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# TRANSPORT AND MAGNETIC PROPERTIES OF $\mathrm{Pb}_{1-x-y}\mathrm{Sn}_y\mathrm{Mn}_x\mathrm{Te}$ $(x \leq 0.16)$*

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Hall constant, conductivity and magnetic susceptibility of $\mathrm{Pb}_{1-x-y}\mathrm{Sn}_y\mathrm{Mn}_x\mathrm{Te}$ semimagnetic semiconductor were investigated as a function of Mn content ($x = 0.04$, 0.09, 0.16, $y = (0.7$–$0.8)$) in the temperature range $T = (4 - 300)$ K. A ferromagnetic phase transition takes place at $T = 5$ K for samples with $x = 0.04$, at $T = 10$ K for $x = 0.09$ and at $T = 20$ K for $x = 0.16$. For crystals with $x \geq 0.09$ the strong temperature dependence of the Hall constant is observed for temperatures below 40 K. Magnetic field characteristics of the Hall effect is strongly non-linear at $T = 4.2$ K. No significant temperature or magnetic field dependence of conductivity is observed in the whole temperature range studied. The observed transport anomalies are due to the anomalous Hall effect.

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The experimental investigations of magnetic and transport properties of $\mathrm{Pb}_{1-x-y}\mathrm{Sn}_y\mathrm{Mn}_x\mathrm{Te}$ semimagnetic semiconductor were performed mostly on crystals with relatively low manganese content ($x \leq 0.04$) [1, 2]. With an increasing Mn concentration one expects a modification of magnetic properties (a relative increase in the role of short range antiferromagnetic interactions) as well as electronic properties (e.g. a change of the band gap from a direct to indirect one is expected for $x > 0.1$ [3]).

The purpose of this work is to monitor systematically the evolution of magnetic and electronic properties in the Mn concentration range extended towards the percolation threshold for fcc magnetic sublattice, i.e. to about 20 at% of Mn.

Our crystals were grown by the Bridgman method. Chemical composition, homogeneity and crystal structure were determined by electron microprobe measurements and by X-ray Debye analysis. The PbSnMnTe crystals with the Mn content up to 16 at.% were found to be homogeneous and second phase inclusions free. For samples with $x = 0.21$ second phase inclusions were found. These crystals were not examined further.

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We studied Hall constant, conductivity and magnetic susceptibility of $Pb_{1-x-y}Sn_yMn_xTe$ semimagnetic semiconductor as a function of crystal composition ($x = 0.04$, 0.09, 0.16, $y = (0.7\text{–}0.8)$) over the temperature range $T = (4\text{–}300)$ K.

At high temperatures magnetic susceptibility of all the samples studied follows the Curie–Weiss law with the positive (ferromagnetic) Curie–Weiss temperature $\theta$ being proportional to the Mn concentration. Low temperature measurements of magnetic susceptibility (presented in Fig. 1) provide a clear evidence

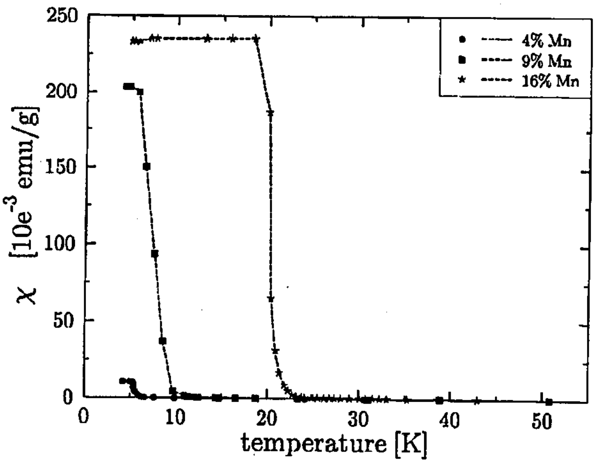

Fig. 1. Temperature dependence of the magnetic susceptibility of PbSnMnTe crystals with different Mn concentration.

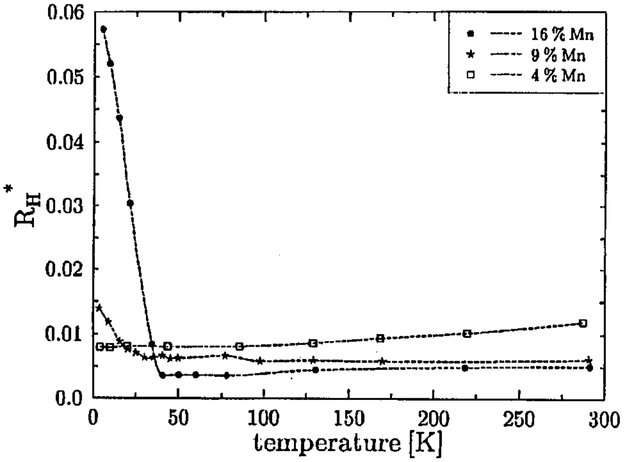

Fig. 2. Temperature dependence of (effective) Hall constant of PbSnMnTe crystals with different Mn content.

for ferromagnetic phase transition at $T_C = 20$ K for samples with $x = 0.16$, at $T_C = 10$ K for $x = 0.09$ and at $T_C = 5$ K for $x = 0.04$.

The dependence of the Hall constant on temperature is presented in Fig. 2. In agreement with previous studies [1], a typical metallic character of transport properties is observed for PbSnMnTe samples with $x = 0.04$. The concentration of carriers (holes) is of the order of $10^{21}$ $\text{cm}^{-3}$, being temperature independent for $T \leq 77$ K. For samples with higher Mn concentration the strong temperature dependence of the Hall constant is observed below $T = 40$ K for $x = 0.16$ and below $T = 25$ K for $x = 0.09$. In these crystals, at low temperatures, we have also observed the strongly nonlinear magnetic field dependence of the Hall voltage (Fig. 3). No significant temperature or magnetic field dependence of conductivity is observed in the whole temperature range studied.

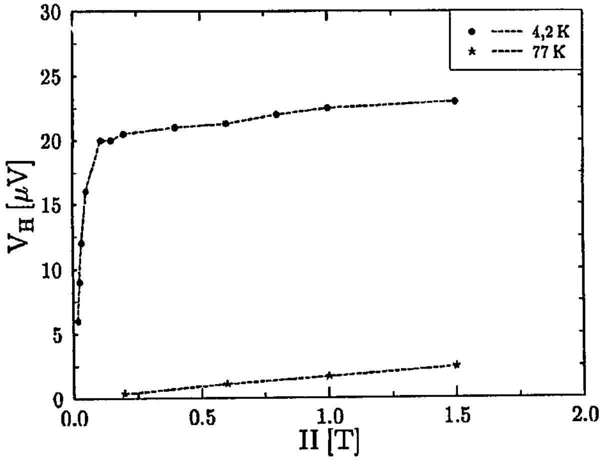

Fig. 3. Magnetic field dependence of the Hall voltage in the sample of PbSnMnTe with $x = 0.16$ at $T = 4.2$ K $< T_C = 20$ K (dots) and at $T = 77$ K $> T_C$ (stars).

The experimentally observed temperature and magnetic field dependence of the Hall effect are, in our opinion, due to the anomalous Hall effect, characteristic of ferromagnetic materials. Surprisingly, the effect is very strong and is observed already at $T \leq 2T_C$, i.e. well above the actual ferromagnetic phase transition. The magnitude of this effect increases with the increasing Mn concentration. For all three samples $T_C(x) > 4.2$ K but in the sample with $x = 0.04$ the ordinary Hall effect dominates whereas the situation is completely reverse for the samples with $x = 0.16$.

In conclusion, we found that the ferromagnetic phase transition takes place in PbSnMnTe crystals with the Mn content up to $x = 0.16$. The strong temperature and magnetic field dependencies of the Hall effect are caused by the anomalous Hall effect.

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