnetic fields of 0.4–9 kOe are presented. It was shown that $\chi_{Mn}(T)$ and $\chi_{Fe}(T)$ in HgTe⟨Mn, Fe⟩ are described by Curie law and for $N_{3d} > 10^{21}$ cm^{-3} — by Curie–Weiss law with negative value of θ_p characterizing the antiferromagnetic interaction between magnetic ions. Thermal treatment of HgTe⟨Fe⟩ samples in Hg vapour at $T = 500$ K in contrast to HgTe⟨Mn⟩ leads to the redistribution of magnetic component only in these samples. A special behaviour of $\chi(T)$ in HgTe⟨Cr⟩ samples was revealed which is different from $\chi(T)$ in HgTe⟨Mn, Fe⟩.

PACS numbers: 75.20.Hr

Study of properties of crystals with $3d$-, $4f$-elements impurities is of great interest from the point of view of obtaining of new material concerning the group of the so-called semimagnetic semiconductors as well as it allows to determine the impurity charge state, to follow the rebuilding of electronic spectrum and magnetic states beginning from the "uninteracted" localized magnetic centres and completing with strong magnetic interaction which leads to appearance of magneto-ordered regions in crystal. Paramagnetic ion state is mostly determined by crystal matrix symmetry where it is placed and by the degree of filling of d-shells.

HgTe crystals doped with Mn, Fe, Cr were obtained by joint melting of high-clean components with following monocrystallization of ingots by Bridgman method. General concentration of doping impurity (Mn, Fe, Cr) was in limits of 10^{18}–10^{21} cm^{-3} and for Mn and Fe it was determined by means of isotopic analysis with an error of $< 20\%$. Concentration of Cr was evaluated from the results of $\chi(T)$ data near 290 K assuming that $\mu_{ef}(Cr^{2+}) = 4.9\mu_B$ [1]. Metallographic analysis on the part of samples with $N_{3d} < 10^{20}$ cm^{-3} after growing did not reveal accumulation or picking out of the second phase. The estimation of charge carriers concentration and of its temperature dependence was carried out from the results of galvanomagnetic studies by compensation method on the samples of $8 \times 1.5 \times 1$ mm^3 of which were further used for magnetic measurements. Magnetic

[§]The research described in this publication was supported by the International Soros Science Education Program of International Renaissance Foundation grant ISSEP SPU042012.

susceptibility research was fulfilled by Faraday method using electronic balance EM-1-3M in the temperature interval of 80–290 K and magnetic fields of < 9 kOe.

Analysis of results was made assuming that direct measured value of χ is the sum of magnetic contributions of lattice (χ_G), of charge carriers (χ_L) and magnetic impurity (χ_d), that is

$$\chi = \chi_G + \chi_L + \chi_d. \tag{1}$$

Quantity of χ_d for each sample was determined as difference $\chi - (\chi_G + \chi_L)$ and at the same time for sum of $\chi_G + \chi_L$ the value of magnetic susceptibility of "pure" HgTe sample with the same charge carriers concentration as for doped crystals was used. Defects magnetic susceptibility in HgTe can be neglected [2].

Electrophysical properties investigations results in $A^{II}B^{VI}$ doped with transition metals of iron group show that impurity atoms in $A^{II}B^{VI}$ crystal lattice are placed in sites of metal sublattice, and for tellurides they are mostly electroneutral [3]. In this case every atom of magnetic impurity must give two electrons for the chemical bounding formation and thus they will be in the charge states of Mn^{2+}, Fe^{2+}, Cr^{2+}.

Experimental results of $\chi(T)$ for HgTe⟨Mn⟩ are described by Curie law ($N_{Mn} < 10^{19}$ cm^{-3}) and by Curie–Weiss law ($N_{Mn} > 10^{19}$ cm^{-3}) and agree with another authors' results (see review papers [4, 5]). Annealing of HgTe⟨Mn⟩ samples in Hg vapours at 500 K leads to the charge carriers concentration change (as in HgTe) but there was no change in the $\chi_{Mn}(T)$ behaviour. There were not observed magneto-field dependences of $\chi(H)$ in HgTe⟨Mn⟩ samples before and after annealing as well.

The temperature dependence of magnetic susceptibility of HgTe⟨Fe⟩ is presented in Fig. 1. When Fe content grows and temperature decreases sample para-

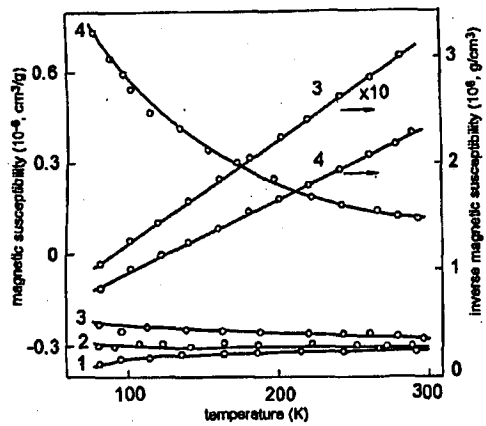

Fig. 1. Temperature dependence of magnetic susceptibility of χ and χ_{Fe}^{-1} of HgTe⟨Fe⟩ samples with different Fe concentration, N, cm^{-3}: 1 — 0; 2 — 3.1×10^{18}; 3 — 1.8×10^{19}; 4 — 2.6×10^{20}.

magnetism increases and in 80–290 K interval it is described by Curie–Weiss law with negative characterizing temperature.

Free Fe^{2+} ion in $A^{II}B^{VI}$ has $3d^6$ electronic configuration. Term of ^5D corresponds to the basic state of this configuration which is splitted by tetrahedral intercrystallic field into doublet ^5D and orbit triplet ^5T [6, 7]. Spin–orbit interaction splits ^5T term into a row of terms in such a way that the basic state for Fe^{2+} is nonmagnetic A^1 singlet. For these ions Van-Vleck paramagnetism is characteristic independent from the temperature. Experimentally it is exhibited in the independence of $\chi(T)$, partially, as noted in [8] in $Hg_{1-x}Fe_xTe$ ($x = 0.015$) in 4–90 K range. When temperature increases there is an essential contribution into magnetic susceptibility from excited states which determines its temperature dependence. Estimated effective ion magnetic moment of Fe in HgTe from temperature dependence equals 4.3–4.7μ_B and weakly differs from 4.9μ_B which Fe^{2+} ion has when orbit magnetic moment is suppressed ($L = 0$).

From received magneto-field dependences of $\chi(H)$ it arises that HgTe⟨Fe⟩ samples before thermotreatment in Hg vapours have no dependences $\chi(H)$, e.g. magneto-ordered states are absent. Annealing of samples leads to the change of the value as well as $\chi(H)$ dependences. It is obvious that during the annealing in HgTe⟨Fe⟩ the redistribution of magnetic ions occurs (clusterization) which causes the appearance of magnetic alignment in separate crystal parts. We will inform about the nature of such alignment and its dependence on Fe content and annealing temperature in next paper.

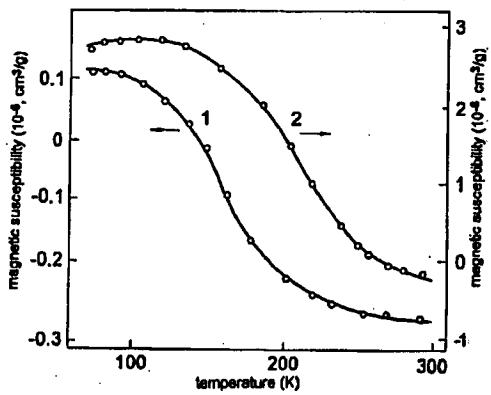

Fig. 2. Temperature dependence of magnetic susceptibility of HgTe⟨Cr⟩, N_{Cr}, cm^{-3}: 1 — 3×10^{18}; 2 — 4×10^{19}.

In Fig. 2 the results of χ measurements via temperature for HgTe⟨Cr⟩ samples are presented. Even at small chromium concentration ($\approx 2 \times 10^{18}$ cm^{-3}) $\chi(T)$ can be described by the Curie–Weiss law only in the high-temperature region (180–290 K) but with positive temperature of θ_p which indicates on the ferromagnetic interaction behaviour between magnetic ions. When temperature lowers one can observe a sharp increase in paramagnetic component of magnetic susceptibility with gradual decrease in paramagnetism growth in 80–120 K interval, and for some

samples its decrease (Fig. 2). Such a behaviour of $\chi(T)$ for HgTe⟨Cr⟩ indicates the complicated character of exchange interactions between the magnetic ions.

As to [9] the similar dependence of magnetic susceptibility versus temperature which is observed in HgTe⟨Cr⟩ occurs in magnetodiluted systems with the so-called competing ferromagnetic and antiferromagnetic interactions. Antiferromagnetic exchange is revealed to be effective when there are long distances between magnetic ions and ferromagnetic — when the distances are short. But the direct exchange can essentially influence the magnetization also at small content of magnetic component when in crystal lattice nonstatistical distribution is observed. It can be assumed that the same situation is observed in HgTe⟨Cr⟩ crystals likewise.

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